Journal of Physics:
Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: Silvia Celli and the KM3NeT Collaboration 2021 *J. Phys.: Conf. Ser.* **2156** 012105

Journal of Physics: Conference Series **2156** (2022) 012105 doi:10.1088/1742-6596/2156/1/012105

KM3NeT: status and perspectives for neutrino astronomy from the MeV to the PeV

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Abstract. KM3NeT is a multi-purpose neutrino observatory, being currently deployed at the bottom of the Mediterranean Sea. It consists of two detectors: ORCA and ARCA (for Oscillation and Astroparticle Research with Cosmics in the Abyss, respectively). ARCA will instrument 1 Gton of seawater, with the primary goal of detecting cosmic neutrinos with energies between several tens of GeV and PeV. Due to its position in the Northern Hemisphere, ARCA will provide an optimal view of the Southern sky, including the Galactic Center. In April 2021, a major step has be taken in the construction of ARCA, bringing the number of detection lines from one to six. ORCA, also currently running in a six-string configuration, is a smaller ($\sim$ few Mtons) and denser array, optimized for the detection of atmospheric neutrinos in the $1 - 100$ GeV. It can also perform low-energy neutrino astronomy studies, e.g. searching for MeV-scale neutrinos expected at core-collapse supernovae. In this contribution, some of the key scientific cases in the field of neutrino astronomy are reviewed and perspectives for their investigation with KM3NeT are presented.

1. Introduction

KM3NeT [1] is a three dimensional array of photo-sensors that can detect the time, position and charge deposit of Cherenkov hits induced by the passage in water of ultra-relativistic charged particles produced at neutrino interactions, thus allowing the reconstruction of the incoming neutrino direction and energy. The ORCA detector is located in French waters, $\sim$ 40 km offshore Toulon at $\sim$ 2.5 km depth, while the ARCA one is based in Italian waters, $\sim$ 80 km offshore Sicily at $\sim$ 3.5 km depth. The two instruments take advantage of the same technology, consisting into a collection of Digital Optical Modules (DOMs), glass spheres hosting 31 $3''$ photo-multiplier tubes (PMTs) as well as the electronics for data acquisition and calibration. 18 DOMs compose a Detection Unit (DU), 115 DUs making up a Building Block (BB). Besides the different location and depth, ORCA is a smaller and denser array with respect to ARCA: the former apparatus instruments DOMs on the same DU at a distance of 9 m while DUs are separated from each other by an average distance of $\sim$ 20 m; in turn, DOMs in a ARCA DU are located at a distance of 36 m while DUs are $\sim$ 90 m apart. In the so-called Phase 2.0 configuration, one BB will be completed in ORCA, while two are expected in ARCA. The current infrastructure hosts six DUs in ORCA, in stable data acquisition since January 2019, and six more in ARCA, operative since April 2021. The different geometry of the detectors allows ORCA and ARCA to explore different energy ranges of the interacting neutrinos: ORCA is optimized for the detection of sub-TeV neutrinos, thus accessing the physics of neutrino oscillations in the atmospheric sector, mainly aiming at the determination of the neutrino mass hierarchy [2];

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ARCA, in turn, has enhanced sensitivity in the multi-TeV domain, where it can fully exploit its potential for observing astrophysical neutrino sources. Neutrino astronomy will be the object of the next Section, where three key scientific cases are investigated: in Sec. 2.1 the prospects for detecting MeV neutrinos from core-collapse supernovae (CCSNe) are described; in Sec. 2.2 the KM3NeT sensitivity towards the observation of point-like sources is shown, as well as its role in assessing and quantifying the hadronic nature of the radiation observed from interesting Galactic sources; finally, in Sec. 2.3 the expectations for measuring a diffuse flux of cosmic neutrinos at the level of the one currently detected by IceCube are discussed. Effective areas of the ORCA6 and ARCA6 detector configurations are presented in Sec. 3, and conclusions are drawn in Sec. 4.

2. Neutrino astronomy at multi-energy scale

Above 100 TeV a flux of diffuse cosmic neutrinos has been detected by IceCube on top of the atmospheric background [3], though to date the origin of such neutrinos remain unveiled. Complimentary KM3NeT observations will be of paramount importance in several aspects: firstly, these will allow to further investigate the spectral and angular distribution of cosmic events, thanks to its optimal energy ($\sim$ 5% for contained events) and angular ($< 0.1^\circ$ for muon-induced events resulting from neutrinos with energy above 100 TeV) resolution, providing multi-flavor precision astronomy; secondly, KM3NeT will clarify the contribution of Galactic sources to such a flux, thanks to its location in the Northern Hemisphere, ensuring a clean visibility of the Galaxy with the upgoing track-like event set, naturally filtered by the Earth out of the abundant atmospheric muon flux. Additionally, the excellent angular resolution achieved for muon tracks is crucial for limiting the contribution of atmospheric neutrinos to this event set. The combination of these characteristics is expected to provide unique insight into the new-born field of neutrino astronomy, as shown in the following for some key scientific cases.

2.1. MeV neutrinos: the case of core collapse supernovae

CCSNe are catastrophic events, which mark the end of a massive star's life and the birth of a neutron star or a black hole. In a typical CCSN, an amount of energy as large as 10^{53} erg can be released in about 10 s, mainly through the emission of a burst of neutrinos with mean energy of $\sim 10-20$ MeV. The interaction of a neutrino with energy below 100 MeV produces a charged lepton traveling up to a few tens of centimeters. However, because the spacing between DOMs in both the KM3NeT detectors only allows the reconstruction of sufficiently extended or bright events (above a few GeVs), the Cherenkov signatures of multi-MeV neutrinos cannot be reconstructed as individual events. Hence, the detection of CCSN neutrinos relies on the observation of a population of coincidences in excess over the background expectation, taking into account all the DOMs in the detector [4]. A coincidence is defined by allowing a maximal time difference of 10 ns between the hit times. The number of PMTs hit in a coincidence is defined as the *multiplicity*. Radioactive decays dominate at low multiplicities, while the contribution of atmospheric muons becomes relevant around multiplicity 6, prevailing above 8. The latter background can be reduced by exploiting the fact that muon tracks typically produce correlated coincidences on multiple DOMs: as shown in Fig. 1, such a filtering can allow ORCA to achieve lower background values than ARCA, thanks to the fact that the denser array can more efficiently identify low-energy atmospheric events. In turn, the CCSN neutrino flux depends on several factors, e.g. the stage when the neutrino signal is emitted, the neutrino luminosity (depending on the progenitor's mass), the star's distance and the spectral slope of neutrino injection. Evaluating the signal in a time window extending 500 ms after the onset of the core-collapse event, corresponding to the typical duration of the accretion phase of the $\bar{\nu}_e$ burst, a detection in KM3NeT is expected at multiplicity values higher than 7 for a reference luminosity of $L_{\bar{\nu}_e} = 4\times10^{52}$ erg, a distance of 10 kpc, a spectral slope $\alpha = 2$, and a progenitor mass of $11M_{\odot}$ and higher. Furthermore, accounting for the expected distribution of CCSNe as a function of the distance to the Earth, the KM3NeT sensitivity estimations towards a CCSN neutrino burst indicate that more than 95% of the Galactic core-collapse supernovae are potentially observable by this detector, in the scenario with progenitor's mass of $11M_{\odot}$ (Fig. 1).

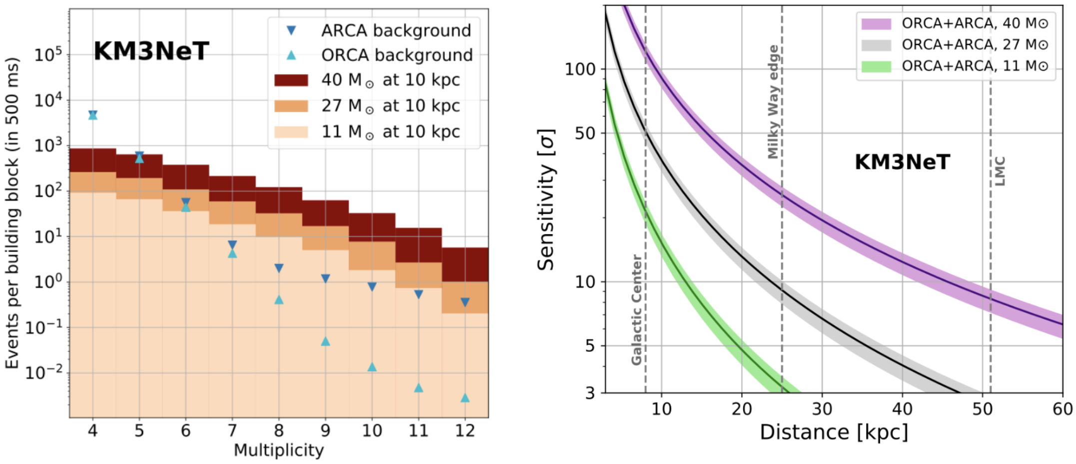

Figure 1. Left: Expected number of events in a KM3NeT BB as a function of the multiplicity, where signal is calculated for different progenitor's mass models. **Right:** KM3NeT (ARCA 2 BBs and ORCA 1 BB) detection sensitivity as a function of the distance to the CCSN [4].

2.2. Very-high-energy neutrino sources in the Galaxy

Detailed spectroscopic and morphological studies in multi-TeV gamma rays have unveiled a variety of energetic sources located in the Plane of the Galaxy. Among these, the most interesting ones are supernova remnants (SNRs), particularly because of the fact that these have been longly believed to be the major contributors to the cosmic-ray (CR) flux observed at Earth up to energies around the *knee* region. In most of the cases, however, the observed radiation has not been clearly addressed to hadronic or leptonic nature, thus preventing any firm conclusion about the origin of Galactic CRs. In this context, the role of neutrinos in clearly identifying proton accelerators is crucial, and in particular the role of KM3NeT because of its strategic position for observing the Galactic Plane, which has been shown to be populated of PeVatron accelerators [5]. This can be appreciated exploring the KM3NeT sensitivity towards a neutrino flux arising from a point-like source located in different sky positions: by using a sample well reconstructed either horizontal or upward-going tracks and implementing a maximum likelihood technique based on pseudo-experiment simulations, 90% confidence level (CL) exclusion limits are determined on flux normalization parameters of both signal and background (for a signal slope of the neutrino differential energy spectrum fixed to 2). In Fig. 2 the results are shown in comparison to similar studies performed with 13 years of ANTARES data taking [6], and 7 years for IceCube [7]. As visible, KM3NeT will increase the sensitivity to neutrino fluxes from point sources by more than a decade at negative declinations with respect to current generation telescopes. The sensitivity should be compared with the expected neutrino flux from e.g. interesting sources located in the Galactic Plane: the latter can be computed individually for each source directly from the observed gamma-ray ones in case these are produced as a result of *in situ* proton-proton collisions, and that no absorption of radiation has occurred from the source to the Earth [8]. The expected KM3NeT/ARCA 90% CL sensitivity is shown in Fig. 3 for the brightest TeV SNR, RX J1713.7-3946, as well as HAWC J1825-134, HAWC J1907+063, and HAWC J2019+368. The analysis demonstrates the capability of the KM3NeT detector to achieve a compelling sensitivity level for 3 of the 4 considered sources in less than 4 years. Interestingly, for the most promising source, HAWC J1825-134, a significant sensitivity is achieved approximately in 1 year.

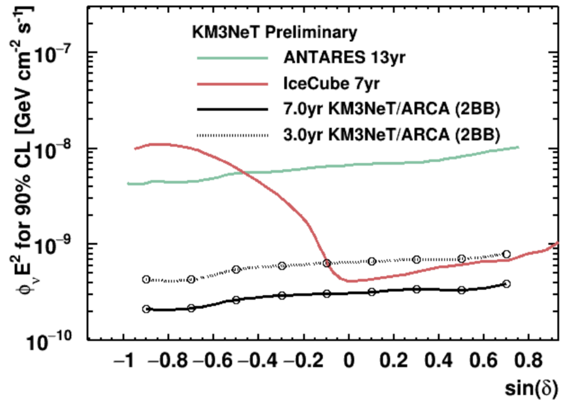

Figure 2. Flux normalization 90% CL upper limits on an E^{-2} differential energy flux of neutrinos from a point-like source with KM3NeT/ARCA (2 BBs) [8], in comparison with ANTARES [6], and IceCube [7].

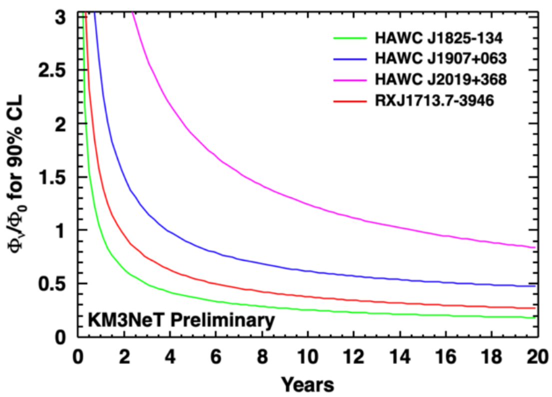

Figure 3. KM3NeT/ARCA (2 BBs) sensitivity at 90% CL towards few interesting sources located in the Galactic Plane, including SNRs, already known in very-high-energy gamma rays [8].

2.3. The diffuse cosmic neutrino flux

The detection and detailed investigation of the astrophysical flux observed by IceCube is one of the main physics goals of KM3NeT/ARCA. In order to explore the detector capabilities towards observing such a flux, an optimized study is performed by assuming that: i) it originates from an isotropic, flavor-symmetric cosmic neutrino flux, and ii) the single flavor differential energy spectrum follows a power law with a cut-off at a few PeV, given by

$$\frac{dN_\nu}{dE_\nu} = 1.2 \times 10^{-8} \left(\frac{E_\nu}{\mathrm{GeV}}\right)^{-2} \exp\left(-\frac{E_\nu}{3\ \mathrm{PeV}}\right) \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\,. \tag{1}$$

Analysis results are shown in Fig. 4, indicating that a high-significance (5σ) detection of the diffuse neutrino flux will be possible exploting a combined event set, made of both track-like and cascade-like events, within one year of operation of one KM3NeT/ARCA BB.

3. Performances of ORCA6 and ARCA6

The KM3NeT configuration consisting of six DUs in the ORCA site is the so-called ORCA6, while it is identified as ARCA6 relatively to six DUs in the ARCA site. A crucial parameter for determining the detector performances is the effective area, which also allows a direct comparison to other existing experiments. This is shown in Fig. 5 with respect to muon neutrino and antineutrino charged current interactions, resulting into muon tracks. Simulated Monte Carlo (MC) samples, selected as to obtain high-purity upward-going neutrino events, shows that at energies below 10 TeV ORCA6 is expected to have a comparable effective area to the ANTARES telescope [9], while at higher energies ARCA6 performs significantly better. Furthermore, already in the six-string configuration, the ARCA6 detector can achieve a median angular resolution of 0.75° for track-like events [10].

4. Conclusions

The construction of the KM3NeT infrastructure is ongoing in two designated sites, where data taking is currently ongoing. The first data collected have shown a good data/MC agreement, indicating a solid understanding of the detector. At this level, the KM3NeT effective area is

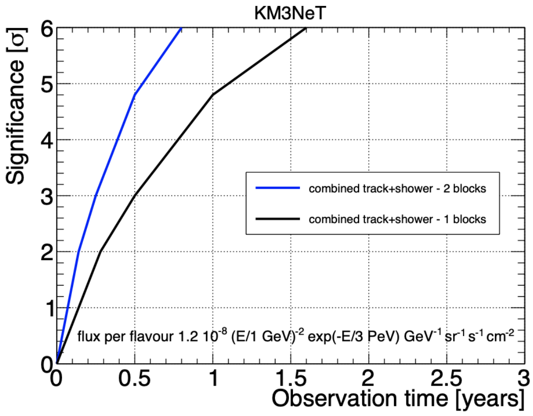

Figure 4. Significance as a function of time for the detection of a diffuse flux of neutrinos corresponding to the signal reported by IceCube, combining cascade-like and track-like events, with either one (black line) or two (blue line) KM3NeT/ARCA BBs.

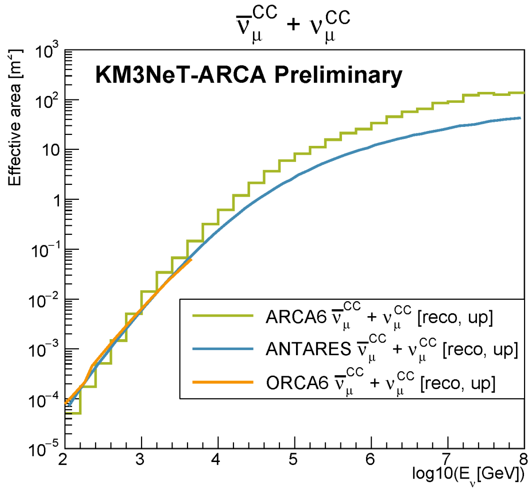

Figure 5. Effective area towards muon neutrino charged current interactions, reconstructed as upgoing in KM3NeT/ARCA6 (green), ANTARES (blue) and KM3NeT/ORCA6 (orange).

already significantly better than the ANTARES one for neutrino energies above 100 TeV. The full extension of the detector will allow to exploit key scientific cases, including i) MeV scale neutrino emissions as a result of CCSNe, ii) multi-TeV neutrinos from point-like and extended sources, particularly those located in the Galactic Plane, and iii) diffuse cosmic neutrinos. Additional science cases can be investigated with water Cherenkov neutrino telescopes, ranging from neutrino physics studies to exotic scenarios of neutrino production.

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