Report on the Status of KM3NeT for the IN2P3 Scientific Council

APC, CPPM, IPHC, LPC, Subatech, LUPM

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1 KM3NeT Description

Scientific Context The observation of a flux of very high-energy cosmic neutrinos by the IceCube experiment marked the birth of neutrino astronomy and raised fundamental questions concerning their origin, spatial distribution, energy spectrum, and flavour composition. Motivated by this discovery, the scientific case for a cubic-kilometre-scale neutrino telescope in the Northern Hemisphere became compelling. A detector located in the Mediterranean Sea would provide coverage of 87 % of the neutrino sky and enables an extensive survey of the Milky Way, including the Galactic Centre.

In parallel, the discovery of a sizeable electron-neutrino admixture in the third neutrino mass eigenstate by reactor experiments such as Daya Bay and RENO opened the possibility to determine the neutrino mass ordering (NMO) through matter effects in atmospheric neutrino oscillations. The determination of the NMO is a central goal in neutrino physics, with far-reaching implications for leptonic CP violation searches and for experimental strategies addressing neutrinoless double-beta decay. A neutrino telescope optimised for an energy range between 1-100 GeV would be ideally placed to make this measurement.

In this context, the KM3NeT Collaboration has developed innovative technologies to construct deep-sea water Cherenkov neutrino telescopes capable of detecting atmospheric and cosmic neutrinos over an exceptionally wide energy range, from a few GeV to several hundred PeV. This capability enables a comprehensive physics programme spanning neutrino oscillation physics, neutrino astronomy, and searches for physics beyond the Standard Model.

KM3NeT Research Infrastructure Three deep-sea sites have been identified for the deployment of KM3NeT: KM3NeT-Fr (ORCA) at a depth of 2500m offshore Toulon (France) to host a telescope optimised for low energy and named ORCA (Oscillation Research with Cosmics in the Abyss), KM3NeT-It at a depth of 3500m offshore Portopalo di Capo Passero (Italy) to host a telescope optimised for high energy and named ARCA (Astroparticle Research with Cosmics in the Abyss), and KM3NeT-Gr, a backup site, offshore Pylos (Greece). The construction of ORCA and ARCA began in 2015 and is expected to be completed by 2030 for ORCA and 2032 for ARCA. The scientific objectives of the Collaboration were originally defined in the 2016 Letter of Intent [1], which identified the discovery of high-energy neutrino sources and the determination of the neutrino mass ordering as the primary goals. These objectives remain unchanged and have been reinforced by results from partial detector configurations and continued technical and analysis developments.

KM3NeT is a recognised experiment at CERN and is part of the European Strategy Forum on Research Infrastructures (ESFRI) roadmap since 2016 as a major European research infrastructure for astroparticle physics. Its inclusion in ESFRI highlights its strategic importance for Europe and its role in providing long-term, open access to a world-class deep-sea observatory for neutrino astronomy and Earth-and-sea sciences.

In 2026, KM3NeT will exist from the roadmap. An application is under review to become an ESFRI Landmark infrastructure.

Scientific Program Upon completion, KM3NeT/ORCA and KM3NeT/ARCA will together provide the world's largest instrumented effective mass across this broad energy range, as shown in Figure 1. Only neutrino interactions occurring within the instrumented volumes are considered; consequently, the effective mass saturates at the highest energies. Since effective mass depends on the analysis strategy, the figure illustrates representative selections with strong rejection of atmospheric muons [2, 3, 4, 5, 6].

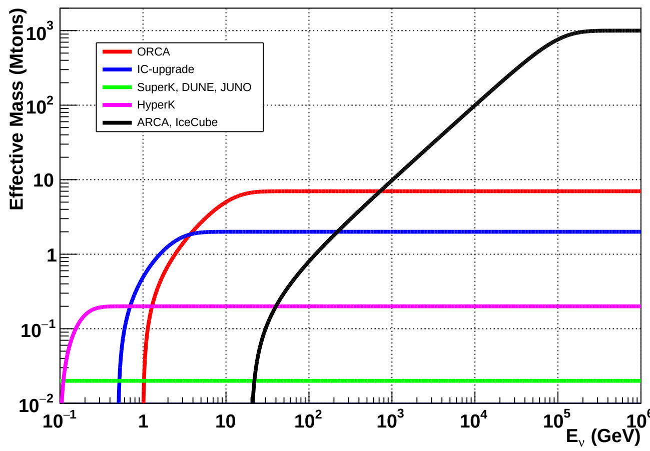


Figure 1: Comparison of the instrumented effective mass of current and future neutrino telescopes [2, 3, 4, 5, 6]

In the few-to-tens-of-GeV energy range, KM3NeT/ORCA will exploit large samples of atmospheric neutrinos traversing the Earth to study oscillations over long baselines. The primary objectives are the determination of the sign of Δm^2_{31} (the neutrino mass ordering) and the resolution of the θ_{23} octant. These measurements will significantly improve the precision of atmospheric oscillation parameters, reduce degeneracies in global fits, and enable sensitive tests of non-standard neutrino interactions and sterile-neutrino scenarios.

KM3NeT/ORCA provides a complementary and independent approach to the determination of the neutrino mass ordering compared to reactor and long-baseline accelerator experiments. While reactor experiments such as JUNO rely on precision measurements of the energy spectrum at short baselines, ORCA exploits atmospheric neutrinos traversing the Earth to probe matter-induced oscillation effects over a wide range of energies and path lengths. Unlike beam experiments (T2K, NOvA and the future DUNE and Hyper-Kamiokande), ORCA does not depend on an artificial neutrino source and simultaneously accesses neutrino and antineutrino channels as well as all flavours. Its sensitivity is driven by different systematics, making ORCA a robust and competitive contributor to global neutrino mass ordering determinations and an essential component of combined analyses with other current and future experiments.

At higher energies, KM3NeT/ARCA is optimised for the detection of TeV–PeV neutrinos and aims to identify and characterise cosmic neutrino sources. Its scientific programme includes measurements of the diffuse astrophysical neutrino flux, searches for steady and transient point sources as well as extended emission regions, and participation in real-time multi-messenger networks in coordination with electromagnetic and gravitational-wave observatories. By using neutrinos as direct probes of hadronic interactions, ARCA will provide unique insight into the environments and mechanisms responsible for cosmic-ray acceleration. ORCA complements these searches by extending sensitivity to lower-energy astrophysical neutrinos. Owing to the design of the digital optical modules, both detectors are also sensitive to neutrinos from core-collapse supernovae.

KM3NeT/ARCA occupies a unique and complementary position in high-energy neutrino astronomy alongside existing and planned neutrino telescopes. Compared to IceCube, ARCA benefits from its location in the Mediterranean Sea, providing excellent visibility of the Southern sky, including the Galactic Centre and a large fraction of the Galactic plane. The superior optical properties of deep seawater yield an enhanced angular resolution for muon neutrinos, strengthening ARCA's sensitivity to point-like and extended sources. In the longer term, ARCA will operate in synergy with the current detectors IceCube and GVD-Baikal and with next-generation Northern Hemisphere detectors such as P-ONE and TRIDENT, enabling full-sky coverage and improved source localisation through combined analyses. Together, these observatories will form a global network of cubic-kilometre-scale neutrino telescopes, advancing neutrino astronomy toward the identification of individual cosmic accelerators.

Both detectors contribute to searches for dark matter via neutrino signals from annihilation or decay in astrophysical objects such as the Sun and the Galactic Centre, and to tests of fundamental symmetries using neutrinos that have propagated over long distances through the Earth. Measurements of atmospheric muons further allow studies of the cosmic-ray flux from a few TeV to several PeV.

In addition to its physics program, the KM3NeT submarine infrastructure constitutes a unique long-term deep-sea observatory. Its cabled and powered nodes host a distributed network of sensors enabling continuous, real-time monitoring of key oceanographic parameters, including temperature, salinity, pressure, currents, dissolved oxygen, and biogeochemical proxies. These measurements support studies of deep-water circulation, climate-related variability, and marine ecosystem dynamics. The fixed seafloor installations also provide opportunities for marine geophysics, including microseismic monitoring, tectonic studies, and contributions to geohazard research such as submarine landslides and tsunami early-warning concepts.

1.1 Infrastructures and Detectors

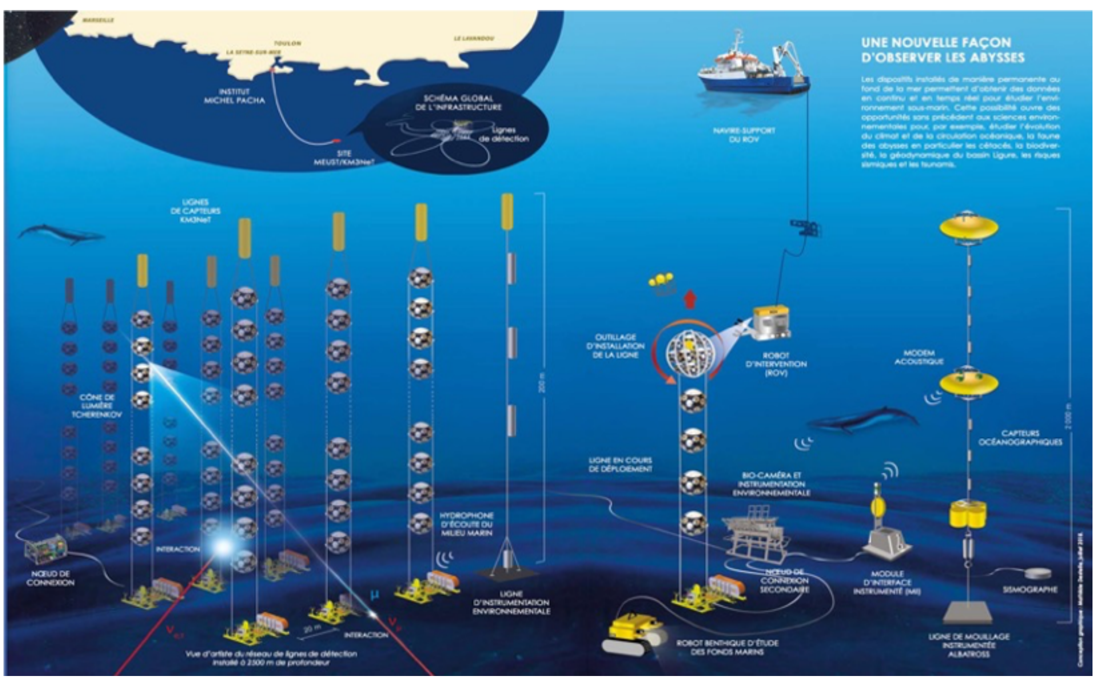


Figure 2: Artist view of the KM3NeT/ORCA infrastructure.

The KM3NeT telescopes consist of arrays of detection units (DUs) each comprising 18 digital optical modules (DOM) made of 31 photo-multiplier tubes (PMTs) as illustrated in Figure 2. This multi-PMT technology has also been adopted by other experiments such as IceCube+, P-one, Trident. The KM3NeT detectors access different neutrino energy ranges by adjusting the inter-DU and inter-DOM spacings. KM3NeT/ORCA, optimized for low energies, features an inter-DU spacing of 20 m and an inter-DOM spacing of 9 m. KM3NeT/ARCA, targetting higher energies, has an inter-DU spacing of 90 m and an inter-DOM spacing of 36 m. Although ORCA and ARCA rely the same technology, their seafloor infrastructure is different.

ORCA comprises 1 building block of detection units. The infrastructure is composed of a shore-station, located at La Seyne sur Mer, 2 deep-sea cables powered in AC, and 4 nodes. Each node provides six to seven outputs onto which are connected daisy chains of four DUs. The ORCA submarine infrastructure is owned by IN2P3 and managed by the Laboratoire Sous Marin Provence Méditerranée (LSPM), an IN2P3 national platform also opened to external users.

The ARCA detector is composed of two building blocks. The blocks are connected to the shore with cables serving a set of junction boxes onto which DUs are connected directly. The two configurations are illustrated in Figure 3 which also reports the currently deployed equipment. At KM3NeT/ORCA, two nodes are currently deployed too which 33 DUs are connected and operational. Two marine operations are planned to add about 12 detection units before the end of 2026 (going to ORCA45). Currently, there are 5 nodes and 51 strings deployed in the KM3NeT/ARCA detector. Figure 3 shows the current layout of both detectors. A sea operation is planned Summer 2026 to deployed 2 new connection nodes and up to 14 DUs more.

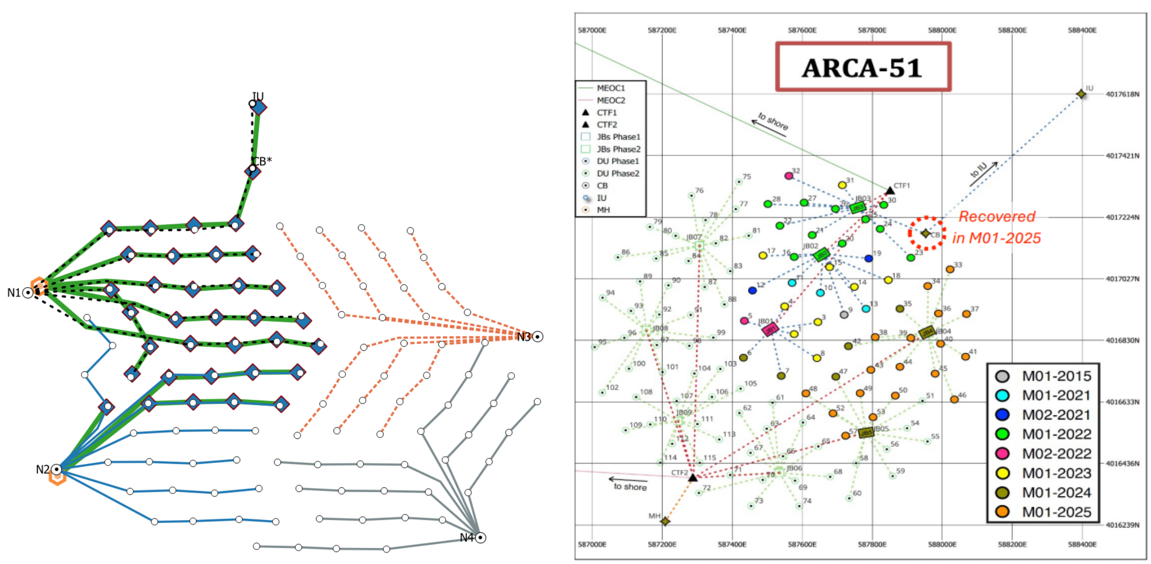


Figure 3: Sea bed infrastructure for ORCA (left) and ARCA 1st building block (right) and present equipment (colored points).

The production of the optical modules is distributed on several sites: Nikhef in Amsterdam, INFN in Caserta, INFN LNS in Catania, INFN in Salerno, Friedrich-Alexander-Universität in Erlangen-Nürnberg, Demokritos Institute in Athens, IPHC in Strasbourg, Subatech in Nantes and University Mohammed V in Rabat. The produced optical modules are transported to the DU integration sites in Nikhef, LPC in Caen and CPPM in Marseille for ORCA, and INFN in Caserta, INFN in Catania, INFN in Genova. Figure 4 shows the current state of the construction of the different elements in both ORCA and ARCA. The deployment of detection units typically takes place during two to three sea operations per year at ORCA and during a single major annual operation at ARCA. The end of the construction is planned beginning of 2030 for ORCA and in 2032 for ARCA.

27-Jan-26	ARCA (198)		ORCA (108)	
	quantity	% completed out of total	quantity	% completed out of total
Optical Modules	1206	33,8%	864	44,4%
Base Modules	71	35,9%	47	43,5%
Detection Units	58	29,3%	36	33,3%

Figure 4: Current status of the construction of the KM3NeT components.

1.2 Data processing

KM3NeT has adopted an all-data-to-shore concept. Each 100 ms, all the data are transmitted to the shore. With the current detector configurations, we have a data-taking rate of about 10-15 Hz for each detector. A data filtering is rejecting the optical background (>99% rejection) and applying several triggers based on the hit topologies to construct events. After filtering, the events are written into run files (3h duration), and copied to CC-IN2P3 and CNAF computing centres each night. In parallel to the writing process, the events are also reconstructed and classified in real-time in the online analysis platform. The reconstruction/classification parameters are stored in a DB to be used afterwards for online analyses (real-time correlation searches and neutrino alerts). In the Tier 1 computing centres (CC-IN2P3 and CNAF), the events are calibrated and reconstructed offline. Monte Carlo productions of atmospheric neutrinos of each flavour, atmospheric muons are produced in a run-by-run approach, where for each run, the detector configuration and data-taking condition are taken into account in the simulation.

The efficiency and performances of the event reconstruction depend largely in the capacity to precisely calibrate the detector responses. The calibration objectives are a relative time precision of <1 ns for the PMT time responses, a PMT efficiency known at a few percents, 20 cm relative localisation and <5° orientation of the optical modules and an absolute pointing uncertainty below 0.1°. To reach these precisions, KM3NeT has developed a multi-step calibration procedure composed of an acoustic positioning relying on a network of reference acoustic beacons, piezo and compass sensors in the DOMs, a time calibration based on nano beacons in each DOM, a few laser beacons. The final step of the calibration is based on the muon track reconstruction.

The absolute pointing of the detectors is a key source of systematic uncertainty in the neutrino direction estimation. Its determination can be done by reconstructing the direction of a known object in the sky. So far, no astrophysical source has been identified. Instead the shadow of the Moon and of the Sun of the cosmic rays is used to measure the deficit of atmospheric muons. For ORCA, the statistics is sufficient to obtain a good estimation. An alternative method is to detect an acoustic source on a boat, precisely positioned by the GPS, with the acoustic sensors. Based on the triangulation, it is possible to reconstruct the position of the emitter and compare it with the GPS position. In ARCA, it is not yet possible to get sufficient atmospheric muon statistics for the Moon/Sun shadows. During the 2025 sea campaign, we have deployed some additional acoustic beacons for which the positions have been precisely calibrated using an emitter in the boat. The analysis of this data is still in progress.

Fig 5 displays the available data sample for all the detector configurations. Despite being still in commissioning, we have already reached a very high data taking efficiency. For example, in 2025-2026, we had an efficiency of 80% in ARCA and 92% in ORCA. The main sources of downtime are the sea-operations, the DAQ commissioning periods, infrastructure upgrades. The calibration counts for about 0.1% of the time. After data quality checks, most of these data runs are usable (>97%).

Finally, the data and Monte-Carlo processing results are available for the Collaboration for high-level data analyses (in Tier-2 computing centres).

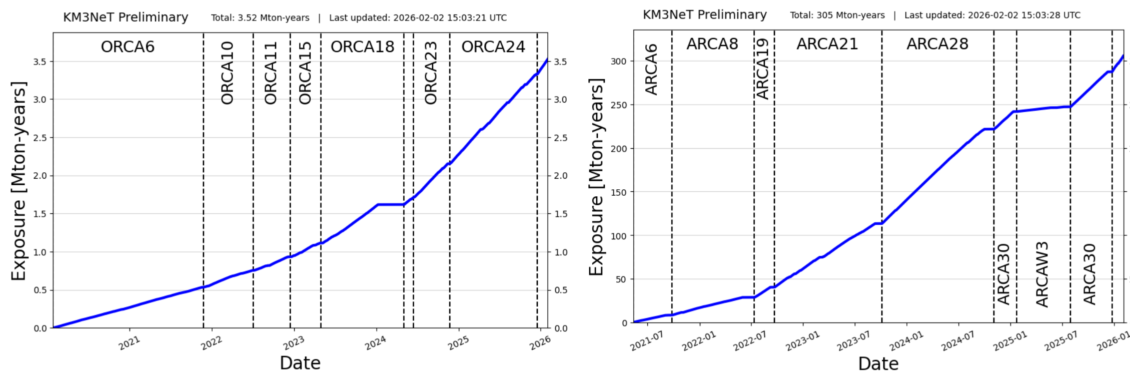


Figure 5: Cummulative exposure of the two detectors (ORCA: left / ARCA: right) for the different detector configurations.

1.3 KM3NeT Collaboration

The KM3NeT Collaboration gathers 68 institutes from 24 countries across five continents and is supported by national funding agencies. The Collaboration counts around 400 members, more or less half/half between technical and scientific resources. This accounts for about 270 FTEs. Since 2021, the Collaboration has grown by 28%.

The KM3NeT research infrastructure adopted a legal entity in January 2026 in the form of an AISBL (Association Internationale Sans But Lucratif) according to Belgian law. The statutes were signed in June 2025 by the five founding members: INFN (Italy), CNRS (France), NWO-i (The Netherlands), INPP/NCSRD (Greece) and the University of Valencia (Spain). The five founding members include those funding agencies that have contributed to the funding for the infrastructure as well as the large majority of the person power for its construction, integration, commissioning and operation. It is expected that all KM3NeT partners will eventually become AISBL members or observers.

Oversight and governance of the Collaboration are ensured by the AISBL Council – composed of representatives appointed by the funding agencies – the Scientific and Technical Advisory Committee – appointed by the AISBL Council – and the Institute Board representing all participating Institutes. Executive management is carried out by the AISBL Director together with the Collaboration Management Team elected under the authority of the Institute Board. The AISBL director is currently N. Leroy.

The organigram of KM3NeT is displayed in Fig 6. The Management Team consists of the Spokesperson, the Deputy Spokesperson, the Physics and Software Manager, the Technical Project Manager, and three site managers for the French, Italian and Greek sites. The first four are elected by the Institute Board for terms of two years, renewable once. The latter three are appointed by the organizations managing the sites. The management team is supported in its every-day activity by Technical and Science Steering Committees, including the coordinators of the technical and scientific subprojects, respectively. The Technical Project Manager leads also a Project Office supporting management activities. Various committees (Publication Committee, Conference Committee, etc.) are also appointed for carrying out specific tasks. Currently, D. Dornic is the deputy spokesperson and N. Lumb is the ORCA site manager.

The Institute Board (IB) is the assembly of member institutes (with a vote) and observer institutes (without a vote) of the Collaboration; its chair is elected by the board every two years. The IB deliberates and decides on the scientific exploitation of the research infrastructure, and the internal rules of the collaboration. The IB also decides on the admission of new members or observers of the collaboration. Currently, A. Kouchner is the IB chairperson.

Engineers and technicians work in the labs of the KM3NeT institutes on the construction and integration of the detector components. Individual scientists usually work in small groups, choosing the research areas and data that interest them most. The scientific output from the Collaboration is shared by all members and is subject to rigorous internal review before results are made public.

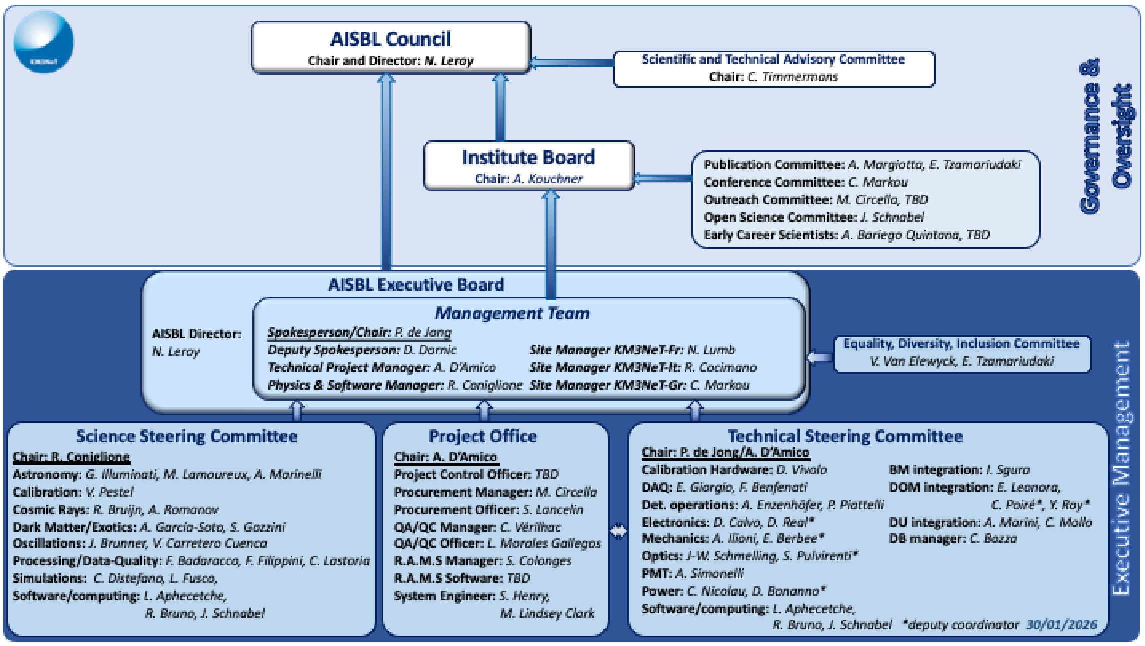


Figure 6: Organigram of KM3NeT

1.4 KM3NeT France

The IN2P3 laboratories involved in KM3NeT are listed in Table 1 together with the responsibilities they hold. In 2025, KM3NeT France is composed of 102 persons for 65.1 FTEs. Annual meetings are organised to federate and organise the French community. Several joint ANR proposals have been submitted, though none has been successful so far.

1.5 Fundings

The construction of the detectors is funded by national agencies. The funding of the KM3NeT/ORCA seafloor infrastructure is secured and funded by France (2 additional nodes + 1 branching unit). The 33 KM3NeT/ORCA deployed DUs have been funded by France (13 DU) and the Netherlands (20 DU).

The funding for 61 additional DUs is secured which allows to construct and deploy 94 out of the 108 DUs required to complete ORCA. It results from additional contributions from France (36 DU), The Netherlands (20 DU) and benefits from of a commercial agreement with BNL (5 DU). The french contribution includes an arrangement with INFN to optimise parts availability to complete KM3NeT/ORCA as early as possible.

The total cost of a DU is around 430k euros. The completion of ORCA (108 DUs) requires the funding of 14 additional DUs.

So far, the Italians have secured the budget for 150 detection units and the corresponding sea floor infrastructure.

Table 1: List of the IN2P3 laboratories involved in KM3NeT with the employed human resources and the responsibilities carried between 2021 and 2026.

Laboratoire	ETP (S/T)	Technical responsibilities	Scientific responsibilities	Management responsibilities
APC	5.9/3.8	Mechanics WG convener RAMS Manager System Engineer Calibration Base QA/QC Manager	Astronomy WG convener Oscillation WG convener (former)	ANTARES Spokesperson KM3NeT IB Chair EDI Committee Chair Technical Project Manager (former)
CPPM	3.6/14.2	Procurement Officer System Engineer Detector Operation Manager ORCA DU Integration WG convener ORCA Marine Operation ORCA seafloor infrastructure ORCA seafloor infrastructure operation ORCA BM integration DU anchor integration Acoustic Positioning ORCA shore station manager Instrument Unit Radioactivity detector MECMA contact person	Oscillation WG convener Astronomy WG convener (former) Online Physics Analysis WG convener	ORCA Site Manager KM3NeT Deputy Spokesperson KM3NeT Spokesperson (former) KM3NeT-Fr Scientific Resp. KM3NeT-Fr Technical Resp. LSPM Director ANTARES Technical Manager CZAR CC-IN2P3
IPHC	0.8/2.0	DOM integration		
LPC Caen	3.0/1.5	DU integration	Calibration WG convener DPDQ WG convener CR WG convener Software & Computing WG convener (former)	CZAR CC-IN2P3
LUPM	0.1/1.0	BM integration		
Subatech	3.5/3.5	DOM integration DOM integration WG convener BM integration (until end 2026)	Software & Computing WG convener	

The operation, maintenance and exploitation of the two KM3NeT detectors is by funded all the member institutes contributing to a common fund.

2 Physics Program

The dataset collected with the two detectors are represented in **??**. Public results, reported in the next paragraphs, are based on samples up to ORCA11 and ARCA21.

2.1 Oscillation and BSM

2.1.1 First results (Oscillations / NMO / BSM)

First ORCA results, using data collected in 2020-2021 with 6 installed DUs, equivalent to 5% of the final detector configuration, were recently published [2]. An update based on a 70% larger data set, corresponding to an exposure of 715 kton-years and comprising about 10^4 neutrino candidates at the final selection level, was subsequently presented at major conferences [7]. The excellent sensitivity of ORCA to neutrino oscillations is illustrated in Fig. 7, showing the well-measured first oscillation maximum in the ν_μ disappearance channel and the contours in the $\Delta m^2_{31} \times \sin^2\theta_{23}$ plane.

Based on the same dataset from 2020-2021, a competitive measurement of the ν_τ normalisation and the ν_τ cross section was also provided [8]. Various BSM models have been studied as well, such as non-standard-interactions [9], neutrino decay [10], non-unitarity mixing [8], quantum decoherence [11] and sterile neutrinos [12]. The analysis based on 0.433 Mton-years of data (ORCA6) has already yielded the world's second-best limits on $|U_{\tau 4}|$ in the case of an eV-scale sterile neutrino and limits on NSI parameters of the same order as the current most stringent limits.

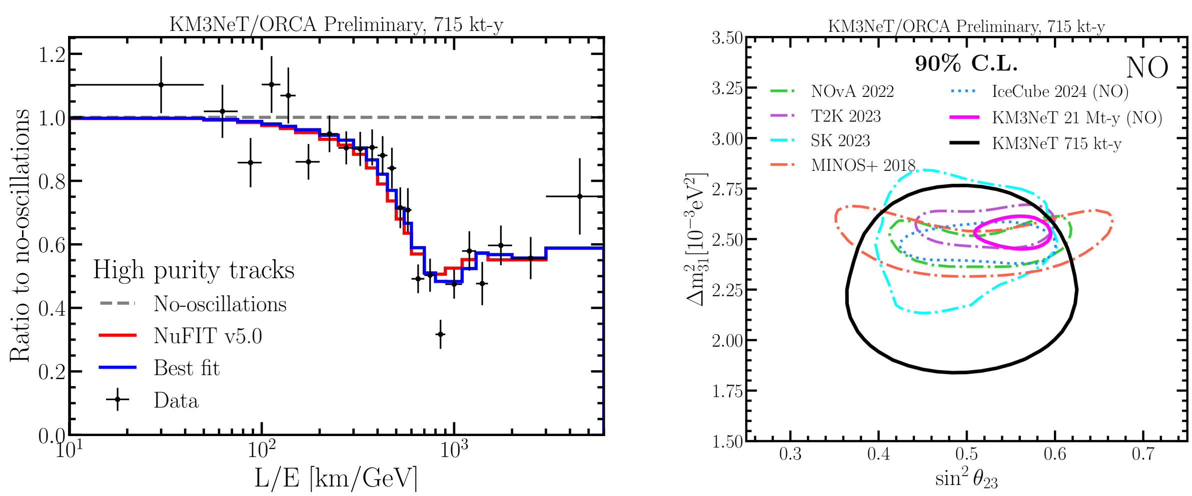


Figure 7: (Left) Distribution in L/E of the high-purity track events (dominated by ν_μ charged-current interaction channel) of the 715 kton-years sample (black crosses), compared to the best fit (blue) and the expectation from a global fit of oscillation data. (red). (Right) Allowed regions at 90% CL for Δm^2_{31} NO (left) and IO (right) and θ_{23} for the 0.715 Mton-years analysis, compared to current results and the 21 Mt-yr projection. In the case of the 21 Mt-yr projection normal ordering and inverted ordering are assumed independently, and the true values used are from NuFit v4.1.

2.1.2 Analysis plan

A major overhaul of the neutrino oscillation analysis tools is currently underway. Particular focus is put on the handling of the various systematic uncertainties to prepare for the expected percent level precision which could be reachable in the near future. In concertation with IceCube analysis groups, it has been decided to model the atmospheric neutrino and muon flux with the recent "Daemonflux" [13, 14], which has been tuned to atmospheric muon measurements. A variety of codes are available to model neutrino interactions with exhibit surprisingly large divergences. This is studied in the "Nuisance" project [15] which is considered as a valid option for near future analyses. Detector related uncertainties will be constrained by measurements with the detector itself. Both stopping atmospheric muons and radioactive decays have been identified as useful calibration sources to constrain both water properties such as absorption and scattering as well as PMT parameters such as their quantum efficiencies. The resulting effects will be implemented into the oscillation fit code by using templates.

The resulting improvements in constraining the various systematic uncertainties in conjunction with the improved performance and higher statistics of a growing detector will allow us to update results on an approximate yearly basis. For summer 2026, results based on an exposure of 1.5 Mton-years are planned to be released from data taking between 2020 and 2023, comprising data form an ORCA detector composed of 6 up to 18 DUs. For 2027, it is planned to extend the analysis to 3 Mton-years, adding data from 2024 and 2025 with the majority of data acquired with 24 DUs. By 2028 a data set of 5-10 Mton-years should become available. For comparison: 3 years of the complete ORCA detector correspond to 20 Mton-years exposure.

2.1.3 Full detector expectation

Atmospheric Oscillation Parameters Due to the combination of a multi-Mton detector with a low detection threshold (few GeV) as illustrated in Figure 1, KM3NeT/ORCA will harvest almost 100,000 neutrino events at analysis level each year. This will correspond to one of the largest atmospheric neutrino event samples ever recorded, as outlined in Figure 8, left. This, together with the improved constraints on the various systematic uncertainties (see above), will allow to perform high precision measurements of the so-called atmospheric neutrino parameters. The contour on the $\Delta m^2_{31} \times \sin^2\theta_{23}$ plane expected for 21 Mton-years (i.e. about 3 year with the full detector) under the NO assumption is reported in Figure 7-(right). For Δm^2_{31}, a precision of 1.5% with an exposure of 20 Mton-years can be expected, nicely complementing the high-precision measurement from JUNO [16] on this parameter. However, for the mixing angle $\sin^2\theta_{23}$ the ultimate precision is indeed expected from atmospheric neutrino experiments such as KM3NeT/ORCA. Here, a few percent precision might be reached, strongly depending on the true value of $\sin^2\theta_{23}$.

Tau neutrino Figure 8, right shows another unique data sample which is accumulated with KM3NeT/ORCA. ν_τ-CC interaction from atmospheric neutrinos can only occur in conjunction with neutrino oscillations as the intrinsic ν_τ component of the atmospheric neutrino flux is marginal. The large majority of these events occur in the energy range between 10 and 50 GeV, close to the first oscillation maximum, as illustrated in Fig. 7-(left). The KM3NeT/ORCA detector is fully efficient at these energies providing an unequalled rate of 3000 ν_τ-CC events per years. This will allow to measure the ν_τ-CC cross section with a precision better than 10% and close to its kinematical threshold.

Neutrino mass ordering The large data sample which will already be accumulated during the construction of the detector over the next few years, will allow to probe the neutrino mass ordering (NMO) more and more accurately. Figure 10-(left) reports the sensitivity to neutrino mass ordering (NMO) after three years of data taking [22] as a function of the true θ_{23} value. Figure 10-(right) provides a comparison of the evolution of the average sensitivity of ORCA between 2020 and 2035 compared to IceCube [5], JUNO [6]

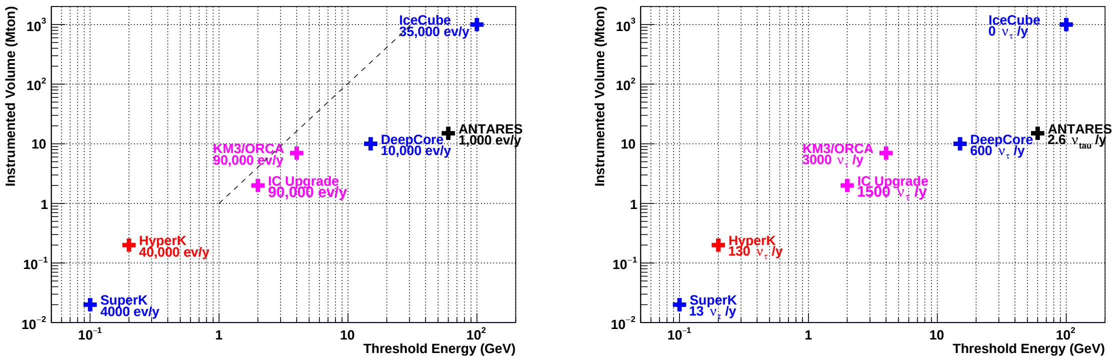


Figure 8: Atmospheric total neutrino events (left) and ν_τ-CC events (right) at analysis level per year for different experiments as function of their effective energy threshold [17, 2, 3, 18, 4, 5, 19, 8, 20, 21]. The color code indicates the experiment status (black: terminated, blue: running, magenta: under construction/data taking, red : future); along the dashed black line one expects approximately equal event numbers.

and DUNE [23] and highlights the unique sensitivity achieved by combining the ORCA and JUNO analyses. The upper line of the bands for ORCA and IC corresponds to normal ordering (NO) and $\theta_{23} = 48°$ while the lower line of the band holds for inverted ordering (IO) or $\theta_{23} = 42°$. For JUNO, the two lines correspond to the choice NO/IO. KM3NeT/ORCA is in a favourable situation with an average sensitivity of 3-5.5σ significance by 2033.

Combining the results from ORCA, JUNO and IceCube could potentially allow to determine earlier the NMO. In particular, a strong synergy exists between atmospheric experiments, such as ORCA and IceCube, and the reactor experiment JUNO. In atmospheric analyses, the determination of the NMO is affected by a degeneracy with Δm^2_{31}, whereas this degeneracy is significantly weaker in JUNO. Lifting this degeneracy – either through a full likelihood combination or simply using JUNO's Δm^2_{31} measurements as an external prior – substantially enhances the NMO sensitivity of atmospheric experiments [24], as illustrated in Figure 9.

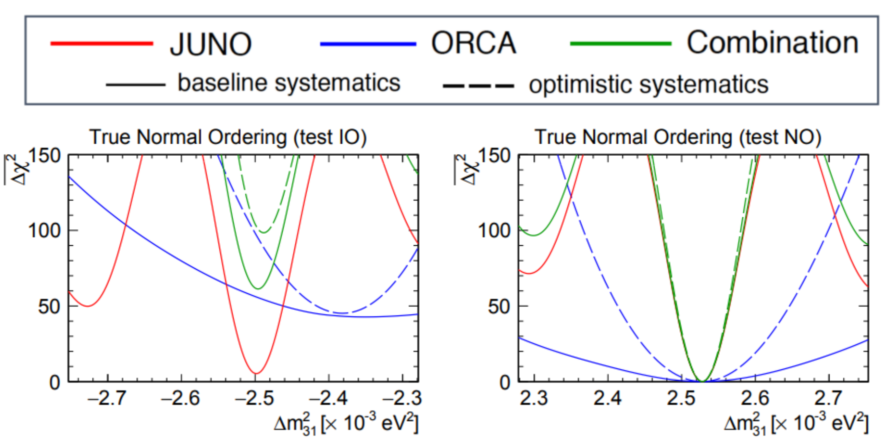


Figure 9: $\Delta\chi^2$ profile for only JUNO (red), only ORCA (blue), and the combination of JUNO and ORCA (green) as a function of test values of Δm^2_{31} for 6 years of data taking assuming baseline (solid) or optimistic (dashed) systematics [24].

To ensure that such a combination remains under the control of the collaborations, a series of joint workshops involving ORCA, IceCube, and JUNO has been organized since 2025. These workshops aim to converge toward common analysis strategies for the combination, in particular for the treatment of systematic uncertainties.

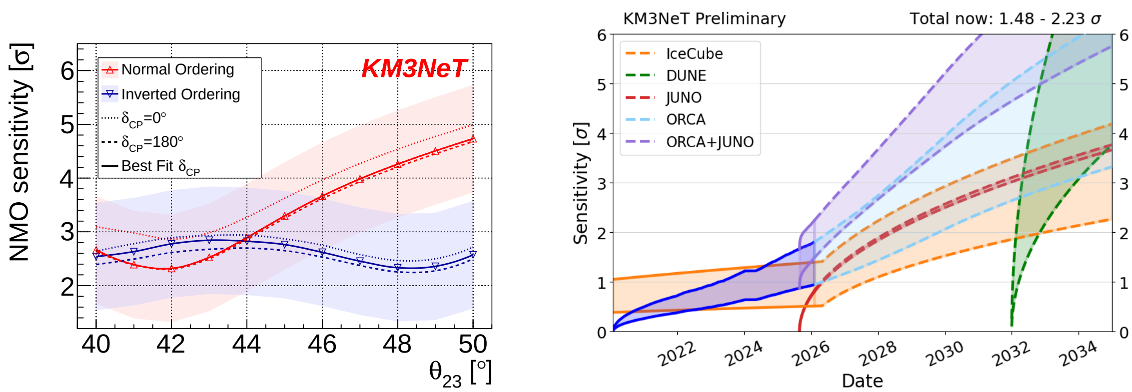


Figure 10: Left: Sensitivity to neutrino mass ordering (NMO) after three years of data taking, as a function of the true θ_{23} value, for both normal ordering (red upward pointing triangles) and inverted ordering (blue downward pointing triangles) under three assumptions for the CP value (Right) Evolution of NMO sensitivity with time for KM3NeT/ORCA, IC-Upgrade [5], JUNO [6], DUNE [23] and the combination KM3NeT/ORCA-JUNO [24]. The bands correspond to different choices of the oscillation parameters.

BSM Various BSM models can be probed, as demonstrated by the analyses of the first KM3NeT/ORCA datasets. The uniquely large sample of ν_τ that KM3NeT/ORCA will collect, will enable stringent test of BSM models (sterile neutrino, non-standard interactions) featuring couplings to the third lepton generation, which are currently only weakly constrained. The results obtained with an exposure of 715 kton-years are already competitive [12, 9]. They are expected to improve by a factor four with an exposure of 21 Mton-years sample (i.e. about 3 year with the full detector), thereby significantly surpassing current best limits.

At higher energies, ARCA will provide a complementary probe of sterile neutrinos by exploiting matter-enhanced oscillation effects of TeV atmospheric neutrinos traversing the Earth, as already demonstrated by IceCube [25].

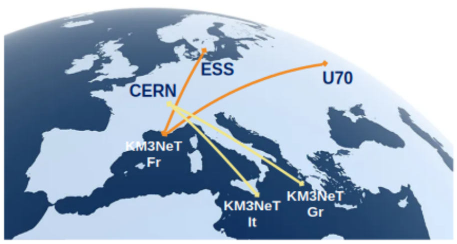
Searches for Lorentz invariance violation (LIV) will also benefit from the complementarity between ORCA and ARCA, as ORCA probes oscillation-phase distortions at the GeV scale while ARCA extends the sensitivity to energy-growing LIV effects using TeV atmospheric neutrinos over Earth-diameter baselines[26].

2.2 Long term perspectives

The KM3NeT technology could also be used for the next generation of high precision accelerator based long baseline experiments (LBL). Preliminary studies indicate that with a modest beam intensity of O(100)kW, an ORCA like detector would allow to collect neutrino samples ten times larger than the upcoming LBL experiments [27]. At these intensities, it would be possible to operate trackers in the beamline and tag the neutrinos [28].

Neutrino tagging consists in associating an observed neutrino interaction with its parent decay ($\pi^\pm \to \mu^+ \nu_m u$) reconstructed with silicon pixel detectors placed in the beamline. Flavour changes induced by neutrino oscillations during propagation are therefore observed on an event-by-event basis, effectively removing the flux-related systematic uncertainties (flavour, chirality, energy) that play a dominant role in upcoming experiments. In addition, the decay reconstruction allows to infer the neutrino energy with a sub-percent relative precision and no bias. As a comparison, reconstructions based on neutrino interactions have a precision of 10-20% and are affected by systematics uncertainties from the interaction modelling. Preliminary studies [28] indicate that a tagged long basedline experiment exploiting an ORCA like detector could reach a δ_{CP} precision of the order of a few degrees.

The tagging technique has recently been demonstrated experimentally using state-of-the-art pixel detectors [29], and the nuSCOPE project [30][1] has been launched to study the possibility of a short-baseline tagged neutrino experiment at CERN aimed at improving our understanding of neutrino interactions. If successful, this project would provide a solid foundation for a tagged LBL experiment. Such an experiment could be implemented using existing infrastructures, as illustrated in Figure 11. Preliminary studies of the beamline for such tagged experiments have been carried out within the CERN Physics Beyond Colliders program and yield promising results [27].



		Baseline km	Energy GeV
U70	KM3NeT-Fr	2600	5.0
ESS	KM3NeT-Fr	1500	2.9
CERN	KM3NeT-It	1300	2.5
CERN	KM3NeT-Gr	1700	3.3

Figure 11: (left) Possible options for a tagged LBL using existing European infrastructures with (right) there respective baseline and energy at first oscillation maximum.

2.3 Astronomy

By combining the ORCA (GeV-TeV) and ARCA (TeV-PeV) data and developing a dedicated program for $\mathcal{O}(10)$ MeV neutrinos from Core-Collapse Supernovae (CCSNe), KM3NeT can search for astrophysical neutrinos over a particularly wide energy range. The breadth of KM3NeT's scope has been demonstrated by the detection in 2023 of the most energetic neutrino observed to date. In addition to characterising the associated signal, the Collaboration performed numerous studies to identify its origin and assess its compatibility with Auger and IceCube observations. This remarkable discovery completes an already wide-reaching neutrino astrophysics program (see Figure 12).

During the past years, the Collaboration has developed a real-time analysis (RTA) system to send alerts to other telescopes and to respond rapidly to external triggers. This framework includes a dedicated CCSN analysis pipeline with an improved low-energy neutrino selection procedure. In addition to the RTA system, KM3NeT has designed high-energy neutrino searches that exploit past ARCA and ORCA data, sometimes combined with ANTARES. These searches have enabled constraining the all-sky and galactic neutrino diffuse fluxes as well as the neutrino fluxes from individual point-like sources and from populations of objects. Finally, KM3NeT has laid the groundwork for future combined analysis involving multiple messengers: simultaneous fits of gamma-ray and neutrino observations using analytical models or the Gammapy software, and sub-threshold searches for coincident neutrino and gravitational-wave (GW) signals.

2.3.1 First results

Ultra-high-energy neutrino : On February 23, 2023, an exceptionally intense signal was observed in ARCA, which was operating in a 21-line configuration at the time. With approximately one third of the

[1] https://nuscope.web.cern.ch/

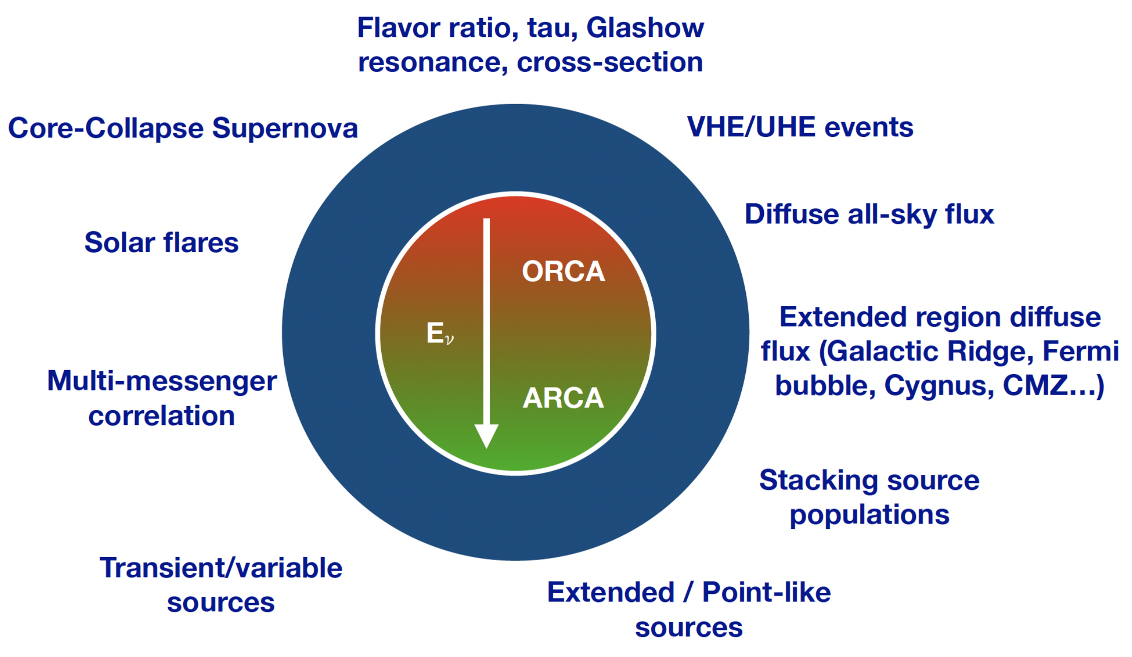


Figure 12: Illustration of the different science cases in the astronomy working group.

PMTs recording light deposition, this event was by far the brightest among the 10^8 events collected by this ARCA configuration over one year. The event brightness and (horizontal) direction were consistent with expectations for a very-high-energy muonic cosmic neutrino, and allowed the background hypotheses to be safely rejected (less than 10^{-3} events expected over one year). The event energy was estimated from the total number of PMT hits, using Monte Carlo simulations. The resulting energy estimates were 120^{+}_{-60} PeV for the muon, and 220^{+570}_{-110} PeV for the parent neutrino assuming a E^{-2} spectrum [31]. Further studies showed a moderate, 2.5σ, tension between this observation and results from Auger and IceCube [32]. The associated neutrino flux measurement, as well as the IceCube high-energy neutrino observations and IceCube/Auger constraints are shown in Figure 13. No coinciding excess of lower-energy neutrinos has been observed.
The event was localised with a larger-than-expected 68% C. L. error region of 1.5°, due to uncertainties on the positions of the detector components; the recent deployment of a new positioning system will allow reducing this uncertainty by up to one order of magnitude. To date, possibly because of the size of its localization area, the origin of the event has not been determined. Its properties have been shown to be compatible with for diffuse neutrino fluxes from blazar [33] and GRB populations [34], as well as with cosmogenic neutrino flux models assuming extreme values of the cosmic-ray source evolution parameters [35]. In addition, no significant coincidence with transient gamma-ray, X-ray, or radio emission has been observed, despite the presence of three extragalactic flaring sources within the event's 1σ localization region [36, 37]. In Summer 2025, we have deployed additional material to largely improve absolute pointing uncertainties. The data is in progress and we expect to have a preliminary result for the Summer conferences. During the next sea campaign Summer 2026, we will continue to deploy additional acoustic emitters to further reduce the pointing uncertainties.

Real-time analysis system : Real-time multi-messenger campaigns, in collaboration with multi-wavelength (radio to γ-ray) and gravitational wave astronomers, could prove crucial in unveiling the sources of the most energetic particles and the acceleration mechanisms at work. Neutrinos would provide insights into the physics of stellar explosions, compact object mergers, and relativistic jets, as well as particle acceleration processes. The main requirement for these multi-messenger studies is the quasi-online communication of potentially interesting observations to partner instruments ("alerts"), with latencies of a few minutes, at

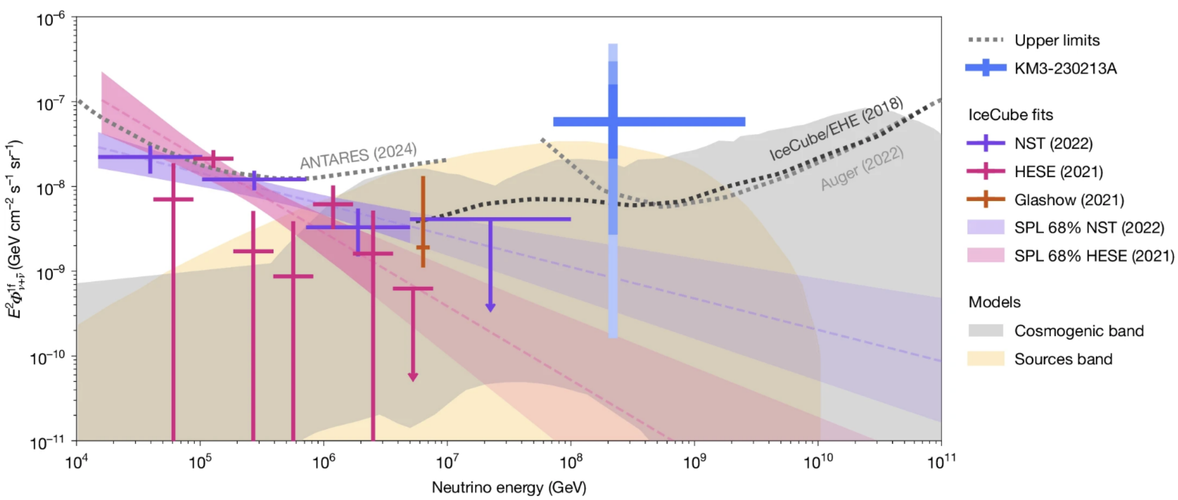


Figure 13: Flux and energy of the VHE event KM3-230213A (blue cross). The $1, 2, 3\sigma$ uncertainties on the flux are indicated by shades of blue. This figure also shows IceCube diffuse neutrino flux measurements in the Northern-Sky track and the High-energy starting event channels, with the corresponding single-power-law fits. The yellow and grey regions illustrate the range of neutrino emission models for source populations and cosmogenic neutrinos, respectively. The grey and black dashed and dotted lines indicate upper limits on the neutrino flux from ANTARES, IceCube, and Auger.

most. Such alerts are the only way to achieve simultaneous observations of transient phenomena by pointing instruments.

With the scientific return from ANTARES, KM3NeT is implementing an online analysis platform (See Figure 14) [38]. This architecture is composed of three main parts : one specific to ORCA (blue rectangle), one to ARCA (green rectangle) and one common to both detectors (red rectangle). In order to limit the huge data flow of each detector, the heavy processing is performed directly on the shore station, and it contains the event reconstructions, the classifiers and the supernova monitor. The common part contains some services (tools to make event display, event storage, monitoring and the internal/external reporting), the SN final processing processes (SN trigger, SN alert and SNEWS sender), the neutrino alert sending module and the online analysis module. The typical delay between the event time and a selected neutrino is <30s (about 10s in average).

The real-time analysis correlation [39] is in operation since a few years, continuously analysing both ORCA and ARCA data to look for time/space correlation for Gamma-ray Bursts (GRBs) detected by SVOM,Fermi and Swift, gravitational Wave (GW) events detected by LIGO and Virgo periods, transient events of different nature detected by multiple observatories like Fermi, Swift, MAXI or HAWC, neutrino events shared by IceCube, Fast Radio Bursts (FRB) reported by Chime and the TNS catalogue, and micro-quasar flares studied through an internal broker which searches for luminosity increase in the light curves from MAXI and Swift-BAT of selected sources. The results of these searches are stored in a DB and are overlooked by shifters. The public reporting in Astronomer's Telegrams or in GCN circulars is planned around the Summer 2026.

The public alert sending is currently under development and is expected to be operational by mid 2026. We are currently performing end-to-end tests of the system and developing tools to precisely assess the angular uncertainty of the selected neutrino events taking into account all the systematics. We are changing deeply the way we are selecting the events for the KM3NeT neutrino alert compared to what has been done in ANTARES or IceCube, by not only selecting the neutrino candidates based only on the neutrino properties but also to add directly in the alert formation the presence in space and time of potential counterparts

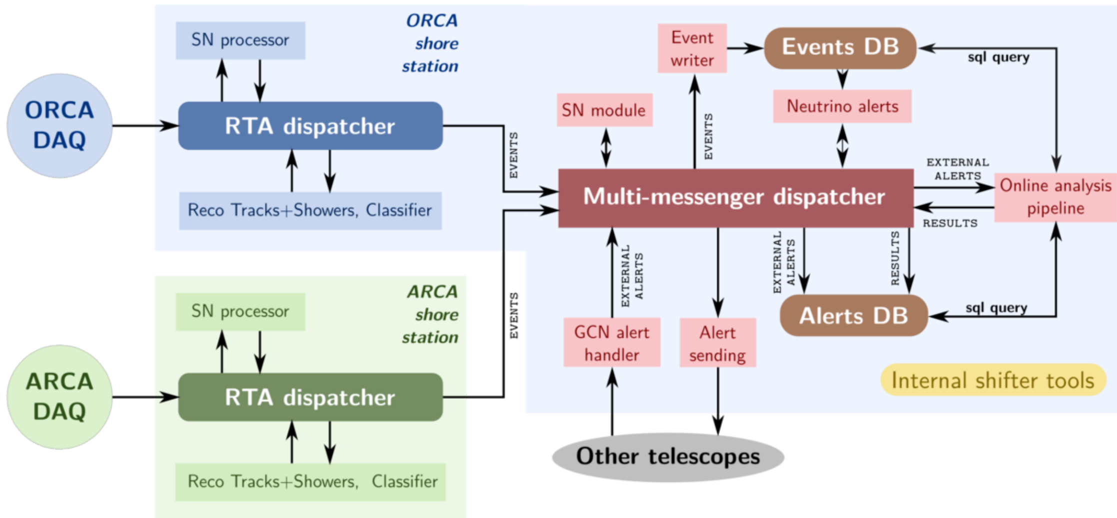


Figure 14: Architecture of the online analysis platform.

previously reported in multi-wavelength astronomy catalogues and in real-time data. This will allow to increase the scientific interest of the KM3NeT alerts. Moreover, for each selected neutrino candidates, an on-fly simulation of the same event 100 to 1000 times will be used to construct properly the error region map taking into account the different systematic errors.

Core-collapse supernovae : individual CCSN neutrinos, due to their low $\mathcal{O}(10)$ MeV energies, are usually not expected to activate more than one DOM, but they may produce multiple PMT hits within this DOM. The initial CCSN neutrino search strategy in KM3NeT therefore focused on identifying an excess of uncorrelated multi-hit signals in many individual DOMs over the expected background from bioluminescence, ^{40}K radioactivity, and atmospheric muons. Since last year, this method has been improved by introducing new selection criteria that exploit the spatial and temporal distributions of hits within each DOM [40]. This improved selection has been tested on three CCSN neutrino emission models based on 3D simulations, for progenitor masses of 11, 27, and $40 M_{\odot}$. For these models, the new selection extends by nearly 30% the distance up to which KM3NeT can detect a CCSN with a 5σ significance. For the 11 $M_{\odot}$, model associated with the lowest neutrino flux, the combined probability for ORCA and ARCA to detect neutrinos from a Galactic CCSN is now larger than 80% and KM3NeT will achieve full Galactic sensitivity once completed, as shown in Figure 15. For the 27 and 40 $M_{\odot}$ models, respectively, KM3NeT's reach currently extends to the Milky Way edge and to the Large Magellanic Cloud.

In the online analysis platform, we have also included a CCSN analysis pipeline to monitor in real-time the combined ARCA+ORCA low-level data. This pipeline includes an interface with the SNEWS2.0 system. So far, the real-time CCSN analysis system has been in operation since several years, and we are mainly waiting for the SNEWS green light to send our data.

Diffuse neutrino emission : A major focus of KM3NeT's astrophysics program is the observation of the all-sky and Galactic diffuse neutrino fluxes discovered by IceCube. A search for the all-sky diffuse flux was performed using 640 days of ARCA data, with detector configurations ranging from 6 to 21 lines [41, 42]. Only upgoing tracks were included, removing the very-high-energy event discussed above. The cosmic neutrino spectrum was modelled as a power law. A likelihood analysis of the observed event energy spectrum, shown on the left panel of Figure 16, showed no significant evidence for a cosmic neutrino component. The best-fit values of the spectral parameters are compatible with IceCube measurements, as shown in the right panel of Figure 16. The same dataset was also analysed in a search for neutrinos from the Galactic Ridge,

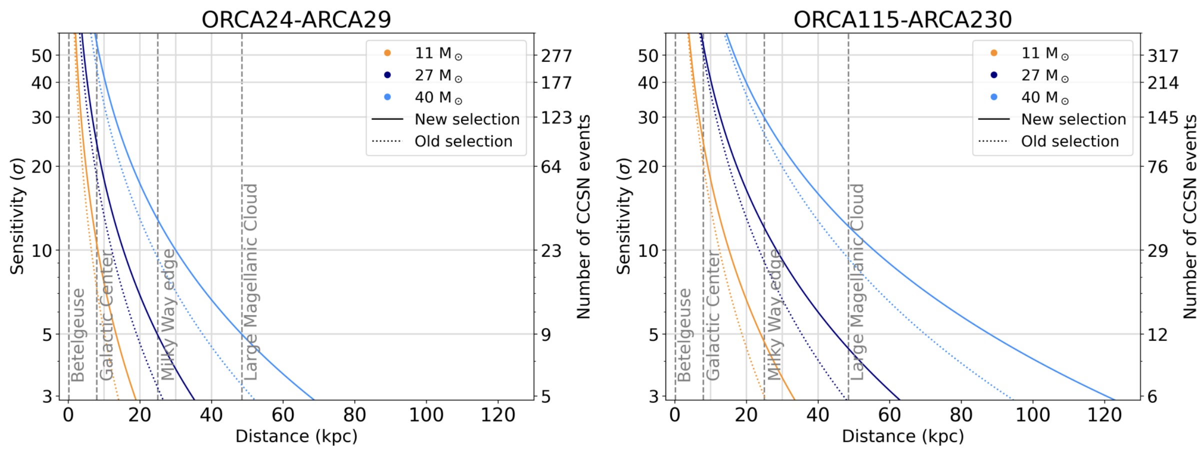


Figure 15: Significance of a CCSN neutrino detection as a function of the supernova distance to Earth for the combined ARCA and ORCA detections and for three CCSN models with different progenitor masses. The dotted and solid lines indicate the old and new selection procedures, respectively. The left panel shows results for recent ARCA and ORCA configurations; the right panel shows expected sensitivities for the completed detectors.

the central region of the Milky Way plane [43]. The number of observed events in the Ridge was not significantly higher than the expected background; the resulting upper limit on the Galactic neutrino flux, displayed in Figure 17, is about an order of magnitude higher than the best-fit fluxes reported by IceCube.

Point-like neutrino sources : The 21-line configuration of ARCA currently allows the reconstruction of tracks with an angular resolution better than 0.3° for events above 100 TeV; the expected resolution for the completed detector is of less than 0.1° [44]. Combined with the detector's extensive sky coverage, this exceptional angular resolution will allow KM3NeT, once completed, to probe point-like or slightly extended neutrino sources with unprecedented sensitivity. A search for neutrinos from 106 candidate sources, selected from catalogues of cosmic-ray and electromagnetic observatories as well as from other neutrino experiments, has been conducted. As in the diffuse flux searches, this analysis was based on an ARCA6–21 upgoing track sample [45].
A binned likelihood analysis of the resulting event energy spectrum showed no significant evidence for cosmic neutrino emission; the corresponding sensitivities and upper limits are displayed in Figure 18. By combining the ARCA6–21 track sample with the full ANTARES track-plus-shower dataset, the ANTARES sensitivity was improved by 20%, yielding a pre-trial 3.9σ excess in the direction of the MG3 J225517+2409 blazar [46]. The computation of the corresponding post-trial p-value is currently in progress. The results for this combined analysis are shown in Figure 19. A search for lower-energy neutrinos (10 GeV to 10 TeV) is also underway, using a sample of upgoing and horizontal tracks corresponding to 1200 days of observation with the ORCA6–18 configuration [47].

Observations from individual sources were stacked to constrain neutrino emission for different source populations: high-frequency peaked BL Lacs, Seyfert galaxies with a hot corona, Ultra-Luminous Infrared galaxies, GRBs, and Fast Radio Bursts [48, 49, 50, 51]. No significant evidence for neutrino emission was observed.

Combining messengers : The collaboration is developing tools to jointly analyse observations from multiple experiments. For combined neutrino and gamma-ray analyses, an extension of `Gammapy`—the official CTAO analysis software—has been implemented to incorporate neutrino observations. This software was used to assess the ability of combined KM3NeT+CTAO [52, 53] and KM3NeT+HAWC analyses to constrain the fraction of the gamma-ray flux induced by hadronic acceleration in Galactic sources. Projected

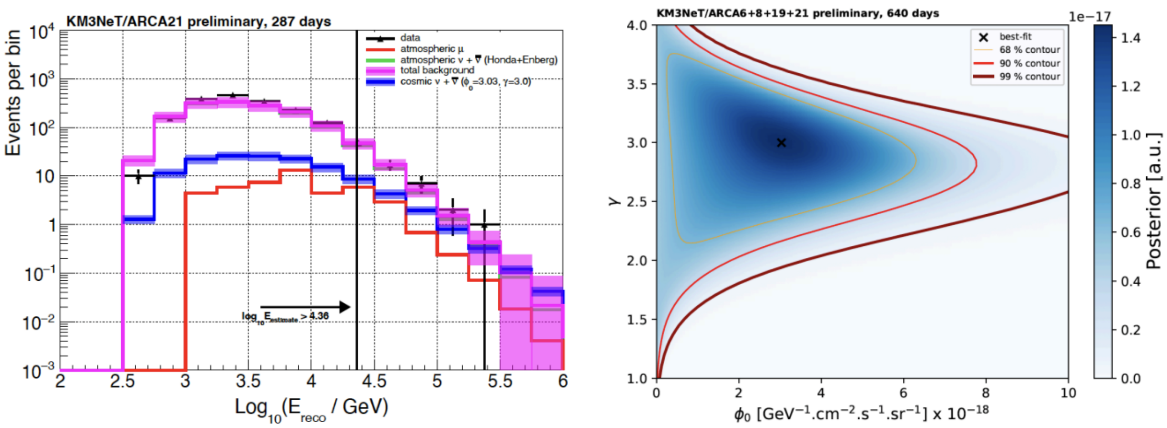


Figure 16: Results of a search for the all-sky diffuse neutrino flux using ARCA6-21 data. Left: reconstructed energy distributions for observed neutrino candidates (black), background expectations (red, green, purple histograms), and the best-fit cosmic neutrino signal (blue). Right: Posterior probability distribution for the flux normalisation ϕ_0 and the spectral index γ.

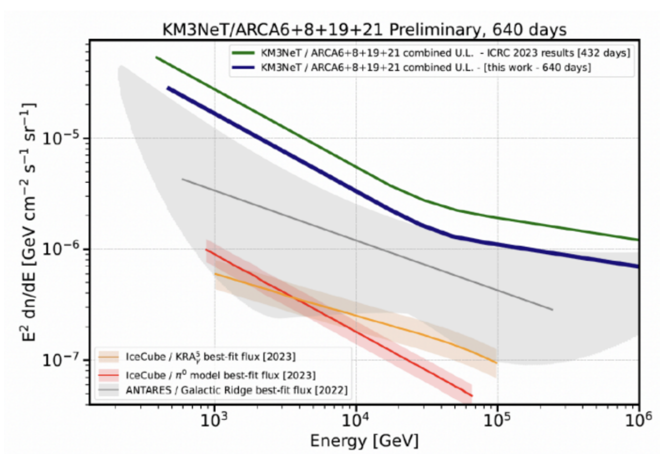


Figure 17: Upper limits on the neutrino flux from the Galactic Ridge from ARCA6-21 with 432 and 640 days of data (green and dark blue, respectively). The best-fit flux obtained in the ANTARES Galactic Ridge analysis is shown by the grey region. The yellow and red regions indicate the best-fit IceCube fluxes obtained from a full-sky search for two different models.

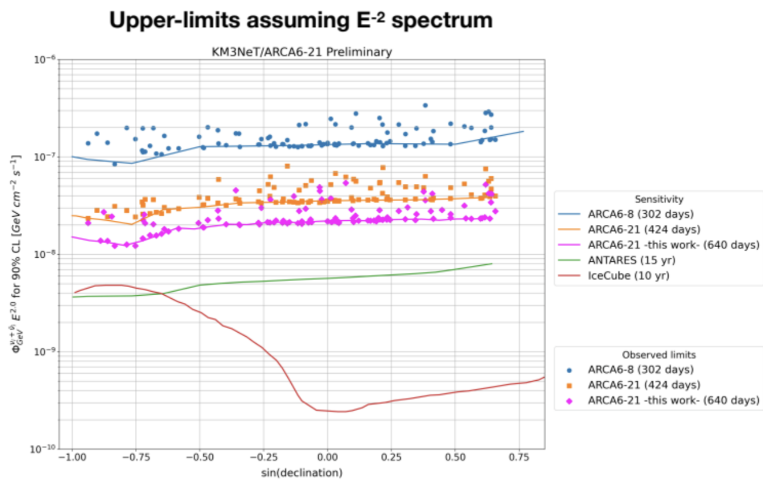


Figure 18: Sensitivities (solid lines) and upper limits on the point-source neutrino flux (dots) are shown as a function of the declination for the current ARCA6-21 analysis (purple), as well as for older analyses (blue and orange). The ANTARES and IceCube sensitivities are indicated in green and red, respectively.

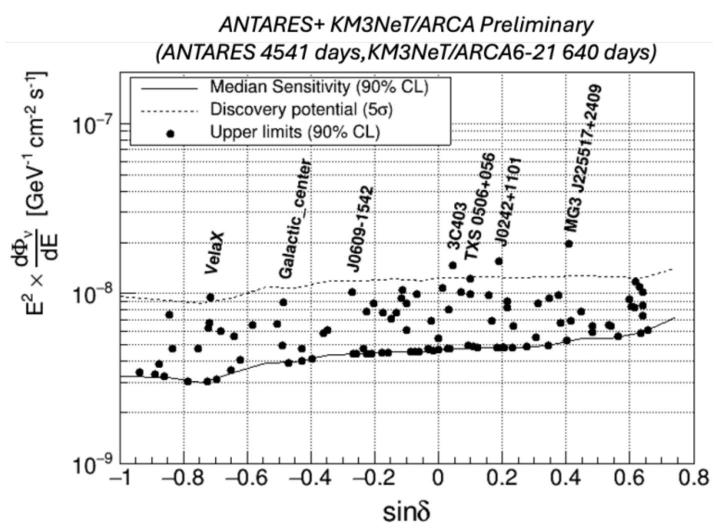


Figure 19: Median sensitivity (solid line) and discovery potential (dashed line) for the combined ANTARES+ARCA6-21 point source analysis, as a function of the declination. The upper limits for each source are indicated by the dots.

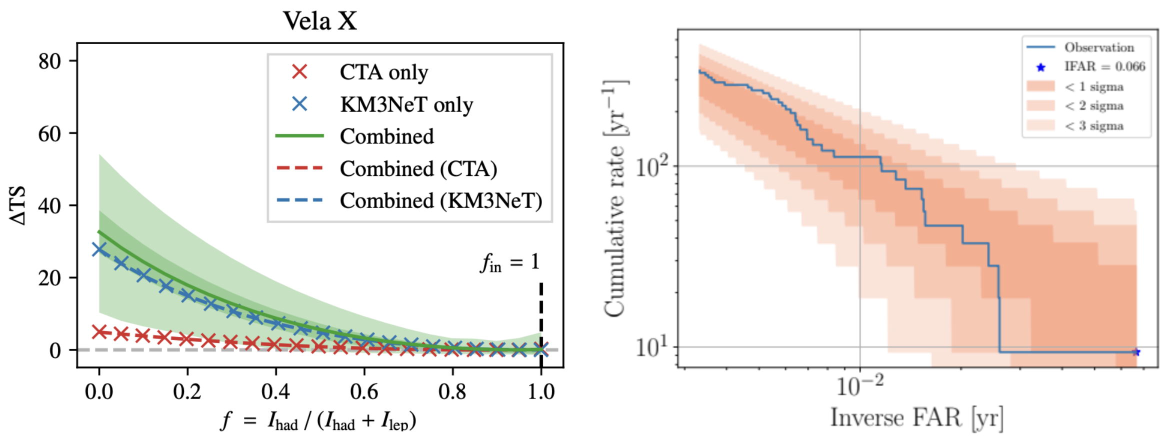


Figure 20: Left: expected profile likelihood of the fraction f of gamma rays produced by hadronic interactions in the Vela X pulsar, combining ARCA230 and CTA. The green band indicates the expectation value and associated $1, 2\sigma$ uncertainties in a scenario where all gamma rays are of hadronic origin. The red and blue lines show individual contributions from CTA and KM3NeT. Right: Observed false-alarm-rate distributions of GW-neutrino coincidences obtained from an analysis ORCA6 data and of the O3 catalogue of Ligo/Virgo. The $1, 2, 3\sigma$ bands for the background-only expectation are shown in shades of orange.

constraints for ARCA230 and CTA are shown in the left panel of Figure 20 for the Vela-X pulsar. For joint neutrino and GW studies, two types of analyses have been developed: a search including GW compact binary coalescence (CBC) signals below the LIGO–Virgo–KAGRA (LVK) trigger threshold, and a search for GW events in time and spatial coincidence with signal-like high-energy neutrino candidates, based on the LVK `X-pipeline` algorithm [54]. Both analyses are conducted by M. Pillas (IAP) in collaboration with APC, IPHC, and University of Catania. Searches based on the LVK O3 run and on ANTARES and ORCA6 data collected during this period yielded no significant GW–neutrino coincidence. As an example, the false-alarm-rate distributions of the GW-neutrino coincidences for the ORCA6 subthreshold analysis are shown in the right panel of Figure 20.

2.3.2 Plan

A priority for the collaboration is to re-evaluate the localisation of the VHE event based on improved measurements of the ARCA line positions, discussed in Section 1.2. If the detector components are well localised, the dominant contribution to the localisation uncertainty should be the uncertainty on the directional reconstruction, estimated to be 0.12°. The collaboration will then conduct a candidate source search within the resulting, substantially reduced, error region, increasing the probability of identifying a significant coincidence.

Another priority is to improve the agreement between data and Monte Carlo simulations of atmospheric muons and neutrinos across the full ARCA and ORCA energy range. In addition to the use of Daemonflux [13, 14], discussed in Section 2.1.2, an extension of the MUPAGE software dedicated to the simulation of muons with energies of at least a PeV is being implemented. The new simulation framework will be used to improve the rejection of atmospheric muons, particularly in searches for diffuse neutrino fluxes and stationary point sources. These studies will form the basis for harmonised event selection, signal evaluation, and background estimation procedures, including not only upgoing tracks but also starting tracks and showers.

A wide range of astrophysical neutrino searches are underway within KM3NeT. To support these efforts, the collaboration is designing generic frameworks to evaluate detector response functions and to perform statistical analyses for all-sky diffuse and point-source searches. These frameworks will be progressively expanded to account for the temporal and spatial characteristics of neutrino emission. Notably, a full-sky, likelihood-based search for the diffuse Galactic neutrino flux is being developed based on tools from the latest ANTARES analysis [55]. The range of neutrino emission models considered will be extended with respect to this analysis, in particular by including models informed by LHAASO observations. The same framework will also be used to investigate time-dependent neutrino emission from CCSNe with dense circumstellar media, microquasars, GRBs, and FRBs.

In addition to standalone analyses, the collaboration plans to develop joint analyses with other experiments, building on existing memoranda of understanding with [LIST]. Joint KM3NeT–IceCube analyses are planned for GRBs and for the diffuse Galactic flux [MORE??]. Development of the `Gammapy` neutrino extension will continue in step with upgrades to the KM3NeT analysis framework. Finally, ongoing joint gravitational-wave–neutrino searches will be extended to include a broader range of GW events and applied to O4 data. Compared to O3, the O4 observing run of LVK overlaps with a larger ORCA configuration and benefits from the deployment of ARCA. Consequently, significantly improved constraints on neutrino fluxes from gravitational-wave emitter populations are expected.

2.4 Dark Matter indirect searches

Neutrino telescopes are also powerful detector to look for indirect detection of Dark Matter, by looking for fluxes of high energy neutrino produced by annihilations of WIMPs accumulated in the core of celestial bodies such as the Sun and the Earth, or in the centre of the Galactic Halo. In the past years, several analyses looking for such signals in the ANTARES data set have been conducted at CPPM, in collaboration with a phenomenologist of LAM. In KM3NeT, Dark Matter indirect detection analyses and prospective studies have so far mainly been performed by the groups of IFIC-Valencia and UPV-Gandia in Spain, and Nikhef in the Netherlands.

Searches for a flux of neutrinos with an energy between few GeV and few TeV towards the direction of the Sun is one of the most promising signal of Dark Matter annihilation trapped inside the Sun. This energy range, limited to few TeV due to the opacity of the Sun to the flux of higher energy neutrinos, in well adapted to the sensitivity of the KM3NeT/ORCA detector. Under the common hypothesis of equilibrium between the WIMP annihilation rate and capture rate by the Sun matter, upper limits on the neutrino flux can be translated to upper limits on the spin-dependent or spin-independent WIMP-nucleon cross-section coming from the WIMP capture. Figure 21 (left) presents the sensitivity of the full ORCA detector on the spin-dependent WIMP-nucleon cross-section compared to existing upper limits [56]. Thanks to its larger detector density and its lower neutrino energy thresholds, ORCA will allow to extend the sensitivity covered by ANTARES in the WIMP mass range 10-100 GeV for the Sun analysis. Thanks to the large detector volume and good angular resolution of ORCA, the expected sensitivities are very competitive with respect to existing limits of Super-Kamiokande and IceCube for low Dark Matter masses.

Complementary, searches with KM3NeT for neutrino fluxes coming from WIMP annihilation towards the Galactic Centre are mainly competitive for high Dark Matter masses by analyses with the ARCA detector. Figure 21 (right) presents the sensitivities obtained with current and future ORCA and ARCA detectors compared to existing limits on the thermally averaged WIMP annihilation cross-section as function of the WIMP mass in the case of the $\tau^+\tau^-$ annihilation channel and a Navarro-Frenk-White density profile of the Milky-Way Dark Matter halo [57]. The current sensitivities obtained with KM3NeT are already competitive with the limits obtained by analysing the full data set of ANTARES, and very stringent limits should be achieved with the complete ARCA detector for Dark Matter masses larger than few TeV.

Beyond the standard WIMP scenario, other exotic physics models can be probed with KM3NeT. Current analyses are in progress to test whether the ultra high energy KM3-230213A neutrino event can originate from heavy Dark Matter decay or from Hawking radiation of primordial Black Holes. Another study concerns a Heavy Neutral Lepton scenario in which those long-lived particles can produced a double-cascade signature at low energies in the detector. Finally, as it was studied in ANTARES, one can also look for signatures of magnetic monopoles or nuclearites.

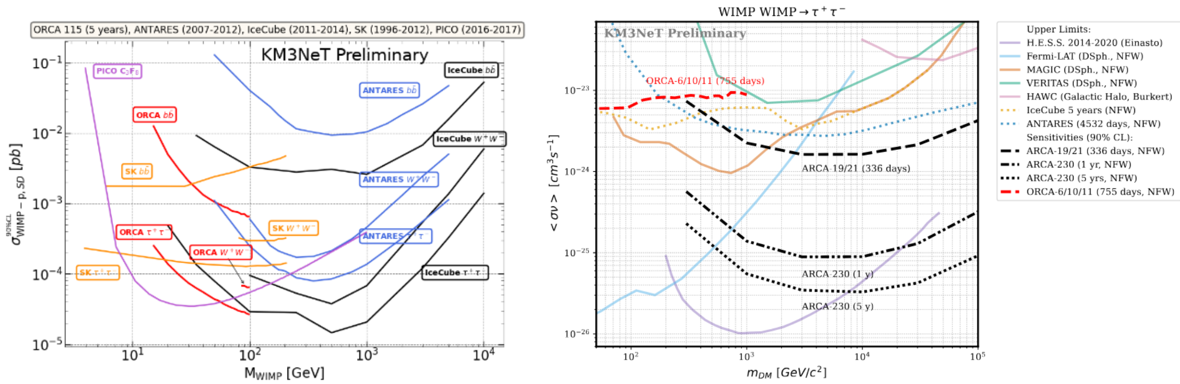


Figure 21: Left: sensitivity of the full KM3NeT/ORCA detector compared with existing limits on the spin-dependent WIMP-nucleon cross-section as function of the WIMP mass coming from neutrino flux produced by Dark Matter annihilations inside the Sun under three different hypotheses of the annihilation channel; Right: sensitivities of the KM3NeT/ARCA and KM3NeT/ORCA detectors compared to existing limits on the thermally averaged WIMP annihilation cross-section as function of the WIMP mass for the $\tau^+\tau^-$ annihilation channel from indirect searches towards the Galactic Centre.

2.5 Cosmic ray physics

Thanks to the large statistic of the well-reconstructed atmospheric muons, it is possible to study the cosmic ray flux between a few TeV to several PeV, i.e. high-energy protons and atomic nuclei from beyond our solar system. KM3NeT can measure the energy spectrum and chemical composition of galactic cosmic rays, based on the multiplicity of the muon bundle. The atmospheric muon or neutrino fluxes allow to constrain the hadronic interaction models in a large energy range. Improved knowledge of the atmospheric muons flux is important as it is a significant background for the astronomy searches and the oscillation studies.

KM3NeT can also bring new insights to investigate key questions in the field, such as a yet to be understood mismatch in the muon number predicted by state-of-the-art hadronic interaction models and air-shower measurements at the highest energies and the flux of so-called prompt muons and neutrinos originating from the decay of particles with heavy quarks that are produced in high-energy atmospheric collisions. The directions of the atmospheric muons are also used to measure the small and large scale anisotropies linked to the propagation of galactic cosmic rays.

At low energies in ORCA, it is possible to use the stopping muons in the detector volume to measure precisely the water properties (i.e. absorption and scattering lengths), an important source of systematic uncertainty for the oscillation studies.

2.6 Earth Tomography

Atmospheric neutrinos can also be used to perform tomography of the Earth, providing new approaches to study the Earth's internal structure and composition, complementary to geoscientific methods mainly based on seisomology, cosmochemistry and petrology. The complementary ranges of energy covered by ORCA and ARCA will allow KM3NeT to perform both oscillation and absorption neutrino tomography [58, **?**]. On one hand, ORCA can exploit matter effects in the oscillations of GeV-scale neutrinos traversing the Earth to measure the electron density along their trajectory, leading to potential constraints on the composition of the traversed matter. Preliminary studies suggest that, once the neutrino mass hierarchy is measured, water-Cherenkov detectors such as ORCA could provide meaningful constraints on the abundance of light elements (and in particular Hydrogen) in the Earth's core, a question which is still debated in the geoscience community [**?**]. On the other hand, ARCA detects neutrinos up to the energy range where the Earth becomes opaque to them. Studying the angle-dependent attenuation of the high-energy (> 50 TeV) neutrino flux may thus set constraints on the matter distribution inside the Earth. Despite the uncertainties related to neutrino tomography are still much bigger than those provided by geoscience methods, this new approach to explore the Earth interior can contribute to constrain future models of the planet. The APC KM3NeT group is at the forefront of this interdisciplinary research topic, having developed tight collaborations with geoscientists from Institut de Physique du Globe de Paris and Laboratoire de Géologie de Lyon which have benefitted from several dedicated fundings (CNRS MITI, LabEx Univ'EarthS and IdEx HERMES Programs at Université Paris Cité).

3 Earth and Sea Science

Measurements in the deep sea are typically performed by deploying and recovering autonomous devices that record data intermittently over a period of months to years. This approach is severely constrained by power and bandwidth limitations, by the absence of real-time interaction with the measurement devices and by the delayed access to the data. A cabled observatory like KM3NeT remedies these disadvantages by providing continuous, high frequency, access to real-time measurements in situ. Furthermore, the large concentration of different sensors at the same location facilitates the study of time and spatial correlations between sensors. This is an important and unique opportunity for performing deep-sea research by scientists from the fields of marine biology, oceanography, environmental sciences, geosciences or seismology.

The KM3NeT instruments allow monitoring the deep sea biodiversity on all scales, from micro-organisms up to the largest marine mammals, which is of utmost societal importance. Most of deep-sea living organisms are bioluminescent, either continuously or in specific circumstances, with light emission patterns dependent on the species. Bioluminescence can thus be used to monitor biological activity, and particularly planktonic diversity in deep waters. The largest organisms like marine mammals can be studied from the distinctive sounds they emit, using the hydrophones placed in the water column. Coupling hydrophone tracking results with the hydrodynamic and biochemical data collected at the same site will allow studying the behaviour, physiology, and ecology of marine mammals, and the anthropogenic impact on these communities.

Cooperation with the Earth and Sea Science community has been established since the beginning of ANTARES, over twenty years ago. The KM3NeT sites are nodes of the European Multidisciplinary Sea floor and water column Observatory (EMSO).

The seafloor network of KM3NeT/ORCA is managed within the framework of the Laboratoire Sous-marin Provence Mediterranee (LSPM [2]) inaugurated in Feb 2023. A national platform of the CNRS (UAR2032), co-piloted by Aix-Marseille University and Ifremer. Its main mission is to construct and maintain the seafloor network (deep sea cables, junction boxes, and power delivery systems) as well as the access of external users (scientific and industrial) that wish to connect instrumentation into the network. Currently, two junction boxes (JB1, JB2) for KM3NeT and a 'scientific junction box' (SJB) have been operated. For each KM3NeT junction box, seven ports are allocated to KM3NeT and one is multi-purpose and can be used for KM3NeT or ESS. The SJB was provided by Ifremer and is dedicated to ESS instrumentation. The network will be expanded in 2027-2029 with a second deep sea cable (reuse of the ANTARES cable) and the addition of two more junction boxes.

The ESS instrumentation that have been connected on the network comprises the M2I on JB1, the Instrumentation Unit on JB1 and various instruments on the SBJ. The M2I hosts an acoustic modem which communicates to the autonomous ALBATROSS mooring line, located a few kilometres from the site. The ALBATROSS (MIO/INSU), hosts various instruments for monitoring oceanographic parameters (sea cur-

[2] https://www.cppm.in2p3.fr/web/fr/LSPM/

rent speed, directions, temperature, see Figure 22, etc.[3]). Also on JB1 is connected the Calibration Unit (CPPM/APC), which provides similar environmental monitoring and also instruments useful for calibration purposes (laser beacon, acoustic beacon, sound velocities). The instrumentation on the SJB comprises the BathyBot/BathyReef benthic crawler (MIO/INSU [4]), a Germanium gamma-ray detector (CPPM, see spectrum in Figure 23), a seismograph (GeoAzur-Nice/INSU), and a stereo biocamera system (IP2I-Lyon). The SBJ and its instruments were operated continuously for about one year (2023-2024), but then unfortunately developed a problem. The SBJ has been recovered and will be reconnected in 2027.

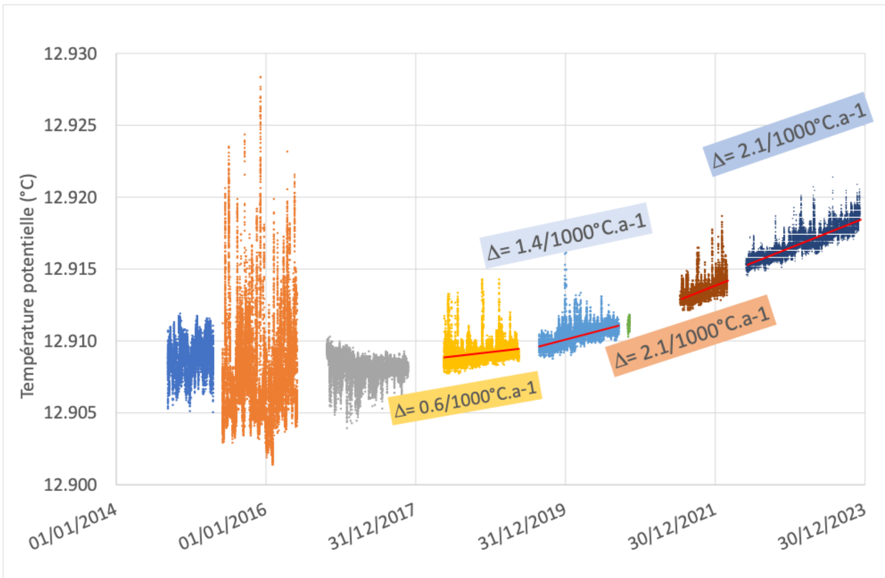


Figure 22: Long term deep sea temperature variation as measured by the ALBATROSS mooring line.

Other additional ESS activities include; the development of a Distributed Acoustic Sensing (DAS) laser system, tested on the some unused fibres of main electro-optic cable (with Alcatel and GeoAzur-Nice/INSU) [59] see Figure 24, the detection of bioacoustic signals from Cetaceans using the KM3NeT hydrophones (with LIS-Univ. Toulon) [60] and the deployment of a large array of high precision temperature sensors (NIOZ-Netherlands) for the study of deep sea internal wave motion [61].

[3] https://www.seanoe.org/data/00720/83244/

[4] https://www.cnrs.fr/en/press/bathybot-robot-wakes-depths-mediterranean

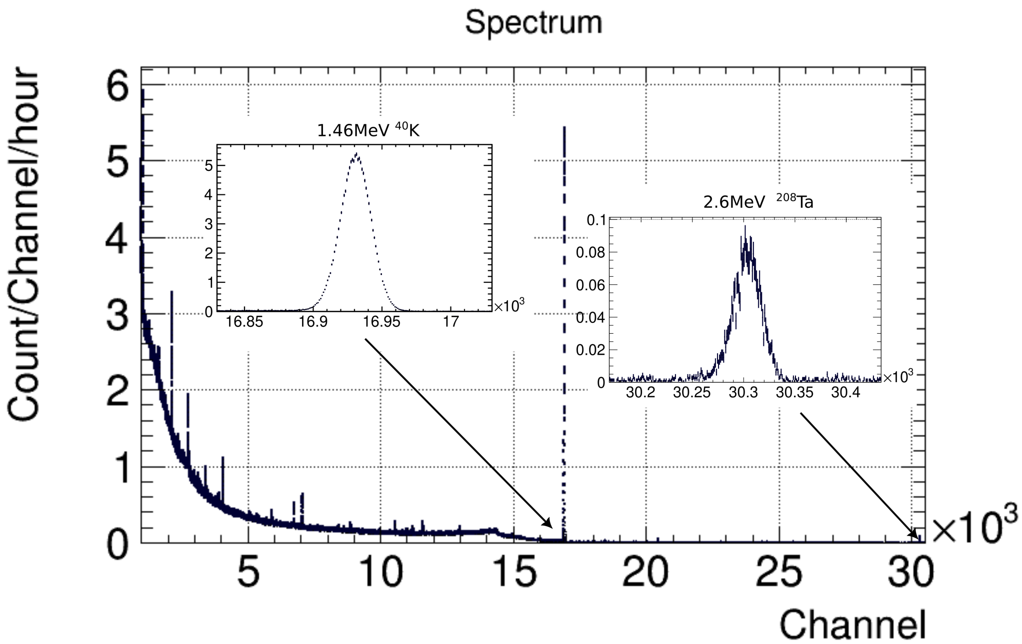


Figure 23: Spectrum from the HPGe collected over 60 days at the LSPM site. The inserts show a zoom over two peaks, the very intense ^{40}K at 1.46 MeV and a much weaker one, the ^{208}Ta at 2.6 MeV.

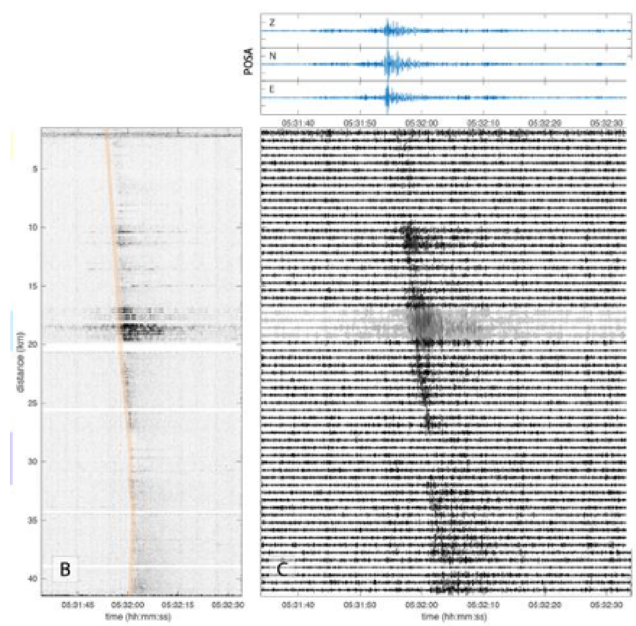


Figure 24: A Magnitude 1.9 earthquake near Frejus detected by the DAS system.

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