Draft version May 17, 2022
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 mergers (NSBH) that produce kilonovae. Kilonovae are known to be longer lasting in the near infrared rather than the optical, while also depending less on the viewing angle and geometry. The Zwicky Transient Facility (ZTF) has thus far performed extensive follow-up in the optical regime during LIGO's third observing run, O3. This summer, the Wide-Field Transient Explorer (WINTER) joins the campaign in the near-infrared Y, J, and short-H bands, giving us a major advantage in searching for the kilonovae resulting from these mergers. We propose to investigate the potential synergization of LIGO, WINTER, and ZTF in order to aid in the discovery of kilonovae and advance our understanding of these events. Using simulated skymaps and kilonova models, we intend to examine, compare, and contrast the performance of each telescope for different potential kilonovae events observed by LIGO during O4. With these results we can then create a follow-up strategy that will optimize use of both WINTER and ZTF while maximizing the possibility for kilonova discovery.

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 by the LIGO/Virgo experiments in 2015 from the coalescence of binary black holes (Abbott et al. 2016), a new age of astronomy has been rapidly ushered in. Multi-messenger astronomy is a rapidly growing field that allows for transients to be observed through many mediums, including gravitational waves and electromagnetic radiation. Since 2015, 50 neutron star black hole (NSBH) mergers (Abbott et al. 2021) and one binary neutron star (BNS) merger have been observed (Abbott et al. 2017). The material ejected in these violent mergers 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). They glow brightly but briefly in the optical region on the timescales of less than one week with a strong angle dependence in this region (also 4). However, kilonova also produce a distinct thermal glow in the near-infrared region that is longer lasting and is less angle and geometry dependent. It is this feature that makes a kilonova distinct from other transients that may be involved in GW events. Kilonova are expected to accompany all BNS mergers and a large fraction of NSBH mergers. The isotropic thermal component is relatively easily observed in comparison to optical, X-ray, and gamma emissions from the same event. Kilonova are rich in spectral lines, and encode a vast amount of information related to the makeup of the merger. By studying kilonova 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 kilonova to trace the history of the merger and further unravel the process of the collision. Lastly, we can use kilonova as a cosmic ruler to verify the Hubble tension (Metzger 2019; Kasen et al. 2017).

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 run jointly by the California Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT). Thus far, LIGO has completed three observing runs, with the Advanced Virgo detector joining the campaign in the second observing run, O2. The fourth observing run, known as O4, is expected to begin in December of 2022 with the Kamioka Gravitational-Wave Detector (KAGRA) expecting to join the search for GW events. While LIGO has detected a significant number of GW events, only one BNS merger event has been found. 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, X-ray, optical, and radio frequencies (Abbott et al. 2017; Metzger 2019). As we prepare for O4, we expect to come across a small number of BNS or NSBH mergers that produce a kilonova. The goal of this project is to be adequately prepared with multiple telescopes to discover these kilonova and perform optimized follow-up. However, even with the addition of the Advanced Virgo and KAGRA detectors, LIGO still can have relatively poor sky localizations. For this project, we will have to take into account the variation of these localizations, which can range from a few to a thousand square degrees. Even so, we hope to use the valuable localization information given by LIGO to begin the search for kilonova with the WINTER and ZTF telescopes and answer fundamental questions about the nature of these violent mergers.

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. WINTER has a 1 degree squared field of view and is intended to perform an all-sky survey. This instrument was intentionally commissioned to perform follow-up on GW events for the following reasons. The majority of the near-infrared region is largely unexplored, giving WINTER a significant advantage in the search for kilonova from GW events. Kilonova are also significantly longer lasting in the infrared, 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. 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 discovery and follow-up observations of kilonovae during O4 and beyond (Frostig et al. 2022).

1.4. *ZTF*

The Zwicky Transient Facility (ZTF) is an optical time-domain survey operating on the Palomar Schmidt Telescope. With a 47 degree squared field of view, ZTF has performed all-sky surveys and monitored transients extensively in the g and r bands. Even with such a large field of view, ZTF obtains images of high quality (Bellm et al. 2019). This facility will allow for a large portion of the night sky to be monitored very quickly, a useful tool in the search for kilonovae. Previous studies have utilized ZTF to search extensively for optical components of BNS and NSBH mergers. Though no kilonovae were discovered by ZTF during O3, we anticipate a high probability of discovery during O4 (Kasliwal et al. 2020). We anticipate that the use of ZTF in combination with WINTER will create an optimized strategy to search for kilonovae from GW events.

2. OBJECTIVES

WINTER and ZTF are incredibly powerful tools in their own rights. How can we optimize the use of each instrument in order to maximize kilonova discovery and observation? With WINTER operating in the near-infrared region and ZTF operating primarily in the optical region, what is the best strategy in order to find kilonova given LIGO localizations? Studies have been performed on observation strategies for each individual instrument, but how do those strategies change when we combine them? All of these questions are the foundation for this project. Using simulated sky maps from LIGO and a given set of kilonova models, we will simulate observations from each telescope using the survey simulating software `simsurvey`. From there, we carefully analyze these observations to directly compare the performance of each telescope. The ultimate goal of the project is to create a program / metric that generates the optimized observing strategy for a given GW event using these results. As mentioned in Section 1.2, the localizations we receive from LIGO are relatively poor, accounting for up to 1000 square degrees. Part of the goal of this project is to figure out how to best map such a large area to the faint limits required for kilonova discovery. There are many strategies that could potentially be used to maximize efficiency. We will continuously reference past studies to glean as much information on past successes and past failures as possible. We will investigate tiling methods with both ZTF and WINTER, as well as a method known as galaxy targeting. 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, and leading to answers for fundamental questions about the nature of the most violent mergers in the universe.

3. APPROACH

For this project, we have a detailed methodology to achieve the objective. We have available to us a set of simulated sky-maps for both BNS and NSBH mergers. We will read in each sky-map and generate an observing plan for both WINTER and ZTF using `gwemop`. We also have access to kilonova models. Altogether, we will run the sky-maps and models for each telescope in `simsurvey`. We intend to adjust the schedules and modify the `simsurvey` code in order to accommodate WINTER. Furthermore, we will analyze the results of the `simsurvey` runs to determine which telescopes perform the best for each sky-map. We will categorize the simulations in which WINTER does better, and the ones in which ZTF performs better. From there, each sky-map will be investigated to determine the best possible strategy for follow-up. We anticipate that there will be many strategies for potential use by the follow-up campaign. Some of which include tiling, where the telescope(s) will survey the entire area within the sky-map to search for the kilonova, or galaxy targeting, intended for when the area of the sky-map is too large to be tiled in a reasonable fashion, in which the telescope(s) will target known galaxies within the localization region since they are more likely to be the source of the GW event. We will also define a criteria for kilonova discovery and photometric classification based on the results of this study. We anticipate creating a pessimistic, realistic, and optimistic criteria with the information gleaned. In general, we intend to perform a comprehensive study in order to best determine observing strategies for follow-up of GW events using both WINTER and ZTF to their fullest potentials.

3.1. *Project Timeline*

Below I have outlined a general schedule for Summer 2022.

- Weeks 0-2: retrieve all sky maps from observing scenarios and generate observing schedules for WINTER and ZTF

- Weeks 2-5: ingesting schedules (WINTER and ZTF), modifying `simsurvey` for WINTER specifications, and running `simsurvey`

- Weeks 5-8: analyzing results of simulations; comparing and contrasting the performances of WINTER and ZTF; determining strategy for follow-up of ZTF-discovered candidates (i.e. cadence and depth)

REFERENCES

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

—. 2017, Phys. Rev. Lett., 119, 161101, doi: 10.1103/PhysRevLett.119.161101

Abbott, R., Abbott, T. D., Abraham, S., et al. 2021, ApJL, 915, L5, doi: 10.3847/2041-8213/ac082e

Bellm, E. C., Kulkarni, S. R., Barlow, T., et al. 2019, PASP, 131, 068003, doi: 10.1088/1538-3873/ab0c2a

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

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, The Astrophysical Journal, 905, 145, doi: 10.3847/1538-4357/abc335

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