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The KM3NeT Project(*)

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Summary. — The KM3NeT research infrastructure in the deep Mediterranean Sea will host a multi-cubic-kilometre neutrino telescope and provide connectivity for continuous, long-term earth and sea science measurements. The KM3NeT neutrino telescope will complement the IceCube telescope at the South Pole in its field of view and surpass it substantially in sensitivity. In this paper the status of the KM3NeT activities is presented.

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1. – Introduction

Observing high-energy cosmic neutrinos opens fascinating opportunities to complement the information gained through electromagnetic radiation. Neutrinos are not absorbed nor deflected on the way from their source to the Earth, they can escape dense environments, and they are inevitably produced in regions where nuclei are accelerated to the energies typical for cosmic rays.

Neutrino telescopes are designed to detect the Cherenkov light emitted by secondary particles produced in neutrino reactions in transparent target media, such as water or ice. The first generation of such detectors, AMANDA at the South Pole [1], ANTARES in the Mediterranean Sea [2] and Baikal [3] in the homonymous Siberian lake, have proven the feasibility of this concept, albeit with instrumented volumes "only" of the order of a percent of a cubic kilometre.

Over the last decade, it has become obvious that km^3-sized detectors are necessary to exploit the scientific potential of neutrino astronomy. A first detector of this size, IceCube [4], is currently being installed at the South Pole. On the other hand, Antares [2],

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Nemo [5] and Nestor [6], the three collaborations operating in the Mediterranean Sea, together with other institutions, participate to the KM3NeT consortium aiming at the construction of a km3-scale neutrino detector in the Mediterranean Sea. The KM3NeT neutrino telescope [7] is to surpass IceCube in sensitivity by a substantial factor and complement it in its field of view. In particular, it will cover the Galactic Centre and a large fraction of the Galactic plane that are hardly visible to IceCube and that contain prime candidates for neutrino emission in the high-energy regime ($E \geq$ TeV).

The KM3NeT consortium (40 Institutions from 10 countries) is funded by the EU with a Design Study in the frame of the FP6 (2006-2009) and a Preparatory Phase in the frame of the FP7 (2008-2012).

The Design Study culminated in the Technical Design Report (TDR) [8] where the main technological options for the construction, deployment and maintenance of KM3NeT are outlined and expected telescope performance presented. For selecting and optimising these solutions, physics priorities had to be defined. For KM3NeT, the prime science objective is the detection and investigation of point-like sources of neutrino emission in the energy range 1–100 TeV, *i.e.* "classical" neutrino astronomy.

The Preparatory Phase defines legal, governance and funding aspects. Production plans for the detector elements, infrastructure features and prototype validation are also defined in the Preparatory Phase as well the assessment of the single- *versus* multi-site option.

2. – Technological challenges and telescope design

The neutrino telescope will be an array of optical modules, *i.e.* photomultiplier tubes (PMTs) in pressure-resistant glass spheres, attached to vertical structures (detection units, DUs). The DUs are anchored on the sea floor and kept vertical by subtended buoys. They are connected to shore via a sea-bottom network of electro-optical cables and junction boxes.

In deep-sea neutrino telescopes coincidences inside local clusters of PMTs are essential for event selection and reconstruction to the reduce optical background from ^{40}K decays and bioluminescence. Such clusters, mounted on mechanical frames called storeys, can either comprise several optical modules with one large PMT each, or one optical module with multiple smaller PMTs.

In the KM3NeT TDR both options are presented. The single-PMT optical module proposed is a 8-inch PMTs with quantum efficiency of about 35% housed in a 13-inch sphere, namely a variant of the set-up used in Antares. The multi-PMT module is an innovative approach where 31 PMTs with 3-inch diameter are fit into one 17-inch glass sphere.

In the Design Study three design options have been investigated for the DU structure and reported in the TDR [8]: a string-like DU, a string with triangle-shape storeys and a flexible tower with horizontal extent. They all share a similar deployment concept: structures are compacted in an easily transportable and deployable configuration that is unfurled once installed on the sea-bed. The main difference in the three concepts is the horizontal distance between PMTs on the same DU. The deployment technique has been successfully tested both for the string-like DU and for the flexible tower DU.

Within the framework of the Preparatory Phase, the consortium is presently undergoing a selection phase of the different options considered. The final aim is the construction of a pre-production model of the detection unit for its final validation.

KM3NeT is a deep-sea multidisciplinary observatory in the Mediterranean Sea that will provide innovative science opportunities for neutrino astronomy but also for Earth and Sea Science. This will be possible through the synergy created by the use of a common infrastructure allowing for long-term continuous operation of a neutrino telescope and marine instrumentation. The technical specifications for the deep-sea infrastructure as well as installation, deployment and maintenance procedures, have been addressed in the Design Study taking into account also the requirements for marine and environmental research activities. The deep-sea cable network consists of one or few main electro-optical cables from shore to primary junction boxes, from where it branches via secondary junction boxes to the DUs. Since the footprint of the detector is not yet decided, the exact configuration of the network is still open. The functionalities of cables, connectors and junction boxes in terms of electrical power distribution and data transmission have been studied in detail and are well defined. They will be implemented based on the existing experience from ANTARES and NEMO. The overall power consumption will be about 125 kW and in the all-data-to-shore scenario the data rate sent to shore will be of the order 25 GByte/s. Continuous position and orientation calibration is necessary to account for the movement of the DUs in the sea current. As in ANTARES, acoustic triangulation methods will be applied, together with orientation measurements by compasses and tilt-meters.

3. – Physics sensitivity and cost

Detailed Monte Carlo simulations have been performed taking into account signal, atmospheric neutrino and atmospheric muon events. Simulation studies have been central in optimising design parameters, in particular with regard to the detector geometry. The results shown here are for a telescope based on flexible towers equipped with large PMTs, but a very similar sensitivity has been obtained for a string detector with multi-PMT OMs for equivalent cost. As already mentioned the telescope has been optimised for point-like sources with E^{-2} spectrum.

The full KM3NeT neutrino telescope will instrument a water volume of 4 to 5 cubic kilometres and thus by far outperforms the initial target of the KM3NeT Design Study, *i.e.* a price tag of 200 million Euro per instrumented km^3 of water. The sensitivity and discovery potential (1 year) of the full KM3NeT detector to point sources emitting a neutrino flux proportional to E_ν^{-2} is shown in fig. 1 as a function of the declination of the source. Sensitivity and discovery potential are calculated with a binned analysis using the Feldman and Cousin method. The shape of the sensitivity curve reflects declination dependences of the visibility, the effective area and the Earth's transparency to neutrinos. Also indicated are the corresponding IceCube sensitivity and discovery potential. The declinations of the TeV gamma sources in the Galactic plane which are prime candidates for high-energy neutrino emission are reported in red on the x-axis of fig. 1. The KM3NeT sensitivity is better than that of IceCube over a large fraction of the full sky (about 3.5π sr), by more than half an order of magnitude on average. There is room for further improvement by optimising the event selection and reconstruction procedures, exploiting energy information and/or using unbinned analysis methods.

4. – Project development and prototypes

A major effort towards the choice of technical solutions started after the conclusion of the Design Study. The aim to be achieved within the Preparatory Phase is the construc-

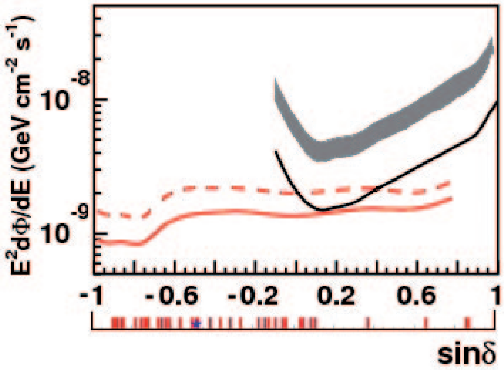

Fig. 1. – (Color online) Sensitivity and discovery potential of the full KM3NeT neutrino telescope to neutrino point-like sources with fluxes proportional to E_ν^{-2} as a function of declination δ (red line extending to $\delta = -90°$). The sensitivity is inferred from a binned analysis of simulation data. The vertical axis indicates the expected exclusion limit at 90% CL for 1 year of livetime. Also shown is the corresponding IceCube sensitivity (black dashed line at positive declinations, taken from [9]). The tick marks in the lower panel indicate the positions of TeV gamma sources in the Galactic plane, the blue star marks the Galactic Centre.

tion of a pre-production model of the DU and its validation. A flexible tower equipped with two multi-PMT OMs per storey is expected to show the best perfomance.

A multi-PMT OM prototype with 31 3″ PMTs is under construction (fig. 2a) and will be tested in the next months. High-voltage bases with a power consumption as low as 140 mW for a complete optical module have been designed for this application. The PMT signals will be processed by dedicated front-end electronics recording time-over-threshold information for each signal and hosted in the OMs. The PMTs cover the directions of view from vertically downwards to about 45° upwards. They are supported by a foam structure and coupled to the glass sphere by optical gel. The overall photocathode area

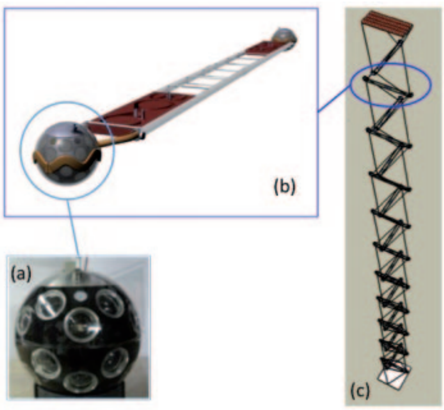

Fig. 2. – (a) Prototype of a multi-PMT optical module; (b) preliminary design of a detection unit storey with multi-PMT optical modules; (c) schematic view of the flexible tower detection unit.

in one such optical module exceeds that of a single-PMT one by more than a factor of three; a further increase is possible by extending the light collection area using reflective rings. The multi-PMT design provides very good separation between single- and multiple-photon hits and some information on the photon direction.

At the same time the design of a flexible tower adapted to host multi-PMT OMs is under way. The flexible tower consists of an anchor unit and 20 horizontal bars of about 6 m length at vertical distances of about 40 m. Adjacent bars are connected by a tetrahedral set of Dyneema ropes, so that they are oriented orthogonally to each other (fig. 2c). Each bar is equipped with 2 multi-PMT optical modules, one at each end (fig. 2b). The main advantage of this kind of structure is that the 3D-arrangement of the OMs in a single DU allows a better track reconstruction by removing the azimutal ambiguties.

A backbone cable along the DUs has been designed for power and data transport, with the target to reduce the numbers of penetrators and connectors (which are expensive and failure-prone) and to implement a topology without major single-point failures. This cable consists of an oil-filled hose with copper conductors and optical fibres inside, operated at equi-pressure with the ambient sea water. At each storey, a break-out unit provides connectivity to one fibre and two copper conductors. The optical network is set up in a star-like topology branching off an optical multiplexer located roughly in the middle of a DU. A prototype of this backbone design has been successfully tested; further verification steps are under way.

A site decision has to be taken inside the Preparatory Phase. Currently, three sites (near Toulon, at the east coast of Sicily and at the west coast of the Peloponnesus) have been proposed. The multi-site *vs.* single-site option is also under investigation.

Once these decisions have been taken, and after the technology validation that will be provided by the pre-production model, the final technical design of the KM3NeT Research Infrastructure will be laid down in a detailed proposal. Assuming that funding, legal and administrative issues are sorted out by then, it will be possible to launch production at that point.

Data taking will start as soon as the first DUs are operational. From a very early stage of its construction on, the data from the KM3NeT neutrino telescope will exceed data from first-generation Northern-hemisphere neutrino telescopes in quality and statistics and thus provide an exciting discovery potential.

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