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Neutrino astronomy at the South Pole: Latest results from the IceCube neutrino observatory and its future development

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ABSTRACT

The IceCube Neutrino Observatory is a cubic-kilometer neutrino telescope located at the geographic South Pole. Buried deep under the Antarctic ice sheet, an array of 5160 Digital Optical Modules (DOMs) is used to capture the Cherenkov light emitted by relativistic particles generated from neutrino interactions. The main goal of IceCube is the detection of astrophysical neutrinos. In 2013 the IceCube neutrino telescope discovered a high-energy diffuse flux of neutrino events with energy ranging from tens of TeV up to few PeV of cosmic origin. Meanwhile, different analyses confirm the discovery and search for possible correlations with astrophysical sources. However, the source of these neutrinos remains a mystery, since no counterparts have been identified yet. In this contribution we give an overview of the detection principles of IceCube, the most recent results, and the plans for a next-generation neutrino detector, dubbed IceCube-Gen2.

1. Introduction

Cosmic accelerators are known to produce hadronic particles with energies exceeding 10^{20} eV, but their identity as well as the acceleration and propagation processes are still not understood. Astrophysical neutrinos are expected to be produced by the interactions of high-energy hadronic particles with surrounding photons and matter. Unlike photons or charged particles, neutrinos can emerge from deep inside their sources and travel across the universe without interference. They are not deflected by interstellar magnetic fields and are not absorbed by intervening matter, providing an unobstructed and intact view of the sources, and unveiling the origin of their parent particles.

2. The IceCube neutrino observatory

The IceCube detector, buried under the South Pole ice sheet, consists of 5160 Digital Optical Module (DOMs) distributed in 86 vertical strings of 1 km length horizontally spaced 125 m apart, each of them instrumented with 60 DOMs spaced 17 m apart vertically. The DOMs are deployed in holes reaching a maximum depth of 2.5 km so that the background of cosmic rays is suppressed by the 1.5 km-thick layer of ice at the top. The overall instrumented volume is a cubic kilometer of highly transparent glacial Antarctic ice, suitable to detect the faint Cherenkov emission from the secondary charged particles produced in neutrino interactions with the ice or the bedrock below at energies above 100 GeV. The more densely instrumented DeepCore sub-array, installed at the bottom center of IceCube with an inter-string spacing of 60 m and an inter-DOM spacing of 7 m, allows a lower detection energy threshold of 10 GeV for neutrino oscillation studies.

Encapsulated in a glass pressure sphere to withstand the extreme pressure in the deep ice, the main components of a DOM are a 10″ PMT (R7081-02 made by Hamamatsu Photonics), embedded high-voltage generation, an LED Flasher Board, and a Main Board containing the analog and digital processing circuitry for PMT pulses. PMT pulse widths and amplitudes are recorded with nanosecond time resolution. Since neutrinos cannot be detected directly, IceCube relies on the precise reconstruction of the neutrino interaction using the charge and the timing information of the Cherenkov photons collected by each DOM. Data collected by a single DOM are transmitted through cables to the IceCube Laboratory (ICL), located at the surface at the center of the array. The data acquisition system (DAQ), which runs in a dedicated computer farm at the ICL, examines the hits across the detector looking for temporal and/or spatial patterns to form the trigger. The DAQ event data are then processed further with approximately 25 filters in order to select a subset of events (about 15%) to transfer over satellite to the Northern Hemisphere.

So far only two event topologies have been observed by IceCube: muon tracks and cascades. A charged current (CC) interaction of a ν_μ will induce a muon that will emit Cherenkov radiation along its trajectory through the detector (muon track). The long lever arm of muons allows for events to be reconstructed with good angular resolution (better that 1° at $E_\nu > 10$ TeV). However, at these energies,

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muons can travel many kilometers from the interaction points: only part of the track is visible in IceCube, making it more difficult to estimate the original neutrino energy. Neutral current (NC) interactions of all neutrino flavors and CC from ν_e and ν_τ can create a particle cascade. The dimensions of the electromagnetic and hadronic particle showers created in these interactions are smaller than the sensor spacing. Due to better containment, the energy resolution for the cascade channel is much better than for tracks, but at the cost of a poorer angular resolution due to a more spherical geometry. A subclass of events can be identified to define a new detection channel: the high-energy starting events (HESE). These events, either tracks or cascades, are selected only when the initial light occurs in the inner part of the detector (fiducial volume). A veto layer of DOMs, surrounding the fiducial volume is used to reject all entering tracks. A detailed description of the HESE veto can be found in [1].

3. Observation of high-energy cosmic neutrinos

In 2013 the IceCube collaboration reported the first observation of a high-energy neutrino flux, currently summing up to a total of 54 cosmic neutrino candidates [2], with deposited energy ranging from 30 TeV to 2 PeV. The analysis uses the HESE channel to select a pure sample of astrophysical neutrino events leading to a detection with a significance of 6.5σ. A maximum likelihood, forward-folding fit of all components (atmospheric muons, atmospheric neutrinos from π/K as well as from charm decay, and an astrophysical flux assuming equal flavor ratio (1:1:1) at Earth) was performed on the energy spectrum. The distribution of the deposited energy of the detected events is shown in Fig. 1 together with the result of the fit, $dN/dE = (2.2 \pm 0.7) \times 10^{-18} \cdot (E/100\ \mathrm{TeV})^{(-2.58 \pm 0.25)}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$. No significant clusters have been found yet.

A separate analysis uses up-going muon tracks only to search for a diffuse flux of astrophysical neutrinos. Using the Earth to filter out the overwhelming atmospheric muon background, this analysis is sensitive to CC ν_μ events coming from the Northern hemisphere. Using 6 years of IceCube data, a significant astrophysical contribution was observed with a significance of 5.6σ, at energies between 191 TeV and 8.3 PeV [3]. The best-fit of the astrophysical $\nu_\mu + \bar{\nu}_\mu$ flux, shown in Fig. 2, is: $dN/dE = (0.\ 90^{+0.30}_{-0.27}) \times 10^{-18} \cdot (E/100\ \mathrm{TeV})^{(-2.13 \pm 0.13)}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$. The data contain 29 events with reconstructed energy greater than 200 TeV, including an exceptionally high-energy muon event with a deposited energy of (2.6 ± 0.3) PeV and a reconstructed median muon energy of (4.5 ± 1.2) PeV. Assuming the best-fit atmospheric energy spectrum from this analysis the p-value of this event being of atmospheric origin has been estimated to be less than 0.005%, strongly suggesting an astrophysical origin. Up to now this event represents the highest energy astrophysical neutrino ever detected. The majority of the high-energy neutrinos are located relatively close to the horizon but no timing or spatial clustering has been found. Furthermore no correlation has been found with any of the gamma-ray source catalogs considered in [3]. Data are well described by an unbroken power law with a harder spectral index than measurements previously reported in [2,5,6]. Fig. 3 compares the measured astrophysical neutrino flux normalization and spectral index with these results and the previous measurement using through-going muon [7]. Substantial tension is

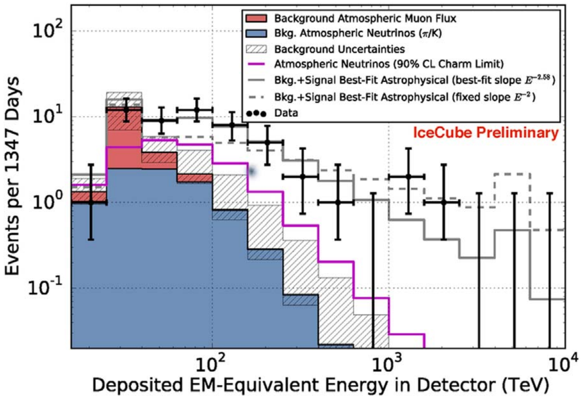

Fig. 1. Distribution of the deposited energy of the high-energy starting events (HESE) observed in four years of IceCube data. The total expected rate of atmospheric muons (red) has been experimentally measured from the data while the energy dependence has been determined by Monte Carlo simulations, to overcome statistical limitations. The expected rate of atmospheric neutrinos is shown in blue, while the hatched area shows uncertainties on the sum of all background. The magenta line represents the experimental 90% bound for the charm component as measured in [3]. The grey line shows the best-fit E^{-2} astrophysical spectrum. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

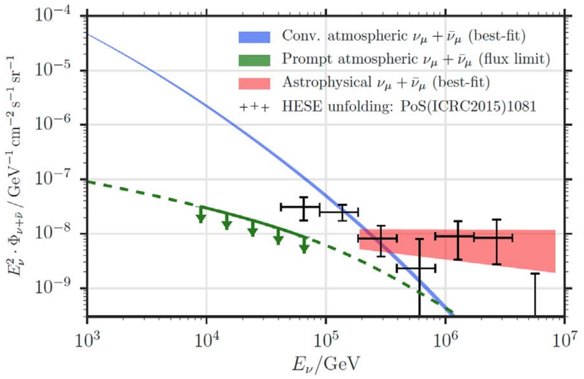

Fig. 2. Best-fit neutrino spectra for the unbroken power-law model [3]. The line widths (blue, red) represent the one sigma error on the measured spectrum where the green line represents the upper limit on the prompt model of [4]. The horizontal width of the red band denotes the energy range of neutrino energies which contribute 90% to the total likelihood ratio between the best-fit and the conventional atmospheric-only hypothesis. The black crosses show the unfolded spectrum published in [2]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

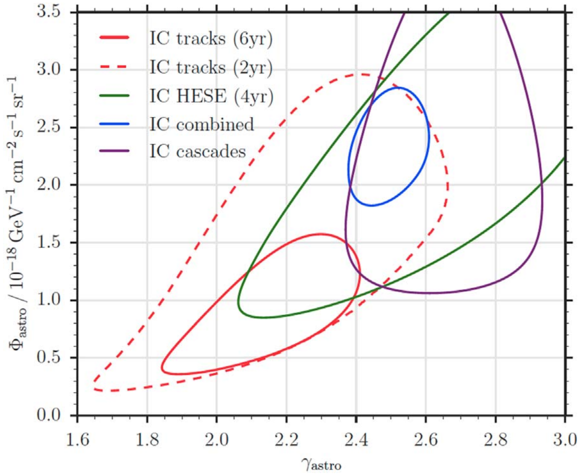

Fig. 3. Results of different IceCube analyses measuring the astrophysical flux parameters: flux normalization (Φ_{astro}) and spectral index (γ_{astro}) [3]. The contour lines show the 90% CL. The result of the muon track diffuse analysis (IC tracks, 6 yr) is shown by the red solid contour line. The red dashed contour shows the result for the previous measurement using through-going muons (IC tracks, 2 yr) [7]. In addition, the results for the most recent analysis of starting events (IC HESE, 4 yr) [2] is shown in green, the complementary cascade channel (IC cascades) [5] in violet, and the results from the analysis combining all IceCube results (IC combined) [6] is shown in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)