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NEUTRINOS AS COSMIC MESSENGERS IN THE ERA OF ICECUBE, ANTARES AND KM3NET

Uli F. Katz*

Erlangen Centre for Astroparticle Physics, University of Erlangen, Germany

* corresponding author: katz@physik.uni-erlangen.de

Abstract. Using neutrinos as cosmic messengers for observation of non-thermal processes in the Universe is a highly attractive and promising vision, which has been pursued in various neutrino telescope projects for more than two decades. Recent results from ground-based TeV gamma-ray observatories and refinements of model calculations of the expected neutrino fluxes indicate that Gigaton target volumes will be necessary to establish neutrino astronomy. A first neutrino telescope of that size, IceCube, is operational at the South Pole. Based on experience with the smaller first-generation ANTARES telescope in the Mediterranean Sea, the multi-Gigaton KM3NeT device is in preparation. These neutrino telescopes are presented, and some selected results and the expected KM3NeT performance are discussed.

Keywords: neutrino astronomy, neutrino telescopes, ANTARES, IceCube, KM3NeT.

1. Introduction

Neutrinos are the only known particles that could complement photons as messengers for astronomical observations. In fact neutrinos have ideal properties: They are not deflected by magnetic fields, they can travel over cosmological distances without absorption, and they can escape dense source regions. Neutrinos with energies in the GeV to PeV region, as discussed in this report, can trace the sources of cosmic rays as they are inadvertently produced in any environment where nuclei are accelerated to energies of the order of a TeV or above. There is just one drawback – the neutrino interaction cross section is so small that huge target masses are required to detect the expected feeble fluxes of such cosmic neutrinos.

Neutrino telescopes use natural water or ice volumes as the target and measure neutrinos through the Cherenkov light induced by the charged secondary particles emerging from their interactions. First-generation devices, typically covering a percent of a Gigaton of target mass, have been successfully constructed and operated in the deep ice of the South Pole (AMANDA [1]), in the Mediterranean Sea (ANTARES [2, 3]) and also in Lake Baikal in Siberia (see [4] for a review of the historical developments and for further references). These experiments have proven the feasibility of neutrino detection in the respective media and have provided a wealth of data, albeit as yet no evidence for cosmic neutrinos.

Theoretical models of neutrino production, constrained by the results of neutrino telescopes and of ground- and satellite-based gamma- and cosmic-ray measurements, indeed strongly indicate that Gigaton-scale target masses are required to establish neutrino astronomy [5]. The first instrument to match this requirement is the IceCube telescope [6] at the South Pole, the successor to AMANDA and completed in Dec. 2010. IceCube is now taking data at full pace, and even though no cosmic neutrino sources have been identified so far, a discovery may well be around the corner. Meanwhile, design and preparatory work for a multi-Gigaton telescope in the Mediterranean Sea, KM3NeT [7], is being pursued. A Technical Design Report [8] has been worked out and funding for a first construction phase is available.

The prime physics objective of neutrino telescopes is to identify high-energy neutrinos from astrophysical objects and thus to resolve the centennial mystery of the origin of cosmic rays. It is important to note that – at least for neutrino energies below a PeV – the field of view of neutrino telescopes is restricted to the lower hemisphere and therefore Galactic neutrino sources are difficult to observe from the South Pole. This also applies for a potentially large neutrino flux from the recently discovered "Fermi bubbles", extended regions above and below the Galactic centre with intense gamma-ray emission [9].

Further physics objectives are the search for a diffuse cosmic neutrino flux and for neutrinos originating from annihilations of Dark Matter particles. Precise measurement of large numbers of atmospheric neutrinos (produced in cosmic-ray-induced air showers) also enable the investigation of neutrino properties, such as oscillation parameters and possibly even the neutrino mass hierarchy [10].

Many more details and references than given below can be found in [11].

2. Current neutrino telescopes: IceCube and ANTARES

Deep-sea and deep-ice environments pose very different constraints on the installation and operation of a neutrino telescope, and both environments exhibit a variety of complementary advantages and disadvantages. To name just a few: light absorption in ice is lower than in water, but light scattering is stronger; the optical background in ice is low, whereas a detector in the deep sea has to cope with high signal rates from ^{40}K decays and bioluminescence; water is a completely isotropic medium, while ice has anisotropies at various length scales that are difficult to determine and to simulate; a detector in ice, once deployed, is rigid, whereas detector components in water constantly move on the deep-sea currents. As a result, the overall structure of the corresponding neutrino telescopes is similar, but the technical solutions differ significantly in detail. Common to all neutrino telescopes is that they consist of vertical units ("strings") carrying optical modules, i.e. photomultipliers in pressure-safe glass spheres.

2.1. IceCube

The IceCube detector is described in [12]. It consists of 86 strings carrying 5160 optical modules with 10-inch photomultipliers oriented vertically downwards. One km^3 of ice between 1450 m and 2450 m depth is instrumented homogeneously, with inter-string distances of 125 m and vertical distances of optical modules of 17 m. Several of the strings are used for densely instrumenting a sub-volume of about 15 Megatons in the very clear ice near the bottom of IceCube ("Deep Core") in order to lower the energy threshold for neutrino detection to some 10 GeV. The IceCube detector was completed in Dec. 2010, but was already taking data in the years before with increasing numbers of strings deployed.

2.2. ANTARES

The ANTARES detector [2] is located 40 km off the French Mediterranean coast near Toulon. It consists of 12 strings anchored by deadweights to the sea floor at a depth of 2475 m and kept upright by submerged buoys at their tops. Each string carries 25 titanium frames ("storeys"), equipped with three optical modules and an electronics container each. The optical modules contain 10-inch photomultipliers that are directed downwards at an angle of 45° with respect to the vertical. Adjacent strings are installed at a distance of about 70 m, and the vertical distance between storeys is 14.5 m (see Fig. 1). A further string, the instrumentation line (IL), carries devices for monitoring environmental parameters. One of the detection strings and the IL are equipped with high-sensitivity hydrophones for the investigation of acoustic detection techniques (AMADEUS system [13], see also [14]). ANTARES data taking started with the commissioning of the first line in 2006 and has been proceeding with the full detector since its completion in 2008.

The strings constantly move in the sea currents, causing deviations of the optical modules from their nominal positions by up to more than 10 m. The

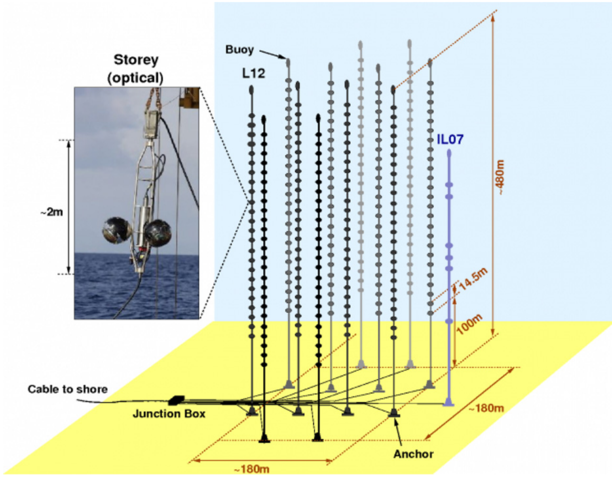

Figure 1. Schematic view of the ANTARES neutrino telescope. The inset shows one of the storeys during deployment. The string denoted IL07 is the instrumentation line in its 2007 configuration. Figure provided by the ANTARES collaboration.

string shapes are monitored using a system of acoustic transponders at fixed positions on the sea floor and hydrophones along the strings. The hydrophone positions are determined by triangulation from the distances inferred from the sound travel times. The orientations of the optical modules are monitored using compasses and tiltmeters. The system warrants the position calibration of the optical modules with accuracy better than 20 cm [15], as required for the precise reconstruction of neutrino events. Time synchronisation between photomultiplier signals of different storeys is achieved at nanosecond level using laser and LED flashers [16].

Each photomultiplier records single photons, mainly from ^{40}K decays and bioluminescence, at a rate of $50 \div 60$ kHz at minimum and much higher in periods of increased bioluminescence activity. To maximise the flexibility in filtering the data for neutrino event candidates, all photomultiplier signals exceeding an adjustable noise threshold (typically 0.3 photo-electron equivalents) are time-stamped and sent to shore via optical fibres, where they are submitted to a filter algorithm running on a computer farm.

3. Some selected results

IceCube and ANTARES have provided a wealth of results that cannot be covered comprehensively in this report; see [12] for a more detailed review of the IceCube results and [11] for a discussion of the various physics topics addressed. Here, only a few selected results will be shown, all based on detection and reconstruction of the $\mu^{\mp}$ emerging from ν_μ or $\bar{\nu}_\mu$ charged current interactions. Note that for these analyses atmospheric muons (i.e. those produced in cosmic-ray-induced air showers) are a vast background when looking upwards and can also fake up-going neutrino events when wrongly reconstructed.

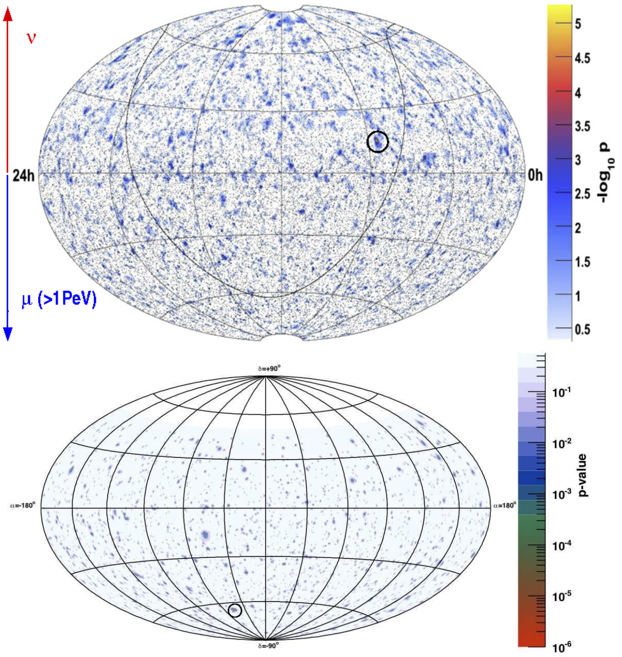

FIGURE 2. Sky maps in equatorial coordinates of the arrival directions of events recorded by IceCube with the 40-string detector configuration [17] (top) and by ANTARES [18] (bottom). In both maps, the colour codes indicate the significance with which the observed event distributions deviate from the expectations for an isotropic flux. The IceCube map is based on reconstructed up-going neutrino events (upper hemisphere) and on down-going atmospheric muon events after a cut that effectively restricts the muon energy to $\gtrsim 1\,\mathrm{PeV}$ (lower hemisphere). The black line indicates the position of the Galactic plane. The ANTARES map is based on reconstructed up-going neutrino events only. The black circles mark the most significant event accumulations, which are compatible with the background expectations in both cases.

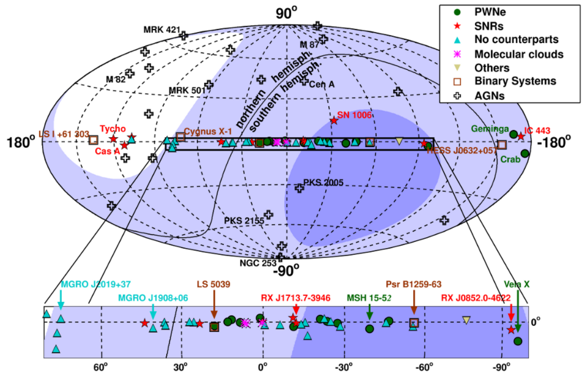

FIGURE 3. Fields of view in Galactic coordinates for neutrino telescopes located at the South Pole and in the Mediterranean Sea, respectively, assuming sensitivity to neutrinos coming from below the horizon. The region left of the black line is visible from the South Pole; the shades of blue indicate the fraction of time a given point in the sky is visible from the Mediterranean Sea (light blue: $> 25\,\%$, dark blue: $> 75\,\%$ of the time). Also indicated are sources of TeV gamma-ray emission. Figure courtesy of A. Kappes.

For energies above a TeV, the muon angular resolution is better than about 1°; the muon energy can be determined from its radiative energy losses with a resolution of about 30 % in $\log_{10}(E_\mu)$.

The primary goal is the search for astrophysical neutrino sources; since in most cases the angular size of such sources is smaller than the angular resolution, they are usually referred to as "point sources". A corresponding signal would be detected as a statistically significant accumulation of events originating from the same celestial direction, on top of the isotropic background of atmospheric neutrinos or muons. In Fig. 2 shows the corresponding sky maps of IceCube and ANTARES are shown. Even though the most significant event clusters found in the data have small p-values (5.2×10^{-6} for IceCube), the probability to find accumulations with this or lower p-values in random distributions of the same numbers of events in the sky map is moderate (18 % for IceCube, 2.6 % for ANTARES). Thus, these findings cannot be interpreted as evidence for cosmic neutrino sources. The resulting sensitivities for point source searches are shown in Fig. 6, together with those expected for KM3NeT.

Figure 3 confirms that two neutrino telescopes located in the Southern and Northern hemisphere, respectively, are necessary to achieve a full sky view for neutrinos. In particular, the Galactic centre and large parts of the Galactic plane are invisible from the South pole, except at very high energies beyond a PeV, where neutrino signals might be identified on top of the atmospheric muon background. Gamma-ray observations and the cosmic-ray spectrum assigned to Galactic origin indicate, however, that Galactic neutrino sources will have an energy cutoff at a few 100 TeV at most.

In order to demonstrate the capability of neutrino telescopes to contribute also to neutrino physics, results by ANTARES on the oscillation of atmospheric muons are shown in Fig. 4. Note that these results cover neutrino energies down to 20 GeV, indicating that even lower energies may be accessible with dedicated deep-sea detectors (cf. Sect. 5).

4. KM3NeT

The KM3NeT neutrino telescope [8] will complement IceCube in its field of view and exceed it substantially in sensitivity. When the KM3NeT effort started out with an EU-funded Design Study (2006–2009), a target price tag of € 200 M for a cubic-kilometre detector was defined. At that time, this was considered utterly optimistic. Meanwhile the construction of 5–6 km^3 for € 220–250 M appears to be feasible. This development has partly been achieved by optimising the neutrino telescope for slightly higher energies, implying larger horizontal and vertical distances of the optical mod-

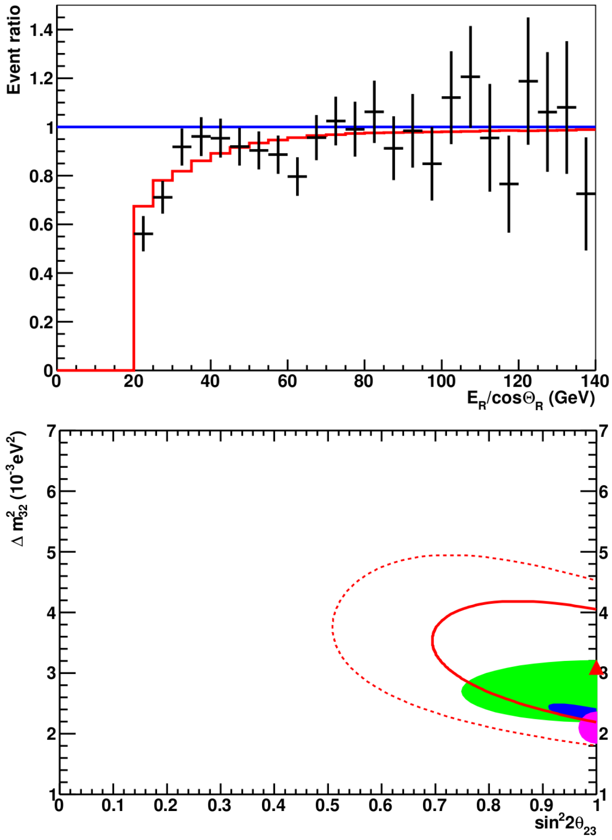

FIGURE 4. ANTARES ν_μ oscillation results [19]: Spectrum of $E_\mathrm{R}/\cos\Theta_\mathrm{R}$ relative to the non-oscillation expectation (top) and the resulting 68 % and 90 % C.L. regions and the best-fit value in the oscillation parameter plane (dashed and solid lines and triangle, bottom). E_R and Θ_R are the reconstructed muon energy and direction, respectively. In the bottom plot, the results of from K2K (green), MINOS (blue) and Super-Kamiokande (magenta) are shown for comparison. Figures taken from [19].

FIGURE 5. A prototype of the KM3NeT optical module. The components on the top are for the connection to the cable along the string. The metal structure inside the sphere serves for cooling purposes. Figure provided by the KM3NeT collaboration.

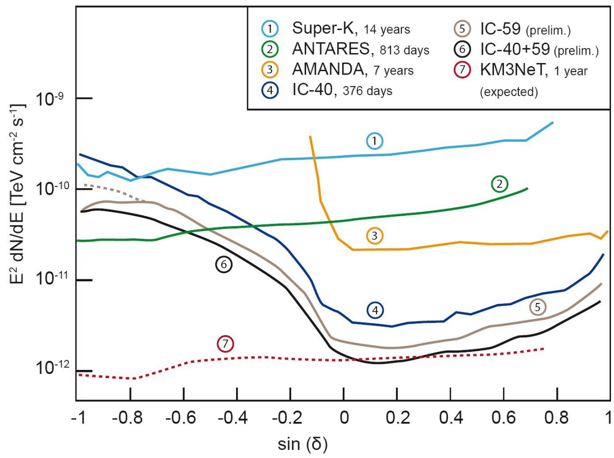

FIGURE 6. Average upper limits (90 % C.L.) on muon neutrino fluxes from point sources as functions of the declination (experimental results for existing neutrino telescopes, expected sensitivity for KM3NeT). Assumed are E_ν^{-2} spectra without energy cutoff. Note that the Super-Kamiokande detector is sensitive to much lower neutrino energies than the other neutrino telescopes. Figure taken from [11].

ules. The main progress, however, is due to the fact that almost all components have been newly designed, in many cases pursuing new approaches. The optical module is shown as an example: Instead of one large photomultiplier, the KM3NeT optical module will contain 31 3-inch photomultipliers plus digitisation electronics (Fig. 5). This triples the photocathode area per optical module, allows for clean separation of hits with one or two photo-electrons, and adds some directional sensitivity.

One major KM3NeT objective is the investigation of potential Galactic neutrino sources. Simulation studies show that KM3NeT will have high sensitivity over a large declination range (see Fig. 6). The sensitivity to extended Galactic sources with an expected energy cutoff in the 10 TeV range has also been investigated. One of the expectedly strongest neutrino sources is the shell-type supernova remnant RX J1713-3946 (see Fig. 3); neutrinos from that source should be detectable with 5σ significance in 5 years if the gamma-ray flux measured by H.E.S.S. is of purely hadronic origin.

Recently, intense gamma-ray emission with an E_γ^{-2} spectrum was measured by the Fermi satellite from two extended regions below and above the Galactic plane ("Fermi bubbles"). Neutrinos from this region could be detectable within less than a year if these gamma-rays originate from hadronic processes and if the power-law flux persists up to $\mathcal{O}(100\,\mathrm{TeV})$ (see Fig. 7, [9] and references therein).

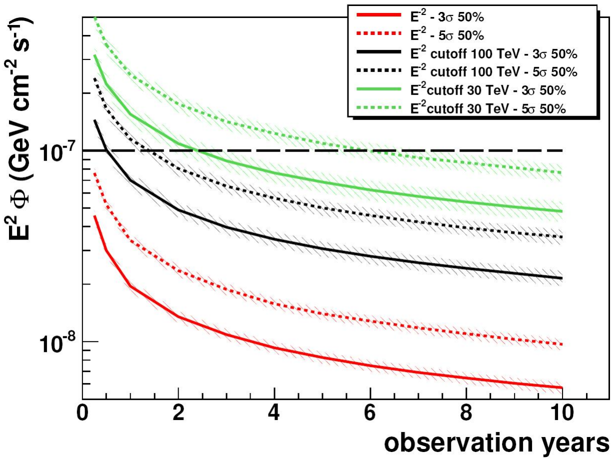

FIGURE 7. Neutrino fluxes from the Fermi bubbles needed for a discovery at 5σ C.L. (solid lines) and 3σ C.L. (dashed lines), at 50 % probability. The vertical axis indicates the constant K_0 for the three flux parameterisations $\mathrm{d}\phi_\nu/\mathrm{d}E_\nu = K_0 \cdot E_\nu^{-2} \cdot \exp(-E_\nu/E_c)$, with $E_c = 30\,\mathrm{TeV}$ (green), $E_c = 100\,\mathrm{TeV}$ (black) and $E_c = \infty$ (red). The line at $K_0 = 10^{-7}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}$ indicates the expected muon neutrino flux under the conditions described in the text. The shaded bands show the variations due to the uncertainty of the atmospheric neutrino flux. Figure taken from [9].

Sufficient funding is available to perform the necessary prototyping activities and to start a first construction phase, expectedly by 2013/14. Final decisions between technical options described in the TDR [8] are currently being made. In particular, after further investigating deployment, sensitivity and cost issues, it was concluded that the baseline technology for the KM3NeT detection units will be strings with single optical modules interconnected by a pair of Dyneema© ropes and an oil-filled equi-pressure backbone cable with optical fibres and copper leads.

5. Fundamental physics with atmospheric neutrinos

Triggered by theoretical studies [10], the capability of densely instrumented neutrino telescopes to determine the neutrino mass hierarchy using atmospheric neutrinos is currently being discussed. Such a measurement would require neutrino detection and reconstruction in the energy range of roughly $3 \div 15\,\mathrm{GeV}$. This fits well the IceCube plans to deploy further strings in the Deep Core region to increase the instrumentation density and lower the energy threshold (PINGU[1] project). A first-phase configuration with densely deployed strings is also being considered for KM3NeT (ORCA[2] project). Both collaborations are currently perform corresponding in-depth case studies, with results expected by summer 2013. A possible confirmation of the capability of a neutrino mass hierarchy measurement might impact significantly on the future plans for neutrino telescopes.

[1] Phased IceCube Next Generation Upgrade
[2] Oscillation Research with Cosmics in the Abyss

6. Summary

Neutrino telescopes in water and ice are taking data and have proven the technology and the feasibility of neutrino detection in both media. We are still awaiting the first significant observation of cosmic neutrinos, which, however, may well be around the corner. With the KM3NeT construction starting soon, the combined sensitivity will further increase, in particular for Galactic sources. Also fundamental measurements of neutrino parameters using atmospheric neutrinos might be within reach.

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Discussion

Peter Grieder — Can you comment on SPATS?

Uli Katz — SPATS stands for "South Pole Acoustic Test System" and denotes a set of microphones deployed, along with IceCube strings, in the top few 100 m of the polar ice layer. SPATS results are reported in several publications by the IceCube collaboration. The probably most important finding is that the absorption length of sound in glacial ice is about 300 m, as opposed to previous assumptions of several kilometres. This is a significant drawback for acoustic detection activities at the South Pole and the future of these activities is unclear.

Peter Grieder — Will you use hydrophones in KM3NeT for acoustic detection?

Uli Katz — The KM3NeT detector units will move in the deep-sea currents, similar to seaweed. Displacements from the nominal positions can be up to 80 m, compared to an accuracy of 20 cm with which the photomultiplier positions need to be known for precise event reconstruction. Constant monitoring of the positions and orientations of the optical modules is thus necessary, which will require acoustic sensors in all optical modules for applying acoustic triangulation methods. It is planned to acquire the data from these sensors continuously, so that they can also be used for acoustic detection studies. The current design is to use Piezo elements glued to the inner walls of the glass spheres; in that case, however, the interpretation of the acoustic signals for detection purposes may be impeded by their distortion in the glass walls.

Fernando Ferroni — Is there any potential with this kind of detectors for helping in determining the neutrino mass hierarchy?

Uli Katz — The IceCube collaboration considering to deploying additional detector strings to instrument the Deep Core region even more densely (PINGU project). There are indications that this setup may enable measurements of atmospheric neutrinos down to a few GeV and to determine the neutrino mass hierarchy via matter-induced oscillation effects during the neutrino propagation through the Earth (see Sect. 5). For deep-sea detectors this approach is difficult due to the background from ^{40}K decays and technical constraints on the inter-string distance.
Note added: Recent studies show that the latter arguments may not be prohibitive for a dense deep-sea installation with sensitivity down to the GeV region.