Latest Results from the IceCube Neutrino Observatory

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Nearly a century after the discovery of cosmic rays their sources remain a mystery. The study of neutrinos along with other cosmic messengers is vital for ultimately identifying the sources of cosmic rays and understanding the nature of the underlying acceleration mechanisms. Neutrinos are especially important as they propagate nearly unperturbed through the universe and point back to their sources. Neutrino astronomy enters a new era with the IceCube neutrino observatory that will instrument a volume of one gigaton of ice by 2011 and is now almost three quarters complete. Current neutrino flux predictions from potential sources suggest that a volume of this scale is needed to detect neutrinos at statistically significant rates. We present the latest results in the search for astrophysical neutrinos from point sources with IceCube and its predecessor AMANDA, which has been operational for the last eight years. We further present limits on the neutrino flux from unresolved sources and indirect searches for dark matter performed with this multi-purpose detector. Future extensions to IceCube and the status of the DeepCore sub-detector, whose construction has already started, will be given together with an outlook for future physics potential.

1 Motivation

Neutrinos combine a unique set of properties that make them ideal cosmic messengers. Photons (γ) scatter and get easily absorbed on the stellar infrared (IR) photons and are cut off above the e^+e^- pair-production threshold of about 50 TeV. Charged particles bend in magnetic fields on their journey from their point of origin to detection. This scrambling of direction of charged particles in the galactic and intergalactic magnetic fields makes a correlation with source candidates extremely difficult. Only at the extremely high energy range (EHE), well

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above about 10 EeV, does the bending become less severe for protons. However even at energies up to 40 EeV significant bending (greater than a few degrees) is expected in the intergalactic magnetic field [1]. This energy is already close to the Greisen-Zatsepin-Kuzmin (GZK) cut-off [2] energy at which protons start to interact with the cosmic microwave background (CMB) to produce pions via delta resonance ($p + \gamma_{\rm CMB} \rightarrow \Delta^+ \rightarrow n\pi^+/p\pi^0$). This process attenuates the cosmic ray flux (significant attenuation for distances of $\sim$ 30 Mpc), but at the same time also provides a "guaranteed" neutrino flux at EHE ranges, through the decay of charged pions.

Neutrinos (ν) are weakly interacting and carry no electric charge. Hence they propagate nearly unperturbed through the universe and therefore point back to their sources. Their tiny interaction cross-section, however, results in major difficulties when trying to detect them. To achieve reasonable event rates, allowing observation of neutrino events with statistical significance, a neutrino telescope must be of substantial size. Further, muons produced in charged-current interactions of TeV scale parent muon neutrinos will travel kilometer ranges in optically transparent media. A volume of this scale needs to be instrumented for a neutrino telescope to track such muons with good pointing resolution. To date, neutrino astronomy is still in its infancy. The only neutrinos identified from beyond our solar system are those from SN1987A.

One of the fundamental questions neutrinos can help solve is about the nature of the sources of high-energy cosmic rays. Are the processes that accelerate gamma-rays to TeV energies also responsible for the acceleration of cosmic rays or are they of leptonic nature ? Neutrinos provide the natural means to distinguish between the two possibilities, since hadronic interactions will also produce charged mesons, all of which decay into final states containing neutrinos. Purely electronic emission processes produce neutrinos only in negligible numbers. Any detection of neutrinos from a specific source would therefore provide very strong evidence for the hadronic model and consequently allow the identification of the sources of cosmic radiation.

2 The IceCube Detector

IceCube is a Cherenkov neutrino telescope currently under construction in the ice near the geographic South Pole. It has the ability to detect neutrinos of all flavors over a wide energy range from about 100 GeV to beyond 10^9 GeV, as well as MeV neutrinos from bursts.

By 2011 the detector will instrument a volume of about one cubic-kilometer of Antarctic deep ice with 86 strings each containing 60 optical sensors [3]. Each sensor consists of a 10 inch photomultiplier tube (PMT), connected to a waveform recording data acquisition circuit capable of resolving pulses with nanosecond precision and having a dynamic range of at least 250 photoelectrons per 10 ns, all engulfed in a pressure sphere. Such a module is called a digital optical module (DOM).

On 80 of the IceCube strings, which will be arranged in a hexagonal pattern with an interstring distance of 125 m, the sensors will be equally spaced between 1450 m and 2450 m in depth. In addition near to the location of each string there will be two surface tanks deployed to form an air shower array that is sensitive to primary shower energies above 300 TeV. Complementing the original 80-string baseline array are six strings, densely instrumented in the deep ice below 2100 m, which has more favorable properties for light propagation. They will be spaced in between the regular IceCube strings at the center of the detector, creating a sub-array, together with the adjacent IceCube strings, which is expected to significantly enhance the sensitivity for the detection of neutrinos in the energy range of 10 - 100 GeV. This DeepCore sub-array will make use of new high quantum-efficiency PMTs, which have approximately 40% higher efficiency compared to the standard IceCube PMTs. A schematic drawing of the IceCube detector including DeepCore is shown in Figure 1. The AMANDA detector completed in 2000 and integrated into the IceCube detector for joint data taking, is also shown.

Figure 1 shows a top view of the current IceCube detector. There are 59 strings deployed,

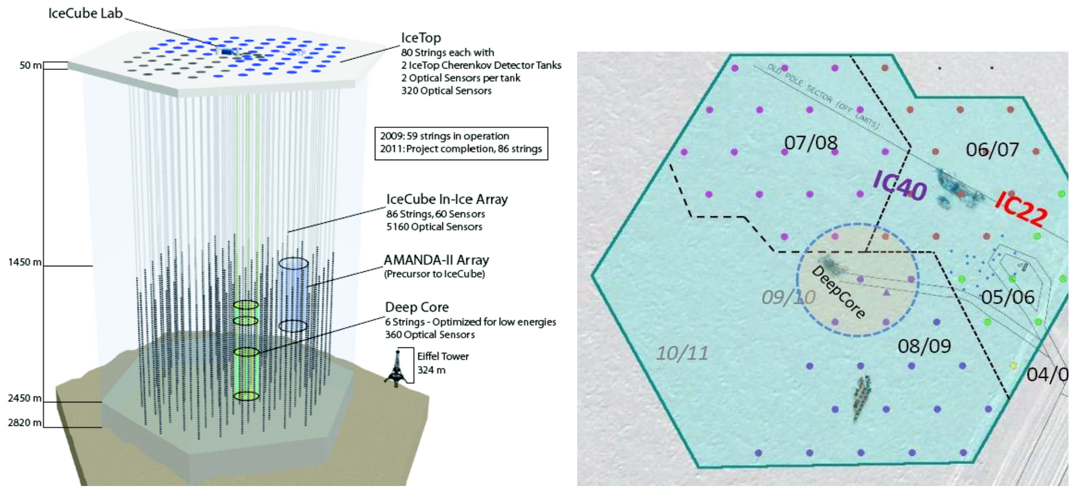

Figure 1: Left: Schematic view of the IceCube detector including the six-string DeepCore in the center of the detector. Right: Satellite view of the current IceCube detector configuration.

including one DeepCore string. The outline also shows the IceCube 22, and 40-string array, which were operational during 2007/2008, and 2008/2009, respectively. The livetime acquired during the corresponding physics run periods is given in Table 1, together with the achieved and expected angular resolution for high energy muon neutrinos.

Detector Configuration	Year	Livetime (days)	Angular resolution (deg)
IC22	2007/2008	276 days	$< 1.5°$
IC40	2008/2009	~1 year	$< 1.2°$
IC58+1*	2009/2010	~1 year	$\sim 1°$
IC80+6*	2011/...	> 5 years	$< 1°$
AMANDA	2000/2009	9 years	$1.5° - 2.5°$

Table 1: Summary of selected detector configurations, years of operation, acquired livetime, and angular detector resolutions. The quoted value for the angular detector resolution is the median angular resolution as achieved in a typical muon neutrino point source analysis [4]. (∗) indicates expected performance. AMANDA is shown for comparison [5].

3 Search for astrophysical neutrinos

To study astrophysical neutrinos, one first needs to find a way to discriminate between events caused by down-going muons, atmospheric neutrinos and those caused by astrophysical neutrinos. The easiest way to eliminate a large fraction of the otherwise overwhelmingly large atmospheric muon background is by looking for up-going events (neutrinos that traversed the Earth). One way to then identify in the obtained up-going sample neutrino candidates from astrophysical sources is through observing clustering of events from a similar direction over the flat atmospheric neutrino background, at a statistically significant level. A complementary way is to search for transient sources, through the observation of neutrinos correlated in time (and/or direction) with other messengers. As part of such multi-messenger searches, IceCube has looked, for example, for neutrinos correlated with satellite observations of gamma-ray bursts (GRBs). A third way is to look for the diffuse flux produced by the sum of all neutrino sources. Such a diffuse neutrino flux might be identified through a break in the measured neutrino energy spectrum, which is expected to fall steeply for atmospheric neutrinos, while cosmic sources are thought to produce harder spectra (E^{-2}).

3.1 Point Sources

Several searches for point sources have been performed using AMANDA and IceCube data applying a variety of different strategies. We describe here a few selected recent results of such searches.

A search for high energy muon neutrinos from point sources has been performed with 3.8 years of livetime acquired with the AMANDA detector during 2000-2006 [5]. The analysis yielded 6595 neutrino candidates from the Northern hemisphere, consistent with atmospheric neutrino background expectations. The search reveals no indication of a neutrino point source and places stringent limits on possible flux from any such source. The information of the neutrino candidate events has been released by the collaboration and is posted on the IceCube website [6].

A similar point source analysis for the Northern hemisphere has been performed using 276 days of livetime with the IceCube 22-string detector. This analysis used a novel unbinned search method, using the point spread function of each neutrino candidate event weighted in significance by an energy estimator. The weight factor was optimized for an E^{-2} spectrum as expected for cosmic sources with second order Fermi acceleration. A skymap of 5114 observed muon neutrino candidate events reveals one hotspot at r.a. 153°, dec 11°. Accounting for all trials the probability for this outcome (p-value) for this analysis is 1.34% (2.2σ), which is consistent with a fluctuation of background [4]. An a priori source list consisting of 28 candidates did not yield any significant excess over expected background. The lowest p-value (0.07) was observed for Blazar 1ES $1959 + 650$.

Point source searches are typically limited to a fraction of the sky due to the selection of up-going events as a way of rejecting the atmospheric muon background. However, through an energy-sensitive selection procedure, one can suppress the background effectively and include the region above the horizon in a point source search [7]. This approach provides sensitivity to the signal spectrum of sources in the EeV energy range, which was previously not accessible due to the absorption of neutrinos with energies above a PeV inside the Earth. With 1877 events in the final selection sample of candidate events between $+55°$ to $-85°$ collected with IceCube in the 22-string configuration during 2007-2008, no significant excess above the atmospheric background was observed (see Figure 2).

The complete IceCube detector will allow for full-sky (4π sr) point source searches, by selecting only events with tracks beginning within the detector's instrumented volume, in contrast to through-going muons (which are dominant in point source searches). The DeepCore detector will be especially useful for such analyses.

3.2 Diffuse neutrino flux

A complementary approach in the search for an astrophysical neutrino signal is to search for a diffuse flux of neutrinos summing over all unresolved nearby and distant neutrino sources. An all-sky search is conducted by looking for an excess at high neutrino energies. To separate the signal from atmospheric neutrino background, an energy-correlated parameter cut is applied after carefully removing from the data any down-going muon background events. In the final selection sample of AMANDA data from 2000-2003 six events were observed, compared to an expected background of seven events. This corresponds to an upper limit (at 90% C.L.) on the diffuse muon neutrino flux from the northern hemisphere of $E^2\phi < 7.4 \times 10^8$ GeVcm^{-2}s^{-1}sr^{-1} for an assumed E^{-2} spectrum with 90% of the simulated signal neutrinos expected between energies of 15.8 TeV and 2.5 PeV The result also constraints prompt (charm) production of atmospheric neutrinos, ruling out some of the highest-yielding models at 90% C.L [8]. A similar analysis technique has also been used for IceCube data collected with the 9-string detector in 2006 [9]. As the sensitivity of this analysis in 137 days of livetime was determined to be slightly poorer than the AMANDA limit, this analysis was used just as a high-level cross-check of the IceCube detector performance and analysis framework. In the signal region defined by the requirement that the number of DOMs hit be larger than 33, six events were observed, while 6.5 were expected. This results is consistent with the AMANDA upper limit.

4 Indirect Searches for Dark Matter

Dark matter could be indirectly detected in IceCube through the observation of neutrinos from self-annihilation or decay processes. Possible signals are an excess neutrino flux from the Sun, or the center of the Earth where dark matter could be gravitationally trapped, or from the galactic halo. In the following we describe a search for muon neutrinos from neutralino annihilations in the Sun performed using IceCube data collected with the 22-string configuration [10]. The data set corresponds to 104 days of livetime in 2007 during which the Sun was below the horizon. The search is focused on five neutralino masses (m_χ above 250 GeV/c^2). The analysis was performed in a blind fashion, by only revealing the position of the Sun after the analysis procedure and background prediction was finalized. The data were processed through four filtering levels in order to reduce the downward-going muon background. The final level utilized a selection criterion based on the product of two multivariate classifier (Support Vector Machine) outputs, trained with six parameters each. No excess of neutrino events from the Sun was observed, thus the 90% confidence level upper limits on the muon flux at the Earth were calculated. Assuming equilibrium between the capture and the annihilation rate in the Sun, the obtained limit can be converted [11] into a limit on the WIMP-nucleon scattering cross-section. A local WIMP density of 0.3 GeV/cm^3 and a Maxwellian velocity distribution with a dispersion of 270 km/s was assumed to obtain the limits on the spin-dependent cross-section. Figure 2 shows the 90% C.L. upper limit on the spin-dependent neutralino-nucleon cross-section as function of the m_χ, compared to other indirect experiments, and to theoretical predictions from MSSM. It can be seen that the IceCube result is very competitive.

5 Conclusions and Outlook

IceCube enters its fourth year of operations, with a continuously growing array as new strings are deployed each season. The detector has been extremely stable and the hardware very reliable. Analyses performed on one year of IceCube 22-string data have achieved or surpassed sensitivity corresponding to several years of AMANDA data. IceCube's chances of successfully identifying extra-terrestrial neutrinos rapidly increase with the detector size, total integrated livetime, and further performance improvements. By 2010 the DeepCore sub-detector will be completed and in 2011 IceCube will reach its final size of one cubic kilometer. Further extensions to the IceCube detector are actively discussed, such as (for example) an IceCube-centered radio array [12].

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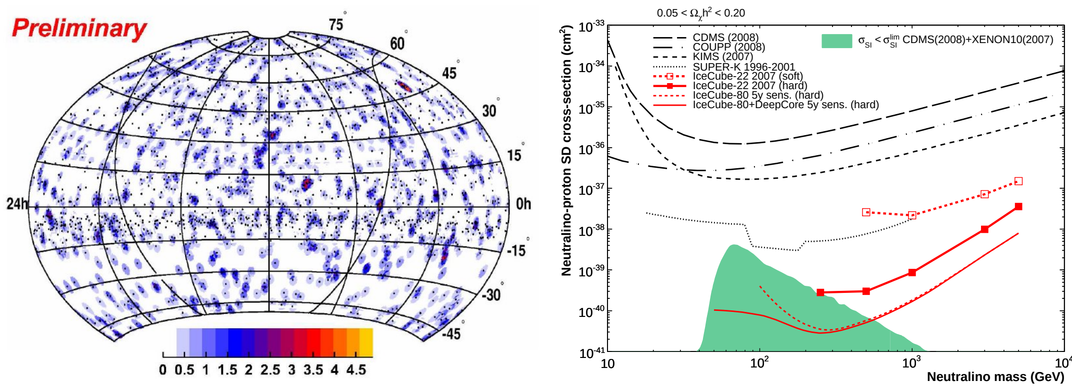

Figure 2: Left: High energy point source analysis including zenith angles from +85 degrees to −50 degrees. Right: Upper limits at the 90% C.L. on the spin-dependent neutralino-proton cross-section (σ^{SD}) for the soft ($\mathrm{b\bar{b}}$) and hard ($\mathrm{W^{+}W}$) annihilation channels, adjusted for systematic effects, as a function of neutralino mass. The shaded area represents MSSM models not disfavored by direct searches based on spin-independent neutralino-proton cross-section (σ^{SI}) . Limits obtained by other experiments are shown for comparison.

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