Astronomy & Astrophysics manuscript no. AA_letter
November 29, 2018

Electromagnetic follow-ups in the era of forecasting gamma-ray bursts

Subtitle here if needed

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November 29, 2018

ABSTRACT

The detection of gravitational waves from the binary neutron star inspiral-merger event GW170817 and the subsequent extended electromagnetic follow-up observations of the resulting kilonova gave us a small taste of multi-messenger astronomy across the spectra of *two* fundamentally different kinds of radiation. The opportunities to conduct such multi-disciplinary studies will increase by two orders of magnitude in the 2030s with Einstein Telescope (ET), LIGO's European successor. ET is expected to anually localise $\gtrsim 5$ binary neutron stars to $\Delta\Omega \lesssim 10\,\mathrm{deg}^2$ with $\gtrsim$ one hour left to merger. This yearly rate can potentially quadruple with the inclusion of a second detector like Cosmic Explorer, the proposed third generation US detector. There will additionally be up to $O(100)$ sources with $\Delta\Omega \sim 20\,\mathrm{deg}^2$. Having so many "well" localised GW sources opens the possibility of doing detailed follow-up observations of the resulting kilonovae with the next generation electromagnetic observatories such as ATHENA, LSST, BlackGEM. Here, we investigate the potential issues in the follow-up work such SNIa posing as kilonovae in the optical band.

Key words. gravitational waves –gamma-ray bursts – kilonovae

1. Introduction

Gravitational waves offer a unique insight into some of the most extreme physical processes in the Universe - including the merger of black holes (BH) and neutron stars (NS), and the first seconds of core-collapse supernovae (SNe) explosions.

With the first direct detection of gravitational waves (GWs) in 2015 by the Advanced Laser Interferometer Gravitational-Wave Observatory (Advanced LIGO; Abbott et al. 2016c), gravitational wave astronomy moved from prospect to reality. The first GW source observed by Advanced LIGO, GW150914, matched the signal predicted for the merger of two black holes with masses 36 and 29 $M_\odot$. Along with being the first direct detection of GWs, GW150914 was also the first detection of such heavy black holes, which had significantly larger masses compared to those measured for galactic high mass x-ray binaries **SA: (citation?)** . Such massive black holes provide an interesting constraint on stellar evolutionary channels at low metallicity (e.g. Abbott et al. 2016a; Belczynski et al. 2016). While no electromagnetic counterpart is generally expected to accompany the merger of two black holes, an intensive multi-wavelength search of the probable location of GW150914 was carried out (Abbott et al. 2016b). Despite yielding a null result, this effort served as a rehearsal in preparation for searches for counterparts to GW sources that *are* expected to be accompanied by an electromagnetic (EM) source.

Only two years after the first detection of merging black holes, the Advanced LIGO and Virgo gravitational wave observatories detected GW170817, with a waveform consistent with the merger of two neutron stars (Abbott et al. 2017c). A spatially and temporally coincident short Gamma Ray Burst (GRB) was also seen by the *Fermi* and *INTEGRAL* satellites (Abbott et al. 2017b). This discovery sparked a global effort to find the counterpart of GW170817 at optical wavelengths, which resulted in the identification of AT2017gfo less than 11 hours later (Abbott et al. 2017d). AT2017gfo faded exceptionally rapidly, and displayed cool temperatures and lines from unusual r-process elements at exceptionally high velocities (Smartt et al. 2017; Arcavi et al. 2017; Pian et al. 2017; Coulter et al. 2017; Kilpatrick et al. 2017). These characteristics marked AT2017gfo as a kilonova; a transient powered by the radioactive decay of short-lived nuclides formed in the merger of two neutron stars.

The detection of electromagnetic counterparts to gravitational waves from merging neutron stars is of exceptional significance for astrophysics. Kilonovae are the predominant site for r-process nucleosynthesis, and so play a critical role in the chemical evolution of galaxies. If a kilonova can be identified and associated with a host galaxy of known redshift, then the degeneracy between inclination angle and distance inherent to a GW signal can be broken. This in turn allows the opening angle of the GRB jet to be constrained, something that has only been done for a handful of GRBs to date (Jin et al. 2018). Gravitational wave sources can also be use to independently determine the Hubble constant H_0 (Abbott et al. 2017a). This of particular interest given the disagreement between measurements of H_0 from Type Ia SNe and from the Cosmic Microwave Background (e.g., Bernal et al. 2016)

The identification of AT2017gfo as the counterpart to GW170817 was realised by the ability of Advanced LIGO-Virgo to localise the GW signal to ~30 deg^2. In addition, at only

40 Mpc, GW170817 was exceptionally close. This enabled the EM counterpart to be identified through targeted observations of galaxies which were at this distance within the GW localisation region (Coulter et al. 2017). Unfortunately such a strategy is only feasible for the nearest GW sources, and rapidly becomes unfeasible beyond $\sim 100-200$ Mpc, both as the number of galaxies within the search volume increases, and as the fraction of galaxies with reliable redshifts decreases. This embarrassment of riches is a serious obstacle for identifying EM counterparts to GW transients in the 2030s with Einstein Telescope (Abernathy et al. 2011).

Einstein Telescope (ET) will consist of three V-shaped interferometers which eliminate blind spots and further allow it to construct a null stream (Sathyaprakash et al. 2012) which can be used to veto spurious events (Wen & Schutz 2005). Additionally, ET will be a xylophone (Hild et al. 2010), i.e., a multi-band detector capable of delivering high sensitivities both at low frequencies (~ 5 Hz) and high frequencies (~ 100 Hz). Here, we focus on the C configuration (ET-C) which offers the highest low-frequency sensitivity as shown in Fig. 1. ET-C will detect $\gtrsim O(10^3)$ binary neutron star inspirals per year out to 1 Gpc (Akcay 2018). A subset of these sources will be close enough that they will be detected a few hours before their respective mergers (Akcay 2018), hence opening up the possibility of alerting EM observatories to conduct follow-up observations *before, during* and after the prompt gamma-ray bursts. Additionally, ET-C will forecast a few potential tidal disruption events per year, in which a neutron star gets tidally torn by a $\sim 5M_\odot$, high-spin black hole companion (Akcay 2018).

To fully exploit the prospect of multi-messenger astronomy, a number of wide-field survey telescopes are either operational, in commissioning, or under construction. Foremost among these is the Large Synoptic Survey Telescope (LSST; LSST Science Collaboration et al. 2009), which has an 8.4 m primary mirror, and will image 9.6 deg^2 in a single pointing. Construction of LSST is well underway, and the telescope is expected to begin full survey operations at the start of 2023. Apart from LSST, the majority of current and next-generation survey telescopes have a relatively small mirror, but a large camera, and are designed to observe $\sim 10-50$ deg^2 in a single pointing to a limiting magnitude of $\sim 20-22$. ZTF (Bellm 2014), GOTO (Dyer et al. 2018) and ATLAS (Tonry 2011) are all currently operational at present, while BlackGEM is currently under construction (Bloemen et al. 2016).

There has been a considerable amount of discussion in the literature as to the optimal strategy to identify an EM counterpart to future GW transients (Gehrels et al. 2016; Coward et al. 2011; Ghosh et al. 2016; Chan et al. 2017; Siellez et al. 2014; Antolini & Heyl 2016). In most cases however, a large number of candidates will be found within the search region, for which further spectroscopic followup observations will be required. This spectroscopic classification bottleneck will remain a problem

Our aim here is to demonstrate exciting EM follow-up studies that can be done by taking advantage of the early GW warning capability of ET. More specifically we consider binary neutron star inspirals out to luminosity distances of ~ 600 Mpc, the expected range of LSST. Within this range, ET-C will be able to detect GWs from inspirals a few hours before a given merger thus provide a window of opportunity for mobilizing the EM observatories in time to witness the birth of the associated kilonova. Furthermore, a pre-GRB GW warning allows us to obtain reference images with EM telescopes immediately prior to a kilonova, reducing the number of unrelated transients that will be found within a given search region. However, in order to fully benefit from ET's early warnings, several issues must be addressed: (i) ET's poor localisation by itself, (ii) large number of supernovae creating a confusion background, (iii) the slow response time of certain EM observatories essential to follow-up. Here, we consider each of these setbacks and suggest solutions which require support from the global astronomy community.

This letter is organized as follows: Sec. 2 provides more details on ET, Sec. 3 investigates the implications of optical follow-up. We use f to denote the quadrupole GW frequency in the detector frame. c is the speed of light and G is Newton's constant.

2. Einstein Telescope

In this section, we compute advance warning times ($T_{\rm AW}$) ET will provide. The computational details are provided in Akcay (2018). To this end, consider a binary neutron star (BNS) system with component masses m_1, m_2 inspiraling at a luminosity distance D with a corresponding redshift z. For GW frequencies of interest to us here ($f \lesssim 10$ Hz), the binary undergoes an adiabatic inspiral dominated by the emission of leading-order (quadrupole) gravitational radiation. By balancing the power emission in GWs to the rate of change of binding energy, we obtain the frequency evolution of the GW frequency

$$\dot{f} = \frac{96}{5}\pi^{8/3}\frac{(GM_c)^{5/3}}{c^5}f^{11/3}, \tag{1}$$

where $M_c = (m_1 m_2)^{3/5}(m_1+m_2)^{-1/5}$ is the chirp mass. After fixing an integration constant, Eq. (1) can be integrated to yield the time left to merger at a given frequency, usually called the inspiral time

$$\begin{aligned}\tau_{\rm insp}(f) &= \frac{5}{256\pi}\frac{c^5}{(\pi G M_c)^{5/3}}f^{-8/3}\\ &= 16.72\,\text{minutes}\left(\frac{1.219M_\odot}{M_c}\right)^{5/3}\left(\frac{10\,\text{Hz}}{f}\right)^{8/3}.\end{aligned} \tag{2}$$

This result can be supplemented with a post-Newtonian series up to $O(c^{-7})$ (Blanchet 2014), but the resulting expressions are rather ungainly and only change $\tau_{\rm insp}$ by $\lesssim 2\%$.

To obtain $T_{\rm AW}$ we must choose f which necessitates a discussion of the effects that GWs have on interferometers (IFOs). A passing GW induces a scalar response in a given IFO known as the GW strain which is a function of GW polarization amplitudes and IFO antenna pattern functions. In frequency domain, the norm of the GW strain is given by $|\tilde{h}(f)| = A h_0 f^{-7/6}|Q|$, where $A = \pi^{-2/3}(5/24)^{1/2}$, $h_0 = c(1+z)^{-1}\tilde{M}^{5/6}/D$ with $\tilde{M} = G(1+z)M_c c^{-3}$ and Q is the IFO quality factor which is a function of source sky location angles (θ, ϕ), its inclination ι, and the relative detector-source polarization angle ψ.

The IFO response to a GW strain is quantified in terms of a signal-to-noise ratio (SNR). As we can not a priori know the angles $\{\theta, \phi, \iota, \psi\}$, we use an angle-RMS-averaged SNR, which for a detector with triangular topology like ET, reads

$$\rho_{\rm ET}(f_1, f_2) = \frac{6}{5}A\,h_0(1+z)^{-1/6}\left[\int_{f_1}^{f_2} df'\,\frac{f'^{-7/3}}{S_n(f')}\right]^{1/2}, \tag{3}$$

where $\sqrt{S_n(f)}$ is the *amplitude spectral density* (ASD) of the detector (also called detector noise) and the factor of 6/5 in Eq. (3) is due to RMS-averaging (Akcay 2018). For each source, this factor may vary by $\sim \pm 30\%$ compared to the average, but will always be > 0 thanks to ET not having any blind spots.

We define $T_{\rm AW}$ to be the time interval between the moment of detection and the merger, therefore we must first define the former. We do this using Eq. (3) as follows: let f_0 be the frequency at which the GW strain equals the detector noise, i.e., $\sqrt{S_n(f_0)} = 2\sqrt{f_0}\tilde{H}_{\rm ET}(f_0)$ where $\tilde{H}_{\rm ET}(f) = 3h_0 f^{-7/6}/5$. The instant of detection is given by $\bar{f} > f_0$ such that $\rho_{\rm ET}(f_0, \bar{f}) = 15$, thus yielding $T_{\rm AW} = \tau_{\rm insp}(\bar{f})$. The total accumulated SNR is given by $\rho_{\rm tot} = \rho_{\rm ET}(f_0, f_{\rm ISCO})$, where $f_{\rm ISCO}$ is the frequency at which the inspiral transitions to plunge. Here, we use the standard approximation from general relativity: $f_{\rm ISCO} \approx c^3\left(6^{3/2}\pi G(m_1+m_2)\right)^{-1} \simeq 1571\left(\frac{2.8M_\odot}{m_1+m_2}\right)$ Hz. Our chosen threshold SNR of 15 is not set in stone; other common choices are 8 and 12, but we choose to be more conservative.

The only free variable left to determine $T_{\rm AW}$ is the luminosity distance D (z is obtained from it and vice versa). In Fig. 1 we display the GW strain for four canonical ($m_1 = m_2 = 1.4M_\odot$) BNS inspirals at $D = 100, 200, 400, 600$ Mpc. ET-C's noise is the thick, red curve with the best sensitivity for $f \lesssim 10$ Hz. In traditional ASD plots, inspiral GW strains scale as $\sqrt{f}f^{-7/6} = f^{-2/3}$ (Colpi & Sesana 2017), hence are straight lines with slopes of $-2/3$ in the figure. The frequencies f_0 where these straight lines intersect ET-C's noise curve are distinguishable below 2 Hz. We list the advance warning times along with the total SNRs for these sources in Table 1, where we show that ET-C is capable of providing up to five hours of early warning before merger, thus offering a tremendous opportunity to electromagnetically observe the merger-GRB-kilonova with available resources in the 2030s. But we should first see if ET can forecast enough BNS events and localise them to make a follow-up campaign worthwhile.

Table 1. Forecasting capabilities of the C configuration of Einstein Telescope summarized in terms of luminosity distance D and the corresponding redshift z. $\bar{f}$ is the threshold frequency at which ET-C accumulates SNR of 15. $T_{\rm AW}$ is the inspiral time from the instant when the GW frequency equals $\bar{f}$. $\rho_{\rm tot}$ is the total accumulated SNR of each inspiral. Last column lists the event rates in the format average$^{\rm max}_{\rm min}$ in units of D^{-3} yr^{-1}. The numbers have been rounded when appropriate.

D (Mpc)	z	$\bar{f}$ (Hz)	$T_{\rm AW}$ (hrs)	$\rho_{\rm tot}$	$R_{\rm av}{}^{\rm max}_{\rm min}$
100	0.022	3.3	5.3	365	$1.54^{4.7}_{0.32}$
200	0.044	4.1	2.9	182	$12.3^{38.}_{2.6}$
300	0.065	4.66	1.9	121	$41.6^{130}_{8.6}$
400	0.085	5.1	1.5	90.5	98.6^{300}_{20}
500	0.10	5.4	1.2	72	193^{590}_{40}
600	0.12	5.7	1.03	60	333^{1020}_{69}

2.1. Event rates binary neutron star inspirals

We base our event rate calculations on $R = 1540^{+3200}_{-1220}$ Gpc^{-3} yr^{-1} inferred from GW170817 (Abbott et al. 2017c). Assuming flat spatial geometry, this translates roughly to 330^{+690}_{-260} yearly BNS events within 600 Mpc. We partition this volume into concentric spheres with radii equalling integer multiples of 100 Mpc. For each sphere, we compute the corresponding average (av), maximum (max), and minimum (min) event rates using R. We present these results in Table 1 along with the redshifts for each distance

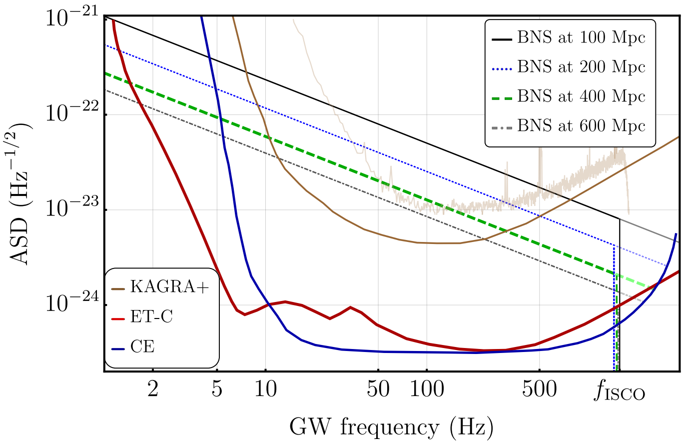

Fig. 1. $1.4M_\odot - 1.4M_\odot$ inspiralling BNS systems sweeping across the sensitivity band of Einstein Telescope's C configuration (thick red curve). The solid (black), dotted (blue), dashed (green), and dot-dashed lines (gray) lines are the redshift-corrected angle-RMS-averaged GW strains, $2\sqrt{f}\tilde{H}_{\rm ET}$, at luminosity distances of $D = 100, 200, 400, 600$ Mpc, respectively. The vertical lines with correspondingly identical patterns (colors) mark the redshifted ISCO frequencies $(1+z)^{-1}f_{\rm ISCO}$ at which point we terminate each inspiral. As the true ISCO frequency is likely larger than $f_{\rm ISCO}$ (Marronetti et al. 2004), the inspirals would continue to nearly 2 kHz indicated by the faded lines in the plot. We also show the strain sensitivity of Cosmic Explorer (thick blue) and KAGRA+ (brown curve). The faint brown curve represents the sensitivity of Advanced LIGO during GW170817. As RMS averaged BNS strains in an L-topology detector (CE, KAGRA+, LIGO) are 2/3 of strains in triangular-topology detector (Akcay 2018), we rescale the CE, KAGRA+, LIGO curves by 3/2 thus making them effectively less sensitive. Otherwise, we would have to draw four additional BNS strains, each of which scaled down by 2/3 in amplitude.

computed using a flat ΛCDM model ($\Omega_k = 0$) with the latest Planck satellite parameters: $\Omega_\Lambda = 0.6911, \Omega_m = 0.3089, H_0 = 67.74$ km s^{-1} Mpc^{-1} (Adam et al. 2016). It is then straightforward to translate D to z [cf. Hogg (1999)].

We see from Table 1 that within $z \lesssim 0.1$, ET-C will annually detect GWs from ~ 40 to 600 BNS transients. Roughly 7% of these will be within 200 Mpc yielding $T_{\rm AW} \gtrsim 3$ hours which means that EM observatories will be alerted $\sim$ 3 - 40 times yearly with the prospects of observing the births of kilonovae. If we assume that future EM observatories would suffice with $T_{\rm AW} = 1$ hour then all BNS transients within 600 Mpc become possible candidates for merger-kilonovae observations. In this case, early warnings would be sent by ET at least once a week and at most three times per day. It is not feasible to have a system in place to observe each one of these events so it will make sense to be selective and focus on the best candidates. These will naturally mostly be the nearest sources which will additionally be favoured by ET because of its limitations with localisation that we discuss next.

2.2. Source localisation estimations

ET will have poor source localisation because all three of its IFOs will be at the same location. However, as our findings in Table 1 indicate, ET-C will detect BNS inspirals hours before the merger during which time the Earth will have rotated by as much as a few dozen degrees. This means that over this time ET can be treated as a network. It is expected that within 1Gpc, ET *alone* will localise approximately 20% of the sources to within 100 deg^2, 2% to within 20 deg^2, and 0.5% to within

$10\,\mathrm{deg}^2$ (Zhao & Wen 2018) [1]. Rescaling to $D = 400\,\mathrm{Mpc}$, corresponding to $T_{\mathrm{AW}} = 1.5\,\mathrm{hrs}$, we obtain $\gtrsim 5$ yearly BNS transients with $\Delta\Omega \lesssim 10\,\mathrm{deg}^2$ and $\gtrsim 20$ transients with $\Delta\Omega \lesssim 20\,\mathrm{deg}^2$.

Our above approximations on localisation should be taken as the pessimistic case as ET will be not be operating alone. Currently suggested companion detectors are the Japanese cryogenic detector KAGRA (Akutsu et al. 2017, 2018), LIGO's successor Voyager in the US (Berger et al. 2016) and its "relative" in India (Unnikrishnan 2013), and finally, Cosmic Explorer (CE): the ambitious third generation US detector with 40 km armlength (Abbott et al. 2017). Assuming a three detector network consisting of ET and two CEs with a total network SNR > 12 and two detectors each with SNR > 5, Mills et al. (2018) find that half of signals will be localised to within 1 deg^2 out to a redshift of $z \sim 0.25$. However, this survey is not concerned with issuing sufficiently early warnings to EM facilities. The problem is that only ET has the extreme low-frequency sensitivity enabling $T_{\mathrm{AW}} \sim$ hours. The other detectors will not accumulate any SNR from BNS inspirals in the $f \lesssim 5\,\mathrm{Hz}$ domain[2]. However, CE will be sensitive enough to accumulate SNR from 5 Hz for BNSs with $D \lesssim 400\,\mathrm{Mpc}$ (Fig. 1). Given that its sensitivity increases steeply between 5 and 10 Hz, CE will accumulate SNR = 5 with 1.5 hours left to merger and SNR = 15 with 1.25 hours left resulting in a total network SNR, $\rho_{\mathrm{net}} \equiv \left(\rho_{\mathrm{ET}}^2 + \rho_{\mathrm{CE}}^2\right)^{1/2} = \{18.8, 27.4\}$ for $\tau_{\mathrm{insp}} = \{1.5, 1.25\}$ hours, respectively. As localisation improves with increasing SNR, this means that an initial $\Delta\Omega$ of $\sim 100\,\mathrm{deg}^2$ can be reduced as the BNS inspirals through its second to last hour before the merger.

This region can be further decreased once the BNS enters a third detector's bandwidth, which will most likely be some future version of KAGRA. We do not have any strain data for the 2030s KAGRA. However, there are plans for a mid 2020s upgrade, KAGRA+, with increased strain sensitivity (brown curve in Fig. 1). Using the same analysis as for CE, we obtain that KAGRA+ will pick up a 400-Mpc inspiral at $\sim 10\,\mathrm{Hz}$ and will accumulate SNR = 5 within a minute. For a less likely 100-Mpc source, KAGRA+ would accumulate SNR > 15 more than a half hour before the merger. Thus, for nearby sources, even KAGRA+ sensitivity could contribute to pre-merger localisation efforts. Given that LSST requires $\sim$ 5 minutes to point anywhere in the sky, KAGRA's contribution will matter. Once again, this is a rather pessimistic estimation as we expect KAGRA's third generation (3G) successor to be more sensitive than KAGRA+.

In short, within 400 Mpc, we can annually expect five BNS transients to be localised to $10\,\mathrm{deg}^2$ 1.5 hours before the merger. We can expect an additional $\sim$ 15 more with initial localisation of $\sim 20\,\mathrm{deg}^2$ which we expect will be narrowed down to $\sim 10\,\mathrm{deg}^2$ about one hour before the merger. We envision a three-stage localisation procedure whereby ET conducts the operations alone until $f \sim 5\,\mathrm{Hz}$ — roughly two hours before merger — at which point CE joins in and, finally, around $f \sim 10\,\mathrm{Hz}$ KAGRA+ (or 3G) starts accumulating SNR with $\gtrsim 15$ minutes left to merger.

3. Implications for optical followup of GW detections

Identifying an optical or near-infrared (NIR) counterpart to a GW is an observational challenge. If a GW is only localised to tens, or even hundreds of square degrees, then we must survey a large area of the sky to find an EM counterpart. While large format CCDs make taking imaging of an area of $\sim$ 100 deg^2 relatively straightforward, we must identify our EM counterpart of interest among the many unrelated astrophysical transients that we expect by chance within the same area. Thus far, this has relied upon large scale efforts to spectroscopically classify credible candidates that are found within the sky localisation of a GW. As an example, for the BH merger GW151226, Smartt et al. (2016) found 49 candidate transients within 290 deg^2, and obtained spectra for 20 of these. While such a survey strategy is the only feasible approach at present, it is clearly an inefficient use of scarce telescope time.

The early warning obtained for future GW events discussed in Sect. 2 offers an alternative approach for finding EM counterparts. In brief, if we can detect a GW with ∼1 hr advance warning, and can localise it to ∼50 deg^2 or better, then we can obtain imaging of this area both immediately prior to, and after, the merger happens. Since the merger will be the only thing that has changed over such a short period of time, identifying an EM counterpart in difference imaging becomes straightforward.

3.1. The rates and nature of contaminants

There are broadly three classes of contaminants that we must consider when searching for EM counterparts to GW; stellar variables and flares such as cataclysmic variables (CV); variability in Active Galactic Nucleii (AGN); and supernovae (SNe). The first class of contaminants show a strong dependence on Galactic latitude (Drake et al. 2014), and are concentrated in the disk of the Milky Way. In addition, for at least some CVs a quiescent counterpart will be visible in deep images, or in other cases prior outbursts may have been detected. We hence expect that CVs and other variable stars will be a relatively minor source of contamination for EM counterpart searches. This is further borne out by Smartt et al. (2016), who found only 3 of 49 potential counterparts to GW151226 to be stellar.

AGN can often be identified through their historical lightcurves, which may show previous variability, or through the presence of a cataloged x-ray or radio counterpart. Given the relatively straightforward removal of stellar and AGN contaminants, we are left with SNe as the dominant contaminant. Again, in the case of GW151226 88% of potential counterparts turned out to be SNe. While there are various subtypes of SNe, within a magnitude limited survey around three quarters of events detected will be Type Ia SNe (LOSS REF). This is simply a consequence of Type Ia SNe being much brighter at maximum light ($M \sim -19.3$) than the most common type of core-collapse SNe ($M \sim -16.5$). So, to first order, our main source of contamination when searching for EM counterparts of GW events will be Type Ia SNe.

In order to obtain an approximate estimate of the number of unrelated transients that will be found in a search for an EM counterpart to a GW, we ran Monte Carlo simulations. We took the volumetric Type Ia SN rate from Dilday et al. (2010), and assumed that the GW event could be localised to a region of ∼30 deg^2. We further assumed an optical survey with a cadence of 4 days, a limiting magnitude ∼22 when searching for a kilonova associated with a GW event, and that the kilonova had an

[1] Zhao & Wen (2018) perform their calculations for ET-D which in fact has slightly worse sensitivity for $f \lesssim 5\,\mathrm{Hz}$ than ET-C, cf. Fig. 19 of Pitkin et al. (2011)

[2] There is a pospect for improving LIGO's low-frequency end called LIGO-LF (Yu et al. 2018).

absolute magnitude of $V = 15$ at peak. We then calculated the number of Type Ia SNe that would be above the limiting magnitude threshold of the survey, *and* where the SN would have not been detected on the previous image taken of the field four nights earlier. In addition, we required the SN to have an apparent magnitude within ±1mag of the kilonova. The results of this are shown in Fig. 2, where we find that for a GW at a distance of a few hundred pc, we will typically have four unrelated SNe Ia that are impossible to distinguish from a kilonova solely on the basis of single filter imaging. In the worst case scenarios, we may have as many as ten contaminants that are observationally similar to the kilonova.

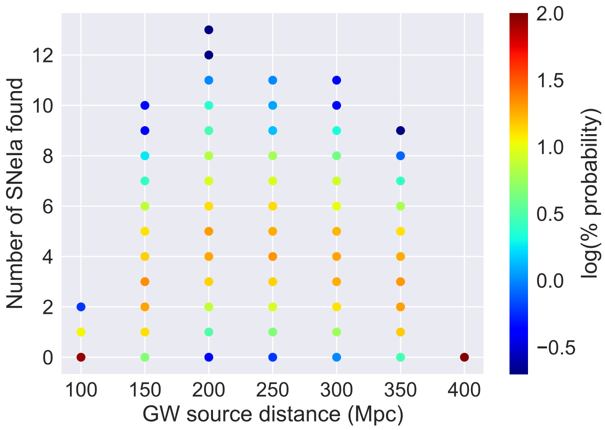

Fig. 2. The probability of finding a particular number of SNe Ia that are likely to be confused with a kilonova, as a function of distance. We assume a survey with a four night cadence, a limiting magnitude of 22, a GW localised to 30 deg^2, and a kilonova with absolute magnitude −15.

This calculation should be taken as an approximate guide, and the exact numbers of contaminants will vary with a number of factors. Higher cadence transient surveys, and better localisation of GW events will reduce the number of contaminants found. On the other hand, simply increasing the depth of a survey will not necessarily improve matters; while some SNe will be detected earlier (and hence ruled out) when their lightcurves are still rising, greater numbers of more distant SNe will also be detected. In any case though, it is reasonable to expect that even in the most favourable scenarios we will always have more than a single plausible candidate counterpart to any future GWs.

3.2. A proposed strategy for EM counterpart detection

We have demonstrated that unrelated SNe Ia will be found within the region to which a GW is localised, and that a few of these are going to appear as new sources with comparable magnitude to a potential kilonova. There are two main reasons why this is a problem. The first is that we will have a finite amount of the 8-m class telescope time required to obtain a spectrum of a counterpart. Taking a low resolution spectrum of a V∼22 source to confirm its nature might take an hour with VLT+FORS2. Obtaining a spectrum of a kilonova and ∼5 unrelated SNe Ia will take commensurately longer.

The second reason why unrelated transients within the GW localisation region is a problem, is that it makes it much harder to obtain spectra of potentially rapidly fading BH+NS mergers, or of the very early (<1 hr) evolution. If we have five sources of comparable magnitude, and it takes ∼1 hr to obtain a spectrum of each, we will only obtain a spectrum of the correct candidate in <1 hr in a minority of cases. The early warning from ET offers a solution to both of these problems. We propose that as soon as sufficient S/N is accumulated to localise a GW to ∼20 deg or better, we take a set of images for that region of the sky *before* the merger occurs. We outline how this would work in practice, using LSST as an example.

The LSST can reach a 5σ limiting magnitude of $r \sim 24.3$ with 2×15 s images. The readout times for each exposure will be 2 s, and as the field of view of LSST is 9.6 deg^2, we will likely be able to cover the entire GW footprint in a small number of pointings. Even allowing 5 minutes for slewing of the telescope, it is likely that obtaining pre-merger images will take at most 10 minutes. Once the merger occurs, then we would take a second set of images. These would be subtracted from the pre-merger template images taken <1 hr before; and the kilonova should be the only thing that has changed over this brief period, making it trivial to identify.

Acknowledgements. S. A. acknowledges support by the EU H2020 under ERC Starting Grant, no. BinGraSp-714626. MF is supported by a Royal Society - Science Foundation Ireland University Research Fellowship.

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