EPJ Web of Conferences **283**, 04009 (2023)
UHECR 2022
https://doi.org/10.1051/epjconf/202328304009

First scientific results of the KM3NeT neutrino telescope

Francesco Benfenati[1,2,*], *Francesco* Filippini[1,2,**], and *Tommaso* Chiarusi[2,***] on behalf of the KM3NeT Collaboration

[1]INFN - Sezione di Bologna, Viale Berti-Pichat 6/2, 40127 Bologna, Italy
[2]Dipartimento di Fisica e Astronomia dell'Università, Viale Berti Pichat 6/2, 40127

Abstract. KM3NeT is a multidisciplinary observatory, for the detection and study of cosmic neutrinos and their sources in the Universe, as well as the measurement of neutrino properties such as the mass hierarchy and oscillation parameters. Two underwater detectors are under construction in the Mediterranean Sea. The configuration of the ARCA detector, located off-shore Sicily, Italy, is optimized for the detection of neutrinos in the energy range of 1 TeV-100 PeV. The ORCA detector off-shore Toulon, France is configured for the measurement of neutrinos with energy from about 100 MeV up to the sub-TeV region. At present, 21 and 14 detection units are taking data at the ARCA and the ORCA sites, respectively. Installation of additional detection units is foreseen in the next few years. In this contribution an overview of the expected performances of the full detectors will be reviewed and the main physics results obtained with ARCA and ORCA, still in their partial configuration, will be reported. Finally, in the context of the multi-messenger scenario the KM3NeT online alert system will be presented.

1 Introduction

Neutrino Astrophysics is a branch of Astroparticle Physics that mainly focuses on the detection of high-energy neutrinos in order to determine the sources and accelerators of primary cosmic-rays, constraining their propagation through the Cosmos. Due to the extremely small cross-section in their weak interaction with matter, neutrinos are the optimal messengers to investigate far and violent phenomena in the Universe, complementary to the charged nuclei and photons which can be diverted or absorbed during their long travel from the sources to Earth. The detection of cosmic neutrinos coming from highly relativistic jets out of Active Galactic Nuclei, micro-quasar systems, Gamma Ray Bursts and other similar objects, represents a clear signature of the occurrence of hadronic interactions in such extremely energetic engines. The measurement of the neutrino fluxes can be used to constrain the composition of the matter surrounding the astrophysical sources, even of those hidden behind optical thick shells, and to disentangle the underlying acceleration mechanisms against the thermal / not thermal processes (e.g. leptonic models). Also neutron star mergers are expected to be intense sources of high-energy neutrinos, whose detection can contribute to a more precise localization of the event in the sky and help constraining the parameter space of the coalescent pair, completing what can be inferred with the detection of the preceding gravitational wave signals, in an effective multi-messenger approach. Finally, other targets of neutrino Astrophysics are supernova recognition, indirect detection of dark matter annihilation in dense matter environments and searches for magnetic monopoles, nuclearities and other exotic-matter candidates.

Neutrino telescopes are optimized for the detection of high-energy extraterrestrial neutrinos. They must first remove the background coming from atmospheric muons and neutrinos generated in cosmic-ray induced air showers in the Earth atmosphere. Generally, atmospheric muons can be removed by using the Earth as a shield when looking for upward-going particles. Moreover, the irreducible background of atmospheric neutrinos becomes less relevant as energy increases, enhancing the probability of observing high-energy cosmic candidates. At the same time, interesting sources might be located in the sky above the neutrino telescope; in this case, if the detector is large enough, some parts of it (generally the peripheral ones) can be exploited as vetoing elements to select only neutrino induced events originating inside the detector volume.

The implementation of a neutrino telescope consists of a large-volume 3D array of photodetectors placed at large depths in a transparent medium, such as water or ice. Cherenkov light, induced by relativistic charged particles passing through the medium, is detected in the array and the recorded information can be used to reconstruct the direction and energy of the incoming neutrino, by which those charged particles were produced. Neutrino telescopes can detect all-flavour neutrino interactions [1]. Together with the pure Astroparticle goals mentioned above, other appealing Physics objectives can be achieved with neutrino telescopes, like the study of the fundamental properties of neutrinos within the Standard Model.

Currently, the largest and most sensitive neutrino telescope on Earth is the IceCube detector, placed at a depth

---

[*] e-mail: francesco.benfenati@bo.infn.it
[**] e-mail: francesco.filippini@bo.infn.it
[***] e-mail: tommaso.chiarusi@bo.infn.it

between 1.4 and 2.4 km below the ice surface at the South Pole. Since 2010, IceCube has been taking data with 1 km^3 size detector. It also has a DeepCore infill, mainly used to study the atmospheric neutrinos below 100 GeV. Exploiting a complementary surface array for a more efficient vetoing approach, IceCube was capable to obtain the first evidence of the presence of cosmic neutrinos [2]. More recent analyses have improved the significance of such observations. This signal is compatible with an isotropic diffuse flux of cosmic neutrinos, at present with only a few associations to possible sources [3].

Along with IceCube, other under-water telescopes are participating to the quest for cosmic neutrinos. Taking the legacy of a precursor installation, and aiming at the km^3 scale, the GVD telescope is under construction in the Baikal lake in Russia. GVD first results are reported in [4], showing a small preliminary excess in the search for diffuse flux of extra-terrestrial neutrinos. In the Mediterranean Sea, the ANTARES neutrino telescope was located at a depth between 2 and 2.45 km below sea level in front of the French coast, 40 km off-shore Toulon. ANTARES operated for 15 years from 2007. Although much smaller than IceCube, ANTARES had been able to obtain significant results in various analyses concerning both neutrino Physics and Astronomy, especially when searching for neutrinos below 100 TeV from the Southern Sky. Dismantled in spring 2022, ANTARES has passed the baton to the next-generation neutrino telescope in the Mediterranean Sea, the KM3NeT observatory, whose first results are described in this contribution.

In Section 2 the two KM3NeT telescopes ARCA and ORCA are introduced. In Section 3 the measurement strategy and the detection performance for both ARCA and ORCA is reviewed. In Section 4 a selection of the most recent scientific results are presented and discussed. Finally, conclusions and outlooks are summarized in Section 5.

2 The KM3NeT ARCA and ORCA detectors

The KM3NeT observatory consists of two neutrino telescopes currently under construction at the bottom of the Mediterranean Sea. ARCA (Astroparticle Research with Cosmics in the Abyss) is located off-shore Portopalo di Capo Passero, Sicily, Italy, at a depth of ~3500 m and ORCA (Oscillation Research with Cosmics in the Abyss) off-shore Toulon, France, at a depth of ~2450 m. ARCA is designed to study cosmic neutrinos and their possible astrophysical sources, as described above in the introductory section. The focus of ORCA is the study of the intrinsic properties of neutrinos, such as the oscillation parameters and the neutrino mass-hierarchy [5].

2.1 The dectection elements and the sea-floor network

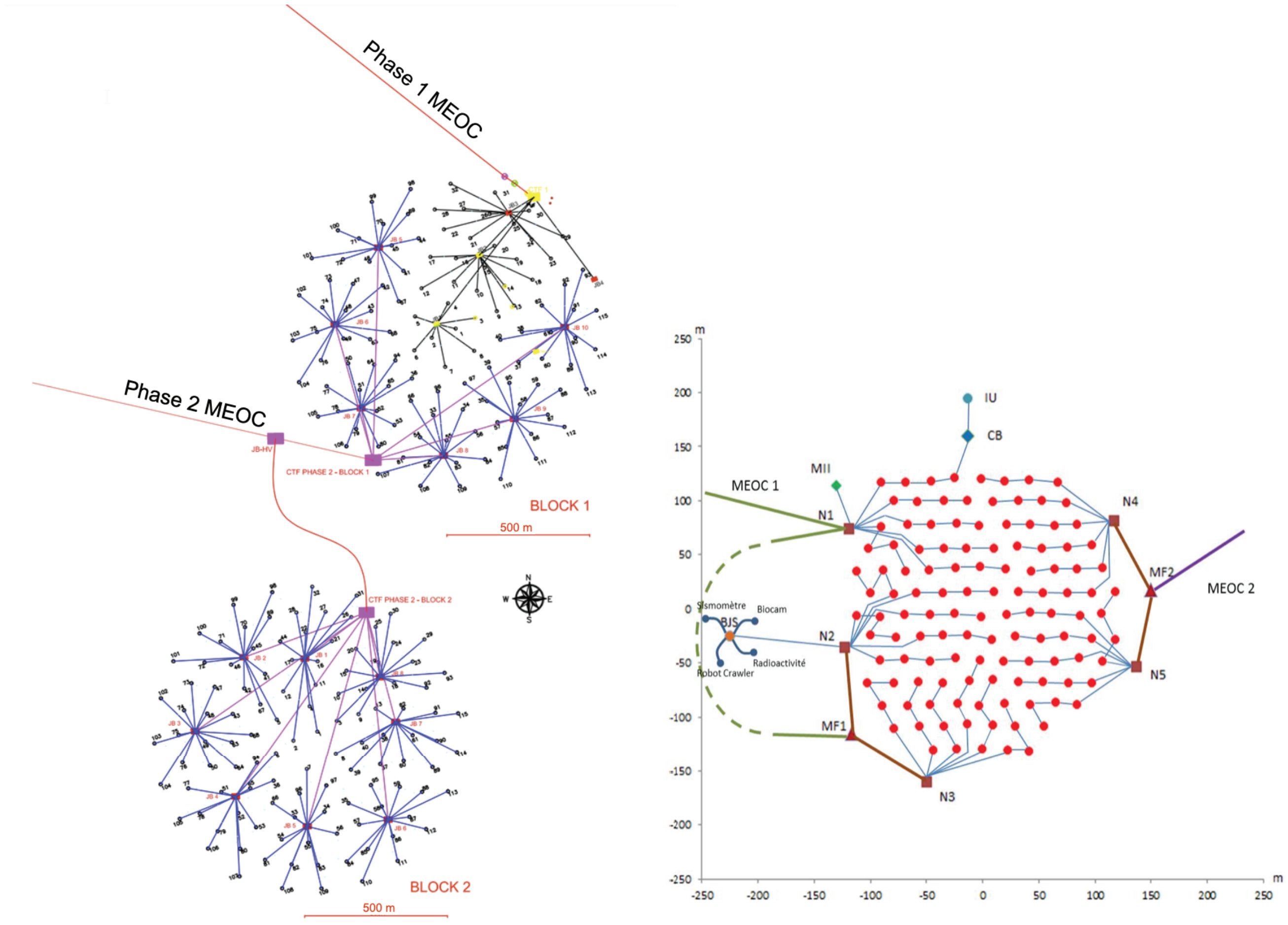
Both ARCA and ORCA are made of vertically aligned Detection Units (DUs), each hosting 18 Digital Optical Modules (DOMs) mounted on Dyneema® ropes. Each DOM contains 31 3-inch photomultiplier tubes (PMTs), calibration and positioning instrumentation and readout electronic boards [6]. Each DU is pulled vertical by a buoy on top and it is anchored to the sea-floor by a special heavy anchor, which hosts a further active element, the DU-Base Module (DU-BM). Together with hosting dedicated instrumentation like hydrophones and other calibration devices, such as lasers and acoustic beacons, the DU-BM concentrates the optical links for the DOM communication, and also acts as the power hub for all the devices of the DU. Groups of DUs are connected to submarine Junction Boxes (in ARCA) or Nodes (in ORCA), which act as electric power hubs for the connected DUs, and concentrate their optical signals via the main electrical-optical cables (MEOCs) up to the shore stations. Although sharing the same detection elements, ARCA and ORCA have different layouts, according to their scientific targets. For accomplishing the detection of very high energy neutrinos (up to ~100 PeV), ARCA must have a large extension, aiming at the size of at least 1 km^3 instrumented volume. For this reason, in ARCA the spacing between the DUs is ~90 m and between the DOMs on each DU is ~36 m. The final configuration of the ARCA installation will be divided in two building blocks of 115 DUs each, connected to shore by two 100 km MEOCs (see Figure 1a). The ORCA instrumented volume is about 7 MTon, ~1% of the ARCA extension. In ORCA the inter-distance between the DUs is 20 m and the DOMs in a DU are spaced by 9 m, allowing for an optimized detection of neutrinos with energies spanning from 100 MeV up to 100 GeV. ORCA is made of one building block of 115 DUs, and it is also connected by two 50 km MEOCs to the shore-station (see Figure 1b).

2.2 The data acquisition model

ARCA and ORCA both implement a trigger-less streaming readout paradigm for data-taking. All the DOMs and DU-BMs independently send continuous streams of data from the PMTs and the acoustic sensors to shore. Such data streams are processed (aggregated and filtered) by a totally online system of software processes running in the computing facilities of the shore station. This approach, also called *all-data-to-shore*, allows to deploy the simplest hardware in the abyssal sites. On shore, the networking infrastructure is modular and the computing resources dynamically scale to cope with a larger and larger incoming throughput from the growing detectors. The details of the KM3NeT data acquisition (DAQ) system are reported in [7]. Although running with two independent DAQ installations, the data taking from the two telescopes is combined at higher level by the KM3NeT online multi-messenger system [8].

2.3 Detector monitoring

KM3NeT detectors are equipped with a live monitoring system, which allows various online checks for determining the detector status and the quality of the data taking with short latencies ranging from few seconds to ∼ 1



(a)

(b)

Figure 1: The ARCA (a) and ORCA (b) sea-floor maps. Each dot stands for a DU, while the straight lines indicate the inter-link cables connecting the DUs to intermediate stages of aggregation devices, up to the main electrical-optical cables (MEOCs). The aggregation designs of the DUs in the detector modules are different: ARCA follows a star-center approach, with groups of up to 14 DUs concentrated on devices called Junction Boxes (red squares); in ORCA, six daisy-chains made of 4 DUs each are concentrated on a device called Node (brown squares).

minute. Examples of such monitoring consists of time-plots of low-level information, such as the PMT single rates and environmental parameters like temperature, humidity and orientation of the DOMs, together with more complex representation of derived quantities, obtained after the data processing, like the per-event hit maps distributed over the active DUs versus the hit-time, or the time-plots of the triggered event rates. All the monitoring plots or complementary information are published on web pages that are used by the Collaboration during the data-taking shifts.

2.4 ARCA and ORCA evolution

Thanks to the scalable features of the KM3NeT DAQ system, the data taking started, for both ARCA and ORCA, immediately after the very first lines were deployed. The data sets used in the analyses presented in this contribution (see Sec.4) are referred to particular layouts of the telescopes, reporting the name of the detector used for collecting the data together with the number of active DUs. ARCA1 and ARCA2 data sets correspond to a period of almost 5 years starting in 2015, during which the KM3NeT Collaboration was engaged to optimize the off-shore detector, the deployment technique and to set up the mass-production stages for DOMs, DU-BMs and other devices of the sea-floor infrastructure. ORCA1 was deployed in early 2019, and the ORCA6 layout was completed in mid-2020. Despite the harsh working conditions occurred during the COVID pandemic, the KM3NeT Collaboration started to boost both the detector mass production and the sea campaigns, reaching the current situation of ARCA21 and ORCA14 in September 2022. During 2023, ARCA32 (see the black sector of Fig.1a) and ORCA24 (see the DUs connected to N1 in Fig.1b) will be completed. Thanks to dedicated funds for enhancing the scientific installations of Italian Southern Regions (PON and PNRR calls [9, 10]), additional ∼100 ARCA DUs will be built in the next 5 years, completing the first ARCA building block and part of the second one. At the same time, thanks to French funds (NEUMED project), also the ORCA detector will increase its instrumented volume up to 48 DUs, fully populating also Node N2, together with the expansion of the sea-floor network by 2 more additional Nodes (N3 and N4).

In addition to the above-mentioned main scientific objective, the measurements of the instruments hosted by the KM3NeT infrastructure and the measurements of the environmental parameters which are taken for calibration purposes (see Sec.2.1) [11] can be exploited for Earth and Marine Sciences studies, offering the opportunity to online monitor the marine ecosystem for long periods of time, and to carry out researches on the deep marine environment and on possible signatures of the climate change.

3 Neutrino measurements and detector performance

3.1 Event signatures

The events detected in KM3NeT can be separated in two distinct classes: track-like events and shower-like events. Track-like events are mostly due to muons originated in charged current ν_μ interactions and they are characterized by long tracks since muons have a long path length in water, while shower-like events are produced by the charged current interactions of ν_e, ν_τ and neutral current interactions of all neutrino flavors, and they are characterized by the presence of electromagnetic or hadronic (or both) showers, as the produced particles propagate only for a few tens of meters. The signature of a charged current interaction of ν_τ with energy larger than $\sim$1 PeV is referred to as a *double-bang* event, since the track of the neutrino induced τ can be long enough to allow a separation between the light yield of the first shower, resulting from the original neutrino interaction, and the light yield of the second shower caused by the τ decay. Background events consist of downward-going muons, which can be produced in the decays of unstable mesons present in the cosmic-ray induced atmospheric showers. At the considered depth, the flux of direct atmospheric muons exceeds by several orders of magnitude the flux of muons created in charge-current interactions of neutrinos. As a consequence, the expected background is almost exclusively constituted of downward-going muons and therefore it can be rejected by restricting signal searches with upward-going events. As mentioned above in Sec.1, atmospheric neutrinos represent background only for Astrophysics searches, while their measurement is the main channel to infer the neutrino oscillation parameters and constrain the mass-hierarchy problem.

3.2 Detector performance

The effective geometrical acceptance of the neutrino telescope scales with the detector size and with the energy of the impinging neutrinos. Useful figures of merit are the effective area and the effective volume, computed thanks to Monte Carlo simulations. Being proportional to the expected rate of reconstructed events, such quantities are proxies of the detection performance, and can be used to benchmark different neutrino telescopes. In Fig.2, ARCA115 and ORCA115 effective volumes are compared to the effective volume of ANTARES: over a wide energy range, the KM3NeT detectors are expected to outperform, by almost an order of magnitude, the ANTARES telescopes. Recent computations show that, already in their current building stage, ARCA21 and ORCA 14 have exceeded the ANTARES effective area all over the respective energy range.

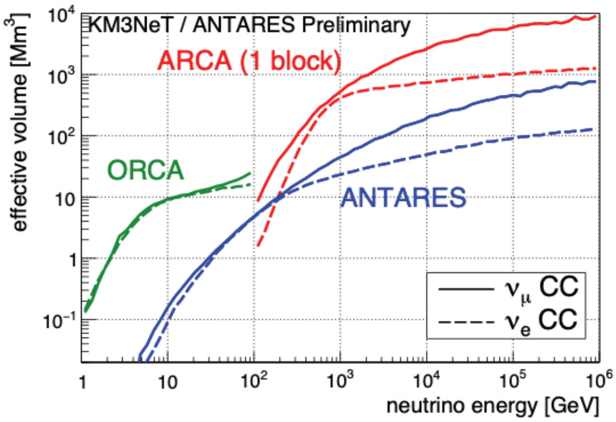


Figure 2: Detector effective volumes as a function of neutrino energy: comparison between ANTARES detector, ORCA and ARCA (1 building block). Solid lines refer to track event signatures (ν_μ charged coupled interactions) while dashed ones to shower signatures (ν_e charged coupled interactions).

The choice to install the KM3NeT telescopes in abyssal sites presents clear complications due to the difficulties of arranging the deployments in such extreme conditions. Moreover the continuous optical background due to ^{40}K decays and the bursts due to bio-luminescence imply a high background level in the acquired data, with respect to the rare neutrino induced signals. On the other hand, the light yield of ^{40}K decays is exploited to optimise the measurement of the relative time-offsets between the PMTs in a DOM [12] and to perform long-term monitoring of the PMT photon detection efficiency.

Another advantage of the sea water is that it is far more homogeneous than ice, with a larger scattering length [1]. This results in a better angular resolution of the under-sea detectors with respect to the under-ice ones. Thanks to Monte Carlo simulations it was possible to compute the angular deviation between the reconstructed neutrino tracks and their true directions as a function of energy. The figure of merit of the ARCA angular resolution, computed for the 2 building blocks configuration, is shown in Fig.3. Due to kinematical effects and for the topology of the event itself, a smaller angular resolution is obtained for track-type events than for shower-type events. For neu-

https://doi.org/10.1051/epjconf/202328304009

trino energies larger than few hundreds of TeV, an angular resolution below 0.1° is obtained.

Thanks to the optimal optical properties of the sea-water, especially at the depth of the ARCA installation, and thanks to a new reconstruction algorithm [13], it has been possible to obtain a sub-degree median angular resolution even for shower-like events from neutrinos with energies larger than 100 TeV. The energy resolution for track-like events in the range 10 TeV$\leq E_\mu \leq$10 PeV is, for the case of ARCA, ~0.27 expressed in $\log_{10}(E_\mu/E_{reco})$ units, where E_μ is the true energy of the simulated muon and E_{reco} is the reconstructed one. For shower-like contained events, and for E_ν >50 TeV, the relative energy resolution gets smaller than 5%.

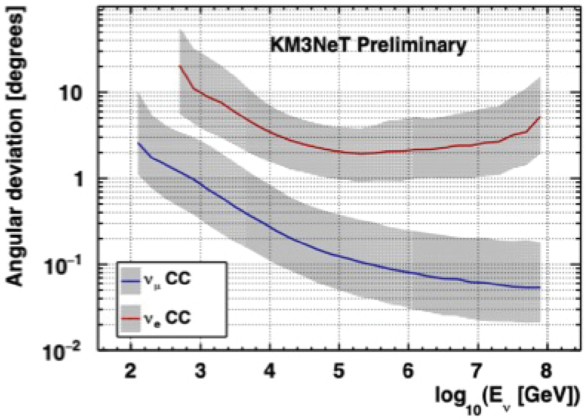


Figure 3: Angular resolution for ARCA track-like events (from ν_μ charged current interactions) and shower-like events (ν_e charged current interactions), as a function of the neutrino energy.

4 Review of selected Physics results

4.1 Atmospheric muon flux depth-intensity relation

Data collected from the first three detection units of KM3NeT, ARCA2 and ORCA1, have been exploited to measure the atmospheric muon flux between 2232 and 3386 meters. This flux is shown to be compatible with the Bugaev flux calculation [14]. In this analysis, the capability of the multi-PMTs layout of the KM3NeT DOM allowed to gather information concerning the number of photons, as well as their arrival times and directions. Coincident photon-hits on different PMTs, here defined to be within a time window of 15 ns, can be exploited in order to discriminate between signals from atmospheric muons, bioluminescence and radioactive ^{40}K decays. The result is a high-purity sample of atmospheric muons. After background rejection, efficiency-corrected muon rates are computed. This information, together with the effective area of a single optical module, coming from ad-hoc simulations, allows to determine the muon flux. The flux itself is then estimated along the detector depth, expressed in meters of water equivalent, as reported in Fig.6. The obtained measurement is in very good agreement with theoretical models, and have shown the synergy and complementarity of the two sites of the KM3NeT experiment. For major details, see [15].

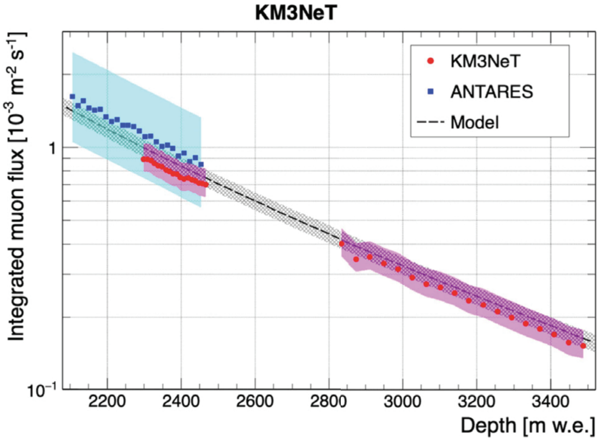


Figure 4: Integrated atmospheric muon flux as a function of depth below the sea level (expressed in meter of water equivalent) measured with ORCA1 and ARCA2 detectors, red points. Bugaev model is reported with black dashed line. ANTARES data are also included as blue point for comparison. Systematic uncertainties are reported as shadowed area.

4.2 Point source studies with ARCA6

One of the main goals in the neutrino astronomy is the identification of the sources of cosmic neutrinos. Therefore a time-integrated binned likelihood analysis was applied on the data acquired with ARCA6, for a total live-time of 92 days. After the event selection, the surviving events were binned in a two-dimensional space, determined by the angular distance of the events to a given source and their energy. A likelihood-ratio test statistic was then computed. A catalogue of 46 candidate sources was selected, and for each of them an E^{-2} spectrum was tested: 6 of them are known to be spatially extended in the sky, and therefore the detector point spread function was modified with a Gaussian or a disk-like smearing. The smallest p-value obtained (~ 0.020), compatible with the background-only hypothesis, was found in correspondence of the radio galaxy Centaurus A (RA,DEC) = (201.36°,-43.02°). No strong neutrino emitters were found in the period of data analyzed (May 2021 - September 2021), and for this reason the 90% upper limit has been calculated for each candidate, as reported in Fig.5. While the effective area of the detector is comparable with the size of ANTARES, the main limiting factor for placing more stringent limits is the short live-time of the used data set.

https://doi.org/10.1051/epjconf/202328304009

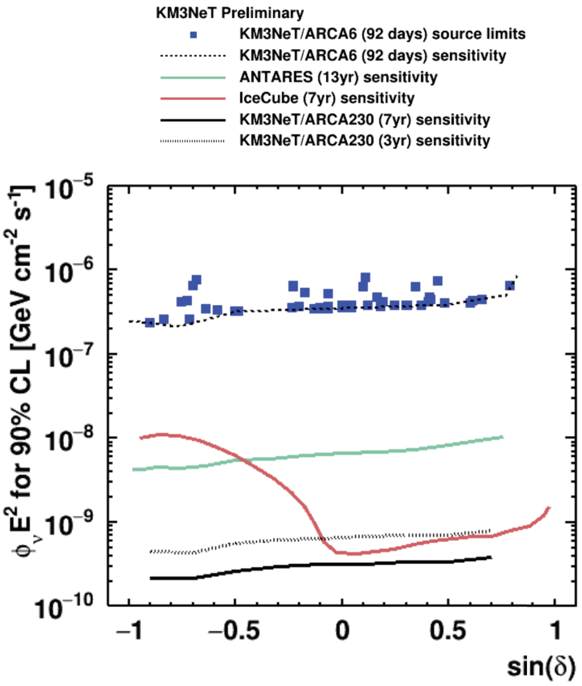


Figure 5: 90% flux limit as a function of declination reported for each candidate source in the catalogue. Sensitivity of ARCA6 (92 days, dashed blue line), ANTARES (13 yr, solid green line) and IceCube (7 yr, solid red line) are shown. The estimated sensitivity for ARCA in its final configuration is also shown, for respectively 3 and 7 years of data-taking (dashed and solid black lines).

4.3 KM3NeT potential for the next core-collapse supernovae

In the final configuration, the KM3NeT detectors will comprise a total of ~200,000 PMTs (grouped in ~6200 Optical modules). Despite the distance of optical modules within a DU, the neutrino telescopes are sensitive to 10 MeV neutrinos from Galactic and near-Galactic core-collapse supernovae. The detection technique exploits the possible excess of photon-hit coincidences on PMTs belonging to the same DOM, over the background. Data from the first six lines of ARCA and ORCA detectors have been analyzed to characterize the background expectation. Signal expectation is instead derived thanks to specific simulations, based on a custom software developed by the KM3NeT Collaboration. Searches for signal over background events is carried out considering time windows of 500 ms: such duration was chosen in order to cover, on average, the majority of the neutrino emission in the supernova accretion phase. In this way the sensitivity of the KM3NeT detectors to the neutrino burst is evaluated [16]. For a supernova at 10 kpc, KM3NeT will be able to estimate the mean energy of the core-collapse supernova neutrinos with sub-MeV accuracy. KM3NeT will be also able to share data of neutrino light curve in quasi-real time with millisecond time resolution. This is crucial for multi-messenger networks such as SNEWS2.0 [17] to confirm the detection and to be able to provide a precise localisation of the source to the astronomy community.

4.4 Diffuse and Galactic ridge neutrino emission

The IceCube Collaboration has reported evidence of a diffuse flux of astrophysical neutrinos in several detection channels [2, 18, 19]. This detection is important in order to complement direct searches for neutrino sources and to shed light on the mechanisms at the origin of acceleration and propagation of high-energy cosmic-rays. Several analyses by the IceCube Collaboration were performed on different data samples: in the single power-law hypothesis, best fit parameters and contour uncertainties showed a mild tension. In this scenario, KM3NeT can represent a complementary observer and provide an independent measurement to fully constrain the diffuse emission. For this reason, the data coming from ARCA6 have been analyzed, searching for an excess of high-energy events, over the atmospheric background. A total livetime of 101 days have been used. The analysis selected tracks with zenith angle larger than 90°, and to further reduce the remaining background, coming from wrongly reconstructed atmospheric muons, a Boosted Decision Tree has been built. No excess was found, and therefore the 90% upper limit has been reported, assuming the best-fit flux reported from the IceCube Collaboration [20]. A possible explanation for the tension observed and the declination distribution of the IceCube events, pointing at a North/South asymmetry of the neutrino flux, can be the presence of a bulk of neutrinos generated inside our Galaxy. Both ANTARES and KM3NeT, being placed in the northern hemisphere, are privileged neutrino observatories for the detection of a possible emission coming from the Galactic center. At the same time, multi-messenger measurements of neutrino and γ-ray spectra from the Galactic center provide a unique possibility to indirectly measure the cosmic-ray spectrum. For these reasons an ON-OFF analysis, based

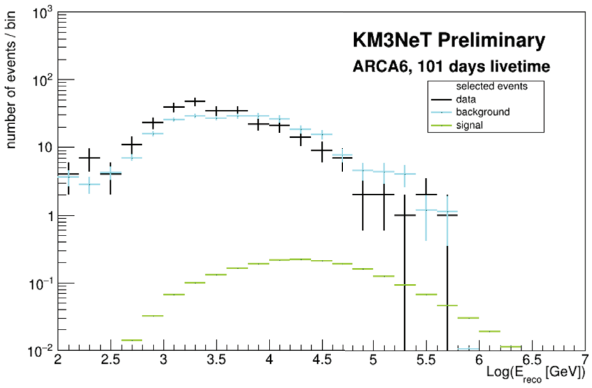


Figure 6: Energy distribution of selected data events (black points). The superimposed energy distributions of atmospheric background (light blue points) and of cosmic neutrino events (green points) estimated from MonteCarlo simulations are also shown.

on the work reported in [21], considering an extension for the Galactic center neutrino emission of $|b_{gal}| < 3°$ and $|l_{gal}| < 40°$, was performed on the data collected from ARCA6. Even in this case no excess was found, and the 90% upper limit has been reported. However, the recent analysis performed by the ANTARES Collaboration, with an extended data set and reported in [22], is pointing to a deviation from the background-only hypothesis above 2σ: future analysis comprising an increased livetime and effective area of the KM3NeT detectors will allow to put even more stringent limits on the neutrino emission originated in the center of our Galaxy.

4.5 IceCube alert follow-up

An analysis pipeline has been developed and put in place in order to follow-up alerts coming from external observatories. In particular, several recent IceCube real-time alerts of potential astrophysical neutrinos (IC211208A, IC220205B, IC220225A, IC220304A), using the complementarity of the ORCA and ARCA data, have been inspected. At the time of the alerts both ARCA and ORCA detectors were operational with respectively 8 and 10 DUs. Each follow-up has been performed searching for a signal excess around the best Active Galactic Nuclei counterpart position. For the analysis, a default ±1 day time window around the alert time has been taken into account. Only for the alert IC211208A, in coincidence with the blazar PKS0735+17 found in a flaring state, an extended time window of 1 month (full December 2021) has also been analyzed. No neutrino candidate has been detected in the standard time window follow-up for all the considered alerts. Only for the search in the extended time window of 1 month, a candidate neutrino event has been detected, with an estimated energy ~18 TeV and fully compatible with the background expectation. Future alerts will be followed-up using a procedure similar but fully integrated in the online framework illustrated in Sec.4.6.

4.6 Online analysis framework

Online multi-messenger searches have already demonstrated the capability to answer to many open questions in Astroparticle Physics. A tight collaboration of neutrino with multi-wavelength (radio to γ-ray) and gravitational wave astronomers could in the near future shed light on the origin of the most energetic particles and the acceleration mechanisms in the Universe. The main requirement for these multi-messenger studies is the fast communication of potentially interesting observations through circulars (“alerts”) sent to partner observatories, with latency of few minutes. With the scientific return of experience from the ANTARES case, the KM3NeT online analysis platform has been designed and implemented: it comprises track and shower reconstruction algorithms from ORCA and ARCA detectors, selection in real time of neutrino sample, receivers and filters of alerts from the external community, analysis pipelines searching for coincidences in time/space around these alerts, selection of a sample of interesting events to send alerts and core-collapse supernovae analysis. Considering the exploited data taking approach used by KM3NeT, i.e. the trigger-less streaming readout, the most consuming processing, in term of computing-resources, is performed directly at the ARCA and ORCA shore stations. The common centralized part contains some services like tools to make event display, event storage, monitoring and the internal/external reporting, the SN final processing, the neutrino alert sending module and the online analysis module.

4.7 Neutrino oscillation studies

From the measurement of the atmospheric neutrino flux with the ORCA detector, it is possible to infer the neutrino oscillation parameters Δm^2_{31} and θ_{23} through ν_μ disappearance, exploiting baselines spanning from tens of meters for downward-going events to ~13000 km for upward-going events. The first results for the oscillation parameters were obtained from a data set consisting in 355 days of livetime with ORCA6 and are reported in [23]. The first measurement shows that oscillations are preferred with a significance of $5.9\,\sigma$ over the “no oscillation” scenario. The contour plot at 90% CL with the sensitivity of ORCA6 to Δm^2_{31} and θ_{23} shows that with almost one year of data for ORCA6 the result is of the same order of magnitude as other competing experiments. This shows a promising scenario when a larger detector is available.

4.8 Moon and Sun shadows

The analysis of the ORCA6 data, corresponding to 499 days live-time, allowed the first observation of the Moon and the Sun cosmic-ray shadows in the downward going atmospheric muon flux [24]. Both the one-dimensional and the two-dimensional analyses in the phase space of the angular distance between the reconstructed event coordinates in the sky and the position of the two celestial objects have been performed. The significance of the observed shadows has been computed according to an ON/OFF approach. The cosmic-ray shadows induced by the Moon and the Sun were detected with a statistical significance of $4.1\,\sigma$ and $6.2\,\sigma$, respectively. By assuming the Moon and Sun nominal coordinates, it was possible to verify the positioning accuracy of the detector array together with additional checks of other possible systematic effects, for example possible time calibration biases. The ORCA detector angular resolution for downward-going muons was found to be $0.8° \pm 0.14°$ for the Sun analysis and $0.49° \pm 0.15°$ for the Moon. Even from these early results it is possible to confirm the high potential of the KM3NeT technology.

5 Conclusions

In this contribution the status and the first results of the KM3NeT neutrino telescopes, ARCA and ORCA, located in two abyssal sites of the Mediterranean Sea, have been reported. The KM3NeT Collaboration has entered in the massive production stage of its detector parts: in the next few years additional DUs will be deployed, aiming to realize 0.7 km^3 size for ARCA and almost half of the ORCA building block. At the time of writing, 21 ARCA DUs and 14 ORCA DUs have been succesfully deployed and are continuously taking data. Selected results from the analyses of the data collected by the ARCA and ORCA detectors since 2015 have been presented. Although still at early stages, the current ARCA and ORCA configurations allow to match, if not exceed, the detection potential of ANTARES. Measurements of the downward-going flux have been exploited to check the detector performance and alignment (e.g. with the Moon and Sun cosmic-ray shadows). Searches for diffuse fluxes and point-like sources, as well as the measurement of the neutrino oscillation parameters have been started, confirming the exceptional potential discovery that can be reached in few years, given the scheduled enlargement of the size of the telescopes. Complementary to the standard data taking chain, an efficient online reconstruction and analysis framework has been optimized to exchange quick alerts with other space and ground-based experiments, such as optical telescopes, X-ray, γ-ray and gravitational wave observatories, promptly contributing to a rich multi-messenger program.

References

[1] T. Chiarusi, M. Spurio, Eur. Phys. J. C **65**, 649 (2010);

[2] M. G. Aartsen *et al.* [IceCube], Phys. Rev. Lett. **111**, 2, 021103 (2013);

[3] M. Aartsen *et al.* [IceCube], Science **361**, 6398, 147 (2018);

[4] V. A. Allakhverdyan *et al.* [Baikal], [arXiv:2211.09447 [astro-ph.HE]];

[5] S. Adrián-Martínez *et al.* [KM3NeT], Journal of Physics G: Nuclear and Particle Physics **43**, 8, 084001 (2016);

[6] E. Leonora *et al.* [KM3NeT], Journal of Physics: Conference Series **1056**, 1, 012031 (2018);

[7] T. Chiarusi *et al.* [KM3NeT], EPJ Web of Conferences, in press. (2023);

[8] W. Assal *et al.* [KM3NeT], J. of Instrumentations **16**, C09034 (2021);

[9] http://www.ponricerca.gov.it;

[10] https://www.mur.gov.it/it/pnrr/missione-istruzione-e-ricerca;

[11] R. Le Breton *et al.* [KM3NeT], JINST **16**, 9, C09004 (2021);

[12] K. Melis *et al.*[KM3NeT], PoS ICRC2017, 1059 (2017);

[13] T. Van Eeden *et al.* [KM3NeT], Zenodo (2022) https://doi.org/10.5281/zenodo.6804829;

[14] E. V. Bugaev, A. Misaki, A. Naumov Vadim, T. S. Sinegovskaya, S. I. Sinegovsky, N. Takahashi, Phys. Rev. D **58**, 054001 (1998);

[15] M. Ageron *et al.* [KM3NeT], EPJC **80**, 2, 99 (2020);

[16] S. Aiello *et al.* [KM3NeT], EPJC **81**, 5, 445 (2021);

[17] The Supernovae Early Warning System, https://snews.bnl.gov/;

[18] M. G. Aartsen *et al.* [IceCube], AAS **883**, 1, 3 (2016);

[19] M. G. Aartsen *et al.* [IceCube], Phys. Rev. Lett. **125**, 12, 121104 (2020);

[20] J. Stettner *et al.* [IceCube], PoS ICRC2019 1017 (2019);

[21] S. Adrian-Martinez *et al.* [ANTARES], Phys. Lett. B **760**, 143 (2016);

[22] A. Albert *et al.* [ANTARES], arXiv:2212.11876 (2022);

[23] L. Nauta *et al.* [KM3NeT], PoS ICRC2021, 1123 (2021);

[24] KM3NeT Collaboration, [arXiv:2211.08977 [astro-ph.IM]].