High-Energy Neutrino follow-up of first gravitational wave event GW150914

Alexis Coleiro¹, Bruny Baret¹, Thierry Pradier² on behalf of the ANTARES collaboration.

¹APC, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, 10 rue Alice Domon et Léonie Duquet, 75205 Paris Cedex 13, France.
²Université de Strasbourg, IPHC, 23 rue du Loess 67037 Strasbourg, France - CNRS, UMR7178, 67037 Strasbourg, France.
E-mail: coleiro@apc.in2p3.fr

Abstract. On September 14th 2015, LIGO/Virgo collaboration has detected the first significant gravitational wave event. Consequently, a neutrino followup was performed using both ANTARES and IceCube online data selection to search for a potential neutrino counterpart to this event. No neutrino candidate in both temporal and spatial coincidence with GW150914 had been detected within ± 500 s from the event. This non-detection was used to constrain the neutrino fluence and the total energy emitted in neutrinos for a standard $E^{-2}$ source spectrum as well as a spectral cutoff at 100 TeV. This first joint study does demonstrate the multimessenger synergies between ANTARES, IceCube and LIGO/Virgo. A coincident gravitational wave and neutrino detection would open a new era in multimessenger astrophysics.

1. Introduction
The observation of two significant gravitational wave (GW) sources by Advanced LIGO on Sept. 14th and Dec. 26th, 2015 [1, 2] represents an important step forward in the study of the latest stage of massive star binary system evolution. By involving a number of observatories from the radio to the gamma-rays and also neutrino detectors to search for a potential counterpart associated to these events, the detection of the first GW events opened the era of time domain multi-messenger astrophysics.

The first GW event, GW150914, corresponds to the coalescence of a stellar-mass black hole binary system at a redshift $z=0.09^{+0.03}_{-0.04}$. While an electromagnetic counterpart (presumably associated with a neutrino emission) is generally expected from a neutron star/black hole or neutron star/neutron star merger (e.g. [3]), current consensus is that black hole/black hole merger does not produce electromagnetic or neutrino counterpart. However, in a dense enough hadronic environment, an accretion disk might form, and relativistic outflow connected to the accretion could be released. Energy dissipation in this outflow would consequently lead to a gamma-ray emission with a potential high-energy ($\gg$ GeV) neutrino counterpart (e.g. [4]).

ANTARES is currently the largest high-energy neutrino (HEN) telescope in the Northern hemisphere. Located in the Mediterranean Sea, 20 km off the Southern coast of France, it is composed of 12 detection lines that detect the Cherenkov light emitted by relativistic upgoing muons, signature of a neutrino interaction close to the detector. IceCube Neutrino Observatory is a cubic-kilometer facility located at the South Pole. Thanks to its large instrumented volume, IceCube has recently discovered an astrophysical HEN diffuse flux [5] whose sources remain
however unknown. In this context, observing campaigns relying both on electromagnetic and multi-messenger facilities may be decisive to identify the origin of these HEN events.

Joint searches of common sources of HEN and GW have already been performed in the past with both ANTARES and IceCube neutrino telescopes [7, 8, 9]. In this proceedings we report the result of the HEN follow-up performed after the detection of GW150914, detailed in [6]. In section 2 we first describe the HEN search methodology and the results. Constraints on the source neutrino fluence and energy are provided in section 3. We conclude in section 4.

2. High-Energy neutrino search and results

We searched for directional and temporal coincidences between GW150914 and reconstructed HEN candidates from both ANTARES and IceCube. Relying on the methodology defined in [10], we searched for (i) temporal coincidences within a ±500 s time window around the GW alert and (ii) spatial overlap between GW150914 90% positional probability contour (see figure 1) and neutrino point spread function.

Figure 1. GW skymap in equatorial coordinates and the reconstructed directions of HEN candidates detected by IceCube.

To this end, we used ANTARES’s online reconstruction pipeline [11] which selects upgoing neutrino candidates with atmospheric muon contamination less than 10%. An energy cut is 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. This is fully consistent with the background expectation. The search for HEN counterpart with IceCube used IceCube’s online event stream with an event selection similar to the one applied for point source searches, but optimized for real-time search. The expected background rate is equal to 2.2 atmospheric neutrino events in the Northern sky (corresponding to atmospheric neutrinos) and 2.2 high energy atmospheric muons from the Southern sky. Within ±500 s around GW150914, three events were found. This observed event rate and the energy of these three events are compatible with the background expectations as well.

3. Constraints on the source

The absence of neutrino candidate both temporally and positionally coincident with GW150914 allows 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 [12].

Figures 2 and 3 show in each direction of the sky the most stringent fluence upper limit (UL) provided either by ANTARES or IceCube (white contour on figure 3 defines the region where ANTARES is the most sensitive). The two detectors constrain different energy ranges. Indeed,
for a $E^{-2}$ spectrum, 90% of ANTARES signal events are in the energy range between 3 TeV and 1 PeV, whereas IceCube signal is within the range 200 TeV – 100 PeV in the Southern hemisphere. For the larger GW probability contour located farther South, we derive upper limits $E^2dN/dE = 1.2^{+0.25}_{-0.36}$ GeV cm$^{-2}$ and $E^2dN/dE = 7.0^{+3.2}_{-2.0}$ GeV cm$^{-2}$ for the two spectral models without and with a cutoff, respectively. For the northern region, the limits are much more constraining due to IceCube high sensitivity in this part of the sky.

![Figure 2](image2.png)  
**Figure 2.** Upper limit on the HEN spectral fluence ($\nu_\mu + \bar{\nu}_\mu$) from GW150914 assuming $dN/dE \propto E^{-2}$.

![Figure 3](image3.png)  
**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.

Using the constraints on the distance of the GW source and the neutrino fluence UL, we derive an UL 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 will depend 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 UL on the total energy radiated in neutrinos are $5.4 \times 10^{54} - 1.3 \times 10^{54}$ erg and $6.6 \times 10^{54} - 3.7 \times 10^{54}$ erg respectively for the spectral model without and with cutoff. This UL could be finally compared to the energy radiated in GW of $\sim 5 \times 10^{54}$ erg.

4. Conclusion
ANTARES and IceCube will continue following-up future GW events, in particular during the second observing run of advanced LIGO, starting in October 2016. Because of the better angular accuracy of the neutrino telescopes ($\sim 0.5^{\circ}$2) compared to GW detectors with 2 interferometers ($\sim 100^{\circ}$2), a coincident detection would drastically constrain the position of the GW source on the sky and thus bring valuable information for subsequent electromagnetic follow-ups.

References
[1] Abbott B P et al. *Phys. Rev. Lett.* **116** 061102 (2016).
[2] Abbott B P et al. *Phys. Rev. Lett.* **116** 241103 (2016).
[3] Metzger B D and Berger E *Astroph. Journal* **746** 48 (2012).
[4] Perna R, Lazzati D and Giacomazzo, B *Astroph. Journal Letters* **821** 18 (2016).
[5] Aartsen M G et al. *Phys. Rev. D* **90** 102002 (2014).
[6] Adrian-Martínez et al. *Phys. Rev. D* **93** 122010 (2016).
[7] Adrian-Martínez et al. *JCAP* **6** 008 (2013).
[8] Baret B. Proc. of the Rencontres de Moriond: 2015 Gravitation 100 years after GR.
[9] Aartsen M G et al. *Phys. Rev. D* **90** 102002 (2014).
[10] Baret B et al. *Astropart. Phy.* **35** 1-7 (2011).
[11] Adrian-Martínez et al. *JCAP* **2** 062 (2016).
[12] Kappes A, Hinton J, Stegmann C and Aharonian F A, *Journal of Phys. Conf. Series* **60** 243 (2007).