Kilonova Detection in LSST

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Abstract

The first observation of gravitational waves (GW) from a binary neutron star collision, known as GW170817, was made by the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo GW observatories, with the discovery of a kilonova, marking the beginning of multi-messenger astronomy. This event occurs when two neutron stars or a neutron star and a black hole collide. The Vera C. Rubin Observatory, located on Cerro Pachón in Chile, a powerful new observatory under construction, will be used to study a wide range of astronomical objects and phenomena, including kilonovae. Its main goal is to conduct the 10-year Legacy Survey of Space and Time (LSST). Our work is done within the Dark Energy Science Collaboration (DESC), one of several science collaborations preparing for the LSST data release. Our project focuses on assessing how well kilonovae will be detected in LSST. To achieve this, we use theoretical models of kilonova light emission known as Kasen models. These models predict the ultraviolet (UV) to infrared (IR) spectrum at intervals of 0.1 days after the neutron star merger, taking into account various factors, such as ejecta mass, ejecta velocity, and lanthanide fraction, influencing the kilonova's luminosity. By utilizing Kasen models, we generated kilonovae light curves for the six LSST bands (u, g, r, i, z, y) at increasing redshifts. These light curves depict how the observed brightness of a neutron star merger changes over time. Through an analysis of these light curves, we find that the number of kilonova models that would be detectable in LSST rapidly decreases with increasing redshift. The findings demonstrate that kilonovae falling below LSST's limiting magnitude remain too faint for detection in single exposure images. However, those that did surpass the threshold can be observed in LSST, holding the potential for groundbreaking discoveries.

I. INTRODUCTION

Kilonovae are rare celestial occurrences, classified as transient events within the field of astronomy, that occur when two neutron stars or a neutron star and a black hole collide. As a result of these collisions, an intensely energetic explosion emerges, releasing a tremendous amount of energy in the form of electromagnetic radiation. The energy released by a kilonova is roughly a thousand times greater than that produced by a typical star explosion (nova), but it is less powerful than a supernova. These collisions not only create ripples in space-time, known as gravitational waves (GW), due to the accelerated motion of celestial objects, but also radiate optical emissions and intense bursts of gamma rays (GRBs). Kilonovae are also thought to be an origin for r-process (rapid neutron capture process) heavy elements. These elements are synthesized within the explosion due to the extraordinary pressure and temperature conditions.

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is a large-scale physics experiment and observatory designed to detect and study gravitational waves through a technique called laser interferometry. It involves the use of lasers and the principle of interference to make highly accurate measurements of length, distance, or vibrations. With its proficient ability to detect incredibly small changes, on the scale of a fraction of the width of an atomic nucleus, this highly sensitive equipment is capable of detecting gravitational wave events.

The first observation of a kilonova was detected through gravitational waves (GW) by Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo GW observatories in August of 2017, known as GW170817. In less than twelve hours after the waves were detected, observations began by the Dark Energy Survey (DES) and the Dark Energy Camera GW-EM Collaboration, using the Dark Energy Camera (DECam) at the Cerro Tololo Inter-American Observatory (CTIO). The DESGW collaboration, an international group associated with the Dark Energy Survey, focuses on searching for optical counterparts to gravitational wave events. The findings found and confirmed the optical counterpart to GW170817 in the galaxy NGC 4993, which is spatially coincident with GW170817 and with a weak, short γ-ray burst. This remarkable discovery inaugurated the era of multi-messenger astronomy. Such groundbreaking astronomy that can use both gravitational waves and electromagnetic radiation to study events of astrophysical interest. As LIGO continues its pursuit of detecting neutron star collisions through gravitational wave detection, the question arises: How effectively will the new Rubin Observatory identify the associated optical emissions?

The Vera C. Rubin Observatory, located on the El Penón peak of Cerro Pachón in northern Chile, is a powerful new observatory under construction. This is a federal project jointly funded by the National Science Foundation (NSF) and the Department of Energy (DOE), with early construction funding received from private donations through the Legacy Survey of Space and Time (LSST) Corporation. The Rubin observatory aims to survey the entire southern sky every three days for a decade, contributing to the study of a wide range of astronomical objects and phenomena. Noteworthy features of the observatory include an 8.4-meter mirror, a 3.2-gigapixel camera, and six filters (u, g, r, i, z, y) covering the wavelength range of 320–1050nm. The Rubin Observatory's LSST Camera stands out as the largest digital camera ever constructed, led by the U.S. Department of Energy’s SLAC National Accelerator Laboratory. The LSST Camera will be mounted to the Simonyi Survey Telescope. The Rubin Observatory’s primary objective will be to conduct the 10-year Legacy Survey of Space and Time (LSST). This survey will observe more astronomical objects than all previous telescopes combined. Its rapid coverage of the sky will enable it to find many transients, including kilonovae.

II. OVERALL RESEARCH OBJECTIVES

In this project, we sought to assess how well kilonovae will be found in the Legacy Survey of Space and Time (LSST) at the Rubin Observatory. Our work began with the Kilonova Data Challenge (KDC), an effort to add simulated kilonovae into DESC Data Challenge 2 (DC2) using tools to insert kilonovae into pre-existing catalogs created by LSST-DESC. DC2 is a simulated sky survey designed to generate data products closely resembling what will be released by the Rubin Observatory, allowing LSST-DESC working groups to use and prepare for the actual data release. DC2 covers six optical bands in a wide fast deep (WFD) area of approximately 300 sq degrees as well as a deep drilling field (DDF) of approximately 1deg^2 simulating 5 years of the planned 10 years. DC2 covers only 1% of the sky while LSST will observe the entire southern sky. The Rubin Science Platform (RSP) is the interface that users will utilize to access processed Rubin Data; it is currently used to serve simulated data through data previews. We utilize DP0.2 which is based on DESC DC2; this simulated image set contains galaxies, stars, supernovae, and variable stars. Image processing was done with the LSST Science Pipelines, and produced the images and catalogs that comprise the DP0.2 data release.

The three main types of images available for DP0.2 are processed visit images, coadded images, and difference images.

The KDC project was initiated with the production of simulated kilonovae using image simulator PhoSim and generated spectral energy distributions (SEDs) with code to predict magnitude based on Kasen models. Then choosing DC2 galaxies to host the kilonovae by using a sample of real galaxies that hosted short gamma ray bursts (sGRBs) which are known to be associated with neutron star collisions. This allowed us to take the completed instance catalogs and produce all simulated images with a complete set of images containing kilonovae, along with other DC2 objects, in u and r-band. Initially, we began with the production of single epoch exposures for simulated kilonovae. As our project advanced, we have transitioned to the use of synthetic source injection to add the same kilonovae into processed DC2 images as co-adds. This approach offers the advantage of extracting more information from multiple input images, enabling us to effectively determine the detectability of kilonovae in LSST images.

III. PROJECT RESULTS

This project revolves around the assessment of kilonova detectability in LSST at the Rubin Observatory. To achieve this, we leveraged established theoretical frameworks for kilonova light emission known as Kasen models introduced by Kasen et al. in 2017. These models offer a comprehensive depiction of the ultraviolet (UV) to infrared (IR) spectrum at intervals of 0.1 days following a neutron star merger, accounting for key variables such as ejecta mass, ejecta velocity, and lanthanide fraction that influence the resulting kilonova luminosity. By utilizing Kasen models, we generated kilonovae light curves for the six LSST bands: u, g, r, i, z and y at increasing redshift values.

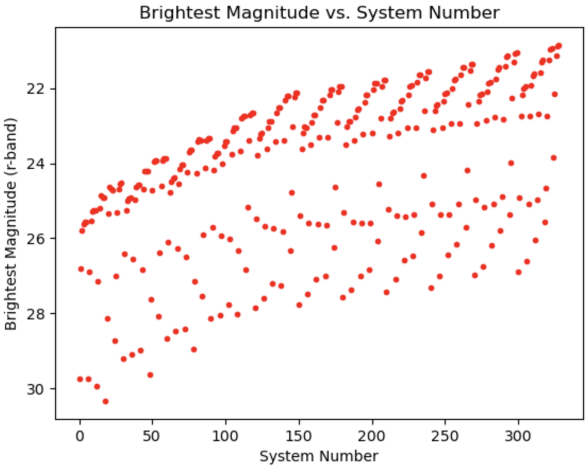

Figure 1 — Plot of r-band brightest magnitude vs. system number

This process is done by using a Jupyter notebook that calculates synthetic AB magnitudes by measuring the flux from the objects at distances corresponding to the given redshifts. It also creates files providing the magnitude for each filter band at a sequence of times. The time starts from 0.05 days after the kilonova begins and goes up to 8.95 days after the merger. In Figure 1, a plot of the brightest magnitude vs. system number for all of the 329 Kasen models (in r-band) is shown.

This process is repeated at various redshifts, starting with z = 0.0099, which is the redshift for GW170817 and then going up to z = 0.5. Then we are able to read these files in another Jupyter notebook that was created to generate and save plots of the kilonova light curves as well as appending the number of visible kilonovae models depending on the limiting magnitude of the 329 models for each band to refer back to.

These light curves serve as dynamic representations of how the luminosity of neutron star mergers evolves over time. Through an in-depth analysis of these light curves, a clear trend emerged: the number of detectable kilonova models within LSST decreases significantly as redshift values increase.

Our findings demonstrate a key observation - kilonovae with magnitudes dimmer than LSST's limiting magnitudes remain beyond the threshold of detectability within single individual exposure images. It's important to note, however, that kilonovae surpassing this magnitude threshold are bright enough for detection and analysis within the LSST framework, holding the potential for groundbreaking discoveries.

Central to our investigation is the evaluation of the intersection between Kasen's theoretical models and LSST's observational parameters. LSST calculates its limiting magnitude for different filters by considering the total system throughput, atmospheric transmission, optics, and detector sensitivity. The findings demonstrate that kilonovae falling below LSST’s limiting magnitude remain too faint for detection in single exposure images. However, those that did surpass the threshold can be observed in LSST, as illustrated in Figures 2 and 3. It is shown as analyzed from the 329 models, the generated lightcurves with

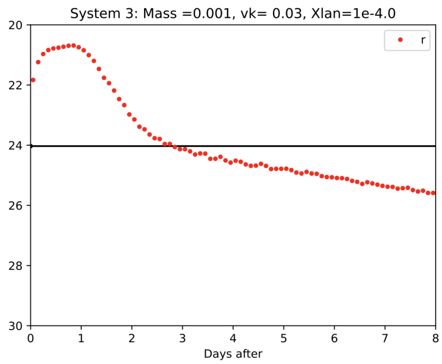

Figure 2 — Kilonova Light Curve #3 at z = 0.0099 showing r-band limiting magnitude. Observable in LSST.

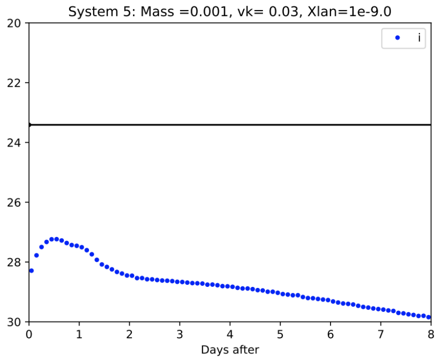

Figure 3 — Kilonova Light Curve #5 at z = 0.2 showing i-band limiting magnitude. Unobservable in LSST.

LSST’s limiting magnitude threshold in the respective bands.

The visual representation in Figure 4 vividly portrays the projected observability of the Kasen kilonova models within LSST's single visit images. These predictions are based on whether each Kasen model, at any given point in its light curve, achieves the requisite luminosity in a specific filter band to surpass LSST's limiting magnitude for that band. This involved iterative recalculations of light curve predictions at varying redshifts, a process that naturally resulted in a notable decline in observable models with increasing redshift values.

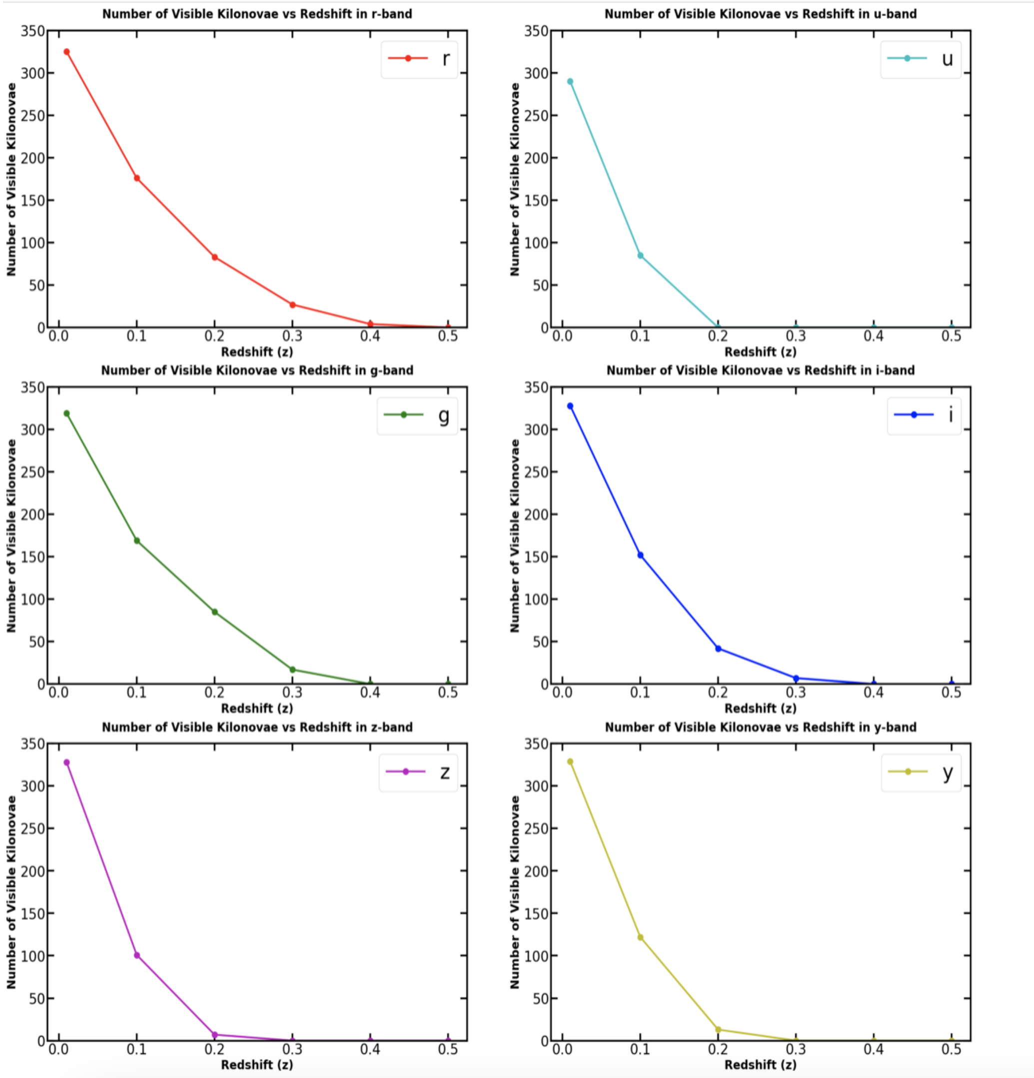

Figure 4 — Number of Visible Kilonovae Models vs Redshift Plots in Various Bands

IV. CONCLUSION

This research project aimed to evaluate the detectability of kilonovae within the Legacy Survey of Space and Time (LSST) at the Rubin Observatory. Kilonovae, rare celestial events resulting from neutron star collisions, offer unique opportunities for studying gravitational waves which offer insight into the universe’s expansion rate, which is one of the most critical topics for research in LSST-DESC regarding dark energy, as well as for studying the synthesis of heavy elements and optical emission.

The project utilized and evaluated the capabilities of Kasen theoretical kilonova light emission models to create light curves of kilonova, a visual representation of the luminosity from a neutron star merger over time, in the LSST bands (u, g, r, i, z, y) with a comparison to their LSST limiting magnitude at an increasing redshift. Through a comprehensive analysis of these Kasen kilonova light curves across LSST filter bands, a clear correlation between the luminosity of kilonovae and their detectability within LSST's observational parameters was revealed. Notably, kilonovae with luminosities falling below LSST's designated limiting magnitude remained beyond the threshold of detectability within single exposure images. However, those that exceeded this threshold exhibited the potential for detection and analysis. It was demonstrated in our findings that the number of detectable kilonova models within LSST decreases significantly as redshift increases.

The intersection between the Kasen theoretical models and LSST's capabilities provided insights into the achievability of detecting kilonovae and their implications for multi-messenger astronomy. This project’s technique involved intricate computational processes, including the utilization of Jupyter Notebooks to generate synthetic magnitudes, light curves, and plots. In summary, this research advances our understanding of kilonova detectability within LSST frameworks, as the Rubin Observatory prepares for the 10-year Legacy Survey of Space and Time. Future work in this section of our project involves the evaluation and assessment of additional theoretical models for further analysis.

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