RECENT RESULTS FROM ICECUBE

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High-energy neutrinos provide a new window onto many processes. Locally, high-rate detection of atmospheric neutrinos allows probes of cosmic ray air shower physics and neutrino oscillations. Neutrinos may also be produced at the acceleration sites of the highest energy cosmic rays and in other astrophysical processes, such as WIMP annihilation, and the detection of such particles would allow unique probes of these processes. Here we review recent results on these subjects obtained with the recently-completed IceCube neutrino detector, with emphasis on the recent observation of neutrinos at PeV energies.

1 IceCube

The IceCube neutrino detector (Fig. 1), located at the geographic south pole, was designed primarily for detection of astrophysical sources of TeV-PeV neutrinos. These are expected to be produced in the sites of high energy cosmic ray acceleration [1], for example by one of the processes:

$$p + \gamma \rightarrow \pi^+ + X \rightarrow \nu_\mu + \mu^+ + X \tag{1}$$

$$p + p \rightarrow \pi^+ + X \rightarrow \nu_\mu + \mu^+ + X \tag{2}$$

Although this paper focuses on astrophysical searches, process (2) is also responsible for high rates of neutrino production in cosmic ray interactions in the Earth's atmosphere, to which we will return later on. To detect the expected low rate of such astrophysical events, IceCube [2] instruments a km^3 of antarctic glacial ice. It detects neutrinos by observing Cherenkov light from secondary charged particles produced in neutrino-nucleon interactions in the ice. This light is detected by an array of 5160 digital optical modules (DOMs), each containing a photomultiplier and readout electronics housed in a glass pressure sphere. These are arranged into an array of 86 vertical strings, each containing 60 DOMs at depths between 1450 m and 2450 m. Outside of the Deep Core low-energy subarray, these DOMs are vertically spaced at 17 meter intervals and the strings are on average 125 m apart horizontally. This sparse instrumentation allows a very large volume to be observed but results in an energy threshold of around 100 GeV. The Deep Core subarray fills in the center of the detector with a denser array of photomultipliers and provides a lower energy threshold of 10 GeV in a region of the array. Deployment of the IceCube array was completed in December 2010, with data-taking on the completed detector beginning May 2011.

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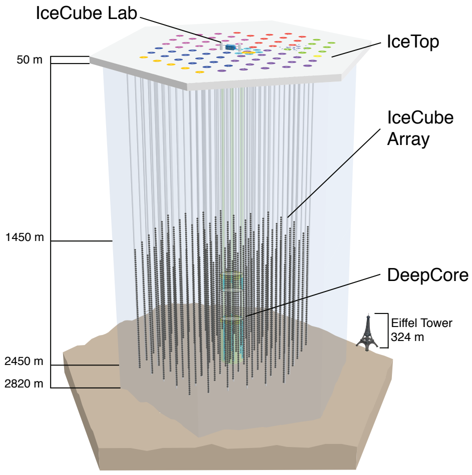

Figure 1: The IceCube neutrino detector. Colors at the surface indicate the year of deployment. The IceTop surface array is a cosmic-ray air shower detector located above IceCube which can be used for direct studies of cosmic rays or as an air-shower veto for the in-ice detector.

2 Detector Performance

Although IceCube is sensitive to all neutrino flavors from all directions, best sensitivity to different processes may prefer certain flavors and directions. As a result of their long track lengths ($\gg$ 1 km at TeV energies), muons produced in ν_μ charged-current interactions both provide good angular resolution ($\sim 1^\circ$, $< 0.5^\circ$ at high energies) and allow the detection of neutrinos with interaction vertices outside the detector volume. Because of the large backgrounds from cosmic ray muons, muon neutrino analyses are usually limited to tracks coming up into the detector from below (the northern sky) where air showers are filtered out by the Earth. Energy resolution is also reduced for uncontained muon neutrino events as the vertex is unobserved and so the muon energy in the detector sets only a lower limit on the energy of the original neutrino. Other neutrino interactions (ν_e, ν_τ, and neutral-current) create electromagnetic and hadronic showers in IceCube with typical lengths of on order 10 meters. On the scale of IceCube's instrumentation, these are well-approximated as point sources of light. Because the event is contained within the detector, much better energy resolution is achievable (10% in deposited energy above 10 TeV) but the lack of extension results in poor angular resolution of typically 15° that is a strong function of energy, improving at high energies where the events emit more light. The topologies of these events and direct observation of the neutrino vertex in contained events generally allows much better rejection of cosmic ray muons, improving sensitivity to downgoing events. Major backgrounds for IceCube are cosmic ray muons in the downgoing region (the south) and, for astrophysical neutrino searches, atmospheric neutrinos from all directions.

3 Results

IceCube has the ability to probe a large variety of physics topics through the measurement of the properties of neutrinos and cosmic rays over six orders of magnitude in energy from the 10 GeV threshold of Deep Core to the highest energy neutrinos at energies above 1 PeV. Described below is a partial list of recent IceCube neutrino results.

3.1 Atmospheric Neutrinos

Atmospheric neutrinos are produced in interactions of cosmic rays with the Earth's atmosphere primarily as a result of the decays of π and K mesons. At very high energies (100 TeV), a component from decays of charmed mesons has been predicted but not yet observed. These are

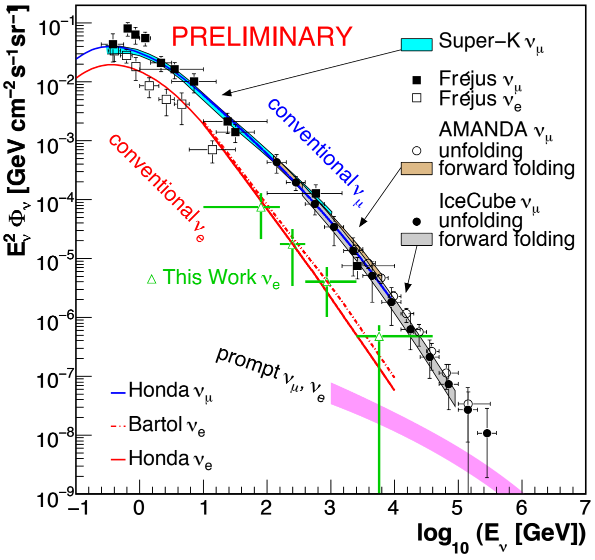

Figure 2: Atmospheric spectral measurements from IceCube and other experiments. Figure taken from Ref. 6. ν_μ measurements shown were taken using the 59-string IceCube array from 2009-2010. ν_e measurements were taken using the Deep Core subarray during 2010-2011.

detected in IceCube at the rate of 100,000 per year, giving the largest sample of atmospheric neutrinos ever obtained. Spectral measurements (Fig. 2) with muon neutrinos[4] have shown good agreement with predictions and with extrapolations from other experiments and are nearing the level required to test models of neutrino production from charmed mesons[5], although no evidence for a charm component has so far been observed.

With the completion of the IceCube array and the Deep Core subarray, it is now possible as well to measure the atmospheric ν_e flux. At TeV energies, the very high $\pi \rightarrow \mu$ branching fraction results in a suppression of ν_e relative to ν_μ, but subtraction of the ν_μ neutral-current rate inferred from ν_μ CC measurements from the measured in-ice shower rate allows a measurement of the ν_e component[6] (Fig. 2).

3.2 Neutrino Oscillations

The very high rate of atmospheric neutrinos in IceCube makes possible measurement of θ_{23} and Δm^2_{23} through measurement of muon neutrino disappearance. This probes a variety of oscillation baselines as a function of the width of the Earth, and so distance to the northern atmosphere, at various angles. Although IceCube is designed to be most sensitive at TeV energies, where the entire width of the Earth is less than one oscillation length, the 10-20 GeV threshold of the Deep Core subarray allows observation of oscillations. Initial results[3] show preliminary sensitivity to neutrino oscillations (Fig. 3). Forthcoming improvements to the analysis and future IceCube extensions such as PINGU will provide more precise measurements of mixing parameters in this high-statistics sample.

3.3 WIMP Annihilation

As the sun moves through the Galaxy, WIMP scattering on solar protons will cause dark matter to accumulate in the sun's core. When the density becomes sufficiently high, the WIMPs will begin to annihilate until an equilibrium is reached between the scattering-cross-section-set accumulation rate and the annihilation rate. Dark matter annihilation to final state leptons (e.g. τ) would be accompanied by production of neutrinos with energies characteristic of the WIMP mass. For masses above 10 GeV, these neutrino events could be detected in IceCube.

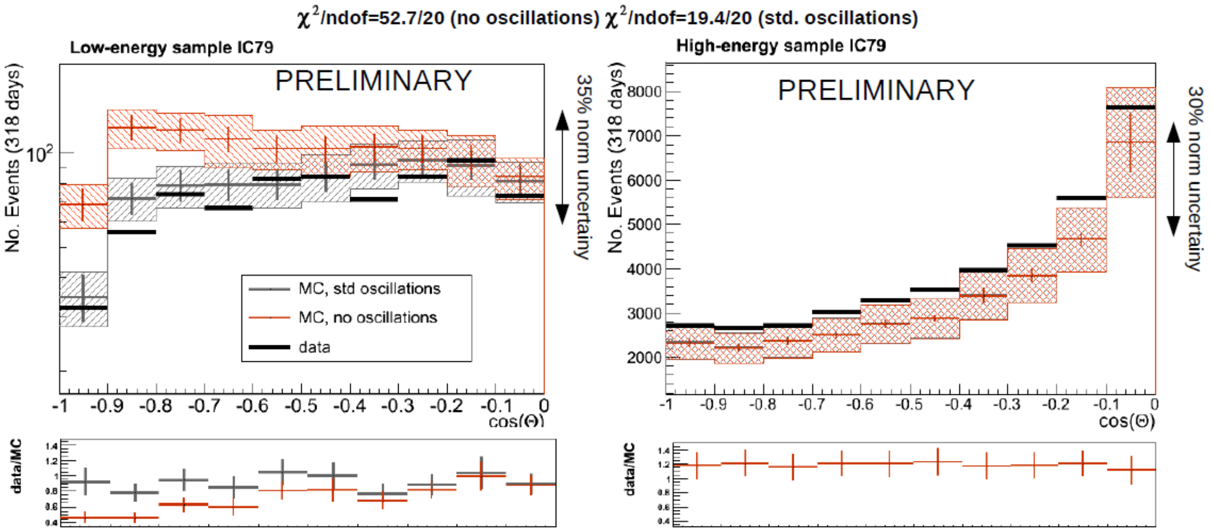

Figure 3: Preliminary Neutrino Oscillation Results in IceCube using 2010-2011 data. Using a preliminary analysis with the IceCube Deep Core subarray, clear evidence for oscillations is visible in the angular distribution of the events, which corresponds to the oscillation baseline. Future measurements will constrain the atmospheric mixing parameters.

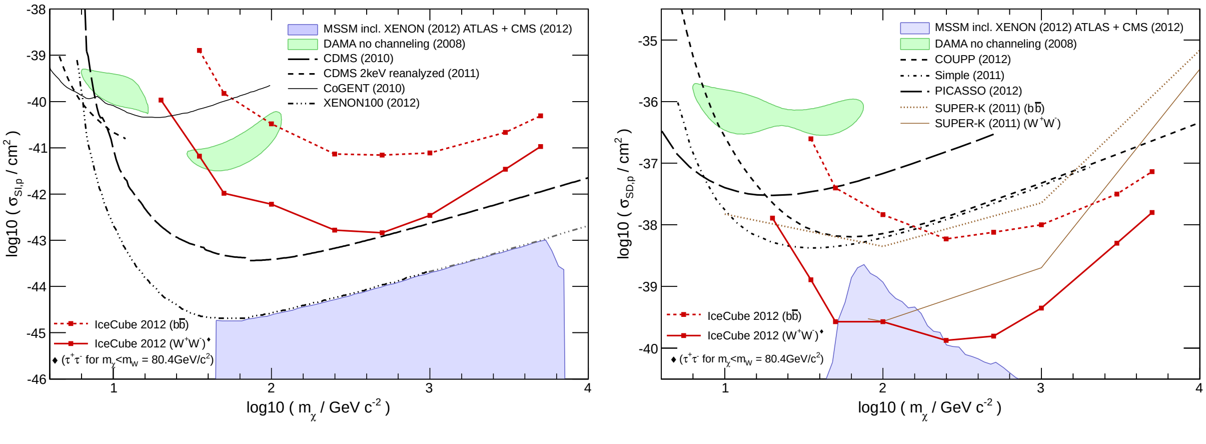

Figure 4: Limits on WIMP properties for spin-dependent (right) and spin-independent (left) channels from IceCube using data from 2010-2011. Equilibrium between accumulation of WIMPs in the solar core by scattering and annihilation implies sensitivity to the scattering cross-section. Because of the spin-$\frac{1}{2}$ target of hydrogen nuclei, sensitivity to spin-dependent interactions (right panel) is enhanced relative to most other experiments. Figures from Ref. 7.

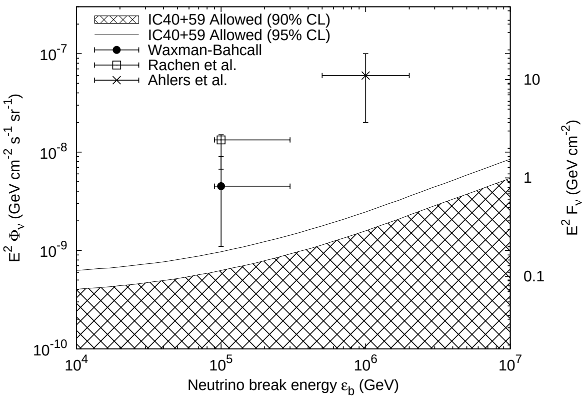

Figure 5: Limits from the IC40+IC59 GRB search (2008-2010 data). The vertical axes show the flux normalizations, while the horizontal axis (ϵ_b) shows the energy at which neutrino production in GRBs becomes efficient. This corresponds to the Δ resonance in the frame of the interactions in the GRB. Several theoretical models ruled out by this result are shown at the top. Figure from Ref. 8.

Table 1: Properties of the two PeV events. Uncertainties on the reconstructed energies include both statistical and systematic components and are dominated by systematic uncertainties in light propagation in the natural ice. The energies at which these events were observed were very close to the energy threshold for this analysis, at which it had sensitivity only to shower (rather than muon) events, typical of neutral-current, ν_e, or ν_τ interactions.

Date	Energy	Topology
Aug. 8, 2011	1040 ± 160 TeV	Shower
Jan. 3, 2012	1140 ± 170 TeV	Shower

Recent limits on this process [7] have begun to be competitive with other techniques (Fig. 4), especially for the spin-dependent cross-section. Neutrino observations will also provide important constraints on the properties of any otherwise-detected dark matter candidate particle by allowing direct probes of its annihilation properties if the scattering cross-section and mass of the candidate are known.

3.4 Gamma-Ray Bursts

Gamma-ray bursts offer one of the most promising candidates for resolution of the origin of ultra-high-energy cosmic rays with IceCube. If they are responsible for the highest-energy cosmic rays, interactions of protons during acceleration with the gamma-rich environment of the burst will inevitably cause the production of charged pions at some level. These will then decay to neutrinos at typical energies of 100 TeV - 1 PeV which will be visible to IceCube. Efforts to detect such neutrinos in coincidence with satellite-detected bursts have so far found no evidence for neutrinos produced in these bursts [8]. As IceCube has reached its design sensitivity at the levels of many predicted astrophysical neutrino fluxes, the limits set by these analyses (Fig. 5) are becoming increasing stringent and have begun to rule out some cosmic-ray interaction models.

3.5 High-Energy Analysis

A search for neutrinos produced by the GZK mechanism [9] recently observed two shower-type events (Tab. 1) with deposited energies of 1 PeV, approximately the analysis threshold. Although these events are much too low in energy to be produced by the GZK mechanism, they also are higher in energy than expected from the atmospheric neutrino spectrum, which should end in IceCube at around 100 TeV.

The major potential background for this type of high-energy neutrino is atmospheric decay of charmed mesons. The observed event rate is inconsistent with standard models [5] of charmed meson decay at 2.8σ, adding to a growing body of hints from other IceCube analyses for a hard spectral component at high energies [10,4,11]. However, the cross-section for very forward charm production is poorly constrained at present and lower-energy observations below 1 PeV will be required to better understand the nature of the neutrino population from which these two events arose. In particular, the flavor composition, energy spectrum, and angular distribution of the high-energy neutrino population will allow us to separate a potential astrophysical flux from the well-understand characteristics of a spectrum from charm decay. The angular spectrum is of particular interest, as downgoing atmospheric neutrinos should be accompanied into IceCube by muons from their parent air showers. The observation of muon-less downgoing neutrino events would then provide a strong suggestion that the events are astrophysical in origin. Answering all of these questions, especially given the 15° angular resolution on the two events, requires more statistics.

An in-progress follow-up analysis on the same 2-year dataset (2010-2012) uses neutrinos of all flavors with vertices contained within IceCube at energies above 50 TeV, approximately the point at which conventional atmospheric neutrinos (from π and K decay) are expected to cross over with any additional high-energy component. Performing an unbiased search for all flavors of neutrinos from all directions in this energy range will allow characterization of whatever neutrino population is responsible for these two PeV events and should clarify their origin.

4 Conclusions

With the completion of the IceCube neutrino detector, its sensitivity has begun to reach the level required to probe many models of astrophysical neutrino production, both from particle physics processes such as WIMP annihilation and cosmic ray acceleration, and to probe non-standard atmospheric neutrino physics such as charmed meson production. Preliminary results from the Deep Core subarray have shown the first evidence for neutrino oscillation measurement capabilities in IceCube and the first direct evidence for neutrino oscillations in the 20-50 GeV energy range. As IceCube has reached the sensitivity to probe astrophysical neutrino production, increasingly stringent limits have been set in some channels such as GRBs, ruling out some models, and the first hints of a neutrino population beyond conventional atmospheric neutrinos have begun to appear. With the observation of two neutrinos at energies above a PeV in 2012, these hints have become stronger although still not conclusive. Additional data from a follow-up analysis to this observation should soon begin to answer many of the questions about the nature and origins of this apparent high-energy component of the neutrino spectrum.

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