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Detecting low-energy transient neutrino signals with KM3NeT

Team: G. de Wasseige (gdewasse@apc.in2p3.fr, 0157277019) for APC, CPPM, IPHC and Subatech groups

Abstract:

We propose to use the KM3NeT to study the transient sky using low-energy neutrinos. While KM3NeT-ARCA has been designed for a higher energy range (TeV) and KM3NeT-ORCA is dedicated to perform neutrino oscillation studies, we believe that the detectors are ideally suited to lead to competitive results in the MeV-GeV regime. We present the main supporting arguments as well as the observation strategy and the science cases for two specific sources.

Note: This document is a complement of *Multi-Messenger neutrino analyses* [1].

1. Introduction

In the era of multi-messenger astronomy, the transient sky holds a place of special importance for the community. Nowadays, high-energy neutrino telescopes systematically provide upper limits on the neutrino flux emitted during remarkable transient events such as compact binary mergers or gamma-ray bursts [2,3]. Contrariwise, the MeV-GeV regime has been poorly studied so far and only a few constraints have been set by e.g., Superkamiokande [4] and IceCube [5,6].

The only transient source that has been observed in this low-energy range so far is the core-collapse supernova (CCSN) SN1987A, which led to 25 MeV neutrino events detected in Kamiokande, the Irvine-Michigan-Brookhaven (IMB) and the Baksan Neutrino Observatory [7]. This unique detection marked the beginning of neutrino astronomy and allowed to confirm the baseline model of core-collapse. Despite hundreds of CCSNs detected in the electromagnetic spectrum since 1987, neutrino telescopes could not perform another observation due to the far distances of these events. It is thus of primary importance to optimize the detection channel of sensitive detectors in anticipation of a forthcoming CCSN. Beyond being used as an early warning of a galactic CCSN, neutrinos can provide unique information on the explosion mechanism, and can be used to probe neutrino oscillation in dense environment [7].

In the GeV range, neutrino experiments have so far focused on the characterization of the atmospheric neutrino flux. The GeV energy domain is therefore still a *terra incognita* in terms of astrophysical neutrino observations. Considering that astrophysical neutrino fluxes typically exhibit a power-law decrease with energy, one can expect that neutrino telescopes in this range could allow us to probe larger neutrino fluxes and possibly identify new astrophysical neutrino sources. Among the sources expected to radiate a GeV neutrino flux, we can mention gamma-ray bursts [8] and solar flares [6].

We propose to use KM3NeT to further explore the MeV-GeV energy range and to seize this experimental opportunity to develop an innovative, promising and cost-effective way to constrain/observe the low-energy astrophysical neutrino flux.

2. Description of KM3NeT

KM3NeT, the next generation neutrino telescope, is currently under deployment in the Mediterranean Sea [9]. It is composed of two different sites sharing the same detector technology: ARCA (*Astroparticle Research with Cosmics in the Abyss*) located offshore Capo Passero in Sicily (Italy) and ORCA (*Oscillation Research with Cosmics in the Abyss*) located close to the ANTARES telescope offshore Toulon (France). While the former will be dedicated to search for cosmic neutrino sources, the latter is designed to detect GeV atmospheric neutrinos passing through the Earth in order to probe the neutrino mass ordering (NMO), because of a denser array of optical modules with respect to ARCA. At the time of writing, 4 ORCA and 1 ARCA strings are taking data. Each string is made of 18 Digital Optical Modules (DOM) with 9(36) m spacing in the ORCA (ARCA) configuration. In view of improving the angular reconstruction and the noise rejection, each KM3NeT DOM is equipped of 31 photomultipliers (PMT) sensitive to the Cherenkov light emitted as a consequence of a neutrino interaction happening in the neighborhood of the detectors.
The construction will continue with higher speed in the following years in order to reach full completion in 2025, with 115 strings on the ORCA site and 230 for ARCA.

3. Event selection and observation strategy

To achieve the proposed goal, two distinct analyses need to be developed: a first one allowing the KM3NeT telescopes to be sensitive in the MeV range (15 - 30 MeV) for supernova detection, and the second one aiming at detecting GeV neutrinos (100 MeV - 10 GeV). The sources emitting in the MeV and GeV ranges may be different as well as the neutrino interactions that could potentially be detected within KM3NeT. Nonetheless, the environmental noise represents the major background at these energies and both analyses will benefit from joint efforts in attempting to model this noise.

While the atmospheric muons constitute the dominant background contribution in high-energy neutrino searches, the sub-GeV range has to face an additional contribution coming from the environment surrounding the detectors. KM3NeT ORCA and ARCA are both immersed in the Mediterranean Sea, where numerous living species have settled down. Among them are bioluminescent microorganisms, which can mimic both correlated and uncorrelated signals in the DOMs of KM3NeT. Furthermore, the salt water used to produce the Cherenkov light as a consequence of the neutrino interaction also adds some light pollution through the decay of ^{40}K.

A thorough characterization of the noise components is therefore a preliminary step. We recommend developing an empirical fit of the ambient noise as well as studying independently each component (or group of components) of the noise. The recent deployment of 4 ORCA lines and the foreseen addition of 2 more lines before 2020 will allow for a better understanding than what was previously used.

3.1 Effect of a noise modeling on the existing MeV event selection

The current supernova analysis in KM3NeT ORCA and ARCA, based on preliminary estimates of the environmental noise, would lead to e.g., a 5-σ observation for a CCSN located at 25kpc with a mass of 27 $M_\odot$, as shown in Fig 1.

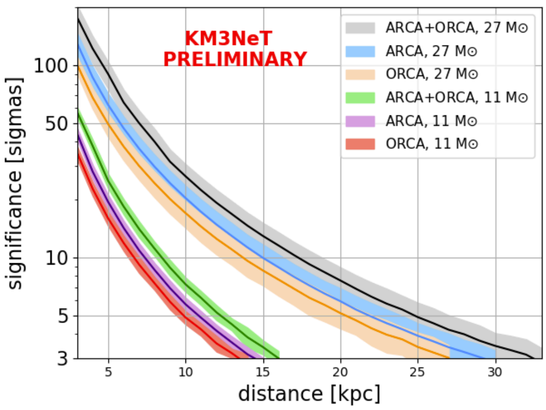

Figure 1: Detection significance of a CCSN neutrino signal in KM3NeT as a function of the distance of the source [13].

The main factor limiting the current sensitivity of KM3NeT to supernova detection is the noise rate recorded by the detectors [10]. Using the noise model to tag pure noise events leaving pre-defined patterns on the DOMs will allow us to reduce this rate and will thus directly lead to enhanced sensitivities. The current selection keeps an event if its multiplicity, i.e. the number of hits recorded by the PMTs within 10 ns, falls between 6 and 10. The lower limit is used to diminish the ambient noise contamination inside of the final sample. We will study the possibility to lower further this limit by using the noise model to differentiate potential neutrino events from noise with a multiplicity below 6. This adjustment may also lead to an enhanced sensitivity to different supernova scenarios, and in particular to time-dependent studies.

3.2 Development of a new GeV event selection

Only ORCA is currently sensitive to an event-by-event analysis in this energy range, with a threshold at 3 GeV using coincident hits recorded by neighbor DOMs. The existing event selection is dedicated to obtain a high-purity sample of atmospheric neutrino events in view of performing oscillation analyses. Preliminary studies of the potential of using ORCA to perform astrophysical searches show that this event selection in full ORCA configuration (115 strings) will be competitive with Superkamiokande as shown in Fig. 2 [11]. For transient neutrino searches, relaxed criteria could be used in view of boosting the sensitivities in short time windows. It is therefore possible to further improve the sensitivity provided that an accurate noise modeling is used.

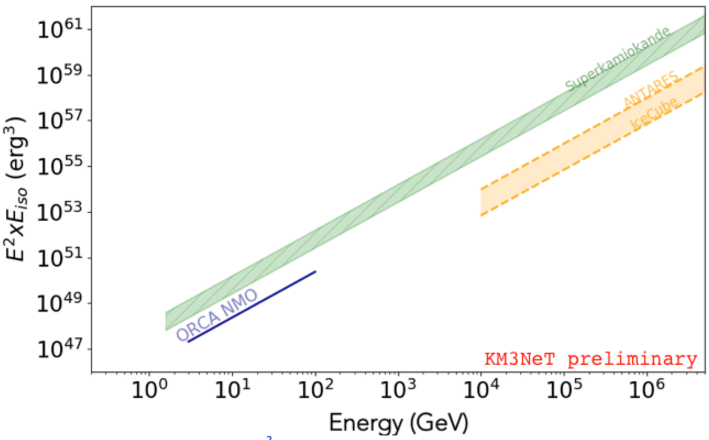

Figure 2: Comparison of E^2xEiso constraints for a neutrino search using KM3NeT-ORCA with the searches performed by Superkamiokande and using high-energy neutrinos. All analyses use a 1000s time window. We assumed the source was placed in an ideal position for ORCA, i.e. leading to upgoing events, while GW170817 was placed in the opposite position for ANTARES.

Recent efforts have focused on single-DOM pattern recognition for sub-GeV neutrinos and environmental noise emission. If a detailed noise model can be developed, one will be able to lower down the threshold using single-DOM based analysis and thus apply it to both ORCA and ARCA detectors. Such an event selection would lead to an increased sensitivity in the 100 MeV - 5 GeV range and place KM3NeT in an ideal position for follow-up searches from transient events detected via electromagnetic or gravitational waves.

4. Examples of potential sources and associated science case

4.1 Galactic Core-Collapse Supernovae

The performances of the current Supernova analysis in KM3NeT are reported in [10].
As previously mentioned, KM3NeT is expected to detect a 27 $M_\odot$ galactic CCSN at the 5-σ level. However, our studies have shown that the sensitivity to specific supernova models is limited. As an example, Standing Accretion Shock Instabilities (SASI) have been estimated to be of the order of 1σ (2σ) in a model independent (dependent) analysis of a 27 $M_\odot$ event. A cleaner event selection based on a better noise model would increase the sensitivity to CCSN signals and improve constraints that can be set on such fast-time variation models.

The KM3NeT Collaboration has recently joined the SuperNova Early Warning System (SNEWS) and will participate to the efforts deployed by the neutrino community to alert electromagnetic partners in case of a galactic CCSN. Beyond the early warning that can be provided, neutrino telescopes can also be combined within a network in view of triangulating the position of the supernova. To achieve a good resolution in this triangulation, clean light curves recorded by the participating neutrino telescopes are required. While the presence of KM3NeT is already helpful, an improvement of the analysis, and thus a cleaner light curve, is needed to compete with capabilities of other large neutrino telescopes such as IceCube.

4.2 Gamma-Ray Bursts

In the particular case of GRBs, GeV and TeV neutrinos are expected from different processes: while TeV neutrinos are predicted as a consequence of the internal shock in the prompt emission phase of the GRBs, GeV neutrinos would be produced by collisions of neutrons and protons following decoupling [8]. Besides offering an evidence of hadronic acceleration mechanisms, the detection of GeV neutrinos from GRBs would also constitute a probe of the amount of matter surrounding the astrophysical object, allowing to better constrain the environment, acceleration process, and progenitor of these phenomena.

Until recently, the Superkamiokande detector, optimized for neutrinos in the MeV-GeV range, was the only neutrino detector able to provide limits on the astrophysical neutrino flux in the GeV regime. It has set, among others, limits from the recent binary neutron star merger [4]. The 50 ktons of Superkamiokande however limit the flux that can be probed, and Mton-scale neutrino devices are needed to search for fainter sources. IceCube, and in particular its low-energy, denser infill detector DeepCore, represents nowadays the only attractive alternative to study the GeV range. Recent developments have allowed IceCube to be sensitive to GeV neutrinos from astrophysical sources such as solar flares or binary mergers [6,5]. Competitive limits from both Superkamiokande and IceCube are thus expected in the upcoming years. Unfortunately, the large photosensors of IceCube-DeepCore, originally optimized to search for neutrinos with energies above 10 GeV, are too distant from each other. Both efficient detection and directional reconstruction are therefore challenging for GeV neutrino interactions. The most appealing alternative to overcome both volume limitations of Superkamiokande and sensitivity limitations of IceCube is the next-generation neutrino telescope KM3NeT.

5. Summary

In the coming years, the fraction of KM3NeT that is deployed and taking data will continuously increase. This will allow us to start probing both MeV and GeV neutrino emission from transient phenomena detected via electromagnetic or gravitational waves. While the examples of galactic core-collapse supernovae and gamma-ray bursts were considered in this white paper, we note that similar analyses may be applied to other transients, such as solar flares, gamma-ray novae, or fast radio bursts. Dedicated analyses for each of these transients will be developed in the coming years within the KM3NeT Collaboration, guaranteeing a large visibility to the impact of KM3NeT in low-energy neutrino astrophysics.

References

[1] D. Dornic for the KM3NeT groups, *Multi-messenger neutrino analyses*, these Prospectives
[2] A. Keivani et al., PoS(ICRC2019)930
[3] M. Colomer et al., PoS(ICRC2019)856
[4] SuperKamiokande Collaboration, Astrophys.J. 857 (2018)
[5] G. de Wasseige et al., PoS(ICRC2019)865
[6] G. de Wasseige, PoS(ICRC2019)866
[7] K. Scholberg, Ann.Rev.Nucl.Part.Sci. 62 (2012)
[8] K. Asano et al., Adv. Astron., 568516 (2015)
[9] KM3NeT Collaboration, J.Phys. G43 (2016) 8
[10] M. Colomer et al., PoS(ICRC2019)857
[11] G. de Wasseige et al., PoS(ICRC2019)934