PROCEEDINGS OF SCIENCE

Atmospheric neutrino oscillations with IceCube

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The IceCube Neutrino Observatory is a cubic-kilometer Cherenkov neutrino detector located in the glacial ice at the geographic South Pole. DeepCore, a denser sub-array within the detector, has a neutrino detection energy threshold of less than 10 GeV. In recent years, IceCube opened a new window for measurements of the atmospheric mixing parameters in ice and became one of the leading instruments measuring atmospheric neutrino oscillations. Furthermore, its data serve as a probe of new physics beyond the standard three-neutrino paradigm and limit the allowed mixing between active and potential sterile neutrino species. This contribution discusses IceCube's most recent measurements of ν_μ disappearance and ν_τ appearance, searches for sterile neutrino mixing, as well as future in-ice measurements of fundamental neutrino properties.

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The IceCube Neutrino Observatory [1] is a cubic-kilometer Cherenkov neutrino detector located at the geographic South Pole. It consists of 5160 digital optical modules (DOMs) grouped in vertical strings deployed in the glacial ice. The high energy part of the in-ice detector consists of 78 such strings with a 125 m lateral and 17 m vertical spacing between the modules. It instruments the depth between approximately 1450 m and 2450 m below the ice surface. The detector has a neutrino detection energy threshold of approximately 100 GeV and has a primary purpose of studying high energy astrophysical neutrinos.

DeepCore [2] is a denser sub-array placed in the center of the bottom part of the main IceCube array. It consists of 8 strings with the vertical spacing of 7 m deployed 40–60 m apart from each other. The sub-array instruments the depth between 2100 m and 2450 m, the region where the glacial ice has the best optical properties with longer optical absorption and scattering lengths. DeepCore has an energy threshold of less than 10 GeV making it a suitable tool for studies of the atmospheric neutrino oscillations. In addition, it benefits from the surrounding IceCube strings that serve as the veto against the atmospheric muon background.

The main effect of atmospheric neutrino oscillations is a transition of ν_μ into ν_τ described by the probability[1]

$$P(\nu_\mu \to \nu_\tau) \approx \sin^2(\theta_{23}) \sin^2\left(\Delta m^2_{32} \frac{L}{4E_\nu}\right), \tag{1}$$

where Δm^2_{32} and θ_{23} are the atmospheric neutrino mass splitting and mixing angle, respectively; E_ν is the neutrino energy, and L is the distance between the neutrino production and detection points. For atmospheric neutrinos, the distance L is given by the neutrino arrival direction. The up-going neutrinos (cosine of the zenith angle $\cos\theta_Z \approx -1$), the distance is about 12700 km, while for down-going neutrinos ($\cos\theta_Z \approx 1$) the travelled distance is only about 20 km.

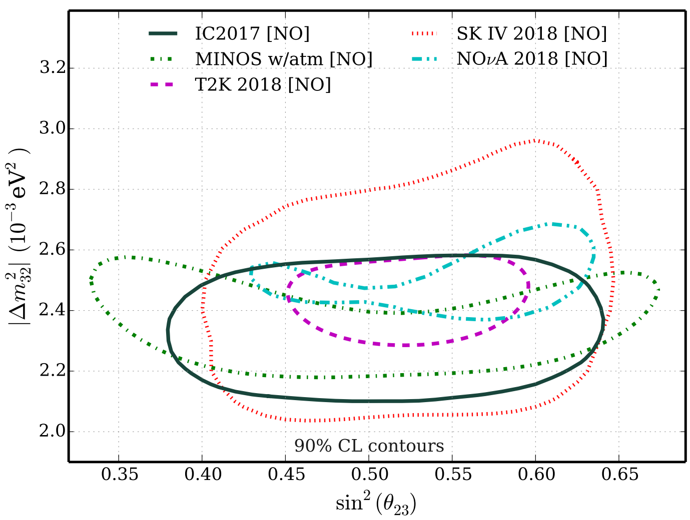

Figure 1: The results of the IceCube measurement of the atmospheric neutrino oscillations compared to the results from other experiments [3].

[1]The two-neutrino approximation is given for simplicity here; actual measurements use the full calculation of neutrino oscillation probabilities in matter.

Since the mixing angle θ_{23} has a value close to 45°, neutrino oscillations result in an almost complete transition of the up-going muon neutrinos with energy of about 25 GeV into tau neutrinos. A precise energy of this ν_μ *disappearance* minimum is given by Δm^2_{32}, while the oscillation amplitude is related to θ_{23}. Measurements of the atmospheric oscillations probe the neutrino oscillation effect at the highest energies possible with terrestrial neutrino sources.

Figure 1 shows the recent IceCube measurement [3] of atmospheric neutrino oscillations in the ν_μ disappearance channel. It uses three years of the IceCube data in the reconstructed energy range between 6 GeV and 56 GeV taken in the 2012–2014 seasons. This analysis is done using the full range of zenith angles, resulting in the simultaneous probing of the baselines between approximately 20 km and 12700 km. This measurement results in the precision for the atmospheric mixing parameters that approach the accuracy of the dedicated accelerator experiments, but performed at higher energies and longer baselines.

A range of anomalies are observed in some of the accelerator, reactor, and radiochemical neutrino experiments. Such anomalies can be interpreted as the result of sterile neutrino mixing beyond the standard three-neutrino paradigm [5]. In this case, the mixing matrix must be non-unitary for the standard three-neutrino mixing. One of the ways to probe it is a measurement of the ν_τ *appearance* given by Equation (1). A normalization of the appeared ν_τ flux smaller than 1 with respect to the standard oscillation expectation might indicate the transition of ν_μ into the hidden sterile sector, while values larger than 1 can be a sign of more exotic neutrino properties. The results of the two IceCube ν_τ appearance measurements [4] are shown in Figure 2. The study marked as *Analysis 1* uses a dedicated event selection with approximately 50% more events than in the muon neutrino disappearance sample used in *Analysis 2*. The measurements are in good agreement with the standard three-neutrino model and are currently among the most precise measurements of the tau neutrino appearance.

Another way to test the aforementioned anomalies is to search for the sterile neutrino mixing

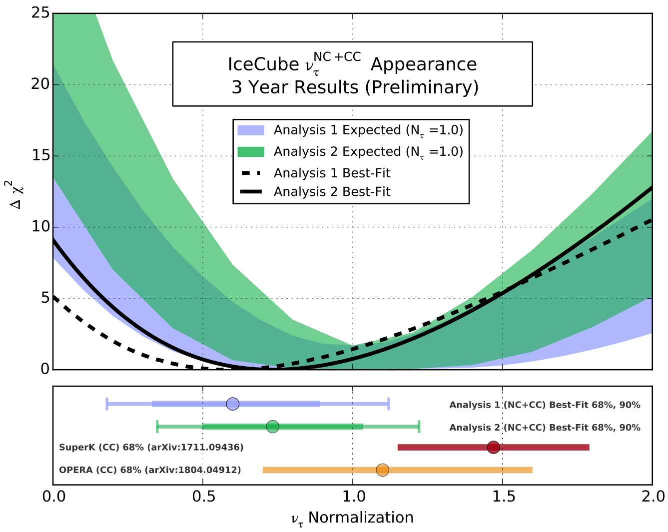

Figure 2: The results of the IceCube ν_τ appearance measurements compared to the results from other experiments [4].

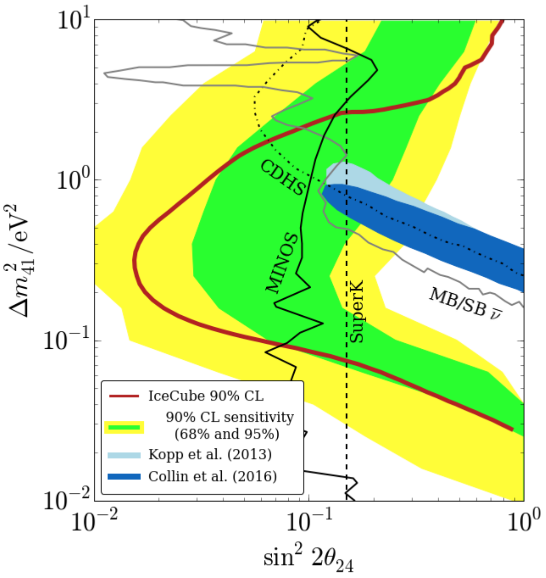

Figure 3: The limit on the allowed sterile neutrino mixing using TeV neutrinos in IceCube [6].

effects directly. IceCube makes a range of searches for sterile neutrinos within the "3+1" model that assumes one heavier sterile neutrino. Figure 3 shows the result of the one-year study [6] probing the mantle-core-mantle resonant enhancement of the $\bar{\nu}_\mu$ transition probability into the sterile neutrino state. Another search [7], shown in Figure 4, tests the matter induced impact of the sterile neutrino mixing on the standard neutrino oscillations governed by Equation (1) using 3 years of DeepCore data. The IceCube searches found no indications of the sterile neutrino mixing and, therefore, place

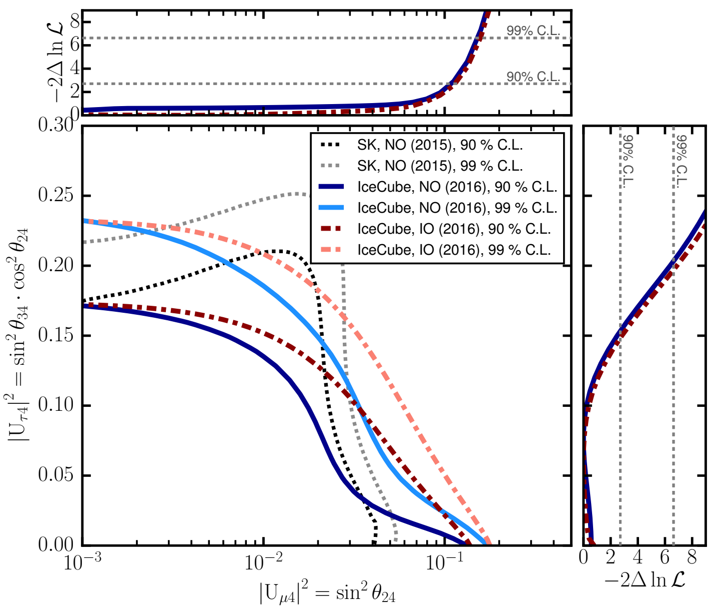

Figure 4: The exclusion contours for the allowed sterile neutrino mixing at $\Delta m^2_{41} = 1$ eV^2 from the DeepCore low energy search [7].

strict limits on the allowed mixing of muon and tau neutrinos with the sterile neutrino state.

In additon to the aforementioned measurements, the IceCube collaboration probed the neutrino mass ordering [8] and placed limits on non-standard neutrino interactions [9]. Currently, several neutrino oscillation studies on the 3 year sample are in preparation as well as the results from up to 7 years of the IceCube data.

In the future, the IceCube Upgrade will provide even more precision to the measurement of the atmospheric neutrino mixing. New 7 strings will have a vertical spacing of approximately 2 m and will be deployed inside the DeepCore volume approximately 20 m apart from each other. New optical modules will use a multi-PMT design resulting in an increase of the effective photo-cathode area. The IceCube Upgrade will also include new calibration devices, which are expected to provide better knowledge about the ice properties, as well as calibrate the new and currently existing DOMs. The detector will have an energy threshold of a few GeV and is expected to have a few percent sensitivity to the atmospheric mixing parameters. The IceCube Upgrade received seed funding in September of 2018 and is expected to be deployed in 2023.

References

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