PROCEEDINGS OF SCIENCE

Gamma-Ray Burst neutrino searches with ANTARES and KM3NeT neutrino telescopes

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Gamma-Ray Bursts (GRBs) are considered promising neutrino emitters. They appear as extremely intense bursts of gamma-ray radiation of extragalactic origin observed isotropically in the sky and constitute the most powerful explosions observable in the Universe. A lot has been learnt about these sources in the last years. However, their jet composition remains an open issue. Within the framework of the fireball model, mesons can be produced in photo-hadronic interactions occurring at internal shocks between shells emitted by the central engine. Following their decays, high-energy gamma rays and neutrinos are expected to be generated. By exploiting data collected by neutrino telescopes, temporal and spatial coincidences between high-energy neutrinos and GRBs can be searched for. In the context of identifying cosmic neutrino sources, an important role has been played over the last decade by ANTARES, the first undersea neutrino telescope located in the Northern hemisphere. Since investigations with ANTARES data have shown no coincidences, it was possible to set limits to the contribution of the detected GRB population to the diffuse neutrino flux, as well as to the neutrino emissions expected from bright GRBs and from the recently detected emitting TeV GRBs. GRBs are also interesting for KM3NeT, the next generation neutrino detectors under construction in two different sites of the Mediterranean Sea. Thanks to their geometry, both KM3NeT detectors will cover a broad neutrino energy range, from MeV to PeV, with a significant improvement as compared to ANTARES. This will enable us to further investigate GRB emissions, providing new insights into their possible neutrino production. In this contribution, the results achieved over the last decade on GRB neutrino searches with ANTARES data are presented, as well as preliminary KM3NeT performances to detect such transient neutrino fluxes.

**** 27th European Cosmic Ray Symposium - ECRS ****
**** 25-29 July 2022 ****
**** Nijmegen, the Netherlands ****

[*] Speaker

PoS(ECRS)097

1. Introduction

Gamma-Ray Bursts (GRBs), being among the most energetic events in the Universe (with energy release between 10^{51} and 10^{54} ergs in few seconds) (see e.g. [1]), are considered potential sites of cosmic ray acceleration up to the highest energies. In such a case, neutrinos are also expected to be produced in interactions between protons (or heavier nuclei) and the intense radiation field of their jets. For this reason, observing a neutrino flux from GRBs would offer evidence that they are accelerators of the so-called Ultra-High-Energy Cosmic Rays (UHECRs), and improve the understanding of the physical mechanisms working in GRB jets, as well as a probe to their composition. If GRBs were purely leptonic sources, the observed radiation would be completely ascribed to processes involving primary electrons, such that there would be no possibility to produce neutrinos in these sources. It is also worth pointing out that multi-messenger searches targeted at GRBs appear very promising; being transients and extremely energetic explosions, GRBs allow a strong reduction of the background accumulated during their very short duration. In addition, neutrinos, being electrically neutral, stable and weakly interacting particles, are ideal messengers in the search for distant astrophysical objects. Thus, unlike protons or charged nuclei, they are not diverted in their path from their source to the Earth. Furthermore, unlike photons, neutrinos are not absorbed while propagating towards the Earth. Interest for GRBs in the neutrino astronomy field grew even more in the last years. In 2013, a diffuse flux of high-energy astrophysical neutrinos from unresolved sources was discovered [2], and from that moment identifying the sources of these neutrinos is one of the key scientific targets of the astroparticle physics community. Additionally, in 2019, gamma-ray emission in the sub-TeV domain was detected for the first time in coincidence with a GRB (namely GRB 190114C) [3] by the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope. Several other bursts have been also observed in subsequent years in association with photons reaching TeV energies. Motivated by this, over the last decade, the neutrino telescopes of the Northern and Southern hemispheres, respectively ANTARES [4] and IceCube [5], have been searching for neutrino signals coincident with GRBs in time and direction (e.g. [6–9] for ANTARES and [10–12] for IceCube). In this contribution, the latest GRB-neutrino searches performed with neutrino telescopes located in the Mediterranean Sea are collected.

2. Mediterranean neutrino telescopes

The deep water of the Mediterranean Sea has been a long time host of neutrino telescopes. Since 2008 to the very beginning of 2022, ANTARES was active, representing the longest-lived neutrino detector operating in the Northern Hemisphere. The detector, anchored at a depth of about 2.475 m and located 40 km off the coast of Toulon (France), instrumented a volume of approximately 0.01 km^3. Currently, the next-generation neutrino telescope KM3NeT is currently under construction at two different sites of the Mediterranean Sea [13]. The ORCA detector, designed for low-energy studies (from a few hundreds of MeV to sub-TeV), lies off the coast of Toulon (France) at a depth of about 2500 m (close to the ANTARES site), while ARCA, dedicated to high-energy studies (up to PeV), is located at a depth of about 3500 m close to the Sicilian coast, in Italy. Even if these detectors aim to achieve different scientific goals, they are built with the same innovative technology, described in detail in [14]. The targeted instrumented volume of KM3NeT is more than one cubic kilometre. Indeed, the goal is to install 115 DUs for ORCA and 230 DUs for ARCA within the next few years. The aim of the dismantled ANTARES detector and the new KM3NeT detectors is common: the search for high-energy neutrinos of astrophysical origin.

There are two event topologies that can be identified in a high energy neutrino telescope: track- and shower-like events. The track events are produced when a muon is generated in a Charged Current (CC) interaction of a muon neutrino in the proximity of the detector. Thanks to the long muon path, the direction of the interacting neutrino can be reconstructed with an angular resolution that is below 1° for ANTARES and ~ 0.1° for KM3NeT-ARCA. Shower events are produced when an electromagnetic and hadronic cascade are generated in a Neutral Current interaction (NC) of a neutrino independently from its flavor, or in a CC interaction of an electron or tau neutrino. All the energy of the cascade is deposited within a few meters from the interaction vertex, hence they are reconstructed as point-like sources of light, thus providing a poorer angular resolution as compared to the track channel, in the order of ~ 2-3° for ANTARES and better than 2° for KM3NeT-ARCA.

3. Latest results from GRB-neutrino searches obtained with ANTARES neutrino telescope data

In the following, the last results obtained by ANTARES thanks to searches for neutrinos in space and time coincidence with GRBs are presented. In Sec. 3.1, an innovative stacking search for astrophysical muon neutrinos from GRBs by using 10 years of ANTARES data in presented. In Sec. 3.2, a dedicated analysis performed for some GRBs characterized by photon emission in the sub-TeV range is summarized. Refer to [8] and [9] for the corresponding extensive works.

3.1 Stacking GRB analysis with 10 years of ANTARES data

This work focuses on improving the predictions on the expected neutrino fluences from GRBs, by considering the wealth of information accumulated over the years thanks to the many astronomical observations, rather than assuming some fixed standard values that do not correctly reproduce the properties of the source sample. Contextually, the different uncertainties due to the poor knowledge of the source dynamics are taken into account and propagated on the produced neutrino spectrum, with the aim of providing a clear understanding of the assumptions and limitations behind the set upper limits.

3.1.1 GRB selection and computation of the stacked muon neutrino fluence

To perform this analysis, in order to reduce the very abundant background coming from atmospheric muons, only up-going track-like events are used, hence only GRBs occurring below the ANTARES horizon at trigger time have been selected. A sample of 784 long GRBs ($T_{90} \geq 2$ s), occurred in the years 2007-2017, is considered in this analysis. The GRB parameters needed for the search (time, direction) and the simulation of expected neutrino fluxes, e.g. photon spectrum, fluence and redshift, are collected from published results of Swift, Fermi,and Konus-Wind. The neutrino fluxes expected from the prompt phase of each GRB of the sample have been computed by the event generator 'Neutrinos from Cosmic Accelerator' (NeuCosmA) [15, 16], which operates within the framework of the fireball model [17]. To estimate the parameter uncertainties that affect the neutrino flux evaluations, one thousand fluxes with different combinations of parameters are

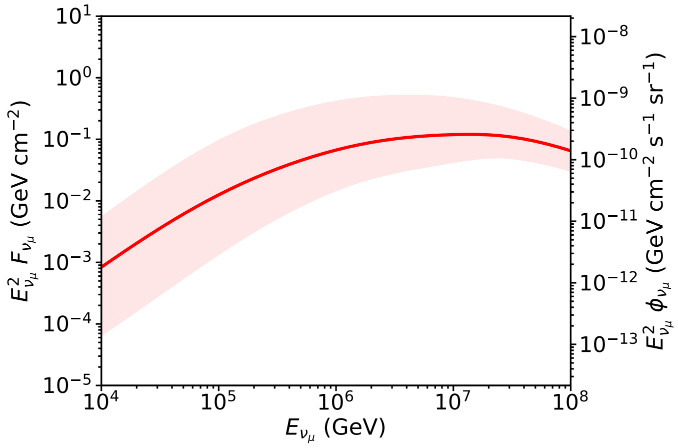

Figure 1: Total neutrino fluence $E^2_{\nu_\mu} F_{\nu_\mu}$ expected from the 784 GRBs (left-hand axis) and corresponding quasi-diffuse neutrino flux $E^2_{\nu_\mu} \phi_{\nu_\mu}$ (right-hand axis). The shaded region indicates the error band, obtained from the sum of the individual maximum ($E^2_{\nu_\mu} F_{\nu_\mu} + 2\sigma$) and minimum ($E^2_{\nu_\mu} F_{\nu_\mu} - 2\sigma$) fluences for each GRB in the sample.

simulated for each GRB. In particular: i) for the bulk Lorentz factor, its correlation with the mean isotropic gamma-ray luminosity $L_{\gamma,\mathrm{iso}}$ as found by [18] is used; ii) redshift values are extracted accordingly to the observed z distribution of long GRBs; iii) a similar procedure of random extraction according to a known distribution of values [19–21] is adopted also for the minimum variability timescale t_v. As result, it has been observed that: (i) Γ is the parameter which impacts the most the GRB-neutrino flux predictions, (ii) t_v contributes more than z to the uncertainty on the neutrino flux predictions from GRBs. Indeed, when letting t_v free to vary, the estimated uncertainty on the neutrino flux expected from the model spans up to several orders of magnitude. The total fluence $E^2_{\nu_\mu} F_{\nu_\mu} \pm 2\sigma$ expected from the cumulative contribution of the selected 784 GRBs in the period 2007-2017 is calculated summing over all the individual neutrino fluences. The result is shown in Figure 1 together with the quasi-diffuse neutrino flux $E^2_{\nu_\mu} \phi_{\nu_\mu} \pm 2\sigma$ induced by the same sources.

3.1.2 Analysis method: signal and background estimation in ANTARES

For each source in the sample, a Monte Carlo (MC) simulation of the expected neutrino signal is performed, while the respective background is estimated directly from off-source data collected by ANTARES. Only track-like events reconstructed within 10° in radius from the expected GRB position and in temporal correlation with the duration of the prompt gamma-ray emission are selected, namely those falling within a search time window around the GRB occurrence ($T_\mathrm{search} \sim T_{90}$). The different environmental conditions in the deep sea and the variation of data-taking efficiency are taken into account both in signal and background estimations. At this point, the statistical analysis is performed trying to maximise the chance of signal detection assuming the internal shock model: a comparison between the expected signal and background probability density functions is needed in order to discriminate between both. This is achieved by considering respectively MC reconstructed track events from both ν_μ-$\bar{\nu}_\mu$ charged current interactions and hadronic showers for signal, while background is estimated from real data. A strategy based on

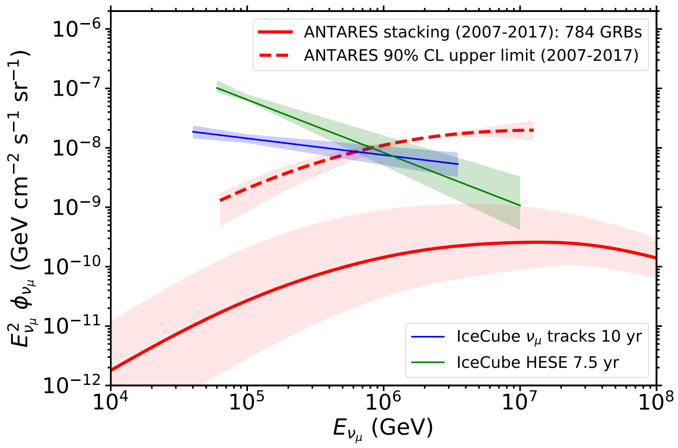

Figure 2: GRB quasi-diffuse flux expected for the 784 selected GRBs (red solid line) and the corresponding ANTARES 90% CL upper limit (dashed red line). The red shaded regions show the 2σ uncertainty around the GRB quasi-diffuse flux, and also around the computed upper limit. IceCube best fits for ν_μ tracks in 10 years [22] and for HESE events in 7.5 years [23] of collected data are shown in blue and green, respectively.

pseudo-experiments, simulating with high statistics a measurement's result, and on the optimisation of the cut on the track reconstruction quality maximising the Model Discovery Potential (MDP), is implemented. See [8] for further details.

3.1.3 Results

ANTARES data from the end of 2007 to 2017 are analysed accordingly to the results of the optimisation procedure, searching for neutrino events in spatial and temporal coincidence with the prompt phase of GRBs. The optimal number of GRBs to stack is obtained, yielding the highest MDP at 3σ. Nonetheless, as a negligible reduction of the $\mathrm{MDP}_{3\sigma}$ would have been obtained when stacking the entire catalogue, the flux from the whole sample of 784 GRBs is investigated, corresponding to a $\mathrm{MDP}_{3\sigma} = 0.03^{+0.11}_{-0.02}$ and a number of signal events $\mathrm{n_s(N_{GRB}} = 784) = 0.03^{+0.14}_{-0.02}$. After unblinding ANTARES data, no event is found in spatial and temporal coincidence with the GRB sample to pass the selection criteria, for an equivalent livetime of the search of 18.9 hours. The absence of signal allows to derive 90% confidence level (CL) upper limits on the computed neutrino fluence, which read as $1.3^{+4.1}_{-0.8} \times 10^{-2}$ GeV cm^{-2} and $0.8^{+5.2}_{-0.7} \times 10^{-1}$ GeV cm^{-2}, corresponding to $1.3^{+0.4}_{-0.8} \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1} and $1.0^{+0.9}_{-0.5} \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}, respectively, in terms of quasi-diffuse flux $\mathrm{E}^2_{\nu_\mu}\phi_{\nu_\mu}$ in the energy range from $\sim$ 60 TeV to $\sim$ 10 PeV. The expected quasi-diffuse neutrino flux from the selected 784 GRBs and the corresponding upper limit are compared with the diffuse astrophysical flux observed by IceCube [22, 23] in Figure 2. From such a comparison, it is possible to conclude that, within standard assumptions of energy partition among accelerated hadrons, leptons and magnetic fields (i.e. baryonic loading equal to 10), GRBs are not the main sources of the astrophysical neutrino flux, possibly contributing less than 10% at energies around 100 TeV. This result is in agreement with previous searches performed by IceCube [10–12].

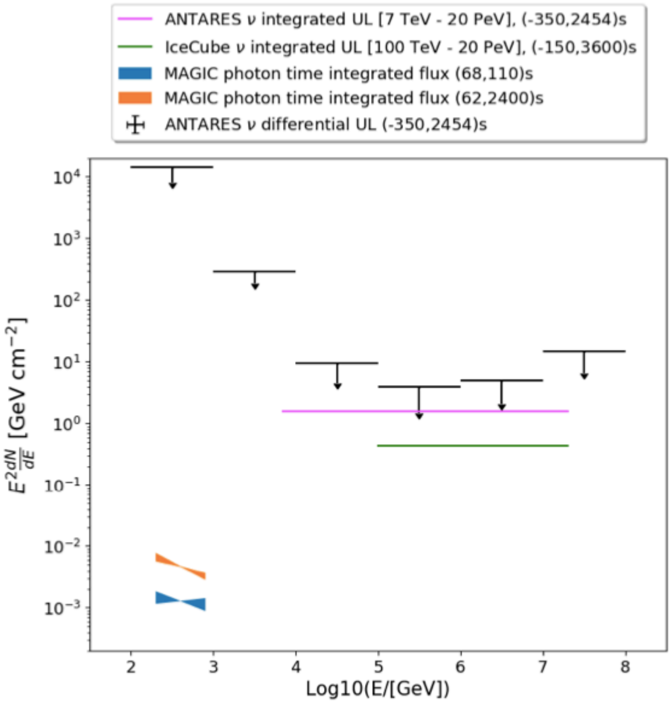

Figure 3: ANTARES 90% differential (black arrows) and integrated (pink line) spectral fluence upper limits as a function of the neutrino energy for GRB 190114C. The pink line shows the limit integrated in the 595% energy range of the analysis. The IceCube upper limits from ATel 12395 are shown for comparison (green line). The MAGIC gamma-ray spectral fluence for the first time bin of the analysis (68-110 s), and for the overall time window (62-2400 s), are shown by the blue orange band, respectively.

3.2 Search for high-energy neutrinos from sub-TeV GRBs with ANTARES data

Even if no significant neutrino flux has been associated with standard GRBs (keV-GeV emission), GRBs emitting in the TeV domain might possibly behave differently from those previously investigated. Indeed, the presence of a high-energy component in their radiation spectra might constitute a promising feature also in terms of neutrino emission. For that reason, ANTARES performed dedicated searches for neutrinos in space and time coincidence with the first GRBs detected by the existing ground-based gamma-ray facilities (Imaging Atmospheric Cherenkov Telescopes, IACTs) at TeV energies: GRB 180720B, detected by H.E.S.S. [24], GRB 190114C, detected by MAGIC [3], and GRB 190829A, also revelead by the H.E.S.S. telescope [25]. For each GRB, the time window of the search is adjusted to cover the interval ranging from the trigger time up to the end of the observations by IACTs, covering both the prompt and afterglow phases. The event selection applied in this work is the one commonly followed in ANTARES for transient sources, detailed in [26]. The spatial search region around each source is optimised for each event. The quality cuts on reconstructed neutrino induced events that allow to reach the most constraining limits are optimised by maximising the signal expectation assuming an E^{-2} neutrino spectrum (expected in the case of the generic Fermi acceleration mechanism), while keeping the false alarm rate below the desired threshold. The selection criteria is chosen so that one neutrino candidate event passing the analysis cuts found in time and space coincidence with the gamma-ray emission leads to a 3σ detection.

Since no neutrino is found in time and space coincidence, upper limits on the neutrino spectral fluence, the total energy release in neutrinos, and the fraction of energy going into pions over that going into electrons, are derived. Details about the results obtained for each GRB can be found in [9]. In particular, the results obtained for GRB190114C are shown (see Figure 3).

4. The future: KM3NeT sensitivity to transient neutrino sources

KM3NeT, the new generation of underwater neutrino telescopes, is currently under construction in the Mediterranean sea. Thanks to its large size and improved detection capabilities, KM3NeT will open new perspectives in neutrino astronomy. In the work presented in [27], a preliminar KM3NeT sensitivity to transient neutrino sources, like GRBs, has been computed. The signal and background coming from a test source in the up-going sky (zenith=70° and azimuth=300°) has been simulated for different time windows (1000 s, 1 day and 10 days) and with spectrum $\propto E^{-2}$ for cosmic neutrinos. By considering only track-like events from ν_μCC interactions, the KM3NeT/ARCA sensitivity to transient neutrino sources, as GRBs, is obtained by optimizing the model rejection potential to find the limit the would be placed on the neutrino flux if no true signal were present, and only the expected background of atmospheric neutrino events (reduced through optimal cuts) was observed. Figure 4 shows the preliminary differential sensitivity obtained for KM3NeT/ARCA (full detector) as a function of the energy, for the three different time windows considered in [27]. Thanks to this analysis, it has been found that, once completed, KM3NeT is expected to improve at least of 2 order of magnitudes the corresponding ANTARES sensitivity to transient neutrino sources between 1 TeV and 100 TeV.

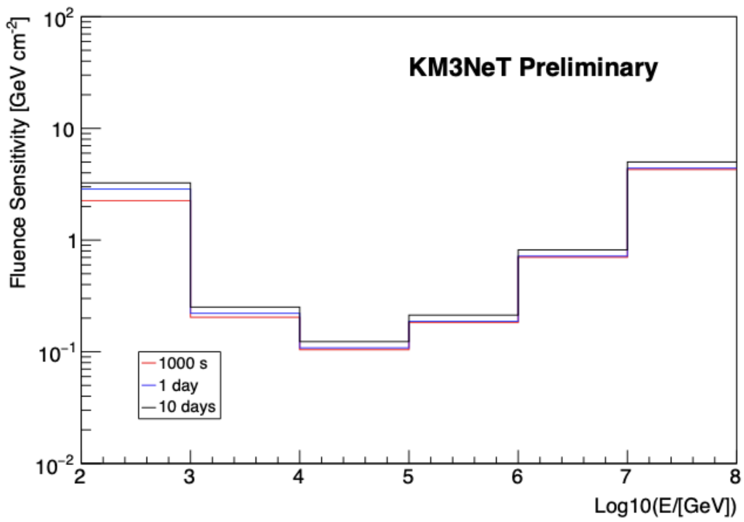

Figure 4: Differential fluence sensitivity as a function of the neutrino energy for the full KM3NeT-ARCA detector, and for time windows equal to 1000 s (red line), 1 day (blue line), and 10 days (black line).

5. Summary and Conclusions

The ANTARES neutrino telescope, thanks to data collected in almost 14 years, has produced relevant physics results. One of its main goals has been the identification of astrophysical sources of high-energy neutrinos. Several investigations have been performed on GRBs, potential UHE-CRs accelerators, and so neutrino emitters. Despite of the lack of GRB-neutrino associations in ANTARES data, the searches performed have allowed to set progressively stronger upper limits to GRB neutrino production, thus limiting also the possible contribution of these sources to the observed astrophysical diffuse neutrino flux. The competitiveness of the results achieved demonstrates the huge potential of the new, cubic kilometre-sized array, KM3NeT/ARCA. Once completed, it is expected to improve at least of 2 order of magnitudes the ANTARES sensitivity to transient neutrino sources, like GRBs.

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