Outlook of the KM3NeT Neutrino Telescope and Latest Results

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Abstract

The KM3NeT research infrastructure includes two neutrino Cherenkov telescopes located in two different abyssal sites of the Mediterranean Sea, ARCA (Astroparticle Research with Cosmics in the Abyss) and ORCA (Oscillation Research with Cosmics in the Abyss). While the detection technology is the same for both telescopes, the scientific goals are distinct thanks to the difference in the geometrical layout. Specifically, the ARCA telescope, a future cubic kilometer detector with more than 4000 sensor modules sparsely distributed, focuses on studying the high-energy astrophysical neutrinos in the TeV-PeV range, while the ORCA telescope, with a denser instrumented detector volume equivalent to about 7 Mton of sea water, is optimised to explore the atmospheric neutrino oscillations in the GeV energy range. With these two installations, KM3NeT can explore a large neutrino energy range thus addressing various science topics. The two detectors are currently under construction, with data taking on-going since the operation of the first detection strings. Data collected with partial configurations of the detectors were analysed and first physics results have been already obtained. An overview of the recent results achieved with the KM3NeT detectors in their current status will be shown in this talk. Also, the expected performance of the full detectors will be presented.

Keywords: neutrino telescopes, neutrino physics, cosmic rays
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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. Neutrinos represent an alternative to photons and cosmic rays to explore the high-energy Universe. Indeed, contrary to charged nuclei and photons which can be diverted or absorbed during their long travel from the sources to Earth, neutrinos are the optimal messengers to investigate violent phenomena in the Universe, due to the extremely small cross section of weak interactions with matter. 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 scenarios. The measurement of neutrino fluxes can be used to constrain the composition of matter surrounding the astrophysical sources, even of those hidden behind optical thick shells, and to disentangle acceleration mechanisms against thermal, or not thermal, processes. Finally, other targets of neutrino astrophysics are search for core collapse supernovae, indirect detection of dark matter annihilation in dense matter environments, and searches for magnetic monopoles and other exotic-matter candidates.

Analyses performed with neutrino telescopes optimised for high-energy neutrinos, like ARCA, 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 [1]. The irreducible background of atmospheric neutrinos becomes less relevant as energy increases, enhancing the probability of observing high-energy cosmic candidates. 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 recorded information can be used to reconstruct direction and energy of incoming parent neutrinos, whose interaction produced those charged particles. Neutrino telescopes can detect all-flavour neutrino interactions. Together with the astroparticle goals mentioned above, other appealing physics objectives can be achieved with neutrino telescopes, like study of fundamental properties of neutrinos within and beyond the Standard Model. Neutrino mass ordering can be determined using neutrinos produced in the Earth atmosphere through interactions of cosmic rays [2].

Currently, the largest and most sensitive neutrino telescope on Earth is the IceCube detector, placed at a depth 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 and it was capable to obtain the first evidence of the presence of cosmic neutrinos [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. 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, it was dismantled in spring 2022 and has passed the baton to the next-generation network of neutrino telescopes 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. The measurement strategy and the detection performance for both detectors is reviewed in Section 3. 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 DETECTORS

The KM3NeT (km^3-scale neutrino telescope) [2] facility consists of two neutrino telescopes currently under construction at the bottom of the Mediterranean Sea. The ARCA (Astroparticle Research with Cosmics in the Abyss) detector is being installed at the KM3NeT-It site, about 100 km offshore the Sicilian coast in front of Capo Passero (Italy) at a sea bottom depth of about 3500 m. The main physics goal of ARCA is the discovery and subsequent observation of astrophysical neutrino sources in the Universe [4]. About 1 km^3 of seawater will be instrumented with $\sim$130,000 photo-multiplier tubes (PMTs) for the detection of Cherenkov light induced by charged particles produced in neutrino interactions. The geometry of ARCA is optimised to maximise its detection efficiency in the neutrino energy range 1 TeV–10 PeV. Being located in the northern hemisphere, ARCA provides a complementary view to IceCube (located at the South Pole). The presence of the Galactic Centre in its field of view opens a a privileged observative window on a possible population of Galactic sources. In parallel, the KM3NeT Collaboration started the construction of the ORCA (Oscillation Research with Cosmics in the Abyss) detector at the KM3NeT-Fr site, 40 km offshore Toulon (France) at a sea bottom depth of about 2500 m. ORCA shares the same technology and detector elements as ARCA, but in a denser configuration to detect neutrinos in the range 1–100 GeV. ORCA instruments a volume equivalent to about 7 Mton of sea water. The main physics goal is the determination of the neutrino mass ordering by measuring oscillation probability patterns of atmospheric neutrinos [5].

2.1. Detector Design

Both ARCA and ORCA are made of vertically aligned Detection Units (DUs), each hosting 18 Digital Optical Modules (DOMs), in order to constitute a three dimensional arrays. The DOM is a pressure-resistant glass sphere housing 31 3-inch photo-multiplier tubes [6, 7] (see Figure 1). A transparent gel is employed to guarantee the optical coupling between the PMTs and the internal surface of the glass spheres. Several instruments are mounted inside the DOM to measure its position and orientation (compass, tilt-meter, acoustic sensor) and to time-calibrate the DOMs (light emitters based on LEDs). The real-time positioning of the DOMs is necessary as the detector elements can move under the influence of sea currents.

Figure 1: Side view of a KM3NeT DOM.

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 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. A set of 115 detection units constitutes a building block of the KM3NeT detectors. Although sharing the same detection elements, ARCA and ORCA differ in the granularity of the sensor modules, according to their scientific targets. For the ARCA-type detection unit the vertical distance between the DOMs is $\sim$36 m, resulting in a total height of the structure of 700 m. The installation of two ARCA building blocks at the KM3NeT-It site is planned, with a horizontal distance between the DUs of $\sim$90 m and a total instrumented volume of $\sim$1 km^3.

The ORCA instrumented volume is 1% of the ARCA extension. In ORCA the inter-distance between the DUs is 20 m and the DOMs are vertically spaced by 9 m, allowing for an optimised 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 main electrical-optical cables (MEOCs) to the shore-station.The analog signals from the PMTs are digitised using a custom electronic board mounted inside each

DOM [8]. When one or more photons impinge on the PMT photocathode and the anode electrical signal crosses the threshold of a discriminator, a level zero (L0) hit is recorded. The crossing time and the time-over-threshold (ToT) of the waveform are recorded and the ToT gives a measure of the pulse amplitude. The high voltage setting of each PMT is tuned in-situ to give an average ToT of 26.4 ns for a single photoelectron (p.e.). A default value corresponding to 0.3 p.e. is set for the discriminator threshold. 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. All L0 hits are assembled in time windows with a fixed size of 100 ms, called L0 timeslices. For power delivery and data transmission, a Vertical Electro-Optical Cable (VEOC) is attached to each DOM. On-shore, once the time calibration is applied, dedicated trigger algorithms look in parallel for the physics events to be saved for offline analysis. For the deployment, the DU is furled onto a spherical structure with a radius of approximately 2 m, called the Launcher of Optical Modules (LOM) Once at the seabed, the DU is connected to the seafloor network using a Remotely Operated Vehicle (ROV). After confirming the functionality of the DOMs, the LOM is remotely released and floats up to the surface, progressively unfurling the detection unit.

2.2. *ARCA and ORCA Evolution*

The first DU of the ARCA detector was deployed in December 2015, followed by two DUs in May 2016. The first DU of ORCA was installed in September 2017. 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 refer 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, during which the KM3NeT Collaboration was engaged to optimise 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. 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 layout of ARCA21 and ORCA14 in September 2022. During 2023, ARCA28 and ORCA18 were completed. Thanks to European dedicated funds for enhancing the scientific installations in Italy, 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, also the ORCA detector will increase the number of active detection strings up to 48 DUs. 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 can be exploited for Earth and marine science 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. DETECTOR PERFORMANCE

3.1. *Neutrino Signatures*

The events detected in KM3NeT can be separated in two distinct classes: *track-like events* and *shower-like events* (see Figure 2).

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. 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 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 lepton decay. Background events consist of down-going muons, which can be produced in the decays of 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 down-going muons that it can be rejected by restricting signal searches to up-going events. Atmospheric neutrinos represent background only for astrophysics searches and their effect is taken into account using statistical methods in each single analysis. They are the main signal to study neutrino oscillation parameters and constrain the mass-hierarchy problem.

3.2. *ARCA Performance*

The effective geometrical acceptance of a neutrino telescope scales with the detector size and with the energy of the imping neutrinos. The effective area is computed thanks to Monte Carlo simulations. Being proportional to the expected rate of reconstructed events, that quantity is connected to the detection performance, and can be used to benchmark different neutrino telescopes. In Figure 3, the ARCA230 effective area is shown and in Figure 4, the effective areas of current partial configurations of the ARCA detectors are compared to the effective area of ANTARES.

Neutrino events are generated over the full-sky with energies in the range $10^2 < E_\nu < 10^8$ GeV using the gSeaGen framework [11]. Atmospheric muons are simulated using the MUPAGE software [12]. All events are passed through the KM3NeT light simulation and detector response software packages. Finally the simulated data stream is processed with the same trigger and reconstruction algorithms used for real data in order to identify and reconstruct interesting events. Also, simulated events are used

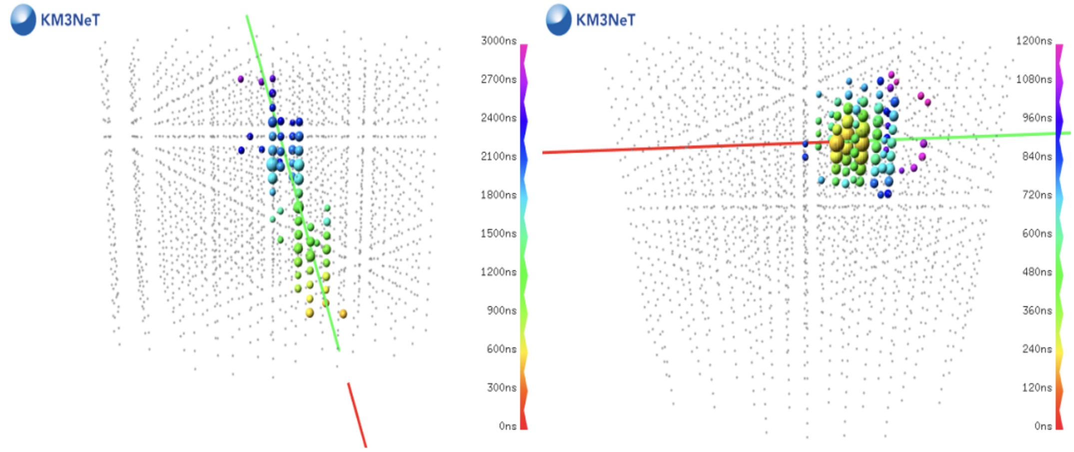

Figure 2: Event displays for a simulated ν_μ CC event (left) and a contained ν_μ NC event (right). In both cases, the incoming neutrino is indicated by the red line, and the outgoing lepton (muon or neutrino) by the green line. The colour scale gives the hit times with respect to the time of the neutrino interaction, while the size of the circles are proportional to the total ToT on each DOM. DOMs without hits are shown by grey dots [2].

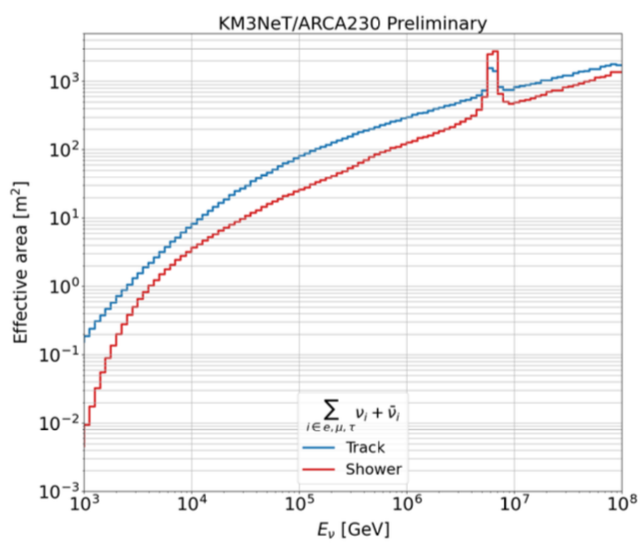

Figure 3: In the figure is shown the effective area of full ARCA detector for the track and shower channel. The effective area contains the sum of interactions from ν_e, ν_μ, ν_τ and averaged over ν, $\bar{\nu}$ [9].

to optimise selection criteria. Details can be found at [9]. The choice to install the KM3NeT telescopes in abyssal sites presents clear complications due to the difficulties of arranging the deployments. Moreover the optical background due to ^{40}K decays and 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 perform long-term monitoring of the PMT photon detection efficiency. The excellent optical properties of water result in unprecedented angular resolution that, in addition to the location in the northern hemisphere, make the Mediterranea Sea a privileged point of observation towards the Galactic plane and centre. Monte Carlo simulations the angular deviation between the reconstructed and true neutrino direction as a function of energy has been calculated. The ARCA angular resolution referred to the complete, referred to the complete and to partial configurations of the detector, are shown in Figure 5. Due to topology of the event itself, the better angular resolution is obtained for track-type events than for shower-type events. With the ARCA6-8 configuration an angular deviation for track-like events of $\sim 1^\circ$ at 100 PeV has been reached, while with the ARCA19-21 configuration the angular resolution is around 0.2°. With the full detector an angular resolution of about 0.06° is expected [10].

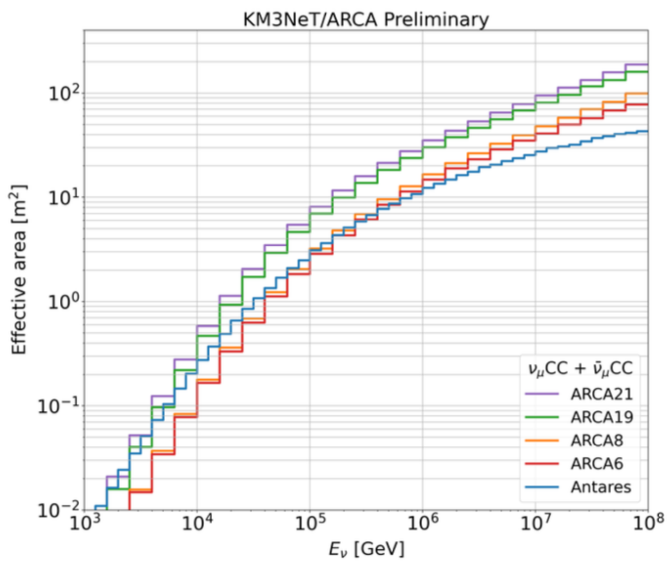

Figure 4: Effective area at selection level for the different ARCA detectors for a flux of $\nu_\mu + \bar{\nu}_\mu$ that interact in the CC interaction. The effective areas are compared with the ANTARES effective area for upgoing events [10].

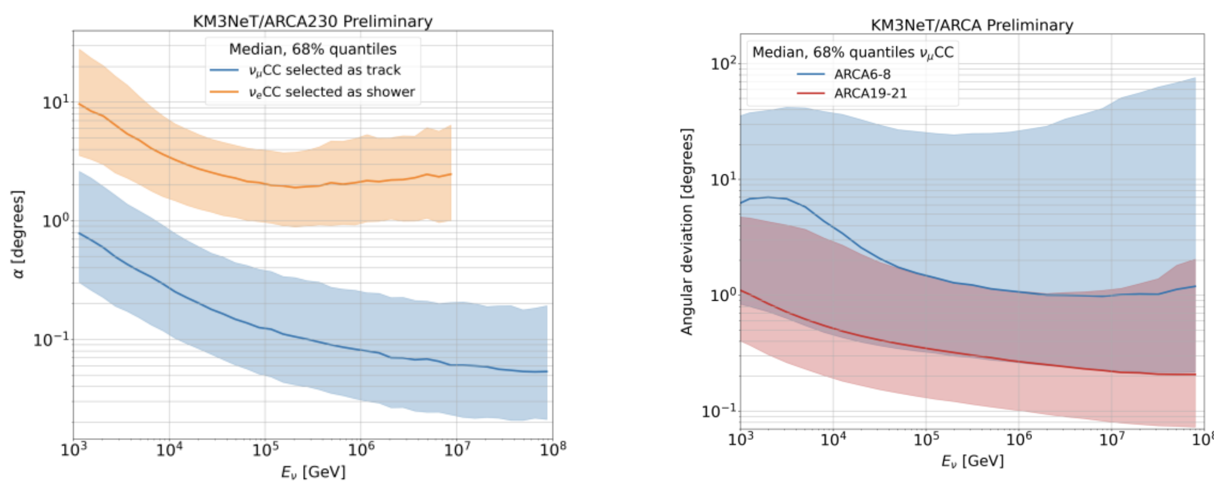

Figure 5: Effective area (left) at selection level for the different ARCA detectors for a flux of $\nu_\mu + \bar{\nu}_\mu$ that interact in the CC interaction [9]. The effective areas are compared with the ANTARES effective area for upgoing events. The angular deviation (right) for the ARCA6-8 and ARCA19-21 periods with their corresponding 68% quantiles [10].

3.3. ARCA Sensitivity and Discovery Potential

The quantities used to describe detector performance are the discovery potential and the sensitivity. The discovery potential is defined as the flux observed with a given significance (e.g., 3σ or 5σ) with a certain probability, i.e., in a given fraction of hypothetical experiments (50% in this contribution). The sensitivity is the flux that can be excluded with a given confidence level (90% in this contribution), if no significant signal is observed. In Figure 6, the final ARCA6-21 E^{-2} point source results for 101 astrophysical objects are compared with the IceCube and ANTARES results and with the expected sensitivity for the full ARCA detector, made by 230 detection units. Neutrino flux from the direction of all candidate sources is consistent with a background-only [10]. Improvement in sensitivity is expected with data from the present configuration ARCA28. Compared to the IceCube sensitivity, the full KM3NeT extends the visible region of the sky thanks to its location in the northern hemisphere [13].

The discovery potential for the starburst galaxy NGC 1068 was studied and is shown in Figure 7. It is located 10^{14} Mpc [15]. A 5σ discovery can be claimed after 3 years of full KM3NeT/ARCA operation. The power law flux with $\gamma = 3.2$ was extended over the full energy range. The interest towards this source is due to the detection of an excess of events coming from its direction with a significance of 4.2σ recently found by the IceCube Collaboration [16]. Given the importance of this source, the model discovery potential (MDP), defined as the minimum flux needed for a 5σ discovery in the 50% of cases (see [4] for more details), is shown. In

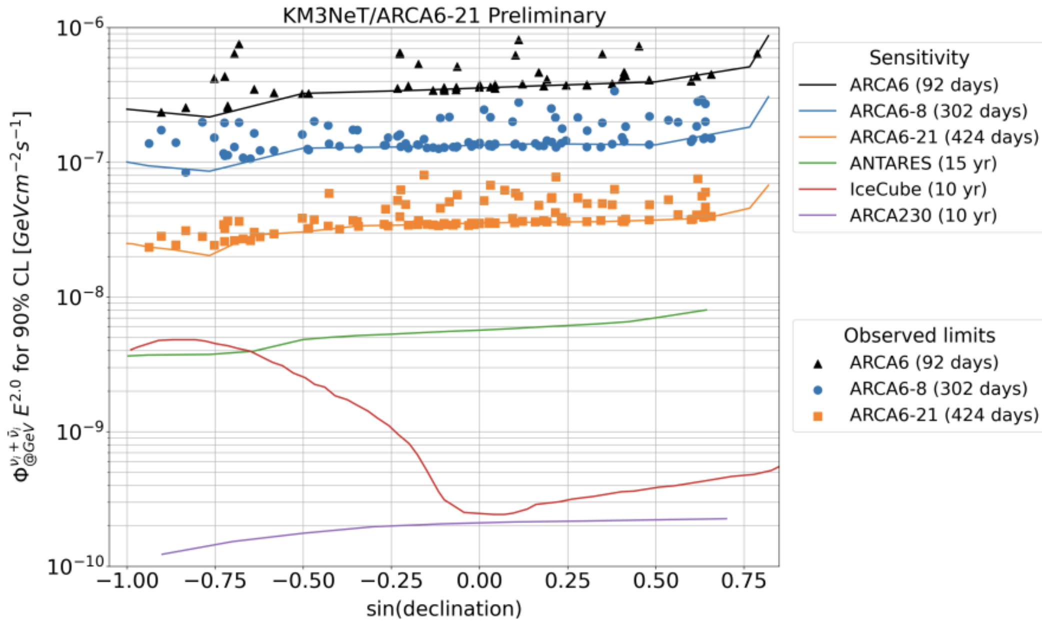

Figure 6: Comparison of the observed limits on the flux for the ARCA6-21 point source analysis as a function of sin(δ), with results of ANTARES 15 years, IceCube and the ARCA230 10 years sensitivity [10].

order to compute it, the event selection is optimised in order to produce the minimum MDP for each bin (see [14] for details). From this analysis KM3NeT/ARCA is expected to discover the IceCube flux in few years.

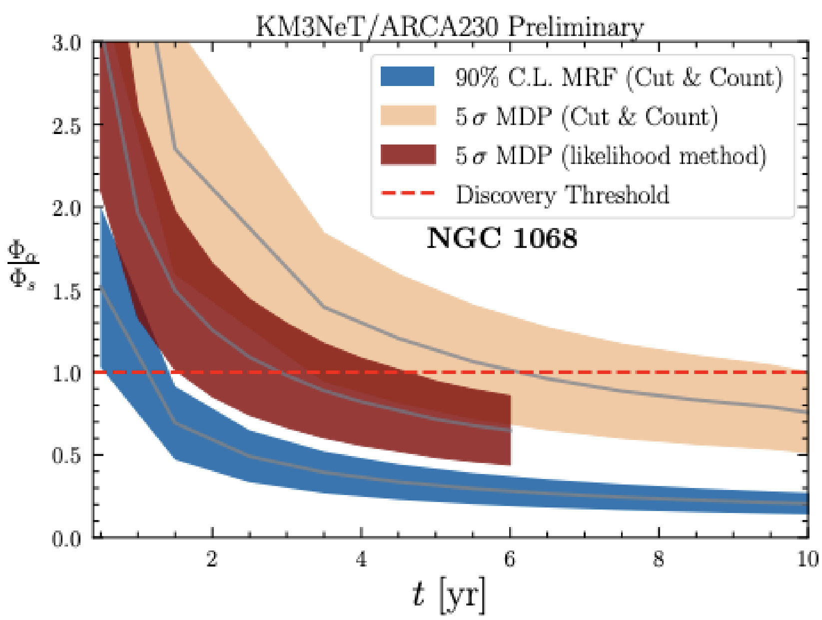

Figure 7: The integrated MRF (blue band) and the MDP (orange band for cut & count and dark red band for the Binned likelihood ratio) are shown as functions of the KM3NeT/ARCA operation time. The bands correspond to the 1σ uncertainty provided by the normalization uncertainty provided by the IceCube fit [14].

4. THE LATEST RESULTS

4.1. KM3NeT/ARCA Diffuse Astrophysical Neutrino Flux

One of the main goals of astrophysics is to provide hints to identify sites and mechanisms of acceleration of very high energy cosmic rays. The measurement of a diffuse flux of cosmic neutrinos can help to solve the mistery. Responsible for the diffuse astrophysical neutrino flux observed at Earth are the high energy cosmic rays which produce neutrinos while traveling from cosmic distances and neutrinos whose source can not be detected individually. The energy spectrum of these neutrinos is typically modeled as a power-law, $\Phi \approx E^{-\gamma}$. In this work, an analysis of the full dataset collected with the KM3NeT/ARCA partial configurations is presented, focusing on the search for a diffuse astrophysical neutrino flux. Calculations were performed using the one-flavour IceCube neutrino flux with $\Phi_0 = 1.44 \cdot 10^{-18}$ and $\gamma = 2.37$ at 100 TeV normalization and considering only upgoing events. A binned likelihood method was used for the statistical analysis of the signal properties (see [17] for more details). The results are shown in Figure 8 and demonstrate the potential of KM3NeT/ARCA for measuring a diffuse astrophysical neutrino flux.

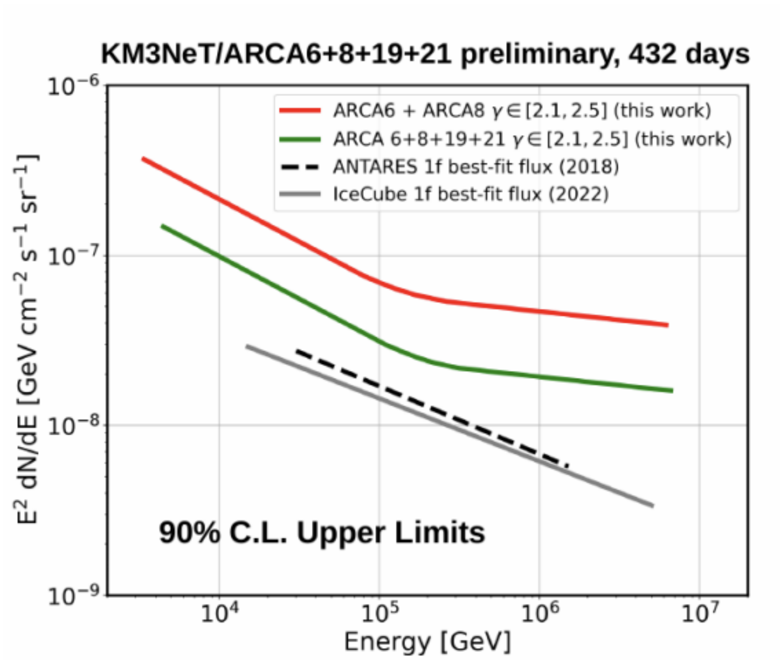

Figure 8: Convolution of U.L.s at 90% C.L. for selected γ in range $[2.1, 2.5]$ for different ARCA partial detector configurations computed for the central 90% energy range of the signal events and a comparison with IceCube's and ANTARES' 1-flavour best fit flux [17].

4.2. Diffuse Neutrino Flux from the Galactic Ridge

The Galactic plane is the most evident source in the sky over a large range of electromagnetic wavelengths. These photons can be produced either in specific sources, positioned on the Galactic plane, or by the interaction of cosmic rays with the interstellar medium. KM3NeT, being placed in the northern hemisphere, is privileged neutrino observatory for the detection of a possible emission coming from the Galactic center. In the innermost part of the Galactic plane, defined here $|l| < 30°$ and $|b| < 2°$, namely the Galactic Ridge, the cosmic ray spectrum is described by a harder spectral index with respect to what locally measured at Earth. The ANTARES Collaboration reported an excess of events coming from the Galactic Ridge incompatible with the background expectation at 96% confidence level [21], and, at the end of June 2023, the IceCube Collaboration has reported evidence of possible emission of high-energy neutrinos from the Galactic plane, with a statistical significance of 4.5σ [22]. An ON-OFF analysis, based on the work reported in [23], was performed on the data collected from ARCA6, ARCA8, ARCA19 and ARCA21, for a total lifetime of 432 days. No excess was found, and a 90% upper limit has been evaluated.

4.3. Core-Collapse Supernova Neutrinos at KM3NeT

The discovery of 25 neutrinos coming from the SN1987A core-collapse supernova (CCSN) by the Super-Kamiokande [24] and other experiments marked the beginning of neutrino astronomy. Due to the low interaction rate of neutrinos, experiments are however only sensitive to close-by supernovae. Since these events are quite rare, it is crucial to optimise the detection channels of all available experiments. KM3NeT's current CCSN search strategy makes the detector's final configuration sensitive to 96% of Galactic CCSNe by leveraging its unique DOM structure. The detection technique exploits the possible excess of photon-hit coincidences on PMTs belonging to the same DOM, over the background. In particular, this analysis uses the multiplicity, defined as the number of PMT hits in a DOM within a 10 ns window, to distinguish CCSN neutrinos from ambient backgrounds (see [19] for details). Signal expectation is instead derived thanks to specific simulations, based on a custom software developed by the KM3NeT Collaboration. With this method, KM3NeT's distance horizon is increased by 23% and with the upcoming ORCA24 and ARCA29 detector configurations it will thus be possible to probe a significant fraction of the Galactic bulge, even for the case of a light progenitor.

4.4. Neutrino Oscillation Studies

During 2020 and 2021, an early configuration of the ORCA detector with six lines was in operation. From the measurement of the atmospheric neutrino flux, it is possible to infer the neutrino oscillation parameters Δm^2_{31} and $\sin^2\theta_{23}$ through ν_μ disappearance. The overwhelming majority of recorded events in ORCA are atmospheric muons and pure noise, which have to be rejected in the selection process. To remove these events, first geometrical selection to reject downgoing events, followed by a Boosted Decision Tree (BDT) machine learning algorithm (see [18] for more details). A high-purity neutrino sample covering 433 kton-years of exposure was extracted. The measurement of neutrino oscillation parameters, as well as the sensitivity to determine the neutrino mass ordering based on this data sample, is presented in Figure 9. With only 5% of its final configuration, the ORCA detector starts to contribute to the measurement of atmospheric neutrino oscillations. The best fit values for the parameters are $\sin^2\theta_{23} = 0.51^{+0.06}_{-0.07}$ and $\Delta m^2_{31} = 2.14^{+0.36}_{-0.25} \cdot 10^{-3}\,\mathrm{eV}^2$ with a preference for Normal Ordering NO = 0.9. The detector deployment is progressing continuously and these measurements will gain in precision as the detector volume increases and the reconstruction and selection efficiencies are improved.

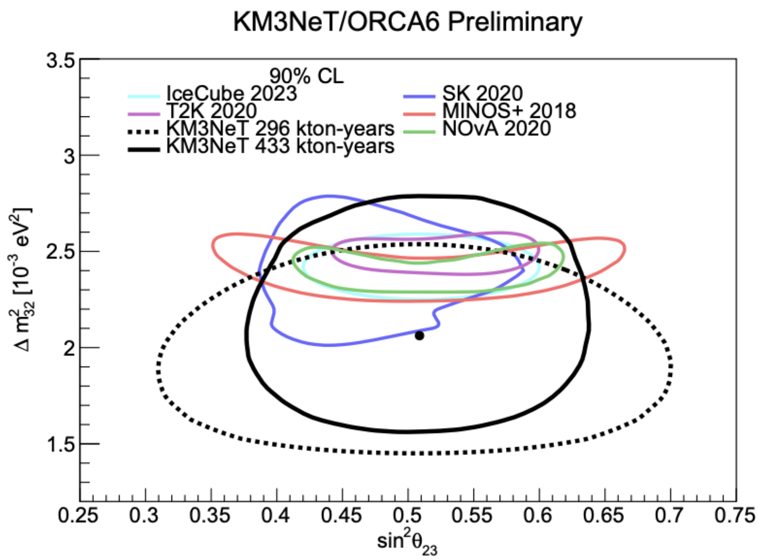

Figure 9: Contour at 90% CL of ORCA6 for the oscillation parameters Δm^2_{31} and $\sin^2\theta_{23}$ compared with other experiments [18].

5. CONCLUSION

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 the massive production stage of its detector parts and in the next few years additional DUs will be deployed. At the time of writing, 28 ARCA DUs and 18 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 configuration exceed the detection potential of ANTARES. Searches for diffuse fluxes and point-like sources, as well as the measurement of the neutrino oscillation parameters have started, confirming the exceptional potential discovery that can be reached in few years.

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