PROCEEDINGS OF SCIENCE

Search for Sterile Neutrinos with KM3NeT/ORCA and ANTARES

The ANTARES and KM3NeT Collaborations[‡] [*]

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Neutrino Telescopes such as ANTARES and KM3NeT are promising candidates to probe exotic oscillation phenomena such as sterile neutrinos. ANTARES (Astronomy with a Neutrino Telescope and Abyss Environmental RESearch) is the largest deep-sea neutrino telescope in operation, covering an area of 0.01 km^3 and taking data since 2007. KM3NeT in totality is much more extended than ANTARES and it is under construction in the Mediterranean Sea. When completed, it will consist of two separate detectors: ARCA (Astroparticle Research with Cosmics in the Abyss), optimised for high-energy neutrino astronomy, and ORCA (Oscillation Research with Cosmics in the Abyss) for neutrino oscillation studies with atmospheric neutrinos. ORCA will have an effective mass of 8 Mtons and a low neutrino energy detection threshold of 1 GeV. For this reason it is a promising candidate to study neutrinos properties. Here we present the upper limits from ANTARES and sensitivities of ORCA to sterile neutrinos in the (3+1) model.

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36th International Cosmic Ray Conference -ICRC2019-
July 24th - August 1st, 2019
Madison, WI, U.S.A.

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1. Introduction

Decades of studies have produced a vast number of results in neutrino physics and astrophysics, most of which are in perfect agreement with only three active neutrinos. Few experimental results present instead some tensions with the framework provided by the standard model, which can be explained with the introduction of light sterile neutrinos, with a mass of ~ 1 eV. Investigating the origin of these anomalies is a top priority in neutrinos physics and the multi-potential of neutrino telescopes can be exploited for this purpose. The ANTARES neutrino telescope [1] has been designed and optimised for the exploration of the high-energy Universe by using neutrinos as cosmic probes. However, its energy threshold of about 20 GeV is sufficient to be sensitive to distortions in the atmospheric neutrino oscillation pattern in the presence of light sterile neutrinos. In the near future, KM3NeT/ORCA which is under construction in the Mediterranean sea, will have an even lower energy threshold, around 1 GeV, which will enable a more precise measurement of the atmospheric neutrino oscillation pattern, significantly enhancing the sensitivity to any sterile neutrino effects. For a detailed description of the analysis made by ANTARES we refer to [2]. In this proceeding we will mainly focus on the details of KM3NeT/ORCA.

2. The ANTARES and KM3NeT/ORCA Detectors

ANTARES is a deep-water neutrino telescope located at a depth of 2400 m in the Mediterranean Sea, 40 km off the coast of Toulon (France). The basic building blocks of the detector are the Optical Modules (OMs). Each OM consists of a pressure resistant glass sphere with a diameter of 17-inches, which houses a single 10” photomultiplier tube (PMT) and the electronics that provide the high voltage. Three OMs are grouped together to form a floor and 25 floors compose a string, for a total of 12 strings. The field of view of the OMs is oriented downwards, at an angle of 45 degrees with respect to the vertical [1].
ORCA is being deployed about 10 km west of the site of the ANTARES detector. Upon completion it will consist of 120 flexible detection units (DUs), each of which comprises 18 Digital Optical Modules (DOMs). A DOM is a pressure resistant, 17-inch diameter glass sphere containing a total of 31 3" PMTs and their associated electronics. The vertical spacing between DOMs is 9 m and the DUs are separated on average by 23 m from each other on the seafloor. Its geometry is optimised for particle physics studies with atmospheric neutrinos in the few GeV range. The total instrumented volume is approximately 8 Mton [3].

3. Interaction rate estimates

Neutrino telescopes are sensitive to sterile neutrinos through their impact on the rate of atmospheric neutrinos arriving at the detector as a function of energy and baseline. This rate is given by the product of the atmospheric neutrino flux and the neutrino cross-section, and is modulated by neutrino oscillation probabilities. For both the analyses of ANTARES and ORCA, the atmospheric neutrino flux is estimated with the Honda model. In particular for ORCA, the HKKM 2014 flux tables (Gran Sasso site) [4] are interpolated in energy and zenith angle. Neutrino cross-sections are obtained from the GENIE neutrino Monte Carlo generator [5] via the gSeaGen application [6].

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Oscillation probabilities are calculated with the OscProb package [7], with the Earth density profile approximated by 42 constant density layers according to the PREM model [8], including realistic estimates of the chemical composition of each layer, which impacts the mass density to electron density conversion.

4. KM3NeT/ORCA: Event Topologies and Simulations

All particles emerging from a neutrino interaction are propagated with KM3Sim, a full photon tracking simulation, based on Geant4, originally part of the HOURS package [9]. KM3Sim generates Cherenkov light from primary and secondary particles and simulates the detection of photons (hits) while taking into account the light absorption and scattering in water as well as the DOM and PMT characteristics. The background due to down-going atmospheric muons is generated with MUPAGE [10]. The second type of background to be taken into account are the randomly distributed PMT hits due to the Cherenkov light from electrons induced by decays of ^{40}K. In this case, single photoelectron hits can be added to the hits induced by charged particles inside a chosen time window. Also the hits in coincidence due to ^{40}K between two PMTs inside the same DOM are taken into account. An uncorrelated hit rate of 10 kHz per PMT was added.
Due to the amount of background it is not possible to save all the data taken by the telescope, therefore trigger algorithms are applied and only the data passing the triggers are saved to disk. Here, reconstruction algorithms are run on the data and the output information from the reconstruction are used to distinguish between the 2 event topologies observed in neutrino telescopes: tracks, those that are induced by CC muon neutrino interactions, having the signature of a straight track passing through or nearby the instrumented volume, and showers, those coming from all other neutrino interaction channels and flavours: all NC interactions and the CC interactions of electron and tau neutrinos. In particular, the reconstructions information is given to the ORCA particle identification (PID), which uses the random decision forest (RDF) technique. In the forest a set of random decision trees is trained on a randomly drawn fraction of all training variables. The output score then reflects the fraction of trees that voted for the predicted class. In ORCA, only binary decision forests are used, which have to decide between two classes. In this way, a tunable output parameter is obtained, which can be used to cut on in the analysis.

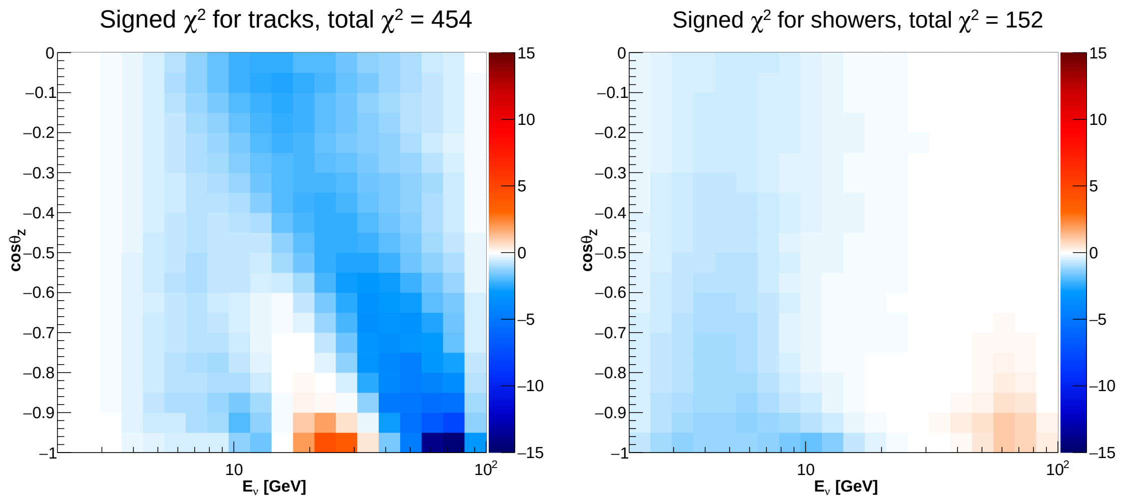
5. Event Distributions

Once we have put together all the information from the previous steps, the sensitivity to sterile neutrinos can be studied through the distribution of χ^2 values as a function of energy and zenith angle. For illustration purposes, we define a signed-χ^2 variable, where:

$$\text{signed-}\chi^2 = \frac{(HP_{Sterile} - HP_{Standard})|HP_{Sterile} - HP_{Standard}|}{\sqrt{HP_{Standard}}} \tag{5.1}$$

being HP the hypothesis taken into account, as a function of reconstructed neutrino energy and cosine zenith for track-like and cascade-like events. Fig. 1 shows the signed χ^2 distribution assuming 3 years of ORCA data taking, $\Delta m^2_{14} = 1$ eV^2 and $|U_{e4}| = 0$, $|U_{\mu 4}| = 0.03$, $|U_{\tau 4}| = 0.1$. The overall χ^2 is also reported in top of the plots. From its value we can see that, in this scenario, the leading

channel is track-like, and that there is a significant excess of events expected at $E \sim 20-30$ GeV for upgoing neutrinos, and an overall deficit of events in other regions.
Fig. 2 instead, shows the same χ^2 distribution but assuming $\Delta m^2_{14} = 10^{-4}$ eV^2. Comparing it with Fig. 1 we can conclude that: (1) a much larger deficit of events is expected around 10 GeV, (2) the cascade channel importance is comparable with the track one, (3) the total χ^2 values are larger, i.e. ORCA is more sensitive to lower Δm^2_{14} values.

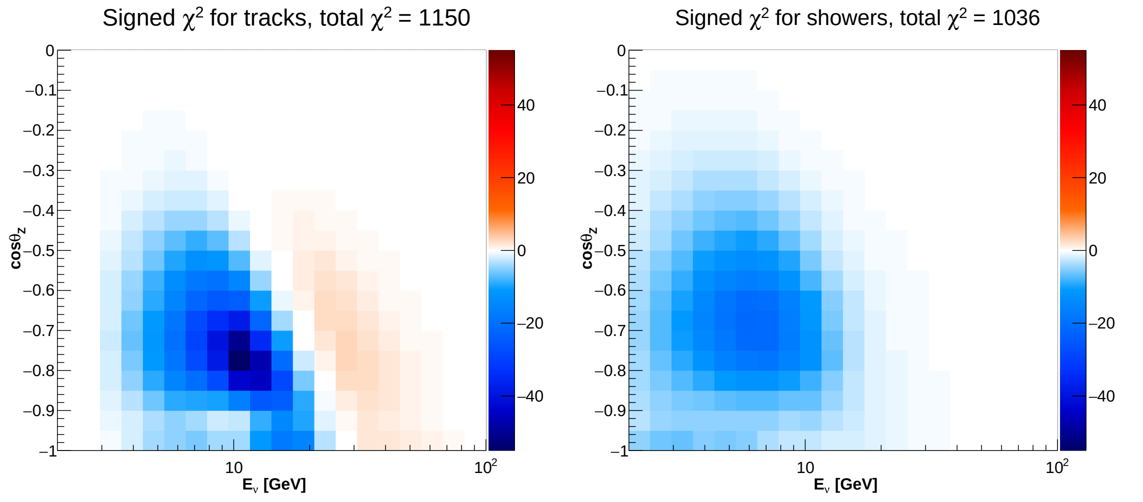


(a) (b)

Figure 1: Signed χ^2 as a function of reconstructed energy and zenith angle for tracks (a) and showers (b) for $\Delta m^2_{14} = 1$ eV^2 and $|U_{e4}| = 0$, $|U_{\mu 4}| = 0.03$, $|U_{\tau 4}| = 0.1$. The total χ^2 value is also reported for each plot.

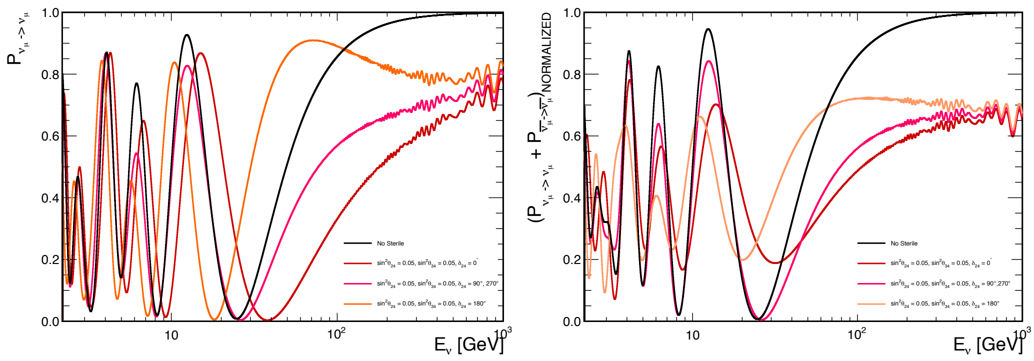
6. KM3NeT/ORCA: Sensitivity to the Sterile Neutrino Mixing Angles

Once we introduce one sterile neutrino, the oscillation probabilities depend on 6 new parameters: one additional squared mass difference (Δm^2_{14}), 3 mixing angles (θ_{14}, θ_{24}, θ_{34}) and two additional CP phases (δ_{14}, δ_{24}). Reactor experiments have constrained the $|U_{e4}| = \sin^2\theta_{14}$ mixing element beyond the sensitivity of ORCA, so we fix this parameter to zero. Since the CP phase δ_{14} is always multiplied by $\sin^2\theta_{14}$, this parameter can be ignored. However, the phase δ_{24} does play an important role as can be seen in the oscillation probabilities shown in Fig. 3 (a). There is an evident shift of the minimum depending on the value of δ_{24}. For completeness, since we are not able to distinguish between neutrinos and antineutrinos, Fig. 3 (b) shows the impact of δ_{24} in this case: even if we lose information, we are still sensitive to the impact of this additional CP phase. For these reasons, the phase δ_{24} is left as a free parameter in our analysis. The impact of δ_{24} has been ignored in some recent analyses from other experiments [12, 13], where δ_{24} was fixed at zero. As we will show, this leads to constraints that are too strong as different values of δ_{24} will cancel some of the effects that would otherwise be visible in such experiments. The remaining standard neutrino parameter values are taken from NuFit v.3.2 [11], also the standard CP phase which is kept fixed during the analysis. Tab. 1 shows the set of priors considered for this analysis.



(a) (b)

Figure 2: Signed χ^2 as a function of reconstructed energy and zenith angle for tracks (a) and showers (b) for $\Delta m^2_{14} = 10^{-4}$ eV^2 and $|U_{e4}| = 0$, $|U_{\mu 4}| = 0.03$, $|U_{\tau 4}| = 0.1$. The total χ^2 value is also reported for each plot.



(a) (b)

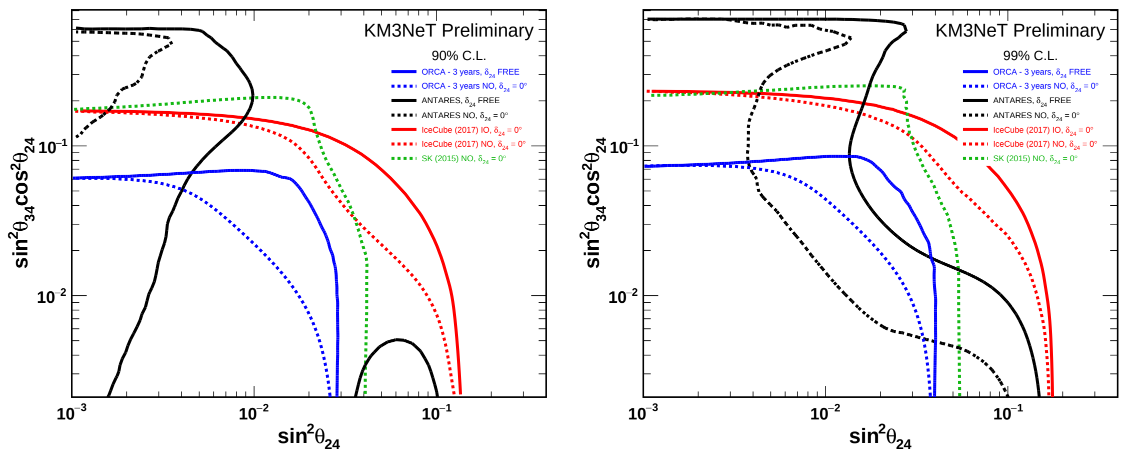
Figure 3: (a) Impact of δ_{24} on the ν_μ disappearance probability. (b) The antineutrino contribution, weighted by the fraction of $\nu_\mu/\bar{\nu}_\mu$ from the atmospheric neutrino flux and by their different cross sections, is added to the neutrino probability and finally normalized to compare it with (a).

Fig. 4 (a) and (b) show the ORCA sensitivity to the mixing angles θ_{24} and θ_{34}, given $\Delta m^2_{41} > 0.1$ eV^2, for 3 years of data taking at 90% and 99% confidence level. At these values of sterile neutrino mass, fast oscillations driven by Δm^2_{41} are not resolved and the analysis becomes independent of its exact size. The sensitivity is compared to the upper limits obtained from other experiments. Dashed lines are the result of the analysis keeping the additional CP phase δ_{24} fixed at zero and assuming normal ordering. Continuous lines instead represent the analysis with δ_{24} free. Due to an approximate degeneracy between the sign of $\cos\delta_{24}$ and the mass ordering, the most conservative contours between normal and inverted orderings for fixed δ_{24} is a good approximation of the result

Parameter	Prior
θ_{13}	$8.54^\circ \pm 0.15^\circ$
$\frac{\Delta m^2_{31}}{10^{-3}\mathrm{eV}^2}$	2.49 ± 0.5
Flux Norm	1 ± 0.10
NC Scale	1 ± 0.05
ν_μ/ν_e Skew	0 ± 0.05
$\nu/\bar{\nu}$ Skew	0 ± 0.03
Energy Slope	0 ± 0.05
Energy Scale	1 ± 0.03

Table 1: Set of priors used for the ORCA sterile neutrino analysis.

of letting this parameter float. In this way, our free δ_{24} results can be more directly compared with the IceCube analysis with inverted ordering (IO). Both figures show that ORCA is competitive in constraining the mixing elements $|U_{\mu 4}|$ and $|U_{\tau 4}|$, and is expected to improve the sensitivity to $|U_{\tau 4}|$ by almost a factor 2 with respect to current limits.

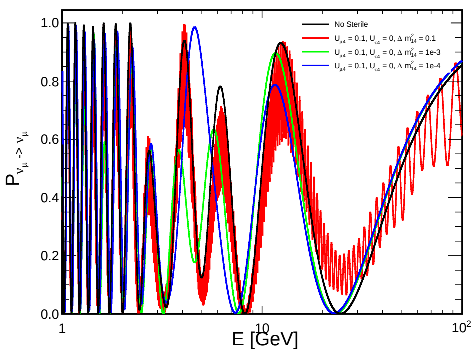


(a) (b)

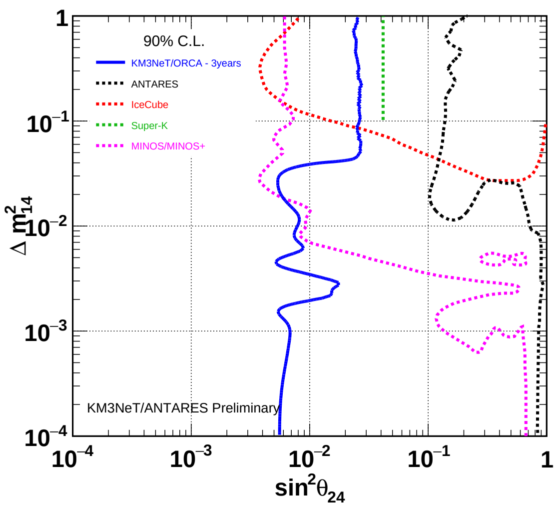
Figure 4: ORCA sensitivity for $\Delta m^2_{41} > 0.1$ eV^2, with 3 years of data taking, on the sterile mixing angles at 90% C.L. (a) and 99% C.L. (b) compared with the upper limits from other neutrino telescopes. Dashed lines correspond to analyses made by fixing δ_{24}. Continuous lines for ORCA and ANTARES correspond to an analysis with δ_{24} free. Since there is a degeneracy between δ_{24} and mass ordering, upper limits from IceCube including IO are also shown which can be compared with the continuous lines from ORCA and ANTARES.

7. ANTARES and KM3NeT/ORCA: Upper Limits and Sensitivity for low Δm^2_{41} Values

For higher values of Δm^2_{41} the oscillation frequency is too high to be resolved in the energy range up to 100 GeV. In this case we need a detector for higher energies such as KM3NeT/ARCA to probe oscillation effects driven by Δm^2_{41}. However, ANTARES and ORCA are sensitive to effects at lower sterile masses. At $\Delta m^2_{41} < 0.1$ eV^2, the current best limits on the $|U_{\mu 4}|$ sterile mixing element come from the MINOS/MINOS+ experiment [14]. For their analysis a vacuum approximation is used since matter effects are expected to be negligible at a baseline of 735 km. With ANTARES and ORCA instead, longer baselines (up to 12000 km) are available to exploit matter effects. However, since the ANTARES energy threshold is ~ 20 GeV and, as shown in fig. 5 (a), the effects of lower sterile masses is more evident for energies below 20 GeV, we do not expect a competitive result from ANTARES.



(a)



(b)

Figure 5: (a) Oscillation probability evaluated with OscProb [7] for a baseline of 12000 km and assuming matter effects with the PREM model [8]. (b) ORCA sensitivity (blue line) and ANTARES upper limits (dashed black line), at 90% C.L. on Δm^2_{14} and θ_{24}. The ORCA sensitivity is evaluated for 3 years of data taking. The ANTARES upper limits are evaluated with the same data sample of Ref. [2], i.e. for the period 2007-2016. Upper limits from other experiments are also reported for comparison.

The low Δm^2_{14} analysis for ANTARES is made with the same dataset of [2] and for ORCA, with the same parameters and systematics of the analysis of section 6.
Fig. 5 (b) shows the sensitivity of ORCA in function θ_{24} and Δm^2_{14} compared also with the upper limits from the other experiments. The plot shows also the upper limit from ANTARES. From the plot it is evident that ORCA sensitivity is very competitive to constrain low sterile masses and it improves the current MINOS/MINOS+ limits of about 2 orders of magnitude for $\Delta m^2_{41} < 10^{-3}$ eV^2. As already stated and expected from Fig. 1 and Fig. 2, ORCA sensitivity appears to be better for low Δm^2_{14} values. This is a result of multiple and longer baselines combined with matter effects that can break degeneracies with the atmospheric mass splitting. The ANTARES upper limits, instead, are not competitive with the other experiments, as expected already from Fig. 5 (a).

8. Outlook

Neutrino telescopes such as ANTARES and KM3NeT have the potential to be used for searches for new physics such as sterile neutrinos. With 10 years of data, ANTARES has excluded regions of sterile mixing space allowed by previous experiments (see Ref. [2]) and ORCA is expected to significantly improve on the capability of present experiments with only 3 years of data taking. The ORCA construction has begun and first neutrinos with the first DUs have been detected [15].

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