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

Subtitle here if needed

Sarp Akcay[1,2], Antonio Martin-Carrillo[3], and Morgan Fraser[3]

[1] Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, 07743, Jena, Germany
[2] School of Mathematics & Statistics, University College Dublin, Belfield, Dublin 4, Ireland
[3] School of Physics, University College Dublin, Belfield, Dublin 4, Ireland

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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 study will increase by two orders of magnitude in the 2030s with Einstein Telescope, LIGO's European successor. Due to its extreme sensitivity in the $1-10$ Hz regime, the Einstein Telescope's C configuration (ET-C) will be capable of detecting inspiralling binary neutron star systems out to luminosity distances of 1 Gpc. For inspirals within half of this distance ET-C will accumulate signal-to-noise ratios of $\gtrsim 15$ with more than an hour left to merger. However, the localization of ET alone is rather poor: within $z = 0.1$ we expect to have ~ 5 binary neutron stars to be localized to $\Delta\Omega \lesssim 10\,\mathrm{deg}^2$. On the other hand, a second less sensitive gravitational-wave detector (such as future KAGRA) would increase the number of well-localized sources to $O(100)$. Thus it is imperative to have at least one companion detector to ET with significantly improved seismic isolation in the 2030s. Having numerous GW sources localized to $\sim 10\,\mathrm{deg}^2$ opens the possibility of doing detailed follow-up observations of the resulting kilonovae with ATHENA, LSST, BlackGEM ... Here we explore this intriguing possibility... Thus, this letter is an appeal/plea(?) to the astronomy community to have in place ...

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 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. 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 by Advanced LIGO, both 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 be sensitive enough to "pick up" GW sources at a few Hz thanks to its cryogenic design and underground housing which will shield it from low-frequency contaminants such as seismic and gravity-gradient noises. Moreover, 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 1000Mpc with SNRs $\gtrsim 30$ (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.

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 3.5 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 $\sim 10-50$ sq degrees 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 the inspiral GWs 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-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. Sec. 4 ... 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 brief discussion on the effects GWs have on interferometers (IFOs). It is a well known result in general relativity that passing GWs induce 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 $|\tilde{h}(f)| = Ah_0 f^{-7/6}|Q|$, 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

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

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. For each BNS source, this factor may vary by $\approx \pm 30\%$, but will always be > 0 thanks to ET not having any blind spots.

We now use Eq. (3) to provide a precise definition of $T_{\rm AW}$. Keep in mind that the advance warning time is the time interval between the moment of detection and the merger, therefore we must first define the former. We do this 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 moment of detection is given by $\bar{f} > f_0$ such that $\rho_{\rm ET}(f_0, \bar{f}) = 15$. Then we immediately have $T_{\rm AW} = \tau_{\rm insp}(\bar{f})$ and 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: $f_{\rm ISCO} \approx \frac{c^3}{6^{3/2}\pi G(m_1+m_2)} \simeq 1571 \left(\frac{2.8M_\odot}{m_1+m_2}\right)$ 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. The corresponding ASDs scale as $\sqrt{f} f^{-7/6} = f^{-2/3}$ thus are straight lines with slopes of $-2/3$ in the figure. ET-C's noise is the thick, brown curve with highest sensitivity for $f \lesssim 30$ Hz. We can clearly see the frequencies f_0 where the straight lines intersect ET-C's noise curve. We list the advance warning times along with the total SNRs for these four sources in Table 1. We can see that ET-C is capable of providing up to five hours of early warning before a GRB. This begs for the opportunity to electromagnetically observe the merger-GRB-kilonova with available resources we may have in the 2030s. But we should first see if ET can forecast enough BNS events and localize them to make a follow-up campaign worthwhile.

Table 1. Forecasting capabilities of the C configuration of Einstein Telescope summarized. $\bar{f}$ 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.

D (Mpc)	$\bar{f}$ (Hz)	$T_{\rm AW}$ (hours)	$\rho_{\rm tot}$
100	≈ 3.3	5.3	365
200	≈ 4.1	2.9	182
400	≈ 5.1	1.5	90.5
600	≈ 5.7	1.03	60.0

We base our event rate calculations on $R = 1540^{+3200}_{-1220}\,{\rm Gpc}^{-3}\,{\rm yr}^{-1}$ 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 2 along with the redshifts for each distance computed using a flat ΛCDM model ($\Omega_k = 0$) with the latest Planck satellite parameters: $\Omega_\Lambda = 0.6911, \Omega_m = 0.3089, H_0 = 67.74\,{\rm km\,s^{-1}\,Mpc^{-1}}$ (Adam et al. 2016). It is then straightforward to translate D to z [cf. Hogg (1999)].

Table 2. Event rates for various luminosity distances out to 600 Mpc with the corresponding approximate redshifts. The units for R in the table are $D^{-3}\,{\rm yr}^{-1}$. The numbers have been rounded when appropriate. SA: Morgan, should we add apparent magnitude to this table?

D (Mpc)	z	$R_{\rm av}$	$R_{\rm max}$	$R_{\rm min}$
100	0.022	1.5	4.7	0.32
200	0.044	12	38	2.6
300	0.065	42	128	8.6
400	0.085	99	300	20
500	0.10	190	590	40
600	0.12	330	1020	69

We can see from Table 2 that an event as near as GW170817 is a one-per-decade occurence, but within $z \lesssim 0.1$, we can expect ET-C to 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 3 to 40 times yearly with the prospects of observing the birth of kilonovae. If we make the bold assumption that future EM observatories would suffice with an hour's warning then all the 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 as often as 3 times per day. It is not feasible or reasonable to expect a system to be in place to observe each one of these events so it will make sense to be selective and focus on the best candidates which will be the nearby sources. And as we write below, ET's limitations with localisation will act as a selection filter.

Discuss localization

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 ~100 sq degrees 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, 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.

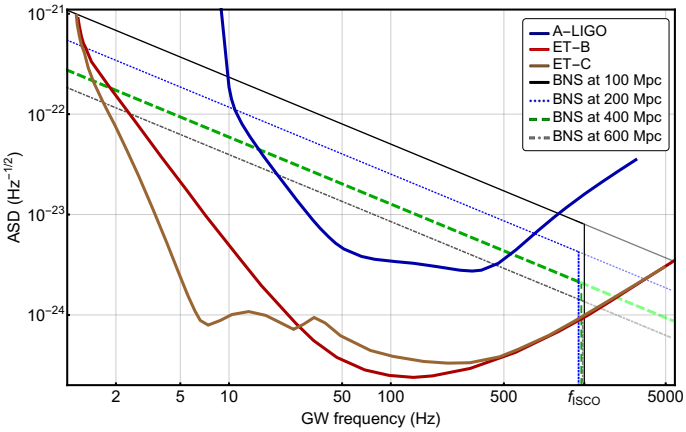

Fig. 1. Typical GW sources that may be harbingers of GRBs in the 2030s: $1.4M_\odot - 1.4M_\odot$ inspiralling BNS systems sweeping across the Einstein Telescope's sensitivity band for both B and C configurations. The solid (black), dotted (blue), dashed (green), and dot-dashed lines (gray) lines are the redshift-corrected angle-RMS-averaged 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. **SA to do:** make ETC thick red, make ETB and ALIGO dashed, bigger x-y labels and tick marks, bigger legend cutoff plot at 2000Hz?

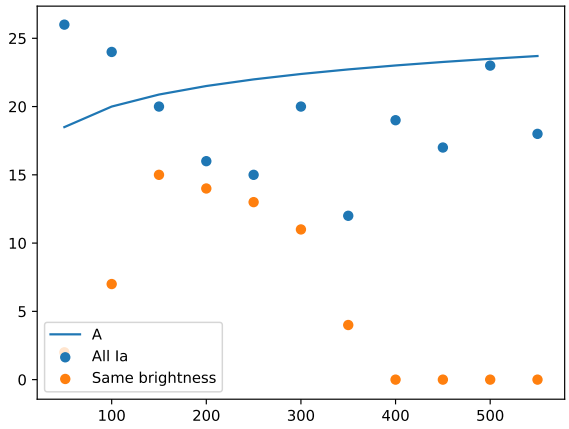

Fig. 2. More or less a placeholder. Number of contaminant SN Ia within our search region as a function of distance...

Morgan: I would suggest repeating this for ~10 deg^2 localisation as well

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 CV outbursts ...

AGN can often be identified through their historical lightcurves, which may show previous variability. Given the relatively straightforward removal of stellar and AGN contaminants, we are left with SNe as the dominant contaminant. Three quarters of SNe are SNe Ia in a mag limited survey (cf LOSS). Also, this is borne out by the experience of Smartt et al. (2016), where they found...

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