Electromagnetic Follow-Up of Gravitational Waves

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1 Motivation

The direct detection of gravitational waves (GW) by advanced LIGO marks the dawn of a new era (Abbott et al. 2016). On September 14, 2015, the first GW detection was the merger of two thirty solar mass black holes! Subsequently, two more black hole (BH) mergers were detected in the four month observing run ("O1"). The second LIGO observing run ("O2") is currently ongoing and Virgo is expected to join soon (results of this run are currently embargoed). The third LIGO-Virgo observing run ("O3") is expected to be nine months in 2018 and is of most relevance to this discussion. The expected sensitivity in O3 to neutron star (NS) mergers is 120–170 Mpc i.e. a factor of 4–12 more in volume than O1.

Thus, in principle, we should expect to start detecting neutron star mergers (NS-NS and NS-BH) soon. It is widely agreed that the detection and study of the anticipated electromagnetic (EM) counterparts will vastly enrich the science returns for the field of GW astronomy. The photometric discovery of the EM counterpart will give a precise location and a spectrum of the host galaxy will give a precise redshift. This will enable a more accurate measurement of basic astrophysical properties such as the luminosity and energetics of this strong-field gravity event. If the spectrum is timely, it may also solve the long-standing mystery of the unknown sites of r-process nucleosynthesis. We might finally pinpoint the heavy element mines.

The models predicting EM emission from NS-NS/NS-BH mergers depend on a wide variety of parameters: ejecta mass, ejecta velocity, opacity, geometry etc. We summarize graphically in Figure 1. Of most relevance to ZTF are the free neutron decay models and the disk wind models. If a small fraction of the free neutrons escape (<2.5%) and beta decay with a half-life of 10 min, we should see an optical transient that lasts for less than one day (Figure 2; Metzger et al. 2015). The location of Palomar is well-suited for an immediate low-latency response to events detected by advanced LIGO (as we don't even have to wait for the earth to rotate for the events to become accessible). The disk wind models give us a a few days instead of a few hours to respond. We emphasize that speed is ZTF's competitive edge in this difficult search for an EM counterpart.

2 Proposed observations

The inherent challenge is that the low frequency of LIGO operation gives very poor on-sky localization. In the early years, the median localization is several hundred square degrees (Kasliwal & Nissanke 2014, Singer et al. 2014). ZTF has a very large FoV of 47 square degrees. Our choice of limiting our on-sky tiles to only two grids implies that we are quite inefficient in mapping the GW localizations. Specifically, based on a simulation done at UW Milwaukee, if we adopt a modified rank-tiling algorithm instead of a contour-covering algorithm, we only lose a factor of 1.7 in inefficiency due to our coarse two-grid choice. Currently, there is no plan for a finer grid choice. Therefore, assuming a median localization of 500 sq deg and factor of 1.7 in spatial mapping inefficiency for "O3", we need 18 pointings to cover the area. Our target depth is 22 mag which is achievable in 600 s (see Figure 2).

On night zero, we propose to obtain our first epoch within a minute of receiving the GW trigger. Since most fast, optical models predict hot emission, our first filter of response will be g-band. We will search in g-band for 1200s total on night zero and split this into two (2x600s) or three epochs (3x400s) separated by at least half hour depending on the time trigger was received and how much time is left before the localization region sets.

On night one, we plan to obtain both g-band and R-band integrations for 600s each. The main goal of this epoch would be to identify any fast evolving events. A week later and a month later, we will repeat in g-band and R-band for 600s each. The main goal of these late epochs would be to photometrically classify all identified transients (e.g. as consistent with supernovae or not).

If an I-band filter is available, it may help us if the opacities from heavy elements pushes the EM emission peak into I-band (e.g. Barnes and Kasen 2013, Kasen et al. 2013). For example, we could add imaging in I-band on night one and replace the g-band exposure with I-band on night seven and night thirty. However, some recent calculations show the emission from radioactive decay of heavy elements peaks beyond 1 micron and is too faint for ZTF (C. Fryer, priv. comm.). The final decision on cadence and filter choice will be fine-tuned based on available information closer to when O3 starts.

In summary, the total number of epochs is 8×600s per trigger on 18 pointings, which is 24.6 hr per trigger including overhead. Currently, we only plan to follow-up NS-NS and NS-BH mergers. The total number of triggers is very uncertain, both in terms of an order of magnitude in predicted rate and in terms of the actual LIGO sensitivity (120–170 Mpc). Roughly, this corresponds to 8–24 yr^{-1}, which given weather and visibility losses reduces to 3–8 yr^{-1}.

3 Supporting observations

Due to the dynamic nature of the optical sky, we are guaranteed to be inundated with false positive transients unrelated to the gravitational wave trigger. We have been refining our software algorithms that quickly sift through the large number of candidates during our *Fermi* Gamma-ray Burst Monitor afterglow search effort (Singer et al. 2013, 2015). The EM-GW challenge has some similarities and some differences. The similarities are that we need to continue to reject foreground asteroids/variable stars and background supernovae/active galactic nuclei. The differences are that compared to a Gamma Ray Burst afterglow, the EM-GW counterpart may be relatively fainter and/or slower and/or redder. Knowing that the EM counterpart is relatively nearby due to the advanced LIGO sensitivity helps further reduce false positives.

The following are some rejection criteria:

1. Movement in detections separated by at least 15 min suggesting the candidate is an asteroid
2. Past history of eruption in PTF/iPTF/ZTF data suggesting the candidate is an old transient. The all-sky MSIP survey will be extremely helpful in rejecting all old transients brighter than 20.5 mag.
3. Previously known radio/X-ray source suggesting the candidate is an active galactic nucleus
4. Previously known optical/infrared quiescent source suggesting the candidate is a stellar flare

The following criteria lead to flags for follow-up spectroscopy and/or multi-band follow-up:

1. Host galaxy within 100 kpc of transient with spectroscopic redshift <0.05 (or photometric redshift <0.1) — this is motivated by advanced LIGO's sensitivity limit to binary neutron star mergers
2. Photometric evolution on hour timescale or day timescale or one-week timescale that is more extreme than supernovae — this serves as a strong discriminant against old supernovae.
3. Hostless candidates with no counterpart in deep iPTF reference co-adds — even though these are unlikely to be local, we plan to flag these events as they are relatively rare but they would be relatively lower priority for follow-up than the first two criterion mentioned here.

To quantify the relative efficacy of each criterion, we discuss the most severe cuts by applying each criterion independently. For GW150914, we had a total of 127676 candidates. Of these, 78951 candidates (62% selection) were not a star, 15624 candidates were not an asteroid (12.2% selection) and 5803 candidates (4.5% selection) passed our machine learning criterion. Only 1007 candidates (0.8% selection) are selected as being coincident with a nearby galaxy (within a 100 kpc ellipse)

Given the importance of the nearby galaxy catalog, two postdocs (David Cook at Caltech and Angela Van Sistine at UWM) have been working hard to complete our census of the local universe (CLU). CLU is based on our narrow-band survey with PTF/iPTF and will soon deliver the most complete catalog of nearby galaxies.

Panchromatic photometric and spectroscopic follow-up of interesting EM-GW candidates will continue to be done by GROWTH: **G**lobal **R**elay of **O**bservatories **W**atching **T**ransients **H**appen. GROWTH is a five year NSF PIRE program, from 2016 to 2020, that facilitates an international collaborative network of astronomers and telescopes dedicated to the study of fast-evolving cosmic transients.

4 Expertise to undertake project

The EM-GW team has been developing the necessary, software and follow-up expertise over the past five years by first proving that afterglows of coarsely localized Fermi-GBM bursts are identifiable (L. Singer, PhD Thesis) and then undertaking end-to-end follow-up of LIGO triggers as they became available. During the first and second GW observing run, iPTF responded to every trigger with a false alarm rate lower than one per month (Kasliwal et al. 2016). The Oschin 48-inch undertook fully automated tiling of the error region accessible from Palomar. We triggered photometric, spectroscopic and panchromatic follow-up with a suite of facilities to characterize the nature of our candidate events (e.g., Figure 4). None of our candidates appear to be associated with the gravitational wave trigger, which is unsurprising given that the GW came from the merger of two stellar-mass black holes. Our radio follow-up yielded no detections either and is summarized in Palliyaguru et al. 2016. The speed of the ZTF ToO response, real-time pipeline and machine learning algorithms will be critical to our efforts.

5 Manpower and time-line

The GROWTH project gives us the necessary manpower to execute the EM-GW rapid response and write papers in a timely manner. We aim to submit papers on EM follow-up at the same time as the GW discovery papers. All ZTF partners are also GROWTH partners. Currently, the EM-GW science team comprises the following faculty and their groups from various ZTF partners: Caltech (Kasliwal, Prince, Hallinan), University of Maryland (Cenko, Singer), University of Wisconsin Milwaukee (Kaplan, Brady), Stockholm University (Goobar, Sollerman, Amanullah), NCU Taiwan (Ngeow, Ip, Kong), Weizmann Institute (Ofek), DESY (Franckowiak).

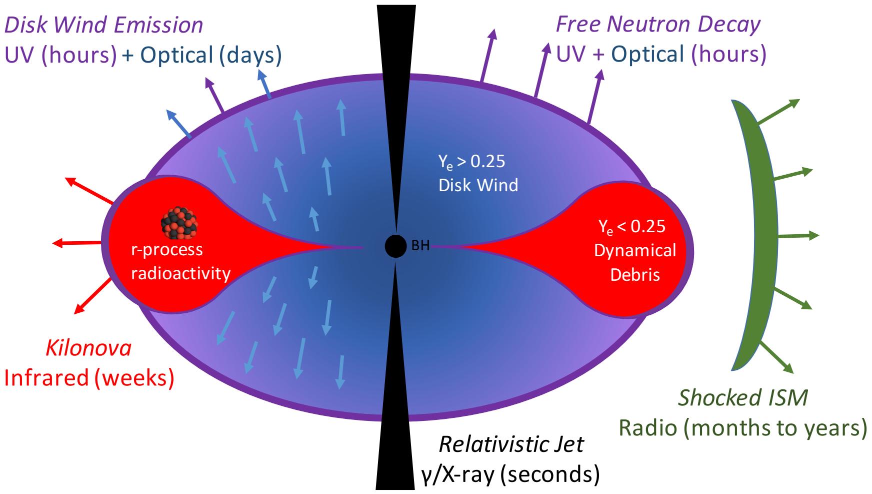

Figure 1 Graphical illustration of various model predictions for electromagnetic emission from neutron star mergers, color-coded by wavelength.

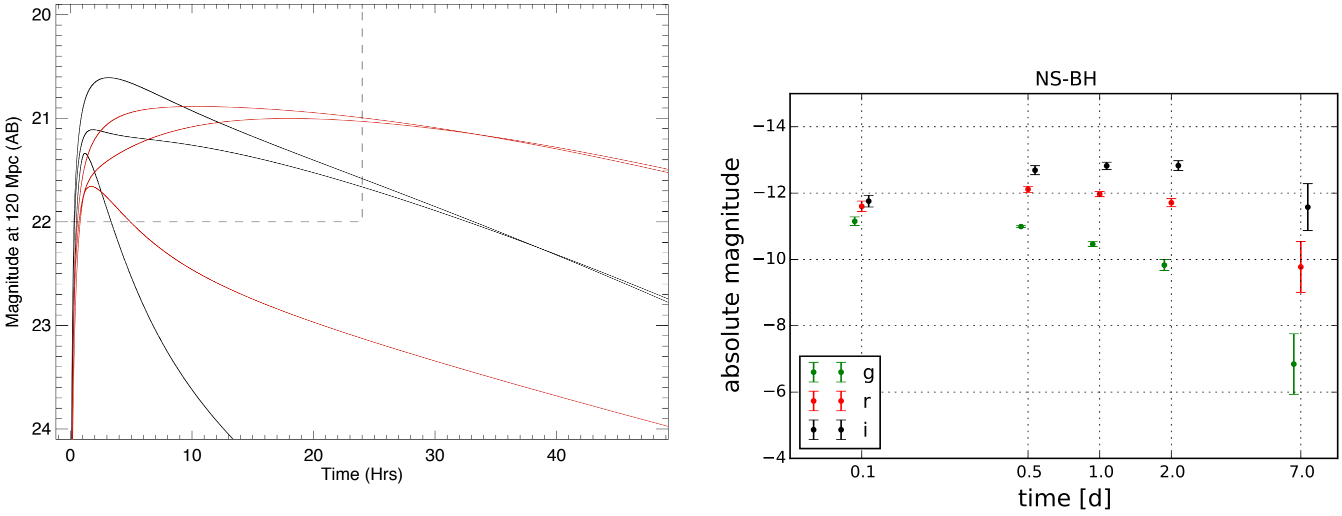

Figure 2 *Left:* Predicted optical counterpart based on free neutron decay [Metzger et al. 2015]. Black lines are g-band and red lines are i-band light curves at 120 Mpc (sensitivity limit of advanced LIGO to binary neutron star mergers in 2018 is expected to be 120-170 Mpc) . The three curves assume three different values for opacity and neutron mass to represent the fast, intermediate and slow light curve evolution cases i.e. ($\kappa_r = 30$ cm^{2}gm^{-1}, $M_n = 3\times10^{-5}\dot{M}_\odot$), ($\kappa_r = 3$ cm^{2}gm^{-1}, $M_n = 3\times10^{-5}\dot{M}_\odot$), ($\kappa_r = 3$ cm^{2}gm^{-1}, $M_n = 3\times10^{-4}\dot{M}_\odot$). Note that g-band is more luminous than i-band at peak but decays faster. Horizontal dashed line denotes the sensitivity of ZTF in 600 s. Vertical dashed line denotes the timescale within which follow-up is undertaken by the GROWTH program. *Right:* Predicted optical counterpart for an NS-BH merger based on Rosswog et al. 2016. The models assume NS mass of 1.2–1.4 $M_\odot$, BH mass of 7$M_\odot$, BH spins of 0.7–0.9 and $\kappa = 10$ cm^{2}gm^{-1}. The error bars denote the full range of magnitudes for the various parameters. This model suggests fainter magnitudes: absolute −13 mag at 100 Mpc corresponds to apparent 22 mag

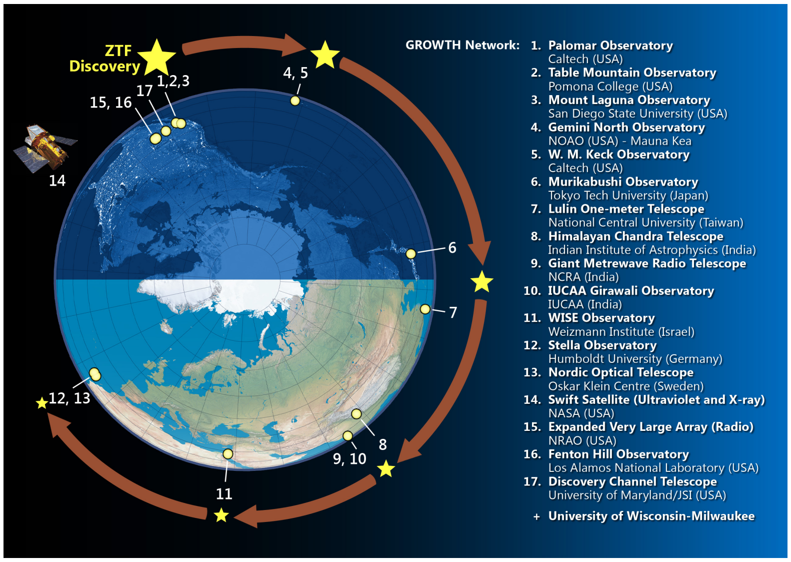

Figure 3 GROWTH is a co-ordinated northern network of astronomers and telescopes unbeaten by sunrise. As the transient fades and the earth rotates, the baton to collect data is relayed from country-to-country (orange arrows). The GROWTH team comprises seven US and seven foreign partner institutions.

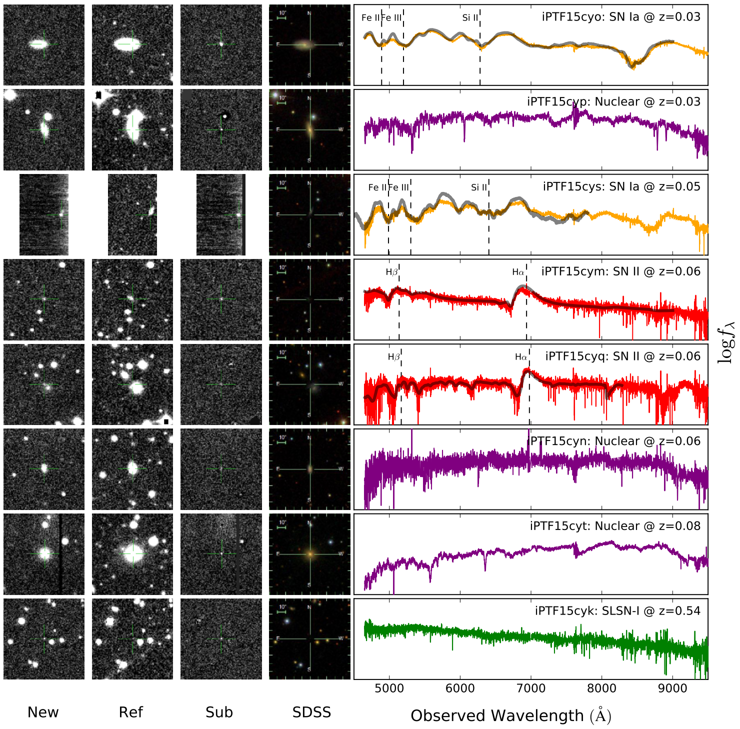

Figure 4 Keck II/DEIMOS classification spectra of eight iPTF candidates obtained within 2 hours of discovery. Also shown, from left to right, the P48 discovery image, reference image, subtraction image and SDSS thumbnail around each candidate location. Colors denote spectroscopic class: SN Ia (red), SN II (blue), Nuclear (purple), SLSN I (green). Overplotted in gray lines is the best match from a supernova spectra library. [Kasliwal et al. 2016]