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Latest Results with the KM3NeT Neutrino Telescope

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KM3NeT is a multi-purpose neutrino observatory being installed in a phased scheme in the Mediterranean Sea. It is composed of two Cherenkov detectors instrumenting water with photomultipliers in different layouts: ORCA, a compact and dense detector optimised for the measurement of fundamental atmospheric neutrino physics, such as mass ordering and oscillations, in the 1-100 GeV energy range, with unprecedented statistics; and ARCA, a set of two telescopes with a volume exceeding a cubic kilometer to catch astrophysical neutrinos from 100 GeV to 10 PeV, with a pointing resolution reaching down to 0.1 degree. The two detectors have a final configuration comprising 115 and 230 detection lines, respectively, and currently 18 lines of ORCA and 28 of ARCA are recording data. An overview of first KM3NeT results and prospects will be presented, with focus on the measurement of oscillation parameters, on the search for sources of extraterrestrial neutrinos, and on the prompt multi-messenger program including the search for correlations of neutrinos with gravitational waves. The physics case of KM3NeT is broad and also covers new physics searches that will also be presented, such as non-standard oscillations, invisible neutrino decay and dark matter.

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1. The KM3NeT Neutrino Telescope

KM3NeT is built as a network of underwater photomultiplier arrays using the sea water as a reactor medium. The Cherenkov light of ultra-relativistic leptons produced by neutrino interactions in the vicinity of the detector is detected by Digital Optical Modules (DOMs) arranged in vertical Detection Units (DUs). Each DOM hosts 31 photomultiplier tubes (PMTs), along with sensors to determine their exact position and orientation. The array spacing is chosen considering different physics cases in target. KM3NeT comprises a dense, compact detector (ORCA, i.e. Oscillation Research with Cosmics in the Abyss) offshore the southern coast of France close to the previous ANTARES site, and a cubic kilometer detector (ARCA, i.e. Astroparticle Research with Cosmics in the Abyss) offshore the coast of Sicily (Italy) [1]. ORCA, with a spacing of 9 m between DOMs and about 20 m between DUs, has access to the energy window of neutrinos between a few GeV and the TeV; it aims to measure neutrino oscillations in atmospheric neutrinos with very high statistics. ARCA, with a spacing of 36 m between DOMs and about 90 m between DUs, is designed to instrument a volume large enough to be sensitive to the very low fluxes of extraterrestrial neutrinos. KM3NeT is currently being constructed: to date ARCA counts 21 DUs, ORCA 18 DUs, all operative; results presented in this proceedings are obtained with the partial configurations of the detectors in different construction phases. Exception made for the different spacing, the detectors share common technologies. The complete design foresees one block of 115 DU for ORCA, and two blocks of 115 DUs each for ARCA. At the current time, the construction of KM3NeT is financially secured for more than two thirds of the total costs.

2. Neutrino Astronomy

Neutrino astronomy is a science *in the making*, whose challenge is the identification of a very faint signal against a large background of neutrinos produced in the Earth's atmosphere. The phenomenology of extraterrestrial neutrinos is various: they are expected from astrophysical processes that produce common particles such as charged pions and muons, which can happen either via p-nucleon or $p - \gamma$ scattering, according to the source environment, and display as a steady or flary emission. An extraterrestrial component of the energy spectrum would give access to the mechanism acting at cosmic acceleration sites. No diffuse excess of extraterrestrial neutrinos is seen in the current 432 days of KM3NeT/ARCA, as shown in Figure 1. This is consistent with the measurement by IceCube considering the relative size of the two detectors. Adopting best-fit parameters by IceCube [2], upper limits to a diffuse neutrino flux are placed at $\Phi_{90} = 3.06 \cdot 10^{-18}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1} [4]. KM3NeT has searched for single neutrino sources in correlation with a catalogue of pre-selected astrophysical objects, not finding any significant post-trial excess as shown in Figure 2. Using an energy dependence as E^{-2}, upper limits are placed according to the sky declination as shown in Figure 2. KM3NeT has an extensive multi-messenger program ongoing. About 40 alerts of run O3 for gravitational waves have been followed up with ORCA, to no detection [4]. All alerts from O4 are currently being followed up with a fast online analysis. In addition, analyses based on single-DOM measurements are performed such as the searches for neutrinos from core-collapse supernovae [4]. For these, the signal would appear as a global rise in the single DOM rate due to neutrinos of MeV energies.

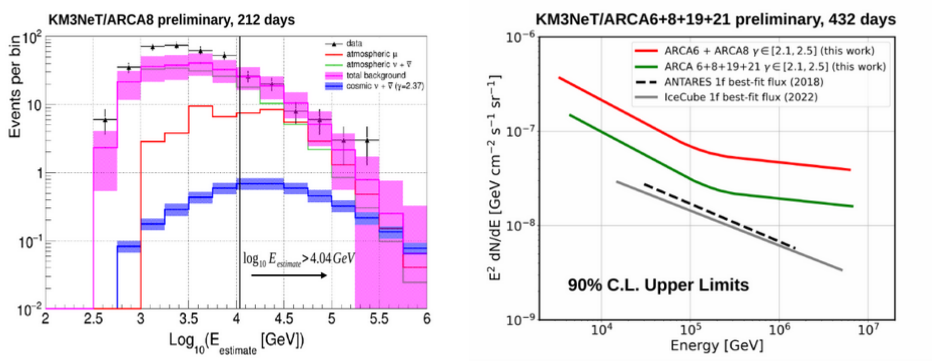

Figure 1: Search for a diffuse flux of extraterrestrial neutrinos with KM3NeT/ARCA. Left panel: reconstructed energy distribution of events in the ARCA8 data set, showing no excess. Right panel: upper limits to a diffuse flux of astrophysical neutrinos assuming best fit $\gamma = 2.37$ from the excess measured by IceCube [2]. Results by ANTARES [3] are shown for comparison.

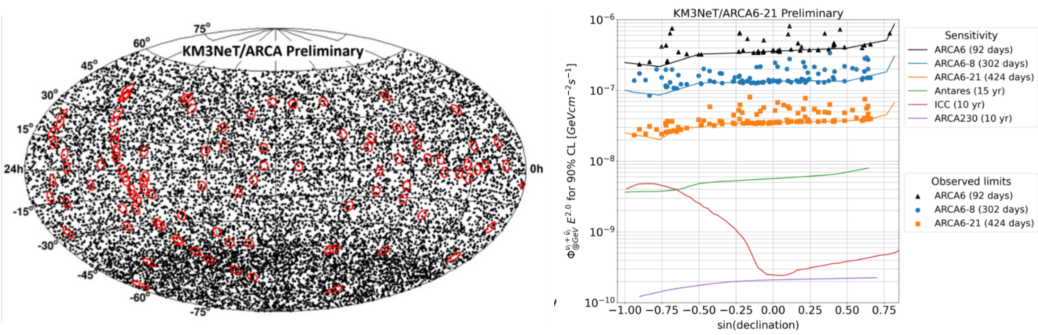

Figure 2: Search for point-like sources of extraterrestrial neutrinos with KM3NeT/ARCA [4]. Left panel: sky distribution of neutrino arrival directions; red circles indicate 2.5° around the candidate source positions. Right panel: estimated sensitivity as a function of the event declination and upper limits for a catalogue of preselected sources. Results are compared with IceCube discovery potential at 5 σ (ICC in the legend) [5].

3. High-precision Measurements of Fundamental Neutrino Properties

The observation of neutrino oscillations, implying that neutrinos have a non-zero mass, is a strong evidence of physics beyond the expectations of the Standard Model. The fine-spaced layout of KM3NeT/ORCA is specifically designed to study the oscillatory behaviour of atmospheric neutrinos with very high statistics. In KM3NeT, flavour oscillations are searched through ν_μ disappearance, which is studied through a count of arrival directions and energies of detected events. Oscillations are seen with a significance larger than 6 standard deviations in L/E distributions with 540 days of the ORCA6 data set corresponding to 433 kton-years (540 days), as illustrated in Figure 3. A fit of oscillation parameters on these data, as shown in the right panel of Figure 3, results in $\sin^2\theta_{23} = 0.51^{+0.06}_{-0.07}$ and $\Delta m^2_{31} = 2.14^{+0.36}_{-0.25} \cdot 10^{-3}\text{eV}^2$, with a slight preference for normal ordering [4]. Joining results from different experiments, the measurement of all oscillation parameters permits to reconstruct the elements of the leptonic mixing matrix [6]. On a longer time scale KM3NeT aims at determining the hierarchy between the third neutrino mass eigenstate

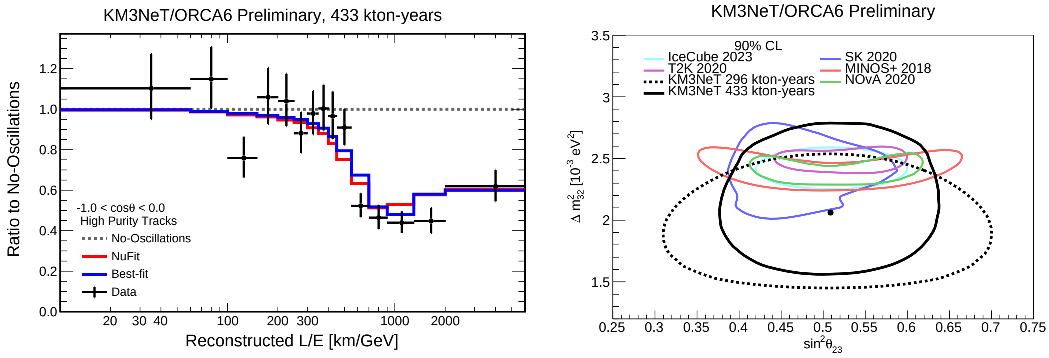

Figure 3: Oscillations in atmospheric neutrinos as seen in the ORCA-6 data sample. Left panel: muon neutrino disappearance as a function of the L/E baseline, indicating the presence of flavour oscillations. Right panel: best fit on atmospheric oscillation parameters $\sin^2\theta_{23}$ and Δm^2_{31}. For comparison, results by IceCube [7], T2K [8], Super-Kamiokande [9], MINOS [10] and NOvA [11] are shown.

and the first two, known as neutrino mass ordering. Indeed, asymmetries in matter effects in propagation through the Earth and different interaction cross section for neutrinos and antineutrinos imply differences in events rates for normal and inverted ordering. Our current understanding of oscillations is challenged by searching for deviations, as in the search for τ appearance [12] and non-standrad interactions (NSI) [13]. In the first of these analyses, a statistical excess of τ neutrinos above the amount predicted by oscillations has been searched for, resulting in no deviations from the expectation. In the second, a Standard Model extension is realised through the introduction of a new operator, of dimension 6, in the Lagrangian. This brings in a four-fermion vertex which induces changes in oscillation probabilities. The same data set of ORCA6 has been searched for NSI and no signal was found. Other effects beyond the Standard Model predictions have been searched for in the KM3NeT/ORCA6 sample, such as neutrino quantum decoherence [4], neutrino decay [4], and sterile neutrinos [4]. KM3NeT also operates as a cosmic-ray detector when analysing atmospheric leptons, mainly muons, with provenience from the above hemisphere. Confirming the precision of the detector's absolute pointing, the effect of shadowing on the cosmic-ray flux due to both the Moon and the Sun is detected with a significance of 4.2 and 6.2 standard deviations, fitted with an extension of 0.49° and 0.65° respectively [14]. New results on the topics mentioned here are expected as more detection units of the KM3NeT detector are installed and connected.

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