Probe for Type Ia Supernova Progenitor in Decihertz Gravitational Wave Astronomy

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Abstract

It is generally believed that Type Ia supernovae are thermonuclear explosions of carbon–oxygen white dwarfs (WDs). However, there is currently no consensus regarding the events leading to the explosion. A binary WD (WD–WD) merger is a possible progenitor of Type Ia supernovae. Space-based gravitational wave (GW) detectors with considerable sensitivity in the decihertz range such as the DECi-hertz Interferometer Gravitational wave Observatory (DECIGO) can observe WD–WD mergers directly. Therefore, access to the decihertz band of GWs would enable multi-messenger observations of Type Ia supernovae to determine their progenitors and explosion mechanism. In this paper, we consider the event rate of WD–WD mergers and to determine the masses of binary mergers. We estimate that a decihertz GW observatory can detect GWs with amplitudes of \( h \sim 10^{-20} \) [Hz\(^{-1/2}\)] at 0.01–0.1 Hz, which is 1000 times higher than the detection limit of DECIGO. Assuming the progenitors of Ia supernovae are merging WD–WD (1 \( M_\odot \) and 0.8 \( M_\odot \)), DECIGO is expected to detect 6600 WD–WD mergers within \( z = 0.08 \), and identify the host galaxies of such WD–WD mergers within \( z \sim 0.065 \) using GW detections alone.

Unified Astronomy Thesaurus concepts: Gravitational wave astronomy (675); Type Ia supernovae (1728)

1. Introduction

Advanced LIGO have detected gravitational waves (GWs) from compact binary mergers. These GWs have revealed the existence of massive stellar black holes, and the origin of r-process elements and short gamma-ray bursts (Abbott et al. 2016a, 2016b, 2017). We are at the dawn of GW astronomy. Ground GW detectors such as advanced LIGO, advanced VIRGO, and KAGRA cover 10–100 Hz. LISA is designed to detect millihertz GWs and will launch during the 2030s (Amaro-Seoane et al. 2017, 2022). The design sensitivity of LISA is \( h \sim 10^{-20} \) [Hz\(^{-1/2}\)] at 0.01 Hz. DECIGO and B-DECIGO, a test version of DECIGO, fill the gap between current ground GW detectors and LISA (Seto et al. 2001; Nakamura et al. 2016). The main target of DECIGO is measuring the stochastic GW background from the early universe. The design sensitivities of DECIGO and B-DECIGO are \( h \sim 10^{-23}–10^{-24} \) [Hz\(^{-1/2}\)] and \( h \sim 10^{-22}–10^{-23} \) [Hz\(^{-1/2}\)] at 0.1–10 Hz, respectively. These sensitivities are very useful to detect high-redshift binary black hole mergers and check the origin of massive stellar binary black holes (e.g., Kinugawa et al. 2014; Belczynski et al. 2016; Kinugawa et al. 2016; Nakamura et al. 2016; Kinugawa et al. 2020; Tanikawa et al. 2022). Furthermore, the GWs from a white dwarf–white dwarf (WD–WD) merger is also \( \sim 0.01–0.1 \) Hz (Dan et al. 2011; Mandel et al. 2018). Thus, WD–WD mergers will become interesting science targets of DECIGO (Seto et al. 2001; Mandel et al. 2018) and other 0.1 Hz GW detectors such as B-DECIGO (Nakamura et al. 2016), TianGO (Kuns et al. 2020), DO (Arca Sedda et al. 2020), and AMIGO (Ni et al. 2020).

WD–WD mergers are one of the most promising candidates of Ia supernova progenitors. Although Ia supernovae have considerable significance as distance indicators in cosmology, many fundamental aspects of their evolution and explosion are still under debate (see the recent review by Ruiter 2020). It is widely accepted that the Ia supernova progenitor system is a carbon–oxygen (C–O) WD in an interacting binary star. However, the nature of the companion star and the WD mass are unclear. The companion star can be a nondegenerate star (main sequence, giant-like, or stripped helium-burning star), or another WD, also known as single degenerate (SD) and double degenerate (DD) scenarios, respectively. The WD mass can be near the Chandrasekhar limit, \( \sim 1.4 M_\odot \) (Chandrasekhar-limit explosion), or below the limit (sub-Chandrasekhar-limit explosion). For the SD scenario with a Chandrasekhar-limit explosion, the WD approaches the Chandrasekhar limit via mass transfer from its nondegenerate companion star (e.g., Whelan & Iben 1973; Nomoto 1982a; Hachisu et al. 1996). For the SD scenario with a sub-Chandrasekhar-limit explosion, a C–O WD accretes helium-rich material from its companion helium star, and initiates a double detonation explosion in which helium detonation on the WD surface leads to detonation of carbon in the WD core (Nomoto 1982b; Woosley et al. 1986; Livne 1990).

The DD scenario with a Chandrasekhar-limit explosion can cause tidal disruption of the lighter WD followed by thermal mass accretion onto the heavier WD (e.g., Iben & Tutukov 1984; Webbink 1984). For the DD scenario with a
sub-Chandrasekhar-mass explosion, three things can occur. First, a dynamical merger of the two C–O WDs initiates carbon detonation directly, referred to as a carbon-ignited violent merger (e.g., Pakmor et al. 2010; Sato et al. 2015). Second, it can result in another explosion mode known as spiral instability (Kashyap et al. 2015, 2017). Lastly, dynamical mass accretion onto the heavier C–O WD from the lighter helium-rich WD triggers a double detonation explosion, referred to as a helium-ignited violent merger or a dynamically driven double-degenerate double detonation (D6) (e.g., Fink et al. 2010; Guillochon et al. 2010; Woosley & Kasen 2011; Pakmor et al. 2013; Shen & Bildsten 2014). In the DD scenario with a Chandrasekhar explosion, a Ia supernova may occur ∼100 yr or more after the WD–WD merger due to slow mass accretion. Conversely, in the DD scenario with a sub-Chandrasekhar-mass explosion, a Ia supernova occurs promptly around the time of the WD–WD merger. Thus, if a sub-Chandrasekhar-mass explosion occurs, the WD–WD merger will emit GW and electromagnetic (EM) signals at the same time, which can be a promising target for multi-messenger astronomy. This can be applied to identifying progenitors of subclasses of Ia supernovae.

In this paper, we consider the event rate of WD–WD mergers and the minimum detection range to observe one WD–WD merger per year, using a nearby galaxy catalog and the relation between Ia supernovae and their host galaxies (Section 2). Furthermore, we investigate the observational performance of DECIGO for WD–WDs via parameter estimation of the inspiral GWs produced from WD–WD mergers. Mainly, we evaluate the detection rate and the ability of these detectors to localize WD–WD mergers and to determine the masses of binary mergers (Sections 3, 4, and 5). Throughout this paper, we use CGS units except for Section 3.

2. Event Rate of WD–WD Mergers

In order to estimate the WD–WD merger rate, we assume that all Ia supernova progenitors are WD–WD mergers. Note that this assumption ignores the possibility of the SD case. However, Maoz et al. (2018) shows that the expected WD–WD merger rate in the Milky Way is 4.5–7 times more than its specific Ia supernova rate. Thus, the WD–WD merger rate from our assumption might be smaller than the actual value.

The Ia supernova rate at z ∼ 0 is

\[(0.301 \pm 0.062) \times 10^{-4} \text{ SN yr}^{-1} \text{ Mpc}^{-3}, \]

determined from the Lick Observatory Supernova Search (LOSS) (Li et al. 2011). We use this value as the fiducial rate of WD–WD mergers to estimate the detection rate in this paper. However, this rate is the averaged volumetric rate of Ia supernovae. The relation between WD–WD mergers and Ia supernovae can be confirmed by the early detection of the first GW from a WD–WD merger and its EM counterpart. This is similar to GW170817, where the relation between binary neutron star mergers and short gamma-ray bursts + kilonovae was revealed (Abbott et al. 2017). We need to determine the minimal detection volume to detect a WD–WD merger per year in nearby galaxies. There are many studies on the rate–size relation of Ia supernova host galaxies (e.g., Sullivan et al. 2006; Totani et al. 2008; Li et al. 2011; Childress et al. 2014; Graur et al. 2015), and these results indicate a relation between the Ia supernova rate and the stellar mass of their host galaxies. In order to estimate the event rate of Ia supernova near our galaxy, we consider the rate–size relation of Ia supernova host galaxies (Li et al. 2011) and the catalog of nearby galaxies within 11 Mpc (Karachentsev et al. 2013). The rate–size relation is

\[ \text{SNe} M = \text{SNe} M (M_0) \times \left( \frac{M_\ast}{10^{10} M_\odot} \right)^{\text{RSS}}, \] (2)

where SNeM, SNeM(M0), and RSS are the Ia supernova rate per century per 1010M⊙, the normalization value, the stellar mass of the galaxy, and the power-law index, respectively. Li et al. (2011) obtained −0.513 ± 0.316, −0.503 ± 0.158, −0.637 ± 0.199, −0.555 ± 0.171, −0.443 ± 0.241, −0.329 ± 0.201, and −0.435 ± 0.195 as RSSs for E, S0, Sa, Sb, Sbc, Sc, and Scd galaxies, respectively. The combined significance with RSS = −0.5 and SNeM(M0) = 0.25 for E, S0, Sa, Sb, Sbc, Sc, and Scd galaxies is −7.4σ (Li et al. 2011). Thus, we adopt −0.50 and 0.25 as RSS and SNeM (M0) in our rate calculations, respectively.

We use the galaxy catalog of Karachentsev et al. (2013) in order to get the stellar masses of nearby galaxies. In this catalog, there are data on 1209 galaxies within 11 Mpc and 951 galaxy masses or lower limits. Figure 1 shows the stellar mass distribution of nearby galaxies. In the case of galaxies whose masses are \( \lesssim 10^{5} M_{\odot} \), we use the lower limits of the galaxy masses as the galaxy stellar masses.

We calculate the Ia supernova rate for each nearby galaxy using Equation (2) and the stellar masses of nearby galaxies from the cataloged data, and then take the sum of the Ia supernova rate in nearby galaxies within 11 Mpc. The summation of the Ia supernova rate in nearby galaxies is

\[ 0.85 \text{ yr}^{-1}. \] (3)

This rate shows that approximately one Ia supernova will occur about once a year in nearby galaxies. If the detection range of a GW detector in the ∼0.01–0.1 Hz band is more than 11 Mpc, a combination of EM observation of supernova and GW observation can be used to determine whether Ia supernova progenitors are WD–WD mergers or not.

3. Gravitational Waveform for Inspiring Binary White Dwarf

In this section, we use c = G = 1. In general relativity, the detector signal of a GW from an inspiraling binary system in
the time domain can be written as (Berti et al. 2005; Maggiore 2007)

$$h(t) \simeq \frac{2m_1 m_2}{r_r(t) d_L} \mathcal{A}(t) \cos(\int_{t'} f_{gw}(t') dt' + \phi_p(t) + \phi_D(t)). \tag{4}$$

where $m_1$ and $m_2$ are the masses of the binary stars, $r_r(t)$ is the orbital relative distance, $d_L$ is the luminosity distance to the binary system, $f_{gw}$ is the frequency of the GW, and $\phi_D(t)$ is the Doppler phase. $\mathcal{A}(t)$ and $\phi_p(t)$ are defined by

$$\mathcal{A}(t) := \sqrt{(1 + \cos^2 \iota)^2 F^+(t)^2 + 4 \cos^2 \iota F^x(t)^2}, \tag{5}$$

$$\phi_p(t) := \arctan\left(\frac{2 \cos \iota F^x(t)}{(1 + \cos^2 \iota) F^+(t)}\right). \tag{6}$$

where $\iota$ is the inclination angle of the binary system. Here, $F^+(t)$ is the antenna pattern functions for the plus polarization mode, and $F^x(t)$ is that for the cross mode (Nishizawa et al. 2009).

As $(2m_1 m_2)/(r_r(t) d_L)$, $\mathcal{A}(t)$, $\phi_p(t)$, and $\phi_D(t)$ vary in time slowly compared to $f_{gw}(t') dt'$, we can calculate the Fourier component $\tilde{h}(f)$ of the detector signal $h(t)$ by the stationary phase approximation (Cutler 1998; Berti et al. 2005; Arun 2006; Maggiore 2007; Takeda et al. 2019)

$$\tilde{h}(f) = A f^{-7/6} e^{i \Psi(f)} G_T(t(f)), \tag{7}$$

with the GW amplitude $A$ and the phase $\Psi(f)$. The geometrical factor for tensor modes $G_T$ is defined by

$$G_T(t) := \frac{5}{4} \mathcal{A}(t) e^{i(\phi_p(t) + \phi_D(t))}. \tag{8}$$

$t(f)$ gives the relation between the time to coalesce and the frequency of the GW before merger (Damour et al. 2001, 2002; Maggiore 2007), which is defined by the condition $f = f_{gw}(t(f))$

$$t(f) := t_c - \frac{5}{256} M^{-5/3}(\pi f)^{-8/3}, \tag{9}$$

where $M = (m_1 m_2)^{3/5}(m_1 + m_2)^{-1/5}$ is the chirp mass and $t_c$ is the coalescence time.

We adopt the inspiral waveform up to Newtonian order in amplitude $A$ and 2.5 post-Newtonian (PN) order in phase $\Psi(f)$ (Santamaria et al. 2010; Khan et al. 2016)

$$A f^{-7/6} = \frac{1}{\sqrt{30 \pi^{5/3}}} M f^{-7/6}, \tag{10}$$

and

$$\Psi(f) = 2 \pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128}(\pi M f)^{-5/3} \sum_{i=0}^{5} \phi_i (\pi M f)^{i/3}, \tag{11}$$

where $\phi_c$ is the phase at the coalescence time and $\phi_i$ are PN coefficients. The amplitude is kept up to the Newtonian order because of the consistency with the order in Equation (9). The binary eccentricity is not considered for simplicity because WD–WDs are expected to have circular orbits due to tidal interactions (Willems et al. 2007; Rui et al. 2010). It has been reported that the deformations due to filling the Roche lobe or the existence of an accretion disk induce typical differences at the level of one percent or less for semi-detached WD–WDs with respect to the average strain amplitude (van den Broek et al. 2012). For WD–WDs whose rotations are synchronized with the orbital motion, it has been reported that finite size effects and a certain universal relation are helpful to identify the individual masses of binary WDs (Wolz et al. 2021). The effects of mass transfer and tidal effects just before merger are studied by Kremer et al. (2017) and McNeill et al. (2020), respectively. However, the chirp effect is larger in the decihertz band because WD–WDs can be observed until just before the merger. Therefore, we concentrate on the mass and position information that can be extracted from the inspiral chirp signal alone, and ignore these effects of the WDs for the sake of generality.

4. Parameter Estimation

In order to investigate the possibility of identifying the properties of WD–WDs as a progenitor of Ia supernova in decihertz GW astronomy, we conducted parameter estimation using a Fisher analysis (Finn 1992; Cutler & Flanagan 1994). A Fisher information matrix gives the Cramer–Rao bound of the system’s parameters. In other words, a Fisher information matrix tells us how precisely we can determine the model parameters by observations under a strong signal and Gaussian noise assumptions. The Fisher information matrix $\Gamma$ is calculated by

$$\Gamma_{ij} := 4 \Re \int_{t_{\text{min}}}^{t_{\text{max}}} df \sum_l \left( \frac{\partial r^i_l(f)}{\partial \lambda^j} \right)^2, \tag{12}$$

where $r^i_l(f)$ is the $l$th detector noise power spectrum and $\lambda^i$ is the $i$th binary parameter. The inverse of the Fisher information matrix gives the rms error of the parameter $\Delta \lambda^i$, calculated by

$$\langle \Delta \lambda^i \rangle_{\text{rms}} := \sqrt{\langle \Delta \lambda^i \Delta \lambda^j \rangle} = \sqrt{\langle \Gamma^{-1} \rangle}^{ij}, \tag{13}$$

where $\Delta \lambda^i$ is the measurement error of $\lambda^i$ and $\langle \cdot \rangle$ denotes ensemble average. Then, the sky localization error is defined by

$$\Delta \Omega_s := 2 \pi \sin \theta \sqrt{\langle \Delta \theta \rangle^2 + \langle \Delta \phi \rangle^2} \tag{14}$$

Hereafter, we simply refer to $(\Delta \lambda^i)_{\text{rms}}$ as $\Delta \lambda^i$, and call it the estimation error of $\lambda^i$.

In total, we have 11 model parameters in general relativity

$$(\log M, \log \eta, t_c, \phi_c, \log d_L, \chi_s, \chi_a, \theta_c, \phi_s, \cos \iota, \psi_p), \tag{15}$$

where $\log \eta, \chi_s, \chi_a$ are the logarithm of the symmetric mass ratio $\eta = m_1 m_2/(m_1 + m_2)^2$, the symmetric and the antisymmetric spin parameter, respectively. The fiducial values of $t_c, \phi_c, \chi_s, \chi_a$ are set to zero. We impose flat priors on the range of allowed values for $\log \eta, \phi_s, \cos \iota, \psi_p$, and spin parameters $(\chi_s, \chi_a)$.

We set the upper cutoff frequency to the frequency at the coalescence time. Here, we roughly give the frequency at which the distance between the WDs is equal to the sum of the WD radius

$$f_{\text{max}} \simeq \frac{1}{\pi} \sqrt{\frac{GM_{\text{tot}}}{(R_1 + R_2)^3}}, \tag{16}$$

from Kepler’s 3rd law. The mass–radius relation for WDs is given by the equilibrium condition for the gravitational pressure and electron pressure (Koester & Chanmugam 1990). For calculation of the upper cutoff frequency, we adopt the
following mass–radius relation

\[ R_* \sim 0.011 \left( \frac{M_*}{M_\odot} \right)^{-1/3} \frac{R_\odot}{M_*}, \]  

based on the fitting of the observational data given by Magano et al. (2017). Once the upper cutoff frequency is determined, the lower cutoff frequency is obtained by the integration time or the observational time using Equation (9). The plotted detector sensitivities are the root of the power spectral densities of their design sensitivities. The GW strains are plotted from an equivalent source amplitude of inspiral GW strains for equal-mass WD–WDs having three different masses together with the spectral strain sensitivities of decihertz GW telescopes. The plotted detector sensitivities are the root of the power spectral densities of their design sensitivities. The GW strains are plotted from an equivalent source amplitude of 2f^{1/2}|\tilde{h}(f)| (Moore et al. 2015). The circle points denote the upper cutoff frequency, the diamond points correspond to 10 yr before coalescence, and the triangle points correspond to 3 yr before coalescence, which are calculated from the time of merger and Equation (9). Compared to the GWs from compact binary mergers such as black holes and neutron stars observed at present by the ground-based detectors, the GWs from WD–WDs are almost monochromatic. However, we observe a slight frequency sweep effect in the decihertz band compared to that in the LISA band.

We evaluated the estimation errors of the WD–WD parameters using a Fisher analysis with DECIGO as a representative decihertz GW detector. We assume that DECIGO is composed of three interferometers sharing arms and has its design sensitivity. We also assume that its orbit is heliocentric. The low-frequency approximation can be applied in all following calculations because the transfer frequency of the detector is \( f_a := c/(2\pi L) \approx 48 \text{ Hz} \), corresponding to an arm length of \( L = 1000 \text{ km} \). Thereby, we ignore the transfer function in the antenna pattern functions (Romano & Cornish 2017). Unless otherwise noted, we conduct parameter estimation for 100 binary systems whose distances are fixed to 11 Mpc, within which about one type Ia SN event is expected per year from Equation (3). to estimate the typical but conservative values of the expected errors. We mainly show the median values of the estimated errors for such multiple sources when the angular parameters (\( \cos \theta^*, \phi^*, \cos \iota, \psi^* \)) are randomly distributed.

5. Results

5.1. Full Period Observation

First, we consider full observations during a 3 yr operation period. Figures 3 and 4 show the fractional errors for the primary and the secondary WD component masses estimated by the Fisher analysis, respectively. The errors are estimated using 100 sources whose angular parameters are random for each mass combination by varying the component mass from 0.4 \( M_\odot \) to 1.3 \( M_\odot \) in 0.1 \( M_\odot \) intervals, and the median values are shown in the color maps. The minimum median value of the signal-to-noise ratio (S/N) is 9.59 for 0.4 \( M_\odot \)–0.4 \( M_\odot \) WD binaries and the maximum median value is 1240 for 1.3 \( M_\odot \)–1.3 \( M_\odot \) WD binaries. The results show that the mass ratio can be measured, and then the WD component mass can be identified in most of the \( m_1 – m_2 \) parameter space. The errors of the secondary WDs are almost the same, slightly smaller than those of the primary WDs. As the chirp mass is very well determined from the phase of the waveform, the error of the component mass is determined by the error of the mass ratio. If
the mass of the primary WD is fixed, as the mass of the secondary WD decreases, the signal moves to a lower frequency band and the chirp effect decreases. As a result, the correlation among the chirp mass $M$, the mass ratio $q$, the coalescence time $t_c$, and the R.A. $\phi$ increases, and the error of the mass ratio tends to increase. Nevertheless, for WD–WDs containing a WD with the mass heavier than 0.8 $M_\odot$, the masses were found to be determined with better than $\sim 10\%$ precision even from the chirp effect alone. We found the best fractional error of $\sim 0.3\%$ for masses of $1.3 M_\odot$ to $0.6 M_\odot$.

Figure 5 shows the median values of the sky localization errors. It indicates that the more massive the mass, the smaller the error. The WD–WDs can be localized with a precision better than $\sim 5 \text{ deg}^2$ even for masses less than 0.8 $M_\odot$. The same trend as shown in Figure 5 was observed for $d_L$. We found that the luminosity distance can be determined with a precision better than 26%. Therefore, the WD–WDs can be localized with the 3D localization volume better than $\Delta V = d_L^3 \Delta \log d_L \Delta \Omega_b \sim 0.5 \text{ Mpc}^3$. In particular, for the WD–WDs containing a WD with one mass heavier than 0.8 $M_\odot$, we can determine the masses with a precision better than $\sim 10\%$, and the position with the 3D localization volume better than $\sim 1 \times 10^{-3} \text{ Mpc}^3$.

5.2. For Multi-messenger Observations

Next, we analyze how the determination precisions change with the different observation times for multi-messenger observations. As one example, we consider the $1 M_\odot$–$0.8 M_\odot$ WD–WD case at 11 Mpc. We change the upper cutoff frequency before coalescence and calculate the parameter estimation errors for 100 WD–WDs whose angular parameters are random, whereas the lower cutoff frequency is fixed to 3 yr before coalescence. Figure 6 shows the dependence of the median value of the estimation errors on the observation times. GWs emitted by WD–WDs are regarded as almost monochromatic waves. The S/N increases as $S/N^2 \sim h_{\text{amp}} T / S_\odot(f)$. Thus, the errors such as $\Delta m_1$ and $\Delta d_L$ seem to improve in proportion to $T^{-1/2}$, but in comparison, the actual errors are worse for shorter observation periods. This is owing to the fact that the chirp effect becomes smaller for shorter observation periods, and the correlations among the mass ratio and other parameters mentioned above become larger, resulting in stronger parameter degeneracy. If we measure for at least two years, from three years to one year before the coalescence, we can determine in advance the masses of the WDs with a precision better than 10% and its position with the 3D localization volume to within $10^{-3} \text{ Mpc}^3$.

Decihertz space-based detectors such as DECIGO are expected to observe WD–WDs at larger distances than LISA. To determine the typical decision precision for such distant WDs, we perform parameter estimation for WD–WDs fixed at a distance that gives the detection limit such that the S/N is approximately 8. Considering the $1 M_\odot$–$0.8 M_\odot$ WD–WD case again, we fix the redshift to $z = 0.08$ such that the median value of the S/N is approximately 8. Table 1 shows the median values of the parameter estimation errors for the logarithms of the component masses, the luminosity distance, the sky localization, and the 3D localization volume.

6. Discussion & Conclusions

If the detection range of a decihertz detector is $D_L \sim 11 \text{ Mpc}$, we may observe one WD–WD merger event per year. We need $h < 10^{-20} \text{ [Hz}^{-1/2}]$ as the detection sensitivity around 0.1 Hz. In Figure 2, AMIGO’s sensitivity is same as this value; hence, the S/N may be small, $\sim 2$. Conversely, the sensitivities of TianGO and B-DECIGO are both $\sim 3 \times 10^{-22} \text{ [Hz}^{-1/2}]$, and
DO’s sensitivity is $\sim 5 \times 10^{-23}$ [Hz$^{-1/2}$]. Thus, TianGO, B-DECIGO, and DO are sufficiently sensitive to detect a WD–WD merger whose S/N is more than 8.

For example, in the case of a 1.0$ M_\odot$–0.8$ M_\odot$ WD–WD merger, the median value of the S/N is approximately equal to 8 when $z = 0.08$ ($\sim 375$ Mpc). The detectable volume can be estimated as $2.2 \times 10^3$ Mpc$^3$. Using Equation (1), it is expected that approximately 6600 Ia supernovae would occur per year during the observational period within the range, assuming that all Ia supernovae are caused by 1$ M_\odot$–0.8$ M_\odot$ WD–WD mergers.

Furthermore, DECIGO can detect many inspirals of WD–WDs more than 3 yr before their mergers in the 0.01–0.1 Hz range. Thus, we can investigate the mass and separation distribution of WD–WDs and the relation between them and their host galaxies. Note that the estimated detection rate strongly depends on the masses of the WDs, as the GW frequency is proportional to the total mass of the WD–WD system (Equations (16) and (17)).

The 3D localization volume of DECIGO $d_\ell^3 \Delta \ln d_\ell \Delta \Omega_z$ for 1$ M_\odot$–0.8$ M_\odot$ WD–WD mergers at $z = 0.08$ is $318$ Mpc$^3$. Conversely, the 3D localization volume of WD–WD mergers within $d_\ell \sim 11$ Mpc is $\sim 10^{-7}$ Mpc$^3$ (Figure 6). DECIGO provides a more useful and easier way to determine the host galaxy and its location compared to the host galaxy identification allowed by LIGO observations. This value is proportional to $d_\ell^6$ due to $\Delta \ln d_\ell \propto d_\ell$ and $\Delta \Omega_z \propto d_\ell^2$. Thus, the 3D localization volume for 1$ M_\odot$–0.8$ M_\odot$ WD–WD mergers within $d_\ell \sim 300$ Mpc ($z = 0.065$) is $\sim 100$ Mpc$^3$. The Milky Way-like galaxy density is one galaxy per 100 Mpc$^3$ (Koppapa et al. 2008); hence, we can identify host galaxies for many WD–WD mergers using GW detections only. It is useful and much easier to do follow-up observations and identify EM counterparts than in the case of LIGO observations.

Multi-messenger (GW and EM) observations, will enable us to put unprecedented constraints on WD–WD merger outcomes and possibly Ia progenitors. First, we can confirm if WD–WD mergers cause prompt explosions and are accompanied by bright astronomical transients, as summarized in Figure 7. Then, if WD–WD mergers result in any transients, we can attribute them to some types of thermonuclear transients. It is given that WD thermonuclear explosions are involved in various types of transients: normal Ia supernovae, subclasses of Ia supernovae (e.g., type Ia supernovae associated with circumstellar matter (CSM), super-Chandrasekhar Ia supernovae, SN 1991T-like, SN 1991bg-like, SN 2002es-like, and Iax supernovae), and Ca-rich transients (see the review by Jha et al. (2019)).

Owing to high-quality mass estimates from GW observations (see Figures 3 and 4), we can assess the importance of WD masses. For example, let us assume that normal Ia supernovae results from WD–WD mergers; they will change their peak magnitudes and decline rates along with the Phillips relation (Phillips 1993) with changing WD masses. Then, we can attribute the physical background of the Phillips relation to WD masses (see “Normal Ia sequence” in Figure 7). By means of numerical simulations of WD explosions, Ruiter et al. (2013) indicated that the peak magnitudes depend on the exploding WD masses, and Shen et al. (2018) showed that the peak magnitudes and decline rates depend on the exploding WD masses partly along with the Phillips relation. Conversely, GW observations will provide information of WD masses independent of such numerical simulations, and can be combined with EM observational results of the peak magnitudes and decline rates.

We further give three possibilities as examples. First, different exploding WD masses may be responsible for the appearance of different transients, such as normal Ia or subclasses of Ia supernovae (see “another sequence” in Figure 7). The violent merger model, one of the WD explosion models that may represent the events after a WD–WD merger, is suggested to cause SN 1991bg-like events for primary WD masses with $\sim 0.9$ $M_\odot$ (Pakmor et al. 2010), and normal Ia supernovae for primary WD masses with $\sim 1.1$ $M_\odot$ (Pakmor et al. 2012). Second, different exploding WD masses may yield an “unexpected sequence” (see Figure 7), ranging from super-Chandrasekhar, 91T-like, 02es-like, and Iax supernovae. We should note that some of them may have SD progenitors, but not DD progenitors. Some super-Chandrasekhar Ia supernovae indicate a massive CSM, like SN 2012dn (Yamanaka et al. 2016). Iax supernovae can have bright companion stars, like SN 2012Z (McCully et al. 2014). This is why we call it the “unexpected” sequence. Third, a WD–WD merger, one of which has a small mass ($\lesssim 0.5$ $M_\odot$), can generate a Ca-rich transient (Perets et al. 2010) as seen in “COWD-HeWD” in Figure 7. Note that a $\lesssim 0.5$ $M_\odot$ WD is thought of as a helium (He) WD.

The direct measurement of WD masses will also facilitate the determination of the combustion process of WDs, and the emission process of Ia supernova ejecta. As for the combustion process, the peak magnitudes can be converted into radioactive nuclear masses, i.e., $^{56}$Ni masses (Ruiter et al. 2013; Shen et al. 2018). Thus, we can assess if carbon detonation, a promising combustion process in sub-Chandrasekhar-mass WDs, can yield EM-observed $^{56}$Ni masses from GW-observed WD masses. As for the emission process, the decline rates can be related to the opacity of supernova ejecta and WD masses.
The primary WDs are limited to C-O WDs. Double detonation with any WD combinations in DD systems has been suggested by Guillochon et al. (2010), Fink et al. (2010), Woosley & Kasen (2011), Pakmor et al. (2013, 2021, 2022), Shen & Bildsten (2014), and Tanikawa et al. (2018, 2019). The (carbon-ignited) violent merger is numerically demonstrated by Pakmor et al. (2010, 2012) and Tanikawa et al. (2015). The spiral instability is reported by Kasyap et al. (2015, 2017). Double detonation in a DD system with an ONe WD can also occur according to Marquardt et al. (2015).

(Hoeflich et al. 1996; Nugent et al. 1997; Maeda et al. 2003; Kasen & Woosley 2009). We can also verify if EM-observed decline rates are consistent with GW-observed WD masses.

Even if a WD–WD merger is a progenitor of any transient, the current GW analysis may not be sufficient to identify the ignition process responsible for the transient, as seen in Figure 8. Several ignition processes in WD–WD mergers have been suggested: double detonation in a mass-transfer phase like the D9 model (Fink et al. 2010; Guillochon et al. 2010; Woosley & Kasen 2011; Pakmor et al. 2013; Shen & Bildsten 2014; Marquardt et al. 2015; Tanikawa et al. 2018, 2019; Pakmor et al. 2021, 2022), carbon detonation in a merger phase, like the violent merger model (Pakmor et al. 2010, 2012; Tanikawa et al. 2015), and carbon detonation via spiral instability in an early and asymmetric accretion disk phase (Kashyap et al. 2015, 2017). If the lighter WD has a sufficiently small mass (say \( \lesssim 0.8M_\odot \)), we can reject the violent merger and spiral instability scenarios, as both models need a massive secondary WD, \( \gtrsim 0.8M_\odot \) and \( \gtrsim 1.0M_\odot \), respectively (Sato et al. 2016; Kashyap et al. 2017, respectively). If the heavier WD has a sufficiently large mass (say \( \gtrsim 1.2M_\odot \)), we can identify the exploding WD as an oxygen-neon (ONe) WD and adopt the model of Marquardt et al. (2015). However, if the secondary WD mass is close to 1.0 \( M_\odot \), we cannot reject any ignition process, because all the ignition processes are possible in such systems. Note that we may support (or reject) the double detonation model if we confirm the presence (or absence) of He-detonation ashes by means of detailed spectroscopic observations, like MUSSES1604D (Jiang et al. 2017) and ZTF18aqaqes/SN 2018byg (De et al. 2017).

In our subsequent paper (H. Takeda et al. in prep.), we will analyze WD–WD mergers in more detail, and distinguish the GW signals of the ignition processes (see Figure 9). The aforementioned ignition processes should have different GW signals, because they cause explosions at different times with respect to the WD–WD merger time (\( \Delta t \)). WDs explode long before their merger or in the mass-transfer phase (\( \Delta t \lesssim 0 \)) in the double detonation models, nearly at the moment of their merger (\( \Delta t \sim 0 \)) in the violent merger model, and several \( 10^2 \) s after their merger or just after the formation of an accretion disk made from a tidally disrupted WD (\( \Delta t \sim 10^3 \) s) in the spiral instability model. The signals from GWs just before they disappear due to explosions or mergers may be different among these processes.

Multi-messenger (GW and EM) observations, will be helpful again to specify alternative ignition processes. GW observations can determine the time of disappearance of GW signals with high accuracy. EM observations can give the ignition time.
with accuracy of ~1 hr even in the present day, where the Zwicky Transient Facility archives 2 hr cadence (Bellm 2014), for example. Thus, we can specify ignition processes in which the WD explosion is later than a WD–WD merger by ~1 hr. If an EM-observed WD explosion happens at 10^5 seconds after a GW-observed WD–WD merger (Δt ~ 10^5 s), magnetically viscous heating in the accretion disk may contribute to the ignition. Note that there is no scenario for WD explosions in this phase to our knowledge. For the case of Δt ~ 10^4 s, we may conclude that the WD explosion occurs along with the classical DD scenario, or near-Chandrasekhar-mass explosion through neutrino cooling (e.g., Iben & Tutukov 1984; Webbink 1984). If that is true, the WD–WD merger remnant experiences slow merging (Yoon et al. 2007), avoiding quasi-static carbon burning, which converts the remnants into oxygen-neon-magnesium WDs (Saio & Nomoto 1985; Schwab et al. 2016). Even if we do not have any transients, we cannot rule out the possibility of a near-Chandrasekhar-mass explosion. The explosion can have a delay time of ~10^5 yr from the WD–WD merger (Yoon et al. 2007), much more than a human (or civilization) lifespan.

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