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

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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 BNSs 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 Advanced LIGO and the Virgo gravitational wave observatories detected GW170817, with waveform consistent with the merger of two neutron stars (Abbott et al. 2017b). A spatially and temporally coincident short Gamma Ray Burst (GRB) was also seen by the *Fermi* and *INTEGRAL* satellites (Abbott et al. 2017a). This discovery sparked a global effort to find the counterpart of GW170817 at optical wavelengths, which resulted in the identification of AT2017gfo less that 11 hours later (Abbott et al. 2017c). 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 identification of AT2017gfo as the counterpart to GW170817 was enabled by the ability of Advanced LIGO-Virgo to localise the GW signal to $\sim$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 **XXX** Mpc, both as the number of galaxies within the search volume increases, and as the fraction of galaxies with reliable redshifts decreases. This embarassment of the riches becomes a serious obstacle for identifying EM counterparts to GW transients in the 2030s with Einstein Telescope becoming operational (et al. 2011).

Einstein Telescope 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 (**cite?**), i.e., multi-band detector capable of delivering high sensitivities both at low frequencies ($\sim 5\,$Hz) and high frequencies ($\sim 100\,$Hz) as we show in Fig. 1. Here, we focus on the C configuration (ET-C) which offers the highest low-frequency sensitivity. ET-C will detect $\gtrsim O(10^2)$ BNS inspirals out to 1000Mpc with SNRs $\gtrsim 30$. A subset of these sources will be close enough that they will be detected a few hours before their respective mergers (**cite Sarp**) hence opening up the possibility of alerting EM observatories to conduct follow-up observations *before, during* and after the prompt gamma-ray bursts. ET-C may even forecast a few tidal disruption events each year where a neutron star gets tidally torn by a $\sim 5M_{\odot}$, high-spin black hole companion. **Morgan:** should we add more details here such as specific numbers for events/year? I was leaving these for Sec. 2

Something on future GW observatories - introduce Einstein Telescope etc. How many events do we expect to see per year? What at the timescales for these coming online

Something on future wide field survey telescopes - e.g. BlackGEM, GOTO, LSST etc

Discuss search strategies discussed in literature - e.g. weighting by galaxy mass etc. Bottleneck is spectroscopic classification.

Intro to rest of paper. Our novel contribution is that we get an early warning for GWs. Can then use this to get templates immediately prior to the GW detection. Outline rest of section.

2. Einstein Telescope

Table 1. Horizon distances of ET-B and ET-C assuming $T_{\rm AW} = 1\,$hour. $R(D_H)$ is the BNS merger rate within a volume of D_H^3 obtained by rescaling the rate inferred from Advanced LIGO's O1, O2 observing periods citeGW170817. $\bar{\rho}_F(D_H)$ is the total SNR accumulated due to a BNS inspiralling at D_H [see Eq. ()].

	ET-B	ET-C
D_H	87 Mpc	613 Mpc
$R(D_H)$	$1^{+2}_{-1}\,\mathrm{yr}^{-1}$	$355^{+730}_{-280}\,\mathrm{yr}^{-1}$
$\bar{\rho}_F(D_H)$	420	58

3. Implications for optical followup of GW detections

Identifying an optical or 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 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. offers an alternative approach for finding EM counterparts. In brief, if we can detect a GW with $\sim$1 hr advance warning, and can localise it to $\sim$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.

Morgan: I would suggest repeating this for $\sim$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; variability in Active Galactic Nucleii (AGN); and supernovae. The first class of contaminants is dominant when within a few degrees of the Galactic plane, moreover **....** 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 SN 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...

Acknowledgements. SA thanks

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Table 2. Forecasting capabilities of Einstein Telescope summarized. ET-B and ET-C refer to the different configurations shown in Fig. . For the advance warning times, we only present the result of the more accurate 3.5PN computation. $\bar{f}_{\rm ET}$ is the threshold frequency at which ET-B/C accumulate SNR of 15 which we take to be our detection criterion. Note that both $T_{\rm AW}$ and $\bar{\rho}_F$ are larger for ET-C due to its improved sensitivity in the 1 Hz $\lesssim f \lesssim$ 30 Hz regime compared to ET-B as is clear in Fig. . These results and those of Table. are summarized in Fig.

D (Mpc)	ET-B			ET-C		
	$\bar{f}_{\rm ET}$ (Hz)	$T_{\rm AW}$	$\bar{\rho}_F$	$\bar{f}_{\rm ET}$ (Hz)	$T_{\rm AW}$	$\bar{\rho}_F$
100	≈ 6.72	47.0 minutes	306	≈ 3.27	5.34 hours	365
200	≈ 11.2	11.6 minutes	152	≈ 4.10	2.87 hours	182
400	≈ 18.2	3.00 minutes	75.7	≈ 5.06	1.51 hours	90.5
1000	≈ 41.3	17.2 seconds	29.8	≈ 6.76	35.6 minutes	35.6

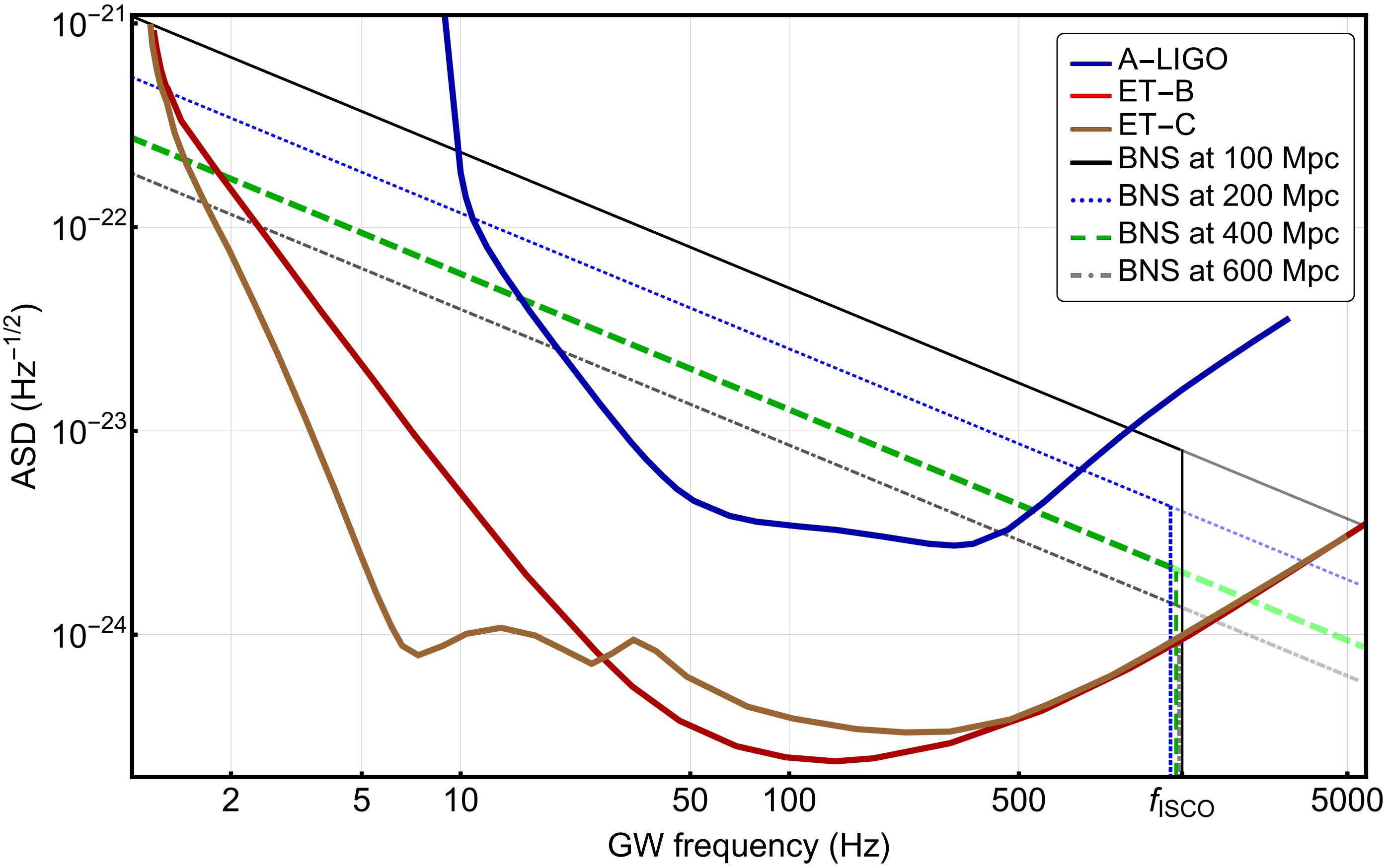

Fig. 1. Typical GW sources that may be harbingers of GRBs in the 2030s: $1.4M_\odot - 1.4M_\odot$ inspiralling BNS systems sweeping across the Einstein Telescope's sensitivity band for both B and C configurations. The solid (black), dotted (blue), dashed (green), and dot-dashed lines (gray) lines are the redshift-corrected RMS-averaged strains, $2\sqrt{f}\tilde{H}_{\rm ET}$, at luminosity distances of D = 100, 200, 400, 1000 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 $f_{\rm ISCO}$ citeMarronetti:2003hx, the inspirals would continue to nearly 2 kHz indicated by the faded lines in the plot (drawn to 5 kHz for aesthetic reasons).

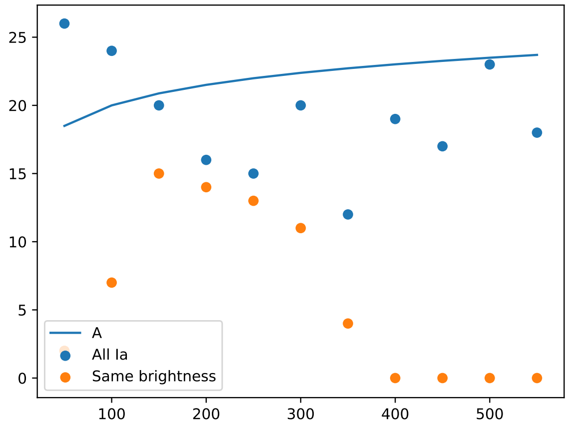

Fig. 2. More or less a placeholder. Number of contaminant SN Ia within our search region as a function of distance...