KM3NeT/ARCA: status of construction and recent physics results

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Abstract. KM3NeT is a multi-site detector devoted to the detection and study of cosmic neutrinos and their sources in the Universe, and to the measurement of the neutrino oscillation parameters. Two underwater detectors are under construction in the Mediterranean Sea, ARCA (Portopalo di Capo Passero, Italy) and ORCA (Toulon, France), optimised respectively for neutrinos in the energy range of 1 TeV–100 PeV and 10 GeV–10 TeV. The mass construction of the detectors has started, and a long-term plan for the completion is in place. At the time of writing this article, 21 (14) detection units are already in operation in the ARCA (ORCA) site from a total of 230 (115). In these proceedings, the major milestones achieved for the construction of the ARCA telescope are discussed. The main physics results obtained with ARCA, in its partial configurations are reported. Finally, an overview of the expected performances of the full detectors will be given.

1 Introduction

Neutrino astronomy is nowadays a well-defined field in astroparticle physics. There are strong expectations around the neutrino experiments which are optimised to detect particles with high energies, $E_\nu > 1$ TeV. Given their neutral electrical charge, neutrinos are not deflected by interstellar magnetic fields but point back to their sources, allowing to identify and study the emitting astrophysical objects using neutrinos as a probe. The cosmic ray energy spectrum has been measured up to energies of 10^{20} eV, however the nature and position in the Universe of the cosmic ray accelerators are still unknown. Recently [1], the IceCube Collaboration published an improved analysis of 10 years of data, reporting the evidence for neutrino emission from the barred spiral galaxy NGC 1068, also known as Messier 77. This is the second neutrino source reported by IceCube after the blazar TXS 0506+056, which was previously identified using a multimessenger approach [2]. The detection of cosmic neutrinos has been interpreted as the "smoking gun" that hadronic processes contribute directly to the cosmic ray acceleration.

Multimessenger astronomy has started to play an emerging role in astroparticle studies. The possibility of joint detections using different mediators, like photons, gravitational waves, high energy cosmic rays, and neutrinos, has already opened new perspectives in cosmic and astronomical studies [3].

In this exciting context, it is urgent to enlarge the network of neutrino detectors to investigate more deeply the reported evidence for cosmic neutrinos. The KM3NeT Collaboration

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wants to play an important role in this endeavour and is currently focusing its activities on the construction of two big underwater neutrino detectors, in the Mediterranean Sea. The ARCA telescope (Astroparticle Research with Cosmics in the Abyss) is designed to detect cosmic neutrinos in the energy range 1 TeV−10 PeV. ARCA is currently under construction at 3500 m depth, 80 km South-East the Sicilian coasts of Portopalo di Capo Passero, Italy. The ORCA detector (Oscillation Research with Cosmics in the Abyss) is optimised to determine the neutrino oscillation parameters, through the detection of atmospheric neutrinos in the energy range 10 GeV−10 TeV. The ORCA site is located 40 km from the French coasts near Toulon, at a depth of 2500 m. These proceedings are focused on ARCA; more details about ORCA can be found in [4–6].

There are three main channels that neutrino telescopes exploit for event selection. The first one is the search for a diffuse cosmic neutrino flux. Neutrino events are collected without any assumption on their directions; an excess of events above the atmospheric neutrino flux is searched for energies higher than $\sim$ 50 TeV [7]. The second channel is the search for point-like neutrino sources in the sky. In this case, a statistical accumulation of events around well-defined positions is expected in the sky map [8]. Finally, a multi-messenger approach can be applied to neutrino studies searching for space-time coincidences with the signals reported by other telescopes even using different cosmic probes.

2 The ARCA neutrino telescope

The detection principle of the KM3NeT detectors exploits the Cherenkov light induced by secondary charged particles generated by neutrino interactions inside or in the vicinity of the telescope. A three-dimensional array of photomultiplier tubes (PMTs), which are the sensitive elements of the detector, are distributed in a large volume of a transparent medium like seawater. Deep seawater has the advantage of small light scattering, which improves the angular resolution of the telescope. The main sources of optical background are the decay of ^{40}K in marine water and the bioluminescence, but considering the different energies that characterise these events with respect to the cosmic neutrinos, this background can be easily taken under control. Being located in the Northern Hemisphere, ARCA provides a complementary view to IceCube (located at the South Pole). In addition, the presence of the Galactic Centre in its field of view will open an observative window on a possible population of Galactic sources.

2.1 The seafloor network

The layout of ARCA is shown in Fig. 1 left. Two main electro-optical cables (MEOC in the picture) provide connectivity and power to the offshore infrastructure. These two MEOCs are 100 km long and are connected to the onshore infrastructure, which allocates the power-feeding equipment and the data centre for detector control and data acquisition. The first MEOC embeds a set of 20 optical fibres to establish a data connection between the seafloor network and the shore station. At the submerged end of this MEOC, a primary node (CTF-1) is installed, which hosts a 10 kW medium voltage converter, and 5 electro-optical output ports. The primary node feeds the so-called Phase-1, see Fig. 1 right, via three secondary nodes called Junction Boxes (JB).

The second MEOC embeds a set of 48 optical fibres; two of these fibres are control lines dedicated to the power system. The cable end is split into two secondary branches through a Y-node. The first branch allocates 22 optical fibres and is terminated with a primary node (CTF-2) designed to power the so-called Phase-2. The CTF-2 was installed on the seafloor

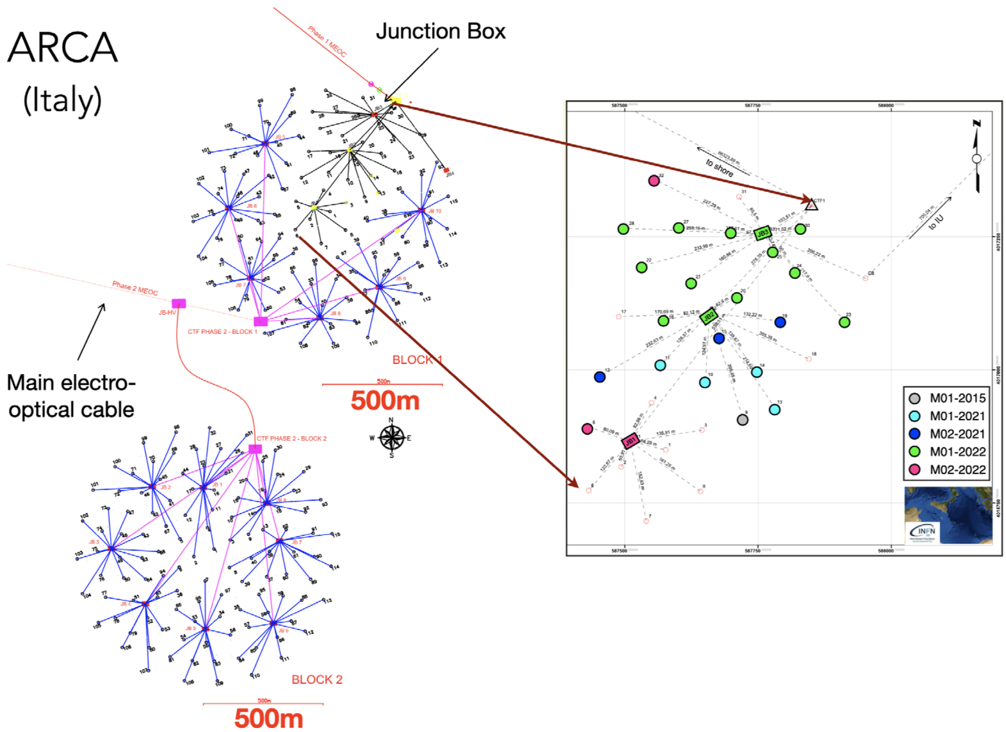

Figure 1. Left: Layout of the completed ARCA detector. Two building blocks of 115 detection units are connected to shore via a network of submarine electro-optical cables and Junction Boxes. Two main electro-optical cables are installed on the seafloor and connected to the onshore laboratory, for power feeding and data acquisition. Right: A zoom of the so-called ARCA Phase-1. The installed detection units (Junction Boxes) are indicated with a coloured circle (rectangle). The colour scheme follows the sequence of marine campaigns indicated by a progressive number and the year.

on November 2022. The remaining 44 fibres are embedded in the second branch, which currently is not equipped at its end with any active termination. The procedure for purchase, construction and installation of the CTF-3 is starting at the time of writing this paper. By design, the CTF-2 will be connected with six JBs, while the CTF-3 will allow for connecting eight JBs. The three CTFs will allow for power and control of the full detector.

2.2 The Junction Box

The ARCA Junction Box has been designed and built to distribute electrical power and an optical fibre channel to the active elements of the detector, which host the PMTs. Its technology was developed by KM3NeT members in synergy with external companies from oil&gas. The goal of the entire JB project was focused on the top-level quality to operate at 3500 m depth during an estimated lifetime of 20 years without any maintenance [9]. The block diagram of the JB is presented in Fig. 2 left. The main core of the JB is the Optical and Power Assembly (OPA), an ensemble of electronics and optical components dedicated to:

- provide power to the various elements of the JB itself;
- provide power to the output ports for the elements of the ARCA telescope;

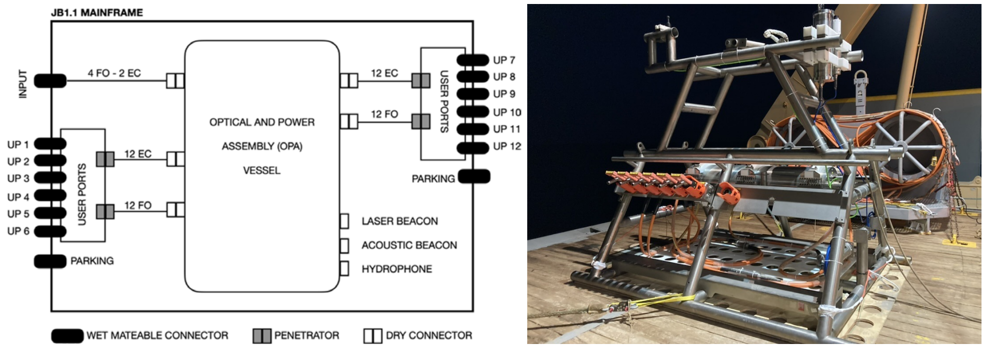

Figure 2. Left: The block diagram of the ARCA Junction Box. A titanium mainframe hosts all the instrumentation and connectors. To improve reliability, the number of connections in water is minimised. The sub-systems, the control and power electronics plus the optical circuits are fully contained in a unique cylinder with a volume of about 100 litres. Right: A JB ready for deployment during a sea campaign. The ROV mateable connectors (in orange) are visible in the front panel; they provide input and output connectivity underwater.

- control and amplification of the optical signal received/sent from/to shore;
- receive the data flow from the telescope and transmit it to shore;
- operate the various instruments mounted on the JB.

The electro-optical system has been designed with all functions intrinsically redundant, where components are duplicated in case of breaking. The electronics boards have been produced with high-reliability components like space, defence or automotive grade.

The electronics is allocated inside a pressure vessel made of titanium grade 2, typically used in this deep-underwater applications. The connectivity with the external world is provided through titanium components produced with high-reliability standards. Dedicated ROV (Remotely Operated Vehicle) mateable connectors[1] are mounted on the mechanical structure of the JB and used as external user ports (Fig. 2 right). The connection to the detection units of the telescope is provided via interlink cables, oil-filled to compensate for the external pressure.

2.3 The detection unit

The detection unit (DU) is the active part of the neutrino detector. It is a vertical structure anchored on the seabed and kept vertical by the buoyancy of its elements. In the ARCA configuration, the DU is 700 m height and hosts 18 Digital Optical Modules (DOMs) [10] with an interspace of 36 m between them. The DU base is a mechanical structure that lies on the seafloor and is equipped with the electronics needed to power and control the DOMs. Two thin Dyneema® ropes are firmly connected to the base and are used to keep the 18 DOMs in place. A thin backbone tube equipped with optical fibres and copper wires for data and power transmission, respectively, runs along the full length of the mooring.

To allow safe transportation and deployment, the DU is folded around a dedicated spherical vehicle at the end of its integration process [11]. Later, the DU is deployed from a boat on the seabed using this spherical structure, as can be seen in Fig. 3. With a precision of about

[1]For this application, we use the Teledyne ODI Nautilus Rolling seal Hybrid (NRH) connectors, see http://www.teledynemarine.com/odi/.

Figure 3. A detection unit enters into the sea. It will go down 3500 m and be deployed on the seafloor. Using a ROV it will be connected to a Junction Box through an electro-optical cable. Finally, the unfurling of the spherical structure will be triggered and the DU will get its final vertical position.

1 m, the DU is placed on the seafloor using an acoustic positioning system. With the support of an ROV, the DU is connected through the interlink to the seafloor network. Once having passed a complete system check performed from shore, the ROV triggers the unfurling mechanism of the vehicle. At the end of this process, the DU gets its final vertical position and the launcher vehicle is finally recovered on the sea surface to be reused.

The sensitive element of the telescope is the Digital Optical Module, a 0.44 m diameter pressure-resistant glass sphere which contains 31 3 inches photomultiplier tubes [12]. The DOM also hosts calibration devices and electronic boards for power, readout and data acquisition [13]. The implemented technology allows for sub-nanosecond timing accuracy of the PMT signal. The dynamic range spans from the single photon up to a cascade of thousands of photons, providing additional information useful for the reconstruction of the energy of the event. Given the presence of 31 PMTs, the DOM has an angular acceptance close to 4π, and can provide a better measurement of the photon direction for neutrino track reconstruction.

The current configuration of ARCA is shown in Fig. 1 right: 21 detection units are in place and taking data. Typically, two sea campaigns per year are organised. The mass production of the detector started in 2021, once the main technical issues were addressed and solved. In Fig. 4, the timeline of the construction of ARCA is reported. The first DU was installed in December 2015; it is still in operation and taking data. Data taking was put on hold during two periods, the former related to an electrical problem with the seabed infrastructure and the latter due to a major upgrade of the shore station. The issues with the infrastructure were solved with a new design of the Junction Box, see Sect. 2.2.

3 Some selected results

3.1 Neutrino point source search

The first analysis [14] devoted to the search for point-like neutrino sources is performed on a data sample equivalent to 92 days of operation, taken with ARCA in a six-line configura-

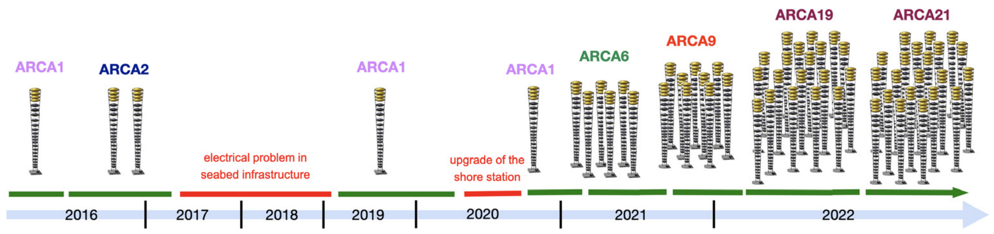

Figure 4. The ARCA detector is growing following the integration activities of the various elements, that are deployed during dedicated marine campaigns. Typically, two campaigns per year are performed, avoiding the winter period. Even if in partial configuration, ARCA is continuously taking data. Two long shutdown periods are reported in red: the first due to an electrical issue in the seabed infrastructure that was fixed with a complete redesign of the Junction Boxes, and the second related to a major upgrade of the shore station which was enlarged to support the full detector with two building blocks.

tion. The neutrino emission is searched among 40 candidate point sources plus 6 extended sources; the 46 candidates are reported on a sky map in Fig. 5 left. A binned likelihood search is applied to the data set corresponding to the period between May and September 2021. Background-only and signal+background samples are built from scrambled real data and Monte Carlo simulations. The neutrino signal is generated with an E^{-2} energy spectrum in a 5° cone around the source.

The most significant source corresponding to the lowest p-value (0.02) is the radio galaxy Centaurus A (RA= 201.36, δ = −43.01), for which 2.6 signal events are fitted. The source is indicated in Fig. 5 left with a yellow arrow. The p-value of ∼ 2% is compatible with the expectation from the pure background hypothesis. Upper limits on the neutrino fluxes for the 46 candidates are evaluated and reported as blue points in Fig. 5 right, together with the ARCA 6-line sensitivity. As a comparison, the ANTARES and IceCube sensitivities are also reported, together with the full ARCA detector expected sensitivity.

3.2 Full detector performances

The complete ARCA detector will be composed of 230 detection units, distributed in two building blocks of 115 DUs each. Dedicated algorithms have been developed in order to reconstruct the neutrino direction and energy. The information of the time and charge of the signal collected by the PMTs is used as an input of these algorithms, together with the real-time position of the PMTs triangulated with an acoustic positioning system.

The neutrino events can be classified into two main topologies: track-like and shower-like events. Track-like events are generated by charge current interactions of ν_μ and are the ideal tool for astronomy, as the secondary muon can travel several kilometres in rock and seawater producing a clean Cherenkov light cone. The angular resolution of ARCA is expected to be better than 0.2° at energies above 10 TeV (Fig. 6 left). For the same events the energy resolution, evaluated as the FWHM of the $\log_{10}(E_{reco}/E_\mu)$ distribution, will be ∼ 0.25.

The shower-like events are produced by neutral current interactions of ν of any flavour, plus charge current interactions of ν_e and ν_τ. In this case, events are typically contained within the detector active volume, hence the energy resolution is improved with respect to track-like events being at the level of 5%. On the other hand, the angular resolution in the same energy region is expected to be ∼ 2°, which is worse than for track-like events.

Another important physics goal of KM3NeT is the detection of supernova neutrinos. The KM3NeT telescope sensitivity to Galactic supernovae and its associated online alert system

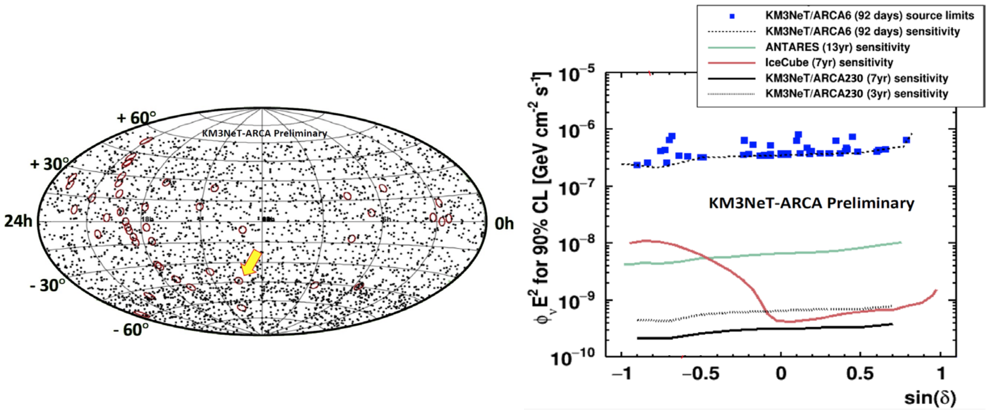

Figure 5. Left: The neutrino sky map of the ARCA 6-line detector with candidate sources indicated with red circles. The yellow arrow points to the source with the best p-value, see text. Right: Upper limits on the cosmic neutrino flux for the candidate sources are reported as blue points. The ARCA sensitivity is displayed as a dashed line and compared to ANTARES and IceCube sensitivities.

for multi-messenger studies was presented during the conference, see [15]. From the time profile of the associated neutrino emission, it will be possible to derive the supernova time-evolution and improve the models that explain how these objects work.

Also at this conference, the analysis of the search for starburst galaxies using the full ARCA detector was presented, see [16]. Using a point-like search approach, the most promising local starburst galaxies are selected and the expected sensitivity of the full ARCA detector to observe point-like neutrino excesses is evaluated. ARCA will have the power to constrain several phenomenological scenarios, providing evidence of the link between star-forming processes and hadronic emissions.

4 The next future

The KM3NeT Collaboration has started the mass construction of ARCA. The integration capability of the various elements of the detector has improved, and a distributed production model has been implemented for the delivery of the full detector, which will be composed of two building blocks in 2030. The KM3NeT Collaboration has currently collected the funds required to complete the first building block and start the construction of the second one. These funds will allow to build ∼130 detection units, the related seafloor infrastructure, and the onshore lab facilities. In the meantime, data will be analysed with the detector in partial configurations, waiting for the final completion.

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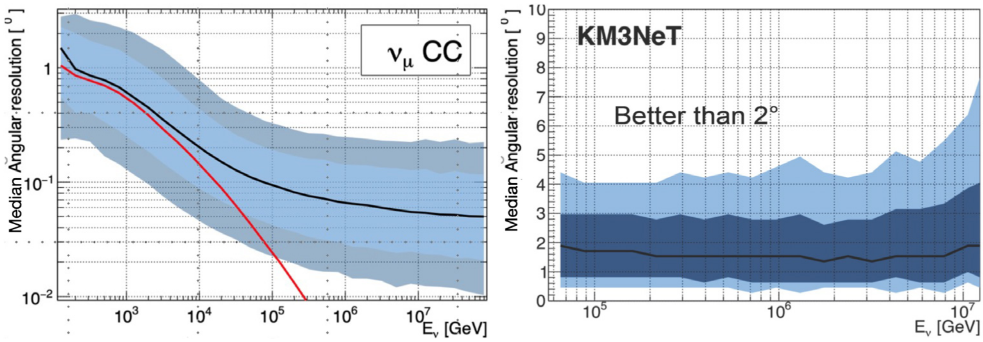

Figure 6. Left: Median angular resolution of the full ARCA detector as a function of the neutrino energy for track-like events. Shadowed areas represent the 50 and 90 percentile. The red line is the angle between the ν_μ and the secondary μ. Right: Median angular resolution of the full ARCA detector as a function of the neutrino energy for shower-like events.

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