

Neutrinos at the 36th International Cosmic Ray Conference 2019

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High-energy neutrinos astrophysics is still a very young field of research. Until recently, the only extra-solar neutrinos observed originated from SN1987A and had MeV energies, well below the energies expected to be emitted from violent cosmic phenomena like supernova remnants, active galactic nuclei and gamma-ray bursts. In 2013, after many decades of efforts, the first cosmic high-energy neutrinos were detected, finally opening this highly anticipated new window for the exploration of the non-thermal universe. In 2017, this was followed by the first plausible association of a high-energy neutrino with a source through a world-spanning multi-messenger campaign. Over 180 contributions at ICRC 2019 impressively demonstrated the dynamics of the field and the importance of multi-messenger efforts. Here, I attempt to provide an overview over the field, presenting a selection from the contributions to ICRC based on the corresponding rapporteur talk at the conference in Madison.

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*Speaker.

1. Introduction

1.1 Year 6 of high-energy neutrino astrophysics

Since the discovery of high-energy cosmic neutrinos with the IceCube detector in 2013 [1], much progress has been made in measuring the spectrum of the TeV–PeV diffuse neutrino flux [2] and its flavor composition [3]. However, for many years there had been no indications for individual neutrino sources. This changed in 2017 with the first plausible association of a high-energy neutrino in IceCube with the active galactic nucleus (AGN) TXS 0506+056 in a multi-messenger campaign [4] and the observation of a neutrino flare in archival data from the same direction [5]. Despite these recent successes, however, many questions remain unanswered: does the observed diffuse neutrino flux consist of several components, how does it continue beyond 10 PeV, what is its flavor composition?

In order to answer these important questions and deliver on the full capabilities of neutrino astronomy, it has become evident, that a new generation of instruments is required that provides higher sensitivities at TeV–PeV energies while covering the full sky, and that extends the energy range of observed neutrino fluxes up to EeV energies. This new generation of instruments is advancing at a rapid pace as evidenced by the many presentations on new ideas, design studies, R&D and construction work at ICRC 2019.

1.2 Neutrinos as cosmic messengers

Neutrinos are unique astrophysical messengers in many aspects. Once produced, their low cross-section allows them to escape even the densest environments of matter and radiation fields: they can reach us from the deepest core of stars, they can penetrate their expanding shell during supernova explosions, and they escape the dense radiation fields in the surroundings of the central engine of AGNs.

Even more so, apart from gravitational waves, they are the only messengers that allow us to observe the whole visible universe up to the highest energies. In contrast, for electromagnetic radiation, the universe loses its transparency with increasing energy beyond ~ 100 GeV through interactions with omnipresent extra-galactic photon fields like the cosmic microwave background radiation. In fact, at PeV energies, the visible universe shrinks to the size of our Milky Way.

Furthermore, neutrinos are an unambiguous tracer for the presence of high-energy hadronic particles thereby taking a unique role in answering one of the most puzzling questions in astrophysics: what are the sources of the ultra-high energy (UHE) cosmic rays that reach energies up to 10^{20} eV? Electromagnetic radiation, in contrast, can be produced both in interactions of electrons and hadrons. While gamma-ray observations have provided convincing evidence for cosmic-ray acceleration in old Galactic supernova remnants up to TeV energies [6], the sources of Galactic PeV cosmic rays as well as extra-galactic UHE cosmic rays still elude detection.

1.3 Neutrinos at ICRC 2019

The high dynamics of the field was impressively demonstrated at ICRC by over 180 contributions in the form of two review and three highlight talks, as well as 75 talks in parallel sessions and over 100 posters. Hot topics were the interpretation of the observed neutrino emission

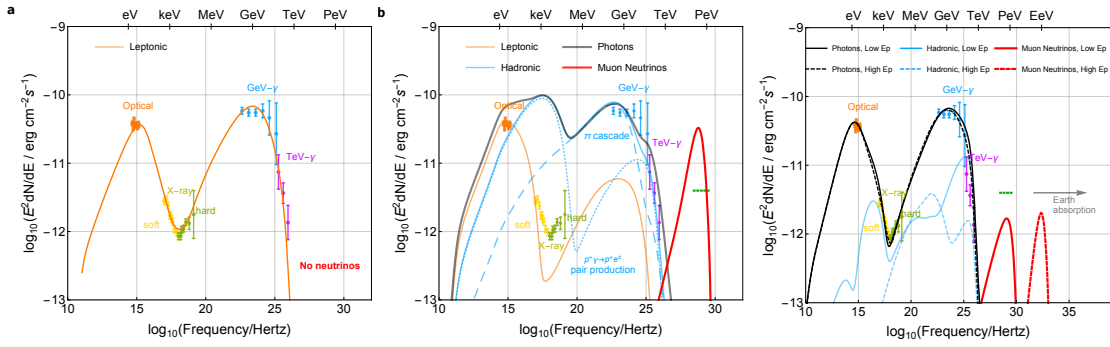


Figure 1: SED measurements of TXS 0506+056 and expected neutrino fluxes (red curves) as a function of frequency/energy for different one zone models during the electromagnetic flare corresponding to IceCube-170922A. All figures taken from [8].

from TXS 0506+056 in particular and blazars in general, as well as understanding the diffuse high-energy neutrino flux in the multi-messenger context. Multi-messenger in general has clearly evolved to one of the central tools in astrophysics with a lot of effort going into setting up the required infrastructure for prompt exchange of information and joint interpretation of data from different experiments. Increasingly more effort also goes into the first detection of EeV neutrinos with a large variety of running and in particular planned detectors, using various detection techniques for neutrino-induced particle showers in air and ice.

This article attempts to give an overview of interesting recent developments in the field, but it is clear that, despite all presentations being of high quality, not all contributions can be mentioned here (note that contributions dealing with dark matter are discussed in [7]). Also, the selection of highlights will naturally be very subjective. The following section provides an overview of our understanding of the origin and properties of cosmic TeV–PeV neutrinos and the plans for new instrumentation. Section 3 discusses developments and future plans in searches for UHE neutrinos followed by Section 4 on MeV neutrinos from core-collapse supernovae and the Sun. Developments and prospects in neutrino physics are presented in Section 5.

2. Origin and properties of TeV–PeV neutrinos

2.1 Neutrino emission from TXS 0506+056

On Sep. 22, 2017, the IceCube detector recorded a high-energy neutrino of about 290 TeV (IceCube-170922A) and sent out a public alert. The alert was followed up by several experiments in neutrinos (ANTARES, Super-Kamiokande [9]), VHE gamma-rays (MAGIC, H.E.S.S., and VERITAS), high-energy gamma-rays (Fermi-LAT, AGILE) and in X-rays, optical, as well as radio [4]. IceCube-170922A was found to be in coincidence with a flare of the blazar TXS 0506+056 as observed by Fermi-LAT at a chance coincidence level of about 3σ [4]. In a subsequent analysis of archival IceCube data, an excess of high-energy neutrino events of 13 ± 5 was found at the position of TXS 0506+056 between September 2014 and March 2015 with a chance significance of 3.5σ [5]. A flaring state in gamma-rays was not observed, though in [10] the authors argue that the

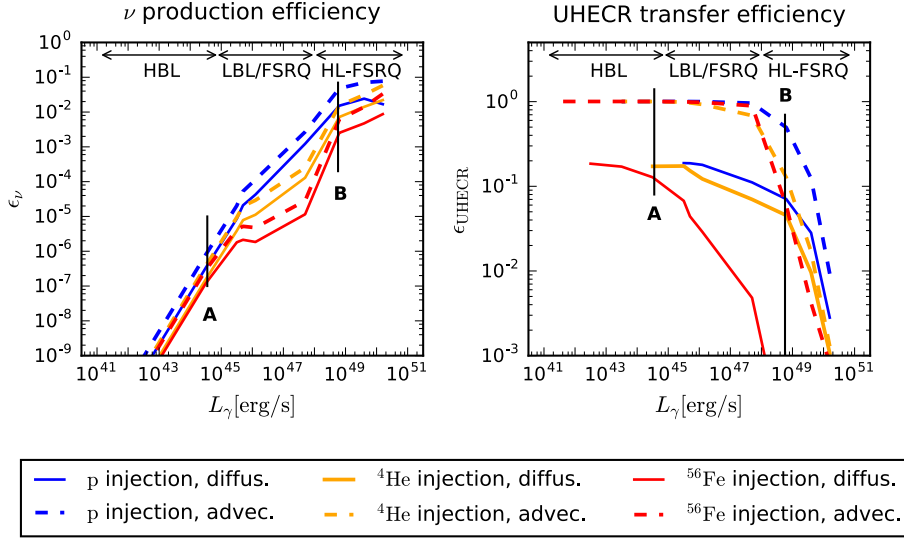


Figure 2: *Left:* All-flavor neutrino production efficiency for blazars of different luminosities. *Right:* Cosmic-ray energy transfer efficiency in the UHE range ($E_{CR} > 10^9$ GeV in the black-hole frame). The colors represent three different pure injection compositions; solid and dashed curves represent diffusive and advective escape, respectively. Taken from [12]. See this paper for details.

spectrum had hardened. Overall, obtaining a consistent picture of this likely first association of a HE neutrino with a source turns out to be challenging.

Figure 1 shows the SED of TXS 0506+056 during the 2017 flare. The approach with the fewest assumptions for modeling the data are so-called one zone models, where all electromagnetic radiation and neutrinos are produced in the same region. Leptonic one zone models (Fig. 1 left) give a good description of the electromagnetic observations but fail to explain the observed high-energy neutrino flux. Hadronic models (Fig. 1 middle, right), on the other hand, produce neutrinos and gamma-radiation through the decay of charged and neutral pions, respectively (references to leptonic and hadronic models can be found in [11]). However, in order to produce a flux of high-energy neutrinos compatible with the observed neutrino event, these models significantly overshoot the observed X-ray flux (Fig. 1 middle) as was shown at the conference by the authors of [11]). Contrariwise, if parameters are adjusted such that the model is compatible with the X-ray data, the neutrino flux is by about a factor ten too low (red solid curve in Fig. 1 right with $E_{p,max} \sim 4.5$ PeV). In addition, the required energy is significantly larger than the Eddington limit which is often used to quantify the physical luminosity available to the jet [11]. This can be alleviated by considering a higher maximum proton energy of $E_{p,max} \sim 1700$ PeV corresponding to the observed UHE cosmic rays (red dashed curve in Fig. 1 right), however, at the expense of a neutrino spectrum peaking significantly above the energy of the observed neutrino. Also explaining the gamma-ray orphaned neutrino flare in 2014–2015 remains a challenge as discussed in [11]. In order to address all these challenges, more sophisticated source models with more than one radiation zone, so called multi-zone models, have been proposed (for references see [11]) but the still thin data bases for such flares prevents a final judgment.

Fueled by the TXS 0506+056 event, blazars have been shifting even more into focus as one

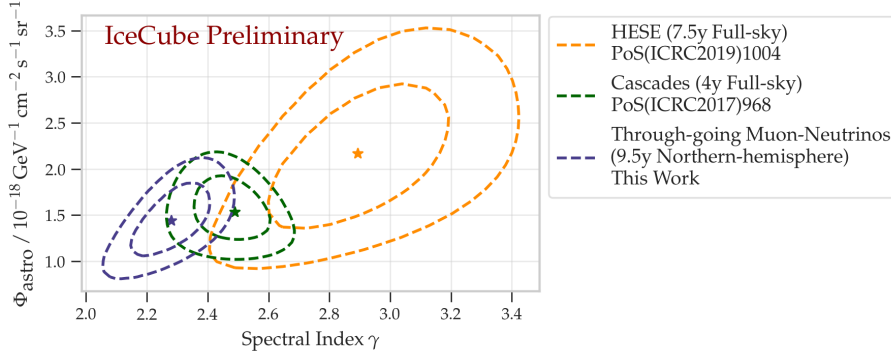


Figure 3: Comparison of the best-fits and profile likelihood contours (68% and 95% C.L.) of different IceCube analyses measuring the astrophysical flux, assuming a single power-law energy spectrum. The y-axis shows the per-flavor normalization anchored at 100 TeV. Taken from [2].

of the prime sites for HE neutrino production: searches for neutrinos from blazars have been performed with the ANTARES ([13]) and IceCube ([14],[15]) detectors, and in [16], [17] and [18] expected neutrino fluxes from blazar flares have been calculated. In [12] the authors model the neutrino flux from low- and high-luminosity blazars including photo-nuclear interactions. The latter is an important ingredient as measurements point to a UHE cosmic ray composition heavier than pure protons [19]. The authors of [12] find that high-luminosity FSRQs with their external photon fields are efficient neutrino emitters but have a low efficiency for the production of UHE cosmic rays as shown in Fig. 2. Vice versa, low-luminosity HBLs are efficient emitters of UHE cosmic rays but inefficient sources for neutrino production due to the missing broadline region.

2.2 Diffuse HE neutrino flux and the multi-messenger picture

Also six years after its discovery, the IceCube detector remains to be the only instrument to observe the diffuse flux of high energy neutrinos with high significance due to its large instrumented volume (at ICRC2019, we have seen results from the ANTARES collaboration showing an excess of events above atmospheric background at 1.8σ compatible with the IceCube measurements [20]).

Like all neutrino telescopes, the IceCube detector [21] detects and reconstructs the direction and energy of the primary neutrino through the Cherenkov light emitted by charged secondary particles generated in neutrino interactions. Detector signatures can be classified into different topologies based on the detected light pattern. *Track-like* events arise from the charged-current interaction of muon neutrinos outside the detector volume where the generated muons travels through the detector, leaving an elongated light pattern (also called *through-going muons*). *Shower-like* events with their spherical light pattern around the interaction vertex arise from neutral current interactions of neutrinos of all flavors, as well as from charged-current interactions of electron neutrinos and tau neutrinos with energies $\lesssim 100$ TeV. *Starting tracks* originate from charged-current muon neutrino interacting inside the detector where both the shower at the interaction vertex and the muon are visible in the detector. The latter two signatures are also referred to as *starting events*. At energies above $\gtrsim 100$ TeV, the showers at the interaction vertex and the tau decay vertex of charged current tau neutrino interactions start to be separable in the IceCube detector (double-cascade events).

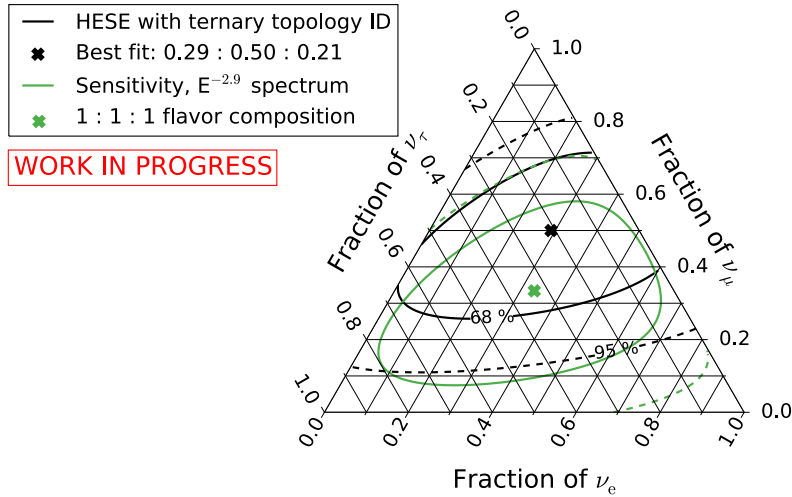


Figure 4: Measured flavor composition of IceCube HESE events with ternary topology ID and sensitivity at the best fit spectrum. Taken from [3].

At ICRC 2019, the IceCube collaboration presented updates of their analyses of high-energy starting (HESE) [22] and through-going muon events [2] with about 2 years increased data taking time, improved treatment of systematic uncertainties as well as re-calibrated and re-processed data sets. Figure 3 shows the best-fit values and uncertainties for the normalization and spectral index of a single power-law flux model to the IceCube data in different channels. Compared to ICRC 2017, the spectrum of through-going muons has softened somewhat but remains consistent with previously reported values. Also the spectrum from the updated HESE sample is compatible with the result shown at ICRC 2017. Overall, the best-fit spectra in the different channels are compatible with each other within uncertainties. Differences between the analyses may be an indication of an additional spectral structure, but the individual samples do not have sufficient power to discriminate between a single and e.g. a double power law.

At the conference, we also saw an update of the flavor ratio measurement by IceCube [3] which is depicted in Fig. 4. For the first time, a non-zero tau flavor content for the best-fit point was presented with $\nu_e : \nu_\mu : \nu_\tau = 0.29 : 0.50 : 0.21$, though a zero tau content still lies well within the 1σ uncertainty interval. This has been possible through the first identification of two double-cascade events with estimated cascade separations of 16–17 m. These are promising astrophysical tau neutrino candidates, thereby breaking the degeneracy between electron and tau neutrinos. One event is the so-called *Big Bird* event from the first HESE sample with a deposited energy of 2 PeV. This event, however, is at the border of the signal region which is background dominated. In an a-posteriori analysis the *tauness* of the event was calculated as 75%. The other event is in a signal dominated region with an estimated *tauness* of 97%. The flavor mixture result is compatible with the expected (1 : 1 : 1) ratio for a pion-production scenario.

Looking at the diffuse neutrino spectrum in the broader multi-messenger picture in an $E^2\phi$ vs. E plot as depicted in Fig. 5 left, it appears that HE gamma-rays, HE neutrinos and UHE cosmic rays have roughly the same energy density which suggests a physically connection. At ICRC, the author of [23] argued that the neutrino flux above 100 TeV can be explained by so-called cosmic-ray

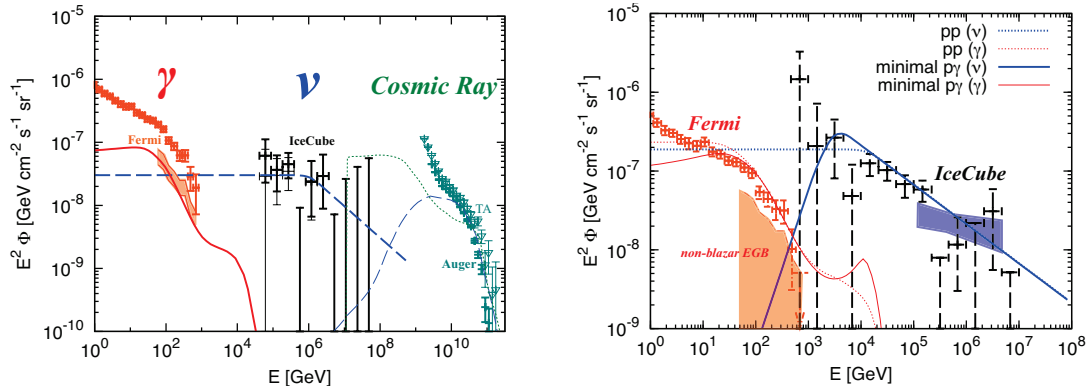


Figure 5: *Left:* High-energy diffuse fluxes of the three messenger particles. *Right:* Diffuse neutrino flux measured in up-going muon neutrino searches (blue shaded) and shower analyses (black data points), as well as the diffuse gamma-ray flux (red data points) and its non-blazar contribution (red shaded). Taken from [23].

reservoir models. In these models, previously accelerated cosmic rays are confined in the “reservoir region”, e.g. starburst galaxies and galaxy clusters, by magnetic fields up to a certain energy above which they escape and are measured as UHE cosmic rays (potentially re-accelerated e.g. in galaxy cluster shocks). Through collisions of cosmic rays with gas in the reservoir region, neutral and charged pions are produced which decay into PeV neutrinos and gamma. The gamma rays cascade down to GeV–TeV energies through interactions with radiation fields whereas the neutrinos can escape the environment unhindered. This model predicts a neutrino spectral break around PeV energies due to the cosmic rays starting to escape the reservoir region. Another interesting aspect is the observed neutrino flux below 100 TeV. In the reservoir model with its pp interactions the predicted diffuse gamma-rays flux (dashed red line in Fig. 5 right) overshoots the observed non-blazar contribution (red shaded area) which indicates that these neutrinos would have to come from so-called hidden cosmic-ray sources in which gamma rays are effectively absorbed [23]. This scenario should be testable with future neutrino detectors like IceCube-Gen2 or an extended KM3NeT detector.

2.3 Searches for point-like neutrino sources and multi-messenger activities

Boosted by the first plausible association of a HE neutrino with a source, contributions to the origin of cosmic neutrinos took up large space at ICRC 2019. As related searches profit significantly from a good angular resolution due to reduced background, up-going charged-current muon neutrino events are the prime channel in analyses of neutrino telescope data (at ICRC, several presentations [24, 25] discussed improvements in event reconstruction in neutrino telescopes). The quest for neutrino sources is not limited to searches with the IceCube detector, though. ANTARES [26], an underwater neutrino telescope in the Mediterranean Sea, has an about 100 times smaller instrumented volume than IceCube. Nevertheless, as it is located in the northern hemisphere, it has a larger sensitivity to muon neutrinos from the southern sky, in particular for energies below $\lesssim 100$ TeV where the background from muons generated in the atmosphere by cosmic-ray interactions is large. For energies above about 100 PeV, also the Pierre Auger Observatory [27] makes

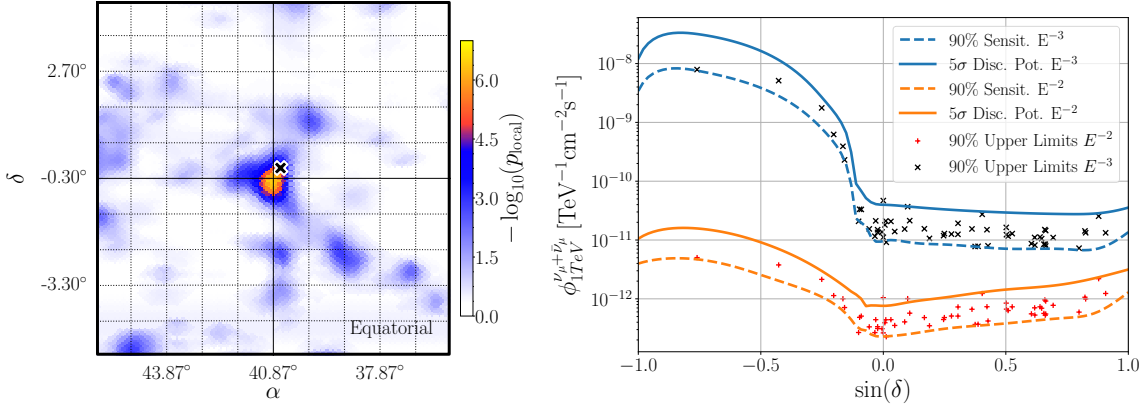


Figure 6: *Left:* Local pre-trial p-value map around the most significant point in the Northern hemisphere. The black cross marks the coordinates of the galaxy NGC 1068. *Right:* 90% C.L. mean sensitivity and 5σ discovery potential as a function of source declination for a neutrino source with an E^{-2} (orange) and E^{-3} (blue) spectrum. Also shown are the 90% upper-limits for a list of sources for an E^{-2} (red) and E^{-3} (black) source spectrum. Taken from [28].

important contributions (see Section 3).

An interesting new result on searches for point-like sources with the IceCube detector was presented by the authors of [28]. The analysis used ten years of data for an unbiased all-sky scan as well as source catalog searches. Though no statistically significant excess was found in either analysis (Fig. 6 right), the Seyfert II galaxy NGC 1068, also known as M77, in the northern catalog shows an intriguing 2.9σ excess after accounting for statistical trials (Fig. 6 left shows the local *pre-trial* value). The Fermi position of this source also coincides with the most significant fluctuation in the northern sky within 0.35° . The entire northern-sky source catalog provides a 3.3σ deviation from the background-only hypothesis with significant contributions from four sources including NGC 1068 and TXS 0506+056. Future data will show whether M77 turns out to be the first identified “steady” HE neutrino source.

As can be seen from Fig. 6 right, the sensitivity of IceCube to point-like sources decreases significantly for sources above the horizon due to the large background of atmospheric muons. On the other hand, for the ANTARES detector most of the southern sky is below the horizon. In conjunction with its smaller instrumented volume, its sensitivity to E^{-2} neutrino spectra turns out to be comparable to that of IceCube in this region as depicted in Fig. 7 left. Therefore, a combined analysis of data from ANTARES and IceCube, presented at ICRC by the authors of [29], leads to about a factor two improvement which demonstrates the high potential for combined analyses of data from different neutrino telescopes. The corresponding sensitivity plot for an $E^{-2.5}$ spectrum in Fig. 7 right emphasizes the importance of the ANTARES detector for sources with soft energy spectra in the southern hemisphere.

The success of the TXS 0506+056 multi-messenger campaign has underlined the importance of a fast and fully developed information-distribution infrastructure providing sufficient information for the evaluation of alerts by other instruments. At ICRC 2019, several talks discussed this aspect, and results obtained so far with IceCube ([30, 31, 32, 33]), ANTARES ([34, 35]), and the AMON [36] observatory network ([37]) were presented. Over the past years, we have seen

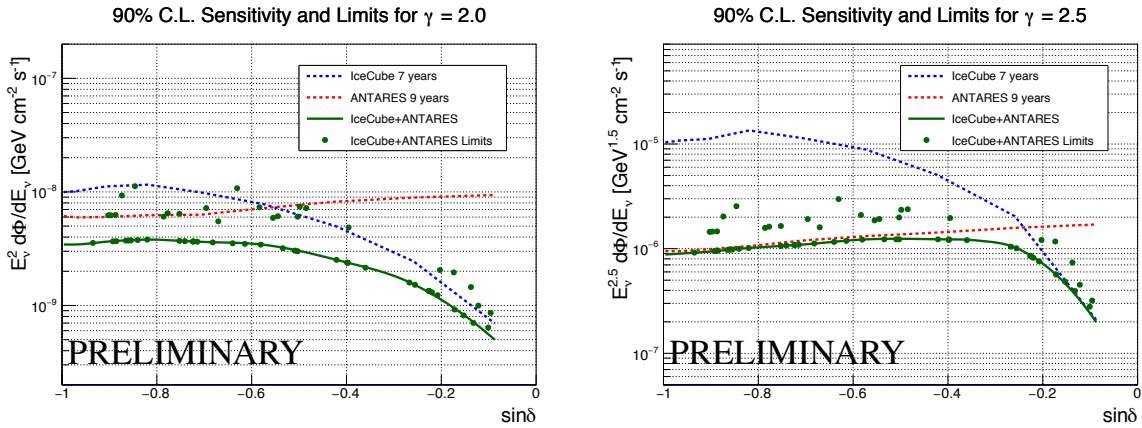


Figure 7: Upper 90% C.L. limits on the signal flux from analyzed candidates (green dots) using a combined ANTARES-IceCube analysis. An unbroken $E^{-\gamma}$ neutrino spectrum is assumed, with $\gamma = 2.0$ (left) and $\gamma = 2.5$ (right). The green line indicates the sensitivity of the combined analysis. The dashed curves indicate the sensitivities for the IceCube (blue) and ANTARES (red) individual analyses. Taken from [29].

significant progress in this area and recent examples show that there are no larger obstacles for coordinated multi-messenger campaigns anymore, while optimizations and extensions continuously improve the performance of the infrastructures.

2.4 New instrumentation

With the discovery of the very first HE neutrinos in 2013 with the IceCube detector a new era of astrophysics has been heralded and the past years have been an exiting time. However, we also had to learn that with the current instrumentation the impact of neutrino astronomy remains limited in particular with respect to diffuse fluxes and steady source emission. For the IceCube detector, the observable energy range for astrophysical HE neutrinos starts at few 10 TeV (below the flux is dominated by atmospheric background) and ends at about 10 PeV due to the steeply falling spectrum. In this energy range, the number of identifiable neutrinos with likely astrophysical origin is of order ten per year. Also, the sensitivity of a single detector is very different throughout the zenith range: best pointing is achieved with up-going charged-current muon neutrino events. However, above a few 10 TeV Earth starts to become opaque for neutrinos leaving only a small sensitivity band around the horizon at PeV energies. Analyses with down-going neutrinos, on the other hand, suffer from the large background of atmospheric muons when using track signatures and the reduced angular resolution of cascade signatures. Therefore, the full exploitation of neutrino astronomy requires larger detectors with similar sensitivity both in the northern and southern hemisphere.

Fortunately, these detectors are currently either already in the construction phase or are planned within the next ten years. Figure 8 shows the possible landscape of neutrino telescopes at the end of the next decade. In the northern hemisphere, the KM3NeT/ARCA detector [38], located in the Mediterranean Sea and successor to ANTARES (for KM3NeT/ORCA see Section 5), will provide an instrumented volume of about 1 km^3 , slightly larger than the current IceCube detector. At ICRC 2019, its status was discussed and first reconstructed atmospheric muon neutrino candidates were

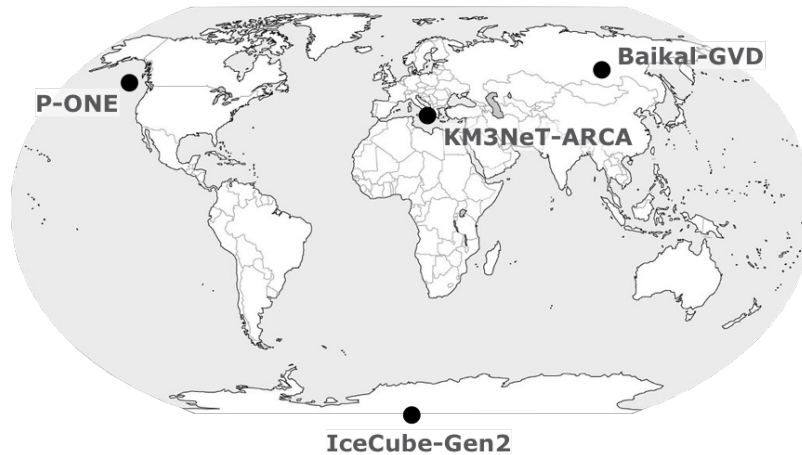


Figure 8: Projected neutrino telescope landscape for high-energy astrophysics in 2025–2030.

presented ([39]) using only two lines (detection units). Eventually, the detector will consist of 230 detection units which, for the first time, will provide sufficient sensitivity to detect the neutrino flux from bright Galactic point-like sources like RX J1713.7-3946 assuming a hadronic production scenario of the observed gamma rays [40] as shown in Fig. 9. Parallel to KM3NeT, the Baikal-GVD detector [41] located in Lake Baikal is under construction. The detector is divided into clusters of 8 strings, each string equipped with 36 optical sensors. Currently, five clusters have been installed and the plan is to have eight clusters deployed until 2021, instrumenting a volume of about 0.4 km^3 . In a next phase, the volume is planned to be increased to 1.5 km^3 . In a talk, the authors of [42] presented the status of this currently largest detector in the northern hemisphere and showed first track and cascade candidates of atmospheric neutrinos as well as first constraints on physics scenarios. A new project called P-ONE [43] plans to utilize the Ocean Networks Canada seafloor infrastructure to build a large-scale neutrino telescope in the northern Pacific. At ICRC, first results from a pathfinder mission, called STRAW, on the optical properties at Cascadia Basin were presented ([44]). In the southern hemisphere, the IceCube collaboration plans to extend the current IceCube detector with 120 additional strings instrumenting a volume of about 8 km^3 (IceCube-Gen2) [45]. In a first phase, dubbed IceCube Upgrade, the current detector will be extended in the Austral seasons 2022/23 by seven strings with horizontal and vertical module spacing of about 20 m and 3 m, respectively, as discussed in [46]. This significantly denser instrumentation compared to IceCube DeepCore will allow to perform precision oscillation physics and test the unitarity of the neutrino mixing matrix. The second main goal is the reduction of systematic uncertainties for the IceCube detector, in particular through a better understanding of the ice properties.

3. Ultra-high energy neutrinos

The great interest in UHE cosmic neutrinos was impressively demonstrated by a large number of talks and posters at ICRC, where many presentations dealt with ideas or pathfinder experiments for future detectors. In contrast to neutrino detectors in the TeV–PeV range, which all utilize the Cherenkov effect either in ice or water, a variety of detection techniques is used or has been suggested to detect UHE neutrinos. A lot of them are based on the detection of radio signals produced

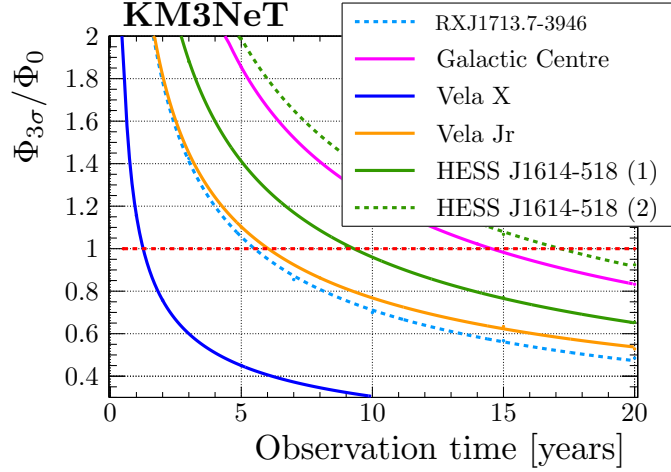


Figure 9: Ratio of the discovery potential at 3σ for KM3NeT/ARCA to the expected flux from selected Galactic sources as a function of the observation time. Taken from [40].

by neutrino-induced particle showers either in air or in ice. Radio signals have the advantage that they can be observed over long distances which allows to monitor large volumes with a moderate number of stations. In case of air showers, they also have the advantage that they can be observed at any time during the day and under any cloud condition. Detection thresholds (currently in the 100 PeV range), however, are much higher than for Cherenkov-based detectors in ice or water.

3.1 Diffuse flux limits and mystery events

Ultra high-energy neutrinos are expected to be produced via the interaction of UHE protons with the cosmic microwave background ($p + \gamma \rightarrow \pi^+ + n \rightarrow e^+ + \nu_e + n$) with a production threshold of $E_p \approx 6 \times 10^{19.6}$ eV. The resulting flux of these so-called cosmogenic neutrinos therefore heavily depends on the composition of UHE cosmic rays as protons in heavier nuclei carry only a fraction of the nucleus energy and the cosmic-ray flux decreases quickly with increasing energy (see Fig. 5 left). Figure 10 displays predictions of cosmogenic neutrino fluxes for different cosmic-ray compositions and source evolutions. With the energy density $E^2 \times \phi$ peaking around 10^{18} eV, currently, the most sensitive detectors for these neutrinos are the ice-Cherenkov based IceCube detector and the air-shower based Pierre-Auger Observatory. Both experiments exclude models with a light (proton) composition to a large extend, compatible with corresponding UHE cosmic-ray composition measurements from Pierre Auger [50]. However, already mixed models are largely unconstrained and heavy models predict an at least factor ten lower flux level.

Above 3×10^{19} eV, the ANITA radio balloon experiment places the strictest constraints. In [52] the authors presented at ICRC results from the third and fourth flight of the ANITA experiment over Antarctica between 2014 and 2016. While the observed candidate events are compatible with background, two events from the ANITA-I and ANITA-III flights, sometimes called “mystery events”, defy an easy explanation. Given their horizontal polarity they match the template for UHE cosmic rays where the radio signal directly reaches the detector. However, the two events clearly come from the Antarctic surface. This points to UHE cosmic tau neutrino candidates with interactions in the ice. The generated tau then emerges from the ice producing an air shower and

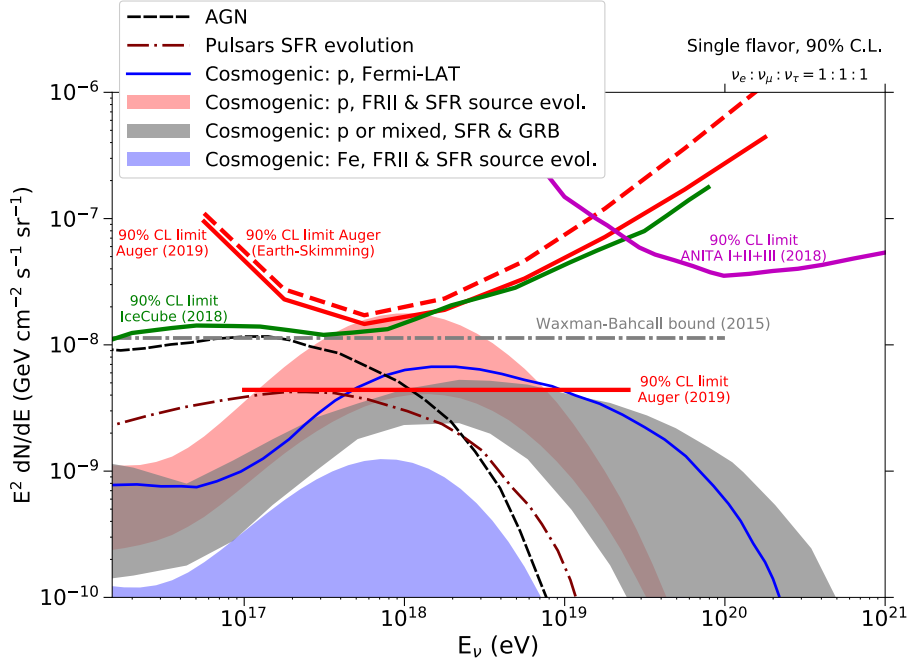


Figure 10: Pierre Auger Observatory upper limit (90% C.L.) to the normalization k of the diffuse flux of UHE neutrinos $\phi_\nu = kE_\nu^{-2}$ (solid straight red line). Also plotted are the upper limits to the normalization of the diffuse flux (differential limits) with a bin width of 0.5 in $\log_{10} E_\nu$ (solid red line - Auger all channels and flavors; dashed red line - Auger Earth-skimming ν_τ only). Similar limits from ANITA I+II+III [47] and IceCube [48] are displayed along with predictions for several neutrino models. All limits and fluxes are converted to a single flavor. Taken from [49].

thereby a radio signal with horizontal polarization. But also this explanation lacks plausibility as the chord length through the Earth is in tension with standard model cross sections. In addition, the tau neutrino flux implied by the observation of the ANITA-III event violates IceCube upper-flux limits as presented in [53] at ICRC. Figure 11 shows the observed ANITA event converted into an incident flux of (mono-energetic) EeV neutrinos (black dot). This primary flux would generate a secondary tau neutrino flux (magenta histogram) through tau-neutrino regeneration in the Earth. The non-observation of such a flux by IceCube (blue upper limit) translates into a corresponding upper limit of the incident flux (magenta point) which is more than two orders of magnitude lower than the flux implied by the ANITA-III event.

3.2 New instrumentation

From the discussion above it is apparent, that instruments with significantly enhanced sensitivities are required to discover UHE neutrinos and verify the cosmogenic production paradigm. A large variety of detection techniques has been suggested to reach this goal which can be categorized into those using in-ice showers and those utilizing air showers. The latter can be generated either by neutrinos interactions (deep) inside the Earth’s atmosphere or by neutrinos interacting shortly below the surface (or in nearby mountains) with the particle shower emerging into the air. The air showers produce radio as well as Cherenkov and fluorescence emission which can be used to detect

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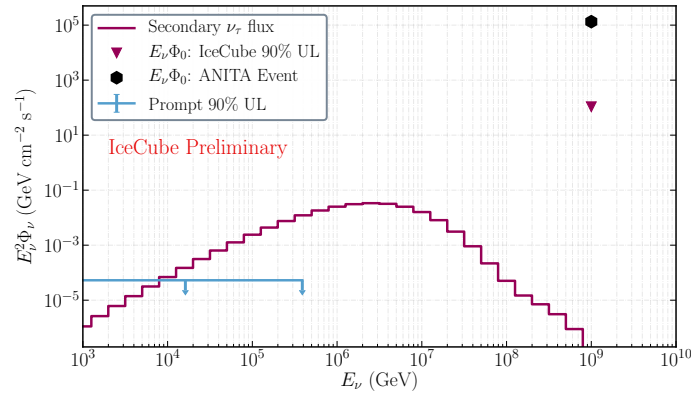


Figure 11: Upper limits (90% C.L.) placed by calculating the secondary neutrino flux (purple histogram) from an incident flux of EeV neutrinos (purple triangle) assuming constant emission over 10^3 s and comparing to the non-observation of IceCube events in the prompt analysis (blue). The flux implied by the ANITA observations is shown in black. Taken from [51].

and reconstruct the direction and energy of the primary neutrino. Figure 12 provides an overview of sensitivities of current and proposed detectors.

Two in-ice instruments for the detection of radio signals from neutrino interactions in the ice of Antarctica (ARA, ARIANNA) have been running since several years and presented results, status and plans at ICRC. Both leverage the order 1 km long attenuation length of radio signals in cold ice. The ARA detector, located at South Pole, currently consists of five stations buried at up to 200 m depth [54]. Each station is composed of four strings, with each string holding two vertically and two horizontally polarized antennas. Recently, a phased array (beam-forming) of ten antennas was installed in one of the stations which allows to lower the per-station trigger threshold thereby increasing its trigger-level effective volume. The ARIANNA detector [55] is located at the Moore’s Bay site on the Ross Ice Shelf and currently consists of seven detector stations each containing a set of four LPDA antennas. These are installed just below the snow surface and point downward into the ice shelf using the ice/seawater boundary as efficient mirror for radio signals, thereby increasing the effective detector volume. With their demonstrator arrays, both collaborations have shown the feasibility of these type of detectors and set upper limits on the diffuse flux of UHE neutrinos. These, however, are still well above flux predictions even for optimistic scenarios. Therefore, plans for a large-scale radio array, RNO, in Antarctica are underway. In [56] the authors presented the plans for this detector which foresee the instrumentation of about 100 km^2 of ice at the South Pole both with shallow and deep stations. A pathfinder array in Greenland is supposed to start construction in 2020.

While ANITA plans to perform further flights with an improved detector [52], new detectors have been suggested to detect up-going showers from tau neutrino. In [59] the authors presented the TAROGE concept, a radio array to be installed on a high mountain in Antarctica. The detection concept follows ANITA, but with its permanent installation features greater livetime and expandability. As a first step, a prototype station consisting of five LPDA antennas was installed atop Mt. Melbourne in Antarctica in February 2019. In a first measurement campaign, data for a RF survey was successfully recorded which is important for evaluation of the suitability of the site. For a

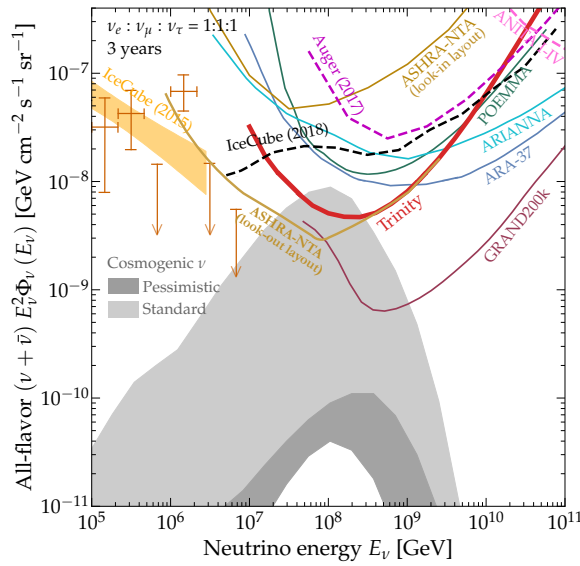


Figure 12: Upper limits on the UHE neutrino flux from running experiments and sensitivities of proposed experiments after three years of data taking. For references to corresponding contributions at ICRC 2019 see main text. Adapted from [57]: ASHRA-NTA (lookout-layout) taken from [58].

detector with ten stations and three years of operation, simulations predict an exposure roughly five times that of ANITA-I,III. The BEACON concept study presented in [60] also intends to install radio receivers on a mountain to look for up-going tau neutrinos above 100 PeV. In order to improve sensitivity, signals from several antennas will be coherently summed (beam-forming) which allows to mask anthropogenic background from known directions and to lower the energy threshold. Simulations show that with 100 stations up to order ten tau neutrinos could be detected for certain flux models. With the planned installation of up to 200,000 antennas, the GRAND concept [61] is on a much larger scale. The antennas would be grouped into sub-arrays of 10,000 units spread over 10,000 km² each at different sites in China. At ICRC, the authors of [62] presented a first stage of this detector, GRANDProto300 (PGP300). It will consist of about 300 antennas distributed over 200 km² which are supposed to be deployed between 2020 and 2021 at an altitude of 3000 m at the rim of the Tibetan plateau. The main goal of GP300 is to demonstrate the viability of the GRAND detection concepts but it will also be sensitive e.g. to air shower physics and the transition from Galactic to extra-galactic cosmic rays [62].

At ICRC, also several experiments have been suggested to use Cherenkov and fluorescence light generated by neutrino induced air showers instead of radio signals to search for UHE earth-skimming cosmic tau neutrinos. Based on proven technologies from gamma-ray and UHE cosmic rays air-shower imaging experiments, the authors of [63] proposed the Trinity detector which would be located on a mountain site and observe the horizon for tau neutrino signatures. Its sensitivity after three years of observation time would reach into the region of current flux predictions. In [64] the authors report about results from the Ashra-I experiment located on Mauna Loa, Hawaii. Due to the utilization of electronic lenses in addition to an optical system, it features a large field-of-view of 42° diameter together with arcminute angular resolution. Compared to Auger, the sensitivity of Ashra-I is still limited and consequently no neutrino has been found up to now. An extension

called Ashra-NTA, however, consisting of four stations located on Mauna Loa, would start to probe current flux predictions after three years of observation time as shown in [58]. Finally, the authors of [65] proposed to use the POEMMA satellite detector in a target-of-opportunity mode to search for cosmic neutrinos above 20 PeV from transient sources.

An interesting new idea for the detection of UHE neutrinos was proposed by the authors of [66]. In an experiment set up at SLAC, they directed an electron beam into a plastic target to simulate a 10^{19} eV neutrino-induced shower in ice. This shower was probed with RF radiation and they were able to record a signal from the radar-like reflection off the ionization in the particle shower. Compared to detection of radiation produced by the shower itself as used in ARA and AR-IANNA, the authors argue that the reflected waves are detectable at a much wider range of angles, thereby largely increasing the aperture. Furthermore, the signal amplitude could be increased by providing higher transmitter power, which might allow to approach energy threshold close to the IceCube energy range. How this method can be implemented in a real neutrino detector still has to be evaluated, though.

4. MeV neutrinos from core-collapse supernovae and the Sun

Though having comparatively low energies, MeV neutrinos play a decisive role in understanding key objects in the universe: core-collapse supernovae and our central star, the Sun. In particular, with today's instrumental capabilities the observation of MeV neutrinos from a core-collapse supernova would provide a wealth of information on this central process of the life of a massive star which is of great importance e.g. for the generation of heavy elements. Neutrino emission from a core-collapse supernova lasts about 10 s and the first and also last time neutrinos (all together about two dozens) from such an event were detected was from SN1987A (see e.g. [67] and references therein). This is because up to now detectors have been limited to supernovae in our Galaxy where the rate is only about two per century. On the other hand, there exists a diffuse flux of MeV neutrinos from past supernovae throughout the universe (DSNB: diffuse supernova neutrino background) which provides a continuous signal.

The Super-Kamiokande (SuperK) detector [68] located in Japan is one of the central instruments in this field. It consists of a large tank of ultra-pure water with the inner walls covered with photomultipliers which detect the Cherenkov light from neutrino interactions. Apart from staying alert for Galactic supernovae, the detection of the DSNB is a prime physics goal. Up to now, searches were not successful due to so far irreducible background as presented at ICRC in [69]. Key for the reduction of this background is the detection of neutrons from the inverse beta decay reaction of the DSNB neutrinos in the detector. This can be achieved with the addition of Gadolinium to the water which has a very high neutron capture rate and emits a gamma-ray cascade with a total energy of about 8 MeV which can be detected with high efficiency. Refurbishment of the detector was completed in early 2019 and data taking can hopefully start soon.

Though IceCube can reconstruct individual neutrinos only above an energy of about 10 GeV due to its sparse instrumentation, MeV neutrinos from a Galactic supernova can be detected via the collective rise of the noise rate in its 5160 optical sensors. In particular, IceCube can measure the time evolution of the neutrino rate from supernovae in the inner part of our Galaxy with high

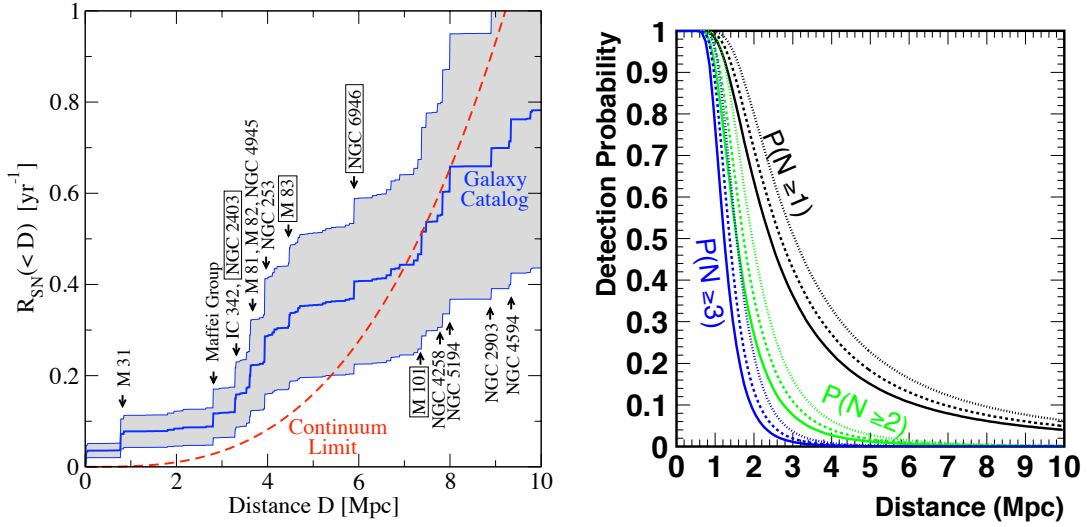


Figure 13: *Left:* Number of expected supernovae in our local Universe within a certain radius. *Right:* Detection probability for supernova neutrinos as a function of distance for Hyper-Kamiokande for different minimum number of detected events. Line styles represent no oscillation (solid), normal ordering (dotted), and inverted ordering (dashed) cases. Both plots taken from [71].

statistical precision as presented in [70] and has an up-time close to 100% which is important as supernovae can occur without warning at any time.

In order to observe supernovae on an even approximately annual basis, the reach of detectors has to be significantly increased to several Mpc as can be seen in Fig. 13 left. The Hyper-Kamiokande (HyperK) detector [72] is a next-generation water Cherenkov detector which will begin construction in 2020 with data taking expected to start in 2027. The working principle is the same as for SuperK but its fiducial volume of 187 ktons will be more than eight times higher than that of SuperK. In [73], the authors reported about status and prospects for HyperK at ICRC, whereas the presentation in [71] focused on supernova neutrinos: HyperK will be able to obtain detailed event-by-event information for a large number of neutrinos from a Galactic supernova and will extend the reach for supernova detection to neighboring galaxies as depicted in Fig. 13 right. It will also have the potential to make a precision measurement of the DSNB. Furthermore, as shown in [74], it will enable high precision measurements of solar neutrino oscillation parameters and to perform first measurements of the hep neutrino process which will provide direct information on the energy processes in the Sun’s core.

5. Neutrino physics

Though the main target of neutrino telescopes is neutrino astronomy, they have proven to be also excellent tools to investigate fundamental neutrino properties using oscillations of atmospheric neutrinos (see for example [75] and [76]). Therefore, dedicated detectors with reduced sensor spacing are now being built both in the Mediterranean Sea (KM3NeT/ORCA) and the Antarctic ice sheet (IceCube Upgrade) which will further enhance these capabilities. The neutrino sector is presently one of the most interesting sectors of the standard model with many unresolved questions.

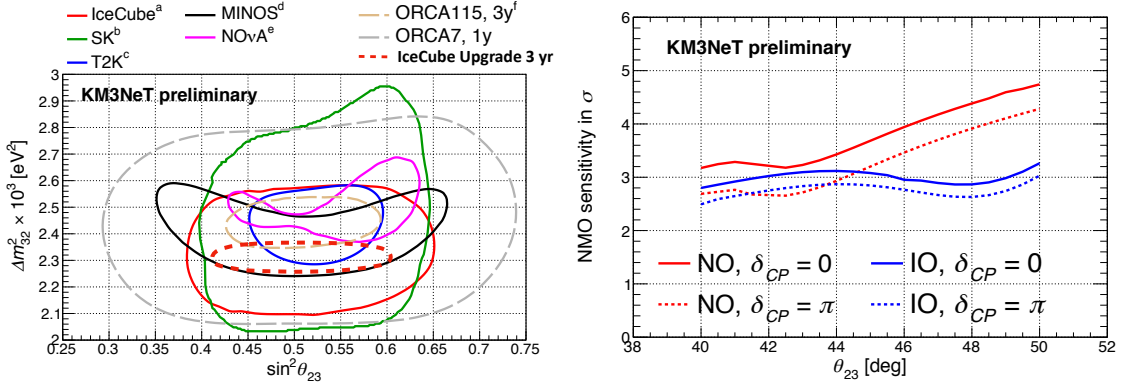


Figure 14: *Left:* 90% confidence level contours in $(\Delta m_{32}^2, \sin^2 \theta_{23})$ plane for various detectors (for references see [77]) ORCA7 denotes the sensitivity for a detector with seven lines and ORCA115 for the full detector with 115 lines. *Right:* Sensitivity to the neutrino mass ordering (NO: normal ordering, IO: inverted ordering) of the full KM3NeT/ORCA detector after 3 years of data taking for different values of the CP phase δ_{CP} . Both plots taken from [77]. Left plot complemented with *IceCube Upgrade 3 yr* contour taken from [78].

Apart from the possible existence of sterile neutrinos and the unknown nature of neutrino masses, even fundamental properties like the absolute neutrino mass scale and the ordering of neutrino masses are unknown.

At ICRC, the authors of [77] presented the status of KM3NeT/ORCA, currently under construction off the coast of southern France, and showed its expected sensitivity to neutrino mass ordering and atmospheric neutrino oscillation parameters. Figure 14 left shows the confidence level contour from current IceCube analyses and the predicted sensitivity of KM3NeT/ORCA to atmospheric oscillation parameters in comparison to other experiments, demonstrating the important role of neutrino telescopes in this field. The full KM3NeT/ORCA detector will also be able to measure the neutrino mass ordering with a significance of $\sim 3\sigma$ or better after three years of data taking as depicted in Fig. 14 right. Furthermore, the IceCube Upgrade [46], to be installed in the 2022/23 season, will significantly enhance IceCube’s sensitivity in neutrino physics as presented in [78] and displayed in Fig. 14 left with respect to oscillation parameters. In particular, this extension will allow IceCube to obtain a tau neutrino normalization measurement with an uncertainty better than 10%, thereby testing the unitarity of the neutrino mixing matrix with unprecedented precision. In combination with JUNO, the IceCube Upgrade will also be sensitive to the mass ordering at the $> 3\sigma$ level after two years of data taking of each experiment [79].

Another interesting property, which becomes accessible with large-scale neutrino telescopes, is the neutrino cross section at TeV–PeV energies where physics beyond the standard model could lead to an alteration of the cross-section. Previous measurements at accelerators were limited to less than 1 TeV. With the Earth as interaction target, the authors of [80] presented at ICRC an improved measurements of the all-flavor neutrino cross-section with the IceCube detector in the energy range between 60 TeV and 10 PeV. They found that the measurement agrees well with the standard model prediction though the uncertainties are still large.

6. Conclusions

Two years after the first likely association of a high-energy neutrino with a source (AGN TXS 0506+056) in a multi-messenger campaign and subsequent finding of an neutrino flare in archival IceCube data, the astrophysics community is still struggling to form a consistent global picture from the observations. Simple one-zone production models don't seem to explain the multi-messenger data whereas multi-zone models are not yet sufficiently constrained to allow for conclusions. Nevertheless, blazars are increasingly seen as prime sites for high-energy neutrino production, with high-luminosity blazars appearing to be efficient neutrino emitters but inefficient production sites for ultra-high energy cosmic rays. The TXS 0506+056 event has also demonstrated the prime importance of a smoothly working infrastructure for multi-messenger campaigns to identify and understand the sources of the cosmic rays, and a lot of work has went into this area.

Six years after the first observation of high-energy cosmic neutrinos, spectrum and flavor composition of the neutrino flux is measured with increasing accuracy. In particular, tau-electron degeneracy starts to get broken with the identification of two tau neutrino candidates in IceCube data which lead to the first best-fit non-zero tau fraction. The number of observed high-energy neutrinos between 100 TeV and 10 PeV, however, remains limited so that, despite indications for varying spectral indices between IceCube analyses, no significant deviation from a simple power law can be derived yet. From the phenomenological side, so-called cosmic reservoir models could explain the observation that roughly equal energy density is found in gamma rays, high-energy neutrinos and ultra-high energy cosmic rays. As these models a.o. predict a break around PeV energies in the neutrino spectrum, they should be testable with future detector like IceCube-Gen2 or an extended KM3NeT detector.

From the discussion above it becomes clear that, despite breakthroughs and significant progress in the past years, new neutrino detectors with increased sensitivity are required to answer the open questions. This not only holds for the TeV to PeV energy range but in particular also for the ultra-high energy range between 100 PeV and EeV, where up to now only upper limits have been obtained. At TeV to PeV energies, several cubic-kilometer scale neutrino telescopes are either under construction (KM3NeT, Baikal-GVD) or in the planning phase (IceCube-Gen2, P-ONE). With the completion of KM3NeT and Baikal-GVD in the first half of the next decade, we will for the first time have cubic-kilometer scale detectors both in the northern and southern hemisphere, providing full-sky coverage in all observation channels and many possibilities for combined analyses. But neutrino telescopes have turned out to be also excellent tools for the investigation of fundamental neutrino properties like oscillation parameters, neutrino mass ordering and neutrino-related physics beyond the standard model (e.g. sterile neutrinos, non-standard cross-sections). This has lead to the current construction of dedicated detectors (KM3NeT/ORCA, IceCube Upgrade) which are optimized for GeV energies. In the ultra-high energy range, the most optimistic models for cosmogenic neutrinos from the interaction of ultra-high energy cosmic rays with the micro-wave background have been ruled out by observations from the Pierre Auger Observatory and IceCube. In order to increase the sensitivity by a factor ten, required to probe also models for a heavier cosmic-ray composition, several new detectors are being proposed which use either radio, Cherenkov or scintillation light emitted by neutrino induced particle showers in ice or in air.

Though the main focus at ICRC was on high-energy neutrinos, MeV neutrinos will quickly

shift into prime focus once a core-collapse supernova explodes in our Galaxy or detectors reach a sensitivity to observe the diffuse supernova neutrino background. For Galactic supernova, Super-Kamiokande and IceCube together with other detectors are well prepared to deliver high-precision data that will allow to test our understanding of these massive explosions to unprecedented levels and will probably lead to a wealth of new insights. A close to 100% live-time is of utmost importance here, as MeV neutrinos from supernovae will reach Earth without warning. The successor to Super-Kamiokande, Hyper-Kamiokande (data taking planned to start 2027), will then also have the potential to make a precision measurement of the diffuse supernova neutrino background and might be sensitive to supernovae in neighboring galaxies.

For neutrinos, ICRC 2019 has been highly interesting. We have seen much progress but as usual also many open questions of which a few can hopefully be answered at the next ICRC in 2021. The hunt for and understanding of cosmic neutrino continuous and remains exciting.

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