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

S. Adrián-Martínez  
*Universitat Politècnica de València*

A. Albert  
*Université de Haute Alsace*

M. André  
*Universitat Politècnica de Catalunya*

M. Anghinolfi  
*Istituto Nazionale di Fisica Nucleare, Sezione di Genova*

G. Anton  
*Friedrich-Alexander-Universität Erlangen-Nürnberg*

*See next page for additional authors*

Follow this and additional works at: [https://digitalcommons.lsu.edu/physics_astronomy_pubs](https://digitalcommons.lsu.edu/physics_astronomy_pubs)

**Recommended Citation**


This Article is brought to you for free and open access by the Department of Physics & Astronomy at LSU Digital Commons. It has been accepted for inclusion in Faculty Publications by an authorized administrator of LSU Digital Commons. For more information, please contact ir@lsu.edu.
Authors

This article is available at LSU Digital Commons: https://digitalcommons.lsu.edu/physics_astronomy_pubs/1086
High-energy neutrino follow-up search of gravitational wave event GW150914 with ANTARES and IceCube
S. Adrián-Martínez et al. (Antares Collaboration, IceCube Collaboration, LIGO Scientific Collaboration, and Virgo Collaboration)
Phys. Rev. D 93, 122010 — Published 23 June 2016
DOI: 10.1103/PhysRevD.93.122010
High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with ANTARES and IceCube

ANTARES Collaboration, IceCube Collaboration, LIGO Scientific Collaboration, and Virgo Collaboration*

We present the high-energy-neutrino follow-up observations of the first gravitational wave transient GW150914 observed by the Advanced LIGO detectors on Sept. 14th, 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 non-detection to constrain neutrino emission from the gravitational-wave event.

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 non-thermal, 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 non-thermal 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 Sept. 14th, 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 \( z = 0.09^{+0.04}_{-0.03} \). The reconstructed mass of each black hole is \( \sim 30 M_{\odot} \). 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 (Section II) and the neutrino follow-up (Section III), we present the joint analysis, results of the search and source constraints, and conclusions (Section IV).

II. GRAVITATIONAL WAVE DATA ANALYSIS AND DISCOVERY

GW150914 was initially identified by low-latency searches for generic GW transients [28–30]. Subsequent 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 203,000 years, equivalent to a significance > 5.1 \( \sigma \) [26]. Source parameters were reconstructed using the LALInference package [32–34], finding black-hole masses \( 36^{+5}_{-4} M_{\odot} \) and \( 29^{+4}_{-4} M_{\odot} \) and luminosity distance \( D_{gw} = 410^{+160}_{-180} \) 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.

* Full author list given at the end of the article.
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 590 deg$^2$ (140 deg$^2$).

III. HIGH-ENERGY NEUTRINO COINCIDENCE SEARCH

High-energy neutrino observatories are primarily sensitive to neutrinos with $\gtrsim$GeV energies. IceCube and ANTARES are both sensitive to through-going muons (called track events), produced by neutrinos near the detector, above $\sim$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 $\mu$s precision.

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 [40] 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 IceCube in the Southern hemisphere gradually falls as the cosmic ray flux declines with energy [41]. 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 [42]. 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 $\sim$ 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 0.014. We found no neutrino events from ANTARES that were temporally coincident with GW150914. This is consistent with the expected background event rate.

<table>
<thead>
<tr>
<th>#</th>
<th>$\Delta T$ [s]</th>
<th>RA [h]</th>
<th>Dec [°]</th>
<th>$\sigma_{\mu \text{rec}}$ [°]</th>
<th>$E_{\mu \text{rec}}$ [TeV]</th>
<th>fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+37.2</td>
<td>8.84</td>
<td>-16.6</td>
<td>0.35</td>
<td>175</td>
<td>12.5%</td>
</tr>
<tr>
<td>2</td>
<td>+163.2</td>
<td>11.13</td>
<td>12.0</td>
<td>1.95</td>
<td>1.22</td>
<td>26.5%</td>
</tr>
<tr>
<td>3</td>
<td>+311.4</td>
<td>-7.23</td>
<td>8.4</td>
<td>0.47</td>
<td>0.33</td>
<td>98.4%</td>
</tr>
</tbody>
</table>

TABLE I. Parameters of neutrino candidates identified by IceCube within the ±500 s time window around GW150914. $\Delta T$ is the time of arrival of the neutrino candidates relative to that of GW150914. $E_{\mu \text{rec}}$ is the reconstructed muon energy. $\sigma_{\mu \text{rec}}$ is the angular uncertainty of the reconstructed track direction [43]. The last column shows the fraction of background neutrino candidates with higher reconstructed energy at the same declination (±5°).

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 [42]. 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.
**IV. RESULTS**

**A. Joint analysis**

We carried out the joint GW and neutrino search following the analysis developed for previous GW and neutrino datasets 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 GeV neutrinos and GWs (which travel at the speed of light in general relativity) traveling to Earth from the source is expected to be < 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 $\sigma^{\text{rec}}_\mu$ (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 non-detection 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 $< 1$ for the two detectors, with p-value $1 - F_{\text{pois}}(N_{\text{observed}} \leq 2, N_{\text{expected}} = 4.4) = 0.81$, where $F_{\text{pois}}$ 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 $\Omega_{gw} = 590 \, \text{deg}^2$, the probability of a background neutrino candidate being directionally coincident is $\Omega_{gw}/\Omega_{\text{all}} \approx 0.014$. We expect $3\Omega_{gw}/\Omega_{\text{all}}$ 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 $1 - (1 - 0.014)^3 \approx 0.04$.

**B. Constraints on the source**

We used the non-detection 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: $dN/dE \propto E^{-2} \exp[-\sqrt{E/100\,\text{TeV}}]$. 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 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 $E^2dN/dE \sim 10^{-1} - 10^{\text{GeV}} \, \text{cm}^{-2}$. 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
To characterize the dependence of neutrino spectral fluence limits on source direction, we calculate these limits separately for the two distinct regions in the 90% credible region of the GW skymap. For the larger region farther South (hereafter South region), we find upper limits $E^2 dN/dE = 7.0^{+3.2}_{-2.0}$ 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 $E^2 dN/dE = 0.10^{+0.12}_{-0.06}$ GeV cm$^{-2}$ and $E^2 dN/dE = 0.55^{+1.29}_{-0.44}$ 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 = $-70^\circ$, 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 models, we obtain the following upper limit on the total energy radiated in neutrinos:

$$E_{\nu,\text{tot}}^{ul} = 5.4 \times 10^{51} - 1.3 \times 10^{54} \text{ erg}$$

$$E_{\nu,\text{tot}}^{ul(\text{cutoff})} = 6.6 \times 10^{51} - 3.7 \times 10^{54} \text{ erg}$$

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

![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 $dN/dE \propto E^{-2} \exp[-\sqrt{E/100\text{TeV}}]$ (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.](image)
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 Gpc$^{-3}$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 ($\sim 1$ deg$^2$ for track events in IceCube [40, 43] and $\sim 0.2$ deg$^2$ in ANTARES [62]) compared to GWs ($\gtrsim 100$ 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 $\mathcal{O}(1 \text{ min})$ for LIGO-Virgo, making data available for rapid analyses.

ACKNOWLEDGMENTS

The authors acknowledge the financial support of the funding agencies: Centre National de la Recherche Scientifique (CNRS), Commissariat à l’énergie atomique et aux énergies alternatives (CEA), Commission Européenne (FEDER fund and Marie Curie Program), Institut Universitaire de France (IUF), IdEx program and UnivEarthS Labex program at Sorbonne Paris Cité (ANR-10-LABX-0023 and ANR-11-IDEX-0005-02), Région Ile-de-France (DIM-ACAV), Région Alsace (contrat CPER), Région Provence-Alpes-Côte d’Azur, Département du Var and Ville de La Seyne-sur-Mer, France; Bundesministerium für Bildung und Forschung (BMBF), Germany; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Stichting voor Fundamenteel Onderzoek der Materie (FOM), Nederlandse organisatie voor Wetenschappelijk Onderzoek (NWO), the Netherlands; Council of the President of the Russian Federation for young scientists and leading scientific schools supporting grants, Russia; National Authority for Scientific Research (ANCS), Romania; Ministerio de Economía y Competitividad (MINECO), Prometeo and Grisolia programs of Generalitat Valenciana and MultiDark, Spain; Agence de l’Oriental and CNRST, Morocco. We also acknowledge the technical support of Ifremer, AIM and Foselev Marine for the sea operation and the CC-IN2P3 for the computing facilities.

We acknowledge the support from the following agencies: U.S. National Science Foundation-Office of Polar Programs, U.S. National Science Foundation-Physics Division, University of Wisconsin Alumni Research Foundation, the Grid Laboratory Of Wisconsin (GLOW) grid infrastructure at the University of Wisconsin - Madison, the Open Science Grid (OSG) grid infrastructure; U.S. Department of Energy, and National Energy Research Scientific Computing Center, the Louisiana Optical Network Initiative (LONI) grid computing resources; Natural Sciences and Engineering Research Council of Canada, WestGrid and Compute/Calcul Canada; Swedish Research Council, Swedish Polar Research Secretariat, Swedish National Infrastructure for Computing (SNIC), and Knut and Alice Wallenberg Foundation, Sweden; German Ministry for Education and Research (BMBF), Deutsche Forschungsgemeinschaft (DFG), Helmholtz Alliance for Astroparticle Physics (HAP), Research Department of Plasmas with Complex Interactions (Bochum), Germany; Fund for Scientific Research (FNRS-FWO), FWO Odysseus programme, Flanders Institute to encourage scientific and technological research in industry (IWT), Belgian Federal Science Policy Office (Belspo); University of Oxford, United Kingdom; Marsden Fund, New Zealand; Australian Research Council; Japan Society for Promotion of Science (JSPS); the Swiss National Science Foundation (SNSF), Switzerland; National Research Foundation of Korea (NRF); Danish National Research Foundation, Denmark (DNRF).

The authors gratefully acknowledge the support of the United States National Science Foundation (NSF) for the construction and operation of the LIGO Laboratory and Advanced LIGO as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors gratefully acknowledge the Italian Istituto Nazionale di Fisica Nucleare (INFN), the French Centre National de la Recherche Scientifique (CNRS) and the Foundation for Fundamental Research on Matter supported by the Netherlands Organisation for Scientific Research, for the construction and operation of the Virgo detector and the creation and support of the EGO consortium. The authors also gratefully acknowledge research...
support from these agencies as well as by the Council of Scientific and Industrial Research of India, Department of Science and Technology, India, Science & Engineering Research Board (SERB), India, Ministry of Human Resource Development, India, the Spanish Ministerio de Economía y Competitividad, the Conselleria d’Economia i Competitivitat and Conselleria d’Educació, Cultura i Universitats of the Govern de les Illes Balears, the National Science Centre of Poland, the European Commission, the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the Hungarian Scientific Research Fund (OTKA), the Lyon Institute of Origins (LIO), the National Research Foundation of Korea, Industry Canada and the Province of Ontario through the Ministry of Economic Development and Innovation, the Natural Science and Engineering Research Council Canada, Canadian Institute for Advanced Research, the Brazilian Ministry of Science, Technology, and Innovation, Russian Foundation for Basic Research, the Leverhulme Trust, the Research Corporation, Ministry of Science and Technology (MOST), Taiwan and the Kavli Foundation. The authors gratefully acknowledge the support of the NSF, STFC, MPS, INFN, CNRS and the State of Niedersachsen/Germany for provision of computational resources. This article has LIGO document number LIGO-P1500271.
Authors


(The ANTAES Collaboration)

Vrije Universiteit Brussel, Dienst ELEM, B-1050 Brussels, Belgium
56 Dept. of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
57 Dept. of Physics, Chiba University, Chiba 263-8522, Japan
58 Dept. of Physics and Astronomy, University of Canterbury, Private Bag 4800, Christchurch, New Zealand
59 Dept. of Physics, University of Maryland, College Park, MD 20742, USA
60 Dept. of Physics and Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, OH 43210, USA
61 Dept. of Astronomy, Ohio State University, Columbus, OH 43210, USA
62 Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark
63 Dept. of Physics, TU Dortmund University, D-44221 Dortmund, Germany
64 Dept. of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA
65 Dept. of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2E1
66 Département de physique nucléaire et corpusculaire, Université de Genève, CH-1211 Genève, Switzerland
67 Dept. of Physics and Astronomy, University of Gent, B-9000 Gent, Belgium
68 Dept. of Physics and Astronomy, University of California, Irvine, CA 92697, USA
69 Dept. of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA
70 Dept. of Astronomy, University of Wisconsin, Madison, WI 53706, USA
71 Dept. of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin, Madison, WI 53706, USA
72 Institute of Physics, University of Mainz, Staudinger Weg 7, D-55099 Mainz, Germany
73 Université de Mons, 7000 Mons, Belgium
74 Technische Universität München, D-85748 Garching, Germany
75 Bartol Research Institute and Dept. of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA
76 Dept. of Physics, Yale University, New Haven, CT 06520, USA
77 Dept. of Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, UK
78 Dept. of Physics, Drexel University, 3141 Chestnut Street, Philadelphia, PA 19104, USA
79 Physics Department, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA
80 Dept. of Physics, University of Wisconsin, River Falls, WI 54022, USA
81 Oskar Klein Centre and Dept. of Physics, Stockholm University, SE-10691 Stockholm, Sweden
82 Dept. of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA
83 Dept. of Physics, Sungkyunkwan University, Suwon 440-746, Korea
84 Dept. of Physics, University of Toronto, Toronto, Ontario, Canada, M5S 1A7
85 Dept. of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA
86 Dept. of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA
87 Dept. of Physics, Pennsylvania State University, University Park, PA 16802, USA
88 Dept. of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA
89 Dept. of Physics and Astronomy, Uppsala University, Box 516, S-75120 Uppsala, Sweden
90 Dept. of Physics, University of Wuppertal, D-42119 Wuppertal, Germany
91 DESY, D-15735 Zeuthen, Germany
92 LIGO, California Institute of Technology, Pasadena, CA 91125, USA
93 Louisiana State University, Baton Rouge, LA 70803, USA
94 Università di Salerno, Fisciano, I-84084 Salerno, Italy
95 INFN, Sezione di Napoli, Complesso Universitario di Monte S.Angelo, I-80126 Napoli, Italy
96 University of Florida, Gainesville, FL 32611, USA
97 LIGO Livingston Observatory, Livingston, LA 70754, USA
98 Laboratoire d’Annecy-le-Vieux de Physique des Particules (LAPP), Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy-le-Vieux, France
99 Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany
100 Nikhef, Science Park, 1098 XG Amsterdam, Netherlands
101 LIGO, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
102 Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos, São Paulo, Brazil
103 INFN, Gran Sasso Science Institute, I-67100 L’Aquila, Italy
104 INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy
105 Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India
106 International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bangalore 560012, India
107 University of Wisconsin-Milwaukee, Milwaukuee, WI 53201, USA
108 Leibniz Universität Hannover, D-30167 Hannover, Germany
109 Università di Pisa, I-56127 Pisa, Italy
110 INFN, Sezione di Pisa, I-56127 Pisa, Italy
111 Australian National University, Canberra, Australian Capital Territory 0200, Australia
112 The University of Mississippi, University, MS 38677, USA
113 California State University Fullerton, Fullerton, CA 92831, USA
150 University of Brussels, Brussels 1050, Belgium
151 Sonoma State University, Rohnert Park, CA 94928, USA
152 Northwestern University, Evanston, IL 60208, USA
153 University of Minnesota, Minneapolis, MN 55455, USA
154 The University of Melbourne, Parkville, Victoria 3010, Australia
155 The University of Texas Rio Grande Valley, Brownsville, TX 78520, USA
156 The University of Sheffield, Sheffield S10 2TN, United Kingdom
157 University of Sannio at Benevento, I-82100 Benevento, Italy and INFN, Sezione di Napoli, I-80100 Napoli, Italy
158 Montclair State University, Montclair, NJ 07043, USA
159 Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy
160 INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy
161 Cardiff University, Cardiff CF24 3AA, United Kingdom
162 National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
163 School of Mathematics, University of Edinburgh, Edinburgh EH9 3FD, United Kingdom
164 Indian Institute of Technology, Gandhinagar Ahmedabad Gujarat 382424, India
165 Institute for Plasma Research, Bhat, Gandhinagar 382428, India
166 University of Szeged, Döm tér 9, Szeged 6720, Hungary
167 Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA
168 University of Michigan, Ann Arbor, MI 48109, USA
169 Tata Institute of Fundamental Research, Mumbai 400005, India
170 American University, Washington, D.C. 20016, USA
171 University of Massachusetts-Amherst, Amherst, MA 01003, USA
172 West Virginia University, Morgantown, WV 26506, USA
173 Universitat de les Illes Balears, IAC3—IEEC, E-07122 Palma de Mallorca, Spain
174 University of Bialystok, 15-424 Bialystok, Poland
175 SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom
176 IISER-TVM, CET Campus, Trivandrum Kerala 695016, India
177 Institute of Applied Physics, Nizhny Novgorod, 603950, Russia
178 Pusan National University, Busan 609-735, Korea
179 Hanyang University, Seoul 133-791, Korea
180 NCBJ, 05-400 Świerk-Otwock, Poland
181 Rochester Institute of Technology, Rochester, NY 14623, USA
182 Monash University, Melbourne 3800, Australia
183 Seoul National University, Seoul 151-742, Korea
184 University of Alabama in Huntsville, Huntsville, AL 35899, USA
185 ESPCI, CNRS, F-75005 Paris, France
186 Università di Camerino, Dipartimento di Fisica, I-62032 Camerino, Italy
187 Southern University and A&M College, Baton Rouge, LA 70813, USA
188 College of William and Mary, Williamsburg, VA 23187, USA
189 Instituto de Física Teórica, University Estadual Paulista/ICTP South American Institute for Fundamental Research, São Paulo SP 01140-070, Brazil
190 University of Cambridge, Cambridge CB2 1TQ, United Kingdom
191 IIIT-Kolkata, Mohanpur, West Bengal 741252, India
192 Rutherford Appleton Laboratory, HSIC, Chilton, Didcot, Oxon OX11 0QX, United Kingdom
193 Whitman College, 345 Boyer Avenue, Walla Walla, WA 99362 USA
194 National Institute for Mathematical Sciences, Daejeon 305-390, Korea
195 Hobart and William Smith Colleges, Geneva, NY 14456, USA
196 Andrews University, Berrien Springs, MI 49104, USA
197 The University of Texas Rio Grande Valley, Brownsville, TX 78520, USA
198 Universität di Siena, I-53100 Siena, Italy
199 Trinity University, San Antonio, TX 78212, USA
200 University of Washington, Seattle, WA 98195, USA
201 Kenyon College, Gambier, OH 43022, USA
202 Abilene Christian University, Abilene, TX 79699, USA