Reanalysis of the binary neutron star merger GW170817 using numerical-relativity calibrated waveform models

Tatsuya Narikawa\(^1\), Nami Uchikata\(^3\), Kyohei Kawaguchi\(^2,4\)\(^,\) Kenta Kiuchi\(^4,5\)
Koutarou Kyutoku\(^1,6,7,5\)\(^,\) Masaaru Shibata\(^4,5\), and Hideyuki Tagoshi\(^2\)

\(^1\)Department of Physics, Kyoto University, Kyoto 606-8502, Japan
\(^2\)Institute for Cosmic Ray Research, The University of Tokyo, Chiba 277-8582, Japan
\(^3\)Graduate School of Science and Technology, Niigata University, Niigata 950-2181, Japan
\(^4\)Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Am M"uhlenberg 1, Potsdam-Golm 14476, Germany
\(^5\)Center for Gravitational Physics, Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan
\(^6\)Theory Center, Institute of Particle and Nuclear Studies, KEK, Tsukuba 305-0801, Japan
\(^7\)Interdisciplinary Theoretical Science (iTHES) Research Group, RIKEN, Wako, Saitama 351-0198, Japan

(Dated: October 22, 2019)

We reanalyze gravitational waves from a binary-neutron-star merger GW170817 using a numerical-relativity (NR) calibrated waveform model, the TF2\(_{+}\)KyotoTidal model. By imposing a uniform prior on the binary tidal deformability \(\tilde{\Lambda}\) the symmetric 90% credible interval of \(\tilde{\Lambda}\) is estimated to be 481\(^{+436}_{-359}\) (402\(^{+465}_{-279}\)) for the case of \(f_{\text{max}} = 1000\) Hz (2048 Hz), where \(f_{\text{max}}\) is the maximum frequency in the analysis. We also reanalyze the event with other waveform models: two post-Newtonian waveform models (TF2\(_{+}\)PNTidal and TF2\(_{+}\)PNTidal), the TF2\(_{+}\)NRTidal model that is another NR calibrated waveform model used in the LIGO-Virgo analysis, and its upgrade, the TF2\(_{+}\)NRTidalv2 model. While estimates of parameters other than \(\tilde{\Lambda}\) are broadly consistent among different waveform models, our results indicate that there is a difference in estimates of \(\tilde{\Lambda}\) among three NR calibrated waveform models. The difference in the peak values of posterior probability density functions of \(\tilde{\Lambda}\) between the NR calibrated waveform models: the TF2\(_{+}\)KyotoTidal and TF2\(_{+}\)NRTidalv2 models for \(f_{\text{max}} = 1000\) Hz is about 40 and is much smaller than the width of 90% credible interval, which is about 700. The systematic error for the NR calibrated waveform models will be significant to measure \(\tilde{\Lambda}\) in the case of GW170817-like signal for the planned third generation detectors’s sensitivities.

I. INTRODUCTION

Binary-neutron-star (BNS) mergers are valuable laboratories for nuclear astrophysics. Matter effects influence the orbital evolution and gravitational radiation through the tidal interaction between the neutron stars (NSs) in the late inspiral phase. Additionally, the presence of material gives rise to electromagnetic emission approximately coincident with gravitational radiation. Because these signatures depend on the properties of nuclear matter, their observations allow us to study various nuclear properties such as the equation of state (EOS) for NS matter.

GW170817 \(^1\) and associated electromagnetic counterparts are used to derive various constraints on NS properties and the underlying EOS. The existence of a blue component in the kilonova/macronova AT 2017gfo \(^2\) might suggest that the merger remnant did not collapse promptly to a black hole. Thus, the maximum mass of the NS should not be as small as \(\lesssim 2M_\odot\) \(^3\) and also the radii of high-mass NS may not be very small, e.g., the radius of the maximum-mass configuration is likely to be larger than 9.60 km \(^4\) (but see also Ref. \(^5\)). At the same time, the short gamma-ray burst GRB 170817A \(^6\) and the absence of magnetar-powered emission in AT 2017gfo suggest that the remnant NS collapsed early in the postmerger phase (but see also Refs. \(^7\)–\(^10\)). Accordingly, a maximum mass of \(\gtrsim 2.3M_\odot\) is also unlikely \(^11\)–\(^14\).

Tidal deformability extracted via cross-correlating gravitational-wave (GW) data of GW170817 with theoretical waveforms gives us more concrete information about the NS than electromagnetic counterparts. The LIGO-Virgo collaboration initially put an upper limit on...
We use Bayesian inference to reanalyze GW170817 with various waveform models that incorporate tidal effects in a different manner. Our analysis follows the one performed in our recent work \[43\], and uses the public data by LVC\[42\]. We calculate the posterior PDF, \(p(\tilde{\theta}|\tilde{s}(t), H)\), for the binary parameters \(\tilde{\theta}\) for the gravitational waveform model, \(H\), given the LIGO Hanford, LIGO Livingston, and Virgo data \(s(t)\) via

\[
p(\tilde{\theta}|\tilde{s}(t), H) \propto p(\tilde{\theta}|H)p(\tilde{s}(t)|\tilde{\theta}, H).
\] (1)

\(p(\tilde{\theta}|H)\) is the prior for the binary parameters. The likelihood \(p(\tilde{s}(t)|\tilde{\theta}, H)\) is evaluated by assuming stationarity and Gaussianity for the detector noise using the noise power spectrum density derived with BayesLine\[43\]. We compute PDFs by using stochastic sampling engine based on nested sampling \[44, 45\]. Specifically, we use the parameter estimation software, LALInference \[46\], which is one of the software of LIGO Algorithm Library (LAL) software suite. We take the frequency range from 23 Hz to \(f_{\text{max}}\). Here, the maximum frequency \(f_{\text{max}}\) is chosen from two values, 1000 Hz or min[\(f_{\text{ISCO}}\), \(f_s/2\)], where.

---

1. https://www.gw-openscience.org/catalog/GWTC-1-confident/single/GW170817/ for Hanford and Virgo, https://dcc.ligo.org/LIGO-P1900011/public for Livingston
$f_{\text{ISCO}}$ is twice the orbital frequency at the innermost stable circular orbit of a Schwarzschild black hole with total mass of the binary, and $f_s$ is the sampling rate of data. We set $f_s = 4096$ Hz. The former choice is made because the TF2$_+\text{KyotoTidal}$ model is calibrated in the frequency range of 10-1000 Hz. The latter choice corresponds to the assumption that the inspiral stage is terminated at the smaller of $f_{\text{ISCO}}$ and $f_s/2$. In this work, we represent the latter choice by $f_{\text{max}} = 2048$ Hz for simplicity.

| Model name         | Point-particle part | Tidal part |
|--------------------|---------------------|------------|
|                    | Amplitude | Phase    | Amplitude | Phase    |
| TF2$_+\text{PNTidal}$ | 3PN       | 3.5PN    | 5+1PN     | 5+2.5PN  |
| TF2+$_\text{PNTidal}$ | 6PN       | 6PN      | 5+1PN     | 5+2.5PN  |
| TF2+$_\text{KyotoTidal}$ | 6PN       | 6PN      | Polynomial | Nonlinear |
| TF2+$_\text{NRTidal}$  | 6PN       | 6PN      | -         | Padé approximation |
| TF2+$_\text{NRTidalv2}$ | 6PN       | 6PN      | Padé approximation | Padé approximation |

TABLE I. Waveform models used to reanalyze GW170817. Our reference model, the TF2$_+\text{KyotoTidal}$ model incorporates TF2$_+$, as the point-particle and spin parts, and NR calibrated tidal effects. The TF2 approximant employs the 3.5PN- and 3PN-order formulas for the phase and amplitude, respectively as the point-particle part, and treats aligned spins and incorporates 3.5PN-order formula in spin-orbit interactions, 2PN-order formula in spin-spin, and self-spin interactions. TF2$_+$ is the TF2 approximant supplemented with phenomenological higher-order PN terms calibrated by SEOBNRv2 for the point-particle part. The TF2+$_\text{NRTidal}$ model is another model whose tidal effects are calibrated by NR. The TF2+$_\text{NRTidalv2}$ model is the upgrade of the TF2+$_\text{NRTidal}$ model. The TF2$_+\text{PNTidal}$ and TF2+$_\text{PNTidal}$ models employ the PN tidal-part phase formula.

B. Waveform models for inspiraling BNSs

We use different analytic frequency-domain waveform models for the inspiral phase. The features of each waveform model are summarized in Table I. The Fourier transform of the gravitational waveform can be written as

$$\tilde{h}(f) = A(f)e^{i\Psi(f)},$$

where the amplitude $A(f)$ and the phase $\Psi(f)$ can be decomposed into the point-particle evolution, the spin effects, and the tidal effects as

$$A(f) = A_{\text{point-particle}}(f) + A_{\text{spin}}(f) + A_{\text{tidal}}(f)$$

and

$$\Psi(f) = \Psi_{\text{point-particle}}(f) + \Psi_{\text{spin}}(f) + \Psi_{\text{tidal}}(f).$$

We use TaylorF2 [47, 48] (hereafter TF2) and phenomenologically extended model of TF2, called TF2$_+$ (see Ref. [42] and below) as BBH baseline, which consists of point-particle and spin parts. Here, the 3.5PN-order formula for the phase and 3PN-order formulas for the amplitude are employed as the point-particle part of TF2 [99]. For TF2$_+$, both the phase and amplitude of the point-particle part are extended to the 6PN-order by fitting SEOBNRv2 model [50, 51].

All waveform models used in our parameter estimation analyses assume that the spins of component stars are aligned with the orbital angular momentum, and incorporate 3.5PN-order formula in couplings between the orbital angular momentum and the component spins [52], 2PN-order formula in point-mass spin-spin, and self-spin interactions [53, 54].

During the BNS inspiral, at the leading order, the induced quadrupole moment tensor $Q_{ij}$ is proportional to the external tidal field tensor $E_{ij}$ as $Q_{ij} = -\lambda E_{ij}$. The information about the NS EOS can be quantified by the tidal deformability parameter $\lambda$ [28, 55]. The leading order tidal contribution to the GW phase evolution (relative 5PN-order) is governed by the symmetric contribution of NS tidal deformation, characterized by the binary tidal deformability $\tilde{\Lambda}$

$$\tilde{\Lambda} = \frac{16}{13} \left( m_1 + 12m_2 \right) m_1^4 \Lambda_1 + \left( m_2 + 12m_1 \right) m_2^4 \Lambda_2, \quad (5)$$

which is a mass-weighted linear combination of the tidal deformability of the both components, where $m_{1,2}$ is the component mass and $\Lambda_{1,2}$ is the dimensionless tidal deformability parameter of each star $\Lambda = \lambda/m^5$. The antisymmetric contribution $\delta\tilde{\Lambda}$ terms are always sub-dominant on the tidal effects to the gravitational-wave phase and the symmetric contribution $\tilde{\Lambda}$ terms dominate [30, 53, 54]. In this paper, we ignore the $\delta\tilde{\Lambda}$ contribution.

The TF2+$_\text{PNTidal}$ model and the TF2+$_\text{PNTidal}$ model denote the waveform models employing TF2 and TF2$_+$ as the BBH baseline, respectively. Both the TF2+$_\text{PNTidal}$ and the TF2+$_\text{PNTidal}$ models employ the 2.5PN-order (relative 5+2.5PN-order) tidal-part phase
The functional forms of the tidal-part phase formula \cite{34} by multiplying $\tilde{\Lambda}$ by the leading, Newtonian (relative 5PN-order) tidal phase, and extends the 2.5PN-order (relative 5+2.5PN-order) tidal-part phase formula, \( \Psi_{\text{PNTidal}} \) model (solid, green) are also presented, which are independent of $\tilde{\Lambda}$ when normalized by the leading tidal phase.

The tidal-part amplitude for both TF2+PNTidal and TF2+KyotoTidal employ the 5+1PN-order amplitude formula given by \cite{34}

\[
A_{\text{PNTidal}}^{\text{KyotoTidal}} = \sqrt{\frac{5\pi\eta}{24}} \frac{M_{\text{tot}}^2 (1 + z)^2}{d_L} \tilde{\Lambda} \left( x^3 - \frac{27}{16} x^5 + \frac{449}{64} x^6 \right),
\]

where $d_L$ is the luminosity distance to the source and $z$ is the redshift.

The TF2+KyotoTidal model is a NR calibrated waveform model for the inspiral phase of BNS mergers \cite{56}. The TF2+KyotoTidal model employs TF2+ as the BBH baseline and extends the 2.5PN-order (relative 5+2.5PN-order) tidal-part phase formula \cite{34} by multiplying $\tilde{\Lambda}$ by a nonlinear correction to model the tidal part of the gravitational-wave phase. The functional forms of the tidal-part phase is

\[
\Psi_{\text{KyotoTidal}}^{\text{tidal}} = \frac{3}{128\eta} \left[ -\frac{39}{2} \frac{\tilde{\Lambda}}{x^{5/2}} \left( 1 + a\tilde{\Lambda}^{2/3} x^p \right) x^{5/2} \right. \]
\[
\times \left. \left( 1 + \frac{3115}{1248} x - \pi x^{3/2} + \frac{28024205}{3302208} x^2 - \frac{4283}{1092} \pi x^{5/2} \right) \right],
\]

where $a = 12.55$ and $p = 4.240$. The tidal-part amplitude is extended by adding the higher-order PN tidal effects to \( \Psi_{\text{PNTidal}} \) as

\[
\Psi_{\text{KyotoTidal}}^{\text{tidal}} = \frac{3}{128\eta} \left[ -\frac{39}{2} \frac{\tilde{\Lambda}}{x^{5/2}} \left( 1 + a\tilde{\Lambda}^{2/3} x^p \right) x^{5/2} \right. \]
\[
\times \left. \left( 1 + \frac{3115}{1248} x - \pi x^{3/2} + \frac{28024205}{3302208} x^2 - \frac{4283}{1092} \pi x^{5/2} \right) \right],
\]

where $a = 12.55$ and $p = 4.240$. The tidal-part amplitude is extended by adding the higher-order PN tidal effects to \( \Psi_{\text{PNTidal}} \) as

\[
\Psi_{\text{KyotoTidal}}^{\text{tidal}} = \frac{3}{128\eta} \left[ -\frac{39}{2} \frac{\tilde{\Lambda}}{x^{5/2}} \left( 1 + a\tilde{\Lambda}^{2/3} x^p \right) x^{5/2} \right. \]
\[
\times \left. \left( 1 + \frac{3115}{1248} x - \pi x^{3/2} + \frac{28024205}{3302208} x^2 - \frac{4283}{1092} \pi x^{5/2} \right) \right],
\]

where $a = 12.55$ and $p = 4.240$. The tidal-part amplitude is extended by adding the higher-order PN tidal effects to \( \Psi_{\text{PNTidal}} \) as

\[
\Psi_{\text{KyotoTidal}}^{\text{tidal}} = \frac{3}{128\eta} \left[ -\frac{39}{2} \frac{\tilde{\Lambda}}{x^{5/2}} \left( 1 + a\tilde{\Lambda}^{2/3} x^p \right) x^{5/2} \right. \]
\[
\times \left. \left( 1 + \frac{3115}{1248} x - \pi x^{3/2} + \frac{28024205}{3302208} x^2 - \frac{4283}{1092} \pi x^{5/2} \right) \right],
\]

where $a = 12.55$ and $p = 4.240$. The tidal-part amplitude is extended by adding the higher-order PN tidal effects to \( \Psi_{\text{PNTidal}} \) as

\[
\Psi_{\text{KyotoTidal}}^{\text{tidal}} = \frac{3}{128\eta} \left[ -\frac{39}{2} \frac{\tilde{\Lambda}}{x^{5/2}} \left( 1 + a\tilde{\Lambda}^{2/3} x^p \right) x^{5/2} \right. \]
\[
\times \left. \left( 1 + \frac{3115}{1248} x - \pi x^{3/2} + \frac{28024205}{3302208} x^2 - \frac{4283}{1092} \pi x^{5/2} \right) \right],
\]

where $a = 12.55$ and $p = 4.240$. The tidal-part amplitude is extended by adding the higher-order PN tidal effects to \( \Psi_{\text{PNTidal}} \) as

\[
\Psi_{\text{KyotoTidal}}^{\text{tidal}} = \frac{3}{128\eta} \left[ -\frac{39}{2} \frac{\tilde{\Lambda}}{x^{5/2}} \left( 1 + a\tilde{\Lambda}^{2/3} x^p \right) x^{5/2} \right. \]
\[
\times \left. \left( 1 + \frac{3115}{1248} x - \pi x^{3/2} + \frac{28024205}{3302208} x^2 - \frac{4283}{1092} \pi x^{5/2} \right) \right],
\]
accurate NR waveforms,
\[
\Psi_{\text{tidal}}^{\text{NRTidalv2}} = \frac{3}{128\eta} \left[ -\frac{39}{2} \tilde{\Lambda} x^{5/2} \right. \\
\left. + \frac{1 + \tilde{n}_1' x + \tilde{n}_3/2 x^{3/2} + \tilde{n}_2' x^2 + \tilde{n}_5/2 x^{5/2} + \tilde{n}_4' x^{3}}{1 + d_1' x + d_3/2 x^{3/2} + d_2' x^2} \right],
\]
(11)

with \(\tilde{n}_1' = c_1' + \tilde{d}_1'\), \(\tilde{n}_3/2 = (c_1' - c_3/2 - c_2' + \tilde{n}_5/2)/c_1'\), 
\(\tilde{n}_2' = c_2' + c_1' + \tilde{d}_2'\), \(\tilde{n}_5/2 = -c_2' + c_3/2 \tilde{d}_2' - \tilde{n}_5/2/c_1'\),
where the known coefficients are \(c_1' = 3115/1248, c_2' = -\pi, c_2' = 28024205/3302208, c_5/2 = -4283\pi/1092\),
and the fitting coefficients are \(\tilde{n}_5/2 = 90.550822, \tilde{n}_5' = -60.253578, \tilde{d}_1' = -15.111208, \tilde{d}_2' = 8.0641096\). They also introduce the tidal amplitude,
\[
A_{\text{tidal}}^{\text{NRTidalv2}} = \sqrt{\frac{5\pi\eta}{24}} \frac{\tilde{M}_{\text{tot}}(1 + z)^2}{d_L} \tilde{\Lambda} x^{-7/4} \times \left( \frac{27}{16} \right) \left( 1 + \frac{449}{108} x + \frac{22672}{9} x^{2.89} \right) \frac{1 + dx^2}{1 + dx^4},
\]
(12)

where \(d = 13477.8\).

In Fig. 1, we show differences in the phase evolution of tidal part among the KyotoTidal, NRTidal, NRTidalv2, and PNTidal models. A difference in the treatment of the tidal effects makes different \(\tilde{\Lambda}\)-dependence. The tidal phase normalized by the leading (relative 5PN-order) tidal phase formula for the KyotoTidal model depends on the binary tidal deformability \(\tilde{\Lambda}\) due to the nonlinear correction. Since the NRTidal, NRTidalv2, and PNTidal models employ the linear-order effects of the tidal deformability, they are independent of \(\tilde{\Lambda}\) when normalized by the leading tidal effect. Figure 1 shows good agreement between the TF2+KyotoTidal model and the TF2+NRTidalv2 model for \(\tilde{\Lambda} \approx 1000\) below 1000 Hz as suggested in Ref. [41]. The NRTidal model gives the largest phase shift, the second is the NRTidalv2 model, the third is the KyotoTidal model, and the PNTidal model gives the smallest, for \(\tilde{\Lambda} \leq 1000\), up to \(\sim 1000\) Hz. The TF2+KyotoTidal model is calibrated only up to 1000 Hz and overestimates tidal effects at frequencies above 1000 Hz. The KyotoTidal model gives the largest phase shift at frequency above 1200 Hz for \(\tilde{\Lambda} = 1000\), and larger phase shift than the one for the NRTidalv2 model at frequency above 1000 Hz (1400 Hz) for \(\tilde{\Lambda} = 1000\) (400).

C. Source parameters

The source parameters and their prior probability distributions are chosen to follow those adopted in our recent work [43], and we mention specific choices made in this work.

We fix the sky location to the position of AT 2017gfo, which is an electromagnetic counterpart of GW170817 [60], for all of our analyses and estimates of the remaining source parameters. Specifically, we estimate the luminosity distance to the source \(d_L\), the binary inclination \(\theta_{\text{IN}}\), which is the angle between the total angular momentum and the line of sight, the polarization angle \(\psi\), the coalescence time \(t_c\), the phase at the coalescence time \(\phi_c\), component masses \(m_{1,2}\), where we assume \(m_1 \geq m_2\), the orbit-aligned dimensionless spin components of the stars \(\chi_{1,2}\) where \(\chi_{1,2} = c\theta_{1,2}/(Gm_{1,2}^2)\) is the orbit-aligned dimensionless spin components of the stars with \(\chi_{1,2}\) are the magnitudes of the spin angular momenta of the components and the binary tidal deformability \(\tilde{\Lambda}\).

For our analysis, we assume a uniform distribution as the detector-frame component mass prior \(m_{1,2} \sim U[0.83, 7.7]M_\odot\) with an additional constraint on the detector-frame chirp mass \(M_{\text{det}} \sim U[1.184, 2.168]M_\odot\), where the chirp mass is the best estimated mass parameter defined as \(M = (m_1m_2)^{3/5}(m_1 + m_2)^{-1/5}\). The prior range for \(M_{\text{det}}\) is the same as that used for LIGO-Virgo analysis [15]. The impact of wider prior range for \(M_{\text{det}}\) on parameter estimation is negligible. We assume a uniform prior on the spin magnitudes and we enforce \(\chi_{1,2} \sim U[-0.05, 0.05]\). This prior range of spin is consistent with the observed population of known BNSs that will merge within the Hubble time [61, 62], and is referred to as low-spin prior for the LIGO-Virgo analysis [15]. We assume a uniform prior on the binary tidal deformability, with \(\tilde{\Lambda} \sim U[0, 3000]\).

III. RESULTS

A. Source properties other than the tidal deformability

In this subsection, we show validity of our analysis as a sanity check by comparison with the LIGO-Virgo results. Figure 2 shows the marginalized posterior PDFs of parameters other than the tidal deformability for different waveform models for \(f_{\text{max}} = 1000\) Hz. Table III presents the 90\% credible intervals of the luminosity distance \(d_L\), the binary inclination \(\theta_{\text{IN}}\), mass parameters (the component masses \(m_{1,2}\), the detector-frame chirp mass \(M_{\text{det}}\), the source-frame chirp mass \(M\), the total mass \(M_{\text{tot}}\), and the mass ratio \(q\)), and the effective spin parameter \(\chi_{\text{eff}} = (m_1\chi_1 + m_2\chi_2)/M_{\text{tot}}\), which is the most measurable combination of spin components, estimated using different waveform models. The source-frame chirp mass is derived by assuming a value of the Hubble constant \(H_0 = 69\) km s\(^{-1}\) Mpc\(^{-1}\) (a default value in LAL).

For comparison of our analysis with the results of the previous LIGO-Virgo analysis [15, 62], we also analyze GW170817 by using the restricted TF2 approximant as the waveform model with 5+1PN-order tidal-part phase formula. This model has the BBH baseline whose amplitude is constructed only from the Newtonian-order point-particle evolution [47, 55, 52, 54] and is implemented in
LALInference. We checked that estimates of parameters other than the tidal deformability we obtained by using the restricted TF2 model are broadly consistent with the LIGO-Virgo results presented in [15, 63].

The estimates of parameters other than the tidal deformability presented in Fig. 2 and Table I show almost no systematic bias associated with a difference among waveform models for both, BBH baseline and tidal parts. The posterior PDFs of these parameters for $f_{\text{max}} = 2048$ Hz are almost the same as the ones for $f_{\text{max}} = 1000$ Hz as illustrated for the TF2_{PNTidal} model in Fig. 2. This is due to the fact that the parameters other than the tidal deformability are mainly measured from information at low frequency region [24] and terms up to 3.5PN-order of the point-particle part for the phase are the same among different waveforms. On the other hand, the tidal deformability is mainly measured from information at high frequency region as discussed in the next section and below.

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|c|c|}
\hline
 & TF2_{PNTidal} & TF2+_{PNTidal} & TF2+_{KyotoTidal} & TF2+_{NRTidal} & TF2+_{NRTidalv2} \\
\hline
Luminosity distance $d_L$ [Mpc] & 40.0$^{+1.4}_{-1.2}$ & 39.8$^{+1.7}_{-1.5}$ & 39.9$^{+1.6}_{-1.4}$ & 39.9$^{+1.2}_{-1.4}$ & 39.6$^{+1.6}_{-1.4}$ \\
Binary inclination $\theta_{\text{BN}}$ [degree] & 147$^{+24}_{-22}$ & 146$^{+24}_{-22}$ & 147$^{+24}_{-22}$ & 147$^{+24}_{-22}$ & 146$^{+25}_{-27}$ \\
Detector-frame chirp mass $M_{\text{det}}$ [$M_\odot$] & 1.1975$^{+0.0001}_{-0.0001}$ & 1.1975$^{+0.0001}_{-0.0001}$ & 1.1975$^{+0.0001}_{-0.0001}$ & 1.1975$^{+0.0001}_{-0.0001}$ & 1.1975$^{+0.0001}_{-0.0001}$ \\
Source-frame chirp mass $M$ [$M_\odot$] & 1.187$^{+0.004}_{-0.002}$ & 1.187$^{+0.004}_{-0.002}$ & 1.187$^{+0.004}_{-0.002}$ & 1.187$^{+0.004}_{-0.002}$ & 1.187$^{+0.004}_{-0.002}$ \\
Primary mass $m_1$ [$M_\odot$] & (1.36, 1.59) & (1.36, 1.58) & (1.36, 1.58) & (1.36, 1.59) & (1.36, 1.58) \\
Secondary mass $m_2$ [$M_\odot$] & (1.18, 1.37) & (1.18, 1.37) & (1.18, 1.37) & (1.18, 1.37) & (1.18, 1.37) \\
Total mass $M_{\text{tot}} := m_1 + m_2$ [$M_\odot$] & 2.74$^{+0.04}_{-0.03}$ & 2.74$^{+0.04}_{-0.03}$ & 2.74$^{+0.04}_{-0.03}$ & 2.74$^{+0.04}_{-0.03}$ & 2.74$^{+0.04}_{-0.03}$ \\
Mass ratio $q := m_2/m_1$ & (0.74, 1.00) & (0.74, 1.00) & (0.75, 1.00) & (0.75, 1.00) & (0.75, 1.00) \\
Effective spin $\chi_{\text{eff}}$ & 0.002$^{+0.015}_{-0.009}$ & 0.003$^{+0.015}_{-0.009}$ & 0.003$^{+0.014}_{-0.008}$ & 0.002$^{+0.013}_{-0.008}$ & 0.003$^{+0.014}_{-0.008}$ \\
\hline
\end{tabular}
\caption{90% credible interval of the luminosity distance $d_L$, the binary inclination $\theta_{\text{BN}}$, mass parameters, and the effective spin parameter $\chi_{\text{eff}}$ estimated using different waveform models. We show 10%-100% regions of the mass ratio with the upper limit $q = 1$ imposed by definition, and those of $m_1$ and $m_2$ are given accordingly. We give symmetric 90% credible intervals, i.e., 5%-95%, for the other parameters with the median as a representative value.}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|c|c|}
\hline
 & $f_{\text{max}} = 1000$ Hz & & & $f_{\text{max}} = 2048$ Hz & & \\
 & Symmetric & HPD & & Symmetric & HPD & \\
\hline
TF2_{PNTidal} & 548$^{+3.39}_{-3.41}$ & 548$^{+3.59}_{-3.61}$ & 537$^{+1.83}_{-1.84}$ & 537$^{+1.94}_{-1.95}$ \\
TF2+_{PNTidal} & 569$^{+1.46}_{-1.46}$ & 569$^{+1.56}_{-1.57}$ & 528$^{+0.89}_{-0.90}$ & 528$^{+1.00}_{-1.01}$ \\
TF2+_{KyotoTidal} & 481$^{+3.79}_{-3.79}$ & 481$^{+4.02}_{-4.02}$ & 402$^{+1.65}_{-1.66}$ & 402$^{+2.02}_{-2.03}$ \\
TF2+_{NRTidal} & 403$^{+3.28}_{-3.28}$ & 403$^{+3.37}_{-3.37}$ & 267$^{+0.80}_{-0.81}$ & 267$^{+1.14}_{-1.15}$ \\
TF2+_{NRTidalv2} & 445$^{+1.22}_{-1.22}$ & 445$^{+1.30}_{-1.30}$ & 312$^{+0.78}_{-0.79}$ & 312$^{+0.99}_{-1.00}$ \\
\hline
\end{tabular}
\caption{90% credible interval of the binary tidal deformability, $\tilde{\Lambda}$, for different waveform models. We report both the symmetric 90% credible interval (Symmetric) and the 90% highest-posterior-density intervals (HPD), for both $f_{\text{max}} = 1000$ Hz (left side) and 2048 Hz (right side), where the median is shown as a representative value.}
\end{table}

\subsection*{B. Posterior of binary tidal deformability}

Before presenting our results obtained with various waveform models, we first compare our results obtained by using the restricted TF2 model that incorporates the 5+1PN-order tidal-part phase with those from the LIGO-
Virgo analysis [15] as a sanity check. While our result of 90% credible symmetric (highest posterior density (HPD)) interval on $\Lambda$ is $347^{+564}_{-243}$ ($347^{+453}_{-295}$) for restricted TF2 with 5+1PN-order tidal-part phase, low-spin prior ($|\chi| \leq 0.05$), and $f_{\text{max}} = 2048$ Hz, the LIGO-Virgo collaborations report $\Lambda = 340^{+580}_{-240}$ (340$^{+499}_{-290}$)$^{15}$ in [15]. Here, both analyses assume a uniform prior on $\Lambda_1$ and $\Lambda_2$ and weighted the posterior for $\Lambda$ by dividing by the prior, effectively imposing a uniform prior in $\Lambda$. The closeness of the inferred credible ranges indicates that our analysis successfully reproduces the results derived by the LIGO-Virgo collaborations. If we assume a uniform prior on $\Lambda$, 90% credible symmetric (HPD) interval on $\Lambda$ is $316^{+504}_{-224}$ (316$^{+307}_{-291}$) for restricted TF2 with 5+1PN-order
Figure 3 shows the marginalized posterior PDFs for the binary tidal deformability $\tilde{\Lambda}$ for different waveform models for both $f_{\text{max}} = 1000$ Hz (left panel) and 2048 Hz (right panel). The blue, cyan, red, green, and orange curves correspond to the TF2+_KyotoTidal model, the TF2+_NRTidalv2 model, the TF2+_NRTidal model, the TF2+_PNTidal model, and the TF2_PNTidal model, respectively. The corresponding 90% credible intervals are presented in Table III. We caution that the TF2+_KyotoTidal model is calibrated only up to 1000 Hz and can overestimate tidal effects at frequencies above 1000 Hz. Thus, the results for $f_{\text{max}} = 2048$ Hz should be regarded as only a reference.

For $f_{\text{max}} = 1000$ Hz (left panel of Fig. 3), the peak values of $\tilde{\Lambda}$ are 400-500 and the 90% credible intervals do not extend to $\geq 900$ for NR calibrated waveform models: the TF2+_KyotoTidal, TF2+_NRTidalv2, and TF2+_NRTidal models. Our results show that the posterior of binary tidal deformability for GW170817 are biased by using different waveform models. The TF2+_KyotoTidal model, the TF2+_NRTidal model, the TF2+_NRTidalv2 model, and the TF2+_PNTidal model are constructed from the same BBH baseline, TF2+, but with different tidal descriptions. Therefore, a difference of estimates among these waveform models reflects directly their different tidal description. The TF2+_NRTidal model gives the smallest median value on $\tilde{\Lambda}$ of 403, the second is the TF2+_NRTidalv2 model of 445, the third is the TF2+_KyotoTidal model of 481, and the TF2+_PNTidal model gives the largest one of 569. This order is derived from the order of the phase shift of different waveform models for a given value of $\tilde{\Lambda} = 400$, up to about 1400 Hz as shown in Fig. 1. The tendency to give smaller estimated values for NR calibrated waveform models than for PN waveform models are consistent with previous results derived in Ref. [64] (see also Ref. [65] for the detail study of systematic biases associated with spin effects). The TF2+_PNTidal and TF2_PNTidal models are constructed from the same tidal part and the different point-particle part. A difference in the posterior PDFs of estimated $\tilde{\Lambda}$ between these models are very small for $f_{\text{max}} = 1000$ Hz. This result shows that the higher-order point-particle terms do not significantly affect the estimate of the binary tidal deformability of GW170817 for $f_{\text{max}} = 1000$ Hz.

For $f_{\text{max}} = 2048$ Hz (right panel of Fig. 3), the peak values of $\tilde{\Lambda}$ are 250-400 and the 90% credible intervals do not extend to $\geq 850$ for NR calibrated waveform models. The width of symmetric 90% credible intervals for $f_{\text{max}} = 2048$ Hz are narrower than those for $f_{\text{max}} = 1000$ Hz. We note that 1400 Hz is approximately corresponds to $f_{\text{ISCO}}$ for estimated mass.
range. The TF2$_{\text{PN tidal}}$ model gives slightly smaller peak value than the TF2+$_{\text{Kyoto tidal}}$ model. This cannot be explained only by the feature of the tidal part as shown in Fig. [1]. This might be due to the effects of the higher-order point-particle terms or the fact that the data at frequencies above 1000 Hz are dominated by the detector’s noise. The difference in the posterior PDFs of estimated $\tilde{\Lambda}$ between the TF2+$_{\text{PN tidal}}$ and TF2$_{\text{PN tidal}}$ models for $f_{\text{max}} = 2048$ Hz is larger than that for $f_{\text{max}} = 1000$ Hz (see Fig. [3] and Table [1]). This is due to the effects of higher-order point-particle terms as discussed in [31].

IV. DISCUSSION

In this section, we discuss the systematic error for waveform models with respect to estimation of the binary tidal deformability. There is a difference among peaks of different waveform models, while the statistical error for the measurement of the binary tidal deformability $\tilde{\Lambda}$ is much larger than the difference among the peaks for GW170817 (see Fig. [3] and Table [1]). Here, we use differences in the peak values of the posterior PDFs of $\tilde{\Lambda}$ as an indicator of the systematic error.

For $f_{\text{max}} = 1000$ Hz, there are differences in the peak values of $\tilde{\Lambda}$, by about 40 between NR calibrated waveform models (the TF2+$_{\text{Kyoto tidal}}$ and TF2+$_{\text{NR tidal v2}}$ models) and by about 110 between NR calibrated waveform and PN waveform models (the TF2+$_{\text{Kyoto tidal}}$ and TF2+$_{\text{PN tidal}}$ models). The statistical errors (the width of 90\% HPD interval) of the binary tidal deformability $\tilde{\Lambda}$ are about 700 for NR calibrated models and about 900 for PN waveform models. We note that the systematic error of $\tilde{\Lambda}$ among different waveform models do not depend on the signal-to-noise ratio (SNR), while the statistical error is proportional to the inverse of SNR for realistic cases. Assuming the detector sensitivity curves at the detection of GW170817, our results suggest that for a signal that has SNR louder than GW170817 (SNR = 32.6) by a factor of about 8, the difference in extraction of $\tilde{\Lambda}$ between the TF2+$_{\text{Kyoto tidal}}$ model and the TF2+$_{\text{PN tidal}}$ model can be significant. Comparing the TF2+$_{\text{Kyoto tidal}}$ with TF2+$_{\text{NR tidal v2}}$ models, the systematic error of $\tilde{\Lambda}$ can be comparable to the statistical error for a higher SNR signal than GW170817 by a factor of about 18. The planned third generation of GW interferometers, e.g., the Einstein Telescope [66–68] or the Cosmic Explorer [69], will provide an opportunity to observe BNS mergers with more than ten times higher SNR than GW170817. Since for GW170817-like signal for the third generation of GW interferometers, the systematic error of $\tilde{\Lambda}$ can be comparable to the statistical error between the TF2+$_{\text{Kyoto tidal}}$ and TF2+$_{\text{NR tidal v2}}$ models, it is needed to improve current waveform models. We leave the study of injecting hybrid waveform signals into the noise assuming the planned third generation detectors’s sensitivities and verifying how well current waveform models recover the injected values for future work.

Â is indeed determined more precisely for all waveform models in our analysis for $f_{\text{max}} = 2048$ Hz than for $f_{\text{max}} = 1000$ Hz as indicated in Sec. [III]. However, since the TF2+$_{\text{Kyoto tidal}}$ model is calibrated by hybrid waveforms only up to 1000 Hz, it is needed to further improve the model in the frequency higher than 1000 Hz, toward the third generation detector era.

V. SUMMARY

We reanalyze GW170817 with a NR calibrated waveform model, the TF2+$_{\text{Kyoto tidal}}$ model. The TF2+$_{\text{Kyoto tidal}}$ model is calibrated in the frequency range of 10–1000 Hz by hybrid waveforms composed of high-precision NR waveforms and the SEOBNRv2T waveforms, and reproduces the phase of the hybrid waveforms within 0.1 rad error up to 1000 Hz. In the TF2+$_{\text{Kyoto tidal}}$ model, the nonlinear effects of the tidal deformability is incorporated. We also reanalyze the event with other waveform models: two PN waveform models (TF2+$_{\text{PN tidal}}$ and TF2+$_{\text{PN tidal}}$), the TF2+$_{\text{NR tidal}}$ model that is another NR calibrated waveform model, and its upgrade, the TF2+$_{\text{NR tidal v2}}$ model.

We compare parameter estimation results with different tidal waveform models. For GW170817, there seems to be almost no systematic biases for extraction of source parameters other than the binary tidal deformability using different waveform models. We find that the PN model tends to overestimate $\tilde{\Lambda}$ compared to the NR calibrated waveform models, while there are also the differences in the estimates of $\tilde{\Lambda}$ among NR calibrated waveform models for $f_{\text{max}} = 1000$ Hz. For a higher SNR signal than GW170817 by a factor of about 18, the difference in the measurement of the binary tidal deformability $\tilde{\Lambda}$ between the TF2+$_{\text{Kyoto tidal}}$ and TF2+$_{\text{NR tidal v2}}$ models can be significant. Therefore, toward the third generation detector era, it is needed to improve current waveform model.

Our results indeed indicate that $\tilde{\Lambda}$ is constrained more tightly for $f_{\text{max}} = 2048$ Hz than for $f_{\text{max}} = 1000$ Hz. For the TF2+$_{\text{Kyoto tidal}}$ model, the 90\% symmetric interval of $\tilde{\Lambda}$ for $f_{\text{max}} = 2048$ Hz is about 7\% narrower than that for $f_{\text{max}} = 1000$ Hz. Though the estimate of $\tilde{\Lambda}$ becomes narrower as the $f_{\text{max}}$ increases, the TF2+$_{\text{Kyoto tidal}}$ model is calibrated only up to 1000 Hz. Since higher frequency data are more informative for $\tilde{\Lambda}$ [31], it is important to improve current waveform models at high-frequencies above 1000 Hz to accurately determine $\tilde{\Lambda}$ from the gravitational-wave data, toward third generation detector era.
ACKNOWLEDGMENT

We thank John Veitch for very helpful explanation of LALInference and Chris van den Broeck for useful discussions. This work is supported by Japanese Society for the Promotion of Science (JSPS) KAKENHI Grant Numbers JP15K05081, JP16H02183, JP16H06341, JP16H06342, JP17H01131, JP17H06133, JP17H06358, JP17H06361, JP17H06364, JP18H01213, JP18H04595, JP18H05236, and JP19K14720, and by a post-K project hp180179. This work is also supported by JSPS Core-to-Core Program A. Advanced Research Networks and by the joint research program of the Institute for Cosmic Ray Research, University of Tokyo, Computing Infrastructure Project of KISTI-GSDC in Korea, and Computing Infrastructure ORION in Osaka City University. T. Narikawa is supported in part by a Grant-in-Aid for JSPS Research Fellows, and he also thanks hospitality of Chriss group during his stay at Nikhef. K. Kawaguchi was supported in part by JSPS overseas research fellowships. We are also grateful to the LIGO-Virgo collaboration for the public release of gravitational-wave data of GW170817. This research has made use of data, software, and web tools obtained from the Gravitational Wave Open Science Center (https://www.gw-openscience.org), a service of LIGO Laboratory, the LIGO Scientific Collaboration and the Virgo Collaboration. LIGO is funded by the U. S. National Science Foundation. Virgo is funded by the French Centre National de la Recherche Scientifique (CNRS), the Italian Istituto Nazionale di Fisica Nucleare (INFN), and the Dutch Nikhef, with contributions by Polish and Hungarian institutes.

FIG. 4. Marginalized posterior PDFs of binary tidal deformability, \( \tilde{\Lambda} \), derived by data of different detector combinations with both \( f_{\text{max}} = 1000 \) Hz (solid) and 2048 Hz (dashed) for the \( \text{TF2+KyotoTidal} \) (left panel) and the \( \text{TF2+NRTidalv2} \) (right panel) models. The distribution derived by the Hanford-only data (blue), that by the Livingston-only data (orange), and that by combined data of Advanced LIGO twin detectors and Advanced Virgo (green, denoted by HLV) are presented. For \( f_{\text{max}} = 2048 \) Hz, a multimodal (bump) structure at high-\( \tilde{\Lambda} \) for the \( \text{TF2+KyotoTidal} \) (\( \text{TF2+NRTidalv2} \)) model appear due to Livingston data.

Appendix A: Separate analysis for the LIGO twin detectors

There is a multimodal structure at the high-\( \tilde{\Lambda} \) region in the posterior PDF of \( \tilde{\Lambda} \) for the \( \text{TF2+KyotoTidal} \) model and a bump structure for the \( \text{TF2+NRTidal} \) and \( \text{TF2+NRTidalv2} \) models for \( f_{\text{max}} = 2048 \) Hz as shown in the right panel of Fig. 3. In this subsection, we present an in-depth study to interpret these features by separate analysis for the LIGO twin detec-
TABLE IV. 90% credible interval of binary tidal deformability, $\tilde{\Lambda}$, with the TF2+KyotoTidal (left side) and the TF2+NRTidalv2 (right side) models, for different detector data and the maximum frequency, $f_{\text{max}}$. The upper group shows the symmetric intervals and the lower shows the highest-posterior-density intervals, where the median is shown as a representative value for both groups.

|       | TF2+KyotoTidal Hanford-only | Livingston-only | TF2+NRTidalv2 Hanford-only | Livingston-only |
|-------|-------------------------------|----------------|---------------------------|----------------|
|       | Symmetric                     | HPD            | Symmetric                 | HPD            |
| 1000 Hz| 357$^{+568}_{-511}$           | 618$^{+637}_{-447}$ | 333$^{+514}_{-291}$     | 582$^{+586}_{-413}$ |
| 2048 Hz| 362$^{+514}_{-295}$           | 607$^{+505}_{-482}$ | 320$^{+481}_{-253}$     | 589$^{+487}_{-484}$ |

In the case of the TF2+KyotoTidal model, the left panel in Fig. [4] suggests that the origin of the bump at high-$\tilde{\Lambda}$ region for $f_{\text{max}} = 2048$ Hz for the HLV combined data is as follows. On the one hand, for the Livingston data, the unimodal distribution for $f_{\text{max}} = 1000$ Hz, whose peak is at about 600, is separated into a bimodal distribution for $f_{\text{max}} = 2048$ Hz that is constructed from twin peaks, a low-$\tilde{\Lambda}$ bump, and a few high-$\tilde{\Lambda}$ bumps. On the other hand, for the Hanford data, the unimodal distribution for $f_{\text{max}} = 1000$ Hz, whose peak is at low-$\tilde{\Lambda}$ region, shrinks for $f_{\text{max}} = 2048$ Hz. As a result, for $f_{\text{max}} = 2048$ Hz, the remaining high-$\tilde{\Lambda}$ peak for the Livingston data produces the bump for the HLV combined data. Moreover, a few high-$\tilde{\Lambda}$ bumps in the case of HLV combined data for $f_{\text{max}} = 2048$ Hz are inherited from the bumps of the Livingston-only data, which are associated with the high-frequency data. The location of the low-$\tilde{\Lambda}$ bump derived by the Livingston-only data is close to the peak of $\tilde{\Lambda}$ of about 250 derived by the Hanford-only data.

In the case of the TF2+NRTidalv2 model, as shown in the right panel of Fig. [4], a bump at the high-$\tilde{\Lambda}$ region in the case of HLV combined data for $f_{\text{max}} = 2048$ Hz are inherited from the peak of the Livingston-only data, $\tilde{\Lambda} \sim 750$.

While a bimodal distribution appears in the posterior PDF of $\tilde{\Lambda}$ with the SEGBNrv4_ROM_NRTidal model in the case of LIGO-Virgo analysis as shown in Fig. 11 in [13], a small high-$\tilde{\Lambda}$ bump at $\tilde{\Lambda} \sim 600$ appears in that with the TF2+NRTidal model presented for $f_{\text{max}} = 2048$ Hz in the right panel of Fig. [3]. Here, SEGBNrv4_NRTidal is constructed from the SEGBNrv4 model [70, 71] as the BBH baseline and the NRTidal model as the tidal part. Supplementary analysis with the TF2+NRTidal model as shown in Fig. [5] demonstrates that the different priors in $\tilde{\Lambda}$ (one uniform and one non-uniform) makes such different distribution between our analysis and the LIGO-Virgo analysis. The LIGO-Virgo collaborations used “Weighted” prior, which assumes a uniform prior on $\Lambda_1$ and $\Lambda_2$ and weighted the posterior for $\tilde{\Lambda}$ by dividing by the prior, effectively imposing a uniform prior in $\tilde{\Lambda}$. Figure [3] shows the dependence of the results on different priors in $\tilde{\Lambda}$, “$\Lambda_1$-flat”, “Weighted”, and “$\tilde{\Lambda}$-flat” for the TF2+NRTidal model with $f_{\text{max}} = 2048$ Hz. This figure demonstrate that the distribution for “$\Lambda_1$-flat” and “Weighted” prior tends to be a bimodal rather than a high-$\tilde{\Lambda}$ bump.

In Ref. [43], it is found that there is a discrepancy in the estimates of binary tidal deformability of GW170817 between the Hanford and Livingston detectors of Advanced LIGO by using the restricted TaylorF2 waveform model. Figure [4] shows that the discrepancy is enhanced with sophisticated waveform models (the TF2+KyotoTidal and TF2+NRTidalv2 models). While the two distributions in the cases of the Hanford-only and Livingston-only data seem to be consistent with each other and also consistent with what we would expect from noise realization (e.g., see Ref. [33]), the results that the width of the 90% credible interval for the Livingston-only data does not shrink as $f_{\text{max}}$ increases indicate that the Livingston’s high-frequency data are not very useful to determine the tidal deformability for GW170817.

[1] B. P. Abbott et al., [LIGO Scientific and Virgo Collaborations], “GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral”, Phys. Rev. Lett. 119, no. 16, 161101 (2017) [arXiv:1710.05832 [gr-qc]].

[2] B. P. Abbott et al., “Multi-messenger Observations of a Binary Neutron Star Merger,” Astrophys. J. 848, no. 2, L12 (2017) [arXiv:1710.05833 [astro-ph.HE]].

[3] M. Shibata, S. Fujibayashi, K. Hotokezaka, K. Kiuchi, K. Kyutoku, Y. Sekiguchi and M. Tanaka, “Modeling GW170817 based on numerical relativity and its im-
FIG. 5. Dependence of the marginalized posterior PDFs of \( \bar{\Lambda} \) on different priors in \( \bar{\Lambda} \) for the TF2+\_NRTidal model with \( f_{\text{max}} = 2048 \) Hz. In addition to PDF of \( \bar{\Lambda} \) for a uniform priors in \( \Lambda_1 \) and \( \Lambda_2 \) (dotted, cyan), we show the PDF for “Weighted”-prior (dashed, magenta), which is weighted by dividing the original prior (also shown by solid yellow curve) and the PDF for a uniform prior in \( \bar{\Lambda} \) (solid, green).

[1] Y. W. Yu, L. D. Liu and Z. G. Dai, “A long-lived remnant neutron star after GW170817 inferred from its associated kilonova,” Astrophys. J. 860, no. 2, L12 (2018) [arXiv:1802.00571 [astro-ph.HE]].

[2] B. Margalit and B. D. Metzger, “Constraining the Maximum Mass of Neutron Stars From Multi-Messenger Observations of GW170817.” Astrophys. J. 850, no. 2, L19 (2017) [arXiv:1710.05938 [astro-ph.HE]].

[3] L. Rezzolla, E. R. Most and L. R. Weih, “Using gravitational-wave observations and quasi-universal relations to constrain the maximum mass of neutron stars,” Astrophys. J. 852, no. 2, L25 (2018) [arXiv:1711.00314 [astro-ph.HE]].

[4] M. Ruiz, S. L. Shapiro and A. Tsokaros, “GW170817, General Relativistic Magnetohydrodynamic Simulations, and the Neutron Star Maximum Mass,” Phys. Rev. D 97, no. 2, 021501 (2018) [arXiv:1711.00473 [astro-ph.HE]].

[5] M. Shibata, E. Zhou, K. Kiuchi and S. Fujibayashi, “Constraint on the maximum mass of neutron stars using GW170817 event” Phys. Rev. D 100, no. 2, 023015 (2019) [arXiv:1905.03656 [astro-ph.HE]].

[6] B. P. Abbott et al. [LIGO Scientific and Virgo Collaborations], “Properties of the binary neutron star merger GW170817,” Phys. Rev. X 9, no. 1, 011001 (2019) [arXiv:1805.11579 [gr-qc]].

[7] B. P. Abbott et al. [LIGO Scientific and Virgo Collaborations], “GW170817: Measurements of neutron star radii and equation of state”, arXiv:1805.11581 [gr-qc].

[8] B. P. Abbott et al. [LIGO Scientific and Virgo Collaborations], “GW170817: Measurements of neutron star radii and equation of state”, arXiv:1805.11581 [gr-qc].

[9] W. Kastaun and F. Öhmne, “Finite tidal effects in GW170817: observational evidence or model assumptions?,” arXiv:1909.12718 [gr-qc].

[10] E. Hallman, O. Just, H. T. Janka and N. Stergioulas, “Neutron-star radius constraints from GW170817 and future detections,” Astrophys. J. 850, no. 2, L34 (2017) [arXiv:1710.06843 [astro-ph.HE]].

[11] A. Bauswein, O. Just, H. T. Janka and N. Stergioulas, “Neutron-star radius constraints from GW170817 and future detections,” Astrophys. J. 850, no. 2, L34 (2017) [arXiv:1710.06843 [astro-ph.HE]].

[12] C. Raithel, F. Özel and D. Psaltis, “Tidal deformability of a long-lived neutron star as the merger remnant of GW170817,” Astrophys. J. 856, no. 2, 101 (2018) [arXiv:1801.04286 [astro-ph.HE]].

[13] S. Ai, H. Gao, Z. G. Dai, X. F. Wu, A. Li, B. Zhang and M. Z. Li, “The allowed parameter space of a long-lived neutron star as the merger remnant of GW170817,” Astrophys. J. 860, no. 1, 57 (2018) [arXiv:1802.00571 [astro-ph.HE]].

[14] E. P. Zhou, X. Zhou and A. Li, “Constraints on interquark interaction parameters with GW170817 in a binary strange star scenario,” Phys. Rev. D 97, no. 8, 083015 (2018) [arXiv:1711.04312 [astro-ph.HE]].

[15] S. Z. Li, L. D. Liu, Y. W. Yu and B. Zhang, “What Powered the Optical Transient AT2017gfo Associated with GW170817?” Astrophys. J. 861, no. 2, L12 (2018) [arXiv:1804.06597 [astro-ph.HE]].

[16] S. Z. Li, L. D. Liu, Y. W. Yu and B. Zhang, “What Powered the Optical Transient AT2017gfo Associated with GW170817?” Astrophys. J. 861, no. 2, L12 (2018) [arXiv:1804.06597 [astro-ph.HE]].
E. E. Flanagan and T. Hinderer, “Constraining neutron star tidal Love numbers with gravitational wave detectors,” Phys. Rev. D 77, 021502 (2008) [arXiv:0709.1915 [astro-ph]].

D. Radice, A. Perego, F. Zappa and S. Bernuzzi, “GW170817: Joint Constraint on the Neutron Star Equation of State from Multimeessenger Observations,” Astrophys. J. 852, no. 2, L29 (2018) [arXiv:1711.03647 [astro-ph]].

T. Damour and A. Nagar, “Effective One Body description of tidal effects in inspiralling compact binaries,” Phys. Rev. D 83, 084051 (2011) [arXiv:1101.1673 [gr-qc]].

J. Vines, E. E. Flanagan and T. Hinderer, “Post-1-Newtonian tidal effects in the gravitational waveform of binary inspirals,” Phys. Rev. D 85, no. 10, 103012 (2012) [arXiv:1203.4352 [gr-qc]].

T. Damour, A. Nagar and L. Villain, “Measurability of the tidal polarizability of neutron stars in late-inspiral gravitational-wave signals”, Phys. Rev. D 85, 123007 (2012) [arXiv:1203.4352 [gr-qc]].

A. Buonanno, B. Iyer, E. Ochsner, Y. Pan and B. S. Sathyaprakash, “Comparison of post-Newtonian templates for compact binary inspiral signals in gravitational-wave detectors”, Phys. Rev. D 80, 084043 (2009) [arXiv:0907.0706 [gr-qc]].

J. Veitch, A. Vecchio, “Bayesian coherent analysis of in-spiral gravitational wave signals with a detector network”, Phys. Rev. D 81, 062003 (2010) [arXiv:0911.3820 [astro-ph.CO]].

T. Narikawa, N. Uchikata, K. Kawaguchi, K. Kiuchi, K. Kytotoku, M. Shibata and K. Taniguchi, “Discrepancy in tidal deformability of GW170817 between the Advanced LIGO twins,” arXiv:1812.06100 [astro-ph].

K. Kawaguchi, K. Kiuchi, K. Kytotoku, Y. Sekiguchi, M. Shibata and K. Taniguchi, “Frequency-domain gravitational waveform models for inspiraling binary neutron stars”, Phys. Rev. D 97, no. 4, 044044 (2018) [arXiv:1802.06518 [gr-qc]].

K. Yagi and N. Yunes, “Love can be Tough to Measure,” Phys. Rev. D 91, 042003 (2015) [arXiv:1409.7215 [gr-qc]].

J. Veitch et al., “Parameter estimation for compact binaries with ground-based gravitational-wave observations using the LALInference software library”, Phys. Rev. D 91, 024032 (2015) [arXiv:1412.6345 [gr-qc]].

M. Pürrer, “Frequency domain reduced order model of aligned-spin effective-one-body waveforms with generic mass-ratios and spins,” Phys. Rev. D 93, no. 6, 064041 (2016) [arXiv:1512.02248 [gr-qc]].

A. Bohe, S. Marsat and L. Blanchet, “Next-to-next-to-leading order spin-orbit effects in the gravitational wave flux and orbital phasing of compact binaries”, Class. Quant. Grav. 30, 135009 (2013) [arXiv:1303.7412 [gr-qc]].

K. G. Arun, A. Buonanno, G. Faye and W. Tichy, “Modeling the Dynamics of Tidally Interacting Binary Neutron Stars up to the Merger,” Phys. Rev. Lett. 114, no. 16, 161103 (2015) [arXiv:1412.4553 [gr-qc]].

T. Dietrich, S. Bernuzzi and W. Tichy, “Closed-form tidal approximants for binary neutron star gravitational waveforms constructed from high-resolution numerical relativity simulations”, Phys. Rev. D 96, no. 12, 121501 (2017) [arXiv:1706.02969 [gr-qc]].

T. Dietrich, A. Samajdar, S. Khan, N. K. Johnson-McDaniel, R. Dudi and W. Tichy, “Improving the NR-Tidal model for binary neutron star systems,” Phys. Rev. D 100, no. 4, 044003 (2019) [arXiv:1905.06011 [gr-qc]].

K. Kawaguchi, K. Kiuchi, K. Kytotoku, Y. Sekiguchi, M. Shibata and K. Taniguchi, “Frequency-domain gravitational waveform models for inspiraling binary neutron stars”, Phys. Rev. D 97, no. 4, 044044 (2018) [arXiv:1802.06518 [gr-qc]].

K. Narikawa, N. Uchikata, K. Kawaguchi, K. Kiuchi, K. Kytotoku, M. Shibata and H. Tagoshi, “Discrepancy in tidal deformability of GW170817 between the Advanced LIGO twins,” arXiv:1812.06100 [astro-ph].
J. Steinhoff, T. Hinderer, A. Buonanno and A. Taracchini, “Dynamical Tides in General Relativity: Effective Action and Effective-One-Body Hamiltonian,” Phys. Rev. D 94, no. 10, 104028 (2016) [arXiv:1608.01907 [gr-qc]].

B. D. Lackey, M. Pürrer, A. Taracchini and S. Marsat, “Surrogate model for an aligned-spin effective one body waveform model of binary neutron star inspirals using Gaussian process regression,” Phys. Rev. D 100, no. 2, 024002 (2019) [arXiv:1812.08643 [gr-qc]].

M. Soares-Santos et al. [DES and Dark Energy Camera GW-EM Collaborations], “The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. I. Discovery of the Optical Counterpart Using the Dark Energy Camera,” Astrophys. J. 848, no. 2, L16 (2017) [arXiv:1710.05459 [astro-ph.HE]].

M. Burgay et al., “An Increased estimate of the merger rate of double neutron stars from observations of a highly relativistic system,” Nature 426, 531 (2003) [astro-ph/0312071].

K. Stovall et al., “PALFA Discovery of a Highly Relativistic Double Neutron Star Binary,” Astrophys. J. 854, no. 2, L22 (2018) [arXiv:1802.01707 [astro-ph.HE]].

B. P. Abbott et al. [LIGO Scientific and Virgo Collaborations], “GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs,” arXiv:1811.12907 [astro-ph.HE].

A. Samajdar and T. Dietrich, “Waveform systematics for binary neutron star gravitational wave signals: effects of the point-particle baseline and tidal descriptions,” Phys. Rev. D 98, no. 12, 124030 (2018) [arXiv:1810.03936 [gr-qc]].

A. Samajdar and T. Dietrich, “Waveform systematics for binary neutron star gravitational wave signals: Effects of spin, precession, and the observation of electromagnetic counterparts,” arXiv:1905.03118 [gr-qc].

S. Hild, S. Chelkowski and A. Freise, “Pushing towards the ET sensitivity using ‘conventional’ technology,” arXiv:0810.0604 [gr-qc].

M. Punțuro et al., “The Einstein Telescope: A third-generation gravitational wave observatory,” Class. Quant. Grav. 27, 194002 (2010).

S. Ballmer and V. Mandic, “New Technologies in Gravitational-Wave Detection,” Ann. Rev. Nucl. Part. Sci. 65, 555 (2015).

B. P. Abbott et al. [LIGO Scientific Collaboration], “Exploring the Sensitivity of Next Generation Gravitational Wave Detectors,” Class. Quant. Grav. 34, no. 4, 044001 (2017) [arXiv:1607.08697 [astro-ph.IM]].

A. Bohe et al., “Improved effective-one-body model of spinning, nonprecessing binary black holes for the era of gravitational-wave astrophysics with advanced detectors,” Phys. Rev. D 95, no. 4, 044028 (2017) [arXiv:1611.03703 [gr-qc]].

M. Pürrer, “Frequency domain reduced order models for gravitational waves from aligned-spin compact binaries,” Class. Quant. Grav. 31, no. 19, 195010 (2014) [arXiv:1402.4146 [gr-qc]].