Early warning of precessing neutron-star black-hole binary mergers with the near-future gravitational-wave detectors

Takuya Tsutsui,1,2,* Atsushi Nishizawa,1 and Soichiro Morisaki3

1Research Center for the Early Universe (RESCEU), Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan
2Department of Physics, Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan
3Department of Physics, University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

Since gravitational and electromagnetic waves from a compact binary coalescence carry independent information about the source, the joint observation is important for understanding the physical mechanisms of the emissions. Rapid detection and source localization of a gravitational wave signal are crucial for the joint observation to be successful. For a signal with a high signal-to-noise ratio, it is even possible to detect it before the merger, which is called early warning. In this article, we estimate the performances of the early warning for neutron-star black-hole binaries, considering the precession effect of a binary orbit, with the near-future detectors such as A+, AdV+, KAGRA+, and Voyager. We find that a gravitational wave source can be localized in 100 deg² on the sky before ~ 10–40 s of time to merger once per year.

Key words: gravitational waves – radiation mechanisms: general – methods: observational – (stars:) gamma-ray burst: general – stars: neutron

1 INTRODUCTION

In 2017, two advanced LIGO (aLIGO) detectors (Aasi et al. 2015; Harry 2010) and advanced Virgo (AdV) (Acernese et al. 2015) detected a gravitational wave (GW) from a coalescence of binary neutron stars (BNS) (Abbott et al. 2017b), dubbed as GW170817. This event was followed up by many electromagnetic (EM) telescopes in broad bands and provided much information on an EM counterpart (Abbott et al. 2017c). From the successful joint observation by GWs and EM waves, the association of a short gamma-ray burst (sGRB) with a merger of BNS was confirmed. Furthermore, there are many benefits for not only sGRB but also the identification of the host galaxy, observations of kilonova (Metzger 2019), measurement of Hubble constant (Schutz 1986) and so on. It is desirable to increase the successful probability of the EM follow-up.

Rapid detection and source localization of a GW signal are crucial for the joint observation to be successful. Then, one of the ways to improve the successful probability is early warning forecasting where and when a binary merger happens (Cannon et al. 2012; Sachdev et al. 2020; Magee et al. 2021). With the alert, one can wait for the merger with EM telescopes pointed there. Then we could observe prompt emission from a BNS merger (Nakar 2007), resonant scattering (Tsang et al. 2012), tidal disruption in neutron-star black-hole (NSBH) binaries (McWilliams & Levin 2011), and so on.

Now there are two aLIGO detectors, AdV, and KAGRA (Somiya 2012), called second-generation (2G) detectors. The 2G detectors can detect GWs but not localize the sources before the merger well (Magee et al. 2021). Those detectors are planned to be upgraded to A+ (Abbott et al. 2016), AdV+ (Degallaix (the Virgo Collaboration) 2018) and KAGRA+ (Michimura et al. 2020) from the O5 observing run starting later than 2025. Furthermore, Voyager (Adhikari et al. 2020) is also planned the construction after 2030. These GW detectors are called 2.5G detectors in this article. They are more sensitive than the current detectors (Fig. 1) so that the early warning by them provides longer time to merger. The early warning of BNS with the 2.5G detectors has been studied (Nitz et al. 2020; Magee & Borhanian 2022). Since the early warning is in the spotlight recently, there are many similar works: early detection with 2G detectors by neural networks (Yu et al. 2021; Baltus et al. 2021; Wei & Huerta 2021), estimations of the performances of early warning with third generation (3G) detectors (Chan et al. 2018; Tsutsui et al. 2021; Nitz & Canton 2021) such as Einstein Telescope (Punturo et al. 2010) and Cosmic Explorer (Abbott et al. 2017a), early warning by consider-
2 ANALYSIS

Non-precessing binaries are frequently considered as GW sources for simplicity. However, in reality, BHs may have non-zero spins. Then a precessing spin induces the amplitude modulation of a GW and help improve the sky localization of a source. We review the GW waveform from a precessing binary in Sec. 2.1. The precession effect is strong for high mass-ratio binaries, and then we consider NSBH binaries. In Sec. 2.2, we estimate the number of NSBH binaries that is strong for high mass-ratio binaries, and then we consider NSBH mergers could be different, we should consider the both possibilities as the targets of the early warning.

The organization of this article is as follows. In Sec. 2, we review waveforms from precessing binaries and the Fisher analysis to estimate the performance of early warning. In Sec. 3, we briefly explain the settings for estimating the performance of early warning for different networks of detectors and discuss the results in Sec. 4, compared with the current EM observations and previous studies on the early warning. Sec. 5 is devoted to a summary.

2.1 Waveform

An analysis in this article to estimate early warning performances is basically same as in (Tsutsui et al. 2021). Thus, we briefly review the waveform in this subsection. The readers can refer to (Tsutsui et al. 2021) for the details.

For ease to read this article, we summarize the independent arguments set for the waveform:

\[ \{ \lambda \} = \{ M, \eta, \chi, t_c, \phi_c, d_L, \theta, \phi, \psi, \theta_j, \kappa, \alpha_0 \}, \]  
(1)

\[ M \] is the chirp mass, \( \eta \) is the symmetric mass ratio, \( \chi \) is the dimensionless spin magnitude of a heavier component (BH), \( t_c \) is the coalescence time, \( \phi_c \) is the coalescence phase, \( d_L \) is the luminosity distance, and \( \theta, \phi \) and \( \psi \) are the longitude and latitude of a GW source, \( \theta_j \) is the inclination angle for the orbital angular momentum, \( \kappa \) is a inner product of unit vectors of the orbital and spin angular momentum and \( \alpha_0 \) is the initial precession angle. We note that the spin magnitude of a lighter component (NS) is neglected here because it is much smaller than \( \chi \) for NSBH binaries. Also, the orbital eccentricity is not considered.

The GW waveform from a precessing compact binary is a product of the amplitude factor and the phase factor for non-precessing case and antenna response factor including the precession effect (see Fig. 1 for the typical spectrum of a GW from the precessing binary):

\[ h_I(f) = Z_I(f) A(f) e^{2i(\Phi_{\text{obs}} - \zeta) + \Phi_{\text{Doppler}}}, \]  
(2)

\[ A(f) = \left( \frac{5\pi}{24} \right)^{1/2} \left( \frac{G^2 M^2}{c^5 d_L} \right) \left( \frac{\pi G M f^{7/6}}{c^3} \right), \]  
(3)

\[ Z_I(f) = (C_+ (\alpha, \beta, \xi) F_{I+, \chi} + C_{\times} (\alpha, \beta, \xi) F_{I, \times}) \]

\[ - i \left( S_+ (\alpha, \beta, \xi) F_{I+, \chi} + S_{\times} (\alpha, \beta, \xi) F_{I, \times} \right) \]  
(4)

The phase factor includes the orbital phase up to 1.5PN from (Will & Wiseman 1996; Tsutsui et al. 2021; Husa et al. 2016; Khan et al. 2016), and the Doppler phase between the \( I \)-th detector at \( \tilde{r}_I \) and the geocenter, \( \Phi_{\text{Doppler}} = -2\pi f f_I \cdot \tilde{n} / c \). The antenna response factor is written by mixtures of the antenna responses for non-precessing one, \( F_{I, +/\times} \), with coefficients originated from precession effect, \( C_{+/\times} \) and \( S_{+/\times} \) (Tsutsui et al. 2021; Lundgren & O’Shaughnessy 2014; Brown et al. 2012; Apostolatos et al. 1994). Although there are three parameters (\( \alpha, \beta, \xi \)) to express the precession effect, the one parameter is defined here because the other parameters are less important to estimate the performance of early warning (Tsutsui et al. 2021):

\[ \beta(v) = \cos^{-1} \left( \frac{1 + \chi \gamma}{\Gamma_j} \right), \]  
(5)

where

\[ \gamma(v) = \frac{|S|}{|L|} = \frac{m_1 \chi}{m_2} v, \]  
(6)

\[ \Gamma_j(v) = \frac{|J|}{|L|} = \sqrt{1 + 2\chi^2 + \chi^2 v^2}, \]  
(7)

\[ \kappa = \frac{\tilde{L}}{|L|} \cdot \frac{\tilde{S}}{|S|}, \]  
(8)

\( v \) is the velocity of the component masses from Kepler law. The frequency dependences of the \( \beta \) for some parameters are in Fig. 2. Since \( \chi = 0 \) or \( \kappa = 1 \) case means non-precessing, \( \beta \) is always zero. We choose 0.5 as our fiducial value of \( \chi \) for our simulated NSBHs. This value is consistent with the estimated primary spin of GW200115 (Abbott et al. 2021b).
Figure 3. The cumulative number of NSBH mergers per year as a function of redshift $z$.

Table 1. $z_{\text{max}}$ and the average number of NSBH mergers per year for the different detector networks. V+ means AdV+ and K+ means KAGRA+.

| network | $z_{\text{max}}$ | the average number of NSBH mergers [1/yr] |
|---------|-----------------|----------------------------------------|
| A+A+V+  | 0.185           | 66.9                                   |
| A+A+V+K+| 0.212           | 99.9                                   |
| 3 Voyagers | 0.517       | 1274                                   |

2.2 Event rate

The number of sources available for the measurement of GW $N$ is estimated here as a function of redshift $z$. The number of sources between redshifts $z$ and $z + dz$ is given by, e.g. (Nishizawa 2016),

$$\frac{dN}{dz} = \frac{4\pi c r(z)^2 \dot{n}(z) T_{\text{obs}}}{(1 + z) H(z)}$$

(9)

where $T_{\text{obs}}$ is the observation time, $\dot{n}(z)$ is the merger rate per unit comoving volume and unit proper time at redshift $z$, $r(z)$ is the comoving distance and $H(z)$ is the Hubble parameter. For the merger rate at $z < 1$, we take a linear evolution,

$$\dot{n}(z) = \dot{n}(0)(1 + 2z),$$

(10)

which is based on the observation of the star formation history and is used in (Nishizawa 2016). For NSBH binaries, we assume $\dot{n}(0) = 30 \, \text{Gpc}^{-3} \text{yr}^{-1}$ (Abadie et al. 2010). The integration of (9) is shown in Fig. 3. A NSBH merger happens 1 per year at $z = 0.05$. For comparison, we show $z_{\text{max}}$ at which SNR = 8 and the number of NSBH mergers for the detector networks in Table 1.

2.3 Fisher analysis

To estimate the parameter errors, we use the Fisher information matrix, $F_{ij}$, defined between $f_{\text{min}} = 5 \, \text{Hz}$ and the innermost stable circular orbit frequency for a Schwarzschild BH, $f_{\text{ISCO}} = \frac{1}{12\sqrt{3}\pi} \frac{G(m_1+m_2)^3}{c^3}$,

$$F_{ij}(f) = 4\Re \int_{f_{\text{min}}}^{f} \frac{\delta_i h^*(f') \delta_j h(f')}{S_n(f')} \, df' + \frac{\delta_{ij}}{(\delta_{kl})^2}.$$  

(11)

1 Recently the merger rate from the observation of NSBH binaries was reported as $\dot{n}(0) = 45^{+55}_{-30} \, \text{Gpc}^{-3} \text{yr}^{-1}$ (Abbott et al. 2021b) when we were preparing the draft. Here we use the previous rate estimated from the population synthesis simulations, but our results hardly change if we take the median rate.

where $\delta_k$ is a partial derivative with respect to the parameter $\lambda_i$. Although $f_{\text{ISCO}}$ ideally depends on $\gamma$ (Jefremov et al. 2015), the dependence can be neglected because our interest is early warning, that is, the low-frequency region of the Fisher matrix $F_{ij}$. We have taken into account the prior effects (the second term) as done in (Tsutsui et al. 2021) where $S_n(f)$ is a power spectral density, $\delta_{ij}$ is the Kronecker delta, and $\delta_{kl}$ is a 1σ error of a Gaussian distribution and is taken as a physical range of the parameter. From the Cramer-Rao inequality (Cutler & Flanagan 1994), the inverse Fisher matrix $F_{ij}^{-1}$ can be recognized as the covariance matrix.

In this article, we quantify the performance of early warning by the 1-sigma statistical errors of the luminosity distance, the sky localization error, $\Delta d_L$ and $\Delta \Omega$, and the number of galaxies in the error volume, $\Delta N$, as functions of time to merger

$$t_c = t = \frac{5}{256}(\pi f)^{-8/3}(\frac{GM}{c^3})^{-5/3},$$

(12)

at the Newtonian order (Maggiore 2008; Creighton & Anderson 2011). The Fisher matrix is calculated for 200 samples with the following choice of fiducial parameters of a spinning BH and a non-spinning NS: the angles, $(\theta, \phi)$ and $(\theta_j, \psi)$, are isotropically sampled. The masses and spins are $\chi = 0.5$, $\kappa = 0$, $m_1 = 7 M_\odot$ and $m_2 = 1.4 M_\odot$. The redshift $z$ is 0.05 from the discussions in Sec. 2.2. In Sec. 3.2, we also consider the performance for other parameters, $\chi = 0.1, 0.2$ and $\kappa = \cos 30^\circ, \cos 45^\circ$, and verify that the estimation errors are not degraded significantly. We consider the 2.5G detectors: A+, AdV+, KAGRA+, and Voyager at Hanford, Livingston and Virgo sites. They are the upgrades of the current detectors at the same sites. Also, as with (Tsutsui et al. 2021), the Earth rotation effect is taken into account, although the observable duration is much shorter than the previous case and the effect is almost negligible.

3 RESULT

3.1 network dependence

Figure 4 are the medians of the network SNR, the sky localization errors $\Delta \Omega$, and distance errors $\Delta d_L$, and the number of galaxies in the error volume $\Delta N$, for the detector networks, (A+, A+, AdV+), (A+, A+, AdV+, KAGRA+), and 3 Voyagers. Since the precession

2 The choice of the number of samples is due to computation time. As the precession effect is not simple, we take ~ 2 days for one network and one parameter set with a reasonable computer. So we have to spend O(a month) in total. Since the estimations are from 200 samples, the results provided in this article have ~ 7% error.
The red dotted line in the network SNR plot represents the precession effect, the sky localization error, the distance error, and the number of galaxies in the error volume. Solid (dashed) lines are without (with) the precession effect. The red dotted line in the network SNR plot represents the SNR threshold for detection at 8. The red dotted lines in the sky localization plot represent the typical field of views of Swift, CTA, and LSST (49000 deg², 70 deg², and 9.6 deg², respectively).

Effect affects the variance of SNR but not the median (the measured relative difference is ≤ 2%), the network SNRs are plotted only for non-precessing cases in Fig. 4. To convert the error volume to the number of galaxies \( \Delta N \), the number density of the galaxies is assumed to be 0.01 Mpc\(^{-3} \) as explained in more detail in (Nishizawa 2017). The time to mergers when \( \Delta \Omega \) and \( \Delta N \) reach typical values are summarized in Table 2.

GW detection alerts are generated when the network SNR exceeds 8 and can be sent out before the merger at 24 s for two A+s and AdV+, 25 s for two A+s, AdV+ and KAGRA+, and 64 s for three Voyagers. At that times, for a precessing (non-precessing) case, the sky localization errors are 323 deg²(625 deg²), 300 deg²(464 deg²), and 423 deg²(1158 deg²), respectively.

In Fig. 4, the estimations with the precession effect are much improved, especially for \( \Delta \Omega \) then \( \Delta N \). However, the improvement for \( \Delta \Omega \) is relatively smaller because \( \Delta \Omega \) has already been well determined by arrival-timing measurements of a GW, and the precession effect does not help much. On the other hand, the degeneracy between the luminosity distance and the inclination angle is broken by precession (Vecchio 2004; Vitale et al. 2014), and then \( \Delta L \) is significantly improved.

Figure 5 is the detection rate for the detector networks, that is, the expected number of the GW sources with the SNR higher than the detection threshold 8. As in the plot of network SNR in Fig. 4, the detection rates are for only a non-precessing case. From Fig. 5, we can find how many events are detectable at a time-to-merger, e.g. the GW events with the detection rate 10 yr\(^{-1} \), which corresponds to \( z \sim 0.1 \) from Fig. 3, can be detected at 3.0 s for A+s and AdV+, 3.7 s for those plus KAGRA+ and 30 s for three Voyagers, before the merger. From the uncertainties of SNRs in 200 samples, the lines in Fig. 5 have the width of distributions (1σ) for the precessing (non-precessing) case; 68% (84%) for A+s and AdV+, 53% (73%) for those plus KAGRA+ and 58% (78%) for three Voyagers.

3.2 Parameter dependence

In the previous subsection, we considered our fiducial set of source parameters. However, in reality, mass and spin parameters have the distributions depending on the astrophysical formation channel and are still highly uncertain (Abbott et al. 2021b). To show parame-
Figure 6. Medians of localization errors with A+ at Hanford and Livingston sites and AdV+ for some parameters. The solid line is for non-precessing case and the dashed lines are for precessing case. The blues are for $(\chi, \kappa) = (0.5, 0)$, the orange for $(0.25, 0)$, the green for $(0.1, 0)$, the purple for $(0.5, \cos 45^\circ)$, pink for $(0.5, \cos 30^\circ)$.

Figure 7. Medians of localization errors with three Voyagers at Hanford, Livingston and Virgo sites for some parameters. The lines and parameters chosen are the same as those in Fig. 6.

ter dependences, we estimate the performances for less-precessing NSBHs with some $\chi$ and $\kappa$.

$\chi$ does not affect the SNR evolutions in our approximated wave-form because it does not appear in GW amplitude. Also, $\kappa$ does not affect the median of the SNR evolution although the variance of SNR is affected (same as Sec. 3.1). Then, the SNR evolutions are same as those in Fig. 4. The estimated performances of $\Delta \Omega$, $\Delta d_L$, and $\Delta N$ are in Fig. 6 and 7. For simplicity, the performances for non-precessing case except for $\chi = 0.5$ and $\kappa = 0$ are omitted in both figures. In both figures, the improvements of $\Delta \Omega$ are almost same because the maximum improvement in the case of $\chi = 0.5$ is not large, that is, the performances for $\Delta \Omega$ are robust even for less-precessing parameters.

For $\Delta d_L$ and $\Delta N$, the result for $(\chi, \kappa) = (0.25, \cos 90^\circ)$ and $(0.5, \cos 30^\circ)$ are almost same with that for $(0.5, \cos 45^\circ)$ and $(0.1, \cos 90^\circ)$, respectively. This is because the time evolutions of $\beta$ for those are almost same between those parameter sets (see Fig. 2). In other word, the improvements for $\Delta d_L$ and $\Delta N$ are proportional to $\beta$, so that we can obtain performances for other parameters from Eq. (5).

Also the component masses can be changed. However, the chirp mass is varied by $\sim 30\%$ in the mass range that EM radiation is expected (Foucart et al. 2018). Then the difference of the performances for the range is $\sim 30\%$ (Tsutsui et al. 2021).

4 DISCUSSIONS

4.1 EM telescopes

Here we compare our results of the sky localization with the field of view (FoV) of typical EM telescopes. The FoV is $\sim 70\,\text{deg}^2$ for CTA-SST (Bartos et al. 2018; Acharyya et al. 2019), $\sim 4900\,\text{deg}^2$ for Swift-BAT (Barthelmy et al. 2005), $\sim 2.6 \times 10^3\,\text{deg}^2$ for Fermi-GBM (Digel & Myers 2001), and $\sim 9.6\,\text{deg}^2$ for LSST (Ivezic et al. 2019). Swift and Fermi are all-sky sweeping surveys. CTA can point to the EM counterpart in $\lesssim 1\,\text{min}$. LSST can tilt by $3.5\,\text{deg}$ in $5\,\text{s}$ and needs $20\,\text{s} - 40\,\text{s}$ for the exposure. From Fig. 4, for the all detector networks, the EM counterpart can be inside the FoV of Swift and
Fermi before \( \sim 100 \) s of the merger. On the other hand, it can be inside that of CTA and LSST before \( O(0.1 - 1) \) s for a non-precessing case and \( O(1 - 10) \) s for a precessing case. Thus, with the early warning for NSBH binary mergers, precursor emissions can be observed before the merger by Swift and Fermi, and prompt emissions and afterglows from sGRB can be observed by CTA and LSST.

So far we have not taken into account latencies produced by the data acquisition of GW detectors and EM telescopes, the detection of a GW signal, and the localization of a GW source. Especially, the parameter inference taking into account the precession effects is computationally costly, and takes around half a day even with a fast method to evaluate likelihood (Smith et al. 2016). The development of a fast localization technique incorporating the precession effect is necessary for early warnings of NSBH events.

4.2 GW Detector networks

In Fig. 4, the results for two A+s and AdV+ are similar to those for two A+s, AdV+, and KAGRA+. However, it does not mean that a fourth detector is unnecessary for multi-messenger observations. The first advantage is duty cycle. The duty cycle that at least three active detectors out of four detectors is much higher than the one that three active detectors out of three detectors, i.e., 51% increases to 82% given a single-detector duty cycle of 80%. The second advantage is multimodality in the sky localization. When three detectors are at work and only the arrival-time differences between detectors are measured, a mirror candidate spot in the sky probability map always appears above/below the plane spanned by the detectors. By adding a fourth detector to the network, a mirror candidate spot can be eliminated. Then EM observers can avoid pointing their telescopes to the fake sky direction. From these two reasons, the fourth detector is important for the multi-messenger astronomy.

4.3 Comparison with previous studies

The similar study on the early warning with the 2.5G detector networks but for BNS has been done in (Nitz et al. 2020). The times of the early warning before merger for \( \Delta \Omega = 100 \text{deg}^2 \) are \( 54 \) s for two A+s and AdV+ and 194 s for three Voyagers. On the other hand, our results for \( \Delta \Omega = 100 \text{deg}^2 \) without the precession effect are 4.2 s for two A+s and AdV+ and 19 s for three Voyagers. Their results are much better than ours. The most dominant reason for the difference is the sources considered. We assume NSBH binaries but they assume BNS. Since the chirp mass of the latter is smaller and its frequency evolution is slower, BNS provide a factor of 4 longer time-to-merger than NSBH binaries, as explicitly seen in (12). There are minor differences which can explain another factor of the difference: the source distance, the credible levels of sky localization error, the sensitivity of Voyager, the detector networks. Since an EM counterpart of NSBH mergers is different from that of the BNS merger, we should consider them as targets for the early warning.

For 3G detectors that will start observations from the mid in 2030s, the early warning for NSBH binary coalescences at \( z = 0.1 \) can be done typically with the times to merger of 12 – 15 minutes and 50 – 300 seconds when the sky localization areas reach 100 deg\(^2\) and 10 deg\(^2\), respectively (Tsutsui et al. 2021). In addition, not only \( \Delta t_L \) but also \( \Delta \Omega \) are significantly improved due to the precessing effect. This is because the sensitive frequency band of the 3G detectors is much broader than that of the 2.5G detectors, particularly at lower frequencies, and allows us to observe NSBH binaries for \( \sim 8 \) hours. Then the Earth rotation and precession effects can break parameter degeneracies much more efficiently.

5 CONCLUSION

The combination of GW and EM observations can provide much information about the source. Rapid detection and source localization of a GW signal are crucial for the joint observation to be successful. It can be done by early warning which forecasts where and when a binary merger happens before the merger (Cannon et al. 2012; Sachdev et al. 2020; Magee et al. 2021). We estimate the performances of the early warning for some detector networks from A+s, AdV+, KAGRA+ and Voyager for precessing and non-precessing NSBH binaries. As a result, we found that the direction can be known with \( \Delta \Omega = 100 \text{deg}^2 \) in \( \sim 10 \) s–40 s before the merger. The improvement by considering the precession effect is about a factor \( \sim 2 \) for the sky localization error but \( \sim 10 \) for the distance error. Therefore the number of galaxies in the error volume is much reduced by considering the precession.

ACKNOWLEDGMENTS

T. T. is supported by International Graduate Program for Excellence in Earth-Space Science (IGPEES). A. N. is supported by JSPS KAKENHI Grant Nos. JP19H01894 and JP20H04726 and by Research Grants from Inamori Foundation. S. M. is supported by NSF PHY-1912649.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

REFERENCES

Aasi J., et al., 2015, Classical and Quantum Gravity, 32, 074001
Abadie J., Abbott B. P., et al., 2010, Classical and Quantum Gravity, 27, 173001
Abbott B. P., et al., 2016, Living Reviews in Relativity, 19
Abbott B. P., et al., 2017a, Classical and Quantum Gravity, 34, 044001
Abbott B., et al., 2017b, Physical Review Letters, 119
Abbott B. P., et al., 2017c, Astrophys. J., 848, L12
Abbott R., Abbott T. D., et al., 2020, The Astrophysical Journal, 896, L44
Abbott R., Abbott T. D., et al., 2021a, GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run (arXiv:2111.03606)
Abbott R., Abbott T. D., et al., 2021b, The Astrophysical Journal Letters, 915, L5
Acernese F., et al., 2015, Classical and Quantum Gravity, 32, 024001
Acharyya A., Agudo I., et al., 2019, Astroparticle Physics, 111, 35
Adhikari R. X., et al., 2020, Classical and Quantum Gravity, 37, 165003
Apostolatos T. A., Cutler C., Sussman G. J., Thorne K. S., 1994, Phys. Rev. D, 49, 6274
Baltus G., Januart J., Lopez M., Reza A., Caudill S., Cudell J.-R., 2021, Phys. Rev. D, 103, 102003
Barthelmy S. D., et al., 2005, Space Science Reviews, 120, 143–164
Barto S. J., et al., 2018, Monthly Notices of the Royal Astronomical Society, 477, 639–647
Brown D. A., Lundgren A., O’Shaughnessy R., 2012, Phys. Rev. D, 86, 064020
Cannon K., Cariou R., et al., 2012, The Astrophysical Journal, 748, 136
Chan M. L., Messenger C., Heng I. S., Hendry M., 2018, Phys. Rev. D, 97, 123014
Creighton J. D. E. J. D. E., Anderson W. G., 2011, Gravitational-wave physics and astronomy: an introduction to theory, experimental and data analysis. Wiley-VCH, http://sci.nii.ac.jp/neid/BB07081613

MNRAS 000, 1–7 (2021)
Cutler C., Flanagan E. E., 1994, Phys. Rev. D, 49, 2658
Degallaix (the Virgo Collaboration) J., 2018, Advanced Virgo+ preliminary studies, https://tds.virgo-gw.eu/?content=3r=14287
Digel S., Myers J. D., 2001, GLAST: Exploring Nature’s Highest Energy Processes with the Gamma-ray Large Area Space Telescope, NASA STI/Recon Technical Report N
Foucart F., Hinderer T., Nissanke S., 2018, Phys. Rev. D, 98, 081501
Harry G. M., 2010, Classical and Quantum Gravity, 27, 084006
Husa S., Khan S., Hannam M., Pürrer M., Ohme F., Forteza X. J., Bohé A., 2016, Phys. Rev. D, 93, 044006
Ivezić Ž., et al., 2019, The Astrophysical Journal, 873, 111
Jeffremov P. I., Tsupko O. Y., Bisnovatyi-Kogan G. S., 2015, Phys. Rev. D, 91, 124030
Kapadia S. J., Singh M. K., Shaikh M. A., Chatterjee D., Ajith P., 2020, The Astrophysical Journal, 898, L39
Khan S., Husa S., Hannam M., Ohme F., Pürrer M., Forteza X. J., Bohé A., 2016, Phys. Rev. D, 93, 044007
Lundgren A., O’Shaughnessy R., 2014, Phys. Rev. D, 89, 044021
Magee R., Borhanian S., 2022, Realistic observing scenarios for the next decade of early warning detection of binary neutron stars (arXiv:2201.11841)
Magee R., Chatterjee D., et al., 2021, First Demonstration of Early Warning Gravitational-wave Alerts, doi:10.3847/2041-8213/abed54, https://doi.org/10.3847/2041-8213/abed54
Maggiore M., 2008, Gravitational Waves: Volume I: Theory and Experiments. Gravitational Waves, OUP Oxford, https://books.google.co.jp/books?id=AqVpQgAACAAJ
McWilliams S. T., Levin J., 2011, The Astrophysical Journal, 742, 90
Metzger B. D., 2019, Living Reviews in Relativity, 25
Michimura Y., Komori K., et al., 2020, Phys. Rev. D, 102, 022008
Nakar E., 2007, Physics Reports, 442, 166
Nishizawa A., 2016, Phys. Rev. D, 93, 124036
Nishizawa A., 2017, Phys. Rev. D, 96, 101303
Nitz A. H., Schäfer M., Canton T. D., 2020, The Astrophysical Journal, 902, L29
Punturo M., et al., 2010, Classical and Quantum Gravity, 27, 194002
Sachdev S., Magee R., et al., 2020, An Early-warning System for Electromagnetic Follow-up of Gravitational-wave Events, doi:10.3847/2041-8213/abc753, https://doi.org/10.3847/2041-8213/abc753
Schutz B., 1986, Nature, 323, 310
Singh M. K., Kapadia S. J., Shaikh M. A., Chatterjee D., Ajith P., 2021, Monthly Notices of the Royal Astronomical Society, 502, 1612–1622
Smith R., Field S. E., Blackburn K., Haster C.-J., Pürrer M., Raymond V., Schmidt P., 2016, Phys. Rev. D, 94, 044031
Somiya K., 2012, Classical and Quantum Gravity, 29, 124007
Tsang D., Read J. S., Hinderer T., Piro A. L., Bondarescu R., 2012, Phys. Rev. Lett., 108, 011102
Tsutsui T., Nishizawa A., Morisaki S., 2021, Physical Review D, 104
Vecchio A., 2004, Physical Review D, 70
Vitale S., Lynch R., Veitch J., Raymond V., Sturani R., 2014, Physical Review Letters, 112
Wei W., Huerta E., 2021, Physics Letters B, 816, 136185
Will C. M., Wiseman A. G., 1996, Physical Review D, 54, 4813–4848
Yu H., Adhikari R. X., Magee R., Sachdev S., Chen Y., 2021, arXiv e-prints, p. arXiv:2104.09438

This paper has been typeset from a TeX/LaTeX file prepared by the author.