Realistic Detection and Early Warning of Binary Neutron Stars with Decihertz Gravitational-wave Observatories

Chang Liu1,2, Yacheng Kang1,2, and Lijing Shao2,3

1 Department of Astronomy, School of Physics, Peking University, Beijing 100871, People’s Republic of China
2 Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, People’s Republic of China; lihao@pku.edu.cn
3 National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, People’s Republic of China

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Abstract

We investigated the detection rates and early-warning parameters of binary neutron star (BNS) populations with decihertz gravitational-wave observatories in a realistic detecting strategy. Assuming the operation time of B-DECIGO is 4 yr, we classified the detectable BNSs based on parameter precision into three categories: (a) sources that merge within 1 yr, which could be localized with an uncertainty of \(\Delta \Omega \sim 10^0 \text{ deg}^2\); (b) sources that merge in 1–4 yr, which take up three-quarters of the total events and yield the most precise angular resolution with \(\Delta \Omega \sim 10^{-2} \text{ deg}^2\) and time-of-merger accuracy with \(\Delta t_c \sim 10^{-1} \text{ s}\); and (c) sources that do not merge during the 4 yr mission window, which enable possible early warnings, with \(\Delta \Omega \sim 10^{-1} \text{ deg}^2\) and \(\Delta t_c \sim 10^{0} \text{ s}\). Furthermore, we compared the pros and cons of B-DECIGO with the third-generation ground-based detectors, and explored the prospects of detections using three other decihertz observatories and four BNS population models. In realistic observing scenarios, we found that decihertz detectors could even provide early-warning alerts to a source decades before its merger while their localizations are still as accurate as ground-based facilities. Finally we found a decrease of events when considering the confusion noise, but this could be partially solved by a proper noise subtraction.

Unified Astronomy Thesaurus concepts: Gravitational wave astronomy (675); Neutron stars (1108); Gravitational wave detectors (676)

1. Introduction

The detection of gravitational waves (GWs) from the binary neutron star (BNS) inspiral GW170817 has opened an exciting era of multimessenger astronomy (Abbott et al. 2017a, 2017b). In combination with the following electromagnetic (EM) counterparts, joint detection of BNS mergers by GW and EM facilities provided us unprecedented opportunities to explore many fundamental questions (Sathyaprakash et al. 2019), including dense matter properties in extreme conditions with associated high-energy astrophysical processes (Abbott et al. 2017c, 2018), tests of general relativity in the strong-field regime (Abbott et al. 2017d, 2019a), and the cosmic expansion with the “standard siren” technique (Schutz 1986; Abbott et al. 2017e).

The prerequisite for a successful multimessenger detection is the prompt communication of source location and other properties from GW data to EM telescopes. For GW170817, the short γ-ray burst (GRB), GRB 170817A, was observed \(\sim 1.7\) s after the BNS merger, while the localization from LIGO/Virgo took hours (Abbott et al. 2017d). People have been studying and improving the low-latency GW triggers (Hooper et al. 2012; Nitz et al. 2018; Abbott et al. 2019b). They have also assessed the detection and early-warning abilities for compact binary mergers observed by current and future ground-based GW detectors, including LIGO, Virgo, and KAGRA (Abbott et al. 2020), as well as the third-generation (3G) detectors, the Einstein Telescope (ET) and Cosmic Explorer (CE; see, e.g., Chan et al. 2018; Sachdev et al. 2020; Nitz & Dal Canton 2021; Singh et al. 2021; Borhanian & Sathyaprakash 2022; Magee & Borhanian 2022).

While the real-time detections and early warnings from ground-based GW detectors have been closely examined, less attention has been paid to decihertz GW detectors. Current decihertz detector proposals (Izumi & Jani 2021) include the space-based interferometers (Yagi & Seto 2011; Sedda et al. 2020; Kuns et al. 2020), the atomic interferometers (Graham et al. 2017; Zhao et al. 2021), and the lunar GW detectors (Jani & Loeb 2021). With space-based decihertz detectors, the research on detections rates (Seto et al. 2001; Geng et al. 2020; Cao et al. 2022; Piórkowska-Kurpas et al. 2021) and parameter estimation (Isoyama et al. 2018; Nair & Tanaka 2018; Nakano et al. 2021) uses simplified detection strategies. Few studies focused on the realistic detection of BNS population and the early warnings from decihertz GW detectors (Liu & Shao 2022). Decihertz space-based GW detectors have a distinct advantage over ground-based ones, for which the GW signals from BNS systems could stay days to years in the decihertz regime, as they will eventually merge in the kilohertz band (Isoyama et al. 2018). By virtue of this, decihertz detectors can observe sources that are not only about to merge, but also solely in the inspiral stage for the duration of observation. For such sources, decihertz detectors could gather enough information from their premerger stages and provide the locations and times of merger in advance to EM facilities. Even after the detectors end their missions, their legacies on source information remain valuable for early warnings for a couple of years.

Another motivation to study the early warnings from decihertz detectors is that BNS systems detected by decihertz detectors will very likely be multiband sources (Mandel et al. 2018), as they will eventually merge in the kilohertz band.
within a reasonable time. Multiband detections would strongly improve the parameter precision, test gravity theories, and boost the success of multimessenger astronomy (Sesana 2016; Vitale 2016; Gerosa et al. 2019; Jani et al. 2019; Grimm & Harms 2020; Liu et al. 2020; Klein et al. 2022). What a premerger alert needs most is the information of source location and time of merger. Theoretically, the localization depends on the detector’s trajectory baseline and the orientation of the source (Liu & Shao 2022). The time of merger accuracy scales inversely with the detector’s frequency bandwidth and the source’s signal-to-noise ratio (S/N; Grover et al. 2014). However, different signal durations, population distributions, detector designs, and mission time make this problem complex.

The aim of this paper is to extend early studies on decihertz BNS early warnings by simulating detections in real observing scenarios, and exploring the distributions of the accuracy in localization and timing. We propose a strategy of realistic detections and investigate early-warning properties of four BNS population models with four space-based decihertz GW observatories using the Fisher information matrix (Finn 1992). Under the combined effects of mission time and signal duration, we proposed a new classification of BNS sources by dividing them into three categories according to the merger time and parameter precision. In addition, we compare the detection performances with the 3G detectors, and discuss the influence of the confusion noise.

The paper is organized as follows. In Section 2, we introduce the population models, and relevant GW detectors. In Section 3 we propose the realistic detecting strategy and provide a new classification of BNS sources. In Section 4, taking B-DECIGO (Kawamura et al. 2021) and one population model as an example, we illustrate typical characteristics of the three BNS categories with distinctive localization and timing abilities, then briefly discuss the implication on EM detections. Section 5 compares the predictions from B-DECIGO with that from 3G detectors, and Sections 6 and 7 compare the detection prospects using other decihertz detectors and other population models, respectively. In Section 8, we briefly discuss the influence of the GW foreground from compact binaries on detection rates. Section 9 concludes the study. Appendices give more information on the merger rate calculation and GW foreground from unresolved double compact objects (DCOs). Throughout this paper, we use geometrized units in which $G = c = 1$.

2. BNS Populations and GW Detectors

In this section, we will introduce the BNS population models (Section 2.1) and decihertz detectors (Section 2.2) that we adopted in this work.

2.1. BNS Population Models

For the cosmic evolution of BNS merger rate, there are various types of population models (for a review, see Mandel & Broekgaarden 2022). In our work, we have implemented four representative classes of them. Their distributions are given in Figure 1 with solid histograms, and the models—abbreviated as “SFR14,” “LN,” “Stan.High,” and “Oce.High”—are introduced as follows:

1. **SFR14**—We assumed that the merger rate evolves with redshift following the fitting formula of star formation rate (SFR) from Madau & Dickinson (2014), and we adopted a local merger rate $R_0 = 44$ Gpc$^{-3}$ yr$^{-1}$ based on the “PDB (ind)” model that is informed by events in GWTC-3 of compact binary mergers (Abbott et al. 2021).

2. **LN**—Many population models are constructed based on a delay time superposed on the SFR, such as the Gaussian delay model, power-law delay model (Virgili et al. 2011), and log-normal delay model (Wanderman & Piran 2015). According to the observations of short GRBs, the log-normal delay model is favored (Sun et al. 2015). We adopted the dimensionless redshift distribution of the log-normal delay model in Equation (A8) of Zhu et al. (2021), and a local merger rate $R_0 = 44$ Gpc$^{-3}$ yr$^{-1}$.

3. **Stan.High**—We adopted the “Stan.High” and “Oce. High” models from Dominik et al. (2013).4 These models have been applied in many other studies (Dominik et al. 2015; Ding et al. 2015; Piórkowska-Kurpas et al. 2021). “Stan.High” is the standard model with a “high-end” metallicity evolution.

4. **Oce.High**—“Oce.High” is the “optimistic common envelope” model with a “high-end” metallicity evolution (Dominik et al. 2013).

Although different population models evolve differently with redshift, most of the population synthetic codes start with the SFR of Madau & Dickinson (2014) and some of them have similar evolving trends (Baibhav et al. 2019). Therefore, similarly to Nitz & Dal Canton (2021), we choose SFR14 as our fiducial model. Without specific mention, our calculations are based on it. Our redshift cutoff is at $z = 10$ and we transform redshift to luminosity distance $D_L$ based on the $\Lambda$CDM model with the matter density parameter $\Omega_M = 0.315$, the dark-energy density parameter $\Omega_{\Lambda} = 0.685$, and the Hubble constant $H_0 = 67.4$ km s$^{-1}$ Mpc$^{-1}$ (Aghanim et al. 2020).

We focus on a typical BNS system where the two component masses, $M_1$ and $M_2$, are both $1.4 M_{\odot}$. According to Nitz & Dal Canton (2021), the localization results can be rescaled to apply to sources with other masses or local merger rates. For other parameters, we choose the dimensionless tidal deformability $\Lambda = 675$; the spins of neutron stars $\chi_{1,2} = 0$; the source

![Figure 1. Solid histograms show the total number of BNSs per year from population models. Dashed–shaded and dashed–dotted histograms show sources that will merger in the fourth year of a 4 yr mission, to be detected by B-DECIGO and DO-Optimal, respectively.](https://www.syntheticuniverse.org)
direction angles, \( \mathbf{d}_1 \in U(-1, 1) \) and \( \mathbf{d}_2 \in U(0, 2\pi) \); and the angular momentum direction angles, \( \mathbf{\hat{d}}_1 \in U(-1, 1) \) and \( \mathbf{\hat{d}}_2 \in U(0, 2\pi) \), where \( U(\cdot, \cdot) \) denotes a uniform distribution.

2.2. GW Detectors

We use four space-based decihertz GW detectors to explore their performance: (i) the baseline mission B-DECIGO (Isoyama et al. 2018; Kawamura et al. 2021), (ii) the full-scale mission DECIGO (Yagi & Seto 2011; Kawamura et al. 2011), (iii) a conservative example DO-Conservative, and (iv) an optimal example DO-Optimal (Sedda et al. 2020, 2021). Later in Section 5, to compare with the next-generation ground-based detectors, we calculate the detection prospects of the B-DECIGO sources to be observed by ET alone as well as a combination of ET and CE ("ET+CE"). We assume that ET (Hild et al. 2011) consists of three detectors located in the same place as the Virgo detector in Italy, and CE (Abbott et al. 2017f) consists of two detectors located at Livingston and Hanford sites as LIGO detectors, respectively. The noise curves of the aforementioned detectors are shown in Figure 2. Readers are referred to Section 2.2 of Liu & Shao (2022) for details.

3. BNS Early-warning Categories

Assuming BNS systems will merge following the prediction of a population model, every year there will be approximately the same amount of merger signals. Contrary to ground-based hectohertz GW detectors, where signal duration \( \ll \) mission lifetime, in decihertz detectors, however, BNS signals could exist from the start of the mission to the merger or even to the end of the mission. Except for those BNSs that merge within the first few days of the mission, all the signals will exist in decihertz detectors long enough to guarantee a relatively stable parameter estimation precision, especially for localization. For long-lasting signals, the detection rates and the localization precision make no difference whether we end the observations a few hours or a day before the merger (see, e.g., Figure 7 in Liu & Shao 2022). Therefore for decihertz space-based detectors, “early warning” is time independent to a certain extent. They can always provide accurate localization and time of merger to both GW and EM detectors for follow-ups. Therefore we pay more attention to mock the realistic detections.

Our realistic detection strategy is performed as follows. From the start of the mission to 20 yr after it, we generate BNS mergers weekly according to the population model and then calculate their S/Ns. If S/N > 8, we claim the detection and calculate their parameter precisions by the Fisher matrix method. The integration interval for S/N and Fisher calculation depends on BNS categories and we will discuss it in the next paragraph. We follow the setups in Liu & Shao (2022) with slight revisions: parameters used in the Fisher information matrix are \( \mathbf{\Xi} = \{ \mathbf{M}, \eta, \mathbf{t}_e, \mathbf{D}_L, \mathbf{d}_1, \mathbf{\hat{d}}_1, \mathbf{\hat{d}}_2, \phi_e \} \), where \( \mathbf{M} \) is the chirp mass; \( \eta \) is the symmetric mass ratio; \( \phi_e \) and \( \mathbf{t}_e \) are the phase and time at the coalescence. Our attention is focused on the estimation of the accuracy of angular resolution, \( \Delta \Omega \), and time of merger, \( \Delta t_e \).

We conservatively set the mission time of the decihertz space-based detectors as \( T_{\text{Mission}} = 4 \) yr and denote the BNS merger time from the start of the mission as \( t_{\text{co}} \). Based on the distribution of \( \Delta \Omega \) and \( \Delta t_e \) in our results, we classify the BNS sources into three categories:

(a) BNSs that merge within 1 yr \( (t_{\text{co}} \leq 1 \text{ yr}) \);
(b) BNSs that merge in 1–4 yr \( (1 \text{ yr} < t_{\text{co}} \leq 4 \text{ yr}) \);
(c) BNSs that only inspiral within the whole 4 yr observational span \( (t_{\text{co}} > 4 \text{ yr}) \).

We use “(a),” “(b),” and “(c)” to denote these categories, and they are annotated in Figure 2 for a BNS signal at \( z = 0.02 \). During the calculation of the S/N and the Fisher matrix, we need to calculate the inner product, which is an integration in the frequency domain, from \( f_{\text{in}} \) to \( f_{\text{out}} \). Categories (a) and (b) contain sources that will merge within \( T_{\text{Mission}} \), and (c) contain sources that merge outside \( T_{\text{Mission}} \). Their signal durations depend on \( t_{\text{co}} \). The larger the \( t_{\text{co}} \), the more time they will stay in the detector. Thus, they enter the detector at \( f_{\text{in}} = \left( t_{\text{co}} / 5 \right)^{3/8} M^{-5/8} / 8 \pi \) and leave

![Figure 2. The amplitude of the sources and detector noises. The sky-averaged effective noise \( \sqrt{S_n^\text{eff}(f)} \) of various detectors (see Equation (29) of Liu et al. (2020)) is given in solid lines; the substracted BNS/Neutron Star-Black Hole (NSBH)/Black Hole-Black Hole (BBH) foregrounds from model "Stan.High" are given in dashed gray lines; the simulated BNS signals, \( 2\sqrt{\text{BH}_n} \), at redshift \( z = 0.02 \), 0.2, and 2.0 are illustrated with dashed-dotted blue lines. Source signals are plotted with a duration of 100 yr. For each source, the short dashed vertical lines mark the times before coalescence. Categories (a), (b), and (c) are annotated on the illustrated source at \( z = 0.02 \).](image-url)
For BNSs in category (a), their signals only stay shortly (≤ 1 yr) in B-DECIGO. As a result, not enough information could be accumulated by the detector to enable precise parameter estimation. Figure 3 shows that the weekly number of detections (S/N > 8) increases gradually from less than one to about four, then becomes stable. Meanwhile, from Figures 4 and 5 we see that ΔΔt and ΔΩ from t0 = 0 to t0 = 1 yr have an improvement of 3–4 orders of magnitude. The reason for localization accuracy can be explained by the trajectory baseline of the detector, which is short at the beginning of the mission, leading to an inaccurate sky localization in category (a).

The majority of the detectable BNS sources in B-DECIGO belong to category (b), which yields the best and most stable parameter estimation results. From Table 1 we notice that the yearly detection rate of this category is more than that of category (a), and the entire category (b) takes up 78% of the total detections. From the second and third panels of Figure 5 (1 yr < t0 ≤ 4 yr) and the white circles in Figure 4 we find that the angular resolutions and timing accuracies are clustered around ΔΩ ≈ 10^{-2} deg^2 and Δt ≈ 0.1 s. Such a steady distribution is unrelated to the integration time, which is the reason why we consider all the BNSs that merge within 1 to 4 yr into this category. Note that we derive our results by integrating tfout = 100 Hz, which is ~ 2 s before the actual final merger. If one wants parameter estimation results from days earlier to execute the early-warning alerts, the white arrow in Figure 4 shows the direction of the changes. We also find that the S/N and redshift distributions are similar for both categories (a) and (b), where sources up to z = 0.45 can be detected.

Category (c) contains a special kind of BNS from space-based detectors. The prominent feature of category (c) is that only nearby sources from us could be observed, judging from the bottom panel of Figure 5 when t0 > 4 yr. Another feature is that the timing accuracy Δt decreases rapidly to ~10^{-1}s in category (c). The reason would be a lack of information due to a short integration interval in the frequency band, which is caused by the quasi-monochromatic waves emitted by the sources that are far from their merger stage. However, although the precision of Δt in category (c) is relatively poor, it is still useful in most cases. The ΔΩ in this category is only slightly less accurate than in category (b), with a mean value of 0.1 deg^2. The baseline of B-DECIGO in the Earth orbit from a 4 yr continuous observation gives rise to such accuracy.

For B-DECIGO, only ~3% of the detected sources belong to category (c), and it cannot detect sources with t0 ≥ 7 yr because of its decreased sensitivity at 0.1 Hz. This nondetection problem does not exist in other decihertz GW detectors such as DO-Conservative, for which ~50% of the detectable sources are in category (c). We will discuss this point in Section 6. As we will see later, the typical detection features of the sources in categories (a), (b), and (c) have similar patterns, regardless of changes in detectors (or sensitivity curves) and population models. Their relative positions on a ΔΩ−Δt plot are similar to those in Figure 4, and the evolution trends of the observables with source merger time t0 are similar to those in Figure 5, while only the numbers of detections and absolute precisions change.

To distinguish binary formation channels, spins and eccentricity measurements are usually stronger indicators. The detection numbers, on the other hand, are not sufficient to determine formation channels. However, the number of detections as a function of redshift may give a hint on the time-delay distribution (Baibhav et al., 2019) and a significant lack of detection also indicates certain population synthetic

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**Figure 3.** Black dots show the detection number per week for B-DECIGO as a function of BNS merger time t0 since the observation starts. We assume that the mission lasts for 4 yr, and have used the population model “SFR14.” The orange dots and shaded area, with labels on the right-hand side, indicate respectively the yearly detection number and the range of BNS local merger rate inferred from GWTC-3, namely in the range of [10, 1700] Gpc^{-3} yr^{-1} (Abbott et al. 2021). The dashed horizontal brown line gives a yearly detection of only one BNS. B-DECIGO could only detect sources that merge within 7 yr after the launch.
parameters (Broekgaarden et al. 2022). We discuss the discrimination of our four models in Section 7.

4.1. The Landscape of Multiband and Multimessenger Detections

We briefly discuss the prospects of joint detections with other GW/EM telescopes regarding the three BNS categories. For category (a), their angular resolutions are not always sufficient to be covered by the field of view (FoV) of EM telescopes. Meanwhile, the signal duration is so short that a low-latency early warning is relatively difficult. Thus, of all three categories, the results from category (a) are similar to those of ground-based GW detections. For category (b), they are the best sources for multiband and multimessenger astronomy. Their long signal duration in decihertz detectors enables precise early-warning information. The accurate parameter precisions keep the same days before the merger with angular resolutions less than typical FoVs of EM telescopes in most cases. This can hardly be achieved by ground-based GW detectors alone. Due to such an accurate localization and timing ability, we investigate the γ-ray burst and kilonova detection rates of sources in category (b) for various EM facilities in great detail in a separate publication (Kang et al. 2022). For category (c), since we obtain the source information years before their mergers with accurate localization, joint detections with both EM and ground-based GW searches would be promising. A problem might raise from the larger Δt, which may prevent the association with the merger signal in ground-based detectors. However, the association of other parameters, such as chirp mass and location, will solve this problem.

5. Comparisons with the Next-generation Ground-based Detectors

In this section, in order to illustrate the pros and cons of space-based decihertz GW detectors, we compare ΔΩ, Δt, and S/N of the BNS sources to be detected by B-DECIGO with that of the ET alone and “ET+CE” (Kalogera et al. 2021). When a BNS signal enters ground-based detectors, the merger phase becomes prominent, such that the effective tidal deformability Λ and the effective spin χ become important to the GW phase evolution. Therefore, we also consider these parameters in the calculations of ET and CE (see, e.g., Gao et al. 2022; Liu & Shao 2022).
Figure 6 compares the results from B-DECIGO with that of ET and “ET+CE.” We note that the S/Ns in ET (“ET+CE”) are a few (dozens) times higher than that of B-DECIGO, which means that all B-DECIGO sources could be identified by 3G detectors when they merge, regardless of their classification. This is especially true for sources in category (c) because they are much closer to us than sources from other categories. In spite of this, from the middle panels we find that the ΔΩ from B-DECIGO is actually 1–4 orders of magnitude better than ET, particularly in categories (b) and (c). But in the most optimistic case where ET and two CEs are operating together at their best designed sensitivity, the localization becomes comparable between B-DECIGO and 3G detectors. The merger time uncertainty Δtc is larger for B-DECIGO than 3G detectors. However, B-DECIGO’s subsecond errors on tc are already sufficient for the preparation of EM observations, not to mention the long enough early-warning time from B-DECIGO that the ground GW detectors cannot provide.

Note that the above analyses only compare the results from B-DECIGO to the 3G detectors. Other decihertz detectors such as DO-Optimal and DECIGO could detect sources farther than 3G detectors (see Table 1). Meanwhile, for the B-DECIGO sources, DO-Optimal and DECIGO could yield higher S/N and more accurate localization. More details are given in the next section. The general trend is that space-based decihertz detectors have better localization ability and worse time of merger accuracy.

6. Other Decihertz Detectors

We begin by analyzing the common features. Figure 7 shows the yearly numbers of detections from DO-Conservative, DO-Optimal, and DECIGO. A summary is given in Table 1. We note that all these three detectors could observe sources with t0 up to 20 yr, since they all have a lower noise level at the frequency range of BNS inspirals for sources in category (c). The numbers of detections, however, vary significantly due to different levels of the total noise.

Figure 8 shows the probability distributions of the redshift z, S/N, Δtcr, and ΔΩ from the four decihertz detectors. The top panel shows the distributions of the redshift, and we also record the largest redshift zmax in Table 1. Instead of using the sky-averaged estimations, our recorded zmax takes into consideration the directional dependency of the source; therefore, it represents the farthest horizon distance. From the bottom two panels in Figure 8 we find that the categories (a), (b), and (c) are more dominant than the detector sensitivity in determining

Figure 6. Distributions of the ratios of S/N (left), angular resolution (middle), and accuracy in the time of merger (right), for the sources to be detected by B-DECIGO over that by ET (upper panels) and “ET+CE” (lower panels). Sources in categories (a), (b), and (c) are given in blue, gray, and green histograms, respectively.
the distributions of $\Delta t_c$ and $\Delta \Omega$. In categories (b) and (c), $\Delta \Omega$ of the sources is always less than $O(1)$ deg$^2$, regardless of the qualities of the detectors, and the timing accuracies of most sources in categories (c) are $\Delta t_c > 1$ s.

We now explore the specialties of decihertz GW detectors one by one. Compared to B-DECIGO, DO-Conservative has a higher noise level at $f > 0.2$ Hz, leading to a significant drop in the number of detections. The weekly detection rates hardly reach one. However, DO-Conservative has a better sensitivity at lower frequencies, which greatly boosts the number of detections in category (c). Thus, it can observe sources that will merge more than dozens of years after the mission ends. Exclusive characteristics for DO-Conservative can be found in the left panels of Figure 9.

Using DO-Optimal, the weekly detection rates of the sources with $t_0 < 4$ yr gradually increase, from 0 to 400, but then drop drastically in category (c). Approximately 2 yr after the detector closes down, the weekly number of detections falls to be fewer than 10. Though DO-Optimal is an upgraded version of DO-Conservative, the parameter distributions for both of them are similar, due to its farther horizon. Exclusive characteristics for DO-Optimal can be found in the right panels of Figure 9.

DECIGO is the most powerful detector in the decihertz band that we consider. Except for the first ~10 weeks, DECIGO will detect all the sources with $t_0 < 4$ yr. Meanwhile, because of its full design with a very high sensitivity, both categories (a) and (b) have the same level of localization and timing abilities, which are orders of magnitude more accurate than the other three detectors.
7. Distinguishing Population Models

In Figure 1 we have presented the redshift distributions of the four BNS population models, as well as the distributions of the merger events detected by B-DECIGO and DO-Optimal in their last year of operation ($3 \text{ yr} < t_{e_0} \leq 4 \text{ yr}$) for each population model and discuss how detectors could help distinguish these models.

In general, though different populations could be clearly distinguished by their original redshift distributions, it is hard for us to tell the differences from the detectable sources—they are unlike the original distributions due to the horizon distance of B-DECIGO and DO-Optimal. Though a dedicated Bayesian analysis might be able to give confident inference to them. Model “Oce.High” has the largest number of sources, leading to the largest detection number for both detectors, which makes it easily recognized. Models “SFR14,” “LN,” and “Stan.High,” however, could not be distinguished by B-DECIGO. The horizon distance of B-DECIGO is $z_{\text{max}} \sim 0.45$, while sources from these three models have similar distributions before $z = 1$. However, after $z = 1$, the number of mergers for model “SFR14” rises, while for models “LN” and “Stan.High” it
drops sharply and remains stable, respectively. Since the horizon of DO-Optimal reaches $z_{\text{max}} \sim 1$, it helps distinguish the other three models. Sources detected from model “SFR14” outnumber the other two, whereas model “LN” has several orders of magnitude fewer detections than model “Stan.High” in the last four redshift bins in Figure 1. Though it is hard to determine the formation channel only by the detection numbers, detectors with larger horizons (such as DO-Optimal/DECIGO) have the ability to discriminate the redshift distribution, e.g., between “SFR14” and “LN.” By identifying the peak of the merger rates, space-based decihertz detectors could give hints on the time delay between star formation and binary mergers.

As we will see in the next section, population models have different contributions to the confusion noise and they will affect the detection rates of various detectors differently. The influence of confusion noise could be another way to discriminate population models.

### 8. The Impact of Confusion Noise

All the results above leave out the consideration of the confusion noise (Christensen et al. 2019; Barish et al. 2021). In reality, the stochastic GWs from the undetectable sources could leave imprints in the detectors, which are determined by the fractional energy density $\Omega_{\text{GW}}$. The amplitude of $\Omega_{\text{GW}}$ contributed from double compact objects is about $10^{-12} \sim 10^{-9}$ at 1 Hz depending on the population properties. It transforms to the confusion noise shown in the gray dotted lines in Figure 2. Appendix B shows the details of the calculation.

It has been shown that the confusion noise from DCOs could be subtracted out by an iteration scheme and a global fit (Cutler & Harms 2006). However, it depends strongly on the specific population model, the sensitivity of the detector, and its operation time, which leads to large uncertainties in the calculation. Nevertheless, as shown by Kudoh et al. (2006) and Yagi & Seto (2011), the full design of DECIGO is adequate for subtracting out the binary foreground.

Here we take a conservative approach. We have calculated the confusion noise based on the population models implemented in our paper (see Appendix B), and estimated the number of detections with or without the confusion noise in Table 2. Note that we do not include DECIGO since it can identify all the sources. We do not have estimations on $\Omega_{\text{GW}}^{\text{NSBH}}$ and $\Omega_{\text{GW}}^{\text{BBH}}$ for population models “SFR14” and “LN,” since they are phenomenological models fitted to the observations. But for models “Stan.High” and “Oce.High,” we obtain an estimation on $\Omega_{\text{GW}}^{\text{NSBH}}$ and $\Omega_{\text{GW}}^{\text{BBH}}$ by their NSBH/BBH population models from Dominik et al. (2013). Such a difference leads to a significant distinction in detection rates.

Table 2 presents the number of detections of the sources that will merge in the first year with or without the confusion noise. Considering the subtraction scheme, the actual numbers of detections should be somewhere in between. We notice that the confusion noise purely from BNS populations only slightly affects our results, especially for B-DECIGO and DO-Conservative where the effect is smaller than 2%. However, since the BBH foregrounds are orders of magnitude larger than that of the BNS, they will affect the numbers of detections severely. B-DECIGO and DO-Conservative will miss ~50% of the detectable sources for the “Stan.High” model and ~80% for the “Oce.High” model. The DCO foreground has the largest impact on DO-Optimal. Its number of detections declines drastically whether in only the BNS foreground or the whole DCO foreground, though the absolute numbers are still greater than those of B-DECIGO and DO-Conservative.

The above results are just for a conservative reference, since we did not subtract the confusion noise due to the complexity of population models and observation periods. For detectors with closer horizon distances, such as DO-Conservative, few subtractions need to be done and our results are closer to reality.

### 9. Discussions

We provide the detections and early-warning predictions of different BNS populations to be observed by space-based decihertz GW observatories with realistic simulations. We show that the detected sources could be divided into three categories based on their properties on a $\Delta f \sim \Delta f_t$ map, which is determined by the specifics of space-based heliocentric-orbit detectors. Sources in category (a) that merge quickly have less accurate localization and timing precision. Sources in category (b) that merge within 1–4 yr after the launch have the most stable and precise parameter estimation results. Sources in category (c) that do not merge within the mission time could still offer early-warning alerts.

We also discuss the landscapes of EM follow-up observations for the three categories and compare the Monte Carlo simulation results from B-DECIGO with ET, “ET+CE,” DO-Conservative, DO-Optimal, and DECIGO. Furthermore, we provide the detection prospects for four different population models and discuss the influence of the confusion noise.

With such strong localization capability from decihertz space-based GW detectors, joint detections with EM telescopes and satellites become possible. Synergy observations might be carried out with, e.g., SWIFT (Gehrels et al. 2004), GECAM (Zhang et al. 2019), eXTP (in’t Zand et al. 2019), EP (Yuan et al. 2018), THESEUS (Ciolfi et al. 2021), WFST (Shi et al. 2018), Mephisto (Lei et al. 2021), ZTF (Graham et al. 2019), and JWST (Gardner et al. 2006). For the EM facilities that have field of views larger than squares-of-degree level, joint detections will almost always succeed as long as EM counterparts reach above their detection thresholds. Therefore, future multimessenger astronomy using decihertz detectors with EM follow-ups will be very promising and will provide interesting science outcomes.

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Facilities: DECIGO, B-DECIGO, DO, ET.

Appendix A
Merger Rate Calculation

In models “SFR14” and “LN,” we assume that the BNS merger rate density evolves with redshift $z$ via

$$R(z) = R_0 f(z),$$

(A1)

where $R_0$ is the local merger rate and $f(z)$ is the corresponding normalized (dimensionless) redshift distribution model. For models “Stan.High” and “Oce.High,” we use the $R(z)$ provided by Dominik et al. (2013) directly. The number of merger events up to redshift $z_{lim}$ within a period $T$ can then be obtained with

$$N(z_{lim}) = T \int_0^{z_{lim}} \frac{4 \pi D_L^2(z) R(z)}{(1 + z)^3 H(z)} dz,$$

(A2)

where $T = 20$ yr (i.e., $\sim 20 \times 52$ weeks), $z_{lim} = 10$ by our choice, and $H(z) \equiv H_0 \sqrt{\Omega_M (1 + z)^3 + \Omega_{\Lambda}}$ is the Hubble parameter at redshift $z$.

Appendix B
GW Foreground from Unresolved DCO Systems

At the decihertz band, a stochastic GW from DCOs is dominated by their inspiral stages, and characterized by its fractional energy density $\Omega_{GW}$ per logarithmic frequency interval,

$$\Omega_{GW}(f) \equiv \frac{1}{\rho_c} \frac{d \rho_{GW}(f)}{d \ln f},$$

(B1)

where $\rho_c = 3 H_0^2/(8 \pi)$ is the critical energy density of the universe. The GW foreground by astrophysical compact binaries is given by (Phinney 2001)

$$\Omega_{GW}^{DCO}(f) = \frac{8^{5/3}}{9} \frac{1}{H_0^2} M_\text{chirp} f^{2/3} \int_0^{\infty} dz \frac{R(z)}{(1 + z)^{4/3} H(z)}.$$

(B2)

Taking a specific population model and integrating Equation (B2), one derives

$$\Omega_{GW}^{DCO}(f) = \Omega_0^{DCO} \left( \frac{H_0}{67.4 \text{ km s}^{-1} \text{ Mpc}^{-1}} \right)^{-3} \times \left( \frac{M}{M_{DCO}} \right)^{5/3} \left( \frac{f}{1 \text{ Hz}} \right)^{2/3},$$

(B3)

where $M_{DCO}$ is the chirp mass of the sources in the population. We choose $M_{BNS} = 1.22 M_\odot$, $M_{NSBH} = 6.09 M_\odot$, and $M_{BBH} = 24.5 M_\odot$ in the calculation. The $\Omega_0^{DCO}$ for various population models are listed in Table 3.

The total GW foreground spectrum $S_b$ is then

$$S_b^{DCO}(f) = \frac{4}{\pi} f^{-3} \rho_c \Omega_{GW}^{DCO}(f),$$

(B4)

which is plotted as dotted gray lines in Figure 2 for model “Stan.High.” The confusion noise of unresolved systems will then modify the noise spectrum of the detector via $S_n^{\text{total}} = S_n^{DCO}(f) + S_n^{\text{instrument}}(f)$. (B5)

We use $S_n^{\text{total}}$ to explore the effects of the confusion noise in Section 8.

ORCID iDs
Chang Liu https://orcid.org/0000-0001-7649-6792
Yacheng Kang https://orcid.org/0000-0001-7402-4927
Lijing Shao https://orcid.org/0000-0002-1334-8853

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Table 3
| BNS | NSBH | BBH |
|-----|-----|-----|
| SFR14 | 4.15 | ... | ... |
| LN | 2.66 | ... | ... |
| Stan.High | 2.40 | 4.50 | 405 |
| Oce.High | 11.0 | 15.8 | 2227 |

Note. The population models “Stan.High” and “Oce.High” for NSBHs and BBHs are taken from Dominik et al. 2013.
