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Status and prospects for the IceCube Neutrino Observatory

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ABSTRACT

The IceCube Neutrino Observatory is located at the geographic South Pole and consists of over 5000 optical sensors embedded in the Antarctic ice along with 81 cosmic ray detector stations on the surface. IceCube was designed to detect high energy neutrinos from extreme astrophysical environments which are potential cosmic ray acceleration sites, such as active galactic nuclei, gamma ray bursts and supernova remnants. The discovery of astrophysical neutrinos by IceCube in 2013 heralded the beginning of neutrino astronomy, and we continue to collect data and explore the properties and potential sources of these neutrinos. An expanded successor called IceCube-Gen2 is in development, with updated optical sensors and calibration devices, and an expanded surface veto. The IceCube-Gen2 detector will search for the sources of cosmic neutrinos and will also include an infill component which will investigate fundamental neutrino physics using atmospheric neutrinos. I will discuss the latest results from IceCube, and the status of IceCube-Gen2.

1. Introduction

The sources of the highest energy cosmic rays are as yet unknown. It is expected that cosmic ray nucleons are accelerated in extreme astrophysical environments with strong magnetic fields and/or shocks, such as gamma ray bursts (GRB), active galactic nuclei (AGN) and supernova remnants. Interactions of protons with other protons and photons in the environment should produce pions which decay to muons, electrons and neutrinos (if charged) and to gamma rays (if neutral). In principle, such environments should therefore produce a simultaneous cosmic ray, electromagnetic and neutrino signature. However, cosmic rays are deflected in flight by magnetic fields and gamma rays above ~ TeV energies are absorbed by the infrared background from starlight. Neutrinos, which travel from their sources to the Earth undeflected and unattenuated except by distance, are an ideal messenger from the high-energy universe. A gigaton-volume, cubic kilometer detector is necessary to detect the cosmic neutrino flux.

2. The IceCube Detector

The IceCube Neutrino Observatory [1] is a cubic-kilometer high-energy neutrino detector built at the geographic South Pole near the Amundsen-Scott South Pole Station. The detector consists of 86 cables called "strings", each instrumented with 60 Digital Optical Modules (DOMs) deployed between 1450 m and 2450 m deep in the glacial ice. The DOM is a glass pressure vessel containing a 10-inch photomultiplier tube (PMT) [2] and digitizing electronics [3], as well as 12 LED flashers for calibration. The central, densely spaced "DeepCore" subarray [4] is equipped with high quantum efficiency PMTs to lower the neutrino detection energy threshold to about 5 GeV. IceCube includes a surface cosmic ray air shower detector, IceTop [5]. IceCube operates continuously throughout the year with uptime over 99%.

IceCube DOMs detect light from particle interactions in the ice. The energy, position, time, and direction of the interacting particles are reconstructed from the pattern of light deposition on the DOMs [6]. Most IceCube events at trigger level are downgoing muons from cosmic ray air showers in the southern hemisphere, observed at rates of 2500–2900 Hz. Neutrinos from these air showers are also observed at the rate of a few mHz. Particle interaction topologies in IceCube are flavor- and interaction-dependent and fall into two primary categories: linear "tracks" and quasi-spherical "showers". Tracks result from muons, either from cosmic ray backgrounds or from ν_μ charged-current (CC) interactions. Showers arise from neutral current (NC) interactions of all neutrino flavors, and from CC interactions of ν_e and most ν_τ . A small fraction of high-energy ν_τ may produce a double cascade from the initial neutrino interaction and subsequent tau lepton decay. IceCube uses two methods to separate astrophysical neutrinos from the atmospheric background. One method selects through-going track-like events from the northern hemisphere. These tracks originate from outside the instrumented volume, increasing the effective area for neutrino detection. The Earth filters out muons from the northern hemisphere, and energy is used to discriminate the expected hard (E^{-2}) astrophysical neutrino component from the soft atmospheric neutrino spectrum. However, this method is not sensitive to the southern hemisphere sky, nor is it sensitive to cascade-type events which should account for the majority of the

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astrophysical neutrino flux, since standard neutrino flavor oscillation predicts a 1:1:1 ratio of $\nu_e:\nu_\mu:\nu_\tau$ at the Earth. The second method selects events of both cascade and track type from the whole sky, but requires that the events start inside the detector, in order to eliminate through-going atmospheric muons which should deposit light on the outer strings of the detector.

IceCube's science program also covers neutrino oscillation physics down to 5 GeV with IceCube DeepCore, indirect dark matter detection, sterile neutrino searches, searches for other physics beyond the standard model such as Lorentz invariance violation, cosmic ray physics, and glaciological studies of the South Pole ice.

IceCube announced the first detection of a diffuse flux of cosmic neutrinos in 2013, using the high-energy all-flavor starting event sample from the whole sky [7]. The discovery was confirmed by the high-energy throughgoing track sample from the northern hemisphere sky [8]. In both samples the directions of the neutrinos were consistent with isotropic distribution, ruling out a single bright source for the observed neutrino flux, and indicating that at least part of the flux was extragalactic in origin. Searches for neutrino excesses correlated spatially and/or temporally with various classes of astrophysical objects showed that GRBs contribute $< 1\%$ of the cosmic neutrino flux [9], blazars identified in the Fermi 2LAC catalog contribute $< 27\%$ of the cosmic neutrino flux [10], and the galactic plane contributes $< 14\%$ [11]. IceCube participated in the multimessenger follow-up of the binary neutron star merger observed by LIGO/Virgo [12,13]. No neutrinos were detected from this source.

Many objects in the high-energy sky are transient (GRBs) or flaring (blazars). Electromagnetic observation of transient objects and flares requires prompt notification to observatories which do not routinely survey the entire sky. IceCube began sending realtime alerts [14] to the public Gamma-ray Coordinates Network (GCN) [15] in 2016, using both starting and high-energy through-going tracks. Alerts are sent with a latency of under one minute and give the direction of origin of the neutrino track, an energy estimate and an estimated probability of the event being of astrophysical origin based on its energy and direction. Since 2016, 14 alerts have been sent.

3. Coincident detection of a flaring blazar and a high-energy neutrino

On September 22, 2017, IceCube sent an alert to GCN. The neutrino which prompted the alert, denoted IC-170922A, was an upgoing, through-going track event with a most likely energy of 290 TeV and a 55.6% probability of being of astrophysical origin [16]. Fig. 1 shows the event view of the track in IceCube. Following the alert, Fermi-LAT detected increased gamma ray flux from a known blazar, TXS 0506+056, which was located inside the directional uncertainty contour of IC-170922A [16]. The Major Atmospheric Gamma Imaging Cherenkov Telescopes (MAGIC) then followed TXS 0506+056 and detected gamma rays at energies up to 400 GeV in 12 hours of observations between September 24 and October 4 [16,17]. This was the first detection of gamma rays at those energies from TXS 0506+056. The gamma ray emission from Fermi and from MAGIC is shown in Figs. 2 and 3 respectively. Correlation between the gamma ray emission and the high-energy neutrino is preferred over a chance coincidence at the 3σ level [16]. The redshift of the blazar was unknown prior to the observation of IC-170922A. Following the multi-messenger observations of TXS 0506+056, the redshift was measured to be 0.3365 ± 0.0010 [18].

Because each IceCube string is independently operable, IceCube has been monitoring the sky even during construction, with an archive of 9 years of data as of the observation of IC-170922A. The archival data was searched in the region of IC-170922A and an excess of high-energy neutrino events with respect to atmospheric backgrounds was observed between September 2014 and March 2015 [19]. The best fit Gaussian time window to the excess is centered on December 13, 2014, with a duration of 110^{+35}_{-24} days. The observed excess is 13 ± 5 events above the expected background from atmospheric neutrinos. The excess is inconsistent with the background-only hypothesis at the $3.5\,\sigma$ level [19]. Fig. 4 shows the archival data from this region in IceCube, and the best fit Gaussian time window to the neutrino excess, along with results from a complementary box-shaped time window analysis.

The IceCube alert system continues to be updated. In 2019 we will be using an improved event selection with a larger sample of high energy through-going tracks, improved signal purity in the starting track sample, and streamlined event information in the alert text. Eventually

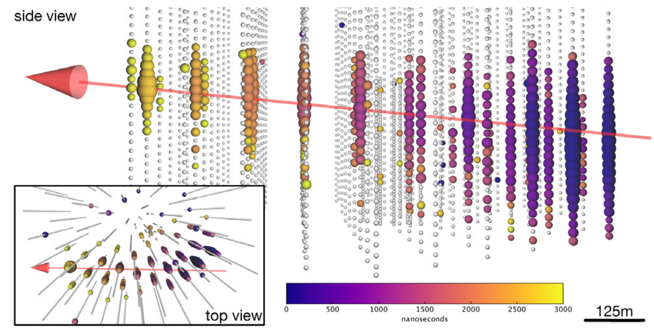

Fig. 1. Event view for IC-170922A, the spheres represent light detected by DOMs. The color code represents the photons arrival times. The arrow shows the best fit track direction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

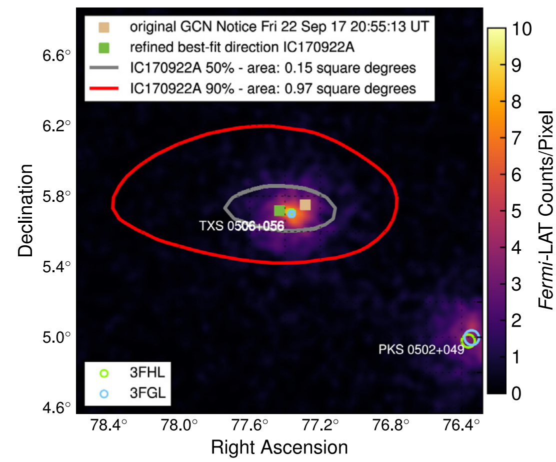

Fig. 2. IC-170922A and gamma ray emission from Fermi-LAT.

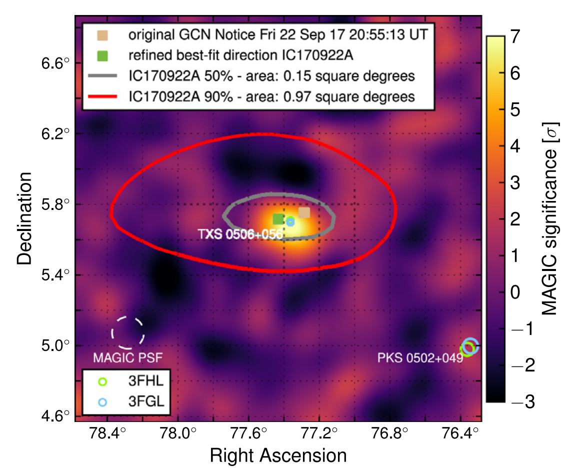

Fig. 3. IC-170922A and gamma ray emission from MAGIC.

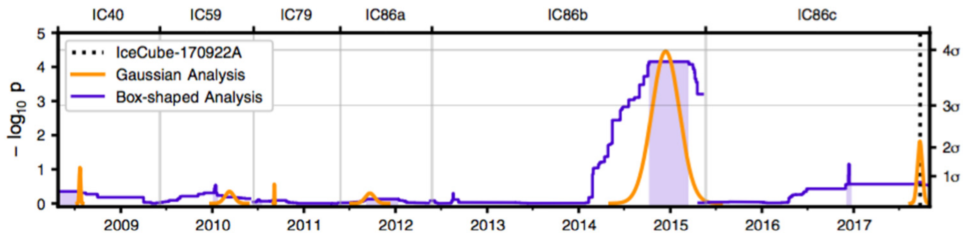

Fig. 4. IceCube archival data from the region of IC-170922A, Apr 5, 2008 to Oct 31, 2017.

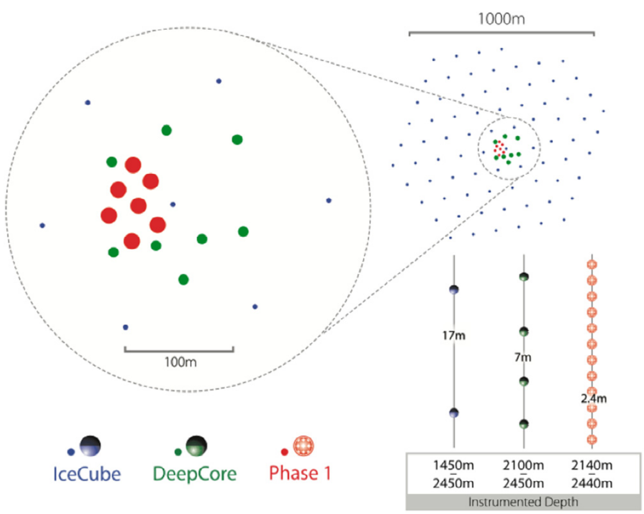

Fig. 5. Map of the planned IceCube Upgrade strings with respect to current IceCube strings. Blue: standard IceCube strings. Green: IceCube DeepCore strings. Red: Upgrade strings . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

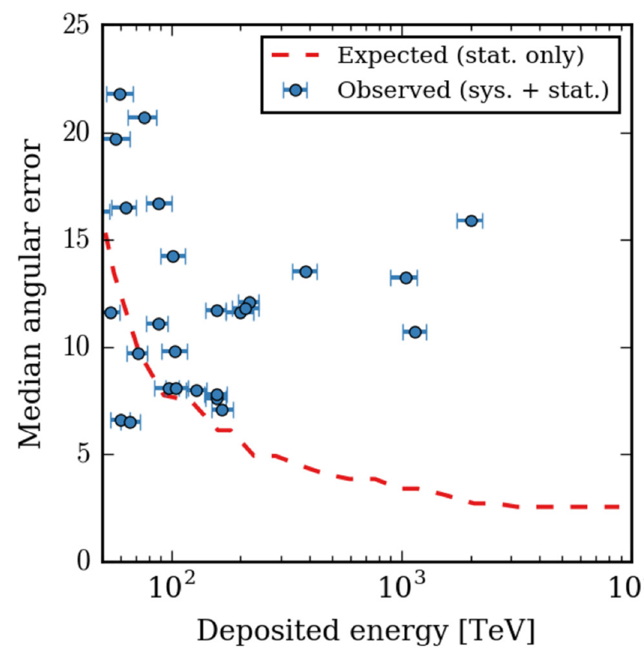

Fig. 6. Measured angular uncertainty of IceCube contained cascades (blue) including both systematic and statistical uncertainty, and expectation from statistical uncertainty only (red dashed line).

IceCube will add new event classes to the alert stream including lower-energy starting events and cascade-type events, which make up the majority of the astrophysical neutrino flux at Earth.

4. The IceCube upgrade and IceCube-Gen2

The next construction phase of IceCube is the IceCube Upgrade, which was approved by the National Science Foundation in 2018 (NSF Award #1719277) and is planned to be completed by 2023. The Upgrade will consist of 7 new strings which will be deployed in the DeepCore subarray in the center of IceCube, as shown in Fig. 5. The new

strings will be instrumented with upgraded photosensors. Three photosensor designs are planned for the Upgrade [20]:

- The mDOM, which consists of 24 3-inch PMTs, adapted from the design used by KM3NeT [21]. An alternate design 3.5 inch PMTs is under consideration. The mDOM has over twice the photon effective area per sensor as the IceCube DOM, and a nearly uniform sensitivity as a function of photon impact angle.
- The D-Egg, which consists of two 8-inch PMTs, one facing upward and one facing downward, with a more UV-transparent glass pressure vessel than what is used in IceCube.
- The pDOM, which is an IceCube DOM with upgraded electronics and calibration devices.

The multi-PMT sensor designs will have increased photocathode area compared to IceCube DOMs, and the increased UV transparency of the D-egg will also increase its sensitivity to the blue end of the Cherenkov spectrum. The Upgrade will collect an order of magnitude more atmospheric neutrino events than IceCube at energies of a few GeV. With this sample, IceCube will perform the world's best measurement of tau neutrino appearance and the world's most stringent test of unitarity in the tau sector of the PMNS matrix.

The sensors will be equipped with calibration devices including LED flashers and cameras [22]. Additionally, stand-alone calibration light sources will be deployed. The Precision Optical CAlibration Module (POCAM) [23] is a specialized device using LEDs in combination with a diffusing sphere in order to produce a nearly homogeneous light source. A prototype has already been tested in water in Lake Baikal and near Vancouver.

The goal of the calibration devices is to improve our models of IceCube sensor response and of the optical properties of the ice, which are our principal sources of systematic uncertainty. The updated calibration will be applied to the entire IceCube archival data set. Fig. 6 shows how much improvement we may expect in the angular reconstruction of cascade-type events by reducing systematic uncertainties. The improvement in reconstruction of cascade events will also increase our ability to detect the double cascade signature of high energy astrophysical tau neutrino events.

The eventual goal of IceCube is to build a next-generation neutrino telescope, IceCube-Gen2, which will instrument a volume about 10 times greater than IceCube. An extended surface array, larger than the footprint of the in-ice detector, will veto cosmic ray air showers and improve our sensitivity to astrophysical sources in the southern hemisphere sky.

Novel sensor technologies are under development for Gen2. The Wavelength-shifting Optical Module (WOM) [20] consists of 2 small

PMTs in a cylindrical tube coated with wavelength-shifting paint. This design increases UV sensitivity and also has a slimmer profile than the IceCube DOM, which decreases the amount of fuel required for drilling since the hole is narrower. For the enlarged surface detector, IceTop-style tanks are impractical, so we are investigating scintillator [24], radio [25] and air Cherenkov [26] methods.

5. Summary

IceCube's observation of a neutrino in coincidence with TXS 0506+056 has opened up an exciting new era in multi-messenger astrophysics. IceCube continues to analyze its large existing data set; many of the properties of the astrophysical neutrino flux are still under study. The IceCube Upgrade project has commenced, which will deliver new precision measurements of neutrino oscillation properties and a recalibrated IceCube data set which will deliver more astrophysical neutrino observations. Eventually, our plan is to build the next generation IceCube-Gen2 detector and discover the sources of astrophysical neutrinos.

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