Earth WIMP searches with IceCube

THE ICECUBE COLLABORATION[1]

[1] *See special section in these proceedings*

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Abstract: Many particle physics models predict massive and stable new particles that can solve the dark matter problem. If these particles are Weakly Interacting Massive Particles (WIMPs), they can be trapped in massive celestial bodies such as the Earth, where they may self-annihilate. The annihilation of these WIMPs into standard model particles can create neutrinos. To search for such neutrino fluxes, large scale neutrino telescopes, such as the cubic kilometre IceCube Neutrino Observatory located at the South Pole, can be used. Recent calculations indicate that the dark matter annihilation rate in the centre of the Earth, and thus the resulting neutrino flux could be within reach of a large neutrino detector. We will present the current status of the first search for neutrinos from WIMP annihilations in the centre of the Earth with the IceCube neutrino detector.

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1 Introduction

Some of the most promising dark matter candidates are Weakly Interacting Massive Particles (WIMPs). In the Minimally Supersymmetric Standard Model (MSSM), the WIMP can take the form of the lightest neutralino. Dark matter particles from the galactic halo become bound in the gravitational potential of the solar system as it passes through the galaxy. These particles may then scatter weakly on nuclei in the Earth and lose energy, becoming trapped by the Earth. Over time, this leads to an accumulation of dark matter in the centre of the Earth. If the accumulated dark matter density reaches a high enough value, it may then self annihilate, generating a flux of neutrinos which is spectrally dependent on the annihilation channel and neutralino mass.

Expected neutrino event rates and energies depend on the specific model and distribution of dark matter under consideration and the chemical composition of the Earth. Taking these variables into consideration leads to a neutrino-induced muon flux from the centre of the Earth varying between $10^{-8} - 10^{5}$ per km^2 per year for WIMPs with masses in the GeV$-$TeV range [1] (Fig. 2), as will be discussed in Section 3. AMANDA [2] and Super-K [3] already ruled out muon fluxes above $\sim 10^3$ per km^2 per year. Still, the possibility of setting even more restrictive limits due to the increased size of the IceCube neutrino observatory (described in Section 2) with respect to previous detectors, motivates the continuation of searches for neutrinos coming from WIMP annihilations in the centre of the Earth. The analysis method is presented in Section 4.

2 The IceCube Neutrino Telescope

IceCube is located in the glacial ice at the geographic South Pole. It consists of an array of digital optical modules (DOMs), designed to collect the Cherenkov radiation produced by high energy, neutrino-induced charged leptons traveling through the detector volume. By recording the number of Cherenkov photons and their arrival times, the direction and energy of the charged lepton, and consequently that of the parent neutrino, may be reconstructed.

IceCube consists of 86 strings, each containing 60 DOMs, deployed between 1450 m and 2450 m in the ice [4]. Of these 86, 8 strings at the centre of IceCube comprise the DeepCore subarray, consisting of more densely instrumented strings and DOMs with higher light collection efficiency. This configuration lowers the energy threshold of IceCube from 100 GeV to 10 GeV. In total, approximately 1 km^3 is instrumented.

While the large ice overburden provides a shield against downward going, cosmic ray induced muons with energies $\lesssim 500$ GeV at the surface, most analyses also use the Earth as a filter and focus on upward going neutrinos. Additionally, low energy analyses mainly focus on DeepCore as a fiducial volume and use the surrounding IceCube strings as an active veto to reduce penetrating muon backgrounds. Further background reduction is achieved by cuts based on topological signatures that differentiate well-reconstructed upgoing neutrino-induced muons from misreconstructed downgoing background muons.

3 Dark Matter from the centre of the Earth

WIMPs accumulated in the centre of the Earth will produce a unique signature in IceCube as vertically upgoing muons. The number of detected neutrino-induced muons depends on the neutralino annihilation rate Γ_A. If the capture rate C is constant in time t, Γ_A is given by [1]

$$\Gamma_A = \frac{C}{2}\tanh^2\left(\frac{t}{\tau}\right),\ \tau = (CC_A)^{-1/2}. \qquad (1)$$

So the equilibrium time τ is defined by the time it takes for the annihilation rate and the capture rate to be in equilibrium, where C_A is a constant depending on the WIMP number density. For the Earth, this equilibrium time is of the order of 10^{11} years if the spin-independent WIMP-proton cross section is $\sigma_p^{SI} \sim 10^{-43}$ cm^2 [5]. Since the age of the solar system is $t_\circ \approx 4.5$ Gyr, $t_\circ/\tau \ll 1$, such that $\Gamma \propto C^2$, i.e. the higher the capture rate, the higher the annihilation rate and thus the muon flux.

The rate at which WIMPs are captured in the Earth depends on the mass and the velocity of the WIMPs. If the WIMP mass is nearly identical to that of one of the nuclear species in the Earth, the capture rate will increase considerably, as is shown in Fig. 1. It should be noted that recent direct detection limits [7] exclude cross sections smaller than $\sigma_p^{SI} = 10^{-43}$ cm^2 over a wide range of WIMP masses. This implies that the normalization in Fig. 1 will be about an order of magnitude lower, as the cross section that is assumed in the calculation for the capture rate is $\sigma = 10^{-42}$ cm^2 [6].

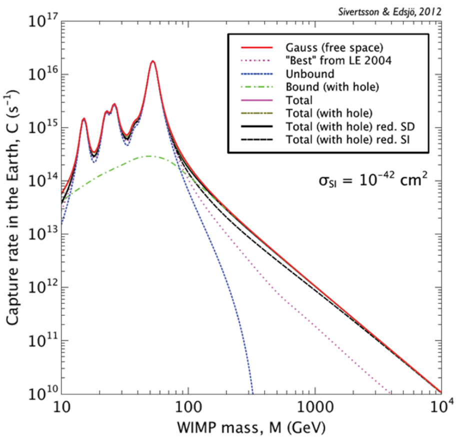

Figure 1: This figure shows the rate at which dark matter particles are captured to the interior of the Earth, for a scattering cross section of $\sigma = 10^{-42}$ cm^2. The peaks correspond to resonant capture on the most abundant elements considered in the Earth model, ^{16}O, ^{24}Mg, ^{28}Si and ^{56}Fe. A dark matter halo density of $\rho_\chi = 0.3$ GeV cm^{-3} is assumed [6].

The capture rate could be higher if the WIMPs have a low velocity with respect to the Earth. This is because the escape velocity v_{esc} of WIMPs inside the Earth is low. It varies from $v_{esc} \sim 11$ km/s at the mantle to $v_{esc} \sim 15$ km/s at the centre. Thus, the higher speed WIMPs will only be captured at the centre where the escape velocity is the highest, whereas the lowest speed WIMPs may be captured anywhere in the Earth.

The WIMP speed distribution is very sensitive to theoretical assumptions, as different models for the halo lead to different WIMP speed distributions. The most popular halo model is the Standard Halo Model (SHM), which is modelled as a smooth, spherically symmetric density component with a non-rotating Gaussian velocity distribution. Galaxy formation simulations including baryons indicate that there is at least one local macrostructural component beyond the SHM. These simulations show that a thick disc of dark matter, with the kinematics similar to the thick disc of stars and a mid-plane density of $0.25-1.5$ times the local dark halo density [8, 9], is formed as the baryonic disc of the Milky Way draws satellites closer to the disc plane by dynamical friction, where they are disrupted by tides [10]. The particles in this dark disc have a lower relative velocity to the Earth compared to the SHM. Therefore, less scattering is needed for the particles in the dark disc to become gravitationally captured. So the dark disk leads to a higher capture rate and thus a higher neutrino-induced muon flux at detectors such as the IceCube neutrino telescope.

Fig. 2 shows the expected [1] muon flux (Φ_μ) for $E_\mu >$ 1 GeV at the Earth's surface as a function of the WIMP mass (M_χ) from neutrinos originating in the Earth. Compared to the flux from the SHM given in the left panel, the flux from the dark disc (right panel) is boosted by two to three orders of magnitude, depending on the specific model.

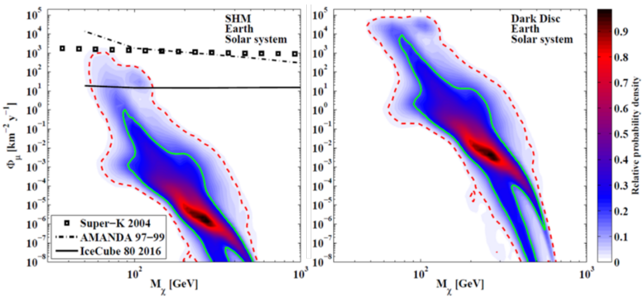

Figure 2: Expected muon flux at the surface of the Earth as a function of the WIMP mass for the SHM (left) and a dark disc model (right) [1].

4 Analysis

The last published Earth WIMP search was performed with the neutrino data recorded by the AMANDA detector over the three year period $1997-99$ [2]. No excess above the expected atmospheric neutrino background was found in this search, so an upper limit could be set on the muon flux (dashed-dotted line in Fig. 2).

A preliminary estimation of the sensitivity of the full IceCube detector was presented in [11] and is shown in Fig. 2 as the solid line. However, this estimation was performed before the construction of IceCube was started. It does not include the DeepCore array and, lacking a precise simulation of the hardware, is based on a simplified simulation of the detector response. The analysis outlined in this paper corrects all these shortcomings by using data taken with the full detector and the current state of the art IceCube simulation and data analysis techniques.

As model predictions for WIMP capture in the Earth favour low masses, the analysis will be optimised for low mass WIMPs ($m_\chi = 50$ GeV, see Fig. 1) that annihilate into $\tau^+\tau^-$. In this annihilation channel, a hard neutrino energy spectrum is produced. The expected neutrino spectrum (solid line) and the neutrino-induced muon spectrum (dashed line) for 50 GeV WIMPs annihilating into $\tau^+\tau^-$ are shown in Fig. 3. As the expected muon energy for this channel is lower than 50 GeV, the DeepCore detector will be crucial in a search for such a signal.

The signal simulations that are used in the analysis are performed using WimpSim [12]. WimpSim is a code that calculates the annihilation of WIMPs inside the Sun or the Earth, collects all the neutrinos that emerge and let these propagate out of the Sun/Earth to the detector. The code includes neutrino interactions and neutrino oscillations in a fully consistent three-flavour treatment.

The neutrino-induced muon flux in IceCube, coming from WIMPs in the centre of the Earth can not be higher than $\sim 10^3$ muons per year. This is a very low rate, compared

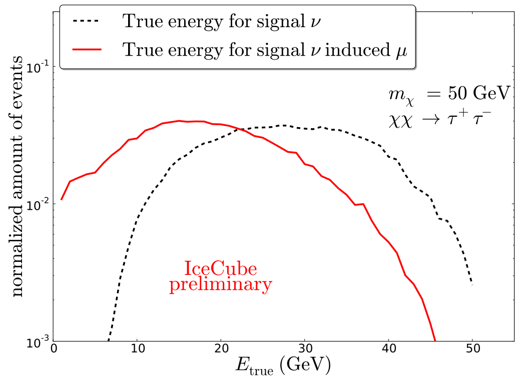

Figure 3: The normalized energy distributions for signal neutrinos and signal neutrino-induced muons, for a WIMP mass of 50 GeV.

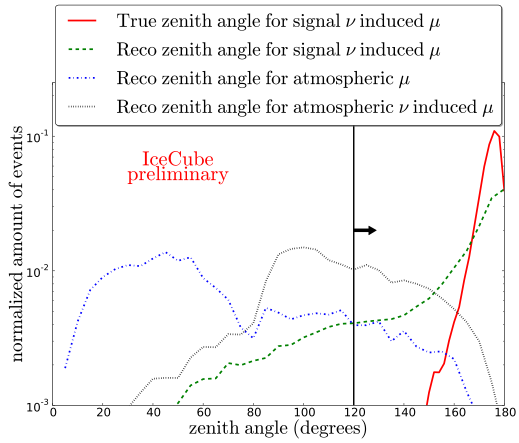

Figure 4: The normalized zenith angle distributions for signal (calculated with WimpSim for a 50 GeV Earth WIMP), background muons (simulated with CORSIKA) and neutrinos (simulated with NuGeN). The vertical line shows the cut value used in this analysis and the arrow indicates the parameter region that is retained.

to the 2.5 kHz rate at which IceCube is taking data. The data is dominated by atmospheric muons, which are background events, so selection cuts have to be developed to remove these events. To get to neutrino level (mHz rate), the data rate has to be lowered by $\sim$6 orders of magnitude.

IceCube has several online filters, that are used to *tag* different types of events. In a first step, we only select events that are tagged by online filters that look for upgoing tracks (one of the online filters that is running mainly for this analysis, optimised to tag low energy, upgoing events). After this online filter selection, the event rate is reduced to 100 Hz, while almost 100% of the signal events that triggered the detector are kept.

In a next step, linear cuts are placed to reduce the content of atmospheric muon events to $\sim$1 Hz. These cuts are based on distributions of event multiplicities and observables from signal and background simulations.

One very straightforward selection to make is a cut on the reconstructed zenith angle. Fig. 4 shows the simulated reconstructed zenith angle distributions for signal (dashed line), atmospheric muons (dashed-dotted line) and atmospheric neutrino-induced muons (dotted line). The solid line shows the true zenith angle distribution for the signal. As the detector acceptance is zenith dependent it is not possible to define an off-source region in this analysis. We thus need to rely on simulations to understand the background, requiring a detailed understanding of systematic uncertainties. A *control region* has to be defined in which we can compare the background simulation with the data. Therefore the zenith angle cut can not be too strict, as we aim to retain a signal free control region. Based on these considerations, the zenith angle cut is chosen such that all events with a reconstructed zenith angle $< 120°$ are removed.

Signal neutrino-induced muons and atmospheric muons do not only differ in direction, but also the visible starting point of the muon tracks are expected to be different. The atmospheric muons always start outside the detector (in the atmosphere) whereas muons from neutrinos can start in the detector. The positions of the starting point of the muon tracks may thus be used as a cut variable. The starting points are reconstructed using an algorithm that tries to find the range of the muon assuming no secondary processes along its path such that we only consider Cherenkov light emitted by the muon. The first step of the algorithm is to look for start and stop points by projecting all the hits (after suspected noise hits have been removed) in the event onto a given seed track. Then it calculates the probability that a DOM in the direction of this seed track is not hit by taking all non-hit DOMs within a certain radius and calculating the probability of having such an amount of non-hit DOMs in the assumption of an infinite track. The next step is to recalculate this probability, but this time with the assumption that the track has a start and/or stop point within the detector volume. The starting point of the muon is then calculated by minimizing the likelihood ratio of the two calculated probabilities.

From Fig. 5, it is clear that this reconstructed starting point is mainly concentrated in the lower central part (DeepCore) for signal events (left panel), while atmospheric muons (right panel) mainly have a reconstructed starting point at the top and side of the detector. This is because the signal is low energetic (see Fig. 3) and will thus mainly be detected by the DeepCore detector. Events with a track that has a reconstructed starting point inside the IceCube volume but well outside the DeepCore volume, either to the side ($r_{\rm vertex} > 490$ m) or above ($z_{\rm vertex} > 180$ m), are removed.

Another variable that is used for cutting is the number of direct hits in the event divided by the direct length ($N_{\rm Dir}/L_{\rm Dir}$, see Fig. 6). Direct hits are hits that are within a time residual t_{res} of (-15,+25) ns according to the reconstructed track. t_{res} is defined by the difference between the measured time and the expected time of the hit, where the expected time of the hit is the time it takes for a Cherenkov photon to travel the same distance without being scattered. So photons with a small t_{res} have not scattered much.

Since the signal consists of vertical tracks parallel to the strings, these events should have more direct hits $N_{\rm Dir}$ than background events traversing the detector in any other direction. Also, the direct length $L_{\rm Dir}$, i.e. the distance between the first and the last direct hit, of a signal event should be small, as the signal muons have a low energy. For atmospheric muons, $N_{\rm Dir}$ and $L_{\rm Dir}$ have a broad distribution, depending on the energy and the direction of the incoming muon. Only events with 0.03 $\rm m^{-1} < N_{Dir}/L_{Dir} < 0.09\ m^{-1}$ are kept.

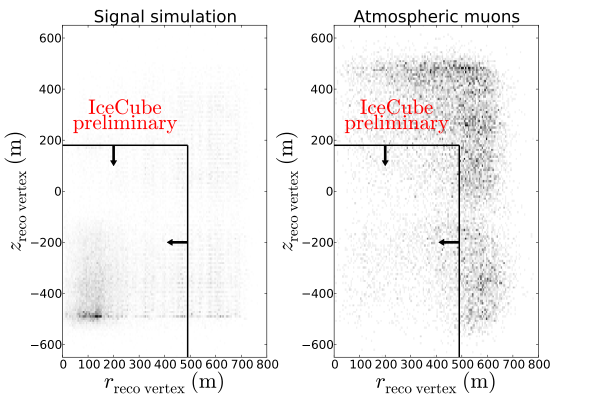

Figure 5: The reconstructed starting point projected in the $r-z$ plane of the detector, with $r=\sqrt{x^2+y^2}$, i.e. the distance to the central axis of the detector in the $x-y$ plane. The point density indicates the event rate. The vertical and horizontal lines show the cut values used in this analysis and the arrows indicate the parameter regions that are retained.

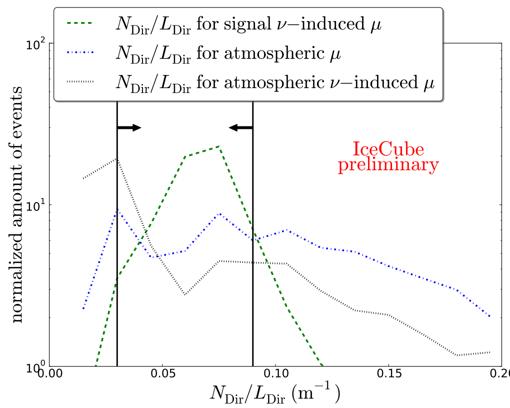

Figure 6: The normalized distributions for $N_{\text{Dir}}/L_{\text{Dir}}$. The vertical lines show the cut values used in this analysis and the arrows indicate the parameter region that is retained.

The last variable that is used at this level is z_{travel}. This is the average drift of hits in the vertical (z) direction

$$z_{\text{travel}} = \sum_{i=1}^{n} \frac{z_i - \langle z_{\text{quartile},1} \rangle}{n}, \tag{2}$$

where n is the number of fired DOMs, z_i is the z position of the i^{th} DOM and $\langle z_{\text{quartile},1} \rangle$ is the mean z position of the first quartile of hits in time. This should be negative for downgoing tracks, i.e. background, and positive for upgoing tracks, i.e. signal (see Fig. 7). Events with $z_{\text{travel}} < 10$ m are removed.

The cut values (except the cut on the zenith angle) are chosen by looping over all possible combinations of cut values and checking which combination brings down the background rate below 1 Hz, while removing as little signal as possible. After this first cut level, the data rate goes down to ~0.8 Hz, while 20-40% of the signal (depending on WIMP mass and channel) is kept. The data is still dominated by atmospheric muons at this level.

Now that the data rate is below 1 Hz, we can reprocess the data using more precise (and more time-consuming)

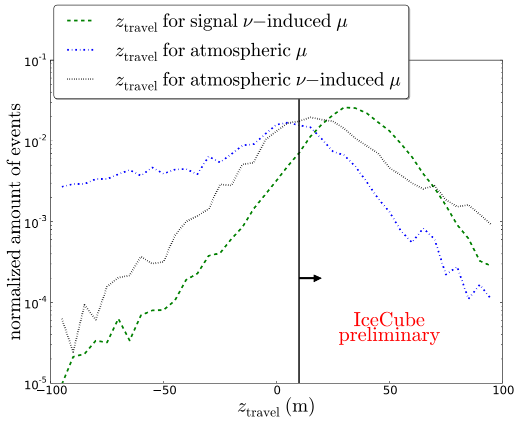

Figure 7: The normalized distributions for z_{travel}. The vertical line shows the cut value used in this analysis and the arrow indicates the parameter region that is retained.

reconstructions. This is important as a good angular resolution is needed to identify tracks that come from the centre of the Earth. These reconstructions will be used to classify events as signal or background like with a boosted decision tree (BDT) from the TMVA software package [13]. We expect to reach the neutrino level (~mHz) after this BDT cut.

Once the atmospheric muon background has been removed, we will search for signal events in the final data set which is dominated by atmospheric neutrinos. These neutrinos come from all over the sky, while the expected signal neutrinos come from the direction of the centre of the Earth. We will use the space angle ψ between the source direction (i.e. the centre of the Earth) and that of the reconstructed track to evaluate the number of signal events μ_s (similar to the method used in the search for dark matter annihilations in the Sun with the 79-string IceCube detector [14]). For signal, this space angle is expected to be close to zero, while for background, this space angle will be evenly distributed over the sky. By doing a statistical analysis on the space angle distribution, one can either detect the presence of signal neutrinos (a peak from the centre of the Earth), or set an upper limit on the dark matter induced neutrino flux.

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