PROCEEDINGS OF SCIENCE

The KM3NeT project and Tier2 computing at Tbilisi State University

G.Papalashvili[a,*] and R.Shanidze[a] on behalf of the KM3NeT Collaboration

[a] *Tbilisi State University,*
3, Chavchavadze Ave., Tbilisi, 0179 Georgia.

E-mail: gogita.papalashvili@tsu.ge

KM3NeT is a European research infrastructure project, which is currently under construction at two locations in the Mediterranean Sea. The project aims to detect the neutrinos in the energy range from a few GeV up to a few PeV with two detectors: ORCA (Oscillation Research with Cosmics in the Abyss) for low energy (>GeV) and ARCA (Astroparticle Research with Cosmics in the Abyss) for high energy (>TeV) neutrinos. A multi-level KM3NeT computing model is necessary to acquire, process and analyse the large amount (up to 1Tb/s) of data from the deep-sea detectors. The computing model is similar to the LHC computing model, with three computing levels (Tiers). In this framework Tier-2 level computing refers to the analysis of processed data and Monde Carlo events at the level of the research groups of the collaboration. This contribution presents the KM3NeT project, its computing model and focuses on the Tier-2 computing infrastructure installed at the Tbilisi State University.

RDP online PhD school and workshop "Aspects of Symmetry"(Regio2021),
8-12 November 2021
Online

*Speaker

PoS(Regio2021)006

1. The KM3NeT Project

KM3NeT [1] is a European research infrastructure which aims to detect and study neutrinos in the energy range covering 6 orders of magnitude, from few GeV (10^9 eV) up to few PeV (10^{15} eV).The KM3NeT collaboration consists of more than 50 groups from universities and research centers of 17 different countries on 4 continents. To achieve its scientific goals, the KM3NeT Collaboration is currently building two detectors in the Mediterranean Sea. ARCA (Astroparticle Research with Cosmics in Abyss) is mainly focused on neutrino astronomy and ORCA (Oscillation Research with Cosmics in Abyss) on neutrino physics. The ARCA detector will be anchored at a depth of 3.5 km, about 100 kilometer off-shore Portopalo di Capo Passero (Sicily, Italy). The ORCA site is about 40 km off-shore Toulon (France), at a depth of 2.5 km. The KM3NeT ARCA and ORCA

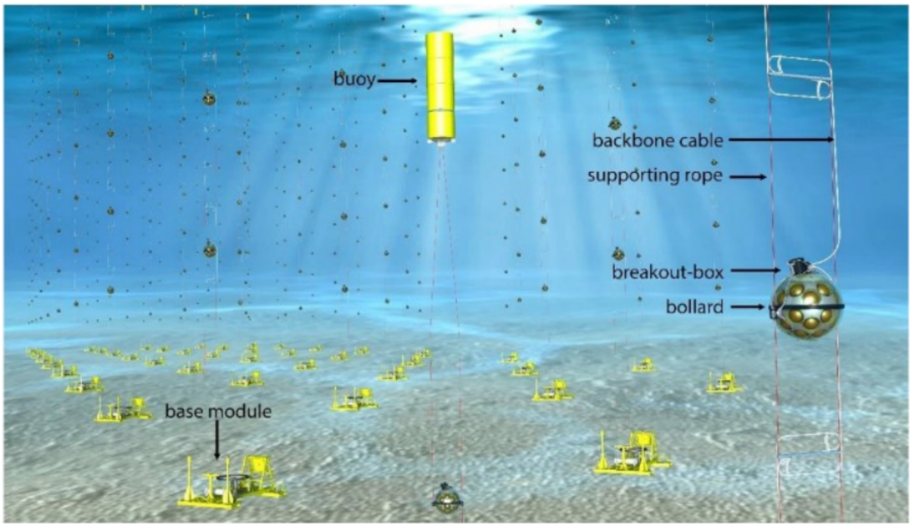


Figure 1: KM3NeT underwater neutrino telescope

detectors consists of photo-multipliers (PMTs) which are housed in pressure resistant transparent spheres, together with electronic boards for signal processing and digitization, positioning and calibration. These detector elements, which are known as DOMs (Digital Optical Module) are basic elements of both KM3NeT detectors. Figure 1 is a pictorial view of a KM3NeT telescope. Each DOM comprises 31 PMTs. Both KM3NeT neutrino telescopes share the same design and technology, with a different density of the active components, depending on the relevant energy range. 18 DOMs are assembled in a vertical line, which is called a detection unit (DU). 115 such DUs make one building block (BB). The vertical distances between ARCA and ORCA DOMs are 36m and 9m respectively. The horizontal distances between DUs in the ARCA and ORCA BB are about 90m and 20m. The main geometrical parameters are shown in Table 1.

Configuration	Depth [m]	Horizontal spacing [m]	Vertical spacing [m]	Detection Unit	Volume [km^3]
ARCA	3500	90	36	2 x 115	1
ORCA	2500	20	9	115	0.006

Table 1: Configurations of the KM3NeT detectors

2. Physics Goals of KM3NeT

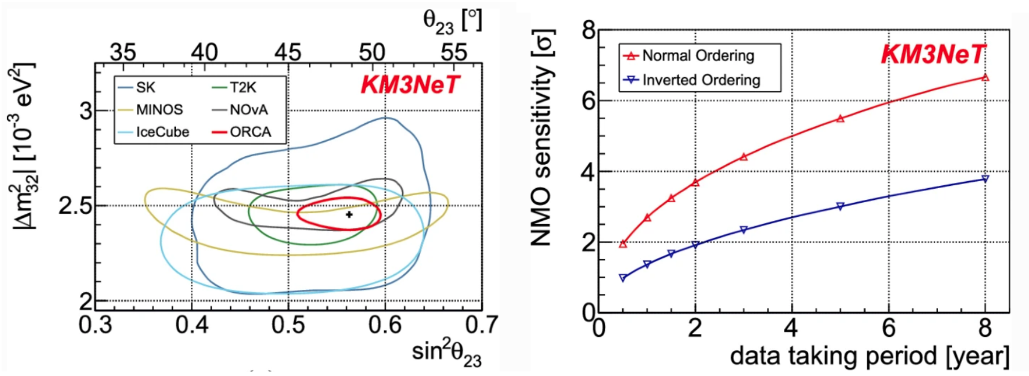
Investigation of the neutrino properties and detection of neutrinos of cosmic origin are among the main objectives of the KM3NeT project. According to the Standard Model of particle physics, neutrinos are fundamental particles of nature, belonging to the class of neutral leptons. Three types of neutrinos ν_e, ν_μ, ν_τ) were introduced in the Standard Model as massless particles. They are very difficult to detect because they interact only weakly with matter. Observation of the neutrino oscillations proved that neutrinos are massive particles, indicating that their properties could be linked to the physics beyond the Standard Model (BSM physics). Investigation of the neutrino properties is in the focus of current fundamental research. In the current standard framework of neutrino physics, three flavour eigenstates (ν_e, ν_μ, ν_τ) are considered to be a superposition of the three mass eigenstates (ν_1, ν_2, ν_3), with masses (m_1, m_2, m_3), where ν_1 is the mass eigenstate with the largest ν_e component, and ν_3 is the one with the smallest. The mixing of flavour ν_α ($\alpha = e, \mu, \tau$) and mass ν_i ($i = 1, 2, 3$) eigenstates are described by the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix, U:

$$\nu_\alpha = \sum_{n=1}^{3} U_{\alpha i} \nu_i$$

Assuming that U is unitary matrix, it can be parametrized in terms of three mixing angles θ_{12}, θ_{13}, θ_{23} and a CP-violating phase δ_{CP}. Neutrino oscillations are sensitive to mass-squared differences $\triangle m^2_{ij} = m^2_i - m^2_j$ $(i, j = 1, 2, 3)$, from which two independent mass-squared differences can be constructed, usually assumed to be $\triangle m^2_{12}$ and $\triangle m^2_{23}$. The ordering of the neutrino mass eigenstates (sign of $\triangle m^2_{23}$) is not yet resolved, it might be $m_1 < m_2 < m_3$ ‘normal ordering’, NO) or $m_3 < m_1 < m_2$ (‘inverted ordering’, IO). Resolving neutrino mass ordering (NMO) is one of the main goals of the current neutrino research.

The KM3NeT/ORCA detector, with a neutrino energy detection threshold of few GeV, allows oscillation research using the atmospheric neutrinos. The sensitivity of ORCA to determine the neutrino mass ordering after 3 years of data taking with ORCA is estimated to be 4.4σ if the true ordering is normal and 2.3σ if inverted. High precision is expected to be achieved in the measurements of oscillation parameters $\triangle m^2_{23}$ and θ_{23}. Proposed measurements of the neutrino oscillation parameters and estimated sensitivities are described in [2].

Detection of high energy neutrinos (above about 1 TeV) of cosmic origin is foreseen with the KM3NeT/ARCA detector. While the existence of such neutrinos has been proven by the IceCube telescope at the South Pole [3], the question of their astrophysical sources remains unanswered. KM3NeT has a view of the sky complementary to IceCube and thanks to an excellent angular resolution for muon neutrinos ($< 0.2^\circ$ for $E > 10$ TeV), it could identify astrophysical sources of



(a) **(b)**

Figure 2: (a) Expected measurement precision of $\triangle m^2_{23}$ and θ_{23} for both after 3 years of data taking at 90% confidence level (red) overlaid with results from other experiments
(b) Sensitivity to NMO as a function of data taking time for both normal (red upward-pointing triangles) and inverted ordering (blue downward-pointing triangles

cosmic neutrinos. KM3NeT/ARCA sensitivity to diffuse, point-like, and extended neutrino sources are described in [4],[5].

ARCA and ORCA could observe neutrino flux with energies about 10 MeV from Galactic and near-Galactic core-collapse supernovae. The supernova signal will be observed through the coincident multiple hits in the DOMs. The time profile of the neutrino signal allows determination of the arrival time of the neutrino burst with a few milliseconds precision for sources up to 5–8 kpc. Observation horizon with at least 5σ sensitivity for the most optimistic model, extends to the Small Magellanic Cloud galaxy about 60 kpc away. The KM3NeT potential for the next core-collapse supernova observation with neutrinos is described in [6]. The architecture of a real time system for core-collapse supernovae is described in [7].

3. Computing Model of KM3NeT

Computing plays crucial role in KM3NeT project. It is used for data acquisition and filtering, detector calibration, reconstruction and analysis of physics events. KM3NeT uses "all data to shore" approach with up to 1 Tb/s data transmission rate from one building block to the shore station. The collaboration is using hierarchical computing and data processing model similar to the model developed for LHC. It is referred to as Tier structure. KM3NeT uses three levels which are represented on Figure 3.

At the first step (Tier-0), all experimental data (PMT signals above the predefined threshold) are transferred to the shore station, where data is filtered by a computer farm according to trigger algorithms and stored in data files. Filtered experimental data is transferred to the Tier-1 computing centers and stored on high performance storage system (HPSS). Currently they are the computing centers of IN2P3 in Lyon (France) and INFN-CNAF in Bologna (Italy). Data processing including calibrations, event reconstructions and simulations are done using Tier-1 computing resources. Reconstructed and simulated data are usually analysed locally with Tier-2 computing at the member

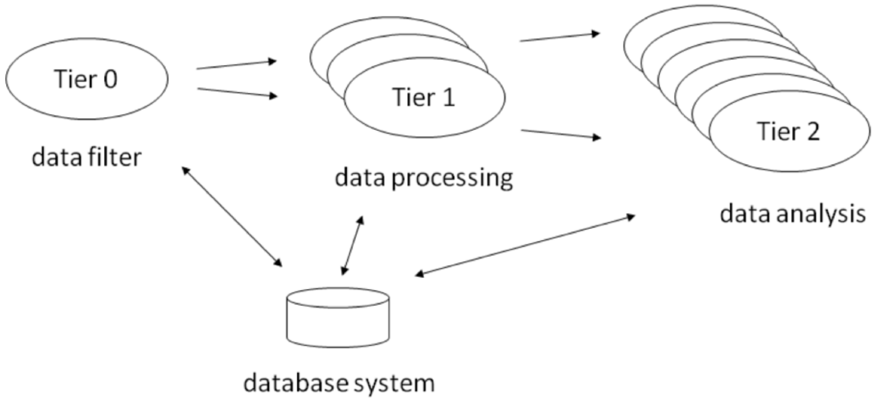


Figure 3: KM3NeT computing model

institutes. A KM3NeT Tier-2 computing infrastructure, consisting of software developed within the KM3NeT collaboration, was installed in Tbilisi State University.

3.1 Tier-2 Computing at Tbilisi State University

Tbilisi State University hosts a Linux based computing infrastructure. It is mainly used as KM3NeT Tier-2 Tbilisi (Tier-2 TSU) hub for local members of the collaboration. KM3NeT real and Monte Carlo data are transferred from Tier-1 centers to Tier-2 TSU. Figure 4 illustrates the dataflow from detector to the final results. Tier-2 TSU software resources consists of KM3NeT software developed in framework of collaboration and most used software used in high energy physics computing as well.

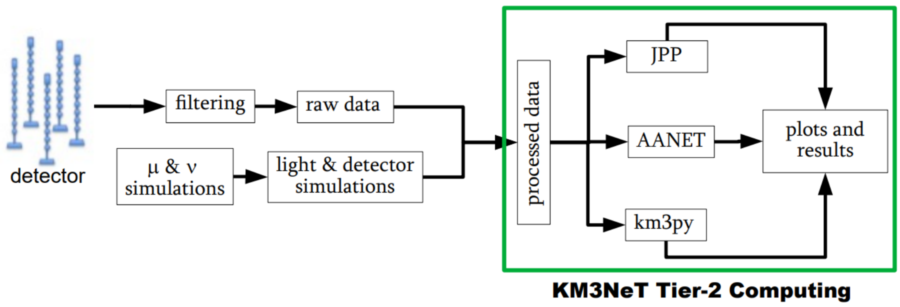


Figure 4: KM3NeT dataflow and analysis scheme

Tier-2 TSU provides software packages which were developed in the KM3NeT collaboration. This includes data analysis and simulations software:

- JPP - general C++ based KM3NeT software framework which includes classes for DAQ, detector monitoring, calibration, reconstructions, simulations, analysis.
- Km3py - python applications and classes for the data IO, monitoring, analysis.
- AANET - python and ROOT based software package for KM3NeT event analysis.

- gSeaGen - GENIE based atmospheric neutrino simulator[8].
- MUPAGE - for simulation of atmospheric muons. It uses parametric formulas for muon flux [9],[10].

In addition, almost all other KM3NeT software are accessible through Docker images.

To make Tier-2 Tbilisi hub more accessible, the python-based user friendly web environment - JupyterHub was installed at local server. As an example, Figure 5 shows the screenshot of JupyterHub environment.

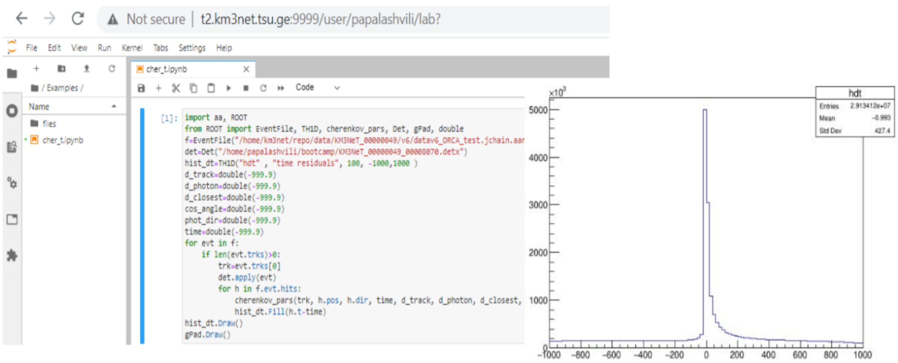


Figure 5: Screenshot of Tier-2 TSU JupyterHUB figure. Left side shows the JuputerHub environment itself and an example of a code. Right side shows the result of the code. The sample distribution represents differences between expected and observed time of hits.

4. First results obtained with KM3NeT

The first KM3NeT detection units were deployed at the Italian (ARCA) and French (ORCA) sites between 2015 and 2017. The current (March 2022) configurations of ARCA and ORCA detector comprises 8 and 10 detection units respectively (ARCA8 and ORCA10). The multi-PMT design of the DOM allows to discriminate between the signals from atmospheric muons and from environmental background mainly due to bioluminescence and ^{40}K decay. This is achieved by exploiting coincidences between different PMTs hits in the same DOM within a time window of 15 ns. The number of PMTs with hits defines DOM multiplicity. The contribution from background is dominant up to a multiplicity of 7. Coincidences from atmospheric muons dominate at a multiplicity of 8 and higher. The atmospheric muons and muon bundles can potentially illuminate all 31 PMTs of a single DOM. The multiplicity coincidence ≥ 8 rates for all the active DOMs in ARCA2 and ORCA1 detectors as a function of seawater depth in 2232–3386 m range is discussed in paper [11]. The result from this paper is presented in Figure 6.

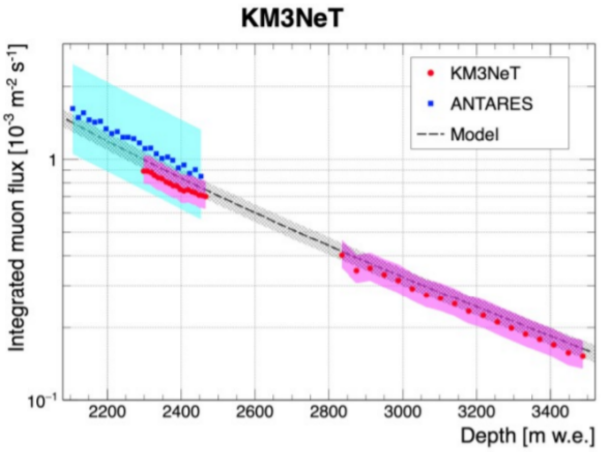
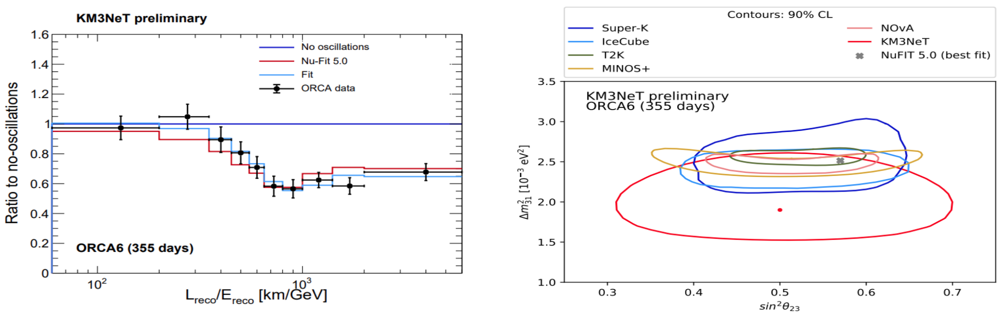


Figure 6: Integrated atmospheric muon flux measured with the ORCA1 and ARCA2 detectors with red dots. The systematic errors are displayed as light red shadowed areas. The Bugaev model of the atmospheric muon flux [12] is drawn with a dashed black line (quoted errors are the grey shadowed area) ANTARES data [13] are included as blue points for comparison (systematic errors are the light blue shadowed area). The depth is expressed in water equivalent (w.e.).

KM3NeT capability for the studies of neutrino oscillations was demonstrated with data obtained with ORCA6 configuration, corresponding to 354.6 days of exposure with the atmospheric muon and neutrino fluxes. Neutrino oscillations were probed with this configuration by measuring the L/E ratio, where E is neutrino energy and L-neutrino baseline (distance between neutrino production vertex and detector). L/E distribution for the ORCA6 data is presented in Figure 7(a). It was found that oscillations are preferred with a confidence level of 5.9σ over the hypothesis of no oscillations. The Likelihood contours for the neutrino oscillations parameters $\triangle m^2_{31}$ and $\sin^2\theta_{23}$ are presented in Figure 7(b) and result to be compatible with of other oscillation experiments. These measurements in KM3NeT/ORCA are described in [14].



(a) (b)

Figure 7: (a) L/E distribution for the ORCA6 data. The no oscillations and nu-fit curves in this figure do not include systematic uncertainties. (b) Contour at 90% CL of ORCA6 as a function of the oscillation parameters. Contours of other experiments have been added for comparison purposes as well as the Nu-Fit best fit value.

5. Summary

European research infrastructure KM3NeT, with two detectors ORCA and ARCA is currently under construction in the Mediterranean Sea. The article presents a multi-level computing model of the KM3NeT collaboration and Tier-2 infrastructure at the Tbilisi State University, which was used for the analysis of the initial ORCA data. Results obtained with this data include:

- Atmospheric muon flux measurement with the multi-PMT digital optical modules of the ORCA1 and ARCA2 detectors as a function of seawater depth.
- First measurement of neutrino oscillations at 5.9σ confidence level with ORCA6 data corresponding to 354.6 days of exposure.

Initial data obtained with the first detection units of the ORCA and ARCA detectors and computing infrastructure, including Tier-2 TSU, for processing and analyzing the data, are clear indications of the physics potential of the innovative KM3NeT project.

Acknowledgements

The authors acknowledge the financial support of the Shota Rustaveli National Science Foundation of Georgia (SRNSFG, FR-18-1268).

References

[1] KM3NeT Collaboration (S. Adrián-Martínez et al), *Letter of Intent for KM3NeT 2.0*, J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

[2] KM3NeT Collaboration (S. Aiello et al), *Determining the neutrino mass ordering and oscillation parameters with KM3NeT/ORCA*, EPJ C82(2021)

[3] IceCube Collaboration (M. G. Aartsen et al), *Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector*, Science 342 (2013) 1242856

[4] KM3NeT Collaboration (S. Aiello et al), *Sensitivity of the KM3NeT/ARCA neutrino telescope to point-like neutrino sources*, Astropart.Phys. 111 (2019) 100

[5] KM3NeT Collaboration (A. G. Sotto et al), *Sensitivity estimates for diffuse, point-like, and extended neutrino sources with the KM3NeT/ARCA*, JINST 16 (2021) 09, C09030

[6] KM3NeT Collaboration (S. Aiello et al), *The KM3NeT potential for the next core-collapse supernova observation with neutrinos*, EPJ C 81(2021), 445

[7] KM3NeT Collaboration (S. Aiello et al), *Implementation and first results of the KM3NeT real-time core-collapse supernova neutrino search*, JINST 16 (2021) 09, C09030

[8] KM3NeT Collaboration (S. Aiello et al), *gSeaGen: The KM3NeT GENIE-based code for neutrino telescopes*, Comput.Phys.Commun. 256 (2020) 107477

[9] Y. Becherini, A. Margiotta, M. Sioli and M. Spurio, *A Parameterisation of single and multiple muons in the deep water or ice*, Astropart.Phys. 25 (2006) 1-13

[10] G. Carminati, A. Margiotta and M. Spurio, *Atmospheric MUons from PArametric formulas: A Fast GEnerator for neutrino telescopes (MUPAGE)*, Comput. Phys. Commun. 179 (2008) 915

[11] KM3NeT Collaboration (M. Ageron et al), *Dependence of atmospheric muon flux on seawater depth measured with the first KM3NeT detection units*, EPJ C80(2020), 99

[12] E.V. Bugaev et al, *Atmospheric Muon Flux at Sea Level, Underground, and Underwater*, Phys. Rev. D 58, 054001 (1998)

[13] J.A. Aguilar et al, *Measurement of the atmospheric muon flux with a 4 GeV threshold in the ANTARES neutrino telescope*, Astropart. Phys. 33 (2010) 86-90

[14] KM3NeT Collaboration (L. Nauta et al), *First neutrino oscillation measurement in KM3NeT/ORCA*, PoS ICRC2021 (2021) 1123