We study gravitational wave searches for merging binary neutron stars (NSs). We use nonspinning template waveforms towards the signals emitted from aligned-spin NS-NS binaries, in which the spins of the NSs are aligned with the orbital angular momentum. We use the TaylorF2 waveform model, which can generate inspiral waveforms emitted from aligned-spin compact binaries. We employ the single effective spin parameter $\chi_{\text{eff}}$ to represent the effect of two component spins ($\chi_1$, $\chi_2$) on the wave function. For a target system, we choose a binary consisting of the same component masses of $1.4M_\odot$ and consider the spins up to $\chi_i = 0.4$. We investigate fitting factors of the nonspinning templates to evaluate their efficiency in gravitational wave searches for the aligned-spin NS-NS binaries. We find that the templates can achieve the fitting factors exceeding 0.97 only for the signals in the range of $-0.2 \lesssim \chi_{\text{eff}} \lesssim 0$. Therefore, we demonstrate the necessity of using aligned-spin templates not to lose the signals outside that range. We also show how much the recovered total mass can be biased from the true value depending on the spin of the signal.

In this work, we investigate fitting factors of the nonspinning templates to evaluate their efficiency in gravitational wave searches for merging NS-NS binaries. We use nonspinning template waveforms for modeling the gravitational waveforms emitted from those binaries. Here, we adopt a simple post-Newtonian waveform model, TaylorF2, in which the wave function is defined in the Fourier domain.

In signal processing, the matched filtering can be the most efficient method for signals of known shape buried in stationary Gaussian noise. Since the inspiral waveforms emitted from merging NS-NS binaries can be modeled almost accurately by the post-Newtonian approximation, the matched filter can be used in the GW search analysis. The match between a detector data stream $x(t)$, consisting of a GW signal and stationary Gaussian noise, and a waveform $h(t)$ is defined as

$$\langle x | h \rangle = 4 \text{Re} \int_{f_{\text{low}}}^{\infty} \hat{x}(f) \hat{h}^*(f) \frac{S_n(f)}{S_n(f)} \, df,$$  

where the tilde denotes the Fourier transform of the time-domain waveform, $S_n(f)$ is the power spectral density (PSD) of the detector noise, and the low frequency cutoff ($f_{\text{low}}$) can be determined by the PSD curve. In this work, we use the zero-detuned, high-power noise PSD of Advanced LIGO and assume $f_{\text{low}} = 10$ Hz. If the normalized waveform is defined as $\tilde{h} = h / (\langle h | h \rangle)^{1/2}$, the signal-to-noise ratio can be obtained by $\rho = \langle x | \tilde{h} \rangle$.

In order to describe aligned-spin binary systems in circular orbits, the wave function should incorporate five extrinsic parameters (luminosity distance of the binary, two angles defining the sky position of the binary with respect to the detector, orbital inclination, and wave polarization), two arbitrary constants (coalescence time $t_c$ and coalescence phase $\phi_c$), and four intrinsic parameters (two masses and two spins). On the other hand, the extrinsic parameters only scale the wave am-
We define the overlap ($P$) by the match between a normalized signal $\hat{h}_s$ and a normalized template $\hat{h}_t$ [28]:

$$P = \max_{t_c, \phi_c} \langle \hat{h}_s | \hat{h}_t \rangle.$$  \hspace{1cm} (2)

Here, the maximization over $t_c$ and $\phi_c$ can be easily performed by using certain analytic techniques [29]. Since we consider only nonspinning waveforms as templates, the overlaps can be distributed in the two-dimensional mass parameter space as

$$P(m_1, m_2) = \max_{t_c, \phi_c} \langle \hat{h}_s | \hat{h}_t(m_1, m_2) \rangle.$$  \hspace{1cm} (3)

The fitting factor (FF) is defined as the best-match between $\hat{h}_s$ and a set of $\hat{h}_t$ [16]:

$$\text{FF} = \max_{\lambda} \langle \hat{h}_s | \hat{h}_t(\lambda) \rangle,$$  \hspace{1cm} (4)

where $\lambda$ represents the physical parameters considered in the template space. The connection of the fitting factor to the overlap can be given as

$$\text{FF} = \max_{\lambda} P(\lambda).$$  \hspace{1cm} (5)

If we use a complete template waveform model that can produce exactly the same shape as the signal waveform, we obtain the fitting factor equal to 1, and the parameter values recovered by the templates are the same as the true values. However, typically, a waveform model cannot be complete; thus, the recovered values are likely to be biased from the true values systematically, and the fitting factor should be lower than 1. Therefore, in our overlap distributions, the recovered masses can be biased because we use nonspinning template waveforms towards the spinning signals. The bias can be easily determined by the distance from the true value ($\lambda_0$) to the recovered value ($\lambda_{\text{rec}}$):

$$b = \lambda_{\text{rec}} - \lambda_0.$$  \hspace{1cm} (6)

The bias corresponds to a systematic error in the GW parameter estimation. As the efficiency of a template waveform model for the search is evaluated by the fitting factor, its validity for the parameter estimation can be examined by the bias [30][32].

We determine the fitting factor and the bias in the following way [20][32][33]. First, we repeat a grid search around $\lambda_0$ until we find the crude location of $\lambda_{\text{rec}}$ in the overlap surface. Note that, we use the chirp mass $M_\text{ch} \equiv (m_1 m_2)^{3/5} / M^{1/5}$ and the symmetric mass ratio $\eta \equiv m_1 m_2 / M^2$, where $M = m_1 + m_2$, because those parameters are much more efficient than the component masses in our analysis [34]. Next, we estimate the size of the contour $P = P / P_{\text{max}} = 0.995$, where $P_{\text{max}}$ is the maximum value in the overlap surface. Finally, we find (almost) the exact location of $\lambda_{\text{rec}}$ by performing a 51 x 51 grid search in the region of $P > 0.995$ and choose the overlap value at that location as the fitting factor.

**FIG. 1:** Fitting factors calculated by using nonspinning templates for aligned-spin NS-NS signals with the same component masses of $1.4M_\odot$. The dotted lines indicate the lines of constant effective spin, $\chi_{\text{eff}} = \{-0.3, -0.2, ..., 0.3\}$ from bottom left.

The waveform function of TaylorF2 is given as

$$h(f) = Af^{-7/6}e^{i\Psi(f)},$$  \hspace{1cm} (7)

where $A$ is the wave amplitude that consists of the masses and the extrinsic parameters. Since we use the normalized waveforms, the amplitude does not affect our analysis. The wave phase is expressed as

$$\Psi(f) = 2\pi f t_c - 2\phi_c - \frac{\pi}{4} + \frac{3}{128\eta v^5} \phi(f),$$  \hspace{1cm} (8)

where $\phi(f)$ is given by the post-Newtonian expansion with the expansion parameter $v = [\pi f M]^{1/3}$. The coefficients of the phase equation are expressed as functions of $\eta$ and the two component spins $\chi_1, \chi_2$ with $\chi_i \equiv S_i / m_i^2$. $S_i$ being the spin angular momentum of the $i$th compact object. We consider the post-Newtonian expansion up to 3.5 pN order where the spin terms are included up to 2.5 pN order [35].

**III. RESULT**

For a target system, we choose a NS-NS binary consisting of the same component masses of $1.4M_\odot$. We consider the spins up to $\chi_i = 0.4$, which corresponds to the spin of the fastest-spinning millisecond pulsar observed so far [36]. Note that, the spins of known pulsars in double neutron star systems are below 0.04 [37]. In order to produce our template waveforms, we vary only the mass parameters fixing the spins to be $\chi_1 = \chi_2 = 0$. We then calculate two-dimensional overlap distributions by using Eq. (2) and obtain fitting factors and biases by using Eqs. (5) and (6), respectively.
In Fig. 1, we show the fitting factors of nonspinning templates (cf. Fig 6 of [38]). One can easily find that the fitting factor contours are symmetric about the line of $\chi_1 = \chi_2$, and they are coincide with the lines of constant total spin. Generally, in aligned-spin systems, the effect of the two component spins can be represented by a single effective parameter [39]. Several definitions for the single parameter have been introduced by Refs. [38, 40, 43]. We adopt the simplest one defined by $\chi_{\text{eff}} = (m_1\chi_1 + m_2\chi_2)/M$, which has been introduced to model the phenomenological template families [41, 42] and used in the recent studies similar to this work [20, 44]. For equal mass systems, the lines of constant total spin are coincide with the lines of constant effective spin. Therefore, the pattern of the contours shows that the fitting factors mainly depend on the effective spin rather than the component spins.

On the other hand, the fitting factors show a significant discrepancy between the positive and the negative effective spins. Typically, a positively (negatively) aligned–spin signal tends to be recovered by a nonspinning template having a larger (smaller) value of $\eta$ than the true value of $\eta$, i.e., $\eta_{\text{rec}} > \eta_0$ ($\eta_{\text{rec}} < \eta_0$), and the size of the bias ($b_\eta$) depends on the spin of the signal. On the other hand, the parameter value of $\eta$ is physically restricted to the range of $0 \leq \eta \leq 0.25$ (Note that the unphysical value of $\eta$ implies complex-valued masses), and this restriction results in a rapid fall-off of the fitting factor when $\eta_{\text{rec}}$ reaches the physical boundaries (for more details, see [17, 20]). In the region of $\chi_{\text{eff}} < 0$, as the magnitude of the effective spin increases, $\eta_{\text{rec}}$ decreases but does not reach the boundary 0 in our spin range because this boundary is sufficiently far from the true value ($\eta_0 = 0.25$). Therefore, the fitting factor gradually decreases with increasing $|\chi_{\text{eff}}|$. However, in the region of $\chi_{\text{eff}} > 0$, $\eta_{\text{rec}}$ is always equal to 0.25, i.e., $b_\eta = 0$ because $\eta_0 \leq \eta_{\text{rec}} \leq 0.25$, and consequently the fitting factors have much lower values. In conclusion, the nonspinning templates are efficient for GW searches, i.e., $\text{FF} \geq 0.97$, for equal mass NN-NS binaries only with the spins of $-0.2 \lesssim \chi_{\text{eff}} \lesssim 0$. Note that, if we choose a binary having sufficiently asymmetric masses so that $\eta_{\text{rec}}$ does not reach the boundaries 0 and 0.25 in the regions of $\chi_{\text{eff}} < 0$ and $\chi_{\text{eff}} > 0$, respectively, then the fitting factors gradually decrease in both the regions (e.g., see Fig. 2 of [20]).

One can infer how the recovered total mass can be biased by understanding the orbital motion of spinning binary systems. When the spin is negatively aligned with the orbital angular momentum, the spin-orbit coupling makes the binary’s phase evolution slightly faster, hence hastens the onset of the plunge phase, as compared to its nonspinning counterpart [45]. For that reason, the negative effective spin decreases the length of the waveform, as compared to the nonspinning case, and such a waveform best matches the one produced by a higher mass nonspinning binary. In a positively aligned-spin system, the spin-orbit coupling makes exactly the opposite effect. Therefore, a positive (negative) aligned-spin binary can be recovered by a lower (higher) mass nonspinning template. In Fig. 2, we show the biases for the total mass of the system, $M_{\text{tot}}$. As described above, one can find the positive biases in the region of $\chi_{\text{eff}} < 0$. However, there are almost no biases in the region of $\chi_{\text{eff}} > 0$. This is due to the constraint on the $\eta$ space. Typically, as $\chi_{\text{eff}}$ increases from 0, the position of $\{M_{\text{rec}}, \eta_{\text{rec}}\}$ tends to move to the upper left hand side from the position of $\{M_0, \eta_0\}$ in the $M - \eta$ plane. However, for equal mass binaries, since $\eta_{\text{rec}}$ is always unbiased due to the physical boundary in this region, its companion $M_{\text{rec}}$ is also unbiased although the $M$ space is unrestricted here.

IV. SUMMARY AND DISCUSSION

We studied the efficiency of nonspinning templates in GW searches for aligned-spin NS-NS binaries. We assumed that the target binary system had the same component masses of $1.4M_\odot$ and calculated fitting factors and biases $b_M$ of nonspinning templates for aligned-spin signals with the spins in the range of $-0.4 \leq \chi_i \leq 0.4$. We found that both the fitting factor and the bias strongly depend on the effective spin ($\chi_{\text{eff}}$) rather than the component spins, and we confirmed that unequal mass binaries also show a similar behavior. In particular, we found a significant discrepancy between the positive and the negative effective spins. In the region of $\chi_{\text{eff}} < 0$, as the magnitude of the effective spin increases, the fitting factor decreases gradually, and the bias ($b_M$) increases steadily up to $+1M_\odot$ at $\chi_1 = \chi_2 = -0.4$. On the contrary, in the region of $\chi_{\text{eff}} > 0$, the fitting factors have much lower values due to the effect of the physical boundary of $\eta$, and almost no biases are shown for all the signals in that region.

We demonstrated that nonspinning templates can achieve the fitting factors exceeding 0.97 for aligned-spin NS-NS binaries in the range of $-0.2 \lesssim \chi_{\text{eff}} \lesssim 0$; thus, they are efficient for GW searches only for the signals in that range. In order not to lose GW signals outside that range, one should take into
account the spin parameters in the template waveforms. The detection pipeline of Advanced LIGO for NS-NS binaries has been using aligned-spin templates, where the magnitude of the component object’s spin is limited to $\chi_i \leq 0.05$ [8].

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