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IceCube Search for Neutrinos Coincident with Gravitational Wave Events from LIGO/Virgo Run O3

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Abstract

Using data from the IceCube Neutrino Observatory, we searched for high-energy neutrino emission from the gravitational-wave events detected by the advanced LIGO and Virgo detectors during their third observing run. We



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did a low-latency follow-up on the public candidate events released during the detectors' third observing run and an archival search on the 80 confident events reported in the GWTC-2.1 and GWTC-3 catalogs. An extended search was also conducted for neutrino emission on longer timescales from neutron star containing mergers. Follow-up searches on the candidate optical counterpart of GW190521 were also conducted. We used two methods; an unbinned maximum likelihood analysis and a Bayesian analysis using astrophysical priors, both of which were previously used to search for high-energy neutrino emission from gravitational-wave events. No significant neutrino emission was observed by any analysis, and upper limits were placed on the time-integrated neutrino flux as well as the total isotropic equivalent energy emitted in high-energy neutrinos.

Unified Astronomy Thesaurus concepts: [Neutrino astronomy \(1100\)](#); [Neutrino telescopes \(1105\)](#); [Gravitational waves \(678\)](#); [Multi-messenger Astrophysics](#); [Gravitational wave astronomy \(675\)](#); [High energy astrophysics \(739\)](#)

1. Introduction

Since the initial discoveries of astrophysical high-energy neutrinos in 2013 (Aartsen et al. 2013, 2014) and gravitational waves (GWs) in 2015 (Abbott et al. 2016), we have entered the exciting era of multimessenger astronomy. We now have over 10 years of IceCube neutrino data from the full-detector configuration (Aartsen et al. 2017) and 90 reported GW events with high astrophysical probability by the Laser Interferometer Gravitational-Wave Observatory (LIGO) Scientific, Virgo, and Kamioka Gravitational Wave Detector (KAGRA) Collaborations (LVK; Abbott et al. 2019; Abbott et al. 2021a, 2021b). This abundance of multimessenger data allows for statistically robust searches for common sources of GWs and high-energy neutrinos. Searches dating back before the individual confident discoveries of astrophysical GWs and high-energy neutrinos have not found significant joint emission (Aso et al. 2008; van Elewyck et al. 2009; Bartos et al. 2011; Baret et al. 2012; Adrián-Martínez et al. 2013; Aartsen et al. 2014a; Adrián-Martínez et al. 2016). Following the first confident GW observation (Abbott et al. 2016), several attempts from IceCube and Astronomy with a Neutrino Telescope and Abyss environmental REsearch (ANTARES) have not found significant emission of coincident high-energy neutrinos (Albert et al. 2017a; Albert et al. 2017b; Albert et al. 2020; Aartsen et al. 2020; Veske et al. 2021b). Searches for neutrinos in the low-energy regime have also been conducted by IceCube (Abbasi et al. 2021), Super-Kamioka Neutrino Detection Experiment (SuperKamioKande; Abe et al. 2021a), Kamioka Liquid-scintillator Anti-Neutrino Detector (KamLAND; Abe et al. 2021b), and Borexino (Agostini et al. 2017).

The discovery of such a joint emission would provide important information about the physics of the source and improve our understanding of the sources of the individual messengers. Currently, the emission of high-energy neutrinos from a GW source is expected to come from formed jets during the GW emission, which accelerates charged particles (Ando et al. 2013). These charged particles would produce mesons. From their decays and the decays of their secondaries, high-energy neutrino emission is expected (Fang & Metzger 2017; Kimura et al. 2018). Moreover, the inclusion of neutrino information to the gravitational-wave observation would help in constraining the location of the source more precisely in the sky, enabling more explorations to be done on it via telescopes with narrow fields of view. These motivations keep the search efforts vibrant despite the estimated low chance for joint detections with the current detectors (Bartos et al. 2011; Baret et al. 2012; Fang & Metzger 2017).

In this article, we present our low-latency follow-up searches and archival searches for high-energy neutrino emission from the GW events detected during the complete third observing

run of advanced LIGO and Virgo detectors (O3). In Section 2, we describe the IceCube detector and its neutrino data used for this analysis, and the GW detector runs followed up in this paper. In Section 3, we provide relevant details about the searches done by two main analysis methods: the unbinned maximum likelihood (UML) and Low-Latency Algorithm for Multimessenger Astrophysics (LLAMA). More detailed discussions on the methods can also be found in our previous publication (Aartsen et al. 2020). Section 4 describes the low-latency operation of the pipelines for following-up the candidate GW event alerts reported during the O3 run at the Gravitational-Wave Candidate Event Database (GraceDB)⁶⁷, and summarizes the results. In Section 5, we present the results of our archival searches using both the LLAMA and UML methods. These archival searches were performed on the 44 confident GW events from GWTC-2.1 (Abbott et al. 2021a)⁶⁸ and 36 GW events from GWTC-3 (Abbott et al. 2021b). These analyses include a search within a time window of ± 500 s around the GW events, a dedicated follow-up on the candidate optical flare from GW190521 (Abbott et al. 2020a; Graham et al. 2020), and an extended two-week search on the neutron-star-containing events by the UML pipeline.

2. The Neutrino and Gravitational Wave Observations

2.1. The IceCube Detector

The IceCube Neutrino Observatory is a cubic-kilometer detector array located at the geographic South Pole (Aartsen et al. 2017). The detector consists of 86 strings drilled deep into ice. These strings hold 60 digital optical modules (DOMs) between depths of 1.5 km and 2.5 km in the Antarctic ice. The main component of the DOMs are photomultiplier tubes used to detect the Cherenkov light emitted by charged particles produced when neutrinos interact in ice.

There are two main event topologies seen within IceCube data: tracks and cascades. Tracks are produced when muon neutrinos undergo charged-current interactions and produce muons that travel along a straight line and deposit Cherenkov light along its path. Cascades, which mainly consist of electromagnetic showers, are generated via charged-current interactions of electron neutrinos and neutral-current interactions of neutrinos of all flavors within the ice. Tracks are excellent at pointing toward various astrophysical sources as they have an angular resolution of $\lesssim 1^\circ$, which is much better

⁶⁷ <https://gracedb.ligo.org/>

⁶⁸ Most of the events in GWTC-2.1 were already reported in catalog GWTC-2 (Abbott et al. 2021c). These were previously analyzed by both the LLAMA and UML searches (Veske et al. 2021b). The LLAMA pipeline reanalyzed them with a refined background distribution, while the UML results remained the same.

than the pointing resolution of cascades ($\gtrsim 10^\circ$; Aartsen et al. 2014b, 2014c).

The analyses presented here use neutrino data from a low-latency data stream known as the Gamma-ray Follow-Up (GFU) Online event stream. The GFU Online event selection is able to rapidly reconstruct neutrino events observed in the IceCube detector, and the data are made available within roughly 30 s, allowing for rapid neutrino follow-ups. The GFU dataset uses track events detected with IceCube, since their pointing resolutions are well suited for follow-up analyses. The details of the selection can be found in Aartsen et al. (2016), and the online version of the dataset, which we use in this article, is described further in Kintscher (2016).

The dataset consists of through-going muon tracks originating primarily from cosmic-ray backgrounds from the atmosphere. In the southern sky, the sample is dominated by the atmospheric muons, while in the northern sky the sample is dominated by atmospheric neutrinos. Atmospheric muons do not contribute to the rate in the northern sky due to Earth absorption. The all-sky neutrino event rate ranges from 6 to 7 mHz depending on the seasonal variation of atmospheric neutrinos (Heix et al. 2019). Overall the rate of astrophysical neutrinos is roughly 3 orders of magnitude lower than that of the atmospheric backgrounds (Aartsen et al. 2016).

2.2. The Third Observing Run of Ground-based Gravitational Wave Detectors

On 2019 April 1 at 15:00 UTC the LIGO and Virgo detectors network (Acernese et al. 2014; Aasi et al. 2015) started their third observing run with an increased sensitivity enabling the detection of gravitational waves from compact binary coalescence at a rate of greater than 1 merger per week (Abbott et al. 2021a, 2021b). During the period of October 1 15:00 UTC to November 1 15:00 UTC, the detectors were not collecting data, thus separating the observation run to two segments, O3a followed by O3b, which ended on 2020 March 27 at 17:00 UTC. The near-realtime analysis of the LIGO–Virgo data by the LIGO Scientific and Virgo Collaborations (LVC) allows for the broadcasting of open public alerts. On the other hand, an in-depth offline analysis provides an update to the catalog of GW events.

In this paper, as a combination of the events from IceCube and the GW events from O3 are used, the analyses becomes dependent on the localizations of both the neutrino and the GW events. Figure 1 compares the sky localizations of the skymaps of the candidate GW events published in the GW catalogs (O1 to O3) and the neutrino events detected by IceCube, within the GFU dataset. The 90% of localizations of both are used to make the comparison. It is seen that we are mainly limited by the localization uncertainties in the GW skymaps. These uncertainties are expected to reduce within the future runs of the ground-based gravitational wave detectors (Abbott et al. 2018).

3. Methods

There are two main searches that we employed: the UML and LLAMA searches. Both the UML and LLAMA analyses performed short-timescale follow-ups for each reported GW event. The analyses searched for neutrino emission within a ± 500 s time window centered around the GW merger time. This time window was used both in the realtime and archival

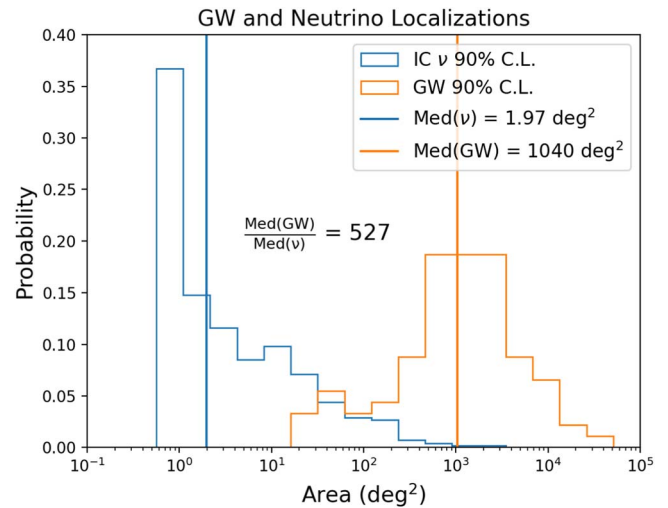


Figure 1. Comparison of the sky localizations of the 90% probability regions of the GW skymaps (orange) and the 90% contours of the neutrino localizations (blue). The skymaps shown here include all 91 GW events from O1, O2, and O3. It can be seen that we are mainly limited by the large areas of the GW skymaps, which reduces if three detectors from LVC detect the event simultaneously.

searches. The time window is a conservative empirical estimate of the delay between the GW and neutrino emission for a model based on gamma-ray bursts (Baret et al. 2011).

Additionally, the UML analysis performed a long timescale analysis on all binary neutron star (BNS) and neutron star–black hole (NSBH) candidates. This search, called the two-week follow-up, is motivated by models that predict neutrino emission on longer timescales from binaries with at least one neutron star (Fang & Metzger 2017; Decoene et al. 2020). We searched within a time period of $[-0.1, +14]$ days around the GW merger times.

Both analyses also performed a neutrino follow-up search on the candidate optical counterpart to the binary black hole (BBH) merger GW190521 observed by the Zwicky Transient Facility (ZTF; Graham et al. 2020). ZTF observed a flaring active galactic nucleus (AGN), J124942.3+344929, which coincided with the 90% credible region of the GW event’s sky localization. This flare can be explained by the accretion of the gas in the AGN disk to the kicked final black hole of the merger (McKernan et al. 2019). The motivation for the neutrino follow-up was the expected formation of a jet accelerating particles due to the chaotic accretion dynamics around the kicked black hole traveling through the AGN disk.

3.1. Unbinned Maximum Likelihood

The UML method tests for a point-like neutrino source coincident with the GW localization region. The likelihood takes the direction, angular error, and reconstructed energy of each neutrino on the sky into account. The sky is divided into equal area bins using the Healpix pixelization scheme (Gorski et al. 2005). We then perform a likelihood ratio test where the test statistic (TS) is the log-likelihood ratio. The TS is computed at each pixel in the sky by maximizing the log-likelihood ratio and weighting the result by the GW localization probability in the given pixel. The pixel with the largest TS value is taken to be the best-fit location for a joint GW–neutrino source, and the associated TS is considered the final

observed TS for the analysis. For a full detailed description of the likelihood and TS used here, see Hussain et al. (2019).

To compute the significance for each GW follow-up, we perform 30,000 pseudo-experiments with scrambled neutrino data to generate a background TS distribution. Then scrambling is carried out by randomly assigning a time for the neutrinos, which is equivalent to a scramble in right ascension, while maintaining the declination dependence of the data. The final observed TS for a given GW event is then compared to its background distribution to compute a p -value.

In the case where the observed TS is consistent with the background, we place 90% confidence level (CL) upper limits (ULs) on the time-integrated neutrino flux, $E^2 F$, assuming an E^{-2} spectrum, where $F = dN/dE dA$. The limits are computed by injecting simulated signal neutrinos into the sky according to the GW localization probability. We then follow the all-sky scan procedure described above to compute a TS for a given value of injected neutrino flux. We run 500 trials for a given injected neutrino flux with a random injection location chosen for each trial. The 90% UL on the neutrino flux is then defined as the flux for which 90% of trials produce a TS value greater than the observed TS value for the GW event.

Upper limits to the isotropical equivalent energy (E_{iso} ULs) are computed in a similar manner. Once again we assume an E^{-2} spectrum and convert our injected E_{iso} into a flux at Earth by sampling a location on the sky as well as a distance to the GW source according to the 3D localization probability provided by LIGO/Virgo. The flux is then converted to an expected number of events observed at IceCube using the dataset's declination dependence and effective area.

Note that all reported ULs are only valid within a certain range of energies. The energy range of our data sample depends strongly on the declination. The central 68% energy range in the southern hemisphere is roughly $5 \times 10^5 \text{ GeV} - 10^7 \text{ GeV}$ and in the northern hemisphere ranges from roughly 5×10^3 to 10^5 GeV .

For the follow-up of the potential optical counterpart of GW190521, AGN J124942.3+344929, we do not include any of the GW spatial information because we are testing for neutrino emission from the precise location of the AGN rather than the full GW contour. We search for neutrinos correlated with the location of the AGN in a 112 day time window after the merger, which is a conservative estimate based on the time profile of the optical flare. This is done in a model-independent manner, with no assumptions on the emission profile in the entire time window. This method is equivalent to the full all-sky scan method described above except the localization skymap is a delta function at the single pixel containing the AGN.

3.2. Low-latency Algorithm for Multimessenger Astrophysics

The LLAMA analysis is based on the calculation of Bayesian probabilities of the observed coincidences of GWs and high-energy neutrinos (Bartos et al. 2019). The odds ratio of the coincidence arising from a joint astrophysical emission of GWs and neutrinos being unrelated, considering any of them being not astrophysical as well, is used as a test statistic. For the analysis of confirmed GW detections followed up in this study, the GW events are assumed to be certainly astrophysical. The origins of the neutrinos are quantified for astrophysical or background scenarios. This requires the effective area of IceCube, past triggers of the GFU stream (which are

predominantly of atmospheric origin), and the reconstructed energies of the neutrinos and their sky localizations. In addition to this, an E^{-2} astrophysical spectrum is assumed. The relation between the GW and neutrinos are quantified via the difference between their detection times, their respective sky localizations, and the mean distance reconstruction of the GW event. Together with the astrophysical emission energy E_{iso} , which is log-uniform between 10^{46} and 10^{51} erg, the distance reconstruction of the GW event accounts for the propagation of the neutrinos in space.

Precomputed background distributions are used for calculating the p -values. In order to include the distance information of the GW events appropriately, different background distributions are constructed for different source types (BNS, NSBH, BBH coalescences). For this purpose, GW events are simulated for each source category, and they are randomly matched with scrambled past GFU detections. The number of neutrinos matched with each GW event is drawn according to a Poisson distribution with a mean corresponding to the average GFU trigger count in 1000 s. The 90% CL upper limits (frequentist limits) on the time-integrated neutrino flux are calculated as described in the appendix of Aartsen et al. (2020).

The neutrino follow-up on the candidate optical counterpart of GW190521 in the LLAMA analysis follows the assumed emission model described in Graham et al. (2020). The model assumes a linearly decreasing gas density around the AGN. The kicked black hole from the merger travels through and accretes gas from the AGN disk. For our neutrino search, we hypothesized a neutrino emission from the particle accelerating jets, which are expected to form due to the accretion. Hence, the intensity of the expected neutrino emission is assumed to be proportional to the accretion rate, which is assumed to be a linearly decreasing emission intensity over time in this model. The start and end times of the accretion were found from the observed light curves by following the same model, which also includes an optical diffusion delay obeying a Maxwell-Boltzmann distribution. The least-squares estimations for the start and end times of the accretion were found to be 23 and 80 days after the merger respectively, the same as that found in Graham et al. (2020). So, we searched for a neutrino emission from a point source located at the AGN's position, free of any diffusion effect, which starts 23 days after the BBH merger and linearly decreases for the following 57 days until it ends.

4. Low-latency Operation

Both the UML (Aartsen et al. 2020) and LLAMA (Countryman et al. 2019; Bartos et al. 2019) analyses deployed low-latency pipelines designed to perform automated neutrino follow-up searches after receiving notices from LVC through the Gamma-ray Coordinates Network (GCN; Hussain et al. 2019; Keivani et al. 2019).

These pipelines allow for rapid neutrino follow-ups and the dissemination of results to the astronomical community via GCN circulars. Low-latency neutrino information can help inform the observing strategies of electromagnetic observatories searching for electromagnetic counterparts to GW events. For example, observatories such as Swift-XRT were able to use IceCube's neutrino follow-up results to narrow the search region for several GW events (Keivani et al. 2021). While no electromagnetic counterparts were found during the O3 observing run, these pipelines show the discovery potential

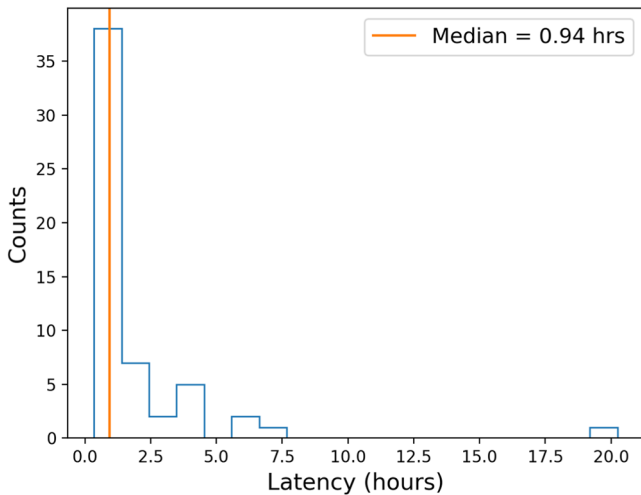


Figure 2. Latency of IceCube GCN circulars relative to GW merger times for all 56 events reported during the O3 observing run. (All of the GCN notices of these GW events can be found at https://gcn.gsfc.nasa.gov/ivc_events.html). The outlier near 20 hr is S190421ar, where the LVC GCN notice was not received until roughly 19 hr after the GW merger. This plot only shows the follow-ups, which were triggered automatically via GCN notices sent by LVC.

of low-latency multimessenger astronomy in identifying joint sources of photons, GWs, and neutrinos.

Both analyses take advantage of the GCN notices to receive information about a given GW event and trigger a dedicated neutrino follow-up search. The pipelines use a python package, PyGCN (Singer 2021), to continuously monitor the GCN system for GCN notices sent by LVC. Due to the low-latency of the GFU Online stream (~ 30 s) and the speed of the follow-up analyses (~ 56 minutes), IceCube was able to rapidly circulate results from neutrino follow-ups to the astronomical community by using subsequent GCN circulars. Figure 2 shows the distribution of response times between the IceCube GCN circulars and the GW merger time. The latency shown in the figure takes the time taken by LVC to send the initial GCN notice into account. Also included in the latency is the final vetting of the IceCube results by the collaboration’s Realtime Oversight Committee (ROC) before sending the IceCube follow-up results via GCN circulars. Follow-ups with observed p -value $\leq 1\%$ in either pipeline or any follow-ups that were deemed interesting to the astronomical community by the ROC, resulted in releasing the directional information of the potentially significant neutrino candidate via GCN circulars.

During O3, there were a total of 56 non-retracted candidate GW events that were publicly shared. We ran follow-ups on these events and four of them resulted in the release of the directional information of a neutrino to the astronomical community. These released coincidences were further followed up by different telescopes and observatories, e.g., Swift-XRT (Page et al. 2020; Keivani et al. 2021) and Karl G. Jansky Very Large Array (Bhakta et al. 2021). For each of these events, the LVC GCN notices and the GCN circular archives are linked. The archives show all follow-ups performed by each observatory, including the follow-ups that use IceCube information. These events were the following:

1. S190517h^{69,70}: This candidate BBH merger event had one neutrino located in the 90% credible sky region of the GW localization. Due to this spatial coincidence, the neutrino’s localization was shared with the community,⁷¹ despite its low statistical significance.
2. S190728q^{72,73}: This candidate BBH merger event originally had a two-detector localization, which did not yield any significant neutrino coincidence. The localization was later improved by the incorporation of the Virgo data, which increased the significance of one of the neutrinos. With the final online skymap the coincidence had the p -values 1.0% and 1.6% for the LLAMA and UML searches, respectively.⁷⁴ Figure 3 shows the various localization skymaps sent by LVC and the associated results from each pipeline, which were reported in low-latency via GCN circulars. The skymaps were refined over a period of roughly 14 hr following the initial GCN notice sent by LVC. It is seen that the p -values from both pipelines become more significant as the localization is refined, since neutrino candidate 3 remains within the high-probability region of the skymap as the GW localization shrinks. Figure 4 shows the zoomed in updated skymap of GW190728_064510 with the coincident neutrino overlaid.
3. S191216ap^{75,76}: This candidate BBH merger event was one of the events for which the results of the two analyses disagreed. It was located relatively close, at ~ 400 Mpc. Due to this atypically close distance for a BBH merger, the neutrino–GW coincidence was favored by the LLAMA search, which assigned a p -value of 0.6%, whereas the UML search obtained a p -value of 22%.⁷⁷ The most interesting response to our GCN notices came after the release of the neutrino coinciding with this event. The High-Altitude Water Cherenkov Observatory (HAWC) sent out another notice saying their most significant subthreshold gamma-ray trigger coincides both with the neutrino and GW’s localizations.⁷⁸ No further counterpart was found from the region and due to the uncertain nature of the gamma-ray trigger the state of the triple coincidence remained inconclusive.
4. S200213t^{79,80}: This event was the only candidate BNS merger for which a coincident neutrino was released. However, it was excluded in the published GW catalogs, since it did not meet the threshold requirements in the offline analysis from LVC (Abbott et al. 2021b). The UML and LLAMA searches obtained p -values of 0.3% and 1.7%, respectively, for the neutrino coincidence.⁸¹

⁶⁹ GW event GCN notice https://gcn.gsfc.nasa.gov/notices_1/S190517h.lvc.

⁷⁰ GCN circular archive <https://gcn.gsfc.nasa.gov/other/GW190517h.gcn3>
⁷¹ <https://gcn.gsfc.nasa.gov/gcn/gcn3/24573.gcn3>
⁷² GW event GCN notice https://gcn.gsfc.nasa.gov/notices_1/S190728q.lvc.
⁷³ GCN circular archive <https://gcn.gsfc.nasa.gov/other/GW190728q.gcn3>
⁷⁴ <https://gcn.gsfc.nasa.gov/gcn/gcn3/25210.gcn3>
⁷⁵ GW event GCN notice https://gcn.gsfc.nasa.gov/notices_1/S191216ap.lvc
⁷⁶ GCN circular archive <https://gcn.gsfc.nasa.gov/other/GW191216ap.gcn3>
⁷⁷ <https://gcn.gsfc.nasa.gov/gcn/gcn3/26460.gcn3>
⁷⁸ <https://gcn.gsfc.nasa.gov/gcn/gcn3/26472.gcn3>
⁷⁹ GW event GCN notice https://gcn.gsfc.nasa.gov/notices_1/S200213t.lvc
⁸⁰ GCN circular archive <https://gcn.gsfc.nasa.gov/other/GW200213t.gcn3>
⁸¹ <https://gcn.gsfc.nasa.gov/gcn/gcn3/27043.gcn3>

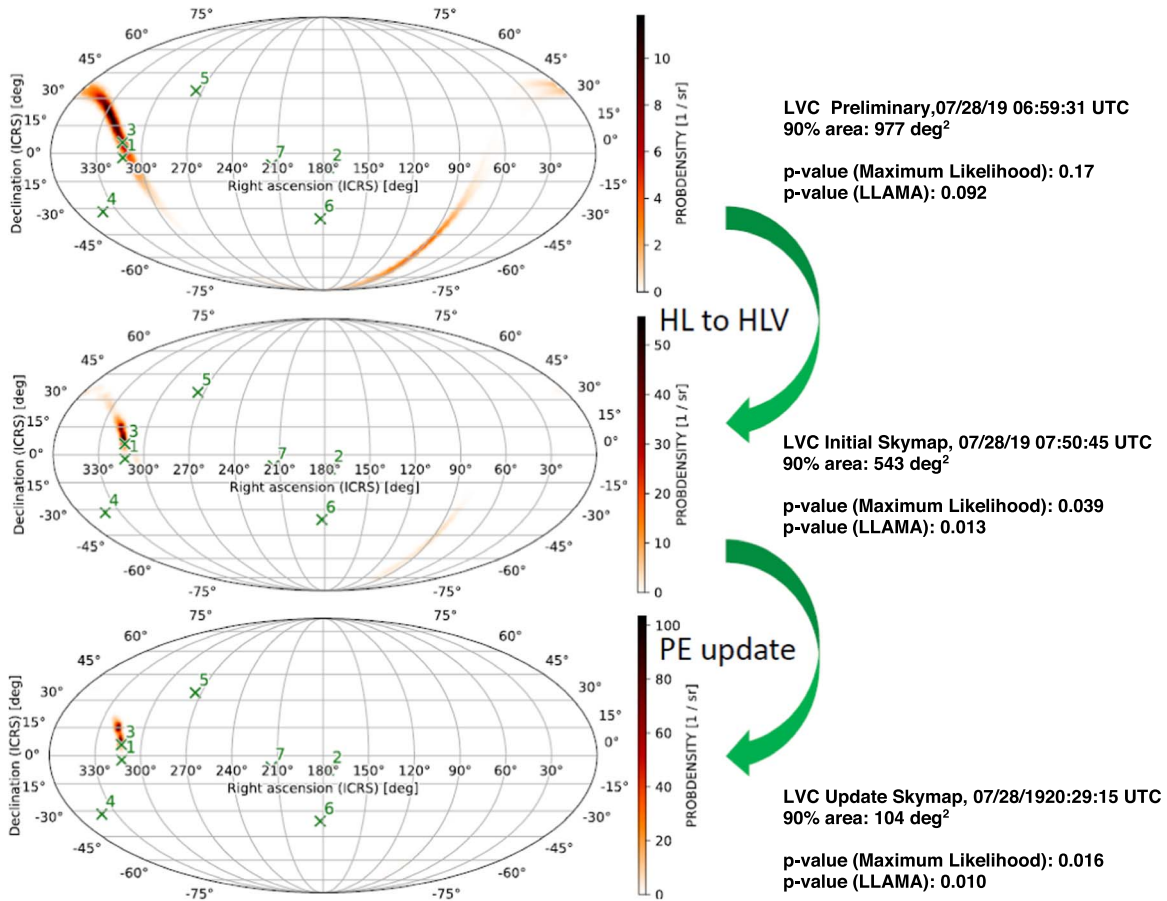


Figure 3. Evolution of the localization skymap for S190728q (https://gcn.gsfc.nasa.gov/notices_1/S190728q.lvc) and associated follow-up results from each pipeline, which were sent via GCN circulars. As the localization is refined, the p -values from both pipeline become more significant. The color map in the figure represents the probability per pixel in the skymap, and the green crosses show the neutrino observations.

Both of these low-latency pipelines are being prepared to continue neutrino follow-ups during the fourth observing run of LIGO, Virgo, and KAGRA detectors, planned to start in 2023.

5. Archival Searches on Catalogs

Once the catalogs containing the confident GW detections were published by LVC, we performed archival searches on these events. There were several GW events added to or subtracted from the catalog when compared to the candidate events shared with the community by LVC during the O3 run. Initially, LVC released the catalog GWTC-2 (Abbott et al. 2021c), which contained 39 events from the first half of O3. These events were analyzed using both UML and LLAMA methods, and no significant neutrino emission was found (Veske et al. 2021b). Later, this catalog was renewed by LVC resulting in the publication of GWTC-2.1 (Abbott et al. 2021a), which has an updated statistic used for the classification of the events as confident detections. This updated catalog has 44 GW events, of which 8 were new when compared to GWTC-2. Three events from GWTC-2 were retracted in the updated catalog. Here, we present the results of the 44 confident events in GWTC-2.1. The 36 common events were reanalyzed by the LLAMA search with a renewed background distribution, which was generated with the latest population estimates for the

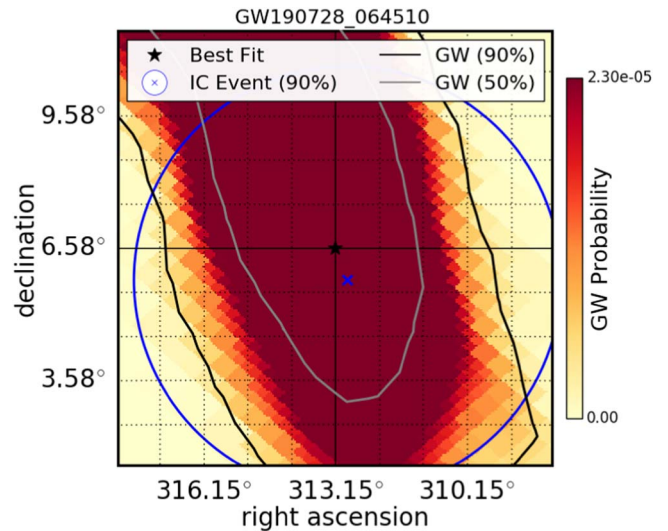


Figure 4. Skymap of GW190728_064510 overlaid with the coincident neutrino. The red region represents the GW localization probability per pixel. The blue cross shows the best-fit neutrino direction with the circle showing the 90% containment angular error region. The neutrino arrived 360 s before the GW merger. The final pre-trial p -values for this event are $p = 0.013$ and $p = 0.04$ with the LLAMA and UML analyses, respectively. The GCN circular describing this event was also sent in realtime (<https://gcn.gsfc.nasa.gov/gcn3/25210.gcn3>).

Table 1
Results for the Events in GWTC-2.1 (Abbott et al. 2021a) for the 1000 s Follow-up

GWTC-2.1			LLAMA		UML		
Event	Type	Area (deg ²)	p -value	E^2F UL (GeV cm ⁻²)	p -value	E^2F UL (GeV cm ⁻²)	E_{iso} UL (erg)
GW190403_051519	BBH	5589.4	0.51	0.14	0.46	0.101	1.86×10^{55}
GW190408_181802	BBH	148.8	0.22	0.048	0.17	0.0512	4.85×10^{53}
GW190412	BBH	20.9	0.27	0.041	0.13	0.0459	8.31×10^{52}
GW190413_052954	BBH	1484.5	0.30	0.087	0.28	0.133	7.01×10^{54}
GW190413_134308	BBH	730.6	0.27	0.34	0.34	0.270	2.84×10^{55}
GW190421_213856	BBH	1211.5	0.81	0.46	0.56	0.393	1.40×10^{55}
GW190425	BNS	9958.2	0.16	0.22	0.94	0.176	1.66×10^{52}
GW190426_190642	BBH	8214.5	0.42	0.17	0.18	0.282	1.25×10^{55}
GW190503_185404	BBH	94.4	0.94	0.54	0.34	0.584	4.99×10^{54}
GW190512_180714	BBH	218.0	0.81	0.23	0.85	0.199	1.74×10^{54}
GW190513_205428	BBH	518.4	0.99	0.043	0.94	0.0514	6.73×10^{53}
GW190514_065416	BBH	3009.7	0.25	0.089	0.44	0.0453	3.96×10^{54}
GW190517_055101	BBH	473.3	0.21	0.48	0.26	0.366	6.05×10^{54}
GW190519_153544	BBH	857.1	0.067	0.15	0.21	0.0914	3.20×10^{54}
GW190521	BBH	1008.2	0.62	0.37	0.63	0.359	1.90×10^{55}
GW190521_074359	BBH	546.5	0.11	0.049	0.15	0.0451	2.36×10^{53}
GW190527_092055	BBH	3662.4	0.65	0.41	0.88	0.326	1.01×10^{55}
GW190602_175927	BBH	694.5	0.31	0.34	0.17	0.370	9.73×10^{54}
GW190620_030421	BBH	7202.1	0.20	0.36	0.23	0.121	4.13×10^{54}
GW190630_185205	BBH	1216.9	0.64	0.15	0.81	0.427	5.31×10^{53}
GW190701_203306	BBH	46.1	1.0	0.039	0.87	0.0385	7.65×10^{53}
GW190706_222641	BBH	653.8	0.99	0.036	0.92	0.0356	3.17×10^{54}
GW190707_093326	BBH	1346.	0.43	0.24	0.63	0.202	4.74×10^{53}
GW190708_232457	BBH	13675.4	0.11	0.11	0.56	0.0720	1.62×10^{53}
GW190719_215514	BBH	2890.1	0.83	0.054	0.91	0.0512	4.90×10^{54}
GW190720_000836	BBH	463.4	0.99	0.13	0.94	0.0872	5.34×10^{53}
GW190725_174728	BBH	2292.5	0.048	0.19	0.59	0.0918	4.04×10^{53}
GW190727_060333	BBH	833.8	0.89	0.38	0.74	0.324	1.53×10^{55}
GW190728_064510	BBH	395.5	0.0084	0.89	0.04	0.315	6.36×10^{53}
GW190731_140936	BBH	3387.3	0.25	0.93	0.61	0.385	1.81×10^{55}
GW190803_022701	BBH	1519.5	0.31	0.037	0.64	0.0354	1.69×10^{54}
GW190805_211137	BBH	3949.1	0.74	0.20	0.93	0.180	2.56×10^{55}
GW190814	BBH*	19.3	1.0	0.24	1.0	0.259	5.68×10^{52}
GW190828_063405	BBH	520.1	0.93	0.21	0.98	0.178	2.74×10^{54}
GW190828_065509	BBH	664.0	0.84	0.38	0.84	0.368	3.73×10^{54}
GW190910_112807	BBH	10880.3	0.22	0.45	0.77	0.177	1.90×10^{54}
GW190915_235702	BBH	396.9	0.56	0.036	0.44	0.0354	3.61×10^{53}
GW190916_200658	BBH	4499.2	0.52	0.16	0.85	0.108	1.22×10^{55}
GW190917_114630	NSBH*	2050.6	0.20	0.19	0.72	0.203	6.37×10^{53}
GW190924_021846	BBH	357.9	0.031	0.037	0.23	0.0346	4.46×10^{52}
GW190925_232845	BBH	1233.5	0.39	0.11	0.59	0.0908	3.41×10^{53}
GW190926_050336	BBH	2505.9	0.13	0.78	0.33	0.280	2.30×10^{55}
GW190929_012149	BBH	2219.3	0.11	0.34	0.22	0.276	1.85×10^{55}
GW190930_133541	BBH	1679.6	0.14	0.038	0.31	0.0427	1.05×10^{53}

Note. GW190814 is labeled as a BBH merger here although the type of the lighter object with $\sim 2.6 M_{\odot}$ is unknown (Abbott et al. 2020b). GW190917_114630 is labeled as NSBH as its estimated source properties are more like that of an NSBH event although the event was found to be significant by a BBH template. The table also shows the area on the sky containing 90% probabilities from the GW skymap.

binary black holes. No appreciable change was found with the previous analysis. The results of the UML analysis for the common events stayed the same. Finally, LVC also published GWTC-3 (Abbott et al. 2021b), a catalog containing the confident GW events observed during the second half of the O3 run (Abbott et al. 2021b). These events were also analyzed as a part of the archival search.

First, we present the results of the searches for neutrino emission within a time window of ± 500 s around the 80 mergers in GWTC-2.1 and GWTC-3. We did not observe a significant neutrino emission from any GW event by any analysis. ULs were placed on the time-integrated, energy-

scaled neutrino flux, E^2F , as well as on E_{iso} , emitted in high-energy muon neutrinos. Table 1 summarizes the results for each follow-up of GW events in GWTC-2.1 performed by both analyses. Similarly, Table 2 shows the results for the GW events in GWTC-3. Figure 5 shows the histogram of the p -values for the collection of GW events from GWTC-1 (Abbott et al. 2019), GWTC-2.1 (Abbott et al. 2021a), and GWTC-3 (Abbott et al. 2021b) from both analyses and the background expectations. The set of events did not show any significant sign of emission. The shown background expectation for the UML analysis was derived from the background TS distributions of each GW. The LLAMA analysis' background p -value

Table 2
Results for the Events in GWTC-3 (Abbott et al. 2021b) for the 1000 s Follow-up

GWTC-3		LLAMA		UML			
Event	Type	Area (deg ²)	p -value	E^2F UL (GeVcm ⁻²)	p -value	E^2F UL (GeVcm ⁻²)	E_{iso} UL (erg)
GW191103_012549	BBH	2519.6	0.53	0.049	0.71	0.049	1.96×10^{53}
GW191105_143521	BBH	728.7	0.27	0.28	0.54	0.267	1.28×10^{54}
GW191109_010717	BBH	1784.3	0.14	0.48	0.05	0.508	5.03×10^{54}
GW191113_071753	BBH	2993.3	0.076	0.52	0.19	0.441	3.12×10^{54}
GW191126_115259	BBH	1514.5	0.77	0.13	1.00	0.138	1.42×10^{54}
GW191127_050227	BBH	1499.2	0.38	0.078	0.83	0.081	2.96×10^{54}
GW191129_134029	BBH	848.3	0.25	0.35	0.30	0.425	8.95×10^{53}
GW191204_110529	BBH	4747.7	0.16	0.36	0.49	0.085	1.46×10^{54}
GW191204_171526	BBH	344.9	0.97	0.26	1.00	0.280	3.96×10^{53}
GW191215_223052	BBH	595.8	0.98	0.26	1.00	0.211	2.98×10^{54}
GW191216_213338	BBH	480.1	0.0049	0.093	0.10	0.071	2.57×10^{52}
GW191219_163120	NSBH	2232.1	0.09	0.26	0.71	0.219	2.80×10^{53}
GW191222_033537	BBH	2299.2	0.95	0.36	1.00	0.375	1.1×10^{55}
GW191230_180458	BBH	1012.2	0.37	0.36	0.28	0.488	3.18×10^{55}
GW200105_162426	NSBH	7881.8	0.20	0.13	0.81	0.095	2.98×10^{52}
GW200112_155838	BBH	4250.4	0.58	0.18	0.79	0.133	8.43×10^{53}
GW200115_042309	NSBH	511.9	0.34	0.038	0.45	0.045	2.12×10^{52}
GW200128_022011	BBH	2677.5	0.46	0.25	0.47	0.243	9.31×10^{54}
GW200129_065458	BBH	81.8	0.033	0.041	0.05	0.406	1.73×10^{53}
GW200202_154313	BBH	159.3	0.0057	0.039	0.06	0.038	2.43×10^{52}
GW200208_130117	BBH	38.0	0.94	0.33	1.00	0.518	9.25×10^{54}
GW200208_222617	BBH	1889.2	0.41	0.045	0.90	0.043	4.98×10^{54}
GW200209_085452	BBH	924.5	0.84	0.50	1.00	0.041	1.81×10^{54}
GW200210_092254	BBH*	1830.7	0.28	0.071	0.79	0.081	2.51×10^{53}
GW200216_220804	BBH	3009.5	0.065	0.066	0.46	0.236	2.82×10^{54}
GW200219_094415	BBH	702.1	0.98	0.23	1.00	0.035	9.57×10^{54}
GW200220_061928	BBH	3484.7	0.23	0.22	0.05	0.357	4.23×10^{55}
GW200220_124850	BBH	3168.9	0.42	0.13	0.53	0.118	6.31×10^{54}
GW200224_222234	BBH	49.9	0.90	0.068	1.00	0.079	9.33×10^{53}
GW200225_060421	BBH	509.0	0.0048	0.10	0.20	0.055	3.03×10^{53}
GW200302_015811	BBH	7010.8	0.16	0.67	0.21	0.531	4.34×10^{54}
GW200306_093714	BBH	4371.2	0.15	0.074	0.57	0.046	9.99×10^{53}
GW200308_173609	BBH	18705.7	0.24	0.38	0.29	0.326	7.18×10^{55}
GW200311_115853	BBH	35.6	1.0	0.047	1.00	0.076	4.38×10^{53}
GW200316_215756	BBH	410.4	0.17	0.066	0.04	0.110	5.19×10^{53}
GW200322_091133	BBH	31571.1	0.23	0.18	0.87	0.148	4.39×10^{55}

Note. GW200210_092254 is labeled as a BBH merger here although the type of the lighter object with $\sim 2.8 M_{\odot}$ is unknown (Abbott et al. 2021b). The central 68% energy range of the events contributing to the limits shown here ranges from 5×10^5 to 10^7 GeV in the southern hemisphere and 5×10^3 GeV – 10^5 GeV in the northern hemisphere.

distribution is seen to be uniform for all kinds of events. The different results for the LLAMA and the UML analyses arise from the inherent differences in the statistical approaches of the two—one being a Bayesian approach including priors of the GW source and the other being a purely frequentist approach. This is also true for the p -values obtained in the low-latency search described in Section 4.

Figure 6 shows the E_{iso} ULs for all GW events in GWTC-1, GWTC-2.1, and GWTC-3 along with the total rest-mass energy of the initial compact objects and the total energy radiated by the system post-merger. The total radiated energy is computed by taking the difference of the total rest-mass energy of the two progenitors and the final remnant object.

No significant neutrino emission was observed in the second archival search presented here, which is the two-week follow-up. There are only three GW events in GWTC-2.1 that may have at least one neutron star in the binary system: GW190425,

GW190814, and GW190917_114630. Also four NSBH events were published in the GWTC-3 catalog: GW191219_163120, GW200105_162426 (marginal event), GW200115_042309, GW200210_092254. All of these events have at least one progenitor object with a mass estimate lower than $3 M_{\odot}$ (Abbott et al. 2021a, 2021b). The two-week follow-up is performed on these seven GW events. Once again, we place 90% ULs on the time-integrated neutrino emission from each of the seven GWs tested here. Table 3 shows the p -values and ULs for these events, and Figure 7 shows the final test statistic maps for these events. There was no difference between the neutron-star-containing events in GWTC-2 and GWTC-2.1.

Finally, no significant neutrino emission was found for the follow-ups on the candidate optical counterpart of GW190521 by both analysis methods. The modeled search of LLAMA yielded a p -value of 0.79, 90% CL upper limit on the E^2F of 0.05 GeV cm⁻², and 90% CL upper limit on E_{iso} of 8×10^{53} erg. The

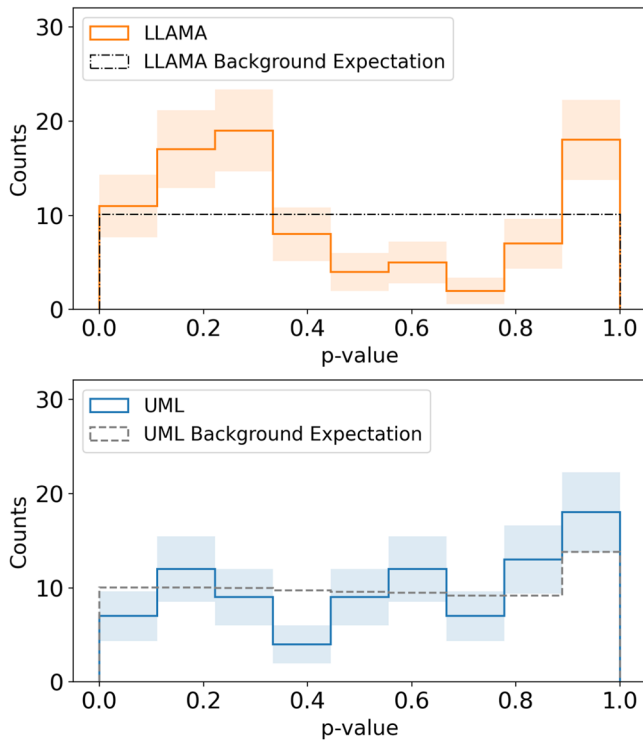


Figure 5. p -value distribution for the LLAMA (top panel) and UML (bottom panel) analyses of the 11 events in GWTC-1 (Abbott et al. 2019), 44 GW events in GWTC-2.1 (Abbott et al. 2021a), and 36 GW events in GWTC-3 (Abbott et al. 2021b). The distributions are consistent with background expectations. The p -value distributions obtained for the events in GWTC-1 were already published in Aartsen et al. (2020). The LLAMA background expectations shown here is taken from that of one representative GW and scaled to 91 GW events. The orange and blue bands represent the Poisson errors on the observed distribution of LLAMA and UML p -values, respectively.

UML analysis found a p -value of 0.25, with a 90% CL upper limit on the time-integrated flux of $E^2F = 0.081 \text{ GeV cm}^{-2}$.

6. Conclusion

Finding joint sources of GWs and high-energy neutrinos can help to shed light on the sources of the highest-energy neutrinos and cosmic rays (Murase & Bartos 2019). Studying these joint sources will also further expand our understanding of energetic outflows from the mergers of compact objects. The completion of the O3 realtime observing run and the release of the update to the second GW catalog, GWTC-2.1, followed by the release of GWTC-3 have provided a substantial increase in the number of reported GW candidates available for follow-up searches.

We developed low-latency pipelines, which ran automated neutrino follow-ups for all GW events reported by LVC during the O3 observing run. Two different analyses, UML and LLAMA, both ran in low-latency and followed up each of the 56 candidate events reported during the O3 run. Four of the follow-up searches resulted in the release of the neutrino candidate’s direction to the public via GCN circulars. This information prompted follow-up searches in electromagnetic observatories such as Swift-XRT, demonstrating the power of low-latency multimessenger observations in informing the observing strategies of other observatories. The unresolved triple coincidence for GW191216, involving a subthreshold gamma-ray trigger from HAWC observatory, triggered the

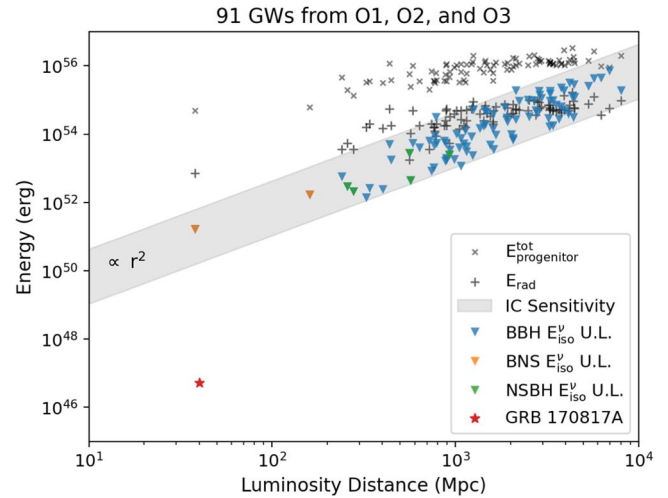


Figure 6. E_{iso} ULs for 91 GW candidates in GWTC-1, GWTC-2.1, and GWTC-3. The blue, green, and orange triangles show the BBH, BNS, and NSBH events, respectively. Note that the 36 GW candidates present in both GWTC-2 and GWTC-2.1 do not have updated skymaps available so the results shown here are using the GWTC-2 skymaps. The black crosses represent the total rest-mass energy of the progenitors of the binary merger. The gray pluses represent the total energy radiated by the binary system. Also shown for reference is the observed E_{iso} in photons by the Fermi Gamma-ray Burst Monitor for GW170817 (red star; Abbott et al. 2017). The gray band represents the best and worst median UL that IceCube can place based on a point-source hypothesis. The E_{iso} ULs for the 11 GW events from GWTC-1 remain the same as those published in Aartsen et al. (2020).

Table 3
Results for the Two-week Follow-up Analysis Using the UML Method

Event	Type	p -value	E^2F UL (GeV cm^{-2})
GW190425	BNS	0.43	0.661
GW190917_114630	NSBH	0.84	0.442
GW190814	BBH	0.59	0.309
GW191219_163120	NSBH	0.67	0.347
GW200105_162426	NSBH	0.47	0.382
GW200115_042309	NSBH	0.68	0.078
GW200210_092254	NSBH	0.13	0.303

Note. Three events from GWTC-2.1 (Abbott et al. 2021a) and four events from GWTC-3 (Abbott et al. 2021b) were followed up as they were the only potential BNS/NSBH candidates.

development of general multimessenger search methods for many messengers (Veske et al. 2021a).

In addition to the low-latency follow-ups, we performed three offline analyses of the GW events reported in GWTC-2.1 and GWTC-3. The first analysis searched for neutrino emission within a ± 500 s time window centered around the GW merger time. Both the UML and LLAMA methods performed this search, and no significant neutrino emission was observed in either search.

The second analysis was a two-week follow-up of all BNS and NSBH candidate events with the UML search. All the GW events followed up in this analysis had at least one progenitor object with a mass estimate of $< 3 M_{\odot}$. No significant neutrino emission was observed, and 90% ULs were placed on the time-integrated neutrino flux from each source.

The third analysis searched for neutrino emission from the potential optical counterpart of the BBH merger GW190521 reported by ZTF. The UML analysis tested a time window of

112 days following the GW merger time, which covers the entire flare in the optical light curve. The UML analysis assumed a uniform neutrino emission within the time window. The LLAMA analysis assumed linearly decreasing neutrino emission in a 57 day time window according to the contemplated emission scenario for the optical flare. No significant neutrino emission was observed in both analysis methods, and we derived 90% ULs on the time-integrated flux and the E_{iso} from the AGN J124942.3+344929.

Apart from the analyses presented here, there also exists a gravitational-wave follow-up analysis with neutrinos of a few 10–100 s of GeV energies detected by IceCube (Balagopal et al. 2021). This upcoming analysis will provide additional information, complimentary to the analyses with high-energy neutrinos presented here. Additionally, a search for extremely low-energy neutrinos, with 0.5–5 GeV energies, from IceCube was conducted and found no significant emission of neutrinos (Abbasi et al. 2021).

The low-latency and archival searches will continue to function during the upcoming O4 run of LVK. It is expected that the O4 operational run will demonstrate enhanced performance, thereby increasing the rate of expected mergers. This would provide more opportunities to conduct multimessenger studies, which may lead to a potential discovery of neutrino and gravitational wave correlations. Additionally, the inclusion of more detectors from LVK will reduce the area of the sky localizations of the GW skymaps. This is also expected to contribute to higher significances in case of coincident detections (Abbott et al. 2018).

Future GW detectors like the Einstein Telescope (ET Science Team 2011) and Cosmic Explorer (Reitze et al. 2019) aim at achieving improved sensitivities and lowering their frequency regime of operation. These improved detectors are expected to enhance the rate of observed merger events with better precision, which will in turn boost the capabilities of multimessenger observations of these sources (Kalogera et al. 2019). The next generation of the IceCube Neutrino Observatory, IceCube-Gen2, is planned to be an eightfold extension to the instrumented volume of the current detector array. It is expected to extend the current energy range of IceCube to several 100 s of PeV (Aartsen et al. 2021). IceCube-Gen2 can potentially help in addressing the question of joint emission of neutrinos and GWs, when used in tandem with future GW detectors.

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Appendix A Skymaps

This appendix includes the skymaps obtained in the context of this analysis. Figure 7 shows the TS maps for the two-week follow-up analysis. Figures 8 and 9 show the skymaps with the GW probabilities and the observed neutrinos within the 1000 s time window in the archival search.

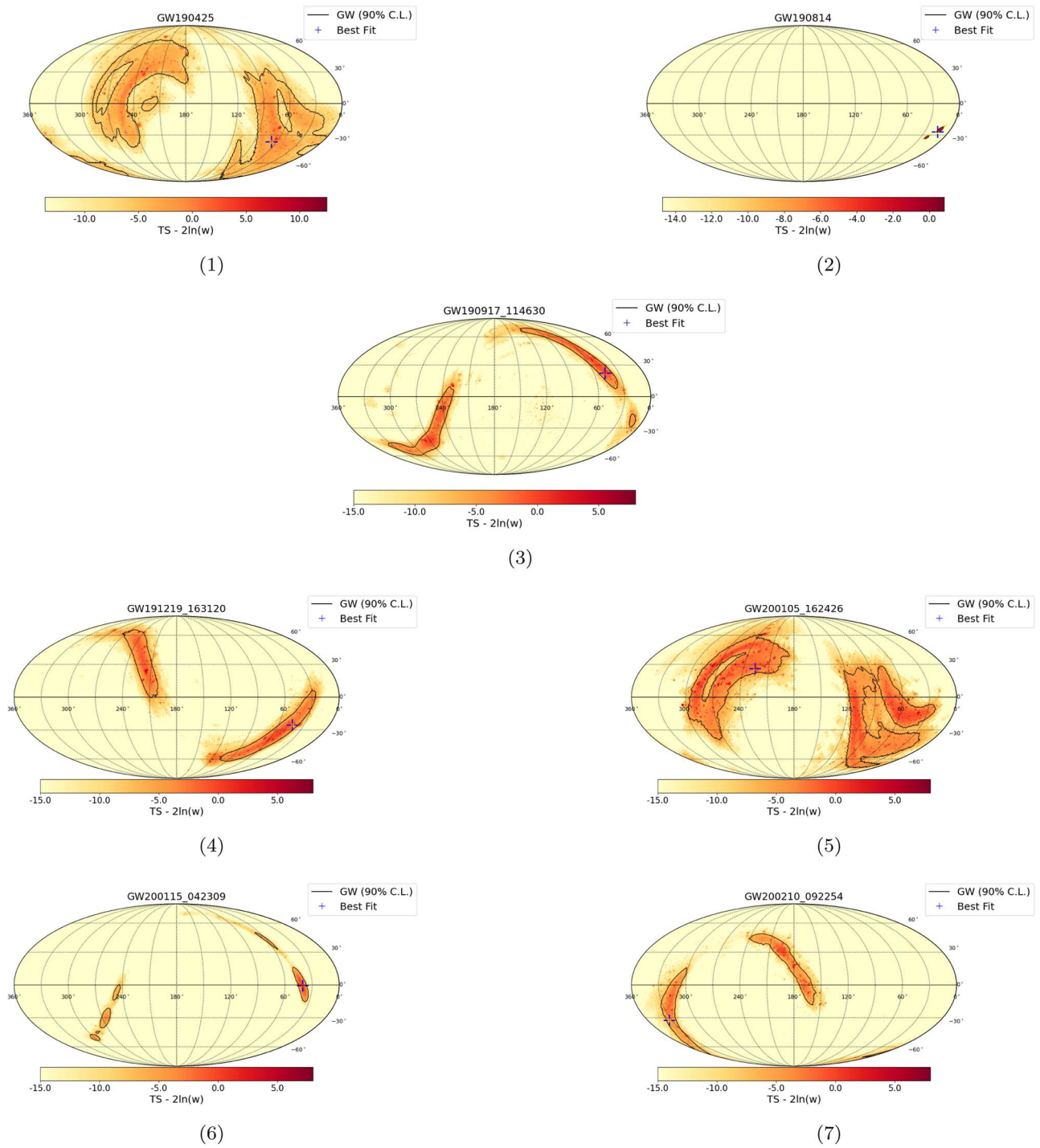


Figure 7. Final test statistic maps for the three BNS and NSBH candidates in GWTC-2.1 (Abbott et al. 2021a), and the four NSBH candidates in GWTC-3 (Abbott et al. 2021b). The pixel with the highest test statistic in the sky is shown in the blue crosshairs. The color scale shows the test statistic weighted by the GW localization information. Here $w = P_{\text{GW}}(\Omega)/A_{\text{pix}}$, where $P_{\text{GW}}(\Omega)$ is the probability of the GW source being in a given pixel and A_{pix} is the pixel area.

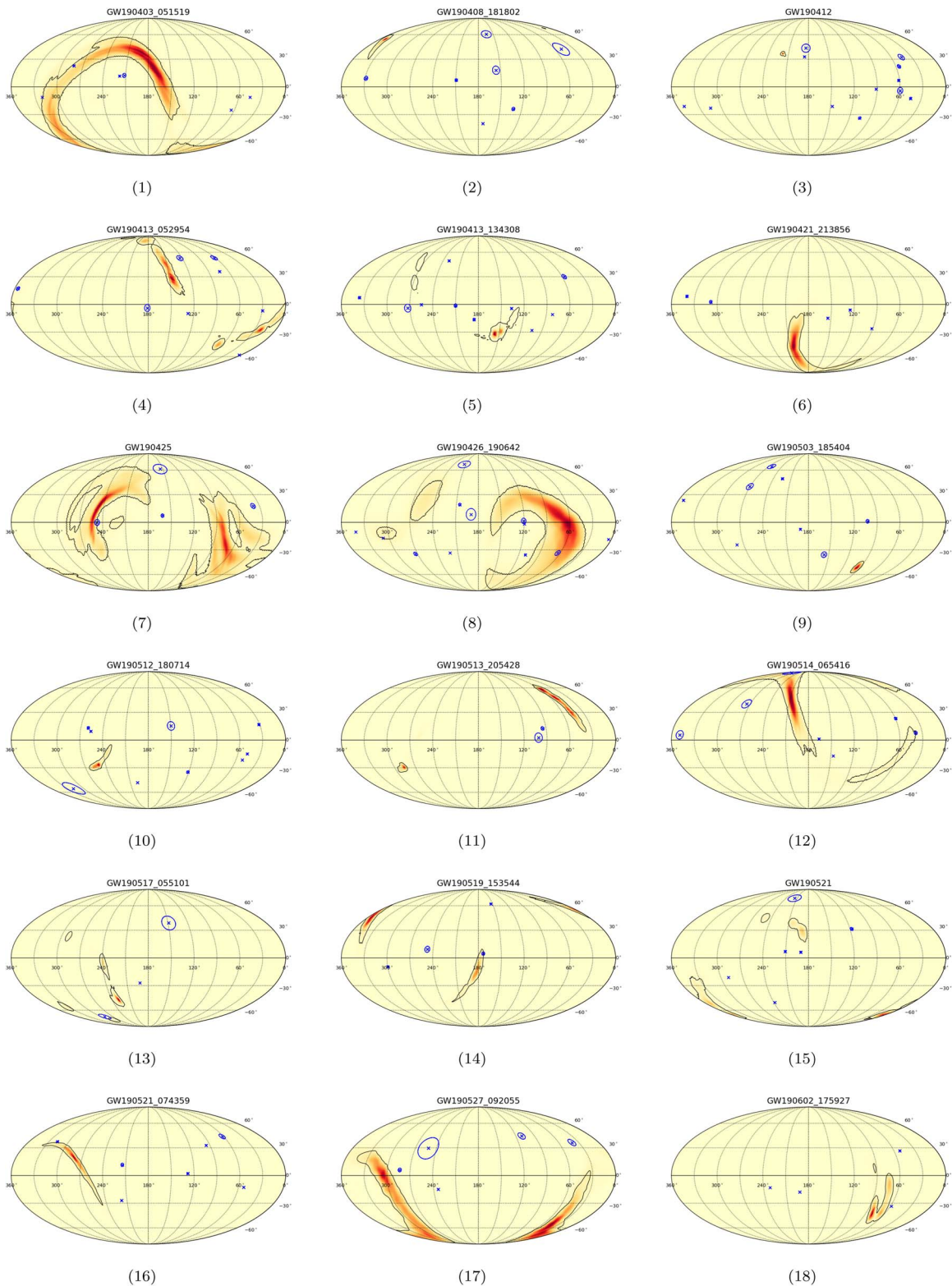


Figure 8. Skymaps for the 1000 s follow-up of all events from the GWTC-2.1 (Abbott et al. 2021a) catalog. Shown in red is the localization probability of the GW event with the black contour representing the 90% containment region of the GW localization. The blue crosses show the best-fit neutrino candidate directions with the blue circles representing the 90% angular error region of the neutrino candidates.

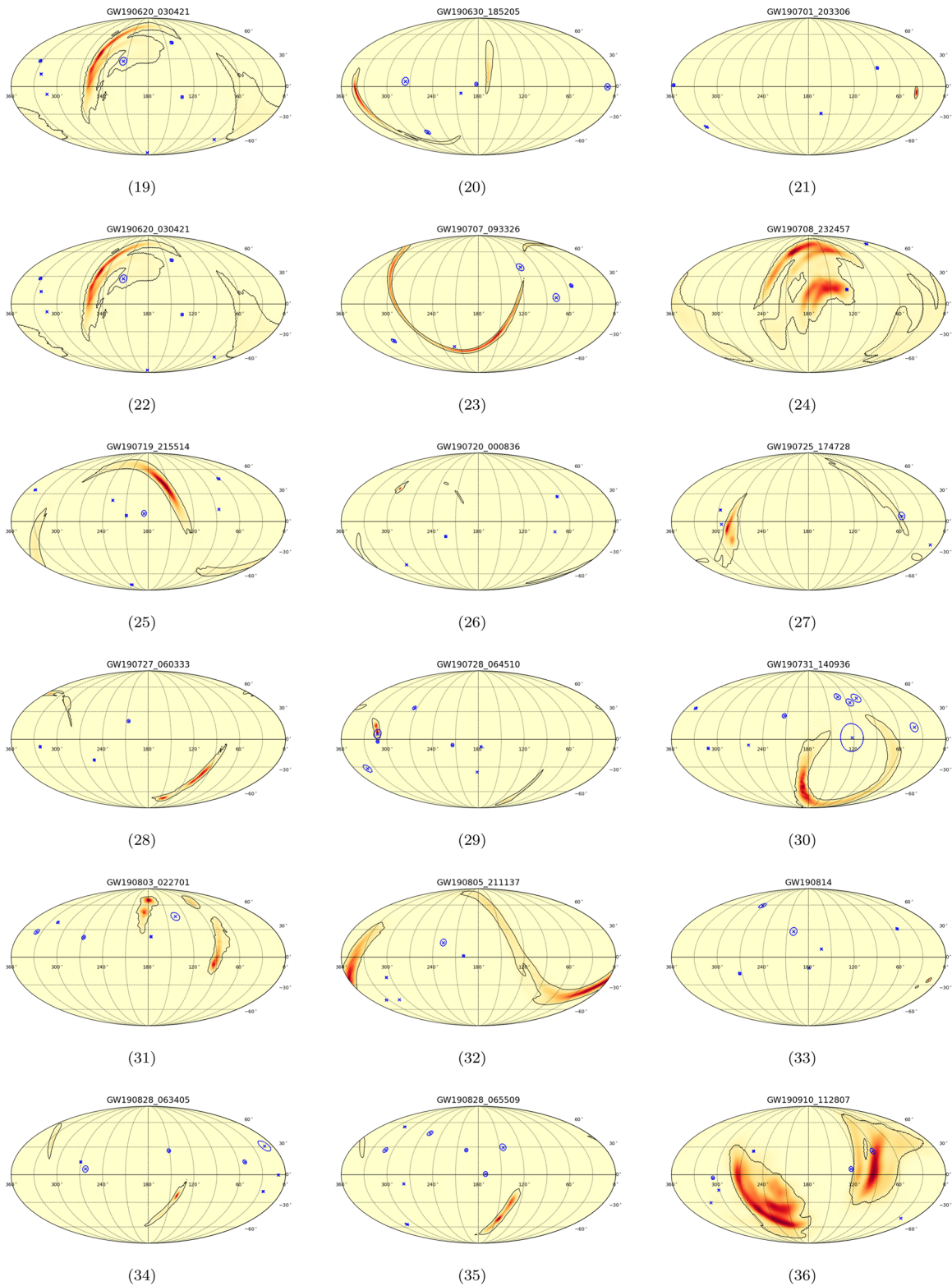


Figure 8. (Continued.)

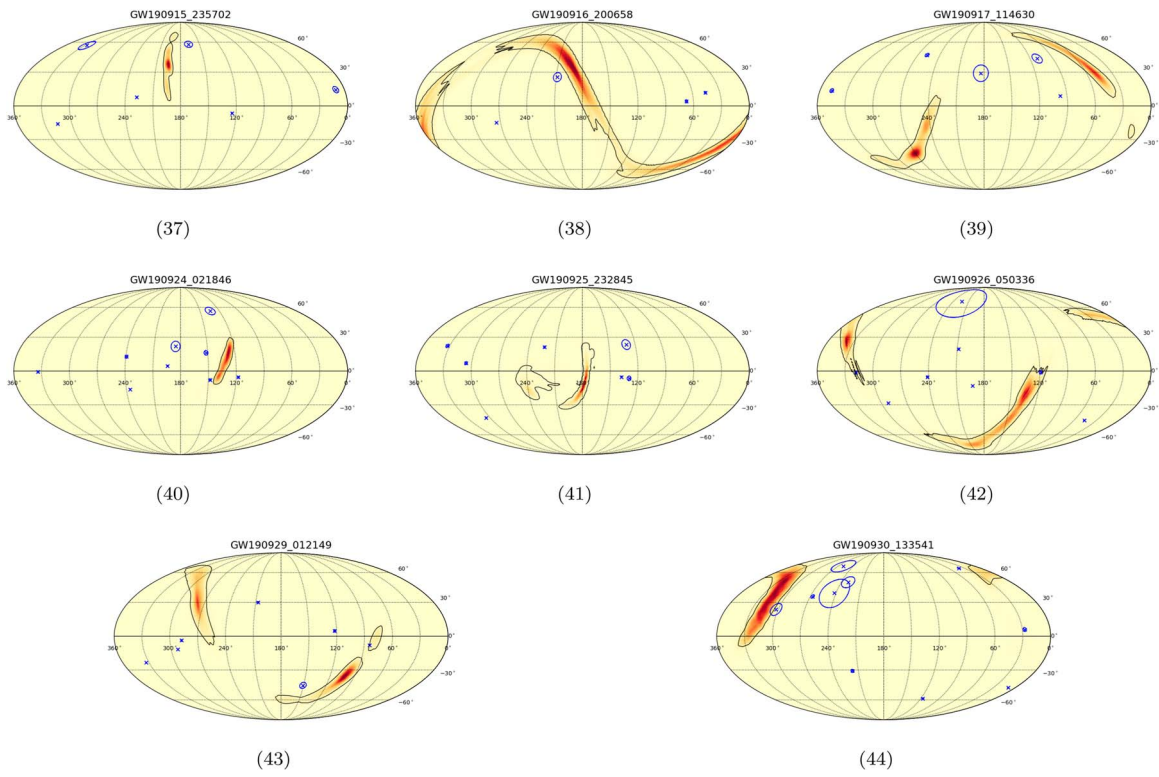


Figure 8. (Continued.)

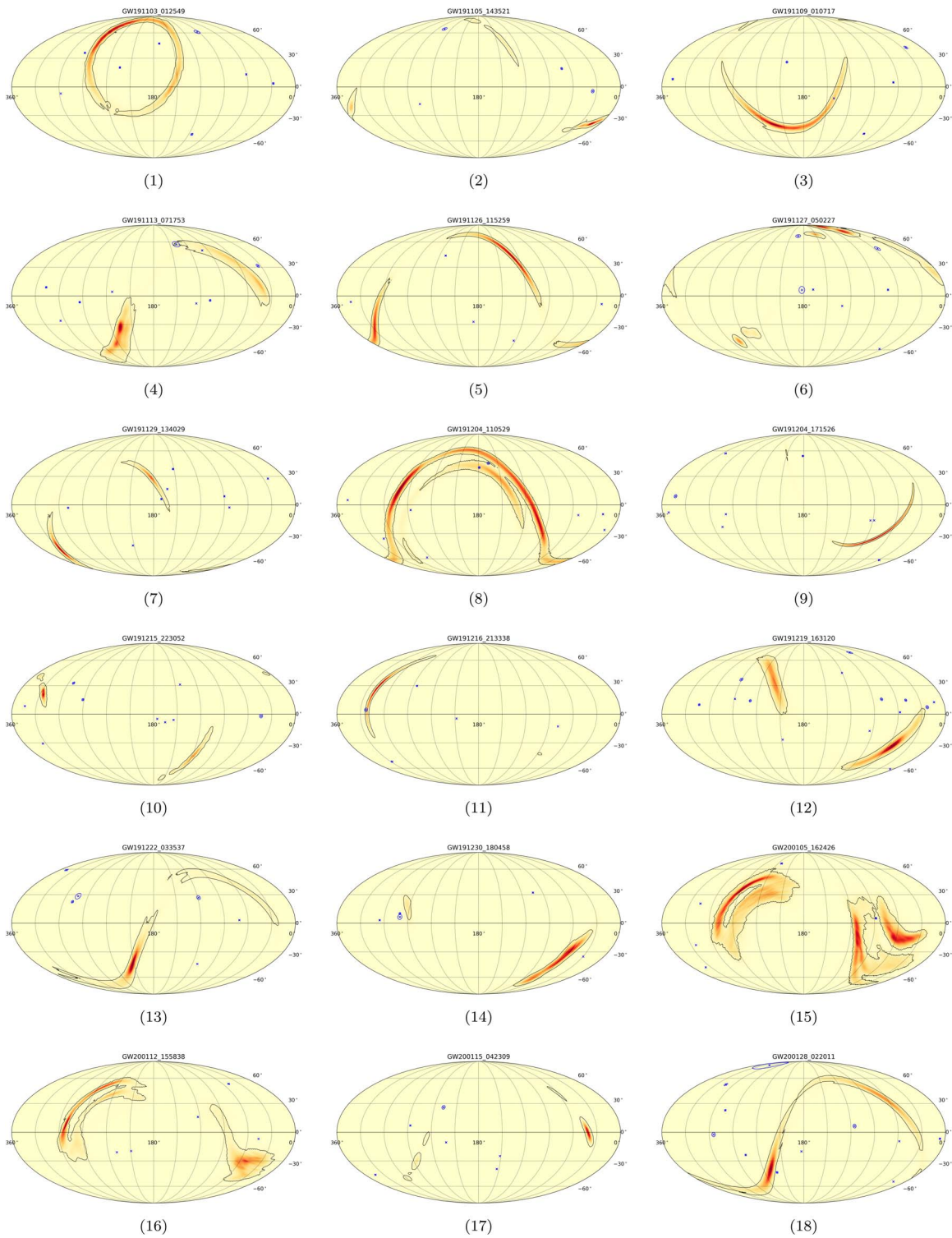


Figure 9. Skymaps for the 1000 s follow-up of all events from the GWTC-3 (Abbott et al. 2021b) catalog.

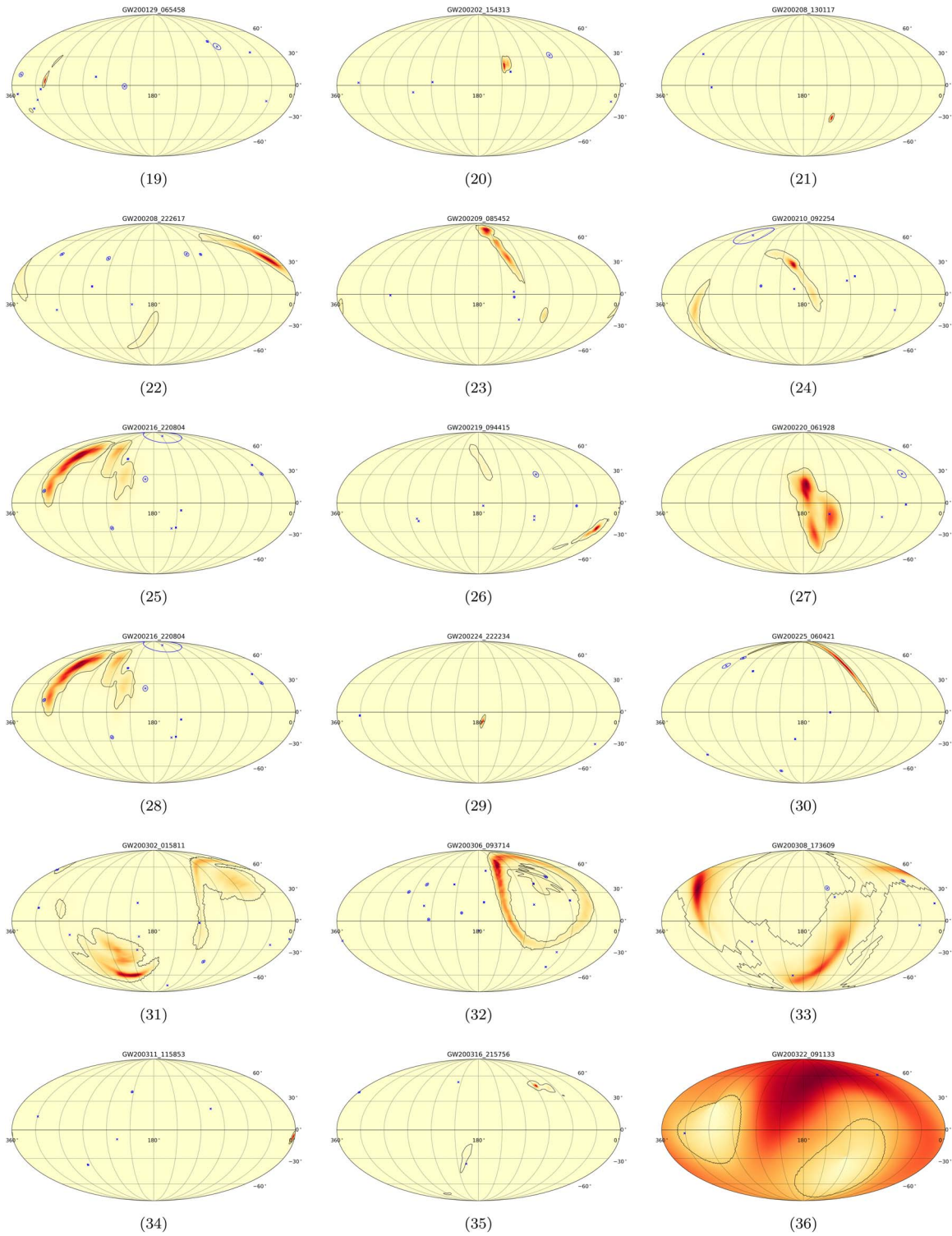

























































Figure 9. (Continued.)

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