PROCEEDINGS OF SCIENCE

Search for neutrino counterparts of cataloged gravitational-wave events detected by Advanced-LIGO and Virgo during run O2 with ANTARES.

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An updated offline search for a neutrino counterpart to gravitational-wave events detected during the second observing run of advanced-LIGO and Virgo (adv-LIGO/Virgo) has been performed with the ANTARES data. The results of this study looking for a prompt neutrino emission within ±500s around the time of the GW alerts are presented.
Meanwhile, the adv-LIGO/Virgo detectors started taking data again on April 2019 for a new scientific run (O3) with enhanced sensitivities. The ANTARES collaboration is actively participating in the follow-up of the gravitational wave public alerts. Preliminary results of the offline follow-up will be discussed for the most relevant gravitational-wave events which are believed to be potential candidates for neutrino emission.

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36th International Cosmic Ray Conference -ICRC2019-
July 24th - August 1st, 2019
Madison, WI, U.S.A.

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1. Introduction

In December 2018, the LIGO and Virgo collaborations published the full catalog of Gravitational-Wave (GW) events from the scientific runs O1 and O2 [1], where four new events were reported. Since the 1st detection in 2015 up to the end of O2 in 2017, a total of 11 events were cataloged.

The ANTARES Collaboration has already published results of online and offline searches for neutrino candidates correlated to five GW events [2, 3, 4, 5]. In this paper, a dedicated offline search for muon neutrinos associated with the remaining six GW events are presented.

All the new six analyzed signals correspond to the coalescence of binary black-hole (BBH) systems at distances ranging from 300 Mpc to about 3000 Mpc and with chirp masses going from 8 to 36 $M_\odot$. With three GW detectors taking data during O2, the 90% localization areas by triangulation range from 40 deg^2 to $\sim$900 deg^2.

By involving a large number of electro-magnetic (EM) observatories observing at different wavelengths and also neutrino detectors to search for a potential emission associated to these events, the detection of the first binary neutron-star (BNS) merger event in August 2017 (GW170817), followed by different EM counterparts all along the spectrum (see e.g. [6, 7]), opened the era of multi-messenger astrophysics.

An EM counterpart, presumably associated with an hadronic emission is generally expected from neutron star/black hole (NSBH) or neutron star/neutron star (BNS) mergers [8] [9]. In the case of hadronic emission, secondary neutrinos are expected to be produced as well. Current modeling of binary black-hole merger evolution do not necessary imply EM or neutrino counterpart. However, in a dense enough hadronic environment, an accretion disk might form and/or a relativistic jet connected to the accretion could be released. In this case, the process might lead to gamma-ray emission with a potential high-energy neutrino counterpart [10] [11].

The good angular resolution of ANTARES (0.4° median angular resolution for muon neutrinos with E_ν >10 TeV could help, in the case of an associated neutrino discovery, to reduce the GW location error box and thus would allow for a rapid pointing and an efficient EM follow-up of the GW event.

A real-time follow-up was performed with ANTARES directly after the reception of the alerts looking for a neutrino counterpart below the ANTARES horizon. No neutrino was observed in coincidence within ±500s around the GW event time. A GCN circular was published for the online search of the events that triggered a follow-up (GCN 21223, 21433, 21479, 21659). Two of the events did not triggered an alert because they did not not pass the thresholds of the real-time.

In this work, a search for a prompt neutrino emission associated with the GW detection is performed over ±500s around the GW event. The muti-messenger approach, requiring space and time coincidence between neutrino and GW detections, allows for background reduction and makes possible a search also for events originating from above the ANTARES horizon, seen as downgoing in the detector frame. Upgoing neutrino-induced muons are the main detection channel for high-energy neutrinos with the ANTARES telescope, since only neutrinos can travel through the Earth. Thus, an upgoing selection allows for a significant rejection of the atmospheric muon background contribution. Here, both the upgoing and the downgoing events are studied to look for a potential neutrino counterpart. This was done for the first time in [4] and the same approach is followed in this paper.

2. Catalogued GW events from O2 not considered in previous neutrino analyses

On this section, the skymaps are shown (Fig 1) in equatorial coordinates with the ANTARES visibility at the time of the alert and the 90% confidence level GW contour for each of the events.

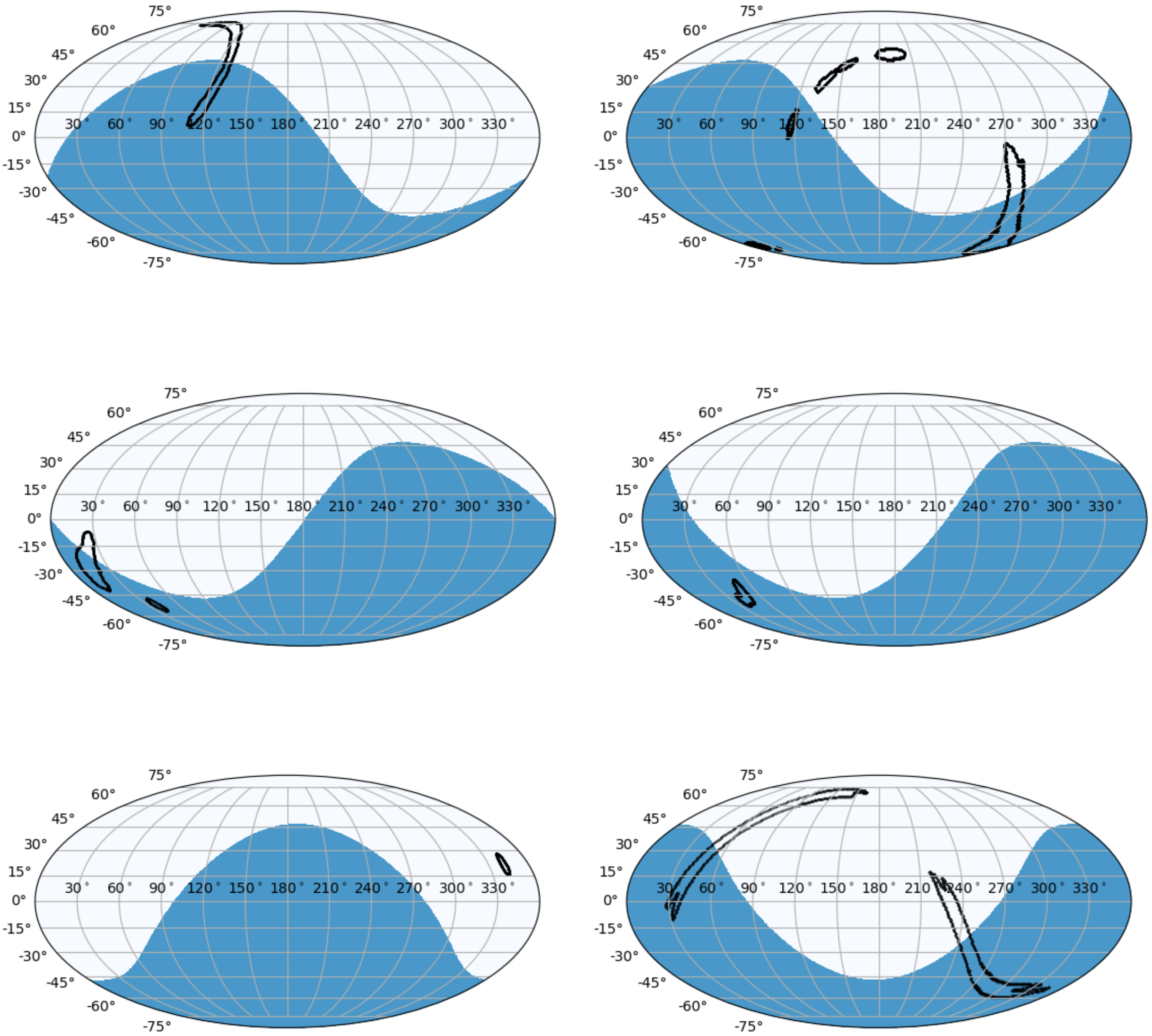

Figure 1: Skymaps in equatorial coordinates of the 6 GW events analyzed on this work. They show the visibility of ANTARES at the time of each alert and the error box for each event. They are shown in chronological order: GW170608 (upper left), GW170729 (upper right), GW170809 (middle left), GW170814 (middle right), GW170818 (bottom left) and GW170823 (bottom right).

The blue area corresponds to the region below the ANTARES horizon. Events originating from this part of the sky are seen as up-going by the ANTARES detector at the time of each alert.

In this analysis, the updated skymaps produced with the *LALInference* [12] reconstruction algorithm are used to evaluate the 90% CL GW localization contour.

3. Optimization method

As in previous GW-netrino analyses [2, 3, 4, 5], the event samples are optimized so that one event passing the analysis cuts, arriving within ±500s around the time of the alert and located inside the 90% GW probability contour leads to a 3σ significance. To this end, the background rate inside the 90% CL GW contour (also referred to as error box), within the 1000s window search needs to be estimated.

In this analysis, the fraction of events expected inside the 90% CL spatial error box of each GW event is inferred directly from data outside the search window. Data is dominated by the atmospheric muon background. The atmospheric neutrino contribution becomes dominant when requiring better reconstructed events. To compensate for the lack of statistics in this region, this contribution is added by using a dedicated run-by-run Monte-Carlo simulation.

When computing the number of events expected in 1000 s, the background rates are assumed to be uniform in time over the ANTARES run duration (of about 12h) [4].

3.1 Event selection

The expected background rates inside the 90% error box and within the 1000 s window are reduced by applying the analysis cuts on the quality parameters of the event reconstruction. In this way, one event passing these cuts and found in space and time coincidence with the GW event, leads to a detection with a 3σ significance. Thus, the optimized cut (or set of cuts) is defined as the value from which the background rate becomes smaller than $p_{3\sigma} = 2.7\times10^{-3}$. The optimization is done blindly by removing the 1000 s time window around the GW event potentially containing the signal. A fixed cut on the estimated angular error of 1° is applied to the full sample.

Table 1: Final cuts obtained for each event and sample.

Event	**Upgoing (Λ)**	**Downgoing (Λ,N$_{hit}$)**
GW170608	-5.55	(-5.3,80)
GW170729	-5.4	(-5.1,100)
GW170809	-5.4	(-5.4,40)
GW170814	-5.6	-
GW170818	-	(-5.4,80)
GW170823	-4.9	(-4.85,90)

For upgoing events, the optimization is done on the reconstruction quality parameter Λ, [13].

For the downgoing events, the energy estimate of the events, computed from the number of hits contributing to the reconstruction of a triggered event (N$_{hit}$), is also used in the optimization in order to have a higher purity sample since atmospheric muons (background) and cosmic neutrinos (signal) are expected to show a different energy spectrum. In this case, the optimized Λ value at $p_{3\sigma}$ is obtained for different cuts in N$_{hit}$. For each set of cuts (Λ,N$_{hit}$), the number of surviving signal events is computed considering an E^{-2} neutrino spectrum. Finally, the set of cuts (Λ,N$_{hit}$)

that maximizes the expected number of signal events while keeping the background below $p_{3\sigma}$ is chosen. The final cut(s) obtained for each event are given in Table 1.

4. Results and discussion

No neutrino in correlation in space and time with any of the GW events studied in this work is found after unblinding of the data sets. Therefore, an upper limit (UL) on the spectral neutrino fluence is provided. The fluence UL corresponds to the value that on average would produce 2.3 detected neutrino candidates, value from which Poisson statistics would lead to at least 1 detected event 90% of the times. As in [4], this limit is obtained by estimating the instantaneous acceptance of ANTARES at the time of the GW event. The results are shown in Fig 3 for the six GW events assuming a neutrino spectrum $\frac{dN}{dE} \propto E^{-2}$. An UL is provided for each position of the sky since the probability that the true localization of the GW event is outside of the error box is non-zero.

From the null detection, a constraint on the isotropic neutrino energy ($E_{\nu,iso}$) emitted by the source can be set. Preliminary results are given in Table 2 an illustrated in Fig. 2 considering the average 90% fluence upper limit in each hemisphere (ϕ_0^{UL}).

Table 2: Limit on the total isotropic neutrino energy emitted.

GW event	redshift (z)	distance (Mpc)	$E_{\nu,iso}$ up [erg]	$E_{\nu,iso}$ down [erg]
GW170608	$0.07^{+0.02}_{-0.02}$	320^{+120}_{-110}	8.3e+53	3.4e+54
GW170729	$0.48^{+0.19}_{-0.20}$	2750^{+1350}_{-1320}	5.0e+55	3.4e+56
GW170809	$0.2^{+0.05}_{-0.07}$	990^{+320}_{-380}	8.4e+54	2.5e+55
GW170814	$0.12^{+0.03}_{-0.04}$	580^{+160}_{-210}	2.1e+54	-
GW170818	$0.2^{+0.07}_{-0.07}$	1020^{+430}_{-360}	-	2.8e+55
GW170823	$0.34^{+0.13}_{-0.14}$	1850^{+840}_{-840}	3.8e+55	2.1e+56

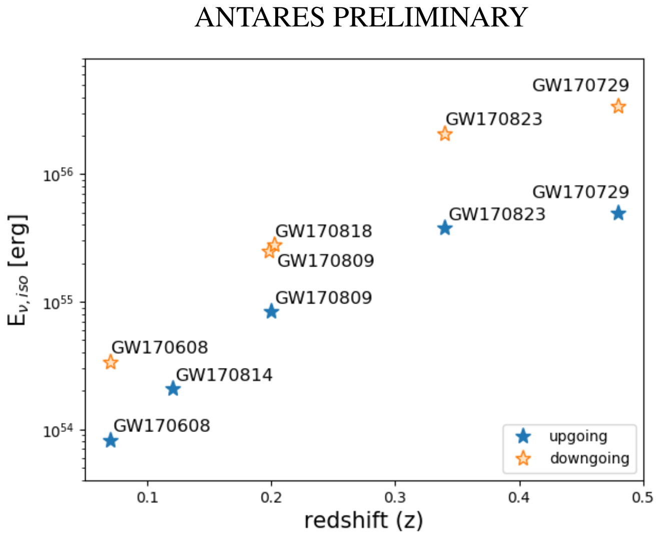

Figure 2: 90% CL upper limits on the total isotropic neutrino energy for the six GW events analyzed, as a function of the redshift estimated for each of them. They are given separately for the ANTARES downgoing sky in orange and for the ANTARES upgoing sky in blue.

ANTARES PRELIMINARY

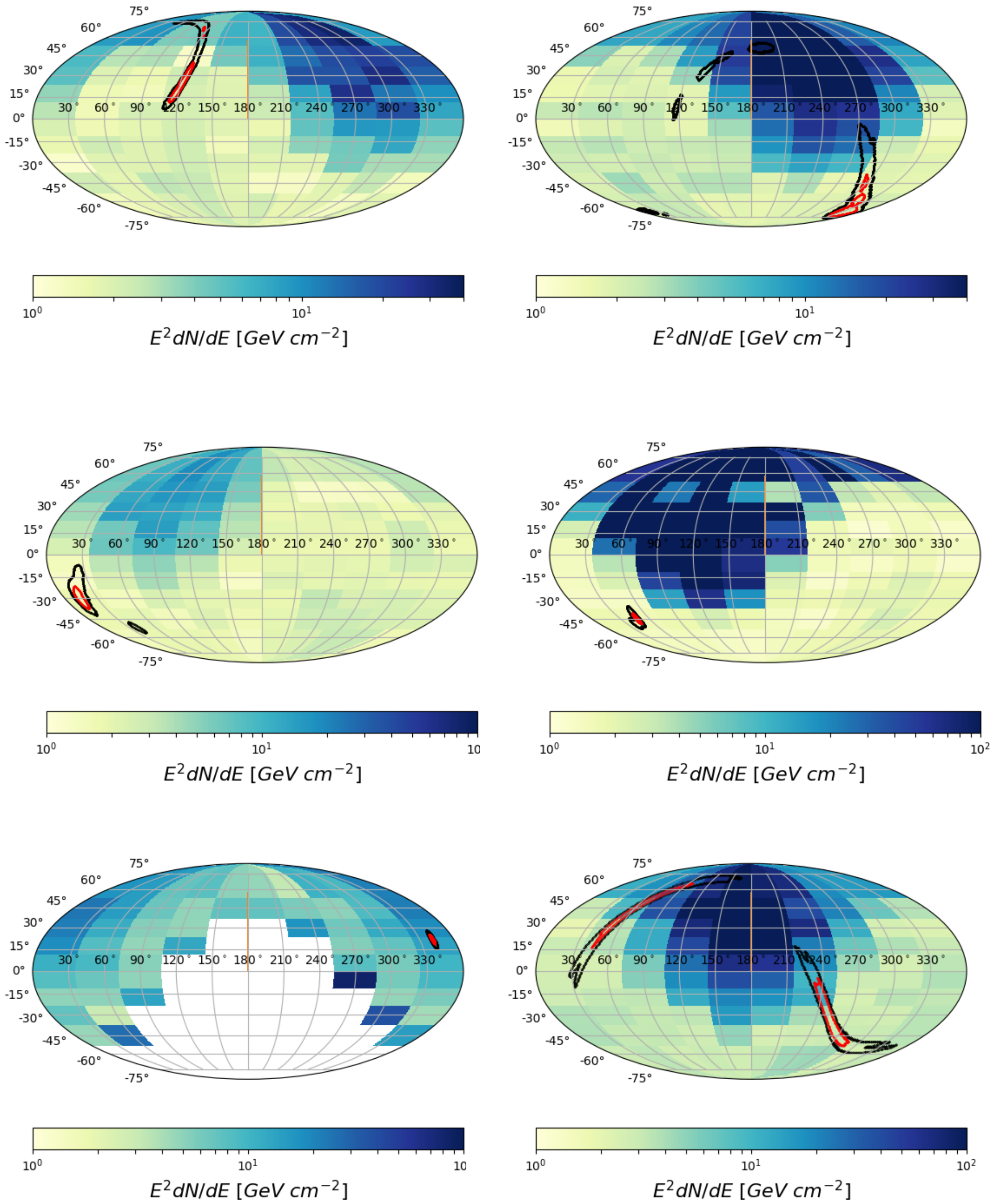

Figure 3: Full sky upper limits (colored scale) as a function the position in the sky in equatorial coordinates, computed assuming an E^{-2} neutrino spectrum. The events are shown in chronological order: GW170608 (upper left), GW170729 (upper right), GW170809 (middle left), GW170814 (middle right), GW170818 (bottom left) and GW170823 (bottom right). The GW 90% (black) and 50% (red) localization contours are superimposed.

The luminosity distance used here is the mean of the reconstructed distance distribution inside the error box, as provided by LIGO-Virgo in [1]. The spectrum is integrated over the energy range [100 GeV,100 PeV], as considered in [4]. The $E_{\nu,iso}$ UL is computed according to Eq. 4.1.

$$E_{\nu,iso} = 4\pi D(z)^2 \int_{100GeV}^{100PeV} \phi_0^{UL} \times E^{-2} E dE \tag{4.1}$$

5. Conclusions and perspectives

Searching in the ANTARES Neutrino Telescope data, and focusing only on the muon neutrino channel for the being, no neutrino emission associated with the six confirmed GW signals from O2 analyzed here has been detected. As a consecutive step of this work, all flavors will be included.

A similar analysis is aimed for the coming relevant BNS and NS-BH events during O3. For the O3 BBH events, a stacking analysis is also planned after the end of data taking by adv-LIGO/Virgo.

The method has been investigated, refined and found to be well suited for transient searches with ANTARES. In particular, it can be applied to localized flaring sources in the downgoing sky where no analysis is typically done. The same method has therefore been used for the search of neutrino counterparts to Fast Radio Bursts [14] and very high-energy Gamma-Ray Bursts.

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