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Interim Report 1: Synergies with WINTER, ZTF, and LIGO for Kilonova Discovery

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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 more long 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 WINTER and ZTF in conjunction with LIGO 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 kilonova events observed by LIGO during O4. With these results we then create a follow-up strategy that will optimize use of both WINTER and ZTF while maximizing the possibility for kilonova discovery.

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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 mediums, 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). There has been predicted to exist two distinct components of the merger ejecta. First is the light, lanthanide free (atomic mass number < 140) dynamical mass ejecta that comes from squeezed polar material seconds before the merger. The emission from this dynamical ejecta is bluer, glowing brightly but briefly in the optical regime on the timescale of one day with a strong angle dependence. Second is the heavy, lanthanide rich (atomic mass number > 140) post merger disk wind ejecta. This neutron rich, high opacity wind produces a distinct thermal glow in the near-infrared region (peaking in the J and K bands, 1.2 and 2.2 μm respectively). This heavier 'red' component is longer lasting and is less angle and geometry dependent, especially in comparison to optical, X-ray, and gamma emissions from the same event. It is this feature that makes a kilonova distinct from other transients that may be involved in GW events (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). Kilonovae are rich in spectral lines, and encode a vast amount of information related to the makeup 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 outside of 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, X-ray, optical, near-infrared, and radio frequencies (Abbott et al. 2017; Kasliwal et al. 2020; Abbott et al. 2017; Dietrich et al. 2020). This event saw successful detection of 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 propel 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 in 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. Even so, we hope to use the valuable localization information given by LIGO to begin the search for kilonovae. As we prepare for O4, we expect to come across a large fraction of BNS or NSBH mergers that produce a kilonova. During O3, no kilonovae were discovered, but there is a high likelihood of detection during O4 (Kasliwal et al. 2020). The goal of this project is to be adequately prepared with multiple telescopes to detect these kilonovae and perform optimized 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. 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 kilonovae from GW events. Kilonovae are also significantly longer lasting in the infrared (with timescales ranging from several days to a week), 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. 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. 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 and is therefore sensitive enough to discover and observe kilonovae. This facility will allow for a large portion of the night sky to be monitored very quickly, another useful tool in the search for kilonovae. Previous studies have utilized ZTF to search extensively for optical components of BNS and NSBH mergers (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 thousands of 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. 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 for 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 describe the Python package simsurvey and how we will be using it to achieve our project goals. In Subsection 3.1.1, I will describe the current kilonova models we will be using. In Subsection 3.1.2, I will discuss the simulated skymaps for the LIGO O4, O5, and O6 observing runs. In Section 3.2, I will discuss the simulated lightcurve results. As I have progressed in my project, I have found that there are many different directions I could take, and I will discuss this in detail in Section 3.3.

3.1. *simsurvey*

The core software I will be using in this project will be a survey simulating software known as `simsurvey`. The premise of the program is as follows. `simsurvey` ingests both a model of the desired type of transient (generally generated with TransientGenerator) and a pointing schedule of the survey (generally inputed as a SurveyPlan that includes the observation times, filters used, sky noise, and can even include information about the individual CCDs). `simsurvey` then uses this information and generates a series of simulated lightcurves and statistics that can give information on the performance of the survey. (Feindt et al. 2019) This project uses `simsurvey` in specific ways in order to achieve our goal. We choose to inject the latest radiative transfer kilonova models (described in more detail in Section 3.1.1) as our desired transient. Kilonovae are unique and require models to be injected rather than generated using TransientGenerator. The current SurveyPlan specifications are adjusted for ZTF to include the filters, the planned observing times, and sky noise specific to this survey. As such, I am currently simulating observations with ZTF. The last key component of this simulation is to input LIGO data. In practice, we will receive localization maps from LIGO only hours after the event occurs. These skymaps give information on where to point ZTF in this simulated observing run. These localizations are inputted into `simsurvey` in order to give the area(s) of the sky that will be observed. I will go into more detail on these skymaps in Section 3.1.2.

3.1.1. *Kilonova Models*

In recent years, many collaborators around the world have worked to create the most up to date radiative transfer models of kilonovae. The script I have been provided with includes a variety of different model types for use with `simsurvey`. The primary model type we will be injecting into `simsurvey` 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.

3.1.2. *Simulated Skymaps*

When LIGO detects the gravitational waves from a BNS or NSBH merger, efficient follow-up is important in order to maxmize the chances of kilonova discovery. LIGO data is used to generate localization maps which predict the area of the sky the signal came 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 valued at 4480 deg^2 (Abbott et al. 2020b). Using the realistic data from O3, new simulated skymaps have been produced for O4 and O5 (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 accurate represent O3. This difference in signal to noise 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.

3.2. *Beyond*

The next portion of the project involves another portion of code known as the Nuclear-physics and Multi-Messenger Astrophysics (NMMA) framework (Pang et al. 2022). This framework serves as the 'missing piece' of the puzzle of observing kilonovae. NMMA takes LIGO observing scenarios and creates kilonovae models that fit the parameters. NMMA also has capabilities similar to `simsurvey`, where it can sample the kilonovae models to create aritifical lightcurves. The next step in this project is to consider WINTER. We will consult previous studies (Frostig et al. 2022; Andreoni et al. 2020) and brainstorm the best set of cadences and filters to use for optimal GW follow-up. We will inject these sets of parameters to modify the NMMA code and observe the results. Then, we will study the relationship between the parameters and how well we observe kilonovae (detection rate, detection efficiency, etc.). The other secondary objective will be to modify `simsurvey` with WINTERs specifications. We will be referencing many other python frameworks that are relevant to this work and NMMA, including `nimbus` (Mohite et al. 2022) and others.

4. CURRENT PROGRESS

So far, I have spent Weeks 1-3 reading many papers in order to understand all of the components that go into this project. As described previously, there are many different pieces that all connect in this work, so it has been important for me to learn about all of them. Next, I have successfully been able to run `simsurvey` and have generated my first lightcurves, shown below in Figure 1. This first run of `simsurvey` used the LIGO event GW190425 as a test case. I inputted the localization map for this event, and I used the Bulladynwind kilonova model. I am satisfied that I have been able to run the script successfully, and in the upcoming weeks will work on modifying the code and testing different parameters to simulate as many kilonova observations with ZTF as possible.

4.1. *Challenges*

This project, like many before it, has come with its challenges and problems. Firstly, I found that there is a high learning curve. Even into Week 4, I am still learning many new things, and it has been difficult to manage all of the new information I am receiving. In particular, I have read almost two dozen different papers that all pertain to this research. Keeping track of each paper, and more importantly the content and information inside each paper, has been tough, but not impossible. I came up with a system that works for me, and I feel like I am finally finding a rhythm. Secondly, I had a lot of trouble getting the code to work properly. Similar to my first point, there is an incredibly high learning curve, and I had to learn a lot of the jargon and formatting required to successfully run the scripts properly. Now, as Week 4 comes to an end, I am getting somewhere and am starting to pick up momentum. I am satisfied with the progress of my work so far, and excited to see what the future holds.

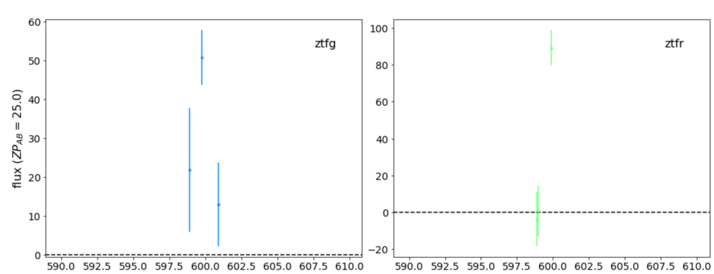

Figure 1. Two sample lightcurves produced by `simsurvey`. On the left represents the lightcurve for the ztf-g filter and the right represents the lightcurve for the ztf-r filter.

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