Physics Capabilities of the IceCube DeepCore Detector

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***Abstract*. IceCube-DeepCore is a compact Cherenkov detector located in the clear ice of the bottom center of the IceCube Neutrino Telescope. Its purpose is to enhance the sensitivity of IceCube for low neutrino energies ($< 1\,\mathrm{TeV}$) and to lower the detection threshold of IceCube by about an order of magnitude to below $10\,\mathrm{GeV}$. The detector is formed by 6 additional strings of 360 high quantum efficiency phototubes together with the 7 central IceCube strings. The improved sensitivity will provide an enhanced sensitivity to probe a range of parameters of dark matter models not covered by direct experiments. It opens a new window for atmospheric neutrino oscillation measurements of ν_μ disappearance or ν_τ appearance in an energy region not well tested by previous experiments, and enlarges the field of view of IceCube to a full sky observation when searching for potential neutrino sources. The first string was succesfully installed in January 2009, commissioning of the full detector is planned early 2010.**

***Keywords*: Neutrino-astronomy, IceCube-DeepCore**

I. INTRODUCTION

Main aim of the IceCube neutrino observatory [1] is the detection of high energy extraterrestrial neutrinos from cosmic sources, e.g. from active galactic nuclei. The detection of high energy neutrinos would help to resolve the question of the sources and the acceleration mechanisms of high energy cosmic rays.

IceCube is located at the geographic South Pole. The main instrument of IceCube will consist of 80 cable strings, each with 60 highly sensitive photo-detectors which are installed in the clear ice at depths between $1450\,\mathrm{m}$ and $2450\,\mathrm{m}$ below the surface. Charged leptons with an energy above $100\,\mathrm{GeV}$ inside or close to the detector produce enough Cherenkov light to be detected and reconstructed using the timing information of the photoelectrons recorded with large area phototubes (PMT). While the primary goal is of highest scientific interest, the instrument can address a multitude of scientific questions, ranging from fundamental physics such as physics on energy-scales beyond the reach of current particle accelerators to multidisciplinary aspects e.g. the optical properties of the deep Antarctic ice which reflect climate changes on Earth.

IceCube is complemented by other major detector components. The surface air-shower detector *IceTop* is used to study high energy cosmic rays and to calibrate
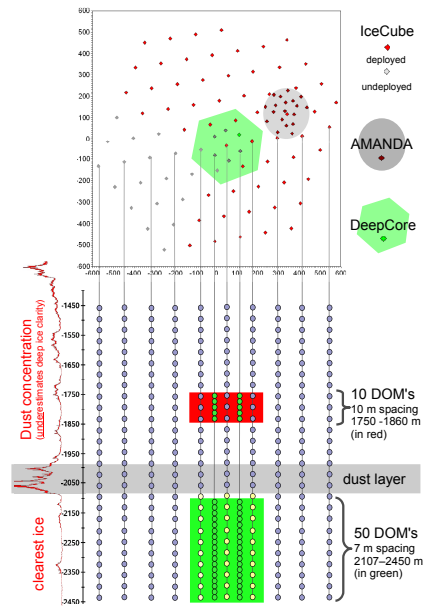

Fig. 1: The geometry of the DeepCore Detector. The top part shows the surface projection of horizontal string positions and indicates the positions of AMANDA and DeepCore. The bottom part indicates the depth of sensor positions. At the left the depth-profile of the optical transparency of the ice is shown.

IceCube. R&D studies are underway to supplement Ice-Cube with radio (*AURA*) and acoustic sensors (*SPATS*) in order to extend the energy range beyond EeV energies. DeepCore will consist of six additional densely instrumented strings deployed in the bottom center of IceCube and is the focus of this paper.

The first DeepCore string has been taking data since its successful installation in January 2009. The Deep-Core detector will be completed in 2010 and will replace the existing *AMANDA-II* detector, which was decomissioned in May 2009. DeepCore will lower the detection threshold of IceCube by an order of magnitude to below $10\,\mathrm{GeV}$ and, due to its improved design, provide new capabilities compared to AMANDA. In this paper we describe the design of DeepCore and the enhanced physics capabilities that may be addressed.

II. DEEPCORE DESIGN AND GEOMETRY
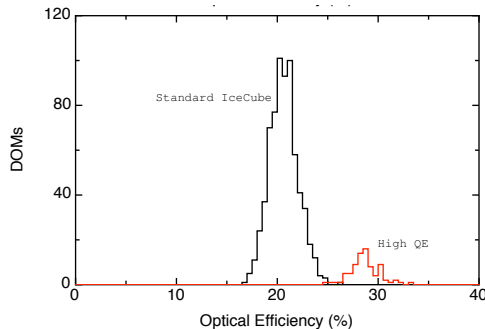
The geometry of DeepCore is sketched in figure 1.

Fig. 2: Results of the quantum efficiency calibration at $\lambda = 405\,\mathrm{nm}$ of the DeepCore phototubes compared to standard IceCube phototubes.

DeepCore is comprised of 6 additional strings, each of which are instrumented with 60 phototubes, in conjunction with the 7 central IceCube strings. The detector is divided into two components. Ten sensors of each new string are at shallow depths between $1750\,\mathrm{m}$ and $1850\,\mathrm{m}$, above a major dust-layer of poorer optical transparency and will be used as a veto-detector for the deeper component. The deep component is formed by 50 sensors on each string and is installed in the clear ice at depths between $2100\,\mathrm{m}$ and $2450\,\mathrm{m}$. It will form, together with the neighboring IceCube sensors the main physics volume.

The deep ice is on average twice as clear as the average ice above $2000\,\mathrm{m}$ [2]. The effective scattering length reaches $50\,\mathrm{m}$ and the absorption length $230\,\mathrm{m}$. Compared to AMANDA a substantially larger number of unscattered photons will be recorded allowing for an improved pattern recognition and reconstruction of neutrino events in particular at lower energies.

Another important aspect is a denser spacing of photosensors compared to IceCube: The horizontal inter-string spacing is $72\,\mathrm{m}$ (IceCube: $125\,\mathrm{m}$). The vertical spacing of sensors along a string is only $7\,\mathrm{m}$ (IceCube: $17\,\mathrm{m}$).

The next major improvement with respect to IceCube and AMANDA is the usage of new phototubes (HAMAMATSU R7081-MOD) of higher quantum efficiency. This hemispherical 10" PMT is identical to the standard IceCube PMT [3], but employs a modified cathode material of higher quantum efficiency (typically $33\,\%$ at $\lambda = 390\,\mathrm{nm}$). Calibrations of the phototubes for DeepCore confirm a sensitivity improvement of $30\,\%$-$40\,\%$ with respect to the standard IceCube PMT (figure 2). Also regular IceCube strings will be equipped with these phototubes within the DeepCore volume.

The net effect of the denser instrumentation is a factor ~ 6 gain in sensitivity for photon detection and superior optical clarity of the ice. This is an imporant prerequisite for a substantially lower detection threshold.

III. DEEPCORE PERFORMANCE

The electronic hardware of the optical sensors is identical to the standard IceCube module [3] and this significantly reduces the efforts for maintenance and operations compared to AMANDA. The DeepCore detector is integrated into a homogeneous data aquisition model of IceCube which will be only supplemented by an additional trigger. Initial comissioning data of the first installed DeepCore string verifies that the hardware works reliably and as expected.

The IceCube detector is triggered if typically a multiplicity of 8 sensors within $\sim 5\,\mu\mathrm{s}$ observe a signal coincident with a hit in a neighboring or next to neighboring sensor. For each trigger, the signals of the full detector are transferred to the surface.

For the sensors within the considered volume the data taking is supplemented with a reduced multiplicity requirement of typically $3-4$. As shown in figure 7, such a trigger is sufficient to trigger atmospheric neutrino events down to a threshold of $1\,\mathrm{GeV}$, sufficiently below the anticipated physics threshold.

The chosen location of DeepCore allows to utilize the outer IceCube detector as an active veto shield against the background of down-going atmospheric muons. These are detected at a $\sim 10^6$ higher rate than neutrino induced muons. The veto provides external information to suppress this background and standard up-going neutrino searches will strongly benefit from a larger signal efficiency and a lower detection threshold as the demands on the maturity of recorded signals decrease.

Even more intriguing is the opportunity to identify down-going ν induced μ, which may, unlike cosmic ray induced atmosperic μ, start inside the DeepCore detector. Simulations [4] show that three rings of surrounding IceCube strings and the instrumentation in the upper part of IceCube are sufficient to achieve a rejection of atmospheric muons by a factor $> 10^6$ maintaining a large fraction of the triggered neutrino signals. A further interesting aspect is the proposal [6] to veto also atmospheric ν by the detection of a correlated atmospheric μ. This could provide the opportunity to reject a substantial part of this usually irreducable background for extraterrestrial neutrino searches.

Triggered events which start inside the detector will be selected online and transmitted north by satellite. Already simple algorithms allow to suppress the background rate by a factor $> 10^3$ and meet the bandwidth requirements while keeping 90% of the signal [4]. A typical strategy requires that the earliest hits are located inside DeepCore and allows for later hits in the veto-region only if the time is causally consistent with the hypothesis of a starting track. A filter which selects starting tracks in IceCube has been active since 2008 and allows performance verification of such filters with experimental data and to benchmark the subsequent physics analysis.

The filtered events are analyzed offline with more sophisticated reconstruction algorithms. Here, the focus is to improve the purity of the sample and to reconstruct direction, energy and the position of the interaction vertex. A particularly efficient likelihood algorithm (`finiteReco` [4]) capable of selecting starting muons
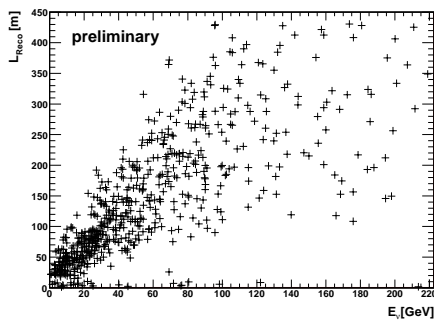
Fig. 3: The reconstructed length of μ contained tracks in DeepCore, based on the reconstructed start- and stop-vertex with the `finiteReco` algorithm. The data are ν induced μ-tracks from the upper hemisphere, which are reconstructed to start within DeepCore.
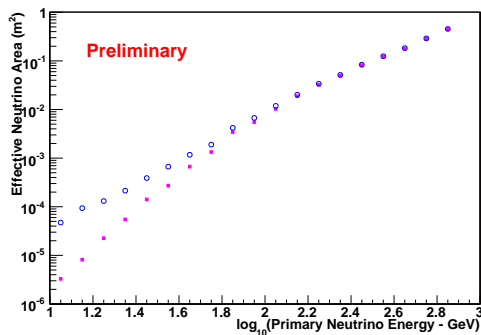

Fig. 4: Effective neutrino detection area of IceCube (trigger level) versus the energy for up-going neutrinos. The squares are IceCube only. The circles represent the area if DeepCore is included.

evaluates the hit probabilities of photomultipliers with and without a signal in dependence of the distance to the track. It estimates the most probable position of the start-vertex and provides the probablity that a track may have reached this point undetected by the veto.

The reconstruction algorithms are still under development but initial results are promising. As an example, figure 3 shows the reconstructed length of μ tracks as function of the ν energy. Already the currently achieved resolution of $\sim 50\,$m results in a visible correlation with the neutrino energy in particular for energies $\leq 100\,$GeV. Note, that the resolution is substantially better for vertical tracks.

The effective detection area of IceCube for neutrinos for triggered events is shown in figure 4. Despite Deep-Core being much smaller than IceCube, a substantial gain of up to an order of magnitude is achieved by the additional events detected in DeepCore. Higher level event selections for specific physics analysis benefit strongly from the higher information content of events and the gain of DeepCore further improves.
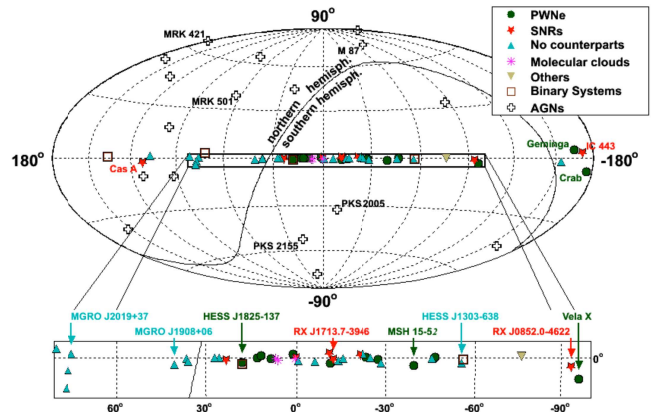

Fig. 5: Interesting celestial objects with known emission of TeV gamma rays.

IV. PHYSICS POTENTIAL

A. Galactic point sources of neutrinos

The analysis of IceCube data greatly benefits from the location at the geographic South Pole because the celestial sphere fully rotates during one sideral day. Azimuthal detector effects are largly washed out because each portion of the sky is observed with the same exposure and same inclination. However, the aperture of the conventional up-going muon analysis is restricted to only the Northern hemisphere and leaves out a large fraction of the galactic plane and a number of interesting objects such as the galactic center (see figure 5). Extending the field of view of IceCube at low energies ($\leq 1\,$TeV) to a full sky observation will greatly enlarge the number of interesting galactic sources in reach of IceCube[1].

The energy spectrum of gamma rays from supernova remnants show indications of a potential cut-off at a few TeV [7]. Under the assumption of a hadronic production mechanism for these gamma rays the corresponding neutrino fluxes would show a similar cut-off at typically half of that cut-off value. The high sensitivity of DeepCore for neutrinos of TeV energies and below will complement the sensitivity of IceCube which is optimized for energies of typically $10\,$TeV and above.

B. Indirect detection of dark matter

The observation of an excess of high energy neutrinos from the direction of the Sun can be interpreted by means of annihilations of WIMP-dark matter in its center. The energy of such neutrinos is a fraction of the mass of the WIMP particles (expected on the TeV-scale) and it depends on the decay chains of the annihilation products. The large effective area of DeepCore and the possibility of a highly efficient signal selection greatly

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[1]Note, that at high energies $> 1\,$PeV the background of atmospheric muons rapidly decreases and also here neutrinos from the Southern hemisphere can be detected by IceCube [8]. However, galactic sources are usually not expected to produce significant fluxes of neutrinos at energies around the cosmic ray knee and above.
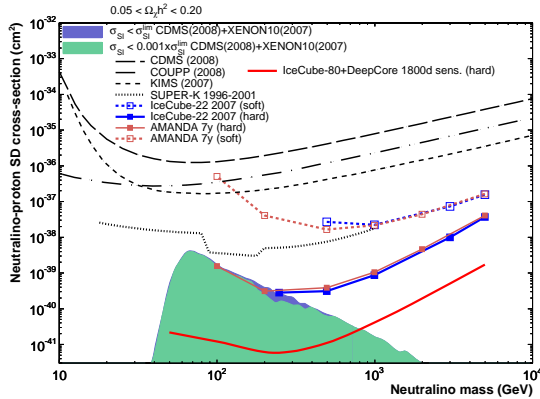
Fig. 6: The expected upper limit of IceCube DeepCore at 90% confidence level on the spin-dependent neutralino-proton cross section for the hard (W^+W^-) annihilation channel as a function of the neutralino mass for IceCube including Deep Core (solid line). Also shown are limits from previous direct and indirect searches. The shaded areas represent MSSM models which are not disfavoured by direct searches, even if their sensitivity would be improved by a factor 1000.

improves the sensitivity of IceCube. In particular it is possible to probe regions of the parameter space with soft decay chains and WIMP masses below ~ 200 GeV and which are not disfavored by direct search experiments.

An example of the sensitivity for the hard annihilation channel of supersymmetric neutralino dark matter is shown in figure 6.

C. Atmospheric neutrinos

DeepCore will trigger on the order of 10^5 atmospheric neutrinos/year in the energy range from $1\,\mathrm{GeV}$ to $100\,\mathrm{GeV}$. Atmospheric neutrinos are largly unexplored in this energy range. Smaller experiments like Super-Kamiokande cannot efficiently measure the spectrum for energies above $10\,\mathrm{GeV}$ and measurements done by AMANDA only start at $1\,\mathrm{TeV}$. In the range between $30 - 50\,\mathrm{GeV}$ decays of charged kaons become dominant over decays of charged pions [10] for the production of atmospheric neutrinos and the systematic error of flux calculations increases. A measurement of this transition could help to reduce systematic errors of the flux of atmospheric neutrinos at TeV energies.

The first maximum of disappearence of atmospheric ν_μ due to oscillations appears at an energy of about $25\,\mathrm{GeV}$ for vertically up-going atmospheric neutrinos [5]. The energy threshold of about $10\,\mathrm{GeV}$ would allow to measure atmospheric neutrino oscillations by means of a direct observation of the oscillation pattern in this energy range. In addition, DeepCore would aim to observe the appearance of ν_τ by the detection of small cascade-like events in the DeepCore volume at a rate which is anti-correlated with the disappearance of ν_μ.
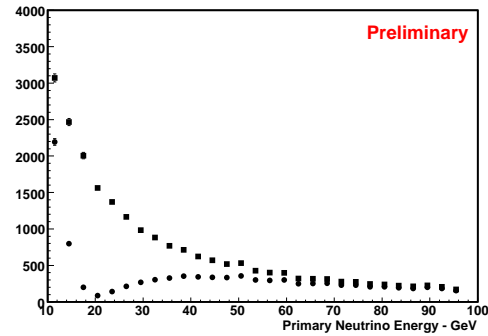

Fig. 7: Number of triggered vertical atmospheric neutrinos per year (per 3GeV) versus the neutrino energy. Events from $1.6\pi\,\mathrm{sr}$ are accepted. Shown are the numbers without (squares) and with (circles) the inclusion of oscillations ($\Delta m^2_{atm} = 0.0024\,\mathrm{eV}^2$, $\sin(2\theta_{23}) = 1$).

Similar to ν_τ, the signature of ν_e events are cascade-events with a large local light deposition without the signature of a track. The dominant background to these events are charged current ν_μ interactions with a small momentum transfer to the μ. Analyses like these will have to be performed considering all three flavors and their mixing. Note, that only for a further reduction of the energy threshold smaller than $10\,\mathrm{GeV}$ matter effects in the Earth's core would become visible [5].

D. Other physics aspects

Two remaining items are only briefly mentioned here.

Slowly moving magnetic monopoles, when catalizing proton decays, produce subsequent energy depositions of $\sim 1\,\mathrm{GeV}$ along their path with time-scales of μs to ms. Initial studies are under-way to develop a dedicated trigger for this signature using delayed coincidences.

DeepCore extends the possibility to search for neutrino emission in coincidence with gamma ray bursts (GRBs) to lower energies. According to [11] GRBs may emit a burst of neutrinos. However, predicted energies are only a few GeV and the event numbers are small ($\sim 10\,\mathrm{yr}^{-1}\,\mathrm{km}^{-2}$). Additional studies are required to evaluate the sensitivity for such signals.

V. SUMMARY AND OUTLOOK

This paper summarizes the enhancement of the physics profile of IceCube by the DeepCore detector. The geometry of DeepCore has been optimized and construction has started. Detailed MC studies and experimental analyses are currently under way to optimize and finalize the analysis procedures. First data from the full detector will be available in spring 2010, the veto will be fully completed latest 2011.

ACKNOWLEDGEMENT

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