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Report on the implementation of the online SN detection system of KM3NeT

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IV. APPLICATON AREA

This document is a formal deliverable for the GA of the project, applicable to all members of the KM3NeT INFRADEV project, beneficiaries and third parties, as well as its collaborating projects.

V. TERMINOLOGY

A complete project glossary is provided:

ORCA: Oscillation Research with Cosmics in the Abyss

ARCA: Astroparticle Research with Cosmics in the Abyss
DOM: Digital Optical Module
PMT: Photomultiplier Tube
DU: Detection Unit (ie, detection line)
CCSN: Core Collapse SuperNova
M: PMT Multiplicity
ORCA1: ORCA detector with 1 DU
ORCA6: ORCA detector with 6 DUs
ARCA2: ARCA detector with 2 DUs
SNEWS: SuperNova Early Warning System
DAQ: Data Acquisition

VI. LIST OF FIGURES

VII. PROJECT SUMMARY

KM3NeT is a large Research Infrastructure that will consist of a network of deep-sea neutrino telescopes in the Mediterranean Sea with user ports for Earth and Sea sciences. Following the appearance of KM3NeT 2.0 on the ESFRI roadmap 2016 and in line with the recommendations of the Assessment Expert Group in 2013, the KM3NeT-INFRADEV project addresses the Coordination and Support Actions (CSA) to prepare a legal entity and appropriate services for KM3NeT, thereby providing a sustainable solution for the operation of the research infrastructure during ten (or more) years. The KM3NeT-INFRADEV is funded by the European Commission's Horizon 2020 framework and its objectives comprise, amongst others, the preparation of the multi-messenger activities in the KM3NeT Collaboration (work package 7).

VIII. EXECUTIVE SUMMARY

The main goal of the WP7 is to lay the path to fully integrate KM3NeT into the global multi-messenger worldwide network. The multi-messenger approach to astronomy makes use of the messenger particles of all four fundamental forces (photon, gravitational wave, neutrino and cosmic ray) to explore and understand the most violent phenomena in the universe such as gamma-ray burst, outburst of active galactic nuclei, fast radio burst, supernova explosion, etc... Supernovae are explosive phenomena that can occur at the end of the life of massive stars. The explosion mechanism is not fully understood, but neutrinos play a fundamental role in it, 99% of gravitational energy is released through neutrinos.

In 1987, the first astrophysical neutrino signal was identified in coincidence with a core-collapse supernova (CCSN) located in the Gran Magellanic Cloud at 50 kpc. The detection of only a few tens of neutrinos was a major discovery. Over 4000 papers have been published related to this event. With the upgraded instruments actually running or in construction, of order of 10^3-10^5 neutrinos are expected for the next galactic CCSN, so the future observation of CCSN neutrinos will clearly be a major breakthrough in particle physics, astrophysics and nuclear physics. The most recent estimation of the CCSN rate is roughly 1 - 4 per century, so we must be prepared for the next one.

The KM3NeT ORCA and ARCA neutrino telescopes in the Mediterranean Sea are expected to observe a significant number of neutrino interactions through the detection of Cherenkov light, mostly induced by inverse beta decay processes in sea water. The unique characteristics of the KM3NeT DOMs (segmented photocathode, photon counting…) facilitate the detection of the MeV neutrinos emitted by nearby supernova explosions. As it is not possible to reconstruct neutrino directions at this low energy, the detection principle relies on a coherent increase of the PMT counting rates on a large fraction of the DOMs in a short time window. The detection of photons in coincidence between the 31 photomultipliers of KM3NeT digital optical modules (DOMs) allows to discriminate the CCSN signal against radioactive decays, bioluminescence and atmospheric muon backgrounds.

Thanks to the WP7 resources, we have been able to evaluate the expected response of the KM3NeT neutrino detectors to core-collapse supernova neutrinos with complete Monte Carlo simulations and exhaustive studies of the background from the first KM3NeT datasets. These results show that KM3NeT will be a very competitive contributor to the network of neutrino detectors observing the next Galactic CCSN.

The real-time analysis is already operational with the two partially-built detectors and the monitoring of the sky has started. The alert sending to SNEWS will be implemented before the end of the year. At the end of 2019 with ORCA6 and ARCA2, KM3NeT will be able to detect a CCSN up to the Galactic Center.

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1. Introduction

The KM3NeT neutrino detectors ORCA and ARCA (Oscillation & Astroparticle Research with Cosmics in the Abyss) are under construction at two underwater sites in the Mediterranean Sea. ORCA is located off the French coast (Toulon), and ARCA off the Italian coast (Capo Passero). The main goal of ORCA is the determination of the neutrino mass ordering, exploiting a densely instrumented detector with sensitivity at the GeV scale. ARCA is dedicated to the search for high energy (TeV-PeV) astrophysical neutrino sources, using a large km^3-scale instrumented volume [1]. However, it is possible to use ARCA for particle physics research (dark matter, sterile neutrino) and ORCA for astronomy (solar flares, merger of neutron stars, X-ray/gamma-ray binaries…). Both detectors are based on the same technology: the Cherenkov light induced by charged secondary particles emerging from neutrino interactions is detected using a three-dimensional deep-sea grid of photo-sensors with single-photon sensitivity and nanosecond time resolution. The core element of the KM3NeT detectors is the digital optical module (DOM) featuring 31 directional photomultiplier tubes (PMTs) in a spherical glass sphere [2]. DOMs are connected in groups of 18 to form a vertical line called detection unit (DU), while a group of 115 DUs forms a building block. ORCA will comprise one building block with an instrumented volume of 8 Mtons of water, ARCA will consist of two building blocks, together covering one cubic kilometre. Both detectors are already collecting data with first detection units since few years. All data above noise threshold are sent to shore via optical fibres and are filtered for event signatures in an online computer cluster (see [2] for more details). The standard analysis chain consists on apply triggers to filter events from the noise (~99% reduction of the rate) and then estimate the event parameters (time, direction, energy, topology, quality) using very performant event reconstruction algorithms.

Although KM3NeT detectors are mainly designed for high-energy neutrino detection, the 10 MeV scale neutrino signal from a CCSN can be identified thanks to the multi-PMT optical module technology and a large instrumented volume. The main interaction channels of these MeV neutrinos in water are:

- Interaction with free protons (Inverse Beta Decay, IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$
- Interaction with free electrons (Elastic Scattering, ES): $e^- + \nu \rightarrow e^- + \nu$
- Interaction with oxygen nuclei: $\bar{\nu}_e + {}^{16}O \rightarrow e^{-(+)} + X$

The dominant process is the Inverse Beta Decay. The outgoing electron or positron induces the production of Cherenkov light that can be detected by the PMTs. The length of the Cherenkov emission is some cm. In particular, IBD interactions lead to charged particle tracks of about $0.5cm * \frac{E_\nu}{MeV}$ length [6]. It is then not possible to reconstruct the event topology because to the short track size from low energy positrons/electrons compared to the large distance between the DOMs.

Therefore, for this SN analysis, we had to develop a completely different analysis based on a real-time monitoring of the DOM counting rates in the full detector. The main challenge is clearly that we need to filter from the huge data rate only few potentially interesting events. As we cannot use the standard filters based on the causality, we have to fight against the ^{40}K, the bioluminescence and the low-energy atmospheric muon background.

In this document, we report on the specific analysis scheme and the computation of the sensitivity to a CCSN neutrino signal (Section 1), the implementation of the SN detection analysis in the online analysis of both KM3NeT detectors (Section 2). Section 3 describes the challenges of such analysis and the status is summarised in Section 4.

2. Sensitivity to a supernova neutrino signal

The detection of neutrinos from SN1987a represents the first multi-messenger source detected both by electromagnetic radiations and neutrinos. Only few tens of detected neutrinos had a huge impact on the understanding of the supernova physics. With the new generation instruments (IceCube, KM3NeT, Super Kamiokande…), we may expect more than 1000 to 100000 neutrinos for the same type of events, it will allow to study in details particle physics, astrophysics and nuclear physics.

A CCSN occurs as a consequence of the collapse of the iron core of a massive star into a proton-neutron star. The explosion is driven by the shock wave originating by the bounce of the infalling matter of the core and propagating to the outer layers. The neutrino emission is articulated in three main phases, each one with a characteristic signal:

1. the breakout burst, marked by a fast (tens of milliseconds) release of neutrinos originated in electron capture processes, resulting in a large peak in the ν_e luminosity;
2. the accretion phase, when the shock stalls and the core is stirred by violent hydrodynamic instabilities, which can last up to several hundred milliseconds and is dominated by $\nu_e - \bar{\nu}_e$.
3. The cooling phase of the core, characterised by an all-flavor neutrino emission with progressively decreasing luminosity, lasting up to some tens of seconds.

The neutrino time profile of the three phases is shown in Figure 1. In this study, only a simulation of the accretion phase is considered. The sensitivity to the ν_e signal of the burst is very low and its contribution can be neglected. The luminosity of the cooling phase is also low compared to the detector background.

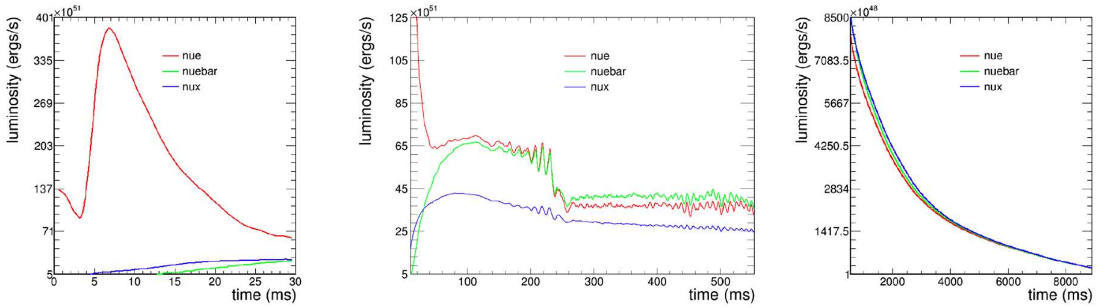

Figure 1: Neutrino luminosity as a function of time expected from simulations of the neutrino burst (left), the accretion phase (middle) and the cooling phase (right) of a CCSN.

The specific SN analysis is based on the detection of a coherent increase of the DOM counting rate in a few hundreds of milliseconds. Background rates have been estimated from the data of the first ORCA and ARCA detection lines deployed in the sea. Three relevant sources of background are of interest for this study: bioluminescence, radioactive decays in sea water (mostly ^{40}K) and atmospheric muons. Coincidences at the few nanosecond-scales between the different PMTs of a DOM are a signature of a multi-photon emission typical of Cherenkov radiation. The number of PMTs in a DOM detecting a photon within a time window of 10 ns is later on referred to as multiplicity (M). Figure 2 shows the coincidence counting rate as a function of the multiplicity. Radioactive decays in sea water and atmospheric muons are the dominant contributions to the multiplicity spectrum in the ranges $M \leq 5$ and $M \geq 8$, respectively. In between, there is a mix of these two components. The contribution of coincidences from uncorrelated photons produced by bioluminescence or radioactive decays becomes negligible above M = 3. Atmospheric muons are mainly rejected by vetoing simultaneous detection of $M \geq 4$ events by several DOMs within one microsecond scale window.

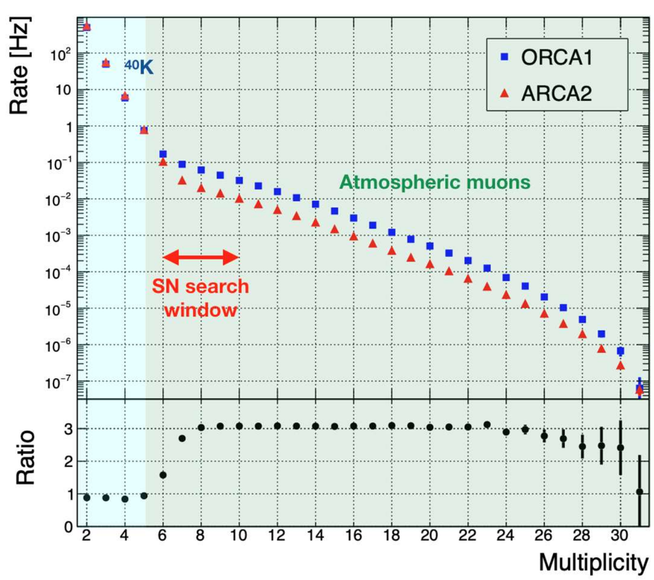

Figure 2: DOM coincidence rates as a function of the multiplicity measured for the ORCA1 and ARCA2 detectors.

The sensitivity of the CCSN search has been determined using state-of-the art 3D simulations from the MPA Garching group [3, 4] that provides the time dependent CCSN neutrino spectrum for the accretion phase for a CCSN stellar progenitor of 27 and 11 $M_{\odot}$. As the SN neutrino signal is strongly variated in time, it is important to get the expected time-dependent profile that will be used directly in the analysis.

CCSN neutrino interactions in the instrumented volume result in an increase of the counting rates of individual PMTs as well as at the various multiplicity levels. Simulations are used to optimise the multiplicity selection in order to discriminate the CCSN neutrino signal from background resulting in the criterion $6 \leq M \leq 10$. The coincidence rates measured for the first two ARCA DUs (ARCA2) and the first ORCA DU (ORCA1) [5] are shown in Fig. 3.

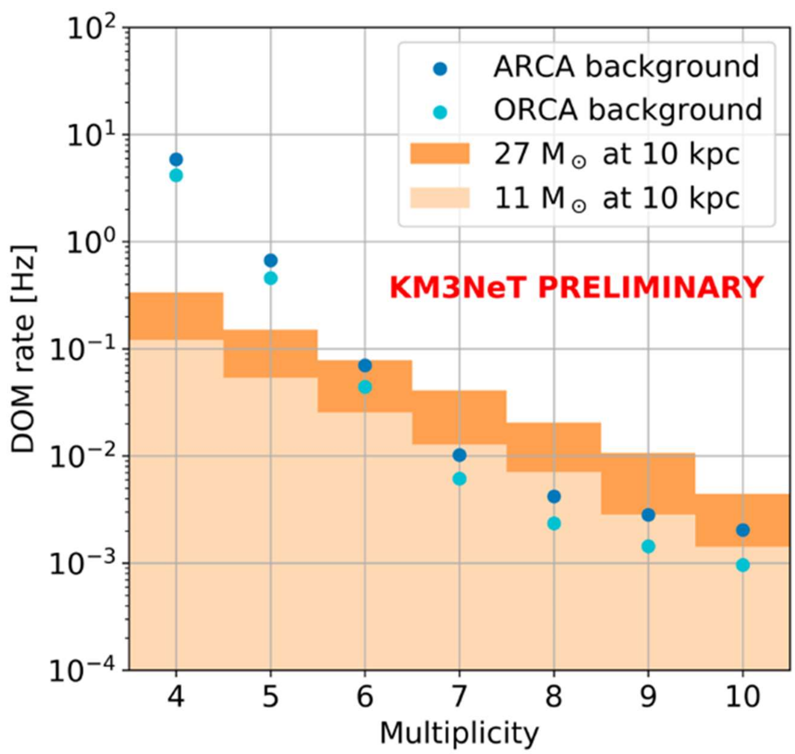

Figure 3: Estimated DOM background rates after muon rejection for ARCA and ORCA compared with the signal expectation at 10 kpc for the 27 $M_{\odot}$ (550 ms window) and the 11 $M_{\odot}$ (350 ms) progenitors.

In Table 1, the expected number of detected events as a function of the multiplicity is reported for the two considered stellar progenitors, with masses respectively of 27 and 11 $M_{\odot}$ at a reference distance of 10 kpc.

M	1	2	3	4	5	6	7	8	9	10
N_{ev} $27M_{\odot}$ (543 ms)	1.6E5	5.0E3	1.0E3	3.8E2	1.7E2	88	46	23	12	5
N_{ev} $11M_{\odot}$ (340 ms)	4.1E4	1.2E3	247	85	38	18	9	5	2	1

Tableau 1 : Expected number of signal events as a function of the multiplicity for one instrumented block. Statistical uncertainties from the Monte Carlo simulations are below 1% up to M = 5 and from 1% to 4% in the 6 ≤ M ≤10 range.

The expected sensitivities for the two extreme mass progenitor assumptions (11 and 27 $M_{\odot}$) is shown in Fig. 4 (left) for ORCA, ARCA and the combination of the two detectors. Combining the two complete KM3NeT detectors, a significance of 5 σ is achieved for a CCSN at 25 kpc with a mass of 27 $M_{\odot}$, ensuring the coverage of the full Galaxy. In the case of the 11 $M_{\odot}$ progenitor, a significance of 5σ is reached beyond the Galactic Centre with the full ORCA detector alone. The error region takes into account the statistical errors and the following systematic effects:

- +- 10% on the variation on the number of active DOMs in the detectors
- +- 20% on the uncertainty from model to model
- \- 15% from the difference between the normal mass ordering (line plotted) and inverted ordering of the neutrino oscillations.

The results for 6 ORCA DUs and 2 ARCA DUs, expected to be operational by the end of 2019, are 5σ discoveries at 9 and 4 kpc for the heaviest and lightest progenitor, respectively (Fig. 4 right).

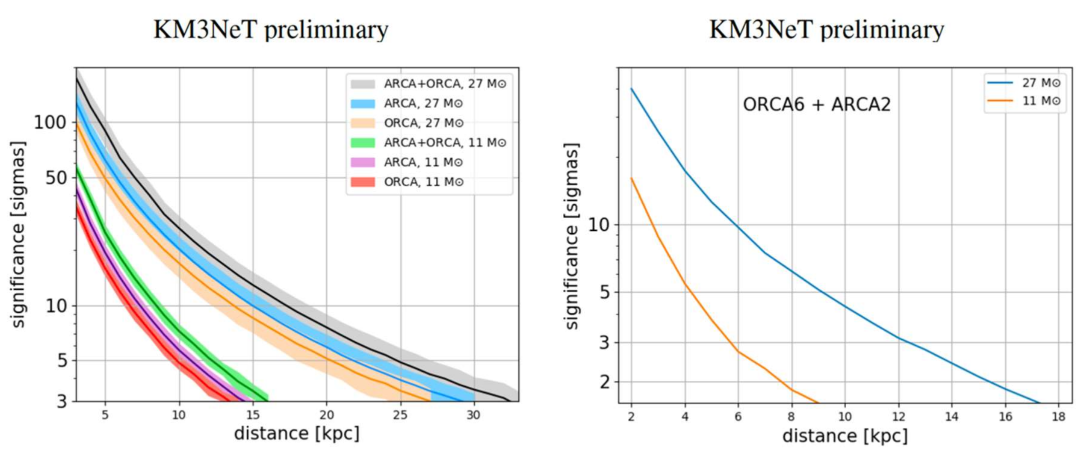

Figure 4: Detection significance of a CCSN neutrino signal as a function of the distance to the source. Left: full ORCA, ARCA and the combination of the two detectors. Right: for the configuration expected late 2019 consisting in 6 ORCA and 2 ARCA DUs.

3. Description of the online supernova framework

An online framework is being developed to handle the triggering of real-time alerts and the participation in the SNEWS network [6]. KM3NeT is implementing an all-data-to-shore data acquisition design. All hit information is sent to shore, where the data streams are assembled in a computer farm. A dedicated data stream containing all coincidences above multiplicity $M \geq 4$ is continuously acquired for online monitoring and permanent storage. The same data stream is simultaneously analysed in real time for the purpose of alert generation. A buffer for the lower multiplicity coincidence data is foreseen in order to store the maximum amount of useful raw data in case an alert is either received or self-generated. The SN processing pipeline shares a common infrastructure with the online event reconstruction for high-energy neutrino events. The structure of the processing chain is outlined in Fig. 3. The design concept is based on a common dispatcher used by multiple clients to receive and send data, making the outputs of all the processing stages simultaneously available to any client. This structure allows for the building of flexible and extensible data processing pipelines. SNEWS requires to have a false alarm rate lower than 1 trigger over 8 days.

Preliminary evaluations have been done with regards to the required time to generate a trigger. The current configuration allows for an alert to be produced within 20 seconds from the generation of the corresponding data off-shore, a fast response compared to the current SNEWS latency. Further optimisation can be foreseen if beneficial for the SNEWS network.

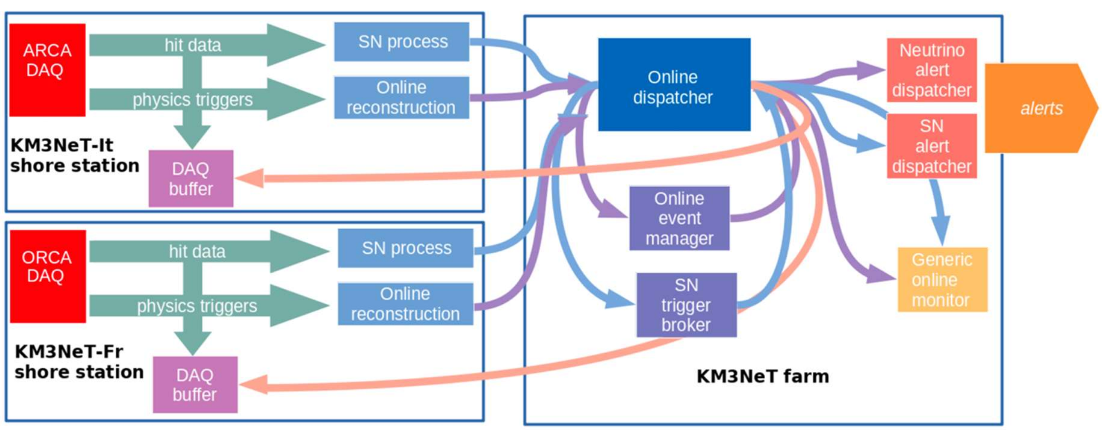

Figure 5: Functional diagram of the KM3NeT DAQ system and online framework outlining the information exchange between the two shore stations and the central farm dedicated to the real-time processing applications.

4. Challenges

As described in the introduction, this SN analysis is a completely different type of analysis compared to what we used to perform in high-energy neutrino telescopes. It does not rely on the event triggers and reconstructions, and cannot benefit from the huge background rejection of the trigger and reconstruction conditions (no causality). We had to develop a complete new analysis strategy based on the detection of a global increase of the PMT counting rates over the complete detectors. This SN analysis has by definition the lowest threshold and is completely background dominated. We had to implement an analysis that allows to monitor the huge data rate to look for a CCSN signal in a 500 ms sliding time windows. We had to define efficient background rejection techniques based on local coincidence to suppress the 40K and bioluminescence contributions and to veto the atmospheric muon background using coincident neighbor DOMs. As the bioluminescence and thus the number of active channels (if the counting rate of a PMT is too high, it passes in high-rate veto and so it is not participating to the acquisition anymore for a short period of time) varies strongly in the time, the developed analysis had to be independent of this time variation.

We have used directly the data to extract the background time distribution to be as close as possible to the real situation. For the preliminary studies presented in Section 2, the background estimations for ORCA and ARCA have been deduced from the data of about few months of the first operating DUs. It requires very deep studies of the data acquisition and the background estimation. It has also served the other KM3NeT analysis as the tools for the SN analysis are very efficient monitoring tools. It also requires very complete simulation of the detector (PMT and electronic responses, water properties, light propagation).

The main limitation is the extrapolation of the background behaviour from 1-2 DUs to the full detector and to the full analysis period. For the alert sending to SNEWS, it requires to monitor perfectly this background level to be able to send supernova alerts with a stable false alarm rate (actually fixed at 1 alert every 8 days).

5. Conclusion and perspectives

Thanks to the WP7 resources, we have been able to evaluate the expected response of the KM3NeT neutrino detectors to core-collapse supernova neutrinos with complete Monte Carlo simulations and exhaustive studies of the background from the first KM3NeT datasets. These results show that KM3NeT will be a very competitive contributor to the network of neutrino detectors observing the next Galactic CCSN.

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