PP25: Searching for optical counterparts of gravitational wave events with LSST

Candidate Number: 725338
Supervisors: Professor Marcelle Soares-Santos, Dr Farrukh Azfar, Professor Ian Shipsey

23rd April 2018

Abstract

The coalescence of a binary neutron star system, known as a kilonova, produces both electromagnetic and gravitational waves (GW). In August 2017, groundbreaking joint observations of optical radiation and gravitational waves from the kilonova GW170817 heralded the era of gravitational-wave astronomy. Kilonova GW detections can provide the next generation of absolute distance measurements in the universe, and when combined with redshift measurements from an optical detection, these multi-messenger measurements enable independent estimates of the Hubble constant. Over the next 10 years, the LIGO-Virgo detectors are expected to make around 1650 kilonova GW detections and therefore efficiently detecting the optical counterpart is essential to maximize science gains through precision cosmology and population studies. The Large Synoptic Survey Telescope (LSST) will begin observing in 2019 and with its fast, deep and wide survey capabilities will be in position to take leadership on this emerging field and efficiently detect kilonova counterparts. In this project, kilonova light curves and the LSST observation survey were simulated using the SNANA code [1]. These simulations enable predictions of the fraction of observable kilonovae within the volume of sensitivity of LIGO-Virgo, that will be detected by LSST (we denote this quantity the efficiency). It was found that the default LSST survey will achieve an efficiency of just 20%, thus highlighting the necessity for a follow-up strategy to GW events. Simple follow-up strategies were devised, which comprise of, in each filter, trying to move an observation to the location of the kilonova in the t_1 days after the GW detection. These strategies achieved over 2.5 times the original efficiency (53%) while causing just 1.18 days of observing time to be lost over the 9.5-year survey. The most successful strategy set the variable $t_1 = 2.5$ days and it was found that setting the maximum allowed slew angle to the kilonova to below 110 degrees negatively affected the efficiency. This investigation succeeded in identifying the relevant variables to develop a follow-up strategy and was able to make recommendations for future strategies. This study lays the foundations for members of the LSST Dark Energy Survey Collaboration to develop a comprehensive follow-up strategy to be used by LSST to efficiently detect the optical counterparts of kilonova GW events.

I. INTRODUCTION

On 17th August 2017 the coalescence of a binary neutron star system, known as a kilonova, was detected for the first time by the LIGO-Virgo gravitational wave (GW) detectors (this event was named GW170817). Two seconds later, an associated gamma ray burst was detected by the Fermi satellite and within 12 hours the exact location of the event was pinpointed by observations of the optical transient[1] that had been predicted. This was the first instance of detection of both the electromagnetic and gravitational-wave transients associated with the same astronomical event and has marked the advent of an era of gravitational-wave astronomy.

This detection alone, which confirmed the existence of this new class of transients, had a significant scientific impact. It enabled an independent distance measurement to the source and an estimate of the Hubble constant. The Large Synoptic Survey Telescope (LSST), with its wide, deep and fast survey capabilities is well suited to lead the search for kilonova optical transients. When LSST begins observing in 2019, we expect to be in a regime in which the LIGO-Virgo interferometers detect many kilonova each year. If the optical transients can be effectively identified, the scientific payoff will be enormous as the measurements will enable precision cosmology[2] and population studies[3]. In particular, precision cosmology is an objective

[1] A transient is a short-lived signal from an astronomical event.

[2] Precision cosmology seeks to determine precisely cosmological parameters. Here, the relevant parameter is the Hubble constant.

[3] Population studies determine the general astrophysical properties of binary neutron star systems, such as the mass distribution.

of the the LSST Dark Energy Survey Collaboration (DESC) who want to implement ‘target of opportunity observations’[4] with LSST for kilonova transients. As a member of the LSST DESC taskforce, this project is designed to first show that the default LSST survey, which does not have a follow-up strategy for kilonova GW events, will detect a small fraction of these optical transients and secondly to determine the principles of a follow-up strategy that can efficiently detect these optical transients in a way that is minimally disruptive to the survey.

In the introduction, section A explains the physics of kilonovae. Sections B and C, discuss respectively why the multi-messenger detection of kilonovae is of interest to the scientific community and why LSST is suitable to lead the search for these transients. Section D describes previous related work and lays out the specific questions that are addressed in this study.

A. *Kilonovae*

Neutron stars form when the core of a large star (10 – 29 solar masses) collapses. They are very dense with masses ranging from 1.4 – 2 solar masses and radii on the order of 10 kilometers. A kilonova[5] is the coalescence of a binary system of either two neutron stars or a neutron star and black hole. In the former case, either a more massive neutron star or a black hole is formed, while in the latter case a more massive black hole is formed. The rate of kilonovae per unit volume in the universe is estimated to be in the region of 1×10^{-6} $\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$ [2][6].

As the binary system’s orbit decays, the orbit becomes more and more circular to the extent that, just before coalescence, when the system emits gravitational waves most strongly, the orbit is approximately circular. This makes the GW signal easily identifiable. Kilonovae also produce gamma-ray bursts which have an ‘afterglow’ in the optical/infrared that lasts up to 2 weeks. The light curve from the only observed kilonova is shown in Fig 1, which is taken from [3].

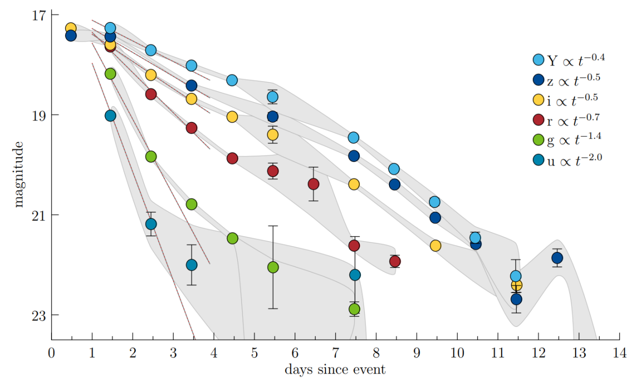

Fig. 1. This figure is taken from [3]. The grey bands display the 95% confidence interval around each data point. Large grey bands are due to poor weather conditions during observations.

B. *Scientific Objectives*

Measurements of kilonovae, through both the optical and gravitational-wave transients, could provide important insights into various astrophysical and cosmological problems.

Firstly, from an astrophysical perspective, observing many kilonovae will enable population studies and tell us about the formation rates of binary neutron star systems. The location of these events will tell us about the galaxy conditions that are favorable for neutron star formation and black hole formation.

From a cosmological perspective, kilonovae can provide the next generation of distance measurements in the universe. For this reason, kilonova GW detections are often referred to as standard sirens (as opposed to standard candles which are detected through their optical transient). From the GW signal, an estimate of the absolute distance to the binary system can be obtained using the inverse relation between the amplitude of the wave and the luminosity distance. The constant of proportionality can be inferred directly from the ‘chirp-like’[7] gravitational waveform. This

[4]These are observations that require interrupting the survey due to an external trigger (in this case the trigger is the GW detection).

[5]Sometimes the term ‘kilonova’ is used to refer to the electromagnetic signature only of a binary neutron star merger. However, as is common, here I use the term ‘kilonova’ to denote the binary neutron star merger event itself.

[6]In reality, the volumetric rate has a power law dependence on (1+z), where z is redshift.

[7]A chirp is a signal in which the frequency increases with time. The behavior is observed because the orbital frequency of the binary system increases as the objects coalesce.

method of measuring cosmological distances is unique for two reasons. Firstly, it is calculated using only general relativity and does not depend on the uncertain astrophysical parameters of the event. Secondly, it is absolutely calibrated, in that it does not require intermediate astronomical distance measurements (the cosmic distance ladder) to be calibrated.

In addition, multi-messenger observations of kilonovae, will enable more precise estimates of the Hubble constant (H_0) independent of the cosmic distance ladder. The Hubble constant defines the expansion rate of the universe and also sets the universe's overall scale. As Bernard Schutz realized over 30 years ago [4], by combining the distance (inferred from gravitational waves) with the redshift (inferred from the optical counterpart) an estimate of the Hubble constant can be obtained. The kilonova detected in August 2017 gave an estimate for the Hubble constant of $70.0\ ^{+12.0}_{-8.0}$ km $s^{-1}Mpc^{-1}$ [5]. A typical kilonova standard siren and electromagnetic counterpart observation will constrain the Hubble constant to an uncertainty of around 15%. A statistical analysis in [6] demonstrates that N multi-messenger observations (where N is not statistically small, i.e. N>4) will reduce the uncertainty in H_0 to around $\frac{15}{\sqrt{N}}\%$.

Currently there are two separate methods of measuring H_0 with high precision: using the cosmic microwave background and using Cepheid variable stars[8]. These methods of measuring H_0 disagree by 3% and have uncertainties of 1% and 2% respectively [7]. Thus, the motive for this project, which was designed by the DESC, is to work towards collecting a large sample of multi-messenger kilonova detections in order make a precision measurement of the expansion rate of the universe (H_0). The objective is to eventually constrain H_0 to within 1-2% uncertainty and be able to determine which of these independent measurements is correct. As shown in Fig 2, this will require approximately 100 observations.

It is clear that multi-messenger kilonovae detections

[8]These are pulsating stars whose period is related to their luminosity.

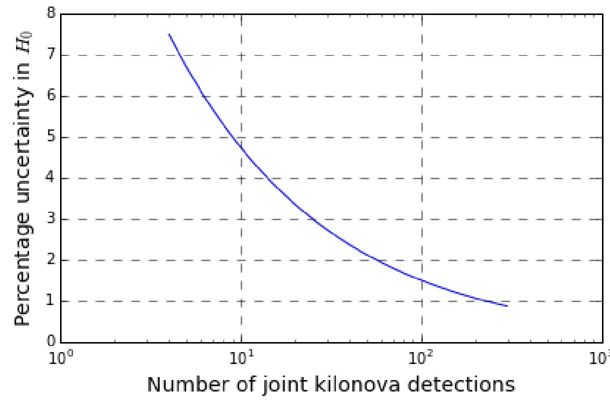

Fig. 2. The statistics behind the plot is motivated by [6]. The plot shows a decay in percentage uncertainty following $\frac{15}{\sqrt{N}}\%$, where N is the number of joint observations of both the electromagnetic and gravitational-wave transients. The plot goes up to N=300 since after this many observations H_0 should be easily constrained to within 1% uncertainty.

can play an important role in tackling various astrophysical and cosmological questions. Therefore, it is necessary to ensure that electromagnetic counterparts are effectively observed to maximize scientific gains.

C. The Large Synoptic Survey Telescope

The Large Synoptic Survey Telescope (LSST) is a ground based telescope that is specialized to carry out a survey of the entire sky visible from northern Chile. The observation region is shown on the sky map in Fig 3. LSST will begin observing in 2019 and over its 9.5-year survey, it will image every sky location over 1000 times. It has a 9.6 square degrees[9] field of view and takes images using pairs of 15-second exposures. It will observe in 6 optical bands (u,g,r,i,z,Y) which cover parts of the infrared, visible and ultraviolet spectrum.

LSST is uniquely wide, deep and fast. This means it can image large areas of sky, to faint magnitudes in short amounts of time. The gravitational wave source can be localized by LIGO-Virgo to a banana-shaped region of sky of approximately 36 square degrees. Therefore, in order to observe the optical counterpart, a faint source must be searched for in a large area of sky.

[9]This is particularly large for a telescope. For example, the Dark Energy Camera which is a state-of-the-art survey telescope has a 3 square degrees field of view.

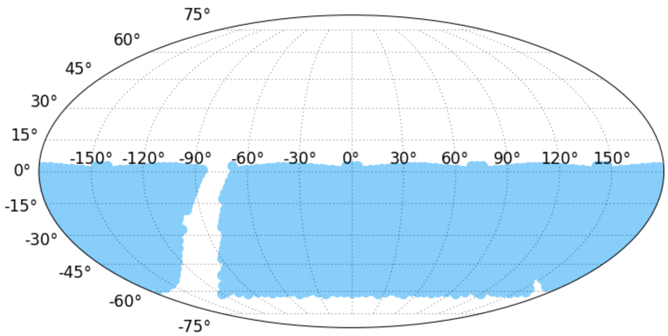

Fig. 3. LSST observation region is in blue. The strip in the southern hemisphere without observations is because LSST cannot image through the plane of the Milky Way.

LSST can cover the whole region of interest with 4-5 observations and thus is well suited to lead the search for optical counterparts.

As LSST balances many scientific objectives, we propose to use LSST to identify kilonova candidates which then allows smaller aperture telescopes to identify the true positive. The false positives will be supernovae as they occur at higher rates than kilonovae. With further observations, it is easy to differentiate between supernovae, whose optical transient lasts for over a month, and kilonovae, whose optical transient lasts for days. Thus, the role of LSST is to identify kilonova candidates while keeping false positives to a manageable number. In this project, we will not be concerned with supernovae contaminants and will focus on ensuring that kilonovae are detected.

D. Previous Work and Open Questions

In recent research about the detectability of optical transients associated with GW events, [8] simulates supernovae and kilonovae in order to determine cuts that can efficiently classify kilonovae. In combination with a kilonova follow-up strategy, which my project aims to guide, these cuts make up the full procedure of identifying the optical counterpart. [9] simulates an untriggered search for kilonovae in 10 different surveys including the LSST survey. It predicts 69 kilonovae will be detected by LSST in the 9.5-year survey and suggests the need for a follow-up strategy to detect the optical transients. [10] experiments with different follow-up strategies and differs from my project in that I consider how a follow-up strategy can fit in with an existing survey.

In this report, the detectability of optical transients associated with gravitational wave events by LSST is investigated by broadly addressing two questions:

1) The default LSST survey does not have a strategy for observing the optical transients associated with GW detections. To what extent will the default survey be successful anyway in observing these transients?
2) What follow-up strategy can improve the probability of successfully detecting the optical transient while minimizing disruptions to the survey?

In order to tackle these questions, it was chosen to take the approach of creating realistic simulations using the SNANA software package [1] (also used in [8] and [9]). These simulations create many kilonova light curves and execute the LSST survey. The criterion that constitutes observing a kilonova was defined and from this, simulations predicted the fraction of kilonovae that would be detected by a given survey. It was found that just 20% of kilonova optical transients inside the volume of sensitivity of LIGO-Virgo would be detected with the default survey and therefore a follow-up strategy that is implemented following a GW detection is necessary as otherwise LSST would miss most transients.

To address the second question, a simple follow-up strategy was devised which consists of finding a pointing[10] that is scheduled near to the kilonova in the few days after the GW detection, and moving it to the location of the kilonova. A compensating swap in the following weeks is then required to ensure that the survey is carried out at every sky location. For each strategy, the fraction of observable kilonovae detected and the cost, which captures the disruption caused to the default survey, were calculated. Optimal parameters for the follow-up strategy were investigated and it was shown that a simple strategy can easily improve the fraction of optical transients detected up to 40%.

[10]A pointing is a single observation/imaging of a sky location.

Through analysis of these results, I was able to make recommendations for the design of future follow-up strategies for LSST and guide further work in this area. This work is novel, in that, to my knowledge, it is the first attempt to create a follow-up strategy to improve the detectability of kilonova optical transients with LSST.

The structure of the remainder of the report is as follows. Part II describes the simplifications that were made to the problem and the simulations. In III, I present the results of simulations with both the default survey and with amended surveys which use a variety of follow-up strategies. In IV, suggestions are made for future follow-up strategies and I conclude in V.

II. METHODS

A. *Simplifications to the problem*

In order to make this project a contained scientific investigation, several simplifications to the problem were made. The main assumption made was that a kilonova could be located precisely by the LIGO-Virgo detectors so that one pointing by LSST would be sufficient to observe the transient. This assumption is valid as the main cost associated with a follow-up strategy is the slew[11] to the region of interest. The size of the region simply determines the number of compensating observations needed ensure all sky locations are imaged in the end and does not affect the extra slew required. The approach taken can easily be generalized to cover an extended localization region as we know that 4-5 pointings will cover the full 36 square degree localization area.

Other choices that were made in order to simplify the problem were, to treat all filters the same in the follow-up strategy, and to ignore the contaminating effect of supernovae when searching for kilonovae.

B. *Simulations of the Kilonova Light Curves*

Kilonova light curves were created with a Monte-Carlo simulation using the observed light curve of GW170817 as a seed. The kilonova light curves were initialized at random times over the 9.5-year LSST survey. They were only created at sky locations that are observable from LSST's earth location in Northern Chile (the blue region in Fig 3).

An important parameter to specify was the number of kilonovae in each simulation. It was assumed that the volumetric rate is constant with redshift and a value of 1×10^{-6} Mpc^{-3} yr^{-1} from [2] was used. Kilonovae were simulated up to a redshift of z = 0.11 (or equivalently a luminosity distance[12] $\sim$ 500 Mpc) as this is the maximum redshift at which the LIGO-Virgo detectors can observe GW sources [11]. From the redshift range, and assuming that $H_0 = 70$ km s^{-1} Mpc^{-1} the survey volume can be calculated. Then, an estimate of the number of kilonovae that LIGO-Virgo is expected to observe during the 9.5 year LSST survey, is computed by taking the product of the volumetric rate, the comoving survey time and the survey volume. The calculation is outlined below.

$$\text{Volumetric rate} = 1 \times 10^{-6}\text{Mpc}^{-3}\text{yr}^{-1}$$

$$\text{Redshift range: } 0.0040 \leq z \leq 0.1100$$

$$\text{Average redshift (volume-weighted), } \bar{z} = 0.0821$$

$$\text{Survey Volume, } V = 1.9365 \times 10^8 \text{ Mpc}^3$$

$$\text{Survey time, } t = 9.4795 \text{ yr}$$

$$\text{Comoving survey time, } \tau = \frac{9.4795}{1+\bar{z}} = 8.7605 \text{ yr}$$

$$\boxed{Number\ of\ kilonovae = rate \times \tau \times V = 1697}$$

It should be noted that these estimations predict 1697 kilonova across the whole of the sky. However LSST, can only observe 45% of the sky, so in fact 763 kilonovae are expected in this observable region. Despite this, throughout the investigation 1697 kilonova were created over the 9.5-year period in each simulation.

[11] Slewing is the process of rotating the telescope to observe a different region of sky.

[12] Luminosity distance is defined by comparing the absolute and apparent magnitude of an astronomical object. It is similar to the comoving distance for small redshifts.

C. Simulations of the LSST Survey using SNANA

The primary computational tool used in this investigation was SNANA – a software package designed for supernova analysis and recently updated for analysis of kilonova and other transients. SNANA takes as input kilonova light curves and the baseline LSST survey and through simulations can predict the number of kilonovae that will be detected according to some inputted detection criteria.

In order to simulate the LSST survey, an observation library containing all of the default pointings in the 9.5-year survey is computed from the baseline survey that was published by LSST. This observation library is computed by taking into account historical weather data and future observation conditions (such as moon position). Each observation includes a point spread function[13], a zero point[14] and a measure of the background sky noise.

D. Follow-up Strategy

The follow-up strategy is an algorithm that amends the LSST survey following a kilonova GW detection. It aims to improve the likelihood of detecting the optical transient while being minimally disruptive to the default survey. The algorithm is implemented after a kilonova GW event and simply involves making a series of swaps in which the locations of two pointings are swapped. It has the following structure:

1) Check to see if the kilonova is already scheduled to be observed in the next t_1 days. If yes do nothing, if no proceed to next step.
2) Find the times in the next t_1 days when the kilonova is visible from LSST. To be considered visible the kilonova must be at an air mass below a threshold value.[15]
3) Find the pointing closest to the kilonova in the next t_1 days and move it to the location of the kilonova. Record the slew angle.
4) Find a pointing in the next t_2 days at the location of the kilonova and move it such that it compensates for step 3. This step ensures that the survey visits all planned sky locations after t_2 days.

The above steps are repeated for each filter (u,g,r,i,z,Y) such that a maximum of 6 swaps may be made for a given kilonova. Note that the strategy does not consider the possibility of forcing a filter change, nor does it treat different filters differently. This is because filter changes, which last 120 seconds, are costly as they cause 4 pointings to be lost.

The algorithm will often fail to carry out the swaps for several reasons. The algorithm may fail at step 2 if the kilonova is too close to the sun and so is never visible during the night. At step 3, the algorithm may fail if there are no observations in the given band in the next t_1 days that coincide with when the kilonova is visible. It may also fail here if the angle between the kilonova and the nearest pointing in the next t_1 days is too large. The algorithm may fail at step 4 if there is no observation in the given band in the next t_2 days at the location of the kilonova, however this is never the case as long as t_2 is sufficiently large ($\geq$50 days).

All 6 swaps in every filter are never achieved for a given kilonova. This is because LSST only observes in a maximum of 4 different filters per night. On top of this, the kilonova will only be visible for a part of the night during which it is unlikely that all 4 of the filters will be used.

Metrics for Evaluating the Follow-up Strategy

The effectiveness of the follow-up strategy is simply measured by the fraction of observable kilonovae that are detected. The detection criterion from [9] was used as this paper created similar simulations using SNANA. The criterion is that two observations of the light curve in any filter are required. A pointing of LSST at the location of the kilonova does not necessarily constitute an observation. Each pointing at a kilonova is characterized by a signal-to-noise ratio (SNR) which

[13] The point spread function describes how a point source forms in the image plane of the instrument. Point spread functions are taken with every observation to account for changes in the imaging due to atmospheric conditions.

[14] Defining a zero point allows for absolute rather than relative measurements of the magnitudes of astronomical objects.

[15] The air mass is a measure of the amount of atmosphere between the telescope and the source. Air mass = 1 when looking directly up out of the atmosphere and it increases with the zenith angle.

is computed from the light curve and the observing conditions at that time (these include the zero point, the point spread function and the sky noise). This SNR is then mapped onto a probability of observation. This map is almost identical for all filters and typically maps SNR $= 5$ to a probability of around 0.5 (an example map is shown in Fig 4). In other words, if LSST images the kilonova light curve with SNR $= 5$, half of the time this will constitute an observation of the kilonova. For reference, objects of apparent magnitude ~ 23 are typically observed with SNR ~ 5 [12].

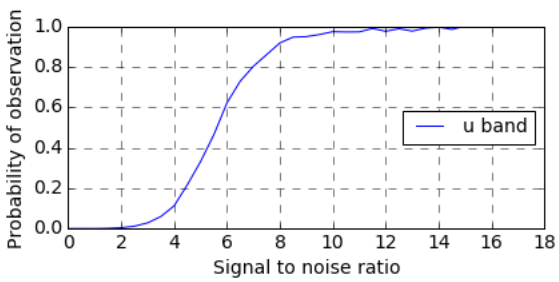

Fig. 4. Map of signal-to-noise ratio to probability of observation. All bands have very similar maps so the u band is chosen arbitrarily.

It is important to note that the criterion used here to constitute a detection is the minimal criterion, in that further observations would be required in order to identify the kilonova by distinguishing it from other contaminating supernova transients. However, as discussed in I-C, we anticipate this contaminant rejection will be done by smaller aperture telescopes and so in this investigation a minimal detection criterion is used.

A cost metric was created to quantify the disruption to the original survey caused by a given search strategy. The cost expresses the total extra slew time added by all of the swaps for all of the kilonovae. Each swap has an associated slew angle which is given by the angle between the location of the kilonova and the original location of the observation that is moved to be at the kilonova. The slew angle can be converted into units of time by calculating the additional overhead time that this slew takes. To estimate the extra overhead time associated with a given slew, a plot of overhead time against slew angle between all LSST pointings was made in Fig 5. The linear regression fit was used to

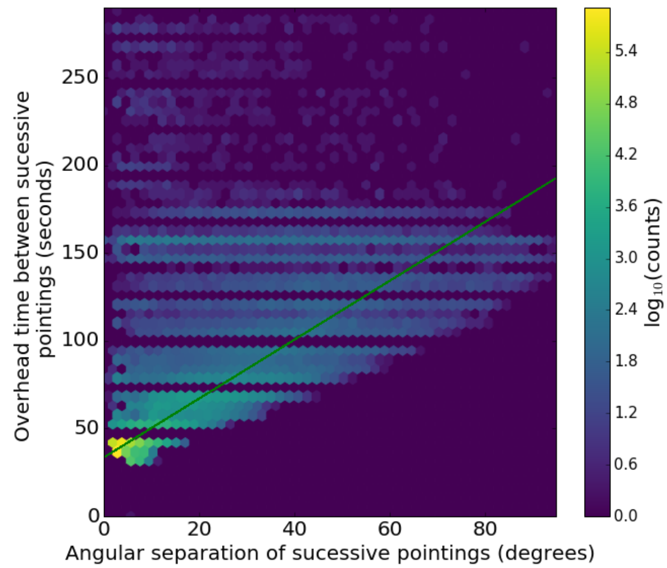

Fig. 5. Green line is a linear regression fit. In units of seconds and degrees: $overhead\,time = 33.5 + 1.7 \times (ang\;sep)$

predict overhead times corresponding to a given slew time. This slew angle must be carried out 4 times to complete a swap – twice to slew to the kilonova and back and twice when slewing to the compensating observation and back. Thus, in order to compute the cost of a follow-up strategy, all of the overhead times associated with a given strategy are multiply by 4 and then summed.

Parameters of the Follow-up Strategy

There are 4 variables in the follow-up strategy algorithm: t_1, the maximum slew angle, t_2 and the maximum air mass. Each is discussed briefly below:

- t_1 is the time period, after the GW detection of the kilonova, in which the algorithm searches for a pointing close to the kilonova to move to the location of the kilonova. A larger value of t_1 increases the chances of a swap being made. However, it decreases the likelihood that the pointing at the kilonova will achieve the required SNR to constitute an observation. Values in the range $0.8 \leq t_1 \leq 5$ days were experimented with.
- The maximum slew angle is imposed in order to maintain a realistic strategy. It would be too costly in terms of observing time wasted to slew

the telescope across the whole sky to observe a kilonova. Angles between 30 and 180 degrees were experimented with.

- t_2 is the time period after the GW detection, in which a later pointing at the location of the kilonova is moved to compensate for the earlier swap. t_2 was held constant at 50 days throughout the investigation as it was always possible to find a pointing in the next 50 days to move for the compensating observation.
- It was chosen that all observations of the kilonova must be at air mass < 2 as this is the air mass condition that all LSST pointings were found to satisfy. This is equivalent to requiring the zenith angle to be smaller than $60°$. Allowing the air mass to be any larger would harm the SNR of the image.

III. RESULTS

A. Detecting Kilonova Optical Transients with the Default LSST Survey

In the simulation, the default LSST survey succeeded in detecting (according to the specified criterion) 252 out of the 1697 kilonovae that were simulated in the LIGO-Virgo volume of sensitivity. Of the 1697 simulated kilonovae, 431 were never observable by LSST. This is because the kilonovae were either only up in the sky during the day or low in the sky at night[16]. Thus, of the kilonovae that LSST can hope to observe, the default survey would observe a fraction, ϵ, which we will call the efficiency[17].

$$\epsilon = \frac{252 \pm 16}{(1697 - 431)} = 0.199 \pm 0.013$$

An efficiency of 19.9% is unacceptably low and on top of this it was calculated that just 12.5% of kilonovae would be observed in the first night when the SNR is greatest. From these results, it is clear that a follow-up strategy which is implemented following a kilonova GW detection by LIGO-Virgo is required.

[16]Below the established air mass limit of 2.

[17]The uncertainty is the statistical uncertainty which is calculated using binomial errors.

B. Detecting Kilonova Optical Transients using a Follow-up Strategy to Amend the LSST Survey

As outlined in II, the two variables of the follow-up strategy are t_1 and the maximum slew angle. These two parameters were varied in turn in order to investigate the values that produce optimal efficiencies.

Optimal Choice of t_1

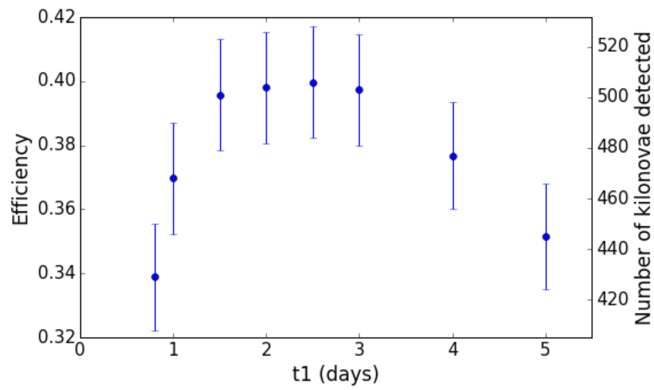

Fig. 6. Kilonova detection rates as t_1 is varied. Maximum slew angle was fixed at 110 degrees.

The results of simulations in which t_1 was varied are shown in Fig 6. In these simulations, the maximum slew angle was held constant at 110 degrees. The efficiency has a maximal value of 0.399 when $t_1 = 2.5$ days and this improves on the efficiency of the default survey by a factor of 2. For $t_1 < 2$ days, the number of swaps that are made for each kilonova limits the efficiency. For $t_1 > 2.5$ days, several swaps are made for most kilonova, however the pointings at the kilonova occur a few days after the GW detection. This means the kilonova light curve has faded in intensity and the pointing is less likely to constitute an observation as the SNR of the light curve will be low.

Optimal Maximum Slew Angle

Fig 7 displays the results of simulations in which the maximum slew angle was varied with $t_1 = 2.5$ days. Increasing the maximum slew angle from 30 degrees up to 110 degrees continuously improved the efficiency of the follow-up strategy up to 0.399. However, increasing this angle beyond 110 degrees did not result in any improvement in kilonova detection rates. This is because increasing the maximum slew angle further results in few additional swaps being made. The key finding of this result is that restricting the maximum slew angle to below 110 degrees negatively affects the efficiency.

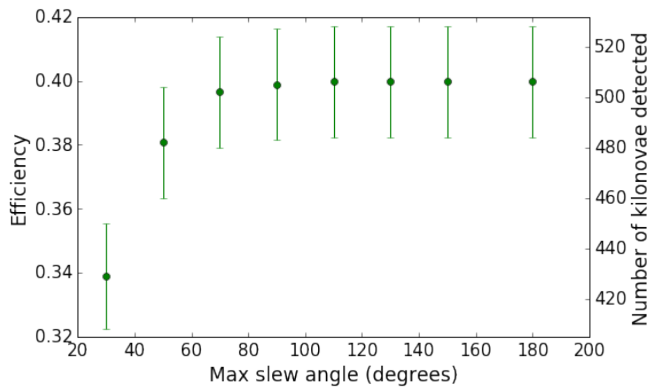

Fig. 7. Kilonova detection rates as the maximum slew angle is varied. t_1 was fixed at 2.5 days.

Cost Considerations

The cost is given by the total extra overhead time incurred by all of the swaps for a follow-up strategy and is computed from the slew angles using Fig 5.

Fig 8 compares the cost for all previously mentioned follow-up strategies plus an enhanced follow-up strategy (with $t_1 = 2.5$ days, maximum slew angle $= 110$ degrees). The enhanced strategy allowed two swaps to be made in each filter for each kilonova (rather than 1 as for the other strategies). The enhanced strategy achieved an efficiency of 0.536 (compared to 0.199 for the default survey), with a cost of 1.18 days. Excluding the enhanced strategy, the optimal follow-up strategy, with efficiency 0.399, had a cost of 0.662 days of observing time. This lost observing time is equivalent to losing 1324 pointings[18] or 0.064% of all pointings.

IV. DISCUSSION

The simple follow-up strategies displayed a large improvement of up to a factor of 2.5 in the fraction of observable kilonovae detected (efficiency) with minimal cost incurred. When estimating the number of kilonovae that will be detected, we must remember that

[18]This calculation is made using the fact that the median overhead time between pointings is 42 seconds.

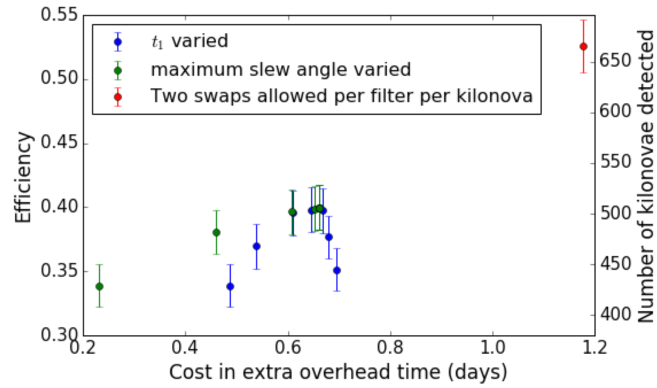

Fig. 8. The green and blue data points are the strategies in which the maximum slew angle and t_1 were varied respectively. When varying the maximum slew angle, we set $t_1 = 2.5$ days and experimented with angles 30, 70, 90, 110, 130, 150 and 180 degrees which go from left to right in the figure. When varying t_1, we set the maximum slew angle to 100 degrees and the follow-up strategies use t_1 values 0.8, 1, 1.5, 2, 2.5, 3, 4 and 5 days which go from left to right in the figure. The data point for $t_1 = 2.5$ days and maximum slew angle $= 110$ degrees is in both green and blue. The red data point, in the top right of the plot, is the enhanced strategy in which two swaps were allowed per band per kilonova ($t_1 = 2.5$ days, maximum slew angle $= 110$ degrees).

in simulations, all of the kilonovae that LIGO-Virgo are expected to see in the 9.5 years were placed in the region of the sky visible by LSST. Accounting for this, it is estimated that with the enhanced follow-up strategy, LSST would observe 305 kilonovae during its 9.5-year survey. These measurements would constrain the Hubble constant to below 1% uncertainty after the entire survey.

In order to understand how future strategies can be improved, it is necessary to analyze the shortcomings of the strategies that were trialled. In particular, the cases in which the detection criterion was not met are investigated. As outlined in II-D, two observations are required to constitute a detection and observations are characterized by the SNR of the light curve. One of the follow-up strategies ($t_1 = 5$ days, maximum slew angle $= 110$ degrees and cost $= 0.687$ days) altered the survey such that 80% of the observable kilonovae were pointed at, at least twice, in the 5 nights following the GW detection. However, just 35% kilonova were classed as detected. Therefore, most of the pointings must have imaged the kilonova with low SNR such that the probability of observation was low. This low SNR could have been due to a combination of significant sky noise, a large air mass close to 2 or a low intensity of the light curve if the pointing was made several days after the GW detection. This suggests the need for modifications to get around this problem and also that the simple strategy is capable of achieving high efficiencies with some modifications. Possible modifications are outlined in the following section for Future Work.

Recommendations for Future Work

Based on my investigation, future work, aiming to optimize the relevant parameters and achieve 90% efficiency, will be done by others in the DESC taskforce. This study can make several recommendations on the way future follow-up strategies can be designed in order to improve efficiencies. Firstly, follow-up strategies which are structured using a similar swapping algorithm should search for pointings to move to the location of the kilonova within 2.5 days of the GW detection. These strategies should allow slews of up to 110 degrees as a lower threshold would negatively affect the efficiency. Secondly, multiple swaps could be made in each band in order to increase the chance of detection. The enhanced strategy, in which the number of possible swaps was doubled, improved the efficiency by 0.137 (0.399 $\rightarrow$ 0.536) while doubling the cost.

An alternative method to get around the problem of many kilonova being imaged but not observed would be to make the pointings deeper. Deeper pointings mean having the aperture open for longer such that fainter objects can be imaged. This would increase the SNR of the image and thus enhance the probability that a pointing at the kilonova results in an observation. This would be effective because, as described in the discussion, a simple follow-up strategy can ensure that 80% of kilonovae are pointed at twice or more in the 5 nights after the GW detection. Therefore, with deeper observations, a simple swap strategy could achieve efficiencies nearing 80%. Making deeper observations incurs an extra cost as the pointing would take longer. However, using the measurement of the distance to the kilonova from the GW detection, a comprehensive strategy can optimize the extra depth of the pointing required to see a kilonova at a given distance.

Apart from allowing for more swaps and making deeper pointings at the kilonovae, future work could investigate distinguishing between filters. The kilonova light curve is less intense in the u and g bands, as can be seen in Fig 1, and so the strategy could prioritize swaps and deeper pointings in the r, i, z and Y bands.

V. CONCLUSIONS

Simulations were used to predict the fraction of observable kilonova optical transients that will be detected by both the default LSST survey and surveys which include a follow-up strategy. Simulations estimated that the default survey will detect just 20% of observable kilonovae, which makes clear the requirement for a follow-up strategy that is used following a kilonova GW detection. A simple follow-up strategy improved the efficiency greatly from 20% to 40% while incurring a cost of just 0.622 days of lost observing time over the 9.5-year survey. The follow-up strategy was performed best with $t_1 = 2.5$ days and it was found that setting the maximum slew angle to below 110 degrees negatively affected the efficiency. Simulations estimated that the optimal strategy would result in 305 multi-messenger kilonova detections in the 9.5-year LSST survey, which would constrain the Hubble constant to within 1% uncertainty. It was recommended that in order to improve the efficiency further, future strategies should allow for more swaps (doubling the number of possible swaps improved the efficiency to 53%) and deeper pointings at the kilonovae.

The principal contributions of this project are three-fold: to highlight the necessity of a follow-up strategy, to show that a simple strategy can greatly improve the efficiency, and to identify the relevant parameters of this strategy. In this way, this study lays the foundations for the LSST Dark Energy Survey Collaboration to develop a comprehensive follow-up strategy which enables efficient discovery of kilonova optical transients by LSST.

REFERENCES

[1] Richard Kessler, Joseph P Bernstein, Cinabro, et al. Snana: a public software package for supernova analysis. (Table 1):1–7, 2009.

[2] Xiang Li, Yi-ming Hu, Zhi-ping Jin, and Yi-zhong Fan. Neutron star-black hole coalescence rate inferred from macronova / kilonova observations. pages 1–5, 2016.

[3] H Lin, D Scolnic, P Cowperthwaite, Neilsen, et al. The electromagnetic counterpart of the binary neutron star merger ligo/virgo gw170817. i. discovery of the optical counterpart using the dark energy camera. pages 1–9, 2017.

[4] Bernard F. Schutz. Determining the Hubble constant from gravitational wave observations. *Nature*, 323(6086):310–311, 1986.

[5] LIGO Scientific Collaboration Virgo Collaboration et al. A gravitational-wave standard siren measurement of the Hubble constant. *Nature, Volume 551, Issue 7678, pp. 85-88 (2017).*, 551:85–88, 2017.

[6] Hsin-yu Chen, Maya Fishbach, and Daniel E Holz. Precision standard siren cosmology. pages 1–11, 2017.

[7] Wendy L Freedman. Cosmology at a Crossroads: Tension With the Hubble Constant Wendy L. Freedman We are at an interesting juncture in cosmology. 2(1929), 2001.

[8] Z Doctor, R Kessler, Chen, et al. A Search For Kilonovae in the Dark Energy Survey. pages 1–17, 2017.

[9] D Scolnic, R Kessler, Brout, et al. How many kilonovae can be found in past, present, and future survey datasets? pages 1–7, 2017.

[10] P. S. Cowperthwaite and E. Berger. A Comprehensive Study of Detectability and Contamination in Deep Rapid Optical Searches for Gravitational Wave Counterparts. 2015.

[11] Hsin-Yu Chen, Daniel E. Holz, Miller, et al. Distance measures in gravitational-wave astrophysics and cosmology. pages 1–9, 2017.

[12] J A Tyson, B Abel, Acosta, et al. LSST: from science drivers to reference design and anticipated data products. pages 1–39, 2014.

[13] A G Kim, N Padmanabhan, Aldering, et al. Distance Probes of Dark Energy. pages 1–45.

[14] LSST Science Collaborations. Science-Driven Optimization of the LSST Observing Strategy. pages 1–312, 2017.

[15] Samaya Nissanke, Daniel E Holz, Dalal, et al. Determining the Hubble Constant from Gravitational Wave Observations of Merging Compact Binaries. 2013.

[16] Iair Arcavi, Griffin Hosseinzadeh, Howell, et al. Optical emission from a kilonova following a gravitational-wave-detected neutron-star merger. *Nature Publishing Group*, 551(7678):64–66, 2017.

[17] Craig J Hogan, Bernard F Schutz, Curt J Cutler, Scott A Hughes, and Daniel E Holz. Precision Cosmology with Gravitational Waves. pages 1–6.

[18] Adam G. Riess, Lucas M. Macri, Hoffmann, et al. A 2.4% Determination of the Local Value of the Hubble Constant. pages 1–65, 2016.