Toward Precision Neutrino Physics with DeepCore and Beyond

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Abstract

DeepCore, the fully contained low energy extension to IceCube, extends IceCube's sensitivity for indirect dark matter searches and atmospheric neutrino oscillation physics, as well as astrophysical neutrino sources in the southern sky. With the first year of DeepCore data we observe a significant sample of atmospheric neutrino-induced cascades, confirming the scientific potential of this approach. We discuss ideas for PINGU, a further IceCube infill array which aims for an energy threshold of around 1 GeV to support a precision IceCube neutrino physics program. In the longer term, we are exploring the feasibility of a precision neutrino physics program with a multi-megaton, sub-GeV detector in the Antarctic ice cap.

Keywords: astroparticle physics, neutrino oscillations, dark matter

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1. Introduction

The IceCube Neutrino Observatory is now fully operational, with the final instrumentation deployed in early 2011. Located at the South Pole, it exploits the Antarctic ice cap to detect neutrinos via Cherenkov radiation emitted by secondary particles produced in neutrino-nucleon interactions in or near the detector. The Digital Optical Modules (DOMs) which detect the Cherenkov light are deployed in a relatively sparse three-dimensional array at depths of

1450-2450 m below the surface of the ice cap: 78 long 'strings' of modules form a triangular grid with a spacing of 125 m, with each string bearing 60 DOMs spaced by 17 m over the 1 km instrumented depth. This detector geometry was optimized for the detection of relatively energetic neutrinos, $E_\nu \gtrsim 1$ TeV, such as might be emitted from astrophysical accelerators of the cosmic rays. At lower energies, the flux expected from astrophysical sources would be obscured by atmospheric neutrinos produced in extensive air showers formed when cosmic rays interact in the Earth's atmosphere. While IceCube remains relatively efficient for neutrinos above roughly 100 GeV, sensitivity to neutrinos at lower energies was not a primary goal of the IceCube design.

An extension of the original IceCube detector, known as DeepCore, was added in order to extend IceCube's reach to lower energies. This extension incorporates 8 additional strings of DOMs, which are deployed in the center of the IceCube array resulting in spacings of 40-75 m between strings. On each string, 50 DOMs are deployed at depths of 2100-2450 m (the bottom third of the main array), for a vertical spacing of 7 m. The DOMs are identical to standard IceCube DOMs, except for the use of high quantum efficiency (HQE) PMTs exploiting Hamamatsu's "super-bialkali" photocathode material, which is approximately 35% more efficient than our standard PMTs (averaged over the detected Cherenkov spectrum). The combination of denser spacing and higher quantum efficiency results in approximately 5 times higher efficiency for the detection of Cherenkov photons in this region, substantially lowering the energy threshold for events in this region.

In addition to the higher density of instrumentaion, the optical properties of the ice at DeepCore depths are naturally superior to those in the rest of the IceCube volume, with scattering lengths up to 40-50 m and considerably longer absorption lengths. This contributes to the lower energy threshold and also improves the quality of the information recorded about every event. The position of DeepCore at the bottom center of IceCube also permits the identification and rejection of events triggered by penetrating atmospheric muons rather than neutrinos with high efficiency, using the non-DeepCore volume as an active veto region. For the purposes of data analysis, the “fiducial” DeepCore detector includes the bottom 22 DOMs of the nearest IceCube strings as well as the additional DeepCore strings; the volume used for vetoing consists of three complete rings of strings, as shown in Fig. 1. For the 2010 data run, when only 79 IceCube/DeepCore strings had been deployed, a smaller DeepCore configuration of 13 strings was used, whereas 20 strings are included in the fiducial detector for the 2011 run (including two deployed in the center of DeepCore as part of the final construction season).

The initial results from analysis of the DeepCore data, discussed in Section 2 below, have led us to investigate the scientific potential of further increases in instrumentation in the DeepCore volume for studies of even lower energy phenomena. Preliminary studies of such a detector, referred to as the Precision IceCube Next Generation Upgrade (PINGU) are discussed in Section 3.

2. DeepCore

Because the focus of DeepCore physics is on neutrinos at relatively low energy, the DeepCore trigger is set to a very low threshold. We demand only three of the 664 total DOMs in the DeepCore fiducial region register “locally coincident” hits due to Cherenkov photons within a 2.5 μs window to trigger readout of the entire IceCube detector. (Locally coincident hits are those in DOMs where one of the four neighboring DOMs on the string also detected a hit within a ± 1 μs window.) This low threshold is possible due to the low noise rates of the DOMs, around 500 Hz on average in the cold and extremely pure ice. This setting produces a DeepCore trigger rate of approximately 185 Hz, primarily due to penetrating atmospheric muons which also meet the primary IceCube trigger condition. An online background rejection algorithm compares the times of each coincident hit in the veto region to the time characteristic of the hits in the fiducial volume, and rejects events where a coincident hit is found with a space-time separation consistent with the speed of light (indicative of a muon passing through the veto region). This algorithm reduces the event rate

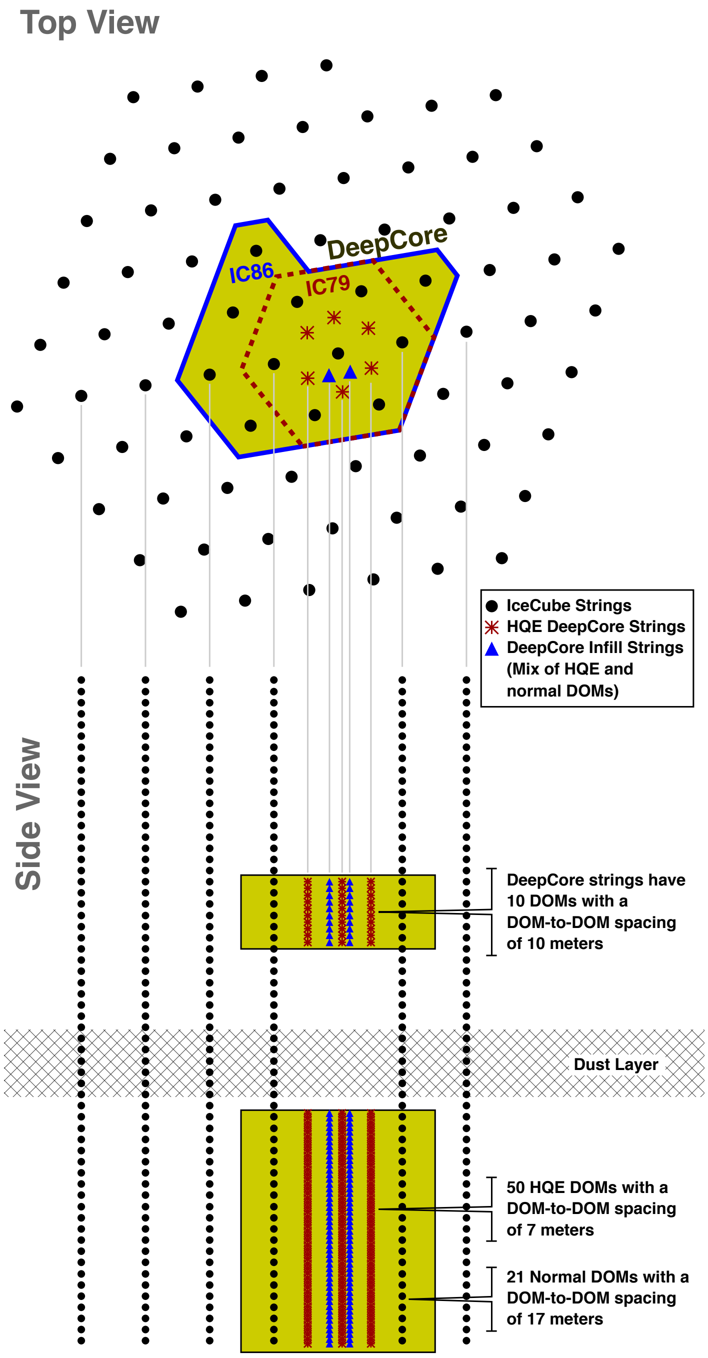

Figure 1: Schematic layout of DeepCore within IceCube. The shaded region indicates the fiducal DeepCore volume, at the bottom center of IceCube, plus an extra layer of DOMs deployed at shallower depths on the DeepCore strings to reinforce the veto against vertically-downgoing atmospheric muons. The rough boundaries of a region of ice with relatively poor optical quality just above DeepCore ("dust layer") is also indicated. This schematic depicts both the DeepCore configuration used in 2010, when 79 IceCube strings were operational, and the final DeepCore layout and fiducial region used in the 2011 run.

to approximately 25 Hz, while retaining over 99% of neutrino-induced events originating within the fiducial volume. These events are then transmitted to the Northern Hemisphere via satellite link for further data reduction offline. Additional details of the trigger and online data selection are available in Ref. [1].

The effective volume of DeepCore as a function of energy is shown in Fig. 2 for muon neutrinos; at these energies, the effective volumes for muon and electron neutrinos are quite similar. Despite the larger physical volume of IceCube, the lower sensor density of the main array means that most events detected below approximately 100 GeV are detected within DeepCore. The slow growth of the effective volume with energy makes it difficult to assign a precise value for the energy threshold of DeepCore, but the array retains an effective volume of 5 MTon (at filter level) for neutrinos with energies as low as 10 GeV. The energy range from 10 GeV to 100 GeV is of considerable interest for a number of topics in particle physics, including indirect searches for dark matter and studies of neutrino oscillations with baselines comparable to the Earth's diameter. It should be noted that the effective volumes shown in Fig. 2 do not include efficiencies related to data analysis beyond the level of the online filter, as these analyses will vary according to the physics topic of interest and the related requirements for background rejection and event reconstruction quality.

An example of the potential benefit from DeepCore's lower trigger threshold and ability to utilize IceCube as an active veto is provided by the identification of neutrino-induced cascades (produced by ν_e charged current and ν_X neutral current interactions) in the first year of DeepCore data, collected from May 2010 until April 2011. Previous searches for these events in AMANDA and IceCube [2–6] have been forced to impose a relatively high energy threshold to avoid the background of events in which an atmospheric muon penetrates to the detector and emits a bright bremsstrahlung cascade, which can be mistaken for a neutrino-induced cascade if traces of the parent muon are not detected. With the active veto provided by IceCube, we can identify and reject such muons with a very high efficiency; our preliminary estimate is that less than 10^{-9} of the atmospheric muons triggering IceCube are misidentified as possible

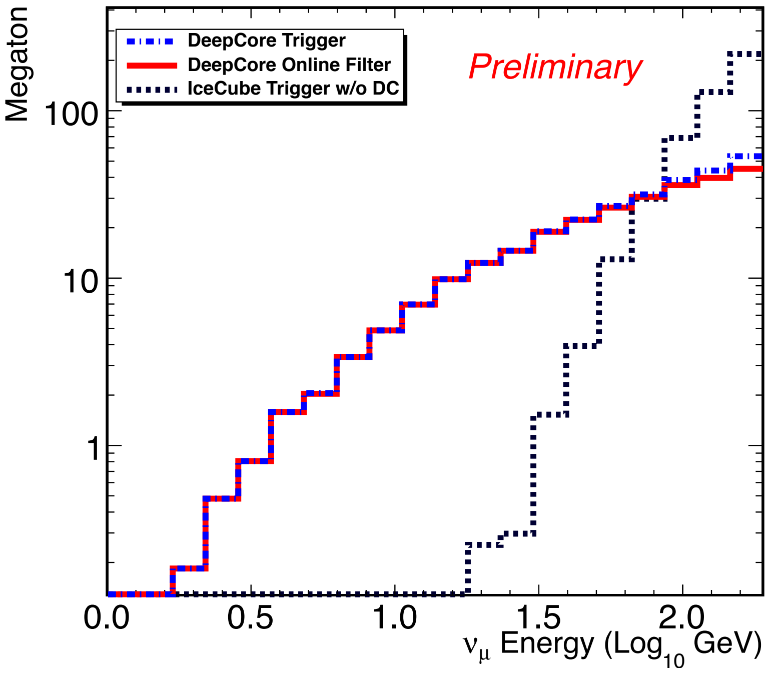

Figure 2: The effective volume of DeepCore and IceCube for the detection of muon neutrinos. The dot-dashed line indicates the effective volume at DeepCore trigger level, while the solid line includes the effect of the online filter. The dotted line shows the originally-proposed IceCube detector, without DeepCore, which would have been relatively insensitive to neutrinos below 100 GeV.

neutrino-induced cascades in DeepCore. This permits us to search for cascades at energies of a few hundred GeV, where the atmospheric electron neutrino flux produces thousands of neutrino-induced cascades per year in DeepCore. As with the initial detection of muon neutrino events using AMANDA [7], atmospheric neutrinos provide a known flux of cascade events which can be used to calibrate the sensitivity of the detector to this new class of neutrino events.

The dominant backgrounds in the 2010 DeepCore cascade analysis are from ν_μ charged current (CC) events where the muon track emanating from the vertex is too short to be detected, and from random correlations of PMT noise hits, which can occasionally exceed the extremely low DeepCore trigger threshold. For the sake of expediency, the latter class of background was eliminated by imposing an artificially higher trigger threshold, increasing the energy threshold in this analysis to approximately 50 GeV. We also made use of relatively simple parameters for discrimination of ν_μ CC events, accepting substantial losses of cascade events in order to obtain a sample consisting predominantly of cascades. The resulting event yield is thus substantially smaller than we expect will be possible using more refined analysis techniques. Nevertheless, we obtain a sample of 1,029 cascade candidate events from the 281 days of live time in the 2010 data set, one of which is shown in Figure 3.

Our preliminary estimate, based on Monte Carlo simulations, is that approximately 60% of the neutrino-induced events in the data set are genuine cascades, with approximately equal proportions of ν_e CC and ν_μ neutral current (NC) events, and a small admixture of ν_e NC. The other 40% of the neutrinos are believed to be due to ν_μ CC events which were not identified by our current algorithm, as shown in Fig. 4. Due to the artificial energy threshold imposed in this analysis, events due to ν_τ arising from oscillations of ν_μ traversing the Earth are expected to make up a very small fraction of this data set. The number of unidentified atmospheric muons in the data is still under investigation, but is believed to be less than 10%. Neither ν_τ nor atmospheric μ events are included in the totals shown in Fig. 4, nor are systematic uncertainties in the number of events to be expected. Although the $\nu_\mu + \bar{\nu}_\mu$ fluxes predicted by the

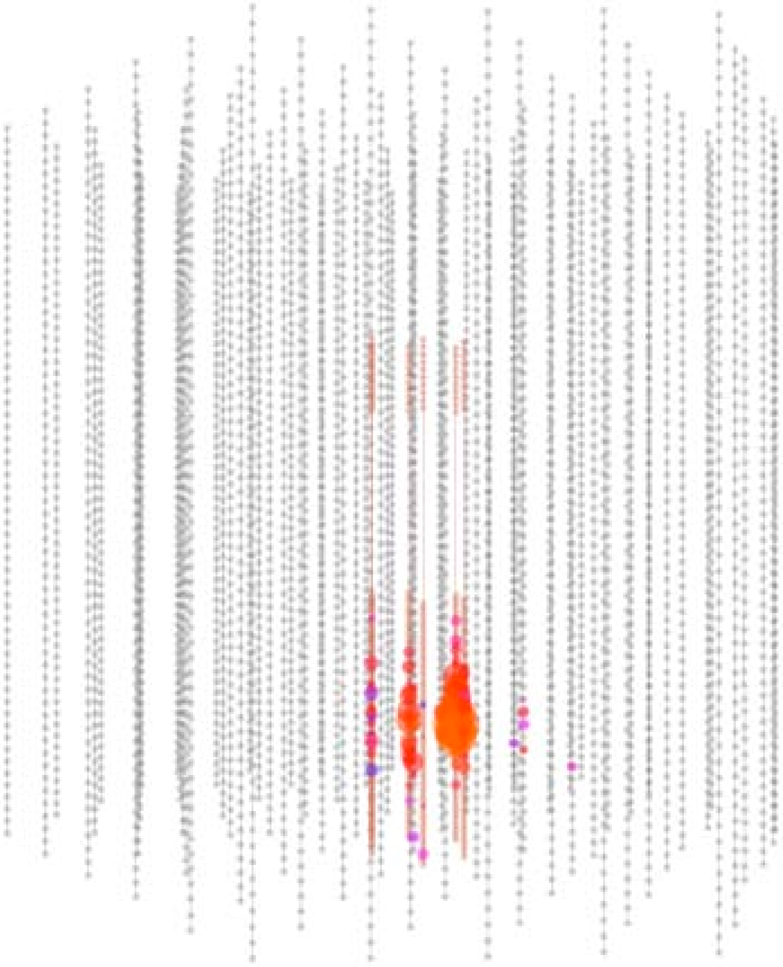

Figure 3: Candidate neutrino-induced cascade observed in DeepCore using the IC79 configuration. Each black dot indicates a DOM. Colored dots represent DOMs that detected light during the event, with the size of the dot proportional to the amount of light detected. The color indicates the relative arrival time of the first photon detected by that DOM, running through the spectrum from red (earliest) to purple (latest).

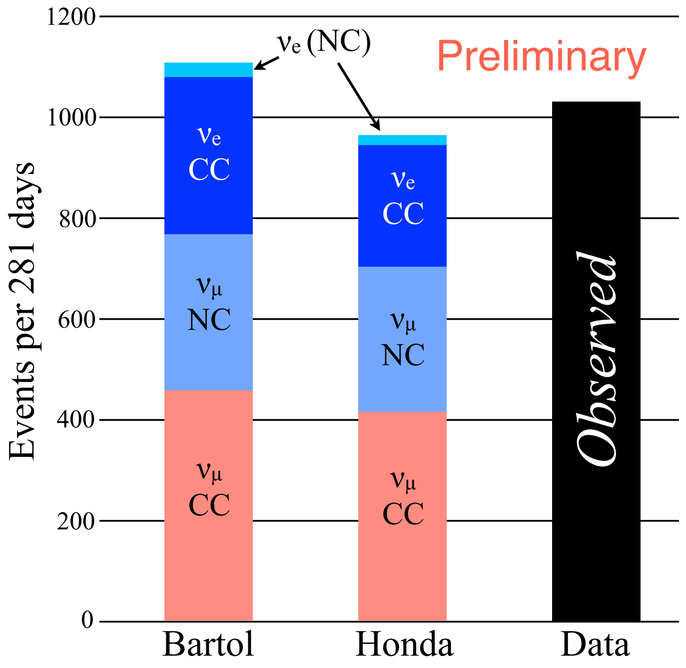

Figure 4: Number of events observed in the atmospheric cascade analysis using 281 days of live time from the 2010 (IC79) run. The columns on the left indicate the number of ν_e and ν_μ events expected for the Bartol and Honda models of the atmospheric neutrino flux. Contributions from atmospheric muons and appearing ν_τ are not included. Systematic uncertainties are under assessment.

two leading models of the atmospheric neutrino flux, those of the Bartol [8] and Honda [9] groups, are quite similar, the differing treatment of kaon production in the two models leads to differences in the predicted $\nu_e + \bar{\nu}_e$ fluxes which are potentially detectable with this analysis, although no statement can be made in this regard until the systematic uncertainties and other effects discussed above are included.

For neutrinos traveling on a baseline equal to the Earth's diameter, $\nu_\mu \to \nu_\tau$ oscillations lead to a maximum in tau neutrino appearance for neutrinos of approximately 24 GeV [10]. If the energy threshold of the cascade analysis can be reduced below this level, a measurement of tau neutrino appearance via an enhancement in the rate of observed neutrino cascades could be possible.

In addition to studies of neutrino physics, the lower energy neutrinos observable with DeepCore enhance the sensitivity of IceCube to indirect evidence of dark matter. The signature of dark matter in IceCube would be a flux of neutrinos produced via the annihilation or decay of dark matter trapped in a gravitational potential well, such as that of the Sun, Earth, or Galaxy. Because the WIMP mass must be relatively low compared to the energy threshold of IceCube, DeepCore plays a major role in IceCube searches for such neutrinos. The projected sensitivity of IceCube, including DeepCore, in searches for dark matter accumulated in the Solar gravitational well is shown in Figure 5. Direct detection experiments, which exploit coherent scattering from heavy nuclei, constrain the spin-independent WIMP-nucleon scattering cross section much more tightly than does IceCube. However, spin-dependent (SD) WIMP-nucleon scattering would not be coherent due to the varying orientation of the nucleon spins, and the limits placed by direct detection experiments on the SD cross section are considerably weaker. As a massive target primarily composed of light nuclei, WIMP capture in the Sun is not significantly enhanced by coherent scattering of WIMPs off nuclei, and conversely is not significantly lessened in models where that coherence is broken. As a result, indirect limits on the SD cross section [11, 12] are lower than those from direct searches [13–17], although they include additional model dependence in the variety of possible annihilation channels.

3. PINGU

The initial success in obtaining a large, low energy neutrino sample with DeepCore has encouraged the IceCube collaboration, plus other participants not previously associated with IceCube, to begin to develop a proposal for a further infill of the DeepCore volume with additional instrumentation. Such an effort would allow a still lower energy threshold and would allow additional precision in the reconstruction and analysis of events already visible with DeepCore. This project is known as the Precision IceCube Next Generation Upgrade (PINGU),

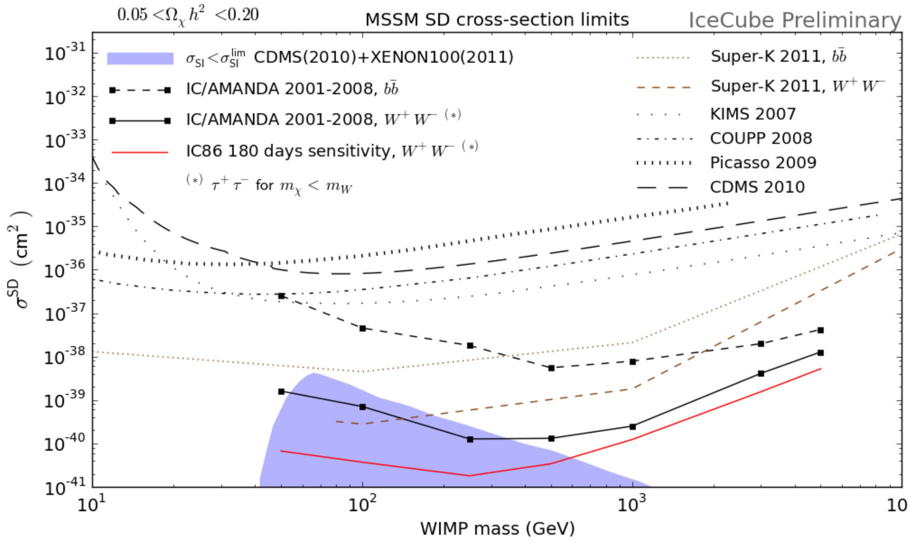

Figure 5: Limits on the spin-dependent WIMP-nucleon scattering cross section from various direct and indirect search experiments, and the projected sensitivity of IceCube with DeepCore ("IC86") for a hard (W^+W^- or $\tau^+\tau^-$) neutrino spectrum arising from neutralino annihilation in the Sun. The shaded region indicates the possible cross sections in MSSM models not already ruled out by direct detection experiments' limits on the spin-independent cross section.

and might consist of around 18-20 strings of additional DOMs, totalling as many as 1,200 additional sensors in the DeepCore volume. The string layout of one configuration under study is shown in Fig. 6, which would nearly quadruple the number of DOMs active in the PINGU fiducial volume.

The events detectable with PINGU would be qualitatively different from the bulk of the events detected with IceCube. In IceCube, most muons leave long tracks of hundreds of meters or more, and the typical interstring spacing is 125 m, three to five times the effective optical scattering length of Cherenkov photons in the ice (depending on depth). In PINGU, with a focus on neutrinos below 10 GeV, all events will be fully contained within the volume, and even ν_μ CC events will produce a relatively short track that will need to be distinguished from the hadronic cascade at the neutrino interaction vertex. On the other hand, the effective scattering length of the ice is nearly 50 m at the depth of PINGU and DeepCore, so there would be 20 or more strings within a single scattering length of an event in the PINGU fiducial volume, capable of detecting unscattered photons from the event. New event reconstruction algorithms optimized for this very different type of events will be required to maximize the scientific returns of PINGU, and are now under development. A meaningful comparison of PINGU performance to DeepCore at analysis level is therefore difficult at this time. For the moment, a comparison of the effective volume of PINGU and DeepCore for electron neutrino events at trigger level is shown in Fig. 7; the effective volume for other neutrino flavors is very similar.

PINGU would provide a considerable increase in the number of neutrinos observed at energies below about 10 GeV. This energy range is of considerable interest for neutrino physics, since matter effects produce substantial distortions of the normal oscillation survival probabilities for neutrinos or antineutrinos at energies of a few GeV traversing the Earth's core, depending on the sign of the neutrino mass hierarchy. Although a direct discrimination of ν and $\bar{\nu}$ based on lepton charge is not possible in a detector such as DeepCore or PINGU, it might be possible to exploit asymmetries in the neutrino and antineutrino interaction cross sections and kinematics to enable a statistical discrimination of the two

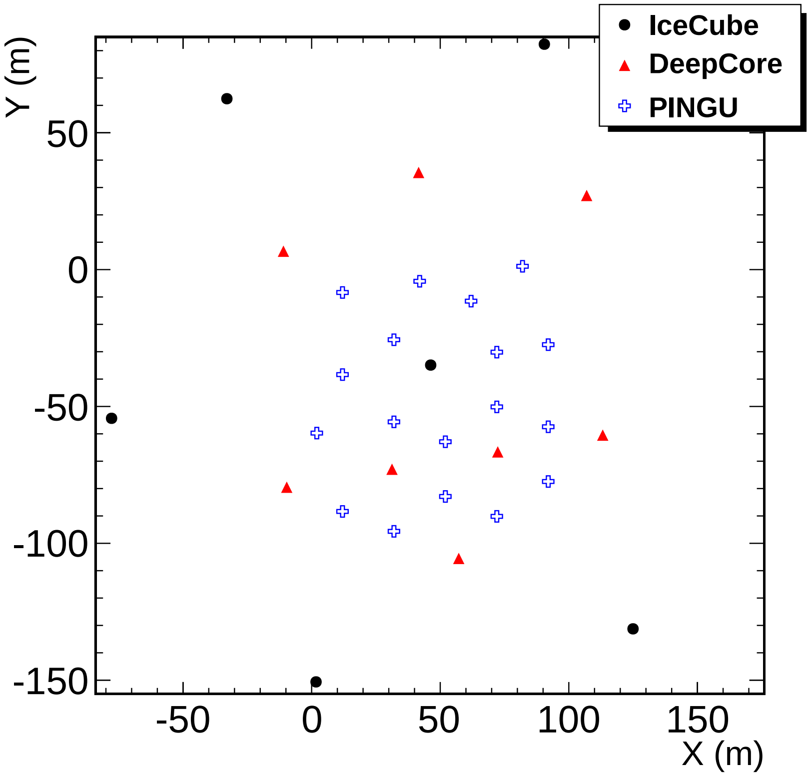

Figure 6: Top view of one string configuration under investigation for PINGU. Circles indicate standard IceCube strings, triangles the existing specialized DeepCore strings, and open crosses mark the positions of 18 new strings foreseen for PINGU. This geometry has a typical interstring spacing of around 30 m, and would provide an approximately fourfold increase in sensor density in the PINGU volume. The coordinate system has its origin at the center of the IceCube array.

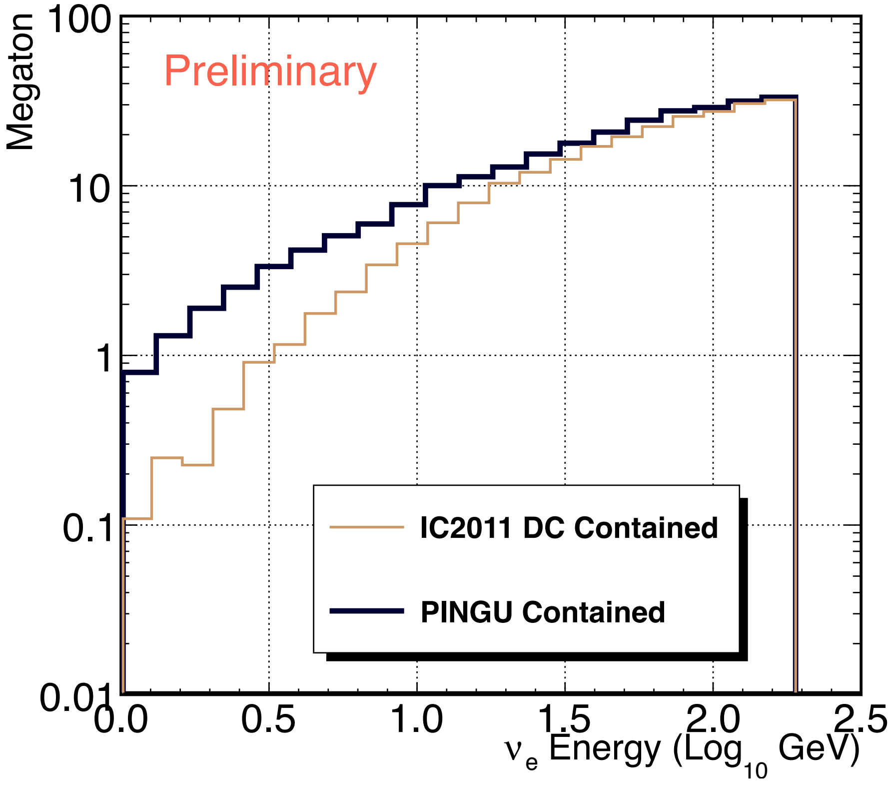

Figure 7: Comparison of the effective volumes of DeepCore ("DC") and PINGU for electron neutrinos interacting within the fiducial volume, at trigger level. PINGU would roughly double DeepCore's effective volume at 10 GeV, with nearly an order of magnitude increase at lower energies. Reconstruction and analysis efficiencies are not included and will reduce the final effective volume.

scenarios [10], given the very high statistics of atmospheric neutrinos potentially detectable with a large detector such as PINGU.

The focus on precision physics at low energies has also led to investigation of new types of DOMs, which might be capable of extracting more information from the dim, low energy events at the GeV scale and perhaps even below. One initial design, shown in Fig. 8, is based on the DOMs planned for the KM3NeT Mediterranean neutrino telescope. This design could house 60 smaller 3" diameter PMTs in a cylindrical glass pressure housing whose diameter is similar to that of a standard IceCube DOM. A multi-PMT DOM such as this could be deployed using the same drilling techniques developed for IceCube, but would provide several times more total photocathode area per module. A dense array of such detectors would thus lead to significantly higher efficiency for collection of Cherenkov photons, and enable more precise reconstruction of lower energy events.

Initial design and performance studies of an extremely dense array based on modules such as this, known as the Megaton Ice Cherenkov Array (MICA), have begun. While the precise design parameters of such a detector are still under investigation, the aim is for a detector with an effective volume of several megatons and an energy threshold around 100 MeV. The physics goals of such an array would include the precision neutrino physics already discussed in the context of PINGU. In addition, we are studying the feasibility of searching for neutrinos from extragalactic supernovae at energies of a few 10's of MeV, where the rapid nature of the neutrino burst might allow us to reduce the energy threshold below what might normally be possible. We are also assessing the possibility of searches for proton decay with MICA.

4. Summary

IceCube has been operational in its final configuration since early 2011. The low-energy IceCube infill array, DeepCore, began taking data in the 2010 data run, with 6 of the final 8 infill strings operational. Analysis of the first year's

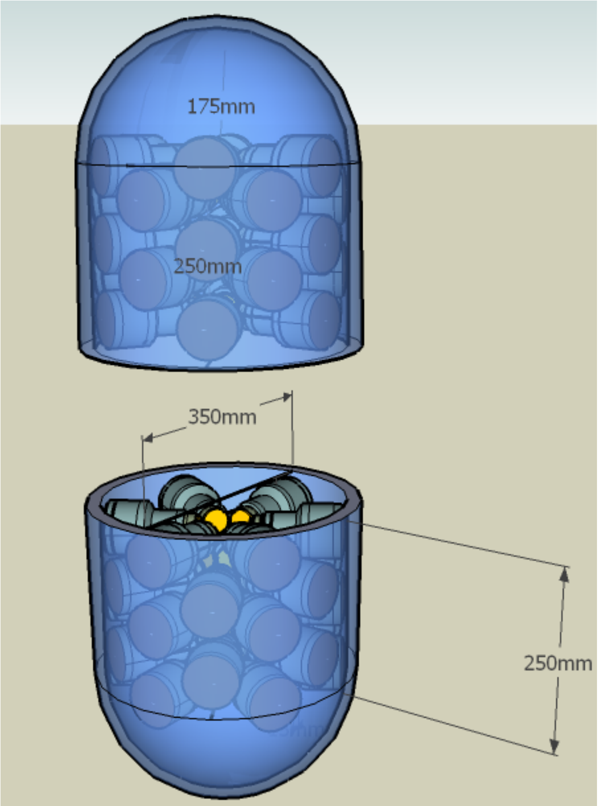

Figure 8: Diagram of a multi-PMT Digital Optical Module, containing sixty 3” diamater PMTs in a cylindrical glass pressure vessel slightly less than a meter tall. The diameter of the DOM is comparable to that of IceCube DOMs, meaning it could be installed using existing IceCube drilling techniques. A prototype of this module is under development in the context of PINGU.

DeepCore data has led to the observation of a high-statistics sample of atmospheric neutrino-induced cascades, including ν_e and neutral current events. We are presently assessing the contributions of atmospheric muons and tau neutrinos to that event sample, as well as systematics associated with the detector response. Efforts are underway to lower the energy threshold of the analysis to permit an observation of tau neutrino appearance with DeepCore. Searches for indirect evidence of dark matter using DeepCore are also underway, and DeepCore promises to substantially improve the sensitivity of IceCube to WIMPs with masses below 100 GeV.

The rapid progress in identifying a large sample of low energy atmospheric neutrino events demonstrates the scientific potential of a dense infill array using the remainder of IceCube as an active veto against penetrating atmospheric muons. We are assessing the reach of a further infill array, known as PINGU, which might lower the energy threshold sufficiently to permit the observation of events at a few GeV. If possible, this would permit a number of interesting measurements of neutrino physics. On a grander scale, we are investigating the feasibility of a multi-megaton detector with an energy threshold significantly below 1 GeV in the Antarctic ice cap.

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