Chapter 1

Observations of diffuse fluxes of cosmic neutrinos

Christopher H. Wiebusch

RWTH Aachen University, III.Physikalisches Institut,
Otto Blumenthal Strasse, 52074 Aachen, Germany,
wiebusch@physik.rwth-aachen.de

In this contribution the current observational results for the diffuse flux of high-energy astrophysical neutrino flux are reviewed. In order to understand the science implications, the measurements in different detection channels are discussed and results are compared. The discussion focuses on the energy spectrum, the flavor ratio and large scale anisotropy.

1. Introduction

For a long time, the detection of high-energy cosmic neutrinos as cosmic messengers has been an outstanding goal of astroparticle physics. Their observation has been proposed by Markov\(^1\) already in the 60th of last century. The proposed method was the detection of up-going muons as signature of a charged-current (CC) muon neutrino interaction below the detector. Based on this signature atmospheric neutrinos were discovered in deep underground detectors\(^2,3\). Soon it was realized that the expected astrophysical fluxes are be small and cubic-kilometer sized detectors would be needed to accomplish the goal.\(^4\) A key concept became the instrumentation of optically transparent natural media with photo-sensors to construct large Cherenkov detectors. A major step was achieved by the BAIKAL collaboration,\(^5\) which first succeeded to install and operate a large volume Cherenkov detector using the deep water of lake Baikal. This effort was rewarded by the first observation of atmospheric neutrino events in an open natural environment,\(^6\) see also contribution by V. Aynutdinov. Shortly after, the AMANDA neutrino telescope successfully demonstrated the feasibility of the construction and operation of a large Cherenkov detector in glacier ice.\(^7\) It was the first neutrino telescope to observe high-energy atmospheric neutrinos in larger quantity\(^8\) and to exclude optimistic astrophysical models.\(^9\) In parallel to these efforts neutrino telescopes in deep oceans have also been brought into operation. The ANTARES neutrino telescope,\(^10\) see also contribution by P. Coyle, increased the effective area with respect to AMANDA and has been operational since 2006. In all these experiments no indications of cosmic...
neutrinos have been found.\textsuperscript{11}

Based on the success of AMANDA, the IceCube detector has been designed.\textsuperscript{12} In total 5160 large area optical sensors have been deployed in the Antarctic ice at the geographical South Pole. They detect the Cherenkov light produced by secondary leptons and hadrons as a result of charged current (CC) and neutral current (NC) neutrino-nucleon interactions inside and outside the instrumented volume. The instrumented depth ranges from 1450 m to 2450 m in the ice. The sensors are attached to 86 vertical cable strings with 60 sensors each and have a horizontal spacing of about 125 m between strings on a hexagonal grid. Along the strings the spacing is about 17 m, resulting in about 1 km$^3$ of instrumented volume. IceCube was completed in its final configuration in December 2010 and fully commissioned in May 2011. Already in its earlier configurations, based on the partly installed detector, a substantial exposure was accumulated and first indications for an astrophysical signal were obtained\textsuperscript{13,14}

2. Summary of detection signatures

The detection of neutrinos from cosmic accelerators, see contributions by Mszros, K. Murase, E. Waxman, P. Lipari and M. Ahlers, is mainly based on their hard energy spectrum which is expected to follow the spectrum of accelerated primary cosmic rays and thus is expected to follow a power-law with a hard spectral index $\phi \simeq \phi_0 \cdot E^{-2}$. The largest signal is expected from close below the horizon and above, as the Earth becomes almost opaque to neutrinos above $\sim 100\text{TeV} - 1\text{PeV}$. Backgrounds are cosmic ray induced atmospheric muons and neutrinos, which however exhibit at high energies a substantially softer spectrum. Other powerful methods to detect astrophysical neutrinos above this background rely on directional and time-correlations of the measured events. However, this requires strong individual sources. Alternatively, the cumulative flux of all cosmic sources is expected to exceed the atmospheric backgrounds at high energies of typically 100TeV. In this paper we focus on the detection of diffuse fluxes. Depending on the luminosity density and strength of the sources, this approach is very promising for the detection of a population of abundant but individually weak extra-galactic sources. Detailed discussions can be found e.g. in Ref. 15\textsuperscript{16,17}

Searching for diffuse neutrino fluxes at high energies requires a rigorous rejection of the overwhelming atmospheric muon background and a precise modelling of the partly irreducible atmospheric neutrino backgrounds. The atmospheric muon background which penetrates from the surface to the depth of the detector can be rejected by focusing on up-going events and/or events that interact within the instrumented volume. Atmospheric neutrinos can only be rejected if they arrive in the detector from above and the corresponding air-shower is either tagged by a surface detector\textsuperscript{18} or by observing correlated atmospheric muons.\textsuperscript{19} For both types of background the signal to background ratio increases with the energy threshold
Observations of a diffuse flux of cosmic neutrinos

of the event selection.

Based on these signatures, neutrino telescopes can be sensitive to all neutrino flavors, in particular when combining different detection channels and strategies. The basic signature of muon neutrino is a high-energy muons track from deep-inelastic CC neutrino-nucleon interactions. Electron neutrinos produce an electromagnetic cascade superimposed by a hadronic cascade at the interaction vertex. The length scale of the cascades is small compared to the spacing of detector sensors. These events are called cascade-like events. Tau neutrinos mostly produce a cascade signature very similar to electron neutrinos with two exceptions. First, at high energies above a PeV the tau travels typically $50 \cdot E_\tau/\text{PeV}$ before it decays. This results in a characteristic signature of two spatially separated cascades, called double-bang. At all energies the tau may decay leptonically into a muon with a branching ratio of $\sim 17\%$ contributing to the track-like signature of muon neutrinos. All flavors contribute equally to cascade-like events via NC interactions.

3. Observational status of different detection channels

3.1. High-energy starting events

Remarkably, the discovery of an astrophysical neutrino signal by IceCube was achieved not in the muon channel that has been the intuitively assumed baseline channel for decades but with a new type analysis: the high-energy starting event analysis (HESE).

The HESE analysis searches for neutrinos interacting inside the detector and is as such sensitive to all neutrino flavors and the full sky. The selection splits the detector into an outer region, which is used to tag and veto muon backgrounds from outside and an inner fiducial mass of about $0.4\text{Gt}$. Accepted events are required to deposit a visible energy of more than $20 - 30\text{ TeV}$ inside the detector. Furthermore the earliest observed Cherenkov photons need to have been recorded within the fiducial volume while in the veto region no early signal in excess of the noise level is allowed. The analysis is based on the combination of essentially four innovative new methods that were not available during the operation of AMANDA and were not available during the design and construction phases of IceCube.

(i) It was realized that a search for starting events would allow for a very simple all-sky search of all flavors, with a high significance because a large fraction of the energy is deposited at the interaction vertex. This has greatly improved the sensitivity, e.g. with respect to the single flavor up-going muon channel.

(ii) The ability to reasonably reconstruct the direction and energy of cascade-like events including a good estimate of the uncertainty based on the precise analysis of measured photomultiplier waveforms. This allowed quantifying the significance of each event as the backgrounds strongly depend on the observed zenith angle.
(iii) The usage of the outer layers of IceCube as veto allowed to model-independently quantify the remaining atmospheric muon background with good precision based on experimental data. It has been shown that the background related to the inefficiency of the veto falls off rapidly with energy and becomes insignificant above $\sim 60\text{TeV}$.

(iv) It was realized that the method of an atmospheric neutrino veto could be successfully applied, greatly reducing the atmospheric neutrino background in the down-going region. The corresponding angular distribution is particularly important to unambiguously reject the hypothesis of a purely atmospheric origin, in particular as the high-energy atmospheric neutrino flux from prompt decays of heavy quarks is largely uncertain.

It is the combination of all four methods in the interpretation of the observation, that made the detection of a cosmic neutrino signal evident and allowed to reject the hypothesis of atmospheric origin with high confidence. As a side remark, this underlines the importance of a not too specific optimization of large scale instruments which aim to explore unknown physics. The implementation of potentially not fully optimized but multi-purpose instruments which deliver higher data and information quality than minimally required allows a large flexibility in methods and fosters unforeseeable innovations which evolve only during the operation of the instrument.

Currently, data from three years of operation have been published. A pure atmospheric origin of the observed signal is rejected with a confidence level of $5.7\sigma$. Most recently, a fourth year of data has been preliminarily released that further increases the significance of the observation to $6.5\sigma$. The observed distributions of energy and zenith, see fig. 1, agree well with the expectation of a hard astrophysical spectrum and is clearly not compatible with the expectation from atmospheric
backgrounds. The per flavor astrophysical flux measured with three years of data is $E^2\phi(E) = 0.84 \pm 0.3 \times 10^{-8}\text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}$, assuming a spectral index $\gamma = 2$ in the energy range between 60TeV and 2PeV. A significant clustering of event directions has not been observed.

A particularly interesting extension of this analysis is to lower the energy threshold for this search. This is achieved by a gradually increasing the veto thickness. The loss in fiducial volume is compensated by larger fluxes at lower energy. The first analysis of this type using two years of data has been able to lower the energy threshold to about 1 TeV and extract the astrophysical signal down to about 10 TeV.

### 3.2. Cascade channel

Closely related to the analysis of starting events are searches dedicated to cascade type events. Here, based on the event reconstruction, track-like event topologies are specifically rejected and a reasonably pure cascade-like sample is obtained. Backgrounds are atmospheric muons with catastrophic energy losses that outshine the muon and thus mimic a cascade-like signature. These can be suppressed by requiring containment of the interaction vertex similar to the HESE analysis. The flux from conventional atmospheric electron neutrinos is considerably smaller (about a factor 20) than that of muon neutrinos and hence poses a relatively small background. The largest background uncertainty arises from prompt atmospheric neutrinos. Advantages of this analysis are a good energy resolution for these contained cascades of the order of the energy scale uncertainty $\approx 10\%$ and a lower energy threshold compared to the muon-channel. Cascade-analyses are usually sensitive to electron and tau neutrinos by CC interactions with a small contribution of NC interactions by all flavors.

Already a pioneering analysis, based on the configuration with only 40 installed detector strings found an excess of events above the atmospheric expectation. Recently, the first year data of the completed detector has been analyzed. The energy spectrum of atmospheric electron neutrinos was measured to be consistent with the theoretical expectation. No indication of a prompt signal was found and the astrophysical component at high energies was confirmed. The most recent results for the measurement of the astrophysical flux, based on two years of data, are reported in Ref. 28. This analysis substantially increases the number of observed high-energy events by also including partially contained events. It largely confirms the findings of the HESE analysis and observes a cosmic signal with significance of more than 4 $\sigma$.

### 3.3. Muon channel

The classical detection channel of neutrino telescopes is up-going muon tracks from CC neutrino-nucleon interactions in and below the detector. The selection of up-
going tracks efficiently eliminates the background of down-going cosmic ray induced atmospheric muons. The Earth’s absorption increases with energy and results in a zenith dependent expectation even for an isotropic diffuse cosmic signal. As the interaction can happen far outside the detector, the effective detection volume is much larger than the geometrical volume resulting in larger event rates than for contained events. However, muons from neutrino-interactions far away have lost a considerable and unknown fraction of their initial energy and carry only little information to distinguish astrophysical from atmospheric neutrinos. In addition, through-going muons deposit only a small fraction of their energy inside the detector. Therefore, the muon energy has to be estimated by the observed energy-loss, resulting in a resolution of about $\sim 50 - 70\%$ for the muon energy as compared to $\sim 10\%$ in case of contained cascades. Diffuse searches using this channel contain potentially the largest number of cosmic neutrinos, but require larger data-sets to observe the same significance as channels with good energy resolution, e.g. contained cascades. An important advantage of the muon channel compared to cascades is the good angular resolution, approaching about $0.1^\circ$ at high energies. Though angular information is not of primary concern in a diffuse search, it is helpful for an efficient rejection of the atmospheric muon background and the selection of high purity data-sets.

The analysis is done as a two-dimensional likelihood fit of the measured energy and zenith angle. Fitting the full data from a few 100 GeV to high energies of a PeV allows to strongly constrain systematic uncertainties.

The first indications of an astrophysical signal in the muon channels were found in the data of IceCube in the 59-string configuration.\textsuperscript{14} Though the final significance of a cosmic signal was only $1.8\sigma$ with respect to the conventional atmospheric background-only hypothesis, this observation has been important not only in the context of promising indications of a cosmic neutrino signal but also in its power to constrain the conventional and prompt atmospheric neutrino backgrounds for the analysis of starting events. Particularly spectacular has been the highest energy muon, which energy in the detector has been estimated to 400 TeV.

Since then, the evidence in this channel has been steadily increasing. A combined analysis using 35,000 events from the 79 string and first year of 86 string configurations (2010-2012) has found evidence for an astrophysical flux above 300 TeV consistent with the HESE result at the $3.7\sigma$ level.\textsuperscript{29} Most recently, the full data from six years of IceCube operation including the 59-string and 79 string configurations as well as four years of IceCube with 86 strings (2009-2015) has been analyzed.\textsuperscript{30} Here, the event selection efficiency has been optimized resulting in a total of about 340,000 muon neutrino events with an estimated purity of better than 99.9%. The significance of an astrophysical flux with the full six years is at the level of $6\sigma$ (rejecting a pure atmospheric origin).

Also notable is the observation of an ultra-high-energy neutrino event,\textsuperscript{31} see Fig. 2. It is a through-going track that deposits an energy of $2.6 \pm 0.3$ PeV within the instrumented volume of IceCube. Based on simulations of events with similar...
Fig. 2. Event-view of the multi-PeV upgoing muon event detected with IceCube. Colored spheres indicated optical sensors that registered a signal, where the size encodes the logarithm of detected charge and the color the arrival time (red early and green late). Left are the three projected views. The reconstructed track is indicated as a line.

topology such an energy loss would be expected from a muon of more than 4 PeV and thus implies an even higher neutrino energy. This makes this event the highest-energy neutrino detected to date. Based on the huge energy, for this event alone the hypothesis of an atmospheric origin can be rejected\(^{30}\) for this event alone by about \(4\sigma\). Though not relevant for the subject of this report, it is worthwhile to note that the directional uncertainty is less than \(0.3^\circ\), but attempts to identify an astrophysical source have not been successful yet. The closest known source of GeV photon emission\(^{32}\) is about \(3^\circ\) away and \(11^\circ\) for known TeV sources.\(^{33}\) The direction is \(11^\circ\) off the Galactic Plane.

3.4. **EHE channel**

In this channel neutrinos of extremely high energies are searched for. This channel targets is very large energy depositions related to events of typically \(10^{17}\) eV energy, as e.g. expected from the GZK effect. Because of the decreasing background of cosmic ray induced atmospheric muons the energy threshold can be gradually reduced towards the horizon. For straight down-going events, the surface detector IceTop is added as a veto. As a consequence of absorption within Earth the region around and above the horizon is particularly important.

It was this type of analysis that initially observed the first neutrino events with PeV energy\(^{34}\) close to its energy threshold. The analysis has been based on an exposure of one year in the 79 string configuration and the first year of full IceCube operation. An update to this analysis\(^{35}\) to 6 years of IceCube operation has further increased the sensitivity, particularly towards high energy. No further events with energies substantially above a few PeV have been observed which results in the currently most constraining exclusion limits for ultra-high-energy neutrinos such as expected from the GZK effect.\(^{36}\) As no further events of higher energy have been
observed with recent data and thus no improved spectral information on the diffuse flux can be deduced, this channel is ignored in the following discussions.

### 3.5. Tau channel

The tau neutrino is interesting because due to oscillations about one third of astrophysical neutrinos are expected to be of tau flavor. Furthermore, due to “regeneration” in tau decays, the Earth is not fully opaque to tau neutrinos. The atmospheric background of high energy tau neutrinos is substantially smaller than even that of prompt neutrinos, and thus any observed a tau neutrino would be astrophysical with high probability.

As discussed above, the detection signature of tau neutrino interactions is mostly similar to electron neutrinos unless their energy exceeds about a PeV. Nonetheless it is interesting to attempt the identification of a double-bang signature in the sample of observed starting events. This has been performed with a modification of the reconstruction algorithm used for starting events. No evidence of a double-bang signature has been found. However, this analysis, close to the detection threshold, is challenging because of systematic uncertainties of the photon propagation through ice and a substantial contribution of tau neutrinos to the observed events cannot be excluded. A more robust approach is to directly search for large double pulse signatures in the recorded waveforms of optical sensors. An independent dedicated search for this signature has not detected a clear double-bang event. However, the sensitivity of this search has not yet reached the observed astrophysical flux level and more data is needed.

### 4. Comparison of observational results

#### 4.1. Energy spectrum

The energy spectrum measured with the most recent data for high-energy starting events is shown in Fig. 3 together with the spectrum obtained from the extension of the analysis towards lower energies. Here, the normalization in each energy bin has been a free parameter in a maximum likelihood fit of the data-set. The best fit spectral index for Fig. 3(a) is $\gamma = 2.58 \pm 0.25$, slightly softer than results based on earlier data. This is consistent with the result in Fig. 3(b) of $\gamma = 2.46 \pm 0.12$ and is also consistent with measurements in the cascade channel which find similar soft indices. The spectrum slightly depends on the assumptions of atmospheric neutrinos from charm decays. A larger charm component would lead to a harder astrophysical spectrum.

Two aspects are particularly interesting. On may wonder about the existence of a possible cut-off at an energy of a few PeV or a possible spectral break in the spectrum. Note, that the under-fluctuation of events just below a PeV deposited energy has previously caused some speculations. However, this fluctuation is not statistically significant and it has decreased with the recently added data.
Observations of a diffuse flux of cosmic neutrinos

(a) Measured deposited energy
(b) Reconstructed energy spectrum

Fig. 3. Results for the high-energy starting event analysis

Clearly visible is the deviation from the hard $E^{-2}$ hypothesis. It seems that the steepness of the slope is dominated by data at lower energy $\lesssim 50\text{TeV}$. As shown in Ref. 25, above an energy of $100\text{TeV}$ the data would be well consistent with also a hard spectrum $\gamma \simeq 2.26 \pm 0.35$.

For the question of a cut-off about 3 events would be expected for a hard $E^{-2}$ spectrum above $2\text{PeV}$, while none were observed. However, with a softer spectrum, as the best fit seems to indicate, this tension is strongly relaxed and a cut-off is not required to describe the observation.

In conclusion, the current statistics is not sufficient to answer questions concerning a possible spectral break or cut-off and future data will improve the picture.

(a) Unfolded neutrino energy distribution
(b) 2-d profile likelihood of the fit spectral index versus flux

Fig. 4. Results of the analysis of up-going muons based on six years data
While the starting event analysis is dominated by cascade-like events from the Southern Sky it is interesting to compare to the energy distribution of up-going muon neutrinos. As the measurement of uncontained muons does not directly allow for a good estimate of the neutrino energy, the spectral unfolding is difficult but benefits from higher statistics of events and well controlled systematics and backgrounds. The measurement with two years of data\textsuperscript{29} resulted in a spectral index slightly harder $\gamma = 2.2 \pm 0.2$ than measured in the cascade dominated channels. This tension has increased with recent data covering 6 years of IceCube\textsuperscript{30} as shown in Fig.4. The left figure shows the reconstructed energy distribution, the right figure the profile likelihood for the extracted astrophysical flux parameters. Note, that the reconstructed neutrino energy spectrum is model dependent. Shown here is the median expected neutrino energy calculated from the measured deposited energy assuming the best fit spectrum. The excess of data is clearly inconsistent with a pure atmospheric origin. With a best fit spectral index of $2.06 \pm 0.13$ the observed spectrum is harder than that of the cascade dominated measurements.

For a quantitative discussion the results for all analyses have to be compared by means of statistical confidence. It is found that the measured flux normalization is often correlated with the fitted spectral index. When analyzing the error contours for all analyses\textsuperscript{41} the apparent tension is reduced to about $2.5\sigma$ which is marginally statistically significant. For this discussion it is furthermore important to highlight the systematic differences between these two measurements. The threshold for the up-going muon signal is a few 100TeV while astrophysical starting events are detected above a few 10TeV. If only high-energy starting events were considered in the comparison, the spectra would be in agreement. Another important difference is the dominance of different hemispheres in both analyses. If the astrophysical flux was non-isotropic or e.g. composed of a galactic and an extra-galactic component a difference between the two analyses could be explained. Additional data will be needed to answer these questions. An extension to this discussion is found in Sec.4.3.

4.2. Global fit and flavor ratio

Based on the different detection channels a global fit of the combined data-sets can be attempted. In Ref. 42 such a global analysis has been performed using six different data-sets\textsuperscript{14291343212225} consisting of up-going muons, contained cascades and starting events. Special care was taken not to double count overlapping data-sets and the combination of systematic uncertainties. For practical reasons, the fit does not include the full systematics of the individual data-sets but combines them as generalized global parameters. These are the energy scale uncertainty, the atmospheric muon background normalization for each data-set and the cosmic ray spectral index which affects the atmospheric neutrino background. Different hypotheses for the astrophysical flux normalization and spectra are tested. The result for a single power-law is a spectral index of $\gamma = -2.50 \pm 0.09$, disfavoring a
Observations of a diffuse flux of cosmic neutrinos

hard spectral index of $\gamma = 2$ at the 3.8$\sigma$ level. This significance is reduced to 2.1$\sigma$ if an exponential cut-off is introduced. Similar to the discussions above, it can be seen in Fig. 5(a), that this tension could be also relaxed without introducing a cut-off if a transition from a softer spectral index at lower energies to a harder spectrum at higher energies is assumed.

\begin{figure}[h]
\centering
\subfloat[Energy spectrum]{\includegraphics[width=0.45\textwidth]{energy_spectrum.png}}\hspace{0.5cm}\subfloat[Flavor triangle]{\includegraphics[width=0.45\textwidth]{flavor_triangle.png}}
\caption{Results of the global fit}
\end{figure}

The flavor ratio of the neutrino flux is particularly interesting, because it allows to constrain the acceleration mechanism. The initial flavor composition at the source is modified by neutrino oscillations and largely smeared out due to the long baseline. Therefore, one expects to observe all neutrino flavors at Earth with a similar flux. However, depending on the injection model of neutrino flavors at the source and the assumed oscillation parameters deviations from the exact $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$ mixing are expected at Earth. Despite of not having directly identified tau neutrino events, they contribute to the observed event rates of the considered detection channels differently. Within the framework of the global fit the flavor ratio can be tested when fitting the flux normalization of each flavor separately in a joint fit. The result is shown in Fig. 5. The measured data is consistent with a mixture of all flavors and pure fluxes of $\nu_e$ and $\nu_\mu$ or $\nu_\tau$ are strongly disfavored. When comparing to different injection scenarios the hypothesis of pure $\nu_e$ as expected from sources with dominating muon decays can be excluded. Both scenarios of an injected ratio $\nu_e : \nu_\mu : \nu_\tau \approx 0 : 1 : 0$ and $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 2 : 0$ are compatible with the data. With more data this measurement is expected to become increasingly important for the understanding of the source mechanism of the measured flux.

4.3. Isotropy

No analysis of the arrival directions of detected neutrinos has yet revealed a statistically significant clustering nor correlation with a known source\textsuperscript{2444,45}. However,
also tests for large-scale anisotropies allow to investigate the important question whether the assumption of isotropy of the cosmic signal is valid or if regions related to a few close sources dominate. In particular, the question whether the observed flux is of galactic or extra-galactic origins can be tested.

An important step is the recent observation of the astrophysical signal also in the up-going muon analyses\textsuperscript{29, 30} see Sec.3.3. This confirms that the flux that was observed in the high-energy starting event analysis mostly by cascades from the Southern hemisphere is accompanied by a roughly equally strong flux of muon neutrinos in the Northern hemisphere. This indicates that at least a substantial fraction of the flux is isotropic and thus presumably extra-galactic.

Fig. 6. Splitting the data samples into regions of the sky: North-South and East-West. The figure shows the orientation of the galactic plane, indicated by the superimposed diffuse gamma emission measured by Fermi-LAT, \url{http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html}. Vertical lines indicate a split by right ascension that results in quadrants in both hemispheres with and without the galactic plane.

Fig. 7. Energy spectra of starting events for Northern and Southern Sky separately.

A straight forward approach is to split the data samples into two separate regions
Observations of a diffuse flux of cosmic neutrinos

of the sky and to compare the observed fluxes. This is indicated in Fig.6.

The simplest test is to compare the Northern and Southern hemispheres. As the Southern hemisphere contains the central part of the Galaxy, differences in the hemispheres may allow to indicate differences between galactic and extra-galactic components. This has been done within the analysis of starting events at lower energy threshold, see Fig.7, the global fit and the analysis of contained cascades. Both hemispheres show a clear excess of an astrophysical signal over the atmospheric background, however, the southern excess seems stronger.

This question is more quantitatively addressed in the aforementioned global fit. It results in a spectral index of $\gamma = 2.0^{+0.3}_{-0.4}$ for the Northern Sky and $\gamma = 2.56 \pm 0.12$ for the Southern Sky, respectively. Note, that the significance of a discrepancy is only 1.1 $\sigma$. The interpretation has to be done carefully, as the observational conditions and systematic uncertainties between north and south strongly differ. The fit of the Northern Sky is dominated by the up-going muon sample which has a higher energy threshold compared to the cascade sample, which dominates the Southern Sky. Furthermore, detector systematics with all sensors directed downward, the absorption of high-energy events by Earth, the rejection of atmospheric neutrino background differs strongly between both hemispheres.

This test has been repeated with contained cascades. This measurement results in very similar spectral indices for North ($\gamma = 2.69^{+0.34}_{-0.34}$) and South ($\gamma = 2.68^{+0.20}_{-0.22}$). Also for this analysis systematics differ between North and South and the energy range is slightly smaller. Obviously, at this point in time the results are not conclusive yet.

Fig. 8. Profile likelihoods for the extracted flux parameters from the fit of the six year up-going muon sample which is split by right ascension.

A test that is not affected by these systematics has been performed in the Northern Sky with the six years up-going muon sample. The sample was split in right ascension instead of declination. The regions, indicated as vertical lines in Fig.6, are chosen such, that the two split samples are of similar statistics but complementary with respect to the galactic plane. The fit result, shown in Fig.8, is a small but not
statistically significant larger flux and softer spectrum from the region including the galactic plane.

Again, a definitive answer whether the flux from the galactic plane differs from the all-sky result can not be deduced. Dedicated tests are underway and additional data will certainly allow to address this question further.

5. Summary and conclusions

In this contribution we have reviewed the observational evidence and approaches to observe diffuse fluxes of astrophysical neutrinos. It is remarkable that only a few years after the initial discovery, the signal could be clearly identified in several detection channels. After the consolidation of the observational evidence substantial progress has been made in characterizing the signal properties, in particular by improving analysis methods and by the comparison of the different results. Several important questions have been addressed, especially the characterization of the energy spectrum, the flavor composition and a possible large-scale isotropy. While we are still awaiting the hopefully soon detection of point sources (see contribution by Ch. Finley), the above questions can be addressed with further improved analyses and new data.

Ultimately IceCube will be limited in sensitivity. Therefore, the need for a next-generation instrument arises. The KM3Net\textsuperscript{46} neutrino telescope in the Mediterranean Sea (see contribution by M. de Jong) and the BAIKAL-GVD neutrino telescope\textsuperscript{47} in lake Baikal (see contribution by Z. Djilibaev) plan to install deep water instrumentations that exceed the size of the IceCube detector. Finally, the design of a next generation instrument at the South Pole, IceCube-Gen2\textsuperscript{48} has started aiming for the scale of 10km\textsuperscript{3} volume (see contribution by O. Botner). Also investigations of possible improvements of the current IceCube performance for the search of cosmic neutrinos by extending the surface detector IceTop acting as a veto\textsuperscript{18} to atmospheric signals are underway.

Acknowledgements

The author would like to thank Hans Niederhausen, Leif Rädel and Sebastian Schoenen for careful reading of the manuscript as well as the whole IceCube collaboration for their contributions.

References

1. M. Markov, On high energy neutrino physics, Proceedings, 10th International Conference on High-Energy Physics (ICHEP 60). pp. 578–581, (1960).
2. C. V. Achar, M. G. K. Menon, V. S. Narasimham, P. V. R. Murthy, B. V. Sreekantan, et al., Detection of muons produced by cosmic ray neutrinos deep underground, Phys.Lett. \textbf{18}, 196–199, (1965). doi: 10.1016/0031-9163(65)90712-2.
Observations of a diffuse flux of cosmic neutrinos

3. F. Reines, M. Crouch, T. Jenkins, W. Kropp, H. Gurr, et al., Evidence for high-energy cosmic ray neutrino interactions, *Phys. Rev. Lett.* 15, 429–433, (1965). doi: 10.1103/PhysRevLett.15.429.

4. T. K. Gaisser, F. Halzen, and T. Stanev, Particle astrophysics with high-energy neutrinos, *Phys. Rept.* 258, 173–236, (1995). doi: 10.1016/0370-1573(95)00003-Y.

5. I. Belolaptikov et al., The Baikal underwater neutrino telescope: Design, performance and first results, *Astropart. Phys.* 7, 263–282, (1997). doi: 10.1016/S0927-6505(97)00022-4.

6. V. Balkanov et al., Reconstruction of atmospheric neutrinos with the Baikal Neutrino Telescope NT-96, (1997).

7. E. Andres, P. Askebjer, S. Barwick, R. Bay, L. Bergstrom, et al., The AMANDA neutrino telescope: Principle of operation and first results, *Astropart. Phys.* 13, 1–20, (2000). doi: 10.1016/S0927-6505(99)00092-4.

8. E. Andres, P. Askebjer, X. Bai, G. Barouch, S. Barwick, et al., Observation of high-energy neutrinos using Cherenkov detectors embedded deep in Antarctic ice, *Nature* 410, 441–443, (2001). doi: 10.1038/35068509.

9. A. Achterberg et al., Multi-year search for a diffuse flux of muon neutrinos with AMANDA-II, *Phys. Rev. D* 76, 042008, (2007). doi: 10.1103/PhysRevD.76.042008, 10.1103/PhysRevD.77.089904.

10. M. Ageron et al., ANTARES: the first undersea neutrino telescope, *Nucl. Instrum. Meth.* A656, 11–38, (2011). doi: 10.1016/j.nima.2011.06.103.

11. J. Aguilar et al., Search for a diffuse flux of high-energy $\nu_\mu$ with the ANTARES neutrino telescope, *Phys. Lett.* B696, 16–22, (2011). doi: 10.1016/j.physletb.2010.11.070.

12. J. Ahrens et al., Sensitivity of the IceCube detector to astrophysical sources of high energy muon neutrinos, *Astropart. Phys.* 20, 507–532, (2004). doi: 10.1016/j.astropartphys.2003.09.003.

13. M. Aartsen et al., Search for neutrino-induced particle showers with IceCube-40, *Phys. Rev.* D89(10), 102001, (2014). doi: 10.1103/PhysRevD.89.102001.

14. M. Aartsen et al., Search for a diffuse flux of astrophysical muon neutrinos with the IceCube 59-string configuration, *Phys. Rev.* D89(6), 062007, (2014). doi: 10.1103/PhysRevD.89.062007.

15. P. Lipari, Proton and Neutrino Extragalactic Astronomy, *Phys. Rev.* D78, 083011, (2008). doi: 10.1103/PhysRevD.78.083011.

16. M. Kowalski, Status of High-Energy Neutrino Astronomy, (2014).

17. M. Ahlers and F. Halzen, Pinpointing Extragalactic Neutrino Sources in Light of Recent IceCube Observations, *Phys. Rev.* D90(4), 043005, (2014). doi: 10.1103/PhysRevD.90.043005.

18. J. Auffenberg, IceVeto: Extended PeV neutrino astronomy in the Southern Hemisphere with IceCube, *AIP Conf. Proc.* 1630, 50–53, (2014). doi: 10.1063/1.4902769.

19. S. Schonert, T. K. Gaisser, E. Resconi, and O. Schulz, vetoing atmospheric neutrinos in a high energy neutrino telescope, *Phys. Rev.* D79, 043009, (2009). doi: 10.1103/PhysRevD.79.043009.

20. J. G. Learned and S. Pakvasa, Detecting tau-neutrino oscillations at PeV energies, *Astropart. Phys.* 3, 267–274, (1995). doi: 10.1016/0927-6505(94)00043-3.

21. M. Aartsen et al., Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector, *Science* 342, 1242856, (2013). doi: 10.1126/science.1242856.

22. M. Aartsen et al., Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data, *Phys. Rev. Lett.* 113, 101101, (2014). doi: 10.1103/PhysRevLett.113.101101.
23. R. Enberg, M. H. Reno, and I. Sarcevic, Prompt neutrino fluxes from atmospheric charm, *Phys. Rev.* **D78**, 043005, (2008). doi: 10.1103/PhysRevD.78.043005.
24. C. Kopper, N. Kurahashi, et al. Observation of Astrophysical Neutrinos in Four Years of IceCube Data. In *Proceeding of the 34th International Cosmic Ray Conference, The Hague, Netherlands, 30 July–6 August 2015*, (2015).
25. M. Aartsen et al., Atmospheric and astrophysical neutrinos above 1 TeV interacting in IceCube, *Phys. Rev.* **D91**(2), 022001, (2015). doi: 10.1103/PhysRevD.91.022001.
26. M. Aartsen et al., Energy Reconstruction Methods in the IceCube Neutrino Telescope, *JINST* **9**, P03009, (2014). doi: 10.1088/1748-0221/9/03/P03009.
27. M. G. Aartsen et al., Measurement of the Atmospheric $\nu_e$ Spectrum with IceCube, *Phys. Rev.* **D91**, 122004, (2015). doi: 10.1103/PhysRevD.91.122004.
28. M. Lesiak-Bzdak, H. Niederhausen, A. Stössl, et al. High energy astrophysical neutrino flux characteristics for neutrino-induced cascades using IC79 and IC86-string IceCube configurations. In *Proceeding of the 34th International Cosmic Ray Conference, The Hague, Netherlands, 30 July–6 August 2015*, (2015).
29. M. G. Aartsen et al., Evidence for Astrophysical Muon Neutrinos from the Northern Sky with IceCube, *Phys. Rev. Lett.* **115**(8), 081102, (2015). doi: 10.1103/PhysRevLett.115.081102.
30. S. Schoenen, L. Rädel, et al. A measurement of the diffuse astrophysical muon neutrino flux using multiple years of IceCube data. In *Proceeding of the 34th International Cosmic Ray Conference, The Hague, Netherlands, 30 July–6 August 2015*, (2015).
31. S. Schoenen and L. Raedel, Detection of a multi-pev neutrino-induced muon event from the northern sky with icecube, *The Astronomer's Telegram* **7856**, 1, (2015). URL: http://www.astronomerstelegram.org/?read=7856.
32. F. Acero, Fermi Large Area Telescope Third Source Catalog, *Astrophys. J. Suppl.* **218**(2), 23, (2015). doi: 10.1088/0067-0049/218/2/23.
33. S. P. Wakely and D. Horan. TeVCat: An online catalog for Very High Energy Gamma-Ray Astronomy. In *Proceedings, 30th International Cosmic Ray Conference (ICRC 2007)*, vol. 3, pp. 1341–1344, (2007). URL: http://indico.nucleares.unam.mx/contributionDisplay.py?contribId=378&confId=4.
34. M. Aartsen et al., First observation of PeV-energy neutrinos with IceCube, *Phys. Rev. Lett.* **111**, 021103, (2013). doi: 10.1103/PhysRevLett.111.021103.
35. A. Ishihara et al. A search for extremely high energy neutrinos in 6 years of IceCube data. In *Proceeding of the 34th International Cosmic Ray Conference, The Hague, Netherlands, 30 July–6 August 2015*, (2015).
36. V. S. Berezinsky and G. T. Zatsepin, Cosmic rays at ultrahigh-energies (neutrino?), *Phys. Lett.* **B28**, 423–424, (1969). doi: 10.1016/0370-2693(69)90341-4.
37. J. F. Beacom, P. Crotty, and E. W. Kolb, Enhanced signal of astrophysical tau neutrinos propagating through earth, *Phys. Rev.* **D66**, 021302, (2002). doi: 10.1103/PhysRevD.66.021302.
38. P. Gondolo, G. Ingelman, and M. Thunman, Charm production and high-energy atmospheric muon and neutrino fluxes, *Astropart. Phys.* **5**, 309–332, (1996). doi: 10.1016/0927-6505(96)00033-3.
39. P. Hallen. On the Measurement of High-Energy Tau Neutrinos with IceCube, PhD thesis, Master's thesis, RWTH Aachen, November 2013. URL https://internal.icecube.wisc.edu/reports/details.php.
40. D. R. Williams, C. M. Vraeghe, D. L. Xu, et al. A Search for Astrophysical Tau Neutrinos in Three Years of IceCube Data. In *Proceeding of the 34th International Cosmic Ray Conference, The Hague, Netherlands, 30 July–6 August 2015*, (2015).
41. H. Niederhausen and S. Schoenen. Xxxxx. IceCube Internal Report ICECUBE-
Observations of a diffuse flux of cosmic neutrinos

XXXX2015, Department Physics and Astronomy, Stony Brook and III.Physikalisches Institut RWTH Aachen University, (2015). available at http://.pdf.

42. M. G. Aartsen et al., A combined maximum-likelihood analysis of the high-energy astrophysical neutrino flux measured with IceCube, *Astrophys. J.* **809**(1), 98, (2015). doi: 10.1088/0004-637X/809/1/98.

43. M. G. Aartsen et al. The IceCube Neutrino Observatory Part II: Atmospheric and Diffuse UHE Neutrino Searches of All Flavors. In *Proceedings, 33rd International Cosmic Ray Conference (ICRC2013)*, (2013). URL https://inspirehep.net/record/1255627/files/arXiv:1309.7003.pdf.

44. M. G. Aartsen et al., Searches for Extended and Point-like Neutrino Sources with Four Years of IceCube Data, *Astrophys. J.* **796**(2), 109, (2014). doi: 10.1088/0004-637X/796/2/109.

45. M. G. Aartsen et al., Searches for small-scale anisotropies from neutrino point sources with three years of IceCube data, *Astropart. Phys.* **66**, 39–52, (2015). doi: 10.1016/j.astropartphys.2015.01.001.

46. A. Margiotta, The KM3NeT deep-sea neutrino telescope, *Nucl. Instrum. Meth.* **A766**, 83–87, (2014). doi: 10.1016/j.nima.2014.05.090.

47. A. V. Avrorin et al., Current status of the BAIKAL-GVD project, *Nucl. Instrum. Meth.* **A725**, 23–26, (2013). doi: 10.1016/j.nima.2012.11.151.

48. M. Aartsen et al., IceCube-Gen2: A Vision for the Future of Neutrino Astronomy in Antarctica. (2014).
