Searches for Dark Matter and High-Energy Neutrinos with IceCube

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The spectrum of cosmic rays includes the most energetic particles ever observed. The mechanism of their acceleration and their sources are, however, still mostly unknown. Observing astrophysical neutrinos can help solve this problem. Because neutrinos are produced in hadronic interactions and are neither absorbed nor deflected, they will point directly back to their source. High-energy neutrinos may also be produced in other processes, such as WIMP annihilation, and the detection of such particles would allow insight into these processes. Here we report on searches for high-energy neutrinos ($> 100\,\mathrm{TeV}$) at the IceCube neutrino observatory, which have recently produced the first evidence for a flux beyond standard expectations from neutrinos generated in the Earth's atmosphere. Additional focus is given to indirect searches for dark matter with IceCube.

1 Introduction

The IceCube neutrino detector[1] is a cubic-kilometer Cherenkov array deployed in the glacial ice at the geographical South Pole. It detects neutrinos by observing Cherenkov light from secondary charged particles created in neutrino-nucleon interactions in the ice or bedrock. The observed events have two main topologies: track-like events from charged-current interactions of ν_μ, creating muons with typical ranges of well over a kilometer at the relevant energies ($> 100\,\mathrm{GeV}$) and cascade-like events due to the hadronic and leptonic showers created in charged-current and neutral-current interactions of ν_e and ν_τ. Using timing information from the photomultiplier tubes (PMTs) in each digital optical module (DOM) deployed in the array, the event directions and deposited energies can be reconstructed. The main systematic errors are due to uncertainties in modeling the natural glacial ice and in determining the absolute energy scale. For cascade events, the uncertainties on deposited energy are on the order of 15%, while the typical median angular resolution is on the order of $10° - 15°$ (for events of about $100\,\mathrm{TeV}$). The angular resolution for track events is much better due to their extension, typically $< 1°$ depending on the exact event topology and energy.

2 High-Energy Astrophysical Neutrinos

High-energy neutrinos can be produced in astrophysical objects by the decay of charged pions from cosmic rays interacting with radiation or gas. These neutrinos travel long distances undisturbed by either magnetic deflection or absorption, making them a unique tracer of cosmic ray acceleration.

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2.1 PeV Neutrinos

IceCube found two cascade-type events with deposited energies of about 1 PeV in an analysis designed to look for extremely high-energy neutrinos from the GZK mechanism[2]. These events represent an excess of 2.8σ above expected backgrounds in the two-year dataset studied by this analysis (May 2010 to May 2012). Even though their energies are too low to be GZK neutrinos, these events were the highest-energy neutrinos detected until then.

2.2 High-Energy Starting Event Search

A follow-up analysis specifically looking for high-energy neutrino events interacting inside of the detector was designed, aiming to lower the energy threshold of the GZK analysis in order to characterize the flux leading to the previously observed PeV events. Looking for such starting events suppresses the background from downgoing atmospheric muons generated in cosmic ray air showers. This analysis has first been performed on the same 2-year dataset[3] as the GZK analysis and has recently been extended to a third year of data[4].

In addition to reducing the expected number of background events from atmospheric muons in three years to 8.4 ± 4.2 (estimated from data by tagging known background events in the outer layer of the detector), the veto condition used in the analysis reduces some of the atmospheric neutrino background for the most downgoing events. At the highest energies, atmospheric neutrinos are very likely to be accompanied by high-energy muons from the same air shower reaching the detector depth[5,6]. These muons will trigger the veto and thus such atmospheric neutrino events are rejected. The number of expected atmospheric neutrino background events from model assumptions is $6.6^{+5.9}_{-1.6}$ in three years of data. After unblinding, a total of 37 events have been observed in the three-year data sample on top of the expected backgrounds. An atmospheric-only explanation is disfavored by 5.7σ using the energy and angular distribution of the events.

Fig. 1 show the energy and declination distributions of the observed events compared to background expectations and best-fit power-law benchmark astrophysical fluxes. For a benchmark E^{-2} spectrum, the best-fit per-flavor flux normalization (assuming a 1:1:1 flavor ratio) is $E^2\Phi_\nu(E) = 0.95 \cdot 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$. When fitting for the spectral index in addition, the per-flavor spectrum is $E^2\phi(E) = 1.5 \times 10^{-8}(E/100\mathrm{TeV})^{-0.3}\,\mathrm{GeVcm^{-2}s^{-1}sr^{-1}}$. As expected, a supression in the northern hemisphere from absorption of the highest-energy neutrinos in the earth can be observed. Overall, the declination distribution is compatible with expectations from an isotropic flux.

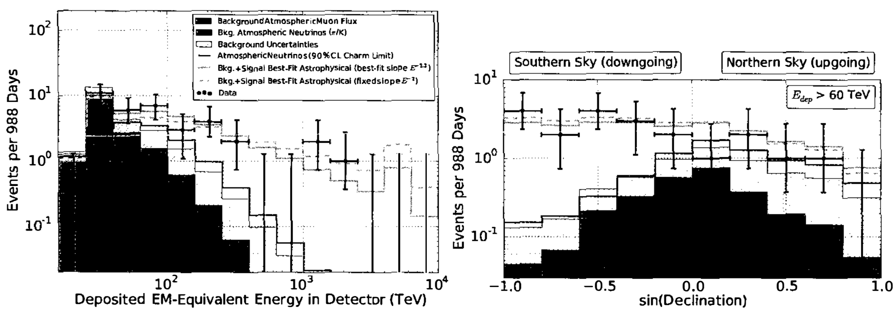

Figure 1 – Deposited energy distribution (left) and declination distribution (right) of the events observed in the 3-year high-energy starting event sample compared to background model expectations and best-fit astrophysical benchmark fluxes with fixed (E^{-2}) and floating ($E^{-\gamma}$) spectral indices. (Background expectations and best-fit astrophysical are stacked.) Figures from [4].

When looking at the full event directions and their directional uncertainties, no significant clustering was found. Fig. 2 shows the event directions in Galactic coordinates. The cluster close to the Galactic Center is the most significant cluster when looking at all cascade-type events and has a p-value of 7%. In addition searches for clustering with the Galactic plane, a catalog of pre-defined source locations, a time-clustering search with GRBs and a self-clustering search using the event times all yielded no significant results.

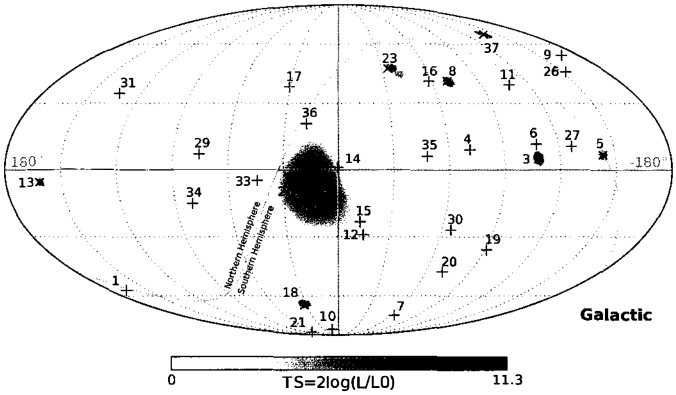

Figure 2 – High-energy starting event directions in Galactic coordinates. Cascade-like events are marked with +, track-like events with ×. The color map shows the test statistic (TS) used for the point-source clustering test at each location. Figure from [4].

To increase the number of high-energy events, a high-energy extension of the IceCube detector is currently being designed. Such a detector upgrade would include a surface array to veto cosmic ray background events and an increased number of in-ice photodetectors. This will increase the volume for starting events (for veto-based analyses) and the effective area for incoming tracks. It also improves the angular resolution while reducing the background contamination.

2.3 Up-going Muon Track Diffuse Search

Recently, an analysis looking for upgoing track-like events entering the detector looking at two years of data (May 2010 to May 2012) has also detected an excess of events above background expectations at energies above about 100 TeV.[7] Since there is almost no overlap in the event selection of this analysis with the starting event selection described in the previous section, this provides an independent confirmation of the previous claim. In this analysis, the background-only hypothesis is rejected by 3.9σ and a best-fit of a astrophysical E^{-2} benchmark spectrum yields results compatible with the starting-event analysis.

3 Indirect Dark Matter Searches

While the existence of dark matter is well established experimentally due to astrophysical and cosmological evidence, its exact nature is still unknown. Many models beyond the Standard Model predict stable or very long-lived weakly-interacting particles that are promising candidates for dark matter. In many models, WIMPs (Weakly Interacting Massive Particles) are their own anti-particles and can self-annihilate. They may be captured in gravitational wells (such as the Sun) where they eventually accumulate until an equilibrium between capture and self-annihilation is reached. The products from self-annihilation are dependent on the particular model, but in general a flux of neutrinos is expected. Such a flux would appear as an excess coming from a variety of of sources: the Sun[8], the Earth[9], the Galactic Halo[10] and Galatic Center as well as extragalactic sources such as dwarf spheroidal galaxies and galaxy clusters[11]. For setting limits, two benchmark annihilation spectra are used to cover the range of possible models: hard spectra from the W^+W^- channel and soft spectra from the $b\bar{b}$ channel. The expected neutrino energies are typically below or around 100 GeV and can be detected at the lower end of the energy range accessible to IceCube.

3.1 Solar WIMPs

The capture of WIMPs in the Sun is sensitive to the WIMP-proton elastic scattering cross-section. Searches for them complement direct searches on Earth. As they scale with the averaged dark matter density along the solar circle, they are more sensitive to low WIMP velocities and they depend only weakly on the underlying WIMP velocity distribution[8]. The study discussed here used the 79-string configuration of IceCube during the last season before completion of the detector, using data collected from May 2010 to May 2011 with a livetime of 318 days. For the first time, this search extended to the Southern Hemisphere. It used the DeepCore infill array to lower the energy threshold to about 35 TeV. Due to the different characteristics of the dominant backgrounds, the dataset was split into a winter and summer set with the Sun being below and above the horizon, respectively. The winter dataset was further split into low-energy and a high-energy subsets. The winter low-energy set and the summer dataset used the DeepCore array to lower the energy threshold while adding most of the detector as an active muon veto. The winter high-energy dataset did not use any particular containment requirement. All three subsets are independent and do not overlap. The final search was conducted using a combined likelihood function. After unblinding and comparing with expected background distributions from atmospheric muons and neutrinos, the observed number of events from the direction of the Sun was consistent with the background-only hypothesis and upper limits on the neutrino flux could be translated into limits on the spin-dependent and spin-independent WIMP-proton scattering cross-sections as a function of the WIMP mass. These limits, compared to results from direct detection experiments are shown in Fig. 3.

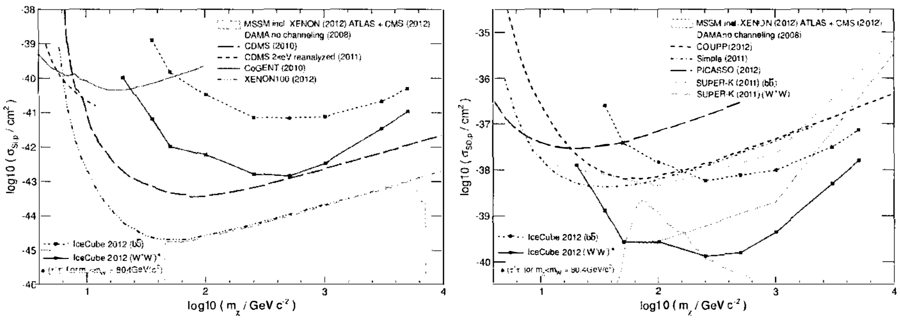

Figure 3 – 90%CL upper limits on $\sigma_{\rm SI}$ (left) and $\sigma_{\rm SD}$ (right) for the W^+W^- and $b\bar{b}$ channels. Systematic uncertainties are included. The shaded region represents an allowed MSSM parameter space (MSSM-25) taking into account recent accelerator, cosmological and direct DM search constraints. Results from Super-K, COUPP (exponential model), PICASSO, CDMS, XENON100, CoGeNT, Simple and DAMA are shown for comparison. Figures from [8].

3.2 Galactic and Extra-Galactic Sources

Galactic and extra-galactic dark matter searches looking for a signal from WIMP self-annihilation probe the thermal average of the annihilation rate, proportional to the product of the annihilation cross-section with the relative WIMP velocity $\langle \sigma v \rangle$. These searches are complementary to solar WIMP searches (and to direct searches) probing the WIMP-nucleon cross-section. Like for the solar WIMP searches, the background of downgoing atmospheric muons can be rejected using veto techniques or by looking for events in the upgoing direction in these analyses. Two searches for a WIMP signal from the Galactic Center were performed on data from the 79-string configuration of IceCube: one search focussing on a lower-energy event sample based on the DeepCore infill detector (30 GeV to 500 GeV) and a second analysis using a larger part of the detector with a focus on higher energies. Fig. 4 shows the IceCube sensitivity on $\langle \sigma v \rangle$ compared to other analyses and experiments[12].

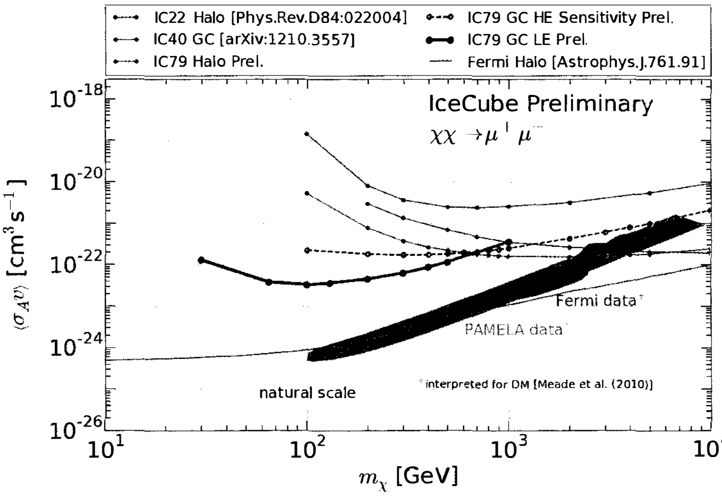

Figure 4 – 90%CL limit (w/o systemetics) for WIMP annihilation in the GC into $\mu^+ \mu^-$ (solid blue) compared to other analyses / experiments. All lines are calculated for the NFW halo model. Shown are also the regions of parameter space which provide a good fit to PAMELA (gray) and Fermi LAT (green) CR electron and positron data.

A Galactic Halo analysis searches for a large-scale anisotropy in the distribution of incoming neutrinos using a selection for upgoing events to reject atmospheric muon backgrounds. Using the large field of view of IceCube, a multipole expansion is used to look for a characteristic anisotropy expected due to the difference in dark matter density in the direction of the Galactic Center compared to the anti-center.

4 Conclusion

The IceCube Neutrino Telescope has reached the sensitivity required to start probing many models of astrophysical neutrino production. There is an increasing evidence for an astrophysical high-energy neutrino flux beyond the expectations from purely atmospheric backgrounds. Further observations with the current detector and future detector extensions are required to detect and study the still unidentified sources of this flux.

IceCube also has a rich program of indirect searches for dark matter from a variety of sources. Some of the current limits, such as the spin-independent limit set by the solar WIMP analysis, are among the most sensitive available to date.

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