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# Probing astrophysical GeV neutrino emissions with IceCube and KM3NeT

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**Abstract.** In the last decade, Cherenkov neutrino telescopes have provided valuable insights into the sources and acceleration mechanisms responsible for the high-energy neutrino flux observed at Earth. These instruments utilise large volumes of naturally occurring optically transparent materials, such as the Antarctic ice for IceCube and the Mediterranean Sea water for KM3NeT. Specifically, IceCube, encompassing a cubic kilometre of glacial ice, and KM3NeT, currently being deployed and soon reaching a similar size, offer complementary sky coverage, ushering in a new era of neutrino astronomy. Although both are optimised for detecting TeV to PeV neutrinos, recent advancements in analysis techniques have lowered the energy threshold and increased sensitivity to astrophysical GeV neutrinos. Despite high background rates at low energies, the large instrumented volumes allow for good sensitivity to transient sources, which in turn can be used to constrain theoretical flux predictions. We examine the case of GRB 221009A and the follow-up analysis of the observing runs of LIGO and Virgo. Furthermore, we discuss ongoing efforts to enhance these sensitivities through dedicated machine learning techniques aimed at improving signal-to-noise discrimination down to 100 MeV.

## 1 Introduction

The rising interest in high-energy neutrino astronomy over the past decade has motivated the development of several large-volume detectors, following the footsteps of the IceCube Neutrino Observatory. In these proceedings we discuss the role that IceCube and KM3NeT play in the search for low-energy (O(GeV)) astrophysical neutrinos.

IceCube is a neutrino detector situated beneath the ice at the geographic South Pole [1]. It monitors a cubic kilometre of Antarctic ice using 5160 Digital Optical Modules (DOMs), each containing a photomultiplier tube (PMT). These DOMs capture Cherenkov light, emitted by charged leptons resulting from neutrino interactions with the ice, enabling the reconstruction of the incoming neutrino's direction and energy.

Similarly, KM3NeT is a Cherenkov neutrino telescope operating at the bottom of the Mediterranean Sea. It comprises an array of Detection Units (DUs), each equipped with 18 DOMs, and each DOM is equipped with 31 3" PMTs [2]. KM3NeT consists of two separate blocks: KM3NeT/ORCA, near Toulon in the south of France, optimised for detecting GeV

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neutrinos, and KM3NeT/ARCA, located near Capo Passero in Sicily, more sensitive to neutrinos with energies ranging from TeV to PeV. The detector is currently being deployed, and it will result in an instrumented volume of about 1 cubic kilometre for KM3NeT/ARCA, and $3.6 \times 10^6$ m$^3$ for KM3NeT/ORCA. Due to its latitude, KM3NeT offers complementary sky coverage to IceCube in the search for high-energy neutrino sources.

While both IceCube and KM3NeT are optimised for detecting high-energy ($E_\nu \gtrsim 10$ GeV) neutrinos, their large instrumented volumes also offer an advantage in the search for few-GeV astrophysical neutrinos. At energies around $E_\nu \sim 1$ GeV, the signature produced in the detector is either comparable to or smaller than the distance between neighbouring DOMs. As a result, energy and direction reconstruction is not feasible at such low energies. However, in the context of multi-messenger astronomy, searching for time correlations between candidate low-energy neutrinos and known transient sources has allowed IceCube to set competitive upper limits on neutrino emissions, comparable to those from Super-Kamiokande [3].

## 2 Low-energy neutrinos from GRB 221009A

On October 9th 2022 the Gamma-ray Burst Monitor, onboard the Fermi satellite, detected an exceptionally bright Gamma-ray Burst (GRB). This event (GRB 221009A) is known to be the brightest GRB ever observed, and it sparked interest in the neutrino community as it represented a unique opportunity to probe GRBs' emission models.

In particular, it is predicted that pion production in the jets of GRB 221009A would produce neutrinos with energies between 1 – 100 GeV [5], hence falling within the sensitivity range of IceCube's low energy selections. Figure 1 shows the upper limits on the neutrino flux as function of energy, obtained with the ELOWEN [6] and GRECO selection [7] as presented in [4]. In the low-energy range, i.e., $E_\nu < 10$ GeV, the ELOWEN sensitivity is limited by the absence of direction reconstruction for neutrinos. However, searching for time correlation with gamma-ray observation allows us to still constrain a significant portion of the parameter space.

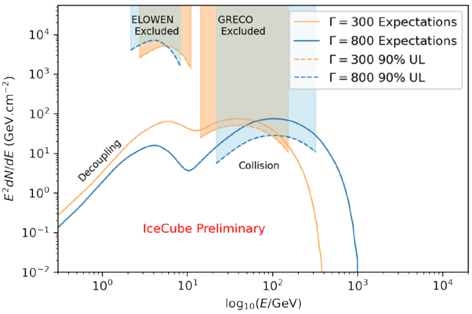

**Figure 1.** IceCube constraints (dashed lines) on neutrino flux predictions (solid lines) of GRB 221009A assuming different values of the Lorentz factor Γ. Figure taken from [4]

## 3 Gravitational wave follow-up

Low-energy neutrinos are also instrumental in searching for coincidences with gravitational waves detected by the LIGO and Virgo observatories. Such observations could provide valuable insights into the nature of compact binary mergers. Similar to the case of gamma-ray bursts (GRBs), neutrinos with energies of a few GeV are expected to originate in the dense environments surrounding these mergers.

As described in [8], the IceCube ELOWEN selection has been used to set upper limits on neutrino emission associated with mergers corresponding to gravitational waves observed at the start of the O4 observing run. With the growing number of detected gravitational wave events, stronger constraints are anticipated through stacking analyses, e.g, as done at higher energies for O1-O2-O3 events in [9].

## 4 Improvements on the IceCube ELOWEN selection

Although neutrinos with energies $E_\nu \sim 1$ GeV do not produce a sufficiently large signature in IceCube for precise directional reconstruction, ongoing efforts described in [10] demonstrate that the current IceCube ELOWEN selection can be enhanced to enable positive versus negative zenith classification of low-energy neutrinos. Notably, 60% of neutrinos passing the ELOWEN selection, with energies in the range $0.5-5$ GeV, can be correctly identified as up-going or down-going with 77% accuracy.

This classification is achieved using dedicated boosted decision trees, which exploit the temporal and spatial distribution of deposited charge along a single IceCube line. The resulting improvement in signal-to-noise ratio enhances the search for neutrino counterparts to transient sources. These advancements are particularly beneficial for studies of well-localized, short-duration transients, such as GRBs.

## 5 Novel KM3NeT MeV-GeV event selection

The unique multi-PMT design of KM3NeT's DOMs provides an opportunity to extract additional information about the small-scale structure of recorded events. The method described here, and further detailed in [11], introduces a novel approach for KM3NeT to search for MeV-GeV neutrinos from transient sources. Neutrinos in this low-energy range fall outside the detector's current sensitivity.

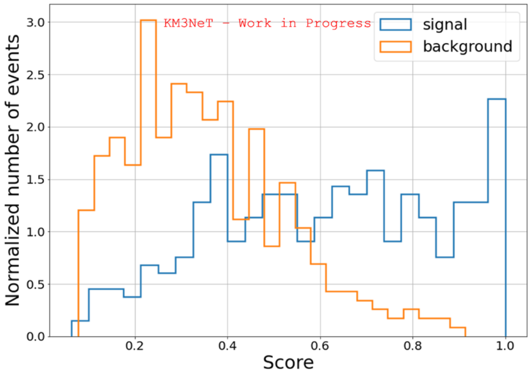

**Figure 2.** GNN Score distribution of single-DOM events from MeV-GeV neutrino simulations (signal), and KM3NeT low level data (background). Figure taken from [11]

A combination of hard cuts and machine learning techniques is expected to improve a single-DOM event selection. This work is motivated by the expectation that the coherent Cherenkov cone signature, produced by the interaction of MeV-GeV neutrinos in water, can be distinguished from dominant background sources in KM3NeT. These backgrounds primarily arise from the radioactive decay of $^{40}$K, abundant in seawater, and bioluminescence.

Single-DOM events are defined as instances where at least three consecutive PMT hits occur on the same module. A PMT registers a hit when it detects signals exceeding 0.3 photo-electrons. For hits to be considered consecutive, they must occur within 30 ns of each other, and hits lasting less than 6 ns are excluded from the selection.

Two datasets were constructed for this analysis: one from simulated MeV-GeV neutrino interactions (signal) and another from low-level detector data (background). Each event is encoded into a 31-node graph, with nodes representing individual PMTs on the DOM. Edges between nodes correspond to geometrically adjacent PMTs, preserving the DOM's spatial structure in the data representation.

These datasets were used to train the Graph Neural Network (GNN) based on the model in [12]. Figure 2 illustrates the model's performance on a previously unseen subset of events, comprising 1,750 samples split evenly between simulation and detector data. The testing subset, representing 40% of the total dataset, was limited by the low statistics available for low-energy neutrino simulations at the time of the analysis.

Preliminary results demonstrate promising separation between signal and background samples, suggesting an improved sensitivity to low-energy neutrinos in KM3NeT by leveraging the multi-PMT DOM design. Additionally, as multi-PMT modules will be included in the upcoming IceCube Upgrade [13], similar methods are being developed for noise rejection in the context of IceCube.

## 6 Conclusions

Over the past decade, Cherenkov neutrino telescopes like IceCube and KM3NeT have significantly advanced our understanding of high-energy neutrino sources and their underlying acceleration mechanisms. By leveraging advanced data analysis and machine learning techniques, these detectors have expanded their capabilities to energies around $E_\nu \sim 1$ GeV, and probed low-energy emissions from transient sources, such as GRBs, as well as gravitational wave counterparts. Efforts to further improve sensitivity in the MeV-GeV range include the use of more sophisticated analysis methods, such as IceCube's zenith reconstruction at $0.5 - 5$ GeV, as well as advancements in detection technologies like KM3NeT's multi-PMT DOMs. These innovations continue to push the frontiers of neutrino astronomy.

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