Target of Opportunity Requests for ZTF Year 2

The ZTF Multi-Messenger Astrophysics Science Working Group

ABSTRACT

In this document we describe the observing requests from the Multi-Messenger Astronomy (MMA) Science Working Group of ZTF for Year 2 of operations. The bulk of the document describes our proposed program to follow-up neutron star binary mergers discovered via their gravitational wave emission by LIGO and Virgo; since no such follow-up was performed in Year 1 of ZTF, we reiterate the science case for these observations, describe in detail our proposed observing plan, and discuss the resources (telescopes, personnel) available to our team to conduct this campaign. Next, we briefly describe the results of our Year 1 programs to conduct target-of-opportunity follow-up of high-energy neutrinos from IceCube and short gamma-ray bursts from the *Fermi*-GBM, as well as our plans to continue these programs going forward.

1 Electromagnetic Follow-up of Gravitational Wave Detections in O3

1.1 Science Goals

The first direct detections of gravitational waves (GWs) from merging black holes by the Laser Interferometric Gravitational Wave Observatory (LIGO) opened an entirely new window onto the universe[1–5]. These systems provide stringent tests of general relativity in the strong gravity regime and established a new population of binary black holes with $M \gtrsim 10\,M_{\odot}$ whose origin remains hotly debated[6], culminating in the 2017 Nobel Prize in Physics.

Despite these remarkable advances, the true power of GWs can only be fully unlocked when combined with electromagnetic (EM) observations, *i.e.,* **multi-messenger astronomy**. EM observations provide astrophysical context to compact object mergers, establishing the environments in which they reside (*e.g.,* old or young stellar populations) and characterizing the properties (mass, velocity, chemical composition) of any outflows (*e.g.,* relativistic jets, neutron-rich ejecta[7,8]).

The promise of joint GW+EM observations was spectacularly demonstrated by the discovery of GW170817, a binary neutron star (NS) merger identified by LIGO and the European Virgo GW detectors at a distance of only 40 Mpc[9,10]. The scientific bounty from this multi-messenger discovery was truly profound – over 70 papers appeared on `astro-ph` the day of the discovery announcement! Here we summarize just a few key results:

•A short burst of gamma-rays ([11]) detected 1.7 s after the GWs confirmed the long-held association with binary NS mergers, and established that GWs travel at the speed of light[12];

•With a distance from GWs and a redshift from the host galaxy (NGC4993[13–18]), it is possible to measure the Hubble constant, H_0, in a manner completely independent of other techniques[19];

•Prior to GW170817, we did not know where half the elements in the periodic table heavier than Fe were synthesized. The light curve and spectra of the UV/optical/near-infrared (NIR) counterpart revealed the presence of heavy element "r-process" nucleosynthesis in the merger ejecta[17,20–27], with a total ejecta mass ($M_{\rm ej} \approx 0.05\,M_{\odot}$) sufficient for binary NS mergers to serve as the dominant production sites of r-process elements in the universe;

•Slowly rising X-ray and radio emission[28–32] imply the presence of a moderately relativistic (Lorentz factor $\Gamma \approx 3$) outflow. This emission could result from a wide-angle "cocoon" formed from jet-ejecta interaction, or from an ultra-relativistic jet viewed slightly off-axis.

Despite the remarkable discoveries enabled by the joint EM+GW detection of GW170817, a number of open questions remain. First and foremost, GW170817 displayed bright ($L \approx 10^{42}$ erg s^{-1}), blue (blackbody temperature $T_{BB} \approx 10^4$ K) UV/optical emission when the counterpart was first discovered, at $\Delta t = 11$ hours post-merger. However, this quasi-thermal emission faded and cooled extremely rapidly, reaching $L \approx 5 \times 10^{41}$ erg s^{-1} and $T_{BB} \approx 6000$ K at $\Delta t = 1$ day post-merger. **The nature of this early UV/optical emission is not currently well understood[33][1].**

One explanation for this early, bright UV/optical component is the radioactive decay of heavy elements synthesized in the merger ejecta[23,24,34]. This scenario requires that some of the ejecta have a high electron fraction ($Y_e \equiv n_e/(n_n + n_p) \gtrsim 0.3$); otherwise large amounts of lanthanide elements would be formed that would suppress any UV/optical emission due to their large opacity[35–37]. Such a **"blue kilonova"** could result from squeezed material ejected along the polar axis of the merger[38], or from a disk wind powered by accretion onto a long-lived NS remnant[39–41].

[1] The UV/optical/NIR evolution observed at $\Delta t \gtrsim 1$ d is well described by lanthanide-rich kilonova models, as would be expected from neutron-rich material tidally ejected prior to merger;[17,20–27]).

Alternatively, the early UV emission may be powered by the cooling of shock-heated material around the NS merger. Such **"shock cooling"** emission may be naturally expected if a relativistic jet is formed and interacts with the dynamical ejecta[25,42] – this is often refereed to as cocoon emission as it comes from the sheath of the possibly stalled jet.

Our objectives in this proposal are two-fold. First, we aim to promptly identify optical counterparts to neutron star (*i.e.,* NS-NS and NS-BH) mergers in order to bring to bear our significant multi-wavelength resources (*e.g.*, GROWTH worldwide network, *Swift*, VLA, etc.) to address the scientific questions posed above (do all NS mergers generate relativistic ejecta? Can these systems reproduce the heavy element abundance pattern observed in the Solar System?). Second, ZTF (both P48 and P60) light curves will help us understand the origin of this early blue component (Is it ubiquitous in NS binary mergers? How does the emission evolve in the first few hours poster merger? How does it depend on the mass ratio, remnant lifetime and viewing angle?).

We emphasize that despite the intense global interest in GW follow-up amongst the transient community, ZTF maintains a number of distinct advantages that make it **a unique facility for optical counterpart searches in the O3 era:**

•*Large Field-of-View:* Because it was both extremely nearby (40 Mpc) and well-localized (30 deg^2), the optical counterpart of GW170817 was discovered "independently" by a number of different groups, including those using narrow-field instruments and a galaxy-targeted approach (*i.e.*, imaging known galaxies in the 3D volume at the distance provided by the GW detection[43]). This approach will become increasingly more challenging in the O3 era, as the larger distance of typical events (120 Mpc on average in O3) means there will be many more galaxies to image, and galaxy catalogs become more incomplete. Wide-field imagers such as ZTF will not suffer from such limitations.

•*Location:* ZTF is one of the few wide-field facilities operating in the Northern hemisphere currently (*c.f.*, DECam, VISTA). Given the higher quandrupolar sensitivity of LIGO Hanford and LIGO Louisiana compared to Virgo, the odds of events being directly overhead (or directly) below North America are relatively higher. And due to the location of Palomar Observatory several hours east of Hawai'i, we may have a several hour heads start on competing wide-area imagers like Pan-STARRS and ATLAS. Particularly if the rapid fading seen in GW170817 is common, this geographic location will be critical to understanding the origin of the early emission from NS binary mergers.

•*Past History of Variability:* Given the large localizations provided by GW detectors, foreground and (particularly) background transients represent a significant source of contamination. Because of its 3-day cadence MSIP survey, ZTF has a recent record of transients and variable sources across the entire visible sky. Thus we can efficiently discard known transients and variables from our follow-up campaigns, limiting these efforts only to very young sources. We are looking forward to the forced photometry service from IPAC which will allow us to identify fainter, slower historic variability as well. **As demonstrated by our short GRB follow-up efforts over the past year, this keeps the number of transients requiring follow-up observations to O(10), even for localizations as large as several thousand square degrees.**

•*Follow-Up Network:* Over the past 1–2 years, ZTF has become fully integrated into the GROWTH follow-up network, providing round-the-clock multi-wavelength follow-up for potential counterparts. Unlike other groups, we are set up to conduct both discovery and follow-up with our network of facilities, thus allowing us to fully capitalize on the (significant) effort of counterpart discovery.

Finally, we note that due to the scheduling of ZTF and LIGO/Virgo observing runs, **the 12 month O3 run will be the sole opportunity for ZTF to conduct GW follow-up during its 3 year prime phase**. After O3, the GW detectors will be offline for approximately one year to increase their sensitivity. Thus, Year 2 of ZTF operations offers the only chance for the collaboration to undertake this high-impact, high-visibility science.

1.2 Observing Strategy

Given the tremendous scientific potential demonstrated by the discovery of GW170817, as well as the one year available within the ZTF prime phase to conduct joint observations with GW detectors, **we request ToO P48 observations of all NS binary (either NS-NS or NS-BH) mergers discovered in O3** (or the one month Engineering Run ER14 that immediately precedes O3). Given the event rate, this corresponds to one expected trigger every other month (see below). Barring a truly exceptional event, we do not anticipate requesting follow up for any binary BH merger, given the lack of EM signals from such events to date.

Here we outline the details of our requested follow-up, including the requested depth, cadence, areal coverage, and anticipated number of triggers. We assume that the two LIGO interferometers will operate with a sensitivity corresponding to a binary NS merger range (*i.e.*, the sky position and orientation average detectability distance) of 120 Mpc, and the Virgo interferometer will operate with a binary NS range of 65 Mpc (based on information from the LIGO-Virgo Collaboration)[44].

•*Depth:* In Figure 1, we plot the *r*- and *g*-band light curves of GW170817, placed at a distance of 120 Mpc (a typical distance for a binary NS merger in O3). Also shown are the median 5σ limiting magnitudes for isolated point sources in 30 s ZTF/P48 images, as taken from Bellm et al. 2019[45].

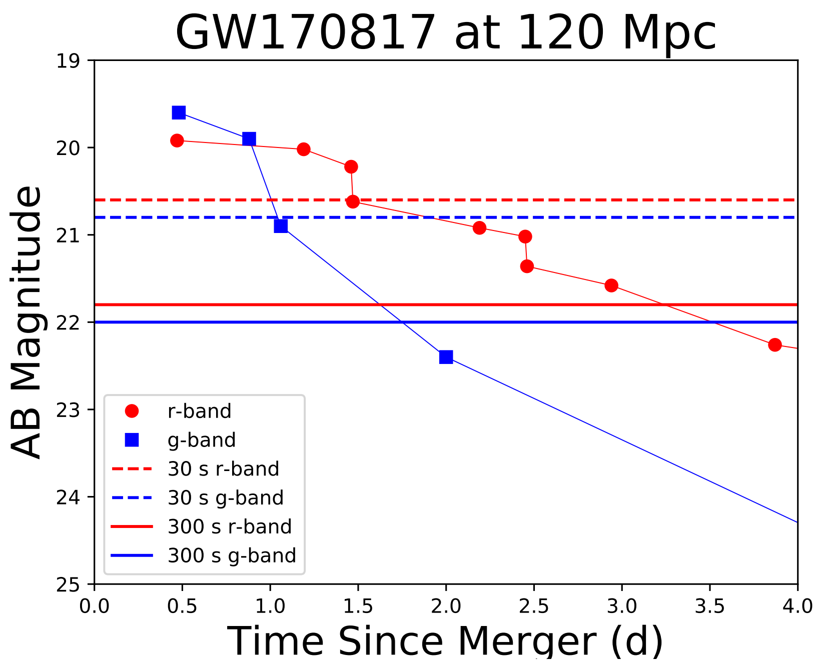

Figure 1. – The *r*- and *g*-band light curves of GW170817, placed at a distance of 120 Mpc (the expected range for binary NS merger detections in O3). Signals as luminous as GW170817 could only be detected within the first day in such 30 s exposures - intrinsically fainter or dust extinguished events require longer exposures to detect even at this early time.

While Figure 1 indicates that a source as luminous as GW170817 would be detected in the standard 30 s exposures, we note that studies of kilonovae associated with short gamma-ray bursts indicate a significant spread in peak luminosity[46,47] – for instance, Ascenzi et al. 2018[47] find that the peak *g*-band absolute magnitude of kilonovae ranges between -12.3 and -16.8 mag, corresponding to observed magnitudes of 23.1–18.6 at $d = 120$ Mpc. Furthermore, GW170817 suffered from little to no dust extinction. Theoretical models suggest that lower ejecta mass, higher mass ratio, shorter remnant lifetime, more equatorial viewing angles may further suppress the optical emission.

For these reasons, we request to obtain longer (than the standard 30 s) exposures for ToO imaging of GW fields. In Figure 1 we plot the anticipated depth for 300 s integrations (assuming sky dominated background), which can be readily achieved with the new guiding capability implemented for P48. Ultimately the longest exposure practical will be limited by the depth of our reference imaging – with the current depth of reference images, this correspond to $\approx$ 300–600 s. We will decide exact exposure time based on available depth of reference images.

•*Filters:* Rapid color evolution is expected to be a strong indicator of kilonova emission (*c.f.*, supernovae and other transients, for which the temperature evolves on a significantly longer time scale). Thus we would prefer to observe in the bluest (*g*) and reddest (*i*) bands possible. However, at the moment there are relatively few sky areas with *i*-band reference images. By default we assume observations will be obtained in *g* and *r*-bands only – however we may consider *i*-band observations as well depending on reference image availability.

•*Cadence:* As is evident from Figure 1, the optical emission from binary NS mergers, even those as luminous as GW170817, will only be visible for a few days at most if located at $d = 120$ Mpc. In addition, the color evolution is most apparent in the first $\approx$ day since the merger.

For this reason we request repeated *g*- and *r*-band imaging of the GW localization **for as long as the relevant fields are visible in the first 24 hours following the merger.** Ideally this will enable real-time counterpart identification and study of the early optical emission even absent any prompt follow-up (*i.e.*, poor weather in Hawai'i.).

If no unique counterpart has been found on the first night (for instance, if there is no rapidly fading blue component from the source, but only a more slowly rising red component), we request a single epoch of multi-color observations on the next $\approx$ 2 nights to continue to search for a counterpart. If necessary, one final epoch will be obtained after $\approx$ 1 week in order to verify that unclassified sources evolve in a manner consistent with unrelated transients (*e.g.*, supernovae, AGN).

•*Area:* According to the LIGO/Virgo observing scenarios document[1], the median GW localization in O3 is expected to have a 90% confidence area of $\approx 150\,\mathrm{deg}^2$. Given that ZTF observes in predefined pointings on the sky, our experience with short

GRB follow-up indicates that such areas require $\lesssim 10$ ZTF/P48 pointings to tile. Given the lack of availability of reference images for the secondary grid, we will only observe fields in the primary grid (and accept the $\approx 10\%$ loss in areal coverage due to chip gaps).

•*Trigger Rate:* There remains significant uncertainty on the volumetric rate of NS binary mergers. The most recent estimates indicate a rate of binary NS mergers between 110 and 3840 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$, with a peak in the probability distribution of $\approx 1000\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$[48]. For a binary NS range of 120 Mpc, this corresponds to an expected number of detections in O3 of $7\,\mathrm{yr}^{-1}$ (90% confidence interval: 0.8–28). Accounting for visibility and weather losses, we assume a rate of triggers accessible to ZTF of ≈ 1 every other month.

The rate of NS-BH mergers is even more uncertain, with only upper limits measured to date. The expected number of detections of such systems in O3 is therefore small, O(1).

•*Summary:* In total, we estimate a request of ToO observations of 6 NS binary mergers discovered in O3. For each trigger, we anticipate observing the 90% confidence localization as long as it is visible for the first 24 hours following the mergers (Night 1), and then (if necessary) at 2–3 additional epochs once per night (Night 2, Night 3, and Night 7). This corresponds to a maximal request of ≈ 14 hours per trigger (≈ 5 hours on Night 1, and 3 hours on Night 2, Night 3, and Night 7).

We anticipate these interrupts will occur at a rate of once every other month, **for a total time request of 84 hours in O3 / Year 2 of ZTF operations**. In context, this corresponds to less than one night of the total P48 observing time each month, or about 9% of the ZTF partnership share of the telescope time (assuming 10 hour nights and 33% weather loss). For comparison, the neutrino and short GRB ToO programs have utilized a total of 10 hours of P48 observing time to date, corresponding to 0.5% of the (actual) P48 observing time (1.3% of the partnership time).

Of course the actual observing program will depend on the true rate of these events, the kilonova luminosity function, etc. We will (by necessity) need to adjust the proposed observing plan to the details of each individual trigger, and can provide updates to the SSC as O3 progresses as we have a better handle on the actual rate of binary NS mergers. We are cognizant of the significant impact of ToO observations on other partnership science, and will work to minimize this as much as possible.

1.3 Resources and Publication Plans

Candidate counterparts identified in P48 imaging will receive high-priority follow-up on a large network of multi-wavelength facilities around the globe (and in space), ensuring ZTF discoveries will a) provide maximal science return, and b) that appropriate credit will accrue to the ZTF team. ZTF is the core node of the GROWTH network, a collaboration of follow-up facilities around the globe to conduct rapid-response observations of rapidly evolving transients. This EM-GW team has a strong track record of successfully obtaining extensive multi-wavelength follow-up for NS binary counterparts.

We plan at least one summary publication on the sample of all GW triggers we follow up with ZTF. Every GW trigger, especially if there is a detection, will probably lead to multiple publications. Given the competitive nature of the field, these will necessarily be prepared on a fast turn-around time. We have a large group of graduate students and postdocs across the ZTF/GROWTH partnership ready and able to conduct such efforts.

2 Neutrino ToO request

2.1 Neutrino ToO during Year 1

Since ZTF began operations, we have received six IceCube alerts (see Tab. 1). Only one could be followed-up with ZTF, and no interesting candidate was identified in the data.

2.1.1 Neutrino Doublet

A neutrino doublet (two or more neutrinos within 100 sec and separated by less than 3.5 deg) arrived on 2018-06-11 23:36:05 UTC. The two neutrinos had $\sim$ 1TeV energies, and were separated by 0.3 sec in time and 3 deg in space. The 90% angular uncertainty on the combined direction was 0.9 deg. We expect $\sim$4 more significant doublets per year. Observations were scheduled by hand for the following night for one field (535). Two 300s exposures were taken on June 12 and another two 300s exposures on June 13. There was another 60s exposure on June 12 and 30s exposures on June 13, 16, 17 and 19. This was the first time we took 300s exposures. The reference image should be deep enough (combines at least 15 images). Image quality looked good, even without guiding.

This was the first ZTF ToO trigger, and automatic scheduling was not in place yet. Scheduling observations came at a large overhead. In the future candidates from neutrino ToOs will be automatically processed by AMPEL, and interesting candidates pushed into the marshal. AMPEL was only running in beta mode at the time of the alert, but we nonetheless managed to filter candidates with AMPEL by hand and push them into the marshal. No interesting candidate was found. Fewer dim candidates than expected were found in the deep images (note that this was the first time such deep observations were performed). This problem was investigated and fixed by IPAC.

Since the doublet stream is a private GCN stream from IceCube, we could not report our results in an ATel.

Table 1. ToO triggers received from IceCube

Type	date	RA	Dec	Error	Comments
Doublet	2018-06-11 23:36:04.87	255.63	13.32	0.90	observed
EHE	2018-09-08 19:59:31.84	145.77	-2.52	0.34	Sun distance 22.68 deg
HESE	2018-10-14 11:52:19.07	225.18	-34.79	1.22	Sun distance 35.73 deg
EHE	2018-10-23 16:37:32.65	269.84	-8.89	0.29	camera down
HESE	2018-10-31 02:02:51.41	182.79	-68.39	1.22	retracted
HESE	2019-01-24 03:44:35	307.19	-32.29	1.23	Sun distance 13 deg

2.1.2 Other Triggers

We were unlucky with the other five IceCube alerts. Three were too close to the Sun to be followed up. One was revealed as a likely atmospheric background events after further checks by IceCube and therefore retracted. Another arrived when the camera was not installed.

2.2 Requested observing strategy

IceCube upgraded its neutrino alert stream by a "gold" and "bronze" sample which will improve our ToO search significantly We expect 10 "gold" sample neutrino alerts with a probability to be of cosmic origin of at least 50% and additional 25 "bronze" neutrino alerts with a signalness of at least 30%. We ask for a ToO follow-up in all 35 alerts.We are aiming to classify all potentially interesting candidates found within the neutrino error circle with an average area of 3 sqrdeg. We assume that approx. 50% of the alerts will be too close to the sun or are retracted by IceCube. Thus, in total, we would potentially trigger on only 18 alerts.

2.3 Papers

We are planning to write several joint IceCube-ZTF papers. First, we plan to write one technical paper explaining our neutrino program using AMPEL. Further paper will follow as our ToO program will result in ATels/GCNs for each successful follow-up observation and in the case of detections, each individiual trigger will likely lead to multiple publications.

3 Short Gamma-Ray Bursts from the *Fermi* GBM

3.1 GRB Triggers in Year 1

Since the beginning of ZTF operations, we have triggered on 6 (poorly localized) short gamma-ray bursts (GRBs) from the GBM instrument on *Fermi*. Table 2 summarizes these efforts.

While none of these triggers has resulted in an afterglow detection, the process has been extremely important as a practice run for GW follow-up in O3. In particular, we identified a number of issues with the pipeline whose resolution benefited the entire consortium (*e.g.*, incorrect gain matching in crowded fields). We also demonstrated that the number of unrelated foreground / background transients requiring classification is manageable, even for search areas as large as several thousand degrees. Finally, while waiting for O3 to begin, the program has served as a valuable means to maintain an engaged and active group (particularly challenging given the geographic distribution involved – US, Europe, India, and Japan).

The effort has also resulted in one of the first ZTF science publications to date: "2900 square degree search for the optical counterpart of short gamma-ray burst GRB 180523B with the Zwicky Transient Facility" (Coughlin et al., in press)[49].

3.2 Request for Year 2

We request to continue this effort, at its current low level, until we receive our first GW trigger in O3. Given this uncertainties in the event rate, this could be a significant fraction of Year 2, or very little time at all. Regardless, the total necessary observing time, based on our experience in ZTF Year 1, is $\lesssim 1$ hour per month (an average of 1 trigger every other month, with $\lesssim 2$ hours of imaging per trigger). As we have improved our response with each subsequent trigger, we are increasing the likelihood of making our first afterglow discovery. Furthermore, this will maintain the momentum and cohesion of the EM-GW follow-up team until the primary science objectives can begin.

3.3 Resources and Publications Plans

As for our EM-GW efforts, we will utilize the GROWTH network for follow-up and classification of any candidate counterparts discovered in our search. As with past GRB counterpart searches, this ensures classification of effectively all viable counterparts.

We plan to publish at the very least a summary paper describing all our GRB follow-up efforts. If we are able to make a detection, this will also be published in a single object paper.

Table 2. ZTF/P48 Short GRB Follow-Up

GRB	Areal Coverage	Probability	Δt	# of Candidates
GRB 180523B	2900 deg^2	0.62	9.1 hr	14
GRB 180626C	300 deg^2	0.87	1.5 hr	0
GRB 180715B	250 deg^2	0.36	10.4 hr	14
GRB 180728B	350 deg^2	0.90	31 hr	0
GRB 180913A	550 deg^2	0.72	8.3 hr	12
GRB 181126B	1400 deg^2	0.77	1.4 hr	11

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