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Follow-up of GW150914 and multi-messenger studies of transient astrophysical sources with the ANTARES neutrino telescope

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Abstract. 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 triggering optical, X-ray and radio observations immediately after the detection of an interesting ANTARES event and also 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. 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 gravitation-wave event, GW150914.

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, but also across the electromagnetic spectrum. 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 telescope (see e.g. [1]), 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 pho-

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tomultipliers 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 2009 [2]. 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 200 alerts have been sent to optical robotic telescopes (TAROT, ROTSE and MASTER) since mid-2009 while 12 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°) with a local galaxy (distance < 20 Mpc).

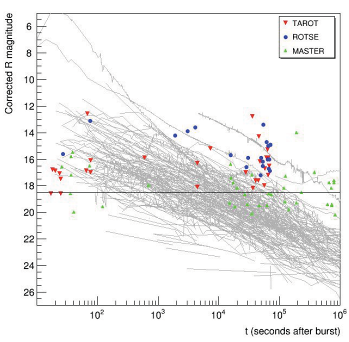

Figure 1. Corrected R-band magnitude as a function of time for 301 GRB afterglows. Red, blue and green dots indicate upper limits on GRB afterglow magnitudes for neutrino alerts observed by TAROT, ROTSE and MASTER respectively. The horizontal dashed line corresponds to the sensitivity of the optical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

From January 2010 to January 2016, 93 alerts with early optical follow-up have been analyzed. No optical counterparts were found and upper limits on the R-band magnitude of a transient astrophysical source have been derived. By comparing these upper limits with optical afterglow light cuves of gamma-ray bursts (GRB), 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 trigger [3]. A similar analysis has been carried out with *Swift*-XRT follow-ups of 12 ANTARES alerts [3]. 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.

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 Earth [4]. No counterparts were detected and upper limits for low-frequency radio luminosity have been derived. Likewise, two ANTARES alerts have been followed by H.E.S.S. and 36 by HAWC since November 2014.

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3 Follow-up analyses

In addition to the follow-up 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 analysis 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).

3.1 High-energy neutrino follow-up of the gravitational-wave event GW150914

The observation of two significant gravitational wave (GW) sources by Advanced LIGO on September 14$^{\mathrm{th}}$ and December 26$^{\mathrm{th}}$, 2015 [5, 6] represents an important step forward in the era of multi-messenger astrophysics.

In a joint analysis with the IceCube and the LIGO/Virgo collaborations [7], we searched for directional and temporal coincidences between GW150914 and reconstructed HEN candidates. Relying on the methodology defined in [8], 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 pipeline [3] 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 ∼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. The absence of neutrino candidate both temporally and positionally coincident with GW150914 allowed us to derive an upper limit on the spectral fluence 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 2 shows in each direction of the sky the most stringent fluence upper limit (UL) provided either by ANTARES or IceCube (the white contour on figure 2 defines the region where ANTARES is the most sensitive) for the spectral model with cutoff.

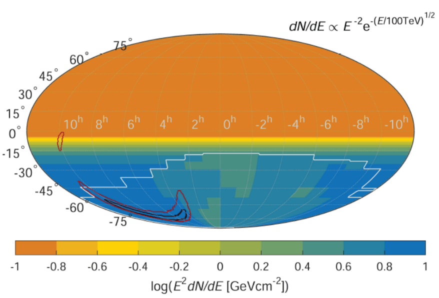

Figure 2. Upper limit on the HEN spectral fluence ($\nu_\mu + \bar{\nu}_\mu$) from GW150914 assuming the spectral model with cutoff at 100 TeV.

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.

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 detector (HESE, see e.g. [1]) and extremely high-energy ones (with energy above 1 PeV) are received by the Astrophysical Multi-messenger Observatory Network (AMON, [9]) and distributed to the community via an alert of the GCN. 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 that 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 three IceCube alerts [10–12]. No neutrino candidates were found compatible with one of the alerts within a time window of ± 1 day. We used these non-detections to derive preliminary 90% confidence level upper limits on the radiant neutrino fluence of these events of the order of ∼15 GeV $\cdot$ cm^{-2} and ∼30 GeV$\cdot$ cm^{-2} for the E^{-2} and the E$^{-2.5}$ spectral models respectively.

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 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. ANTARES will continue following-up future GW events during the second observing run of advanced LIGO, starting in December 2016. Because of the better angular accuracy of the 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.

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