Astroparticle and neutrino oscillation research with KM3NeT

V. Kulikovskiy for the KM3NeT collaboration
Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

Summary. — Two next generation underwater neutrino telescopes are under construction in the Mediterranean sea by the KM3NeT collaboration. The first, ORCA, optimised for atmospheric neutrinos detection will be capable to determine the neutrino mass hierarchy with $> 3\ \sigma$ after three years of operation, i.e. as early as 2023. The second, ARCA, is optimised for high energy neutrino astronomy. Its location allows for surveying most of the Galactic Plane, including the Galactic Centre and the most promising source candidates. Neutrino diffuse emission flux measured by the IceCube collaboration can be observed with $5\ \sigma$ in less than one year.

1. – Technology and performance

KM3NeT, located in the abysses of the Mediterranean Sea, is a distributed research infrastructure that will host a high energy neutrino telescope (ARCA), offshore from Capo Passero, and an atmospheric neutrino detector (ORCA), offshore from Toulon in France, for the determination of the neutrino mass hierarchy [1].

The KM3NeT detectors use a new directional optical module (DOM) that hosts thirty one 3-inch PMT. This DOM has a total PMT effective area similar to the ANTARES [2] storey with three 10-inch PMTs. Multi-PMT technology allows better light direction estimation and better optical background suppression by using time coincidence between PMT signals. PMTs and their digitization electronics as well as positioning/calibration instrumentation are stored inside 17-inch glass sphere (the same one that is used to store one ANTARES PMT). This concept allows furling of the detection unit (string with 18 DOMs) for the deployment, which means more units deployment during each marine operation. It is especially important since one detector block should contain 115 detection units.

ARCA has two detector blocks instrumenting about 1 Gt. For events with muon neutrino charge current interaction (track-like events) the neutrino angular resolution is $< 0.2°$ while the muon energy resolution is $< 27\%$. For the other neutrino flavours and neutral current interactions (shower-like events) the angular resolution is $\lesssim 2°$ while neutrino energy resolution is $\sim 5\%$. ORCA detector has one detector block that instruments about 5.7 Mt. Zenith angular resolution is $< 5°$ for $E_\nu > 10$ and ν energy resolution is $< 30\%$ for both event types.

Although being designed for high energy neutrinos, both KM3NeT detectors are sensitive to the prompt MeV neutrinos from the supernova explosions by observing the global light rate increase in the detector. Preliminary studies show coverage for the whole Galaxy thanks to the optical background suppression features of the DOMs.

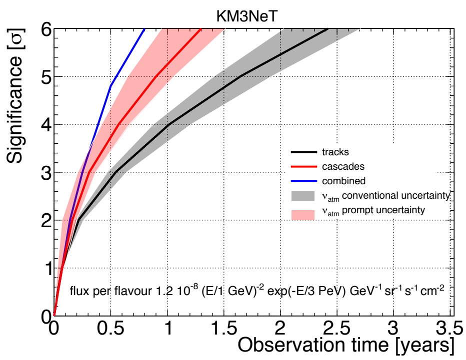
The future KM3NeT participation in multi-messenger programs [3] will exploit the high connection between neutrinos and other cosmic messengers: electromagnetic signals, from X-rays to high energy gamma-rays, charged cosmic rays, gravitational waves.

Both detector sites have the underwater infrastructure ready for the detection units connection. Data taking at ARCA site is ongoing with two detection units already.

2. – ARCA

2·1. *Diffuse flux*. – The discovery of high energy diffuse emission is well established by the IceCube collaboration [4]. Slight differences between the emission spectrum at different latitudes suggest presence of a galactic contribution with a softer spectrum and an extragalactic contribution with a harder spectrum [5]. The ARCA detector has better visibility of the Galactic plane. Together with good angular resolution, both for track and cascade events it makes it the ideal instrument to probe the galactic contribution and to study the source on the southern sky.

The sensitivity of the ARCA detector to the neutrino flux measured by IceCube has been evaluated using both track-like events reconstructed up to 10° above the horizon and cascade-like events in the full angular range. The results of this analysis show that a significance of 5 σ can be reached in less than one year (Figure 1 left).



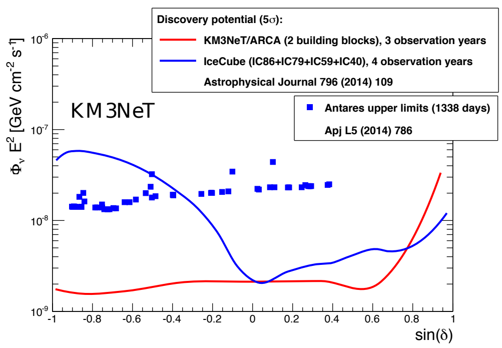


Fig. 1. – Left: Significance as a function of observation time for the diffuse flux of neutrinos measured by IceCube for the cascade channel (red line), muon channel (black line) and combined analysis (blue line). The bands represent the uncertainties due to the conventional and prompt component of the neutrino atmospheric flux. Right: 5 σ discovery potential as a function of the source declination (red line) for one neutrino flavour, for point-like sources with a spectrum $\propto E^{-2}$ (ARCA, IceCube) and upper limits on particular sources for the ANTARES detector.

2·2. *Enhanced diffuse flux regions*. – Study of the enhanced diffuse areas is planned for the Fermi Bubbles and the Galactic Ridge, following the analysis scheme developed and used for the ANTARES data [6, 7]. The limited size of the region allows background measurement in the off regions. Off-zones are defined as fixed regions in equatorial coordinates which have identical size and shape as the on-zone but shifted in right ascension to have no overlap between them. In local coordinates, such off-zones have the same, sidereal-day periodicity as the on-zone and span the same fraction of the sky, but with some fixed delay in time.

At the Galactic plane the neutrinos are expected to be produced in the interactions of the galactic cosmic rays with the interstellar medium and radiation fields. Recent simulations of nonuniform cosmic-ray (CR) transport model with a radially dependent diffusion coefficient are able to explain the high-energy diffuse gamma-ray emission along the whole Galactic plane, as well as the hardening of CR spectra around 250 GeV and two possible CR cut-offs, at 5 PeV and 50 PeV, compatible with observations [8]. The flux predicted by this model in the inner Galactic plane (|latitude| $< 30°$ and |longitude| $< 4°$) can be detected at the level of 5 σ after 5 years.

2˙3. *Point sources.* – For the detection of neutrinos from point-like sources, the most suited are the track-like events thanks to their subdegree angular resolution. Atmospheric muon background should be suppressed. The event selection optimisation was performed for the general point sources with E_ν^{-2} spectrum. For 3 years of ARCA 5 σ discovery potential fluxes are $E^2\Phi \approx 2 \cdot 10^{-9}$ GeV cm^{-2}s^{-1} for sin(declination) < 0.6 (Figure 1 right). This is more than the order of magnitude below the same discovery potential fluxes for IceCube with similar exposure at sin(declination) < -0.2. This difference grows up for the softer neutrino spectrums since the IceCube selection prefers higher event energies to suppress the atmospheric muon background in the Southern hemisphere. At high declinations track analysis looses its sensitivity due to atmospheric muon veto. Cascade events can recover sensitivity in this area. Event selection optimisation including vertex containment inside the detector volume reaches 5 σ discovery potential at the level of $E^2\Phi \leq 5 \cdot 10^{-9}$ GeV cm^{-2}s^{-1} which is rather independent on the declination [1].

The most intense high energy gamma ray sources have been also considered. The super novae remnants (SNR) and in particular young shell-type SNR RXJ1713.7-3946 may be partly responsible for the galactic cosmic rays acceleration. The detected gamma-ray spectrum of SNR RXJ1713 extends up to 100 TeV. The neutrino spectrum used for the sensitivity estimation is derived from gamma-ray spectrum according to [9]. The analysis adapted for the track-like events reaches about 3 σ sensitivity in 4 years.

Recently, a new track reconstruction algorithm was developed. It provides more well reconstructed events and better ν angular resolution: $< 0.1°$ for $E > 100$ TeV and almost reaches the intrinsic angle for $E < 10$ TeV. Also, different multivariate analysis tools are tested to discriminate the signal from two background components (atmospheric ν and μ) which have different energy and angular spectra. In particular, Random Forest algorithm performs well for this task. The first very preliminary results show that observation time may be reduced by one year to reach 3 σ discovery for RXJ1713 [10].

For transient and periodic sources the correlations in space and time between X-ray, optic and high energy gamma-ray telescopes and gravitational waves detectors restricts the background and boosts the sensitivities.

3. – ORCA

3˙1. *Atmospheric neutrino oscillation studies.* – A variety of experiments with solar, atmospheric, reactor and accelerator neutrinos well established mixing of neutrino flavour eigenstates (ν_e, ν_μ, ν_τ) and neutrino states with different masses. These oscillation experiments are not sensitive to the absolute value of neutrino masses but only to the squared-mass splittings. One squared-mass splitting ($\delta m^2 \simeq 7.5 \times 10^{-5}$ eV^2) is provided by the solar and reactor neutrino observation, while the other ($\Delta m^2 \simeq 2.5 \times 10^{-3}$ eV^2) is extracted from the atmospheric neutrino sector. Only two observed mass splittings fit well with the standard scheme with tree mass states. In the so-called normal hierarchy (NH) the smaller mass splitting (δm) is associated with the two smaller mass states separated by bigger (Δm) splitting from the third state, while in the inverted hierarchy (IH) the smallest mass state is separated by bigger splitting (Δm) from the two heavier states. The neutrino mass hierarchy (NMH) determination will be the next milestone for particle physics and cosmology. NMH affects the electron neutrino mass measured in beta decays and the rates of speculative neutrinoless double beta decay. It also serves as an input to cosmological models.

The atmospheric neutrinos of known composition oscillate in the Earth on the way to ORCA. The oscillation probability depends on the azimuth angle that defines the path inside the Earth and the ν energy. The oscillation is different from oscillation in vacuum due to the presence of electrons that distinguish electron neutrinos by additional charged current interaction. The oscillations in matter become dependent on the neutrino hierarchy, which will appear in ORCA data as different patterns in detected ν_e and ν_μ event distributors of zenith angle and energy. At certain energies and angles the relative flux differences between two hierarchies can be as large as 10%; the electron neutrino channel being the most robust against detector resolution effects.

Figure 2 (left) shows the expected performance of ORCA to determine the NMH as a function of the assumed θ_{23} and CP phase. For a true IH the significance is essentially independent of θ_{23}. For a true NH, the significance is bigger for higher θ_{23}. If the current value of θ_{23} from the global fits of around 42° is assumed, ORCA will determine the hierarchy with a median significance of 3 σ in approximately three years. The ORCA data are relatively insensitive to the CP phase, the significance being reduced by at most 20–30% depending on the true value of $\delta_{\rm CP}$. Figure 2 (right), shows the median significance as a function of time for a variety of assumptions. Many of the possible systematic uncertainties (oscillation parameters, CP phase, overall flux factor, NC scaling, ν/anti-ν skew, μ/e skew, energy slope) are actually fitted from the data itself when determining the NMH.

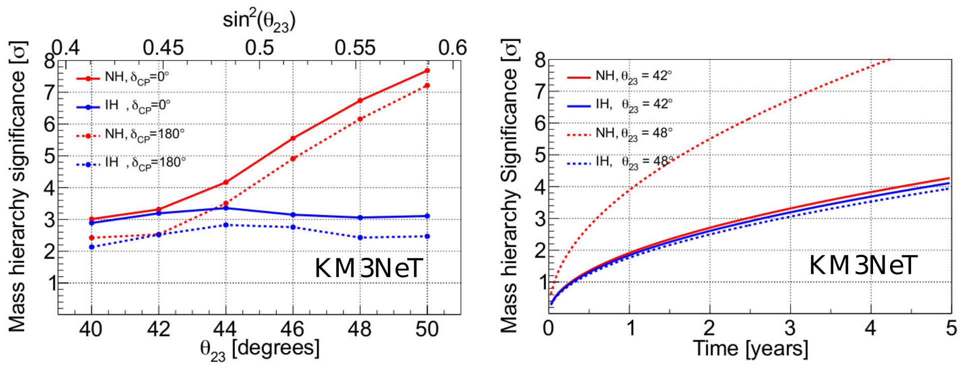


Fig. 2. – The projected NMH sensitivity for a 115 string ORCA detector. (Left) after 3 years, as a function of θ_{23}. (Right) as a function of time for the indicated scenarios.

Three years of data taking with ORCA will provide the new precise measurement of atmospheric neutrino oscillation parameters: $\sin^2\theta_{23}$ with 2–3% uncertainty and Δm^2_{32}

with 4–10%. The unitarity of the mixing matrix can be tested with the ν_τ appearance in the atmospheric neutrino flux. Sterile neutrinos and non standard interactions can be searched with ORCA since their existence would modify significantly the E_ν-azimuth distributions of detected neutrinos. ORCA will also provide tomographic information on the electron density of the Earth's interior. This new technique is complementary to standard geophysical methods that probe mass density.

3·2. *Dark matter*. – Observations in astronomy and cosmology provide irrefutable evidence that the vast majority of the matter in the Universe comprises of gravitationally interacting non-luminous matter which cannot be described with the existing Standard Model. The current abundance of this dark-matter can be explained by its weakly interactive massive particles (WIMP) composition. WIMPs could be captured in the Sun after scattering off nuclei (spin-dependent or spin-independent weakly interaction), accumulate and self-annihilate producing a flux of neutrinos. The neutrino flux depends on the WIMP mass and the decay channels. The decays are assumed with 100% branching ratio to $\tau\bar{\tau}$ or $b\bar{b}$ to estimate optimistic or pessimistic detection scenarios, correspondingly. The sensitivities for scattering cross-section are shown in Figure 3 in comparison with upper limits provided by current experiments [11]. Since the Sun is primarily made of protons, ORCA can place strong constraints on the spin-dependent cross-section.

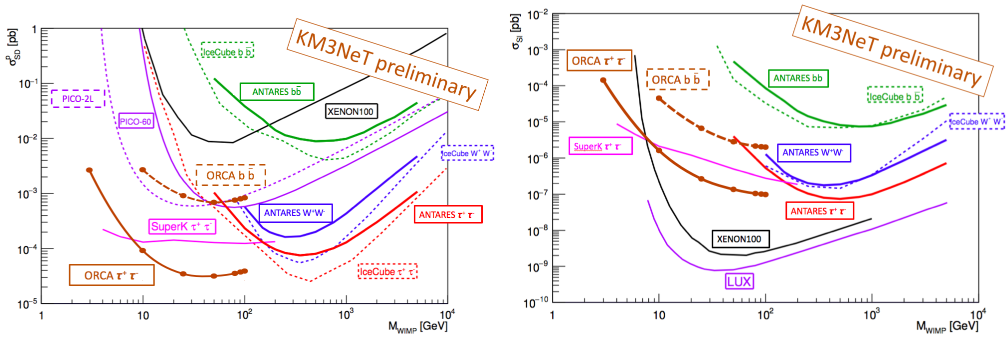


Fig. 3. – 90% C.L. average upper limits on the spin-dependent (left) and spin-independent (right) WIMP-proton cross-section after 3 years of data taking, based on counting both ν_μ and ν_e events coming from the direction of the Sun. Current upper limits are shown for comparison.

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