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Review

Monitoring and Multi-Messenger Astronomy with IceCube

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Abstract: IceCube currently is the largest neutrino observatory with an instrumented detection volume of 1 km^3 buried in the ice-sheet close to the antarctic South Pole station. With a 4π field of view and an up-time of >99%, it is continuously monitoring the full sky to detect astrophysical neutrinos. With the detection of an astrophysical neutrino flux in 2013, IceCube opened a new observation window to the non-thermal Universe. The IceCube collaboration has a large program to search for astrophysical neutrinos, including measurements of the energy spectrum of the diffuse astrophysical flux, auto- and cross-correlation studies with other multi-messenger particles, and a real-time alert and follow-up system. On 22 September 2017, the IceCube online system sent out an alert reporting a high-energy neutrino event. This alert triggered a series of multi-wavelength follow-up observations that revealed a spatially-coincident blazar TXS 0506+056, which was also in an active flaring state. This correlation was estimated at a 3σ level. Further observations confirmed the flaring emission in the very-high-energy gamma-ray band. In addition, IceCube found an independent 3.5σ excess of a time-variable neutrino flux in the direction of TXS 0506+056 two years prior to the alert by examining 9.5 years of archival neutrino data. These are the first multi-messenger observations of an extra-galactic astrophysical source including neutrinos since the observation of the supernova SN1987A. This review summarizes the different detection and analysis channels for astrophysical neutrinos in IceCube, focusing on the multi-messenger program of IceCube and its major scientific results.

Keywords: neutrino; monitoring; multi-messenger

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1. Introduction

One outstanding question in modern astroparticle physics is which processes lead to non-thermal emission in the Universe. To learn about these processes, we rely on messenger particles that carry information about their astrophysical origin. One of these messenger particles is neutrinos produced in hadronic interactions along with cosmic rays and high-energy gamma rays [1]. Compared to cosmic rays, neutrinos have the advantage that they point back to their place of origin as they are almost massless, electrically neutral, and only interact weakly. Due to their small cross-section, they can leave their production site and travel nearly un-attenuated over cosmological distances and thus are a smoking gun for hadronic processes at the sources [2,3]. However, for the same reason, neutrinos are very difficult to observe as most of them will pass through a detector without interacting. In addition, there is a huge foreground of atmospheric neutrinos and muons that are produced in air showers resulting from cosmic-ray interactions with molecules in Earth's atmosphere [4], which can trigger the detector as well. These make the detection of astrophysical neutrinos very challenging [5,6].

This review is focused on the multi-messenger program of IceCube explaining the functionality and the scientific results.

2. The IceCube Neutrino Observatory

The detection of neutrinos in IceCube relies on the measurement of Cherenkov-light produced by secondary particles from neutrino interactions. Due to the small cross-section of neutrinos, a large detection volume transparent to Cherenkov-light is needed. The IceCube detector is located at the geographic South Pole and utilizes the clear Antarctic ice-sheet close to the Amundsen-Scott station as the detection volume [7].

The IceCube detector consists of 5160 light sensors, called digital optical modules (DOMs), that house photomultiplier tubes (PMT) of 10 inches in diameter [8], as well as read-out electronics and calibration devices [9]. The DOMs are located at a depth between 1.5 km and 2.5 km below the surface and are attached to 86 strings with a DOM-to-DOM distance of about 17 m. The strings are arranged in a hexagonal pattern with a string-to-string spacing of about 125 m. At the center of IceCube, an infill array called DeepCore is deployed, consisting of seven strings with high-quantum efficiency DOMs, a DOM-to-DOM spacing of 7 m, and a string-to-string spacing of about 40–70 m [10]. The Neutrino Observatory is completed by a surface detector called IceTop, consisting of 81 stations with two tanks per station. Each tank houses two DOMs in frozen water that can measure charged particles from cosmic-ray air showers on the surface [11].

The detector construction was completed in 2011, although IceCube was already taking data in partial configuration since 2006 [12]. IceCube runs continuously with an operational up-time of >99% [7]. With read-out electronics onboard, the DOMs send their data to the surface where a large computing farm applies global trigger conditions, requiring, e.g., several local coincidences within the full detector. These trigger conditions are mainly based on the number of local coincidences. Once a global trigger decision is made, the individual data of the DOMs are gathered together by an event builder and written to a file. The typical delay until the event has been completely built is about 5 s from detection in the DOMs. The event builder hands the event over to the processing and filtering system that automatically applies calibration constants, runs initial reconstructions, and selects events with about 25 different filters. The overall processing and filtering typically takes an additional 20 s. A special real-time system is running in parallel sending alerts for special events. Data are automatically sent to IceCube's data center located in Madison, WI, via a satellite system for further processing and analysis [7].

With an energy threshold of about 100 GeV, the IceCube detector measures mainly atmospheric muons and neutrinos produced in cosmic-ray-induced air showers, which are the main background in searches for astrophysical neutrinos. The energy threshold is lowered to less than 10 GeV for events that are detected with the DeepCore infill array [10]. Atmospheric muons are detected at a seasonal varying rate of about 2.5 kHz–2.9 kHz [7]. All atmospheric muons are coming from above, as muons cannot traverse more than several km of ice. Given their low cross-section, atmospheric neutrinos come from all directions except at extremely high-energies when the Earth absorption becomes important [13]. About every seven minutes, a neutrino with an energy of >1 TeV is recorded. With a 4π field of view, IceCube is continuously monitoring the full sky for astrophysical events, and a few hundred astrophysical neutrinos are detected by IceCube each year [14].

3. Detection and Characterization of an Astrophysical Neutrino-Flux

The primary challenge in measuring the flux of astrophysical neutrinos is the discrimination against the background. There are two different signatures of events that can be distinguished in IceCube. Track-like events result from charged-current muon neutrino interactions where the produced muon can travel several km in the ice, emitting a track-like light signal. All other types of neutrino interactions result in a cascade-like signature as the produced particle showers span only a few meters. The light emission appears nearly point-like because the extension of the particle cascade is small compared to the DOM spacing. In principle there can also be events with two separated cascades connected by a track-like signature from taus produced in the charged–current tau neutrino interaction. However, this signature has not yet been observed. Track-like events typically have a very good median angular resolution of about 1° at 1 TeV energy, while cascade events are typically reconstructed with a median resolution of ~16° at 1 TeV energy [15]. On the other hand, the reconstruction of the energy of a cascade is more precise because the cascade typically is fully contained in the detector. This is not the case for a track-like event, and thus, the estimation of the true neutrino energy has very large uncertainties.

To suppress the background of atmospheric muons, IceCube uses two different techniques. It is possible to use the outer layers of the detector as a veto, so that only contained events starting in the detection volume are selected [16]. This selection, called the High-Energy Starting Event (HESE) selection, works efficiently for high-energy events because the veto capability increases with larger light output of the events, but as a result of the containment condition, the detection volume is limited. The second technique uses the Earth as a shield against atmospheric muons by selecting only up-going, through-going events [14]. Since the selection is based in the directional information, an accurate track-reconstruction is required. The effective detection volume can be larger than the instrumented volume as muons produced outside the detector can propagate into the detector. However, with this technique, only neutrinos form the Northern Hemisphere are selected. While atmospheric muons can be suppressed by these event selection techniques, atmospheric neutrinos impose here an irreducible background. For the HESE sample however, atmospheric neutrinos from the Southern Hemisphere are also suppressed because muons from the same air shower will accompany the neutrino and trigger the veto [16]. In both selections, the astrophysical flux contribution appears as an additional excess of neutrinos at high energies as the spectral shape of atmospheric neutrinos and astrophysical neutrinos is different.

In 2013, the first detection of a high-energy astrophysical neutrino signal was published by the IceCube collaboration [16]. Using the HESE sample, a clear excess above the background distribution was observed [17–19]. The discovery was confirmed by the high-statistics through-going muon neutrino sample (up-going tracks) [14]. The resulting best fit spectrum of the through-going muon neutrino analysis is shown in Figure 1 (left) together with the unfolded spectrum of the HESE spectrum.

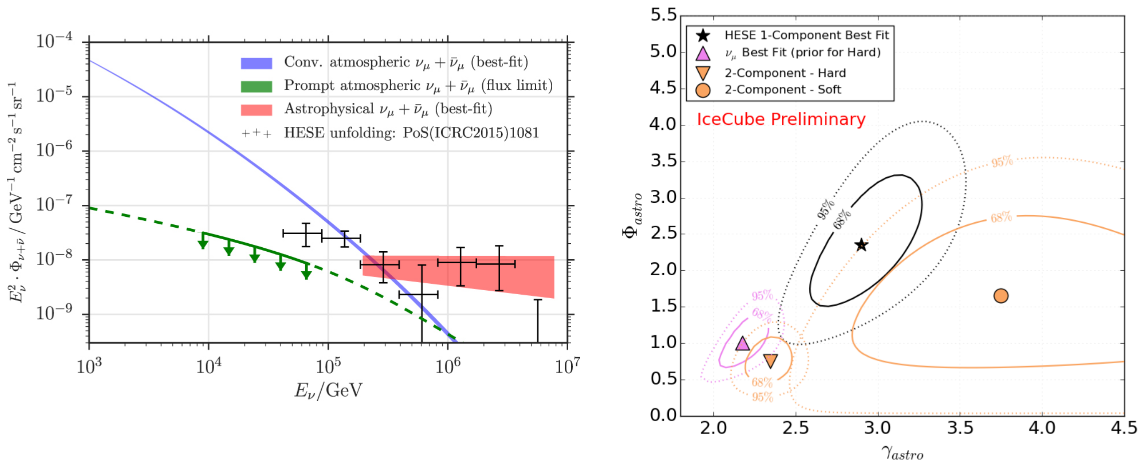

Figure 1. (**Left**): Neutrino flux components as a function of neutrino energy. Shown are the atmospheric neutrino flux caused by π/K-decay (conventional), the astrophysical best fit single power-law spectrum (red), the unfolded neutrino spectrum from the starting event technique, and an upper limit on the contribution of atmospheric neutrinos from heavy meson decay (prompt). The width of the bands gives the energy range that contributes 90% to the sensitivity [14]. (**Right**): Contour plot of the HESE best-fit astrophysical spectral index vs. best-fit normalization at 100 TeV. Shown is the single power-law fit in black (one component), where the best-fit point is marked with a black star. The red (two-component, hard) and yellow (two-component, soft) contours show the best-fit components assuming a double power-law hypothesis with the high-energy up-going muon best fit (blue) [20] as a prior for the hard component [19].

The shape of the spectrum is under careful investigation. Currently, a single power-law is in agreement with the data, and there is no need for a cut-off or a broken power-law [19,20]. However, data from the two selections are described by spectral indices that are only marginally compatible, as can be seen in Figure 1 (right). In the latest update of the through-going track search, the spectral index has been fitted to -2.19 ± 0.1 [20], while the HESE spectral index was $-2.91^{+0.33}_{-0.22}$ [21]. From Figure 1 (left), one can however see that the extracted spectra agree within the uncertainties. The discrepancy can be caused by multiple reasons: the different energy ranges of each event selection, the different parts of the sky probed by each selection, the different interaction and observation channels, or different systematic uncertainties for each sample. From a multi-messenger point of view, the shape of the astrophysical neutrino spectrum is of great interest, as it will help to understand the composition of the cosmic-ray spectrum.

Another property of interest is the flavor ratio of the observed astrophysical flux. For most distant sources, a flavor ratio of ν_e:ν_μ:ν_τ of about 1:1:1 is expected [22,23]. The distinction of track-like events and cascade-like events can constrain the $\nu_e + \nu_\tau$:ν_μ ratio. To resolve the degeneration in ν_e and ν_τ detection, specific searches for tau neutrino candidates are performed. In the latest study, two tau-neutrino candidates have been found, yielding a fit flavor ratio of 0.87:1.5:0.63, which is fully compatible with an equal flavor ratio [24]. A single flavor flux can be excluded, while a zero contribution of ν_τ flux can not be excluded yet. Further investigations of these two tau neutrino candidates are ongoing.

In both selections, the highest energy events are likely of astrophysical origin, e.g., the through-going events with energies >200 TeV have a probability of >50% to be of an astrophysical nature [14]. In Figure 2, a sky map in equatorial coordinates shows the direction of all through-going tracks with energies >200 TeV and all starting events where the markers indicate if they are of a cascade or track-like nature. The effect of Earth's absorption of neutrinos at the highest energies can be seen as only a few events are observed from the upper Northern Hemisphere (declination > 45°). No clear cluster can be found from the sky map, and the arrival directions are compatible with a uniform distribution. If no source can be identified by the auto-correlation of neutrinos alone, a multi-messenger approach is needed to identify astrophysical neutrino sources.

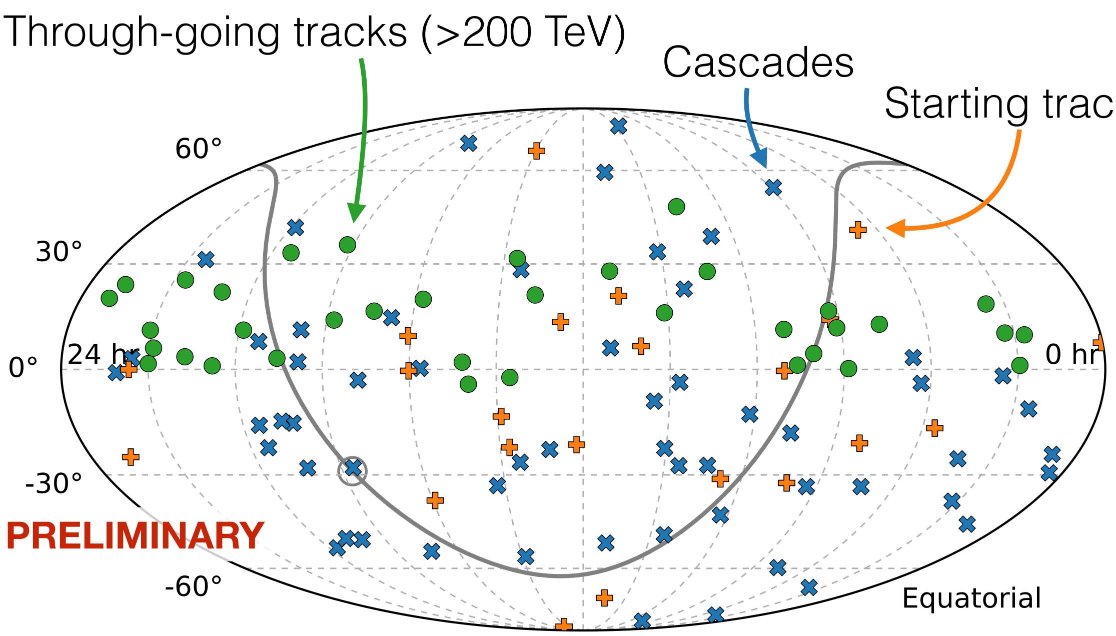

Figure 2. Sky map of the arrival directions of the highest energy events in equatorial coordinates. Events from the starting event technique are subdivided into cascade-like (blue "×") and track-like (orange "+") events. Through-going muon neutrino tracks (green "o") with energies > 200 TeV are shown, as well [25]. The galactic plane is indicated by the gray line.

4. Searching for Sources of Astrophysical Neutrinos

Besides identifying astrophysical events individually or by their cumulative energy distribution, it is also possible to detect an astrophysical neutrino flux from an astrophysical source that appears (nearly) point-like. In this case, several neutrinos cluster either spatially and/or in time. The search for sources of astrophysical neutrinos can be sub-divided into several categories: auto-correlations (Section 4.1), off-line cross-correlations with other messenger particles (Section 4.2), and correlations due to real-time/follow-up programs (Section 4.3).

4.1. Auto-Correlation

A general way to test for point-like neutrino emission is an auto-correlation of neutrinos and a scan of each direction in the sky. For this type of search, an unbinned likelihood analysis is performed, taking spatial and energy information from a large statistic sample into account [26]. The latest point-like source search has been optimized for a source spectrum similar to the total diffuse muon neutrino flux [27]. This search did not find a significant excess in about 500 k events recorded in eight years of IceCube operation limited to the Northern Hemisphere. A more general search, not optimized for a specific source spectrum and covering the full sky taking seven years of IceCube data, has been also insignificant [28]. Special extension, e.g., to lower the energy threshold by advanced event selection techniques has been performed [29]. Due to the huge amount of background on the Southern Hemisphere, IceCube's sensitivity to point-sources is weaker in this part of the sky. Here, ANTARES has complementary neutrino information, as this is the part of the sky that ANTARES can observe through the Earth [30]. This complementarity motivated an analysis combining data from IceCube and ANTARES. Even with their much weaker angular resolution, cascades can also be used to search for spatial clustering [15].

In addition to energy and spatial information, the background can be further suppressed by taking time information into account. The background can be assumed to be approximately uniformly distributed in time, while, e.g., the emission profile of neutrinos from gamma-ray bursts is very short bursts with a characteristic time scale of less than a second. In addition, taking also temporal clustering into account, an analysis can become much more sensitive. Such all-sky time-dependent analyses are performed, e.g., to search for neutrinos from gamma-ray bursts [31,32] or from fast radio bursts [33]. Based on the non-observation of time-dependent neutrino sources so far, constraints on minute-scale transient astrophysical neutrino sources can be set [34].

In addition to looking for single sources only, one also can search for a population of weak neutrino sources using two-point correlation methods as, e.g., a power spectrum of spherical harmonics or a two-point auto-correlation test [35,36]. Furthermore, in the full-sky scan for point-like sources, one can search for an excess of small p-values, which would indicate the existence of multiple sub-threshold sources. Non-observation makes it possible to put constraints on the source density and luminosity distribution of the source population [27].

4.2. Correlation Using Multi-Messenger Astronomy

Due to the large number of trials in a generic search that tests each spot in the sky, even a local significant spot will become non-significant after the correction for the trials factor. Using a physically-motivated set of pre-selected neutrino candidate sources, e.g., from observations in other multi-messenger experiments, the discovery potential can be largely enhanced. These analyses include tests for large-scale anisotropies like the Galactic Plane [37,38]. The test for individual sources is a pre-defined source list motivated by gamma-ray observations [27,28] or stacking searches of sources of a specific class, e.g., on the contribution of Fermi-2LAC blazars to the diffuse TeV-PeV neutrino flux [39]. In addition, direct correlation studies with other messenger particles are performed such as correlations between the arrival directions of IceCube neutrino events and ultra-high-energy cosmic rays detected by the Pierre Auger Observatory and the Telescope Array [40]. In the context of multi-messenger correlation, also searches for correlations between gravitational wave events detected by Advanced LIGO and high-energy neutrinos from ANTARES and IceCube have been performed. The results are also compatible with only the background [41–43].

4.3. Real-Time Program

Many processes in the non-thermal Universe show a strong time variability. Thus, timely follow-up observations are crucial to detect neutrinos from such processes. Even though IceCube can look back in archival data once an interesting astrophysical event has been observed, in general, this is not the case for other observatories. Very High Energy (VHE) gamma-ray telescopes, such as Imaging Air Cherenkov Telescopes (IACTs), have a typical field of view of a few degrees; for those experiments, a prompt follow-up observation is only possible if they are notified in time. In 2014, IceCube detected a muon neutrino with multiple PeV energy [44]; however, follow-up observations are only triggered after the analysis of the whole data acquisition, which typically requires a year. To avoid this unnecessary latency, since 2016, the IceCube collaboration established a real-time alert system at the South Pole [45]. The alert system runs live in parallel with the initial reconstruction of individual events and checks for local neutrino excesses and special high-energy events. Currently, there are four different streams implemented in the real-time system: The first stream looks for neutrino doublets from the Northern Hemisphere that are in tight spatial and temporal coincidence. The second one runs an online analysis to find an excess of multiple neutrinos within up to three weeks from a known gamma-ray source position [46]. The other two streams are single-event streams. One looks for high-energy starting events and was motivated by the HESE analysis that led to the discovery of the astrophysical neutrino flux. This stream puts as an additional constraint on the event requiring a track-like topology in order to have reliable directional information. Only well-reconstructed events are sent out as alerts for follow-up observations. The other single-event stream was motivated by a search for neutrinos produced by the GZK effect and looks for extreme high energy events.

Once one of these streams finds an event or a cluster of events above a threshold, the real-time system sends an alert via a special iridium satellite to the north and distributes the alert to the Gamma-ray Coordinated Network (GCN) [47] via the Astrophysical Multi-Messenger Observatory Network (AMON) [48]. The alert has a typical delay of about 33 s after the detection of the event at the South Pole. This is achieved by splitting the transmitted data into two separate parts. The first message contains only minimal information including the alert stream, the direction, and a few key parameters like deposited charge in units of photoelectrons, which is related to the energy of the event and directional uncertainties. In a second message, the full event information is sent north for further inspection of the event. A few hours later, once refined reconstructions are completed, a revision of the alert is made public [45].

The alert rate of IceCube is of several events per year. The alerts were followed up by various multi-messenger observatories [49] like PTF, ZTF, HAWC, VERITAS, MAGIC, HESS, Fermi LAT, Fermi GBM, Swift, and others.

Likewise, IceCube has a program for fast response to alerts from other multi-messenger observatories. A special fast response analysis was set up that tests for coincident events within a small time range [50]. Fast response analyses run on the advice of the real-time oversight committee that should be contacted under roc@icecube.wisc.edu for follow-up proposals. The results of a fast response analysis are shared as an astronomers' telegram [51], e.g., [52–56].

5. Neutrinos from the Direction of Blazar TXS 0506+056: A Multi-Messenger Success

On 22 September 2017, the IceCube real-time system sent out an extreme-high energy alert [57] for which a refined circular was distributed a few hours later [58]. An event view of the event called IceCube-170922A is shown in Figure 3. The direction of the event was reconstructed with an uncertainty of less than $(1^\circ)^2$ at 90% CL and points to right ascension 77.38° and declination 5.69° (J2000), which is located in the Orion constellation (see Figure 3, right). The event deposited

(23.7 ± 2.8) TeV energy within the detector and had an estimated neutrino energy of about 290 TeV assuming an $E^{-2.13}$ power-law spectrum with a lower bound of 183 TeV at 90% CL [59]. The probability of this event to be of astrophysical origin was 56.5% assuming the best-fit astrophysical spectrum from [14] and taking the zenith and energy of the event into account. Within 43 sec after the detection, a GCN notice was sent via AMON encouraging other observatories to follow-up on this sky location.

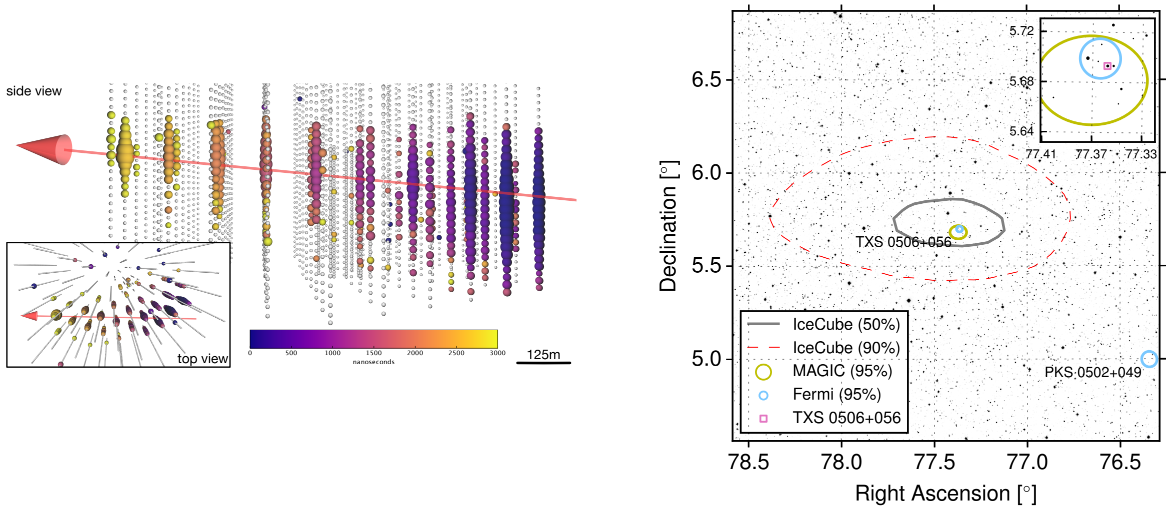

Figure 3. (**Left**): event view of the real-time alert IceCube-170922A. The spheres represent DOMs of the detector, where the size of the spheres is proportional to the detected charge and the color corresponds to the arrival time. The red arrow indicates the best fit reconstruction. A top view of the event can be seen in the inset [59]. (**Right**): sky map in equatorial coordinates around the direction of IceCube-170922A. In the background, a V-band view of the sky is shown. The 50% and 90% uncertainty contours of IceCube-170922A are shown. Overlaid are the MAGIC and Fermi-LAT contours of the gamma-ray excess at 95% CL. As an inset, a zoom on the event direction is shown. The event direction is located near the arm of Orion [59].

On 28 September 2017, the Fermi collaboration reported that the blazar TXS 0506+056, located at right ascension 5 h 9′ 25.96″ (77.36°), declination +5° 41′ 35.32″ (5.69°), which is contained in the 3FGLand 3FHLcatalogs [60,61], located 0.16° away from the best fit direction of IceCube-170922A and thus inside the uncertainty contour, was exhibiting a flaring state with an increased flux of about a factor of six above the long time average [62]. The contour of the Fermi-LAT excess and the source location of the TXS 0506+056 source are indicated in Figure 3. The correlated emission of the neutrino events with the gamma-ray flux was favored on the 3.0 σ level compared to a pure chance coincidence of a neutrino alert in spatial and temporal coincidence with a flaring source in the extra-galactic Fermi-LAT catalog [59]. This significance takes already into account that IceCube sent out nine alerts prior to IceCube-170922A, and IceCube would have sent out 41 additional alerts if the system would have been running before 2016 without finding a counterpart.

The VHE gamma-ray telescopes HESS, VERITAS, and MAGIC made observations the night following the neutrino alert. All three telescopes had no positive detection [59] in VHE gamma rays. After Fermi reported that TXS 0506+056 was in a flaring state, all three VHE telescopes resumed their observations. MAGIC, which initially had non-optimal weather conditions, found an excess of 374 ± 62 photons with energies up to 400 GeV above the background after several nights of observation with a total of 12.9 h [59]. This was the first observation in VHE gamma rays of this source.

Follow-up observations of 23 observatories have been reported from which 19 reported an observation with detection ranging over multi-messenger and multiple electromagnetic wavelengths from radio to VHE gamma rays. A multi-wavelength light curve of TXS 0506+056 can be found in Figure 4 where the time of the neutrino alert is indicated by a black vertical line [59]. In the left panel, the long time average flux can be seen in the radio, optical, and gamma-ray band for several years.

In spring 2017, the flux level enhanced strongly in the gamma ray and radio band. The right panel shows the flux level around the time of the neutrino alert. From the gamma-ray flux, one can see that at the time of the neutrino alert, the source was in a high flux state. The follow-up observations in VHE gamma rays and the X-ray band showed that there was also significant variability in the total flux. In addition, also spectral variability can be seen from the measurement of the photon index by Swift. The Spectral Energy Distribution (SED) of the event shows the typical two bump structure of a blazar [59]. By another follow-up observation, the red-shift of TXS 0506+056 was measured to z = 0.3365 $\pm$ 0.0010 [63]. An independent upper bound could be set on the red-shift due to the observation of VHE gamma rays. Depending on the extra-galactic background light model, the limit on the red shift was $z < 0.61 - 0.98$ at 95% CL [59]. Considering this red-shift, TXS 0506+056 is one of the most luminous blazars known today and about an order of magnitude more luminous than Markarian 421 and Markarian 501.

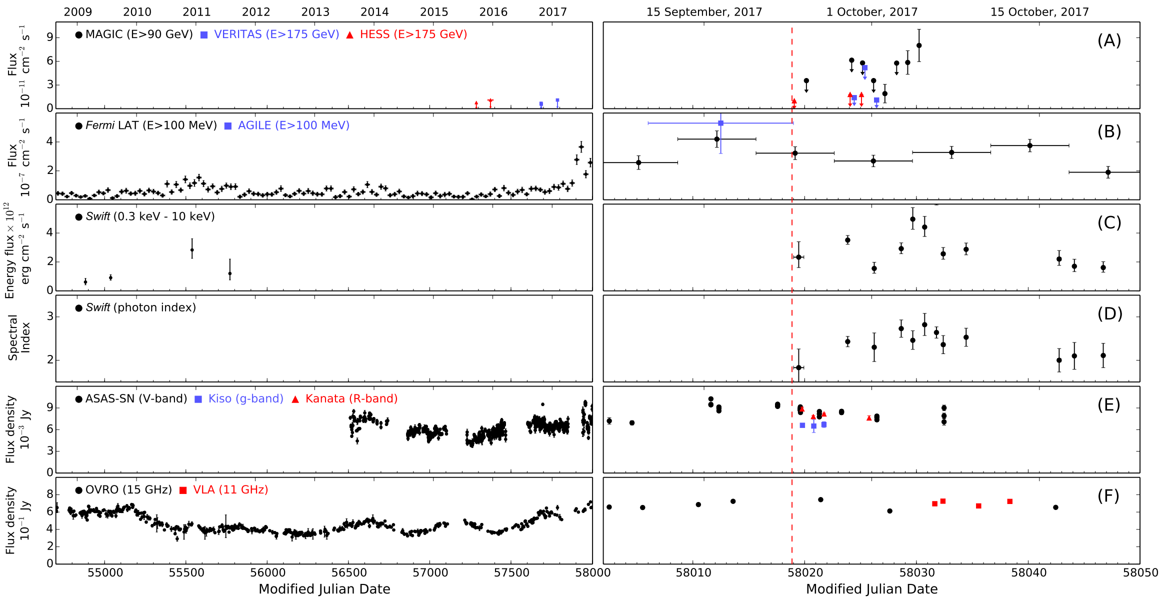

Figure 4. Multi-wavelength light curve of TXS 0506+056 from several experiments (see legend). The different panels show from top to bottom the VHE gamma-ray flux (**A**), the gamma-ray flux (**B**), the energy flux in the X-ray band (**C**), the spectral photon index in the X-ray band (**D**), the flux density in the optical band (**E**), and the flux density in the radio band (**F**). The scaling of the time axis is changed from the left to the right panel, where the left panel shows the light curve over several years, while the right panel shows several weeks around the alert event. The time of the neutrino alert is indicated by a dashed vertical line. Note that from radio and gamma ray, data are available for nearly every time point, while for VHE gamma ray and X-ray-only the observation as follow-up to the alert is available [59].

Motivated by the positive detection of a counter part to IceCube-170922A the IceCube collaboration inspected the direction of the blazar TXS 0506+056 [64] using seven years of archival data using a high statistic sample of well-reconstructed tracks that was used for the latest search for point-like neutrino sources [28]. The sample was extended with data up to October 2017 to about 9.5 years of data using the selection described in [45].

The analysis method presented in [28] was applied to the direction of TXS 0506+056 testing for a time-integrated flux of a neutrino point source. Using the seven-year data sample, the best-fit single power-law point-source flux had a flux normalization of $(0.9^{+0.6}_{-0.5}) \times 10^{-16}\,\mathrm{TeV^{-1}cm^{-2}s^{-1}}$ at a pivot energy of 100 TeV and a spectral index of 2.1 $\pm$ 0.3 with a p-value of 1.6% corresponding to a significance of 2.1σ [64]. If extending the sample up to October 2017 (which includes the time of the neutrino alert, the significance increased to 4.1σ [64]. Note that the seven-year result was an independent result to the chance coincidence and the astrophysical probability of the alert event, while the 9.5 year result included the alert event and, thus, is a posterior result and not independent.

In addition to a time-integrated search for neutrino emission, the direction of TXS 0506+056 was also tested for time-dependent neutrino emission using two emission profiles: a Gaussian-shaped and a box-shaped profile. In Figure 5, the negative $\log_{10}$ of the local p-value for both methods is shown as a function of the central time of the time profile T_0. The best-fit profile for the Gaussian profile is shown for each sub-sample in orange, while the p-value as a function of the central time of the box profile is shown in blue. The best-fit time-ranges for the box profile are marked in light-blue. For both analyses, the largest excess was not around the time of the neutrino alert IceCube-170922A, which is marked as a dashed black vertical line, but at the end of the year 2014. For the Gaussian profile, the best fit parameters were a flare on 13 December 2014 $\pm$ 21 days with a width of 100^{+35}_{-24} days and a local p-value of 3×10^{-5} [64]. For the box profile, the best fitted flare was centered on 26 December 2014, with a width of 158 days and a local p-value of 7×10^{-5}. Correcting both p-values for the total observation time taking the duration of each sub-sample into account yielded a significance of 3.7σ and 3.5σ for the Gaussian and box profile, respectively. As the true profile is unknown, taking the better fit and applying a trial factor of two gave a trial-corrected significance of 3.5σ [64].

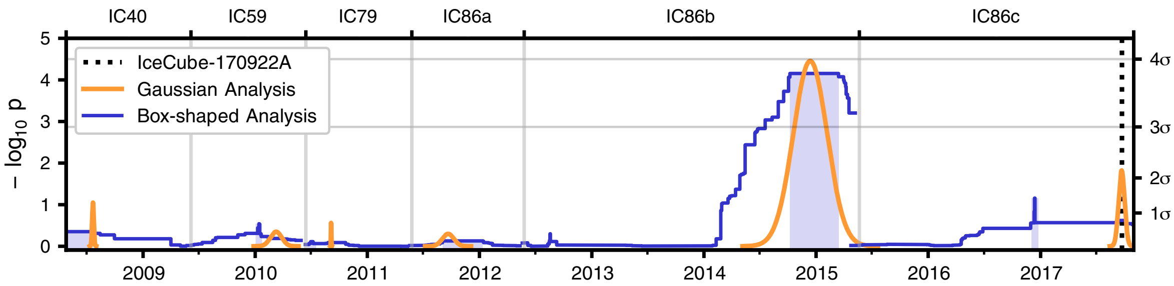

Figure 5. Negative $\log_{10}$ of local p-value (**left**) and significance (**right**) of the time-dependent analysis as a function of time. Sub-samples are separated by gray vertical lines and labeled at the top. The best-fit Gaussian profile for each sub-sample is shown in orange where the height corresponds to the local significance. For the box-shaped analysis, the local p-value as a function of the central window time is shown, and the largest excess is marked by a light blue band for each sub-sample. The largest excess of both methods can be seen for the end of the year 2014 with a local significance of about $4\,\sigma$. The time of the neutrino alert is marked by a vertical dashed line. The local excess of the Gaussian analysis at the time of the alert was mainly driven by the alert event itself [64].

This time-dependent result can be interpreted as evidence for a neutrino flare from the direction of TXS 0506+056. Note that this evidence is independent of the 3.0σ preference for correlated emission of the alert neutrino IceCube-170922A and the flare of TXS 0506+056. The evidence for a neutrino flare was found in the analysis years after the data had been recorded by the IceCube detector. Thus, no timely follow-up observations were performed, and information from other multi-messenger observations of the source at the time of the neutrino flare are limited, as can be seen in Figure 4. In the GeV gamma-ray band, no flare can be seen.

The equivalent time-integrated flux estimated from TXS 0506+056 will make up about 1% of the total observed astrophysical flux observed by IceCube [64]. The flux is fully compatible with limits set on the 2LAC blazar contribution to the observed astrophysical neutrino flux [39]. These limits constrain the 2LAC blazar contribution to the observed astrophysical flux to less than 27% at 90% CL assuming an $E^{-2.5}$ spectrum and to less than 40–80% assuming an E^{-2} spectrum for energies larger than 200 TeV [39]. Studies on other individual blazars are currently on-going.

6. Conclusions

Multi-messenger observations are necessary to understand the nature of the non-thermal Universe because different messenger particles carry complementary information about their sources. Neutrinos have a key role as they help to identify source locations of cosmic rays and give information about the underlying processes. Due to their small cross-section and mass, the information carried by neutrinos is nearly unaltered by propagation effects.

With the detection of an astrophysical neutrino flux in 2013, the IceCube detector opened a new observation window to observe the cosmos [16]. However, until now, no high-energy neutrino source could be identified [27,28]. With 10 years of data taking and and no indication of a steady neutrino point source, its detection will be challenging with the current detector geometry as the discovery potential increases as a squared root of the acquisition time. In the long term, high-energy extensions of neutrino detectors are in preparation like the IceCube-Gen2 detector [65,66] and KM3NeT [67,68] to enhance the statistics and thus the sensitivity to astrophysical neutrino sources. In addition, also an improved understanding of the detector and thus a reduction of systematic uncertainties, e.g., by the IceCube-Upgrade [69], will help to improve the sensitivity of the already existing data, by re-analyzing them with better knowledge of the systematic uncertainties.

In the near future, the most promising avenue for the detection of an astrophysical neutrino source is the identification via multi-messenger campaigns of variable and transient sources.

With the implementation of a real-time alert system, the IceCube collaboration has set up a tool to trigger observations by other multi-messenger observatories [45]. The success of this program is illustrated by the observation of a very high energy neutrino alert in spatial and temporal correlation with a flaring blazar for which chance coincidence was rejected to the level of 3σ [59]. This observation that involved 24 different observatories and telescopes is a great success of multi-messenger observation and fast follow-ups.

In addition, IceCube with its ability to monitor the full sky continuously over about 10 years can perform analysis on archival data. Motivated by the preference of the correlated emission of the neutrino alert IceCube-170922A and the flare of the blazar TXS 0506+056, IceCube reanalyzed its archival data, finding a neutrino flare with a length of about 100 days centered on December 2014 at the 3.5σ level [64]. The location of TXS 0506+056 with a declination of $+5.69°$ is in an optimal spot for the IceCube detector as this declination is where the maximal sensitivity for neutrino point-like sources is reached. Unfortunately, only limited multi-wavelength data are available for the time of the neutrino flare, which prevents any study of correlations with gamma rays. The general success motivates a close cooperation and fast follow-up observations in multi-messenger astronomy, but also motivates a continuous monitoring of a large part of the sky.

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Abbreviations

The following abbreviations are used in this manuscript:

AMON	Astrophysical Multi-messenger Observatory Network
ANTARES	Astronomy with a Neutrino Telescope and Abyss environmental RESearch project
CL	Confidence Level
DOM	Digital Optical Module
GBM	Gamma-ray Burst Monitoring
GCN	Gamma-Ray Coordinate Network
GZK	Greisen–Zatsepin–Kuzmin effect

HAWC	High Altitude Water Cherenkov
HESE	High Energy Starting Event
LAT	Large Area Telescope
MAGIC	Major Atmospheric Gamma Imaging Cherenkov Telescopes
PMT	Photo-Multiplier Tube
PTF	Palomar Transient Factory
SED	Spectral Energy Distribution
VERITAS	Very Energetic Radiation Imaging Telescope Array System
VHE	Very High-Energy
ZTF	Zwicky Transient Facility
3FHL	The Third Catalog of Hard Fermi Large Area Telescope Sources
3FGL	The Third Catalog of Fermi Source

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