Status and Future of Neutrino Astronomy and the Global Neutrino Network

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Abstract. Attempts to build neutrino telescopes at the cubic kilometre scale date back to the 1970s. It took until 2010 when the first detector of this size, IceCube, started data taking. In 2013, IceCube has detected a diffuse flux of cosmic neutrinos, and in 2017 first evidence for an individual source has been obtained. In-depth exploration of the landscape of the high-energy neutrino universe requires even larger detectors, and it requires detectors on both hemispheres of the Earth. Two devices on the Northern hemisphere are currently under construction and started data taking with initial configurations. Further progress in the field calls for global coordination. The instrument to achieve worldwide cooperation and coordination is the Global Neutrino Network, GNN. This review includes a sketch of goals and achievements of GNN.

1. A fifty-year voyage

First ideas to build large neutrino detectors underground or underwater date back to the late 1950s. It took half a century from the first proposal to build big underwater telescopes [1] to the discovery of cosmic neutrinos with the IceCube detector at the South Pole [2]. This voyage, with many of its ups and downs, is described in much detail in [3,4] where also references to landmark publications of the voyage can be found.

Pioneering efforts to install a deep underwater detector in the Pacific Ocean close to Hawaii started in the 1970s. This project, named DUMAND, was regrettablly terminated in 1995. Instead, the worldwide first underwater telescope was installed in Lake Baikal. Its geometrical volume was not much larger than twice the Super-Kamiokande volume, but anyway it delivered a first proof of principle for the underwater method. The Baikal detector comprised 196 (i.e. close to 200) Optical Modules and was christened NT200. Soon it was bypassed by AMANDA, installed in Antarctic ice, and completed in 2000. With ~0.02 cubic kilometers the geometrical volume of AMANDA was ten times larger than that of NT200 but still a factor 50 below the volume which already the original DUMAND proposal from 1978 had considered.

Next in the game was ANTARES, some kilometers off Toulon in the Mediterranean Sea. It was completed in 2008 and is still taking data. Its size is almost the same as that of the meanwhile terminated AMANDA. Both AMANDA and ANTARES have measured the spectrum of atmospheric neutrinos up to ~100 TeV but did not find any excess at high energies, as it is expected from a flux of cosmic neutrinos. This, eventually, was achieved with IceCube, AMANDA’s successor, which reached the cubic kilometer scale. Actually its geometrical volume is just 1 km³. It comprises 5160 Optical Modules (OMs) housing 10-inch photomultipliers.
IceCube was completed in December 2010. In 2012, two cascade-like events with about one PeV energy were detected which could hardly be interpreted as being of atmospheric origin (significance 2.8σ). A more sophisticated analysis (called HESE, for High Energy Starting Events) revealed a significant excess which – with more data – stepwise increased from 4.1σ (first 2 years of data) to almost 10σ. The first HESE analysis was published in 2013 [2] and is considered the discovery of high-energy cosmic neutrinos.

2. The past decade: becoming global

Soon after the first HESE results, a second IceCube analysis looked to muon tracks crossing the detector from below and also found a significant excess at higher energies [5]. Interestingly, the spectrum of through-going muons seemed to be a bit harder than that derived from HESE events: the spectral indices are about -2.3 (track events) and -2.8 (HESE events). Although the two indices may still be considered compatible within errors, the effect raises questions: Is the difference – if real – due to a change of the spectral slope (the two analyses prefer slightly different energy regions, the HESE events a lower one than the muon-track analysis)? Or is it a systematic effect due to the reconstruction in a highly light-scattering and layered medium like Antarctic ice? It is obvious that this problem calls for an independent detector of similar size but with different systematics.

ANTARES could also identify an excess of neutrino events at highest energies, although with a much lower significance (1.8σ) than IceCube [6]. Within errors, size and slope are compatible with the IceCube results, see figure 1.

Figure 1. Corridors for the spectra of cosmic neutrinos as derived from the IceCube HESE analysis (blue), the IceCube analysis of upward going muons (green) and cascades and muons in ANTARES (red). The dashed line indicates the spectrum of atmospheric muons and the red line a $E^{-2}$ spectrum of cosmic neutrinos with a high-energy cut-off. Figure taken from [7].

Different systematics is one aspect which calls for cross checks and a global effort. The other is the request for full-sky coverage. With upgoing muon tracks IceCube can “see” only neutrinos from the Northern hemisphere. It is only at highest energies that this view can be extended to the Southern side,
due to the following argument: Downward muon tracks are dominated by muons from cosmic air showers (“atmospheric muons”) which punch down to the detector. Their spectrum behaves as $E^{-3.7}$. Therefore, the high-energy tail of muons generated in interactions of cosmic neutrinos (supposed to behave as $E^{-2.0}$ to $E^{-2.3}$) has a chance to be separable against the background of atmospheric muons. Due to that, IceCube data can improve the sensitivity of ANTARES at the Southern sky. Figure 2 illustrates the effect of combining data from both detectors, with the goal to search for point sources of cosmic neutrinos at the Southern hemisphere [8]. It demonstrates that for a hard spectrum the effect of adding IceCube to ANTARES data can yield a factor of up to two even at IceCube’s “wrong” hemisphere.

**Figure 2.** Results of a combined ANTARES-IceCube search for point sources. Top: 90% C.L. upper limits on the one-flavor neutrino flux normalization candidates (green dots) as a function of the source declination, assuming an unbroken $E^{-\gamma}$ neutrino spectrum, with $\gamma = 2.0$ (a) and $\gamma = 2.5$ (b). Green line: sensitivity of the combined analysis. Dashed curves: sensitivities for the IceCube (blue) and ANTARES (red) individual analyses. Bottom: ratio between the best individual sensitivity and the combined sensitivity as a function of the source declination for the spectral indices $\gamma = 2.0$ (a) and $\gamma = 2.5$ (b). Figure taken from [8].

Similar combined analyses between ANTARES and IceCube have also been performed for galactic diffuse emission and galactic dark matter.

An umbrella for these data combinations has been created by the Global Neutrino Network, GNN. It was founded in 2013 and includes the collaborations ANTARES, Baikal, IceCube and KM3NeT. Its main goals are the following:

- Shaping a global community in high-energy neutrino astronomy
- Develop a common strategy for devices complementing each other
- Increase the sensitivity by combining data from different experiments
- Cross-check results with different systematics
- Cooperate in multi-messenger campaigns and alert strategies
- Exchange knowledge, software, methods and people
- Organize topical workshops (external and internal, both biannual)
• Edit a monthly (internal) newsletter “GNN Monthly”

Successful work is done along all of these directions. The newsletter GNN Monthly has become a particularly successful instrument for community shaping.

3. Where do we go?
Much has been achieved in the recent decade:

• With the discovery of a diffuse flux of cosmic neutrinos, IceCube has opened the window of high-energy neutrino astrophysics. However, the landscape is not yet charted: no steady point sources have yet been identified. Also, there remain uncertainties about spectrum and flavor composition of the diffuse flux.
• With the blazar TXS 0506+056, a first candidate for a variable source of high-energy neutrinos has been identified [9].
• Several source classes (gamma-loud blazars, Gamma Ray Bursts, Flat Spectrum Radio Quasars and others) have been excluded as sole sources of the observed diffuse flux.
• The flux from several individual sources seems to be in reach, provided the observed gamma rays from these sources are dominantly of hadronic origin.
• There are good reasons to assume that with several cubic kilometers of instrumented volume, the high-energy neutrino landscape can indeed be explored [10]. Detectors at the Northern hemisphere have an optimal view to the central parts of our Galaxy which gives them a particular role in this exploration.

Until recently, there was one km³-scale detector at the South (IceCube) and one substantially smaller detector in the North (ANTARES). The first-generation Baikal detector NT200 has terminated data taking almost decade ago. This situation is going to be changed now: two Northern km³-scale detectors are presently under construction.

The one is called KM3NeT [11]. It is being deployed at two sites. The one site is 100 km offshore Capo Passero in Sicily and will host KM3NeT-ARCA. This detector is conceived to consist of two blocks of about 0.6 km³ volume each and will focus to astrophysics questions (ARCA stands for Astroparticle Research with Cosmics in the Abyss). The second site is 40 km offshore Toulon in France and named ORCA (Oscillation Research with Cosmics in the Abyss).

One KM3NeT block will consist of 115 strings each carrying 18 OMs. Each OM houses 31 small-size photomultipliers. The difference between ARCA and ORCA is the vertical and horizontal spacing. ARCA with its large spacing will focus to high-energy events. ORCA with a four to five times smaller spacing will study neutrino oscillations. With six strings perfectly operating over more than six months, ORCA has successfully validated its approach and is now planned to be completed in 2024. ARCA is a bit behind and envisages completion in 2026.

The other detector is named Baikal-GVD (GVD stands for Gigaton Volume Detector). It is being installed in Lake Baikal, Siberia, and is configured from independent clusters [12,13]. Half of the detector, with a total of 2016 OMs in 7 clusters, has already been deployed. The final configuration is planned to be completed in 2024, with 4320 OMs in 15 clusters.

In the very recent years, another initiative named P-ONE has emerged. It envisages a cubic kilometer scale detector off the Canadian Pacific coast [14]. This project is currently in the R&D phase. If realized, it could add observation power on the Northern hemisphere.

The volumes of these two (or three) detectors at the Northern hemisphere could add up to 3-5 km³. While KM3NeT and Baikal-GVD are being built, the IceCube collaboration envisages a further step forward: IceCube-Gen2 [10]. This detector is conceived to consist of a ~8 km³ optical array (containing the existing IceCube detector as a densely instrumented part) and a huge radio array. Figure 3 sketches the configuration.
The radio array covers the energy region from 10 PeV to more than 10 EeV, the enlarged optical array focuses to the region 10 TeV – 50 PeV and the existing IceCube to the region 100 GeV – 5 PeV. Seven new strings will be placed across IceCube’s high density region DeepCore and extend its sensitivity to below 10 GeV. This will allow even better oscillation studies than with DeepCore alone.

Figure 3. Top view of the envisioned IceCube-Gen2 Neutrino Observatory facility. Left: The radio array consisting of 200 stations. Second from left: IceCube-Gen2 strings in the optical high-energy array. 120 new strings (shown as orange points) are spaced 240 m apart and instrumented with 80 optical modules (mDOMs) each, over a vertical length of 1.25 km. The total instrumented volume in this design is 7.9 times larger than the current IceCube detector array (blue points and third from left). Right: the layout for the seven IceCube Upgrade strings relative to existing IceCube strings. Figure taken from [10].

Compared to IceCube, IceCube-Gen2 will increase the neutrino effective area by almost a factor ten. For burst-like phenomena, the volume of the observable universe will increase by a factor ten at 100 TeV to about hundred at 100 PeV (the latter due to the radio array). IceCube-Gen2 will be able to measure the spectrum of cosmic neutrinos with much more statistics and extend it into the region above 100 PeV.

The conclusions for status and future of the field can be summarized as follows:
- The high-energy neutrino window to the Universe is opened.
- Neutrino astronomy is an extremely dynamical field.
- The Global Neutrino Network aims to ensure worldwide coherence and cooperation.
- The next decade will see two detectors on the cubic-kilometer scale in the North: Baikal-GVD and KM3NeT-ARCA, and possibly even a third one (P-ONE).
- Construction of IceCube-Gen2 with 10 km³ optical detector volume will start mid 2020s and will hopefully be completed in the early 2030s.
- Mid 2020s and later, the landscape of neutrino sources will hopefully be filled with more and more entries, eventually answering the question about the origin of cosmic rays.

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