Draft version February 8, 2023
Typeset using LaTeX **twocolumn** style in AASTeX631

Synergies with WINTER, ZTF, and LIGO for Kilonova Discovery

Faith K. Bergin [1] Shreya Anand [2]
(Caltech LIGO SURF 2022)

[1] *Department of Physics and Astronomy, Purdue University, West Lafayette, IN 47907, USA*
[2] *Division of Physics, Mathematics, and Astronomy, California Institute of Technology, Pasadena, CA 91125, USA*

ABSTRACT

During LIGO's fourth observing run (O4), we expect to discover more gravitational wave (GW) events than ever before, including binary neutron star (BNS) and neutron star black hole (NSBH) mergers that produce electromagnetically bright kilonovae. The Zwicky Transient Facility (ZTF) has thus far performed extensive follow-up in the optical regime during LIGO's third observing run, O3. During O4, the Wide-Field Transient Explorer (WINTER), designed specifically for gravitational wave follow-up, will join the campaign in the near-infrared Y, J, and short-H bands. We investigate the potential of combining the resources of both WINTER and ZTF to create an observing strategy suited for joint gravitational wave and electromagnetic discoveries. We use the Nuclear and Multi-Messenger Astrophysics (NMMA) Bayesian Python pipeline to simulate WINTER's observations of kilonovae with different Target of Opportunity (ToO) triggering criteria and observing setups. We draw from a simulated population of LIGO observations and radiative transfer kilonova models. This study begins to assess kilonova parameter recovery with WINTER. In the future, we hope to simulate the combined WINTER/ZTF observing system to determine the most effective follow-up strategy for a given LIGO gravitational wave alert and integrate it into the campaign starting in O4.

Keywords: Black Holes (162) — Gravitational Wave Astronomy (675) — Gravitational Wave Sources (677) — Infrared Telescopes (794) — Neutron Stars (1108) — R-process (1324) — Kilonova

1. INTRODUCTION

1.1. *Kilonovae*

Since the discovery of gravitational waves in 2015, a new age of astronomy has been ushered in. Multi-messenger astronomy is a rapidly growing field that allows for transients to be observed through many media, including gravitational waves and electromagnetic radiation. In particular, a certain portion of gravitational wave sources are binary neutron star (BNS) and neutron star black hole (NSBH) mergers. The material ejected in these violent events undergoes a rapid neutron capture process known as r-process nucleosynthesis. The radioactive decay of the various unstable nuclei creates a unique transient known as a kilonova (Metzger 2019). Seconds before the merger, neutron rich material is squeezed and accelerated through the polar regions, creating a gamma ray burst (GRB) and shock heating the material around it. Some of the neutron rich material is also tidally disrupted and creates a torus shape as the material expands and decompresses into space. Both the squeezed polar material and the tidally disturbed equatorial material compose the dynamical mass ejecta of the merger. Seconds after the merger, outflows from the accretion disk around the merger remnant compose a disk wind ejecta. Within these different mass ejecta components, both light and heavy r-process elements are created. The lighter elements (atomic mass number < 140), known as the lanthanide poor component, glow brightly but briefly in the optical regime on the timescale of one day with a strong angle dependence. The heavier, lanthanide rich (atomic mass number $>$ 140) component produces a distinct thermal glow. The high opacity of the heavier elements shifts the light to peak in the near-infrared region (J and K bands, 1.2 and 2.2 μm respectively). This 'red' component is longer lasting and less angle- and geometry-dependent, especially in comparison to optical, X-ray, and gamma-ray emissions from the same event. It is this feature that makes a kilonova distinct from other GW counterparts (Metzger 2019; Kasen et al. 2017).

Kilonovae are expected to accompany all BNS mergers and a fraction of NSBH mergers (those where the black hole is not significantly more massive than its companion neutron star (Frostig et al. 2022)). Kilonovae are rich in spectral lines and encode a vast amount of information related to the composition of the merger. By studying kilonovae from these events, we can obtain information about r-process nucleosynthesis and gain a deeper understanding of how our universe is enriched with heavy elements like gold and uranium. We can also use these kilonovae to trace the history of the merger and further unravel the process of the collision. Joint multi-messenger observations of kilonovae can help constrain the nuclear equation of state. Lastly, we can use kilonovae as a cosmic ruler to resolve the Hubble tension (Metzger 2019; Kasen et al. 2017; Dietrich et al. 2020).

In 2017, LIGO detected the gravitational wave signal associated with a BNS merger. Only 10.9 hours after the alert was sent out, the kilonova was discovered in the host galaxy NGC 4993. This event, known as GW170817, is unique because it marks not only the first ever BNS merger detection, but also the first time there had been successful follow-up in the gamma-ray, X-ray, optical, near-infrared, and radio frequencies (Abbott et al. 2017; Kasliwal et al. 2020; Abbott et al. 2017; Dietrich et al. 2020). The astronomical community successfully detected both the 'blue' UV/optical kilonova component (which faded within days) and the 'red' near infrared kilonova component (which lasted for almost two weeks) for the first time. Thus far, only two BNS mergers have been found, with GW170817 being the only one with a kilonova discovery. The NSBH candidate list is far more uncertain, but there have been a substantial number of observations by LIGO (The LIGO Scientific Collaboration et al. 2021). For this project, we hope to further the discovery of kilonovae from both BNS and NSBH mergers during the upcoming LIGO observing runs.

1.2. *LIGO*

In September of 2015, the Laser Interferometer Gravitational-Wave Observatory (LIGO) first detected gravitational waves from the coalescence of binary black holes in an event known as GW150914 (Abbott et al. 2016). LIGO consists of two detectors; one in Livingston, LA and the other in Hanford, WA and is operated by the California Institute of Technology (Caltech), the Massachusetts Institute of Technology (MIT), and collaborators all over the world. Thus far, LIGO has completed three observing runs, with the Advanced Virgo detector in Italy joining the campaign during the second observing run, O2. The fourth observing run, known as O4, is expected to begin in March 2023. O4 will see the Kamioka Gravitational-Wave Detector (KAGRA) in Japan join the search for GW events. However, even with all four detectors online, localizations can range from tens to thousands of square degrees (Kasliwal et al. 2020; Abbott et al. 2020a). As such, one of the key challenges for electromagnetic follow-up campaigns will be to map these large areas to the faint limits required for kilonova discovery. During O3, no kilonovae were discovered, but during O4, we expect to come across a large fraction of BNS or NSBH mergers that produce a kilonova, and as such, there is a high likelihood of detection (Kasliwal et al. 2020). The goal of this project is to be adequately prepared with multiple telescopes to detect these kilonovae and perform efficient follow-up.

1.3. *WINTER*

The Wide Field Transient Explorer (WINTER) is a new instrument designed specifically to perform follow-up observations of kilonovae from BNS and NSBH mergers. WINTER will operate on a dedicated 1-meter telescope at Palomar Observatory in the near-infrared Y, J, and short-H bands, which are centered at 1.0, 1.2, and 1.6 μm (Frostig et al. 2022; Lourie et al. 2020). WINTER has a 1 deg^2 field of view and is expected to see first light by the end of 2022. This instrument was intentionally commissioned to perform follow-up on GW events for the following reasons. Wide-field near-infrared surveys are rare, giving WINTER a significant advantage in the search for kilonovae from GW events. Kilonovae are also significantly longer lasting in the near-infrared (with timescales ranging from several days to a week) (Metzger 2019), making for a higher likelihood of detection. In addition, it has been shown that WINTER will have a greater advantage in searching for kilonovae resulting from NSBH mergers (Frostig et al. 2022). These mergers are more often associated with the neutron rich 'red' kilonova with near infrared emission that falls perfectly in the range of WINTER's capabilities (Metzger 2019). This is important given that no kilonova has been detected from an NSBH merger event thus far, and we hope to increase the chances of discovery for these types of events during O4. Overall, WINTER will be a powerful tool in the follow-up campaign during O4 and beyond.

1.4. *ZTF*

The Zwicky Transient Facility (ZTF) is an optical time-domain survey operating on the 48-inch Samuel

Oschin Schmidt Telescope at Palomar Observatory (Graham et al. 2019; Bellm et al. 2019; Masci et al. 2019). With a 47 deg^2 field of view, ZTF has performed all-sky surveys and monitored transients extensively in the g and r bands. ZTF is capable of detecting objects as faint as the 22nd magnitude in a 300 second exposure and is therefore sensitive enough to discover and observe kilonovae. This facility allows for a large portion of the night sky to be monitored very quickly, another useful tool in the search for kilonovae. We anticipate that the use of ZTF in combination with WINTER will explore the potential of a new strategy to search for electromagnetic signals from GW events.

2. OBJECTIVES

Many of the LIGO localization maps received by astronomers as part of a GW event alert are relatively poor, accounting for up to thousands of square degrees of sky area (Abbott et al. 2020b). What is the best strategy to map such large areas to the faint limits required for kilonova discovery and observation? How can we incorporate multiple electromagnetic telescopes to best support the observation of such large localization areas?

First, we need to understand each instrument and account for each of their unique benefits. For this project, we consider both the Zwicky Transient Facility (ZTF) and the newly commissioned Wide field Transient Explorer (WINTER). Each of these telescopes are very powerful in their own rights. ZTF is very well established. Many studies have been performed on ZTF's performance (Masci et al. 2019). Particularly, ZTF has already been instrumental in many studies searching for more kilonovae from LIGO GW alerts (Kasliwal et al. 2020). WINTER, however, is a new instrument that has not yet seen first light (as of the writing of this document). While studies have extensively simulated WINTER's performance for the upcoming LIGO fourth observing run (Frostig et al. 2022), we have yet to understand its benefits in collaboration with other instruments such as ZTF. How can we optimize the use of each instrument in order to maximize kilonova discovery and observation? This is the foundational question for this project. Using a new Python framework known as Nuclear and Multi-Messenger Astrophysics (NMMA), we can begin to answer this question. Using simulated LIGO O4 observing scenarios from a study performed by Petrov et al. (2022), the latest radiative transfer kilonova models, and NMMA, we can begin to assess how well each instrument can retrieve kilonova parameters from both gravitational wave and electromagnetic joint analysis. ZTF is already built into the NMMA framework. The goal of this project is to modify NMMA to include WINTER and then to perform a joint WINTER and ZTF analysis to determine how well each of the instruments perform together. This is significantly different than the original direction of the project. All of the changes will be noted in Section 4. This project entails many steps that will be expanded upon in the next section. The potential for kilonova discovery and observation serves as the engine for this project, leading to answers to fundamental questions about the nature of the most violent mergers in the universe.

3. APPROACH

Here I will outline the approach I am taking to achieve these objectives in great detail. In Section 3.1, I will briefly discuss Target of Opportunity (ToO) analysis and triggering criteria. In Section 3.1.1, I will discuss the study, Petrov et al. (2022) that provides the simulated LIGO skymaps used for this project. In Section 3.2, I will describe the kilonova models used in. In Section 3.3, I will go over the NMMA framework and how we anticipate performing the study. Section 4 will outline a few of the changes made from the original project (notably those made between Interim Reports 1 and 2). Section 5 will discuss next steps and future possibilities for this work.

3.1. *ToO Analysis and Triggering Criteria*

When a LIGO GW event alert is sent out during O4, we anticipate that both WINTER and ZTF will perform what is known as Target of Opportunity (ToO) analysis. This means each instrument will halt their normal survey operations and follow up on a specific target, or in this case a given localization skymap. But how do we decide which instruments follow up which event, or if they even choose to conduct follow-up at all? This metric is known as triggering criteria, where we decide whether to trigger a ToO analysis with WINTER, ZTF, or both instruments. Before we can perform any sort of study, we need to decide what criteria to input into NMMA. The first step in this project was creating triggering criteria for WINTER. ZTF already has fairly well established triggering criteria, but WINTER is a new instrument that has not yet taken any data. As such, we do not know what the observation data or uncertainties will look like. In order to come up with triggering criteria for WINTER, we reference a past study in which an end-to-end simulation was performed to find how well WINTER observes BNS mergers, Frostig et al. (2022). We use the recommendations from this study to simulate different cadences for ToO observations. In addition, we utilized data from a study, Petrov et al. (2022), in which they simulated LIGO localization skymaps for

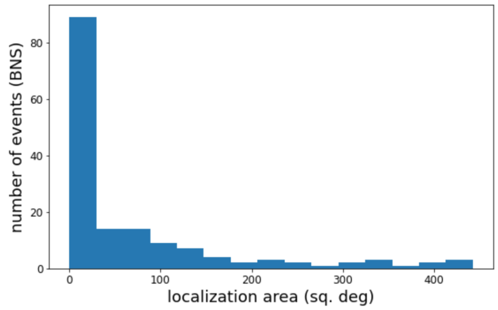

Figure 1.

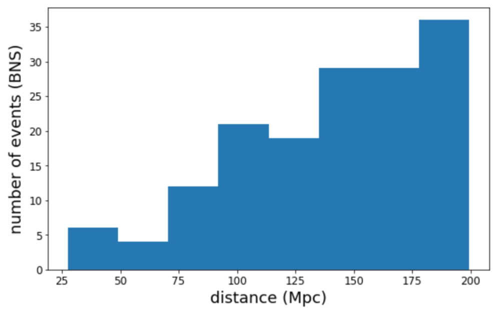

Figure 2.

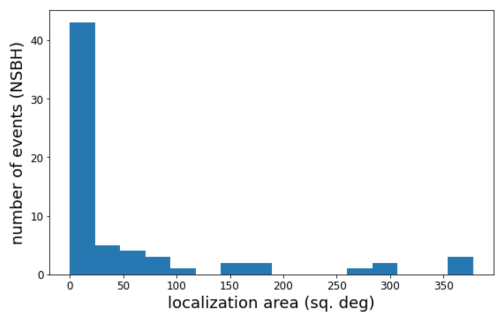

Figure 3.

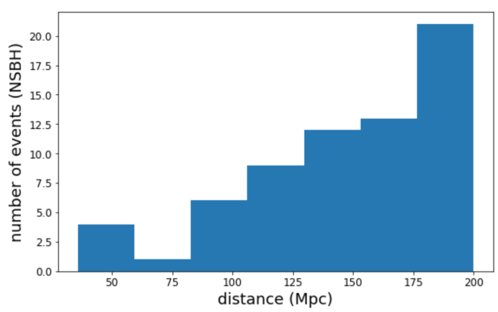

Figure 4.

O4. I will go into more depth in Section 3.1.1, where I describe how I used this data to brainstorm triggering criteria for WINTER.

3.1.1. *Simulated Skymaps from Petrov et al. (2022)*

When LIGO detects the gravitational waves from a BNS or NSBH merger, efficient follow-up is important in order to maximize the chances of kilonova discovery. LIGO data is used to generate localization maps that predict the area of the sky the signal originated from. Understanding the types of localizations we will receive from future LIGO observing runs O4 and beyond is essential in supporting the follow-up campaigns searching for electromagnetic counterparts to GW sources. During O3, many of the sky localizations were much larger than predicted, with the median localization area estimated to be 4480 deg^2 (Abbott et al. 2020b). Using the realistic data from O3, new simulated skymaps have been produced for O4 by Petrov et al. (2022). GW events (including BNS and NSBH mergers) are injected into `ligo.skymap`, as well the detector parameters including planned sensitivity upgrades. The simulations were improved upon by including single detector triggers (whereas previously coincidence in 2 or more detectors was required) and by lowering the signal to noise threshold for detection to more accurately represent O3. This difference in signal to noise ratio made a significant impact on the predicted observations of LIGO GW sources. While the localization areas remain large, the detection rates and detection efficiencies change significantly, which greatly affects the work of this project and many other observing campaigns across the world following up on GW events.

With these updated skymaps for O4, we can perform a statistical analysis to get a better idea of what kinds of events may be observed during O4. From these skymaps, I was able to perform statistical analysis. There were 1482 BNS merger events and 2492 NSBH merger events simulated. Note that these are the unnormalized numbers of simulations and do not reflect the number of events we expect to see during O4, but rather they reflect a population of the types of events that we are likely to observe during O4. Figures 1 through 4 show the number of events over a distribution of skymap localization areas in square degrees for both BNS and NSBH mergers. We also plotted the number of events expected to occur at certain distances for both BNS and NSBH mergers. These histograms allowed us to understand how many events may occur within reasonable observing distances and with reasonable localization areas. From these statistics, we determined that the first triggering criteria to test with WINTER would be as follows. WINTER would only trigger on events out to 200 Megaparsecs and with localization areas of less than or equal to 450 deg^2. This is a shallower and wider approach. In the future, we anticipate also testing other triggering criteria with WINTER, such as events out to 250 Mpc and with localization areas of 350 deg^2 or less, for example. However, for now, we will only input the first triggering criteria into NMMA.

3.2. *Kilonova Models*

In recent years, many collaborators around the world have worked to create the most up to date radiative transfer models of kilonovae. NMMA includes a variety of different model types for use. The primary model type we will be using with NMMA is called the Polarization Spectral Synthesis in Supernovae, or POSSIS model, created by Mattia Bulla. POSSIS is a general multi-dimensional Monte Carlo code modelling radiative transfer in supernovae and kilonovae (Bulla 2019). We use both the original model, but also include models with updated parameters, such the Bulladynwind model, which accounts for the dynamical ejecta mass as well as the disk wind ejecta mass. Additionally, we include a version of the model specifically tailored to NSBH merger parameters, which, as discussed earlier in section 1, maintain different geometries and different ejecta dynamics than BNS mergers. In general, the POSSIS model operates on four parameters: the dynamical ejecta mass, the disk wind ejecta mass, the inclination angle, and the half-opening angle.

3.3. *Results from NMMA*

The Nuclear and Multi-Messenger Astrophysics (NMMA) framework is a multi-messenger pipeline that targets joint analysis of GW and EM data (Pang et al. 2022). NMMA uses `bilby` (Ashton et al. 2019) as a baseline to simulate observations.

Its outputs include a corner plot with kilonova parameter estimations and light curves to show the results of the EM observations. NMMA performs inference to get posterior probabilities on the kilonova model parameters with results shown in a corner plot. NMMA also outputs a simulated light curve from the chosen instrument.

ZTF is already built into this framework. Figure 5 shows the posterior probabilities simulating ZTF-like cadence on a kilonova light curve. This run used the ZTF g, r, and i filters with 300-second exposures. The inputted model kilonova had the following values: a luminosity distance of 421.0025 Mpc, a dynamical ejecta mass of 0.027 $M_\odot$, a wind ejecta mass of 0.137 $M_\odot$, an inclination angle of 1.069 rads, and a half opening angle of 21.363 degrees. The parameter estimation has large uncertainties for certain parameters. It represents well how ZTF observations alone may not be sufficient to confidently discover kilonovae and are unable to effectively distinguish between different kilonova models.

Additionally, I was able to add WINTER to the framework. Figure 6 shows the posterior probabilities simulating a WINTER-like cadence including the WINTER triggering criteria (21st magnitude with 6-day cadence) with 300-second exposure in the J band. I was also able to add the near-infrared Y and short H bands into the program (though no analysis has yet been performed in these wavelengths). We have determined that while the WINTER parameter estimation uncertainties are less, there is not better accuracy. This indicates that WINTER may be able to perform better in certain aspects of kilonova discovery and observation. In addition, there is valid reason to combine both WINTER and ZTF, as it is clear that both may have strengths in different parameter analyses. Additional quantitative analysis will need to be performed in order to determine the exact deviations of each instrument from the true values of each parameter.

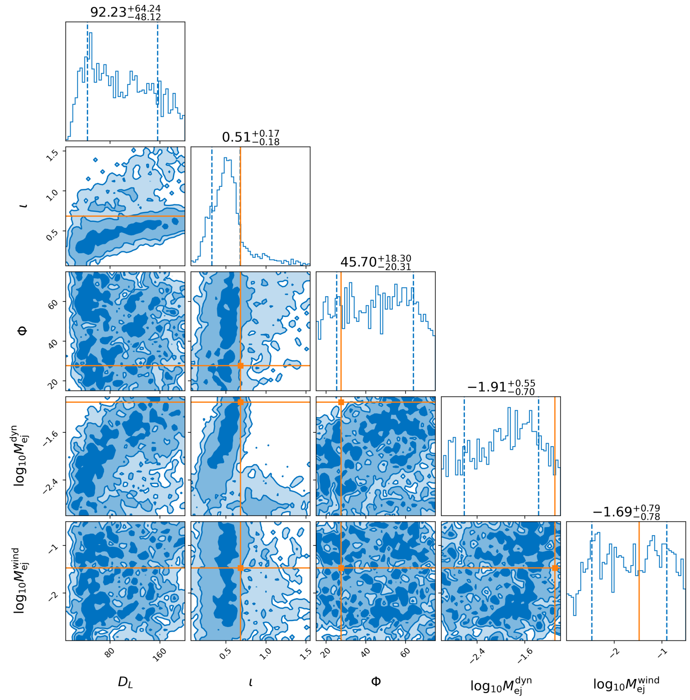

Figure 5. The first corner plot generated by NMMA with ZTF alone. This shows the kilonova parameter estimation for luminosity distance, D_L, inclination angle ι, half opening angle ϕ, and the two mass ejecta components, M_{dyn} and M_{wind}. Note that the orange line represents the true value of the parameter(s)

4. CHANGES FROM ORIGINAL PROJECT

In previous studies, we anticipated the use of the survey simulating software Python package, `simsurvey`. However, as my mentor and I progressed through the project, we found that NMMA would better suit our needs. `simsurvey` alone simulates the actual survey pointings of each telescope. While this may be helpful in

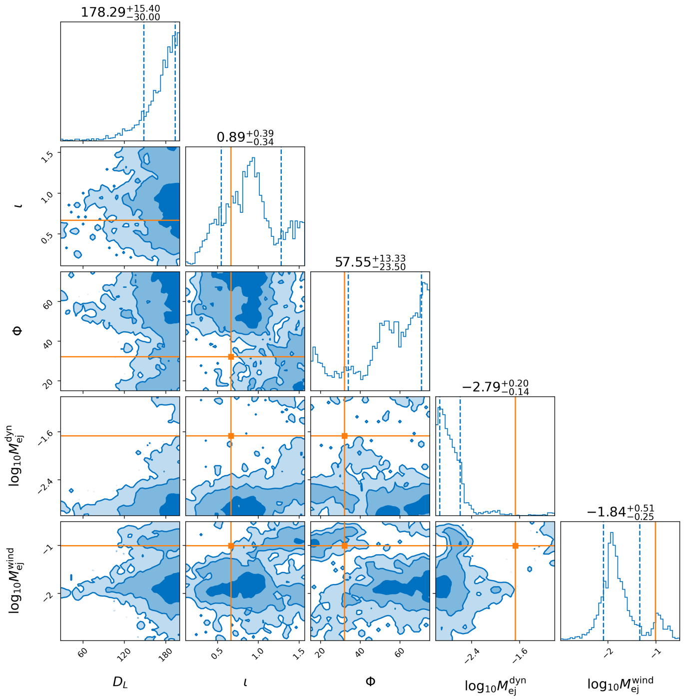

Figure 6. The second corner plot generated by NMMA with WINTER alone. This shows the kilonova parameter estimation for luminosity distance, D_L, inclination angle ι, half opening angle ϕ, and the two mass ejecta components, M_{dyn} and M_{wind}.

later steps of our project, we realized we needed a way to perform joint analysis with both electromagnetic and gravitational wave data so we could get a better picture of how well each instrument can observe in conjunction with LIGO. This project is truly a multi-messenger astronomy project and as such we need to use software that accounts for each messenger to maximize scientific gain. In addition, we did not get as far in the analysis as anticipated at the beginning of the project. Luckily for us, there is still much work to be done and many exciting possibilities for the future discussed in Section 5.

5. FUTURE WORK

While the project for Summer 2022 ha concluded, there is much exciting work to be done far into the future with this work. The most obvious next step is to combine both the WINTER and ZTF instruments into NMMA and see how well they work together to detect different kilonovae parameters. Looking forward, there will likely be a Python script developed using this work as well as other Python frameworks including `nimbus` (Mohite et al. 2022) and `simsurvey`. This script would eventually allow users to input LIGO parameters and output an effective and efficient observing strategy that determines the best use of the instruments that astronomers may have available to them. This would be a low-latency script designed to assist astronomers around the world in the search for future kilonovae.

I would like to thank LIGO Laboratory and the LIGO Scientific Collaboration, the California Institute of Technology, and the LIGO Summer Undergraduate Research Fellowship program for giving me the incredible opportunity to work on this research. I'd like to thank Shreya Anand for her tremendous support in this project. I would also like to thank my colleagues in the NMMA group Michael Coughlin and Weizmann Kiendrebeogo for their assistance with running the NMMA framework. I would also like to thank Alan Weinstein, the head of the LIGO SURF Program, for his support throughout the program and beyond. I also gratefully acknowledge the support from the National Science Foundation Research Experience for Undergraduates (NSF REU) program.

REFERENCES

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016, PhRvL, 116, 061102, doi: 10.1103/PhysRevLett.116.061102

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, Phys. Rev. Lett., 119, 161101, doi: 10.1103/PhysRevLett.119.161101

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, ApJL, 848, L12, doi: 10.3847/2041-8213/aa91c9

—. 2020a, Living Reviews in Relativity, 23, 3, doi: 10.1007/s41114-020-00026-9

—. 2020b, Living Reviews in Relativity, 23, 3, doi: 10.1007/s41114-020-00026-9

Ashton, G., Hübner, M., Lasky, P. D., et al. 2019, ApJS, 241, 27, doi: 10.3847/1538-4365/ab06fc

Bellm, E. C., Kulkarni, S. R., Graham, M. J., et al. 2019, PASP, 131, 018002, doi: 10.1088/1538-3873/aaecbe

Bulla, M. 2019, Monthly Notices of the Royal Astronomical Society, 489, 5037, doi: 10.1093/mnras/stz2495

Dietrich, T., Coughlin, M. W., Pang, P. T. H., et al. 2020, Science, 370, 1450, doi: 10.1126/science.abb4317

Frostig, D., Biscoveanu, S., Mo, G., et al. 2022, ApJ, 926, 152, doi: 10.3847/1538-4357/ac4508

Graham, M. J., Kulkarni, S. R., Bellm, E. C., et al. 2019, Publications of the Astronomical Society of the Pacific, 131, 078001, doi: 10.1088/1538-3873/ab006c

Kasen, D., Metzger, B., Barnes, J., Quataert, E., & Ramirez-Ruiz, E. 2017, Nature, 551, 80, doi: 10.1038/nature24453

Kasliwal, M. M., Anand, S., Ahumada, T., et al. 2020, ApJ, 905, 145, doi: 10.3847/1538-4357/abc335

Lourie, N. P., Baker, J. W., Burruss, R. S., et al. 2020, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 11447, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 114479K, doi: 10.1117/12.2561210

Masci, F. J., Laher, R. R., Rusholme, B., et al. 2019, PASP, 131, 018003, doi: 10.1088/1538-3873/aae8ac

Metzger, B. D. 2019, Living Reviews in Relativity, 23, 1, doi: 10.1007/s41114-019-0024-0

Mohite, S. R., Rajkumar, P., Anand, S., et al. 2022, The Astrophysical Journal, 925, 58, doi: 10.3847/1538-4357/ac3981

Pang, P. T. H., Dietrich, T., Coughlin, M. W., et al. 2022, NMMA: A nuclear-physics and multi-messenger astrophysics framework to analyze binary neutron star mergers, arXiv, doi: 10.48550/ARXIV.2205.08513

Petrov, P., Singer, L. P., Coughlin, M. W., et al. 2022, The Astrophysical Journal, 924, 54, doi: 10.3847/1538-4357/ac366d

The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, et al. 2021, arXiv e-prints, arXiv:2111.03606. https://arxiv.org/abs/2111.03606