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MULTI-MESSENGER OBSERVATIONS WITH THE KM3NET TELESCOPE: SEARCH FOR HIGH ENERGY NEUTRINOS COINCIDING WITH FAST RADIO BURSTS

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Abstract. The KM3NeT experiment is a next-generation neutrino telescope, consisting of two separate detection structures, organised as arrays of light sensors, and immersed in the depths of the Mediterranean Sea. The two detectors are the Oscillation Research with Cosmics in the Abyss (ORCA detector), located off the coast of France and the Astrophysics Research with Cosmics in the Abyss (ARCA detector), off the coast of Sicily. Identical in the design but differing by scale, these two detectors observe neutrino interactions in the sea water through Cherenkov light produced by the interaction products at different energy ranges. Specifically, ORCA aims at detecting atmospheric neutrinos to study their oscillation parameters, while ARCA will focus at higher energies on astrophysical neutrinos and the characterisation of their sources. Among the latter topic, Fast Radio Bursts (FRB) are good candidates for multi-messenger emissions due to the huge energy involved in their burst. I will present the method and criteria of a multi-messenger analysis intended to search for spatial and temporal coincidences of astrophysical neutrino signals from KM3NeT with FRBs. The search uses a FRB catalogue of around 800 sources among which 14 occured in the period ranging from January 2020 to March 2021, and were visible from the KM3NeT site.

Keywords: astrophysics, neutrino, multi-messenger, FRB, KM3NeT

1 Introduction

Starting with the detection of the first galactic supernova SN1987A, seen both in photons and neutrinos, and followed later by the first binary neutron star merger (Abbott et al. 2017), seen in gamma rays and gravitational waves, the astronomy has entered the multi-messenger era. Since then, several distant events of the Universe have been monitored in more than one channel of observation (Greus & Losa 2021), so-called *Universe messengers*. Observing an event in several channels is highly interesting, as different emissions have different production processes and tell a different story of their source. Until recently, the most favored messenger is the photon, coming at various energies along the electromagnetic spectrum. In the 2000's, a very puzzling type of emission has been detected in the radio band, the Fast Radio Burst (FRB) (Zhang 2022). A colossal amount of energy emitted coherently over a very short period of time (less than a millisecond), coming from extragalactic distances, is definitely intriguing but has not been fully yet explained. A way to increase our knowledge of FRBs and their sources is to use multi-messenger observations implying a FRB and another type of messenger, like the multi-wavelength observation of FRB20200428* and a Hard X-Ray burst coming from the magnetar SGR1935+2154 (Andersen et al. 2020). Along with electromagnetic radiations, gravitational waves and cosmic rays, neutrinos are a newly observed type of cosmic messengers that are showing a growing interest in the field of astrophysics. Travelling extragalactic distances without being impeded, carrying direct information of their production mechanisms, neutrinos are a privileged channel to understand the sources that produced them. A large-volume neutrino telescope, the KM3NeT experiment, is being built in the Mediterranean Sea, and will be able to conduct surveys of the sky, real-time analyses and high energy neutrino searches for multi-messenger purposes (Aiello et al. 2023). Although the detector is not fully built yet, the infrastructure already allows for data taking and analyses. This work is focused on the selection of neutrino events that originate from the same time and location in the sky as FRBs that have been observed already and could be correlated to them. After introducing the KM3NeT experiment, and stating the characteristics of a possible dual emission of neutrinos and FRBs, the strategy of this analysis will be presented.

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*FRB are registered as their observation time, in the format *FRBYYYY-MM-DD*

2 The KM3NeT Experiment

KM3NeT is a large volume neutrino detector, plunged at the bottom of the Mediterranean Sea, continuously monitoring the flux of neutrinos coming from both the atmosphere and the more distant Universe. The signal from neutrinos is catched through the Cherenkov light emitted by ultrarelativistic neutrino interaction products in the sea water. The KM3NeT telescope is able to recover both the energy and direction of the interacting neutrino (Adrián-Martínez et al. 2016). The experiment is composed of two different detectors, equal in design and differing only by scale, in order to probe two different energy ranges at the best possible sensitivity. As can be seen on Fig. 1, ORCA (Oscillation Research with Cosmic in the Abyss) focuses on lower energies and the detection of atmospheric neutrinos to understand further the neutrino oscillations, whereas ARCA (Astrophysics Research with Cosmic in the Abyss) targets higher energies in search for astrophysical sources. The Cherenkov radiation is collected by PMTs, grouped in Digital Optical Modules (DOMs). DOMs each have 31 PMTs and are arranged by 18 in strings, held straight by an anchor at the bottom and a buoy at the top. The strings, called Detection Units, are 200 m high in ORCA and separated on the seabed by 20 m, and 700 m high in ARCA and separated by 90 m. Both detectors are in the deep sea, shielded from atmospheric particles by 2400 m of water in the case of ORCA and 3500 m for ARCA. The construction of the detectors started in 2015 and by this decade KM3NeT will be the largest instrumented volume for neutrino detection in the Northern Hemisphere. It follows the ANTARES experiment, that took data from 1999 to 2022, but thanks to the larger infrastructure will be more sensitive on the whole energy range (see the effective volumes of the two experiments in Fig. 1). Although the detector is under construction, and only reaching 13% of the foreseen final size, its design allows to conduct data taking and physics analyses, implying a limited sensitivity. The energy range covered by ARCA and ORCA is unprecendented (Adrián-Martínez et al. 2016), from the GeV to the PeV, allowing to work on different topics. First, atmospheric neutrinos produced by cosmic rays in the atmosphere in the range from 1 GeV to 100 GeV are very abundant, and by accumulating statistics one can constrain neutrino oscillation parameters and determine the neutrino mass ordering (Gupta et al. 2022). Then, at higher energies (above the TeV) fluxes of atmospheric neutrinos are less important, allowing to study astrophysical neutrinos and constraining models of their sources. Recently, the first neutrino observations were made by IceCube, on neutrino-emitting galaxies NGC 1048 and TXS 0506+056 (Kurahashi et al. 2022), or an evidence of the Galactic Plane signal in the neutrino channel (Sclafani & Huennefeld 2023). KM3NeT will have access to different astrophysical sources in the Southern Hemisphere, notably the Galactic Center. It will be therefore essential to work together with telescopes located in the South, like the Square Kilometer Array, in order to combine surveys of the experiments, send and receive alerts. Additionally, KM3NeT can detect a Supernova thanks to its large flux in the MeV range (Aiello et al. 2021), and is also sensitive to some exotic sources (Aiello et al. 2022). The pointing capabilities of KM3NeT at high energies can be used to search for multi-messenger observations, connecting a neutrino emission with another transient emission like a Fast Radio Burst.

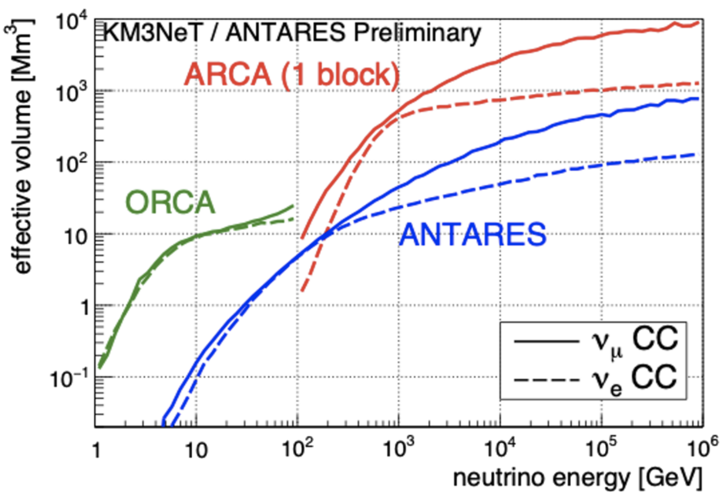

Fig. 1. Planned effective volumes of the detectors of KM3NeT, ORCA and ARCA, compared to the actual effective area of ANTARES. Credit: Hallmann, Steffen, KM3NeT collaboration meeting, Bari, 16/06/17.

3 Fast Radio Bursts in the Multi-Messenger Context

Since the first detection in 2007, several hundreds of FRBs have been observed, from which a few properties on the progenitors have been derived such as the duration, fluence, dispersion measure, rotation measure and scattering. They encode the properties of the bright coherent bursts coming from extra-galactic distances, emerging from a mechanism that has an environment with an energetic, dense, perturbed and magnetized plasma (Zhang 2022). This plasma is therefore a possible source of hadronic accelerations and by conventional processes, like the photopion process (Metzger et al. 2020), source of high energy neutrinos. In addition, thanks to the first and only multi-wavelength detection of the FRB 20200428, associated with the galactic magnetar SGR1935+2154, models of neutrino production from magnetars have emerged. From these models, it is possible to extrapolate the expected neutrino fluxes and energies and to optimise the neutrino analysis for events similar to the ones associated with SGR1935+2154 (see sketch on Fig. 2 for the possible production sites near the magnetar). Eventually, the analysis conducted needs to be as model-independent as possible, since FRB sources are not constrained yet. The Cut-and-Count analysis is then well suited for this purpose.

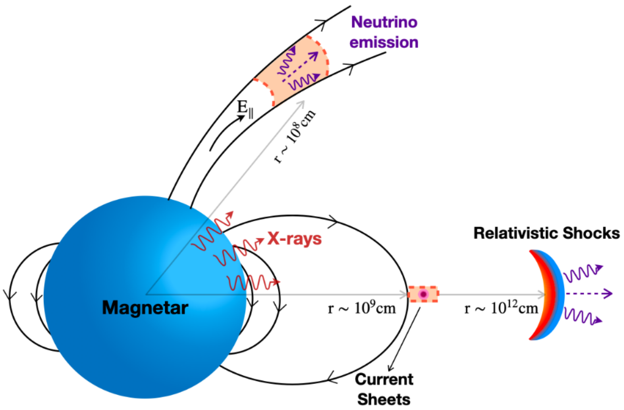

Fig. 2. Sketch of three neutrino production sites from the surroundings of a magnetar: the magnetosphere (top), current sheets region and relativistic shocked region. Neutrinos are propagating along the purple arrows. Metzger et al. (2020).

4 Analysis Strategy

The data used in this analysis consists of up-going muon neutrino event candidates recorded from January, 1st 2021 to March 31st, 2022. The ORCA detector being under construction, only 6 detection units were running, about 5% of the final size of ORCA. During this period, 43 FRBs were detected from various radiotelescopes, 14 of which were visible from the site of KM3NeT. In order to correlate in time the FRB and possible neutrino signal, a time window of 1000 s was chosen, centered around the FRB. To be properly model-independent and to have a significant correlation, the method put forward is the binned Cut-and-Count analysis (see references in Aiello et al. 2023). An ON zone is defined around the FRB direction, as well as an OFF zone. The OFF zone is the declination band (or elevation band in some cases) centered around the FRB declination (elevation), having a similar background as the ON zone. It is used to compute the background, from data scrambled in time (thus the arrival direction is also scrambled), and then re-scaled to the size of the ON zone. Cuts are performed on both the dataset and the corresponding simulation that is used to estimate the signal. Namely, the size of the ON region is one parameter, and the probability of the event to be an astrophysical neutrino, expressed in terms of a classifier (*Boosted Decision Tree*) score, is the other one. The tool used to optimize the two cuts in this low-signal environment is the Model Rejection Factor (Hill & Rawlins 2003). A certain value of the factor is computed from the Feldman-Cousins average upper limit (Feldman & Cousins 1997), using the classifier score and ON region size pair, and by scanning over this two-parameter space the optimal parameter pair is found where the factor is minimized. The analysis is prepared in blinded mode, on simulated rather than real data. The optimization results before un-blinding the data (and then using events from the ON region instead of simulations) are shown in Fig. 3, where the 14 bursts studied are shown in the all-sky map, along with their ON regions that have been optimized. The radii range from 5° to 13°, which can be considered large but are explained by the lack of statistics in this small region of the sky, and in such a reduced time window.

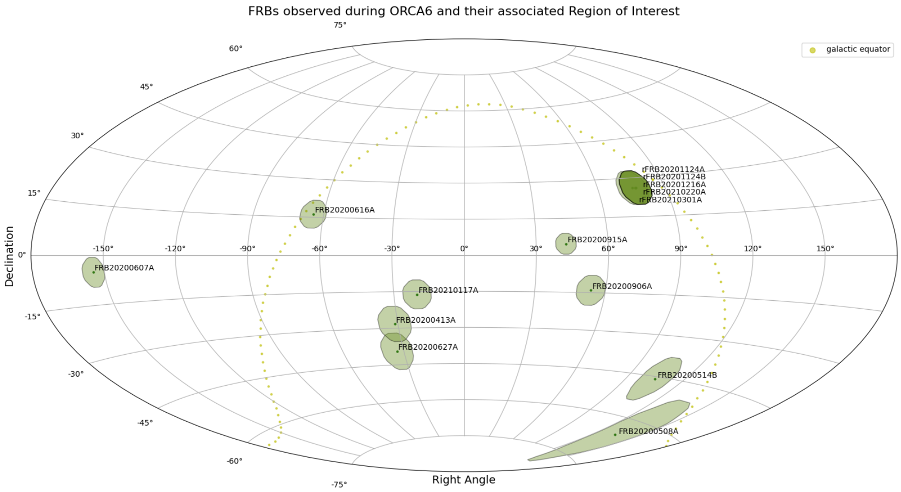

Fig. 3. Skymap, in equatorial coordinates, of the 14 studied FRBs. Green disks around the direction of FRBs represent the regions from where neutrinos could be associated to significant signal. Yellow dots indicate the Galactic Equator.

5 Conclusions

A short presentation of the experiment KM3NeT has been made. The analysis strategy for the neutrino-FRB correlated observations has been presented, leading to the optimization result presented. The un-blinding of the data will be realized shortly to obtain the result of the analysis. Eventually, the analysis will complement those of IceCube (Aartsen et al. 2018; Abbasi et al. 2023) and ANTARES (Albert et al. 2018), searching in several years of neutrino data and finding no significant coincidence with FRB observations. In the future, the analysis can be improved, on the one hand by the increase of statistics and size of KM3NeT and on the other hand by the increase of the FRB detection rate. Indeed, there is an estimate of about 5000 FRB per sky per day (Connor et al. 2016), with only a fraction of them detected by radiotelescopes today. The arrival of the Square Kilometer Array (SKA) in the scope of the radio detection experiments will allow to detect a much larger part of this large population of FRBs.

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