ANTARES and KM3NeT Overview

Sara Rebecca Gozzini, on behalf of the ANTARES and KM3NeT collaborations

Erlangen Center for Astroparticle Physics, Erwin Rommel Strasse 1, 91058 Erlangen Germany

Abstract

The ANTARES underwater neutrino telescope has been operating for more than twelve years with a successful and wide physics program, which will be broadened by the KM3NeT infrastructure, currently under construction in the Mediterranean Sea. The two configurations of KM3NeT, ARCA offshore Sicily (IT) and ORCA offshore Toulon (FR), will investigate the high-energy astrophysical neutrino landscape, and perform precision measurements of oscillation parameters with atmospheric neutrinos. ARCA is designed to have excellent angular resolution and a very large volume, instrumenting 1 km^3 of water. ORCA is optimised for detection in the $\gtrsim$ 3 GeV energy range with a dense geometry. The two detectors share the same technology and data access philosophy, being modular units of a unique infrastructure. Results and perspectives in neutrino astrophysics searches (steady and transient sources, multimessenger programs and diffuse astrophysical neutrino fluxes), in neutrino oscillation research, in indirect dark matter detection, and in sea and Earth science will be presented.

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1. ANTARES AND KM3NET

ANTARES is an underwater Cherenkov detector situated in the Mediterranean Sea 40 km offshore from Toulon. It is composed of 12 detection lines instrumented with photomultiplier cameras [1]. These measure light emitted from charged particles and allow for an energy and directional reconstruction of their arrival direction. A small fraction of these particles originates from a neutrino interaction occurring in the vicinity of the detector. The very large background of downgoing muons produced in atmospheric interactions of cosmic rays is avoided by considering events with arrival directions crossing the Earth. ANTARES has successfully operated for more than 12 years, motivating the expansion realised through the KM3NeT European research infrastructure, composed of a network of underwater neutrino telescopes in the Mediterranean Sea [2]. The KM3NeT detectors currently under construction consist of three building blocks: one compact detector for atmospheric physics studies (ORCA), in deployment close to the ANTARES site, and two large-volume detectors aimed at catching astrophysical neutrino fluxes (ARCA), in deployment offshore the coast of Sicily. Each of these building blocks will consist of 115 detection lines, with the same geometry but different spacing (see Figure 1).

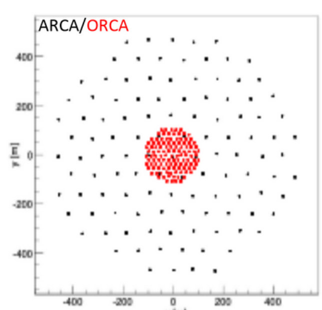

FIGURE 1: Layout of the KM3NeT building block. Inter-string spacing: ORCA: 23 m, ARCA: 90 m. Inter-DOM spacing: ORCA: 9 m, ARCA: 36 m.

2. KM3NET FIRST DATA

The 6 deployed detection lines of ORCA and 1 detection line of ARCA have already provided good quality data [3]. The atmospheric muon rate measured as the function of the depth is well fitting the model [4]. Candidate neutrino events are isolated requiring their arrival direction to come from across the Earth. An upgoing neutrino event seen by photomultipliers of 2 detection lines is shown in Figure 2.

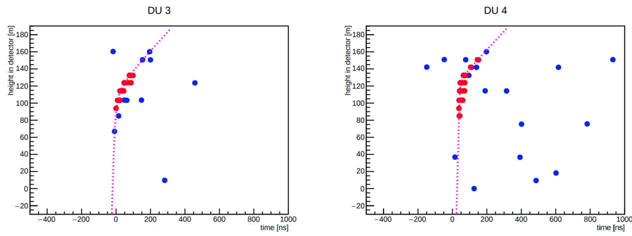

FIGURE 2: Height versus time in the detector for one of the selected neutrino candidates detected with 2 lines of ORCA [3].

3. OVERVIEW OF MAIN RESULTS

3.1. Neutrino Astronomy

One of the main challenges for ANTARES is the measurement of neutrinos of extraterrestrial origin. The large-volume building blocks of KM3NeT are designed to largely improve the sensitivity to high-energy neutrino fluxes. These telescopes run different search programs in this context:

1. Search for a diffuse high-energy excess in the neutrino spectrum
2. Search for clusters in space- and or time (autocorrelation)
3. Search for correlation with underlying catalogue of preselected astronomical objects
4. Multi-messenger prompt search relying on quick exchange in a network of instruments, looking for transient phenomena

ANTARES measures a 1.8 σ excess in the high-energy region over the diffuse atmospheric neutrino flux. The excess is due to 50 events observed (27 ν_μ + 23 ν_e), with 36±8 expected from background, over a lifetime of 3380 days (Figure 3). Such a measurement permits to perform a best likelihood fit of the normalization and spectral index of this diffuse cosmic flux, yielding $\Phi_0^{1f}(100TeV) = (1.5 \pm 1.0) \times 10^{-8} GeV^{-1} cm^{-2} s^{-1} sr^{-1}$ with spectral index $\Gamma = 2.3^{+0.4}_{-0.4}$ [5]. The astrophysical flux reported by IceCube [6] can be seen by KM3NeT-ARCA with 5σ median significance after one year of operation (Figure 4).

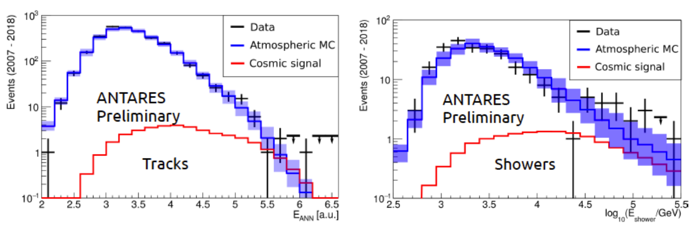

FIGURE 3: Reconstructed energy distributions for ν_μ (left) and ν_e (right) events, as black markers. The blue line represents the expected atmospheric flux from a Monte Carlo simulation. In red is the prediction for cosmic neurino flux.

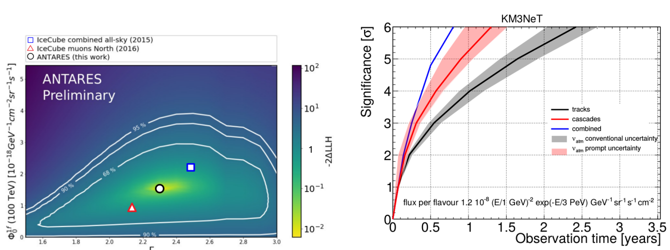

FIGURE 4: Left: Best likelihood fit of the diffuse cosmic flux normalization and spectral index [5]. Right: Significance reached with KM3NeT to IceCube flux benchmark [2].

No source has been identified so far in a data set counting 3136 days of lifetime (over 11 years), for a total of 8754 ν_μ and 195 ν_e events, when scanning the full-sky distribution of their arrival directions in $1^\circ \times 1^\circ$ steps (top panel of Figure 5). Similarly, no correlation has been found matching the same data set with an underlying catalogue including both interesting astrophysical sources and IceCube events [7], as shown in the bottom panel of Figure 5. A dedicated search has been conducted in the direction of the recent neutrino source reported by IceCube [8], showing no counterpart in ANTARES [9].

KM3NeT will largely contribute to the identification of an astrophysical neutrino signal. Its all-sky sensitivity will reach the current world-best with 6 years of operation. For the strongest Galactic sources, a high-energy neutrino flux could be detected with 3σ significance in less than one year [11] (Figure 6).

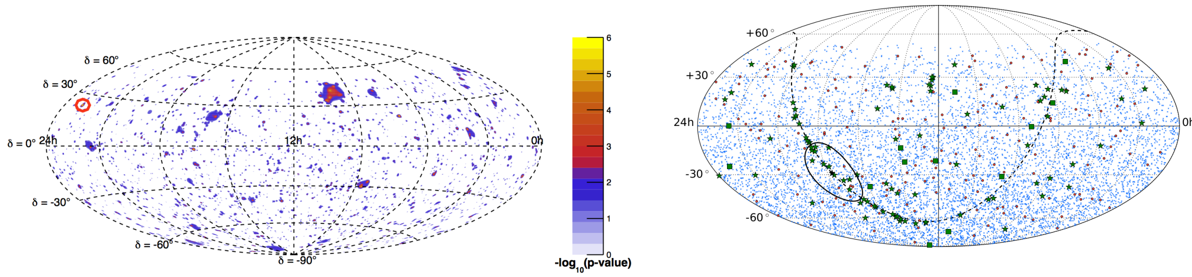

FIGURE 5: Top: Pre-trial $p - value$ map for a point-like source of the ANTARES visible sky. The red circle indicates the location of the most significant cluster at (RA, δ) = (343.7°, 23.6°). Bottom: catalogue-based search. Blue dots: ANTARES ν_μ events. Red dots: ANTARES ν_e events. Stars: 112 preselected source candidates. Squares: 54 IceCube HESE events [7].

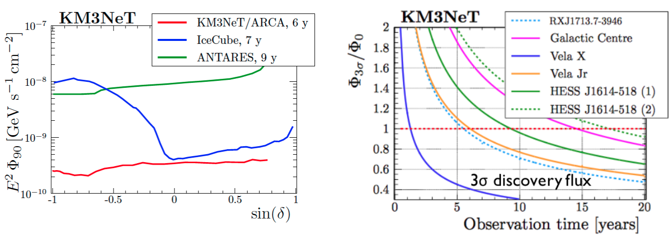

FIGURE 6: Left: Sensitivity as a function of sky declination for 6 years of KM3NeT operation (red line) compared with 9 years of ANTARES (green) and 7 years of IceCube (blue). Right: Discovery fluxes for selected Galactic sources, assuming spectrum from γ-ray measurement and fully hadronic scenario [10].

3.2. Multi-Messenger Program

Multi-messenger astronomy has proven itself essential in the connection of interesting neutrino events with transient astrophysical phenomena. ANTARES participates in a network for quick exchange of *alerts* (space/time correlation) between optical, X-ray, radio, γ ray and gravitational wave instruments:

1. Reception of GCN notices (γ-ray coordination network)
2. Processing online reconstruction within a few seconds
3. Sending out alerts to partners in network

KM3NeT will have large impact on the multi-messenger prompt alert system [10], including a search for neutrinos in coincidence with gravitational wave events, similarly to the current ANTARES follow-up program [12].

3.3. Indirect Search for Dark Matter

Neutrino detectors are versatile instruments and have a very wide physics program, which includes the possibility to search for particles outside the Standard Model. Dark matter messengers such as neutrinos, produced either as primary or as secondary products of a WIMP pair annihilation, are searched through different channels in the direction of potential sources such as the Galactic Centre or the Sun. The limits derived from searching a Galactic Centre excess in 11 years of data recorded by ANTARES is shown in Figure 7, together with an estimate of KM3NeT sensitivity to WIMP pair annihilation.

3.4. Measurement of Neutrino Oscillation Parameters

Atmospheric neutrinos, which are regularly measured with ANTARES and KM3NeT, come in large majority from the decay of charged pions, resulting in a flavour ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ at production. This ratio is affected by flavour oscillation occurring between production and detection site, resulting in a suppression of vertical upgoing ν_μ crossing the Earth. The oscillation parameter $\theta_{23} : \Delta m^2_{23}$ is measured in ANTARES data through ν_μ disappearance, from an energy threshold of about 20 GeV, that permits to be sensitive to the first atmospheric oscillation minimum. Assuming maximum mixing, a mass difference of $\Delta m^2_{32} = (3.1 \pm 0.9) \cdot 10^{-3}$ eV^2 is obtained, in good agreement with the world average value [14]. This threshold will go as low as 3 GeV for ORCA, whose sensitivity to θ_{23} / Δm^2_{23} is shown in Figure 8.

3.5. Neutrino Mass Ordering

The measurement of the neutrino mass ordering is one of the primary goals of KM3NeT. It is realised thanks to matter effects on atmospheric neutrinos crossing the Earth which creates a resonance in the oscillation probabilities at energies around 2-8 GeV. Indicator parameter is the number of atmospheric neutrino events measured for several energies and baselines (represented on

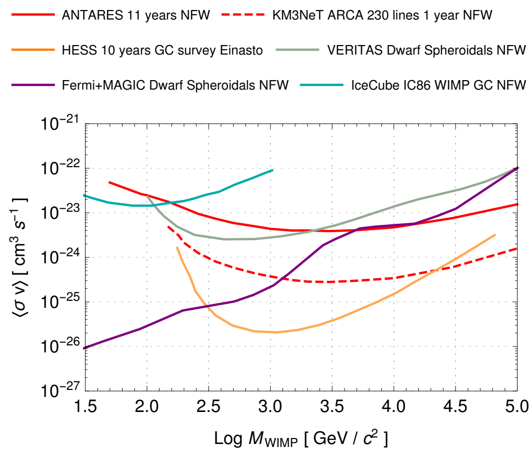

FIGURE 7: Upper limits at 90% C.L. on the thermally averaged cross-section for WIMP pair annihilation set with 11 years of ANTARES data, and sensitivity for 1 year of KM3NeT-ARCA 230 lines for the WIMP WIMP $\rightarrow \tau^+\tau^- \rightarrow \nu_\mu \bar{\nu}_\mu$ channel [13].

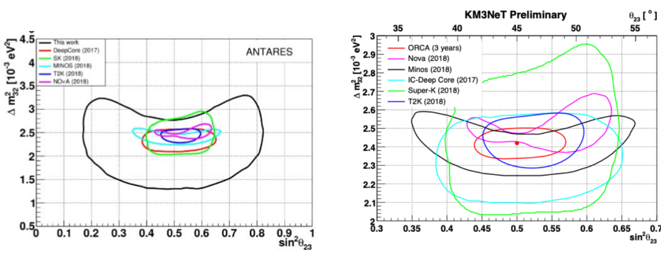

FIGURE 8: Measurement of oscillation parameters with 10 years of ANTARES (left) and sensitivity for 3 years of ORCA (right).

the axes in Figure 9 as Reco E and Reco $\cos\theta_z$, respectively). This is compared with the number of expected events for normal or inverted ordering using $\Delta\chi^2$ statistics, as shown in Figure 9. The sensitivity to this measurement relies on the $\nu\bar{\nu}$ asymmetry that affects flux and cross-section in the GeV energy range. KM3NeT-ORCA might be able to unravel netrino mass ordering with 3σ significance after 3 years of data taking [11].

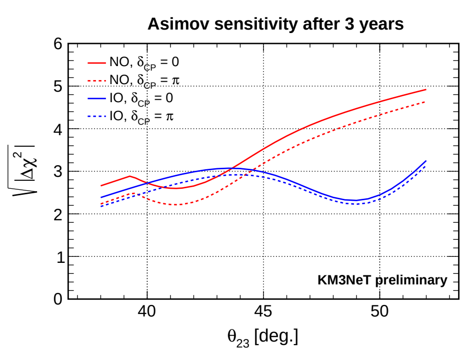

FIGURE 9: Sensitivity to the neutrino mass ordering with 3 years of KM3NeT-ORCA.

4. CONCLUSIONS

The ANTARES telescope has been smoothly and succesfully running on long-term, providing a broad range of results, and the first lines of KM3NeT are currently taking data. With the large-volume building blocks of KM3NeT-ARCA, the Northern Hemisphere will be instrumented with a km^3 detector which will bring a fundamental contribution to the measurement of astrophysical ν, complementing the IceCube field of view, as well as to the multi-messenger alert programs. At the same time, KM3NeT-ORCA will measure atmospheric ν with unprecedented statistics opening the way for the measurement of fundamental ν properties, such as oscillations and mass ordering. KM3NeT is a European multidisciplinary infrastructure that will cover also topics outside the strict neutrino physics program, such as marine science and Earth science.

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