# Neutrino Follow-Up Analysis of GRB 221009A with KM3NeT

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**Abstract.** Gamma-ray bursts are powerful explosions emitting high-energy photons, followed by a less energetic afterglow emission. They occur at a rate of a few per day in the observable Universe. After more than fifty years of detection and characterisation in the electromagnetic spectrum, they are considered potential sources of extragalactic cosmic rays. Despite no neutrinos have been detected so far in coincidence with these violent phenomena, numerous models predict neutrino emissions by different mechanisms.
On October 9th, 2022, several experiments, including the Swift and the Fermi satellites, detected an extraordinarily bright burst, referred to as GRB 221009A, for which the LHAASO observatory reported photons detection up to ~10 TeV. This energetic transient event presented an exceptional opportunity for the search for neutrinos in temporal and spatial coincidence.
The KM3NeT undersea neutrino infrastructure was operating with 21 lines of the ARCA telescope and 10 lines of the ORCA detector at the time of this event, allowing for a real-time search for neutrinos from GRB 221009A. A refined study including data reprocessing and systematics effects was conducted covering multiple time windows in a wide energy range, from MeV up to a few PeVs. This contribution summarises the main results of the analyses, focusing on how KM3NeT performs the follow-up of gamma-ray bursts in a multi-messenger context.

## 1 Introduction: GRB 221009A

GRB 221009A is a gamma-ray burst (GRB) event with an unprecedentedly large fluence value ($\sim 0.19$ erg·cm$^{-2}$) and isotropic-equivalent luminosity (around $10^{54}$ erg·cm$^{-1}$), which has earned it the alias of the *Brightest Of All Time* (BOAT) [1]. The reasons for this outstanding measured intensity are thought to be its proximity, with a redshift of $z = 0.151$, combined with a very collimated jet emission [2]. The $T_{90}$ central emission time was estimated to be around 327 s [3].

The sky location of GRB 221009A (Dec=+19.77350° and R.A.=288.26452° as reported by Swift [4]) was extensively observed by numerous satellites and ground-based facilities, marking one of the largest follow-up campaigns ever. The LHAASO Collaboration reported the detection of photons above 10 TeV compatible with GRB 221009A, representing the highest energy ever detected from a GRB so far [5, 6]. The Fermi-LAT satellite also reported the highest energy photons ever detected for this instrument, ~ 99 GeV [7].

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No neutrino event has ever been found to be in correlation with a GRB event. However, there are many theoretical models proposed that could explain a neutrino emission, like photomeson production, jet propagation processes or subphotospheric production (see review at [8]). The remarkable properties of GRB 221009A motivate a dedicated search for neutrinos coming from this event, as presented in this contribution.

## 2 The KM3NeT neutrino detectors

KM3NeT [9] is a research collaboration building two underwater neutrino telescopes in the Mediterranean Sea. The detectors consist of three-dimensional arrays of Photomultiplier Tubes (PMTs) that can detect the Cherenkov light induced by the products of the neutrino interaction. The PMTs are housed within spherical structures known as Digital Optical Modules (DOMs), which are arranged along vertical strings called Detection Units (DUs) [10].

KM3NeT/ARCA, located 100 km offshore Portopalo di Capo Passero (Sicily, Italy), has a separation between DOMs that optimises the neutrino detection in the TeV−PeV energy range. KM3NeT/ORCA, located 40 km away from Tolon (France), has a larger DOM density that allows to cover the GeV−TeV neutrino energy range. MeV neutrinos can also be detected through a global increase in the PMT light coincidence rate in single DOMs.

At the time of GRB 221009A, the location of the event was above the local horizon of the KM3NeT detectors, a region of the sky dominated by atmospheric muon background events. Both ARCA and ORCA were taking good-quality data suitable for physics analyses, with ARCA operating 21 DUs and ORCA 10 DUs. These values represent around a 9% of the planned full-detector configuration.

## 3 Correlation analyses results

Three days after GRB 221009A occurred, the KM3NeT Collaboration reported the results of a real-time search for neutrino counterparts [11]. No candidate neutrino events were found during the time window $[T_0 - 50\,\mathrm{s}, T_0 + 5000\,\mathrm{s}]$. Additionally, a real-time analysis in the MeV range was conducted, with no significant detection.

Later, a refined search was conducted using recalibrated data that include the dynamical positioning of the DUs by acoustic methods. These analyses also incorporate the use of Monte Carlo simulations to characterise the expected neutrino signal, in order to improve the event selections and derive upper limits in the non-detection case. All the GeV−PeV searches consider the typical differential neutrino flux $\Phi(E) = \Phi_0(E/E_0)^{-2}$, with $E_0 = 1$ GeV.

The analyses in the GeV−PeV energy range are based on a standard ON/OFF binned technique [12]. The ON region is defined as the area where the signal is expected, while the OFF region comprises sky bands used to estimate the expected atmospheric background. For time windows longer (shorter) than a day, equatorial (local) bands are used for the OFF region to account for the effect of the Earth's rotation. The expected background in the ON region is determined by

$$n_{\mathrm{bckg}} = \frac{\Omega_{\mathrm{ON}}}{\Omega_{\mathrm{OFF}}} \times \frac{T_{\mathrm{ON}}}{T_{\mathrm{OFF}}} \times N_{\mathrm{OFF}}, \tag{1}$$

where $\Omega$ is the solid angle, $T$ is the time window covered and $N_{\mathrm{OFF}}$ is the number of events in the OFF region after the final event selection.

The analyses employ track-like events, which have a topology of the light inside the detector compatible with a straight line. These events provide the best angular resolution, with an estimated median value of 0.8° for ARCA and 1.2° for ORCA after considering

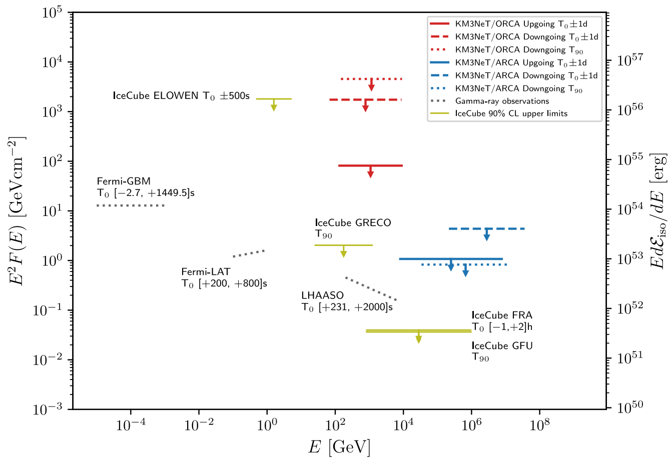


**Figure 1.** 90% CL upper limits on the energy-scaled time-integrated per flavor neutrino flux from GRB 221009A, for ORCA (red lines) and ARCA (blue lines). The right axis indicates the differential isotropic equivalent energy. The results obtained by IceCube, taken from [14], are also shown (green lines). For visualization purposes, the gamma-ray observations are also included (gray dashed lines), from Fermi-GBM [15], Fermi-LAT [7], and LHAASO [5].

systematic effects like the detector's absolute orientation. Cascade-like events, which are those with a quasi-spherical light topology, are not considered for these analyses.

Four different cases are inspected. The $[T_0, T_0 + T_{90}]$ and $[T_0 - 50\text{s}, T_0 + 5000\text{s}]$ time windows are analysed using only downgoing events (i.e. events above the detector's local horizon), given the KM3NeT visibility of GRB 221009A. The $T_0 \pm 1$ day period is also inspected in two separate event selections, one above the local horizon and another one below. The latter, called upgoing search, focuses on events crossing the Earth before reaching the detector and is motivated by the fact that the integrated visibility of GRB 221009A for KM3NeT is $\sim 45\%$ at the declination of the event.

The event selection is optimized to reduce the atmospheric background to a level in which one event inside the ON region is sufficient to provide at least a $3\sigma$ significance. Among all the event selections that satisfy this condition, the one chosen is the one that maximizes the detector's effective area, which is the quantity that provides the expected number of signal events when convoluted with a flux. Systematic effects, like the seawater properties, are considered in the computation of the effective area.

The results for these searches are presented in [13]. No candidate neutrino event has been found inside the ON region for any of the searches performed. Therefore, upper limits on the neutrino emission from GRB 221009A have been derived, considering the effective area of the detector configuration used. The most restrictive limits in the normalisation factor $\Phi_0$ are found for the upgoing searches, which are $6.2\times10^{-6}$ GeV$^{-1}$cm$^{-2}$s$^{-1}$ for ARCA and $4.7\times10^{-4}$ GeV$^{-1}$cm$^{-2}$s$^{-1}$ for ORCA. This is expected provided the lower atmospheric contamination in this part of the sky compared to the other searches, which favours a larger effective area.

An independent search for a burst of $\bar{\nu}_e$ in the MeV energy range has been also conducted, exploring for a global increase in the PMT coincidence rate of single DOMs. The sensitive energy range of the search is 5−30 MeV. No significant excess has been observed, leading for the determination of upper limits on the total time-integrated neutrino flux and on the total energy emitted in isotropically distributed MeV neutrinos by the source. These results have been derived for a quasi-thermal neutrino flux $F_{\bar{\nu}_e}(E) \propto E^2 \exp(-3E/\langle E\rangle)$ at $\langle E\rangle = 15\,\mathrm{MeV}$. Two time windows have been inspected: $[T_0, T_0 + T_{90}]$, with a total $\bar{\nu}_\mathrm{e}$ upper limit flux of $2.5 \times 10^9$ cm$^{-2}$, and $[T_0 - 50\mathrm{s}, T_0 + 5000\mathrm{s}]$, with a $4.8 \times 10^9$ cm$^{-2}$ upper limit value.

Figure 1 shows the obtained upper limits for the most relevant searches. The $x$-axis represents the neutrino energy, with the horizontal lines covering the 90% sensitivity range. The $y$-axis represents the energy-scaled time-integrated per flavour neutrino flux $E^2F(E)$. The most restrictive limit for ARCA is given by the $T_{90}$ search, which is favoured since $E^2F(E)$ is a time-integrated quantity. The same argument does not apply to ORCA due to the larger atmospheric muon background. In this case, the most restrictive limit in $E^2F(E)$ is given by the upgoing search, as in the case of $\Phi_0$.

## 4 Conclusions

Multiple searches for neutrinos in correlation with GRB 221009A have been performed using data from the KM3NeT detectors. No candidate neutrino events were found in any of the searches, which motivated the determination of upper limits in the neutrino emission from this outstanding GRB. In contrast to the results of the IceCube Collaboration, these results are limited by the visibility of the event and the current partial detector configuration. However, the derived limits can be useful to probe different neutrino emission models from GRBs.

The real-time platform of KM3NeT, which is currently active, continues to search correlations between neutrinos and GRBs. Future analyses will benefit from large detector configurations and the addition of cascade-like events, which will improve the current sensitivity to cosmic neutrinos by at least one order of magnitude.

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