Search for neutrino signals in correlation with GRB 221009A using KM3Net/ARCA data

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Abstract

The following report presents a reproduction of the fast response analysis carried out by the KM3Net collaboration concerning the astrophysical event GRB 221009A. The data used for this purpose is the original dataset measured by the neutrino telescope ARCA, restricted to track-like events only. The procedurial method is explained and results show no evidence of neutrino signals in the detector in correlation with the GRB. A possible explanation is then proposed assuming certain predictions of LIV theories. This work was carried out under the supervision of Juan Palacios, member of the KM3Net collaboration, during the IFIC Summer Student Programme 2023.

Introduction

Gamma Ray Bursts, usually refered to as GRBs, are some of the most energetic and mysterious phenomena in the universe. Firstly discovered in 1967, these astrophysical sources manifest as bright transient events in the gamma-ray band, followed by an afterglow: a broadband transient with wavelengths ranging from radio to GeV-TeV gamma-rays which extends over a longer timescale of hours or even days [1]. Origin of GRBs is usually attributed to the collapse of rapidly rotating massive stars or the merger of binary neutron stars. Current models predict the production of high-energy neutrinos from acceleration processes which occur during the burst. As a result, GRBs make up the perfect candidates for being subject of study in the context of multimessenger astronomy [2-5].

The 9th of October, 2022, at around 14:00 UT, one of the instruments onboard the satellite *Swift*, the Burst Alert Telescope (BAT), reported the detection of a transient event in the gamma-ray band.

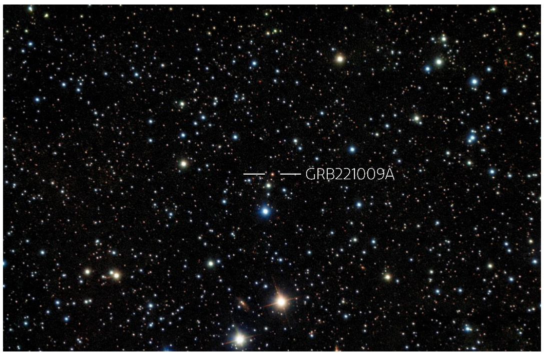

Figure 1: *Observations of GRB 221009A from Gemini South Telescope in Chile taken in the morning of Friday, October 14th, 2022. Source: "Telescopes Standing Sentry". NOIRLab. Retrieved January 17, 2023. https://noirlab.edu/.../noirlab2224a.jpg*

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Soon after, NASA's *Fermi* spacecraft confirmed the sighting and classified it as a Gamma-Ray Burst: GRB 221009A. Months later, precise measurements and results were provided by the Large High Altitude Air Shower Observatory (LHAASO) [6], reporting the detection of 64,000 photons with energies over 0.2 TeV detected within the first 3000 seconds of the burst, thus becoming the most energetic GRB to have ever been witnessed by the scientific community, see Figures 1 and 2.

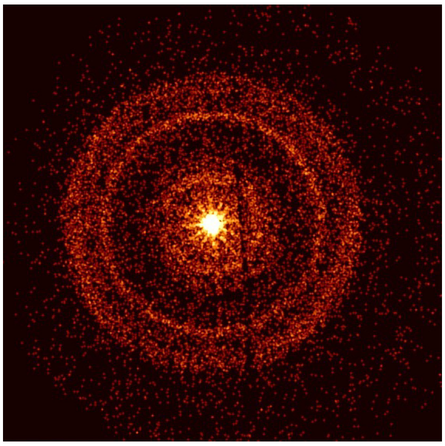

Figure 2: *Swift's X-ray image of the afterglow of GRB 221009A. X-rays are scattered by dust in the Milky Way, creating the rings around the GRB. Source: NASA/Swift/A. Beardmore (University of Leicester). https://www.nasa.gov/.../image/xrtimagecrop.jpg*

Because of this, GRB 221009A was nicknamed "the BOAT" (Brightest of All Time). However, its relevance was already acknowledged during the first hours following up the burst. A GRB of such magnitude was expected to emit high-energy particles, including neutrinos, which meant that a rapid analysis of data from different neutrino telescopes had to be performed to know whether high-energy neutrinos had been detected in coincidence with the GRB.

	Right Ascension (α)	Declination (δ)	Uncertainty Radius	Trigger Time (T_0)
Swift	19h 13m 03s	+19º 48’ 09"	0.05º (1.3σ)	14:10:17.000 UT
Fermi	19h 22m 00s	+22º 15’ 00"	1.0º (1.0σ)	13:16:59.000 UT

Table 1: *Location of the GRB in the sky in equatorial coordinates (J2000), uncertainty radius for the position and trigger time as measured by both satellites. Source: Dichiara et al. GCN 32632 (Swift) and Veres et al. GCN 32636 (Fermi-GBM).*

Fast response analysis

By *fast response analysis*, we understand the quick analysis carried out hours after the event as an instant follow up in the lookout for possible neutrino events associated with the GRB, which is crucial to rapidly inform the astrophysical community of any results via the General Coordinates Network[1] (GCN).

Spatial position and starting time information for the GRB was provided by *Swift* and *Fermi*’s entries on the GCN. The values for right ascension, declination and trigger time measured by both satellites is presented in Table 1. To perform the analysis we will use the position with lowest uncertainty (*Swift*) and the former starting time measured (*Fermi*). This gives us the following parameters to work with:

$$\begin{aligned} \alpha &= \text{19h 13m 03s} \\ \delta &= +19^{\circ}\ 48'\ 09'' \\ T_0 &= \text{13:16:59.000 UT} \end{aligned} \tag{1}$$

The data used is made up of all track-like events detected by the neutrino telescope ARCA[7] during a time span of 9 hours, starting at 09:00 UTC. As we will see later, the position of the GRB was in the down-going sky during all this time, which meant that more noise coming from atmospheric muons would then be found in our signal.

Selection cuts

Before we apply any algorithms to the data, it is essential to make sure that we are working with *good* events, meaning well reconstructed events which have a high likelihood of being generated by the high-energy neutrinos we are looking for. To achieve this, we remove from the data those events which do not satisfy certain conditions. This process is done in two separate phases: a first standard *"minimum quality cut"* and a second *"analysis cut"*, specifically taylored towards the analysis we want to perform. The *"minimum quality cut"* applies the filters shown below:

- Energy > 10 GeV
- Likelihood > 0
- Track length > 0 m
- $\beta_0 > 0$

[1] The GNC is is a public collaboration platform run by NASA for the astronomy research community to share alerts and rapid communications about high-energy, multimessenger, and transient phenomena.

Where the likelihood is a parameter measuring the quality of the reconstruction of the track, while β_0 is the angular resolution of the direction of the reconstructed track. Finally, the *"analysis cut"* in our case is applied using the following parameters:

- Energy > 1 TeV
- Likelihood > 155

All events which have been selected make up the dataset which will be used for the analysis. We can see in Figures 3 and 4 how the distributions of certain variables change when both selection cuts are applied to the data, revealing the underlying information that we can study for our purpose.

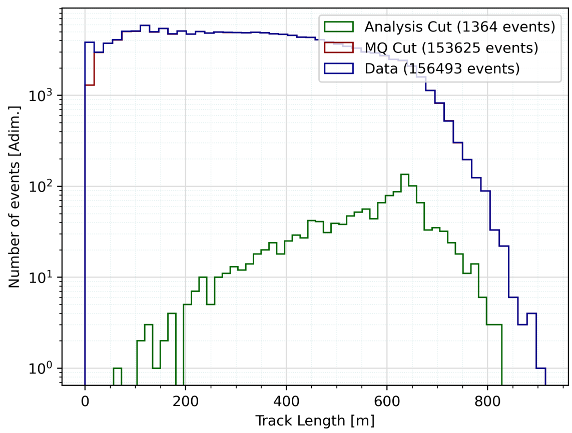

Figure 3: *Distribution for the track length after each selection cut showing 9h of measured data.*

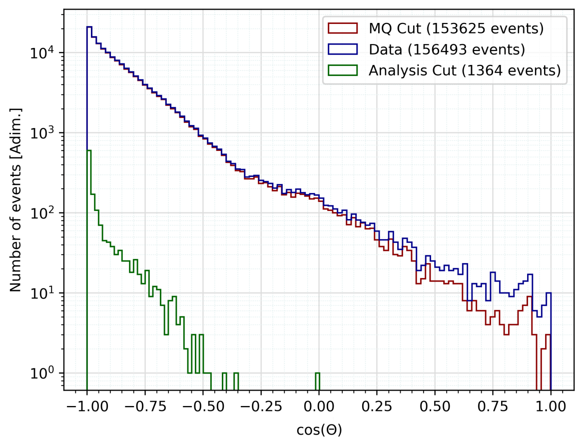

Figure 4: *Distribution for the direction of the incoming tracks (9h) after each cut, where θ is the nadir angle in local hor. coordinates.*

Time Window

In order to search for events in temporal coincidence with the GRB, we define a time interval $\mathbf{T_{ON}}$, the time window during which we would expect to detect neutrinos coming from the direction of the GRB, with a duration of 5050 seconds. Consequently, we define the complementary time interval $\mathbf{T_{OFF}}$, as the time during which we only expect background signal coming from the direction of the GRB, see Figure 5. We will use the events detected during T_{OFF} to compute the background (expected flux of neutrinos without GRB) and compare it to the number of events detected during T_{ON}.

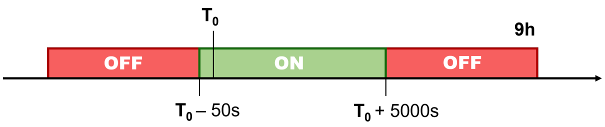

Figure 5: *Schematic representation of the time window selected around the trigger time T_0.*

Spatial window

It is important to note that, during the 9 hours of data measured by the detector, the position of the GRB in the sky varies overtime, see Figure 6. It will sometimes be useful to change between local *horizontal* (elevation, azimuth) and *equatorial* (right ascension, declination) coordinates. The former change overtime due to the rotation of the Earth, while the latter are stationary.

We will consider our region of interest to be a radius of interest (**RoI**) **of 2º** around the exact position of the GRB, defining a solid angle in the sky denoted as $\mathbf{\Omega_{ON}}$. Furthermore, the initial and final elevations of the GRB during the time window T_{ON}, give an elevation band which defines a solid angle $\mathbf{\Omega_{OFF}}$. These values are:

$$\begin{aligned} elevation\ (T_0 - 50\,s) &= 39.29^\circ \\ elevation\ (T_0 + 5000\,s) &= 55.95^\circ \end{aligned} \tag{2}$$

Taking into account the RoI, **the elevation band considered results in: [37.29º - 57.95º]**. It is now easy to compute the solid angles Ω_{ON} and Ω_{OFF}.

Background characterization

Once the values of T_{ON}, T_{OFF}, Ω_{ON} and Ω_{OFF} are known, it is possible to calculate $\langle N_b \rangle$, the expected value for the number of events from the background detected during the time window T_{ON} in the solid angle Ω_{ON} around the GRB, as is shown in (3).

$$\langle N_b \rangle = N_{OFF} \frac{T_{ON}}{T_{OFF}} \frac{\Omega_{ON}}{\Omega_{OFF}} \tag{3}$$

Where N_{OFF} is the number of events inside the elevation band during T_{OFF}.

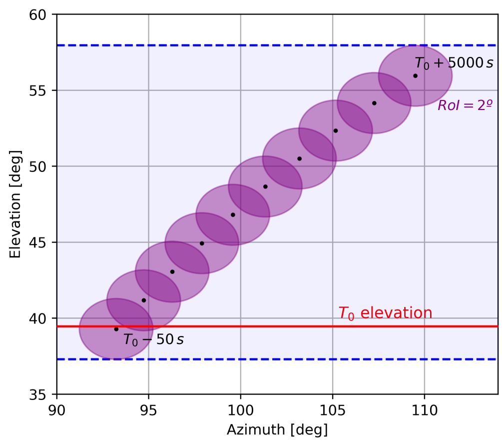

Figure 6: *Movement of GRB 221009A in local horizontal coord. during the time window $[T_0 - 50\,s, T_0 + 5000\,s]$ in intervals of 561 seconds, as seen by ARCA. The elevation band is shown in blue.*

Assuming events follow a **Poisson** distribution, we can write the expected background for the region of interest as in (4). This is basically the number of events we would expect to detect in the direction of the GRB in the absence of a flare during a time equal to the duration of T_{ON}.

$$N_b = \langle N_b \rangle \pm \sqrt{\langle N_b \rangle} \tag{4}$$

Once calculated, we should compare this value to the number of events detected inside the region Ω_{ON} during T_{ON}, events in spatial and temporal correlation with the GRB, which we will refer to as *"signal events"*. To do so, we simply select those events inside the elevation band and detected during T_{ON} whose angular distance to GRB 221009A is smaller than 2 degrees. The complete algorithm for the analysis is shown in Figure 7.

Results

When applied to the full dataset, the analysis reveals the following results for the expected background and the number of *"signal"* events, respectively:

$$\boxed{\begin{aligned} &N_b = (77 \pm 6) \cdot 10^{-3} \\ &N_s = 0 \end{aligned}} \tag{5}$$

As we can see, no events were detected in correlation with GRB 221009A. From the Poisson distribution, we obtain the significance of our result: we can affirm that the absence of events in the direction of the GRB during the time window T_{ON} was given by fluctuations of the background with a probability of 92.6% . This is obtained from expression (6) with $k = 0$, characteristic of the distribution.

$$Pr(N_s = k) = \frac{N_b^k\, e^{-N_b}}{k!} \tag{6}$$

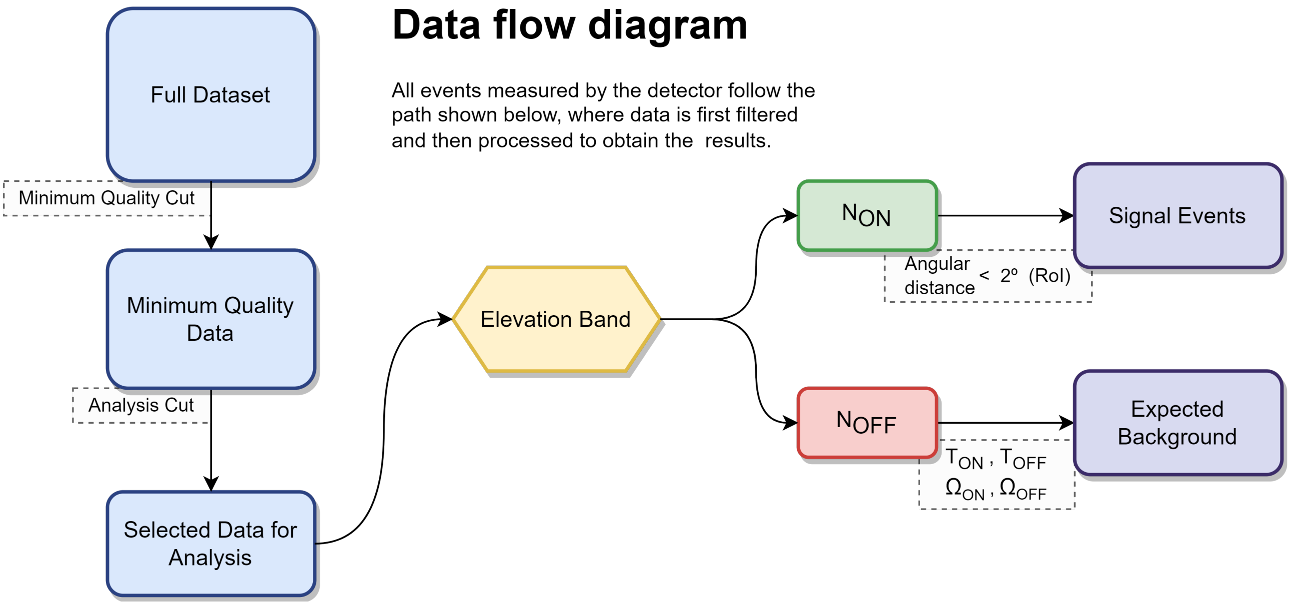

Figure 7: *Schematic representation of the complete algorithm for the data analysis.*

Discussion

As surprising as it may seem, no events were detected by neutrino telescopes (ARCA, IceCube...) in correlation with the brightest GRB ever witnessed by the scientific community [8-9]. This raises many questions regarding the current state of knowledge of high-energy phenomena such as Gamma Ray Bursts, as well as our ability to detect astrophysical neutrinos. How could it be possible that what we believe is one of the primary sources of high-energy neutrinos in the universe left no footprint in our detectors?

There are two possible answers to this question. The first one is: we were simply not lucky enough. A large number of neutrinos reached our detector after propagating through the universe, but none of them interacted, leaving no trace behind. Neutrinos are known for being very weakly interacting particles and we should not rule out this possibility from happening. The second one is: maybe we found nothing because neutrinos just were not there. In many theories of Quantum Gravity, there are non-conventional effects related to high-energy phenomena. For instance, Lorentz Invariance Violation (LIV) theories propose effects in the propagation of high-energy particles which deviate from Special Relativity [10]. In this scenario, very energetic neutrinos could experience a delay in the time of flight from the source to the detector compared to photons in the gamma-ray spectrum. This would mean that the time window used during our analysis could be completely out of focus for the arrival of neutrinos from GRB 221009A. Therefore, it is strongly encouraged that a new analysis of this type is performed shifting, or even selecting a new time window both for the estimation of the background and the search for a signal in correlation with the GRB in an attempt to incorporate possible LIV effects in the propagation of high-energy neutrinos.

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