The IceCube Neutrino Observatory is a cubic kilometer ice Cherenkov neutrino detector, located at the geographic South Pole, detecting neutrinos of energy above about 100 GeV. In the last couple of years IceCube has established the existence of a high-energy astrophysical neutrino flux in the 100 TeV - PeV range at the level of $10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ per flavor with a significance of 5.7σ. DeepCore, a region of denser instrumentation at the lower center of the detector, detects low-energy atmospheric neutrinos (< 100 GeV), which are used to study neutrino oscillations with a precision comparable to that of the leading experiments in the field. The following paper discusses the latest results on both of these topics.

1 Neutrinos from hell

More than a hundred years have passed since the discovery of cosmic rays. During this time multiple experiments have measured them over a wide energy range, including the most energetic particles ever detected, with EeV energies [1]. Despite detailed knowledge of their energy spectrum, the origin of the highest energy component (above PeV energies) remains a mystery [2]. Fermi shock acceleration in extreme environments, such as Active Galactic Nuclei, remains a preferred explanation, although other more exotic scenarios cannot yet be ruled out.

When cosmic rays reach the atmosphere of the Earth, they interact, producing a shower of particles, including charged mesons and eventually neutrinos. In the same way, it is expected that cosmic rays interact either with other matter particles or photon fields near their production site and/or cosmic microwave background photons as they propagate through the Universe. The observation of very high energy cosmic rays thus implies the existence of a similarly high energy astrophysical flux of neutrinos. Such a flux, when found, will cast light on the origin of high energy cosmic rays and will allow us to observe the Universe in a fundamentally new way.

1.1 IceCube: An instrument for neutrino astronomy

IceCube is an ice Cherenkov neutrino detector located at the geographic South Pole, using the Antarctic ice as a detection medium [3]. The detector consists of 5,160 Digital Optical Modules (DOMs), which are glass spheres containing a 10" PMT, together with the electronics necessary for signal digitization and readout [4]. The DOMs are deployed on vertical strings, with a total of 86 of them, each one holding 60 DOMs. The standard IceCube inter-string distance is 125 m, while the typical DOM-to-DOM distance within a string is 17 m. The instrumented volume amounts to a cubic kilometer, located between depths of 1450 m and 2450 m.

The measurement of a flux of astrophysical neutrinos in IceCube is mainly affected by two sources of background: atmospheric muons and atmospheric neutrinos, both produced in cosmic rays. 

a see http://icecube.wisc.edu/collaboration/authors/current for full author list.
ray interactions in the Earth’s atmosphere. Muons can only reach the detector from above ($\cos\theta_z > 0$); they are fully absorbed in the Earth below the detector’s horizon ($\cos\theta_z \leq 0$). Atmospheric neutrinos, on the other hand, come from all directions up to PeV energies. Above this energy, absorption of neutrinos as they cross the Earth becomes a sizeable effect.

Two strategies are used to suppress background sources for measuring an astrophysical neutrino flux:

- Focus on high energy neutrinos. The astrophysical neutrino flux is expected to follow an $E^{-2}$ power law [5], which is substantially harder than the $E^{-3.7}$ flux of atmospheric neutrinos from $\pi/K$ decays [6]. Events above the crossover energy of the fluxes, expected between 10-100 TeV depending on the flavor, are most likely to come from an astrophysical neutrino flux.

- Use the detector itself as veto. Atmospheric muons produce Cherenkov light as they enter the instrumented volume of the detector. By using edge layers of the detector as veto and looking exclusively for events that start inside the fiducial region, a significant part of the background can be reduced. This approach also reduces the background of high energy atmospheric neutrinos from above the detector, as they have a large probability of being accompanied by a TeV muon [7]. Figure 1 shows how the veto scales with the number of photons observed for one of the studies presented next.

![Figure 1](image)

**Figure 1 –** Fiducial volume scaling evaluated at four different photo-electron counts. Left: Overhead view, showing the positions of the IceCube strings and the boundaries of the fiducial volume for events with a given total photon count. Right: Side view, showing the modules along strings.

### 1.2 Analysis of diffuse neutrino signals

The first evidence of astrophysical neutrinos came from a search which made use of both of the strategies described above with two years of detector live time [8], and has been updated to include three years of data [9]. A complementary study has also been performed using a dynamic veto to extend the analysis to lower neutrino energies [10]. Reducing the analysis threshold makes the overall contribution of background higher than for the original search, but it results in a more precise fit of the contributions of muon background and atmospheric neutrinos.

A total of 283 cascade-like and 105 track-like events were found in the first two years of the extended search. Figure 2 shows how the events are distributed as a function of deposited energy in the detector separated into the northern and southern sky. The simulation describes the data accurately, and events with energies around the transition between background and
signal regions can be clearly observed for the southern sky. Above 50 TeV of reconstructed energy there is large overlap with the sample that gave first evidence of an astrophysical flux.

Diffuse searches which target muon tracks from $\nu_\mu$ interactions have also been performed. The arrival direction of muons can be reconstructed with sub-degree accuracy, thus it is possible to forgo using the outer layers of the detector as a veto and rely on the Earth absorbing the atmospheric muon background. Following this strategy produces a sample with higher statistics, although it is restricted to “up-going” events. In the latest search of this kind an excess of data over the expectation from atmospheric neutrinos, with a significance of 3.7 standard deviations, was found. The excess, shown in Fig. 3, is both consistent with an isotropic astrophysical neutrino flux and with the searches described above.

A joint likelihood analysis of the three diffuse searches mentioned, plus three separate studies previously published [11,12,13], has been performed. In the fit, the data is assumed to be explained by four components: an astrophysical flux, atmospheric muons, atmospheric neutrinos from $\pi/K$ decays, and atmospheric neutrinos from the decay of charmed mesons. The flux of charmed mesons decay before losing energy so neutrinos from these decays have a harder spectrum than those from $\pi/K$ decays.
normalization and spectral index of the different components are fit to the data.

Figure 4a shows the best fit to the data, which corresponds to a single unbroken power law, with a flux normalization of $6.7^{+1.2}_{-1.1} \times 10^{-18}$ (GeV sr cm$^{-2}$ s$^{-1}$) at 100 TeV, and a spectral index of $-2.50 \pm 0.09$, which is significantly different from the $\gamma = -2$ typically assumed. The flux quoted is valid in the range between 25 TeV and 2.8 PeV. No evidence is found for more complicated spectral shapes (e.g. cut-off, broken power law).

Taking the event topology into account allows us to perform a fit of the neutrino flavor composition observed at Earth. A 30% probability for the classifier to identify events with a muon track as cascades is included in the fit. Figure 4b shows the result of this study, which corresponds to an equal contribution of $\nu_\mu$ and $\nu_e$, and no contribution from $\nu_\tau$. The canonical scenario of having equal contributions of all flavors is compatible with the one-sigma error of the result. A previous result, which relied on a more limited data sample, yielded compatible results with a stronger degeneracy between electron and tau neutrino flavors [14].

Figure 4 - Results from the global fit of diffuse analyses. In (a): Best fit neutrino spectra for the single power law model. The blue and red shaded areas correspond to 68% C.L. allowed regions for the conventional atmospheric and astrophysical neutrino flux, respectively. The flux of atmospheric neutrinos from charmed mesons is fitted to zero, its 90% C.L. upper limit is shown in green. In (b): Profile likelihood scan of the flavor composition at Earth. The best fit composition is marked with x, 68% and 95% confidence regions are indicated. Ratios corresponding to three flavor composition scenarios at the sources of the neutrinos are also shown.

1.3 Origin of the astrophysical neutrino flux

The incoming direction of the neutrino candidates above a reconstructed energy of 50 TeV which start in the detector was tested for clustering. Cascade events have a typical angular resolution of 10°, while tracks can attain sub-degree angular resolutions. The result of a point source analysis returns no significant deviation from the background-only expectation [9].

A strategy which bridges diffuse from point-source searches is the study of the neutrino flux from a population of astrophysical objects. This approach, known as “stacking”, has been used for Gamma Ray Bursts [15] and recently for the Blazars identified in the Fermi catalogue. Since no significant deviation from background has been observed from any of these classes of objects, a limit on the upper limit on the contribution to the diffuse flux of astrophysical neutrinos was derived. The upper limit contribution of the Blazars from the Fermi catalogue is between 8% and 17%, depending on the correlation assumed between the gamma-ray flux and the neutrino flux [16].
2 Neutrinos from heaven

Atmospheric neutrinos, a source of background in the search for neutrinos from hell, are used to study the phenomenon of neutrino oscillations with IceCube. Because neutrinos are massive particles with mixed flavor and mass eigenstates, the probability for one to be emitted with flavor \( \alpha \) and to interact as a different flavor \( \beta \) is nonzero and depends on its energy \( E \) and the distance it has traveled \( L \). For atmospheric neutrinos above a few GeV, which travel from a few kilometers to the entire diameter of the Earth (\( \sim 12700 \) km), the dominant effect of oscillations is \( \nu_\mu \) disappearance, which can be approximated as

\[
P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2 \left( 1.27 \Delta m^2_{31} L/E \right).
\]

Here, the large mass splitting \( \Delta m^2_{31} \approx \Delta m^2_{32} \) and the mixing angle \( \theta_{23} \) are the fundamental parameters of the phenomenon. Maximal disappearance of \( \nu_\mu \) is reached at \( E\nu \approx 25 \) GeV for neutrinos that cross the entire Earth, moving to shorter baselines for lower energies. This disappearance effect is the target of oscillation measurements with neutrino telescopes [17].

2.1 IceCube DeepCore: An instrument for particle physics

The central lower part of IceCube houses a region with denser instrumentation known as DeepCore. In this region, eight irregularly spaced strings were deployed, with a reduced spacing from 125 m to 40-70 m. These strings hold DOMs with 30% higher efficiency than the standard IceCube DOMs. The DOMs on a string are separated by 7 m, instead of the 17 m spacing in the standard IceCube strings [18]. Their instrumentation begins at a depth of 2 km and it goes until the bottom of the detector. The first 10 DOMs of the dedicated DeepCore strings are situated above the naturally occurring dust layer which divides the detector (see Fig. 1) and are used to veto atmospheric muons. The fiducial volume used for analysis starts below the dust layer. The volume has a height of 350 m, and has a radius of approximately 150 m. The fiducial volume encloses about 500 DOMs with reduced spacing, which results in a threshold for detection and reconstruction of neutrinos of 10 GeV, where atmospheric neutrino oscillations can be measured.

2.2 Neutrino oscillation analysis in DeepCore

The study of neutrino oscillations in DeepCore presented here is a measurement of the disappearance pattern of \( \nu_\mu \) [19]. Muon neutrinos undergoing charged current interactions constitute the signal. The main source of background are single atmospheric muons, which trigger the detector at a rate \( 10^5 \) higher than the signal, and can mimic the light pattern produced by a neutrino interaction. Neutral current interactions of all flavors and charged current interactions of \( \nu_e \) and \( \nu_\tau \) constitute a secondary source of background, and add up to about a third of the total signal rate.

DeepCore data selection

Neutrinos are separated from muons using a similar strategy as for the high energy analyses, i.e. vetoing events when there are hints that a particle is entering the fiducial volume. Events starting within the detector are most likely to be neutrinos. For this study the veto is independent of the charge observed by the detector, and it is defined as the region surrounding the fiducial volume, described above.

Different cut variables are defined based on the light deposited before the time at which the event triggers the detector. In their current implementation, which aim for a muon contamination smaller than 5%, genuine starting events have a large probability of being rejected due to noise. Figure 5 demonstrates how the background is reduced at three different stages of the
event selection. In the final step the atmospheric muon contamination of the “up-going” part of the sample is less than 2%.

The neutrino events selected for analysis are those interactions which produce photons that did not suffer strongly from scattering before detection. A delay of 20 ns from the geometric arrival time is allowed. The events which fulfill this condition can be reconstructed with little dependence on the properties of the South Pole ice, which vary as a function of depth. Figure 6a shows how direct hits align with the expectation from a muon track emitting Cherenkov light.

Two reconstructions are applied to the direct hits of every event, which differ by having one or no muons in the final state particles. Neutrino interactions with a muon track are most likely to come from $\nu_\mu$ scattering and thus are favored in the selection. Events which fulfill these criteria are reconstructed with a precision of $10^\circ$ in zenith angle, and $25^\circ$ in energy at 20 GeV. Figure 6b shows the energy distribution of the events selected to study oscillations. Muon neutrinos dominate the sample, and a strong disappearance effect is present below 50 GeV.

Data analysis and results

The data is analyzed by comparing data and simulation in a two-dimensional $8 \times 8$ histogram in reconstructed energy and zenith angle. Only events that pass through the Earth ($\cos \theta_{\text{geo}} < 0$) and have been reconstructed with an energy between $\log_{10}(E/\text{GeV}) = [0.8, 1.75]$ are consid-
In 953 days of detector live time, a total of 5174 neutrino candidates were selected. The oscillation parameters that fit the data best are, assuming a normal mass ordering, $\Delta m^2_{32} = 2.72^{+0.19}_{-0.20} \times 10^{-3} \text{eV}^2$ and $\sin^2 \theta_{23} = 0.53^{+0.12}_{-0.14}$. There is no significant preference found for the mass ordering. The total error of the measurement has an equal contribution from statistics and systematic effects. The level of contamination from atmospheric muons, obtained by fitting tagged muons from data to the final sample, is 1%, consistent with the expectation from simulation.

![Figure 7](image)

Figure 7 – Neutrino oscillations results. In (a): Distribution of events as a function of reconstructed $L/E$. Data are compared to the best fit and assuming no oscillations on top. The ratio of data and best fit to the case without oscillations at the bottom. Bands indicate estimated systematic uncertainties. In (b): 90% confidence contours of the result in comparison with other experiments. The log-likelihood profiles for individual oscillation parameters are also shown (right and top). A normal mass ordering is assumed.

Data and simulation are in very good agreement, with a $\chi^2$/d.o.f. = 54.9/56 for the full two-dimensional histogram analyzed. The $L/E$ distribution, shown in Fig. 7a, also demonstrates the agreement but now in a variable which does not enter the analysis directly. The 90% confidence contours on the oscillation parameters are shown in Fig. 7b, together with those of the experiments leading the field. This is the first time that a very large volume neutrino telescope has measured neutrino oscillations with a precision comparable to dedicated experiments [20,21,22].

3 Summary and conclusions from heaven and hell

The last five years have been an exciting time for neutrino astronomy. Data taken by the IceCube neutrino telescope have demonstrated the existence of a high energy astrophysical diffuse neutrino flux, now observed as tracks and cascades, both starting in and crossing the detector. The different searches give compatible results, and a global study of them allows us to measure the flux precisely and is giving first hints on the flavor composition at Earth. While the sources of these neutrinos remain unknown, the lack of association with Gamma Ray Bursts and Blazars from the Fermi catalogue discards both object classes as the main source of the observed flux.

At drastically different energies, below a 100 GeV, data acquired with the DeepCore subarray have been used to study atmospheric neutrino oscillations. Systematic uncertainties, a big concern for such a sparsely instrumented detector, have been kept under control, and do not dominate the result yet. The errors obtained are, for the first time for a very large volume neutrino telescope, of the same order of magnitude as those of the leading experiments in the field. Improvements will come soon from refinements in the event selection and particle reconstruction, as well as from including neutrinos which do not produce a muon in the fit.
A possible way to resolve the sources of astrophysical neutrinos, and improve the precision of oscillation studies and determine the ordering of the neutrino masses, is the IceCube Gen2 + PINGU proposal [23, 24]. On the high-energy front, the baseline proposal involves the deployment of 120 new strings surrounding IceCube, with an increased spacing of up to 300 m. On the low-energy side, 40 additional strings with 60-90 DOMs each would be placed inside the current DeepCore volume, reducing the energy threshold to less than 10 GeV and significantly increasing the light collected per event.

References