

Multi-messenger studies of transient and variable astrophysical sources with the ANTARES neutrino telescope

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By constantly monitoring at least one complete hemisphere of the sky, neutrino telescopes are well designed to detect neutrinos emitted by transient astrophysical sources. In particular, the ANTARES telescope is currently the largest high-energy neutrino detector in the Northern hemisphere. Searches for ANTARES neutrino candidates coincident with multi-wavelength and multi-messenger transient phenomena are performed by looking for neutrino emission spatially and temporally coincident with transient astrophysical events detected across the electromagnetic spectrum or with new messengers as gravitational wave signals, and also by triggering optical, X-ray and radio observations immediately after the detection of an interesting ANTARES event. The latest results of the multi-messenger analyses performed with ANTARES will be presented in this contribution. In particular, we will focus on the neutrino follow-up performed after the detection of the first gravitational-wave events.

1 Introduction

Time-domain astroparticle physics has entered an exciting period with the recent development of wide-field-of-view instruments, communication strategies and low latency alert triggering of gravitational wave and high-energy neutrino (HEN) signals. In particular, neutrinos represent unique probes to study high-energy cosmic sources. They are neutral, stable and weakly interacting. Contrary to cosmic rays (CRs), they are not deflected by the magnetic fields and unlike high-energy photons, they are not absorbed by pair production via $\gamma\gamma$ interactions with cosmic microwave and infrared backgrounds. A HEN diffuse flux of cosmic origin has been identified by the IceCube telescope¹, the sources of which have still to be identified. In this context, multi-messenger approaches consisting in simultaneously looking for the same sources with both neutrino telescopes, gravitational wave interferometers and/or multi-wavelength facilities can constitute a viable mean of locating HEN/CR sources and thus further understanding the acceleration mechanisms at play in these sources.

The ANTARES neutrino telescope is currently the largest neutrino telescope in the Northern hemisphere. Located in the Mediterranean Sea, 20 km offshore Toulon (France), it is composed of 885 photomultipliers installed on 12 detection lines, sensitive to the Cherenkov light emitted by relativistic up-going muons produced by the interaction of HEN close to the detector.

In particular, search for transient sources of HEN is promising since the short timescale of emission drastically reduces the background level, mainly composed of atmospheric muons and neutrinos and consequently increases the sensitivity and discovery potential of neutrino telescopes. This contribution briefly presents the most recent results of the ANTARES multi-messenger program.

2 ANTARES neutrino alerts

A multi-wavelength follow-up program of ANTARES alerts, denoted TAToO (Telescopes-ANTARES Target of Opportunity) has been operating since 2009². It triggers optical and/or X-ray observations within a few seconds after the detection of selected high-energy neutrino events. In particular, more than 250 alerts have been sent to optical robotic telescopes (TAROT, ROTSE and MASTER) since mid-2009 while 13 X-ray targets of opportunity have been sent to the XRT instrument on board the Swift satellite since mid-2013.

The angular resolution of the neutrino direction is better than 0.5° at high energy (> 1 TeV). Three online neutrino trigger criteria are currently used in TAToO: *(i)* detection of at least two neutrino candidates with similar directions (angular separation below 3°) within 15 minutes; *(ii)* detection of a single high-energy (> 7 TeV) neutrino candidate; *(iii)* detection of a neutrino candidate directionally consistent ($< 0.5^\circ$) with a local galaxy (distance < 20 Mpc).

From January 2010 to July 2017, 169 alerts with early optical follow-up have been analyzed (see Figure 1). No optical counterparts were found and upper limits (ULs) on the R-band magnitude of a transient astrophysical source have been derived. By comparing these ULs with optical afterglow light curves of gamma-ray bursts (GRBs), it becomes possible to reject a GRB association with each neutrino alert, in particular when the optical follow-up is performed within a few minutes after the neutrino trigger³. A similar analysis has been carried out with Swift/XRT follow-up observations of 13 ANTARES alerts within a few hours after the alert triggers³. The probability to reject the GRB hypothesis reaches more than 70% if the X-ray follow-up occurs within 1.1 hour after the trigger.

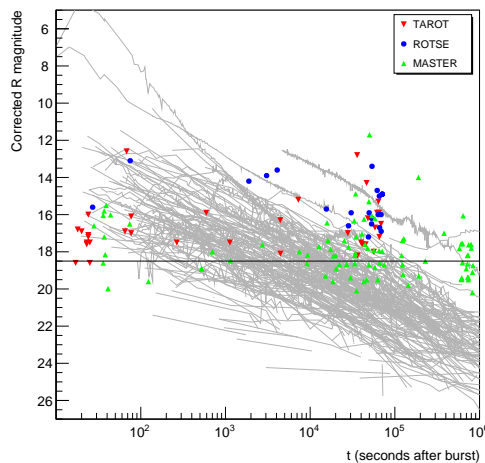


Figure 1 – Corrected R-band magnitude as a function of time for 301 GRB afterglows. Red, blue and green dots indicate upper limits on GRB afterglow magnitudes for the 169 neutrino alerts observed by TAROT, ROTSE and MASTER respectively within a short timescale after the neutrino alert. The horizontal line corresponds to the sensitivity of the optical telescopes.

Follow-up observations of ANTARES neutrino candidates are now performed over a broad range of the electromagnetic spectrum. Recently, the Murchinson Widefield Array (MWA), a low frequency (80 – 300 MHz) precursor of the Square Kilometre Array, searched for radio counterpart of two candidate high-energy neutrino events consistent with the locations of galaxies within 20 Mpc of Earth⁴. No counterparts were detected and ULs for low-frequency radio luminosity have been derived. Likewise, 2 ANTARES alerts have been followed by H.E.S.S. and 36 by HAWC since November 2014. Since early 2017, the optical follow-up program also involves the SVOM/GWAC telescopes located in China. Their very wide field-of-view and fast response capability (< 20 s) are well suited to the search and detection of transient sources.

Multi-wavelength follow-up of the neutrino alert ANT150901A

A high-energy (~ 50 TeV) neutrino candidate (ANT150901A) has been detected by ANTARES on September 01, 2015 at RA = 16h25'42", Dec = $-27^\circ 23' 24''$ (median angular error of ~ 18 arcmin). Due to the high-energy nature of this event, an alert has been sent to the electromagnetic follow-up partners after a delay of 10 s. Swift/XRT started observing the region around the neutrino event 9 hours after the trigger. One of the 8 sources identified in the field was uncatalogued, relatively bright and variable above the ROSAT All Sky Survey limit (as deep as 5×10^{-13} erg cm $^{-2}$ s $^{-1}$). Further observations performed with Swift/XRT showed that this source, located at 0.14° from the most likely position of the neutrino, was experiencing an outburst with a timescale of ~ 2 days (see Figure 2). In parallel to these X-ray observations, optical follow-up was performed with MASTER 10 hours after the detection of the neutrino candidate and leads to the detection of a bright catalogued star (USNO-B1.0 0626-0501169).

Consequently to the detection of the transient X-ray source, the ANTARES collaboration decided to notify the astronomical community through a GCN notice and an Astronomer's Telegram⁵ to request further multi-wavelength observations to characterize the X-ray source. 19 observatories answered to this trigger, covering the whole electromagnetic spectrum. IceCube has also reported a non-detection. These follow-up observations finally pointed out to USNO-B1.0 0626-0501169 being a young accreting G-K star, or a binary system of chromospheric active stars (RS CVn), undergoing a X-ray flaring episode. Thus, the coincident neutrino detection is probably due to chance, with a probability of $\sim 3\%$.

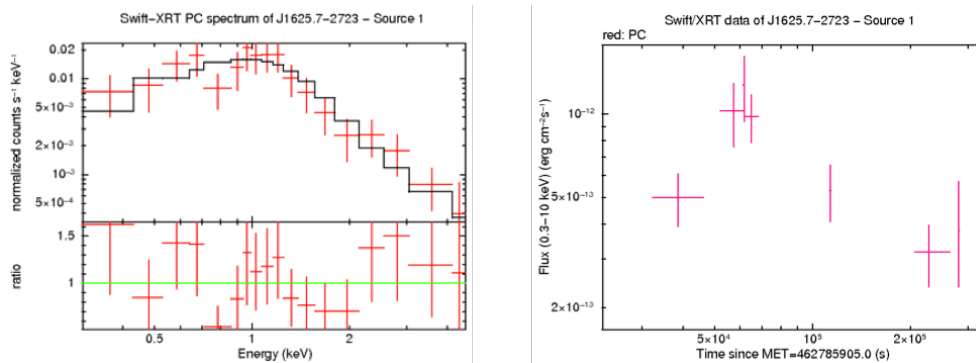


Figure 2 – Left: X-ray spectrum of the transient source discovered by Swift in the field of ANT150901A. Right: Swift/XRT lightcurve of the same source.

3 Real-time follow-up activities of ANTARES

In addition to the follow-up electromagnetic observations described above, specific strategies are developed to look for neutrino events in both time and space coincidence with transient events announced by an alert distributed through the Gamma-ray Coordinated Network (GCN). Hereafter, we describe the follow-up analyses performed with ANTARES after the detection of the first gravitational wave event by LIGO/Virgo in September 2015 (Section 3.1) and following the detection of high-energy neutrino candidates by IceCube (Section 3.2) while searches for neutrino counterparts of catalogued astrophysical variable and transient objects are described in Sections 3.3 and 3.4.

3.1 High-energy neutrino follow-up of the gravitational wave events

The observation of two significant gravitational wave (GW) sources by Advanced LIGO on September 14th and December 26th, 2015^{6,7} represents an important step forward in the era of multi-messenger astrophysics.

In a joint analysis with the IceCube and the LIGO/Virgo collaborations⁸, we searched for directional and temporal coincidences between GW150914 and reconstructed HEN candidates. Relying on the methodology defined in Baret et al.⁹, we looked for (i) temporal coincidences within a ± 500 s time window around the GW alert and (ii) spatial overlap between the 90% probability contour of GW150914 and the neutrino point spread function. To this end, we used ANTARES’s online reconstruction pipeline² which selects up-going neutrino candidates with atmospheric muon contamination less than 10%. An energy cut was also applied to reduce the background of atmospheric neutrinos which finally leads to an event rate of 1.2 events/day. Consequently, the expected number of neutrino candidates within 1000 s is 0.014. This corresponds to a Poisson probability of observing at least one background event of $\sim 1.4\%$. No neutrino candidates temporally coincident with GW150914 were found with ANTARES while IceCube detected 3 events within the ± 500 s time window. Both results are fully compatible with the background expectations.

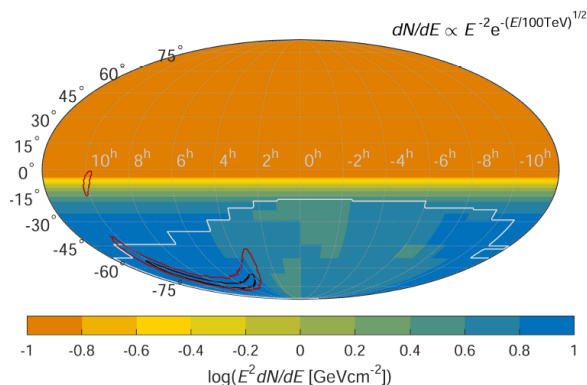


Figure 3 – Upper limit on the HEN spectral fluence ($\nu_\mu + \bar{\nu}_\mu$) from GW150914 assuming the spectral model with cutoff at 100 TeV.

The absence of neutrino candidate both temporally and positionally coincident with GW150914 allowed us to derive an UL on the spectral fluence ϕ^a emitted in neutrinos by the source at 90% confidence level, as a function of the location of the source in equatorial coordinates. Two different spectral models were considered: a standard $dN/dE \propto E^{-2}$ model and a model with a spectral cutoff at 100 TeV expected for sources with exponential cutoff in the primary proton spectrum. Figure 3 shows in each direction of the sky the most stringent fluence UL provided either by ANTARES or IceCube (the white contour on Figure 3 defines the region where ANTARES is the most sensitive) for the spectral model with cutoff.

Using the constraints on the distance of the GW source and the neutrino fluence UL, we derived the ULs on the total energy emitted in neutrinos by this source. This was obtained by integrating the emission between 100 GeV and 100 PeV for each spectral model and each location in the sky map. The total energy UL depends on the source distance and equatorial coordinates. To account for these uncertainties, the lowest and highest total energy UL within the 90% confidence level interval are provided. The ULs on the total energy radiated in neutrinos are $5.4 \times 10^{51} - 1.3 \times 10^{54}$ erg and $6.6 \times 10^{51} - 3.7 \times 10^{54}$ erg respectively for the spectral model without and with cutoff. These ULs could be finally compared to the energy radiated in GW of $\sim 5 \times 10^{54}$ erg.

Similar results¹⁰ have been published following the detection of GW151226 and LVT151012⁷. For GW151226, the source position constrained to within a 3D volume (direction on the sky

^a defined as $dN/dE = \phi E^{-\alpha}$.

and distance) was used to derive a direction-dependent constraint on the total energy radiated in neutrinos, by integrating the spectrum over the range [100 GeV; 100 PeV] (see Figure 4).

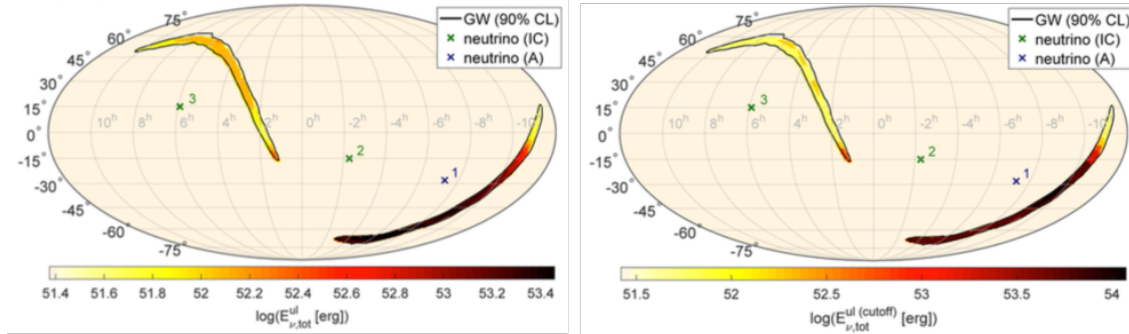


Figure 4 – Upper limit on the total energy radiated in neutrinos for GW151226 as a function of the source direction, assuming a neutrino spectrum $dN/dE \propto E^{-2}$ (left) and $dN/dE \propto E^{-2}e^{-(E/100\text{TeV})^{1/2}}$ (right).

3.2 Follow-up of IceCube HEN events

IceCube is currently the largest neutrino telescope. Located at the geographic South Pole, it is composed of 86 detection lines distributed over a cubic-kilometer of ice. High-energy events starting into the detector¹ (HESE) and extremely high-energy ones (EHE, with energy above 1 PeV) are received by the Astrophysical Multi-messenger Observatory Network (AMON¹¹) and distributed to the community via an alert of the GCN^b. A coincident detection by both IceCube and ANTARES would be a significant proof of the astrophysical origin of these neutrino candidates and would point directly to the position of the source in the sky. In this context, the ANTARES collaboration is performing a follow-up analysis of each IceCube event whose position is below the horizon of ANTARES (which could consequently yield to an up-going event at the time of the alert). Up to now, ANTARES has followed the four alerts (3 HESE and 1 EHE) in the field-of-view of the telescope. Two other events occurred in the field-of-view of ANTARES but were retracted by IceCube after further analysis which revealed a background origin. No neutrino candidates were found compatible with one of the alerts within a time window up to ± 1 hour. We used these non-detections to derive preliminary 90% confidence level ULs on the radiant neutrino fluence^c of these events of the order of $\sim 15 \text{ GeV cm}^{-2}$ and $\sim 30 \text{ GeV cm}^{-2}$ for the E^{-2} and the $E^{-2.5}$ spectral models respectively (see Table 1). These results have been published as GCN circulars within some hours after the alerts^{12, 13, 14, 15}.

Table 1: Fluence upper limits for each IceCube neutrino candidate.

IceCube event	Fluence UL (GeV cm^{-2})	
	$dN/dE \propto E^{-2}$	$dN/dE \propto E^{-2.5}$
IC160731A (EHE)	14	27
IC160814A (HESE)	15.7	43
IC161103A (HESE)	13	32
IC170321A (HESE)	16	26

^b<https://gcn.gsfc.nasa.gov/amon.html>

^ccomputed as $\int_{E_{min}}^{E_{max}} E dN/dE dE$; with E_{min} and E_{max} , respectively the 5% and 95%-quantiles of the detectable energy range.

3.3 *Looking for a neutrino counterpart to gamma-ray bursts and fast radio bursts*

Transient astrophysical events are observed all over the electromagnetic spectrum and in particular at both ends of the spectrum, in the radio and gamma-ray domains where we respectively observe fast radio bursts (FRBs) and GRBs. While the latter are probably related to either the collapse of massive stars or the merger of two compact objects, the sources producing the former are still unknown. If hadrons are accelerated in relativistic outflows of both GRBs and FRBs, TeV-PeV neutrinos might be produced by photo-hadronic interactions. Dedicated offline analyses are performed by the ANTARES collaboration^{16, 17, 18}. In particular, a stacked analysis based on the full ANTARES data sample from 2008 to 2016 enables to constrain the contribution of GRBs to the diffuse flux of cosmic neutrinos. On the other hand, looking for individual GRBs and FRBs helps to constrain theoretical models of neutrino emission.

ANTARES is able to react to external alerts sent through the GCN after the detection of a GRB. Data analysis can be done in two alternative ways. A search for muon-track neutrino counterpart in the standard online dataset is performed in real-time within 15 min around the detection and 2° from the GRB position. To ensure the quality of the data at the alert time, the detector stability is checked over several hours before the alert. The result of the search is sent by email within 15 min after the release of the GCN. In case of a coincident neutrino detection, a dedicated offline analysis is run to confirm the result and compute its significance (expected to be higher than 3σ in most of the cases). More than 500 GRB alerts have been followed by ANTARES so far.

Alternatively, a specific data taking mode is activated jointly with the standard one in case of a GRB alert. All raw data covering a preset period (typically 2 minutes, depending on the background rate, the number of data processing computers, and the size of the RAM) are saved to disk without any filtering¹⁹. Data buffering in the filter processors enables to store the data up to about one minute before the actual GCN alert. In most cases, it consequently includes data collected by ANTARES before the GRB occurred, which can be used to search for a neutrino signal occurring before the gamma ray emission. These unfiltered data can be analysed with a less strict filtering compared to the standard online filtering and a reconstruction algorithm optimised for energies below 1 TeV²⁰ can be applied to increase the detection efficiency (by a factor of ~ 2 at 100 GeV and $\sim 30\%$ at 10 TeV). A dedicated algorithm searching for time and space correlations in a small region of interest around the GRB position is finally used as in standard offline analyses. An analysis based on this approach has recently been published by the ANTARES collaboration to test the photospheric model²¹ of neutrino emission in GRBs¹⁶. No neutrino events have been detected in temporal and spatial coincidence with four bright GRBs (GRB 080916C, 110918A, 130427A and 130505A) and upper limits at 90% C.L. on the expected neutrino fluxes were derived¹⁶.

As for FRBs, the Parkes radiotelescope, located in Australia, is the main discovery instrument so far and the SURvey for Pulsars and Extragalactic Radio Bursts (SUPERB) is underway on this instrument²². One of the main obstacle for constraining the nature of the FRBs is the latency between the detection of the burst and the starting of multi-wavelength and multi-messenger follow-up observations aimed to identify an FRB counterpart. The SUPERB program was designed to drastically reduce the time needed to send a notification to the community. In this context, ANTARES is receiving alerts issued by the SUPERB collaboration in case of a Fast Radio Burst detection since 2015. The ANTARES collaboration has recently been involved in the multi-wavelength and multi-messenger study of FRB 150215 detected with the Parkes radiotelescope by SUPERB²³. The datastream was searched for up-going track events from a point-like source within a time window of up to ± 1 day around the FRB detection in a region of interest of 2° centered on the position of the Parkes beam center. No neutrinos were detected coincident with this transient event. Consequently, a neutrino radiant fluence UL at 90% confi-

dence level has been computed together with an UL on the total energy emitted in high-energy neutrinos (assuming a redshift of $z = 0.56$ as constrained by radio data). The results lead to a radiant fluence UL of $\sim 1.4 \times 10^{-2}$ erg cm $^{-2}$ and a total energy of 1.4×10^{55} erg when assuming a spectral model $dN/dE \propto E^{-2}$.

3.4 Looking for a neutrino counterpart to flaring sources

Microquasars, blazars and GRBs are supposed to share the same physical mechanisms based on the accretion of gas onto a black hole which power the relativistic jets of material ejected from both sides of the compact object. However, some major issues are still open: what is the particle acceleration mechanism at work in these systems? Is it unique? Constraining the jet composition and its baryonic content would help answering these questions since it may impact the outflow-launching process.

Looking for electromagnetic counterparts to interesting neutrino candidates can enable to constrain a GRB origin as discussed in Section 2. On the other hand, offline searches for neutrino counterparts to catalogued microquasars, blazars and GRBs are underway. In particular, a work recently published by the ANTARES collaboration has been used to search for neutrino emission during the flares from Galactic X-ray binaries²⁴. A total of 34 X-ray binaries have been studied, with no significant detections, allowing some of the more optimistic models for hadronic acceleration in these sources to be rejected at 90% C.L. (see Figure 5).

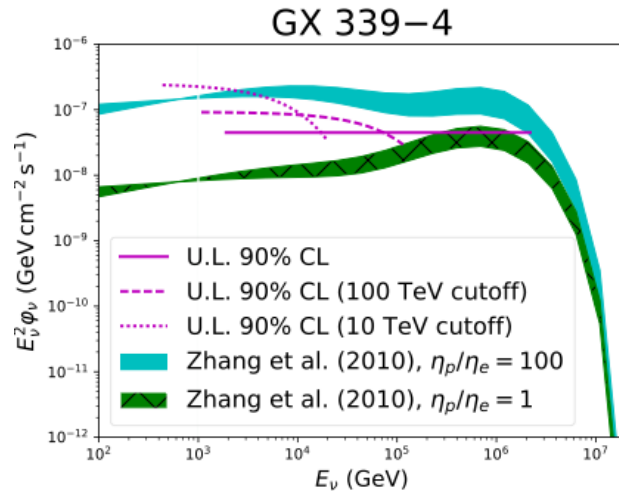


Figure 5 – Upper limit at 90% C.L. on the neutrino flux from the microquasar GX 339-4. Different spectral models are considered (E^{-2} , $E^{-2}\exp(-E/10 \text{ TeV})$ and $E^{-2}\exp(-E/100 \text{ TeV})$). These ULs are compared to the prediction of the hadronic models of Zhang et al.²⁵ with different baryonic loadings.

On the other hand, several bright blazars studied by the TANAMI collaboration^d through radio and gamma-ray data, are located within the 50% error box of the reconstructed arrival directions of the IceCube/HESE PeV neutrino events IC #14 and IC #20. A dedicated study performed with ANTARES revealed signal-like events from two bright blazars in the field of IC#14, although this is also consistent with background fluctuations. A lack of such events from the field of IC #20 excludes a neutrino spectrum softer than $E^{-2.4}$ as being responsible for this event²⁶.

4 Conclusion

By simultaneously monitoring at least half of the sky, neutrino telescopes are well-suited to detect transient sources. In this context, multi-messenger approaches are destined for a bright

^d<http://pulsar.sternwarte.uni-erlangen.de/tanami/>

future and will help to probe the physical processes at work in these objects. In particular, a multi-wavelength follow-up program has been operating in ANTARES since 2009 and enables to increase the sensitivity of the telescope by looking for a coincident electromagnetic detection both in time and space. Furthermore, the ANTARES collaboration is deploying specific strategies to search for joint detections of neutrinos and other messengers such as GWs. Because of the better angular accuracy of neutrino telescopes compared to GW detectors with two interferometers, a coincident detection would drastically constrain the position of the GW source on the sky, bringing valuable information for subsequent electromagnetic follow-ups. In the near future, KM3NeT, the next generation of European neutrino telescopes currently under deployment in the Mediterranean sea, will greatly improve the sensitivity to neutrino point-sources (by of factor of ~ 50 with respect to ANTARES between 5 GeV and a few PeV). On the other hand, it will provide a high-purity sample of astrophysical neutrinos together with a an improved angular resolution ($\sim 0.2^\circ$ for muon track events and $\sim 1.5^\circ$ for showers) that will enable significant improvement on the multi-messenger and electromagnetic follow-up activities.

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