The KM3NeT neutrino telescopes in the Mediterranean Sea: Current status and prospects focusing on KM3NeT/ORCA

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Abstract. The KM3NeT research infrastructure is building second-generation neutrino telescopes in the depths of the Mediterranean Sea. The KM3NeT/ARCA detector at a depth of about 3500 m off the coast of Sicily, Italy, focuses on the detection of high energy (E > TeV) neutrinos from astrophysical sources. The KM3NeT/ORCA detector at a depth of about 2500 m off the coast of Toulon, France, is aimed at studying low energy (E > GeV) atmospheric neutrinos for measuring the neutrino mass hierarchy and for gaining insight on fundamental neutrino properties. In this contribution, results obtained during the early stages of the detector construction as well as the expected performance of the completed detectors are presented.

1 Introduction

The current knowledge about the Universe comes mostly from photons and cosmic rays. Theoretical models predict the copious production of high energy neutrinos (> TeV) by hadronic acceleration in the environment of astrophysical sources. Neutrinos, being neutral and weakly interacting, are not deflected by galactic and extra-galactic magnetic fields and are not significantly absorbed by interstellar matter. They point to their sources over all energy ranges and distance scales, and hence are uniquely valuable as cosmic messengers. The detection of neutrinos from astrophysical sources and the measurement of their flux can therefore pave the way towards answering basic questions about the origin and nature of cosmic rays and shed light on the acceleration mechanism of ultra-high energy cosmic rays, which remains elusive, although more than a century has passed since their discovery.

The determination of fundamental neutrino properties is of great importance to the theory. The discovery of neutrino oscillations, implying that neutrinos have non-zero masses, is the first deviation from the Standard Model (SM) prediction and suggests the existence of new physics beyond the SM. The determination of the neutrino mass hierarchy and neutrino oscillation parameters is of key importance for establishing the theoretical framework for neutrino oscillations.

The KM3NeT Collaboration is building two neutrino telescopes in the depths of the Mediterranean Sea, ARCA and ORCA, with a broad physics programme that includes both neutrino astronomy and fundamental neutrino physics. The main physics goals of the two detectors are different, hence they have a different geometry, but they share the same technology. The ARCA (Astroparticle Research with Cosmics in the Abyss) detector focuses

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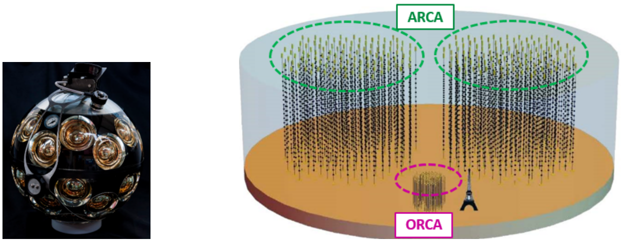


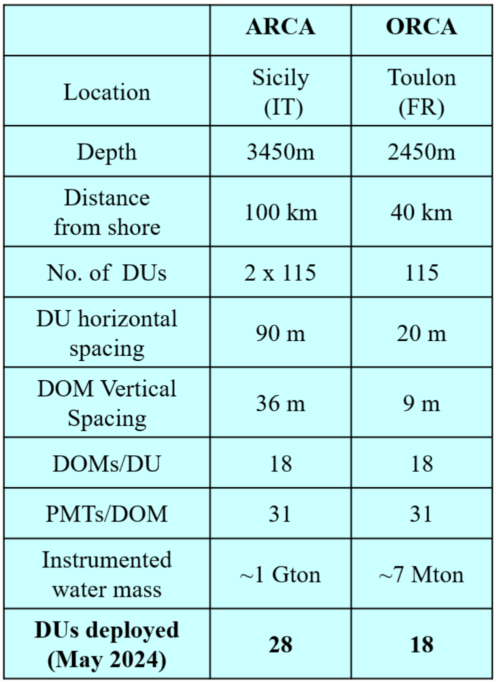
Figure 1. The KM3NeT DOM (left); an illustration of the ARCA and ORCA detector configurations (right).

on the detection of high energy ($E >$ TeV) neutrinos from astrophysical sources and on the identification of these sources. The ORCA (Oscillation Research with Cosmics in the Abyss) detector is designed for studying atmospheric neutrino oscillations in the energy range 1 - 100 GeV. Atmospheric neutrinos are generated by cosmic ray interactions in the Earth's atmosphere, at all zenith angles and over a wide energy spectrum, and their large propagation distance makes them ideal for studying neutrino oscillations. The ORCA detector is aiming to determine the neutrino mass hierarchy and to provide improved measurements of neutrino oscillation parameters.

2 The KM3NeT detectors

The KM3NeT collaboration [1] is constructing two water Cherenkov neutrino telescopes at two different sites in the Mediterranean Sea. ARCA is located at a depth of $\sim$ 3500 m, offshore Portopalo di Capo Passero in Sicily, Italy and when completed, it will comprise two Building Blocks (BBs) instrumenting a volume of about a cubic-kilometer. ORCA is located at a depth of $\sim$ 2500 m, offshore Toulon, France and will comprise one densely built block instrumenting a mass of about 7 Mtons of water. Both detectors share the same technology. Each BB will host 115 Detection Units (DUs) which are vertical lines anchored to the seabed, each holding 18 Digital Optical Modules (DOMs) [2]. The DOMs are pressure-resistant glass spheres, each housing 31 3-inch photomultiplier tubes (PMTs) and the associated electronics. Each DOM is equipped with a compass, a tiltmeter and a piezo-electric sensor to allow for an estimation of their orientation and position, as the shape and orientation of the DUs are affected by the sea currents. The distances between the DUs as well as the vertical spacing between DOMs on the same DU are different for the two detectors since they probe different energy ranges, and therefore the detector configurations are optimised for the corresponding physics goals. The KM3NeT DOM, an optical sensor with an innovative design, is shown in Figure 1 together with an illustration of both detector geometries. A table with the main characteristics of the two detection configurations, is shown in Figure 2.

As neutrinos are weakly interacting particles, large volumes of water need to be instrumented in order to accumulate significant statistics of neutrino events to achieve the physics goals. Neutrino detection is based on the observation of the Cherenkov light induced by relativistic charged particles produced in charged-current (CC) and neutral-current (NC) neutrino interactions. The Cherenkov photons can produce signals ("hits") in the PMTs. The photon arrival time and the position and direction of the hit PMTs are used to reconstruct the neutrino direction and energy. Different trigger conditions and reconstruction algorithms are employed for the two main event topologies: track-like events, when Cherenkov photons are emitted along the muon track from CC $\nu_\mu/\bar{\nu}_\mu$ interactions or CC $\nu_\tau/\bar{\nu}_\tau$ interactions with a muon in



	ARCA	**ORCA**
Location	Sicily (IT)	Toulon (FR)
Depth	3450m	2450m
Distance from shore	100 km	40 km
No. of DUs	2 x 115	115
DU horizontal spacing	90 m	20 m
DOM Vertical Spacing	36 m	9 m
DOMs/DU	18	18
PMTs/DOM	31	31
Instrumented water mass	~1 Gton	~7 Mton
DUs deployed (May 2024)	**28**	**18**

Figure 2. The characteristics of the ARCA and ORCA detector configurations.

the final state, and shower-like events with a point-like emission of Cherenkov photons due to the electromagnetic and/or hadronic showers produced in CC $\nu_e/\bar{\nu}_e$ interactions, all other CC $\nu_\tau/\bar{\nu}_\tau$ interactions and all flavour NC $\nu/\bar{\nu}$ interactions.

In addition, the design of the KM3NeT DOM makes it possible to use the PMT hit multiplicity within a short time window in a single DOM to detect O(10) MeV neutrinos from Core-Collapse supernovae (CCSN) and distinguish the signal from the main KM3NeT background sources as well as from atmospheric or astrophysical neutrinos.

The vast majority of the triggered events are due to the decay of ^{40}K in sea water, to bioluminescence and to atmospheric muons produced together with atmospheric neutrinos by cosmic ray interactions in the Earth's atmosphere. Although the detectors are deployed in great depth to provide shielding from the atmospheric muon background, a fraction of down-going muons can still reach the detector and produce measurable signals. In order to suppress the background from atmospheric muons, only events reconstructed with an up-going direction are considered, since the Earth provides screening against all particles except neutrinos.

The results presented here have been obtained during an initial phase of both detectors: ORCA comprising of 6 DUs, referred to as ORCA6, and ARCA comprising of 6-21 DUs, referred to as ARCA6-21.

3 Atmospheric neutrinos with the ORCA detector

3.1 First results from the ORCA6 detector

The atmospheric muon neutrino flux has been measured with ORCA6 data [3] in the energy range between 1 GeV and 100 GeV, an energy region where only few measurements exist by other experiments. A high-purity sample of atmospheric neutrinos is selected. The energy spectrum of $\nu_\mu(\bar{\nu}_\mu)$ CC events is extracted by unfolding the experimentally measured energy distribution of the selected events. The measurement is shown in Figure 3 and it is found in good agreement with the HKKM14 conventional flux model [4].

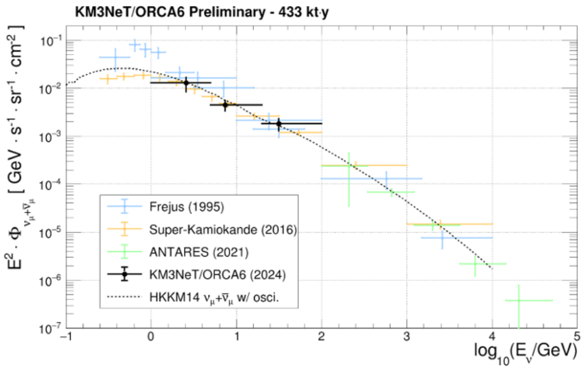


Figure 3. The atmospheric neutrino flux measurement using ORCA6 data is compared with measurements from ANTARES, Super-Kamiokande and Frejus.

For the neutrino mass hierarchy measurement as well as for neutrino astronomy, both a good reconstruction of the neutrino direction and a reliable estimate of its energy are mandatory. The small size of the ORCA6 detector limits the energy resolution for high energy muon tracks emerging from CC $\nu_\mu/\bar{\nu}_\mu$ interactions. The good performance of the ORCA6 detector in terms of pointing accuracy is inferred from the observation of the atmospheric muon shadowing effect due to the absorption of primary cosmic rays by the Moon and the Sun [5] as shown in Figure 4.

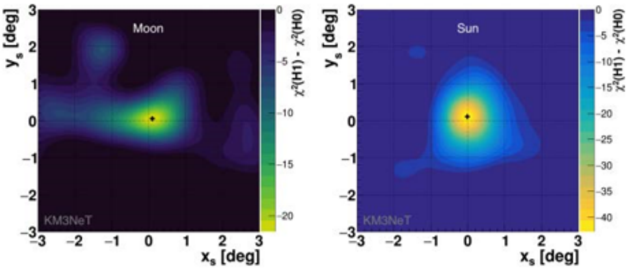


Figure 4. The Moon (left) and the Sun (right) CR shadow using ORCA6 data [5].

The event classification adopted in the atmospheric neutrino oscillation analyses is based on a BDT trained to differentiate atmospheric neutrinos from background due to atmospheric muons and random noise. Selected events are required to have a low atmospheric muon score. A second BDT is then employed to assign a Particle Identification score (PID) to the events in order to characterize the events as tracks or showers. The track class is further divided in well-reconstructed tracks and poorly-reconstructed tracks based on the atmospheric muon score. As a result, the events are categorized as: “High Purity Tracks”, “Low Purity Tracks” and “Showers” [6], [7].

The procedure for constraining the oscillation parameters Δm^2_{31} and θ_{23} is based on the maximization of a binned likelihood for the 2-dimensional distribution of events in bins of re-

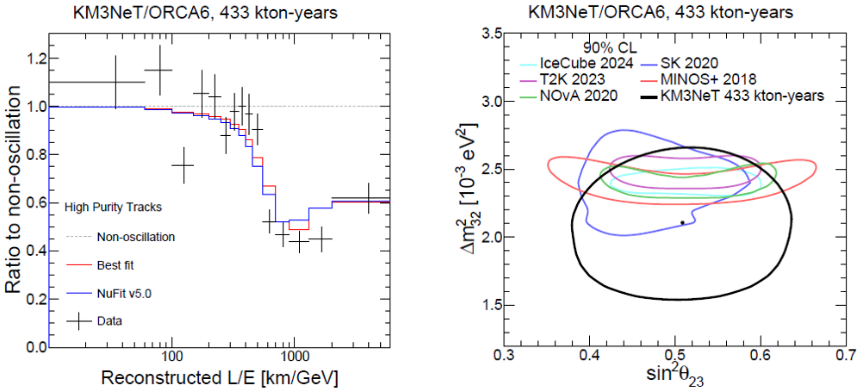


Figure 5. Left: Ratio to the non-oscillations hypothesis as a function of the reconstructed path length over neutrino energy, L/E, for data (black), the best-fit (blue), and NuFit (red) for the High Purity Tracks class. Right: 90% CL contour for the oscillation parameters $sin^2\theta_{23}$ and Δm^2_{32} from ORCA6 assuming NO compared to measurements by other experiments [7].

constructed energy and direction and by fitting the model prediction to the ORCA6 data. For illustration purposes, the results of the fit are transformed to the ratio of the reconstructed path length over neutrino energy (L/E) and are normalized with respect to the "non-oscillations" hypothesis as shown for the High Purity Tracks class in Figure 5 (left). The dip due to oscillations is clearly visible. The 90% CL contour for the oscillation parameters $sin^2\theta_{23}$ and Δm^2_{32} from ORCA6 are compared to measurements by other experiments in Figure 5 (right). The ORCA6 countour is less competitive compared to other experiments, but it will rapidly become more stringent as the detector is growing and the statistics of the data collected is increased. The best-fit values for the parameters are [7]

$$sin^2\theta_{23} = 0.51^{+0.04}_{-0.05} \text{ and}$$

$$\Delta m^2_{31} = 2.14^{+0.25}_{-0.35} \times 10^{-3}\text{eV}^2 \text{ for normal hierarchy (normal ordering, NO)}$$

$$\text{and } \Delta m^2_{31} = [-2.25, -1.76] \times 10^{-3}\text{eV}^2 \text{ for inverted (IO),}$$

with $2\ \ln(L_{NO}/L_{IO}) = 0.31$. The IO is dis-favoured at a p-value of 0.25.

One of the prime physics goals of ORCA is the observation of oscillations of atmospheric ν_e and ν_μ neutrinos into τ neutrinos (tau appearance). The ratio of measured ν_τ flux to the one expected in the standard three-flavour oscillation scenario, referred to as the τ normalisation parameter, n_τ, has been measured with ORCA6 data [8] for CC-only and CC+NC. Significant deviations from 1 for this ratio would be a strong indication for new physics. The τ normalisation parameter is found slightly lower than expected, but still consistent with n_τ = 1 as shown in Figure 6 (left).

Using the ORCA6 data sample, a search for neutrino Non-Standard Interactions (NSIs), which appear in several extensions of the SM, has been performed [9]. No significant deviation from standard interactions was found, with the resulting constrains on the coupling strengths being comparable to the most stringent ones to date, as shown in Figure 6 (right).

3.2 Sensitivities for the ORCA detector

A considerable improvement of both the direction definition and energy estimate is to be obtained with the complete ARCA and ORCA detectors. The corresponding increase in

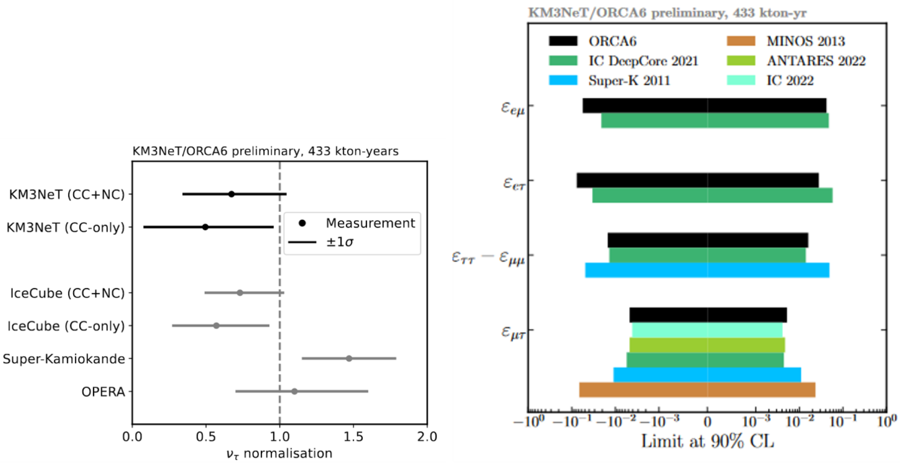


Figure 6. Left: The ORCA6 tau normalisation results for CC-only and CC+NC are compared to other experiments. Right: Comparison of the 90% CL limits for the NSI coupling strengths $\epsilon_{e\mu}$, $\epsilon_{e\tau}$, $\epsilon_{\tau\tau} - \epsilon_{\mu\mu}$, $\epsilon_{\mu\tau}$ to existing limits by other experiments.

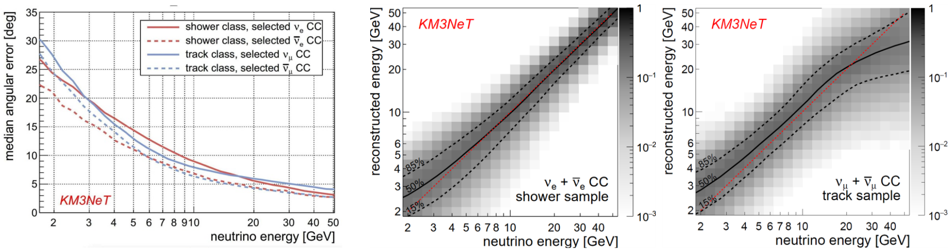


Figure 7. Median direction resolution for CC events as a function of true neutrino energy for events classified as shower-like and as track-like (left). Probability distribution of the reconstructed energy for CC events as a function of true neutrino energy for events classified as shower-like (middle) and track-like (right). The 50%, 15% and 85% quantiles and the diagonal line (perfect energy reconstrunction, red) are shown.

effective area and the increased data statistics, will result in significant improvement of the sensitivity for all studies.

The expected performance of the complete ORCA detector is shown in Figure 7, in terms of angular and energy resolution for track-like and shower-like events. The median direction resolution for neutrinos with $E_\nu = 10$ GeV is well below 10° for ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$ CC events, and is dominated by the intrinsic ν–lepton scattering kinematics [10]. The energy resolution for ν_e CC and $\bar{\nu}_e$ CC events classified as shower-like and for ν_μ CC , $\bar{\nu}_\mu$ CC events classified as track-like are shown in Figure 7 right. At $E_\nu = 10$ GeV, an energy resolution $\Delta E/E \approx 25\%$ is obtained for ν_e CC events and $\Delta E/E \approx 35\%$ for ν_μ CC events, as it is probable that tracks are not fully contained in the detector volume.

The ORCA sensitivity to the neutrino mass hierarchy (ordering, NMO) is shown in Figure 8 (left), as a function of the data taking period. After three years of data taking with the complete ORCA detector, a sensitivity of 4.4 σ to the neutrino mass hierarchy will be reached if it is normal (NO) and of 2.3 σ if it is inverted (IO) [10]. The 90% CL contour on

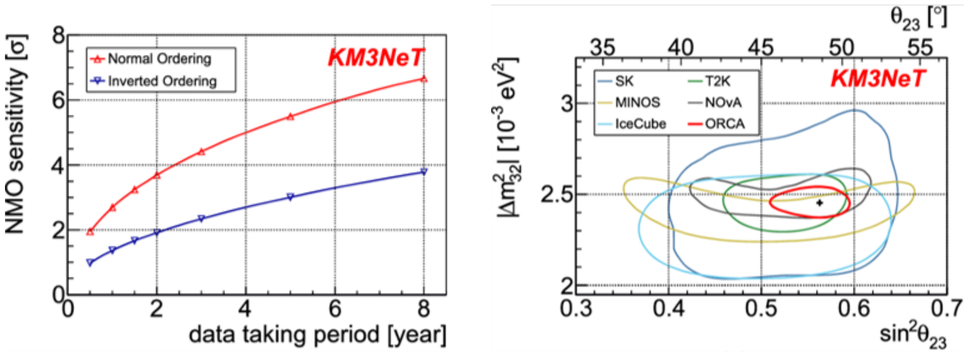


Figure 8. Left: Sensitivity to the NMO as a function of data taking time for normal (red) and inverted ordering (blue). Right: 90% CL contours for the oscillation parameters $sin^2\theta_{23}$ and Δm^2_{32} comparing the ORCA precision to other experiments [10].

$sin^2\theta_{23}$ and Δm^2_{32} is shown in Figure 8 (right) demonstrating that precision measurements of the neutrino oscillation parameters will be obtained after three years of data taking with the complete ORCA detector.

Assuming normal hierarchy, the sensitivity to the ν_τ appearance for CC-only is shown in Figure 9 as a function of the ORCA data taking period. After three years of operation, the tau normalisation parameter, n_τ, can be constrained with ORCA to ± 20% at 3σ-level.

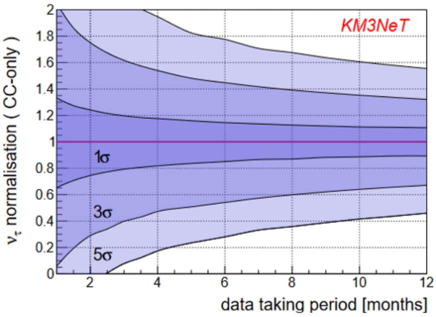


Figure 9. ORCA sensitivity to ν_τ appearance (tau normalisation) for CC-only as a function of the operation time.

4 Neutrino astronomy with the ARCA detector

The pointing accuracy of a neutrino telescope is decisive for the identification of distant astrophysical neutrino sources. At energies above 100 TeV, where the astrophysical neutrino contribution is larger than the atmospheric neutrino background, the median angular resolution for the complete ARCA detector is expected at the order of 0.1° for tracks and below 2° for showers.

4.1 First results from the ARCA6-21 detector

The potential of the ARCA detector to measure a diffuse flux of astrophysical neutrinos with the early detector configurations is investigated, assuming an unbroken power law for the neutrino energy spectrum. The ARCA6-21 sensitivity is shown in Figure 10 and is compared

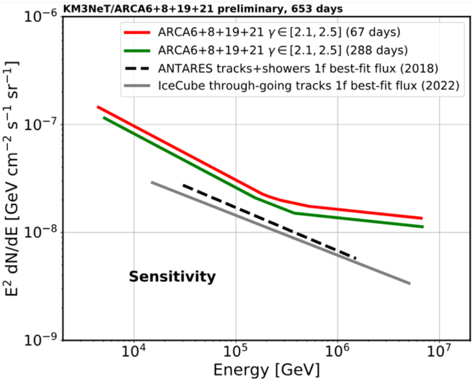


Figure 10. ARCA6-21 sensitivity to a diffuse flux of astrophysical neutrinos [11] compared to the ANTARES [12] and IceCube [13] experiments.

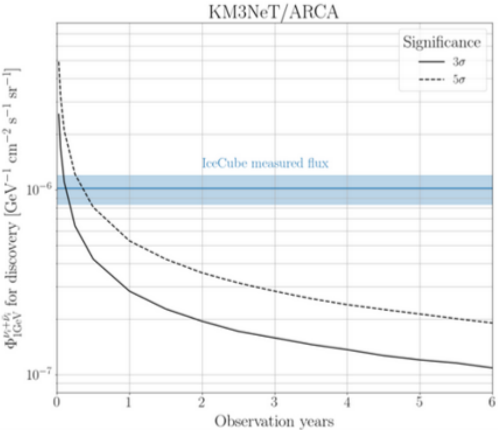


Figure 11. 3σ and 5σ discovery flux of ARCA as a function of observation time for a diffuse astrophysical neutrino flux with spectral index $\gamma = 2.37$ [14]. The blue band represents the measured flux normalisation of IceCube including statistical and systematic uncertainties [15].

to the ANTARES [12] and IceCube [13] experiments. The ARCA6-21 sensitivity at this early stage of the construction is not competitive, demonstrating however the KM3NeT capabilities, as a significant improvement will result from the increase in the size of the detector and the accumulated livetime.

4.2 Sensitivities for the ARCA detector

The discovery potential of ARCA for a diffuse astrophysical neutrino flux is shown in Figure 11 as a function of observation time for an energy spectrum with a spectral index $\gamma = 2.37$. Assuming an all-sky diffuse astrophysical neutrino flux as observed by the IceCube Collaboration [15], half a year of operation of ARCA in its complete configuration is needed to provide a measurement with 5σ significance to confirm the IceCube measurement.

5 Conclusions

Selected first results from the KM3NeT telescopes have been presented, obtained with partial configurations of the ARCA (ARCA6-21) and ORCA (ORCA6) detectors at the early stages of the construction. These first results, in some cases already competitive to other experiments, demonstrate the capabilities of KM3NeT for a broad physics program including neutrino astronomy, neutrino physics, cosmic ray physics, multi-messenger studies, dark matter and phyiscs beyond the SM, etc. The corresponding expectations for the complete detector arrays have also been reported. Currently ARCA and ORCA consist of 28 DUs and 18 DUs, respectively, with a significant increase in the accumulated data statistics.

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