Report on the Status of KM3NeT for the IN2P3 Scientific Council

APC, CPPM, IPHC, LPC, Subatech, LUPM

September 25, 2021

1 Introduction

The main objectives of the KM3NeT[1] Collaboration are *i)* the discovery and subsequent observation of high-energy neutrino sources in the Universe and *ii)* the determination of the neutrino mass ordering (NMO). To meet these objectives, the KM3NeT Collaboration is in the process of building a new research infrastructure comprising a network of deep-sea neutrino telescopes in the Mediterranean Sea. The KM3NeT infrastructure is included in the ESFRI roadmap.

The detectors consists of 3D arrays of detection units each comprising 18 digital optical modules (DOM) made of 31 photo-multiplier tubes (PMTs) as illustrated in Figure 1. Various neutrino energy ranges can be accessed with this technology by simply adjusting the the spacing between lines and between DOMs. Two detectors are under construction: one offshore Toulon (France) and one offshore Capo Passero (Italy). The former is called ORCA (Oscillation Research with Cosmics in the Abyss) and features a dense DOM geometry optimised to study the neutrino oscillation in the GeV energy range with atmospheric neutrinos. The later is called ARCA (Astronomy Research with Cosmics in the Abyss) and features a sparser DOM geometry adapted to the study of high-energy neutrino sources in the Universe.

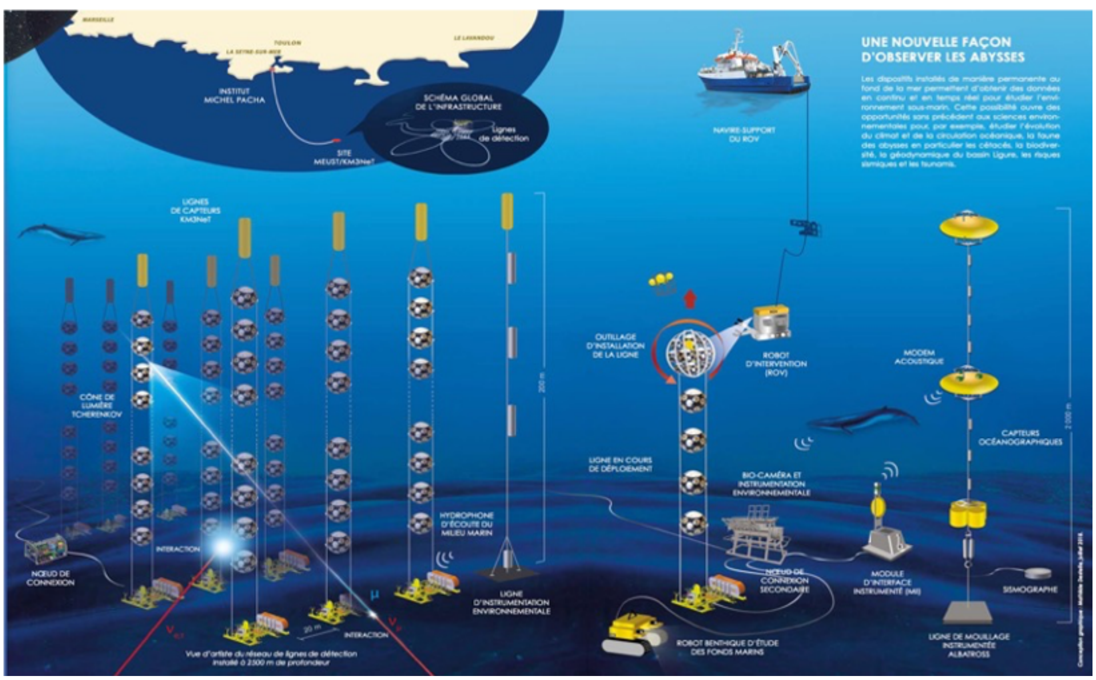


Figure 1: Artist view of the KM3NeT/ORCA infrastructure.

[1] http://www.km3net.org

Beyond the two main objectives mentioned above, the detectors offer a wide range of scientific opportunities not only in fundamental physics but also in astrophysics, earth and sea sciences. The full description of the physics program can be found in the Letter of Intent [1] and in the documents provided for the 2017 IN2P3 *conseil scientifique* [2, 3]. This report focuses on the evolution of the project since 2017 and in particular on the KM3NeT/ORCA detector.

The project federates a wide french scientific community which is described in Section 2 together with the responsibilities held by the french groups. Section 3 provides a description of the main technical achievements since 2017. The scientific achievements during the same period are reported in Section 4. Finally, Section 5 describes the prospects for completing the detectors, including the financial and human resources status, and the long term scientific prospects.

2 Project Federation at the National Level

At the international level, the KM3NeT Collaboration comprises 56 institutes distributed across 17 countries and four continents. Sites for integration of the various detector elements are located in France, Germany, Greece, Italy, Morocco, Netherlands and Spain.

The IN2P3 laboratories involved in KM3NeT are listed in Table 1 together with the responsibilities they hold. Since 2017, LUPM (Montpellier) and LPC (Caen) have joined the Collaboration. The resulting reinforcement of the french technical teams greatly reduces the risk of delays in completion of the detector construction, which was identified as a concern at the *conseil scientifique* held in 2017.

Laboratory	EFT (S/T)	Technical responsibilities	Management responsibilities
APC	3.25/2.9	Calibration Unit	KM3NeT Technical Manager ANTARES Spokesperson Chair Conference Committee Co-coord Oscillation Physics
CPPM	4.1/17.1	DU integration Sea operations control room/power system Instrumentation Unit Junction boxes	KM3NeT Spokesperson Co-coord Oscillation Physics Co-coord data-taking Co-coord Neutrino Astronomy Coord KM3NeT Outreach
IPHC	0.75/2.2	DOM integration	
LPC	2/0.6	Anchor integration	
LUPM	0.1/1.5	Base module integration	
Subatech	2/2.25	DOM integration	

Table 1: List of the IN2P3 laboratories involved in KM3NeT with the employed human resources.

The ORCA submarine infrastructure offshore Toulon is owned by IN2P3. The Laboratoire Sous Marin Provence Méditerranée (LSPM), an IN2P3 national platform, has been recently created to manage the facility in conjunction with the Aix-Marseille University and Ifremer. The platform offers the possibility for external users to connect deep sea instrumentation to the infrastructure thus increasing its scientific return.

3 Technical Achievements since 2017

Since the previous *conseil scientifique*, major technical realisations were achieved and six lines have been deployed and operated at the KM3NeT/ORCA site for more than a year without any failure. Similarly for the ARCA site, a junction box has been deployed and 8 DUs are taking data. These accomplishments demonstrates in-situ the validity of the KM3NeT technology. The following paragraphs describe in more detail the technical achievment performed in the IN2P3 laboratories.

Submarine Infrastructure The CPPM realised major works on the submarine infrastructure with the repair of the first node and the replacement of a large portion of the deep sea cable connecting the node to the shore. In parallel, a second node was designed, built and successfully deployed by the CPPM team. With two ndoes the current seafloor network can host about 50 detection units as shown in Figure 2

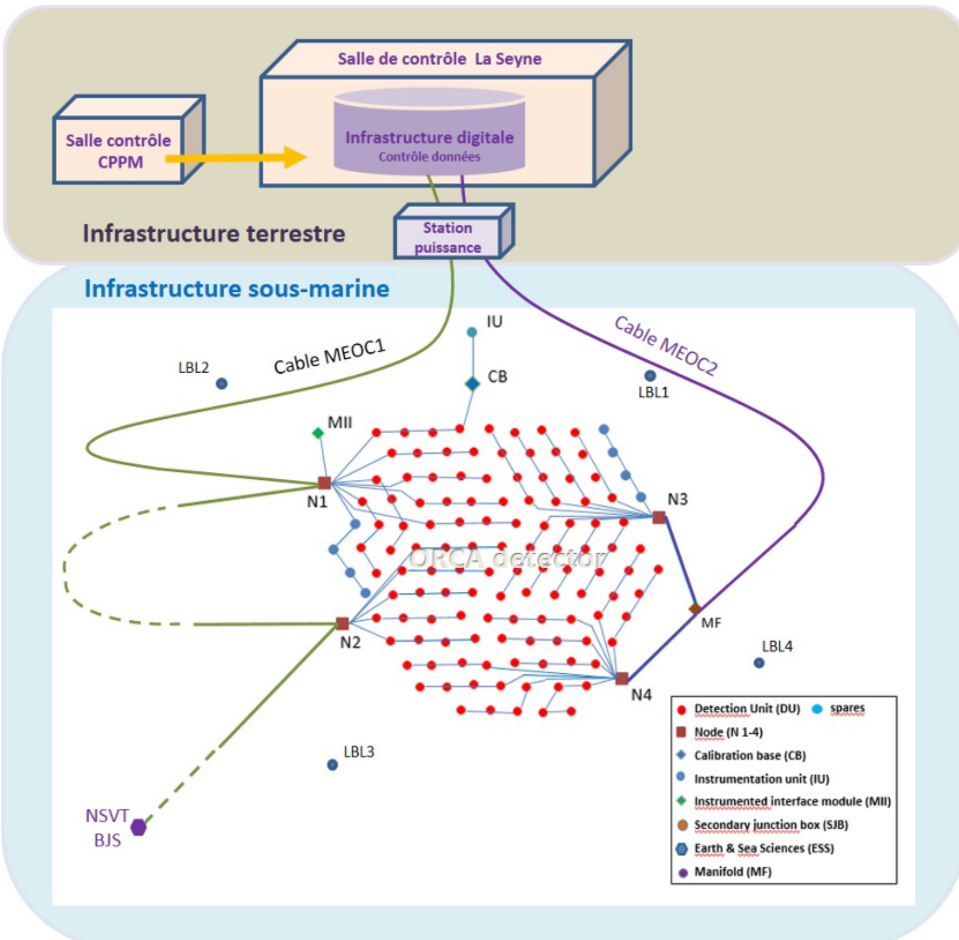


Figure 2: Seafloor layout of the ORCA array, node N1 and N2 are deployed and operational

Detection Units The IN2P3 teams have contributed to the construction of detection units (DUs) with the fabrication of 76 DOMs (36 in Subatech and 36 in IPHC), the integration of 13 base modules (11 in CPPM and 2 in LUPM), the final integration of 16 DUs rolled on the launching vehicle and the deployment of 6 DU.

Calibration and Monitoring Instruments The calibration base (CB) and the instrumentation unit (IU) were respectively designed and built by the APC and CPPM teams [4]. The CB hosts a Laser Beacon for time calibration and a long-baseline acoustic emitter and a hydrophone, which are part of the positioning system for the DOM. The IU host instruments to monitor the water properties. The CPPM also designed and integrated a high-purity germanium gamma spectrometer for real-time monitoring of the radioactivity in the deep sea.

Anti-fouling R&D activities are also pursued by the CPPM and Subatech teams to find an anti-fouling solution to be applied on the DOMs.

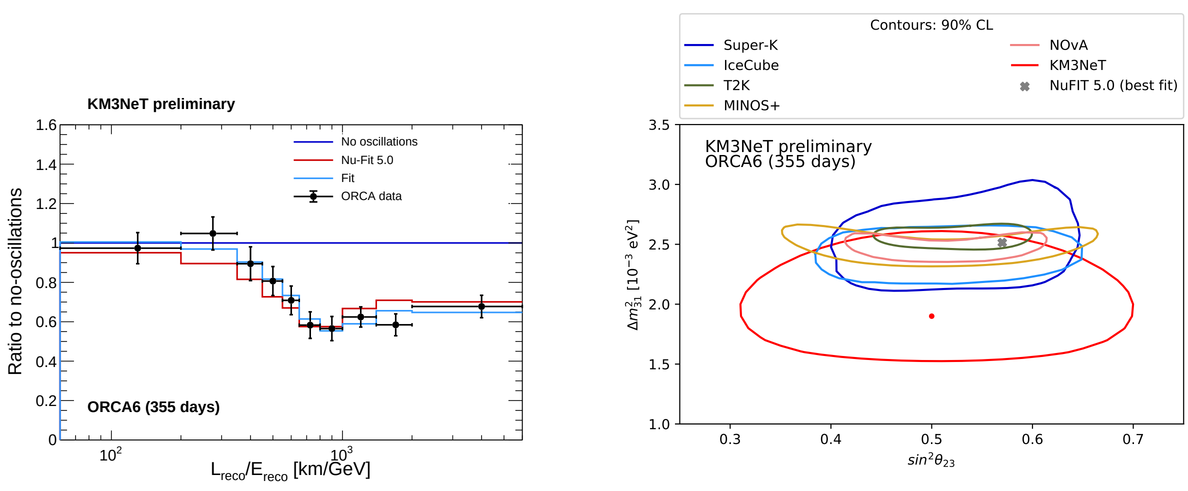
Earth and Sea Science It is planned that several innovative deep sea sensors will be connected to the seafloor network early next year (BathyBot-MIO, Seismograph-GeoAzur, Gamma detector-CPPM, Biocameras-IP2I). The INSU/GeoAzur have used the ORCA main electro-optical cable to demonstrate the feasibility of Distributed Acoustic Sensing using the optical fibres of deep sea telecommunication cables [5]. The LIS/Univ. Toulon group use the acoustic positioning hydrophones for bio-acoustic tracking of cetaceans in the vicinity of the detector.

As a recognition for these developments at the forefront of technology, the CPPM teams were awarded the *Cristal Collectif du CNRS* in 2019.

4 Scientific Achievements since 2017

4.1 Neutrino oscillation with the first KM3NeT/ORCA data

The modular design of the KM3NET allows physics analyses to be performed as the detector construction proceeds. Hence, following the major progress in the detector construction, the first data samples could be collected and promptly analysed. A first neutrino oscillation measurement was presented at the 2021 summer conference [6] using the data collected by the six KM3NeT/ORCA DUs during 354.6 days. Figure 3(a) shows the baseline to energy ratio event distribution where the oscillation pattern is clearly visible. A statistical analysis concluded that the no-oscillation hypothesis was excluded with a confidence level of 5.9 œ. A measurement of the atmospheric neutrino oscillation parameters was performed and is reported in Figure 3(b). The resulting contour in the $\Delta m^2_{32} - \sin^2\theta_{23}$ is approaching to being competitive with other experiments. Hence, the first 6 DUs installed at KM3NeT/ORCA not only validate the KM3NeT technology, but they also demonstrate the soundness of the experimental/calibration methods and the readiness of the analysis tools.



(a) (b)

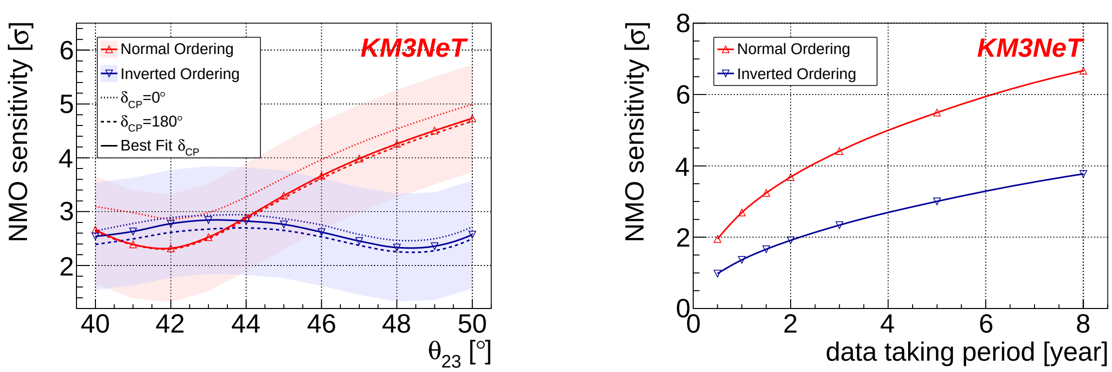
Figure 3: (a) Baseline to energy distribution for the data collected with the KM3NeT/ORCA first six DU (black) and the fit distribution (light-blue). The expected number of events assuming the *no oscillation* hypothesis (purple) and the overall best fit oscillation parameters [7] value (red) are also overlaid. (b) Contour at 90% CL of the oscillation parameters obtained with the data collected with the KM3NeT/ORCA first six DU (red). Contours of other experiments [8, 9, 10, 11, 12] have been added for comparison purposes as well as the overall best fit value [7]

4.2 Sensitivity studies to neutrino oscillation with the complete detector

In parallel to the first data analyses, sensitivity studies to the neutrino oscillation with the full KM3NeT/ORCA detector have been updated.

NMO The sensitivity to the NMO was updated with respect to the Letter of Interest [1] to include improvements on the trigger, reconstruction and particle identification methods. The modelling of the detector response has been made more realistic and many more systematic uncertainties have been considered. The sensitivity to the NMO after three years of data taking is reported as a function of θ_{23} for both NMO in Figure 4(a). Assuming the current best estimates for θ_{23} [7], the NMO sensitivity is 4.4σ if the true NMO is NO and 2.3σ if it is IO. Figure 4(b) shows the sensitivity for both NMO as a function of data taking time. The NMO can be determined at 3σ level after 1.3 years if the true NMO is NO, and after 5.0 years if it is IO.

For comparison, the combination of NOvA and T2K data after the completion of both experiments by 2026 may be able to reach similar sensitivity in the case of true NO, but is effectively insensitive to the NMO in the true IO scenario with currently favoured mixing parameters [13]. The only other significant competitor in this decade, JUNO, is expected to reach a maximum sensitivity of 3σ over the lifetime of the experiment [14].

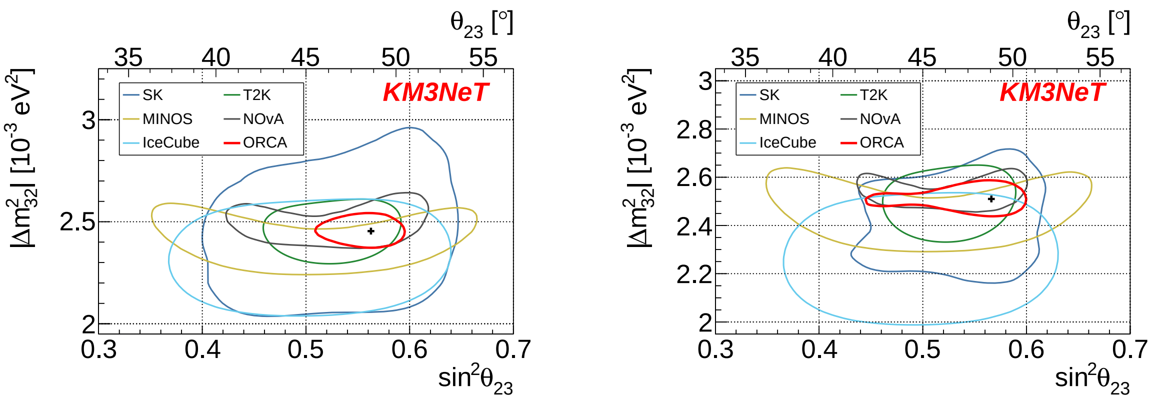


(a) (b)

Figure 4: (a) Sensitivity to NMO after three years of data taking, as a function of the true θ_{23} value, for both normal (red upward pointing triangles) and inverted ordering (blue downward pointing triangles) under three assumptions for the δ_{CP} value: the world best fit point for NO, IO reported in [7] (plain line), 0° (dotted line) or 180° (dashed line). The coloured shaded areas represent the sensitivity that 68% of the experiment realisation would yield, according to the Asimov approach [15]. (b) Sensitivity to NMO as a function of data taking time for both normal (red upward pointing triangles) and inverted ordering (blue downward pointing triangles) and assuming the oscillation parameters reported in [7].

Atmospheric Neutrino Oscillation Parameters This analysis also derived the expected sensitivity to the atmospheric oscillation parameters. Figure 5 shows the expected contours in the $\Delta m^2_{32} - \sin^2\theta_{23}$ plane and illustrates the precision improvements that KM3NeT/ORCA will be able to provide on these parameters compared to the current knowledge.

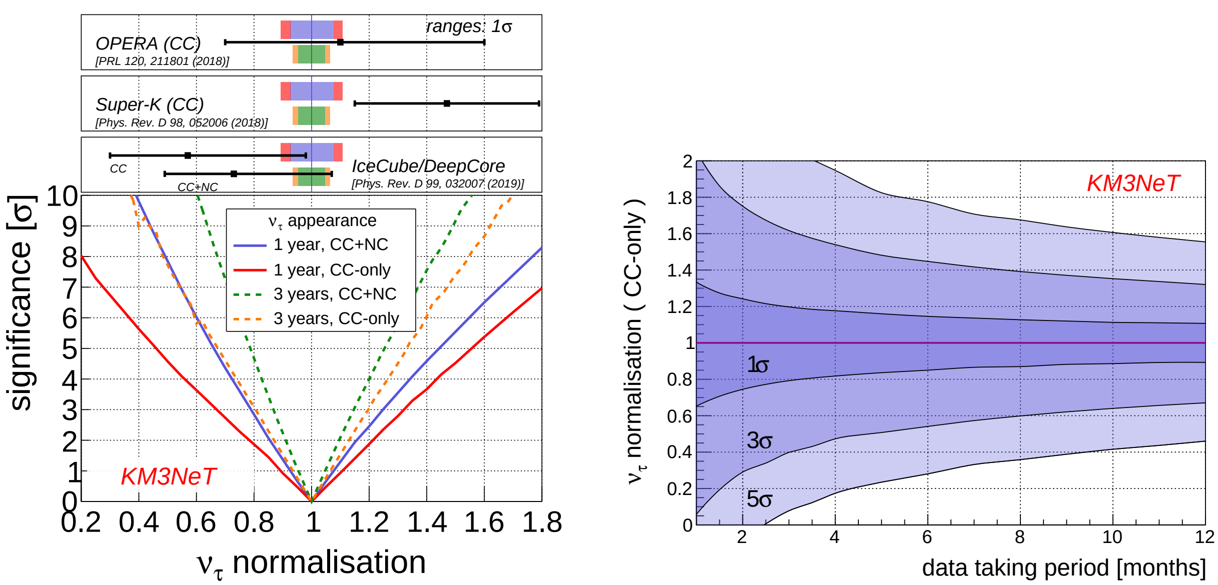
$\overset{(-)}{\nu}_\tau$ **appearance** KM3NeT/ORCA will also be able to constrain the mixing matrix unitarity using the $\overset{(-)}{\nu}_\tau$ appearance channel by measuring the normalisation factor $n_{\overset{(-)}{\nu}_\tau}$ of the $\overset{(-)}{\nu}_\tau$ contribution. The sensitivity to this parameter after one year and three years of operation for charge current (CC) and CC+ neutral current (NC) normalisation factor is shown for a scan in $n_{\overset{(-)}{\nu}_\tau}$ in Figure 6(a). In Figure 6(b), the sensitivity for CC-only normalisation is presented as a function of operation time. KM3NeT/ORCA will already be able to



(a) (b)

Figure 5: Expected measurement precision of Δm^2_{32} and θ_{23} for both NO (a) and IO (b) after 3 years of data taking at 90% confidence level (red) overlaid with results from other experiments [8, 9, 10, 11, 12] and the oscillation parameters reported in [7] (black cross).

confirm the exclusion of non-appearance with high statistical significance with few months of data-taking. For CC the normalisation can be constrained to $\pm 30\%$ at 3σ-level and to $\pm 10\%$ at 1σ-level after one year of data taking. After three years, the normalisation can be constrained to $\pm 20\%$ at 3σ-level, and to $\pm 7\%$ at 1σ-level. The measured $\overset{(-)}{\nu}_\tau$ normalisation is robust against an incorrectly assumed sign of the still undetermined NMO. This enables KM3NeT/ORCA to measure $\overset{(-)}{\nu}_\tau$ appearance already during an early phase of construction [16].



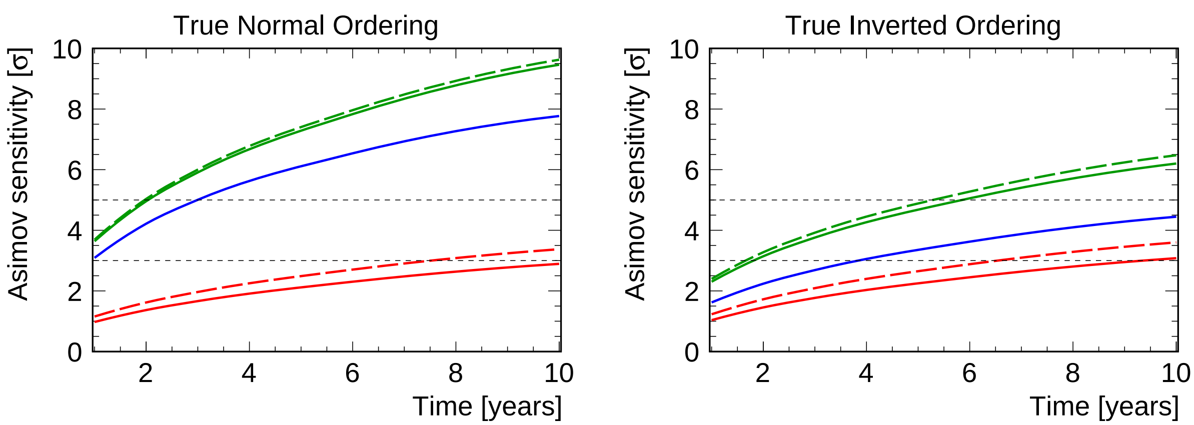
(a) (b)

Figure 6: Sensitivity to $\overset{(-)}{\nu}_\tau$ appearance for CC and CC+NC normalisation scaling after one and three years of operation (a). Measurements from other experiments [17, 18, 19] at 1σ level are shown for comparison. In (b), $\overset{(-)}{\nu}_\tau$ appearance sensitivity for CC scaling is presented as a function of data taking period.

Sterile Neutrino Studies were also performed to evaluate the sensitivity to KM3NeT/ORCA to the existence of a light sterile neutrino [20]. After three years of data taking, KM3NeT/ORCA can improve current limits on $\sin^2\theta_{34}\cos^2\theta_{24}$ by about a factor of two, for an eV-mass sterile neutrino. For lower sterile neutrino masses, down to $\Delta m^2_{41} \to 10^{-5}$ eV, KM3NeT/ORCA will be able to improve current limits on $\sin^2\theta_{24}$ by about two orders of magnitude, and up to two orders of magnitude for the effective parameter $\sin^2 2\theta_{\mu e}$. The KM3NeT/ORCA sensitivity to $\sin^2\theta_{14}$ is comparable to current upper limits. Finally, KM3NeT/ORCA will able to improve current limits on $\sin^2\theta_{34}$ by about a factor two for an eV-mass sterile neutrino, and it will be the first experiment able to constrain θ_{34} in the very low sterile mass region.

Combination with JUNO The sensitivity of a combined analysis of the JUNO and KM3NeT/ORCA experiments to determine the neutrino mass ordering was performed [21]. This combination is particularly interesting as it significantly boosts the potential of either detector, beyond simply adding their neutrino mass ordering sensitivities, by removing a degeneracy in the determination of Δm^2_{31} between the two experiments when assuming the wrong ordering. A 5σ determination of the neutrino mass ordering is expected after 6 years of joint data taking for any value of the oscillation parameters. As shown in Figure 7, this sensitivity would be achieved after only 2 years of joint data taking assuming the current global best-fit values for those parameters for normal ordering.

If the true NMO is inverted, this combined measurement of JUNO and ORCA is likely to be the first 5σ determination of the NMO. While a similar joint fit of JUNO, NOvA and T2K experiments has also demonstrated 5σ potential, it would require sub-percent precision on Δm^2_{31} from long-baseline experiments in the true IO scenario [13].



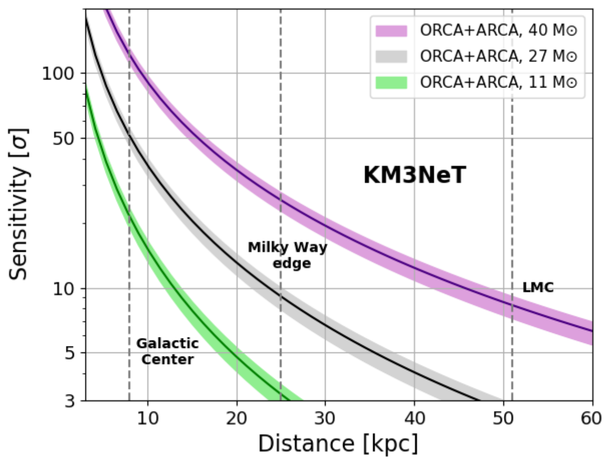
(a) (b)

Figure 7: NMO sensitivity as a function of time for only JUNO (red), only KM3NeT/ORCA (blue), and the combination of JUNO and KM3NeT/ORCA (green), considering 2 (solid) or 4 (dashed) Taishan NPP reactors, corresponding respectively to 8 or 10 reactor cores at 53 km from JUNO for NO (a) and IO (b).

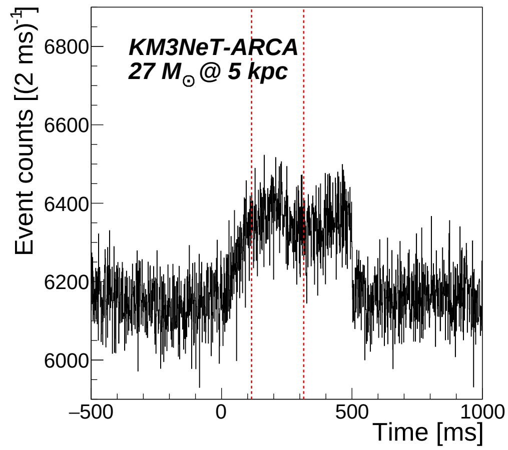
4.3 SuperNova and Multi-messenger Astronomy

Thanks to the segmented optical module, KM3NeT is becoming a very efficient core-collapse supernova (CCSN) detector [22]. At the 0(10 MeV) energies, it is not possible to reconstruct the events individually. The detection principle relies on the detection of an increase of the coincidence rates of the PMTs over the background contributions from atmospheric muons, radioactive decays and bio-luminescence activities. In Figure 8(a), the sensitivity for the combination of the ORCA and ARCA detectors is reported as a function of the distance to the source for the three considered progenitors. More than 95% of the Galactic core-collapse supernovae can be observed by the KM3NeT detectors. KM3NeT will thus contribute to the observation of the next Galactic explosion. The sensitivity to the black-hole forming case (20 M_{Sun}) extends beyond the Large Magellanic Cloud. Once detected, KM3NeT is also able to compute the detected neutrino light-curve and extract the T_0 time of the neutrino signal, the shape of the light-curve, the SASI oscillation pattern and also the energy spectrum parameters [22].

Since 2019, the CCSN analysis has been implemented in real-time [23] and it constantly monitors the raw data of both ORCA and ARCA detectors. An alert system has also been implemented and fully connected to the SNEWS network. In 2021, the SNEWS program is being upgraded to SNEWS 2.0 [24] for which more information will be transmitted to improve the scientific return of the next Galactic or close-by supernovae.



(a)



(b)

Figure 8: (a) KM3NeT detection sensitivity as a function of the distance to the CCSN for the three progenitors considered : 11 M_{Sun} (green), 27 M_{Sun} (black) and 40 M_{Sun} (purple). The error bars include the systematic uncertainties. (b) Detected neutrino light-curves in the full ARCA detector for the 27 M_{Sun}.

Neutrino astronomy is possible at GeV-TeV energies with ORCA. For example, cosmic ray acceleration in winds of X-ray/γ-ray binaries, in choked GRBs or in hidden jets in core-collapse SN may provide low-energy neutrinos <1 TeV. Even at lower energies (<10 GeV), we may expect neutrinos from solar flares. The poor angular resolution is counter-balanced by the larger expected event statistics. To be able to fully exploited this scientific window, we are implementing a real-time analysis framework. It contains a neutrino alert sending system and an online correlation analyses [25].

Thanks to the unprecedented angular resolution, the extended energy range ($\sim$10 MeV; $>$ 10 PeV) and the full sky coverage, KM3NeT will play an important role in the rapidly evolving multi-messenger field [1]. ARCA is dedicated to the search for high-energy (TeV-PeV) astrophysical neutrino sources, using a large km3-scale instrumented volume. Combining the data of ORCA and ARCA provides a very large energy range. KM3NeT is entering into the global network of multi-messenger observations by performing analysis with KM3NeT data, in particular targeting transient events such as GRBs, flaring active galactic nuclei (AGN), mergers of compact objects (black holes, neutron stars), core-collapse supernovae, or tidal disruption events. In particular, KM3NeT has an excellent view of the galactic centre/plane. Partners of KM3NeT in the global multi-messenger network are IceCube, the gravitational wave detectors LIGO/Virgo, and a large set of telescopes, observing electromagnetic radiation from radio to gamma rays. The high energy physics program has been detailed in four documents presented at the IN2P3 strategy (https://indico.in2p3.fr/event/19952/).

The French groups have been pioneer in the introduction of multi-messenger activities in the ANTARES Collaboration.

4.4 Earth Tomography

Neutrinos can also be used to perform tomography of the Earth, i.e. the study of the Earth's internal structure and composition. Thanks to the good complementary of the energy range covered by ORCA and ARCA, KM3NeT will be the first experiment to perform both oscillation and absorption neutrino tomography [26]. Resonance effects in the oscillations of GeV neutrinos traversing the Earth will allow KM3NeT/ORCA to measure the electron density along their trajectory, leading to potential constraints of the proton-to-nucleon (Z/A) ratio in the traversed matter. Absorption tomography aims at the detection of neutrinos in the TeV-PeV range with KM3NeT/ARCA. At PeV energies, the Earth is opaque for neutrinos which leads to a reduction of the upgoing neutrino flux at the detector side from which conclusions can be drawn about the density of the inner layers of the Earth. Despite the uncertainties related to neutrino tomography are still much bigger than those provided by geoscience, this new approach to explore the Earth interior can contribute to constrain future models of the planet.

5 Scientific and Technical Prospects

5.1 Funding

The experience gained in assembling and deploying the first six KM3NeT/ORCA line allows to extrapolate the completion of the full ORCA detector (115 DUs) by end of 2025, assuming no limitations due to availability of funding.

The total cost of KM3NeT/ORCA is estimated at about 54 ME with a low operation cost. Previous and current funds (NUMerEnv-IN2P3/CPER/FEDER/DRRT: 7.6 ME and those of Nikhef) allow a total of another 27 DUs to be constructed and connected, summing up to 33 operational DUs. Various funding requests are pending (NUMED-IN2P3/CPER:8.8 ME) and in preparation (PEPR).

Some of the IN2P3 KM3NeT groups also received support for postdoctoral positions from various H2020 projects (KM3NeT-INFRADEV, ESCAPE, REINFORCE, EOSC-FUTURE).

At the international level, the long term goal of the KM3NeT Collaboration is to adopt an European Research Infrastructure Consortium (ERIC) as its legal identity. This would facilitate the perennity and long term operation of the infrastructure.

5.2 ANTARES

The ANTARES detector has been reliably taking data continuously since its first detection strings were deployed in 2005. As of 2021, the KM3NeT/ORCA and KM3NeT/ARCA detector have reached performances superior to those of ANTARES. For example Figure 9 shows that the new detectors offer an effective area larger than ANTARES and cover a wider energy range. Consequently, the ANTARES detector will be decommissioned and dismantled by summer 2022.

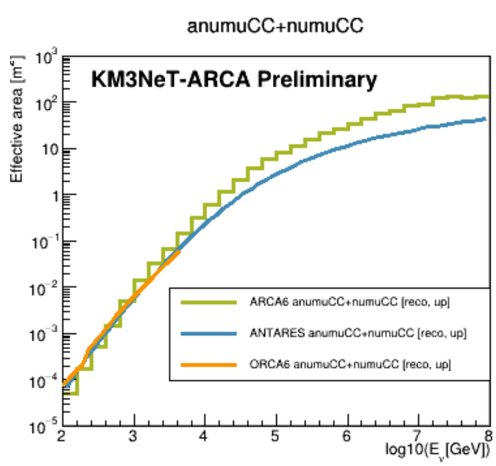


Figure 9: Effective area for the detectors ARCA6 (green), ORCA6 (orange) and ANTARES (blue). It is computed at reconstruction level for upgoing muon neutrino events.

5.3 P2O

Studies were made on the possibilities to use KM3NeT/ORCA as far detector for a long baseline neutrino experiment with a neutrino beam made at the U70 accelerator complex in Protvino (Russia). The project was thus named P2O. The initial study [27] showed that P2O would offer a sensitivity to the CP violating phase which would be comparable to the one of the DUNE or T2HK experiments. Since then, a new experimental concept was elaborated [28] and drastically changed the prospects improving the sensitivity to δ_{CP} by more than a factor 2 as shown in Figure 10. In this new version, P2O would not be limited by systematic uncertainties which would then open the way to precision measurements.

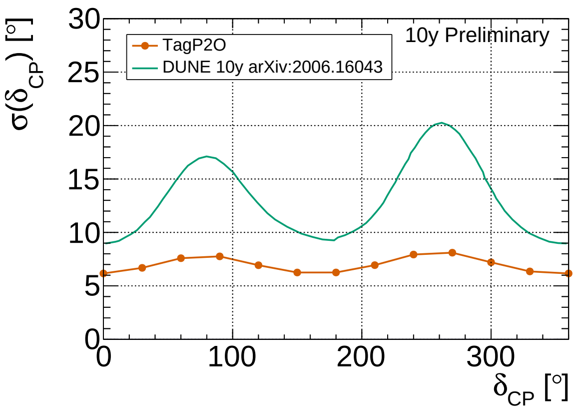


Figure 10: Precision on δ_{CP} as function of the true δ_{CP} value. The TagP2O expectation are presented (orange) assuming a 450 kW beam power for 10 years of operation. For reference, the expectation for the DUNE experiment for the same duration are overlaid (green).

The concept relies on the very large size of KM3NeT/ORCA, which will be more than 100 times larger than the next generation detectors. This asset allows to operate P2O with a modest beam intensity. At these intensities, it appears that the technology being developed for the HL-LHC would be sufficient to instrument the beam line with silicon trackers. Those trackers would allow to reconstruct the kinematics of each and all neutrinos produced by the $\pi^+ \to \mu^+\nu_\mu$ decays with energy resolutions better than 1%. Using time and angular coincidence each neutrino observed in KM3NeT/ORCA could be individually matched with the one reconstructed kinematically. Such an association would remove most of the systematic uncertainties and would allow to reach energy resolutions inaccessible with conventional neutrino detectors.

The development of this idea is pursued in collaboration between the IN2P3 groups, IHEP (Protvino), Kurchatov Institute (Moscow) and CERN in the context of the Physics Beyond Collider Study Group. An JCJC-ANR was obtained to perform a feasibility study.

P2O unique potential would greatly increase the physics case of KM3NeT/ORCA. It would open a bright future beyond the NMO determination and would put IN2P3 at the very top of neutrino physics within the coming decade.

6 Conclusions

Since 2017, when the project was last evaluated by the *conseil scientifique* of IN2P3, very important milestones have been reached. The most significant one is the observation of atmospheric neutrino oscillation with the data collected over one year by the first six detection units. This result demonstrates the validity of the KM3NeT technology, the soundness of the experimental method and the readiness of the analysis and calibration tools. Sensitivity studies with the full detector were also performed or updated with more robust hypotheses and methods. Major results are to be expected from KM3NeT for both neutrino oscillation and astronomy in this decade even at an early stage. Hence, no technical obstacle are expected to hinder the success of the experiment. The construction is progressing and funding is secured for the construction and installation of the next 27 detection units allowing to have 33 operational detection units.

In the longer term, preliminary studies show that KM3NeT/ORCA could be employed as far detector for a long baseline neutrino experiment with a tagged beam. This setup features unique capabilities by offering large statistics and low systematic uncertainties thus opening the way to precision measurements of the neutrino oscillation.

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