Highlights from the IceCube Neutrino Observatory

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Abstract. The IceCube Neutrino Observatory has been collecting data for more than a decade. During this time, it has heralded the birth of neutrino astronomy with the discovery of the astrophysical neutrino flux. In recent years, significant results and discoveries have emerged from this detector. In these proceedings, I review some of the latest highlights from the IceCube collaboration, including the first neutrino view of our own Milky Way and the first identification of potential extragalactic neutrino sources.

1 Introduction

The IceCube Neutrino Observatory is a cubic-kilometer detector located at the South Pole and buried in the Antarctic ice [1]. The glacial ice serves as both a target for neutrino interactions and as a Cherenkov radiator for the secondary charged particles produced during these interactions. Cherenkov photons are collected by a three-dimensional array of 5,160 photomultipliers deployed along 86 strings following an octagonal footprint and buried between 1,450 meters to 2,450 meters in depth. Each string supports 60 Digital Optical Modules (DOMs) arranged vertically, with a spacing of 17 meters between DOMs and 125 meters between strings [2].

A denser sub-array, called DeepCore, consisting of 8 strings with a horizontal separation of about 70 meters and a vertical DOM spacing of 7 meters, allows for a reduction in the neutrino energy threshold. Additionally, IceTop, a surface array of detectors, reconstructs cosmic-ray air showers in the 300 TeV to 1 EeV energy range and provides a cosmic ray veto for in-ice events. IceCube was completed in 2010 and has been operating continuously with a detector uptime exceeding the 99%.

2 Signals and Backgrounds

The primary goal of IceCube is to detect astrophysical neutrinos. At TeV energies, neutrinos predominantly interact with matter through Deep Inelastic Scattering (DIS), which occurs via either the exchange of a W boson (charged-current interactions), or a Z boson (neutral-current interactions). Charged-current interactions of muon neutrinos produce muons that traverse the detector, leaving a track-like pattern in the DOMs signals. Neutral-current interactions, as well as charged-current interactions involving electron, –or tau neutrinos at energies below the PeV scale–, generate electromagnetic and hadronic showers resulting in cascade-like light patterns.

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Track-like events provide accurate angular resolution (0.1° to 1°) since the interaction vertex may lie outside the detector, effectively increasing the detection volume. However, their energy resolution is limited due to the stochastic nature of the muon energy losses. Conversely, cascades have excellent energy resolution (about 15%) [3] but limited angular resolution due to their spherical light pattern (about 10° above 100 TeV).

The primary backgrounds in neutrino observatories are atmospheric muons and neutrinos, both produced by cosmic-ray interactions with atmospheric nuclei. Atmospheric muons arise from the decay of charged mesons (mostly $\pi^{\pm}/K^{\pm}$). Atmospheric neutrinos originate from the same decays while at lower energies (~GeV), additional neutrinos are produced from muon decay.

Atmospheric muons can penetrate the overburden of ice and reach the detector from above, while the Earth serves as a shield for up-going muons. Neutrinos, being weakly interacting particles, can traverse the Earth, making indistinguishable the atmospheric neutrinos from the astrophysical ones on an event-by-event basis. To mitigate this background, IceCube employs two main strategies. The first strategy consists of selecting good quality through-going tracks and keep only those with up-going directions, rejecting in this way most of the down-going atmospheric muons. The second strategy selects only starting events inside the detector by using a veto region on the boundaries of the detector. By identifying only starting events it is possible to eliminate through-going atmospheric muons and, for vertical down-going zenith angles, atmospheric neutrinos as these are accompanied by muons produced in the same air shower.

3 Diffuse Astrophysical Neutrino Flux

In 2013, IceCube confirmed the existence of a diffuse astrophysical neutrino flux, with an energy density comparable to that of the extragalactic gamma-ray background (EGB) and Ultra-High-Energy Cosmic Rays (UHECRs). This flux can be interpreted as the aggregated emission from all neutrino sources in the Universe. While the spectrum is expected to be more complex, it can be approximated at first order by a single power-law (SPL) model ($\Phi_\nu = \Phi_0 E^{-\gamma}$) defined by two parameters: the normalization, Φ_0, and the spectral index, γ. Figure 1 summarizes the current measurements of the SPL parameters from various IceCube datasets. One of the results, labeled as GlobalFit in Fig. 1, uses a combination of two datasets, one consisting on through-going tracks events, and a dataset of cascades events. The ESTES [5] analysis also shown in Fig. 1 uses a novel selection technique that takes advantage of both starting track events by applying a dynamic veto per event.

In addition to the SPL model test, the analyses also explored a minimally model-dependent approach by fitting the normalization of an E^{-2} spectrum in different energy bins. This so called *segmented fit* allows to explore deviation from a SPL model. Figure 2 compares the segmented fit results from the ESTES and GlobalFit analyses, revealing a largely featureless spectrum, though the GlobalFit result hints at possible deviations from the SPL model.

At the highest energies, IceCube is searching for cosmogenic neutrinos, Extremely High Energy (EHE) neutrinos produced by interactions of UHECRs with the cosmic microwave background (CMB). After analyzing 12.6 years of data, three events, below 10 PeV and consistent with astrophysical origins, were observed. As no EHE neutrino event were detected, IceCube constrains the expected flux of cosmogenic neutrinos, as shown in Fig. 3 and giving, for the first time from neutrino data only, a constrain on the proton fraction of UHECR of less 70% [11]. Unlike the direct analysis of UHECR composition, the results on neutrino data are independent of the uncertainties of the hadronic interaction models.

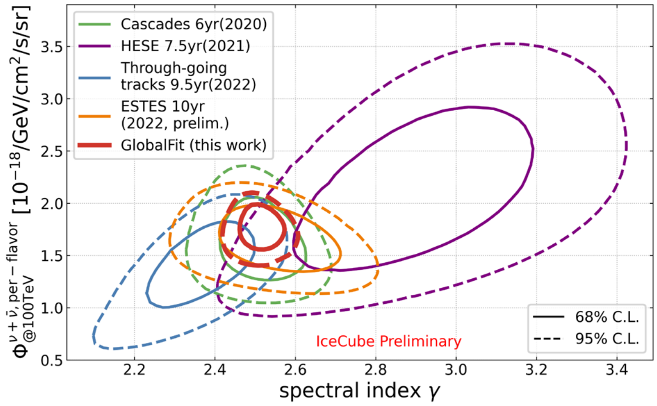

Figure 1. Result of the combined fit of tracks and cascades GlobalFit (in red) under the assumption of an astrophysical SPL neutrino flux and for the ESTES sample (in orange). Previous results from measurements using single event channels are shown for comparison. The sensitive neutrino energy ranges and neutrino flavor probed are different among the different samples. Figure taken from [6].

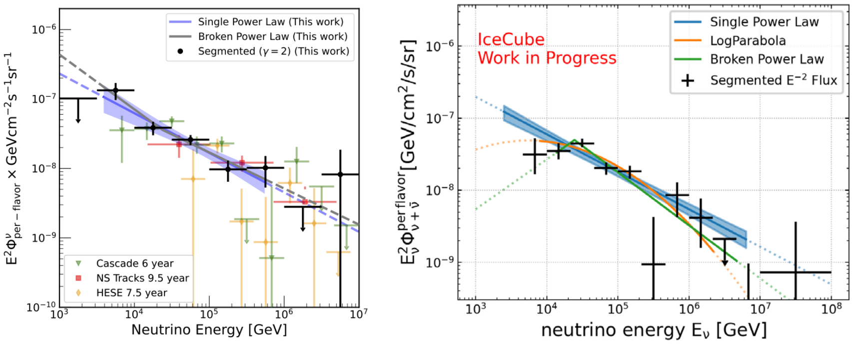

Figure 2. The per flavor astrophysical neutrino flux shown as a function of energy for the ESTES dataset (left) and the GlobalFit (right). The black points are the segmented power law flux measurement assuming a spectral index of $\gamma = -2$. See [5] and [6] for more details.

4 Astrophysical Neutrino Sources

4.1 The Milky Way

A portion of the diffuse astrophysical neutrino flux originates from our Milky Way. Galactic cosmic rays injected in the Galaxy diffuse during their propagation due to random galactic magnetic fields. This diffusive motion is responsible for the softening of the observed CR spectral index (from ~ 2 to ~ 2.7). The consequence of this galactic diffusion is an increased residence time of CRs in the Galaxy, during which they interact with the interstellar medium and produce pions. These pions decay, generating a diffuse galactic flux of both neutrinos and gamma rays. Recently, IceCube detected neutrino emission from the Galactic plane with a significance of 4.0σ. The analysis utilized cascades events reconstructed with a Deep

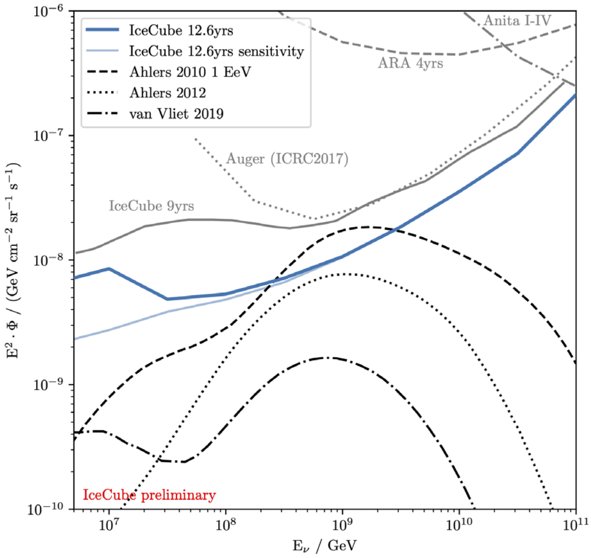

Figure 3. Differential upper limit (90% C.L.) on the neutrino flux for neutrino energies ranging from 3 PeV to 100 EeV compared to other neutrino detectors (ARA, ANITA) and Auger results on neutrinos. Also shown are some models of cosmogenic neutrinos. Figure taken from [11].

Learning algorithm to improve directional resolution [8]. The search employed a template fit based on neutrino predictions from cosmic ray interactions with galactic gas, along with models of galactic neutrino emission (see Fig. 4). The level of the observed Galactic neutrino flux, however, contributes less than 10% of the total cosmic neutrino flux. In contrast to the gamma-ray sky, the extragalactic neutrino component appears to dominate the full sky, outshining nearby sources such as our own Galaxy.

4.2 Extragalactic Sources

Extragalactic neutrino sources can be identified by searching for clusters of neutrino events near specific coordinates. To leverage IceCube's directional capabilities, through-going tracks are typically used for these point source searches, as they provide the best angular resolution. IceCube has been looking for point sources since its construction stage. In "time-integrated" searches, the time of arrival of the neutrino is not considered as the sources are assumed to be steady neutrino emitters. This is in contrast to time-dependent searches that target flares or variable emission from sources. IceCube's recent time-integrated point-source analysis revealed NGC 1068 as a significant emitter with a global significance of 4.0σ [4]. Figure 5 shows the local p-value map around the most significant direction. NGC 1068 is a Seyfert galaxy powered by a supermassive black hole and located at relatively close distance of about 14.4 Mpc. The core of NGC 1068 is obscured with large amounts of material making it possibly the brightest intrinsically Seyfert galaxy in X-rays. The mechanism responsible of the neutrino emission is believed to be the disk-corona model [12]. In this model electrons and protons are accelerated in the high magnetic field regions associated with the black hole and the accretion disk, producing gamma rays. The corona, a hot plasma above the accretion disk, provides in turn a dense X-ray target photon field for protons in $p\gamma$ interactions leading to the TeV neutrino emission. This hot corona is also responsible of the obscuration of

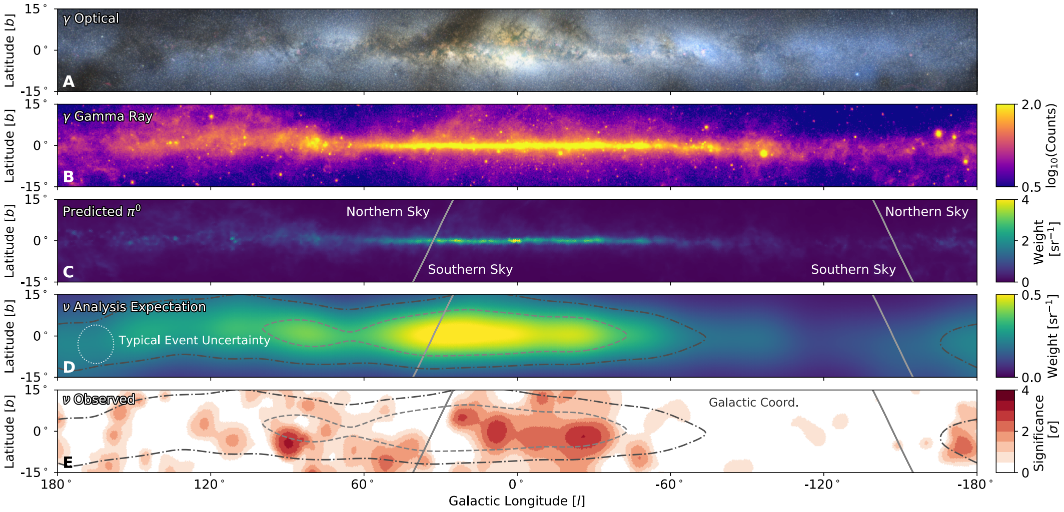

Figure 4. The plane of the Milky Way Galaxy in photons and neutrinos. Panels are in galactic coordinates. Panels A,B show the observations in optical and gamma rays. Panel C are the neutrino expectation from a CR interaction model based on gamma-ray data. Panel D is the result of panel C after going through detector effects. Neutrino data is shown in panel E. Figure taken from [8].

gamma rays, which explains why the TeV gamma-ray emission from NGC 1068 is at least one order of magnitude lower than that of neutrinos [4].

Since the disk-corona model offers a plausible explanation for the neutrino emission observed from NGC 1068 while also accounting for the absence of gamma-ray emission, several IceCube searches have investigated this mechanism by focusing on sources which are opaque to gamma rays. Two of these searches targeting Seyfert galaxies and X-ray-bright sources reported a marginal excess of neutrinos from individual sources: CGCG 420-015 at a 2.5σ [9] significance level and NGC 4151 at 2.9σ [10] (see Fig. 6). However the combined emission resulting from the *stacking* of individual sources could not be observed, implying that the parameters of disk-corona model explaining the observed flux from NGC 1068 do not appear to be shared among other similar sources.

5 The Future

In the near future IceCube will start the construction of the IceCube Upgrade [7]. The IceCube Upgrade consists on the deployment of seven additional in-filled strings (see Fig. 7), strategically placed within the detector to increase its sensitivity to lower-energy neutrinos (∼ GeV). While the IceCube Upgrade is designed to target GeV neutrinos, it will be equipped with novel calibration devices which will allow for more precise calibration of the Antarctic ice. This refined calibration will help reduce systematic uncertainties, leading to improved angular and energy reconstructions for neutrinos across all energies. The primary scientific goal of the IceCube Upgrade include precision measurements of atmospheric neutrino oscillations. The IceCube Upgrade is currently scheduled to be installed during the 2025/26 Antarctic summer season.

On a longer timescale IceCube is planning to develop a next-generation high-energy neutrino observatory known as IceCube-Gen2. Its implementation and science goals are summa-

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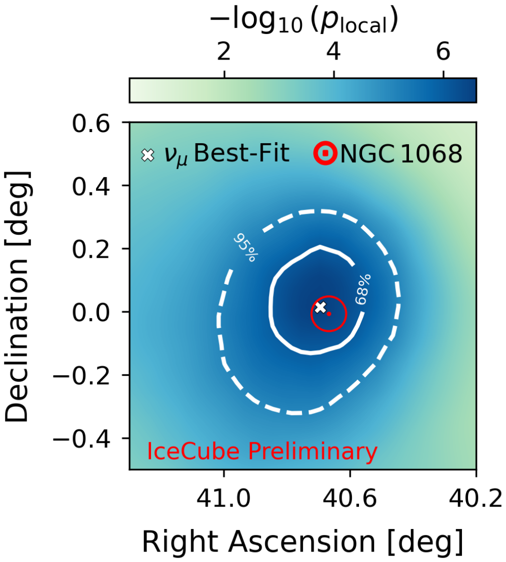

Figure 5. Local pre-trial p-value maps around the source NGC 1068. The red circle indicates the location of the source and the cross shows the best-fit location. Contours correspond to 68% (solid) and 95% (dashed) confidence regions.

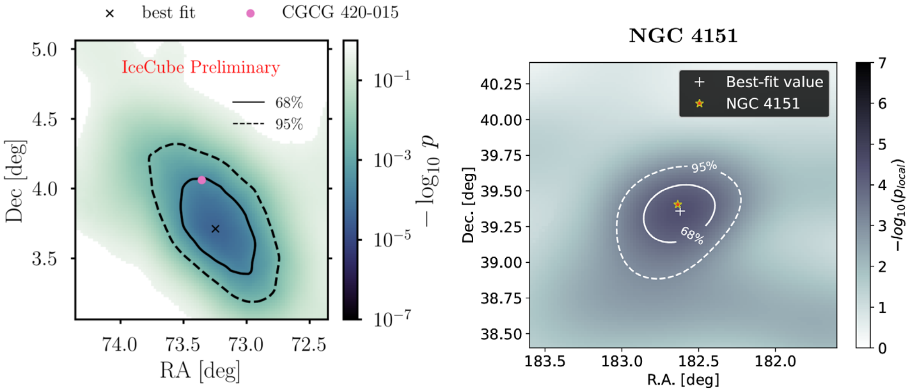

Figure 6. Local pre-trial p-value maps around CGCG 420-015 (left) [9] and NGC 4151 (right) [10]. See caption of Fig. 5 for more details.

rized in the technical design report [13]. The IceCube-Gen2 detector will be a wide-band neutrino observatory covering energies from MeV up to EeV by integrating different detection technologies for neutrinos. An optical array with an instrumented volume almost an order of magnitude larger than IceCube will be complemented with a 500 km^2 radio array detector in order to significantly expand the sensitive energy range of the observatory. A surface detector array for CR detection will complete the detector making it a unique observatory to exploit the enormous scientific opportunities in astroparticle physics. IceCube-Gen2 will be capable of detecting a neutrino source with a flux equivalent to NGC 1060 at a 5σ significance level within just two years of operation. Additionally, IceCube-Gen2 will enable precise measurements of the spectral shape of the neutrino diffuse emissions and, in conjunction with future astroparticle facilities, it will open the possibility to do multimessenger spectroscopy.

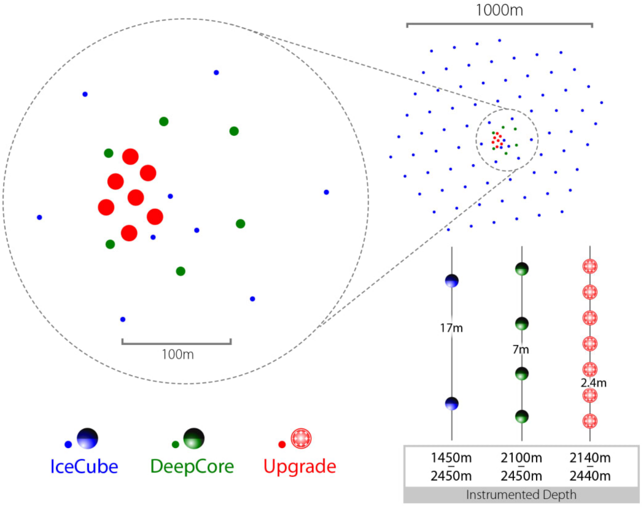

Figure 7. The IceCube Upgrade array geometry. Red marks indicate the layout of the 7 IceCube Upgrade strings with the IceCube high-energy array and its sub-array DeepCore.

6 Conclusion

IceCube continues to advance our understanding of astroparticle physics. The diffuse astrophysical neutrino flux has been consolidated and we are entering an era of precision measurement. In this regard, IceCube continues to investigate and characterize this flux and deviation from a simple power law emission models seems to appear in data. The first sources of neutrinos are being unveiled starting with the first picture of the Milky Way with neutrinos. Extragalactic sources are being identified informing phenomenologists to develop models of neutrino emission which could lead us to the discovery of new sources. However neutrino astronomy is never that simple and we can expect more surprises.

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