



Deep Search for Joint Sources of Gravitational Waves and High-energy Neutrinos with IceCube during the Third Observing Run of LIGO and Virgo

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Abstract

The discovery of joint sources of high-energy neutrinos and gravitational waves has been a primary target for the LIGO, Virgo, KAGRA, and IceCube observatories. The joint detection of high-energy neutrinos and gravitational waves would provide insight into cosmic processes, from the dynamics of compact object mergers and stellar collapses to the mechanisms driving relativistic outflows. The joint detection of multiple cosmic messengers can also elevate the significance of the common observation even when some or all of the constituent messengers are subthreshold, i.e., not significant enough to declare their detection individually. Using data from the LIGO, Virgo, and IceCube observatories, including subthreshold events, we searched for common sources of gravitational waves and high-energy neutrinos during the third observing run of the Advanced LIGO and Advanced Virgo detectors. Our search did not identify significant joint sources. We derive constraints on the rate densities of joint sources. Our results constrain the isotropic neutrino emission from gravitational-wave sources for very high values of the total energy emitted in neutrinos ($>10^{52}$ – 10^{54} erg).

Unified Astronomy Thesaurus concepts: [High energy astrophysics \(739\)](#); [Neutrino astronomy \(1100\)](#); [Gravitational wave astronomy \(675\)](#); [Gravitational wave sources \(677\)](#)

1. Introduction

With the discoveries of new cosmic messengers, multi-messenger astrophysics has become a reality. Astrophysical high-energy (\gtrsim TeV) neutrinos (HENs) were discovered in 2013 (IceCube Collaboration 2013; M. G. Aartsen et al. 2014a) by the IceCube Neutrino Observatory (IceCube; M. Aartsen et al. 2017, 2024). With the gravitational-wave (GW) discoveries by Advanced LIGO (J. Aasi et al. 2015) and Advanced Virgo (F. Acernese et al. 2015), including the detection of binary black hole (BBH) coalescences (B. P. Abbott et al. 2016a, 2016b, 2017a, 2017b) and a binary neutron star (BNS) coalescence in their first two observing runs (B. P. Abbott et al. 2017c, 2019a), a new messenger has become available for multimessenger astronomy. IceCube has been taking data in its full 86-string configuration continuously

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since 2011 (M. G. Aartsen et al. 2017a) overlapping with The LIGO Scientific, Virgo, and KAGRA (LVK) Collaboration (B. P. Abbott et al. 2019b; R. Abbott et al. 2021a, 2024, 2023a; The LIGO Scientific Collaboration et al. 2025a) observing runs, which have included the discovery of 218 probable cosmic compact binary sources. The multimessenger observation of the merging BNS system GW170817 (B. P. Abbott et al. 2017c) established connections between GW sources and emissions in the electromagnetic spectrum from gamma rays to radio (B. P. Abbott et al. 2017d).

What was missing from the observed multimessenger repertoire of GW170817 were HENs, which were expected but not observed (S. Ando et al. 2013; A. Albert et al. 2017a; K. Murase & I. Bartos 2019). HENs are predicted to be emitted from the jets forming after the time of GW emission. These jets are expected to accelerate charged particles, leading to the production of mesons, and the subsequent decay of these mesons should result in the emission of detectable HENs (S. Ando et al. 2013; K. Fang & B. D. Metzger 2017; S. S. Kimura et al. 2018). Consequently the detection of HENs will carry information about the hadronic processes consequent to GW emissions. Short gamma-ray bursts (GRBs) have also been expected from such jets, one of which was observationally confirmed with GW170817. However, despite this expected connection between GRBs and HENs, the searches for HENs coincident with GRBs have not yielded any significant detection. The searches constrained the HEN emission from GRBs, with stricter constraints for long GRBs (M. G. Aartsen et al. 2017b; R. Abbasi et al. 2022a, 2024a, 2024b). The searches for HENs coincident with GWs can also illuminate the GRB–HEN relation better, thanks to the observed connection between BNS mergers and short GRBs.

The large overlap between the LVK observation schedules and the nearly continuous operation of IceCube allows searches for common sources of HENs and GWs. Consequently, multiple searches have been executed, including some before the discovery of astrophysical GWs (S. Adrián-Martínez et al. 2013, 2016; M. G. Aartsen et al. 2014b, 2020a; A. Albert et al. 2017a, 2017b, 2019, 2020; G. De Wasseige et al. 2019; A. Keivani et al. 2019; D. Veske et al. 2022; R. Abbasi et al. 2023a, 2023b). IceCube (R. Abbasi et al. 2026), Super-Kamiokande (K. Abe et al. 2016, 2018, 2021), KamLAND (S. Abe et al. 2021), and Borexino (M. Agostini et al. 2017) also searched for coincident low-energy neutrinos. While successive searches have produced better and better constraints on source populations, the improving quality and growing size of the data did not result in a confident multimessenger discovery with neutrinos and GWs together.

With the growing interest in such searches (S. Ando et al. 2013) and their results (A. Keivani et al. 2021), methodology (Y. Aso et al. 2008; V. van Elewyck et al. 2009; I. Bartos et al. 2011, 2019; B. Baret et al. 2012; S. Countryman et al. 2019; D. Veske et al. 2020, 2021; Z. Marka et al. 2022) and theory have progressed (S. S. Kimura et al. 2018; K. Fang et al. 2019; O. de Bruijn et al. 2020; D. Guetta et al. 2020), forming a firm foundation for the comprehensive search for common sources of the GWs and HENs we describe in this paper.

Cosmic phenomena accompanied by accretion can cause acceleration of hadrons. HENs can provide information about the acceleration mechanisms and their environments (F. Halzen & D. Hooper 2002; S. Razzaque et al. 2003;

A. Loeb & E. Waxman 2006; I. Bartos et al. 2012). Indeed, IceCube observed neutrinos from a range of origins, including a diffuse flux potentially with unresolved point sources (M. G. Aartsen et al. 2013; IceCube Collaboration 2013), the blazar TXS 0506+056 (A. Albert et al. 2018; IceCube Collaboration et al. 2018; A. Keivani et al. 2018), the active galaxy NGC 1068 (R. Abbasi et al. 2022b), and from the Milky Way (R. Abbasi et al. 2023c). However, the majority of observed IceCube cosmic neutrinos are not associated with any identified source. This motivates studies which focus on neutrino emission from observable and well-characterizable sources, such as GW sources.

Discovery and observation of joint sources of HENs and GWs will have a multifold impact, including a better understanding of emitter physics, source localization, and messenger characterization (S. Ando et al. 2013; K. Fang & B. D. Metzger 2017; S. S. Kimura et al. 2018). A coincident detection with a GW event can shed light on the jet physics involved. For example, a coincidence without a gamma-ray counterpart in a BNS merger can indicate the presence of a choked jet. In addition there are different estimations for the jet energetics. Searches for joint emissions constrain possible jet characteristics with or without detections. HEN observations can also significantly constrain the sky localization of joint events, greatly decreasing the cost of follow-up searches with narrow field-of-view instruments. For example, IceCube sky location reconstruction for charged-current ν_μ interactions typically has an angular uncertainty $\lesssim 1^\circ$ (M. G. Aartsen et al. 2020b), much smaller than tens to hundreds, or even thousands, of square degrees that are normal for GW sky localizations (B. P. Abbott et al. 2020). Consequently, joint MM observations can constrict the sky localization of the observed events, making further follow-ups much more feasible.

The current wealth of multimessenger data provides the opportunity for statistically refined searches (D. Veske et al. 2021) aimed at identifying common cosmic sources of GWs and HENs. In this article, we describe a comprehensive archival search for HEN emission from GW candidates observed during the entirety of the Advanced LIGO and Advanced Virgo detectors’ third observing run (O3), including subthreshold event candidates, i.e., candidate events with higher false alarm rates than in catalogs. This search complements the previous searches and represents the most sensitive offline search done for joint emission of HEN and GW events, using a more extended dataset including data from a more sensitive run of the GW detectors. Having summarized the state of the field, we continue in Section 2 where we describe the IceCube detector and the specific neutrino data that are used in our analysis. In Section 3, we describe the GW detectors and the GW data. In Section 4, we present the core concepts and distinctive aspects of our search methodology, implemented through the LLAMA analysis software (S. Countryman et al. 2019), while also pointing to more intricate methodological discussions in previous works (e.g., I. Bartos et al. 2019; M. G. Aartsen et al. 2020a; D. Veske et al. 2021). Section 5 presents the outcomes of our search. Finally, in Section 6, we contextualize our findings and offer perspectives on future directions in this field.

2. The IceCube High-energy Neutrino Detector and Its Data

IceCube is positioned at the geographic South Pole in Antarctica, utilizing a cubic kilometer of clear ice for its detection medium (M. G. Aartsen et al. 2017a). The IceCube Collaboration has deployed 5160 optical modules distributed across 86 vertical strings, to observe the depths of Antarctic ice between 1500 and 2500 m. The main sensors within the optical modules are photomultiplier tubes designed to capture Cherenkov light emission resulting from the interactions of neutrinos within the ice.

IceCube neutrino events can be broadly categorized as tracks and cascades. Tracks are events where muons or antimuons traverse a linear trajectory, leaving a trail of detected Cherenkov light in their path. Atmospheric muons and atmospheric muon neutrinos are the major sources of background contamination for the set of astrophysical neutrino induced tracks events. Cascades refer to showers occurring in the ice, originating from charged-current interactions of electron neutrinos or neutral-current interactions. These event topologies have different relevance for multimessenger searches depending on their different directional accuracy on the sky. For tracks, the typical reconstruction accuracy is $\lesssim 1^\circ$ (M. G. Aartsen et al. 2020b), whereas for cascades it is $\gtrsim 10^\circ$. In this search, we use tracks-based neutrino triggers due to their better localization which is crucial for multimessenger astronomy.

IceCube maintains a duty cycle exceeding 99% and can observe neutrinos from the entire sky (A. Pizzuto et al. 2021). IceCube data based on muon tracks consist primarily of background signals from muons and neutrinos originating in the Earth's atmosphere. The background in the Northern Hemisphere primarily comprises atmospheric neutrinos, while in the Southern Hemisphere, atmospheric muons predominate. As a result, the detector has less background in the Northern Hemisphere and the energy threshold for the detection of tracks in the Northern Hemisphere can be kept significantly lower ($\mathcal{O}(1)$ TeV) than that in the Southern Hemisphere ($\mathcal{O}(100)$ TeV).

The data analysis presented here relies on low-latency (~ 30 s) event reconstruction, facilitating timely multimessenger follow-up endeavors to IceCube events, known as the Gamma-ray Follow-Up (GFU) data stream (IceCube Collaboration et al. 2016; T. Kintscher & the IceCube Collaboration 2016; E. Blaufuss et al. 2019). GFU events are well-reconstructed tracks, which enable precise sky localization essential for effective collaborative astrophysics with electromagnetic observatories. Although the low-latency property is not relevant for this article, the LLAMA pipeline has also been used in real-time searches for coincident GW and HEN events, and in that case the low latency is crucial (A. Keivani et al. 2019).

The analysis presented is based on a considerably larger number of candidate cosmic HEN events compared to the number of GW candidates, in average ~ 6.4 neutrinos in the search time window of each candidate GW event.

3. Gravitational-wave Detectors and Their Data

The LIGO and Virgo detectors (J. Aasi et al. 2015; F. Acernese et al. 2015) are Michelson-type interferometers spanning multiple kilometers. LIGO has two nearly identical

detectors, separated by 3000 km, situated in Hanford, Washington and in Livingston, Louisiana within the US. Virgo operates a single detector located in Cascina, Italy.

On 2019 April 1, the LIGO and Virgo detectors commenced O3, which was divided into two periods. The initial part (O3a) encompassed the period from 2019 April to September, while the second part (O3b) spanned 2019 November to 2020 March. Over the course of O3, the GW detectors amassed datasets of unprecedented size and quality at the time (A. Buikema et al. 2020; R. Abbott et al. 2021a, 2023a; F. Acernese et al. 2023), with the GW strain data now being publicly accessible (R. Abbott et al. 2023b).

Not every IceCube GFU candidate coincided with GW detector observations as their duty factors were lower during O3 than IceCube's. For the first half of O3 they were 71% for Hanford, 76% for Livingston, and 76% for Virgo; in the second half of the run, they were 79%, 79%, and 76%, respectively (D. Davis et al. 2021). The cosmic reaches of the Hanford, Livingston, and Virgo detectors remained comparable during the first and second parts of O3: 108 Mpc, 135 Mpc, and 45 Mpc of BNS inspiral range (L. S. Finn & D. F. Chernoff 1993; H.-Y. Chen et al. 2021) versus 115 Mpc, 133 Mpc, and 51 Mpc, respectively (R. Abbott et al. 2023b).

The optimal joint treatment of events from IceCube, LIGO, and Virgo in the analysis relies on the localizations of both neutrinos and GWs detected by the network. Given the better accuracy of neutrino localization compared to GW localization, this approach significantly enhances the sky-localization potential for joint multimessenger candidates to $\mathcal{O}(1)$ deg², beyond the localization capabilities of the GW network alone ($\mathcal{O}(10\text{--}1000)$ deg²), presenting new opportunities for electromagnetic observations in low latency or using archival data.

The analysis presented relies on GW candidates, having a false alarm rate below 2 day^{-1} from GWTC-2.1 (The LIGO Scientific Collaboration et al. 2021b) and GWTC-3.0 (The LIGO Scientific Collaboration et al. 2021a). Most of these events are subthreshold compared to the conventional thresholds for confident detections, such as having an estimated probability of astrophysical origin (p_{astro}) greater than 0.5 (R. Abbott et al. 2023a, 2024).

We consider events from three template-based searches using compact binary coalescence (CBC) waveforms (R. Abbott et al. 2023a) commonly used by LVK: GstLAL (C. Messick et al. 2017; S. Sachdev et al. 2019; C. Hanna et al. 2020; K. Cannon et al. 2021), Multi-Band Template Analysis (T. Adams et al. 2016; F. Aubin et al. 2021), and PyCBC (B. Allen 2005; B. Allen et al. 2012; T. Dal Canton et al. 2014; S. A. Usman et al. 2016; A. H. Nitz et al. 2017; G. S. Davies et al. 2020). The latter was implemented in two versions, PyCBC-broad and PyCBC-BBH.

A total of 2210 GW candidates from CBC searches are used here in the joint GW + HEN analysis. This set includes the 79 CBC candidates confidently identified by at least one of the template-based searches with a p_{astro} greater than 0.5, of which 10%–15% may be contamination from triggers of terrestrial origin (R. Abbott et al. 2023a). When a CBC trigger appeared in the candidate lists of multiple pipelines, the metadata (localization, p_{astro} , etc.) associated with the pipeline having the highest probability of astrophysical origin was used in the joint analysis.

A total of 481 nonpublic candidates from the all-sky search for generic GW bursts from O3 (R. Abbott et al. 2021b) were

also selected for joint analyses. The selected triggers were produced by the coherent Wave Burst (cWB) search pipeline (S. Klimenko et al. 2016; M. Drago et al. 2021), specifically designed to find candidates without explicit model prediction. The cWB pipeline, even in its generic all-sky mode, is capable of finding some of the CBC triggers (R. Abbott et al. 2021b, 2023a). We are using cWB-allsky triggers with selection criteria based on the correlation coefficient (S. Klimenko et al. 2016), which quantifies the relative proportion of the coherent energy in the detector network’s data, requiring it to be greater than 0.8 for Hanford–Livingston detections and greater than 0.5 for Hanford–Virgo and Livingston–Virgo detections (R. Abbott et al. 2021b). For the cases of selected Hanford–Livingston candidates where Virgo data were also available, we produced the three-detector localizations dedicated for the analysis presented here, as source localization overlap is a deciding factor in multimessenger searches.

4. Methodology

Our analysis has two parts. First, we analyze the GW triggers one by one and find the HEN coincidence significance for each of them. Second, we evaluate them collectively to learn about the astrophysical population of jointly GW- and HEN-emitting sources.

4.1. Analysis of Individual Events

Previous studies of joint sources of GWs and HENs using subthreshold trigger sets from both types of messengers during the initial GW detectors era and the first observing run of Advanced LIGO (Y. Aso et al. 2008; V. van Elewyck et al. 2009; I. Bartos et al. 2011; B. Baret et al. 2012; S. Adrián-Martínez et al. 2013; S. Ando et al. 2013; M. G. Aartsen et al. 2014b; A. Albert et al. 2019) employed likelihood methods. The analysis presented here employs the LLAMA pipeline (S. Countryman et al. 2019), which was previously used for neutrino follow-up of confident GW candidates (M. G. Aartsen et al. 2020a; D. Veske et al. 2022; R. Abbasi et al. 2023a). The LLAMA pipeline uses an optimal model-dependent method (I. Bartos et al. 2019) for GW + HEN searches. LLAMA uses prior probabilities informed by astrophysics and detector characteristics to combine several hypotheses optimally for a physical model and reduces the problem to a simple test of two hypotheses. The odds ratio of having a multimessenger detection or not becomes the optimal test statistic (TS) for the physically motivated model.

Our priors are on the distribution of the source parameters $\theta = \{D_L, \Omega_s, t_s, E_{\text{GW}}, E_\nu\}$, which are the luminosity distance of the source D_L ($\propto D_L^2$ prior distribution up to the GW detection range), its sky position Ω_s (uniform prior distribution over the sky), the reference time for the astrophysical event t_s (uniform distribution in the observing period), and the isotropic equivalent emission energies in GWs E_{GW} and in HENs E_ν . Beyond solving the optimal testing problem, the use of assumed emission energies also allows the use of the distance information from GW triggers optimally, which further increases the statistical power of the search (I. Bartos et al. 2019). For GWs, the emission energies (log uniform distribution in $[10^{-1}, 10^1] M_\odot c^2$) were chosen by considering the released energies in CBCs that have a total mass between $2 M_\odot$ and $200 M_\odot$.

Short GRBs produced in BNS mergers are the most promising known high-energy emission mechanism for

coincident GW and HEN detection, where the energy emitted in HENs is expected to be comparable with the energy emitted in gamma rays (S. S. Kimura et al. 2017; D. Biehl et al. 2018; K. Murase & I. Bartos 2019). Consequently, the HEN emission energies (log uniform distribution in $[10^{46}, 10^{51}]$ erg) were chosen according to an empirical distribution of short GRB photon emission energies (E. Berger 2014). We assume the differential number density of the neutrino emission energy spectrum is a power law with an exponent of -2 , which is expected for neutrinos from cosmic rays accelerated by Fermi acceleration (L. O. Drury 1983; N. Kurahashi et al. 2022).

Although searches for HENs coincident with GRBs have not yielded any detection (S. Ando et al. 2013; K. Fang & B. D. Metzger 2017; S. S. Kimura et al. 2018), a potential correlation between GWs and HENs may still be explained through the GRB connection. As neutrino emission is less confined by beaming or opacity, a neutrino observed in coincidence with a neutron star merger would indicate an off-axis, electromagnetically obscured, or failed GRB source.

Our observational inputs (x) from the GW side are the localization, candidate event detection time, signal-to-noise ratio (ρ), and for template-based searches source distance information and p_{astro} . From the neutrino detector side, the inputs are the reconstructed time of arrival, energy proxy (related to the energy deposited in the detector), direction, and angular uncertainty of the HENs.

The standard prompt search time window is ± 500 s and was established on the assumption of a GRB source model (B. Baret et al. 2011). Our signal likelihood is a maximum when there is no time difference between the neutrino and the GW candidate, and it decreases to zero linearly as the time difference approaches ± 500 s. We evaluate all of the neutrino candidates coincident with the GW trigger within this time window together.

Our analysis is based on testing a signal hypothesis H_s : the GW and at least one HEN come from the same astrophysical source, against multiple background hypotheses: both the GW and HENs are noise originated (H_n), the GW is astrophysical while all HENs are noise originated (H_c^{GW}), i.e., atmospheric muons or neutrinos, and finally the GW is noise originated and a HEN is astrophysical (H_c^ν). Other very low probability occurrences (about 2 orders of magnitude less probable than the aforementioned cases), which include more than one astrophysical but unrelated messengers (i.e., a GW coming from an astrophysical event and a neutrino coming from a separate astrophysical event), are ignored. In the case of HENs, noise refers to atmospheric muons or neutrinos. We combine the background hypotheses by using their prior probabilities, which were calculated using our assumed source parameters and detector characteristics. Our TS is

$$\text{TS}(x) = \frac{P(x|H_s)P(H_s)}{P(x|H_n)P(H_n) + P(x|H_c^{\text{GW}})P(H_c^{\text{GW}}) + P(x|H_c^\nu)P(H_c^\nu)}. \quad (1)$$

The prior probability of H_s is an overall constant in the TS and does not affect any of our results.

The analysis presented here differs from previous analyses with LLAMA (M. G. Aartsen et al. 2020a; D. Veske et al. 2022; R. Abbasi et al. 2023a) where we used only confident detections of GWs (e.g., $p_{\text{astro}} > 0.5$) and thus the first and third terms in the denominator of Equation (1) were taken as zero. The original analysis method in I. Bartos et al. (2019) is suitable for analyses with confident or subthreshold GW triggers, where only ρ was used to estimate the signalness of

the GW candidates. Here we improve it for the triggers of the template-based searches by using an additional input: $p_{\text{terr}} = 1 - p_{\text{astro}}$, which is the estimated probability of terrestrial origin for the GW triggers. For these triggers, we modify the way we calculate the joint probability density of noise origin for GWs and signal-to-noise ratio as

$$P(\rho, \text{GW noise}) = P(\rho)P(\text{GW noise}|\rho) = \left[\frac{P(\rho|\text{GW noise})R_{\text{bgGW}} + 3\rho_{\text{min}}^3/\rho^4(4\pi D_{L-\text{max}}^3 \dot{n}_{\text{GW}\nu}/3)}{R_{\text{bgGW}} + 4\pi D_{L-\text{max}}^3 \dot{n}_{\text{GW}\nu}/3} \right] \times p_{\text{terr}}. \quad (2)$$

Here we used $P(\text{GW noise}|\rho) = p_{\text{terr}}$. The expression in the square brackets is $P(\rho)$. Here R_{bgGW} is the rate of GW background triggers, $\dot{n}_{\text{GW}\nu}$ is the rate density of astrophysical multimessenger emitting events, and $D_{L-\text{max}}$ is the horizon distance of the GW detectors for the minimum signal-to-noise ratio in our dataset $\rho_{\text{min}} \approx 5.6$. We take $\dot{n}_{\text{GW}\nu}$ constant as $23.9 \text{ Gpc}^{-3} \text{ yr}^{-1}$, which is the most recent estimate of the local rate density of BBH mergers (R. Abbott et al. 2023c) that make up the most of the detections. For this calculation only, we ignore cosmological expansion for simplicity, which may have a minuscule negative effect on the statistical power of the search, but it does not have a direct effect on our physical inferences otherwise. The probability $P(\rho)$ is estimated by using the conditional distributions of ρ when the GW candidate is of noise or astrophysical origins, and the two scenarios' expected relative frequencies. The conditional distributions are $P(\rho|\text{GW noise})$ and $3\rho_{\text{min}}^3\rho^{-4}$, respectively, for noise and astrophysical origins. While the former is estimated empirically, the latter can be derived assuming homogeneously distributed sources that are detected according to a ρ threshold (B. F. Schutz 2011). The relative frequencies are proportional to R_{bgGW} and $(4/3)\pi D_{L-\text{max}}^3 \dot{n}_{\text{GW}\nu}$.

In order to evaluate the significance of each joint candidate, we use the Bayesian odds ratio in Equation (1) as a TS. We find the frequentist significance by comparing the odds ratio for each event to a distribution built empirically using background data and simulations. Coincidences are simulated by randomly matching neutrinos from the GFU stream and the GW trigger events we analyze at the detection rate of the GFU stream (6.4 neutrino triggers per GW trigger on average in 1000 s of search window). We use different background distributions for CBC and cWB triggers.

4.2. Population Analysis

The individual analysis described above can uncover individual events that become high significance once GW and neutrino information is combined. We carried out a separate population analysis that combines significances from multiple events and aims to find an excess significance from the whole dataset to examine the presence of a joint emission from any of the events. In this case, even if no individual event is sufficiently significant to claim a discovery, we can statistically infer the presence of a signal by finding that the significance distribution shows an excess of high-significance events compared to what would be expected from background.

For our population study we constructed a new TS, TS_{pop} (Equation (3)), because the new question we would like to answer now is whether there are any detections in the dataset or not. When the a priori expected number of multimessenger

events in the dataset is low, the optimal TS is equivalent to the sum of the individual TSs from the individual observations. Hence, we construct TS_{pop} as the sum of the test statistics of the analyzed events. Here, a single event should be understood as the combination of neutrinos within the search time window with a GW candidate. The sum is over all such combinations in the whole observation run:

$$\text{TS}_{\text{pop}} = \sum_i \text{TS}(\mathbf{x}_i). \quad (3)$$

While such a population study does not identify specific joint events as significant, it has more power to test whether there are such events in the dataset. It can be thought of as a more efficient trials correction that uses all the information in the whole dataset.

The p -value of this analysis was found by constructing an appropriate background distribution. This was done by repeatedly sampling events from our previously generated background events as many as the analyzed events (2210 for CBC and 481 for cWB) and summing their TSs.

In order to constrain the rate density of joint GW + HEN emitters, we need to characterize the behavior of the new TS when there are different numbers of multimessenger events in the dataset. For this, we injected simulated multimessenger signals to the background event set and created TS_{pop} distributions with different numbers of simulated MM events (0, 1, 2, ...). These essentially differ from the zero multimessenger event case by the individual TS of the extra multimessenger events. In order to create such multimessenger events we artificially injected a GW signal and a neutrino from the same source location. For this we simulate GW events and combine them with neutrinos.

The additional subthreshold GW events were generated by injection simulations using BAYESTAR (L. P. Singer & L. R. Price 2016; L. P. Singer et al. 2016). We simulated GW events using the properties of the LIGO and Virgo detectors and taking into account the properties of the observed populations for each detector combination during O3 (R. Abbott et al. 2023a). For each source type of BNS, neutron star–black hole (NSBH) binaries, and BBH, we performed randomized injections for the corresponding source populations' parameter (mass, spin, sky position, inclination, and distance) distributions, calculated the signal-to-noise ratio, and generated the corresponding localizations considering a network of at least two detectors. The POWERLAW + PEAK model (C. Talbot & E. Thrane 2018) with the median estimations of the parameters from the analysis of GWTC-3.0 (R. Abbott et al. 2023c) was used for the mass distribution of the injected BBH mergers. For neutron stars, we used $1.4 M_{\odot}$. With the insufficient observational preference for the mass distribution of NSBH binaries, we simply drew the black hole masses from the primary mass distribution of the BBH mergers and the neutron star masses as $1.4 M_{\odot}$. For the simulated GW events we assigned p_{astro} values by using the public injection set for GW detection pipelines (The LIGO Scientific Collaboration et al. 2023). We found the injection in that dataset that has the most similar parameters to the parameters of our injections, for each of our injections, and assigned the same p_{astro} value. This is done by defining a unitless statistic that quantifies the similarity of the events based on the product of the differences in the parameters (χ_{eff} spin parameter, chirp mass, luminosity distance, and the sky

position in the detector frame) scaled by the expected measurement uncertainties.

The background neutrinos for each injected GW signal are drawn from the scrambled GFU sample. The 90% central energy range of the GFU sample ranges from 500 GeV – 50 PeV, assuming a source with an ϵ^{-2} spectrum. This simple spectrum can be viewed as a nominal spectrum without the complicated different structures predicted in theoretical studies, and we generate signal neutrinos assuming this spectrum for the differential number density. We inject one Monte Carlo-generated signal neutrino corresponding to the injection sky-localization position of the signal GW event.

The population upper limit at a confidence level (CL) then can be found by the standard Neyman’s construction (J. Neyman 1937) by requiring the probability of having TS_{pop} for the same sample size containing injected MM signal (s) being higher than the observed TS_{pop} to be CL or higher.

The upper limit on the multimessenger (MM) rate density $\dot{n}_{\text{GW}\nu}$, depending on the neutrino emission energy E_ν and the GW source type (\mathcal{S} , e.g., BNS, NSBH, and BBH) can be calculated as

$$P(\text{TS}_{\text{pop}} > \text{TS}_{\text{pop}}^{\text{observed}} | E_\nu, \mathcal{S}, \dot{n}_{\text{GW}\nu}) = \sum_{\#_{\text{MM}}=0}^{\text{No of obs. GW events}} P(\text{TS}_{\text{pop}} > \text{TS}_{\text{pop}}^{\text{observed}} | \mathcal{S}, \#_{\text{MM}}) P(\#_{\text{MM}} | E_\nu, \mathcal{S}, \dot{n}_{\text{GW}\nu}) = \text{CL}, \quad (4)$$

where the sum is over the MM event count in the dataset ($\#_{\text{MM}}$) whose occurrence probability is

$$P(\#_{\text{MM}} | E_\nu, \mathcal{S}, \dot{n}_{\text{GW}\nu}) = \text{Poisson}(\#_{\text{MM}}, \text{Mean} = \dot{n}_{\text{GW}\nu} \times T_{\text{obs}} \int 2\pi f(D_L, z) p_{\text{det}}^\nu(E_\nu, D_L, \delta) p_{\text{det}}^{\text{GW}}(\mathcal{S}, D_L) \cos \delta d\delta dD_L), \quad (5)$$

where $p_{\text{det}}^\nu(E_\nu, D_L, \delta)$ and $p_{\text{det}}^{\text{GW}}(\mathcal{S}, D_L)$ are the detection probabilities of neutrinos and GWs, respectively, from an event with total neutrino emission energy E_ν and the specific GW event type \mathcal{S} , as a function of luminosity distance D_L , and declination (δ). The total observation time is represented by T_{obs} , $\text{Poisson}(a, \text{Mean} = b) = b^a e^{-b}/a!$ is the probability of a Poisson point process for a happened events with mean b , while $f(D_L, z)$ gives the distribution of MM events as a function of distance and redshift z . Considering cosmological expansion:

$$f(D_L, z) = (1+z)^{-1} \frac{dV_c}{dD_L} = \frac{c}{(1+z)^3 H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}} \frac{dz}{dD_L} D_L^2, \quad (6)$$

assuming a constant rate in comoving volume V_c where c is the speed of light, $H_0 = 67.9 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is the Hubble constant, $\Omega_m = 0.3065$, and $\Omega_\Lambda = 0.6935$ are the energy densities of matter and cosmological constant (Planck Collaboration et al. 2016). We find $p_{\text{det}}^{\text{GW}}(\mathcal{S}, D_L)$ by calculating the detection fraction of our injected GW events as a function of their distance for different source types, averaged over their remaining properties including their sky positions. The sky averaging is a sensible approximation as the GW detection

probability would have a mild dependency on the sky location after averaging only over the Earth’s rotational motion. On the other hand, the detection probability of neutrinos has a strong dependency on the declination after being averaged only over the Earth’s rotational motion. Therefore its declination-dependent form was used, which is the Poisson probability of observing at least one neutrino. The mean number of detected neutrinos for this Poisson probability is expressible in terms of the effective area of the detector A_{eff} and the isotropically equivalent emitted energy in neutrinos (E_{iso}) as

$$\langle n_\nu \rangle (E_{\text{iso}}, D_L, \delta) = \frac{1}{3} \frac{E_{\text{iso}}}{4\pi D_L^2 \ln(\epsilon_{\text{max}}/\epsilon_{\text{min}})} \times \int \frac{A_{\text{eff}}(\epsilon, \delta)}{\epsilon^2} d\epsilon, \quad (7)$$

where the ratio of the limits of the relevant energy range is $\epsilon_{\text{max}}/\epsilon_{\text{min}} \approx 10^6$, the factor of 1/3 accounts for the fact that only one-third of the astrophysical HENs are expected to be muon neutrinos (H. Athar et al. 2006; S. Pakvasa et al. 2008), and we assumed an ϵ^{-2} spectrum for the emitted neutrino number density (see also Equation (3) in M. G. Aartsen et al. 2020a). For isotropic emissions, isotropically equivalent emission energy is equal to the total emitted energy: $E_{\text{iso}} = E_\nu$. For beamed emissions with beaming factor f_{beam} , $E_{\text{iso}} = f_{\text{beam}} E_\nu$ within the emission cone and zero outside. With these we can write the probability of detecting neutrinos as

$$p_{\text{det}}^\nu(E_\nu, D_L, \delta) = 1 - \exp(-\langle n_\nu \rangle (E_\nu, D_L, \delta)). \quad (8)$$

5. Results

5.1. Individual p -values

There are on average 6.4 GFU track neutrinos within any 1000 s time segment in our data. Of the 2210 CBC candidate events, five did not have coincident neutrinos within the ± 500 s search time window around the GW trigger time, resulting in individual p -values of one for each of these events. Altogether 14,491 time-coincident neutrino tracks were identified and analyzed under a joint source hypothesis; none of them had a sufficiently high significance to claim a detection considering the number of analyzed GW triggers.

The lowest p -value candidate, presented in Figure 1, has an individual p -value of 3.8×10^{-4} (0.84 posttrials after multiplying by the number of analyzed events). The GW trigger is likely to be of terrestrial origin ($p_{\text{terr}} = 0.997$), but would be classified as a BNS candidate if it were an astrophysical signal. Coincident neutrino number 6, which produces most of the significance, has a reconstructed energy of 2.4 TeV. Its sky position is right above the equator, corresponding to the high-sensitivity declination region of the IceCube detector, while its energy is not particularly outstanding from the expected background. The reconstructed mean localization distance for the GW candidate’s source is 295 Mpc. The GW trigger occurred 222 s after the arrival time of neutrino number 6.

The cumulative distribution of all of the p -values for CBC candidates is shown in Figure 2. It is consistent with a uniform p -value distribution, which is expected in the absence of any joint emission. The Kolmogorov–Smirnov test p -value when

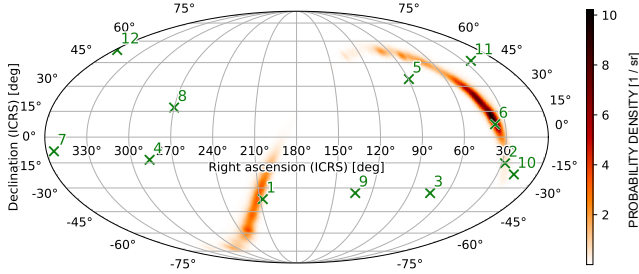


Figure 1. Joint sky localization showing all neutrino candidates coincident with a GW BNS candidate at GPS time = 1262142545.615. Neutrino number 6 gives the dominant contribution to the significance.

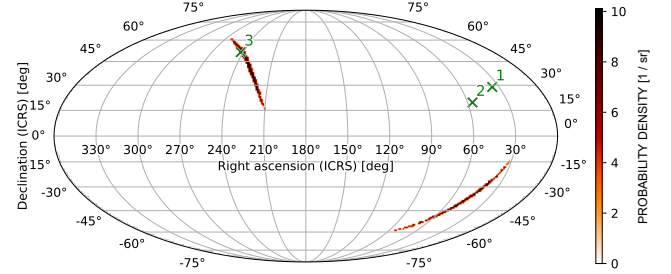


Figure 3. Joint sky localization showing all neutrino candidates coincident with a GW burst candidate at GPS time = 1241247887.938. Neutrino number 3 gives the dominant contribution to the significance.

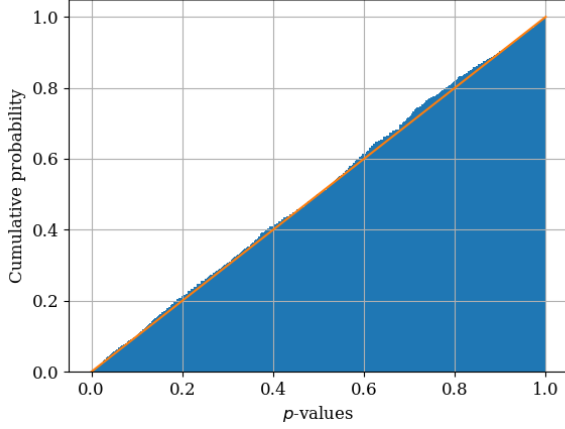


Figure 2. Cumulative distribution of the p -values from the CBC part of the analysis. The orange line is a reference for a uniform distribution.

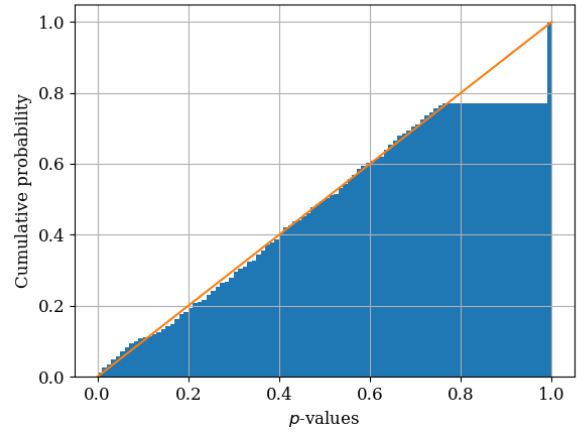


Figure 4. Cumulative distribution of the p -values from the cWB part of the analysis. The orange line is a reference for a uniform distribution. The discrete behavior at the right side is due to cWB sky localizations not having smooth probability distributions, most of the sky possessing exactly zero probability.

comparing to a uniform distribution is 0.05, which is consistent with the expectation from background.

For cWB events, we similarly did not have a sufficiently high-significance case to claim a joint detection considering the number of analyzed triggers. The lowest p -value candidate, with an individual p -value of 4.3×10^{-4} (0.21 posttrials after multiplying by the number of analyzed events), is shown in Figure 3. Coincident neutrino number 3, which produces most of the significance, has a reconstructed energy of 2.3 TeV. It was detected 154 s after the GW trigger.

The cumulative distribution of all of the p -values of the cWB part of the analysis is shown in Figure 4. It is consistent with a uniform p -value distribution with a discrete behavior at high p -values. This discrete behavior is caused by cWB sky localizations not containing low probability densities below a certain threshold, which causes nonsmooth distributions. The Kolmogorov–Smirnov test p -value is 0.67 in comparison with a uniform distribution with a similar discrete behavior.

We provide the properties of the neutrino triggers that produce individual p -values of 0.01 or less in Table 1 in the Appendix.

5.2. Population Constraints

When the whole dataset was analyzed collectively, we obtained a p -value of 0.22 for CBC triggers and 0.18 for cWB triggers. Consequently, we conclude that there is no significant sign of joint detection of GW and HEN in our dataset. We obtained frequentist 90% upper limits for the rate density of multimessenger events related to CBC triggers, assuming a

homogeneous distribution in comoving volume. HEN emission from CBC sources is expected to be beamed. We calculate different limits assuming an isotropic neutrino emission and a beamed emission with a beaming factor of $f_{\text{beam}} \sim 100$ (W. Fong et al. 2015). We find the limits for different time-integrated bolometric neutrino emission luminosities (total E_ν), which are assumed to be the same for all GW events. For the beamed emission we assume the total energy to be concentrated in a solid angle of $4\pi/f_{\text{beam}}$, directed isotropically without considering correlations with the GW emission geometry. This is a conservative assumption as the beamed jets are predicted to be directed along the orbital axis of the binaries along which the GW emission is also more powerful.

The limits on the GW + HEN source population are shown in Figure 5 together with the estimated 90% credible intervals of the rate densities of different CBC sources (R. Abbott et al. 2023c). We show the BBH rate density at $z = 0.2$, based on a model in which the BBH rate density evolves as $(1+z)^\kappa$ with an estimated $\kappa = 2.9^{+1.7}_{-1.8}$. For any of our GW + HEN limits we do not assume such a redshift evolution. Since the observed sources are all below $z \lesssim 1$, this modeling difference can bring at most $\mathcal{O}(1)$ variations to the compared BBH rate, which would not change our conclusions substantially. We can constrain any HEN emission from a GW source if our derived upper limits lie below the estimated rate density of GW sources. However, the upper limits at 90% CL and the 90% credible intervals can only be compared with the caveat that one is a frequentist concept and the other a Bayesian one.

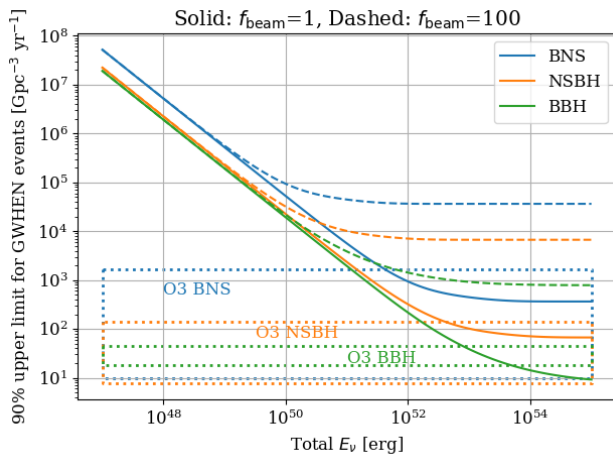


Figure 5. 90% upper limits on the GW + HEN source population for different CBC source types as a function of the total neutrino emission energy from each source. We assume identical neutrino emission characteristics for sources with an ϵ^{-2} spectrum. The GW-related properties are according to the injections, which were guided by the O3 inferences (R. Abbott et al. 2023c). The upper limits are shown for isotropic neutrino emission with solid lines and for a beamed emission with a beaming factor of 100 with the dashed lines. The rectangular regions described by dotted lines correspond to the estimated rate densities of the corresponding GW sources after O3 with 90% credibility (R. Abbott et al. 2023c).

The 90% CL population upper limits assume neutrino emission with an ϵ^{-2} spectrum between 100 GeV and 100 PeV. The energy bounds of the spectrum were chosen according to the sensitivity of IceCube to track events as in previous analyses (M. G. Aartsen et al. 2020a; R. Abbasi et al. 2023a). Although these bounds can vary from model to model, the multimessenger upper limits weakly depend on these bounds as they enter the calculation only logarithmically (Equation (7)) for an ϵ^{-2} spectrum.

Even our most stringent joint source population upper limit shows that neutrino emission from GW sources can only be constrained at very high neutrino emission energies (time-integrated bolometric luminosity $> 10^{52}$ – 10^{54} erg) with isotropic emission. These energies can be compared with the beaming-corrected most energetic short GRB energies of $\sim 10^{51}$ erg (E. Berger 2014). For beamed neutrino emissions or lower total neutrino emission energies, which correspond to typical GRB emission characteristics, the upper limits on the joint source rate densities lie above the estimated rate densities of GW sources; hence they do not constrain the joint emission from GW sources. The limits of beamed emissions remain higher compared to isotropic emission at high neutrino emission energies as the fact that there is a limited solid angle of emission also bounds the chance of neutrino observation independent of the emission strength. The 90% upper limits that converge at the higher end of neutrino emission energies are set by the detection capabilities of the GW detectors, since a sufficiently high number of neutrinos can be detected from such energetic emissions, and neutrino detection from a joint emission would not be constraining. That is also mostly the reason why limits for BBH mergers reach lower values compared to BNS and NSBH mergers, as BBH mergers are detected by LIGO and Virgo much more easily due to the higher amplitude of emitted GW waves in the detectors’ sensitive frequency band. On the other hand, for lower neutrino emission energies, the upper limits are set by the neutrino detection capabilities. These upper limits present the

first constraints on the HEN emission from the population of CBCs. Previous constraints have been placed using only candidate GW bursts from the first observing run of Advanced LIGO (A. Albert et al. 2019).

In the context of the short GRB source population, we note that the rate of observable (on-axis) GRBs is estimated to be around 1% of the O3 BNS rate shown on Figure 5. While no HENs were observed in coincidence with a detected GRB, there is still room for observable neutrino emission from neutron star binary mergers through off-axis emission or from electromagnetically opaque environments. The GW + HEN population limits presented here starts to chart that territory.

6. Conclusion and Outlook

The discovery and multimessenger observation of cosmic sources involving HENs and GWs hold the potential to shed light on the origin of the highest-energy neutrinos and cosmic rays, reveal high-energy emission from GW engines, enable more effective electromagnetic follow-up efforts, and enhance our understanding of source dynamics. A detailed examination of the O3 data and coincident IceCube event candidates has significantly expanded the analyzed dataset, thereby facilitating a new search.

An LLAMA analysis, employing a model-dependent statistically optimal approach, was applied to all subthreshold GW candidates within the O3 catalogs and all time-coincident IceCube event candidates. We searched for neutrino emission within a ± 500 s time window centered around each GW merger time. No significant neutrino emission was observed during the search for individual GW candidates. The intersections of the coinciding sky localizations showed the potential effectiveness of multimessenger searches in guiding the observing strategies of electromagnetic observatories by significantly reducing the area that needs to be scanned by telescopes.

The absence of a GW + HEN definitive detection resulted in constraints on the population of cosmic multimessenger sources, involving both GWs and neutrinos. These limits can constrain the fraction of HEN-emitting GW sources only at very high neutrino emission energies and for isotropic emission. This implies that the joint detection of GWs and HENs is mainly limited by the neutrino detection capabilities, providing additional motivations for the next generation of neutrino detectors. We expect enhanced chances for the joint detection of GWs and HENs, and improvements for such analyses with the development of the next-generation neutrino detectors.

The fourth observing run of LVK (O4) is ongoing, with improved sensitivity (S. Soni et al. 2025; Virgo Collaboration 2025). Beyond the confirmed 128 CBC mergers identified with $p_{\text{astro}} \geq 0.5$ and thousands of subthreshold candidates from the first portion of O4 (The LIGO Scientific Collaboration et al. 2025a), there are already additional hundreds of significant mergers and subthreshold candidates to investigate for joint emission with neutrinos that were identified in low latency (The LIGO Scientific et al. 2025; The LIGO Scientific Collaboration et al. 2025a). Real-time multimessenger searches involving HENs and GWs are currently operational on both confident and subthreshold GW candidates collected during O4. The successful operation of O4 (The LIGO Scientific Collaboration et al. 2025b) showcases improved performance, consequently expanding the scope of

investigated compact object mergers. The growing network of GW detectors will give rise to a heightened rate of GW exploration and more confined source localizations, which in turn will provide more opportunities for conducting multi-messenger studies, increasing the likelihood of discovering common sources of neutrinos and GWs.

The next-generation ground-based GW detectors Einstein Telescope and Cosmic Explorer are currently in their design phase, with the goal of significantly expanding the cosmic volume reach by orders of magnitude (D. Reitze et al. 2019; B. Sathyaprakash et al. 2011; V. Kalogera et al. 2019; ET Design 2020). The planned space-based GW detectors LISA (K. Danzmann 2000; P. Amaro-Seoane et al. 2017), TianQin (J. Luo et al. 2016), and Taiji (W.-H. Ruan et al. 2020) will probe the millihertz frequency regimes. Simultaneously, the neutrino detectors are poised to increase their instrumented volumes with the next-generation detector projects IceCube-Gen2 and KM3NeT (S. Biagi & the KM3NeT consortium 2012; M. G. Aartsen et al. 2021). Anticipating a substantial increase in both the rate and quality of observations from these future detectors, we look forward to heightened chances and excitement surrounding future multimessenger discoveries (S. Márka et al. 2010; S. Márka 2012; S. Ando et al. 2013; I. Bartos & M. Kowalski 2017; P. Mészáros et al. 2019; K. Murase & I. Bartos 2019).

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Data Availability

Supplemental data for this article can be found at the Harvard Dataverse at <https://dataverse.harvard.edu/dataverse/icecube> and doi:10.7910/DVN/34B5AP.

Appendix











































Table 1 provides the properties of the neutrino triggers that produce individual p -values of 0.01 or less.

Table 1
Properties of the Coincident Neutrinos That Produce a p -value of 0.01 or Less

| GW Event GPS Time | p -value (10^{-3}) | Energy (GeV) | R.A. (deg) | Decl. (deg) | 90% Containment Radius (deg) | Δt (s) |
|-------------------|-----------------------------|-----------------|---------------|----------------|---------------------------------|-------------------|
| CBC Events | | | | | | |
| 1262142545.615 | 0.38 | 2416 | 37.31 | 7.46 | 2.62 | -222 |
| 1258769976.671 | 0.52 | 2553 | 213.01 | 24.91 | 2.40 | -232 |
| 1260567236.512 | 0.52 | 890 | 323.19 | 4.53 | 4.08 | -43 |
| 1264693411.565 | 0.83 | 1045 | 138.52 | 14.12 | 1.59 | -59 |
| 1261317209.144 | 1.1 | 4260 | 11.03 | 53.31 | 5.23 | 412 |
| 1240986884.531 | 1.3 | 1222 | 161.03 | 39.41 | 3.41 | 3 |
| 1248922975.872 | 1.7 | 1099 | 11.80 | 43.66 | 0.86 | -79 |
| 1251996593.946 | 1.9 | 6656 | 341.15 | 3.53 | 0.43 | 85 |
| 1261395060.713 | 2.0 | 1227 | 7.32 | 25.41 | 2.17 | 55 |
| 1242369559.803 | 2.3 | 4938 | 67.79 | 80.85 | 6.24 | -148 |
| 1245646385.592 | 2.6 | 2615 | 181.93 | -5.55 | 1.07 | -131 |
| 1259556411.479 | 3.5 | 921 | 342.74 | 51.25 | 2.98 | -309 |
| 1257878102.660 | 3.8 | 1549 | 78.01 | 15.62 | 2.17 | -286 |
| 1262800092.537 | 5.6 | 702 | 289.72 | 0.23 | 1.22 | 85 |
| 1257317013.751 | 5.7 | 1264 | 91.41 | 35.29 | 3.07 | -209 |
| 1248959867.938 | 5.8 | 2090 | 62.89 | 29.51 | 2.60 | 25 |
| 1239281492.824 | 6.1 | 1385 | 60.72 | 19.89 | 1.03 | 49 |
| 1246655423.219 | 7.9 | 16865 | 277.26 | -7.61 | 0.43 | 295 |
| 1258085887.274 | 8.3 | 1708 | 23.33 | 17.38 | 2.29 | 3 |
| 1238533707.234 | 8.3 | 2344 | 299.04 | 22.97 | 1.37 | 23 |
| 1249072561.974 | 9.3 | 1986 | 125.07 | 31.54 | 4.65 | 296 |
| 1262751997.732 | 9.6 | 1448 | 81.07 | 55.20 | 1.27 | -46 |
| cWB Events | | | | | | |
| 1241247887.938 | 0.43 | 2268 | 242.35 | 51.34 | 3.20 | 154 |
| 1259085330.234 | 1.1 | 1960 | 197.90 | 25.78 | 3.13 | 6 |
| 1266181040.000 | 1.3 | 2636 | 144.50 | 7.87 | 1.27 | 389 |
| 1258325594.125 | 4.3 | 330 | 7.44 | 19.58 | 4.03 | 171 |
| 1250185147.797 | 8.9 | 710 | 131.95 | 11.31 | 2.04 | -19 |


Note. Sky coordinates are in right ascension (R.A.) and declination (Decl.). The time difference Δt is the neutrino detection time minus the GW event time.







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