

# Status of the IceCube Neutrino Observatory

## IceCube Collaboration

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## Abstract

The IceCube neutrino telescope, to be constructed near the Antarctic South Pole, represents the next generation of neutrino telescope. Its large 1 km<sup>3</sup> size will make it uniquely sensitive to the detection of neutrinos from astrophysical sources. The current design of the detector is presented. The basic performance of the detector and its ability to search for neutrinos from various astrophysical sources has been studied using detailed simulations and is discussed.

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## 1. Introduction

The observation of high energy neutrinos from distant astrophysical sources will open a new window on the sky, which will provide new information on the acceleration mechanisms at work in these objects and insight into the nature of cosmic radiation. The techniques of neutrino astronomy are now well known and there are several reviews on these schemes and their physics potential [1–3]. The AMANDA detector in the deep ice of the South Pole has successfully demon-

strated our ability to observe neutrinos by detecting the atmospheric neutrino flux at the expected level [4,5]. AMANDA has also been used to set limits on various astrophysical neutrino fluxes from point sources such as AGN and GRB, diffuse neutrino emission and WIMP annihilation in the sun [6,7].

The field of neutrino astronomy is on the threshold of a new era with the planned construction of the 1 km<sup>3</sup> IceCube neutrino detector [8]. The IceCube neutrino detector to be deployed more than 1 km deep in the antarctic ice at the

South Pole around the existing AMANDA detector represents the leap in instrumented volume and sensitivity over existing neutrino telescopes which will, hopefully, allow us to see sources through this new window on the universe for the first time.

The IceCube detector is designed to be sensitive to all three neutrino flavors over a wide range of energies. Muons induced from  $\nu_\mu$  neutrinos can be observed from  $10^{11}$  eV to over  $10^{18}$  eV, while  $\nu_e$  and  $\nu_\tau$  induced cascades can be reconstructed at energies above  $10^{13}$  eV and  $\tau$  events can be identified at energies above a PeV [9]. In this paper we describe the design of the IceCube detector, as well as the expected performance and current plans for deployment. A more detailed description of the performance capabilities of the IceCube detector can be found in [10].

## 2. The IceCube detector

The IceCube Cherenkov detector will be  $1 \text{ km}^3$  of ice instrumented with 4800 photomultiplier tubes (PMTs) deployed on a grid of 80 strings with 60 optical modules (OM) on each string. The grid spacing will be approximately 125 m and each string is instrumented over a depth of 1400–2400 m. A schematic view from the top of the detector is

shown in Fig. 1. At the surface there are 160 ice Cherenkov detectors that will provide detection of air showers at energies of  $\sim 1 \text{ PeV}$  and above.

The 60 OMs on each string are spaced at 17 m intervals. The PMT signals will be digitized within the OM housing, where they are given a time stamp with 5 ns accuracy and transmitted to the central counting house on the ice surface. Fig. 2 shows the geometric arrangement of a string and a CAD drawing of an OM. The OM digital signals at the surface will be processed by a string processor, an event trigger processor and subsequently an event builder. After the events are built in the DAQ they will be processed by reconstructing them in real time. They will subsequently be filtered into physics data sets and used in on-line detector monitoring. The trigger rate, dominated by downward going cosmic ray induced muons, is expected to be around 1700 Hz, while the atmospheric muon type neutrino events will be about 300 per day. A filtered dataset of 10 GBytes/day will be transmitted to the northern hemisphere for immediate further processing and physics analysis.

Construction of the detector is expected to begin in the Austral summer of 2004/2005 and continue for six years. During this construction period the detector will be in operation and grow in size

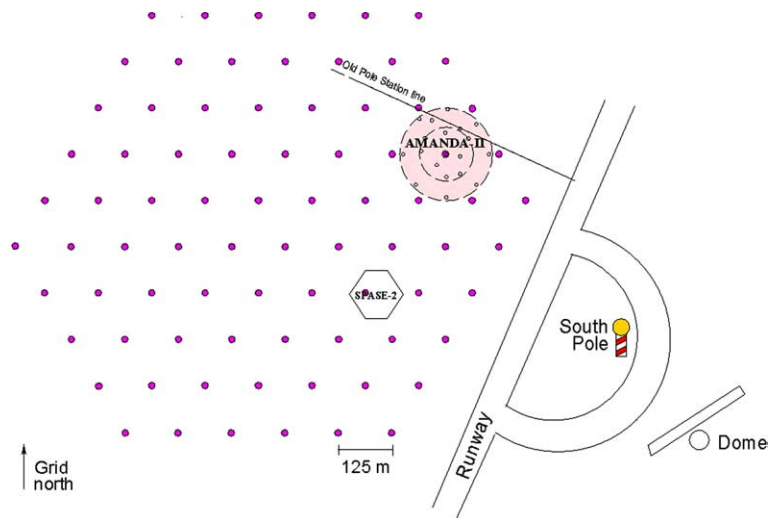


Fig. 1. Schematic diagram of the IceCube detector showing the arrangement of the 80 strings at the south pole station. The existing AMANDA detectors and the SPASE air shower array will be embedded in the new detector.

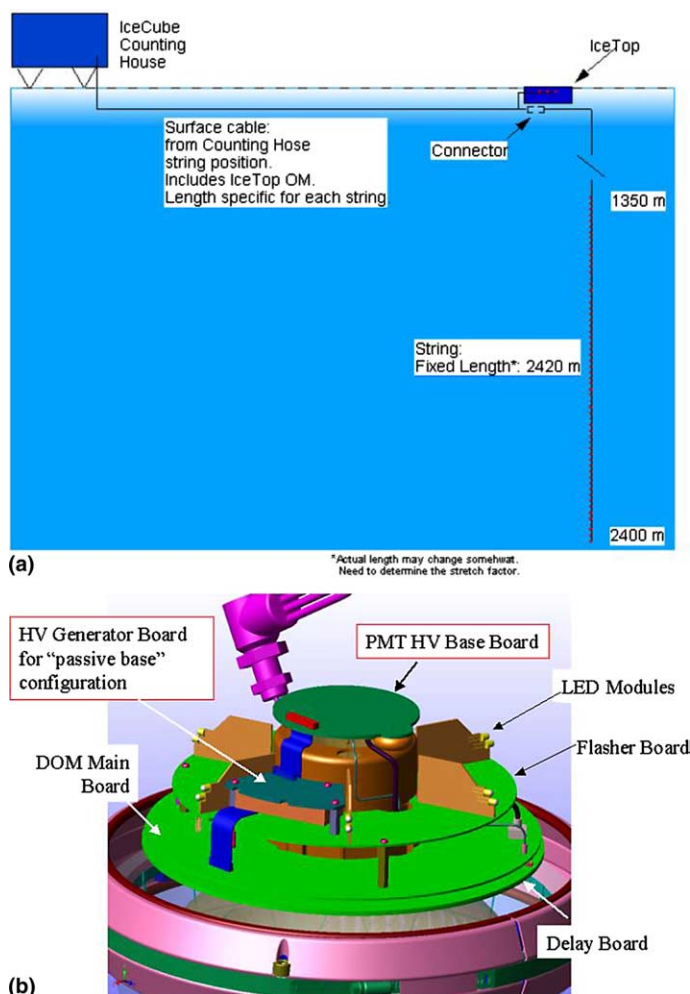


Fig. 2. (a) planned arrangement of the 60 optical modules on a string along with the surface air-shower detector. (b) preliminary design of the optical module (OM).

with each new string becoming operational within days of deployment.

### 3. General performance characteristics

Using detailed simulations we have analyzed the expected response of the detector to cosmic ray induced muons, atmospheric neutrinos and to a possible hard neutrino spectrum [10]. Table 1 shows the event counts for the three sources after one year of on-time at both the trigger level and filtered level with full re-

Table 1

Event rates are given for one year of signal and background. The signal expectation corresponds to a source flux of  $E_v^2 \times dN_v/dE_v = 10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}$

	Trigger	Level 2
Astrophysical $\nu$	$3.3 \times 10^3$	$1.1 \times 10^3$
Atom $\nu$	$8.2 \times 10^5$	$9.6 \times 10^4$
Cosmic ray $\mu$	$4.1 \times 10^{10}$	$10 \times 10^4$

The expectation for atmospheric neutrino induced muon events is based on [15] and it includes the prompt component according to [16] (rqpm).

construction and cuts applied to reduce the cosmic ray induced muon background. For an assumed flux of the hard neutrino source of

$E_v^2 \times dN_v/dE_v = 10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}$  we should observe more than 1000 events.

Shown in Fig. 3 are both the effective area and angular resolution for muons of various energies as a function of the zenith angle. Notice that for neutrinos greater than 100 TeV the selection allows for observation of downward going events because the background becomes so low at these energies. The angular resolution is below one degree at energies over 1 TeV and we expect to do better when we include the information from the waveform digitization.

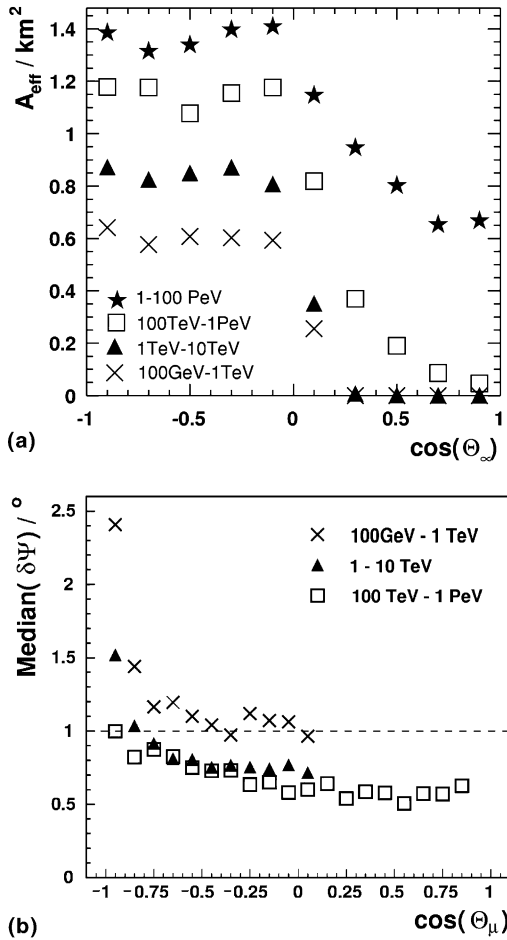


Fig. 3. (a) the effective area as a function of cosine zenith angle after all background removal cuts for different energy ranges. (b) the median space angle pointing resolution for muons versus cosine zenith angle of the incident track.

#### 4. Sensitivity to astrophysical sources of neutrinos

Theoretical models for the fluxes of diffuse high energy neutrinos are linked to the known flux of very high energy cosmic rays [11–14]. Shown in Fig. 4 is the predicted sensitivity of IceCube for detecting a diffuse flux with an  $E^{-2}$  spectrum. The harder spectrum enables discrimination from the background atmospheric neutrino flux. Fig. 5 shows an event display for simulated muons of 10 TeV and 6 PeV, respectively. An effective energy cut can be applied by cutting on channel hit multiplicity. For one year of observation a cut of 227 hits would leave an atmospheric neutrino background of 8 events, while a source strength of  $E_v^2 \times dN_v/dE_v = 10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}$  would yield 74 signal events. After one year we are well below the Waxman and Bahcall diffuse bound. After three years of running an overall flux limit of  $E_v^2 \times dN_v/dE_v = 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}$  is obtained (Fig. 6). For the Mannheim, Protheroe and Rachen model we achieve a sensitivity of 2% of the predicted flux and for the model of Stecker and Salamon we achieve a sensitivity of  $2.3 \times 10^{-4}$  of the prediction.

For point sources of astrophysical neutrinos additional background rejection can be achieved

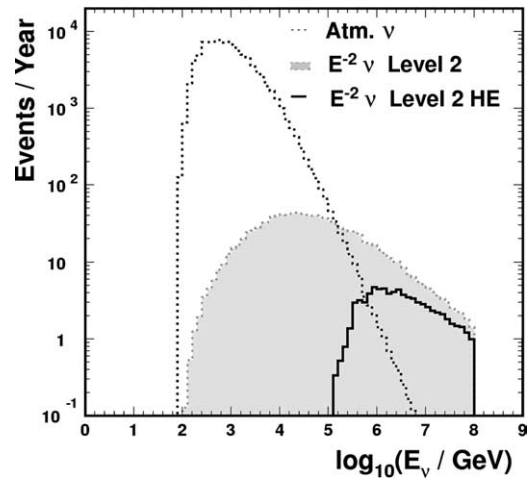


Fig. 4. Energy spectra of detected neutrinos for the atmospheric neutrino background (dashed) and a hypothetical  $E^{-2}$  source before (shaded) and after (solid line) an energy cut. A flux of  $E_v^2 \times dN_v/dE_v = 10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}$  was assumed.

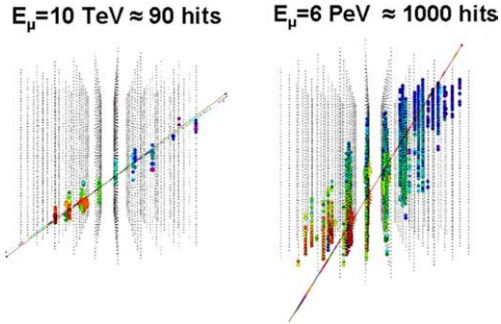


Fig. 5. Event display of simulated muon tracks of 10 TeV and 6 PeV, showing the difference in the number of tubes hit.

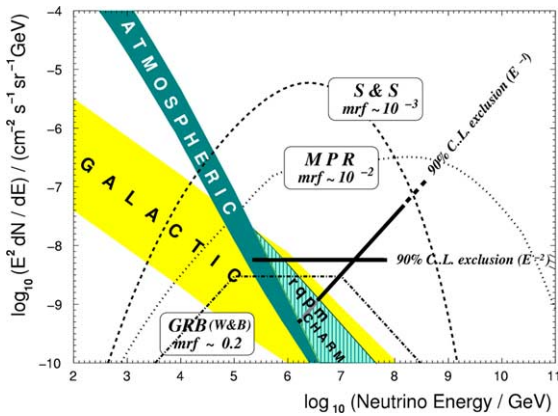


Fig. 6. Expected sensitivity of the IceCube detector. The thick solid line indicates the 90% c.l. limit setting potential for an  $E^{-2}$  type spectrum for a time period of three years (see text for details). The thin solid line illustrates the GRB sensitivity for the reference spectrum [12].

using the neutrino direction. By searching in a one degree radius we can reduce the background sufficiently with a channel hit cut of 30. This suppresses atmospheric neutrinos below about 1 TeV and allows an almost background free detection sensitivity for point sources. The average flux upper limit of  $E_v^2 \times dN_v/dE_v = 5.5 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}$  can be obtained after one year. After five years the sensitivity approaches  $E_v^2 \times dN_v/dE_v = 1.7 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}$ .

For detection of high energy neutrino emission from  $\gamma$ -ray bursts IceCube will cut on both direction and time as given by satellite observations allowing an essentially background free search.

Waxman and Bahcall's predicted energy spectrum for GRB neutrinos is also shown in Fig. 6. For 500 bursts IceCube would expect 13 neutrino events with 0.1 background expectation. The flux limit we should achieve is 20% of the predicted flux.

In addition to the searches listed above, IceCube will also perform sensitive searches for supernovae neutrino emission and dark matter candidate WIMP particles. Cosmic ray composition studies will also be performed using the combined surface air shower detectors of Ictop in coincidence with the muon detection capability of the IceCube detector.

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