High-Energy Neutrino Astronomy: Where do we stand, where do we go?

Christian Spiering

DESY, Zeuthen, Germany; christian.spiering@desy.de

Abstract First ideas for doing neutrino astronomy with deep-underwater detectors date back to 1960, first attempts to build such a neutrino telescope to the year 1973. It took, however, further 40 years before extraterrestrial neutrinos could be identified with the IceCube neutrino telescope in the deep Antarctic glacier. This is a real breakthrough – the opening of a new window to the Universe. The present article sketches the long path towards that discovery and summarizes the present experimental results and our present understanding of them. Much is still to be done before we can say that we have "charted the landscape of high-energy neutrinos", and I will discuss the roadmap towards that goal.

Keywords: neutrino astronomy, cosmic rays, extraterrestrial neutrinos, multi-messenger astronomy

1. History

The march towards underwater neutrino telescopes started forty years ago at the 1973 International Cosmic Ray Conference. There, a few physicists from the USA, Japan and Russia discussed for the first time building such a device: the Deep Underwater Muon and Neutrino Detector (DUMAND). Actually, the idea for detecting the Cherenkov light of charged particles deep underwater had already been raised 13 years earlier by Moisej Markov [1]. The original DUMAND design from 1978 envisaged an array of about 20,000 photomultipliers (PMs) spread over a 1.26 cubic kilometer volume. Due to technical and financial reasons the project was terminated in 1995 [2].

Starting in 1981, Russian physicists explored Lake Baikal as the site for a "Russian DUMAND". In 1995 the first two (atmospheric) neutrino candidates were separated from the 1994 data, taken with the 3 strings deployed at that time. NT200, with 8 strings and 196 PMs was completed in April 1998 and has been taking data since then.

In 1988, F. Halzen and J. Learned proposed to deploy a neutrino telescope in deep Polar ice. This marked the starting point for AMANDA (Antarctic Muon And Neutrino Detection Array). The array was completed in January 2000 and eventually comprised 19 strings with a total of 677 PMs, directly at the geographical South Pole. AMANDA has been switched off in April 2009, after 9 years of data taking in its full configuration. It provided 6595 atmospheric neutrinos, several important upper limits, but no clear indication of any extraterrestrial neutrino signal.

Several projects have been pursued in the Mediterranean Sea, but only one made it to a working neutrino telescope: the ANTARES neutrino telescope, consisting of 12 strings, each carrying 25 PM-triplets. With a geometrical volume of 0.01 km³ it has almost the same size as AMANDA had. ANTARES was constructed in 2002-2008. It has convincingly demonstrated that a detector with precise angular resolution can be reliably operated in the deep sea.

The breakthrough, however, came only with IceCube. This detector consists of 5160 digital optical modules (DOMs) installed on 86 strings at depths of 1450 to 2450 m. A string carries 60 DOMs. The decommissioned AMANDA was replaced by DeepCore, a high-density sub-array of eight strings at the center of IceCube. DeepCore has smaller spacing and more sensitive PMs than IceCube and sits in the clearest ice layers. This results in a threshold of about 10 GeV and opened a new venue for oscillation physics. The first IceCube string was deployed in January 2005, the last at Dec. 18, 2010: finally, the idea of a cubic-kilometer detector became reality!

2. Detection Principles

Neutrino telescopes are large-volume arrays of "optical modules" (OMs) installed in open transparent media like water or ice, at depths that completely block the daylight. The OMs record the Cherenkov light induced by charged secondary particles produced in reactions of high-energy neutrinos in or around the instrumented volume. The neutrino energy and direction can be reconstructed from the hit pattern recorded

In detecting cosmic neutrinos, three sources of backgrounds have to be considered: (i) *atmospheric neutrinos* from cosmic-ray interactions in the atmosphere, which can be separated from cosmic neutrinos only on a statistical basis; (ii) down-going punch-through *atmospheric muons* from cosmic-ray interactions, which are suppressed by several orders of magnitude with respect to the ground level due to the large detector depths. They can be further reduced by selecting upward-going or high-energy muons or by self-veto methods sensitive to the muon entering the detector; (iii) *random backgrounds* due to photomultiplier (PMT) dark counts, ^{40}K decays (mainly in sea water) or bioluminescence (only water), which impact adversely on event recognition and reconstruction [3].

Typical event topologies in underwater/ice neutrino telescopes include *a)* tracks of muons, either generated in neutrino interactions or in air showers above the detector and *b)* contained particle cascades induced by charged or neutral current interactions of neutrinos in the geometrical volume [3]. Extraterrestrial neutrinos can be distinguished from atmospheric neutrinos by *1)* their harder spectrum (i.e. an excess at higher energies), by *2)* showing a local excess at the sky map or by *3)* coinciding locally and timely with a transient event (flare, burst) observed in electromagnetic radiation (in future also gravitational radiation!).

3. Where do we stand?

In this section, I will summarize the most important findings from searches for diffuse fluxes (*1*), for point source searches (*2*) and for transient sources (*3*).

3.1. Diffuse extraterrestrial fluxes

Atmospheric neutrino fluxes have been precisely measured with AMANDA, ANTARES and IceCube. The results are in agreement with predicted spectra – with the exception of IceCube data, which extend to energies where extraterrestrial neutrinos start dominating over atmospheric neutrinos.

The discovery of extraterrestrial neutrinos in IceCube was heralded by two cascade-like events each with about 1PeV energy, dubbed *Ernie* and *Bert* [4]. They were found in data taken in 2010 and 2011. The two events represented a – still moderate – 2.8σ excess over the expectation for atmospheric neutrinos. The sheer energy, however, made them more promising candidates for cosmic neutrinos than anything found earlier. Figure 1 shows the two events.

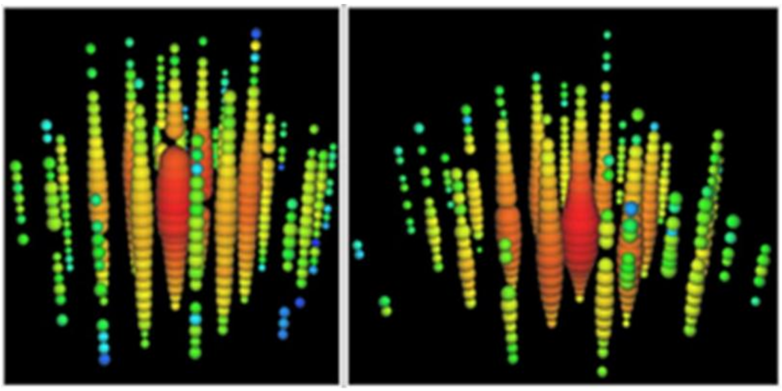

Fig1. *The first two PeV events detected in IceCube. Left "Bert" (1.04 PeV), right "Ernie" (1.14 PeV). The colored spheres mark hit optical modules. Their size is proportional to the logarithm of the amount of detected light, the color indicates the time (red: early, blue: late). The diameter of the light field is more than half a kilometer, while the particle cascade itself has a cigar form with ~20 m length and ~30 cm diameter.*

Motivated by this result, an alternative analysis of the same data was performed. It constrained the event to start in the inner volume of IceCube (using the outer part as veto layer), and at the same time considerably lowered the threshold compared to the first analysis, from 0.5 PeV down to 30 TeV (HESE analysis, for High Energy Starting Event). It provided 28 events, with the energies deposited in the detector ranging from ~ 30 TeV to 1.14 PeV and a significance of 4.1σ [5]. Meanwhile four years of data have been fully analyzed, resulting in 54 events, one of them a cascade event with ~ 2 PeV. A purely atmospheric origin of these events is excluded with a significance of 6.5σ. Figure 2 shows the distribution of the deposited energy, including the background and the fitted astrophysical component.

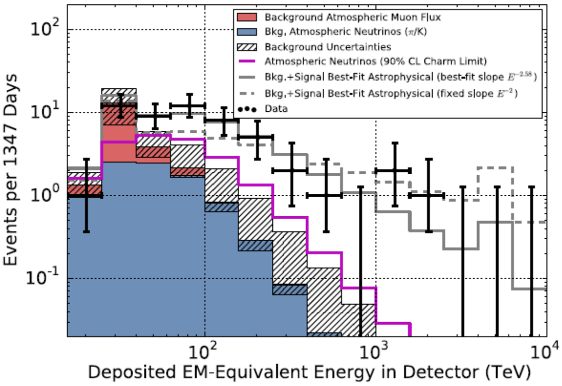

Fig2. *The distribution of the energy deposited in IceCube, for the 54 HESE events (see text). The astrophysical component is best fitted with an $E^{-2.58}$ shape (solid line) while the dashed line shows the results for the canonical E^{-2} shape. About 21 events can be statistically assigned to atmospheric backgrounds (filled histograms). The dashed areas reflect the uncertainties for the flux of atmospheric neutrinos [7].*

The sky-map of the 54 events shows a slight clustering about 10 degrees off the Galactic center (for IceCube: slightly above the horizon). That these events cannot be due to a quasi-point source with less than 1° extension has been demonstrated by ANTARES [6]. If the spectrum would be E^{-2} or steeper, ANTARES would have identified the source at lower energies, looking to upward moving muons (for

ANTARES the Galactic center is below the horizon).

Other searches for diffuse neutrino fluxes studied up-going muon tracks produced in neutrino interactions outside the detector and yielding up-going muons passing the detector. The most advanced of these analyses is based on two years of data and provided a 3.7σ evidence for astrophysical neutrinos. The spectral indices and the flux normalization obtained for the extraterrestrial component still differ from analysis to analysis, as shown in Fig.3 left.

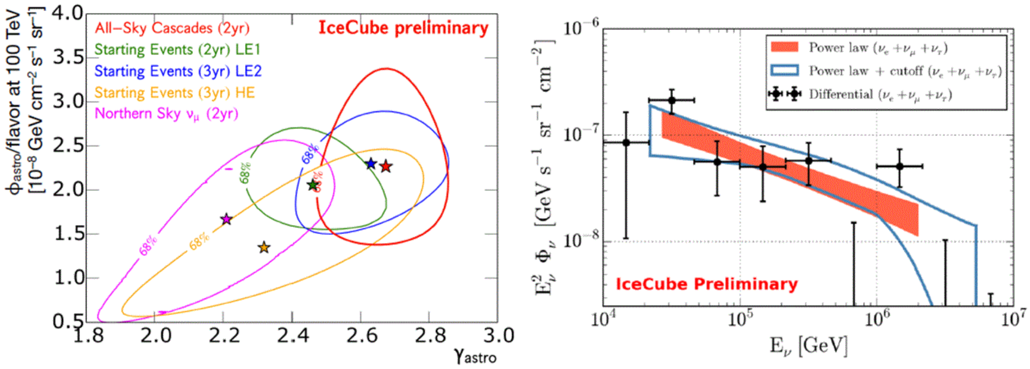

Fig3. *Left: flux normalization versus spectral index from various analyses. Right: Differential flux from various analyses, the red band with fitting a single slope, the blue contour allowing for a cut-off [8].*

Figure 3 (right) shows the differential flux from different analyses, with a spectrum apparently steeper than E^{-2}. It is fitted with a single-slope unbroken spectrum and with a cut-off. More statistics and tests are needed to understand the reasons for the differences.

Definitely, a detector with different systematics would help, like KM3NeT in the Mediterranean Sea or GVD in Lake Baikal. The extraterrestrial contribution as such can be considered firm by now, but the details on spectrum and flavor composition will need to be scrutinized by independent measurements.

3.2. Search for steady point sources

Traditionally point-source searches are performed with the help of long tracks from upward-going muons which provide sufficiently good angular resolution (0.3°– 0.5° for IceCube and 0.1°– 0.2° for KM3NeT). No point sources have been found, neither by ANTARES nor by IceCube (the statistics of Baikal NT200 was much too small to compete with ANTARES). Figure 4 shows the upper limits to the flux obtained by ANTARES and IceCube as a function of the declination. The extension of IceCube's sensitivity to the Southern hemisphere is due to the fact that at very high energies the background from down-going muons can be kept sufficiently small, so that IceCube can look southwards. This possibility is mostly lost for fluxes with a high-energy cut-off (see the dashed curve). ANTARES, on the contrary, covers part of the Northern hemisphere since it is not located at the North Pole.

The somewhat disappointing picture of only upper limits might be mitigated by the fact that the remaining step to identify the predicted fluxes from some sources like the Crab nebula or sources in the Cygnus region is only a factor 2-5; therefore a detection in the next 3-5 years seems a reasonable expectation, either with IceCube itself or with KM3NeT and its superior angular resolution.

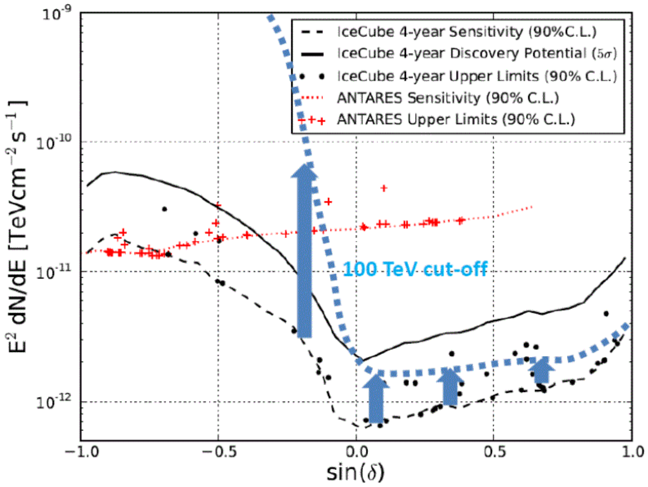

Fig4. *Upper limits/sensitivities to the flux from point sources obtained with ANTARES and with IceCube (modified Figure from [9]).*

3.3. Search for transient sources

Many searches for time-dependent emissions of extraterrestrial neutrinos have been performed by all four detectors, Baikal-NT200, AMANDA, ANTARES and IceCube, notably the recent target-of-opportunity programs of ANTARES and IceCube. Strong constraints on models could be set for prompt neutrino emission from Gamma-Ray Bursts using 4 years of data. For GRB searches the small spatial and temporal windows (a very few degrees and some seconds, respectively) dramatically reduce the background from atmospheric neutrinos and would make a doublet of events in coincidence with a GRB already highly significant. Figure 6 shows the constraints on a doubly broken power-law spectrum versus the first break energy ε_b and the normalization Φ_0 of the GRB flux, derived from 506 GRB and only one coincidence of a low-energy neutrino with a GRB, consistent with an atmospheric neutrino. The model of Ahlers et al. assumes that only neutrons escape from the fireball and contribute to ultra-high energy cosmic rays, the model of Waxman and Bahcall allows even all protons to escape.

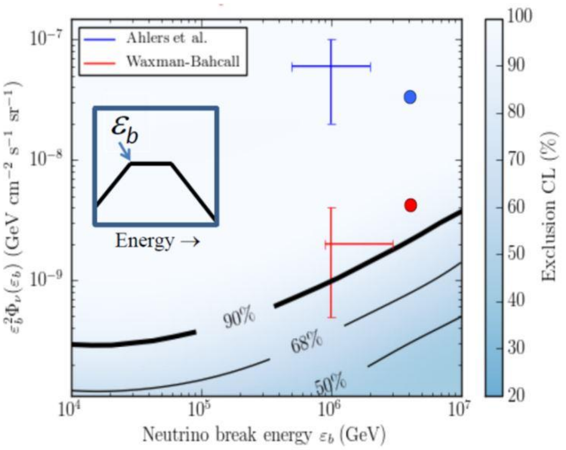

Fig5. *Constraints on flux normalization and break energy of two fireball models (modified Fig. from [10].*

Follow-up programs start from alerts issued by ANTARES or IceCube [11],[12]. These alerts are distributed in real-time to Imaging Cherenkov Telescopes (Gamma Ray Follow-up), satellites (X-ray follow-up) or robotic optical telescope (Optical Follow-Up, OFU). Alerts are due to neutrino multiplets or single neutrino events of extremely high energy. This approach boosts the discovery potential for astrophysical sources and can be used to constrain models of their high-energy neutrino and gamma-ray emission. I will report here one intriguing observation made with the OFU of IceCube [13].

An alert was sent on March 20th, 2012 to satellites and optical telescopes. This alert was based on a neutrino doublet with the two events roughly one degree from each other and arriving within 1.7 seconds. In the follow-up observation performed by the Palomar Transient Factory (PTF) ten days later, a previously unknown supernova was found, only 0.14 degrees from the mean neutrino direction. Figure 6 shows the location of the two events and the supernova. However, the age of the supernova at the time when the neutrino vents arrived was already169 days at least. Therefore the detection was classified as a coincidence and assumed that the neutrinos have no relation to the supernova. On the other hand, as I learned at this meeting, there are models able to explain such a delay between a beamed neutrino signal and the optical bursts [14].

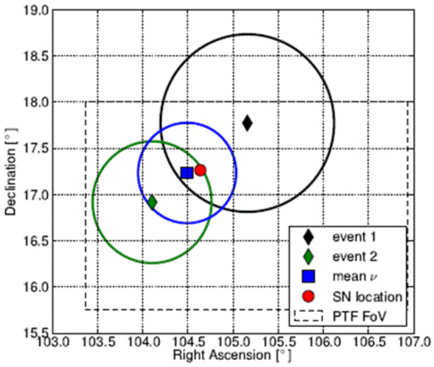

Fig6. *Location of the 2 neutrinos that triggered the follow-up observation with PTF and the SN location [13].*

3.4. Where do we stand and what is needed

The discovery of cosmic high-energy neutrinos with IceCube is a landmark event and a real breakthrough. Apart from this discovery, models on a number of steady and transient sources have been severely constrained or falsified – which is also an advance of knowledge. But still, not a single point source (neither steady nor transient) has been detected. Moreover, the knowledge of spectrum and flavor composition is still fuzzy. Astronomy, however, means just this: identification of individual sources, measurement of their spectrum, measurement of possible time variations; in addition coverage of the full sky.

More statistics and an incrementally improved understanding of the detector may help IceCube improving the understanding of spectrum and flavor composition, and possible even detect a first individual source. But the big leap will come only with a next generation of telescopes: KM3NeT and GVD at the Northern hemisphere and IceCube-Gen2 at the South Pole. When finished, theses detector will cover 5-10 cubic kilometers of water (North) or ice (South) and will improve the sensitivity of IceCube by a factor 5-20, depending on the event signature. Moreover they will allow a full-sky observation, with a better view to the center of the Galaxy from the North. The next chapter gives a short description of the three projects.

3. Where do we go?

3.1. KM3NeT

KM3NeT comprises two deep-sea installations, the one located off-shore Toulon (France), the other at Capo Passero (Sicily), with a potential third site in Greece [15]. KM3NeT will consist of blocks with 115 strings each and 18 optical modules (OM) per string. Each OM houses 31 small photomultipliers. The diameter of the high-energy blocks ("ARCA") is about 1 km (see Fig.7), that of the single low-energy block in France ("ORCA") is 100 m. ARCA will address the highest energies, in the footsteps of IceCube. ORCA, with its small string spacing an efficient light collection, will have an energy threshold in the few-GeV range and will be sensitive to effects of the neutrino mass hierarchy by measuring atmospheric neutrinos having crossed the Earth.

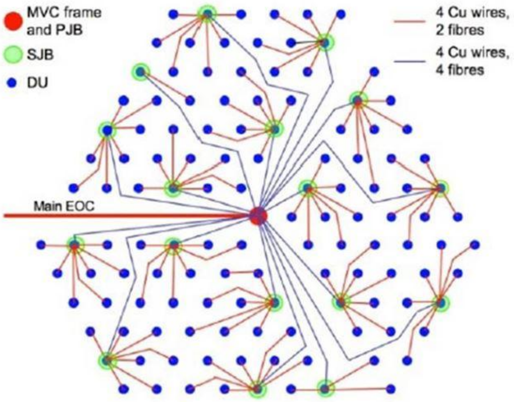

Fig7. *Top view of an ARCA block, covering an area of about 1 km^2. DU (blue dots) stands for "Detection Unit" (i.e. a string), JB stands for "Junction Boxes" of different hierarchy levels The main electro-optical cable (EOC) links the detector to the shore station, which is 70 km away for the Italian site.*

A 24–string prototype of ARCA and a 7-string prototype of ORCA are just under construction (KM3NeT Phase-1). A second phase of KM3NeT will consist of full ORCA at the Toulon site and two ARCA blocks in Italy. ARCA Phase-2 will scrutinize the diffuse IceCube signal but also has a good chance to detect first galactic point sources. Eventually, ARCA will consist of 5 blocks, either all at the Italian site or shared between Italy and Greece.

3.2. GVD

The Baikal *Gigaton Volume Detector* (GVD) will have a modular structure with functionally independent sub-arrays. Each of these "clusters" consists of 8 strings each carrying 36 optical modules [16]. The OMs are equipped with 10-inch photomultipliers. For the first phase of GVD, 10-12 clusters are envisaged, covering ~0.4 km^3 of deep water. This phase is planned to be concluded in 2020/21. In the second phase, the detector will be expanded to 27 clusters covering ~1.5 km^3 of water. Figure 8 gives a top view of the 27-string phase. The distance to shore is about 3.5 km. The small box shows location and cabling of a single cluster.

After a 5-year prototyping phase, a first cluster of GVD has been completed in April 2015 and takes data since then. With 0.4 km^3 volume, also GVD Phase-1 will be able to scrutinize the diffuse IceCube signal.

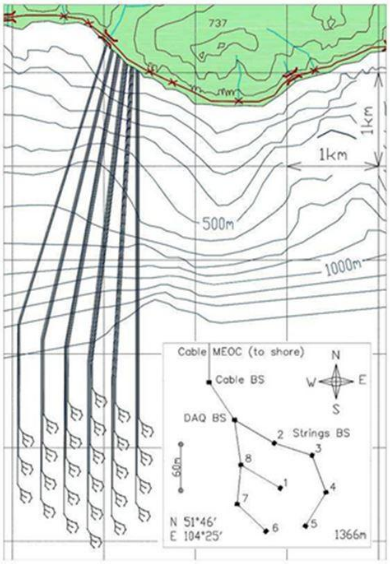

Fig8. *Top view of the Baikal Gigaton Volume Detector GVD with 27 clusters. The small box sketches a single cluster.*

3.3. IceCube-Gen2

IceCube is planned to be expanded w.r.t. to high-energies by an expansion of the deep-ice detector and by a huge surface detector. Oscillation physics and dark matter detection will be addressed by a high-density array, much denser than the present DeepCore array in the center of IceCube. This detector was christened PINGU. Its main goal is determining the neutrino mass hierarchy with the help of atmospheric neutrinos, similar to ORCA (see Section 3.1).

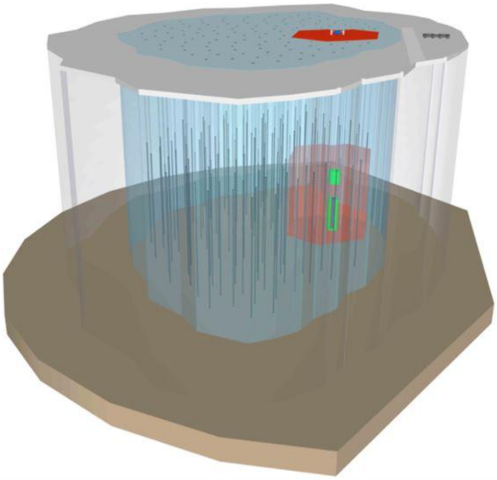

Fig9. *Artists view of IceCube-Gen2 The red array is the present IceCube, including the high-density part DeepCore (the two green inner cylinders). The big blue blob is IceCube-Gen2 with its 100-140 widely spaced strings. The surface array shown in this figure has the same footprint like the deep detector (about 10 km²). It might, however, be expanded by another order of magnitude in area, thereby increasing the acceptance of the veto against particles related to an air shower. Not shown in the figure is the extremely dense PINGU part within DeepCore.*

The high-energy expansion is named IceCube-Gen2 [17]. The deep-ice detector would be enlarged to 7–10 km³, naturally with a larger spacing and consequently a much higher threshold than IceCube. The surface detector would cover an area of up to 100 km². It would allow separating muons produced by neutrinos in the ice layer between the surface and the deep detector from punch-through muons from the surface, since the latter are accompanied by an air shower detected in the surface array. This could enlarge the statistics for high-energy neutrinos from the Southern hemisphere by a factor 2–4.

Figure 9 shows an artist's view of IceCube-Gen2. Start of construction and final configuration depend on several factors, including the outcome of the first phases of KM3NeT and GVD. A present (optimistic) plan assumes start of deployment in 2021/22.

3.4. The global view

In 2013, representatives of the collaborations ANTARES, Baikal-GVD, KM3NeT and IceCube have signed a Memorandum of Understanding for cooperation within a Global Neutrino Network (GNN). GNN aims for extended inter-collaboration exchanges, a coherent strategy planning and exploitation of the resulting synergistic effects.

The next logical step on the road towards high-energy neutrino astronomy is clear: construction of the two Northern detectors (0.4 km² in Lake Baikal and 1.0–1.5 km³ in the Mediterranean Sea), with completed detectors in 2020–22. At this point, GNN would include a total volume of 1.5–2 km³ in the North and 1 km³ in the South, the latter with a cumulated statistics of more than 10 years. 5–8 years later, one would have 4–6 km³ in the North and 7-10 km³ in the South. My personal guess is that we are already close to observing point sources and we will detect them not later than in midst of the 2020s. The case for the detectors at the end of the 2020s is even more compelling: measuring spectrum and variability of individual sources and making neutrinos a real key for understanding the non-thermal Universe!

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