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100th ANNIVERSARY OF THE BIRTH OF B M PONTECORVO

High-energy neutrino astronomy: a glimpse of the promised land

Ch Spiering

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Abstract. **In 2012, physicists and astronomers celebrated the hundredth anniversary of the detection of cosmic rays by Viktor Hess. A year later, in 2013, the first evidence of extraterrestrial high-energy neutrinos emerged, promising fundamental insight into the origin of cosmic rays. The evidence was obtained from the data from the IceCube neutrino telescope at the South Pole. When the idea of this telescope was first discussed at the 1973 International Cosmic Ray Conference, it was beyond anyone's imagination that it would take a biblical forty years before the first discoveries would be made and the promised land of the high energy neutrino would first be glimpsed. This paper sketches the development towards highly sensitive detectors, describes the latest results from the IceCube and ANTARES neutrino telescopes, and takes a look into the future.**

1. Introduction

The year 2012 marked the hundredth anniversary of the detection of cosmic rays by Viktor Hess. As we know today, cosmic rays consist essentially of protons and nuclei of heavier elements; electrons contribute only at the level of one percent. Since cosmic rays are electrically charged, they are deflected by cosmic magnetic fields on their way to Earth. Precise pointing — i.e., astronomy — is only possible with electrically neutral, stable particles: electromagnetic waves (i.e., gamma rays at the energies under consideration) and neutrinos. High-energy neutrinos, with energies much beyond a GeV, must be emitted as a by-product of collisions of charged cosmic rays with matter. Actually, only neutrinos provide irrefutable evidence of the acceleration of hadrons, because gamma rays may also stem from inverse Compton scattering of accelerated electrons and other electromagnetic processes. Moreover, neutrinos can escape much denser celestial environments than light: therefore, they can be tracers of processes that stay hidden from traditional and gamma-ray astronomy. At the same time, however, their extremely low reaction cross section makes their detection a challenge and requires huge detectors.

This article follows the evolution toward IceCube, the first detector with a realistic discovery potential, sketches recent relevant results obtained with large neutrino telescopes, and tries looking into the future. Recent reviews of the field can be found in [1–3], and a detailed review on the history is contained in [4].

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2. The idea

The initial idea of neutrino astronomy beyond the Solar System rested on two arguments. The first was the expectation that a supernova stellar collapse in our Galaxy would be accompanied by an enormous burst of neutrinos in the 5–50 MeV range. The second was the expectation that fast rotating pulsars must accelerate charged particles in their Tera-Gauss magnetic fields. Either in the source or on their way to Earth, they must hit matter or radiation fields and generate pions, with neutrinos as decay products of the pions.

Today, for interactions with a photon gas, we write

$$\mathrm{p} + \gamma \to \Delta^+ \to \pi^+ + \mathrm{n}\,,$$
$$\pi^+ \to \mu^+ + \nu_\mu \to \mathrm{e}^+ + \nu_\mathrm{e} + \bar{\nu}_\mu + \nu_\mu\,. \qquad (1)$$

The resulting neutrino flavor ratio is approximately $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ at the sources. Neutrino oscillation turns this into a ratio of 1 : 1 : 1 upon arrival at Earth.

Since this talk was given at the occasion of Bruno Pontecorvo's 100th birthday, it is worth remembering that Eqn (1) reflects his concept of generating a second (muonic) neutrino via pion decay [5], whereas the transformation from a flavor ratio 1 : 2 : 0 to 1 : 1 : 1 goes back to his idea of neutrino oscillations [6, 7]. Indeed, much of what we do in high-energy neutrino astronomy is deeply rooted in some of the basic ideas of this visionary physicist.

The first thoughts to detect cosmic high-energy neutrinos underground or underwater date back to the late fifties. In 1960, Kenneth Greisen and Frederick Reines discussed the motivations and prospects for such detectors [8, 9]. In the same year, on the 1960 Rochester Conference, Moisei Markov published his groundbreaking idea "...to install detectors deep in a lake or a sea and to determine the direction of charged particles with the help of Cherenkov radiation" [10]. This appeared to be the only way to reach detector volumes beyond the scale of 10^4 t.

3. DUMAND: start of the adventure

The real march toward underwater neutrino telescopes started forty years ago at the 1973 International Cosmic Ray Conference. There, a small group of physicists from the USA, Japan, and Russia for the first time discussed building such a device: the Deep Underwater Muon and Neutrino Detector (DUMAND). The original design from 1978 envisaged an array of about 20,000 photomultipliers (PMs) spread over a 1.26 km^3 volume (Fig. 1a). The PMs would record the arrival time and amplitude of Cherenkov light emitted by muons or particle cascades. The size of the array was based "... on relatively scant information on the expected neutrino intensities and was difficult to justify in detail; the general idea was that neutrino cross sections are small and high-energy neutrinos are scarce, so the detector had better be large" [11].

During the 1960s, no predictions or serious estimates for neutrino fluxes from cosmic accelerators were published. Actually, many of the objects currently considered top candidates for neutrino emission (quasars, pulsars, X-ray binaries, gamma ray bursts) were discovered only in the 1960s and 70s. The situation changed in the 1970s, when these objects were identified as possible neutrino emitters, although still with highly uncertain flux predictions.

First DUMAND discussions at the 1978 DUMAND workshop [12] focused on neutron star binary systems as point-like sources of high-energy neutrinos (specifically Cygnus X-3), neutrino signals from apparent sources of TeV-γ-ray (none of them significant at that time!), and diffuse fluxes.

A large number of papers on expected neutrino fluxes were published during the 1980s. The fluxes were found to depend strongly (a) on the energy spectrum of the γ-ray sources, which could only be guessed since the first uncontroversial TeV-γ observation of the Crab nebula in 1989 [13] and (b) on the supposed ν/γ ratio, which depends on the unknown thickness of matter surrounding the source.

Confronted with the oceanographic and financial reality, the size of DUMAND was reduced in several steps to a 216-PM version (DUMAND-II), to be deployed close to Hawaii at a depth of 4.8 km. It took more than three decades from the 1978 DUMAND design to the actual completion of a cubic kilometer detector: the IceCube Neutrino Observatory at the South Pole (see Fig. 1b)!

The pessimistic and optimistic numbers for signal events given in the 1988 DUMAND proposal [14] differed by 2–4 orders of magnitude and left it open whether DUMAND-II would be able to detect neutrino sources or whether this would remain the realm of a future cubic kilometer array. In 1990, Venjamin Berezinsky estimated the array size necessary to detect extragalactic sources as 0.1–1.0 km^2 [15]. DUMAND-II, with a 25,000-m^2 area, fell just below these values.

In 1987, the DUMAND collaboration operated a test string for some hours from a vessel and measured the muon

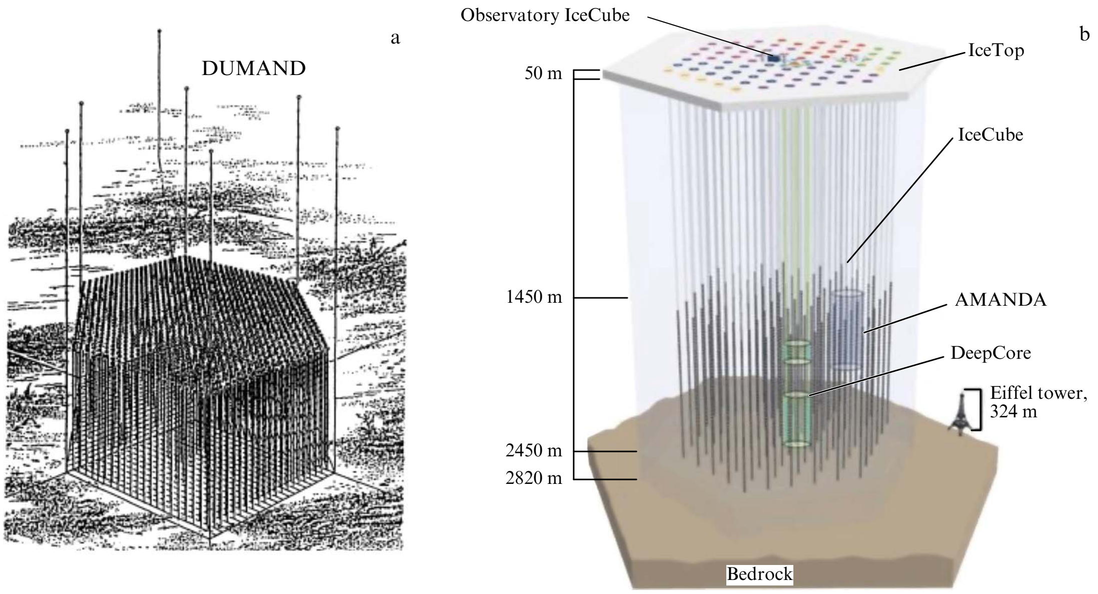

Figure 1. A cubic kilometer detector: from dream to reality. (a) The DUMAND configuration conceived in 1978 and (b) the IceCube detector completed in 2010.

intensity as a function of depth [16]. One year later, the DUMAND-II proposal was submitted and another six years later the first full-scale string was deployed. Due to leakage problems, the communication to shore failed. The recovered string was analyzed and a redeployment prepared. But in spite of the remarkable progress compared to ocean technology at that time, the risk aversion of funding agencies led to a termination of DUMAND in 1995.

Since then, the goal to begin high-energy neutrino astronomy was carried forward at the South Pole, in the Mediterranean Sea, and in Lake Baikal.

4. The long road: from NT200 to IceCube

4.1 NT200 in Lake Baikal

In 1980, Alexander Chudakov proposed using the deep water of Lake Baikal in Siberia as the site for a "Russian DUMAND." In late winter, the lake is covered by a thick ice layer, which allows deploying underwater equipment without any use of ships. The first shallow-site experiments with small PMTs started in 1981, and soon a site in the southern part of Lake Baikal, 3.6 km from shore and at a depth of about 137 m, was identified as the optimal location for a detector. In 1984 and 1986, first stationary strings were deployed and recorded downward moving muons [17].

In 1989, a preliminary version of what was later called the NT200 project was developed, an array comprising 192 optical modules on 8 strings [18]. The volume of NT200 was only twice that of Super-Kamiokande (or about 10^{-4} km^3), but the possibility of seeing bright signals emerging outside the geometrical volume made the detector much more sensitive to some high-energy processes.

NT200 started with the deployment of a 3-string array [19] with 36 optical modules in 1993. The first two upward moving muons, i.e., neutrino candidates, were separated from the 1994 data. In 1996, a 96 OM array with four NT200 strings was operated [20] and provided the first textbook neutrino events like the one shown in Fig. 2.

NT200 was completed in April 1998 and has been taking data since then.

4.2 AMANDA

In 1988, Francis Halzen and John Learned released the paper "High Energy Neutrino Detection in Deep Polar Ice" [21]. This spectacular idea marked the starting point for AMANDA (Antarctic Muon And Neutrino Detection Array). Holes for the PMs were proposed to be drilled into the ice with pressurized hot water. In 1993–1994, after tests in Greenland and at the South Pole, the first array with 80 PMs on four strings was deployed at the South Pole — however, at a too shallow depth, where the ice is still very bubbly [22]. In 1995–1996, a second 4-string array was installed at a depth of 1500–2000 m, where the bubbles have disappeared. It took some time to prove that the ice quality was indeed sufficient for reconstruction, but in 1996 AMANDA could also provide the first clear upward going muon events from neutrino interactions [23]. The array was upgraded stepwise until January 2000 and eventually comprised 19 strings with a total of 677 PMs.

AMANDA was switched off in April 2009, after 9 years of data taking in its full configuration. It provided 6595 atmospheric neutrinos and several important upper limits, but no clear indication of any extraterrestrial neutrino signal.

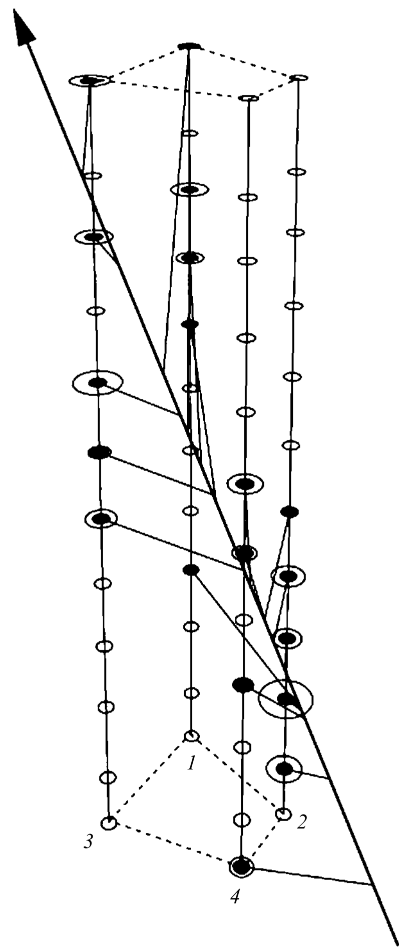

Figure 2. One of the first upward moving muons from a neutrino interaction recorded with the 4-string stage of the Baikal detector in 1996 [20]. The Cherenkov light from the muon is recorded by 19 channels.

Actually, there was one short moment of hope. In 2005, while analyzing the data taken in 2000–2003, five events where identified from the direction of the Active Galaxy 1ES1959 + 650. Interestingly, three of them came within 66 days in 2002 [24]. Two of these three neutrinos coincided within about a day with gamma-ray flares observed by the gamma-ray telescopes HEGRA and Whipple (see Fig. 3). Moreover, one of these two flares was not accompanied by an X-ray flare, a so-called 'orphan flare', which one would expect for a hadron flare where the X-ray flux accompanying electron flares is absent. This result was quickly followed by two theoretical papers, one claiming that the corresponding neutrino flux would not fit any reasonable assumption on the energetics of the source [25] and the other claiming that scenarios yielding such fluxes were conceivable [26]. This curious gamma-neutrino coincidence initiated considerations to send alerts to gamma-ray telescopes in case time-clustered neutrino events from a certain direction appeared. Such alert programs are currently operating between IceCube and the gamma-ray telescopes MAGIC (La Palma) and VERITAS (Arizona).

4.3 Mediterranean projects: NESTOR, ANTARES, and NEMO

The exploration of the Mediterranean Sea as a site for an underwater neutrino telescope started in 1989 when Russian physicists measured, from a ship, the muon counting rate as a

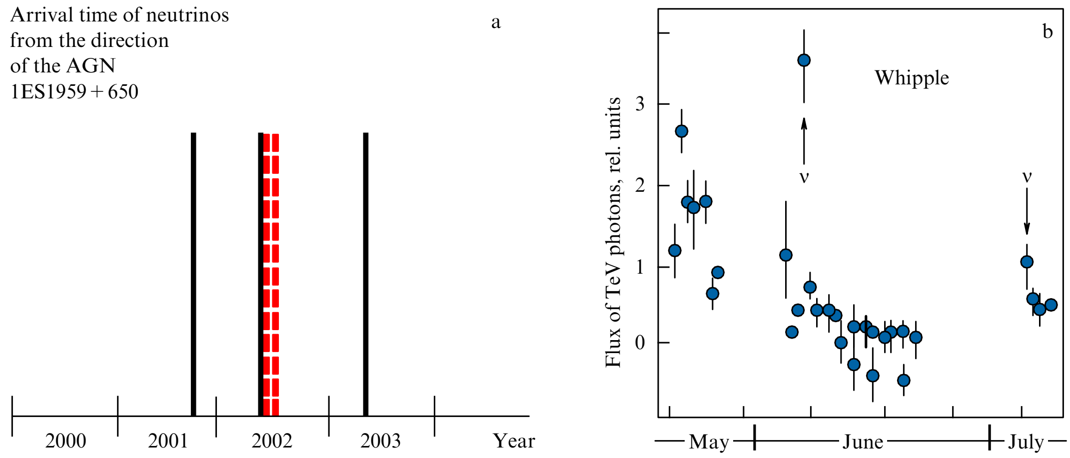

Figure 3. The 'curious' coincidence of neutrino events from the direction of an AGN with gamma flares from the same source. The second and third of the three events recorded in 2002 (dashed) coincide within about one day with peaks seen by the Whipple telescope.

function of depth [27]. In July 1991, a Greek–Russian collaboration deployed a hexagonal structure with 14 PMs down to a depth of 4100 m, at a site close to Pylos on the coast of Peloponnesus. This was the start of the NESTOR project. NESTOR was conceived to consist of seven towers, each comprising 12 hexagonal floors, spread over a volume of 0.1 km^3. In 2004, a single prototype floor was deployed and operated for about one month [28]. Its operation was terminated due to a failure of the cable to shore. Data taken with this prototype demonstrated the detector functionality and provided a measurement of the atmospheric muon flux [29].

The second Mediterranean project is ANTARES, which started in the mid-1990s; a full proposal was presented in 1999 [30]. ANTARES consists of 12 strings, each carrying 25 PM-triplets. With a geometrical volume of 0.01 km^3, it is almost the same size as AMANDA. ANTARES was constructed between 2002 and 2008. It has convincingly demonstrated that a detector with precise angular resolution can be reliably operated in the deep sea [31].

The latest of the Mediterranean attempts is NEMO [32]. The project was launched in 1998, with the objectives to study the feasibility of a cubic kilometer detector, to develop corresponding technologies, and to identify a suitable site. The location is at a depth of 3.5 km, about 100 km off the south-eastern coast of Sicily. Several prototypes of towers ('rope-ladders' of bars with PMs at each end) have been deployed and recorded downward moving muons [33]. At present, eight towers are being built and are planned to be deployed by early 2016. Later, they will be integrated into a large future Mediterranean detector, KM3NeT (see Section 6).

4.4 IceCube

IceCube [34, 35] consists of 5160 digital optical modules (DOMs) installed on 86 strings at depths of 1450 to 2450 m. A string carries 60 DOMs with 10-inch PMs housed in glass spheres. Signals are digitized in the DOMs and sent to the surface via copper cables. Three hundred twenty further DOMs are installed in IceTop, an array of detector stations on the ice surface directly above the strings (see Fig. 1b). AMANDA, initially running as a low-energy sub-detector of IceCube, was decommissioned in 2009 and replaced by DeepCore, a high-density sub-array of eight strings at large depths (in the clearest ice layer) at the center of IceCube. DeepCore collects photons with about six times the efficiency of full IceCube, due to its smaller spacing, better ice quality, and the higher quantum efficiency of new PMs. Together with the veto provided by IceCube, this results in a threshold of about 10 GeV and has opened a new venue for oscillation physics and indirect dark matter search.

The first, single IceCube string was deployed in January 2005, six years after submission of the initial proposal to NSF [36]. The following seasons resulted in 8, 13, 18, 19, 20, and 7 strings, respectively. The last of 86 strings was deployed on 18 December 2010.

Finally, the idea of a cubic-kilometer detector was realized!

5. Results

Large neutrino telescopes underwater and in ice would never have been built without the primary goal of identifying and understanding cosmic accelerators. But actually they are multi-purpose devices, with a shopping list of impressive length. They are used to search for signatures of dark matter particles and other exotic forms of matter, like magnetic monopoles. They allow studying neutrino oscillations and other problems of particle physics — like cross sections for neutrino interactions and heavy-particle production at the highest energies. IceCube, in addition, has a sensitivity to phenomena much below the nominal energy threshold of these detectors: to MeV neutrinos from a supernova collapse. Such neutrinos are emitted in a ≈10-second burst and lead to slightly enhanced counting rates of all PMs. Last but not least, charged cosmic rays can be studied — either with the help of downward going punch-through muons from air showers or, as in the case of IceCube, by an air shower array installed at the surface (IceTop).

In what follows, I focus on the search for high-energy extraterrestrial neutrinos and on the study of neutrino oscillations with atmospheric neutrinos. It is at these frontiers where the most remarkable progress of the last 2 years has happened. Recent results come from IceCube [37] and ANTARES [38], while Baikal NT200 has provided important limits in the past, notably on diffuse fluxes of extraterrestrial neutrinos and on the flux of magnetic monopoles [39, 40].

5.1 Atmospheric neutrinos

Atmospheric neutrinos and muons are produced in cosmic-ray interactions in the atmosphere. Up to energies of about 100 TeV, their flux is dominated by neutrinos from pion and kaon decays. The corresponding neutrinos are referred to as 'conventional' atmospheric neutrinos. Their spectrum follows approximately an $E^{-3.7}$ shape. At higher energies, 'prompt' atmospheric neutrinos from the decay of charm and bottom particles take over. These particles decay before having a chance to further interact. Therefore, the resulting neutrinos closely follow the primary cosmic ray power-law spectrum with its $E^{-2.7}$ shape.

Figure 4 shows the spectra published by various experiments. The data points range up to 200 TeV (ANTARES [41]) and 400 TeV (IceCube-40 [1] [42]) and are (still!) quite compatible with the predictions for conventional atmospheric neutrinos. In particular, no significant excess at high energies has been observed yet. Improved statistics from IceCube (79 and 86 string configurations) will soon allow testing flux models for prompt neutrinos or provide evidence for extraterrestrial neutrinos. They would show up as a shoulder at some 100 eV.

Data points are given for muon neutrinos and electron neutrinos. The spectrum of muon neutrinos must be deconvoluted from the measured $\mathrm{d}E/\mathrm{d}x$ of the recorded muons, taking into account that these muons (a) lose energy before reaching the detector and (b) carry only part of the neutrino energy. For electron neutrinos, the first of these issues does not play a role: electron showers have lengths of the order of 10 m; therefore, the events are contained and all energy carried by the electron becomes visible. On the other hand, electron cascades can hardly be distinguished from hadronic cascades, which form the final state of most ν_τ interactions and of all neutral current interactions. Therefore, the ν_e flux can only be obtained via a delicate subtraction procedure leading to relatively large errors. Within these errors, the IceCube data are very compatible with the predictions for conventional electron neutrinos from the atmosphere.

Atmospheric neutrinos also provide a tool to investigate neutrino oscillations. The oscillation length scales with E_ν. For distances of the order of Earth's diameter, the first oscillation minimum is at $E_\nu \simeq 24$ GeV. The suppression of the observed ν_μ flux is a function of the neutrino energy and of the zenith angle and allows extracting the oscillation parameters θ_{23} and Δm^2_{23}. Figure 5 shows the constraints in the oscillation parameter space from different experiments, including ANTARES and IceCube/DeepCore [43]. The constraints from DeepCore data are half way between those of ANTARES, on the one hand, and those of MINOS, Super-

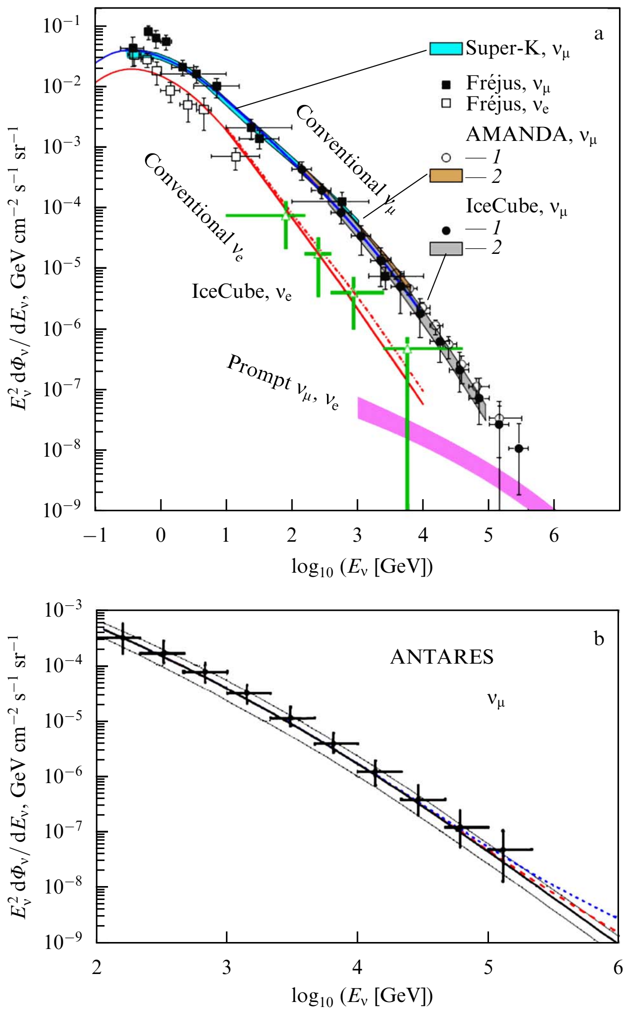

Figure 4. (Color online.) Energy spectrum of atmospheric neutrinos as measured by various experiments. (a) IceCube-40 data are given for muon and electron neutrinos and are quite compatible with calculations for conventional atmospheric neutrinos [42]. *1* and *2* give the results obtained by two different methods to unfold the neutrino spectrum from the measured muon energy losses. (b) The side shows the muon neutrino spectrum as measured with ANTARES.

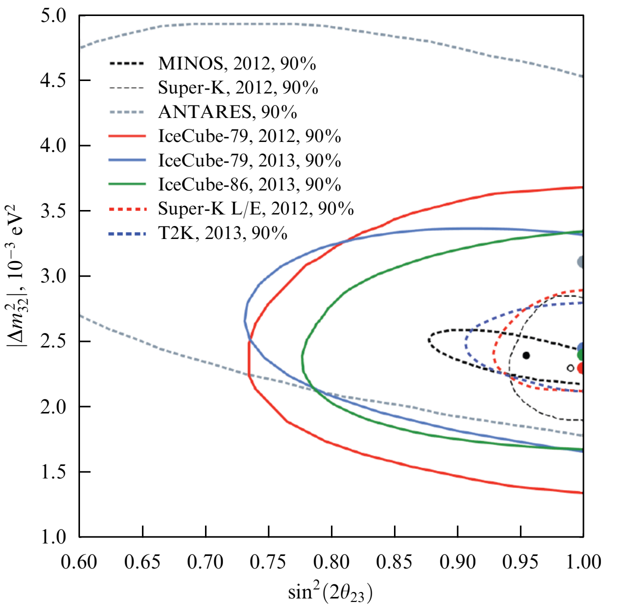

Figure 5. (Color online.) Constraints in the oscillation parameter space from different experiments. The three independent IceCube analyses are based on one year of data, two for Icecube-79, one for IceCube-86 (solid lines). The constraints from ANTARES (gray dashed line) are weaker, those from MINOS, Super-K, and T2K are much stronger. More data and better analysis techniques will considerably improve the IceCube constraints. (Figure taken from [43].)

[1] IceCube-40 denotes the IceCube configuration with 40 installed strings.

Kamiokande, and T2K on the other. Preliminary estimates show that over a few years, DeepCore can reach a similar sensitivity as the last three experiments. The real promise, however, lies in further increasing the density of IceCube's core (project PINGU) and determining the neutrino mass hierarchy (see Section 6).

The great scientific breakthrough of 2013 was obtained at the high-energy frontier, as is described in Section 5.4. On the other hand, progress with neutrino oscillations is similarly impressive. Competing in this field with the best accelerator experiments and with Super-K was certainly beyond the expectations of most experts. The prospect of being a main player in fixing the neutrino mass hierarchy is even more exciting.

5.2 Steady point sources

High-energy cosmic neutrinos can be identified either as the accumulation of events pointing to a particular celestial direction ('point-like sources') or as extended diffuse emission, ranging from a few degrees (as for nearby supernova remnants) to the fully diffuse, essentially isotropic neutrino flux.

Cosmic neutrinos from a given source would cluster around the source direction. Event statistics have grown and analysis methods have been continuously improved over the years, e.g., by including energy estimators in the analyses or by passing from methods with fixed widths of the search bin to 'unbinned' methods. This has led to a tremendous progress.

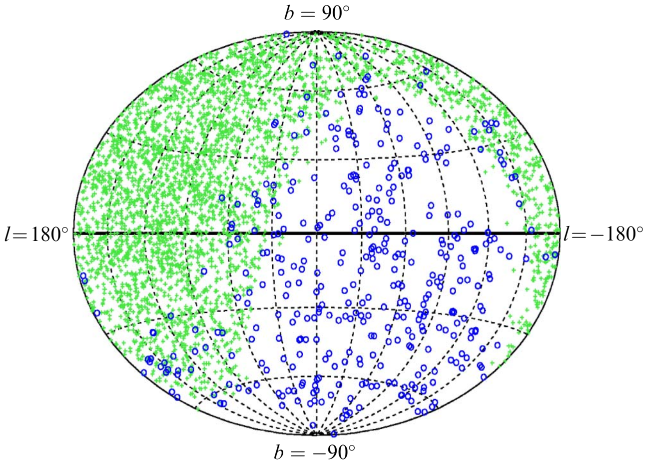

Figure 6. (Color online.) Combined sky map of upward moving muons recorded with AMANDA and Baikal NT200 (figure compiled in 2005).

A nice demonstration of how the sky maps in AMANDA and IceCube have evolved with time can be found in Fig. 3 in [44]. It started with a meager 17 upward-muon events in 1999 and ended with some 10^4 events in 2012: a fantastic factor-1000 pace in statistics and in sensitivity (see Fig. 8 below)! In Fig. 6, we show another historical sky map from 2005, which combines data from AMANDA (2000-2003) and NT-200 in galactic coordinates.

Today, the sensitivity frontier is defined by ANTARES for the southern sky and IceCube for the northern sky (both having their best sensitivity to point-like sources by looking down, i.e., through Earth, to the other hemisphere). Figure 7 shows the sky maps of ANTARES and IceCube in equatorial coordinates [38, 45].

ANTARES has used only upward muons, and the map extends to the Northern Hemisphere because ANTARES is not just at the North Pole and its field of view sweeps over different parts of the sky during one day. By contrast, IceCube does not change its field of view with Earth's rotation. Instead, access to the southern sky is obtained by raising the energy threshold for downward muons — losing sensitivity at low energies but keeping it for energies of PeV or above. Figure 8 gives the sensitivities/upper limits obtained from various experiments. We note that the sensitivity has indeed improved by a factor of more than 1000 from the first AMANDA analysis (AMANDA 10-string array) to that of the four years of IceCube data.

Naturally, the IceCube sensitivity to an E^{-2} flux from the Southern Hemisphere is worse than for Northern sources, because the analysis relies exclusively on the tiny high-energy tail of the neutrino flux. For unbroken E^{-2} spectra, a cubic-kilometer detector at the South Pole can compete with a northern first-generation detector like ANTARES up to a declination of 45°. This means that there is a broad declination region where the combination of IceCube and ANTARES data will give a better sensitivity than IceCube or ANTARES alone. Such combined analyses are presently underway.

Optimistic flux predictions for some sources are a factor of 3–10 below present IceCube limits. This does not rule out a

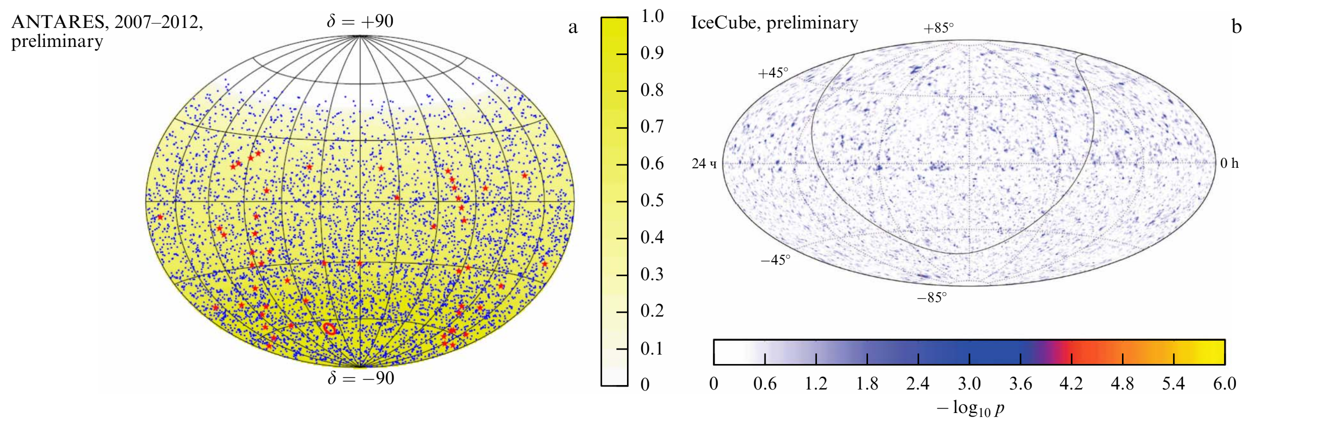

Figure 7. (Color online.) Skymaps of ANTARES, (a) at 5 years and IceCube, (b) at 4 years with 40, 59, 79, and 86 strings [45]. The color in Fig. a codes the visibility to ANTARES, the color in Fig. b codes the significance of the excesses.

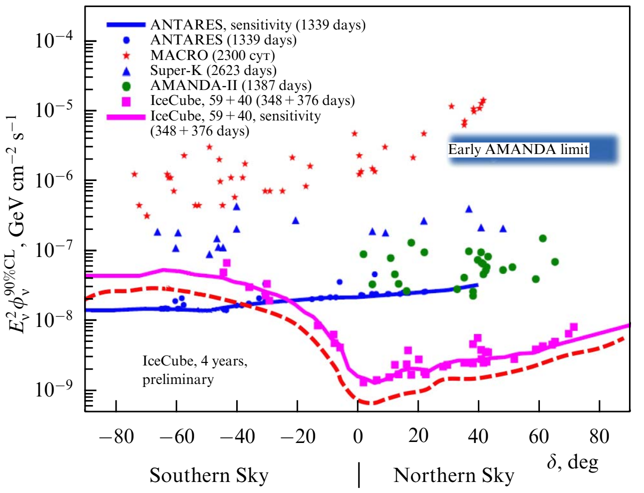

Figure 8. (Color online.) Point source neutrino flux sensitivities (median expected limits at 90% C.L.) and upper limits for selected sources from various experiments: Super-Kamiokande, AMANDA, the various stages of IceCube and ANTARES. (See [2] for references.)

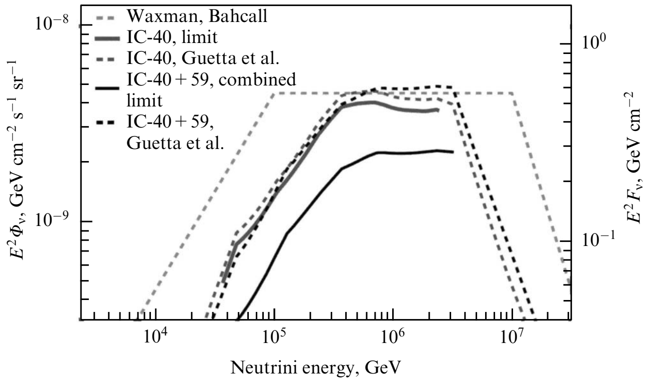

Figure 9. Comparison of initial IceCube results to predictions normalized to observed gamma-ray spectra [47] and to the high-energy cosmic-ray spectrum (Waxmann & Bahcall [46]. (Figure taken from [48].)

discovery with the standard point-source analysis focused on TeV energies, but there is no guarantee of success.

5.3 Transient sources

Many astrophysical sources are known to have a variable flux at different wavelengths. Examples for such flaring sources are active galactic nuclei, soft gamma-ray repeaters, and gamma-ray bursts (GRB). Binary systems often show a periodic behavior, as pulsars do. Reduction of the search window to the time interval of flares or bursts reduces the background from atmospheric neutrinos.

Here, I report results on GRBs, which can last from less than a second to several hundred seconds. GRBs are now known to be of extragalactic origin and have been suggested as dominant sources for the cosmic rays at the highest energies [46]. In the GRB fireball model, cosmic-ray acceleration should be accompanied by neutrinos produced in the decay of charged pions created in interactions between high-energy cosmic-ray protons and gamma rays [46, 47]. Both IceCube and ANTARES have searched for coincidences of neutrinos with GRBs. In [48], no coincidences of IceCube events with any of 215 GRBs were reported, with an expectation of 5.2 coincidences (Fig. 9) according to [47]. The 90% C.L. upper limit was a factor of 3.7 below the fluxes predicted by fireball models. However, it did not take long to show that the predictions turned out to be too optimistic in several aspects [49]. With revised calculations, the predicted fluxes are again below the published IceCube limits. Since then, however, data for ≈ 300 additional GRBs have been analyzed, and the corresponding sensitivity is at the same level as the revised predictions. This seriously challenges the hypothesis of GRBs being a dominant source of cosmic rays.

ANTARES has presented results of a similar search, based on 296 GRBs in 2007–2011 [49]. No coincidences have been observed. Naturally, the flux limit averaged over all 296 bursts is much worse than that of IceCube with its 30-times-larger area. On the other hand, a discovery of a particularly close GRB, with an optimum orientation of the jet to Earth and a low Lorenz factor of jetted matter — but outside IceCube's field of view — cannot be excluded. This makes continued ANTARES searches important.

5.4 Diffuse fluxes: step to the promised land?

It has been shown in [51] that the first evidence of high-energy astrophysical neutrinos is expected from a diffuse isotropic flux, if the source candidates are dominantly extragalactic and not dominated by a few galactic sources. This is a consequence of the fact that neutrinos propagate through all the Universe with negligible absorption, resulting in an unresolved flux from all the faint and distant extragalactic sources.

Searches for diffuse fluxes use the measured energy as the primary criterion for separating cosmic and atmospheric neutrinos. A certain distinction of the one from the other can be obtained from

(1) the ratio between the numbers of cascade events and muon events (which is related to the flavor ratio),

(2) the angular distribution, and

(3) the absence of signals from accompanying punch-through muons from a possible parent air shower if the neutrinos come from above.

The flavor ratio and angular distribution of cosmic and atmospheric neutrinos are slightly different. The most important criterion is the energy, and therefore diffuse analyses critically depend on a good understanding of the detector response as a function of energy and on a reliable prediction of the background, most notably that from prompt atmospheric neutrinos [52]. The latter dominate the high-energy tail of atmospheric neutrinos, and their flux has substantially larger uncertainties than that of conventional atmospheric neutrinos.

It has been shown in [53] that the cascade topology has the highest sensitivity for the detection and characterization of high-energy excesses. A combination of all signatures (cascades, downward moving muons, upward moving muons) gives the best chance to detect a cosmic diffuse neutrino flux and distinguish if from prompt atmospheric neutrinos. This is impressively demonstrated by the recent IceCube analyses.

The first candidate for a cosmic neutrino was obtained in 2012 from an analysis of the IceCube-59 data, studying the energy losses of about 22,000 neutrino-generated upward going muons within the detector [54]. An event view of the highest-energy muon, arriving from 1.2 degrees below the horizon, is shown in Fig. 10a. The muon enters the detector with an energy of about 400 TeV, while the most likely energy of the parent neutrino is 0.5–1 PeV. The excess w.r.t. to

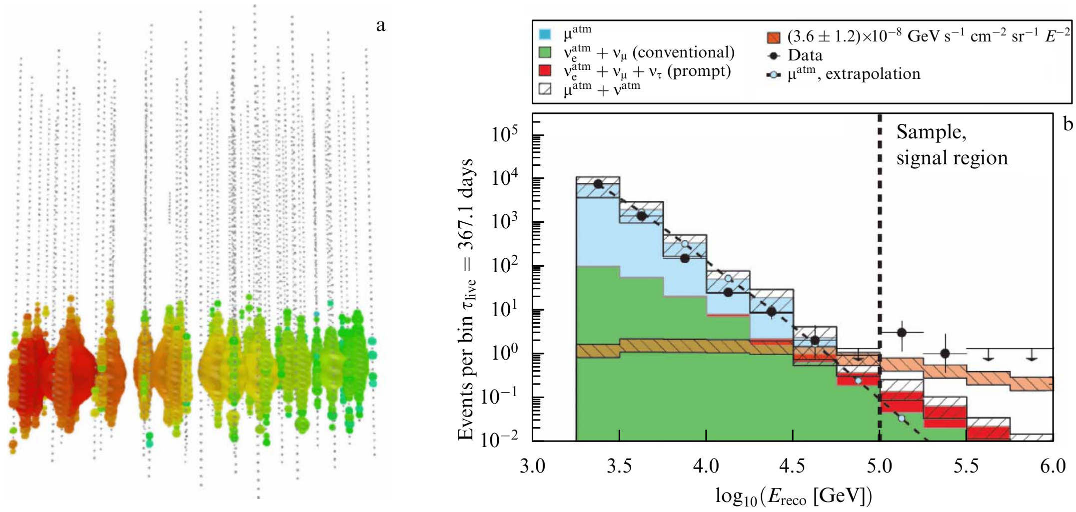

Figure 10. (Color online.) (a) Highest-energy neutrino event from the IceCube-59 analysis — a muon entering the detector with about 400 TeV of energy, corresponding to a most likely neutrino energy in the range of 500 TeV–1 PeV [55]. (b) Reconstructed energy distribution of contained cascades recorded with IC-40 [56]. The white hatched area shows the distribution of atmospheric neutrinos and muons, including systematic and statistical uncertainties. The orange band indicates the estimate for extraterrestrial neutrinos derived from the HESE analysis described below. The highest two data points correspond to 4 neutrino events (including one from the burn sample that was not used for the significance calculation).

atmospheric conventional and prompt neutrinos is based on this and a second, somewhat less energetic muon and has a rather low significance of 1.8σ. Translating to an upper flux limit, we arrive at $E^2\Phi < 1.4 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} for an E^2 spectrum, or at 3.8 times the value predicted for prompt neutrinos calculated in [57]. Due to the delicate background determination, the final result appeared only recently [55].

A 2011 analysis focused on contained cascades recorded with the IceCube-40 detector. These cascades deposit all their energy within the detector volume, giving a much clearer correlation to the neutrino energy than in the case of muons. The mentioned analysis provided an excess that was compatible with the high background left by filters. However, a re-analysis with optimized cuts could reduce the background considerably while keeping the 4 events of the first analysis with the highest energies (between 140 and 220 TeV) [56]. The energy distribution of the sample is shown in Fig. 10b. The excess has a significance of 2.7σ over the background of 0.25 events from atmospheric muons and neutrinos. Again, the delicate and Monte Carlo intensive background determination considerably delayed the release of the final result. A recent similar analysis of the IceCube-59 data provided a nearly negligible excess and did not add much significance [58].

A clear step to the PeV scale was made with two events discovered in a search for ultra-high energy neutrinos [59], as expected for instance, from GZK interactions of high energy protons with the CMB photon field [60]. The actual energy threshold of the event filter was about 500 TeV. Data for the search had been taken in 2010 and 2011 with the 79-string and 86-string configurations. Two neutrino-induced cascade events passed through all filters, with reconstructed energies of 1.04 and 1.14 PeV, and were dubbed Ernie and Bert (see Fig. 11). The two events represent a still moderate 2.8σ excess over the expectation for atmospheric neutrinos. The sheer energy, however, made them more promising candidates for

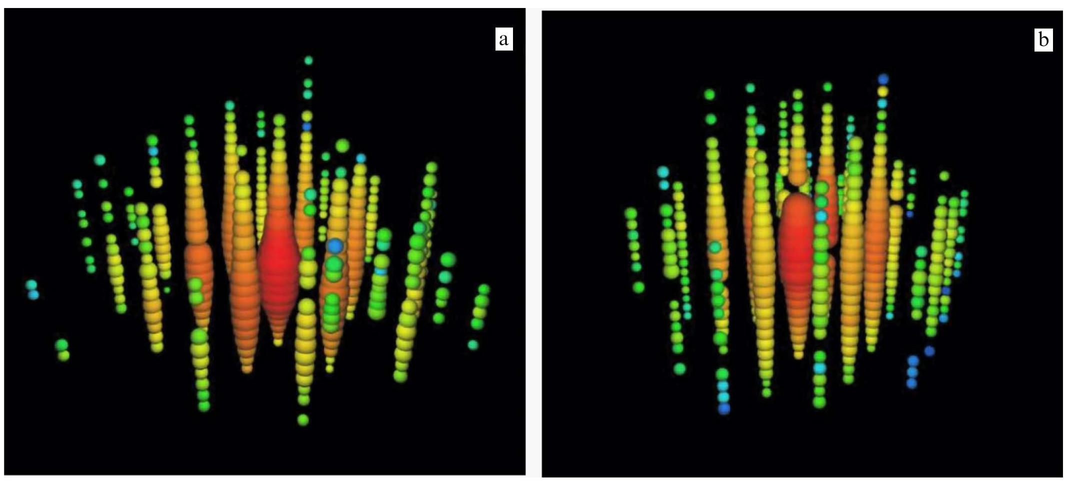

Figure 11. (Color online.) The two observed events from August 2011 (Ernie) and January 2012 (Bert). Each sphere represents a DOM. Colors represent the arrival times of the photons (red — early, blue — late). The size of the symbols is a measure for the recorded number of photo-electrons.

cosmic neutrinos than anything found earlier. Their energy was not high enough for a plausible origin from GZK processes, the primary motivation for this analysis. They were also considered unlikely to originate from the Glashow resonance, because only about 10% of such interactions would deposit 1.2 PeV or less in the detector in cascade-like signatures.

Motivated by this result, an alternative analysis of the same data was performed. It constrains the event to start in the inner volume of IceCube (using the outer part as a veto layer), and at the same time considerably lowers the threshold compared to the first analysis (to some tens of TeV). New features of this approach included a method for determining the atmospheric muon background directly from the data and a calculation of the probability that a down-going atmospheric neutrino is accompanied by muons that fire DOMs in the veto layer and reject the event as a neutrino candidate. The results were first presented on 14 May 2013 at a conference and eventually published in [61]. There, 28 events are given, with energies deposited in the detector ranging from $\approx$ 30 TeV to 1.14 PeV. Figure 12 shows the distribution of the deposited energies. Ernie and Bert keep their top position in energy. Notably, the events at somewhat lower energies ($\approx$ 30TeV – 250 TeV) can hardly be explained solely by atmospheric neutrinos or by muons moving unrecognized from above into the detector. The contribution of such background sources to the total of 28 events is calculated as $10.6^{+5.0}_{-3.6}$ events, resulting in a statistical significance of $\sim 4.1\sigma$. The energy spectrum up to 1 PeV is compatible with an E^{-2} spectrum at a level of $E^2\Phi = (1.2 \pm 0.4) \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}. The absence of events at energies above 1 PeV requires either a cutoff of the E^{-2} spectrum at several PeV or a softer spectrum, e.g., $E^{-2.2}$.

A global fit to all data (standard cascade analysis of 40 and 59 strings, upward muon analysis of 59 strings, and the starting-event analysis with 79/86 string data) has been applied in [52]. It includes the contribution from prompt neutrinos as a free parameter and a cut cosmic neutrino spectrum of the form $E^{-2} \exp(E/E_{\rm cut})$. The result is compatible with the fit of the 28-event sample alone: $E^2\Phi = (1.0^{+0.8}_{-0.5}) \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} for the cosmic neutrino contribution, $E_{\rm cut}$ in the 1–6 PeV range, and $\Phi_{\rm prompt}$ being (2.8 ± 2.0) times the prompt flux calculated in [57].

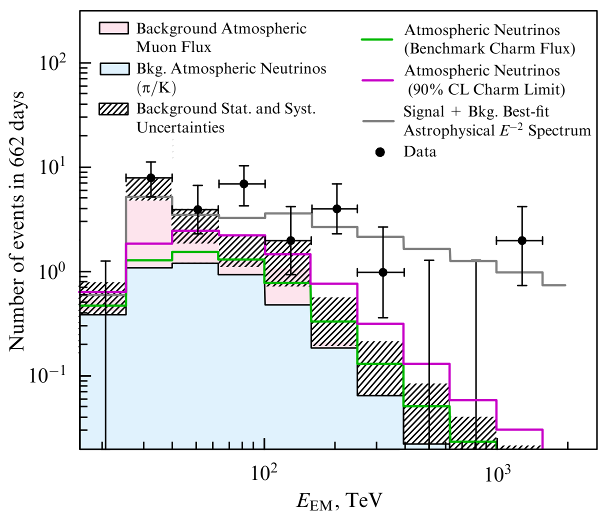

Figure 12. (Color online.) Distribution of the deposited energies of the 28 events compared to model predictions. The horizontal axis shows the energy released in the detector ($E_{\rm EM}$) under the assumption of only the electromagnetic contribution [61].

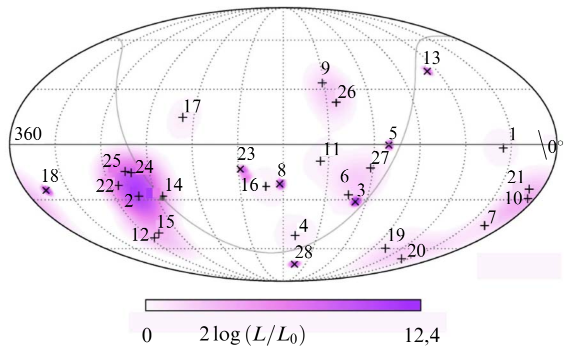

Figure 13. (Color online.) Skymap in equatorial coordinates of the 28 events. The galactic plane is shown as a gray line, the galactic center as a filled gray square. Best-fit locations for showers are indicated by crosses and for muons by angled crosses. The coloring indicates the probability of a point-like source at that position. The cluster close to the galactic center has a chance probability of about 8%, i.e., it is not significant.

The arrival directions of the 28 events are shown in Fig. 13. There is no significant clustering at any point of the sky, including the intriguing accumulation close to the galactic center.

Interpreting these results is tempting and was tried in almost 50 papers that appeared in 2012 and 2013. A nearly complete collection of references can be found in [62] and [63]. Explanations include extragalactic and galactic acceleration processes and the decay of superheavy dark matter. However, the still limited statistics, the fact that the main significance has been obtained with just one special method (the high-energy starting-event analysis), and the insufficient understanding of the prompt neutrino contribution [64] make it premature to draw clear conclusions.

Fitting the data from all analyses without any cosmic contribution is possible if one omits the two PeV events, albeit with an extremely high contribution of prompt neutrinos [52]. On the other hand, most down-going prompt atmospheric neutrinos should have been accompanied by down-going muon, and these would have been tagged by the veto. Moreover, the prompt neutrino signal is related to the spectrum of down-going muons for which such a contribution would be reflected by a high-energy shoulder. A corresponding analysis of IceCube muons is presently underway and will shed more light on this question.

It is also too early to derive source hypotheses based on the cascade-to-muon ratio, first because the contamination by background events is different for cascade and for muon events, and second, again, due to the low statistics. It is, however, worth keeping in mind that the high-energy starting-track analysis suppresses muon-track events in comparison with cascade events in a way that makes the ratio of 21 cascades to 7 tracks very compatible with a 1 : 1 : 1 flavor ratio.

Soon, we will know more. A third event on the PeV scale (christened Big Bird) has been found when inspecting a 10% burn sample of the second year of IceCube-86 data. A next step is the continuation of the path started with studying upward muons in IceCube-59 — the analysis that in 2012

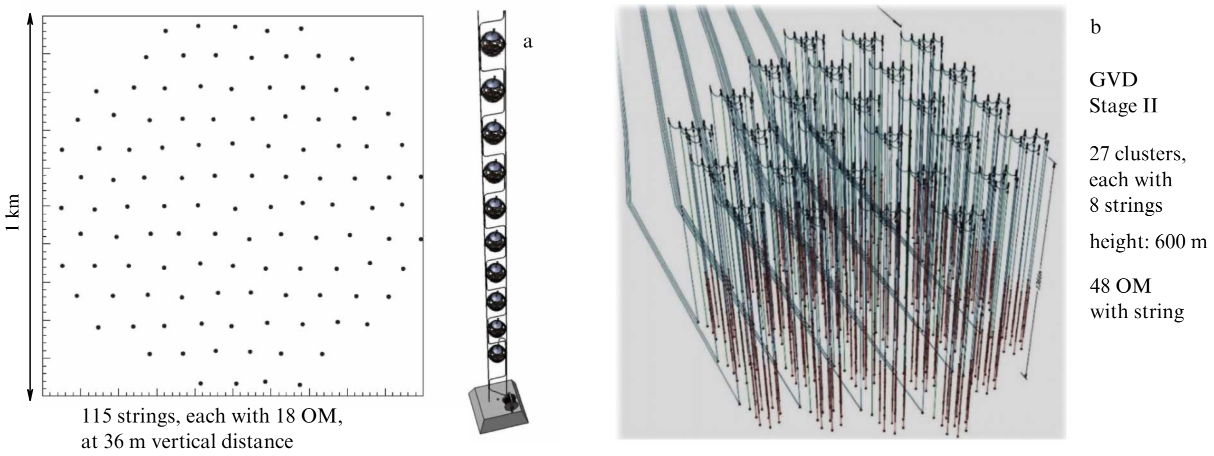

Figure 14. (a) Top view of one of the six envisaged KM3NeT blocks. (b) Artist view of GVD stage-II, with a total volume of about 1.5 km^3

provided the highest-energy muon, $\sim$ 400 TeV (see Fig. 10). A corresponding analysis of the IceCube-79 and -86 data is underway, and the results will likely be released before summer 2014. Also, the standard cascade analyses of IceCube-40 and 59 will be extended to data from the later IceCube configurations.

6. The future

With IceCube, the sensitivity to point sources and to diffuse fluxes has been improved by a factor of more than a thousand over the situation in the mid nineties. No indications of extraterrestrial point-like sources have been found yet, but optimistic source models mean a discovery with IceCube is still possible — with several more years of IceCube data and improved analysis methods. The first breakthrough, however, was obtained when integrating over the full sky, showing evidence of an extraterrestrial contribution in the diffuse flux.

More than five decades after the first conceptual ideas, and four decades after the first practical proposals to build high-energy neutrino telescopes, we may be close to a turning point. We are likely catching a first glimpse of the promised land of the high-energy neutrino Universe!

This has important consequences for the future strategy of the field. For the first time one feels justified in giving the ‘green light’ to the construction of a second detector on the cubic kilometer scale in the Northern Hemisphere. The danger of building such a second cubic-kilometer array and then ‘seeing nothing’ seems unfounded now. This does not yet guarantee the identification of point-like sources, but it does make their discovery more likely than ever before. Certainly, the exact configuration of large northern neutrino telescopes should be optimized according to further findings of IceCube: How important are tracks? How important are cascades? How good should the energy and angular reconstruction be in both cases? Etc. But the way to start building such detectors (in the North as well as as an extension of IceCube) has opened.

There are two projects in the Northern Hemisphere: KM3NeT in the Mediterranean Sea and GVD (Gigaton Volume Detector) in Lake Baikal.

KM3NeT will likely be built in the form of several separate blocks of the kind shown in Fig. 14a. After an EU-funded design study and a following preparatory phase (resulting in a conceptual design report (CDR) and a technical design report (TDR) [65]), the KM3NeT community has recently developed into a formal collaboration. They envisage to installing a detector ≈ 5 km^3 in volume from 2014 on. The total investment cost is estimated to be around 225 m euros. The present plan foresees deployment of building blocks. A total of six building blocks could be deployed at three sites: close to Toulon, close to Sicily, and close to Pylos.

At present, about 40 million euros have been assigned to prepare infrastructures and demonstrator configurations at the French and Italian sites (KM3NeT Phase-1). The next step will be KM3NeT Phase-1.5, which will comprise a one or two full cubic kilometer block and allow doing physics at the level Icecube is doing it now. This would require an additional 50–70 m euros on top of the assigned 40 million.

In Russia, the Baikal Collaboration plans the stepwise installation of a kilometer-scale array in Lake Baikal, the Gigaton Volume Detector, GVD [66]. It consists of clusters of strings. Realizing that the originally planned size of half a cubic kilometer is no longer enough, an array four times larger is presently being studied, as sketched in Fig. 14b. In 2008–2013, the basic elements and an engineering array with the first full-scale string and two half-strings were tested. A conceptual design report is available in [67].

What about the South Pole? Recent evidence of extraterrestrial neutrinos quite obviously suggests that IceCube be extended to larger volumes and optimized for higher energies (a detector tentatively named DecaCube). The first studies on such arrays have been presented recently [68].

One possible configuration is shown in Fig. 15, with 100 widely spaced strings arranged around IceCube. With a volume of 7 km^3, this array would have 3 (7) times the IceCube sensitivity for muon tracks (cascades), with an energy threshold of about 10 TeV. A starting-track analysis like that presented in Section 5.4 would yield 4–8 times more signal events than with IceCube-86 (somewhat depending on the achievable background suppression close to the borders of the array). With a next-generation array, one must seek to clearly identify point sources, and therefore optimization to muon tracks with their superior pointing will be important.

A further improvement in the selection of down-going cosmic neutrino events could be achieved by extending the present IceTop array by a factor of $\sim$ 50, of course using a much cheaper technology and wider spacing than for

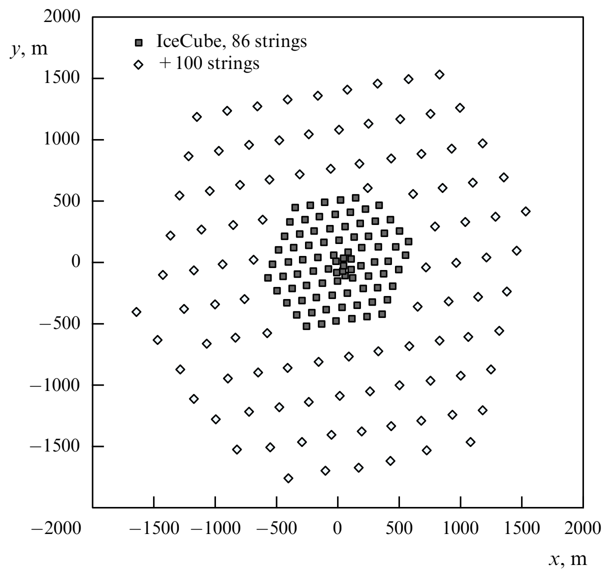

Figure 15. Top view of a possible design of DecaCube, a high-energy extension of IceCube, here with 100 additional strings and a total volume of about 7 km^3 [68].

IceCube. This array could veto atmospheric neutrinos beyond some 100 TeV with very high efficiency.

The present focus of the IceCube collaboration, however, is on the PINGU project. PINGU stands for Precision IceCube Next Generation Upgrade (see the letter of intent of the IceCube-PINGU collaboration [69]). The primary goal of PINGU is to determine the mass hierarchy of neutrinos. PINGU exploits the effect of resonance and parametric oscillations of atmospheric neutrinos propagating through Earth. For energies below 10–15 GeV, these oscillation would cause a pattern in the energy-zenith plane, which could be measured by PINGU. The baseline design of PINGU consists of 40 additional strings, each with 60 DOMs arranged in the inner part of DeepCore. The energy threshold is a few GeV. Figure 16 shows the estimated significances for the mass hierarchy, to be determined by several existing or planned experiments.

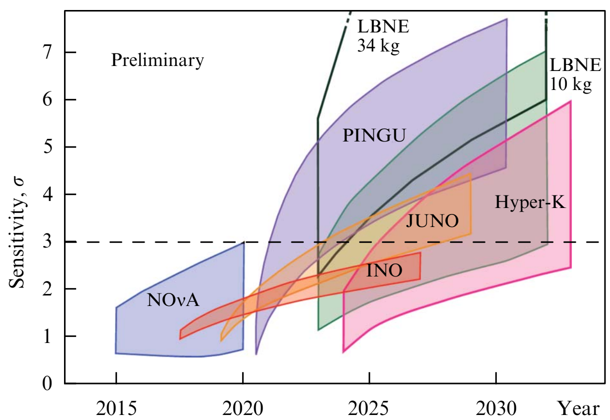

Figure 16. (Color online.) Estimated significance for the mass hierarchy to be determined by several existing or planned experiments, following [70]. The widths of the bands cover the range of expected sensitivities. They depend on the true hierarchy (for NOvA and LBNE), on different true values of the *CP* phase δ, on different assumptions on the achievable energy resolution (for JUNO), and, for atmospheric neutrinos, on the mixing angle θ_{23} ranging from the first to the second octant. The estimated sensitivity for PINGU is the one presented in [69], and all other curves are a union of the ranges presented for the two hierarchies presented in [70].

A similar study is being performed for the Mediterranean Sea (project ORCA [71]). It also includes the option to send a pure ν or $\bar{\nu}$ beam from Protvino to the ANTARES site [72].

7. Conclusion

The plans for PINGU and ORCA close the circle and lead this presentation back to its beginning and to the occasion at which it was given — the hundredth birthday of Bruno Pontecorvo. Pontecorvo would have found the year 2013 to be as exciting for neutrino science as our community does. After the determination of the last mixing angle θ_{13} in 2011 and 2012, 2013 provided a huge opportunity to determine the mass hierarchy, with projects like LBNO/LBNE, JUNO, and PINGU/ORCA. On the high-energy frontier, we have apparently achieved the long-awaited breakthrough and discovered the first neutrinos from distant cosmic accelerators. A new window on the high-energy universe is being opened, and we hope that in the next decade we can really harvest the fruits of the 40-year work in our field!

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