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The IceCube neutrino observatory: status and initial results

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Abstract. The IceCube collaboration is building a cubic kilometer scale neutrino telescope at a depth of 2 km at the geographic South Pole, utilizing the clear Antarctic ice as a Cherenkov medium to detect cosmic neutrinos. The IceCube observatory is complemented by IceTop, a square kilometer air shower array on top of the in-ice detector. The construction of the detector is nearly finished with 79 of a planned 86 strings and 73 of 80 IceTop stations deployed. Its completion is expected in the winter 2010/11. Using data from the partially built detector, we present initial results of searches for neutrinos from astrophysical sources such as supernova remnants, active galactic nuclei, and gamma ray bursts, for anisotropies in cosmic rays, and constraints on the dark matter scattering cross section. Further, we discuss future plans and R&D (research and development) activities towards new neutrino detection techniques.

1 Introduction

The origin and acceleration of cosmic rays to energies beyond 10^{20} eV is one of the big open questions in astroparticle physics today. Astrophysical objects that are promising source candidates include supernova remnants or microquasars in our own galaxy, or, for cosmic rays at the highest energies, extragalactic objects like active galactic nuclei or gamma-ray bursts. Carrying electric charge, the cosmic rays are deflected in magnetic fields during their propagation and possibly do not point back to their source; an effect which is stronger at lower energies. However, hadronic cosmic rays interacting in matter or photon fields at the source should produce high energy neutrinos that would arrive at Earth undeflected and their energy spectrum will carry valuable information of the physical processes at the source. For a recent review see e.g. Anchordoqui and Montaruli (2010).

To detect the small expected flux of astrophysical neutrinos large detector volumes are necessary. Currently, the most competitive limits on the neutrino flux in the TeV and PeV energy range are placed by Cherenkov telescopes using natural transparent media like water or ice as a detection medium. These include fresh water, e.g. the Baikal neutrino telescope (Aynutdinov et al., 2009) in Lake Baikal, sea water, e.g. the ANTARES neutrino telescope (Coyle, 2009) in the Mediterranean Sea, or glacial ice as used for the IceCube neutrino observatory presented here.

2 The IceCube observatory

The IceCube observatory is currently under construction at the geographic South Pole. It comprises a 1 km^3 in-ice detector measuring Cherenkov light from charged particles traversing the ice and the IceTop air shower array on the surface. The in-ice detector consists of 5160 digital optical modules (DOMs) installed on 86 vertical strings instrumented at depths between 1450 m and 2450 m and deployed into the ice using a hot water drill. Each DOM consists of a photomultiplier tube (PMT) (Abbasi et al., 2010e) housed in a glass pressure sphere and electronics to digitize, timestamp, and transmit signals to the central data acquisition system (Abbasi et al., 2009b) located in the IceCube laboratory on the surface. IceTop is made up of 160 clear-ice tanks, each equipped with a low-gain and a high-gain DOM. Pairs of IceTop tanks, called stations, are installed below the snow surface, on top of the in-ice strings. Recent results from IceTop have been presented at this conference (Kislat, 2011).

The IceCube observatory with all its components is schematically shown in Fig. 1. Eighty strings of the in-ice array are installed on a regular triangular grid with a spacing of 125 m. In their center, in the deep, exceptionally clear ice,

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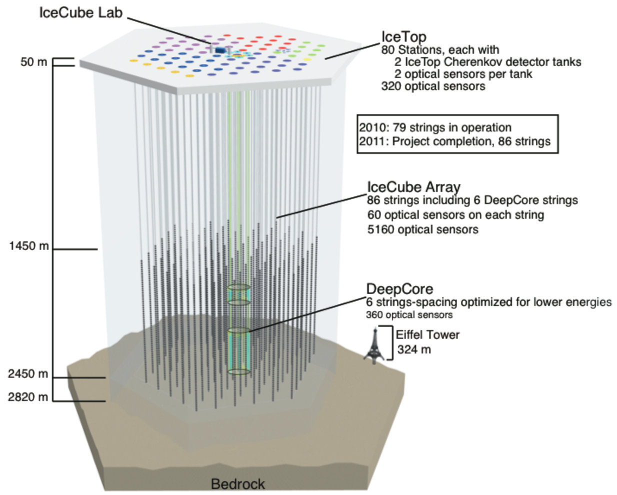

Fig. 1. Schematic of the IceCube neutrino observatory.

the DeepCore array is installed. It consists of six additional strings with high quantum efficiency DOMs and with closer spacing, both horizontally and between the DOMs. Using the outer strings as a veto against atmospheric muons, DeepCore is designed to lower the energy threshold of IceCube to $< 100\,\mathrm{GeV}$ (Wiebusch, 2009). Currently, in the austral winter 2010, 79 of the 86 IceCube strings, including the six DeepCore strings, and 73 out of 80 IceTop stations have been deployed and are successfully taking data. The construction will be completed in the austral summer 2010/2011.

The trigger rate of the currently operating 79 string detector is approximately 2.3kHz, mostly caused by muons from extensive air showers penetrating the ice into the deep in-ice detector. Atmospheric neutrinos only contribute about 30mHz to the overall trigger rate. Although atmospheric muons are a valuable tool for calibration, discriminating neutrinos from the atmospheric background is the big challenge in the experiment. It is achieved by using the Earth as a filter against atmospheric muons and searching for events with an upward-going track as a signature, originating from muons produced in neutrino interactions in the ice or bedrock around the detector. Due to the neutrino-nucleon cross section increasing with increasing neutrino energy, the Earth becomes opaque to neutrinos at PeV energies. At these energies, the characteristic neutrino signature are downward-going tracks, and neutrinos are discriminated from atmospheric muons by the harder energy spectrum expected from cosmic sources. An astrophysical neutrino flux would eventually emerge as a hard component from the measured energy spectrum.

Apart from muon neutrinos, identified by the “track like” signature of the muon produced in a charged current interaction, IceCube is also sensitive to all other neutrino flavors. Electromagnetic and/or hadronic cascades developing in interactions of neutrinos of all flavors inside the detector volume are detected as “point like” sources of light due to the large spacing of the DOMs compared to the dimensions of the cascade. Here, the signature of a neutrino is a cascade observed in the detector without an incoming particle track.

3 Recent results

IceCube has delivered a variety of interesting and competitive scientific results already during its construction phase, taking data with the partially completed detector. In the following, selected recent results from the IceCube neutrino observatory will be presented.

3.1 Neutrino point sources

The IceCube collaboration has performed several different searches for point-like neutrino sources, including all sky searches for steady sources, sources variable in time, and observing pre-selected sources of special interest.

Time integrated search. For the first time, an all sky search has been performed with the data from the IceCube 40 string configuration measured during 375.5 days of live time in 2008 and 2009 (Abbasi et al., 2010b). The analyzed data consist of approximately 40000 track like events. 40% of the events originate from the northern hemisphere (upward-going events) and are dominated by atmospheric neutrinos in the ten to a few hundred TeV energy range. The remaining events, coming from the southern hemisphere, predominantly consist of high energy atmospheric muons propagating into the in-ice detector. They are selected to have typical energies in the PeV range where the flux of cosmic neutrinos is expected to emerge from the softer atmospheric muon spectrum.

The data are analysed using an unbinned likelihood ratio method (Braun et al., 2008). Based on the reconstructed direction of the track and an energy estimator we search for an excess of events exceeding the background hypothesis. The data are modeled as a two component mixture of signal and background, leaving the source strength and spectral slope as free parameters in the likelihood maximization. The sky map of all events used in the search is shown in Fig. 2 together with the p-values calculated for each direction. The highest significance (pre-trial p-value: $5.2 \cdot 10^{-6}$) is observed in the direction 113.75° right ascension, 15.15° declination. In trials using scrambled data sets, 18% of all scrambled data sets have an equal or higher significance somewhere in the sky.

The non-observation of a neutrino point source allows us to place upper limits on the neutrino flux from point-like sources. In Fig. 3 the sensitivity and discovery potential for sources with an E^{-2} energy spectrum are shown as a function of declination. Upper limits on the muon (anti-)neutrino flux for 35 a priori selected point-source candidates (Abbasi et al., 2010b) are indicated.

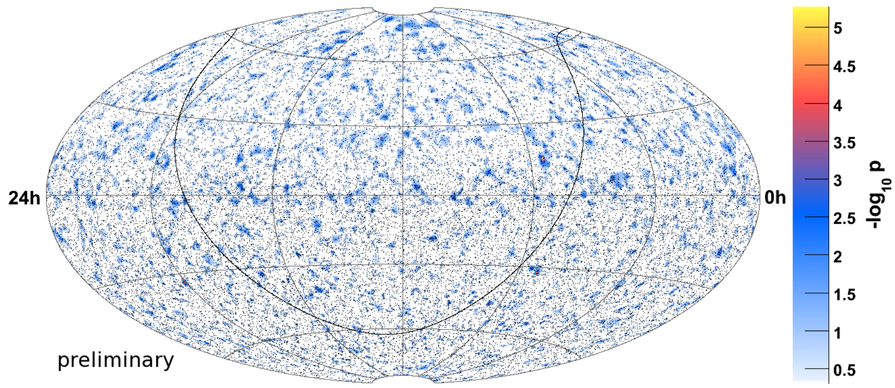

Fig. 2. IceCube 40 string sky map and pre-trial p-values. The black dots represent the directions of all events used in the analysis. The color scale represents the pre-trial p-values.

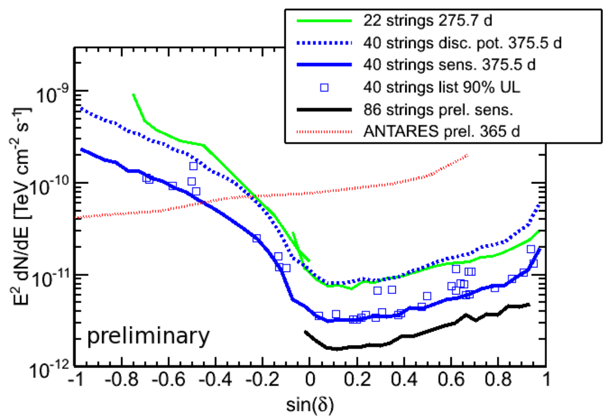

Fig. 3. Sensitivity for a point-like source with an E^{-2} flux of muon neutrinos and anti-neutrinos as a function of declination. Upper limits (90% C.L.) on the flux from 35 a priori selected sources are given (blue squares). For comparison, sensitivities from a previous analysis (Abbasi et al., 2009a) and the predicted sensitivity for the full IceCube detector and the ANTARES experiment (Coyle, 2009) are indicated. In addition the discovery potential for the IceCube 40 string configuration is shown.

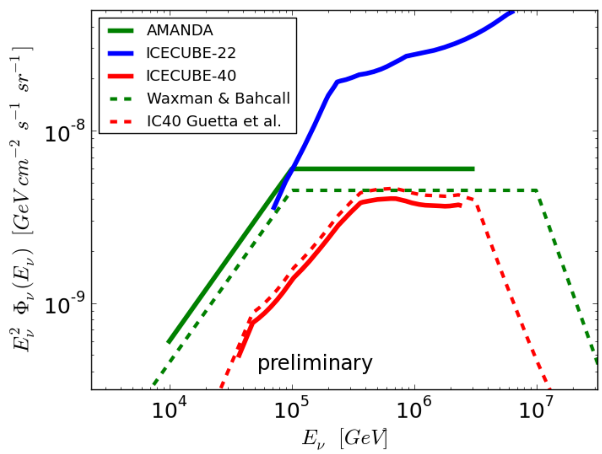

Fig. 4. IceCube 40 string upper limit (red curve) on the prompt neutrino flux from gamma-ray bursts (90% C.L.) compared to previous limits obtained with the AMANDA-II detector (Achterberg et al., 2008) and the IceCube 22 string configuration (Abbasi et al., 2010a). The dashed red curve is the expected flux summed over all 117 individually modelled GRBs (see text for details).

Neutrinos from gamma-ray bursts. Gamma-ray bursts (GRBs), like all transient astrophysical sources that are expected to produce neutrinos, allow for very sensitive analyses since the expected background can be largely reduced by requiring coincidence in both direction and time with the observed event. We have performed a search for prompt neutrino emission from 117 satellite detected gamma-ray bursts in the northern hemisphere in IceCube 40 string configuration data. The expected neutrino flux from each GRB was individually modeled using the model described in Guetta et al. (2004). We use an unbinned maximum likelihood analysis, assigning each IceCube event a signal probabiblity based on its angular and temporal distance from the GRB and taking into account an energy estimator. No coincident events have been observed and an upper limit on the prompt neutrino flux from GRBs has been calculated. Fig. 4 shows the model dependent upper limits at 90% confidence level.

Further point source searches. Several other searches for neutrinos from point like sources have been performed with IceCube data. Results from a stacking analysis using starburst galaxies (Dreyer, 2010) and from a search for spatial coincidence with the highest energy cosmic rays observed by the Pierre Auger and HiRES experiments (Lauer, 2011) have been reported at this conference.

Further analyses on a-priori defined lists of point-source candidates, including both, galactic and extra-galactic, and steady and time-variable sources, have resulted in the most stringent upper limits on the neutrino fluxes existing today for various source classes.

3.2 Diffuse neutrino fluxes

The diffuse neutrino flux is constituted by atmospheric neutrinos, cosmogenic neutrinos produced in the interaction of ultra high energy cosmic rays with the cosmic microwave background radiation, and a superposition of fluxes from unresolved point-like sources.

We have performed a search for an excess of muon (anti-) neutrinos in the atmospheric neutrino spectrum using the data from the IceCube 40 string configuration. The data were modeled as a composition of atmospheric neutrinos, prompt atmospheric neutrinos (a hard component originating mainly from the decay of charm particles) and an astrophysical contribution with an E^{-2} energy spectrum. The flux normalisation and corrections to the spectral shape were left as free parameters in the likelihood function used. The resulting atmospheric neutrino energy spectrum is in very good agreement with model predictions. No excess above the expected flux of atmospheric neutrinos has been observed. We place the currently most stringent upper limits on a diffuse flux of astrophysical neutrinos. At 90% confidence level the upper limit on a muon neutrino flux following an E^{-2} spectrum is $E^2\Phi < 8.9\cdot 10^{-9}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$ in the energy range $4.54 < \log_{10}(E_\nu/\mathrm{GeV}) < 6.84$. Figure 5 shows the measured muon neutrino energy spectrum and the upper limit on an E^{-2} neutrino flux. We exclude several of the more optimistic astrophysical neutrino production models at the 5σ level: the AGN jet-disk correlation model (Becker et al., 2005), the AGN jet model (Mannheim, 1995), and the blazar model (Stecker, 2005). We exclude a diffuse neutrino flux at the level of the WB upper bound (Waxman and Bahcall, 1998) at the 3σ level.

3.3 Indirect dark matter searches

IceCube also performs indirect searches for dark matter particles gravitationally trapped in the center of the Sun and the Earth. Their signature is a flux of neutrinos from a well defined direction produced in the annihilation of dark matter particles into standard matter, where the energy of the produced neutrinos depends on the mass of the dark matter particles and the dominant annihilation channel. The non-observation of an excess of neutrinos from the direction of the center of the Sun, the Earth, or the galactic center allows us to place upper limits on the dark matter-nucleon interaction cross section as a function of the mass of the dark matter particle for different dark matter models.

One promising dark matter candidate is the lightest supersymmetric particle, the neutralino. We have searched for an excess of neutrinos from the direction of the Sun in the data of the IceCube 22 string detector. No events above the expected background have been observed. For neutralinos with spin-independent interactions with ordinary matter, IceCube is only competitive with direct detection experiments if the neutralino mass is sufficiently large. On the other hand, for neutralinos with mostly spin-dependent interactions, IceCube places the most stringent limits for neutralino masses above 250 GeV (Abbasi et al., 2009c).

3.4 Cosmic ray anisotropy

With over 10^9 cosmic ray induced atmospheric muons measured every year in the in-ice detector, IceCube is well suited to study anisotropies in the cosmic ray flux. We have analysed the arrival directions of $4.3\cdot 10^9$ atmospheric muons detected with the IceCube 22 string configuration. The median energy of the cosmic ray particles inducing the air showers is 20 TeV and the muons are reconstructed with a median angular resolution of 3°. We observe a large scale anisotropy in the right ascension of the arrival directions with a first harmonic amplitude of $6.4\cdot 10^{-4}$ (Abbasi et al., 2010d). Our result represents the first measurement in the multi-TeV energy range covering the entire southern hemisphere. The phase of the observed anisotropy matches the one of previously measured cosmic ray anisotropies in the northern hemisphere by the Tibet (Amenomori et al., 2006) and Milagro (Abdo et al., 2009) experiments, indicating that we observe a continuation of the effect measured by these experiments.

4 R&D activities

To enhance the capabilities of the IceCube observatory the collaboration conducts a vigorous R&D program. The detection of the small neutrino flux predicted at the highest energies ($E_\nu > 10^8$ GeV) requires detector target masses of the order of 100 gigatons, corresponding to 100 km^3 of ice. The optical Cherenkov neutrino detection technique is not easily scalable from 1 km^3-scale telescopes to such large volumes. Promising techniques with longer signal attenuation lengths, allowing for the sparse instrumentation of large volumes of Antarctic ice, are the radio and acoustic detection methods. The radio approach utilizes the Askaryan effect, the coherent emission of radio waves from the charge asymmetry developing in an electromagnetic cascade in a dense medium (Askaryan, 1962). Acoustic detection is based on the thermo-acoustic sound emission from a particle cascade depositing its energy in a very localized volume causing sudden expansion that propagates as a shock wave perpendicular to the cascade (Askaryan et al., 1979).

The IceCube collaboration has developed and installed several test setups to study the feasibility of these techniques at the South Pole. This includes the development of sensors and data acquisition systems suitable for Antarctic conditions and the measurement of the properties of the ice relevant for the propagation and detection of radio or acoustic signals. The quantities of interest include the signal attenuation length, the noise level, the depth dependent index of refraction (or sound speed accordingly), and the characterization of possible transient backgrounds. IceCube's radio extension consists of several radio frequency detectors for the frequency range from 100 MHz up to 1 GHz and calibration equipment deployed as part of the IceCube array at depths between 5 m and 1400 m (Landsman et al., 2010).

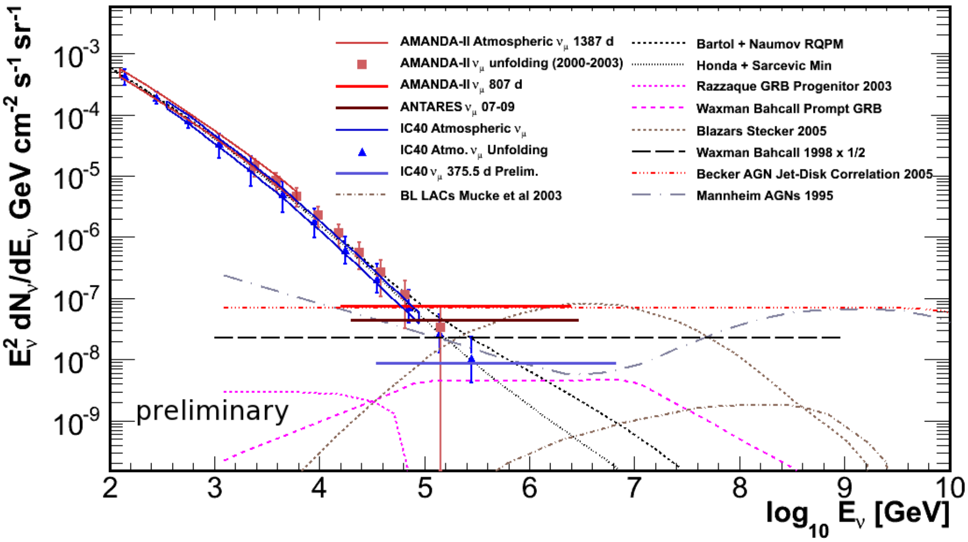

Fig. 5. Atmospheric muon neutrino spectrum measured with the IceCube 40 string configuration and upper limit (90% C.L.) on an E^{-2} astrophysical diffuse neutrino flux (blue curves; see also Grullon (2010)). The blue triangles are the result from an independent unfolding analysis of IceCube 40 string data (Abbasi et al., 2011). For comparison several experimental limits (Abbasi et al., 2009d, 2010c; Achterberg et al., 2007; Anton, 2010) and theoretical flux predictions for atmospheric (Barr et al., 2004; Enberg et al., 2008; Fiorentini et al., 2001; Honda et al., 2007) and astrophysical (Becker et al., 2005; Mannheim, 1995; Mücke et al., 2003; Razzaque et al., 2003; Stecker, 2005; Waxman and Bahcall, 1997, 1998) neutrinos are given.

The South Pole Acoustic Test Setup (SPATS) comprises four strings instrumented with acoustic transmitters and receivers co-deployed in IceCube boreholes at depths down to 500m (Karg, 2011).

We also investigate the possibility of extending the IceTop air shower detector with an array of radio antennas, measuring the coherent geosynchrotron radiation emitted by air shower electrons and positrons in the Earth's magnetic field. The radio signal in the frequency band from a few MHz to 150MHz constitutes a third, complementary measurement of the air shower properties in addition to the charged particles on ground level measured with IceTop and the hard muon component measured in the in-ice detector. We expect improved sensitivity in the following three different physics analyses. Cosmic ray composition studies will be enhanced through an independent measurement of the depth of the shower maximum. Ultra high energy cosmic ray photons can be detected over an increased range of zenith angles as air showers without a muon component in the deep-ice. The extended detection area can be used as a veto against air shower muon bundles in the in-ice detector in searches for extremely high energy neutrinos. As a first step towards a radio surface detector, a Radio Air Shower Test Array (RASTA) is described in Böser (2010).

5 Conclusions

The IceCube observatory is very close to its completion and is detecting neutrinos on a regular basis. About 20000 neutrinos have already been observed with the partially built detector. The measured neutrino flux is still in good agreement with atmospheric expectations, but we are beginning to explore astrophysically interesting flux regions.

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