PROCEEDINGS OF SCIENCE

Status and outlook of KM3NeT neutrino telescopes

Cristiano Bozza[a,*] **for the KM3NeT Collaboration**

[a] *Università di Salerno and INFN Gruppo Collegato di Salerno, Via Giovanni Paolo II 132, Fisciano, Italy*

E-mail: cbozza@unisa.it

The KM3NeT Collaboration is incrementally building a network of water-Cherenkov neutrino observatories in the Mediterranean Sea, consisting of two telescopes, named ARCA (Astroparticle Research with Cosmics in the Abyss) and ORCA (Oscillation Research with Cosmics in the Abyss), sharing the same detection technology. ARCA, located off the shores of Sicily, in its completed shape will be a cubic-kilometre scale modular telescope made of 230 detection units, optimised for neutrino astronomy in the TeV-PeV energy range. ORCA, off the shores of Toulon (France), will be a 7-Mton modular telescope made of 115 detection units, focused on neutrino oscillations and neutrino mass ordering, for neutrinos in the 1-100 GeV energy range. At the current time, ARCA consists of 21 detection units whereas ORCA has 18 already installed. Both telescopes have been already taking data for a few years, providing good understanding of backgrounds as well as of the expected signals and hence of the scientific potential of KM3NeT. The technique for neutrino detection and measurement is reviewed, along with outlooks for the completion of the two telescopes and the expected performances for detection of astrophysical neutrino sources, measurement of neutrino oscillation parameters and neutrino mass ordering. Contributions of KM3NeT to global efforts for multimessenger astronomy are also discussed. Early physics outputs of both telescopes are reported.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

*Speaker

PoS(EPS-HEP2023)058

1. Introduction

The KM3NeT Collaboration is currently building two neutrino telescopes in the Mediterranean Sea, with a broad physics and astrophysics programme. ARCA (Astroparticle Research with Cosmics in the Abyss) and ORCA (Oscillation Research with Cosmics in the Abyss) designate each telescope's main task, although there are significant and beneficial overlaps between the two. Unlike charged particles, neutrinos are not deflected by galactic and extra-galactic magnetic fields, retaining very good pointing capabilities to their source; they do not interact with the cosmic microwave background; and unlike photons, they are not stopped by interstellar matter. Hence, they are ideal deep-space messengers, provided the telescopes are able to collect sizeable integrated fluxes for the observational purposes. Models predict the production of high-energy (typically TeV to PeV) neutrinos, by hadronic acceleration and interaction processes in observationally point-like sources [1] such as supernovae remnants, pulsar wind nebulae, active galactic nuclei with supermassive black holes, and in some scenarios of dark matter particle annihilation. In a lower energy range, neutrino telescopes can observe and measure the flux of atmospheric neutrinos produced in the opposite Earth hemisphere, including the effects of propagation in the Earth matter while oscillating, providing competitive sensitivity to the neutrino mass ordering [2]. Thanks to their modular structure, KM3NeT telescopes are also able to detect neutrinos from supernovae with energies of the order of MeV.

In order to have meaningful statistics of events in few years' observation timespan, large volumes of water are needed, to work as Cherenkov radiator for the charged particles produced in charged-current and neutral-current interactions of neutrinos. Sea water is cheap and has good optical properties for this use. The Mediterranean Sea offers excellent visibility for neutrinos from the Galactic Centre and most of the Galactic Plane. The Collaboration has a strong European core, but nevertheless includes relevant participations from Africa, Asia and Oceania.

The detector technology that has been chosen is modular and allows incremental construction of the telescopes, which are able to take data even at a very early stage. The basic unit is the DOM (Digital Optical Module), which is a pressure-resistant sphere hosting 31 photomultipliers; a DU (Detection Unit) is a vertical line, anchored to the seabed and held in tension with a buoy, hosting 18 DOMs with even vertical spacing (36 m for ARCA, 9 m for ORCA). A *building block* (BB) is an approximately cylindrical arrangement of 115 DUs deployed in a regular pattern (90 m spacing for ARCA, 20 m for ORCA). ORCA will be made of one BB, instrumenting 7 Mton of water; ARCA is designed to be made of two equal blocks, with a total number of 230 DUs, 4140 DOMs and instrumenting 2 Gton of water. Under the effect of sea currents, the shape and orientation of each DU are continuously changing. A compass and a tiltmeter, hosted on

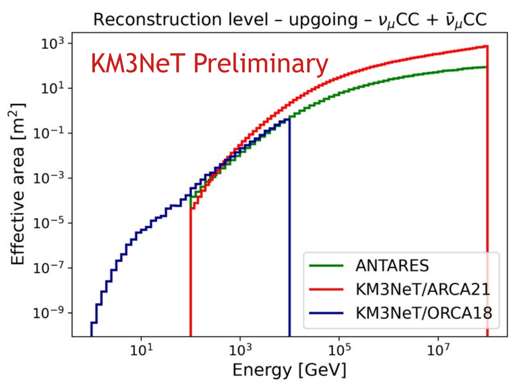

Figure 1. Current effective areas of ARCA and ORCA compared to ANTARES.

the electronics Control Board in each DOM, provide orientation information. Acoustic beacons provide reference positions in water, and the arrival times of the acoustic waves, measured by suitable sensors hosted in the DOM, provide precise positioning information.

The effective areas for neutrino interactions for ARCA with 21 DUs and for ORCA with 18 DUs are shown in Fig. 1. In the respective energy range, they already exceed by far the effective area of ANTARES. The expected effective area for full ARCA will exceed the effective area of IceCube at most angles and energies. As a result, the overall detection sensitivity is expected to be comparable or higher for KM3NeT.

The observed patterns of PMT signals in the DOMs depend on the flavour and type of interaction of the incoming neutrino and result in two main topological classes: track-like events are associated to charged-current interactions of ν_μ and of ν_τ with subsequent muonic decay, while shower-like events originate from all other interaction channels, where only hadronic and electromagnetic showers are produced. This includes charged-current interactions of ν_e and ν_τ with non-muonic decays, as well as neutral-current interactions. The most relevant background is due to downward-going atmospheric muons produced in cosmic-ray interactions above the detector.

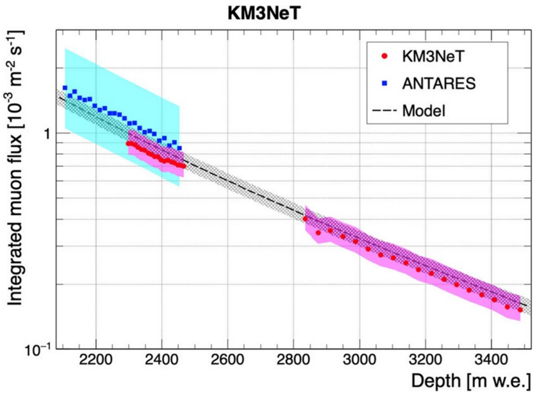

Figure 2. Muon flux vs. depth, measured by KM3NeT [3] and ANTARES, compared to the available model.

2. Current and projected performances of KM3NeT detectors

The first measurement that shows the ability of KM3NeT's telescopes to effectively take data is the muon-depth relationship [3], i.e. the measurement of the flux of down-going atmospheric muons as a function of the measurement depth, shown in Fig. 2. The KM3NeT data points, obtained partially by ORCA and partially by ARCA, are compatible with the available model of atmospheric muon flux [4]. The result obtained shows that although the two telescopes have different DOM and DU configurations and different environmental conditions, using the same underlying technology for ORCA and ARCA helps keep systematic effects under control.

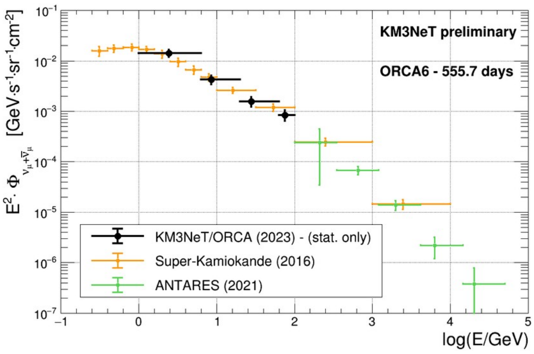

Figure 3. Measurements of atmospheric neutrino flux by KM3NeT/ORCA with 6 DUs, ANTARES and SuperKamiokande showing good agreement.

The atmospheric neutrino flux measured at the ORCA site is shown in Fig. 3. The KM3NeT data provided by ORCA nicely extend the range of measurements of ANTARES towards lower energies, and are found to be compatible with those measured by the SuperKamiokande detector.

It is not trivial to obtain good pointing accuracy with neutrino telescopes in seawater, continuously changing their shapes under the action of currents, but the acoustic positioning system described above fulfills its task to define the position of each DOM at any time during data taking. A quantitative proof that the performances of the telescopes in the current status are already suitable for astronomy purposes is illustrated by the observation of the cosmic ray shadow of the Moon and Sun with ORCA in its 6-DU configuration [5] (Fig. 4).

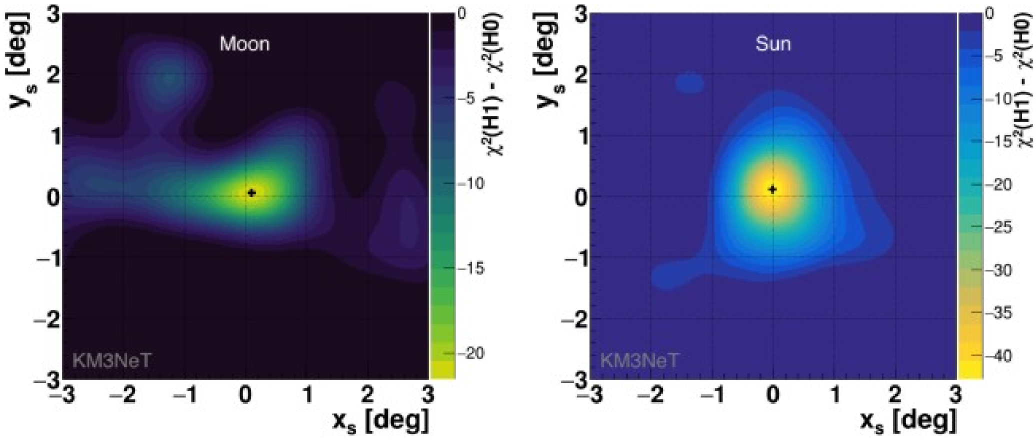

Figure 4. Left: neutrino shadow of the Moon. Right: neutrino shadow of the Sun.

3. Neutrino astronomy with ARCA

Identification of astrophysical sources of neutrinos requires a significant pointing accuracy of the telescope. It improves with increasing size of the instrumented volume. Fig. 5 shows the expectation for full ARCA. At energies above 100 TeV, the angular resolution for ν_μ track-like events is of the order of 0.1°. ν_e shower-like events provide better performance for neutrino energy estimation (see Fig. 6), of the order of 15% above 100 TeV; on the other hand, muon tracks frequently exit the instrumented volume, so the error on neutrino energy is always above 100%. The ARCA telescope is being used to search for the point-like astrophysical neutrino sources, i.e. high-energy neutrino emitters with angular extension of the order of the angular resolution or smaller. Candidate sources include active galactic nuclei, supernovae remnants, etc. So far, only upper limits have been set, as illustrated in Fig. 7, displaying sensitivity curves at various construction stages and with increasing observation time. The final sensitivity of

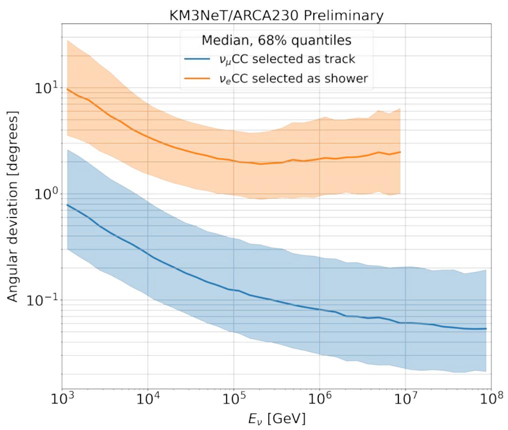

Figure 5. Direction reconstruction accuracy in ARCA for ν_μ CC track-like and ν_e CC shower-like events.

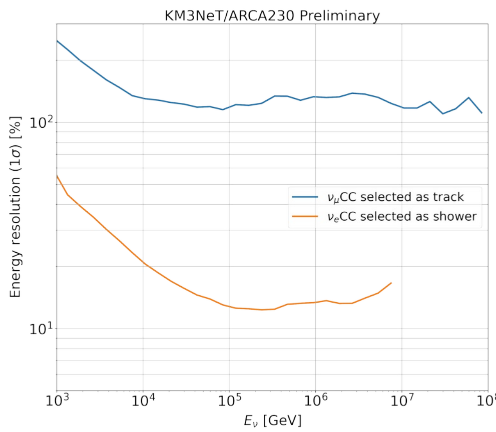

Figure 6. Energy resolution in ARCA for ν_μ CC track-like and ν_e CC shower-like events.

PoS(EPS-HEP2023)058

ANTARES will be approached by the next upgrades of the ARCA telescope, and the final sensitivity with 2 BBs will outperform IceCube, notably in the angular region that points towards the centre of the Milky Way. Upper limits for individual sources are also shown.

The search for neutrinos emitted by the Galactic Ridge is also underway. In this case, ARCA cannot compete yet with IceCube and ANTARES, but the outlook looks promising.

KM3NeT is entering the ballpark of the measurement of the diffuse flux of high-energy neutrinos. Fig. 8 shows that the data taken by partial versions of ARCA, with limited data taking times, are only an order of magnitude clear of detecting the flux of astrophysical high-energy neutrinos. A scientifically meaningful contribution by KM3NeT to such measurement is expected to be ready very soon. As a global outlook, one BB of ARCA should be able to detect the diffuse neutrino flux at 5σ with 1 year's data taking, and two BBs should need just 0.6 years.

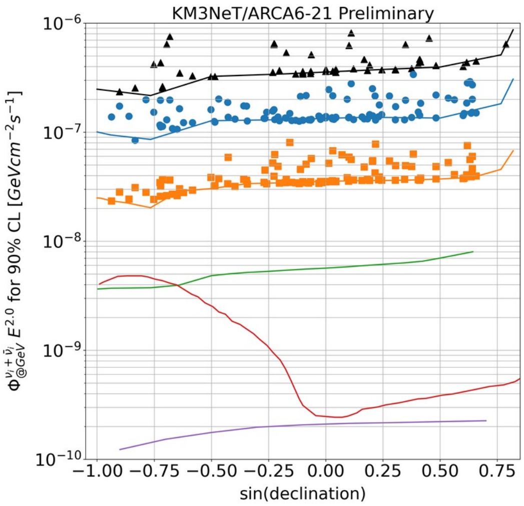

Figure 7. Point-source sensitivity [6]. Black: ARCA6; blue: ARCA6-8; orange: ARCA6-21; green: ANTARES; red: IceCube 10 years; magenta: ARCA230, 10 years.

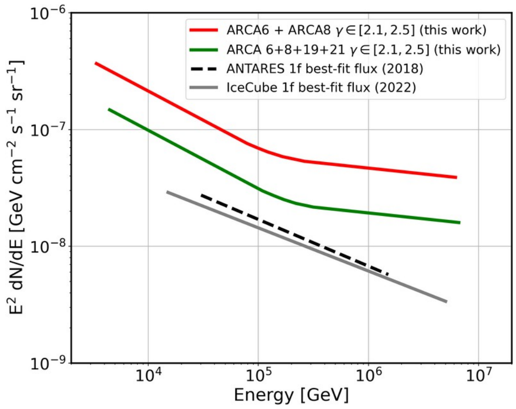

Figure 8. Diffuse flux of high-energy neutrinos. KM3NeT upper limits [7] are approaching the measurements by ANTARES and IceCube.

4. Neutrino Physics with ORCA

The smaller size and denser configuration of ORCA, optimised for the energy range 1-100 GeV, makes it well suited for oscillation studies with atmospheric neutrinos propagating through the Earth, and in particular for the measurement of the neutrino mass ordering [8].

Data collected with 6 DUs installed in ORCA already provide compelling evidence of neutrino oscillations at 5.9 σ (see Fig. 9). The ORCA6 estimates of oscillation parameters are:

$$\sin^2\theta_{23}=0.51^{+0.06}_{-0.07}\,;\,\Delta m^2_{31}=2.14^{+0.36}_{-0.25}\times 10^{-3}eV^2$$

with a mild preference for normal mass ordering: $2\log\left(L_{NO}/L_{IO}\right)=0.9$.

More statistics is already available and the related analysis is underway. Few years' data will be sufficient to discriminate the mass ordering at 4σ or better with favourable mixing angles (e.g. $\theta_{23}=48.6\,°$).

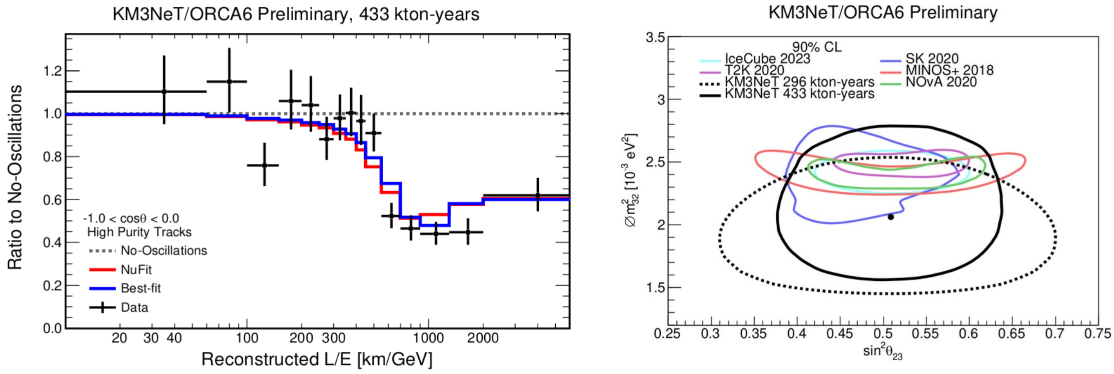

Figure 9. Neutrino oscillations measured by ORCA [9].

ORCA data are being used to unveil possible evidence of Non-Standard-Interactions. [10]. In a simple model, the effective Hamiltonian can be cast in the shape:

$$H_{eff}=\frac{1}{2E}U\begin{bmatrix}0 & 0 & 0\\ 0 & \Delta m_{21}^2 & 0\\ 0 & 0 & \Delta m_{31}^2\end{bmatrix}U^{+}+$$

$$+\sqrt{2}G_F n_e(x)\begin{bmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon_{e\tau} & \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau}\end{bmatrix}$$

The upper limits obtained for one combination of these interaction parameters are shown in Fig. 10.

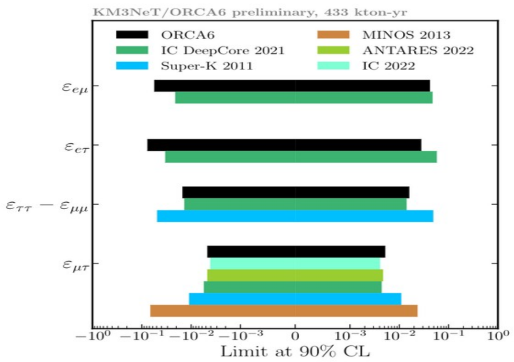

Figure 10. Upper limits obtained for a combination of Non-Standard-Interactions of neutrinos using ORCA 6

ORCA is also looking for signals of directionally correlated neutrino production by WIMPs (Weakly Interacting Massive Particles), accumulating around the Sun or around the centre of the Milky Way, and annihilating to several channels ($\mu^+\mu^-$, $\tau^+\tau^-$, b^+b^-, W^+W^-, $\nu_\mu\ \overline{\nu}_\mu$). So far, upper limits on such phenomenology, separately for each annihilation channel have been established, as shown in Fig. 11.

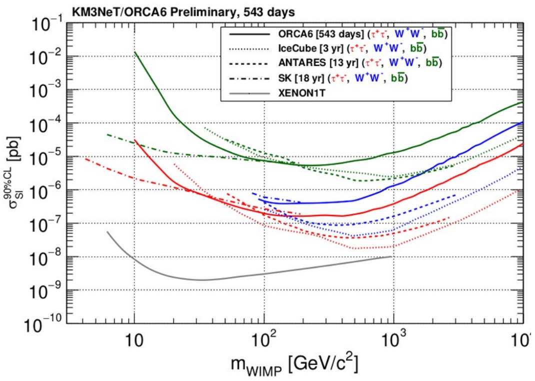

Figure 11: Dark Matter search in ORCA. Upper limits compared to other experiments.

5. ARCA/ORCA combined searches

ARCA and ORCA are following up alerts from other neutrino telescopes, gamma-ray bursts, transients and gravitational waves. This research program exploits both offline searches and a complex online alert and processing system. No relevant signal has been detected so far by KM3NeT [11].

Most supernova neutrinos have relatively low energies, with the emission spectrum peaking around 10 MeV and with tails between 20 and 40 MeV. They are unlikely to be detected as complex events in ARCA or ORCA. However, a single DOM is already a supernova detector, thanks to the directional information provided by the photomultipliers it contains. Discrimination of supernova neutrino signals over the background of ambient radioactivity and atmospheric muons is obtained by combining the average direction, signal concentration, multiplicity and signal intensity [12] (via Time-over-Threshold of the photomultipliers). Fig. 12 shows the expected performances in a configuration of telescopes that can be reached in about one year from the present paper, namely ARCA29+ORCA24.

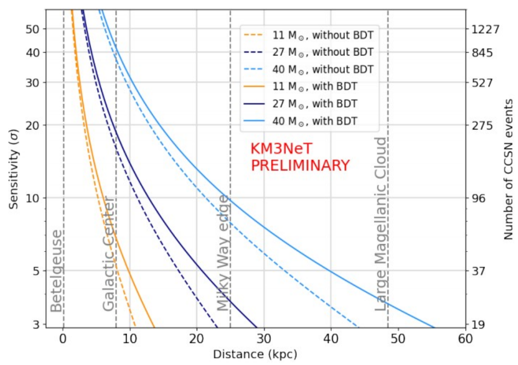

Figure 12. Supernova detection capabilities with ARCA29 + ORCA24.

6. Conclusions

The KM3NeT neutrino telescopes are under steady construction and first analyses have already been performed with partial configurations of both ARCA and ORCA. The technology of KM3NeT has proved to be effective and the telescopes, while in preliminary shapes, are already providing interesting physics and astronomy measurements, in some cases already competitive with established detectors. Scientifically fruitful results are within reach in the next years.

References

[1] S. Aiello et al. (KM3NeT Collab.), doi:10.1016/j.astropartphys.2019.04.002

[2] S. Aiello et al. (KM3NeT Collab.), doi:10.1140/epjc/s10052-021-09893-0

[3] S. Aiello et al. (KM3NeT Collab.), doi:10.1140/epjc/s10052-020-7629-z

[4] S. I. Klimushin, E. V. Bugaev, and I. A. Sokalski, doi:10.1103/PhysRevD.64.014016

[5] S. Aiello et al. (KM3NeT Collab.), doi:10.1140/epjc/s10052-023-11401-5

[6] R. Muller et al. (KM3NeT Collab.), PoS(ICRC2023)1018

[7] V. Tsourapis et al. (KM3NeT Collab.), PoS(ICRC2023)1195

[8] V. Carretero (KM3NeT Collab.), PoS(ICRC2023)996

[9] S. Aiello et al. (KM3NeT Collab.), doi:10.1140/epjc/s10052-021-09893-0

[10] A. Lazo Pedrajas (KM3NeT Collab.), PoS(ICRC2023)998

[11] J. Palacios Gonzalez et al. (KM3NeT Collab.), PoS(ICRC2023)1521

[12] S. Aiello et al. (KM3NeT Collab.), doi:10.1140/epjc/s10052-021-09187-5