Swift Follow-up Observations of Gravitational-wave and High-energy Neutrino Coincident Signals

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Abstract

Electromagnetic observations of gravitational-wave and high-energy neutrino events are crucial in understanding the physics of their astrophysical sources. X-ray counterparts are especially useful in studying the physics of the jet, the energy of the outflow, and the particle acceleration mechanisms in the system. Ultraviolet and optical observations can help us constrain the mass and velocity of the outflow and provide hints on the viewing angle. We present the Neil Gehrels Swift Observatory prompt searches for X-ray and UV/optical counterparts to the joint gravitational-wave and high-energy neutrino coincident events that happened during the third observing run of LIGO/Virgo. Swift observed the overlap between gravitational-wave and neutrino error regions for three of the considerable (p-value < 1%) joint gravitational-wave and high-energy neutrino coincident alerts, which were generated by the IceCube Neutrino Observatory in real time after triggering by the LIGO/Virgo gravitational-wave public alerts. The searches did not associate any X-ray or UV/optical counterparts with any of the joint gravitational-wave and high-energy neutrino coincident events; however, the follow-up of these alerts significantly improved the tilting techniques covering regions between the gravitational-wave sky maps and the neutrino’s error regions, making the real-time system ready for future potential discoveries. We discuss the details of each follow-up procedure, the results of each search, and the plans for future searches.

Unified Astronomy Thesaurus concepts: X-ray astronomy (1810); X-ray sources (1822); Gravitational waves (678); Cosmological neutrinos (338); Particle astrophysics (96)

1. Introduction

Multimessenger searches have opened up new doors to astrophysical source discoveries, which result in understanding the physics of the sources and the underlying mechanisms that produce the messenger particles and waves. Notably, the GW170817 event (Abbott et al. 2017a), which was detected by the LIGO and Virgo detectors (Aasi et al. 2015; Acernese et al. 2015) and was immediately found to be in coincidence with GRB-170817A (Goldstein et al. 2017; Savchenko et al. 2017), started an extensive multimessenger search, resulting in the discovery of a kilonova and in expanding our knowledge about binary neutron star (BNS) systems (Abbott et al. 2017b). Around the same time, the IceCube-170922A neutrino candidate detected by the IceCube Neutrino Observatory was found to be associated with a flaring blazar, TXS 0506+056, which also initiated broad follow-up observations in different wavelengths (Aartsen et al. 2018).

Although we have observed a couple of significant multimessenger events so far, we have not yet been able to identify any significant joint sources of gravitational waves (GWs), neutrinos, or electromagnetic waves (Barts et al. 2011; Aartsen et al. 2014, 2020a, 2020b; Adrián-Martínez et al. 2016; Albert et al. 2017a, 2017b, 2019). In a BNS merger event, it is thought that high-energy neutrinos are produced in nonthermal dissipative processes, such as relativistic outflows (Barts et al. 2013; Murase & Bartos 2019), and could produce short gamma-ray bursts (GRBs) within two seconds of the merger. The case of GW170817/GRB170817 was strong evidence for the presence of such systems. No neutrinos were found to be spatially coincident with the GW170817 event (Albert et al. 2017b) within ±500 s of the merger. This was consistent with a short GRB observed at a large off-axis angle (Albert et al. 2017b; Margutti et al. 2017; Alexander et al. 2018; Ioka & Nakamura 2018; Mooley et al. 2018; Ruan et al. 2018). Typical opening angles for short GRBs are between 5° and 10° (Berger 2014). If the angle between the GRB jet and our line of sight is larger than the opening angle, the short GRB is considered to be off-axis. The off-axis angle for GRB170817 was found to be 20°–30° (Albert et al. 2017b; Alexander et al. 2018; Mooley et al. 2018; Troja et al. 2018).

Although it is more likely for neutrinos to be produced in a compact binary system including one neutron star, that is, a BNS or a neutron star–black hole (NSBH), it is still possible to detect neutrinos from a binary black hole (BBH) merger if the black holes are in a gas-rich environment that they can accrete from (Murase & Bartos 2019). Such a scenario could arise within the accretion disk of active galactic nuclei (Barts et al. 2017; Stone et al. 2017; McKernan et al. 2019; Yang et al. 2019a, 2019b, 2020a, 2020b). A candidate counterpart for a black hole merger has already been detected by the Zwicky Transient Facility, which, if true, would support this emission...
scenario (Graham et al. 2020). Nonetheless, these systems need further studies to better understand their properties and the expected electromagnetic and neutrino emission from them.

For the second observing period of LIGO/Virgo, the joint search for coincident gravitational-wave and high-energy neutrino events was upgraded and performed in near real time (Countryman et al. 2019), and a low-latency joint search continued for the LIGO/Virgo observing run O3 with two methods (Bartos et al. 2019; Hussain et al. 2019; Keivani et al. 2019). Triggered by LIGO/Virgo’s public alerts, the real-time analyses are run in IceCube to search for spatially correlated neutrinos within a \( \pm 500 \) s time window around the GW trigger time (Baret et al. 2011). For any GW candidate and for each correlated neutrino, a \( p \)-value is calculated that indicates the consistency of the lack of a relation with the observed neutrinos and the candidate GW source. An overall \( p \)-value considering the full combination is also calculated. If a \( p \)-value \(< 0.01\) is achieved from the IceCube analysis, a Gamma-ray Coordinates Network (GCN) circular encourages the community to do further follow-up observations in the direction of the most significant correlated neutrino (Aartsen et al. 2020a).

The Neil Gehrels Swift Observatory followed up three of the coincident GW+neutrino candidates (S190728q, S191216ap, S200213t) during O3 (2019 April 1 to 2020 March 27) under our Swift Cycle 15 guest investigator program. During this period, there were a total of 56 GW candidates from which only these three events had a coincident neutrino with a \( p \)-value of less than \( 1\% \). The goal of these observations was to identify electromagnetic counterparts of GW+neutrino events. Here, we report the results of these searches, as well as the techniques we have developed to define the most probable parts of the joint GW+neutrino candidate. An overview of pointed Swift follow-up of all GW triggers in O3 is given in Page et al. (2020) and Oates et al. (2021, submitted), for X-Ray Telescope (XRT) and UltraViolet/Optical Telescope (UVOT), respectively.

In Section 2, the techniques we used to perform the tiled observations of GW+neutrino candidate localization with Swift will be presented. In Section 3, the details of each Swift follow-up observation will be presented after reviewing the general properties of the respective gravitational-wave and neutrino events, for all candidates. We will discuss the likelihood of these GW+neutrino alerts being real coincident events based on different possible source scenarios capable of producing joint GW+neutrino alerts, in the last section (Section 4).

2. Techniques

One of the great advantages of the GW+neutrino searches comes from the fact that the 90\% containment region of a neutrino event is by far smaller than that of a GW event, which provides a great opportunity for observatories with smaller fields of view to search for electromagnetic counterparts of gravitational waves.

The ideal case to follow up a joint GW+neutrino candidate event with Swift happens when the neutrino is relatively well localized; that is, its 90\% containment radius is \( \lesssim 1^\circ \). In such cases, Swift can easily use one of its on-board tiling patterns to conduct follow-up searches: 7 tiles for \( 12^\circ < R < 33^\circ \), 19 tiles for \( 33^\circ < R < 47^\circ \), or 37 tiles for \( 47^\circ < R < 66^\circ \), where \( R \) is the neutrino’s 90\% containment radius. In cases where the neutrino’s 90\% containment radius is \( \gtrsim 1^\circ \), the Swift+LVC +IceCube team needs to make a decision on how many tiles to dedicate to the follow-up of the alert based on the joint GW+neutrino probability density map and the observing priorities.

In the case where error regions are significantly larger or not optimally covered by the nominally hexagonal Swift tiling techniques, Swift has the ability to perform large-scale arbitrary tiling, which was first developed to meet the needs of covering the large tiling areas required for follow-up GW-only triggers (Evans et al. 2016; Tohuvavohu et al. 2018). In the case of a LVC+IceCube trigger, the convolved probability map, produced by multiplying the GW and IceCube probability maps, is taken, and an optimal tiling solution is calculated by placing overlapping tiles on the probability map. This starts by defining a grid of fixed-space tiles, centered on the region of highest probability. Tiles are added at these fixed positions which cover the regions of highest probability. The fixed spacing of the tiles means that there is overlap between them, which ensures full coverage of the probability region without the gaps that might otherwise occur when covering a uniform region with the approximately circular Swift-XRT field of view. For small circular error regions, this algorithm reproduces the 7-, 19-, and 37-tile automated tiling regions, with the added benefit that it can handle much larger and nonuniformly shaped error regions. The tiling algorithm adds tiles in reverse order of probability, so the highest probability is covered first, then down to the lowest. The tiling algorithm continues to add tiles covering the remaining regions of highest probability until either a defined maximum number of tiles is reached or the total integrated probability covered by the tiles reaches a maximum value.

The list of tile coordinates is then fed into a high-fidelity observation planning algorithm (Tohuvavohu et al. 2018), which is based upon the current Swift observing plan and the visibility of the tiles and calculates an optimized observing time line, prioritizing both speed of completion and coverage of the highest probability regions earliest. Due to the complexity of these tiling plans, they require a ground station contact to upload to Swift before execution can begin. Typical latencies for Swift ground-station contacts are around 40 minutes, although longer gaps can occur. In the case of S190728q and S191216ap, this tiling method was utilized, and the tiling patterns that resulted can be seen in Figures 1 and 2.

3. Observations

In this section, three different gravitational-wave events (S190728q, S191216ap, S200213t) detected by LIGO/Virgo will be reviewed along with the respective neutrino candidates from IceCube and the follow-up observations performed by Swift. The Swift-XRT data were analyzed using the standard GW analysis pipeline (see Evans et al. 2016; Klingler et al. 2019; K. L. Page et al. 2021, in preparation). For details of the source detection methodology, see Evans et al. (2020). The Swift-UVOT data were analyzed using the UVOT GW pipeline (see Oates et al. 2021, submitted). All candidate UVOT sources were manually vetted.

3.1. LIGO/Virgo S190728q Candidate

The LIGO Scientific Collaboration and the Virgo Collaboration (LVC) reported the identification of the compact binary merger candidate S190728q on 2019 July 28. The estimated false-alarm rate of the event calculated through the LVC online analysis was determined to be \( 2.5 \times 10^{-23} \) Hz, or about one in
$10^{15}$ yr (LIGO Scientific Collaboration & Virgo Collaboration 2019a). Initially, the gravitational wave signal was classified to have the following probabilities: mass gap ($52\%$), binary black hole ($34\%$), NSBH ($14\%$), binary neutron star ($<1\%$), or terrestrial ($<1\%$). Assuming an astrophysical origin for the event, the lighter object was calculated to have a mass of less than three solar masses. Using the bayestar.fits.gz sky map, the 90% credible region was estimated to be $543$ deg$^2$. However, upon further analysis, the gravitational wave classification was modified to the following probabilities: BBH ($95\%$), mass gap ($5\%$), NSBH ($<1\%$), or BNS ($<1\%$). With the new preferred sky map LALInference.offline.fits.gz, the 90% credible region was also updated to be $104$ deg$^2$, and there is strong evidence that the lighter object may not be lighter than three solar masses (LIGO Scientific Collaboration & Virgo Collaboration 2019b). The source distance was estimated to be $858 \pm 192$ Mpc at the 90% credible level.

The GW alert triggered several observatories in real time, and many follow-up observations were performed that included the search for low-energy neutrino candidates by the IceCube Neutrino Observatory.

**IceCube Neutrino Candidate:** IceCube searched its data for track-like muon neutrino candidates within a 1000 s time span centered around the GW candidate S190728q alert time of 06:45:10.529 UTC on 2019 July 28 (IceCube Collaboration 2019a). In the initial search, no significant track-like events were captured by IceCube during this time frame. However, further analysis based on the updated GW sky map found one neutrino candidate in spatial (R.A., decl. = $312^\circ.87$, $5^\circ.85$; J2000) and temporal (time offset of $-360$ s) coincidence with the GW candidate S190728q (IceCube Collaboration 2019b). The 90% containment radius for this neutrino candidate was $4^\circ.81$. Overall, two hypothesis tests were conducted on the neutrino candidate. One utilized a maximum-likelihood analysis, which yielded an overall $p$-value of $0.014$ ($2.21\sigma$; Hussain et al. 2019), while the other utilized a Bayesian approach, which yielded an overall $p$-value of $0.01$ ($2.33\sigma$; Bartos et al. 2019). These $p$-values quantify the unrelatedness between the candidate GW source and the observed neutrinos.

**Swift Observations:** Swift observed the direction of the IceCube track-like muon neutrino candidate (IceCube Collaboration 2019b), which was consistent with the sky localization of gravitational-wave candidate S190728q (LIGO Scientific Collaboration & Virgo Collaboration 2019b), covering $\sim 14.5$ deg$^2$ in 145 tiles (Figure 1), to cover the most probable regions of the joint GW and neutrino localization (Tohuvavohu et al. 2019). The observations ran from 2019 July 28 at 19:27 UT to 2019 July 29 at 11:41 UT, that is, $46–104$ ks or $12.8–28.9$ hr after the LVC trigger. The average sensitivity of the observations was $\sim 2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (0.3–10 keV).

Three X-ray sources were detected. The automated analysis pipeline assigns each source a “rank” of 1–4 that describes how likely it is to be related to the GW trigger, with 1 being the

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10 The masses of the lightest object ranged between 2.5 and 5 solar masses, which are the masses of the heaviest observed neutron star and the lightest black hole, respectively.

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![Figure 1](image-url). Tiling map of Swift-XRT to follow up the joint LIGO/Virgo S190728q and IceCube neutrino candidate. The blue circle shows the 90% containment circle of the IceCube neutrino candidate.
most likely and 4 being the least likely. All three sources matched known X-ray sources. We used a power-law spectrum with $N_H = 3 \times 10^{20}$ cm$^{-2}$ and photon index $\Gamma = 1.7$ to convert the measured count rates to fluxes for comparison with catalogs; all three sources had fluxes below their catalogued values and were therefore assigned rank 4 and are not considered as likely counterparts to the joint GW+neutrino candidate. Details of these sources are listed in Table 1.

Only one UVOT source was of interest after manual inspection of optical sources tagged by the UVOT pipeline. This source was observed because of a target of opportunity (ToO) of an object initially reported by the Zwicky Transient Facility as ZTF19abjethn (AT2019lvs; Kasliwal et al. 2019). This object was identified as a Cataclysmic Variable (Smartt et al. 2019), and as such this object is not considered as the likely counterpart to the joint GW+neutrino candidate.

### 3.2. LIGO/Virgo S191216ap Candidate

On 2019 December 16, LVC reported the detection of the compact binary merger candidate S191216ap (LIGO Scientific Collaboration & Virgo Collaboration 2019c). The false-alarm rate estimated by the online analysis was calculated to be about $10^{-23}$ Hz, or one in $10^{15}$ yr. The GW signal was classified with the following probabilities: mass gap (>99%), BBH (<1%), NSBH (<1%), BNS (<1%), or terrestrial (<1%). Assuming astrophysical origins, there was a 19% probability that the lighter compact object had a mass that was less than three solar masses. The latest public classification identified this event as a BBH with 99% probability. The 90% credible region was identified to be 300 deg$^2$ using the bayestar.fits.gz,0 sky map. The distance of the event was reconstructed to be 376 ± 70 Mpc at 90% credible interval.

Further analysis was performed, and the new classification of the event was described by the following probabilities: BBH (>99%) and mass gap (<1%), and the rest remained the same.

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**Figure 2.** Tiling map of Swift-XRT following up the joint LIGO/Virgo S191216ap and IceCube neutrino candidate. The blue circle shows the 90% containment circle of the IceCube neutrino candidate.

**Table 1**

| Source          | Match                 | R.A.          | Decl.         | Err$_{90}$ | $F_{12}^a$ | Flag$^b$ | Rank |
|-----------------|-----------------------|---------------|---------------|------------|------------|----------|------|
| S190728q_X1     | 1RXS J205242.6+081039 | 313\°1761     | 6\°1785       | 6\°9       | 4.6 (±1.9) | Good     | 4    |
| S190728q_X2     | 1RXS J205421.7+090229 | 313\°58716    | 9\°0381       | 6\°9       | 2.6 (±1.3) | Good     | 4    |
| S190728q_X3     | XMMSL2 J204928.9+060159 | 312\°37177    | 6\°0305       | 6\°2       | 4.7 (±1.6) | Good     | 4    |

Notes.

$a$ $F_{12}$ is 0.3–10 keV flux in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$, calculated assuming a power-law spectrum with photon index $\Gamma = 1.7$ and $N_H = 3 \times 10^{20}$ cm$^{-2}$.

$b$ Flags Good/Reasonable/Poor refer to a spurious detection rate of ∼0.3%, 1%, and 10%, respectively; see Evans et al. (2020) for details.

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11 https://www.swift.ac.uk/ranks.php
Table 2

X-Ray Sources Found in the Swift Follow-up Observations of the Joint LIGO/Virgo S191216ap and IceCube Neutrino Candidate

| Source          | Match         | R.A.   | Decl. | Err(μ) | $F_{12}$ | Flag | Rank |
|-----------------|---------------|--------|-------|--------|----------|------|------|
| S191216ap_X1    |               | 322°1300 | +4°8310 | 6'1 | 3.2+1.3/−1.6 | Good | 3   |
| S191216ap_X2    | XMMSL2 J212817.4+034848 | 322°0752 | +3°8154 | 7'7 | 6.7+2.4/−1.1 | Good | 4   |
| S191216ap_X3    | 2SXPS J213053.0−040229 | 322°7186 | +4°0414 | 5'5 | 6.5+2.7/−2.4 | Good | 4   |
| S191216ap_X4    |               | 325°4550 | +4°9553 | 6'7 | 0.87+0.54/−0.37 | Good | 3   |
| S191216ap_X5    |               | 325°3284 | +5°2847 | 6'9 | 0.55+0.33/−0.21 | Good | 3   |
| S191216ap_X6    |               | 325°7216 | +5°3197 | 6'6 | 0.75+0.18/−0.13 | Good | 3   |
| S191216ap_X7    |               | 325°1842 | +4°3350 | 5'8 | 0.13+0.04/−0.03 | Good | 3   |
| S191216ap_X8    |               | 325°1995 | +4°4645 | 5'5 | 0.24+0.08/−0.06 | Good | 3   |
| S191216ap_X9    |               | 325°1114 | +4°3588 | 5'3 | 0.28+0.10/−0.08 | Good | 3   |
| S191216ap_X10   |               | 325°0271 | +4°3106 | 6'9 | 0.14+0.07/−0.05 | Good | 3   |
| S191216ap_X11   | IRXS J213242.1+042357 | 325°1709 | +4°4052 | 6'2 | 0.16+0.06/−0.05 | Good | 4   |
| S191216ap_X12   |               | 325°9441 | +5°7457 | 7'0 | 0.16+0.07/−0.05 | Good | 3   |
| S191216ap_X13   |               | 325°9867 | +5°1896 | 8'0 | 0.10+0.05/−0.03 | Good | 3   |
| S191216ap_X14   | 2SXPS J213032.7+050216 | 325°6371 | +5°0384 | 7'5 | 1.1+0.6/−0.4 | Good | 4   |
| S191216ap_X15   |               | 325°6096 | +5°1020 | 7'2 | 0.16+0.07/−0.05 | Good | 3   |
| S191216ap_X16   | 2SXPS J213122.3+050236 | 325°8443 | +5°0437 | 5'4 | 0.20+0.05/−0.03 | Good | 4   |
| S191216ap_X17   |               | 325°9324 | +5°4210 | 6'0 | 0.17+0.08/−0.06 | Good | 3   |
| S191216ap_X18   |               | 325°7879 | +5°5795 | 4'6 | 0.21+0.08/−0.06 | Good | 3   |
| S191216ap_X19   |               | 325°9901 | +4°7273 | 7'4 | 0.13+0.08/−0.06 | Good | 3   |
| S191216ap_X20   |               | 325°8833 | +4°9008 | 5'9 | 0.31+0.10/−0.08 | Good | 3   |
| S191216ap_X21   |               | 325°9354 | +5°3867 | 7'4 | 1.1+0.7/−0.8 | Poor | 3   |

Note. See Table 1 for column definitions.

as in the initial analysis (LIGO Scientific Collaboration & Virgo Collaboration 2019d). Along with this, the new preferred sky map was LALInference.fits.gz, and the 90% credible region was decreased to 253 deg$^2$ (LIGO Scientific Collaboration & Virgo Collaboration 2019e). As with previous detections, the GW alert prompted other observatories to collect data in real time. Follow-up searches of collected data were also performed by observatories such as the IceCube Neutrino Observatory.

IceCube Neutrino Candidate: In a follow-up search by IceCube, one neutrino candidate was found in spatial (R.A., decl. = 323°19, 4°53; J2000) and temporal (time offset of −43 s, with the neutrino being detected before the GW alert) coincidence with the GW alert S191216ap (Hussain 2019). The IceCube search was initially planned to be performed in a 1000 s time window centered around the S191216ap alert time 21:34:01 UTC. However, power issues occurred at the experimental site during the time of 21:33:21 UTC, which interfered with the data collection quality. Thus, only data collected before this time was considered. The neutrino candidate detected by IceCube underwent both the maximum-likelihood and Bayesian analyses. These hypothesis tests obtained $p$-values of 0.104 (1.26σ) and 0.0059 (2.52σ), respectively.

It is also worth noting that the ANTARES Neutrino Observatory (with a lower sensitivity compared to IceCube for these candidates) did not detect any counterpart neutrino candidate for the S191216ap event (Ageron et al. 2019).

Swift Observations: Swift carried out 100 observations of the overlap between the LVC (LIGO Scientific Collaboration & Virgo Collaboration 2019c) and the IceCube (Hussain 2019) error regions for the GW trigger S191216ap (Evans et al. 2019a). The observations were taken on 2019 December 17, from 03:56 UT to 09:14 UT, that is, 23−42 ks or 6.4−11.7 hr after the LVC trigger. The average sensitivity of the observations was $\sim 2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (0.3−10 keV; Figure 2). This covered 3.3% of the probability in the reported sky map using bayestar.fits.gz, 5.8% after convolving with the 2MPZ galaxy catalog, as described by Evans et al. (2016), and 65% of the probability contained within the combined GW and neutrino localizations. The pointings and associated metadata were also reported to the Treasure Map12 (Wyatt et al. 2019, 2020).

Swift-XRT detected three X-ray sources. One of these was rank 3 (uncataloged in X-rays, with flux below the upper limit generated from existing surveys), and two of rank 4 (catalogued in X-rays, with a catalogued flux consistent with or brighter than our measured flux).

Further searches were performed by Swift (Evans et al. 2019b) after the High-Altitude Water Cherenkov (HAWC) Observatory revealed a relatively significant subthreshold event at R.A., decl. = 323°53, 5°23 (J2000) coincident with the updated localization of the neutrino event found 80 s after the time of coalescence (HAWC Collaboration 2019). Swift observations covered the HAWC error region for ~500 s per tile from 2019 December 19 at 18:18 UT to 2019 December 20 at 02:20 UT (i.e., 75−104 ks or 20.8−28.9 hr after the LVC trigger), with a sensitivity of $\sim 4 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. Additionally, ~3 ks of observations were conducted for each of the galaxies listed by Singer et al. (2019). These observations ran between 2019 December 19 at 23:41 UT and 2019 December 20 at 12:09 UT (i.e., 94−139 ks or 26.1–38.6 hr after the LVC trigger), with a sensitivity of $10^{-13}$ erg cm$^{-2}$ s$^{-1}$. A total of 18 X-ray sources were detected in these searches: 14 of rank 3 and four of rank 4. Given these ranks, none of these are strong candidates for the counterpart to the GW event. Details of these sources are listed in Table 2.

12 http://treasuremap.space/alerts?graceids=S191216ap
Only one UVOT source was of interest after manual inspection of sources flagged by the UVOT pipeline. This source is at position R.A., decl. (J2000) = 322°0254, 2°5390 with an estimated uncertainty of 0°7 (radius, 90% confidence). It had a $u$-band magnitude of 17.35 ± 0.08 mag. This source was also reported by MASTER (Lipunov et al. 2019) and is consistent with the CV CSS 151110: 212806+023221. The TNS name is AT 2020ae. As such, this object is not considered as the likely counterpart to the joint GW+neutrino candidate.

The Swift-UVOT data were analyzed using the UVOT GW pipeline (see Oates et al. 2021, submitted, for full details). We provide a brief overview here. The pipeline searches the UVOT sky images to identify new transient sources that might be the counterpart to the GW event. For each observation, the HEASoft flood utility uvotdetect (based on SExtractor; Bertin & Arnouts 1996) is run for that exposure to search for sources. All sources found are then run through a series of checks to determine if they are previously catalogued (known) sources, extended sources, sources due to image artifacts, or minor planets. The pipeline reliably finds new sources if they are isolated from existing sources and not affected by defects in the UVOT images (artifacts) caused by very bright sources. Small images (thumbnails) are produced for all candidates, and also for all nearby galaxies reported in the GLADE Catalog (Dálya et al. 2018), whose positions were observed by UVOT. This enables rapid manual inspection to evaluate the reliability of possible UVOT counterparts. Candidate inspection is important because scattered-light artifacts (Page et al. 2014), which are inherently difficult to predict, may be identified by the pipeline as new objects. In addition, galaxy images are manually scrutinized for changes in brightness or for any new point sources, by comparing with the archival UVOT image if available or the DSS image. After manual inspection, we consider sources to be of interest if they are deemed to be astrophysical in origin and are new or have brightened by $3\sigma$ compared to archival values.

3.3. LIGO/Virgo S200213t Candidate

The LVC observed the compact binary merger candidate S200213t on 2020 February 13 (LIGO Scientific Collaboration & Virgo Collaboration 2020a). The detected GW event had a false-alarm rate of approximately $1.8 \times 10^{-9}$ Hz, or once every one year and nine months. The classification of the GW signal was described by the following probabilities: BNS (63%), terrestrial (37%), BBH (<1%), mass gap (<1%), and NSBH (<1%). The probability that the lighter compact object is lighter than three solar masses was >99% when assuming astrophysical origins. Additionally, the 90% credible region was identified as 2587 deg$^2$, with a distance of 201 ± 80 Mpc, when using the preferred bayestar.fits.gz,1 sky map. Another analysis was performed, and the preferred sky map was updated to the bilby.fits.gz,0 sky map, while the 90% credible region was 282 deg$^2$ (LIGO Scientific Collaboration & Virgo Collaboration 2020b). However, another round of analysis revealed a new preferred sky map, LALInference.fits.gz,0 and a new 90% credible region of 2326 deg$^2$ (LIGO Scientific Collaboration & Virgo Collaboration 2020c). LVC reported that the last circular superseded the previous Bilby analysis, which was based on an outdated estimate of the detector calibration uncertainty. Upon detection, the GW alert initiated other observatories such as the IceCube Neutrino Observatory and the Pierre Auger Observatory to look for neutrino detections using real-time analyses.

IceCube Neutrino Candidate: IceCube detected one neutrino candidate that was in coincidence with GW alert S200213t both spatially (R.A., decl. = 45°21, 31°74; J2000) and temporally (−175.94 s). The neutrino candidate underwent both the maximum-likelihood and Bayesian analyses. These hypothesis tests obtained p-values of 0.003 (2.75σ) and 0.0174 (2.11σ), respectively (IceCube Collaboration 2020). The 90% containment radius for this neutrino candidate was estimated as $0.43$. No neutrino candidates were detected by the ANTARES detector or the Pierre Auger Observatory during a ± 500 s interval from the S200213t alert time of 04:11:04 UTC on 2020 February 13 (Ageron & ANTARES Collaboration 2020; Alvarez-Muniz et al. 2020).

Utilizing the obtained localization area of the joint GW+neutrino candidate detection area, follow-up observations for host galaxy candidates were conducted (Paek et al. 2020). The Lemonsan Optical Astronomical Observatory, the Deokheung Optical Astronomy Observatory, and the Sobaeksan Optical Astronomy Observatory examined these host galaxies but found no electromagnetic counterparts (Paek et al. 2020).

Swift Observations: Swift observed the field of the IceCube track-like muon neutrino candidate (IceCube Collaboration 2020) consistent with the sky localization of GW candidate S200213t (LIGO Scientific Collaboration & Virgo Collaboration 2020a), covering ∼0.5 deg$^2$ in seven tiles to cover the most probable regions of the joint GW+neutrino localization (Countryman et al. 2020). The observations were taken on 2020 February 13, from 09:54 UT to 16:20 UT, that is, 21–44 ks or 5.8–12.2 hr after the LVC trigger. The average sensitivity of the observations was $~8 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (0.3–10 keV; Figure 3). Since the 90% containment radius for this neutrino candidate was $0.43$, there was no need to find the convolved sky maps of GW and neutrino events; instead, Swift used one of its on-board tiling patterns to observe the location of the IceCube neutrino candidate coincident with the GW sky map. The typical sensitivity for this search was $2 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (0.3–10 keV).

Note that the Swift pointings in Figure 3 look more opaque compared to Figures 1 and 2, because for the case of S200213t, a few consecutive orbits of individual observations were performed for each pointing, with slightly different settling positions, and therefore multiple overlapping medium transparencies were combined to make it appear more opaque. In the other two figures, the pointings are filled with medium transparency for illustration.

In total, three X-ray sources were found with detection flag “good,” all of which were classified as “rank 3,” that is, uncatalogued in X-rays, but with fluxes below historical upper limits. Two further “rank 3” sources were found with detection flag “poor,” indicating that they are likely spurious. Details of these sources are listed in Table 3.

No sources were considered to be of interest after manual inspection of sources flagged by the UVOT pipeline. However, Swift followed up two Zwicky Transient Factory sources: ZTF20aamvznj (AT2020ca; Kasliwal et al. 2020) and ZTF20aanakcd (AT2020cmr; Reusch et al. 2020). ZTF20aamvznj is most likely a Type II supernova at distance ∼350 Mpc (Oates et al. 2021, submitted), while ZTF20aanakcd was identified as a Type IIn supernova at $z = 0.077$ through the identification of Balmer emission features in an optical
Neither of these objects are considered to be the counterpart to the joint GW + neutrino candidate.

4. Discussion

Table 4 summarizes the information about the three GW + neutrino candidates that were followed up by Swift and were discussed in this paper. While it turned out that the first two GW candidates (S190728q and S191216ap) in this study were most likely from BBH mergers, the last one, S200213t, was categorized as a BNS with 63% probability. As we discussed, it is thought that high-energy neutrinos are produced in nonthermal dissipative processes, such as relativistic outflows (Bartos et al. 2013; Murase & Bartos 2019), and could produce short gamma-ray bursts within two seconds of the merger. There was no short GRB associated with the S200213t GW candidate.

The nondetection of a significant neutrino association for the gravitational-wave events is consistent with our expectation. For BBH events, high-energy neutrinos are only expected if the merger occurs in a gas-rich environment, and even then the neutrino flux at the observed distances has an expected number of detected neutrinos below one. For our likely BNS event, while here neutrino emission is expected, given the source distance, the flux at Earth likely corresponds to an expected detection probability of \( \approx 1 \) (Albert et al. 2017b).

The highest statistical significance among our alerts was 2.75\( \sigma \) for the S200213t GW event, which is not high enough to claim a significant coincidence. Moreover, the neutrino was detected 176 s before the GW event, which is probably before the BNS started to distort. This time offset reduces the likelihood of the joint signal being from the same source.

The lack of counterpart detection with Swift for the first two triggers discussed here—S190728q and S191216ap—is not surprising, as these triggers were both reclassified by the offline GW analysis as probable BBH events, from which most models do not predict EM emission. Further, the Swift
coverage of these events was far from complete in terms of the GW+neutrino combined localization probability. For S200113t, XRT covered the entire 90% probability of the neutrino localization (UVOT coverage is roughly 30% less, due to its smaller field of view). The upper limit from these observations is ~3 orders of magnitude below the typical short GRB afterglow flux at the time of our observations (see Figure 4 of Evans et al. 2017). Given the GW distance (201 ± 80 Mpc) compared to the median Swift short GRB redshift (z ~ 0.7, D_L ~ 3.8 Gpc), this means any GRB within our observations was 5–6 orders of magnitude less luminous than typical Swift-detected short GRBs. We can thus rule out with high confidence the presence of a normal, on-axis short GRB within the combined GW+neutrino localization. However, we cannot rule out the possibility either of a so-called “naked” GRB—where the circumburst medium is of such low density that little or no afterglow is produced—or the presence of a GRB whose jet was not oriented toward Earth: in the case of GW170817, which was marginally off-axis, no X-ray afterglow was detected until 9 days after the GW event. Further, if the GW and neutrino events are not associated, then the Swift observations covered less than 1% of the very large GW localization. The lack of UVOT detection likewise argues against the presence of an on-axis GRB. It is tempting to also argue against the presence of a blue kilonova like that seen by UVOT from GW170817 (Evans et al. 2017). However, because the UVOT observations of that event did not start until T0+0.6 day (by which time our observations of S200113t had concluded), we do not know how bright an analogous signal would have been in UVOT at the time of our observations.

While this search did not conclusively identify a multimessenger counterpart, the study demonstrated the feasibility and need for such follow-ups. Improving statistical methods could be extremely useful in searching for multiple messengers (Veski et al. 2021). For LIGO/Virgo/KAGRA’s upcoming O4 observing run, the number of expected detections will dramatically increase compared to O3. In addition, the discovery of the black hole merger GW190521 (Abbott et al. 2020a) and its candidate electromagnetic counterpart (Graham et al. 2020) could further substantially increase the interest in the multimessenger follow-ups of BBH mergers. Other than the counterpart, the properties of GW190521 also point toward an active galactic nucleus origin (Abbott et al. 2020b), including its possibly high eccentricity (Gayathri et al. 2020). Therefore, the extension of the Swift GW+neutrino follow-up mission, along with the optical and high-energy follow-ups of possible Swift+GW+neutrino candidates, will be an exciting science target for the O4 observing run.

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