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IceCube: Astrophysics Results

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With the identification of a diffuse flux of astrophysical ("cosmic") neutrinos in the TeV-PeV energy range, IceCube has opened a new window to the Universe. However, the corresponding cosmic landscape is still uncharted: so far, the observed flux does not show any clear association with known source classes. The present talk summarizes the recent astrophysics results from IceCube, starting with the observed flux of cosmic neutrinos and the related constraints on its spectrum and flavour composition, continuing with the search for steady individual sources, and ending with the search for transient emission of neutrinos. It also sketches IceCube's multimessenger program. Finally, it gives a short outlook on plans to considerably enlarge IceCube and to study the high-energy neutrino sky in much more detail than the present array permits.

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1. Introduction

With the discovery of a flux of high-energy neutrinos of astrophysical origin ("cosmic neutrinos") in 2013 [1], the Icecube Neutrino Observatory has opened a new window to the Universe of non-thermal cosmic processes. IceCube covers 1 km^3 of Antarctic ice which is about the same volume as, nearly fourty years ago, was conceived for the Deep Underwater Muon and Neutrino Detector (DUMAND) off the coast of Hawaii. The DUMAND 1978 design envisaged an array of about 20 000 photomultipliers spread over a 1.26 cubic kilometer volume of water. This project was terminated in 1995, but the baton was taken by the projects NT200 in Lake Baikal, AMANDA at the South Pole, ANTARES in the Mediterranean Sea and, again at the South Pole, IceCube [2]. A next generation of arrays is under construction or planned: KM3NeT in the Mediterranean Sea [3], the Gigaton Volume Detector GVD in Lake Baikal [4], and IceCube-Gen2 [5].

The primary goal of these detectors is identifying the sources of high-energy cosmic rays. In contrast to charged particles, neutrinos are not deflected in cosmic magnetic fields and keep their direction; in contrast to gamma rays they provide a direct, water-tight prove for the acceleration of hadrons in the emitting sources. This makes them unique tracers of sources of cosmic rays. On the other hand, due to their small interaction cross section they are difficult to detect: The "neutrino effective area" of the 1 km^3 IceCube detector (essentially the geometrical area multiplied with the interaction probability, the trigger and selection efficiency and the transparency to neutrinos of the Earth) is less than 1 m^2 at 1 TeV and of the order of 100 m^2 at 100 TeV [18]. It is therefore no surprise that it took several decades to detect cosmic neutrinos.

Neutrino telescopes are multi-purpose detectors. Apart from investigating cosmic neutrinos, they exploit atmospheric neutrinos to study neutrino oscillation [6], to search for sterile neutrinos [7] or to test fundamental laws of physics. They are used to search for neutrinos from Dark Matter annihilations in the Sun or the Galactic halo, to search for exotic particles like magnetic monopoles, or to study muons from cosmic ray induced air showers.

This paper focuses to the search for neutrinos from cosmic acceleration processes.

2. The IceCube Neutrino Observatory

The IceCube Observatory [8] is located at the geographical South Pole. It consists of the main IceCube array with its subarray DeepCore and the surface array IceTop. The main array comprises 5160 digital optical modules (DOMs) installed on 86 strings at ice depths of 1450 to 2450 m and covers 1 km^3 of ice. A string carries 60 DOMs. DeepCore, a high-density sub-array of eight strings at the center of IceCube, has smaller spacing and DOMs with more sensitive photomultipliers than IceCube and sits in the midst of the clearest ice layers.This results in a threshold of about 10 GeV and opens a new venue for oscillation physics. The threshold of the full IceCube detector is about 100 GeV. In its final configuration, IceCube takes data since spring 2011, with a duty cycle of more than 99%. It collects almost 10^5 clean neutrino events per year, with nearly 99.9% of them being of atmospheric origin.

3. Diffuse Fluxes

It has been predicted since long that the first evidence for extragalactic cosmic neutrinos would be provided by a diffuse flux rather than by single-source signals [9]. The first tantalizing hint to cosmic neutrinos came from two shower-like events with energies ≈ 1 PeV, discovered in 2012 and dubbed "Ernie" and "Bert" [10]. A follow-up search of the same data (May 2010 to April 2012) with a lowered threshold (30 TeV) provided 25 additional events. This analysis used only events starting in a fiducial volume of about 0.4 km^3 (High Energy Starting Events, or "HESE"), using the other 60% of IceCube as veto against all sorts of background. Energy spectrum and zenith angle distribution of the 27 events excluded an only-atmospheric origin with 4.1σ but suggested that about 60% were of cosmic origin, at energies above 100 TeV even about 80% [1]. A four-year data set with 54 neutrinos provided another shower-like PeV event (deposited energy ≈ 2 PeV) and confirmed a dominant cosmic contribution with nearly 6.5σ. Very recently, the results from a six-year sample have been presented [11], with 82 events above 30 TeV. Figure 1 shows the energies deposited by these events inside IceCube.

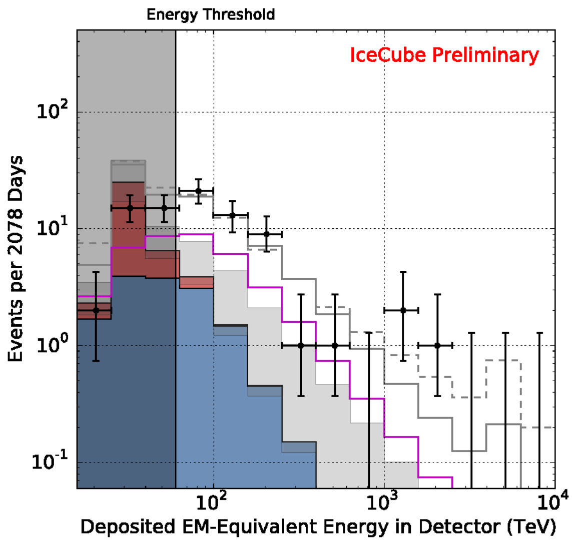

Figure 1: Distribution of the energy deposited by 82 events from the six-year HESE analysis. Backgrounds of atmospheric origin come from punch-through downgoing muons and from atmospheric neutrinos. While the flux of neutrinos from π and K decays is well known (blue region), the neutrino flux from charm decays in the atmosphere is uncertain and dominates the uncertainty of all background sources (gray region with 1σ uncertainties). The best-fit astrophysical spectra are shown as gray lines, for a single power-law spectrum as solid line, for a two power-law model as dashed line. See [11] for details.

A 5.6σ excess of high-energy cosmic neutrinos is also seen in the spectrum of secondary muons generated by neutrinos that have traversed the Earth, with a zenith angle less than 5 degrees above the horizon ("upward throughgoing muons"[12]). Figure 2 shows the median neutrino energy. It is calculated for each energy deposited by the muon in the detector, assuming the best-fit spectrum. The highest energy muon has deposited 2.6 ± 0.3 PeV inside the instrumented volume, which corresponds to a most probable neutrino energy of about 9 PeV.

While both analyses (HESE and throughgoing muons) have reached a significance for a strong non-atmospheric contribution of more than 5σ , the spectral indices of the astrophysical flux from both analyses disagree: $\gamma = 2.92 \pm 0.33/0.29$ for the HESE events (unbroken spectrum $E^{-\gamma}$) and $\gamma = 2.19 \pm 0.10$ [13] for the throughgoing muons. Adding two more years to the HESE sample has

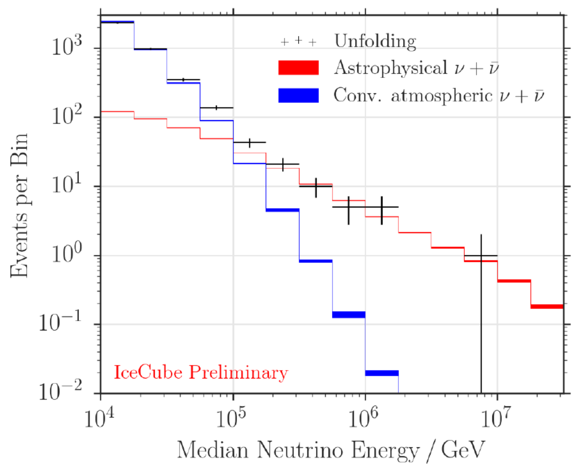

Figure 2: Spectrum of the median neutrino energy derived from the energy deposit of throughgoing muons with zenith angles less than 5 degrees above horizon (8 years sample [13]).

resulted in a softer energy spectrum since all events of the recent two years have energies below 200 TeV. Fig.3 shows the two fits under the assumptions of a single-power law. The possibility that all but the three PeV HESE events emerge from pion/Kaon/charm decays in the atmosphere is excluded by their zenith angle distribution.

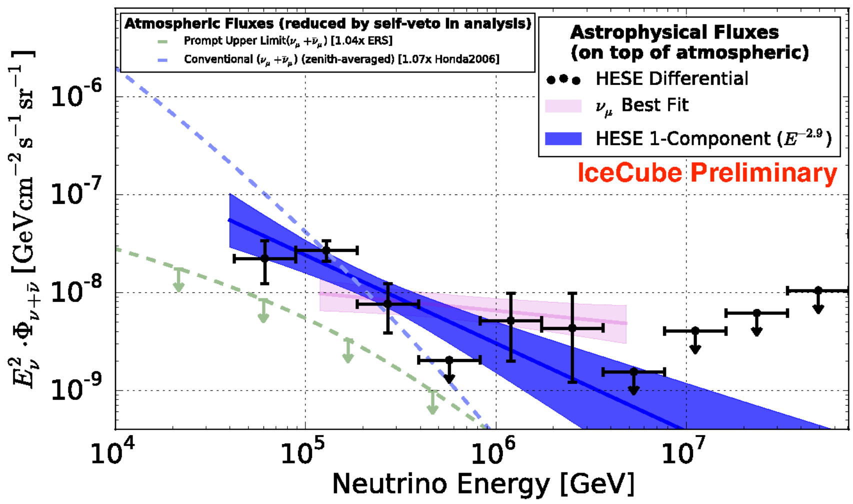

Figure 3: Best-fit of the per-flavor neutrino fluxes as a function of energy. The black points with 1σ uncertainties are extracted from a combined likelihood fit of all background components together with an astrophysical flux component with an independent normalization in each band (assuming an E^{-2} spectrum within each band and atmospheric neutrino and muon fluxes subtracted). The best-fit conventional flux and the upper limit for prompt neutrinos are shown separately, not taking into account the HESE self-veto which actually reduces their contribution. The blue band shows the 1σ uncertainties of a single power-law fit to the HESE data. The pink band shows the fit for the muon neutrino data, again with 1σ uncertainties. Its length indicates the approximate range providing 90% of the significance of this analysis [11].

In [14] the flavor ratio of the astrophysical neutrino flux has been investigated. It is consistent with an observed flavor ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ and also with source neutrino ratios 1:2:0 (pion decay) and 0:1:0 (pion decay with suppressed muon decay) while largely excluding 1:0:0 (neutrinos from neutron decay). This analysis made no attempt to identify tau neutrinos, the observation of which would be a smoking gun for astrophysical sources. A very recent analysis searched for tau decays (double-bang signature) and did not observe candidates [15]. From this, the constraints in Fig. 4 have been derived, shown together with the results from [14].

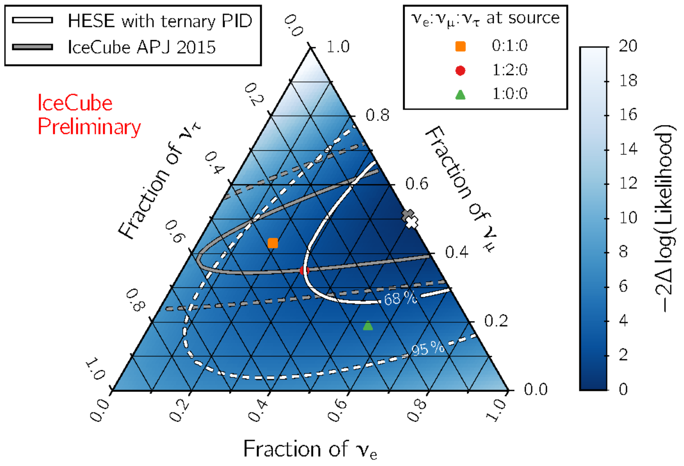

Figure 4: All-flavor ("ternary PID") ratio measurement on the six-year HESE sample [15]. The best fit is marked with ×. Compositions expected at Earth are marked for three different source scenarios. The gray lines show the previously published constraints from [14].

The hope to see any clustering of the HESE and muon-track events at highest energies has not fulfilled. An initial indication of clustering of HESE events close to the Galactic center has vanished with more statistics.

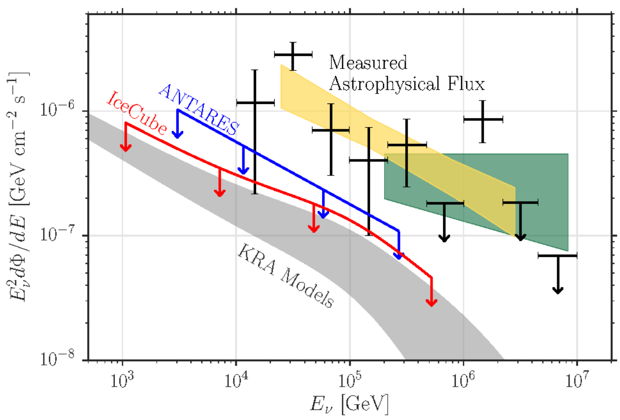

Figure 5: Upper limits on the three flavor neutrino flux from the Galaxy with respect to KRA model predictions [16] and the measured astrophysical flux [17]. Dots, yellow and green bands have the same meaning as the bands in Figure 3.

A recent analysis has used 7 years of the medium-energy ν_μ data (which are optimized to search for point sources, see next section) to set constraints on the diffuse emission of neutrinos from the Galactic plane [17]. The resulting limits are shown in Fig.5 and compared to the flux of the HESE and highest-energy ν_μ data. They exclude that more than 14% of the observed diffuse astrophysical flux come from the Galactic plane. However, the limit is not far from model predictions (gray band). Joining IceCube and ANTARES data and exploiting cascade-like events in addition to the ν_μ sample may drive the sensitivity into the region predicted by KRA models.

4. Search for steady point sources

For the standard steady-source search, a sample of throughgoing muons with good angular resolution (median error smaller 1 deg) is selected. In the lower hemisphere, the Earth acts as filter against muons generated in the atmosphere. In the upper hemisphere, a radical energy cut removes most of the atmospheric muons which have a rather soft energy spectrum, but naturally also rejects all but the most energetic cosmic neutrinos. Therefore only hard-source spectra would result in a significant number of events from the upper hemisphere (for IceCube: South).

Figure 6 shows the all-sky plot of seven years data, with 422 791 upward muons from neutrino interactions and 289 078 downward muons, the latter almost all from atmospheric showers. The downward sample contains also 961 tracks starting inside the detector, i.e. generated in neutrino interactions [18].

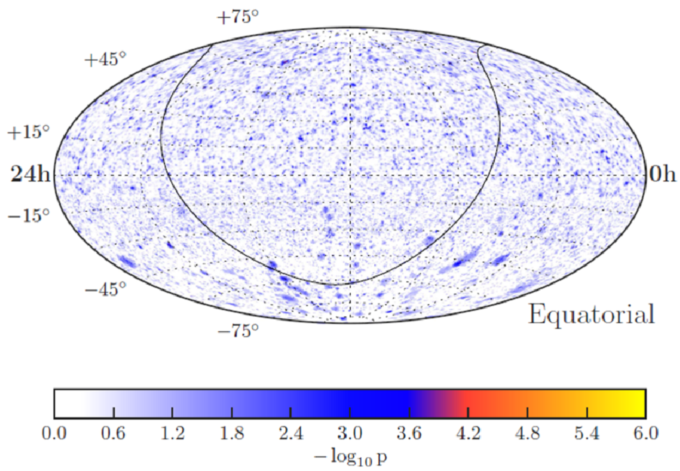

Figure 6: All-sky plot of seven years IceCube data in equatorial coordinates. Shown is the negative logarithm of the pre-trial p-value, assuming no clustering as null-hypothesis [18].

No significant excess is found, resulting in the flux constraints show in Figure 7. Apart from sensitivities and limits for selected sources, the discovery potential is shown, i.e. the flux that would lead to a 5σ discovery of a source in 50% of the cases.

One can then compare these values to predictions for selected sources. Fig.8 compares our sensitivities and the obtained 90% upper limits to predictions [19] for three blazars. The limits are within a factor 5 of the predictions, for Mkr 421 even slightly below predictions. Similar relations hold for the Crab nebula – always optimistically assuming that the gamma flux observed from these sources is basically due to π^0 decay and not to inverse Compton scattering.

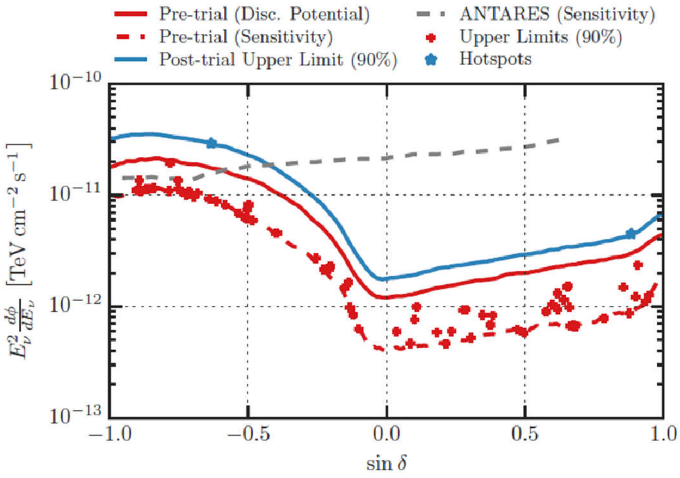

Figure 7: Discovery potential and sensitivity (red solid and dashed, respectively) versus declination, assuming an unbroken E^{-2} neutrino spectrum. Upper limits of 32 pre-selected source candidates are given as red crosses, the blue line represents the upper limit for the most significant spots in each half of the sky (actual positions of the spots are given by blue stars). The gray line shows the results from ANTARES. See [18] for details.

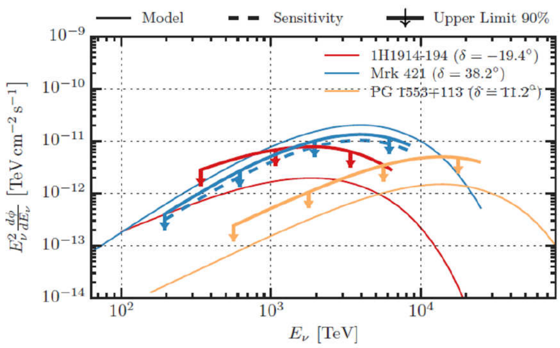

Figure 8: Differential energy spectra versus neutrino energy for blazars of the BL Lac type compared to model predictions [19]. Thick lines give the 90% upper limits from IceCube, thin lines represent the model. The sensitivities of the Icecube search are shown as dashed line. 90% upper limit and sensitivity are shown for the energy interval where 90% the events originate that are most signal-like [18].

From these figures one could conclude that an improved angular reconstruction and twice more data could bring us close to discovery. For blazars, however, this hope is downsized by various blazar stacking analyses, none of them yielding an excess in the directions of blazars. The most recent one [20] indicates that only 4-6% of the observed diffuse astrophysical muon neutrino flux could come from blazars, see Fig. 9.

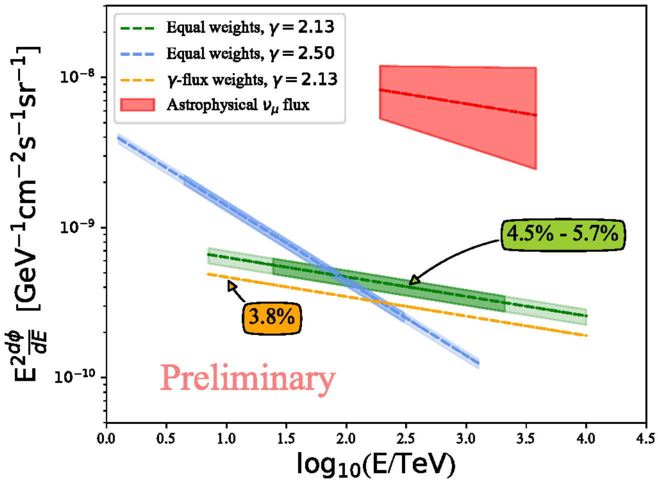

Figure 9: 90% upper limits on the flux from neutrinos from blazars of the Fermi 2FHL HBL catalogue using different assumptions on the spectral shape of the blazars. Dark shaded bands indicate the region where IceCube has highest exclusion power for the model under consideration, the light shaded bands would contain 90% of a possible signal with the spectral indices given in the Figure top left. Also, weighting according to the observed gamma-ray flux and equal weighting of the blazars is distinguished [20].

5. Search for transient sources

To improve the signal-to-background ratio one can search for transient signals, preferentially in coincidence with an observation in electromagnetic waves. Examples are flares of Actice Galactic Nuclei (AGN) or Gamma-Ray Bursts (GRB). GRBs are interesting objects since there are models which assume that they are the dominant source of the measured cosmic-ray flux at highest energies, either by neutron escape [22] or by escape of both neutrons and protons [23] from the relativistic fireball. Naturally models where protons a kept in the acceleration region and only neutrons escape and constitute the observed cosmic ray flux give a higher neutrino/cosmic ray ratio. IceCube limits on neutrinos from GRBs have drastically improved over the recent years. A recent analysis has combined the searches for spatial and temporal coincidences of upward and downward tracks and cascade-type events with 1172 GRB. No significant correlations between the gamma-ray signals and neutrinos have been observed. Figure 10 shows exclusion contours for double broken power-law spectra, with breaks from $E^{-1} \times \varepsilon_b$ to E^{-2} at energy ε_b, and from E^{-2} to $E^{-4} \times (10\varepsilon_b)^2$ at an energy $10\varepsilon_b$.

Both models, those with cosmic ray escape via neutrons and those which allow additionally for cosmic ray escape via protons, are excluded at over 90% confidence level, with most of the model assumption phase space excluded at over the 99% confidence level, greatly constraining the hypothesis that GRBs are significant producers of ultra-high energy cosmic rays in the prompt GRB phase.

30 years after the discovery of supernova SN1987 it is worth to highlight that IceCube runs a supernova trigger, with a duty time of more than 99%. The trigger reacts to a collective rise in photomultiplier counting rates on top of the dark-noise rate. This rise would be due to the feeble signals from ν_e reactions close to a photomultiplier. A 1987A-type supernova at 30 kpc distance

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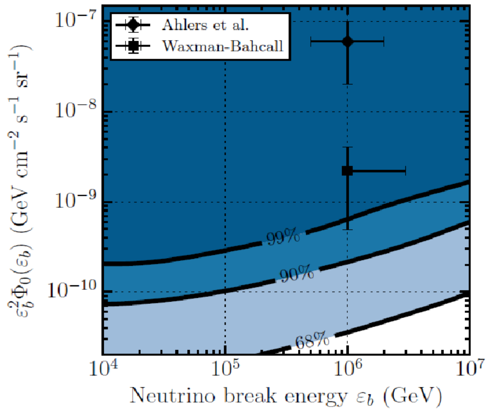

Figure 10: Excluded regions for 99%, 90% and 68% confidence level of the generic double broken power law neutrino spectrum as a function of the first break energy ε_b and per-flavor quasi-diffuse flux normalization derived from upward and downward muon tracks and all-sky cascades.

(edge of the Galaxy) would lead to an collective-rate enhancement with a significance of about 20 standard deviations, and even at distance of the Large Magellanic Cloud (50 kpc) the excess would reach $6-7\sigma$ [24]. IceCube is part of the SuperNova Early Warning System (SNEWS [25]), together with the underground neutrino detectors Borexino, Super-Kamiokande, LVD and Kamland which, in the case of a significant coincidence from more than one of the detectors, would alarm the astronomers community. However, no significant neutrino signal has been recorded yet, neither with the analogous trigger of IceCube's predecessor AMANDA nor with that of IceCube.

6. Real-time alert and follow-up programs

With no steady sources of high-energy neutrinos observed so far, neutrinos produced during transient astrophysical events are a viable alternative. High-energy neutrinos from the prompt phase of GRBs or MeV neutrinos from a supernova collapse as discussed in the previous example are just two examples. Coincident detections could enhance the significance of the IceCube observation and, more generally, contribute to the mosaic of informations from different messengers, providing a more complete picture of the source. Since IceCube has nearly 4π acceptance (depending on energy), it could could trigger detections with pointing devices like optical or gamma-ray telescopes, which otherwise would have been missed.

IceCube runs a number of high-energy alert and follow-up programs [26] which react to particular individual events . Neutrino alert candidates are identified in real-time at the South Pole. A brief message sent to the North is automatically issued to the Gamma-Ray Coordinates Network (GCN [27]) via the Astrophysical Multimessenger Observatory Network (AMON [27]). In parallel, quality checks are applied and the directional and energy reconstruction refined. Results from that are completed within a few hours and lead to an updated alert notification in the form of a CGN circular. IceCube runs two of these alerts: a "HESE Track alert" which is issued if a track-like HESE event is recorded (4.8 events expected per year, with 1.1 being of astrophysical origin) and an "EHE Track Alert" which is based on a selection which originally targets cosmological neutrinos (10 PeV to 1 EeV) but here is modified to be sensitive down to 500 TeV (about 5 alerts per year).

Apart from these public alerts, IceCube also issues alerts to optical, X-ray and gamma-ray observatories which are based on neutrino *multiplets*. These alerts are based on individual agreements with these observatories. The multiplets can be due to phenomena on the second-to-minute scale (high-energy neutrinos from relativistic jets in SN or GRB), or to phenomena of the hour-to-week scale (like AGN flares). None of the alerts yet has led to a significant correlation, although at least two cases have generated some initial excitement. The one [28] was a neutrino doublet detected in March 2012 which triggered follow-up observations by the Palomar Transient Factory (PTF). PTF found a Type IIn supernova within an error radius of 0.54 deg of the direction of the doublet. A Pan-STARRS1 survey, however, showed that its explosion time was at least 158 days before the neutrino alert, so that a causal connection is unlikely. The second case [29] was the first triplet: three muon neutrino candidates arriving within 100 s of one another at February 17, 2016. Follow-up observations by SWIFT's X-ray telescope, by ASAS-SN, LCO and MASTER at optical wavelengths, and by VERITAS in the very-high-energy gamma-ray regime did not detect any likely electromagnetic counterpart. In a refined reconstruction, the directions of the events changed slightly, so that the triplet turned to a double-doublet (error circle of the one event overlapping with those of the two others, but not all three with each other). Still, these two cases impressively illustrate the potential of and challenges for future follow-up campaigns. Although no significant correlations have been detected so far, the Icecube alerts and the triggered electromagnetic-domain observations herald the era of multi-messenger observation. This remark also applies to the follow-up programs where IceCube scrutinizes its own data to search for correlations with signals from Gravitational Waves [30].

7. Summary and Outlook

Four years after the detection of cosmic neutrinos, we have learned a lot about their spectrum and flavor composition. We have learned that blazar jets and GRBs can contribute only a small fraction to the observed astrophysical neutrino flux. The spectral features of this flux (single power law or two power law) open new questions about the contributing source classes. No individual sources have been detected yet. The non-observation of neutrinos coinciding with GRBs strongly constrains models which attribute the highest-energy cosmic rays to GRBs. Neutrino events possibly related to supernova explosions have been observed, although with a non-negligible probability for a chance occurrence. No neutrinos have been observed that could be attributed to the GZK effect, but the non-observation starts constraining evolution scenarios for ultra-high energy cosmic rays sources (not addressed in this report).

IceCube continues collecting data. A twofold statistics combined with improved directional precision, also for cascade-like events, and better understanding of systematics effects will considerably improve the understanding of what has been observed so far and may even provide first detection of individual (point-like or extended) sources. IceCube's capabilities, however, are limited by its size. Therefore a next generation experiment, IceCube-Gen2 [5] is under development. For point sources it will have five times better sensitivity than IceCube, and the rate for events at energies above a few hundred TeV will be ten times higher than for IceCube. Together with its

Northern partners GVD in Lake Baikal and KM3NeT/ARCA in the Mediterranean Sea, IceCube-Gen2 will start charting a neutrino landscape to which IceCube has enabled a first glance.

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