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High-energy neutrino follow-up search of gravitational wave event GW150914 with ANTARES and IceCube

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We present the high-energy-neutrino follow-up observations of the first gravitational wave transient GW150914 observed by the Advanced LIGO detectors on September 14, 2015. We search for coincident neutrino candidates within the data recorded by the IceCube and ANTARES neutrino detectors. A possible joint detection could be used in targeted electromagnetic follow-up observations, given the significantly better angular resolution of neutrino events compared to gravitational waves. We find no neutrino candidates in both temporal and spatial coincidence with the gravitational wave event. Within ±500 s of the gravitational wave event, the number of neutrino candidates detected by IceCube and ANTARES were three and zero, respectively. This is consistent with the expected atmospheric background, and none of the neutrino candidates were directionally coincident with GW150914. We use this nondetection to constrain neutrino emission from the gravitational-wave event.

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I. INTRODUCTION

Advanced LIGO's first observation periods [1,2] represent a major step in probing the dynamical origin of high-energy emission from cosmic transients [3]. The significant improvement in gravitational wave (GW) search sensitivity enables a comprehensive multimessenger observational effort involving partner electromagnetic observatories from radio to gamma-rays, as well as neutrino detectors. The goals of multimessenger observations are to gain a more complete understanding of cosmic processes through a combination of information from different probes, and to increase search sensitivity over an analysis using a single messenger [4–6].

The merger of neutron stars and black holes, and potentially massive stellar core collapse with rapidly rotating cores, are expected to be significant sources of GWs [3]. These events can result in a black hole plus accretion disk system that drives a relativistic outflow [7,8]. Energy dissipation in the outflow produces nonthermal, high-energy radiation that is observed as gamma-ray bursts (GRBs), and may have a ≫GeV neutrino component at comparable luminosities.

Multiple detectors have been built that can search for this high-energy neutrino signature, including the IceCube Neutrino Observatory—a cubic-kilometer facility at the South Pole [9–11], and ANTARES [12–14] in the Mediterranean sea. The construction of the KM3NeT cubic-kilometer scale neutrino detector in the Mediterranean Sea has started in December 2015 with the successful deployment of the first detection string [15]. IceCube is planning a substantial increase in sensitivity with near-future upgrades [16,17]. Another facility, the Baikal Neutrino Telescope is also planning an upgrade to cubic-kilometer volume [18]. An astrophysical high-energy neutrino flux has recently been discovered by IceCube [19–22], demonstrating the production of nonthermal high-energy neutrinos. The specific origin of this neutrino flux is currently unknown. Multimessenger analyses constraining the common sources of high-energy neutrinos and GWs have been carried out in the past with both ANTARES and IceCube [23–25].

On September 14, 2015 at 09:50:45 UTC, a highly significant GW signal was recorded by the LIGO Hanford, WA and Livingston, LA detectors [26]. The event, labeled GW150914, was produced by a stellar-mass binary black hole merger at redshift $z = 0.09^{+0.03}_{-0.04}$. The reconstructed mass of each black hole is ~30 $M_\odot$. Such a system may produce electromagnetic emission and emit neutrinos if the merger happens in a sufficiently baryon-dense environment, and a black hole plus accretion disk system is formed [27]. Current consensus is that such a scenario is unlikely, nevertheless, there are no significant observational constraints.

Here we report the results of a neutrino follow-up search of GW150914 using ANTARES and IceCube. After brief descriptions of the GW search (Sec. II) and the neutrino follow-up (Sec. III), we present the joint analysis, results of the search and source constraints, and conclusions (Sec. IV).

II. GRAVITATIONAL WAVE DATA ANALYSIS AND DISCOVERY

GW150914 was initially identified by low-latency searches for generic GW transients [28–30]. Subsequent

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analysis with three independent matched-filter analyses using models of compact binary coalescence waveforms [31,32] confirmed that the event was produced by the merger of two black holes. The analyses established a false alarm rate of less than 1 event per 203000 years, equivalent to a significance $>5.1\sigma$ [26]. Source parameters were reconstructed using the LALINFERENCE package [32–34], finding black-hole masses $36^{+5}_{-4}\ \mathrm{M}_\odot$ and $29^{+4}_{-4}\ \mathrm{M}_\odot$ and luminosity distance $D_{\mathrm{gw}} = 410^{+160}_{-180}$ Mpc, where the error ranges correspond to the range of the 90% credible interval. The duration of the signal within LIGO's sensitive band was 0.2 s.

The directional point spread function (sky map) of the GW event was computed through the full parameter estimation of the signal, carried out using the LALINFERENCE package [33,34]. The LALINFERENCE results presented here account for calibration uncertainty in the GW strain signal. The sky map is shown in Fig. 1. At 90% (50%) credible level (CL), the sky map covers 610 deg^2 (150 deg^2).

III. HIGH-ENERGY NEUTRINO COINCIDENCE SEARCH

High-energy neutrino observatories are primarily sensitive to neutrinos with ≫GeV energies. IceCube and ANTARES are both sensitive to through-going muons (called track events), produced by neutrinos near the detector, above ∼100 GeV. In this analysis, ANTARES data include only up-going tracks for events originating from the Southern hemisphere, while IceCube data include both up-going tracks (from the Northern hemisphere) as well as down-going tracks (from the Southern hemisphere). The energy threshold of neutrino candidates increases in the Southern hemisphere for IceCube, since downward-going atmospheric muons are not filtered by the Earth, greatly increasing the background at lower energies. Neutrino times of arrival are determined at μs precision.

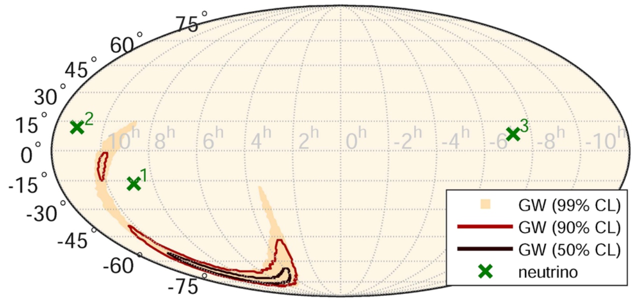

FIG. 1. GW skymap in equatorial coordinates, showing the reconstructed probability density contours of the GW event at 50%, 90% and 99% CL, and the reconstructed directions of high-energy neutrino candidates detected by IceCube (crosses) during a ±500 s time window around the GW event. The neutrino directional uncertainties are $< 1°$ and are not shown. GW shading indicates the reconstructed probability density of the GW event, darker regions corresponding to higher probability. Neutrino numbers refer to the first column of Table I.

Since neutrino telescopes continuously take data observing the whole sky, it is possible to look back and search for neutrino counterparts to an interesting GW signal at any time around the GW observation.

To search for neutrinos coincident with GW150914, we used a time window of ±500 s around the GW transient. This search window, which was used in previous GW-neutrino searches, is a conservative, observation-based upper limit on the plausible emission of GWs and high-energy neutrinos in the case of GRBs, which are thought to be driven by a stellar-mass black hole—accretion disk system [35]. While the relative time of arrival of GWs and neutrinos can be informative [36–38], here we do not use detailed temporal information beyond the ±500 s time window.

The search for high-energy neutrino candidates recorded by IceCube within ±500 s of GW150914 used IceCube's online event stream. The online event stream implements an event selection similar to the event selection used for neutrino point source searches [39], but optimized for real-time performance at the South Pole. This event selection consists primarily of cosmic-ray-induced background events, with an expectation per 1000 seconds of 2.2 events in the Northern sky (atmospheric neutrinos), and 2.2 events in the Southern sky (high-energy atmospheric muons). In the search window of ±500 s centered on the GW alert time (see below), one event was found in the Southern sky and two in the Northern sky, which is consistent with the background expectation. The properties of these events are listed in Table I. The neutrino candidates' directions are shown in Fig. 1.

The muon energy in Table I is reconstructed assuming a single muon is producing the event. While the event from the Southern hemisphere has a significantly greater reconstructed energy [41] than the other two events, 12.5% of the background events in the same declination range in the Southern hemisphere have energies in excess of the one observed. The intense flux of atmospheric muons and bundles of muons that constitute the background for

TABLE I. Parameters of neutrino candidates identified by IceCube within the ±500 s time window around GW150914. ΔT is the time of arrival of the neutrino candidates relative to that of GW150914. $\mathrm{E}^{\mathrm{rec}}_{\mu}$ is the reconstructed muon energy. $\sigma^{\mathrm{rec}}_{\mu}$ is the angular uncertainty of the reconstructed track direction [40]. The last column shows the fraction of background neutrino candidates with higher reconstructed energy at the same declination (±5°).

No.	ΔT [s]	RA [h]	Dec [°]	$\sigma^{\mathrm{rec}}_{\mu}$ [°]	$\mathrm{E}^{\mathrm{rec}}_{\mu}$ [TeV]	Fraction
1	+37.2	8.84	−16.6	0.35	175	12.5%
2	+163.2	11.13	12.0	1.95	1.22	26.5%
3	+311.4	−7.23	8.4	0.47	0.33	98.4%

IceCube in the Southern hemisphere gradually falls as the cosmic ray flux declines with energy [42]. The use of energy cuts to remove most of this background is the reason that IceCube's sensitivity in the Southern sky is shifted to higher energies.

An additional search was performed using the high-energy starting event selection described in [19]. No events were found in coincidence with GW150914.

The IceCube detector also has sensitivity to outbursts of MeV neutrinos (as occur for example in core-collapse supernovae) via a sudden increase in the photomultiplier rates [43]. The global photomultiplier noise rate is monitored continuously, and deviations sufficient to trigger the lowest-level of alert occur roughly once per hour. No alert was triggered during the ±500 second time-window around the GW candidate event.

The search for coincident neutrinos for ANTARES within ±500 s of GW150914 used ANTARES's online reconstruction pipeline [44]. A fast and robust algorithm [45] selected up-going neutrino candidates with ~ mHz rate, with atmospheric muon contamination less than 10%. In addition, to reduce the background of atmospheric neutrinos [46], a requirement of a minimum reconstructed energy reduced the online event rate to 1.2 events/day. Consequently, for ANTARES the expected number of neutrino candidates from the Southern sky in a 1000 s window in the Southern sky is 0.015. We found no neutrino events from ANTARES that were temporally coincident with GW150914. This is consistent with the expected background event rate.

IV. RESULTS

A. Joint analysis

We carried out the joint GW and neutrino search following the analysis developed for previous GW and neutrino data sets using initial GW detectors [23,25,35,47]. After identifying the GW event GW150914 with the cWB pipeline, we used reconstructed neutrino candidates to search for temporal and directional coincidences between GW150914 and neutrinos. We assumed that the *a priori* source directional distribution is uniform. For temporal coincidence, we searched within a ±500 s time window around GW150914.

The relative difference in propagation time for $\gg$GeV neutrinos and GWs (which travel at the speed of light in general relativity) traveling to Earth from the source is expected to be $\ll 1$ s. The relative propagation time between neutrinos and GWs may change in alternative gravity models [48,49]. However, discrepancies from general relativity could in principle be probed with a joint GW-neutrino detection by comparing the arrival times against the expected time frame of emission.

Directionally, we searched for overlap between the GW sky map and the neutrino point spread functions, assumed to be Gaussian with standard deviation $\sigma_\mu^{\rm rec}$ (see Table I).

The search identified no ANTARES neutrino candidates that were temporally coincident with GW150914.

For IceCube, none of the three neutrino candidates temporally coincident with GW150914 were compatible with the GW direction at 90% CL. Additionally, the reconstructed energy of the neutrino candidates with respect to the expected background does not make them significant. See Fig. 1 for the directional relation of GW150914 and the IceCube neutrino candidates detected within the ±500 s window. This nondetection is consistent with our expectation from a binary black hole merger.

To better understand the probability that the detected neutrino candidates are consistent with background, we briefly consider different aspects of the data separately. First, the number of detected neutrino candidates, i.e. 3 and 0 for IceCube and ANTARES, respectively, is fully consistent with the expected background rate of 4.4 and $\ll 1$ for the two detectors, with p-value $1-F_{\rm pois}(N_{\rm observed}\leq 2, N_{\rm expected}=4.4)=0.81$, where $F_{\rm pois}$ is the Poisson cumulative distribution function. Second, for the most significant reconstructed muon energy (Table I), 12.5% of background events will have greater muon energy. The probability that at least one neutrino candidate, out of 3 detected events, has an energy high enough to make it appear even less background-like, is $1-(1–0.125)^3 \approx 0.33$. Third, with the GW sky area 90% CL of $\Omega_{\rm gw} = 610\ \deg^2$, the probability of a background neutrino candidate being directionally coincident is $\Omega_{\rm gw}/\Omega_{\rm all} \approx 0.015$. We expect $3\Omega_{\rm gw}/\Omega_{\rm all}$ directionally coincident neutrinos, given 3 temporal coincidences. Therefore, the probability that at least one of the 3 neutrino candidates is directionally coincident with the 90% CL skymap of GW150914 is $1-(1–0.015)^3 \approx 0.04$.

B. Constraints on the source

We used the nondetection of coincident neutrino candidates by ANTARES and IceCube to derive a standard frequentist neutrino spectral fluence upper limit for GW150914 at 90% CL. Considering no spatially and temporally coincident neutrino candidates, we calculated the source fluence that on average would produce 2.3 detected neutrino candidates. We carried out this analysis as a function of source direction, and independently for ANTARES and IceCube.

The obtained spectral fluence upper limits as a function of source direction are shown in Fig. 2. We considered a standard $dN/dE \propto E^{-2}$ source model, as well as a model with a spectral cutoff at high energies: $dN/dE \propto E^{-2}\exp[-\sqrt{(}E/100\ \mathrm{TeV})]$. The latter model is expected for sources with exponential cutoff in the primary proton spectrum [50]. This is expected for some galactic sources, and is also adopted here for comparison to previous

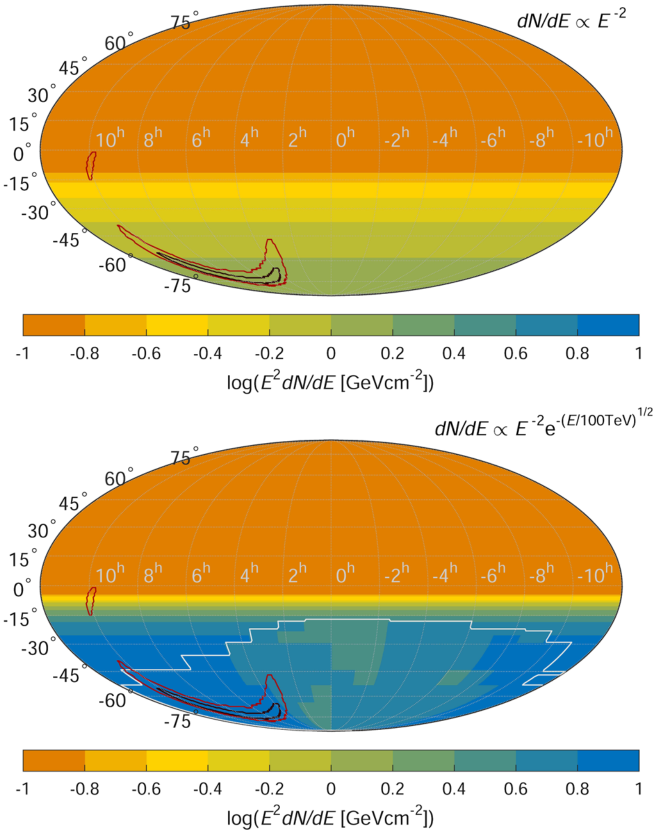

FIG. 2. Upper limit on the high-energy neutrino spectral fluence ($\nu_\mu + \bar{\nu}_\mu$) from GW150914 as a function of source direction, assuming $dN/dE \propto E^{-2}$ (top) and $dN/dE \propto E^{-2}\exp[-\sqrt{(}E/100\ \mathrm{TeV})]$ (bottom) neutrino spectra. The region surrounded by a white line shows the part of the sky in which ANTARES is more sensitive (close to nadir), while on the rest of the sky, IceCube is more sensitive. For comparison, the 50% CL and 90% CL contours of the GW sky map are also shown.

analyses [51]. For each spectral model, the upper limit shown in each direction of the sky is the more stringent limit provided by one or the other detector. We see in Fig. 2 that the constraint strongly depends on the source direction, and is mostly within $E^2 dN/dE \sim 10^{-1} - 10\ \mathrm{GeV\,cm^{-2}}$. Furthermore, the upper limits by ANTARES and IceCube constrain different energy ranges in the region of the sky close to the GW candidate. For an E^{-2} power-law source spectrum, 90% of ANTARES signal neutrinos are in the energy range from 3 TeV to 1 PeV, whereas for IceCube at this southern declination the corresponding energy range is 200 TeV to 100 PeV.

To characterize the dependence of neutrino spectral fluence limits on source direction, we calculate these limits separately for the two distinct areas in the 90% credible region of the GW skymap. For the larger region farther South (hereafter *South region*), we find upper limits $E^2 dN/dE = 1.2^{+0.25}_{-0.36}\ \mathrm{GeV\,cm^{-2}}$ and $E^2 dN/dE = 7.0^{+3.2}_{-2.0}\ \mathrm{GeV\,cm^{-2}}$ for our two spectral models without and with a cutoff, respectively. The error bars define the 90% confidence interval of the upper limit, showing the level of variation within each region. The average values were obtained as geometric averages, which better represent the upper limit values as they are distributed over a wide numerical range. For the smaller region farther North (hereafter *North region*), we find upper limits $E^2 dN/dE = 0.10^{+0.12}_{-0.06}\ \mathrm{GeV\,cm^{-2}}$ and $E^2 dN/dE = 0.55^{+1.79}_{-0.44}\ \mathrm{GeV\,cm^{-2}}$. As expected, we see that the limits are much more constraining for the North region, given the stronger limits at the Northern hemisphere due to IceCube's greatly improved sensitivity there. Additionally, we see that the 90% confidence intervals for the South region, which is much more likely to contain the real source direction than the North region, are fairly small around the average, with the lower and higher limits only differing by about a factor of 2. The upper limits within this area can be considered essentially uniform. We observe a much greater variation in the North region.

To provide a more detailed picture of our constraints on neutrino emission, we additionally calculated neutrino fluence upper limits for different energy bands. For these limits, we assume $dN/dE \propto E^{-2}$ within each energy band. We focus on Dec $= -70°$, which is consistent with the most likely source direction, and also with most of the GW sky area's credible region. For each energy range, we use the limit from the most sensitive detector within that range. The obtained limits are given in Table II.

We now convert our fluence upper limits into a constraint on the total energy emitted in neutrinos by the source. To obtain this constraint, we integrate emission within [100 GeV, 100 PeV] for each source model. The obtained constraint will vary with respect to source direction as we saw above. It will also depend on the uncertain source distance. To account for these uncertainties, we provide the range of values from the lowest to the highest possible within the 90% confidence intervals with respect to source direction and the 90% credible interval with respect to source distance. For simplicity, we treat the estimated source distance and its uncertainty independent of the source direction. We consider both of the distinct sky regions to provide an inclusive range. For our two spectral

TABLE II. Upper limits on neutrino spectral fluence ($\nu_\mu + \bar{\nu}_\mu$) from GW150914, separately for different spectral ranges, at Dec $= -70°$. We assume $dN/dE \propto E^{-2}$ within each energy band.

Energy range	Limit [GeV cm^{-2}]
100 GeV–1 TeV	150
1 TeV–10 TeV	18
10 TeV–100 TeV	5.1
100 TeV–1 PeV	5.5
1 PeV–10 PeV	2.8
10 PeV–100 PeV	6.5
100 PeV–1 EeV	28

models, we obtain the following upper limit on the total energy radiated in neutrinos:

$$E^{\mathrm{ul}}_{\nu,\mathrm{tot}} = 5.4 \times 10^{51}\text{–}1.3 \times 10^{54}\ \mathrm{erg} \tag{1}$$

$$E^{\mathrm{ul(cutoff)}}_{\nu,\mathrm{tot}} = 6.6 \times 10^{51}\text{–}3.7 \times 10^{54}\ \mathrm{erg} \tag{2}$$

with the first and second lines of the equation corresponding to the spectral models without and with cutoff, respectively. For comparison, the total energy radiated in GWs from the source is $\sim 5 \times 10^{54}$ erg. This value can also be compared to high-energy emission expected in some scenarios for accreting stellar-mass black holes. For example, typical GRB isotropic-equivalent energies are $\sim 10^{51}$ erg for long and $\sim 10^{49}$ erg for short GRBs [52]. The total energy radiated in high-energy neutrinos in the case of GRBs can be comparable [53–57] or in some cases much greater [58,59] than the high-energy electromagnetic emission. There is little reason, however, to expect an associated GRB for a binary black hole merger (see, nevertheless, [60]).

V. CONCLUSION

The results above represent the first concrete limit on neutrino emission from this GW source type, and the first neutrino follow-up of a significant GW event. With the continued increase of Advanced LIGO-Virgo sensitivities for the next observation periods, and the implied source rate of 2–400 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ in the comoving frame based on this first detection [61], we can expect to detect a significant number of GW sources, allowing for stacked neutrino analyses and significantly improved constraints. Similar analyses for the upcoming observation periods of Advanced LIGO-Virgo will be important to provide constraints on or to detect other joint GW and neutrino sources.

Joint GW and neutrino searches will also be used to improve the efficiency of electromagnetic follow-up observations over GW-only triggers. Given the significantly more accurate direction reconstruction of neutrinos ($\sim 1\,\mathrm{deg}^2$ for track events in IceCube [40,41] and $\sim 0.2\,\mathrm{deg}^2$ in ANTARES [62]) compared to GWs ($\gtrsim 100\,\mathrm{deg}^2$), a joint event candidate provides a greatly reduced sky area for follow-up observatories [63]. The delay induced by the event filtering and reconstruction after the recorded trigger time is typically 3–5 s for ANTARES [44], 20–30 s for IceCube [64], and $\mathcal{O}(1\ \mathrm{min})$ for LIGO-Virgo, making data available for rapid analyses.

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