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Searches for Dark Matter in the center of the Earth with the IceCube detector

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Several models predict that dark matter is constituted of Weakly Interacting Massive Particles (WIMPs). Such particles would be attracted by the gravity of massive astronomical objects such as black holes, stars, and the Earth. WIMPs can lose energy through scattering with matter and become trapped in the gravitational field of these objects. They can then annihilate or decay resulting in production of Standard Model particles. The neutrinos thus created will escape, as they pass through ordinary matter almost unaffected. This contribution describes the search for WIMPs accumulated in the center of the Earth using the IceCube neutrino observatory located at the geographic South Pole. Results from the analysis with one year of IceCube data from 2011 will be presented along with the sensitivity for several additional years of data.

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1. Introduction

In 1933, Fritz Zwicky obtained evidence of unseen mass that he called *dunkle Materie*, 'Dark Matter' [2], in the Coma cluster of galaxies. More than 80 years after the discovery of missing mass, the physical origin of dark matter is still unclear. Several candidates have been proposed[3], the most discussed of which is the weakly interacting massive particle (WIMP). Heavy celestial bodies, such as the Earth, can potentially capture WIMPs. The accumulated WIMPs can then self-annihilate at a rate proportional to their number density in the Earth, thus generating neutrinos with a spectrum that depends on the WIMP mass and annihilation channel.

2. The IceCube Neutrino telescope

IceCube is a cubic-kilometer neutrino detector installed in the ice at the geographic South Pole [4] between depths of 1450 m and 2450 m, completed in 2010. Reconstruction of the direction, energy, and flavor of the neutrinos relies on the optical detection of Cherenkov radiation emitted by charged particles produced in the interactions of neutrinos in the surrounding ice or the nearby bedrock. The DeepCore subarray as defined in this analysis includes 8 densely instrumented strings optimized for low energies plus 12 adjacent standard strings.

While the large ice overburden above the detector provides a shield against downward going, cosmic ray induced muons with energies $\lesssim$ 500 GeV at the surface, most analyses focus on up-ward going neutrinos employing the entire Earth as a filter. Additionally, low energy analyses use DeepCore as the fiducial volume and the surrounding IceCube strings as an active veto to reduce penetrating muon backgrounds. The search for WIMP annihilation signatures at the center of the Earth takes advantage of these two background rejection techniques as the expected signal will be vertically up-going and of low energy.

3. Earth Dark Matter searches with IceCube

To estimate a flux of neutrino coming from the annihilation of WIMPs in the center of the Earth, we have to know the cross section for scattering by nuclei in the Earth, the capture rate C , the annihilation rate Γ_a and the probability to have a production of a neutrino through the decay of their annihilation products. The theoretical framework used to calculate the first two can be found [26]. If this capture rate C is constant, the WIMP annihilation Γ_a is given by : $\Gamma_a = \frac{C}{2}\tanh^2(\sqrt{CC_A}t)$. With C_A the probability of WIMP pair annihilation per unit time.

Γ_a has to be evaluated at $t_\oplus = 4.5x\ 10^9$years, the present age of the Earth. But $\sqrt{CC_A}t_\oplus$ is smaller than 1. The equilibrium has not yet been reached, and so the annihilation rate is not maximum.

C, the WIMP capture rate, depends on their mass, their velocity in the halo, and their local density. The velocity distribution is assumed to be Maxwellian ('Standard Halo Model') with a dispersion of 270km/s. The value of the local Dark Matter density is still under debate [6], with estimates ranging from ≈ 0.2 GeV/cm^3 to ≈ 0.5 GeV/cm^3.

We adopt a value of 0.3 GeV/cm^3 as suggested in [7] in order to compare to other such studies. 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 shown in Fig. 1.

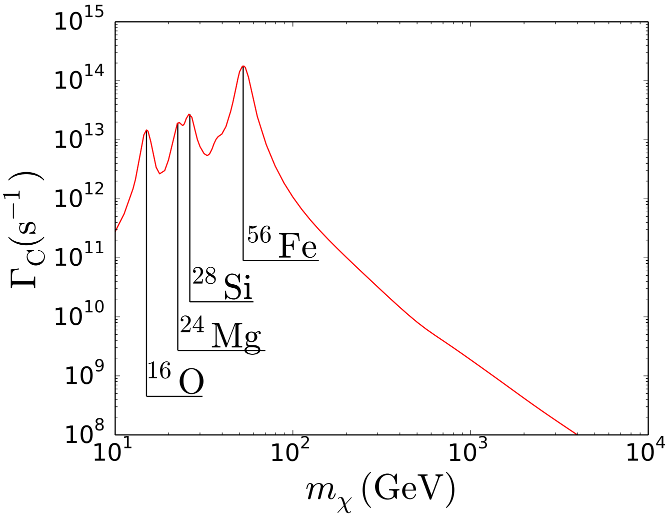

Figure 1: Rate at which WIMPs particles are captured in the interior of the Earth [8] for a scattering cross section of $\sigma_{SI} = 10^{-44}$ cm^2 . The peaks correspond to resonant capture on the most abundant elements in the Earth [9]: ^{56}Fe, ^{16}O, ^{28}Si and ^{24}Mg and their isotopes.

The capture rate could be higher if the velocity distribution of WIMPs with respect to the Earth is skewed towards low values, as only WIMPs moving slower than the Earth's escape velocity of 30km/s can be captured.

4. Background

As signal neutrinos originate near the center of the Earth, they induce a vertically up-going signal in the detector. This is however a special direction in the geometry of IceCube, as the strings are also vertical. While in other point source searches, a signal-free control region of the same detector acceptance can be defined by changing the azimuth, this is not possible for an Earth WIMP analysis. Consequently, a reliable background estimate can only be derived from simulation.

Two types of background have to be taken into account: the first type consists of atmospheric muons produced by cosmic rays in the atmosphere above the detector. Although these particles enter the detector from above, a small fraction will be reconstructed incorrectly as up-going.

The second type of background consists of atmospheric neutrinos. This irreducible background is coming from all directions.

5. Analysis : One year

The one-year analysis used the data taken in the first year of the fully deployed detector (from May 2011 to May 2012) with a livetime of 327 days. During the optimization of the event selection, only 10% of the complete dataset was used to check the agreement with the simulations. The size of this dataset is small enough to not reveal any potential signal, and hence allows us to maintain statistical blindness.

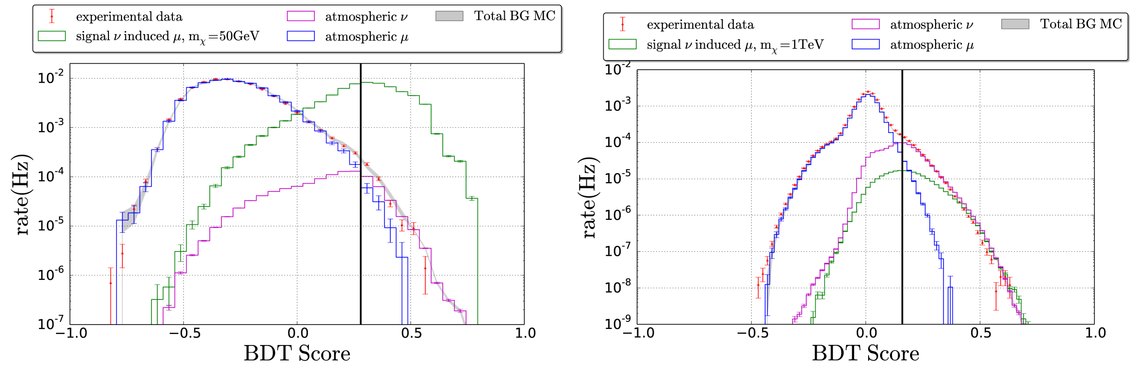

Figure 2: BDT score distributions at pre-BDT level for the low energy analysis (left) and for the high energy analysis using the *Pull-Validation* method (right). Signal distributions are upscaled to be visible in the plot. Signal and backgrounds are compared to experimental data from 10% of the first year of IC86 data. For the atmospheric neutrinos, all flavors are taken into account. In gray, the sum of all simulated background is shown. The vertical lines indicate the final cut value used in each analysis, where high scores to the right of the line are retained.

To be sensitive to a wide range of WIMP masses, the one year analysis is split into two parts that are optimized separately. The high energy event selection aims for an optimal sensitivity for WIMP masses of 1 TeV and the $\chi\chi \rightarrow W^+W^-$ channel. The event selection for the low energy part is optimized for 50 GeV WIMPs annihilating into tau leptons.

After a first set of linear cuts, the datasample is split regarding reconstructed energy. Both analyses use Boosted Decision Trees (BDTs) to classify background and signal events. This machine learning technique is designed to optimally separate signal from background after an analysis-specific training [10] by assigning a score between -1 (background-like) and +1 (signal-like) to each event.

Due to small statistics of simulation we found it necessary to apply the smoothing techniques described bellow. The high energy analysis uses *Pull-Validation* [11], a method to improve the usage of limited statistics.

The low energy analysis tackles the problem of poor statistics of the atmospheric muon background simulation in a different way. In this part of the analysis, only a single BDT is trained (Fig. 2-left), and after the cut on the BDT score, the reconstructed zenith distribution is smoothed using a Kernel Density Estimator (KDE) [12, 13] with gaussian kernel and choosing an optimal bandwidth [14].

To analyze the dataset for an additional neutrino signal coming from the center of the Earth, we define a likelihood test, that has been used in several IceCube analyses before (e.g. [15, 16]). Based on the background (f_{bg}) and signal distribution (f_s) of space angles Ψ between the reconstructed muon track and the Earth center (i.e. the reconstructed zenith angle), the probability to observe a value Ψ for a single event is $f(\Psi|\mu) = \frac{\mu}{n_{obs}} f_s(\Psi) + (1 - \frac{\mu}{n_{obs}}) f_{bg}(\Psi)$. Here, μ specifies the number of signal events in a set of n_{obs} observed events. The likelihood to observe a certain number of events at specific space angles Ψ_i is defined as $\mathscr{L} = \prod_i^{n_{obs}} f(\Psi_i|\mu)$. Following the procedure in [17], the ranking parameter $\mathscr{R}(\mu) = \frac{\mathscr{L}(\mu)}{\mathscr{L}(\hat{\mu})}$ is used as test statistic for the hypothesis testing, where $\hat{\mu}$ is the best fit of μ to the observation. A critical ranking $\mathscr{R}^{90}$ is defined for each signal strength, so that 90% of all experiments have a ranking larger than $\mathscr{R}^{90}$. This is determined by 10^4 pseudo experiments for each injected signal strength. The sensitivity is defined as the expectation value for the upper limit in case that no signal is present. This is determined by generating 10^4 pseudo experiments with no signal injected.

Due to the lack of a control region, the background estimation has to be derived from simulation. Therefore, systematic uncertainties of the simulated datasets were carefully studied. The effects of the uncertainties were quantified by varying the respective input parameters in the simulations.

Different types of detector related uncertainties have to be considered : the efficiency of the DOM to detect Cherenkov photons, the anisotropic scattering in the South Pole ice, the reduced scattering lenght of photons in the refrozen ice of the holes, the scattering and absorption lenghts. The uncertainties on the models of the background physics are also taken into account : the atmospheric flux, the neutrino oscillation parameters, the neutrino-nucleon cross section, the rate of coincidences of atmospheric neutrinos and atmospheric muons. Adding these uncertainties in quadrature results in a total of +34%/-48% in the low energy analysis and +32%/-35% for high energies. For the limit calculation, they are taken into account by using a semi-bayesian extension to the Feldman-Cousins approach [18].

6. Result : One year

As mentioned before, only 10% of the data were used for quality checks during the optimization of the analysis chain. Half of this subsample was used to train the BDTs and therefore these events could not be used for the later analysis. After the selection criteria were completely finalized, the zenith distributions of the remaining 95% of the dataset were examined (Fig. 3). No statistically significant excess above the expected atmospheric background was found from the direction of the center of the Earth.

Using the method described in Section 5, upper limits at the 90% confidence level on the volumetric flux $\Gamma_{\mu \to \nu} = \frac{\mu_s}{t_{\mathrm{live}} \cdot V_{\mathrm{eff}}}$ were calculated from the high and the low energy sample for WIMP masses between 10 GeV and 10 TeV in the hard and in the soft channel. The 90% C.L. limits obtained are shown in Fig. 4. The upper limit on the number of signal neutrinos, the volumetric flux, the WIMP annihilation rate inside the Earth and the resulting muon flux can be found in the paper [1].

7. Outlook : analysis multi-years

IceCube is currently in the process of a preparing a multi-year analysis. Using more than one year of data will improve the sensitivity by a factor of the square root of the number of years. In addition, a plan to improve the event selection is in the works. One such improvement would be to utilise IceCube hexagonal structure to reconstruct the track of the event. This analysis will also benefit from an improvement in reconstructions over previous analyses. The analysis will also focus more on the low energy region, where resonant capture will give stronger limits. We still have to make a positive identification of any Dark Matter particle, instead of only setting upper limits on their existence. The WIMP exclusion limits can move by varying the assumptions about their

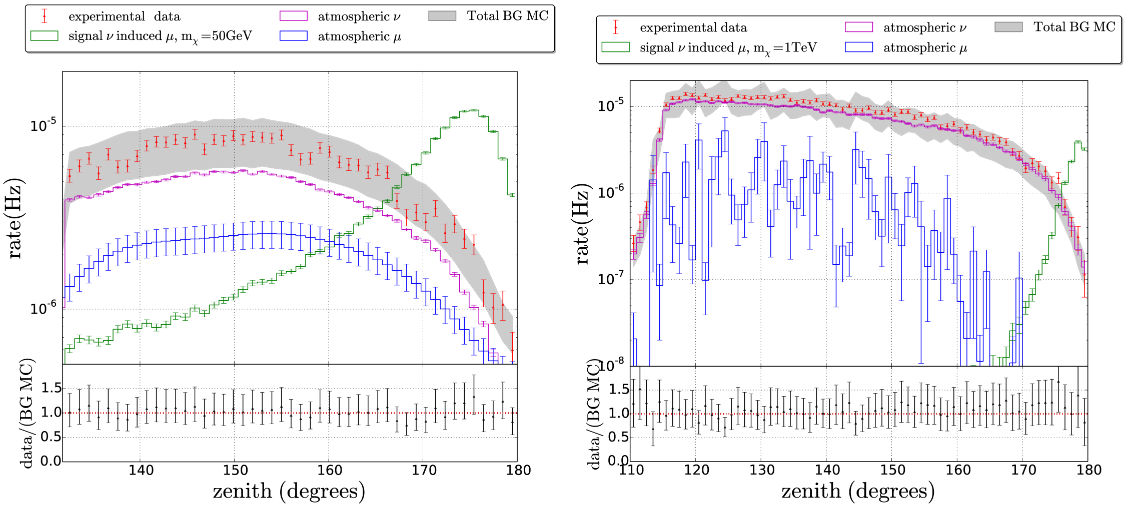

Figure 3: Reconstructed zenith distributions of 1 year of IC86 data (statistical uncertainties only) compared to the simulated background distributions, which include statistical and systematic uncertainties. For the atmospheric neutrinos, all flavors are taken into account. In the low energy analysis (left) the distributions were smoothed by a KDE and in the high energy analysis (right) the Pull-Validation method was used. Signal distributions are upscaled to be visible in the plot. The gray areas indicate the total predicted background distributions with 1 sigma uncertainties, including statistical and systematic uncertainties.

properties such as their speed, or the Galilean invariant interaction operators that can arise form the exchange of a heavy particle of spin less than or equal to one when WIMPs have spin 0, 1/2, 1[26]. So looking for WIMPs annihilations in the center of the Earth with the IceCube detector is still an important test. The sensitivity presented here will set strong limits on the existence of WIMPs.

8. Conclusion

Using one year of data taken by the fully completed detector, we performed the first IceCube search for neutrinos produced by WIMP dark matter annihilations in the center of the Earth. No evidence for a signal was found and 90% C.L. upper limits were set on the annihilation rate and the resulting muon flux as function of the WIMP mass. Assuming the natural scale for the velocity averaged annihilation cross section, upper limits on the spin-independent WIMP-nucleon scattering cross section could be derived. The limits on the annihilation rate are up to a factor 10 more restrictive than previous limits. For indirect WIMP searches through neutrinos, this analysis is highly complementary to Solar searches. In particular, at WIMP masses around 50 GeV, due to resonant capture by iron nuclei in the Earth the sensitivity of this analysis exceeds that of searches for WIMP annihilations in the Sun. The corresponding limit on the spin-independent cross section presented here is the best set presently by IceCube. The next analysis combining several years of data will further improve the sensitivity.

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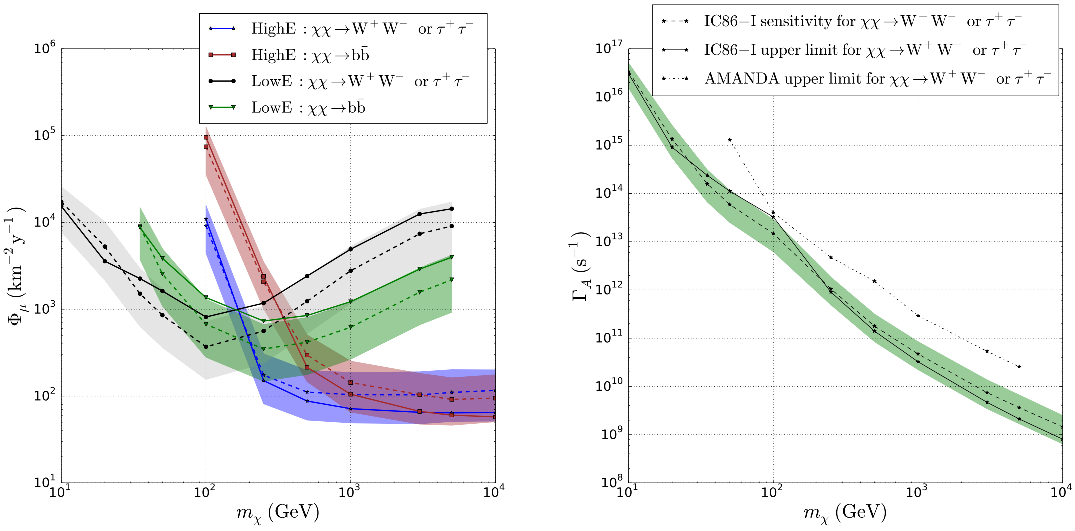

Figure 4: Right: Individual upper limits at 90% confidence level (solid lines) on the muon flux Φ_μ for the low and high energy analysis. Systematic uncertainties are included. For the soft channel, $\chi\chi \to b\bar{b}$ is assumed with 100% braching ratio, while for the hard channel the annihilation $\chi\chi \to \tau^+\tau^-$ for masses ≤ 50 GeV and $\chi\chi \to W^+W^-$ for higher masses is assumed. A flux with mixed branching ratios will be between these extremes. The dashed lines and the bands indicate the corresponding sensitivities with one sigma uncertainty. Left: The combined best upper limits (solid line) and sensitivities (dashed line) with 1 sigma uncertainty (green band) on the annihilation rate in the Earth Γ_A for 1 year of IC86 data as a function of the WIMP mass. For each WIMP mass, the sample (high energy or low energy) which yields the best sensitivity is used. Systematic uncertainties are included. The dotted line shows the latest upper limit on the annihilation rate, which was calculated with AMANDA data [19, 20].

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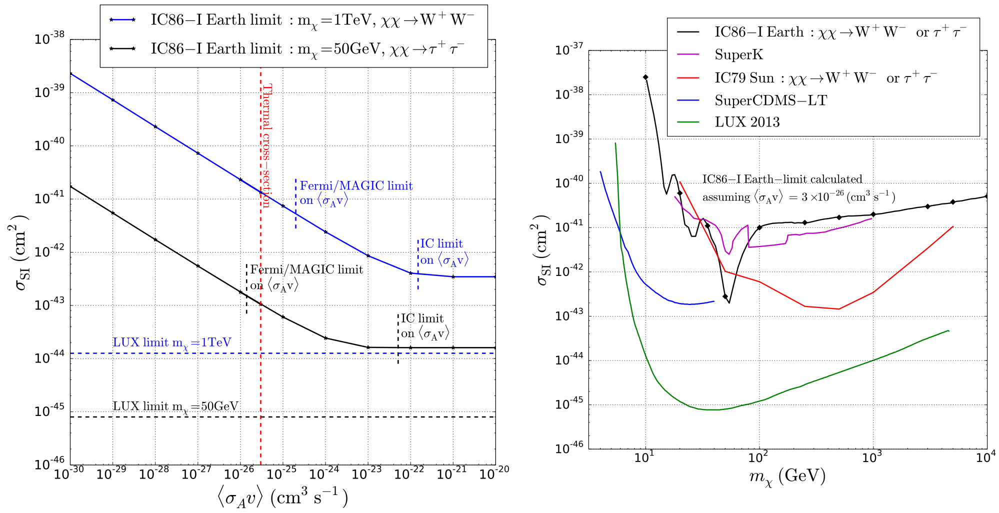

Figure 5: Right : Upper limits at 90% confidence level on $\sigma^{SI}_{\chi-N}$ as a function of the annihilation cross section for 50 GeV WIMPs annihilating into $\tau^+\tau^-$ and for 1 TeV WIMPs annihilating into W^+W^-. Systematic uncertainties are included. As a comparison, the limits of LUX [21] are shown as dashed lines. The red vertical line indicates the thermal annihilation cross section. Also indicated are IceCube limits on the annihilation cross section for the respective models [16], as well as the limits from a combined analysis of Fermi-LAT and MAGIC [22] Left : Upper limits at 90% confidence level on $\sigma^{SI}_{\chi-N}$ as a function of the WIMP-mass assuming a WIMP annihilation cross section of $\langle\sigma_A v\rangle = 3\cdot 10^{-26}\text{cm}^3\text{s}^{-1}$. For WIMP masses above the rest mass of the W bosons, annihilation into W^+W^- is assumed and annihilation into $\tau^+\tau^-$ for lower masses. Systematic uncertainties are included. The result is compared to the limits set by SuperCDMSlite [23], LUX [21], Super-K [24] and by a Solar WIMP analysis of IceCube in the 79-string configuration [15]. The displayed limits are assuming a local dark matter density of $\rho_\chi = 0.3$ GeV cm^{-3}. A larger density, as suggested e.g. by [25], would scale all limits linearly.

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