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A DESGW Search for the Electromagnetic Counterpart to the LIGO/Virgo Gravitational Wave Binary Neutron Star Merger Candidate S190510g

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ABSTRACT

We present the results from a search for the electromagnetic counterpart of the LIGO/Virgo event S190510g using the Dark Energy Camera (DECam). S190510g is a binary neutron star (BNS) merger candidate of moderate significance detected at a distance of $227\pm92$ Mpc and localized within an area of $31\, (1166)$ square degrees at 50\% (90\%) confidence. While this event was later classified as likely non-astrophysical in nature within 30 hours of the event, our short latency search and discovery pipeline identified 11 counterpart candidates, all of which appear consistent with supernovae following offline analysis and spectroscopy by other instruments. Later reprocessing of the images enabled the recovery of 6 more candidates. Additionally, we implement our candidate selection procedure on simulated kilonovae and supernovae under DECam observing conditions (e.g., seeing, exposure time) with the intent of quantifying our search efficiency and making informed decisions on observing strategy for future similar events. This is the first BNS counterpart search to employ a comprehensive simulation-based efficiency study. We find that using the current follow-up strategy, there would need to be 19 events similar to S190510g for us to have a 99\% chance of detecting an optical counterpart, assuming a GW170817-like kilonova. We further conclude that optimization of observing plans, which should include preference for deeper images over multiple color information, could result in up to a factor of 1.5 reduction in the total number of followups needed for discovery.

1. INTRODUCTION

Binary neutron star mergers such as GW170817 (Abbott et al. 2017a), in which both a gravitational wave and its electromagnetic counterpart were detected, can
be used for measurements such as an independent calculation of the Hubble constant (Schutz 1986; Del Pozzo 2012; Abbott et al. 2017; Soares-Santos & Palmese et al. 2019), or even to probe the growth of structure from peculiar velocities (Palmese & Kim 2020). For this reason, the Dark Energy Survey (DES; Dark Energy Survey Collaboration et al. 2016) launched the gravitational wave (GW) program (DESGW) in 2015. This program works to quickly identify the optical counterparts to GW events, particularly the kilonovae (KN) expected from binary neutron star mergers to be used for cosmology. These transients are produced by the radioactive decay of r-process nuclei synthesized in the merger ejecta and are predicted to be rapidly fading (typically within a few days; Kasen et al. 2017), thus require follow up shortly after the announcement of the trigger. The identification of the KN associated with GW170817 (Soares-Santos et al. 2017; Abbott et al. 2017b; Coulter et al. 2017; Cowperthwaite et al. 2017; Evans et al. 2017; Andreoni et al. 2017; Hu et al. 2017; Utsumi et al. 2017; Valenti et al. 2017; Shappee et al. 2017; McCully et al. 2017; Kasliwal et al. 2017) in the nearby galaxy NGC 4993 (Palmese et al. 2017; Blanchard et al. 2017) is an example of DESGW’s ability to quickly identify these transients and characterize them.

The Laser Interferometer Gravitational-wave Observatory (LIGO; Aasi et al. 2015) and Virgo (Caron et al. 1999) Collaboration (LVC) recently completed its third observing run (O3), from April 2019 through March 2020. During this time, there were 56 publicly reported GW candidates, 14 of which thought to have been originated from binary systems where at least one object’s mass was consistent with a neutron star. In previous LVC observing runs, 11 total events (confirmed GW and marginal triggers) were observed within roughly 14 months (Abbott et al. 2019). The increase in number of GW triggers in O3 relative to earlier runs is due to a significant increase in sensitivity (Abbott et al. 2018) for all three detectors. This also means that, while the LVC network are detecting more events, many of these events are further away than the first two runs and poorly localized.

While the optical counterparts of these events are challenging to detect with small telescopes, the Dark Energy Camera (DECam; Flaugher et al. 2015) is optimally suited to find these sources (as shown in Soares-Santos et al. 2016, 2017). DECam’s 4m primary mirror allows us to quickly cover large areas of sky down to the limits required to detect EM counterparts of LVC’s sources. DECam has been widely used by the community to search for GW counterpart searches. For example, the Global Relay of Observatories Watching Transients Hap-

pen (GROWTH; Goldstein et al. 2019; Andreoni et al. 2019b) collaboration has employed DECam data wide-area searches for several GW candidate events, including S190511g (Andreoni et al. 2019a). None of the search teams have identified a new GW event counterpart since GW170817. In order to interpret the lack of detection, and make informed decisions for future searches, an in-depth analysis including simulation-based efficiency study is required. While general studies using average depth have been published (Carracedo et al. 2020), this is the first study to utilize simulations that include the impact of observing conditions and observation plan. Such an analysis had not been published until now. See also our companion paper on S190814bv, a neutron star black hole candidate event (Morgan 2020), and a standard siren analysis using S190814bv with DES galaxies (Palmese et al., in prep.).

In this paper we present the DESGW search for the KN counterpart to LVC candidate event S190511g. We include results from simulations that allow us to make quantitative statements about sensitivity in light of realistic observing conditions and strategy choices. The paper is organized as follows: in Section 2 we summarize the search and discovery pipeline used by the DESGW program and give an overview of the candidates discovered; in Section 3 we discuss the method for detecting candidates and for using simulated supernova (SN) and KN light curves; in Section 4 we present the results of our search and discovery pipeline as well as simulation analysis; Section 5 discusses our search efficiency and implications for future follow up strategies; finally, we summarize our analysis in Section 6.

2. DATA

2.1. The LIGO/Virgo event S190511g

All three LVC detectors (LIGO Livingston, LIGO Hanford, and Virgo) recorded the event, with a 98% initial probability of being a binary neutron star (BNS) event, a 2% probability of having a non-astrophysical origin, and a false alarm rate of 1 per 37 years. The 50% (90%) confidence regions spanned 575 deg² (3462 deg²) in the initial LVC bayestar localization map. At 10:08:19 UTC on May 10, the LVC released an updated map from the LaLInference pipeline (Veitch et al. 2015), decreasing the 50% and 90% confidence regions to 31 deg² and 1166 deg² respectively, and refined the distance estimate to 227 ± 92 Mpc, or $z = 0.05 ± 0.02$ (using flat ΛCDM cosmology with $H_0 = 70 \text{ km/s/Mpc}$ and $\Omega_m = 0.3$) (LIGO Scientific Collaboration & VIRGO Collaboration 2019b). On May 10, 20:43:51 UTC the classification of the nature of the event was updated to 85% BNS and 15% non-astrophysical. Finally at 20:18:44 UTC on
May 11, the LVC updated this probability to being non-
astrophysical origin at 58% and of a BNS to 42% as well
as updating the false alarm rate to 1 in 3.6 years.

2.2. DECam Observations

DECam was used for two nights to conduct target-of-
opportunity imaging of the LIGO/Virgo GW compact
binary merger candidate S190510g (LIGO Scientific Col-
laboration & VIRGO Collaboration 2019a). Since the
initial classification of S190510g was a BNS merger with
high probability, the GROWTH collaboration chose to
trigger DECam (NOAO proposal 2019A-0205). All ex-
posures from this proposal were immediately made pub-
lic (Andreoni et al. 2019a). GROWTH initiated EM
follow up on May 10th at 06:00:25.488 UTC. The ob-
serving plan on this evening was based on the original
LVC bayestar probability map. The updated LVC LAL-
Inference map disfavored most of the region observed
on the first night. As a result GROWTH prepared a
new observing plan for the second night (Andreoni et al.
2019a). This plan consisted of observing for ~1.5 hrs be-
ginning at 22:53:04 UTC on May 10. 80 exposures total
were taken in the g, r, and z bands for 40 seconds each.
Each filter visited roughly same area of the sky, approx-
imately 30 minutes apart, in order to eliminate moving
objects. The 10σ depths for each band are $m_z = 20.58$
mag, $m_r = 21.72$ mag, and $m_g = 21.67$ mag, where
the average seeing was 1.33 arcsec, the average airmass
was 1.71, and the average attenuation due to cloud was
4%. These observations covered ~65% of the probabili-
ty region, as shown in Figure 1. Plans to follow up this
event for a third night were retracted due to the updated
classification probability of this event. Our analysis uses
only the exposures from the second night of observations
as to include only the high probability region from the
LALInference LVC map.

3. METHODS

3.1. Search and Discovery Pipeline

Images from DECam were downloaded directly to
Fermi National Accelerator Laboratory from Cerro
Tololo Inter-American Observatory (CTIO) via the Na-
tional Center for Supercomputing Applications (NCSA).
Once the search exposures became available, we immedi-
ately started initial image processing, parallelized to run
on a CCD by CCD basis, via the DESGW Search and
Discovery Pipeline (Herner et al. 2020). The pipeline
consists of three major stages: Single-Epoch (SE) pro-
cessing, difference imaging, and post-processing.

SE processing (Morganson et al. 2018) consists of im-
age correction and astrometric calibration. This stage
uses SExtractor (Bertin & Arnouts 1996) to create a
list of bright objects in each image, which is fed into
scamp for astrometric calibration (Bertin 2006). We use
the GAIA-DR2 catalog (Gaia Collaboration et al. 2016,
2018) in this stage, which allows reductions of DES as-
strometric uncertainties to below 0.03″. The outputs of
SE processing are the inputs to the difference imag-
ing (diffimg) stage, designed for the DES supernova
diffimg pipeline (Kessler et al. 2015), but modified to
work with wide-survey images. Diffimg subtracts one
or more template images from the search image. Tem-
plate images are taken in the same area of sky before
the event, or after the event is expected to have faded
if pre-existing templates are unavailable. Our group is
able to use all DES images as templates, including those

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Summary of candidates identified by the DESGW short latency pipeline and exposures used for analysis. Here we show one of the three distinct localization regions from the LALInference map. The blue contours show a single region of the LVC 90% and 50% localization contours, the yellow line and shaded area is the DES footprint, and green dots indicate our candidates. A single pointing of DECam exposures are shown as red hexes which cover ~84 deg² total and contain ~65% of the total probability.}
\end{figure}
not yet publicly released, as well as all public non-DES DECam images. Combining public DECam data and not-yet-released DES data, we are able to improve on the depth of template images by roughly $\sim \sqrt{2}$ within the DES footprint. After the \textit{diffing} subtraction is complete, post-processing takes candidate objects identified and applies a cut based on the machine learning algorithm (\textit{autoscan}) score (Goldstein et al. 2015a,b). Furthermore, forced photometry (described in Kessler et al. (2015)) is applied in this step, as well as host galaxy matching and additional requirements such as detections in multiple bands and/or on multiple nights. For S190510g, these requirements were only a detection in two or more exposures and a machine learning score adequate to reject non-astrophysical sources. We eliminated known asteroids using the minor planet center, but since a second night of exposures were not taken in the region of interest, we did not eliminate other asteroids from our candidate list. Finally, the resulting candidate list was vetted via human inspection, as described in Section 3.2. The stamps for each of the DESGW candidates are shown in Figure 2.

3.1.1. Pipeline Performance

Roughly 26% of the image processing jobs took between $0 - 30\min$ to complete, 23% took $0.5 - 1\hr$, 22% took $1 - 1.5\hr$, 14% took $1.5 - 2\hr$, while the rest took $>2\hr$ to complete. The image processing section of our pipeline runs on a parallelized CCD per CCD basis. This means that for the 80 exposures used for this analysis, there were $\sim$5000 jobs total. Post processing also runs on a CCD per CCD basis after image processing has finished. This step takes $\sim$20 min to finish when running with all exposures. We note that this turnaround time is significantly longer than the GROWTH team reported in (Andreoni et al. 2019a). This is likely due to a combination of having, on average, more template images and applying a more complete correction set in the SE stage, such as correcting for the brighter-fatter effect (Bernstein et al. 2017).

3.2. Candidate identification

In total, there were 1165 candidates identified after post-processing. The final candidate list was published in GCN 24480 at 12:24 pm May 11 UTC (Soares-Santos 2019). The primary cuts for our candidates require no SExtractor errors in image processing, such as masking of objects overlapping the transient or inability to measure the flux, and an \textit{autoscan} score of at least 0.9 out of 1.0. This cut found 96 candidates (20 with \textit{autoscan} score $> 0.95$), while the final 11 were selected via visual inspection. The key properties we looked for when performing visual inspection is a host galaxy in the template image, a non-noisy template image, and no regions of over or under-subtraction. We also took into consideration the possibility that the candidate could be an AGN since we are unable to resolve objects that are close to the center of the host galaxy and therefore disfavored stamps where the candidate is not distinguishable from the host galaxy. Further, we note that no candidate from our pipeline is fully dismissed until there is secondary follow-up or enough evidence to definitively categorize the object. For a single night of observations, our goal is to rapidly identify objects that are the most obvious candidates, then refine our search criteria as we observe more epochs.

Additionally, we matched candidates to hosts and used DES data to measure properties of the host, such as photometric redshift, absolute magnitude, stellar mass, and star formation rate, as well as the separation of the candidate and the host at the redshift of the nearest potential host galaxy. Photometric redshifts have been computed using Directional Neighborhood Fitting (DNF; De Vicente et al. 2016), while the galaxy properties have been computed using the Bayesian Model Averaging method as described in Palmese et al. (2020). The coordinates and other information about each of our candidates can be found in Table 1, and information about their host galaxies is listed in Table 2.

4. RESULTS

4.1. Candidate Classification

The first stage of analysis, performed as exposures became available, presented 11 candidates (of which 6 were also detected by GROWTH) that were produced via the DESGW Search and Discovery Pipeline discussed in Section 3. Follow up from other observatories is crucial for determining if a candidate is the GW counterpart through rejection of false positives. The Korea Microlensing Telescope Network (KMTNet) followed up five of our candidates, desgw-190510a, desgw-190510c, desgw-190510i, and desgw-190510k (GCN 24493 and 24529: Im et al. 2019b,a), at the KMTNet South Africa (SAAO), Chile (CTIO), and Australia (SSO) stations showing that each of these candidates did not have significant fading over $\sim$1 day, but did show very slow or no fading, therefore deeming these candidates likely supernovae. Additionally desgw-190510c was observed by Swift-XRT (GCN 24541; Evans et al. 2019), showing no XRT source found, as well as with Magellan (GCN 24511; Gomez et al. 2019), which found a broad feature consistent with H-$\alpha$ at a redshift of 0.06 and suggests a good match to a Type II SN approximately one week after peak brightness. Finally, desgw-
190510h was initially detected by ATLAS on March 13, 2019 and later classified as a Type Ia SN at redshift 0.07 roughly a few days after maximum light by the Spectral Classification of Astronomical Transients (SCAT) survey and desgw190510-b was recorded by Gaia on Jan 30, 2019 and reported as a “blue hostless transient”. This transient can also be seen in previous DES images dating about 2.5 years ago, though with not enough information to classify it with certainty, thus we provide no host information in Table 2. This leaves only 4 candidates, desgw-190510d, e,f, and g, that were not classified by secondary follow-up, and thus still potential counterpart candidates.

The remaining information about each candidate that can be used to determine if a candidate is viable can be found in Table 2. The table reports photometric redshift, star formation rate, stellar mass, and absolute magnitude of the hosts, computed using DES Year 3 data (Abbott et al. 2018). Furthermore, galaxies are ranked based on their probability of association, which can be computed using the skymap information, the galaxies’ position and redshift (Singer et al. 2016), assuming a flat ΛCDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 0.3$.

### 4.2. Recovered Candidates

Using the same exposures, the GROWTH collaboration reported a list of 13 candidates (GCN 24467; Andreoni et al. 2019). Seven of the GROWTH candidates were not listed in the initial DESGW candidate list reported in GCN 24480. Candidates DG19bexl and DG19nouo were found in the final stages by our autoScan score cut ($\geq 0.9$) and DG19nouo was rejected due to visual inspection. Candidates DS19qcsuo and DG19llhkk both had a detection in a single exposure, where two were required to be picked up as a candidate. The overlapping search exposures for these candidates failed in the HOTPANTS step of our pipeline. Reprocessing of these exposures with an updated (current) version of the DESGW pipeline did identify these candidates. Similarly, candidates DG19ukvo and DG19oahn were not found in our initial processing of the data due to HOTPANTS errors in all exposures. DG19oahn was later found in reprocessing, while DG19ukvo continued to have processing failures in 2 out of the 3 exposures. The fraction of missing candidates is consistent with the overall failure rate of 28% for all jobs that were submitted on that night, where $\sim 15\%$ of total jobs failed due to issues in HOTPANTS. These failures are largely due to the observing conditions described in Section 2.2. Finally, candidate DG19ootl was never found in our pipeline. The templates used for this exposure were taken from not yet publicly available DES images and thus did not show any source in the difference image. Candidates, including those initially detected only by GROWTH, are shown in Figure 2.

### 5. DISCUSSION

#### 5.1. Understanding Search Efficiency

To better understand our search efficiency, we performed an off-line analysis using SuperNova ANAlysis software suite (SNANA) (Kessler et al. 2009). These simulations produce SN & KN lightcurves as they would be observed during our observations. Each KN simulation randomly assigns an ejecta mass, ejecta velocity, and lanthanide fraction based on the Kasen KN model (Kasen et al. 2017). The SN simulations use the SALT2 model for SN Ia (Guy et al. 2010) and templates for the core collapse SN (SN CC) are taken from Kessler et al. (2010) and Jones et al. (2018).

Using these simulations, we computed the detection efficiency for each KN model given our observing conditions, the results of which are shown in Figure 3. The KN simulations used for this analysis produce events that use a distance distribution consistent with that reported by the LVC as well as being located within the 65% probability area that was surveyed. The efficiency of each model, represents the fraction of light curves that are detected to be brighter than our five-sigma limiting magnitude at the time of DECam observations.

Next, we used these simulations to examine the color magnitude space for both KN and SN (Figure 4). For this analysis, we use both KN and SN simulations. Here we require the detected object is brighter than our five-sigma limiting magnitude. Additionally, we require the object’s host-galaxy photometric redshift is consistent with the LVC luminosity distance posterior at the 3σ confidence level. Additionally, the simulated SNe were distributed in redshift according to to measured volumetric rates of SNe-Ia and SNe-CC.

#### 5.2. Implications for Search Efficiency

Figure 3 shows likelihood that we would have been able to detect a KN produced by this event given the observing conditions and depth of observations. Here we show all possible sets of KN parameters and note that a GW170817-like KN follows a two component model, red and blue, where the blue component is dominant at early times in the light curve evolution. Assuming S190510g is a GW170817-like KN located within our exposures,
our simulations show that we would have a 99% chance of detecting the counterpart KN. However, a wide range of KN models would have been outside of our sensitivity range and thus unobservable.

While we have the ability to detect such a source, it is challenging to determine a candidate to be KN or SN with a single night of observations in the absence of spectroscopic information. To demonstrate the difficulty of this task we examined the color magnitude space of the simulated KN and SN events. All KN simulations are shown as the blue contours in the left panel of Figure 4, with the parameters for the blue component of GW170817 (ejecta velocity = 0.3c, lanthanide fraction = $10^{-4}$ and ejecta mass =0.025$M_\odot$) highlighted as orange dots. Meanwhile the color magnitude distribution of SN simulations is shown by the green contour on the right panel of Figure 4. All DESGW S190510g candidates from this event (depicted as red crosses in Figure 4) fall within the possible 90% color-magnitude regions of SN events. For a KN roughly one day after burst, and given only this color-magnitude information, each of these candidates could be either a SN or KN.

5.3. Implications for Follow Up Strategy

In the first half of the O3 observing run, most of the events that included a neutron star did not have a good localization (i.e. hundreds of deg$^2$) as well as being far away (>200 Mpc) when compared to GW170817. While it would be ideal to cover 100% of the localization area with multiple filters, limited telescope time and poor localization maps make this very challenging. In the following, we show that prioritizing sufficiently deep images as opposed to covering large areas and/or using multiple filters, will result in a higher chance of detecting counterparts.

To show how many events it would take to have a 50% (99%) chance of detecting one counterpart, we have to consider the cumulative probability inside the LVC localization map that was observed ($\Sigma_{\text{spatial}}$), the fraction of DECam that was live during observations ($\epsilon_{\text{camera}}$), the probability that the event is astrophysical in nature ($\epsilon_{\text{real}}$), and our likelihood of being able to detect a KN at that distance given the observing conditions (i.e. the
Table 1. Candidates that pass the DESGW pipeline cuts as well as visual inspection from the first stage of analysis. If the candidate matches a candidate from the GROWTH team’s candidate list, the GROWTH name is stated. If additional follow up conducted by other telescopes verified the candidate as SN the classification is listed. Those labeled only “SN” did not have sufficient information for specific classification.

| DES (GROWTH) Name   | mag $g$       | mag $r$       | mag $z$       | RA (deg)       | DEC (deg)       | autoscan Score | Classification |
|---------------------|---------------|---------------|---------------|----------------|----------------|----------------|----------------|
| desgw-190510a       | 22.53 ± 0.19  | 20.93 ± 0.04  | 20.77 ± 0.10  | 91.526744      | -35.541616     | 0.950          | SN             |
| desgw-190510b       | 21.19 ± 0.05  | 21.13 ± 0.05  |               | 93.704382      | -36.980727     | 0.950          |                |
| desgw-190510c       | 21.72 ± 0.1   | 20.37 ± 0.02  | 20.35 ± 0.06  | 92.851468      | -36.517324     | 0.970          | SN I           |
| desgw-190510d       | 20.36 ± 0.03  | 19.92 ± 0.2   | 20.77 ± 0.11  | 87.311398      | -35.95853      | 0.970          |                |
| desgw-190510e       | 20.56 ± 0.03  | 20.66 ± 0.03  | 20.82 ± 0.09  | 89.100926      | -30.473987     | 0.970          | SN I           |
| desgw-190510f       | 22.16 ± 0.13  | 21.30 ± 0.05  |               | 92.294458      | -34.884684     | 0.970          |                |
| desgw-190510g       | 22.48 ± 0.17  | 21.92 ± 0.09  |               | 92.468923      | -34.08657      | 0.963          |                |
| desgw-190510h       | 21.23 ± 0.08  | 20.29 ± 0.03  | 20.56 ± 0.07  | 87.762354      | -27.958502     | 0.960          | SN             |
| desgw-190510i       | 20.15 ± 0.15  | 20.15 ± 0.04  | 20.47 ± 0.08  | 91.936973      | -30.824747     | 0.915          | SN             |
| desgw-190510j       | 20.65 ± 0.04  | 20.83 ± 0.04  |               | 92.307977      | -35.149829     | 0.900          | SN             |
| desgw-190510k       | 20.15 ± 0.03  | 19.53 ± 0.03  |               | 87.146843      | -35.994357     | 0.920          |                |

Here, $P_i$ is the probability of being able to detect a KN from a single GW event. $P_{\text{one}}$ is the cumulative probability of being able to detect a single counterpart given $N$ GW events (Annis & Soares-Santos 2016). For this calculation, we find that if we assume there is a kilonova associated with S190510g that is GW170817-like, i.e. $\epsilon_{\text{efficiency}} = 0.993$, we would need to observe 3 (19) identical events with $\Sigma_{\text{spatial}} = 0.65$, $\epsilon_{\text{camera}} = 0.8$, $\epsilon_{\text{real}} = 0.42$, and $\epsilon_{\text{efficiency}} = 0.993$ in order to have 50% (99%) probability of identifying the event using the current strategy. Since there is no way of knowing that the event will have a lightcurve similar to GW170817, we also calculate this using the average efficiency value of all KN parameters, $\epsilon_{\text{efficiency}} = 0.553$ with all other parameters the same. Here we find that we would need 6 (36) events to reach 50% (99%) likelihood of detecting the counterpart.

We then repeat this calculation assuming the observing strategy uses one filter instead of three. If we conserve the telescope time used and area surveyed per event, we can then increase the exposure time from 40 seconds to 170 seconds. In this scenario, the efficiency for a GW170817-like KN is 0.995, meaning we would again need 3 (19) events to have 50% (99%) likelihood of detection. Using the average efficiency in this scenario though, 0.742, we would only need 4 (27) events to have 50% (99%) likelihood of detecting a counterpart. By increasing the depth of our observations, we become sensitive to more KN models and will thus need to observe fewer total GW events to have a high probability of making a detection.

6. CONCLUSION

We performed a follow up analysis of the GW trigger S190510g, using DECam target of opportunity time data from May 11th 2019. We demonstrated the DESGW team’s ability to quickly process new images in real time, averaging ~1hr for image processing to complete. The final DESGW candidate list is summarized in Table 1, with five candidates, desgw-190510a, c, i, j, and k being ruled out due to secondary follow up efforts by KMTNet, Swift-XRT, and Magellan. Similarly, candidates desgw-190510b and h have been identified based on previous observation as recorded in the Transient Name Server. This leaves 4 candidates from the DESGW candidate list that were not classified by secondary follow-up. Each of these candidates have color information that is consistent with SN.
assuming the light curve has the same physical parameters as GW170817 using the Kasen et al. (2017) model (Fig. 3) within our observations. However, this efficiency is not uniform across all KN models. We also used KN and SN simulations to study where in color magnitude space they land. We find that all of our candidates are consistent with both KN and SN using this metric.

To make ourselves more sensitive to all KN models, we suggest prioritizing longer exposure times over multiple filters and covering large portions of the localization area for future observations. Using exposures that are 4 times longer than those used for this follow up, we would only need to observe 4 events (identical to S190510g) to have a 50% chance of detecting a KN counterpart within the 65% probability region observed and with these observing conditions, compared to the 6 events needed using the current strategy.

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Figure 3. Summary of detectable kilonovae given the observing conditions of May 11th, 2019. Simulations are set within the LVC distance range of S190510g. Parameters determining the components of the KN, ejecta mass ($M_{ej}$), ejecta velocity ($v_{ej}$), and the log of lanthanide ($\log X_{lan}$) fraction, are taken from (Kasen et al. 2017). The coloring and labeling in each box denotes how likely we would be able to detect a KN with the given parameters assuming the event is within our observations. The box labeled “N/A” is a combination of parameters not available in the Kasen et al. 2017 parameters. Additionally, we highlight the set of parameters that were identified as the likely red and blue component of GW170817 as red and blue boxes.

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Figure 4. DESGW candidates (red) as compared to where kilonovae and supernovae would be expected to live in color magnitude space given the observing conditions of our observations (i.e., 36 hours after merger, sky brightness, etc.). All simulations run using SNANA (Kessler et al. 2009). Kilonovae simulations were generated with a burst date consistent with that reported by LVC, and at a distance consistent with the LVC distance distribution (blue contours). The KN parameters, ejecta velocity, mass, and lanthanide fraction are randomly selected from the parameters described by Kasen 2017. Simulations with the same Kasen parameters as the blue component of GW170817 (ejecta velocity = 0.3c, lanthanide fraction = $10^{-4}$ and ejecta mass =0.025$M_\odot$) are shown as orange dots. Supernovae simulations consist of Type Ia and CC SN, and are generated using a peak date ranging 4 months centered around May 10th, with redshift also consistent with S190510g’s distance distribution. The contours show 50% and 90% density of simulations.

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