Prospects for the Early-Warning Detection of Electromagnetic Counterparts from Compact Binary Mergers

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Abstract

We have entered a new era of scientific discovery since the LIGO-Virgo-KAGRA (LVK) Scientific Collaboration's fourth observing run (O4) began in May, 2023. Previous studies have demonstrated that early-warning (EW) alerts, or alerts of gravitational-wave (GW) detection sent prior to the merger of two compact objects, are possible in O4. However, the prospects for capturing EM counterparts using EW alerts have not yet been studied. This work aims to investigate the challenges presented to EM follow-up and identify ways to mitigate potential obstacles. We develop a framework for simulating EW GW detection and alert generation for a binary neutron star merger to the observation of a kilonova counterpart using the Zwicky Transient Facility. We conclude with a discussion on current findings and future improvements to the simulation.

1. Introduction

The fourth observing run (O4) of the LIGO-Virgo-KAGRA (LVK) Scientific Collaboration began on May 24^{th}, 2023, initiating new opportunities for astrophysical discovery. This network of four ground-based interferometers can detect gravitational waves (GWs) from the mergers of compact objects, such as binary black hole (BBH), binary neutron star (BNS), and neutron star-black hole binary (NSBH) mergers. Compact binary coalescences involving at least one neutron star could produce electromagnetic (EM) counterparts which can be observed and used to gain more information about their source. To date, we have only one such confirmed joint detection of GWs and an EM counterpart. GW170817 (Abbott et al. 2017c) was a merger of two neutron stars detected by the LIGO and Virgo interferometers on August 17^{th}, 2017. A short gamma-ray burst (GRB), GRB 170817A, was independently observed by the Fermi Gamma-ray Burst Monitor (Fermi) approximately 1.7 s after the merger (Abbott et al. 2017b). The EM counterpart from GW170817 was also observed in UV, optical, infrared, X-ray, and radio (Abbott et al. 2017). GW170817 acted as a standard siren, providing a new measurement of the Hubble constant using GWs (Abbott et al. 2017a).

In order to capture more events like GW170817, it is critical that we provide EM observatories with prompt notification of GW detection. If observatories are not pointed toward the location of the source before or at the time that the objects collide and merge, we may miss vital information about the physics of merger. This presents a need for early-warning (EW) GW alerts, which are alerts sent to observatories prior to merger. It has been demonstrated that EW GW detection is possible in O4 (Sachdev et al. 2020; Magee et al. 2021; Magee & Borhanian 2022). However, this has not been studied from the perspective of EM observatories. There are several limitations to observing EM counterparts, such as the orientation of the merging binary with respect to the observatory, the luminosity of the counterpart, the field-of-view (FOV) of the instrument, and latency added to point at the source.

The goal of this study is to investigate the challenges presented to the EM follow-up of GW events with EW alerts. We begin by constructing a framework to perform an end-to-end simulation from EW GW event detection to observing the event's EM counterpart with a given instrument. We describe methods used to analyze GW data with EW in Sec. 2. In Sec. 3, we outline the procedure taken for simulating the GW detection and EM follow-up. Discussion of current results and plans for future work can be found in Sec. 4.

2. Methods

In order to identify candidate GW events, we perform matched-filtering on the data. Matched-filtering is a method to extract signals from noisy data by cross-correlating the detector output with a template gravitational waveform signal

(Allen et al. 2012). The shape of the waveform depends on the parameters of the source, such as component masses and spins. The input to matched-filtering is a template bank containing a discrete set of waveforms that spans the desired parameter space of the search and accounts for a variety of binary systems.

The output of matched-filtering is a signal-to-noise ratio (SNR) time-series, or the strength of the signal compared to the strength of the noise present as a function of time. The better the match of the template with the data, the higher the SNR. A peak in the SNR in a GW detector's data which passes a preset threshold would produce a trigger in the detector. The template from this trigger provides us with an estimate for the parameters of the source. Triggers found in coincidence in multiple detectors are elevated to the status of an event.

As opposed to BBH and NSBH systems, BNS systems have a long inspiral phase, spending approximately 10-15 minutes in the band of the GW detectors at design sensitivity (Sachdev et al. 2020). This makes BNS systems ideal candidates for EW. We can use matched-filtering to accumulate enough SNR to identify a forthcoming event and send an EW alert to observatories up to ~ 60 s before merger. For EW, matched-filtering begins at 10 Hz. The template waveforms are then truncated at various frequencies corresponding to a time before merger for a 1.4 $\mathrm{M}_{\odot}$ - 1.4 $\mathrm{M}_{\odot}$ component mass BNS system: 29 Hz, 32 Hz, 38 Hz, 49 Hz, 56 Hz, and 1024 Hz corresponding to $\sim$ 58 s, 44 s, 28 s, 14 s, 10 s, and 0 s before merger respectively.

We can study the performance of an EW pipeline by adding injections, or simulated GW waveform signals, to the data. We can then run a matched-filtering search to test injection recovery with our template bank. The detector data can be real or simulated and recolored to a given sensitivity, such as the expected O4 sensitivities.

3. Simulation

3.1. Gravitational-Wave Detection We begin by generating a set of 10,000 BNS injections with masses $(1.0-2.4)\mathrm{M}_{\odot}$. The injections are non-spinning, since we expect BNSs merging within a Hubble time to have low spins (Zhu et al. 2018). We add those injections to simulated GW detector data for a three detector network (LIGO-Hanford, LIGO-Livingston, and Virgo), recolored to O4 sensitivities. We do not include the KAGRA detector due to its low sensitivity range for BNS merger distances. For the matched-filtering, we use the BAYESTAR software (Singer & Price 2016). BAYESTAR synthesizes matched-filtering triggers from the injections and produces a list of detected GW events. For triggers, we impose an SNR threshold of 4.0 to be considered found. We require that a trigger is coincident in two or more detectors in order to be considered an event. This criteria is also used in O4, as we want to ensure we are not making detections due to noise.

BAYESTAR also constructs skymaps, or 2D maps of probability distributions for the location of the GW source in the sky, using the output of matched-filtering. During LVK observing runs, skymaps are generated using BAYESTAR for GW events and given to EM observatories so that they can locate any potential EM counterparts. The faster these skymaps can be provided, the greater the chance of making an EM discovery. BAYESTAR has been optimized for the EW framework, adding just 0.5 s of latency per event for EW triggers (Magee et al. 2021).

Matched-filtering is performed to realize events with the 6 different cutoff frequencies: 29 Hz, 32 Hz, 38 Hz, 49 Hz, 56 Hz, and 1024 Hz. From the 10,000 injections, 5 events are found at 29 Hz, 6 at 32 Hz, 10 at 38 Hz, 30 at 49 Hz, 39 at 56 Hz, and 122 at 1024 Hz. Skymaps are then produced for each event and fed into the EM follow-up simulation, which is described in the next section. An example skymap from the GW detection simulation is shown in Fig. 1. The event was able to be localized at all 6 cutoff frequencies. The SNR grows as the binary evolves closer to merger. At 29 Hz, the event has a network SNR of 12.2. Network SNR is defined as $\rho_{\mathrm{network}} = \sqrt{\rho_H^2 + \rho_L^2 + \rho_V^2}$ where ρ_H is the SNR in the LIGO-Hanford (H) detector data, and similarly for the LIGO-Livingston (L) and Virgo (V) detectors. At 1024 Hz, it has a network SNR of 37.5. The SNR grows as the binary evolves closer to merger, and the higher the SNR, the better constrained the skymap's probability regions will be.

3.2. Electromagnetic Follow-Up BNS mergers are known progenitors of some of the short GRBs and kilonova transients in the universe but observing both GRBs and kilonovae depends on the orientation of the binary system with respect to Earth (Abbott et al. 2017b; Darbha & Kasen 2020). Moreover, the transient produced by a BNS merger must pass an instruments brightness threshold in order to be considered discovered. Sources of latency inherent to

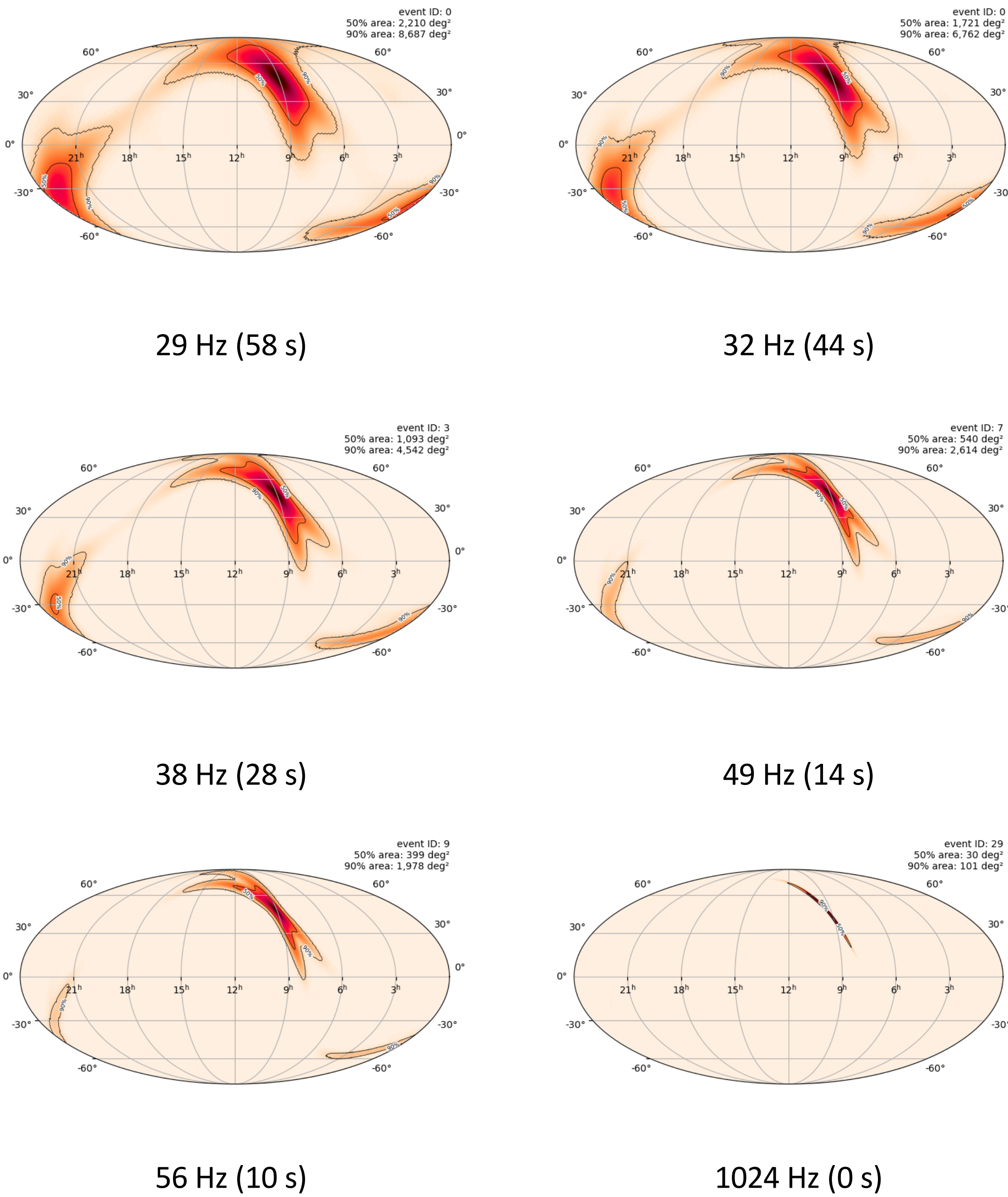

Figure 1: The evolution of the skymap for one event as the binary evolves closer to the time of merger. Declination is indicated in degrees and right ascension in hours. The template cutoff frequency is shown below the skymap, along with the number of seconds at which it was detected before merger shown in parentheses. The percent credible regions describe the probability which you would find the actual location of the event within the region. For example, the 90% credible region means that if you were to perform many measurements of the source location, 90% of the time you would find the true position of the source in this enclosed region. The number of square degrees enclosed by the probability regions decreases as we get closer to merger because the SNR is increasing.

EM follow-up include the time it takes to point an instrument toward the location of the source and the exposure time required to take an image. We aim to take into account all of these aspects when performing this end-to-end simulation.

The inputs to our EM follow-up simulation are the skymaps generated for events in the GW detection simulation. We use the software package `simsurvey` (Feindt et al. 2019) to create our observing plan, generate transients, and determine observable counterparts. We begin by considering the Zwicky Transient Facility (ZTF) as our observatory.

We first use `simsurvey` to construct an observing plan given the time of detection, instrument FOV and filters, a set of coordinates for pointings, and some level of sky noise. Next, we load in a model for the transient. We take our transient to be a kilonova from a BNS merger following the Bulla model (Bulla 2019; Dhawan et al. 2020). For now, we examine transients with randomly assigned parameters.

We generate 1,000 transients within the skymap region and determine if their lightcurves are discovered. An example skymap from an injection found at 29 Hz with transients overlaid is shown in Fig. 2. If the transient is too faint to be observed by the instrument, the transient is labeled `meta_notobserved`. If the transient is bright enough to be observed and its lightcurve can be realized, it is labeled `meta_detected`. The true location of the injection is also shown. In this example, the `meta_detected` are not close enough to the true source positon, and thus the counterpart would not be considered as discovered. We found that increasing the cut-off frequency (decreasing the skymap's probability regions) did not necessarily increase the number of transients discovered. However, with this framework, we can fine-tune the parameters in order to develop a simulation that is not only more streamlined, but also more realistic to the expectations of current BNS population models.

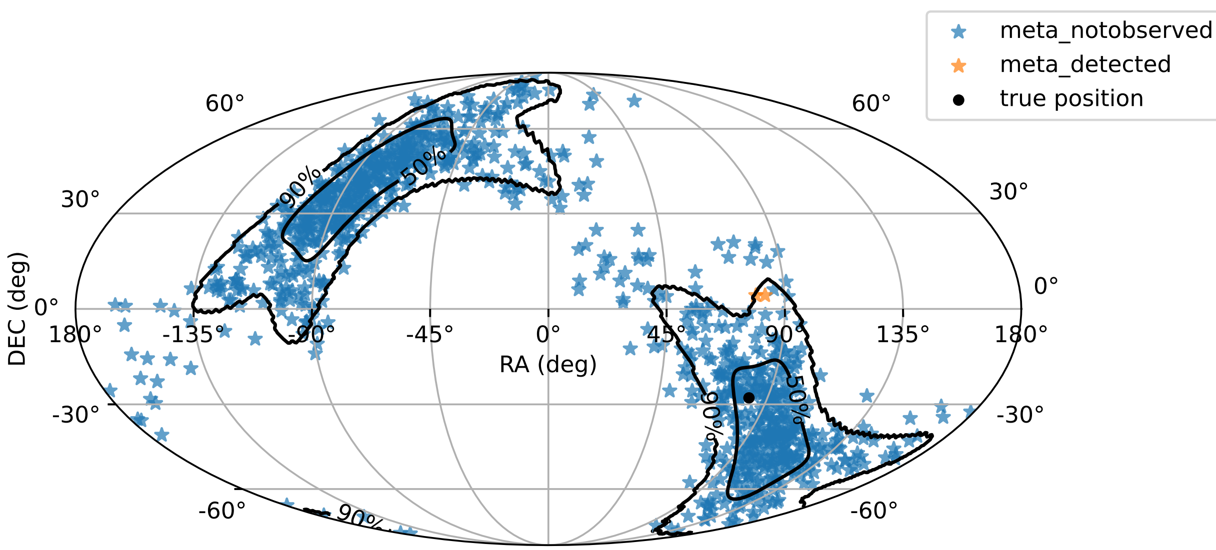

Figure 2: A skymap from a found injection with a 29 Hz cutoff frequency and an SNR which surpassed the detection threshold. 1,000 kilonova transients, each with random parameters, were generated within regions of non-zero probability on the skymap and are overlaid here. A star shown in blue and labeled `meta_notobserved` indicates that the transient was not bright enough to be observed by the instrument. If it is bright enough, it is labeled `meta_detected` and shown in orange. The true position of the injected source is marked with a black dot.

4. Discussion & Future Work

One may ask, looking at Fig. 1, is the source well-localized at 29 Hz, $\sim$ 60 s before merger? The answer depends greatly on your instrument and the brightness of the counterpart. It is still worthwhile to send out an EW alert with the probability distribution for the location of the source as early as possible in order to have the best chance at capturing the counterpart. Although, the skymaps for BNS systems closer to merger are easier for an instrument to tile and image efficiently. A goal for the future of this study is to determine the most effective way to tile and image an EW skymap at any given time prior to merger.

Here we have demonstrated an end-to-end method from GW detection to EM follow-up using ZTF. The instrument performing the EM observation can be changed and the parameters of the transient can be fine-tuned to better represent the injected population, and hence current BNS population models. For further analyses, we will also increase both the number of injections and transients in order to have a larger sample of events to study. Additionally, we will implement a criterion for an injection to be considered discovered by an instrument, such as that a transient with `meta_detected` must overlap with at least 10% of the true location of the source. Results from `simsurvey` take just seconds to produce, and we will parallelize the workflow to be able to analyze thousands of events at once.

In this current framework, we do not include pipeline latency, or the time it would take for a matched-filtering pipeline to process the data. This must be accounted for when considering how early the event is detected with respect to the time of merger, but will depend on the pipeline used. We will continue to develop this study with these further implementations and gain a better understanding of the prospects for observations of EM counterparts in current and future LVK observing runs with the available state-of-the-art EM instruments.

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