STATUS AND RESULTS FROM THE ICECUBE NEUTRINO OBSERVATORY

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The IceCube neutrino observatory is currently under construction in the deep ice at the geographic South Pole, reaching 75% completion whilst already taking data. When completed in 2011, it will consist of nearly 5000 digital optical modules on more than 80 strings, capable of detecting the Cherenkov radiation from high-energy neutrino-induced charged leptons. The detection of astrophysical neutrinos can help identify the sources of the high energy cosmic rays since other messengers, such as photons or protons, are absorbed or deflected during propagation. The cubic-kilometer under-ice instrument, complemented by an extensive air-shower array, allows access to neutrino energies up to the PeV range, and to sensitivities below expected neutrino fluxes from some astrophysical sources if they accelerate hadrons. I will summarize current results of IceCube and its predecessor AMANDA, as well as the physics capabilities of the full observatory.

1 Introduction

The main goal of the IceCube neutrino observatory[1] is the search for high-energy extraterrestrial neutrinos, which may reveal the origin of cosmic rays and offer insight into the most energetic phenomena in the universe. Neutrinos have very small interaction cross sections, travelling astronomical distances freely. In addition, they cannot be deflected by intergalactic magnetic fields due to the absence of electric charge, and thus they point back to their origin (see figure 1 (a)).

The most interesting neutrino sources include Active Galactic Nuclei and Gamma-Ray Bursts (GRBs). According to our understanding, these very energetic astronomical phenomena can produce mesons when the ejected particle beams interact with matter and photons near the sources. Very high energy neutrinos are then produced through decays such as $\pi^\pm \to \mu^\pm \nu_\mu$ and, subsequently, $\mu^\pm \to e^\pm \nu_\mu \nu_e$.

I will first present the IceCube observatory, its design and current status, as well as the detection principle. Then, I will review several recent physics results and ongoing searches, and conclude with a description of our future plans.

2 The IceCube Neutrino Observatory

IceCube was planned and designed following the success of its predecessor AMANDA (Antarctic Muon And Neutrino Detector Array[3]), which is now a part of IceCube. The baseline design

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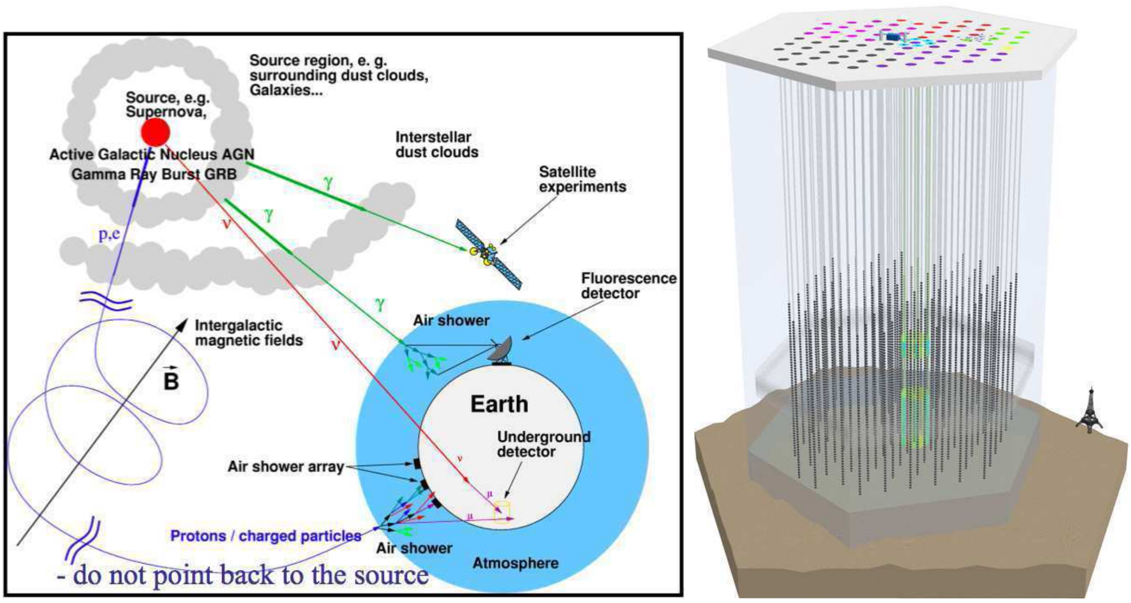

Figure 1: Left (a): Multi-Messenger astronomy. Right (b): The complete IceCube neutrino observatory, including DeepCore and the most dense dust layer at a depth of 2100 m.

of IceCube consists of 4800 digital optical modules (DOMs [2]) on 80 vertical cables (strings), arranged in a hexagonal grid and placed at depths between 1450 m and 2450 m in the clear ice beneath the surface of the South Pole (see figure 1 (b)). The strings are deployed into water-filled holes, previously bored to a depth of 2500 m with a hot-water drill. Once deployed and frozen in, the DOMs become permanently inaccessible. The ice layer above the detector efficiently shields it from low-energy atmospheric muons. The vertical distance between consecutive DOMs is 17 m, and neighbouring strings are 125 m apart on average. The housing of the DOMs consists of a 33 cm glass sphere, capable of withstanding very high pressure. With an improved detector technology and a size of one cubic kilometre, IceCube is expected to drastically improve timing and angular resolutions with respect to AMANDA.

In addition, IceCube also includes an air-shower array called IceTop, located at the surface above the in-ice telescope. It consists of 80 stations, each equipped with four DOMs in two tanks filled with optically clear ice. IceTop was designed to study cosmic ray and air shower physics up to 10^{18} eV by itself and in coincidence with the in-ice array. By tagging air showers with downgoing muons, it also provides an alternative calibration scheme for the in-ice array and a veto against downgoing muon background.

The particle detection principle relies on the blue and near-UV Cherenkov light emission from relativistic charged leptons moving faster than the speed of light in the ice. The DOMs include a 10-stage 25 cm Hamamatsu photomultiplier tube (PMT) capable of detecting this faint light. A DOM can record the signal waveform whenever one or more photons are detected and produce a “hit”. In order to avoid noise i.e. isolated hits (with no nearby hits in space or time), a local coincidence condition requires neighbouring DOMs to record a hit before an event trigger is formed. Single Majority Triggering (SMT) requires the coincidence of hits in at least eight DOMs within a time window of 5 μsec (for the 40-string detector), or at least 6 DOMs for IceTop.

The signal from the PMT is digitized, time-stamped and buffered by the onboard electronics, and sent to the surface data acquisition system, where the DOM pulses are sorted into a time-ordered stream. Two different waveform digitizers are contained onboard: an Analog Transient Waveform Digitizer (ATWD) at a sample rate of up to 300 MHz during 400 ns, and a Fast

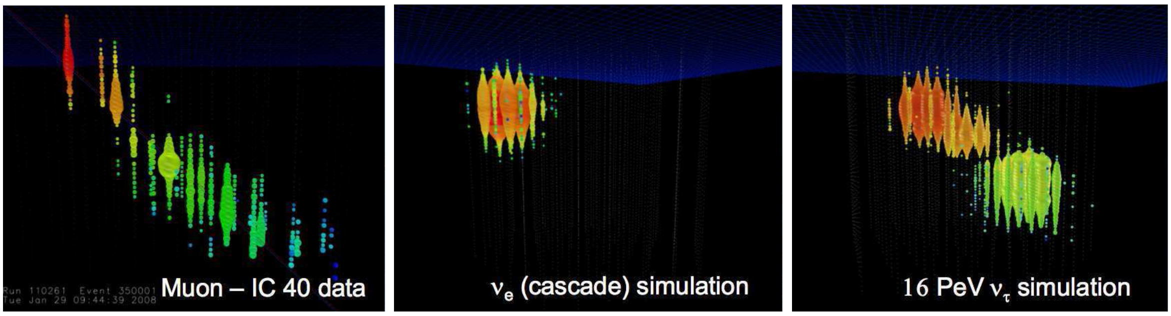

Figure 2: Neutrino signatures: a track-like muon signature, a cascade-like electron signature, and a double bang from a tau creation/decay.

Analog to Digital Converter (FADC) at 40 MHz for 6400 ns. All DOMs are synchronized to a GPS clock with an accuracy of 2 ns. Moreover, calibration runs for neighbouring DOMs can be taken using the integrated LEDs. Cables from all strings converge into the IceCube Laboratory (ICL), a two-story elevated building on the surface, in the middle of the array. It was commissioned in January 2007 and houses all the electronics needed for data-taking, archiving, filtering and data reduction. Due to the limited bandwidth for transfer over NASA's Tracking and Data Relay Satellite System (TDRSS, 55 GB/day in 2009), the data needs to be processed and filtered on-line. Only triggered events that passed the filters are sent to the northern hemisphere. Additionally, all raw data is being written to tapes.

IceCube started data-taking in 2006 with a nine-string array, continued in 2007 with 22 strings, and in 2008 with 40 strings, demonstrating an excellent stability (see table 1). Nineteen additional strings have been deployed during the 2008-2009 austral summer.

3 Event detection and reconstruction

Maximum likelihood fitting techniques are used to reconstruct the direction and energy of each event, taking into account corrections for the absorption and scattering properties of photons in the ice as a function of depth.

The three different flavours of neutrinos can be identified by their distinctive patterns (see figure 2):

- A ν_e interaction in the ice ($\nu_e + N \rightarrow e + X$) produces a small ($\sim$ 10 m) electromagnetic shower. As the typical cascade size and scattering length ($\lambda_{scattering} \sim$ 20 m) are small compared to the inter-string distance, the direction of the incoming electron neutrino is difficult to reconstruct. However, as these events are mostly contained in the detector, the energy reconstruction is quite accurate ($\sigma \sim 0.18$ in $log_{10}(E/GeV)$). The Cherenkov light spreads over a spherical volume relative to the electron energy.

- A ν_μ interaction in the ice gives rise to a secondary muon that travels long distances in the ice in a straight line. The light pattern is a Cherenkov cone along a straight track (see figure 2), with additional light from stochastic processes such as bremsstrahlung, pair-production and photo-nuclear interactions (if the muon energy is high enough). Due to the large detection volume, providing long lever arms, and the digitization inside the DOMs, allowing for an excellent time resolution, the angular resolution of the track-like events is below 1° at an energy of 1 TeV in the 40-string detector, and the energy resolution $\sim$ 0.3 - 0.4 in $log_{10}(E/GeV)$. These values may be further improved using new reconstruction techniques and a more precise ice model.

- One of the characteristic signatures of a ν_τ interaction is the so-called "double bang": two consecutive cascades, one at the production and one at the decay of the tau lepton. Additionally, the tau produces Cherenkov radiation between the cascades. Another possible signature is the "(inverted) lollipop", where the tau decay (production) cascade is outside the detector volume. At high energy, cascades from tau production/decay are easy to distinguish from electron neutrino cascades.

The main background to point source search in IceCube are muons and neutrinos from cosmic ray interactions in the atmosphere (see table 1). Point source searches expect a signal excess from the direction of known sources. At the depth of the detector, the flux of atmospheric muons (downgoing) is a factor 10^6 larger than the flux of atmospheric neutrinos. Most of the atmospheric muons can be cut away by considering only upgoing events, but the atmospheric neutrinos will have to be distinguished from their astrophysical counterparts using other characteristics such as energy deposition.

Year	IceCube Strings	Cosmic Ray muon rate	Atmospheric neutrino rate
2005	1	5 Hz	
2006	9	80 Hz	1.5/day
2007	22	550 Hz	28/day
2008	40	1000 Hz	110/day
2011	80	1650 Hz	220/day

Table 1: Atmospheric event rates for different IceCube configurations

The pointing resolution of the 40-string detector has also been studied in a moon shadow analysis. The moon can block cosmic rays from reaching the earth, and a 4.2 σ deficit of atmospheric muons from cosmic rays was observed within 0.7° around the direction of the moon, using 3 months of data taken with the 40-string detector in 2008.

4 Results

4.1 Point source search

Point source searches are one of the main goals of IceCube, and the most promising way to detect astrophysical neutrinos. Figure 3 shows the limits on the neutrino flux from various point sources, for the AMANDA [4] and IceCube [5] detectors (9 strings and 22 strings). The skymap obtained with IceCube 22 strings can be seen in figure 4. The most significant excess of events in the sky at 2.2 sigma after accounting for all trials.

4.2 Gamma ray bursts

Being amongst the most energetic astronomical phenomena, Gamma ray bursts may produce very high energy neutrinos along with photons, and have been proposed as possible sources of ultra-high energy cosmic rays [11]. The detection of neutrinos from a GRB would provide evidence for the acceleration of ultra-high energy cosmic rays in GRBs. The best limit on neutrino emission from GRBs comes from the AMANDA telescope: the upper limit on the diffuse flux normalization times E^2 for the Waxman-Bahcall model at 1 PeV is 6×10^{-9} GeV $cm^{-2}\ s^{-1}\ sr^{-1}$ with 90% of the events expected within the energy range from $\sim$ 10 TeV to $\sim$ 3 PeV [12, 13]. The limit was obtained in a search for muon neutrinos from 419 GRBs detected by the BATSE satellite between 1997 and 2003.

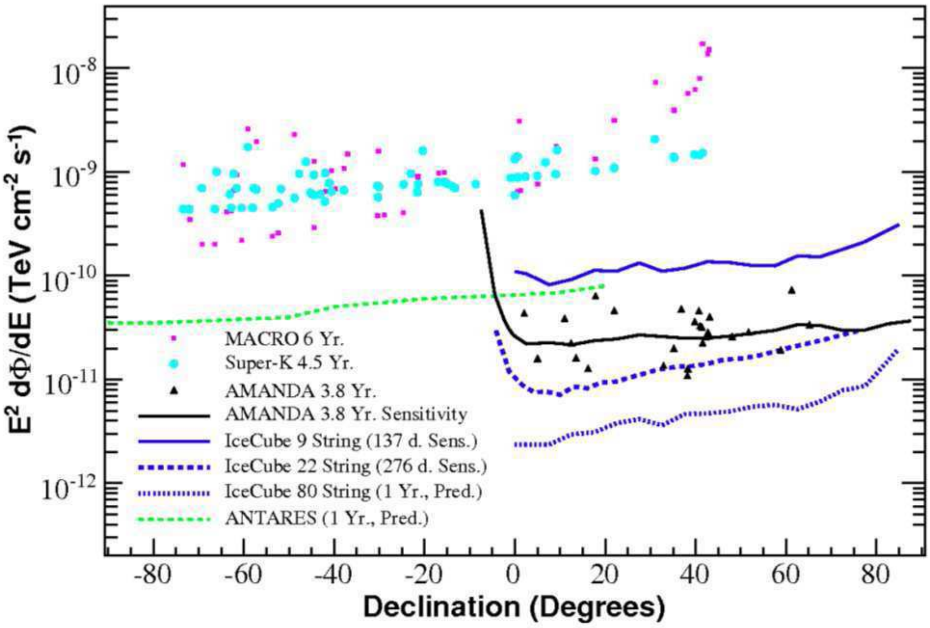

Figure 3: Limits on the neutrino flux from various point sources as a function of declination. Note that IceCube looks through the earth at the northern hemisphere. Also shown are limits from MACRO [6], Super-K [7], and predicted sensitivity for ANTARES [8].

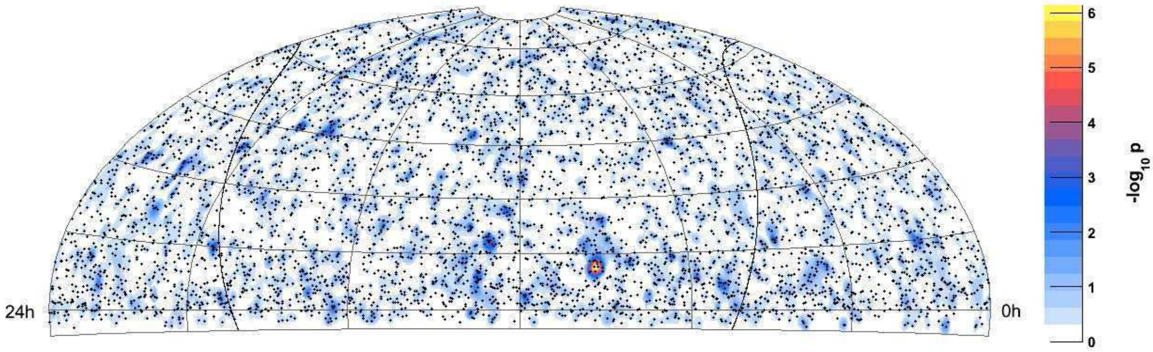

Figure 4: Equatorial sky map of events (points) and pre-trial significances (p-value) obtained with IceCube 22 strings in the unbinned point source search in 2007. The solid curve is the galactic plane.

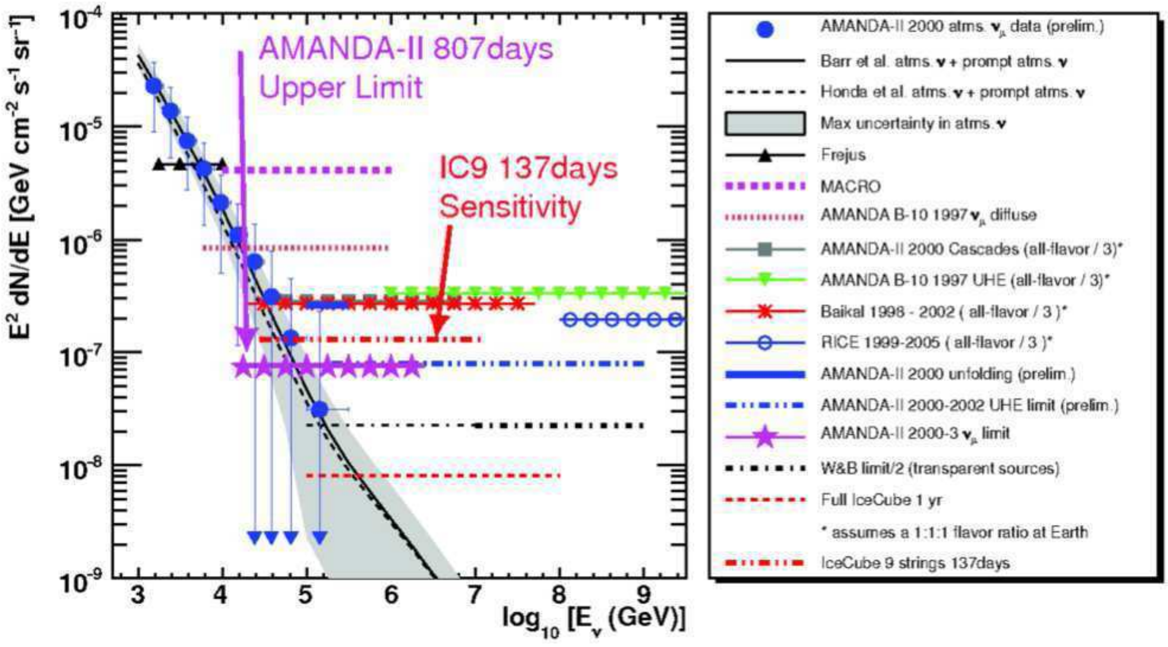

Figure 5: Upper limits on the ν_μ flux from diffuse sources with an E^{-2} energy spectrum [9].

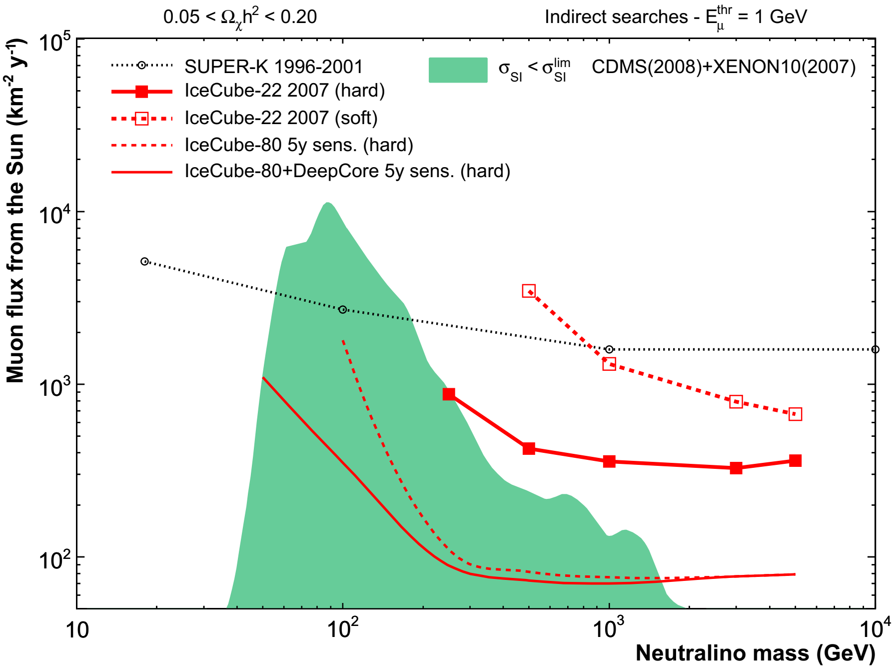

Figure 6: Upper limits at the 90% confidence level on the muon flux from neutralino annihilations in the Sun with IceCube 22-strings for the soft ($b\bar{b}$) and hard ($W^+W^-/\tau^+\tau^-$) annihilation channels [16]. The shaded area represents MSSM models not disfavoured by direct searches. Also shown is the expected sensitivity of full IceCube + DeepCore, as well as limits from Super-K [10].

A search for neutrinos from GRBs using the 22-string IceCube detector is currently nearing completion. Time and position information is now obtained from the Swift and Fermi satellite data.

The analysis of the brightest ever GRB, 080319B, yielded no excess above the background[14]. Unfortunately, IceCube was running in a nine-string configuration at the time of this GRB.

4.3 Diffuse search

Several diffuse neutrino flux analyses are looking for extraterrestrial neutrinos from unresolved sources. These can be astrophysical neutrinos from objects that produce a flux that is too faint to be detected individually, or cosmogenic neutrinos that originate in interactions of high-energy protons with the cosmic microwave background. A signal would be an excess of high-energy events over the expected atmospheric neutrino background, which has a softer energy spectrum than extraterrestrial neutrinos[15]. Searches have been performed with the AMANDA detector[15], and with the 9-string IceCube detector in 2006. Upper limits on the ν_μ flux have been derived (see figure 5).

4.4 Indirect dark matter search

IceCube is also actively looking for neutrinos as a signature of dark matter in the centre of the Sun (or the Earth) where weakly interacting massive particles (WIMPs) can accumulate and annihilate. One of the most promising candidate particles is the stable and massive neutralino, that can self-annihilate to Standard Model particles that produce neutrinos in the energy range from a few GeV to tens of TeV.

No excess over the expected background has been observed for this indirect search in the centre of the Sun with the 2007 data[16]. Upper limits have been obtained on the annihilation rate of captured neutralinos in the Sun and converted to limits on WIMP-proton cross-sections, for neutralino masses in the range 250 - 5000 GeV. Figure 6 shows upper limits at the 90% confidence level on the muon flux from neutralino annihilations in the Sun with IceCube 22-strings. These results are the most stringent limits to date on neutralino annihilation in the Sun.

4.5 Other physics objectives

Other topics and active analyses not described here include cosmic ray physics with IceTop[17], the search for exotic particles and processes (magnetic monopoles[18], Q-Balls, SUSY, TeV gravity), the search for violation of Lorentz Invariance[19], neutrino oscillation studies[20] and searches for neutrinos from Supernovae.

5 Future plans

IceCube plans to finish the baseline construction by the end of the 2010/2011 austral summer, including six extra strings with high quantum efficiency DOMs, making up a dense inner core of strings ("DeepCore")[21], hence improving the detection efficiency of low energy events. Both the horizontal interstring (72 m) and vertical DOM spacings are denser in this section. Out of the 60 DOMs on these strings, 10 will be placed above the central dust layer in the ice (with a vertical spacing of 10 m), and the remaining 50 at a vertical spacing of 7 m in the clearest ice below ($\lambda_{scattering} \sim$ 40-50 m and $\lambda_{absorption} \sim$ 220-230 m at 440 nm light wavelength, compared to ($\lambda_{scattering} \sim$ 20 m and $\lambda_{absorption} \sim$ 110 m above). This, combined with the use of the surrounding standard IceCube modules as a veto, will lower the detection threshold below 100

GeV, allowing more efficient neutrino oscillation and WIMP studies, as well as tau physics and southern sky point source searches.

The possibility of increasing the sensitivity of IceCube at higher energies is also under consideration. One idea is to surround IceCube by another ring of strings, increasing the sensitivity to weak astrophysical signals with hard spectra. New techniques for covering much larger volumes are also being tested with radio and acoustic devices deployed on IceCube strings.

6 Conclusion

Within the next few years, the cubic-kilometre neutrino telescope IceCube will collect an unprecedented number of neutrino events over a broad energy region, which will guarantee a high discovery potential. The ongoing searches for point sources, WIMP annihilations and GRBs look promising. DeepCore as well as the hybrid high-energy extensions will take IceCube's physics potential beyond what was originally planned.

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