NOAO Observing Proposal *Longterm proposal* **Panel:** *For office use.*
Date: August 15, 2019 **Category:** EGAL - Other

SOAR Spectroscopy of LIGO/Virgo O3 Transients

Abstract of Scientific Justification *(will be made publicly available for accepted proposals)*:
The discovery last year of the optical counterpart of a binary neutron star merger – a kilonova – was one of the highlights of observational astrophysics of the early 21st Century. The merger was first detected, by the LIGO/Virgo Collaboration (LVC), via the merger's gravitational wave signal (GW170817). After a period of downtime for maintenance and upgrades, the LVC is preparing for its next observing campaign, O3, which is scheduled to run from October 2018 to September 2019. Our team, which, using the DECam, was one of the teams to independently discover the GW170817 kilonova, has proposed (in a separate NOAO proposal) to use continue its earlier DECam imaging program to perform a public search & discovery program for optical signatures of GW events during the LVC O3. While the GW170817 kilonova was a bright nearby event, and thus very easy to identify by visual inspection, future kilonovae will be on average 3 times more distant. Thus, they will likely be fainter and much harder to distinguish quickly from other astronomical transients without spectroscopy. Nonetheless, if the GW170817 kilonova was a typical kilonova with a typical kilonova luminosity, we expect that up to $\sim$90% of LVC O3 kilonovae will be in reach of the SOAR-4m+Goodman spectrograph. We therefore propose a SOAR-4m+Goodman spectrograph Target of Opportunity program for the rapid spectroscopic classification of kilonova candidates from the DECam public imaging search & discovery program, and the subsequent nightly follow-up for detailed study of the identified kilonovae.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	SOAR	Goodman	2	bright	Oct - Jan	Oct - Jan
2						
3						
4						
5						
6						

Scheduling constraints and non-usable dates *(up to six lines)*.

This is a Target-of-Opportunity (ToO) proposal. The number of nights listed in the above table are the maximum number of night equivalents requested. The length of the individual interrupts vary (up to the permitted maximum of 2.5 hours). We expect to request no more than a total of 6 interrupts (95% confidence). Note: we are also submitting to the Brazilian TAC. The time requested above is the full time required for this project: if both proposals are approved, we will apportion the time between the partners proportionally.

Investigators *List the name, status, and current affiliation for all investigators. The status code of "P" should be used for all investigators with a Ph.D. or equivalent degree. For graduate students, use "T" if this proposal is a significant part of their thesis project, otherwise use "G".*

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Scientific Justification *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

GW170817 was the first binary neutron star (BNS) merger ever observed. The detection by the LIGO/Virgo Collaboration (LVC) in coincidence with a short gamma-ray burst by Fermi-GBM inaugurated the era of multi-messenger astronomy with gravitational waves (GW) [1]. The discovery of its optical counterpart, 12 hours after the merger and by several independent teams including our own [2], enabled panchromatic imaging and spectroscopy, which galvanized the astronomical community. Our team's successful DECam-based effort was built upon infrastructure of the Dark Energy Survey (DES) and counts on expertise from DES, LVC, and many talented individuals world-wide. We designed, implemented, and executed the most comprehensive search program for the first two LVC campaigns. We demonstrated, first with the binary black hole (BBH) merger GW150914 [3, 4] and then with GW170817 [2], our ability to efficiently search the entire GW detector sensitivity volume and discover the optical counterparts of GW events to depths fainter than any other facility to date. The wide-ranging scientific impact of GW170817 includes the realization of the long-held hypothesis of a new class of astrophysical transients, kilonovae [5], and of a new independent and powerful cosmological probe, standard sirens [6].

Having established DECam as the leading instrument in searches for optical counterparts of GW events [2, 3, 4] we have proposed (in a separate NOAO proposal) to use DECam to perform *a public search & discovery program for optical signatures of GW events* during the LVC observing campaign 3 (O3), from 10/2018 to 9/2019. There is an issue, though. The GW170817 kilonova was a singularly bright ($i \approx 17.5$ @ Day 0.5) and nearby (40 Mpc) event, and thus very easy to identify. It is estimated that 50% of kilonovae detected during LVC O3 will be within 120 Mpc, and 90% within 200 Mpc[7]. Assuming that last year's kilonova was of typical luminosity, it is then expected that a kilonova at 120 Mpc would be $\sim$2.4 mag fainter than GW170817 ($i \sim 20$ @ Day 0.5), and one at 200 Mpc $\sim$3.5 mag fainter ($i \sim 21$ @ Day 0.5). Therefore, the LVC O3 kilonovae are likely to be fainter and much harder to distinguish from other astronomical transients (e.g., supernovae [SNe] and short gamma-ray bursts [GRBs]) via a purely imaging-based search & discovery program. In other words, we expect, even after making well-motivated stringent cuts from the DECam program, that there will still be a generous handful of candidates remaining that require spectroscopy for quick and robust identification of the actual kilonova. ***Therefore, here we propose a SOAR-4m Target of Opportunity (ToO) program for the rapid spectroscopic classification of kilonova candidates from the DECam (or a similar) public imaging search & discovery program, and the subsequent nightly follow-up for the identified kilonova.***

Such a spectroscopic program would have several benefits. First, it would permit the rapid *public* dissemination of the location and classification of the spectroscopically confirmed kilonova, permitting the immediate, thorough, and efficient follow-up by the worldwide astronomical community. Second, it would provide data on the evolution of the optical spectrum of a new kilonova, aiding in the modeling of the new kilonova in particular and in the exploration of any population variations in the optical properties of this newly discovered class of transients in general (see, e.g., Fig. 1). Finally, it would also provide data on the population of the candidates netted by the imaging-based search & discovery program that *appeared* kilonova-*like* but turned out to be something else. This latter point is important not only for investigating subtle similarities and differences in the optical properties between kilonova and kilonova-*like* events (e.g., GRBs), but also to help improve the culling process for future imaging-based kilonova search & discovery programs.

Finally, we note that our team is submitting a nearly identical SOAR-4m ToO proposal to the Brazilian TAC, which emphasizes the cross-partnership nature of this project. The observations and analyses will be carried out by this inter-institutional team.

References

[1] Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, Phys. Rev. Lett., 119, 161101
[2] Soares-Santos, M., Holz, D. E., Annis, J., et al. 2017, ApJ, 848, L16
[3] Soares-Santos, M., Kessler, R., Berger, E., et al. 2016, ApJ, 823, L33
[4] Annis, J., Soares-Santos, M., Berger, E., et al. 2016, ApJ, 823, L34
[5] Metzger, B. D., Martínez-Pinedo, G., Darbha, S., et al. 2010, MNRAS, 406, 2650
[6] Holz, D. E., & Hughes, S. A. 2005, ApJ, 629, 15
[7] Chen, H.-Y., Holz, D. E., Miller, J., et al. 2017, arXiv:1709.08079
[8] Nicholl, M., Berger, E., Kasen, D., et al. 2017, ApJ, 848, L18
[9] Villar, V.A., Guillochon, J.. Berger, E., et al. 2017, *ApJL*, 851, 21

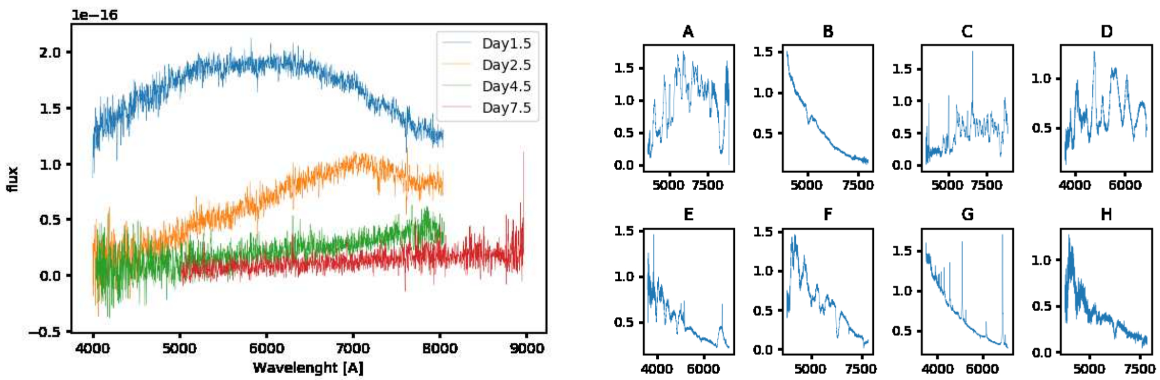
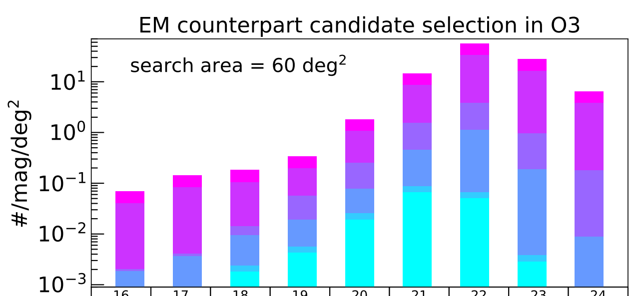


Figure 1: *(left)* SOAR optical spectra of GW170817 from Nicholl et al. (2017) taken at +1.5, +2.5, +4.5, and +7.5 days after the merger event. (Spectra downloaded from `https://kilonova.space/kne/GW170817/`.) *(right)* Examples of SOAR spectra from an assortment of SNe: A=2010as (Ib/c), B=2015L (I-p), C=2010ae (Ia-p), D=2016bro (Ia), E=2018nw (II), F=2018po (Ia), G=2017ijn (IIn), H=2017hvt (Ia). (Spectra downloaded from `https://wiserep.weizmann.ac.il/spectra/list`.)



	16	17	18	19	20	21	22	23	24
ALL	4.20	8.64	10.99	20.00	109.01	875.68	3425.31	1698.40	389.51
N OBS	2.44	5.11	6.30	11.85	65.11	522.52	2045.93	1000.15	231.63
ML SCORE	0.12	0.25	0.86	3.46	15.19	93.09	232.72	57.65	10.86
HOST	0.11	0.22	0.58	1.14	4.71	27.93	67.49	11.53	0.54
COLOR	0.03	0.04	0.14	0.34	1.55	5.31	4.05	0.23	0.01
LC SHAPE	0.02	0.03	0.11	0.26	1.17	3.98	3.04	0.17	0.01

Figure 2: *The DECam search & discovery candidate selection for spectroscopic follow-up*. The need for a robust classification pipeline to find binary neutron star counterparts in O3, as uniquely done in [2], is shown here in the (i-band) magnitude distribution of all transient candidates expected to be found by a DECam search & discovery imaging sequence for a GW trigger. The last row ("LC_SHAPE") is the expected distribution of candidates remaining after all the image-level culling procedures have been run. This is the distribution of candidates we use for the simulations in the Observing Run Technical Description.

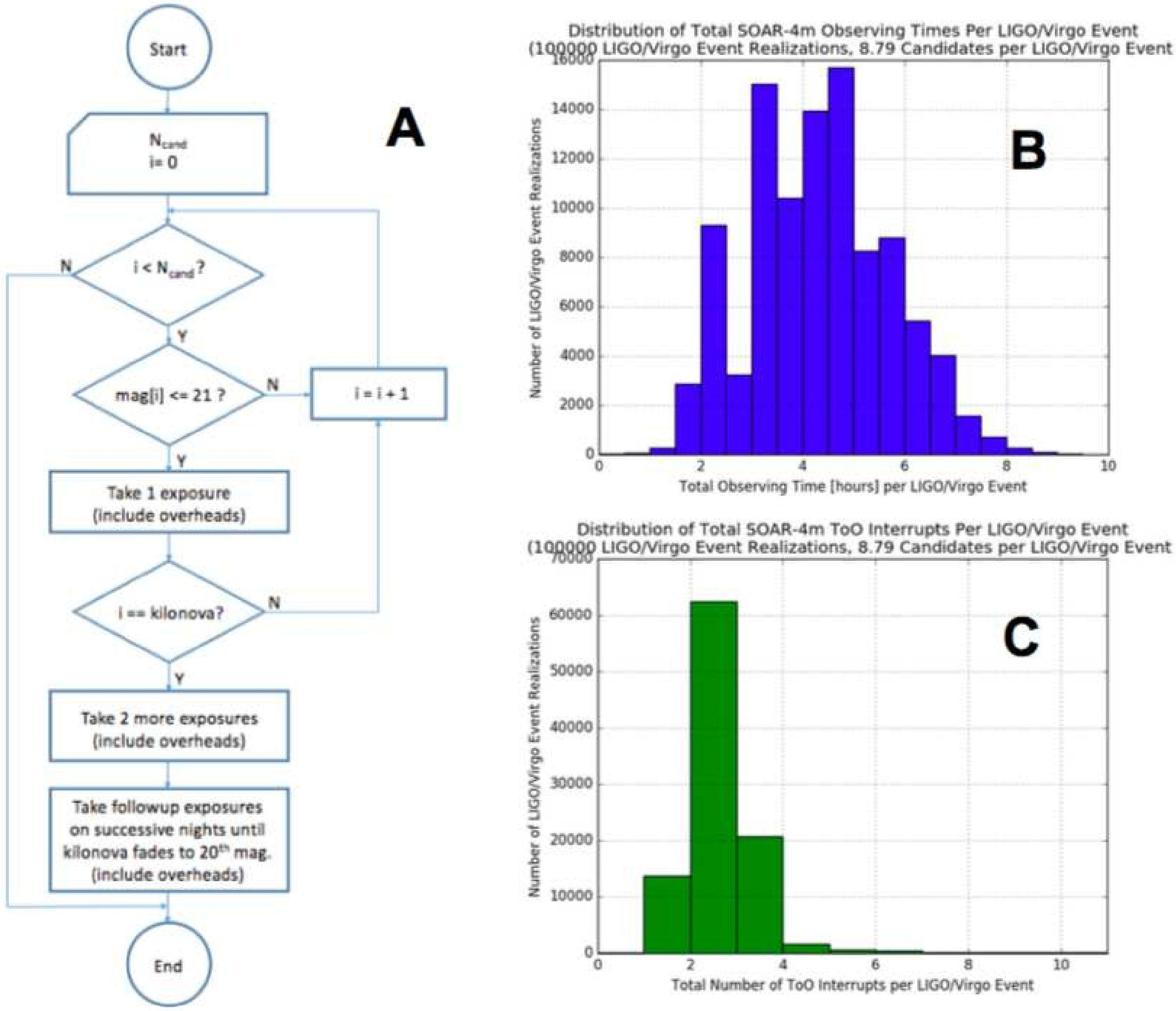


Figure 3: *(A) A simplified flow-chart for a single realization of a simulated SOAR follow-up of a single GW event, where $N_{\rm cand}$ is the total number of candidates from an imaging search & discovery program.* For the simulations here, $N_{\rm cand}$ is either 8 or 9, but averages overall to 8.79. The distribution of i-band magnitudes for the candidates is drawn from the "LC_SHAPE" row in Fig. 2, and the overall average number of candidates (8.79) is just the sum of the entries in the 'LC_SHAPE" row. *(B)* Results of the simulation (using 100,000 realizations): histogram of the total durations of SOAR ToO interrupt time [in hours] for a single LVO O3 event. *(C)* Results of the simulation (using 100,000 realizations): histogram of the total number of SOAR ToO interrupts for a single LVO O3 event. (Note that the number of interrupts does not scale exactly as the total duration of interrupt time, since the number of hours per interrupt will vary between the "search & discovery" phase and the follow-up phase of the observations for a given kilonova event.)

Experimental Design *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science. (limit text to one page)*

Since the occurrence and location of a gravitational wave event (and any consequent optical counterpart) are not known in advance, this proposal is by necessity a Target-of-Opportunity (ToO) proposal. Following the current SOAR ToO policy, we understand that, under standard circumstances, the maximum duration of any given ToO "interrupt" is 2.5 hours (including on-sky overheads), and the maximum number of interrupt authorizations is 18 in any semester, and we have tailored our proposed program with these constraints in mind. Due to the nature of our targets (a list of candidate optical counterparts pre-culled by an imaging search & discovery survey) – and the desire to catch a kilonova before or at peak brightness – we request "Instant Activation" mode, although will make every effort to provide as much advanced warning as possible.

Based on calculations from the LIGO/Virgo Collaboration (LVC), there are expected to be $\sim$18 merger events (8 binary neutron star mergers, 1 neutron star/black hole merger, and 9 best-localized binary black hole mergers) over the LIGO/Virgo O3 season worthy of optical follow-up, distributed roughly as follows over the next 3 NOAO observing semesters: 5 in 2018B, 9 in 2019A, & 4 in 2019B. *(Since we wish to cover the entirety of the O3 season, we request long-term status.)* It is unlikely that black hole mergers will have any optical afterglow; so, for this spectroscopic proposal, we reduce these numbers by half. And, by taking only Southern sky events, we reduce them by another half. Thus, for 2018B, we consider following $\approx 5/4 = 1.25$ events. Since such small numbers are notoriously uncertain, we conservatively round up to 2 events to follow up in 2018B.

The kilonova for last year's binary neutron merger, GW170817, was exceptionally bright and easy to identify. Future events are likely to be fainter and much harder to distinguish from other transients (e.g., SNe Ia) found in the initial imaging-based search & discovery phase of identifying the optical counterpart. Therefore, spectroscopy is necessary for the quick and robust identification of the optical counterpart among the set of candidates remaining after an initial cull from an imaging survey search. (Details in the Observing Run Technical Description.)

Our plan is to use the Goodman spectrograph on the SOAR-4m telescope: (1) to spectroscopically identify the kilonova hiding among a small list of candidates provided by an initial imaging survey based search (e.g., the proposed continuation of the DECam search for optical counterparts); (2) once identified, to obtain a higher-S/N optical spectrum of the kilonova, suitable for detailed modeling; and (3) to obtain additional high-S/N spectra of the kilonova on successive nights until it is effectively too faint for useful follow-up on SOAR. To speed the classification of the candidates and the identification of the kilonova, we will perform a quick "on-the-fly" processing of the data while observing. ***As part of this design, we are committed to the immediate and public posting of the identification of the kilonova and classification of all candidates observed, to permit immediate, thorough, and efficient follow-up by the general astronomical community.*** (Final spectra and detailed analysis will be published in a normal – but timely – preprint and refereed journal publication, with the final spectra uploaded to a public webpage.)

We note that, for a ToO program, remote observing is key, and we have an observing team in place that is experienced with remote operations with the Goodman spectrograph. In addition, our primary remote observing site for this program would be the Fermilab Remote Operations Center (West), which members of our team have used successfully for a set of SOAR+Goodman remote observing runs during 2017B.

Proprietary Period: 18 months

Use of Other Facilities or Resources *(1) Describe how the proposed observations complement data from non-NOAO facilities. For each of these other facilities, indicate the nature of the observations (yours or those of others), and describe the importance of the observations proposed here in the context of the entire program. (2) Do you currently have a grant that would provide resources to support the data processing, analysis, and publication of the observations proposed here?"*

1) Public alerts, fostering a community for multi-messenger astronomy: Understand that this is such important science that it calls for the consolidation of a community, our DECam program will go beyond making the raw data public and invest in creating a platform to share candidates (selected as seen in Fig. 2) and coordinate follow-up observations by our own team members, partners, and the community at large. The availability of triggers, however, is *independent* of the success of our DECam program: as occurred with GW170817, all teams will quickly announce their discovery and, therefore, we will be able to trigger SOAR observations.

2) Follow-up resources & partnerships: In order to ensure that our team has the resources to do the most exciting science, as well as discovery, we have made a concerted effort to propose for several facilities and partner with other teams internationally:
Blanco: We have requested 19.5 nights on DECam to perform a public search and discovery program for LIGO/Virgo events throughout O3 (PI: Soares-Santos).
IRTF: We have requested 2 hours per night over 4 nights on SPeX to do spectroscopic follow-up in IR of our kilonovae (PI: Soares-Santos, co-Is: Tucker, Allam).
Gemini: US-Brazil-Chile proposal for 58 hours on GMOS-S, Flamingos2, GNIRS, NIRI, GMOS-N for follow-up. Our team includes: Brazil-PI (de Carvalho), co-Is (Lin, D'Andrea, Palmese, Scolnic).
Subaru: We are collaborating with the J-GEM team, which proposed to use the HSC to perform searches of from Hawaii. We plan to complement each other's observations, achieving all-sky coverage of BNS events. DESGW members (Annis, Sako, Soares-Santos) is leading this initiative.
ENGRAVE: This is a proposed large program by the ESO community (all telescopes) to provide immediate optical/IR spectroscopic and imaging follow-up of GW counterpart candidates. Our co-Is (Sullivan, Smith) members of ENGRAVE will enable rapid observations of our candidates.
Taipan: We are collaborating with members of the Taipan survey (Davis) to enable follow-up to obtain peculiar velocity maps for our cosmology analysis.

3) Observing, data processing, publications: We have a team of experienced observers both on-site and at the remote observing facility at Fermilab. We have access to significant grid computing resources at Fermilab and other remote sites. We have successfully utilized these resources in our previous follow-up campaigns to perform timely difference imaging processing (Herner, Kessler, Sako). We also have resources from Brandeis University, to help support operations, analysis effort, travel, and publications.

Long-term Details *If you are requesting long term status, list the observing runs (telescope, instrument, number of nights) requested in subsequent semesters to complete the project.*

We wish to cover the entirety of the LIGO/VIRGO O3 season, which is scheduled for the October 2018 to September 2019 time frame, and which overlaps NOAO observing semesters 2018B, 2019A, and 2019B. Based on the discussion in the Experimental Design and Observing Run Technical Description for 2018B, we expect to need ≈3.6 night equivalents on the SOAR-4m+Goodman Spectrograph in 2019A and ≈1.6 night equivalents in 2019B.

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the PI during the last 2 years for regular proposals, and at any time in the past for survey proposals (including participation of the PI as a Co-I on previous NOAO surveys), together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal. Please include original proposal semesters and ID numbers when available.*

⋆ The PI is a member of the Dark Energy Survey (DES) (2012B-0001) and was a co-I on NOAO proposals 2015B-0187, 2016B-0124, and 2017B-0110, establishing the DESGW counterpart search and discovery program which is the basis of this proposal. Results from our program, achieved in the first two LVC observing campaigns, are published in:

1. Scolnic, D., Kessler, R., Brout, D., et al. 2018, ApJ, 852, L3
2. Guidorzi, C., Margutti, R., Brout, D., et al. 2017, ApJ, 851, L36
3. Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, Nature, 551, 85
4. Palmese, A., Hartley, W., Tarsitano, F., et al. 2017, ApJ, 849, L34
5. Fong, W., Berger, E., Blanchard, P. K., et al. 2017, ApJ, 848, L23
6. Blanchard, P. K., Berger, E., Fong, W., et al. 2017, ApJ, 848, L22
7. Alexander, K. D., Berger, E., Fong, W., et al. 2017, ApJ, 848, L21
8. Margutti, R., Berger, E., Fong, W., et al. 2017, ApJ, 848, L20
9. Chornock, R., Berger, E., Kasen, D., et al. 2017, ApJ, 848, L19
10. Nicholl, M., Berger, E., Kasen, D., et al. 2017, ApJ, 848, L18
11. Cowperthwaite, P. S., Berger, E., Villar, V. A., et al. 2017, ApJ, 848, L17
12. Soares-Santos, M., Holz, D. E., Annis, J., et al. 2017, ApJ, 848, L16
13. Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, ApJ, 848, L12
14. Doctor, Z., Kessler, R., Chen, H. Y., et al. 2017, ApJ, 837, 57
15. Cowperthwaite, P. S., Berger, E., Soares-Santos, M., et al. 2016, ApJ, 826, L29
16. Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016, ApJS, 225, 8
17. Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016, ApJ, 826, L13
18. Annis, J., Soares-Santos, M., Berger, E., et al. 2016, ApJ, 823, L34
19. Soares-Santos, M., Kessler, R., Berger, E., et al. 2016, ApJ, 823, L33

⋆ The PI was also PI on the NOAO proposal 2017A-0260, which established the Blanco Images of the Southern Sky (BLISS), with the goal of expanding DECam coverage beyond the footprints of existing surveys and processing the existing public DECam data to enable science that benefit from large area coverage, such as DESGW. BLISS imaged 1,200 deg^2 of new sky in *griz* and we finished processing all DECam public images with the DES data. The reduced images are used by DESGW as templates for image subtraction, and contributed to the GW170817 discovery paper (Soares-Santos, M., Holz, D. E., Annis, J., et al. 2017, ApJ, 848, L16). The BLISS catalogs are also being used in several analyses which we plan to publish soon: search for new dwarf galaxies in the Milky-way (Drlica-Wagner et al.), deep learning-based morphological classification of galaxies (Barchi, de Carvalho et al.). A public release of all BLISS data products is planned for Fall 2018.

The PI is also co-I on the proposal 2018A-0914 (BLINK), which has DECam time through Brazil exchange with SOAR, and surveys a 1,000deg^2. While data taking for BLINK is ongoing in 2018A, images are being processed by our team using the same pipeline we used for BLISS.

Observing Run Details for Run 1: SOAR/Goodman

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for queue and Gemini runs).*

We propose to use a setup almost identical to that of Nicholl et al. (2017)[8], who were able to follow the GW20170817 kilonova event with reasonable S/N using the Goodman spectrograph from Day 1.5 to Day 7.5 (Figure 1), a period when the kilonova faded from $i \approx 18$ to $i \approx 21$ [9] using an exposure time of 3×900 sec with the 400 l/mm grating.

As noted above in the Experimental Design section, we expect 1–2 gravitational wave merger events to follow up spectroscopically during 2018B. Based on extrapolations from the DECam "search & discovery" of the GW170817 optical counterpart [2], we expect each merger to yield an average of 8.79 candidates between i=16 and i=24 (or 5.57 candidates between i=16 and i=21); see Figure 2.

Based on the Nicholl et al. (2017) SOAR+Goodman spectra, we anticipate we can achieve the S/N necessary to classify whether a given candidate is a true kilonova or just another transient (like a supernova; see Fig. 1) using a single 900 sec exposure for $i \leq 19$) candidates, a single 1200-sec exposure for $i \sim 20$ candidates, and a single 1800-sec exposure for $i \sim 21$ candidates. We leave fainter candidates to programs on larger telescopes, like our proposed partner program on Gemini-South. We will work our way through the list of candidates until we either finish the list (finding no kilonova) or identify the kilonova. Once we identify the kilonova, we will take two additional exposures of the same exposure time in order to build S/N suitable for model fitting. We will follow up a confirmed kilonova brighter than i=20, requesting interrupts on all successive nights until it fades below i=20. We ran a simple simulation containing 100,000 realizations of our program (Fig. 3), assuming an average of 8.79 candidates between i=16 and 24, with initial i-band magnitudes drawn randomly from the expected magnitude distribution of candidates (Fig. 2), and included all relevant overheads (e.g., slewing, target acquisition, readout, observing a standard star each night, etc.). Also, to compensate for possibly worse sky transparencies relative to the clear sky conditions that the Nicholl et al. (2017) spectra were observed under, we multiplied the science target exposure times by a factor of 1.25. The resulting histograms of hours and number of interrupts required to search, discover, and follow up each LIGO/Virgo event are provided in Figure 3: 50% of the time, we complete the process in 4.3 hours (2 interrupts); 95% of the time in 6.7 hours (3 interrupts), and 100% of the time in 9.5 hours (11 interrupts). We anticipate 1-2 events during the 2018B period, which would indicate a total equivalent of 1.9 nights (2 LIGO/Virgo events $\times$ a maximum of 9.5 hours per event = 1.9 nights), which we round to 2 nights equivalent. Finally, we anticipate that we might need to be selective in our choice of candidates if we approach the effective maximum number of interrupts permitted our program.

Instrument Configuration

Filters: None	Slit: 1.0	Fiber cable:
Grating/grism: 400 l/mm	Multislit:	Corrector:
Order: 1st	λ_{start}: 3500	Collimator:
Cross disperser:	λ_{end}: 7500	Atmos. disp. corr.: yes

R.A. range of principal targets (hours): 20 to 13

Dec. range of principal targets (degrees): -90 to 15

Special Instrument Requirements *Describe briefly any special or non-standard usage of instrumentation.*

NOAO observing proposal LaTeX macros v3.0.