



# Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory

ANTARES Collaboration, IceCube Collaboration, The Pierre Auger Collaboration,  
and LIGO Scientific Collaboration and Virgo Collaboration  
(See the end matter for the full list of authors.)

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## Abstract

The Advanced LIGO and Advanced Virgo observatories recently discovered gravitational waves from a binary neutron star inspiral. A short gamma-ray burst (GRB) that followed the merger of this binary was also recorded by the *Fermi* Gamma-ray Burst Monitor (*Fermi*-GBM), and the Anti-Coincidence Shield for the Spectrometer for the *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*), indicating particle acceleration by the source. The precise location of the event was determined by optical detections of emission following the merger. We searched for high-energy neutrinos from the merger in the GeV–EeV energy range using the ANTARES, IceCube, and Pierre Auger Observatories. No neutrinos directionally coincident with the source were detected within  $\pm 500$  s around the merger time. Additionally, no MeV neutrino burst signal was detected coincident with the merger. We further carried out an extended search in the direction of the source for high-energy neutrinos within the 14 day period following the merger, but found no evidence of emission. We used these results to probe dissipation mechanisms in relativistic outflows driven by the binary neutron star merger. The non-detection is consistent with model predictions of short GRBs observed at a large off-axis angle.

*Key words:* gamma-ray burst: general – gravitational waves – neutrinos

## 1. Introduction

The observation of binary neutron star mergers with multiple cosmic messengers is a unique opportunity that enables the detailed study of the merger process and provides insight into astrophysical particle acceleration and high-energy emission (e.g., Faber & Rasio 2012; Bartos et al. 2013; Berger 2014; Abbott et al. 2017a). Binary neutron star mergers are prime sources of gravitational waves (GWs; e.g., Abadie et al. 2010), which provide information on the neutron star masses and spins (e.g., Veitch et al. 2015). Kilonova/macronova observations of the mergers provide further information on the mass ejected by the disruption of the neutron stars (e.g., B. Abbott et al. 2017, in preparation; Metzger 2017).

Particle acceleration and high-energy emission by compact objects are currently not well understood (e.g., Mészáros 2013; Kumar & Zhang 2015) and could be deciphered by combined information on the neutron star masses, ejecta mass, and gamma-ray burst (GRB) properties, as expected from multi-messenger observations. In particular, the observation of high-energy neutrinos would reveal the hadronic content and dissipation mechanism in relativistic outflows (Waxman & Bahcall 1997). A quasi-diffuse flux of high-energy neutrinos of cosmic origin has been identified by the IceCube observatory (Aartsen et al. 2013a, 2013b). The source population producing these neutrinos is currently not known.

On 2017 August 17, the Advanced LIGO (Aasi et al. 2015) and Advanced Virgo (Acernese et al. 2015) observatories recorded a GW signal, GW170817, from a binary neutron star inspiral (Abbott et al. 2017b). Soon afterward, *Fermi*-GBM and *INTEGRAL* detected a short GRB, GRB 170817A, from a consistent location (Abbott et al. 2017a; Goldstein et al. 2017; Savchenko et al. 2017). Subsequently, ultraviolet, optical, and infrared emission was observed from the merger, consistent with kilonova/macronova emission. Optical observations allowed the precise localization of

the merger in the galaxy NGC 4993, at equatorial coordinates  $\alpha(\text{J2000.0}) = 13^{\text{h}}09^{\text{m}}48^{\text{s}}.085$ ,  $\delta(\text{J2000.0}) = -23^{\circ}22'53''.343$  (Abbott et al. 2017c; Coulter et al. 2017a, 2017b), and at a distance of  $\sim 40$  Mpc. At later times, X-ray and radio emissions were also observed (Abbott et al. 2017c), consistent with the expected afterglow of a short GRB at high viewing angles (e.g., Abbott et al. 2017a).

High-energy neutrino observatories continuously monitor the whole sky or a large fraction of it, making them well suited for studying emission from GW sources, even for unknown source locations or for emission prior to or after the GW detection (Adrián-Martínez et al. 2016a; Albert et al. 2017a). It is also possible to rapidly analyze the recorded data and inform other observatories in the case of a coincident detection, significantly reducing the source localization uncertainty compared to that provided by GW information alone.

In this Letter, we present searches for high-energy neutrinos in coincidence with GW170817/GRB 170817A by the three most sensitive high-energy neutrino observatories: (1) the ANTARES neutrino telescope (hereafter ANTARES; Ageron et al. 2011), a 10 megaton-scale underwater Cherenkov neutrino detector located at a depth of 2500 m in the Mediterranean Sea; (2) the IceCube Neutrino Observatory (hereafter IceCube; Aartsen et al. 2017), a gigaton-scale neutrino detector installed 1500 m deep in the ice at the geographic South Pole, Antarctica; and (3) the Pierre Auger Observatory (hereafter Auger; Aab et al. 2015b), a cosmic-ray air-shower detector consisting of 1660 water-Cherenkov stations spread over an area of  $\sim 3000$  km<sup>2</sup>. All three detectors joined the low-latency multi-messenger follow-up effort of LIGO–Virgo starting with LIGO’s second observation run, O2.

Upon the identification of the GW signal GW170817, preliminary information on this event was rapidly shared with partner observatories (Abbott et al. 2017c). In response,

IceCube (Bartos et al. 2017a, 2017b, 2017c), ANTARES (Ageron et al. 2017a, 2017b), and Auger (Alvarez-Muniz et al. 2017) promptly searched for a neutrino counterpart and shared their initial results with partner observatories. Subsequently, the three facilities carried out a more in-depth search for a neutrino counterpart using the precise localization of the source.

This Letter is organized as follows. In Section 2, we present the neutrino searches carried out by ANTARES, IceCube, and Auger, as well as the results obtained. In Section 3, we present constraints on processes in the merger that can lead to neutrino emission. We summarize our findings and conclude in Section 4.

## 2. Searches and Results

Neutrino observatories detect secondary charged particles produced in neutrino interaction with matter. Surface detectors, such as Auger, use arrays of widely spaced water-Cherenkov detectors to observe the air-shower particles created by high-energy neutrinos. In detectors such as ANTARES and IceCube, three-dimensional arrays of optical modules deployed in water or ice detect the Cherenkov radiation from secondary charged particles that travel through the instrumented detector region. For these detectors, the secondary particles can create two main event classes: track-like events from charged-current interactions of muon neutrinos and from a minority of tau neutrino interactions and shower-like events from all other interactions (neutral-current interactions and charged-current interactions of electron and tau neutrinos). While energy deposition in track-like events can happen over distances of  $\mathcal{O}(\text{km})$ , shower-like events are confined to much smaller regions.

For all detectors, neutrino signals must be identified on top of a persistent background of charged particles produced by the interaction of cosmic-ray particles with the atmosphere above the detectors. This discrimination is done by considering the observed direction and energy of the charged particles. Surface detectors focus on high-energy ( $\gtrsim 10^{17}$  eV) showers created close to the detector by neutrinos from near-horizontal directions. In-ice and in-water detectors can select well-reconstructed track events from the up-going direction where the Earth is used as a natural shield for the dominant background of penetrating muons from cosmic-ray showers. By requiring the neutrino interaction vertex to be contained inside the instrumented volume, or requiring its energy to be sufficiently high to be incompatible with the down-going muon background, even neutrino events originating above the horizon are identifiable. Neutrinos originating from cosmic-ray interactions in the atmosphere are also observed and constitute the primary background for up-going and vertex-contained event selections.

All three observatories, ANTARES, IceCube, and Auger, performed searches for neutrino signals in coincidence with the binary neutron star merger event GW170817, each using multiple event selections. Two different time windows were used for the searches. First, we used a  $\pm 500$  s time window around the merger to search for neutrinos associated with prompt and extended gamma-ray emission (Baret et al. 2011; Kimura et al. 2017). Second, we searched for neutrinos over a longer 14 day time window following the GW detection, to cover predictions of longer-lived emission processes (e.g., Gao et al. 2013; Fang & Metzger 2017).

### 2.1. ANTARES

The ANTARES neutrino telescope has been continuously operating since 2008. Located deep (2500 m) in the Mediterranean Sea, 40 km from Toulon (France), it is a 10 Mt-scale array of photosensors, detecting neutrinos with energies above  $\mathcal{O}(100)$  GeV.

Based on the originally communicated locations of the GW signal and the GRB detection, high-energy neutrino candidates were initially searched for in the ANTARES online data stream, relying on a fast algorithm that selects only up-going neutrino track candidates (Adrián-Martínez et al. 2016b). No up-going muon neutrino candidate events were found in a  $\pm 500$  s time window centered on the GW event time—for an expected number of atmospheric background events of  $\sim 10^{-2}$  during the coincident time window. An extended online search during  $\pm 1$  hr also resulted in no up-going neutrino coincidences.

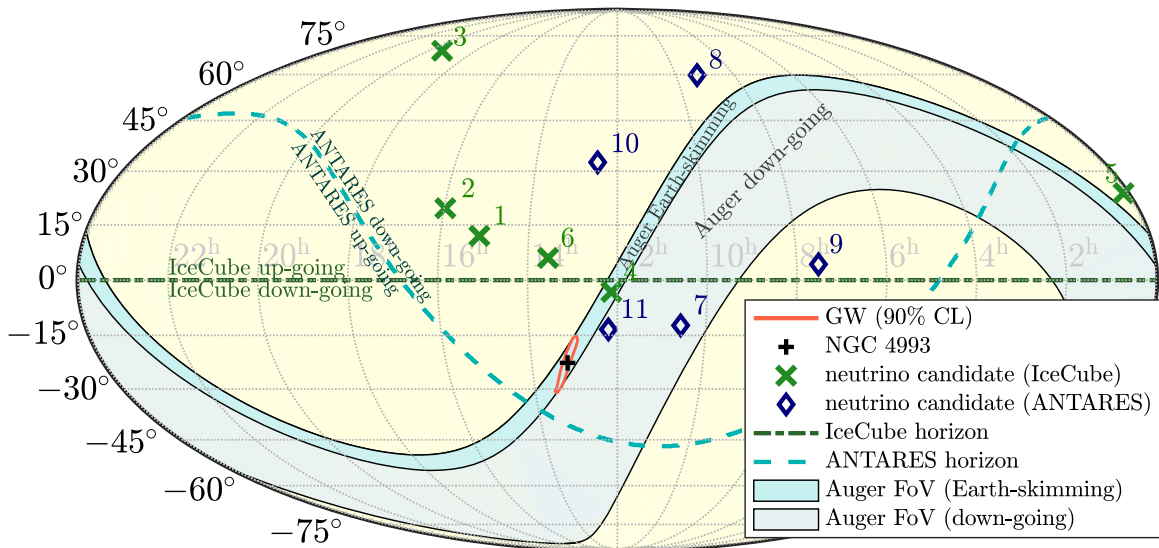
As it subsequently became clear, the precise direction of origin of GW170817 in NGC 4993 was above the ANTARES horizon at the detection time of the binary merger (see Figure 1). Thus, a dedicated analysis looking for down-going muon neutrino candidates in the online ANTARES data stream was also performed. No neutrino counterparts were found in this analysis. The results of these low-latency searches were shared with follow-up partners within a few hours for the up-going search and a few days for the down-going search (Ageron et al. 2017a, 2017b).

Here, ANTARES used an updated high-energy neutrino follow-up of GW170817 that includes the shower channel. It was performed with the offline-reconstructed data set that incorporates dedicated calibration in terms of positioning, timing, and efficiency (Aguilar et al. 2011, 2007; Adrián-Martínez et al. 2012). The analysis has been optimized to increase the sensitivity of the detector and extended to the longer time window of 14 days.

The search for down-going neutrino counterparts to GW170817 was made feasible as the large background affecting this data set can be drastically suppressed by requiring a time and space coincidence with the GW signal. It was optimized, independently for tracks and showers, such that a directional coincidence with NGC 4993 within the search time window of  $\pm 500$  s would have  $3\sigma$  significance. Muon neutrino candidates were selected by applying cuts on the estimated angular error and the track quality reconstruction parameter. While ANTARES is sensitive to neutrino events with energy as small as  $\mathcal{O}(100)$  GeV, the energy range corresponding to the 5%–95% quantiles of the neutrino flux for an  $E^{-2}$  signal spectrum is equal to [32 TeV; 22 PeV]. For such a flux, the median angular uncertainty, defined as the median value of the distribution of angles between the reconstructed direction of the event and the true neutrino direction, is equal to  $0^\circ.5$ .

Shower events were selected by applying a set of cuts primarily devoted to reducing the background rate (Albert et al. 2017b). The energy range corresponding to the 5%–95% quantiles of the neutrino flux for an  $E^{-2}$  signal spectrum is equal to [23 TeV; 16 PeV], while the median angular error is  $6^\circ$  with this set of relaxed cuts.

No events temporally coincident with GW170817 were found. Five background track events (likely atmospheric muons), not compatible with the source position, were detected (see Figure 1). We used this non-detection to constrain the neutrino fluence (see Figure 2) that was computed as in Adrián-Martínez et al. (2016a).



**Figure 1.** Localizations and sensitive sky areas at the time of the GW event in equatorial coordinates: GW 90% credible-level localization (red contour; Abbott et al. 2017b), direction of NGC 4993 (black plus symbol; Coulter et al. 2017b), directions of IceCube’s and ANTARES’s neutrino candidates within 500 s of the merger (green crosses and blue diamonds, respectively), ANTARES’s horizon separating down-going (north of horizon) and up-going (south of horizon) neutrino directions (dashed blue line), and Auger’s fields of view for Earth-skimming (darker blue) and down-going (lighter blue) directions. IceCube’s up-going and down-going directions are on the northern and southern hemispheres, respectively. The zenith angle of the source at the detection time of the merger was  $73^{\circ}8$  for ANTARES,  $66^{\circ}6$  for IceCube, and  $91^{\circ}9$  for Auger.

The search over 14 days is restricted to up-going events, but includes all neutrino flavors (tracks and showers). We applied quality cuts optimized for point-source searches that give a median pointing accuracy of  $0.4^{\circ}$  and  $3^{\circ}$ , respectively, for track and shower events (Albert et al. 2017b). No events spatially coincident with GRB 170817A were found.

Compared to the upper limits obtained for the short time window of  $\pm 500$  s, those limits are significantly less stringent above 1 PeV, where the absorption of neutrinos by the Earth becomes important for up-going events. Below 10 TeV, the constraints computed for the 14 day time window are stricter due to the better acceptance in this energy range for up-going neutrino candidates compared to down-going events (see Figure 2).

## 2.2. IceCube

IceCube is a cubic-kilometer-size neutrino detector (Aartsen et al. 2017) installed in the ice at the geographic South Pole in Antarctica between depths of 1450 m and 2450 m. Detector construction was completed in 2010, and the detector has operated with a  $\sim 99\%$  duty cycle since. IceCube searched for neutrino signals from GW170817 using two different event selection techniques.

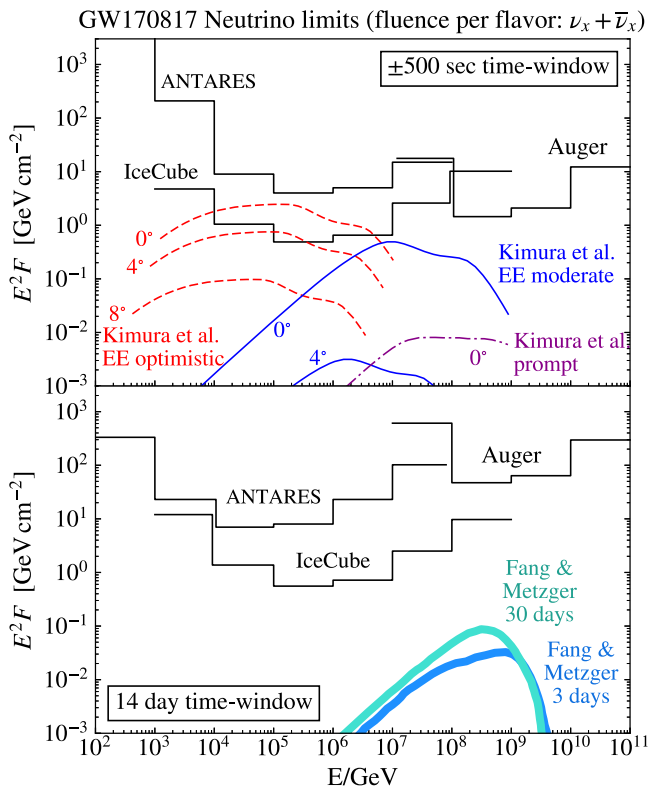
The first search used an online selection of through-going muons, which is used in IceCube’s online analyses (Aartsen et al. 2016; Kintscher & The IceCube Collaboration 2016) and follows an event selection similar to that of point source searches (Aartsen et al. 2014a). This event selection picks out primarily cosmic-ray-induced background events, with an expectation of 4.0 events in the northern sky (predominantly generated by atmospheric neutrinos) and 2.7 events in the southern sky (predominantly muons generated by high-energy cosmic rays interactions in the atmosphere above the detector) per 1000 s. For source locations in the southern sky, the sensitivity of the down-going event selection for neutrinos below 1 PeV weakens rapidly with energy due to the rapidly increasing atmospheric muon background at lower energies. Events found by this track selection in the  $\pm 500$  s time window

are shown in Figure 1. No events were found to be spatially and temporally correlated with GW170817.

A second event selection, described in Wandkowski et al. (2017), was employed offline. This uses the outermost optical sensors of the instrumented volume to veto incoming muon tracks from atmospheric background events. Above 60 TeV, this event selection has the same performance as the high-energy starting-event selection (Aartsen et al. 2014b). Below this energy, additional veto cuts similar to those described in Aartsen et al. (2015) are applied, in order to maintain a low background level at energies down to a few TeV. Both track- and cascade-like events are retained. The event rate for this selection varies over the sky, but is overall much lower than for the online track selection described above. Between declinations  $-13^{\circ}$  and  $-33^{\circ}$ , the mean number of events in a two-week period is 0.4 for tracks and 2.5 for cascades. During the  $\pm 500$  s time window, no events passed this event selection from anywhere in the sky.

A combined analysis of the IceCube through-going track selection and the starting-event selection allows upper limits to be placed on the neutrino fluence from GW170817 between the energies of 1 TeV and 1 EeV, as shown in Figure 2. In the central range from 10 TeV to 100 PeV, the upper limit for an  $E^{-2}$  power-law spectral fluence is  $F(E) = 0.19(E/\text{GeV})^{-2} \text{ GeV}^{-1} \text{ cm}^{-2}$ .

Both the through-going track selection and the starting-event selection were applied to data collected in the 14 day period following the time of GW170817. Because of IceCube’s location at the South Pole and 99.88% on-time during the 14 day period, the exposure to the source location is continuous and unvaried. No spatially and temporally coincident events were seen in either selection during this follow-up period. The resulting upper limits are presented in Figure 2. At most energies these are unchanged from the short time window. At the lowest energies, where most background events occur, the analysis effectively requires stricter criteria for a coincident event than were required in the short time window; the limits are correspondingly higher. In the central range from 10 TeV to



**Figure 2.** Upper limits (at 90% confidence level) on the neutrino spectral fluence from GW170817 during a  $\pm 500$  s window centered on the GW trigger time (top panel), and a 14 day window following the GW trigger (bottom panel). For each experiment, limits are calculated separately for each energy decade, assuming a spectral fluence  $F(E) = F_{\text{up}} \times [E/\text{GeV}]^{-2}$  in that decade only. Also shown are predictions by neutrino emission models. In the upper plot, models from Kimura et al. (2017) for both extended emission (EE) and prompt emission are scaled to a distance of 40 Mpc and shown for the case of the on-axis viewing angle ( $\theta_{\text{obs}} \lesssim \theta_j$ ) and selected off-axis angles to indicate the dependence on this parameter. The shown off-axis angles are measured in excess of the jet opening half-angle  $\theta_j$ . GW data and the redshift of the host galaxy constrain the viewing angle to  $\theta_{\text{obs}} \in [0^\circ, 36^\circ]$  (see Section 3). In the lower plot, models from Fang & Metzger (2017) are scaled to a distance of 40 Mpc. All fluences are shown as the per the flavor sum of neutrino and anti-neutrino fluence, assuming equal fluence in all flavors, as expected for standard neutrino oscillation parameters.

100 PeV, the upper limit on an  $E^{-2}$  power-law spectral fluence is  $F(E) = 0.23 \times (E/\text{GeV})^{-2} \text{ GeV}^{-1} \text{ cm}^{-2}$ .

The IceCube detector is also sensitive to outbursts of MeV neutrinos via a simultaneous increase in all photomultiplier signal rates. A neutrino burst signal from a galactic core-collapse supernova would be detected with high precision (Abbasi et al. 2011). The detector global dark rate is monitored continuously, the influence of cosmic-ray muons is removed, and low-level triggers are formed when deviations from the nominal rate exceed pre-defined levels. No alert was triggered during the  $\pm 500$  s time window around the GW candidate. This is consistent with our expectations for cosmic events such as core-collapse supernovae or compact binary mergers that are significantly farther away than Galactic distances.

### 2.3. Pierre Auger Observatory

With the surface detector (SD) of the Pierre Auger Observatory in Malargüe, Argentina (Aab et al. 2015b), air showers induced by ultra-high-energy (UHE) neutrinos can be

identified for energies above  $\sim 10^{17}$  eV in the more numerous background of UHE cosmic rays (Aab et al. 2015a). The SD consists of 1660 water-Cherenkov stations spread over an area of  $\sim 3000 \text{ km}^2$  following a triangular arrangement of 1.5 km grid spacing (Aab et al. 2015b). The signals produced by the passage of shower particles through the SD detectors are recorded as time traces in 25 ns intervals.

Cosmic rays interact shortly after entering the atmosphere and induce extensive air showers. For highly inclined directions their electromagnetic component gets absorbed due to the large grammage of atmosphere from the first interaction point to the ground. As a consequence, the shower front at ground level is dominated by muons that induce sharp time traces in the water-Cherenkov stations. On the contrary, showers induced by downward-going neutrinos at large zenith angles can start their development deep in the atmosphere producing traces that spread over longer times. These showers have a considerable fraction of electrons and photons that undergo more interactions than muons in the atmosphere, spreading more in time as they pass through the detector. This is also the case for Earth-skimming showers, mainly induced by tau neutrinos ( $\nu_\tau$ ) that traverse horizontally below the Earth's crust, and interact near the exit point inducing a tau lepton that escapes the Earth and decays in flight in the atmosphere above the SD.

Dedicated and efficient selection criteria based on the different time profiles of the signals detected in showers created by hadronic and neutrino primaries, enable the search for Earth-skimming as well as downward-going neutrino-induced showers (Aab et al. 2015a). Deeply starting downward-going showers initiated by neutrinos of any flavor can be efficiently identified for zenith angles of  $60^\circ < \theta < 90^\circ$  (Aab et al. 2015a). For the Earth-skimming channel typically only  $\nu_\tau$ -induced showers with zenith angles  $90^\circ < \theta < 95^\circ$  can trigger the SD. This is the most sensitive channel to UHE neutrinos, mainly due to the larger grammage and higher density of the target (the Earth) where neutrinos are converted and where tau leptons can travel tens of kilometers (Aab et al. 2015a). The angular resolution of the Auger SD for inclined showers is better than  $2.5^\circ$ , improving significantly as the number of triggered stations increases (Bonifazi & Pierre Auger Collaboration 2009).

Auger performed a search for UHE neutrinos with its SD in a time window of  $\pm 500$  s centered at the merger time of GW170817 (Abbott et al. 2017c), as well as in a 14 day period after it (Murase et al. 2009; Gao et al. 2013; Fang & Metzger 2017).

The sensitivity to UHE neutrinos in Auger is limited to large zenith angles, so that at each instant they can be efficiently detected only from a specific fraction of the sky (Abreu et al. 2012; Aab et al. 2016). Remarkably, the position of the optical counterpart in NGC 4993 (Abbott et al. 2017c; Coulter et al. 2017b, 2017a) is visible from Auger in the field of view of the Earth-skimming channel during the whole  $\pm 500$  s window as shown in Figure 1. In this time period, the source of GW170817 transits from  $\theta \sim 93.3^\circ$  to  $\theta \sim 90.4^\circ$  as seen from the center of the array. The performance of the Auger SD array (regularly monitored every minute) is very stable in the  $\pm 500$  s window around GW170817, with an average number of active stations amounting to  $\sim 95.8 \pm 0.1\%$  of the 1660 stations of the SD array.

No inclined showers passing the Earth-skimming selection (neutrino candidates) were found in the time window  $\pm 500$  s around the trigger time of GW170817. The estimated number of background events from cosmic rays in a 1000 s period is  $\sim 6.3 \times 10^{-7}$  for the cuts applied in the Earth-skimming analysis (Aab et al. 2015a).

The absence of candidates in the  $\pm 500$  s window allows us to constrain the fluence in UHE neutrinos from GW170817, assuming they are emitted steadily in this interval and with an  $E^{-2}$  spectrum (Aab et al. 2016). Single-flavor differential limits to the spectral fluence are shown in Figure 2, in bins of one decade in energy. The sensitivity of the observatory is largest in the energy bin around  $10^{18}$  eV. The single-flavor upper limit to the spectral fluence is  $F(E) = 0.77(E/\text{GeV})^{-2} \text{ GeV}^{-1} \text{ cm}^{-2}$  over the energy range from  $10^{17}$  eV to  $2.5 \times 10^{19}$  eV.

In the 14 day search period, as the Earth rotates, the position of NGC 4993 transits through the field of view of the Earth-skimming and downward-going channels. As seen from the Pierre Auger Observatory, the zenith angle of the optical counterpart oscillates daily between  $\theta \sim 11^\circ$  and  $\theta \sim 121^\circ$ . The source is visible in the Earth-skimming channel for  $\sim 4\%$  of the day and in the downward-going channel for  $\sim 10.5\%$  ( $\sim 11.1\%$ ) in the zenith angle range  $60^\circ < \theta < 75^\circ$  ( $75^\circ < \theta < 90^\circ$ ). No neutrino candidates were identified in the two-week search period. Single-flavor differential limits to the spectral fluence are shown in Figure 2. The corresponding upper limit to the spectral fluence is  $F(E) = 25(E/\text{GeV})^{-2} \text{ GeV}^{-1} \text{ cm}^{-2}$  over the same energy interval as for the  $\pm 500$  s time window, where the difference is due to the relatively long periods of time when the source of GW170817 is not visible in the inclined directions.

### 3. Discussion

The nature of high-energy emission from the binary merger and its aftermath is not yet clear. We compared the expected spectral fluence for different emission scenarios to our observational upper limits to probe the properties of the merger and its aftermath. Here, we briefly outline the relevant information from electromagnetic observations and present our results for the different emission scenarios.

The merger occurred at a distance of  $\sim 40$  Mpc, which is the distance of its host galaxy NGC 4993, identified through electromagnetic observations (Abbott et al. 2017c; Coulter et al. 2017a, 2017b). The prompt gamma-ray emission from the source, GRB 170817A, had an observed isotropic-equivalent energy of  $E_{\text{iso}} \approx 4 \times 10^{46}$  erg, as recorded by *Fermi*-GBM (Abbott et al. 2017a). This is orders of magnitude below typical observed short GRB energies (Berger 2014; Abbott et al. 2017a).

Prompt gamma-ray emission in at least some short GRBs is followed by a weaker, extended emission that can last for hundreds of seconds (Norris & Bonnell 2006; Kimura et al. 2017). *Fermi*-GBM did not detect a temporally extended emission following GRB 170817A, placing a constraint of  $\sim 2 \times 10^{46} \text{ erg s}^{-1}$  for a 10 s long emission period over 1 keV–10 MeV (Abbott et al. 2017a), significantly below typical luminosities observed for extended emission.

The very faint gamma-ray emission, along with its observed, delayed afterglow, are consistent with a typical short GRB viewed off-axis (Fong et al. 2017; Fraija et al. 2017; Granot et al. 2017; Haggard et al. 2017; Hallinan et al. 2017; Ioka & Nakamura 2017; Kim et al. 2017; Margutti et al. 2017; Murguia-Berthier et al. 2017; Troja et al. 2017). A GRB is

viewed off-axis if its viewing angle  $\theta_{\text{obs}}$ , defined as the angle between the jet axis and the line of sight, is greater than the jet opening half-angle  $\theta_j$  (Granot et al. 2002). The viewing angle inferred from the data is  $\theta_{\text{obs}} \gtrsim 20^\circ$ , while typical opening half-angles for short GRBs are within  $\theta_j \approx 3^\circ\text{--}10^\circ$  (Berger 2014).

GW data combined with the measured redshift of the host galaxy further provide constraints on  $\theta_{\text{obs}}$ . Here, we assume that the jet axis is aligned with the binary's total angular momentum vector. Adopting the Hubble constant from cosmic microwave background measurements by the Planck satellite (Ade et al. 2016), these data are consistent with  $\theta_{\text{obs}} = 0$ , but also allow for a misalignment of  $\theta_{\text{obs}} \leq 28^\circ$  at a 90% credible level. Adopting the Hubble constant from Type Ia supernova measurements (Riess et al. 2016) gives a similar result with maximum misalignment of  $\theta_{\text{obs}} \leq 36^\circ$  at a 90% credible level (Abbott et al. 2017d).

Considering this off-axis scenario, we examined the expected high-energy neutrino emission from a typical GRB observed at different viewing angles. The most promising neutrino-production mechanism from GRBs is related to the extended gamma emission, due to its relatively low Lorentz factor resulting in high meson production efficiency (Kimura et al. 2017). In Figure 2, we compared our observational constraints with the expected neutrino fluence from the GRB's extended emission. For the on-axis (i.e.,  $\theta_{\text{obs}} \lesssim \theta_j$ ) spectral fluence  $F_{\text{on}}$ , we assumed the results of Kimura et al. (2017), rescaled to 40 Mpc. We approximated the observed off-axis spectral fluence,  $F_{\text{off}}(E)$ , for these models using  $F_{\text{off}}(E) = \eta F_{\text{on}}(E/\eta)$ , where the scaling factor  $\eta = \delta(\theta_{\text{obs}})/\delta(0)$  accounts for different Doppler factors  $\delta(\theta_{\text{obs}}) = [\Gamma(1 - \beta \cos(\theta_{\text{obs}} - \theta_j))]^{-1}$  (Granot et al. 2002).

For comparison, we also examined the expected neutrino flux associated with the prompt GRB emission (e.g., Moharana et al. 2016; Kimura et al. 2017). This emission phase is less favorable for neutrino production than the extended emission. We see in Figure 2 that prompt emission from a single merger event is unlikely to produce a detected neutrino for the considered observatories, even if viewed on-axis.

Another proposed explanation for the faintness of gamma-ray emission is the interaction of the GRB jet with ejecta material from the merger (Gottlieb et al. 2017; Kasliwal et al. 2017; Piro & Kollmeier 2017). Energy deposition by the jet into the neutron star ejecta can form a cocoon that expands outwards at mildly relativistic speeds over a wide opening angle. Faint gamma-ray emission is then expected during the breakout of this cocoon from the outer tail of the ejecta (Gottlieb et al. 2017).

High-energy neutrino production in this scenario may significantly exceed the observed gamma-ray emission as neutrinos can escape through the ejecta even before it becomes transparent to gamma-rays. This scenario resembles that of a jet burrowing through the stellar envelope in a core-collapse event (Mészáros and Waxman 2001; Razzaque et al. 2003; Bartos et al. 2012; Murase & Ioka 2013). Nevertheless, if the observed gamma-rays come from the outbreak of a wide cocoon, it is less likely that the relativistic jet, which is more narrowly beamed than the cocoon outbreak, also pointed toward Earth.

We further considered an additional neutrino-production mechanism related to ejecta material from the merger. If a rapidly rotating neutron star forms in the merger and does not immediately collapse into a black hole, it can power a relativistic wind with its rotational energy, which may be responsible for the sometimes observed extended emission

(Metzger et al. 2008). Optically thick ejecta from the merger can attenuate the gamma-ray flux, while allowing the escape of high-energy neutrinos. Additionally, it may trap some of the wind energy until it expands and becomes transparent. This process can convert some of the wind energy to high-energy particles, producing a *long-term* neutrino radiation that can last for days (Murase et al. 2009; Gao et al. 2013; Fang & Metzger 2017). The properties of ejecta material around the merger can be characterized from its kilonova/macronova emission.

Considering the possibility that the relative weakness of gamma-ray emission from GRB 170817A may be partly due to attenuation by the ejecta, we compared our neutrino constraints to neutrino emission expected for typical GRB parameters. For the prompt and extended emissions, we used the results of Kimura et al. (2017) and compared these to our constraints for the relevant  $\pm 500$  s time window. For extended emission we considered source parameters corresponding to both optimistic and moderate scenarios in Table 1 of Kimura et al. (2017). For emission on even longer timescales, we compared our constraints for the 14 day time window with the relevant results of Fang & Metzger (2017), namely, emission from approximately 0.3 to 3 days and from 3 to 30 days following the merger. Predictions based on fiducial emission models and neutrino constraints are shown in Figure 2. We found that our limits would constrain the optimistic extended-emission scenario for a typical GRB at  $\sim 40$  Mpc, viewed at zero viewing angle.

#### 4. Conclusion

We searched for high-energy neutrinos from the first binary neutron star merger detected through GWs, GW170817, in the energy band of  $[\sim 10^{11}$  eV,  $\sim 10^{20}$  eV] using the ANTARES, IceCube, and Pierre Auger Observatories, as well as for MeV neutrinos with IceCube. This marks an unprecedented joint effort of experiments sensitive to high-energy neutrinos. We have observed no significant neutrino counterpart within a  $\pm 500$  s window, nor in the subsequent 14 days. The three detectors complement each other in the energy bands in which they are most sensitive (see Figure 2).

This non-detection is consistent with our expectations from a typical GRB observed off-axis, or with a low-luminosity GRB. Optimistic scenarios for on-axis gamma-attenuated emission are constrained by the present non-detection.

While the location of this source was nearly ideal for Auger, it was well above the horizon for IceCube and ANTARES for prompt observations. This limited the sensitivity of the latter two detectors, particularly below  $\sim 100$  TeV. For source locations near, or below the horizon, a factor of  $\sim 10$  increase in fluence sensitivity to prompt emission from an  $E^{-2}$  neutrino spectrum is expected.

With the discovery of a nearby binary neutron star merger, the ongoing enhancement of detector sensitivity (Abbott et al. 2016) and the growing network of GW detectors (Iyer et al. 2011; Aso et al. 2013), we can expect that several binary neutron star mergers will be observed in the near future. Not only will this allow stacking analyses of neutrino emission, but it will also bring about sources with favorable orientation and direction.

The ANTARES, IceCube, and Pierre Auger Collaborations are planning to continue the rapid search for neutrino candidates from identified GW sources. A coincident neutrino, with a typical position uncertainty of  $\sim 1$  deg<sup>2</sup> could significantly

improve the fast localization of joint events compared to the GW-only case. In addition, the first joint GW and high-energy neutrino discovery might thereby be known to the wider astronomy community within minutes after the event, opening a rich field of multi-messenger astronomy with particle, electromagnetic, and gravitational waves combined.

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A. Albert<sup>1</sup>, M. André<sup>2</sup>, M. Anghinolfi<sup>3</sup>, M. Ardid<sup>4</sup>, J.-J. Aubert<sup>5</sup>, J. Aublin<sup>6</sup>, T. Avgitas<sup>6</sup>, B. Baret<sup>6</sup>, J. Barrios-Martí<sup>7</sup>, S. Basa<sup>8</sup>, B. Belhorma<sup>9</sup>, V. Bertin<sup>5</sup>, S. Biagi<sup>10</sup>, R. Bormuth<sup>11,12</sup>, S. Bourret<sup>6</sup>, M. C. Bouwhuis<sup>11</sup>, H. Brânzaș<sup>13</sup>, R. Bruijn<sup>11,14</sup>, J. Brunner<sup>5</sup>, J. Bustó<sup>5</sup>, A. Capone<sup>15,16</sup>, L. Caramete<sup>13</sup>, J. Carr<sup>5</sup>, S. Celli<sup>15,16,17</sup>, R. Cherkaoui El Moursli<sup>18</sup>, T. Chiarusi<sup>19</sup>, M. Circella<sup>20</sup>, J. A. B. Coelho<sup>6</sup>, A. Coleiro<sup>6,7</sup>, R. Coniglione<sup>10</sup>, H. Costantini<sup>5</sup>, P. Coyle<sup>5</sup>, A. Creusot<sup>6</sup>, A. F. Díaz<sup>21</sup>, A. Deschamps<sup>22</sup>, G. De Bonis<sup>15</sup>, C. Distefano<sup>10</sup>, I. Di Palma<sup>15,16</sup>, A. Domi<sup>3,23</sup>, C. Donzaud<sup>6,24</sup>, D. Dornic<sup>5</sup>, D. Drouhin<sup>1</sup>, T. Eberl<sup>25</sup>, I. El Bojaddaini<sup>26</sup>, N. El Khayati<sup>18</sup>, D. Elsässer<sup>27</sup>, A. Enzenhöfer<sup>5</sup>, A. Ettahiri<sup>18</sup>, F. Fassi<sup>18</sup>, I. Felis<sup>4</sup>, L. A. Fusco<sup>19,28</sup>, P. Gay<sup>6,29</sup>, V. Giordano<sup>30</sup>, H. Glotin<sup>31,32</sup>, T. Grégoire<sup>6</sup>, R. Gracia Ruiz<sup>6,33</sup>, K. Graf<sup>25</sup>, S. Hallmann<sup>25</sup>, H. van Haren<sup>34</sup>, A. J. Heijboer<sup>11</sup>, Y. Hello<sup>22</sup>, J. J. Hernández-Rey<sup>7</sup>, J. Höfl<sup>25</sup>, J. Hofestädt<sup>25</sup>, G. Illuminati<sup>7</sup>, C. W. James<sup>25</sup>, M. de Jong<sup>11,12</sup>, M. Jongen<sup>11</sup>, M. Kadler<sup>27</sup>, O. Kalekin<sup>25</sup>, U. Katz<sup>25</sup>, D. Kießling<sup>25</sup>, A. Kouchner<sup>6,32</sup>, M. Kreter<sup>27</sup>, I. Kreykenbohm<sup>35</sup>, V. Kulikovskiy<sup>5,36</sup>, C. Lachaud<sup>6</sup>, R. Lahmann<sup>25</sup>, D. Lefèvre<sup>37</sup>, E. Leonora<sup>30,38</sup>, M. Lotze<sup>7</sup>, S. Loucatos<sup>6,39</sup>, M. Marcelin<sup>8</sup>, A. Margiotta<sup>19,28</sup>, A. Marinelli<sup>40,41</sup>, J. A. Martínez-Mora<sup>4</sup>, R. Mele<sup>42,43</sup>, K. Melis<sup>11,14</sup>, T. Michael<sup>11</sup>, P. Migliozi<sup>42</sup>, A. Moussa<sup>26</sup>, S. Navas<sup>44</sup>, E. Nezi<sup>8</sup>, M. Organokov<sup>33</sup>, G. E. Pávlaș<sup>13</sup>, C. Pellegrino<sup>19,28</sup>, C. Perrina<sup>15,16</sup>, P. Piattelli<sup>10</sup>, V. Popa<sup>13</sup>, T. Pradier<sup>33</sup>, L. Quinn<sup>5</sup>, C. Racca<sup>1</sup>, G. Riccobene<sup>10</sup>, A. Sánchez-Losa<sup>20</sup>, M. Saldaña<sup>4</sup>, I. Salvadori<sup>5</sup>, D. F. E. Samtleben<sup>11,12</sup>, M. Sanguineti<sup>3,23</sup>, P. Sapienza<sup>10</sup>, F. Schüssler<sup>39</sup>, C. Sieger<sup>25</sup>, M. Spurio<sup>19,28</sup>, Th. Stolarczyk<sup>39</sup>, M. Taiuti<sup>3,23</sup>, Y. Tayalati<sup>18</sup>, A. Trovato<sup>10</sup>, D. Turpin<sup>5</sup>, C. Tönnis<sup>7</sup>, B. Vallage<sup>6,39</sup>, V. Van Elewyck<sup>6,32</sup>, F. Versari<sup>19,28</sup>, D. Vivolo<sup>42,43</sup>, A. Vizzoca<sup>15,16</sup>, J. Wilms<sup>45</sup>, J. D. Zornoza<sup>7</sup>, J. Zúñiga<sup>7</sup>,

(ANTARES Collaboration)

M. G. Aartsen<sup>46</sup>, M. Ackermann<sup>47</sup>, J. Adams<sup>48</sup>, J. A. Aguilar<sup>49</sup>, M. Ahlers<sup>50</sup>, M. Ahrens<sup>51</sup>, I. Al Samarai<sup>52</sup>, D. Altmann<sup>53</sup>, K. Andeen<sup>54</sup>, T. Anderson<sup>55</sup>, I. Ansseau<sup>49</sup>, G. Anton<sup>53</sup>, C. Argüelles<sup>56</sup>, J. Auffenberg<sup>57</sup>, S. Axani<sup>56</sup>, H. Bagherpour<sup>48</sup>, X. Bai<sup>58</sup>, J. P. Barron<sup>59</sup>, S. W. Barwick<sup>60</sup>, V. Baum<sup>61</sup>, R. Bay<sup>62</sup>, J. J. Beatty<sup>63,64</sup>, J. Becker Tjus<sup>65</sup>, K.-H. Becker<sup>66</sup>, S. BenZvi<sup>67</sup>, D. Berley<sup>68</sup>, E. Bernardini<sup>47</sup>, D. Z. Besson<sup>69</sup>, G. Binder<sup>62,70</sup>, D. Bindig<sup>66</sup>, E. Blaufuss<sup>68</sup>, S. Blot<sup>47</sup>, C. Boehm<sup>51</sup>, M. Börner<sup>71</sup>, F. Bos<sup>65</sup>, D. Bose<sup>72</sup>, S. Böser<sup>61</sup>, O. Botner<sup>73</sup>, E. Bourbeau<sup>50</sup>, J. Bourbeau<sup>74</sup>, F. Bradascio<sup>47</sup>, J. Braun<sup>74</sup>, L. Brayeur<sup>75</sup>, M. Brenzke<sup>57</sup>, H.-P. Bretz<sup>47</sup>, S. Bron<sup>52</sup>, J. Brostean-Kaiser<sup>47</sup>, A. Burgman<sup>73</sup>, T. Carver<sup>52</sup>, J. Casey<sup>74</sup>, M. Casier<sup>75</sup>, E. Cheung<sup>68</sup>, D. Chirkin<sup>74</sup>, A. Christov<sup>52</sup>, K. Clark<sup>76</sup>, L. Classen<sup>77</sup>, S. Coenders<sup>78</sup>, G. H. Collin<sup>56</sup>, J. M. Conrad<sup>56</sup>, D. F. Cowen<sup>55,79</sup>, R. Cross<sup>67</sup>, M. Day<sup>74</sup>, J. P. A. M. de André<sup>80</sup>, C. De Clercq<sup>75</sup>, J. J. DeLaunay<sup>55</sup>, H. Dembinski<sup>81</sup>, S. De Ridder<sup>82</sup>, P. Desiati<sup>74</sup>, K. D. de Vries<sup>75</sup>,



G. de Wasseige<sup>75</sup>, M. de With<sup>83</sup>, T. DeYoung<sup>80</sup>, J. C. Díaz-Vélez<sup>74</sup>, V. di Lorenzo<sup>61</sup>, H. Dujmovic<sup>72</sup>, J. P. Dumm<sup>51</sup>, M. Dunkman<sup>55</sup>, E. Dvorak<sup>58</sup>, B. Eberhardt<sup>61</sup>, T. Ehrhardt<sup>61</sup>, B. Eichmann<sup>65</sup>, P. Eller<sup>55</sup>, P. A. Evenson<sup>81</sup>, S. Fahey<sup>74</sup>, A. R. Fazely<sup>84</sup>, J. Felde<sup>68</sup>, K. Filimonov<sup>62</sup>, C. Finley<sup>51</sup>, S. Flis<sup>51</sup>, A. Franckowiak<sup>47</sup>, E. Friedman<sup>68</sup>, T. Fuchs<sup>71</sup>, T. K. Gaiser<sup>81</sup>, J. Gallagher<sup>85</sup>, L. Gerhardt<sup>70</sup>, K. Ghorbani<sup>74</sup>, W. Giang<sup>59</sup>, T. Glauch<sup>57</sup>, T. Glüsenkamp<sup>53</sup>, A. Goldschmidt<sup>70</sup>, J. G. Gonzalez<sup>81</sup>, D. Grant<sup>59</sup>, Z. Griffith<sup>74</sup>, C. Haack<sup>57</sup>, A. Hallgren<sup>73</sup>, F. Halzen<sup>74</sup>, K. Hanson<sup>74</sup>, D. 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Koirala<sup>81</sup>, H. Kolanoski<sup>83</sup>, L. Köpke<sup>61</sup>, C. Kopper<sup>59</sup>, S. Kopper<sup>92</sup>, J. P. Koschinsky<sup>57</sup>, D. J. Koskinen<sup>50</sup>, M. Kowalski<sup>47,83</sup>, K. Krings<sup>78</sup>, M. Kroll<sup>65</sup>, G. Krückl<sup>61</sup>, J. Kunnen<sup>75</sup>, S. Kunwar<sup>47</sup>, N. Kurahashi<sup>93</sup>, T. Kuwabara<sup>87</sup>, A. Kyriacou<sup>46</sup>, M. Labare<sup>82</sup>, J. L. Lanfranchi<sup>55</sup>, M. J. Larson<sup>50</sup>, F. Lauber<sup>66</sup>, M. Lesiak-Bzdak<sup>90</sup>, M. Leuermann<sup>57</sup>, Q. R. Liu<sup>74</sup>, L. Lu<sup>87</sup>, J. Lünemann<sup>75</sup>, W. Luszczak<sup>74</sup>, J. Madsen<sup>94</sup>, G. Maggi<sup>75</sup>, K. B. M. Mahn<sup>80</sup>, S. Mancina<sup>74</sup>, R. Maruyama<sup>95</sup>, K. Mase<sup>87</sup>, R. Maunu<sup>68</sup>, F. McNally<sup>74</sup>, K. Meagher<sup>49</sup>, M. Medici<sup>50</sup>, M. Meier<sup>71</sup>, T. Menne<sup>71</sup>, G. Merino<sup>74</sup>, T. 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Rhode<sup>71</sup>, M. Richman<sup>93</sup>, S. Robertson<sup>46</sup>, M. Rongen<sup>57</sup>, C. Rott<sup>72</sup>, T. Ruhe<sup>71</sup>, D. Ryckbosch<sup>82</sup>, D. Rysewyk<sup>80</sup>, T. Sälzer<sup>57</sup>, S. E. Sanchez Herrera<sup>59</sup>, A. Sandrock<sup>71</sup>, J. Sandroos<sup>61</sup>, M. Santander<sup>92</sup>, S. Sarkar<sup>50,98</sup>, S. Sarkar<sup>59</sup>, K. Satalecka<sup>47</sup>, P. Schlunder<sup>71</sup>, T. Schmidt<sup>68</sup>, A. Schneider<sup>74</sup>, S. Schoenen<sup>57</sup>, S. Schöneberg<sup>65</sup>, L. Schumacher<sup>57</sup>, D. Seckel<sup>81</sup>, S. Seunarine<sup>94</sup>, J. Soedingrekso<sup>71</sup>, D. Soldin<sup>66</sup>, M. Song<sup>68</sup>, G. M. Spiczak<sup>94</sup>, C. Spiering<sup>47</sup>, J. Stachurska<sup>47</sup>, M. Stamatikos<sup>63</sup>, T. Stanev<sup>81</sup>, A. Stasik<sup>47</sup>, J. Stettner<sup>57</sup>, A. Steuer<sup>61</sup>, T. Stezelberger<sup>70</sup>, R. G. Stokstad<sup>70</sup>, A. Stöbl<sup>87</sup>, N. L. 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Regimbau<sup>261</sup>, L. Rei<sup>254</sup>, S. Reid<sup>257</sup>, D. H. Reitze<sup>196,200</sup>, W. Ren<sup>207</sup>, S. D. Reyes<sup>239</sup>, F. Ricci<sup>230,291</sup>, P. M. Ricker<sup>207</sup>, S. Rieger<sup>205</sup>, K. Riles<sup>313</sup>, M. Rizzo<sup>252</sup>, N. A. Robertson<sup>196,241</sup>, R. Robie<sup>241</sup>, F. Robinet<sup>223</sup>, A. Rocchi<sup>228</sup>, L. Rolland<sup>203</sup>, J. G. Rollins<sup>196</sup>, V. J. Roma<sup>264</sup>, R. Romano<sup>198,199</sup>, C. L. Romel<sup>242</sup>, J. H. Romie<sup>202</sup>, D. Rosińska<sup>251,345</sup>, M. P. Ross<sup>346</sup>, S. Rowan<sup>241</sup>, A. Rüdiger<sup>205</sup>, P. Ruggi<sup>225</sup>, G. Rutins<sup>222</sup>, K. Ryan<sup>242</sup>, S. Sachdev<sup>196</sup>, T. Sadecki<sup>242</sup>, L. Sadeghian<sup>216</sup>, M. Sakellariadou<sup>347</sup>, L. Salconi<sup>225</sup>, M. Saleem<sup>311</sup>, F. Salemi<sup>205</sup>, A. Samajdar<sup>338</sup>, L. Sammut<sup>201</sup>, L. M. Sampson<sup>284</sup>, E. J. Sanchez<sup>196</sup>, L. E. Sanchez<sup>196</sup>, N. Sanchis-Gual<sup>280</sup>, V. Sandberg<sup>242</sup>, J. R. Sanders<sup>239</sup>, B. Sassolas<sup>221</sup>, P. R. Saulson<sup>239</sup>, O. Sauter<sup>313</sup>, R. L. Savage<sup>242</sup>, A. Sawadsky<sup>229</sup>, P. Schale<sup>264</sup>, M. Scheel<sup>243</sup>, J. Scheuer<sup>284</sup>, J. Schmidt<sup>205</sup>, P. Schmidt<sup>196,260</sup>, R. Schnabel<sup>229</sup>, R. M. S. Schofield<sup>264</sup>, A. Schönbeck<sup>229</sup>, E. Schreiber<sup>205</sup>, D. Schuette<sup>205,217</sup>, B. W. Schulte<sup>205</sup>, B. F. Schutz<sup>205,231</sup>, S. G. Schwalbe<sup>232</sup>, J. Scott<sup>241</sup>, S. M. Scott<sup>220</sup>, E. Seidel<sup>207</sup>, D. Sellers<sup>202</sup>, A. S. Sengupta<sup>348</sup>, D. Sentenac<sup>225</sup>, V. Sequino<sup>212,227,228</sup>, A. Sergeev<sup>323</sup>, D. A. Shaddock<sup>220</sup>, T. J. Shaffer<sup>242</sup>, A. A. Shah<sup>332</sup>, M. S. Shahrar<sup>284</sup>, M. B. Shaner<sup>303</sup>, L. Shao<sup>233</sup>, B. Shapiro<sup>246</sup>, P. Shawhan<sup>270</sup>, A. Sheperd<sup>216</sup>, D. H. Shoemaker<sup>210</sup>, D. M. Shoemaker<sup>271</sup>, K. Siellez<sup>271</sup>, X. Siemens<sup>216</sup>, M. Sieniawska<sup>251</sup>, D. Sigg<sup>242</sup>, A. D. Silva<sup>211</sup>, L. P. Singer<sup>274</sup>, A. Singh<sup>205,217,233</sup>, A. Singhal<sup>212,230</sup>, A. M. Sintes<sup>296</sup>, B. J. J. Slagmolen<sup>220</sup>, B. Smith<sup>202</sup>, J. R. Smith<sup>224</sup>, R. J. E. Smith<sup>196,201</sup>, S. Somala<sup>349</sup>, E. J. Son<sup>326</sup>, J. A. Sonnenberg<sup>216</sup>, B. Sorazu<sup>241</sup>, F. Sorrentino<sup>254</sup>, T. Souradeep<sup>214</sup>, A. P. Spencer<sup>241</sup>, A. K. Srivastava<sup>299</sup>, K. Staats<sup>232</sup>, A. Staley<sup>245</sup>, M. Steinke<sup>205</sup>, J. Steinlechner<sup>229,241</sup>, S. Steinlechner<sup>229</sup>, D. Steinmeyer<sup>205</sup>, S. P. Stevenson<sup>253,344</sup>, R. Stone<sup>297</sup>, D. J. Stops<sup>253</sup>, K. A. Strain<sup>241</sup>, G. Stratta<sup>316,317</sup>, S. E. Strigin<sup>256</sup>, A. Strunk<sup>242</sup>, R. Sturani<sup>350</sup>, A. L. Stuver<sup>202</sup>, T. Z. Summerscales<sup>351</sup>, L. Sun<sup>290</sup>, S. Sunil<sup>299</sup>, J. Suresh<sup>214</sup>, P. J. Sutton<sup>231</sup>, B. L. Swinkels<sup>225</sup>, M. J. Szczepańczyk<sup>232</sup>, M. Tacca<sup>209</sup>, S. C. Tait<sup>241</sup>, C. Talbot<sup>201</sup>, D. Talukder<sup>264</sup>, D. B. Tanner<sup>200</sup>, M. Tápai<sup>312</sup>, A. Taracchini<sup>233</sup>, J. D. Tasson<sup>266</sup>, J. A. Taylor<sup>332</sup>, R. Taylor<sup>196</sup>, S. V. Tewari<sup>343</sup>, T. Theeg<sup>205</sup>, F. Thies<sup>205</sup>, E. G. Thomas<sup>253</sup>, M. Thomas<sup>202</sup>, P. Thomas<sup>242</sup>, K. A. Thorne<sup>202</sup>, E. Thrane<sup>201</sup>, S. Tiwari<sup>212,289</sup>, V. Tiwari<sup>231</sup>, K. V. Tokmakov<sup>257</sup>, K. Toland<sup>241</sup>, M. Tonelli<sup>218,219</sup>, Z. Tornasi<sup>241</sup>, A. Torres-Forné<sup>280</sup>, C. I. Torrie<sup>196</sup>, D. Töyrä<sup>253</sup>, F. Travasso<sup>225,238</sup>, G. Traylor<sup>202</sup>, J. Trinastic<sup>200</sup>, M. C. Tringali<sup>289,304</sup>, L. Trozzo<sup>219,352</sup>, K. W. Tsang<sup>209</sup>, M. Tse<sup>210</sup>, R. Tso<sup>196</sup>, L. Tsukada<sup>276</sup>, D. Tsuna<sup>276</sup>, D. Tuyenbayev<sup>297</sup>, K. Ueno<sup>216</sup>, D. Ugolini<sup>353</sup>, C. S. Unnikrishnan<sup>314</sup>, A. L. Urban<sup>196</sup>, S. A. Usman<sup>231</sup>, H. Vahlbruch<sup>217</sup>, G. Vajente<sup>196</sup>, G. Valdes<sup>197</sup>, N. van Bakel<sup>209</sup>, M. van Beuzekom<sup>209</sup>, J. F. J. van den Brand<sup>209,269</sup>, C. Van Den Broeck<sup>209,354</sup>, D. C. Vander-Hyde<sup>239</sup>, L. van der Schaaf<sup>209</sup>, J. V. van Heijningen<sup>209</sup>, A. A. van Veggel<sup>241</sup>, M. Vardaro<sup>248,249</sup>, V. Varma<sup>243</sup>, S. Vass<sup>196</sup>, M. Vasúth<sup>244</sup>, A. Vecchio<sup>253</sup>, G. Vedovato<sup>249</sup>, J. Veitch<sup>241</sup>, P. J. Veitch<sup>267</sup>, K. Venkateswara<sup>346</sup>, G. Venugopalan<sup>196</sup>, D. Verkindt<sup>203</sup>, F. Vetrano<sup>316,317</sup>, A. Viceré<sup>316,317</sup>, A. D. Viets<sup>216</sup>, S. Vinciguerra<sup>253</sup>, D. J. Vine<sup>222</sup>, J.-Y. Vinet<sup>261</sup>, S. Vitale<sup>210</sup>, T. Vo<sup>239</sup>, H. Vocca<sup>237,238</sup>, C. Vorvick<sup>242</sup>, S. P. Vyatchanin<sup>256</sup>, A. R. Wade<sup>196</sup>

L. E. Wade<sup>279</sup>, M. Wade<sup>279</sup>, R. Walet<sup>209</sup>, M. Walker<sup>224</sup>, L. Wallace<sup>196</sup>, S. Walsh<sup>205,216,233</sup>, G. Wang<sup>212,317</sup>, H. Wang<sup>253</sup>, J. Z. Wang<sup>258</sup>, W. H. Wang<sup>297</sup>, Y. F. Wang<sup>287</sup>, R. L. Ward<sup>220</sup>, J. Warner<sup>242</sup>, M. Was<sup>203</sup>, J. Watchi<sup>292</sup>, B. Weaver<sup>242</sup>, L.-W. Wei<sup>205,217</sup>, M. Weinert<sup>205</sup>, A. J. Weinstein<sup>196</sup>, R. Weiss<sup>210</sup>, L. Wen<sup>259</sup>, E. K. Wessel<sup>207</sup>, P. Weßels<sup>205</sup>, J. Westerweck<sup>205</sup>, T. Westphal<sup>205</sup>, K. Wette<sup>220</sup>, J. T. Whelan<sup>252</sup>, B. F. Whiting<sup>200</sup>, C. Whittle<sup>201</sup>, D. Wilken<sup>205</sup>, D. Williams<sup>241</sup>, R. D. Williams<sup>196</sup>, A. R. Williamson<sup>260</sup>, J. L. Willis<sup>196,355</sup>, B. Willke<sup>205,217</sup>, M. H. Wimmer<sup>205</sup>, W. Winkler<sup>205</sup>, C. C. Wipf<sup>196</sup>, H. Wittel<sup>205,217</sup>, G. Woan<sup>241</sup>, J. Woehler<sup>205</sup>, J. Wofford<sup>252</sup>, K. W. K. Wong<sup>287</sup>, J. Worden<sup>242</sup>, J. L. Wright<sup>241</sup>, D. S. Wu<sup>205</sup>, D. M. Wysocki<sup>252</sup>, S. Xiao<sup>196</sup>, H. Yamamoto<sup>196</sup>, C. C. Yancey<sup>270</sup>, L. Yang<sup>356</sup>, M. J. Yap<sup>220</sup>, M. Yazback<sup>200</sup>, Hang Yu<sup>210</sup>, Haocun Yu<sup>210</sup>, M. Yvert<sup>203</sup>, A. Zadrożny<sup>327</sup>, M. Zanolin<sup>232</sup>, T. Zelenova<sup>225</sup>, J.-P. Zendri<sup>249</sup>, M. Zevin<sup>284</sup>, L. Zhang<sup>196</sup>, M. Zhang<sup>335</sup>, T. Zhang<sup>241</sup>, Y.-H. Zhang<sup>252</sup>, C. Zhao<sup>259</sup>, M. Zhou<sup>284</sup>, Z. Zhou<sup>284</sup>, S. J. Zhu<sup>205,233</sup>, X. J. Zhu<sup>201</sup>, M. E. Zucker<sup>196,210</sup>, J. Zweizig<sup>196</sup>, and

(LIGO Scientific Collaboration and Virgo Collaboration)

<sup>1</sup> GRPHE—Université de Haute Alsace—Institut universitaire de technologie de Colmar, 34 rue du Grillenbreit BP F-50568-68008 Colmar, France

<sup>2</sup> Technical University of Catalonia, Laboratory of Applied Bioacoustics, Rambla Exposició, E-08800 Vilanova i la Geltrú, Barcelona, Spain

<sup>3</sup> INFN—Sezione di Genova, Via Dodecaneso 33, I-16146 Genova, Italy

<sup>4</sup> Institut d'Investigació per a la Gestió Integrada de les Zones Costaneres (IGIC)—Universitat Politècnica de València. C/Paranimf 1, E-46730 Gandia, Spain

<sup>5</sup> Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

<sup>6</sup> APC, Univ Paris Diderot, CNRS/IN2P3, CEA/Irfu, Obs de Paris, Sorbonne Paris Cité, France

<sup>7</sup> IFIC—Instituto de Física Corpuscular (CSIC—Universitat de València) c/ Catedrático José Beltrán, 2 E-46980 Paterna, Valencia, Spain

<sup>8</sup> LAM—Laboratoire d'Astrophysique de Marseille, Pôle de l'Étoile Site de Château-Gombert, rue Frédéric Joliot-Curie 38, F-13388 Marseille Cedex 13, France

<sup>9</sup> National Center for Energy Sciences and Nuclear Techniques, B.P.1382, R.P.10001 Rabat, Morocco

<sup>10</sup> INFN—Laboratori Nazionali del Sud (LNS), Via S. Sofia 62, I-95123 Catania, Italy

<sup>11</sup> Nikhef, Science Park, Amsterdam, The Netherlands

<sup>12</sup> Huygens-Kamerlingh Onnes Laboratorium, Universiteit Leiden, The Netherlands

<sup>13</sup> Institute of Space Science, RO-077125 Bucharest, Măgurele, Romania

<sup>14</sup> Universiteit van Amsterdam, Instituut voor Hoge-Energie Fysica, Science Park 105, 1098 XG Amsterdam, The Netherlands

<sup>15</sup> INFN—Sezione di Roma, P.le Aldo Moro 2, I-00185 Roma, Italy

<sup>16</sup> Dipartimento di Fisica dell'Università La Sapienza, P.le Aldo Moro 2, I-00185 Roma, Italy

<sup>17</sup> Gran Sasso Science Institute, Viale Francesco Crispi 7, I-00167 L'Aquila, Italy

<sup>18</sup> University Mohammed V in Rabat, Faculty of Sciences, 4 av. Ibn Battouta, B.P. 1014, R.P. 10000 Rabat, Morocco

<sup>19</sup> INFN—Sezione di Bologna, Viale Bertini-Pichat 6/2, I-40127 Bologna, Italy

<sup>20</sup> INFN—Sezione di Bari, Via E. Orabona 4, I-70126 Bari, Italy

<sup>21</sup> Department of Computer Architecture and Technology/CITIC, University of Granada, E-18071 Granada, Spain

<sup>22</sup> Géoazur, UCA, CNRS, IRD, Observatoire de la Côte d'Azur, Sophia Antipolis, France

<sup>23</sup> Dipartimento di Fisica dell'Università, Via Dodecaneso 33, I-16146 Genova, Italy

<sup>24</sup> Université Paris-Sud, F-91405 Orsay Cedex, France

<sup>25</sup> Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen Centre for Astroparticle Physics, Erwin-Rommel-Str. 1, D-91058 Erlangen, Germany

<sup>26</sup> University Mohammed I, Laboratory of Physics of Matter and Radiations, B.P.717, Oujda 6000, Morocco

<sup>27</sup> Institut für Theoretische Physik und Astrophysik, Universität Würzburg, Emil-Fischer Str. 31, D-97074 Würzburg, Germany

<sup>28</sup> Dipartimento di Fisica e Astronomia dell'Università, Viale Bertini Pichat 6/2, I-40127 Bologna, Italy

<sup>29</sup> Laboratoire de Physique Corpusculaire, Clermont Université, Université Blaise Pascal, CNRS/IN2P3, BP 10448, F-63000 Clermont-Ferrand, France

<sup>30</sup> INFN—Sezione di Catania, Viale Andrea Doria 6, I-95125 Catania, Italy

<sup>31</sup> 31, Aix Marseille Université CNRS ENSAM LSIS UMR 7296 13397 Marseille, France; Université de Toulon CNRS LSIS UMR 7296, F-83957 La Garde, France

<sup>32</sup> Institut Universitaire de France, F-75005 Paris, France

<sup>33</sup> Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France

<sup>34</sup> Royal Netherlands Institute of Sea Research (NIOZ) and Utrecht University, Landsdiep 4, 1797 SZ 't Horntje (Texel), the Netherlands

<sup>35</sup> Dr. Remeis-Sternwarte and ECAP, Friedrich-Alexander-Universität Erlangen-Nürnberg, Sternwartstr. 7, D-96049 , Germany

<sup>36</sup> Moscow State University, Skobel'syn Institute of Nuclear Physics, Leninskie gory, 119991 Moscow, Russia

<sup>37</sup> Mediterranean Institute of Oceanography (MIO), Aix-Marseille University, 13288, Marseille, Cedex 9, France; Université du Sud Toulon-Var, CNRS-INSU/IRD UM 110, F-83957, La Garde Cedex, France

<sup>38</sup> Dipartimento di Fisica ed Astronomia dell'Università, Viale Andrea Doria 6, I-95125 Catania, Italy

<sup>39</sup> Direction des Sciences de la Matière—Institut de recherche sur les lois fondamentales de l'Univers—Service de Physique des Particules, CEA Saclay, F-91191 Gif-sur-Yvette Cedex, France

<sup>40</sup> INFN—Sezione di Pisa, Largo B. Pontecorvo 3, I-56127 Pisa, Italy

<sup>41</sup> Dipartimento di Fisica dell'Università, Largo B. Pontecorvo 3, I-56127 Pisa, Italy

<sup>42</sup> INFN—Sezione di Napoli, Via Cintia I-80126 Napoli, Italy

<sup>43</sup> Dipartimento di Fisica dell'Università Federico II di Napoli, Via Cintia I-80126, Napoli, Italy

<sup>44</sup> Dipartimento de Física Teórica y del Cosmos & C.A.F.P.E., University of Granada, E-18071 Granada, Spain

<sup>45</sup> Dr. Remeis-Sternwarte and ECAP, Friedrich-Alexander-Universität Erlangen-Nürnberg, Sternwartstr. 7, D-96049 Bamberg, Germany

<sup>46</sup> Department of Physics, University of Adelaide, Adelaide, SA 5005, Australia

<sup>47</sup> DESY, D-15738 Zeuthen, Germany

<sup>48</sup> Department of Physics and Astronomy, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

<sup>49</sup> Université Libre de Bruxelles, Science Faculty CP230, B-1050 Brussels, Belgium

<sup>50</sup> Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark

<sup>51</sup> Oskar Klein Centre and Dept. of Physics, Stockholm University, SE-10691 Stockholm, Sweden

<sup>52</sup> Département de physique nucléaire et corpusculaire, Université de Genève, CH-1211 Genève, Switzerland

<sup>53</sup> Erlangen Centre for Astroparticle Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany

<sup>54</sup> Department of Physics, Marquette University, Milwaukee, WI, 53201, USA

<sup>55</sup> Dept. of Physics, Pennsylvania State University, University Park, PA 16802, USA

<sup>56</sup> Dept. of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

<sup>57</sup> III. Physikalisches Institut, RWTH Aachen University, D-52056 Aachen, Germany

<sup>58</sup> Physics Department, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA

- <sup>59</sup> Department of Physics, University of Alberta, Edmonton, AB T6G 2E1, Canada
- <sup>60</sup> Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA
- <sup>61</sup> Institute of Physics, University of Mainz, Staudinger Weg 7, D-55099 Mainz, Germany
- <sup>62</sup> Department of Physics, University of California, Berkeley, CA 94720, USA
- <sup>63</sup> Department of Physics and Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, OH 43210, USA
- <sup>64</sup> Department of Astronomy, Ohio State University, Columbus, OH 43210, USA
- <sup>65</sup> Fakultät für Physik & Astronomie, Ruhr-Universität Bochum, D-44780 Bochum, Germany
- <sup>66</sup> Department of Physics, University of Wuppertal, D-42119 Wuppertal, Germany
- <sup>67</sup> Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA
- <sup>68</sup> Department of Physics, University of Maryland, College Park, MD 20742, USA
- <sup>69</sup> Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA
- <sup>70</sup> Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
- <sup>71</sup> Department of Physics, TU Dortmund University, D-44221 Dortmund, Germany
- <sup>72</sup> Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea
- <sup>73</sup> Department of Physics and Astronomy, Uppsala University, Box 516, SE-75120 Uppsala, Sweden
- <sup>74</sup> Department of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin–Madison, Madison, WI 53706, USA
- <sup>75</sup> Vrije Universiteit Brussel (VUB), Dienst ELEM, B-1050 Brussels, Belgium
- <sup>76</sup> SNOLAB, 1039 Regional Road 24, Creighton Mine 9, Lively, ON P3Y 1N2, Canada
- <sup>77</sup> Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, D-48149 Münster, Germany
- <sup>78</sup> Physik-department, Technische Universität München, D-85748 Garching, Germany
- <sup>79</sup> Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA
- <sup>80</sup> Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA
- <sup>81</sup> Bartol Research Institute and Dept. of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA
- <sup>82</sup> Department of Physics and Astronomy, University of Gent, B-9000 Gent, Belgium
- <sup>83</sup> Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany
- <sup>84</sup> Department of Physics, Southern University, Baton Rouge, LA 70813, USA
- <sup>85</sup> Department of Astronomy, University of Wisconsin–Madison, Madison, WI 53706, USA
- <sup>86</sup> Earthquake Research Institute, University of Tokyo, Bunkyo, Tokyo 113-0032, Japan
- <sup>87</sup> Department of Physics and Institute for Global Prominent Research, Chiba University, Chiba 263-8522, Japan
- <sup>88</sup> CTSPS, Clark-Atlanta University, Atlanta, GA 30314, USA
- <sup>89</sup> Department of Physics, University of Texas at Arlington, 502 Yates Street, Science Hall Rm 108, Box 19059, Arlington, TX 76019, USA
- <sup>90</sup> Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA
- <sup>91</sup> Université de Mons, B-7000 Mons, Belgium
- <sup>92</sup> Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA
- <sup>93</sup> Department of Physics, Drexel University, 3141 Chestnut Street, Philadelphia, PA 19104, USA
- <sup>94</sup> Department of Physics, University of Wisconsin, River Falls, WI 54022, USA
- <sup>95</sup> Department of Physics, Yale University, New Haven, CT 06520, USA
- <sup>96</sup> School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, GA 30332, USA
- <sup>97</sup> Department of Physics and Astronomy, University of Alaska Anchorage, 3211 Providence Drive, Anchorage, AK 99508, USA
- <sup>98</sup> Department of Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, UK
- <sup>99</sup> IMAPP, Radboud University Nijmegen, Nijmegen, The Netherlands
- <sup>100</sup> Laboratório de Instrumentação e Física Experimental de Partículas—LIP and Instituto Superior Técnico—IST, Universidade de Lisboa—UL, Lisboa, Portugal
- <sup>101</sup> Osservatorio Astrofisico di Torino (INAF), Torino, Italy
- <sup>102</sup> INFN, Sezione di Torino, Torino, Italy
- <sup>103</sup> Universidade de São Paulo, Instituto de Física, São Paulo, SP, Brazil
- <sup>104</sup> University of Adelaide, Adelaide, SA, Australia
- <sup>105</sup> Centro Atómico Bariloche and Instituto Balseiro (CNEA-UNCuyo-CONICET), San Carlos de Bariloche, Argentina
- <sup>106</sup> Instituto de Tecnologías en Detección y Astropartículas (CNEA, CONICET, UNSAM), Buenos Aires, Argentina
- <sup>107</sup> Universidad Tecnológica Nacional, Facultad Regional Buenos Aires, Buenos Aires, Argentina
- <sup>108</sup> Universidad Nacional Autónoma de México, México, D.F., México
- <sup>109</sup> Universidad de Santiago de Compostela, Santiago de Compostela, Spain
- <sup>110</sup> Gran Sasso Science Institute (INFN), L'Aquila, Italy
- <sup>111</sup> INFN Laboratori Nazionali del Gran Sasso, Assergi (L'Aquila), Italy
- <sup>112</sup> Department of Physics and Astronomy, Lehman College, City University of New York, New York, NY, USA
- <sup>113</sup> INFN, Sezione di Napoli, Napoli, Italy
- <sup>114</sup> Institute of Space Science, Bucharest-Magurele, Romania
- <sup>115</sup> Universidad Industrial de Santander, Bucaramanga, Colombia
- <sup>116</sup> Observatorio Pierre Auger, Malargüe, Argentina
- <sup>117</sup> Observatorio Pierre Auger and Comisión Nacional de Energía Atómica, Malargüe, Argentina
- <sup>118</sup> University Politehnica of Bucharest, Bucharest, Romania
- <sup>119</sup> “Horia Hulubei” National Institute for Physics and Nuclear Engineering, Bucharest-Magurele, Romania
- <sup>120</sup> Università di Napoli “Federico II”, Dipartimento di Fisica “Ettore Pancini,” Napoli, Italy
- <sup>121</sup> Ohio State University, Columbus, OH, USA
- <sup>122</sup> Bergische Universität Wuppertal, Department of Physics, Wuppertal, Germany
- <sup>123</sup> Laboratoire de Physique Subatomique et de Cosmologie (LPSC), Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
- <sup>124</sup> Università Torino, Dipartimento di Fisica, Torino, Italy
- <sup>125</sup> Max-Planck-Institut für Radioastronomie, Bonn, Germany
- <sup>126</sup> Institut de Physique Nucléaire d’Orsay (IPNO), Université Paris-Sud, Univ. Paris/Saclay, CNRS-IN2P3, Orsay, France
- <sup>127</sup> Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
- <sup>128</sup> Università del Salento, Dipartimento di Matematica e Fisica “E. De Giorgi,” Lecce, Italy
- <sup>129</sup> INFN, Sezione di Lecce, Lecce, Italy
- <sup>130</sup> Universidade Federal do Rio de Janeiro, Instituto de Física, Rio de Janeiro, RJ, Brazil
- <sup>131</sup> Institute of Nuclear Physics PAN, Krakow, Poland
- <sup>132</sup> Karlsruhe Institute of Technology, Institut für Kernphysik, Karlsruhe, Germany

- <sup>133</sup> Colorado State University, Fort Collins, CO, USA
- <sup>134</sup> RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- <sup>135</sup> Karlsruhe Institute of Technology, Institut für Experimentelle Kernphysik (IEKP), Karlsruhe, Germany
- <sup>136</sup> Universität Siegen, Fachbereich 7 Physik—Experimentelle Teilchenphysik, Siegen, Germany
- <sup>137</sup> Universidad de Granada and C.A.F.P.E., Granada, Spain
- <sup>138</sup> Università di Catania, Dipartimento di Fisica e Astronomia, Catania, Italy
- <sup>139</sup> INFN, Sezione di Catania, Catania, Italy
- <sup>140</sup> Universidad Autónoma de Chiapas, Tuxtla Gutiérrez, Chiapas, México
- <sup>141</sup> Università di Milano, Dipartimento di Fisica, Milano, Italy
- <sup>142</sup> Universidade de São Paulo, Escola de Engenharia de Lorena, Lorena, SP, Brazil
- <sup>143</sup> Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, México
- <sup>144</sup> Universidade Estadual de Campinas, IFGW, Campinas, SP, Brazil
- <sup>145</sup> Instituto de Tecnologías en Detección y Astropartículas (CNEA, CONICET, UNSAM), and Universidad Tecnológica Nacional—Facultad Regional Mendoza (CONICET/CNEA), Mendoza, Argentina
- <sup>146</sup> Pennsylvania State University, University Park, PA, USA
- <sup>147</sup> INFN, Sezione di Milano, Milano, Italy
- <sup>148</sup> Politecnico di Milano, Dipartimento di Scienze e Tecnologie Aerospaziali, Milano, Italy
- <sup>149</sup> Case Western Reserve University, Cleveland, OH, USA
- <sup>150</sup> University of Chicago, Enrico Fermi Institute, Chicago, IL, USA
- <sup>151</sup> Università del Salento, Dipartimento di Ingegneria, Lecce, Italy
- <sup>152</sup> Instituto de Astronomía y Física del Espacio (IAFE, CONICET-UBA), Buenos Aires, Argentina
- <sup>153</sup> Departamento de Física and Departamento de Ciencias de la Atmósfera y los Océanos, FCEyN, Universidad de Buenos Aires and CONICET, Buenos Aires, Argentina
- <sup>154</sup> Universidade Federal Fluminense, EEIMVR, Volta Redonda, RJ, Brazil
- <sup>155</sup> Nationaal Instituut voor Kernfysica en Hoge Energie Fysica (NIKHEF), Science Park, Amsterdam, The Netherlands
- <sup>156</sup> Universidade Federal do Rio de Janeiro (UFRJ), Observatório do Valongo, Rio de Janeiro, RJ, Brazil
- <sup>157</sup> Universidade de São Paulo, Instituto de Física de São Carlos, São Carlos, SP, Brazil
- <sup>158</sup> Universidade Federal do Paraná, Setor Palotina, Palotina, Brazil
- <sup>159</sup> IFLP, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- <sup>160</sup> Universität Hamburg, II. Institut für Theoretische Physik, Hamburg, Germany
- <sup>161</sup> Fermi National Accelerator Laboratory, USA
- <sup>162</sup> Stichting Astronomisch Onderzoek in Nederland (ASTRON), Dwingeloo, The Netherlands
- <sup>163</sup> New York University, New York, NY, USA
- <sup>164</sup> Karlsruhe Institute of Technology, Institut für Prozessdatenverarbeitung und Elektronik, Karlsruhe, Germany
- <sup>165</sup> Michigan Technological University, Houghton, MI, USA
- <sup>166</sup> Experimental Particle Physics Department, J. Stefan Institute, Ljubljana, Slovenia
- <sup>167</sup> Center for Astrophysics and Cosmology (CAC), University of Nova Gorica, Nova Gorica, Slovenia
- <sup>168</sup> Instituto de Física de Rosario (IFIR)—CONICET/U.N.R. and Facultad de Ciencias Bioquímicas y Farmacéuticas U.N.R., Rosario, Argentina
- <sup>169</sup> Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), Universités Paris 6 et Paris 7, CNRS-IN2P3, Paris, France
- <sup>170</sup> SUBATECH, École des Mines de Nantes, CNRS-IN2P3, Université de Nantes, France
- <sup>171</sup> Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, RJ, Brazil
- <sup>172</sup> University of Łódź, Faculty of Astrophysics, Łódź, Poland
- <sup>173</sup> University of Łódź, Faculty of High-Energy Astrophysics, Łódź, Poland
- <sup>174</sup> Universidade Estadual de Feira de Santana, Feira de Santana, Brazil
- <sup>175</sup> Palacky University, RCPTM, Olomouc, Czech Republic
- <sup>176</sup> Colorado School of Mines, Golden, CO, USA
- <sup>177</sup> Centro Federal de Educação Tecnológica Celso Suckow da Fonseca, Nova Friburgo, Brazil
- <sup>178</sup> Universidade Federal do ABC, Santo André, SP, Brazil
- <sup>179</sup> Benemérita Universidad Autónoma de Puebla, Puebla, México
- <sup>180</sup> Université Libre de Bruxelles (ULB), Brussels, Belgium
- <sup>181</sup> Centro de Investigación y de Estudios Avanzados del IPN (CINVESTAV), México, D.F., México
- <sup>182</sup> Louisiana State University, Baton Rouge, LA, USA
- <sup>183</sup> Università di Roma “Tor Vergata”, Dipartimento di Fisica, Roma, Italy
- <sup>184</sup> INFN, Sezione di Roma “Tor Vergata,” Roma, Italy
- <sup>185</sup> Universidade Federal de Alenas, Brasília, Brazil
- <sup>186</sup> Charles University, Faculty of Mathematics and Physics, Institute of Particle and Nuclear Physics, Prague, Czech Republic
- <sup>187</sup> Centro de Investigaciones en Láseres y Aplicaciones, CITEDEF and CONICET, Villa Martelli, Argentina
- <sup>188</sup> Unidad Profesional Interdisciplinaria en Ingeniería y Tecnologías Avanzadas del Instituto Politécnico Nacional (UPIITA-IPN), México, D.F., México
- <sup>189</sup> Università dell’Aquila, Dipartimento di Scienze Fisiche e Chimiche, L’Aquila, Italy
- <sup>190</sup> KVI—Center for Advanced Radiation Technology, University of Groningen, Groningen, The Netherlands
- <sup>191</sup> Vrije Universiteit Brussels, Brussels, Belgium
- <sup>192</sup> INAF—Istituto di Astrofisica Spaziale e Fisica Cosmica di Palermo, Palermo, Italy
- <sup>193</sup> University of Nebraska, Lincoln, NE, USA
- <sup>194</sup> Northeastern University, Boston, MA, USA
- <sup>195</sup> School of Physics and Astronomy, University of Leeds, Leeds, UK
- <sup>196</sup> LIGO, California Institute of Technology, Pasadena, CA 91125, USA
- <sup>197</sup> Louisiana State University, Baton Rouge, LA 70803, USA
- <sup>198</sup> Università di Salerno, Fisciano, I-84084 Salerno, Italy
- <sup>199</sup> INFN, Sezione di Napoli, Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy
- <sup>200</sup> University of Florida, Gainesville, FL 32611, USA
- <sup>201</sup> OzGrav, School of Physics & Astronomy, Monash University, Clayton, VIC 3800, Australia
- <sup>202</sup> LIGO Livingston Observatory, Livingston, LA 70754, USA
- <sup>203</sup> Laboratoire d’Annecy-le-Vieux de Physique des Particules (LAPP), Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy, France
- <sup>204</sup> University of Sannio at Benevento, I-82100 Benevento, Italy and INFN, Sezione di Napoli, I-80100 Napoli, Italy

- <sup>205</sup> Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-30167 Hannover, Germany
- <sup>206</sup> The University of Mississippi, University, MS 38677, USA
- <sup>207</sup> NCSA, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
- <sup>208</sup> University of Cambridge, Cambridge CB2 1TN, UK
- <sup>209</sup> Nikhef, Science Park, 1098 XG Amsterdam, The Netherlands
- <sup>210</sup> LIGO, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
- <sup>211</sup> Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos, São Paulo, Brazil
- <sup>212</sup> Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy
- <sup>213</sup> INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy
- <sup>214</sup> Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India
- <sup>215</sup> International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bengaluru 560089, India
- <sup>216</sup> University of Wisconsin–Milwaukee, Milwaukee, WI 53201, USA
- <sup>217</sup> Leibniz Universität Hannover, D-30167 Hannover, Germany
- <sup>218</sup> Università di Pisa, I-56127 Pisa, Italy
- <sup>219</sup> INFN, Sezione di Pisa, I-56127 Pisa, Italy
- <sup>220</sup> OzGrav, Australian National University, Canberra, ACT 0200, Australia
- <sup>221</sup> Laboratoire des Matériaux Avancés (LMA), CNRS/IN2P3, F-69622 Villeurbanne, France
- <sup>222</sup> SUPA, University of the West of Scotland, Paisley PA1 2BE, UK
- <sup>223</sup> LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, F-91898 Orsay, France
- <sup>224</sup> California State University Fullerton, Fullerton, CA 92831, USA
- <sup>225</sup> European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy
- <sup>226</sup> Chennai Mathematical Institute, Chennai 603103, India
- <sup>227</sup> Università di Roma Tor Vergata, I-00133 Roma, Italy
- <sup>228</sup> INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy
- <sup>229</sup> Universität Hamburg, D-22761 Hamburg, Germany
- <sup>230</sup> INFN, Sezione di Roma, I-00185 Roma, Italy
- <sup>231</sup> Cardiff University, Cardiff CF24 3AA, UK
- <sup>232</sup> Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA
- <sup>233</sup> Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam-Golm, Germany
- <sup>234</sup> APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, F-75205 Paris Cedex 13, France
- <sup>235</sup> Korea Institute of Science and Technology Information, Daejeon 34141, Korea
- <sup>236</sup> West Virginia University, Morgantown, WV 26506, USA
- <sup>237</sup> Università di Perugia, I-06123 Perugia, Italy
- <sup>238</sup> INFN, Sezione di Perugia, I-06123 Perugia, Italy
- <sup>239</sup> Syracuse University, Syracuse, NY 13244, USA
- <sup>240</sup> University of Minnesota, Minneapolis, MN 55455, USA
- <sup>241</sup> SUPA, University of Glasgow, Glasgow G12 8QQ, UK
- <sup>242</sup> LIGO Hanford Observatory, Richland, WA 99352, USA
- <sup>243</sup> Caltech CaRT, Pasadena, CA 91125, USA
- <sup>244</sup> Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thege Miklós út 29–33, Hungary
- <sup>245</sup> Columbia University, New York, NY 10027, USA
- <sup>246</sup> Stanford University, Stanford, CA 94305, USA
- <sup>247</sup> Università di Camerino, Dipartimento di Fisica, I-62032 Camerino, Italy
- <sup>248</sup> Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy
- <sup>249</sup> INFN, Sezione di Padova, I-35131 Padova, Italy
- <sup>250</sup> Institute of Physics, Eötvös University, Pázmány P.s. 1/A, Budapest 1117, Hungary
- <sup>251</sup> Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland
- <sup>252</sup> Rochester Institute of Technology, Rochester, NY 14623, USA
- <sup>253</sup> University of Birmingham, Birmingham B15 2TT, UK
- <sup>254</sup> INFN, Sezione di Genova, I-16146 Genova, Italy
- <sup>255</sup> RRCAT, Indore MP 452013, India
- <sup>256</sup> Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia
- <sup>257</sup> SUPA, University of Strathclyde, Glasgow G1 1XQ, UK
- <sup>258</sup> The Pennsylvania State University, University Park, PA 16802, USA
- <sup>259</sup> OzGrav, University of Western Australia, Crawley, WA 6009, Australia
- <sup>260</sup> Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands
- <sup>261</sup> Artemis, Université Côte d'Azur, Observatoire Côte d'Azur, CNRS, CS 34229, F-06304 Nice Cedex 4, France
- <sup>262</sup> Institut FOTON, CNRS, Université de Rennes 1, F-35042 Rennes, France
- <sup>263</sup> Washington State University, Pullman, WA 99164, USA
- <sup>264</sup> University of Oregon, Eugene, OR 97403, USA
- <sup>265</sup> Laboratoire Kastler Brossel, UPMC-Sorbonne Universités, CNRS, ENS-PSL Research University, Collège de France, F-75005 Paris, France
- <sup>266</sup> Carleton College, Northfield, MN 55057, USA
- <sup>267</sup> OzGrav, University of Adelaide, Adelaide, SA 5005, Australia
- <sup>268</sup> Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland
- <sup>269</sup> VU University Amsterdam, 1081 HV Amsterdam, The Netherlands
- <sup>270</sup> University of Maryland, College Park, MD 20742, USA
- <sup>271</sup> Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, GA 30332, USA
- <sup>272</sup> Université Claude Bernard Lyon 1, F-69622 Villeurbanne, France
- <sup>273</sup> Università di Napoli "Federico II," Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy
- <sup>274</sup> NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
- <sup>275</sup> Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy
- <sup>276</sup> RESCEU, University of Tokyo, Tokyo, 113-0033, Japan
- <sup>277</sup> Tsinghua University, Beijing 100084, China



- <sup>278</sup> Texas Tech University, Lubbock, TX 79409, USA  
<sup>279</sup> Kenyon College, Gambier, OH 43022, USA  
<sup>280</sup> Departamento de Astronomía y Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain  
<sup>281</sup> Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi, I-00184 Roma, Italy  
<sup>282</sup> National Tsing Hua University, Hsinchu City, 30013 Taiwan, Republic of China  
<sup>283</sup> Charles Sturt University, Wagga Wagga, NSW 2678, Australia  
<sup>284</sup> Center for Interdisciplinary Exploration & Research in Astrophysics (CIERA), Northwestern University, Evanston, IL 60208, USA  
<sup>285</sup> University of Chicago, Chicago, IL 60637, USA  
<sup>286</sup> Pusan National University, Busan 46241, Korea  
<sup>287</sup> The Chinese University of Hong Kong, Shatin, NT, Hong Kong  
<sup>288</sup> INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy  
<sup>289</sup> INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy  
<sup>290</sup> OzGrav, University of Melbourne, Parkville, VIC 3010, Australia  
<sup>291</sup> Università di Roma “La Sapienza,” I-00185 Roma, Italy  
<sup>292</sup> Université Libre de Bruxelles, Brussels 1050, Belgium  
<sup>293</sup> Sonoma State University, Rohnert Park, CA 94928, USA  
<sup>294</sup> Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain  
<sup>295</sup> Montana State University, Bozeman, MT 59717, USA  
<sup>296</sup> Universitat de les Illes Balears, IAC3—IEEC, E-07122 Palma de Mallorca, Spain  
<sup>297</sup> The University of Texas Rio Grande Valley, Brownsville, TX 78520, USA  
<sup>298</sup> Bellevue College, Bellevue, WA 98007, USA  
<sup>299</sup> Institute for Plasma Research, Bhat, Gandhinagar 382428, India  
<sup>300</sup> The University of Sheffield, Sheffield S10 2TN, UK  
<sup>301</sup> Dipartimento di Scienze Matematiche, Fische e Informatiche, Università di Parma, I-43124 Parma, Italy  
<sup>302</sup> INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy  
<sup>303</sup> California State University, Los Angeles, 5151 State University Drive, Los Angeles, CA 90032, USA  
<sup>304</sup> Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy  
<sup>305</sup> Montclair State University, Montclair, NJ 07043, USA  
<sup>306</sup> National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan  
<sup>307</sup> Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, ON M5S 3H8, Canada  
<sup>308</sup> Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain  
<sup>309</sup> School of Mathematics, University of Edinburgh, Edinburgh EH9 3FD, UK  
<sup>310</sup> University and Institute of Advanced Research, Koba Institutional Area, Gandhinagar Gujarat 382007, India  
<sup>311</sup> IISER-TVM, CET Campus, Trivandrum Kerala 695016, India  
<sup>312</sup> University of Szeged, Dóm tér 9, Szeged 6720, Hungary  
<sup>313</sup> University of Michigan, Ann Arbor, MI 48109, USA  
<sup>314</sup> Tata Institute of Fundamental Research, Mumbai 400005, India  
<sup>315</sup> INAF, Osservatorio Astronomico di Capodimonte, I-80131, Napoli, Italy  
<sup>316</sup> Università degli Studi di Urbino “Carlo Bo,” I-61029 Urbino, Italy  
<sup>317</sup> INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy  
<sup>318</sup> Physik-Institut, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland  
<sup>319</sup> American University, Washington, DC 20016, USA  
<sup>320</sup> University of Białystok, 15-424 Białystok, Poland  
<sup>321</sup> University of Southampton, Southampton SO17 1BJ, UK  
<sup>322</sup> University of Washington Bothell, 18115 Campus Way NE, Bothell, WA 98011, USA  
<sup>323</sup> Institute of Applied Physics, Nizhny Novgorod, 603950, Russia  
<sup>324</sup> Korea Astronomy and Space Science Institute, Daejeon 34055, Korea  
<sup>325</sup> Inje University Gimhae, South Gyeongsang 50834, Korea  
<sup>326</sup> National Institute for Mathematical Sciences, Daejeon 34047, Korea  
<sup>327</sup> NCBJ, 05-400 Świerk-Otwock, Poland  
<sup>328</sup> Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland  
<sup>329</sup> Hillsdale College, Hillsdale, MI 49242, USA  
<sup>330</sup> Hanyang University, Seoul 04763, Korea  
<sup>331</sup> Seoul National University, Seoul 08826, Korea  
<sup>332</sup> NASA Marshall Space Flight Center, Huntsville, AL 35811, USA  
<sup>333</sup> ESPCI, CNRS, F-75005 Paris, France  
<sup>334</sup> Southern University and A&M College, Baton Rouge, LA 70813, USA  
<sup>335</sup> College of William and Mary, Williamsburg, VA 23187, USA  
<sup>336</sup> Centre Scientifique de Monaco, 8 quai Antoine 1er, MC-98000, Monaco  
<sup>337</sup> Indian Institute of Technology Madras, Chennai 600036, India  
<sup>338</sup> IISER-Kolkata, Mohanpur, West Bengal 741252, India  
<sup>339</sup> Whitman College, 345 Boyer Avenue, Walla Walla, WA 99362 USA  
<sup>340</sup> Indian Institute of Technology Bombay, Powai, Mumbai, Maharashtra 400076, India  
<sup>341</sup> Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126 Pisa, Italy  
<sup>342</sup> Université de Lyon, F-69361 Lyon, France  
<sup>343</sup> Hobart and William Smith Colleges, Geneva, NY 14456, USA  
<sup>344</sup> OzGrav, Swinburne University of Technology, Hawthorn, VIC 3122, Australia  
<sup>345</sup> Janusz Gil Institute of Astronomy, University of Zielona Góra, 65-265 Zielona Góra, Poland  
<sup>346</sup> University of Washington, Seattle, WA 98195, USA  
<sup>347</sup> King’s College London, University of London, London WC2R 2LS, UK  
<sup>348</sup> Indian Institute of Technology, Gandhinagar Ahmedabad Gujarat 382424, India  
<sup>349</sup> Indian Institute of Technology Hyderabad, Sangareddy, Khandi, Telangana 502285, India  
<sup>350</sup> International Institute of Physics, Universidade Federal do Rio Grande do Norte, Natal RN 59078-970, Brazil  
<sup>351</sup> Andrews University, Berrien Springs, MI 49104, USA

- <sup>352</sup> Università di Siena, I-53100 Siena, Italy  
<sup>353</sup> Trinity University, San Antonio, TX 78212, USA  
<sup>354</sup> Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands  
<sup>355</sup> Abilene Christian University, Abilene, TX 79699, USA  
<sup>356</sup> Colorado State University, Fort Collins, CO 80523, USA  
<sup>357</sup> Deceased, 2016 August.  
<sup>358</sup> Deceased, 2017 February.  
<sup>359</sup> Deceased, 2016 December.