

# KM3NeT: a cubic-kilometre-scale deep sea neutrino telescope in the Mediterranean Sea

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**Abstract.** The groups presently pursuing neutrino telescope projects in the Mediterranean Sea, ANTARES, NEMO, and NESTOR, formed the KM3NeT consortium [1] aiming at the construction of a cubic-kilometre-scale neutrino telescope in the Northern hemisphere to complement the sky coverage of IceCube and have an unsurpassed sensitivity and angular resolution - down to  $0.1^\circ$  at 100 TeV. This challenging project will require the installation of thousands of photon detectors with their related electronics and calibration systems several kilometres below the sea level. The realisation of this project will provide the scientific community with a very powerful instrument to study many astrophysical objects, including supernova remnants, active galactic nuclei, gamma-ray bursts and possibly also dark matter. The construction of this detector will require the solution of technological problems common to many deep submarine installations, and will help pave the way for other deep-sea research facilities. In April 2008 the KM3NeT consortium has published the Conceptual Design Report (CDR) [1] for the KM3NeT telescope. The Design Study phase has now passed its mid-point and will culminate in 2009 with the KM3NeT Technical Design Report (TDR), detailing the design and the expected physics performance of the future detector. Concurrent with the publication of the CDR, an EU-funded Preparatory Phase began, which will lead through to the start of telescope construction.

We present the physics objectives and outline the technological aspects of this new project.

**Keywords:** Neutrino telescope, Neutrino astronomy, KM3NeT

## I. INTRODUCTION

Despite the great success of astrophysics based on observations of electromagnetic radiation, some limitations appear due to photon interactions with the infrared or cosmological diffuse backgrounds, and inside their sources. Cosmic rays are another promising probe used for the understanding of the universe, but the GZK effect limits the observation depth above 100 EeV, whereas at lower energies magnetic fields deflect protons and make searches for point-like sources impossible.

The neutrino has no electrical charge and no magnetic moment, and therefore is not affected by magnetic fields; it interacts only weakly with other particles, and there-

fore is an ideal candidate for high energy astronomy. Besides, it allows for accessing the heart of the sources.

## II. NEUTRINO DETECTION PRINCIPLE WITH UNDERWATER TELESCOPES

A neutrino telescope is based on the detection of the Cherenkov light emitted in a transparent medium during the passage of a muon or more generally of one or more charged particles exceeding the speed of light in the medium, thus allowing for the reconstruction of their trajectories and energies. The primary particle that one aims to observe being a neutrino, its weak interaction requires large detection volumes, realisable in ice or deep water. The interaction of the neutrino with a nucleus in the vicinity of the instrumented area produces one charged lepton of the same flavor as the incoming neutrino, accompanied by a shower of hadronic particles at the vertex (charged current - CC - interaction:  $W^\pm$  exchange), or only one shower at the vertex, the neutrino itself being just scattered (neutral current - NC - interaction:  $Z^0$  exchange). The Cherenkov light produced by charged particles is detected by a set of photomultiplier tubes (PMTs) installed in a large volume. These PMTs are housed in pressure-resistant glass spheres, the sphere unit + PMT being called optical module (OM). The PMT signals are digitised and sent to the surface. Essential parameters are the total photocathode area  $\times$  the quantum efficiency, the time resolution ( $O(ns)$ ), the PMT sensitivity (single photo-electron), the dynamic range, the OM spatial distribution, and the optical quality of the medium in which the Cherenkov light propagates. Table I gives a summary of the required characteristics for the KM3NeT neutrino telescope. The irreducible contributions to the angular uncertainty come from the intrinsic angle between the neutrino and the secondary muon, and from light scattering and chromatic dispersion in the sea water.

The final design of the cubic-kilometer-scale neutrino telescope is not yet decided, but a typical layout has been used for first estimations of the performance of such an apparatus. The OM number, composition and arrangement in space are currently being optimised. The so-called "reference detector" is made of  $15 \times 15$  detection units carrying 37 OMs each, spaced vertically by 15.5 m. The distance between the detection units on the sea bed is 95 m. In this typical detector, each OM contains 21 3-inch-PMTs, covering essentially the downward-looking hemisphere. All the sensitivity estimates given in this

write-up are part of the CDR [1], and are made on the basis of this typical example.

The “golden channel” for neutrino telescopes are  $\nu_\mu$  CC interactions, providing high energy muons travelling over up to several kilometers in matter. The long muon track traversing the detector can be precisely reconstructed. On the other hand, the final states involving high energy electrons ( $\nu_e$  CC interactions) provide an high energy electromagnetic shower superimposed on the hadronic one at the interaction point. In this case the neutrino direction is more difficult to estimate, but a better energy reconstruction is possible; as for UHE  $\nu_\mu$  for which the secondary muon generates high energy showers on its path, the charge dynamic range of the PMTs and their readout is an important parameter.

Overall single-photon time resolution	< 2 ns
Position resolution of OMs	< 40 cm
Charge dynamic range	100 photo-electrons/25 ns
Two-hit time separation	< 25 ns
Two-photon coincidences	efficiency > 50% purity dominated by random coincidences of marine background light
Dark noise rate	< 20% of K40 rate
OM failure rate	< 10% over 10 years without major maintenance

TABLE I  
DESIGN GOALS FOR THE KM3NET NEUTRINO TELESCOPE.  
RESOLUTIONS ARE GIVEN AS RMS VALUES.

### III. SOURCES OF MUONS AND NEUTRINOS

**Atmospheric background:** the cosmic rays, made up of protons and heavier nuclei, initiate cascades in the Earth’s atmosphere, generating a large number of neutrinos and muons superimposed on the astrophysical signal:

**atmospheric neutrinos** constitute an irreducible background of  $\nu_\mu$  and  $\nu_e$ , up-going as well as down-going since the Earth is transparent at the neutrino energies involved. The main difference between these neutrinos and those of astrophysical origin resides in their energy spectrum: the atmospheric neutrino flux decreases as  $E^{-3.7}$  whereas astrophysical flux is expected to be much harder, decreasing roughly as  $E^{-2}$ , with a cutoff in the 10 TeV to 1 PeV range.

**atmospheric muons** are absorbed by the Earth and are thus downward-going only, but their number is approximately  $10^6$  times higher than the number of muons generated by the atmospheric neutrinos, at 2500 meters depth. To reduce this background, the neutrino telescopes are optimised to observe upward muons, i.e. muons produced by neutrinos having crossed the Earth. Moreover, in order to minimise the number of downward atmospheric muons, the neutrino telescopes are located at large depth, using water or ice as shielding. Indeed, the flux of vertical atmospheric muons varies by a factor 20 between depths of 5000 m and 2500 m.

**The astrophysical potential sources of neutrinos** range from Supernova Remnants to Active Galactic Nu-

clei, with a large uncertainty on the neutrino production coming from our current weak knowledge of the internal mechanisms in these objects:

**In Supernova Remnants (SNRs)** proton acceleration may lead to the production of detectable neutrinos. Current observations of SNRs in X and gamma rays do not yet allow for drawing a final conclusion on the production mechanisms of these radiations. Two models are possible: an electronic model, in which X-rays and gamma rays are produced by synchrotron radiation of electrons and by the inverse Compton effect, respectively; an hadronic model, in which protons are accelerated, generating pions by collision. The neutral pions decay in gammas, while decay cascades of charged pions provide neutrinos in the proportion  $(\nu_e, \nu_\mu, \nu_\tau) = (1,2,0)$ . On Earth, because of neutrino oscillations, this proportion becomes (1,1,1). In observations from the HESS experiment [2], the simplest electronic models are disfavored by the shape of the observed gamma spectra. A direct observation of neutrinos, even with low statistics, would clarify without ambiguity the processes involved in the SNRs. Studies have been performed to assess the potential signals from Galactic sources with TeV gamma ray emission, in the KM3NeT case [3].

**Micro-quasars** also constitute a promising source of high energy neutrinos ( $\mathcal{O}(1 \text{ TeV})$ ). They consist of a central black hole ( $M \sim 10 M_\odot$ ) whose accretion disc is fed by a companion star. Two jets, typically a light year long, are emitted perpendicularly to the disc, and their ends create lobes emitting radio waves. Like in the case of SNRs, the types of interactions within the jets are decisive for the existence of neutrino production [4][5]. Since micro-quasars are gamma ray emitters, an evaluation of the neutrino flux can be carried out on the basis of photon flux [3][6]: ANTARES or AMANDA require several years of observation to detect a micro-quasar, while a cubic kilometre-scale neutrino telescope would be more than an order of magnitude more sensitive.

**Active Galactic Nuclei (AGN)**, made up of a super-massive black hole (typically  $10^8 M_\odot$ ) and jets perpendicular to the plane of the accretion disk, are promising sources of high energy neutrinos in case of hadronic interactions within the jets [7]. Recent observations of the Auger experiment may favor this scenario [8].

**Gamma Ray Bursts (GRBs)** are observed by satellites since 1967. Most of the time, they are followed by an afterglow in X radiation, optical light, and sometimes radio waves. The isotropy of GRBs sources as well as measurements of their redshifts prove their extragalactic origin; they are associated to core-collapse supernovae explosions or merges of heavy compact objects (neutron stars, black holes). According to the most popular GRB fireball model [9], the energy of emitted neutrinos could reach 100 TeV. If the fluxes are large enough, the observation by a cubic-kilometre-scale neutrino telescope will be possible using selected time windows framing the detections by the satellites and ground based

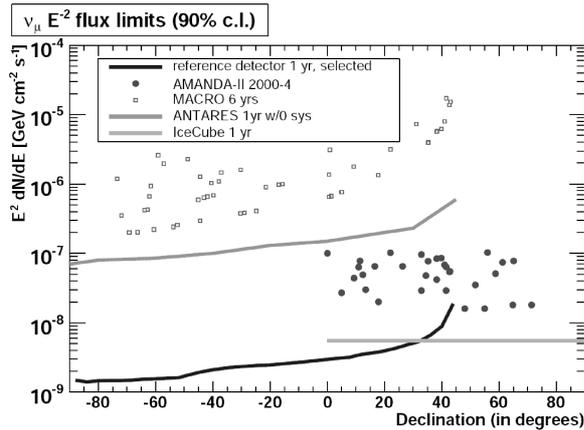


Fig. 1. Expected  $\nu_\mu$  point source sensitivity for a KM3NeT typical detector for one year data taking, assuming an  $E^{-2}$  energy spectrum (lower solid line) [1]. The upper solid line is the ANTARES expected limit and the solid line at positive declinations is the IceCube one. The filled dots and open squares are the results from AMANDA and MACRO respectively, for searches for signals from specific source candidates.

observatories [10]. Event rates have been estimated by several authors, for example see [11].

The angular resolution of a neutrino telescope in the  $\nu_\mu$  CC channel plays an important role for identifying neutrino point sources. The atmospheric neutrino background and the mis-reconstructed atmospheric muon background can be strongly reduced by the definition of a tight search cone around the direction of the source ( $\mathcal{O}(0.4^\circ)$ ). The great advantage of a deep-sea cubic-kilometre-scale neutrino telescope is its angular resolution, which is better than  $0.2^\circ$  at 10 TeV and around  $0.1^\circ$  above 100 TeV, while in ice the light scattering effect limits the angular resolution to  $0.5 - 1^\circ$ . An estimate of the neutrino energy helps to benefit from the harder energy spectrum of astrophysical neutrinos as compared to the atmospheric background.

Figure 1 shows the expected performances of the KM3NeT typical detector in point sources searches.

**Diffuse neutrino fluxes:** the sum of the whole galactic and extra-galactic sources leads to a flux of possibly detectable diffuse neutrinos. This diffuse flux is assumed to be isotropic, therefore it has to be identified by its energy spectrum which is expected to be much harder than that of the atmospheric neutrino background. In this case, the reconstruction of the neutrino direction is less important than in the point-source searches, while a better estimate of the energy is mandatory. The expected energy resolution is 0.3 in  $\log E$  for high energy muon final states. Besides, the  $\nu_e$  CC final state will contribute to the sensitivity for diffuse neutrino fluxes, thanks to the better energy reconstruction achievable in this case.

Figure 2 shows the expected performances of the KM3NeT typical detector for diffuse flux searches.

#### Conclusion on sensitivity

The neutrino energy range of central interest for  $E^{-2}$  point source searches is roughly 1 TeV to 1 PeV. Below this range, the sensitivity remains reasonable for low energies (Dark Matter range), whereas for higher

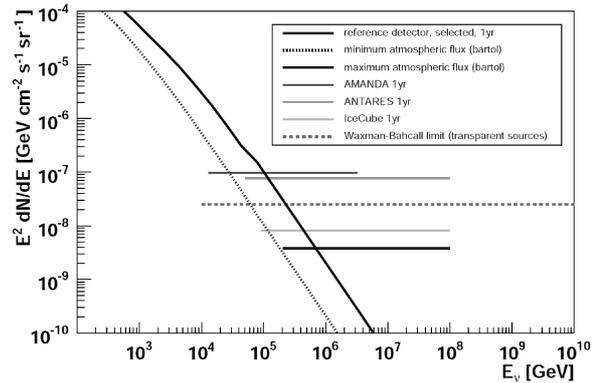


Fig. 2. Expected  $\nu_\mu$  diffuse flux sensitivity for a KM3NeT typical detector for one year data taking, assuming an  $E^{-2}$  energy spectrum (lowest horizontal line) [1]. The other horizontal solid lines, from bottom to top, are the IceCube, ANTARES and AMANDA sensitivities/upper limits for one year of data taking. The horizontal dashed line shows the theoretical Waxman-Bahcall limit, the curves falling with  $E$  indicate the band of atmospheric neutrino flux expectations.

energies, one has to take into account the absorption of the neutrinos by the Earth: the KM3NeT design has to be sensitive to downward-going neutrinos of ultra high energy (Cherenkov light from up to  $10^\circ$  above horizon).

The dependence of the sensitivity on the detector configuration has been investigated in simulation studies [12]; this process is now in its final phase. Homogeneous configurations appear as a good compromise between detectors made of separated clusters of high OM density - efficient for low energies -, and ring-shaped detectors, better suited for higher energies.

#### IV. TECHNICAL DESIGN OPTIONS

KM3NeT is foreseen to be a long-term observatory, with at least 10 years of operation without major maintenance operations. The solutions investigated are inspired mainly by the pilot projects (ANTARES, NEMO, NESTOR), by other existing deep-sea infrastructures [13], and by new developments that are conducted in collaboration with industry. The optimisation target is a cost-effective design which matches the physics goals described in the previous section.

##### A. Photo-sensors

Several options for photo-sensors housed in pressure-resistant glass spheres are under study: one or two large PMTs (8" or 10"), or several 3" PMT per OM. To remove optical background which generates mainly single photoelectrons, a local set of PMTs has to be able to distinguish one photon from two in a given time window (typically 20 ns). The charge resolution of a standard PMT (30%) does not allow for direct 1-2 photon separation on a given PMT, thus requiring local coincidences between at least 2 units. This condition is naturally satisfied in the multi-PMT OMs, in which up to 31 small 3" PMT allow for photon counting. For OMs housing only one large PMT, it is necessary to gather them into local clusters, or to use segmented photocathodes.

### B. Data acquisition and information technology

Following a concept of “all-data-to-shore”, all PMT signals above a given threshold (typically 1/3 of a single photo-electron) will be sent to the shore. The overall data rate will be of the order 100 Gb/s. On shore, a computer farm will perform the online filtering to reduce this rate by about 5 orders of magnitude.

Different options exist for the electronics performing the digitisation of the PMT signals and handling their transport to the shore [1]. Due to the large path and data rates, optical fibers will be mandatory for the communication from the shore to the basis of the detection units, while the data transmission along the detection units themselves could be performed by copper wires as well as by optical fibers.

### C. Mechanical structures and deployment

Concerning the mechanical structure, which is strongly linked to the deployment method, two major options are envisaged: detection units without horizontal extent (strings), and detection units with horizontally extended storeys (towers). The former solution can carry one multi-PMT OM per storey, or several OMs housing a single large PMT each. The latter solution, based on the principle developed by NEMO [14], is made of horizontal arms of a few meters length carrying 4 or 6 OMs each [15]. For the deployment of NEMO-like towers, a compact configuration is deposited on the sea bed, and then an acoustic signal triggers the unfolding of the tower, under the buoyancy of a buoy at its top. The wet connections between towers and junction boxes are then performed with a Remotely Operated Vehicle. Concerning strings, two options of deployment are possible: a deployment from the sea surface (ANTARES like [16]), or an unfurling deployment from the sea bed, using buoyancy or operation from surface.

### D. Deep-sea infrastructure

The deep-sea infrastructure consists of one or several main electro-optical cables connecting the shore station to a deep-sea network made of junction boxes and secondary cables. This network must be able to provide about 50 kW of electrical power to the detector and to sustain the 100 Gb/s data rate. Compliance with industrial standards will impose stringent constraints on design parameters such as the number of optical fibres or copper leads per cable. The KM3NeT infrastructure will also provide interfaces for earth and marine science instrumentation. It is foreseen that such devices are installed both in the neutrino telescope volume, if they are compatible and complementary, and in dedicated marine science nodes at some distance to the neutrino telescope to avoid adverse interferences.

### E. Calibration

An acoustic positioning set-up has to provide the OM positions with a precision better than 40 cm. This will be performed by a network of transponders and receivers,

allowing for the computation of the OM positions by triangulation. This method is currently successfully used by ANTARES [16].

The stability of the timing calibration of the OM signals will be monitored by synchronisation signals sent from shore, and using LED/Laser flashers installed in the detector.

The absolute pointing of the telescope will be checked in several ways: first, the position of each detection unit socket will be measured carefully from the sea surface, using acoustic triangulation coupled to GPS positioning and precision pressure probes. A second and independent way to check the absolute pointing may be the measurement of coincident down-going events between a sea surface detector and the deep-sea telescope. Finally, the accumulation of data will enable to use the Moon shadow on cosmic rays in order to have a clear confirmation of the absolute pointing.

### F. Towards KM3NeT construction

In the ongoing Design Study (EU FP6), the design of the KM3NeT research infrastructure will be worked out and described in the Technical Design Report (TDR) by the end of 2009. In parallel, since March 2008, a 3-year KM3NeT Preparatory Phase project (KM3NeT-PP, EU FP7) addresses the political, funding, governance and strategic issues that need to be settled before the start of construction.

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