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Performance of the KM3NeT high-energy neutrino telescope

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Summary. — KM3NeT is a European deep-sea research infrastructure incorporating a neutrino telescope with a volume of a few cubic kilometre at the bottom of the Mediterranean Sea. Detector response to point-like sources is presented in terms of sensitivity (flux that can be excluded at 90% CL) and discovery potential (flux that can be detected at 5σ above the background noise).

PACS `95.55.Vj` – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors.
PACS `29.40.Ka` – Cherenkov detectors.

1. – Introduction

The observation of extraterrestrial high-energy neutrinos will provide unique information on the most violent and highest energy processes in our Galaxy and far beyond. Their measurement will allow for new insights into the acceleration mechanisms, clarifying the role of the hadronic component. Candidate neutrino sources in the cosmos are numerous, such as supernova remnants, pulsars and microquasars in the Galaxy, while possible extragalactic sources include active galactic nuclei and gamma-ray bursts. On Earth, neutrinos are detected indirectly through muons produced in weak charged current interaction. In transparent media, muon tracks can be reconstructed detecting light produced via Cherenkov effect, with 3D arrays of optical sensors. High-energy neutrino astronomy requires detector volumes of the km^3-scale hosted in deep water or in deep Antarctic ice, where several thousands of metres of water (or ice) reduce the flux of atmospheric muons by several orders of magnitude.

KM3NeT is an international consortium with the aim to build a research infrastructure in the Mediterranean Sea hosting an underwater multi-km^3 high-energy neutrino telescope. This project has been funded by the European Union with a Design Study

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(2006–2009) and a Preparatory Phase (2009–2012). The Km3NeT Design Study was concluded with the publication of the Technical Design Report (TDR) [1] that outlines the main technologies. The detector design presented in the TDR is optimised for the detection of point-like sources with a power law energy spectrum E^{-2} in the TeV–PeV energy range. A final design, based on detection units (DU) made of flexible towers hosting the photomultipliers (PMT), has been defined at the end of 2010. The detector is made of two building blocks consisting of 154 DUs arranged on the seabed in a roughly circular layout. The positions are irregular at the level of 20 m and the average distance is about 180 m. Each DU is a sequence of 20 rigid bars, 6 m long, placed orthogonally to each other with a vertical spacing of 40 m. Each bar is equipped with two optical modules containing 31 PMTs with a diameter of about 3 inch and a 30% peak quantum efficiency.

2. – Simulation of telescope performance and results

The simulation of detector response to astrophysical neutrino fluxes provide a guideline for detector design and optimisation. The software used in this work has been developed by the ANTARES Collaboration [2] and adapted to km^3-scale detectors. The code provides a complete simulation of the incident neutrinos of energy in the range 10^2–10^8 GeV, including their interaction in the medium and the propagation of the resulting secondary particles, the light generation and propagation in water and the detector response. The backgrounds due to atmospheric muons and neutrinos, both produced by the interaction of primary cosmic rays with the atmosphere, and the optical background (^{40}K and bioluminescence) are also considered. Atmospheric neutrinos are isotropically generated assuming the Bartol Flux [3], while atmospheric muons are simulated through MUPAGE [4]. After the event generation, a track reconstruction algorithm [5] is employed to estimate muon (and consequently neutrino) direction from the arrival times of the photons on the PMTs. The simulated events are analysed through statistical technique to identify a weak neutrino signal from a cosmic source amongst the large background of atmospheric muons and neutrinos. For point-like source the principal features that distinguish signal from background are the angular and energy distribution. In fact, the background is isotropically diffused while the signal is clustered around the direction of the neutrino source with a spread depending on the detector angular resolution. Moreover, the differential energy spectrum of the signal expected from Fermi acceleration mechanisms is close to E^{-2}, harder than that of atmospheric neutrinos due to the showering process in the atmosphere, that approximately follows a power law of $E^{-3.7}$ above 100 GeV. According to the statistical approach applied in this work (the "binned" method), the sky is divided into bins of declination and right ascension and the fluctuations on the number of detected events are analysed inside each bin. Two quantities are evaluated to describe the detector performance: the discovery potential and the sensitivity. The discovery potential is calculated optimising event selection to minimise the true signal flux required to obtain an observation at significance level of 5σ with 50% probability [6]. The selection is based on the size of the search cone around the source, the track reconstuction quality parameter and the number of hit PMTs which is related to the neutrino energy. When no significant signal eccess is observable, experiments can only set an upper limit. In this case, the same kind of event selection described above is optimised to minimise the upper limit that can be placed on the neutrino flux model

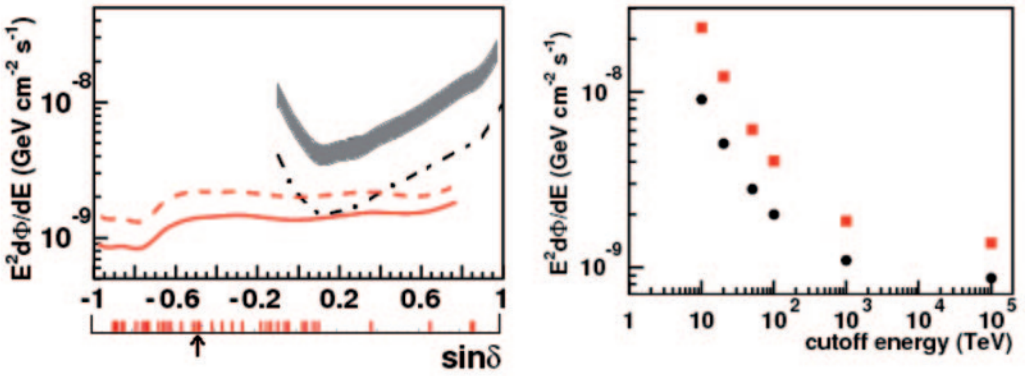

Fig. 1. – Left panel: discovery flux (5σ, 50% probability; dashed line) and sensitivity (90% CL; full line) of the full KM3NeT detector to neutrino point sources with an E^{-2} spectrum for one year of observation, as a function of the source declination. Both are estimated with the binned analysis method. The dash-dotted line is the IceCube flux sensitivity for one year, estimated with the unbinned method and a likelihood that exploits the reconstructed energy information [8]. IceCubes discovery flux (5σ, 50% probability) is also indicated (shaded band). Right panel: evolution of the one year flux sensitivity (90% CL; dots) and discovery flux (5σ, 50% probability; squares) for point sources at a declination of $-60°$ as a function of the assumed cut-off of the energy spectrum.

from a source, if no signal is detected [6]. This average flux limit is called sensitivity and it is calculated following the Feldman-Cousins approach [7].

Figure 1 shows sensitivity and discovery potential of the full KM3NeT telescope for one year of observation. In the left panel of fig. 1 sensitivity and discovery potential are calculated as a function of source declination assuming a neutrino energy spectrum proportional to E^{-2}. For comparison, the plot also shows the same quantities for the IceCube neutrino telescope placed at the South Pole. The position of galactic gamma-ray sources [9] that are candidate neutrino sources is shown by red ticks at the bottom of the horizontal axis while the position of the Galactic Centre is indicated by an arrow. Galactic sources are expected to extent to lower energies with respect to extragalactic ones. The dependence of discovery flux and sensitivity flux on the cut-off energy is shown in the right panel of fig. 1 for a point-source at a declination of $-60°$. When the cut-off energy decreases from 1 PeV to 10 TeV the sensitivity worsens by an order of magnitude.

In conclusion, KM3NeT extends substantially the visible region of the sky with respect to IceCube and even improves the discovery potential in the same field of view. Most of galactic sources are in the field of view covered by KM3NeT and for several of them a significant detection after some years of observation time is expected, as confirmed by a dedicated study for the RXJ1713.7-3946. Simulations aiming at futher optimisation of the detector layout and reconstruction algorithms for known sources (*i.e.* RXJ1713.7-3946) are ongoing.

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