DESGW Optical Follow-up of BBH LIGO-Virgo Events with DECam

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Abstract. The DESGW program is a collaboration between members of the Dark Energy Survey, the wider astronomical community, and the LIGO-Virgo Collaboration to search for optical counterparts of gravitational wave events, such as those expected from binary neutron star mergers or neutron star-black hole mergers. While binary black hole (BBH) events are not expected to produce an electromagnetic (EM) signature, emission is certainly not impossible. The DESGW program has performed follow-up observations of four BBH events detected by LIGO in order to search for any possible EM counterpart. Failure to find such counterparts is still relevant in that it produces limits on optical emission from such events. This is a review of follow-up results from O1 BBH events and a discussion of the status of ongoing uniform re-analysis of all BBH events that DESGW has followed up to date.

Keywords. gravitational waves

1. Introduction

Are black hole mergers visible? Many observatories are engaged in following up LIGO events in an effort to localize the source and to begin study of the matter involved in the merger. Supermassive black holes often have accretion disks and jets—quasars are among the brightest objects in the universe. Stellar-mass black holes with accretion disks are visible in the x-ray, often remarkably so. Stellar-mass black holes without accretion disks may still be visible as they plow through the galactic interstellar medium, but they will be of magnitude ~ 22 in i-band at distance ~ 100pc (Heckler *et al.* 1996; Chisholm *et al.* 2003), rendering them invisible at the distances of the LIGO black holes. However there is the possibility of an unexpected optical counterpart, perhaps from the ubiquitous magnetic field induced jet.

Why DES and DECam? The combination of the collecting area of the 4m diameter Blanco Telescope at NOAO's Cerro Tololo International Observatory in Chile with the 3 deg^2 field-of-view of the Dark Energy Camera (DECam; Flaugher *et al.* 2015) gives us an unrivaled ability to cover large areas of sky to faint magnitudes; we are unique in the Southern hemisphere.

2. Methods and Results

Recap of O1. During O1, DESGW was able to follow up two events from LIGO (sky maps shown on the left in Figure 1). Among ground-based instruments, DESGW was the most complete in both depth and area covered. Our group and its partners have
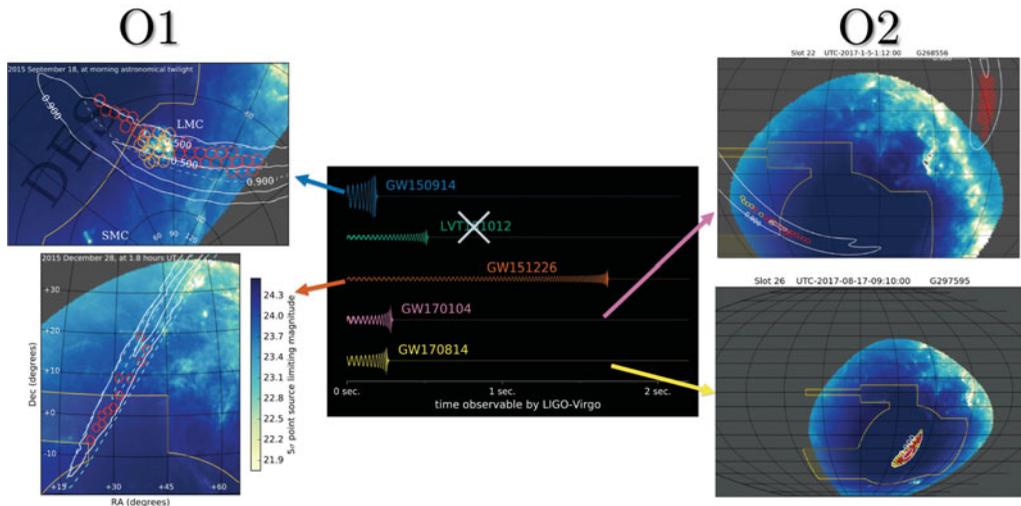
Figure 1. The middle panel (from LIGO's web gallery) shows the fitted chirp signals from each of the five gravitational wave events detected by LIGO so far. The two panels on the left show DESGW's observing plan for the two 2015 events, overlaid with the localization probability maps from LIGO. The two panels on the right show the same for the two 2017 events. Note that GW170814 was also observed by the Virgo detector, and therefore was localized much more precisely. Also note that LIGO did not send a trigger for the marginal LVT151012 event.

published on these events (GW150914: Soares-Santos *et al.* 2016, Annis *et al.* 2016; GW151226: Cowperthwaite *et al.* 2016). While the total probability coverage (P_{total} in Table 1) was quite small for each event in O1, the exercise and analysis were critical for future endeavors in DECam optical follow-up.

Improvements for O2. Between the first and second LIGO observing runs (and continuing throughout O2), the DESGW team made marked improvements in both our difference imaging (`diffimg`; Kessler *et al.* 2015) and post-processing pipelines. Both pipelines are described in further detail in Herner *et al.* (2017).

Difference Imaging. There were two main improvements in the `diffimg` pipeline over the past year: (1) the ability to run nightly, or "on the fly"; and (2) incorporation of the ability to use templates from *after* a given event to subtract from that event's search images. We can now image the area at a much later time and use these as templates. We have now done this using the BLISS Survey (NOAO propID 2017A-0260) for the first three BBH events with good success; we effectively doubled our ε_{camera} (see Table 1) for GW150914 with this strategy.

Post-processing. We also completely reworked the post-processing pipeline (`postproc`). The `postproc` code now creates a number of plots useful for assessing detections and `diffimg` efficiency. Two of these plots are shown in Figures 2 and 3. The code also has a new step which checks the outputs of `diffimg`, allowing the user to quickly and easily diagnose problems in the pipeline.

Update on O2. During O2, we followed up two LIGO triggers (as shown in Figure 1). GW170104 was not well placed for observations from the Blanco telescope, but we managed 14% of the spatial localization area. Analysis of that event is ongoing. GW170814 was better for us, since the new smaller probability contours from LIGO+Virgo lay directly in the middle of our survey footprint. This is obviously helpful observationally, but high-quality template images are also necessary for effective difference imaging. The DES
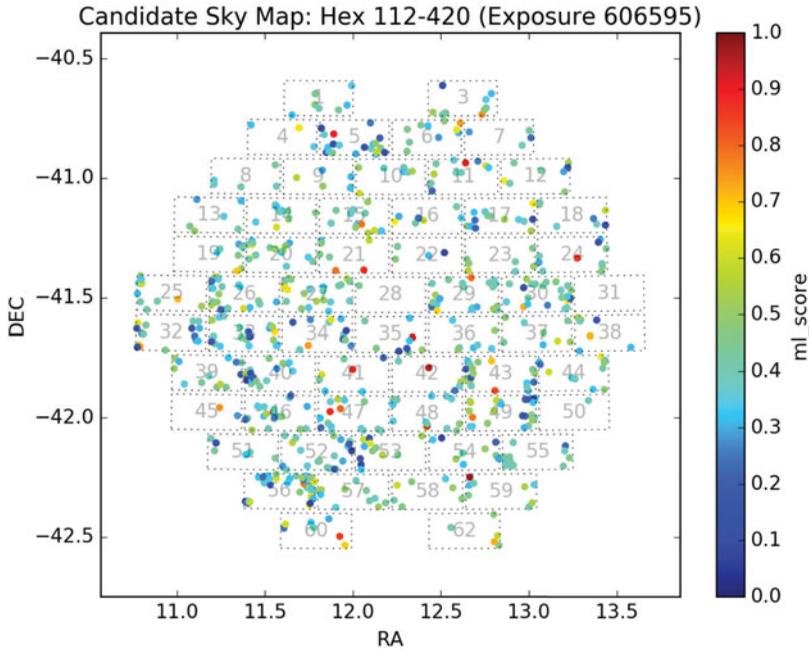
Figure 2. Example hex map output by the postprocessing pipeline. It shows all candidates within a certain exposure, with their associated machine learning scores (these are an assessment of how good the detection was).

Table 1. For each event, three statistics are given (defined in Annis & Soares-Santos 2016): (1) $\Sigma_{spatial}$, the summed probability inside the LIGO spatial localization map covered by the bounding box of images taken; (2) ε_{camera}, the fraction of the space within the bounding box which is covered with live CCDs, and (3) ε_{sky}, the fraction of the area imaged that a source would have been visible in (dominated by limiting magnitude). The multiplication of these three gives the probability that the imaging element was able to detect the source: P_{total}.

Event	$\Sigma_{spatial}$	ε_{camera}	ε_{sky}	P_{total}
GW150914	0.11	$0.8 \cdot 0.34$	0.8	0.024
GW151226	0.02	0.8	0.8	0.013
GW170104	0.14	0.96	0.8*	0.11*
GW170814	0.84	0.96	0.8*	0.65*
Total				***.790***

*Preliminary. We have not yet made a definite calculation of ε_{sky} for the most recent two events, but it is reasonable to expect a value of 0.8. Using that assumption, we get the total probabilities given in the rightmost column.

footprint comprises the majority of DECam images taken to date. As shown in Table 1, we were able to cover 84% of the final map (it was shifted slightly from the original).

It should also be noted that a third O2 BBH event was announced recently (after the conference), labeled GW170608. We did not follow up this event because the bulk of the probability was much too far north to be reached.

3. Conclusion

We have followed up four BBH events, and to date no viable candidates have been found in the data. There is still analysis to be done. For our purposes, LIGO events are
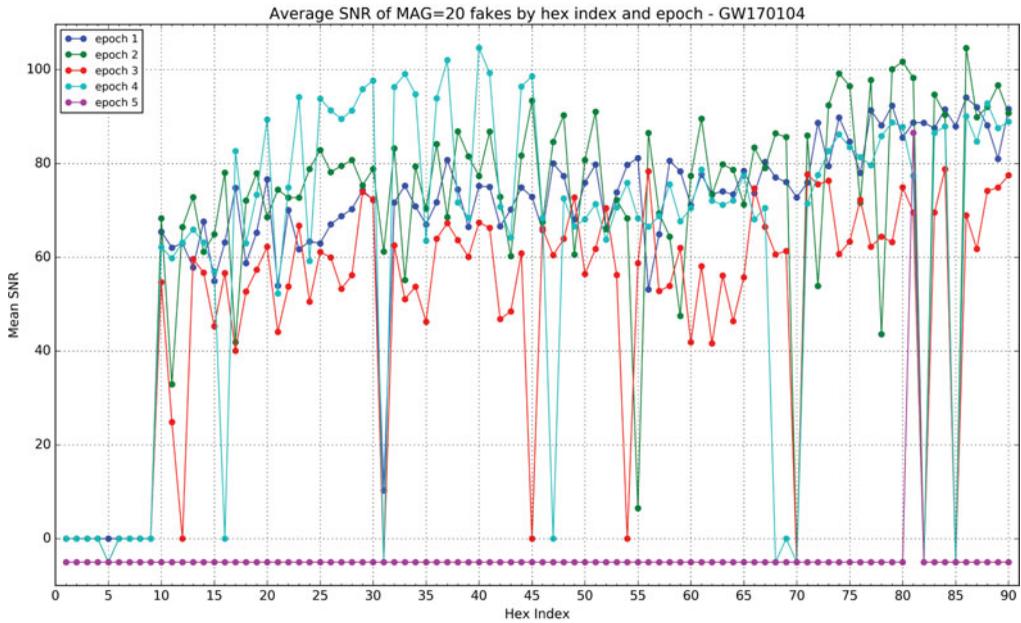
Figure 3. Signal-to-noise ratio (SNR) of artificially implanted signals (fakes) of constant magnitude for the LIGO event GW170104. These artificial transients are arranged on a uniform grid across the sky. The horizontal axis is labeled with indices representing the 90 different pointings on the sky. The vertical axis shows the average SNR of all fakes within a certain pointing, separated into five epochs. For most pointings, four epochs were observed. On this plot, mean SNR values of 0 and -5 are assigned to exposures which have not been processed or taken.

cumulative. If one wants to place a 95% confidence limit at a given magnitude, $P_{total} \geqslant 3$ is necessary. We are well on our way to this goal. With the increased detection rate expected in the next LIGO-Virgo run, it is reasonable to expect this milestone can be reached within that run.

References

Annis, J. & Soares-Santos, M. 2016, PoS (ICHEP2016) 1217
Annis, J., Soares-Santos, M., Berger, E. *et al.* 2016, *ApJ* (Letters) 823, L34
Chisholm, J. R., Dodelson, S., & Kolb, E. W. 2003, *ApJ*, 596, 437
Cowperthwaite, P. S., Berger, E., Soares-Santos, M., Annis, J. *et al.* 2016, *ApJ* (Letters) 826, L29
Flaugher, B., Diehl, H. T., Honscheid, K. *et al.* 2015, *AJ*, 150, 150
Heckler, A. F. & Kolb, E. W. 1996, *ApJ* (Letters) 472, L85
Herner, K. *et al.* 2017, *J. Phys.: Conf. Ser.* 898, 032050
Kessler, R., Marriner, J. *et al.* 2015, *AJ* 150, 172
Soares-Santos, M., Kessler, R., Berger, E., Annis, J. *et al.* 2016, *ApJ* (Letters) 823, L33