

# IceCube: An overview of physics results

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**Abstract.** Cosmic rays and neutrinos are intimately related. And though TeV-PeV astrophysical neutrinos have been observed, their sources and their relation to potential sources of cosmic rays remain unknown. Recently, the blazar TXS 0506+056 has been identified as a candidate neutrino source. In parallel, IceCube has conducted numerous searches for other potential neutrino sources. These proceedings are limited in scope, given the large breadth of science results by IceCube: A description of the astrophysical neutrino flux; a review of the real-time program that enables multi-messenger follow-up of neutrinos; a summary of the observations of TXS 0506+056; a recap of the search for neutrino point sources with 7 years of IceCube data; an account of the tantalizing capabilities of IceCube and ANTARES to detect Milky Way neutrinos and a description of a method to identify Glashow resonance events.

## 1 Introduction

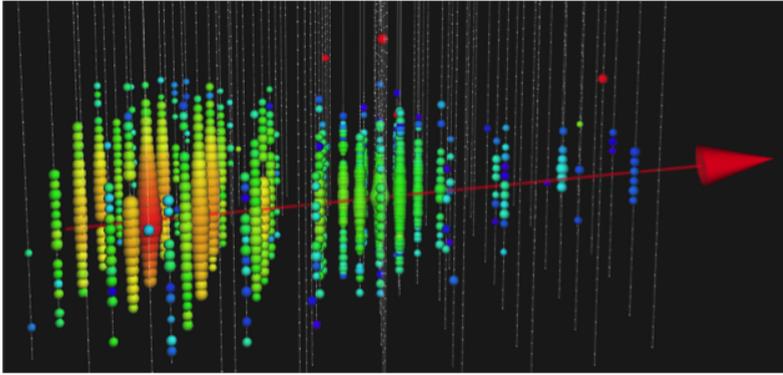
Four astronomical messengers enable the study of the non-thermal universe at the highest energies: gravitational waves, cosmic rays, gamma rays and neutrinos. Cosmic rays are the most challenging to use astronomically, as their directional information is lost when they are deflected by galactic and inter-galactic magnetic fields. High-energy (HE or  $\sim$ GeV) and very-high-energy (VHE or  $\gtrsim$ 100 GeV) gamma ray instruments have been extremely successful, enabling the study of extragalactic sources, such as active galactic nuclei or gamma ray bursts and galactic sources such as pulsar wind nebulae or supernovae remnants. Gamma rays are, however, attenuated via their interaction with the extragalactic background light, limiting their extragalactic use. Neutrinos, though hard to detect, provide new information. Neutrinos can travel without attenuation across the visible universe.

Collisions of cosmic rays at or near their production sites are expected via the interaction with local photon fields or local matter. Pions are produced, which then decay into neutrinos and gamma rays. Gamma rays however may be also be produced in non-hadronic processes. Only neutrinos can unequivocally identify cosmic ray sources.

The discovery of an all-sky, isotropic flux of VHE neutrinos by IceCube and the recent observation of a neutrino source candidate, the blazar TXS 0506+056, are pushing neutrinos to the forefront of multi-messenger astrophysics. These proceedings summarize work presented at the VLVNT 2018 by the IceCube collaboration. For brevity only some topics will be highlighted: The characteristics of the all-sky flux, the real-time program by IceCube, the observation of neutrinos from the blazar TXS 0506+056, the search for neutrino point sources, a search for neutrinos from Milky Way's galactic plane conducted by IceCube

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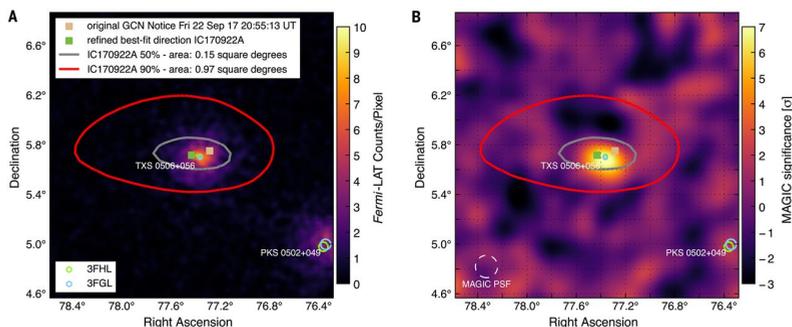
**Figure 1.** IceCube-160427A, the first real time neutrino alert sent by IceCube, on April 27, 2016. It is a starting  $\nu_\mu$  event. Here DOMs are indicated as dots. Colored spheres are DOMs reporting signals, with red being early and blue, being late. The red arrow indicates the best reconstructed track hypothesis.

and the ANTARES neutrino telescope and finally the description of a method to identify the muonic component of hadronic showers including an application in the search for Glashow resonance events.

IceCube is a neutrino telescope in operation at the South Pole. It consists of a 3-dimensional array of sensors, digital optical modules or DOMs, monitoring one cubic kilometer of highly transparent antarctic ice. Neutrinos interacting within or near the detector produce secondary particles that travel faster than the speed of light in ice. The secondary charged particles produce Cherenkov light, which is detected by the DOMs. There are two main channels of detection of neutrinos: tracks are made by muons product of  $\nu_\mu$  charged current interactions and cascades that are made by all flavors via various mechanisms.

Though they are the traditional neutrino astronomy channel, tracks were not the discovery channel. Instead they confirmed the observation of astrophysical neutrinos [1]. Because the planet has to be used to filter down-going muons, only the northern sky is visible using tracks. The energy of astrophysical neutrinos is harder than that of the irreducible atmospheric neutrino background. Though the neutrino energy is not directly accesible, the deposited secondary muon energy distribution differs from atmospheric neutrinos to astrophysical events. Furthermore atmospheric neutrinos are not isotropic. More atmospheric neutrinos are expected in the horizontal than in the vertical direction. The astrophysical spectrum as measured with tracks is described by a power law in energy with index -2.19 in an energy range from 200 TeV to 10 PeV.

The discovery of astrophysical neutrinos was actually made using the *High-Energy Starting Event* or HESE method [2]. Here a *veto* region is defined in the outer parts of the detector. For a given event, first light must be observed in the *fiducial* volume, of about 0.5 km<sup>3</sup> surrounded by the veto. For sufficiently large amounts of light, or photomultiplier tube charge, deposited by an event, the veto is very effective at filtering the intense down-going cosmic ray muon background. Both energy and direction are used to measure the astrophysical spectrum and distinguish signal from background. HESE is sensitive to neutrinos from all the sky ( $4\pi$  sr) and all flavors. HESE events are approximately 80% showers and 20% starting tracks. An interesting feature of the spectrum as measured by HESE is that is quite soft, it has an index of  $-2.89$  [3]. However IceCube has shown that above 200 TeV, it is compatible with an index of  $-2.19$ . This may be an indication of two populations of neutrino sources. At the highest energies, neutrinos are related to cosmic rays and gamma rays as described above,



**Figure 2.** Sky map of IceCube-170922A in J2000 equatorial declination and right ascension. Both panels include the direction uncertainty regions corresponding to 50% and 90% containment. Also shown on both panels is the known location of the blazar TXS 0506+056. The left plot (A) overlays Fermi data accumulated over 9.5 years. The right plot (B) overlays MAGIC data above 100 GeV in this region.

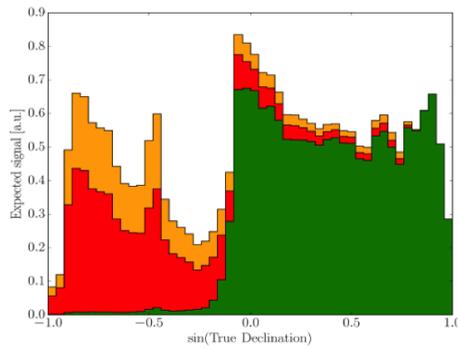
but at lower energies, and because the neutrino spectrum overshoots the extragalactic gamma ray background, neutrino sources may be gamma- and cosmic-ray-dark.

## 2 IceCube’s realtime program

Even with tracks, IceCube’s angular resolution is relatively poor. Multi-messenger campaigns, in which electromagnetic observations are made simultaneously with neutrinos may enable the identification of sources. Starting on April 2016, IceCube has sent 18 real-time alerts for events that have a high probability of being astrophysical. Both starting and through-going tracks are distributed [4]. After a promising event has been detected and reconstructed a GCN notice is sent. Typical latencies for GCN notice are only  $\sim 1$  minute. Within about 3 hours more advanced reconstruction methods are applied offline to the event and a GCN circular is distributed with more information. Fig. 1 shows event IceCube-160427A, the first alert sent. Realtime alerts are currently being redesigned to uniformize how the information is presented and to provide clear thresholds for astrophysical probability. Two new streams will be available. A *Gold* stream will consist of through-going and starting events that have a signal probability above 50%. This channel will have a rate of  $\sim 8$ -10 alerts per year, similar to the existing system. A *Bronze* stream will have a lower threshold of 30% with a rate of 24-30 alerts per year (Gold alerts are automatically Bronze alerts). The start of operation of the new alerts is imminent.

## 3 The TXS 0506+056 blazar and IceCube-170922A

On September 22, 2017 IceCube issued the real-time alert IC-170922A. This event, with a likely neutrino energy of 290 TeV, had a tight reconstruction uncertainty of only 0.97 deg.sq (90% containment). Within days, Fermi LAT and MAGIC reported that the blazar TXS 0506+056, located well within the the uncertainty region reported by IceCube, was flaring in HE and VHE gamma rays. Furthermore, this was the first VHE detection of this blazar. The chance temporal and directional coincidence was ruled out at  $3\sigma$  level [5]. Interest in this blazar resulted in a redshift measurements of  $z = 0.3365$ . This blazar, though not the nearest ones to Earth, is the most luminous known in its class. This results in it being in the



**Figure 3.** Relative contribution to the sensitivity to the galactic plane using ANTARES tracks (red), ANTARES showers (orange) and IceCube tracks (green) as a function of declination.

top 0.3% brightest blazars detected by Fermi. Fig. 2 shows the alert IceCube-170922A with Fermi and MAGIC data.

IceCube examined its 9.5 year archival data, excluding the IC-170922A event, in the direction of TXS 0506+056 and found  $3.5 \sigma$  evidence for a flare of 13 neutrinos lasting 110 days starting on late 2014. Interestingly, this period does not show strong HE emission [6].

The fact that there are blazars that are closer to Earth than TXS 0506+056 and that there some of these have a flux as strong as TXS 0506+056, has lead to the speculation that not all blazars are neutrino sources and that TXS 0506+056 is somehow special [7].

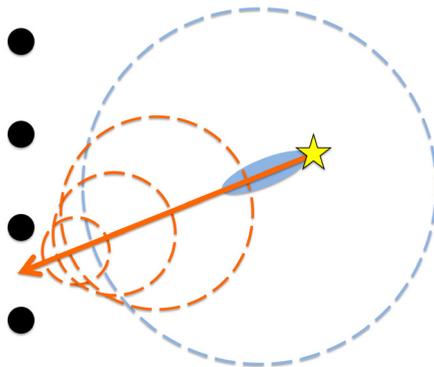
## 4 Search for neutrino point sources

We have searched 7 years – from 2008 to 2015 – of IceCube data for spatial self-correlations to identify neutrino point sources [8]. This study has been performed using both the northern hemisphere and the southern hemisphere. In the north, data is dominated by  $\sim 80,000$  atmospheric neutrinos per year, while in the south it's dominated by 35,000 down-going high-energy muons per year. The data set also includes  $\sim 200$  starting tracks per year due to down-going neutrinos. The inclusion of starting tracks improves the sensitivity of the analysis near  $\sim 100$  TeV in the southern sky. Extrapolating the astrophysical spectrum to the threshold of detection in this analysis results in 200-2400 events per year.

The search is conducted using a likelihood ratio method, that compares the background only hypothesis to a signal plus background hypothesis. The signal hypothesis is described in terms of the number of signal events,  $n_s$  and the spectral index of the spectrum,  $\gamma$ . We do not find evidence for a point source by looking at the entire sky. We also search in the direction of 64 promising objects, but do not find evidence for neutrino emission either. Over the northern sky, the study is able to detect a source with a strength of  $E^2 d\phi/dE \sim 10^{-12}$  TeV cm $^{-2}$  s $^{-1}$  with a significance of 5 sigma.

## 5 A joint IceCube-ANTARES study of the galactic plane

Galactic cosmic rays interact with interstellar gas in the Milky Way, producing both gamma rays and neutrinos. Fermi has already observed GeV gamma rays from the galaxy. Nevertheless our understanding of the propagation and diffusion of cosmic rays is still limited. An observation of neutrinos from the galactic plane would enable a study of these processes at



**Figure 4.** In hadronic showers with an early muon, the earliest light in some DOMs is from the muonic component, because the muons travel faster than the speed of light in ice. Here Cherenkov light produced by the muon is shown in orange, while earliest light by the cascade is in blue.

energies higher than that of Fermi, and separating the pionic component. Models that detailed cosmic rays in the galaxy can be extrapolated to higher energies and tested.

A joint study of galactic diffuse emission has been performed [9] by the mediterranean neutrino telescope ANTARES and IceCube. In the case of ANTARES, both tracks and cascades are used <sup>1</sup>. For IceCube track data was used. Fig. 3 shows the relative contribution of IceCube and ANTARES events to this study.

No evidence for correlation with the galactic plane was found. The study showed that no more than 8.5% of the all-sky astrophysical flux may originate in the galactic plane. Using the  $KRA_\gamma$  model [10] as a reference and assuming a 5 PeV cutoff in the cosmic ray spectrum, approximately matching the knee, the joint sensitivity is at 80% of the neutrino flux level predicted by the model.

## 6 Muons in hadronic showers

Hadronic cascades, e.g. those initiated by mesons, include a muonic component. At PeV energies, approximately 10 muons, with an energy greater than 10 GeV are expected. The muon with the longest range may be identified by observing the earliest light in some of the DOMs that participate in an event. This is because muons travel at  $\lesssim c$ , while light on ice travels at about  $2/3$  that value. This is illustrated in Fig. 4.

New event reconstruction methods that include a muonic component have been developed [11]. Early light from the muonic component can be used to significantly improve the angular uncertainty. For a typical PeV cascade, the (50% containment) angular uncertainty corresponds to  $\sim 100$  deg.sq. With these new methods the uncertainty may be reduced by as much as a factor of 6.

A particularly interesting case in which we can use this new method is in the search Glashow resonance events. The interaction of  $\bar{\nu}_e$  with atomic electrons has an s-channel resonance for a neutrino energy of 6.3 PeV and results in an on-shell  $W^-$ . Two thirds of the decay modes of the  $W^-$  result in hadronic cascades. The visible energy in the cascade is expected to be  $\sim 5.9$  PeV. A Glashow resonance may be identified by observing a muonic component and by measuring a visible energy close to that of expectations.

<sup>1</sup>Angular resolution for both tracks and cascades in ANTARES is  $\sim 0.1 - 0.5^\circ$  and  $3 - 5^\circ$  respectively

The observation of a Glashow resonance event would have many astrophysical implications: It is the only channel in IceCube that allows the exclusive observation of anti-neutrinos. It also implies that the astrophysical spectrum extends up to, at least, 6.3 PeV. Finally by observing  $\bar{\nu}_e$ , information can be obtained on the flavor flux ratios at Earth, which under standard oscillations are expected to be similar, but not necessarily exactly 1:1:1.

## 7 Other IceCube contributions at this conference

Besides what has been described and as expectable at VLVNT, a wide range of science results were presented by IceCube, including: detailed studies of TXS 0506+056 and IC-170922A [12–15]; a detailed study of the HESE spectrum and neutrino flavor ratios [16]; a search for tau neutrinos [19]; ANTARES/IceCube studies of dark matter [17] and point sources [18]; a search for correlations between the highest energy cosmic rays and neutrinos [20]; constraints on ultra-high-energy neutrino fluxes [21]; IceCube capabilities to study oscillations with the Upgrade and sterile neutrinos [22]; improvements to reconstruction [23, 24] and spectral deconvolution [25]. Finally a status of the IceCube Upgrade and plans for IceCube Gen2 were also presented [26].

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