

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

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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 $f_{\max} = 1000$ Hz (2048 Hz), where f_{\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 $f_{\max} = 1000$ 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 $\sim 2M_{\odot}$ [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 [3, 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

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the binary tidal deformability $\tilde{\Lambda}$ of the binary as $\tilde{\Lambda} \lesssim 800$ with the prior on the dimensionless NS spin being chosen to be $|\chi| \leq 0.05$ [1]. This limit is later corrected to be $\tilde{\Lambda} \lesssim 900$ in Ref. [15], where the result of updated analysis is also reported as, e.g., $\tilde{\Lambda} = 300_{-230}^{+420}$ for a particular set of assumptions. The constraint can be further improved by assuming the EOS to be common for both NS [16, 17] (but see also Ref. [18]) as is also done in an independent analysis [19, 20]. These constraints are used to investigate the NS EOS [21–23] as well as those for quark and hybrid stars [24–26]. While it has been claimed based on a limited number of numerical-relativity (NR) simulations that $\tilde{\Lambda} \gtrsim 400$ is necessary to account for the ejecta mass of $\approx 0.05M_{\odot}$ required to explain AT 2017gfo [27], later systematic investigations reveal that this argument is premature [5].

An accurate theoretical waveform template is crucial to extract accurately the tidal deformability of NSs from the observed gravitational-wave data. For the early stage of the inspiral, the waveforms including the linear-order tidal effects derived by post-Newtonian (PN) calculation are useful [28, 29]. However, the PN expansion becomes invalid as the orbit becomes relativistic, and thus, the error of the waveform becomes large in the late stage [30–33]. Such errors would cause the systematic bias in the parameter estimation, and it would be in particular problematic for estimating the tidal deformability because the tidal effects on the waveform become most significant just before the merger [34, 35]. The effective-one-body (EOB) formalism can solve this problem by incorporating the higher-order PN correction by re-summation techniques and calibrating them to NR waveforms [34, 36–39]. However, such calibration is performed only focusing on binary black holes (BBHs), and the calibration of the tidal correction employing NR simulation data of BNSs is also required.

Dietrich *et al.* have derived a gravitational waveform model, `NRTidal`, for BNSs based on high-precision NR simulations [40]. Improved reanalyses of GW170817 with more sophisticated waveform models calibrated by NR simulation of BNS merger have been performed employing such a model [15]. Indeed, it is pointed out that the value of the tidal deformability tends to be overestimated if the PN models are employed for the parameter estimation [1]. Recently its upgrade, the `NRTidalv2` model, which is calibrated by more precise NR waveforms, has been derived [41]. Kawaguchi *et al.* have also developed a model (hereafter the `KyotoTidal` model) for frequency-domain gravitational waveforms of inspiraling BNSs [42]. In particular, this model is derived independently from the `NRTidal` model employing different NR waveforms. Since the `NRTidal` model is so far the only NR calibrated waveform model that is used for parameter estimation of gravitational waves from BNS mergers, the analysis comparing these three NR-calibrated waveform models would help us to understand the systematic biases in resulting constraints on tidal deformability.

In this paper, we reanalyze the data around

GW170817 against a NR calibrated waveform model, the `TF2+KyotoTidal` model and present constraints on the binary tidal deformability. We also reanalyze the event with other waveform models: two PN (`TF2_PNTidal` and `TF2+PNTidal`), `TF2+NRTidal`, and `TF2+NRTidalv2` models.

The remainder of this paper is organized as follows. In Sec. II, we explain the methods for parameter estimation including waveform models used to reanalyze GW170817. In Sec. III, we present results of our analysis of GW170817, a comparison of our analysis with the LIGO-Virgo analysis and a separate analysis for the LIGO twin detectors. In Sec. IV, we discuss a systematic error in estimation of the binary tidal deformability among waveform models. Section V is devoted to a summary. In Appendix, we present an in-depth study of our results by separate analysis for the LIGO twin detectors to interpret the origin of the complex structure at high- $\tilde{\Lambda}$ region for the posterior probability density function (PDF) of $\tilde{\Lambda}$ (see also Ref. [43]). Unless otherwise stated, we employ the units $c = G = 1$, where c and G are the speed of light and the gravitational constant, respectively.

II. PARAMETER ESTIMATION METHODS

A. Data and Bayesian inference

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 LVC¹. We calculate the posterior PDF, $p(\vec{\theta}|\vec{s}(t), H)$, for the binary parameters $\vec{\theta}$ for the gravitational waveform model, H , given the LIGO Hanford, LIGO Livingston, and Virgo data $\vec{s}(t)$ via

$$p(\vec{\theta}|\vec{s}(t), H) \propto p(\vec{\theta}|H)p(\vec{s}(t)|\vec{\theta}, H). \quad (1)$$

$p(\vec{\theta}|H)$ is the prior for the binary parameters. The likelihood $p(\vec{s}(t)|\vec{\theta}, H)$ is evaluated by assuming stationarity and Gaussianity for the detector noise using the noise power spectrum density derived with BayesLine². 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_{\max} . Here, the maximum frequency f_{\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-T1700406/public> for Livingston

² <https://dcc.ligo.org/LIGO-P1900011/public>

f_{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+_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_{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
<code>TF2_PNTidal</code>	3PN	3.5PN	5+1PN	5+2.5PN
<code>TF2+_PNTidal</code>	6PN	6PN	5+1PN	5+2.5PN
<code>TF2+_KyotoTidal</code>	6PN	6PN	Polynomial	Nonlinear
<code>TF2+_NRTidal</code>	6PN	6PN	-	Padé approximation
<code>TF2+_NRTidalv2</code>	6PN	6PN	Padé approximation	Padé approximation

TABLE I. Waveform models used to reanalyze GW170817. Our reference model, the `TF2+_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+_NRTidal` model is another model whose tidal effects are calibrated by NR. The `TF2+_NRTidalv2` model is the upgrade of the `TF2+_NRTidal` model. The `TF2_PNTidal` and `TF2+_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

$$\tilde{h}(f) = A(f)e^{i\Psi(f)}. \quad (2)$$

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

$$A(f) = A_{\text{point-particle}}(f) + A_{\text{spin}}(f) + A_{\text{tidal}}(f) \quad (3)$$

and

$$\Psi(f) = \Psi_{\text{point-particle}}(f) + \Psi_{\text{spin}}(f) + \Psi_{\text{tidal}}(f). \quad (4)$$

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` [49]. 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 \mathcal{E}_{ij} as $Q_{ij} = -\lambda\mathcal{E}_{ij}$. The information about the NS EOS can be quantified by the tidal deformability parameter λ [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 [28]

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

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 subdominant on the tidal effects to the gravitational-wave phase and the symmetric contribution $\tilde{\Lambda}$ terms dominate [30, 33]. In this paper, we ignore the $\delta\tilde{\Lambda}$ contribution.

The `TF2_PNTidal` model and the `TF2+_PNTidal` model denote the waveform models employing `TF2` and `TF2+` as the BBH baseline, respectively. Both the `TF2_PNTidal` and the `TF2+_PNTidal` models employ the 2.5PN-order (relative 5+2.5PN-order) tidal-part phase

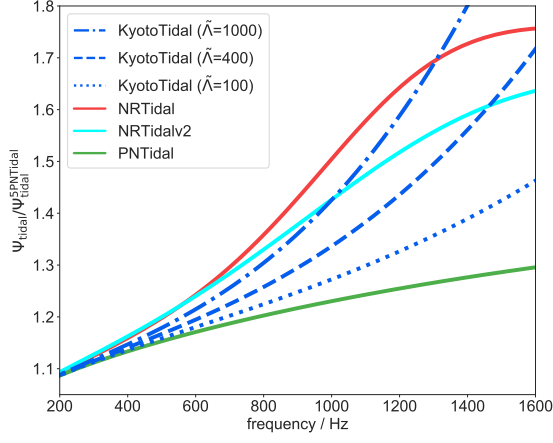


FIG. 1. Tidal phase in the frequency domain normalized by the leading, Newtonian (relative 5PN-order) tidal phase formula. Here, we use $(m_1, m_2) = (1.35M_\odot, 1.35M_\odot)$. We show $\tilde{\Lambda} = 1000$ (dot-dashed, blue), 400 (dashed, blue), and 100 (dotted, blue) for the `KyotoTidal` model. The `NRTidal` model (solid, red), the `NRTidalv2` model (solid, cyan), and the 5+2.5PN-order tidal-part phase formula, `PNTidal` (solid, green) are also presented, which are independent of $\tilde{\Lambda}$ when normalized by the leading tidal phase.

formula [34]

$$\Psi_{\text{tidal}}^{\text{PNTidal}} = \frac{3}{128\eta} \left[-\frac{39}{2} \tilde{\Lambda} x^{5/2} \times \left(1 + \frac{3115}{1248} x - \pi x^{3/2} + \frac{28024205}{3302208} x^2 - \frac{4283}{1092} \pi x^{5/2} \right) \right], \quad (6)$$

where $x = (\pi M_{\text{tot}} f)^{2/3}$ is the dimensionless PN parameter, $M_{\text{tot}} = m_1 + m_2$ is the total mass, and $\eta = m_1 m_2 / (m_1 + m_2)^2$ is the symmetric mass ratio. The tidal-part amplitude for both `TF2+PNTidal` and `TF2+NRTidal` employ the 5+1PN-order amplitude formula given by [34]

$$A_{\text{tidal}}^{\text{PNTidal}} = \sqrt{\frac{5\pi\eta}{24} \frac{M_{\text{tot}}^2 (1+z)^2}{d_L}} \tilde{\Lambda} x^{-7/4} \times \left(-\frac{27}{16} x^5 - \frac{449}{64} x^6 \right), \quad (7)$$

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 [42, 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 [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

$$\Psi_{\text{tidal}}^{\text{KyotoTidal}} = \frac{3}{128\eta} \left[-\frac{39}{2} \tilde{\Lambda} \left(1 + a \tilde{\Lambda}^{2/3} x^p \right) \right] x^{5/2} \times \left(1 + \frac{3115}{1248} x - \pi x^{3/2} + \frac{28024205}{3302208} x^2 - \frac{4283}{1092} \pi x^{5/2} \right), \quad (8)$$

where $a = 12.55$ and $p = 4.240$. The tidal-part amplitude is extended by adding the higher-order PN tidal effects to Eq. (7) as

$$A_{\text{tidal}}^{\text{KyotoTidal}} = \sqrt{\frac{5\pi\eta}{24} \frac{M_{\text{tot}}^2 (1+z)^2}{d_L}} \tilde{\Lambda} x^{-7/4} \times \left(-\frac{27}{16} x^5 - \frac{449}{64} x^6 - b x^r \right), \quad (9)$$

where $b = 4251$ and $r = 7.890$. In the `KyotoTidal` model, the hybrid waveforms constructed from high-precision NR waveforms and the `SEOBNRv2T` waveforms [50, 51, 57–59] are used for model calibration in the frequency range of 10-1000 Hz. The phase difference between the `TF2+KyotoTidal` model and the hybrid waveforms is smaller than 0.1 rad up to 1000 Hz for $300 \lesssim \tilde{\Lambda} \lesssim 1900$ and for the mass ratio $q = m_2/m_1 \leq 1$ between 0.73 and 1 [42]. In [42], it is shown that the mismatch between the `TF2+KyotoTidal` model and the hybrid waveforms is always smaller than 1.1×10^{-5} in the frequency range of 10-1000 Hz.

The `NRTidal` model is another approach to describe tidal effects calibrated by NR waveforms [40]. The `TF2+NRTidal` model employs `TF2+` as the BBH baseline. For the tidal effects, this model extends the linear-order effects by effectively adding the higher-order PN terms of the tidal contribution to the gravitational-wave phase. As shown in Ref. [40], the expression of the tidal phase is given by the form of a rational function:

$$\Psi_{\text{tidal}}^{\text{NRTidal}} = \frac{3}{128\eta} \left[-\frac{39}{2} \tilde{\Lambda} x^{5/2} \times \frac{1 + \tilde{n}_1 x + \tilde{n}_{3/2} x^{3/2} + \tilde{n}_2 x^2 + \tilde{n}_{5/2} x^{5/2}}{1 + \tilde{d}_1 x + \tilde{d}_{3/2} x^{3/2}} \right], \quad (10)$$

where $\tilde{d}_1 = \tilde{n}_1 - 3115/1248$, the other parameters are $(\tilde{n}_1, \tilde{n}_{3/2}, \tilde{n}_2, \tilde{n}_{5/2}) = (-17.428, 31.867, -26.414, 62.362)$ and $\tilde{d}_{3/2} = 36.089$. We do not consider the tidal-part amplitude for this model following the original form [40].

The `TF2+NRTidalv2` model is an upgrade of the `TF2+NRTidal` model [41]. Specifically, they derive a new expression for the tidal phase which is calibrated to more

accurate NR waveforms,

$$\Psi_{\text{tidal}}^{\text{NRTidalv2}} = \frac{3}{128\eta} \left[-\frac{39}{2} \tilde{\Lambda} x^{5/2} \right. \\ \left. \times \frac{1 + \tilde{n}'_1 x + \tilde{n}'_{3/2} x^{3/2} + \tilde{n}'_2 x^2 + \tilde{n}'_{5/2} x^{5/2} + \tilde{n}'_3 x^3}{1 + \tilde{d}'_1 x + \tilde{d}'_{3/2} x^{3/2} + \tilde{d}'_2 x^2} \right], \quad (11)$$

with $\tilde{n}'_1 = \tilde{c}'_1 + \tilde{d}'_1$, $\tilde{n}'_{3/2} = (\tilde{c}'_1 \tilde{c}'_{3/2} - \tilde{c}'_{5/2} - \tilde{c}'_{3/2} \tilde{d}'_1 + \tilde{n}'_{5/2}) / \tilde{c}'_1$, $\tilde{n}'_2 = \tilde{c}'_2 + \tilde{c}'_1 \tilde{d}'_1 + \tilde{d}'_2$, $\tilde{d}'_{3/2} = -(\tilde{c}'_{5/2} + \tilde{c}'_{3/2} \tilde{d}'_1 - \tilde{n}'_{5/2}) / \tilde{c}'_1$, where the known coefficients are $\tilde{c}'_1 = 3115/1248$, $\tilde{c}'_{3/2} = -\pi$, $\tilde{c}'_2 = 28024205/3302208$, $\tilde{c}'_{5/2} = -4283\pi/1092$, and the fitting coefficients are $\tilde{n}'_{5/2} = 90.550822$, $\tilde{n}'_3 = -60.253578$, $\tilde{d}'_1 = -15.111208$, $\tilde{d}'_2 = 8.0641096$. They also introduce the tidal amplitude.

$$A_{\text{tidal}}^{\text{NRTidalv2}} = \sqrt{\frac{5\pi\eta}{24}} \frac{M_{\text{tot}}^2 (1+z)^2}{d_L} \tilde{\Lambda} x^{-7/4} \\ \times \left(-\frac{27}{16} x^5 \right) \frac{1 + \frac{449}{108} x + \frac{22672}{9} x^{2.89}}{1 + dx^4}, \quad (12)$$

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 $\tilde{\Lambda} \simeq 1000$ 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 ~ 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 about 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 θ_{JN} , which is the angle between the total angular momentum and the line of sight, the polarization angle ψ , the coalescence time t_c , the phase at the coalescence time ϕ_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 $\chi_{1,2} = cS_{1,2}/(Gm_{1,2}^2)$ is the orbit-aligned dimensionless spin components of the stars with $S_{1,2}$ 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 $\mathcal{M}^{\text{det}} \sim U[1.184, 2.168]M_\odot$, where the chirp mass is the best estimated mass parameter defined as $\mathcal{M} = (m_1 m_2)^{3/5} (m_1 + m_2)^{-1/5}$. The prior range for \mathcal{M}^{det} is the same as that used for LIGO-Virgo analysis [15]. The impact of wider prior range for \mathcal{M}^{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 II presents the 90% credible intervals of the luminosity distance d_L , the binary inclination θ_{JN} , mass parameters (the component masses $m_{1,2}$, the detector-frame chirp mass \mathcal{M}^{det} , the source-frame chirp mass \mathcal{M} , the total mass M_{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 $H_0 = 69 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (a default value in LAL).

For comparison of our analysis with the results of the previous LIGO-Virgo analysis [15, 63], 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, 48, 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 II 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

$f_{\max} = 2048$ Hz are almost the same as the ones for $f_{\max} = 1000$ 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 [34] 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.

	TF2_PNTidal	TF2+PNTidal	TF2+_KyotoTidal	TF2+_NRTidal	TF2+_NRTidalv2
Luminosity distance d_L [Mpc]	$40.0^{+7.3}_{-14.4}$	$39.8^{+7.5}_{-14.7}$	$39.9^{+7.3}_{-14.6}$	$39.9^{+7.4}_{-14.5}$	$39.6^{+7.7}_{-14.6}$
Binary inclination θ_{JN} [degree]	147^{+24}_{-32}	146^{+24}_{-27}	147^{+24}_{-28}	147^{+24}_{-27}	146^{+25}_{-27}
Detector-frame chirp mass \mathcal{M}^{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 \mathcal{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}]	$2.74^{+0.04}_{-0.01}$	$2.74^{+0.04}_{-0.01}$	$2.74^{+0.04}_{-0.01}$	$2.74^{+0.04}_{-0.01}$	$2.74^{+0.04}_{-0.01}$
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)
Effective spin χ_{eff}	$0.002^{+0.015}_{-0.009}$	$0.003^{+0.015}_{-0.009}$	$0.003^{+0.014}_{-0.008}$	$0.002^{+0.015}_{-0.008}$	$0.003^{+0.014}_{-0.008}$

TABLE II. 90% credible interval of the luminosity distance d_L , the binary inclination θ_{JN} , mass parameters, and the effective spin parameter χ_{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.

Model	$f_{\max} = 1000$ Hz		$f_{\max} = 2048$ Hz	
	Symmetric	HPD	Symmetric	HPD
TF2_PNTidal	548^{+500}_{-415}	548^{+433}_{-463}	376^{+584}_{-284}	376^{+442}_{-353}
TF2+_PNTidal	569^{+496}_{-431}	569^{+441}_{-470}	428^{+540}_{-280}	428^{+414}_{-353}
TF2+_KyotoTidal	481^{+436}_{-359}	481^{+379}_{-402}	402^{+465}_{-279}	402^{+419}_{-316}
TF2+_NRTidal	403^{+378}_{-299}	403^{+328}_{-337}	267^{+491}_{-180}	267^{+409}_{-228}
TF2+_NRTidalv2	445^{+412}_{-330}	445^{+357}_{-370}	312^{+498}_{-208}	312^{+407}_{-263}

TABLE III. 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 $f_{\max} = 1000$ Hz (left side) and 2048 Hz (right side), where the median is shown as a representative value.

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-

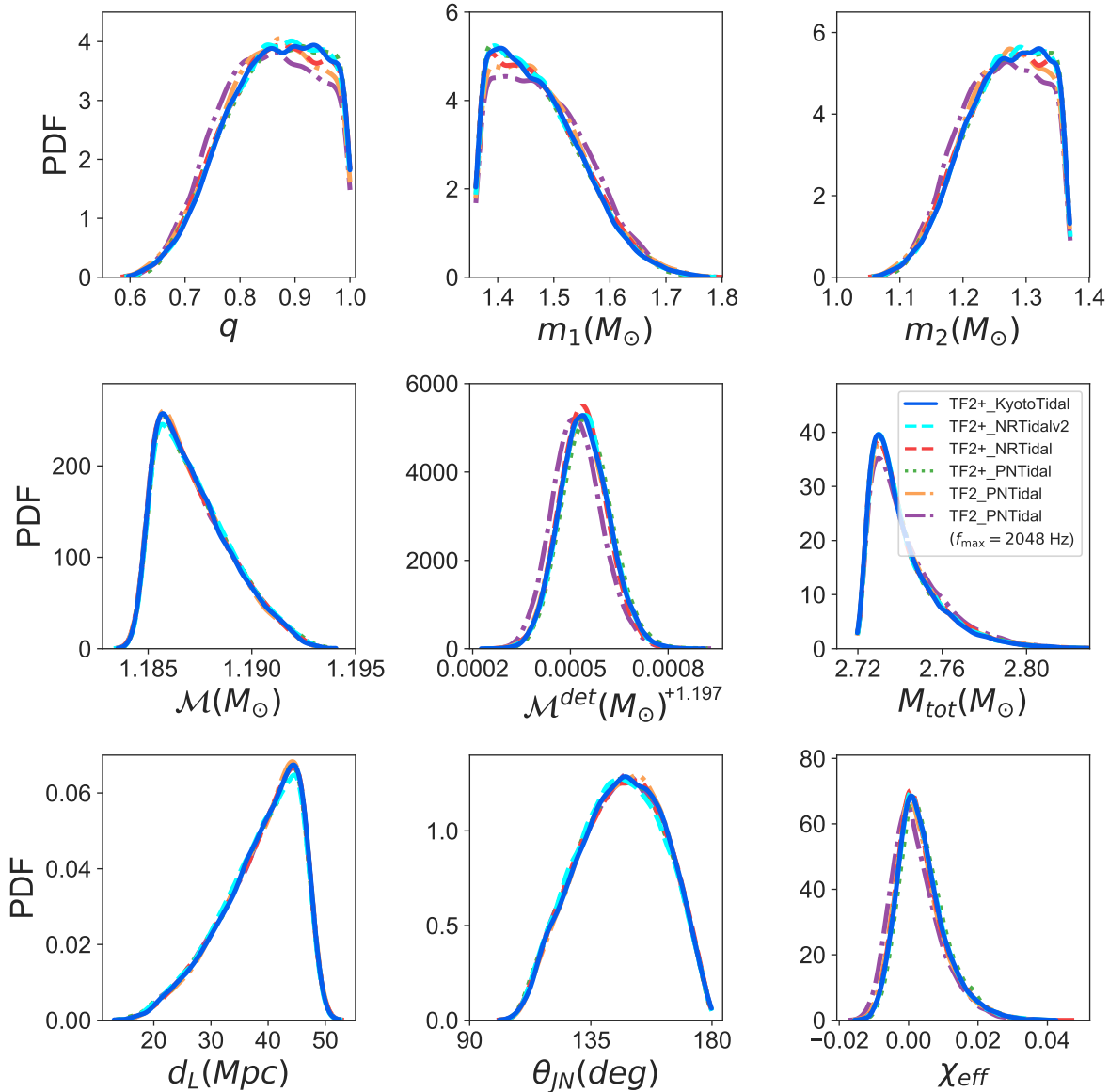


FIG. 2. Marginalized posterior PDFs of various parameters derived by different waveform models. The blue, cyan, red, green, and orange curves correspond to the TF2+_KyotoTidal model, the TF2+_NRTidalv2 model, the TF2+_NRTidal model, the TF2+_PNTidal model, and the TF2_PNTidal model, respectively. The top-left, top-middle, top-right, middle-left, center, middle-right, bottom-left, bottom-middle, and bottom-right panels show the mass ratio q , the primary mass m_1 , the secondary mass m_2 , the source-frame chirp mass \mathcal{M} , the detector-frame chirp mass \mathcal{M}_{det} , the total mass M_{tot} , the luminosity distance to the source d_L , the inclination angle θ_{JN} , and the effective spin parameter χ_{eff} , respectively. Here, we show the distribution for $f_{\text{max}} = 1000$ Hz, except for the TF2_PNTidal model, for which the intervals for both $f_{\text{max}} = 1000$ Hz and $f_{\text{max}} = 2048$ Hz are given.

Virgo analysis [15] as a sanity check. While our result of 90% credible symmetric (highest posterior density (HPD)) interval on $\tilde{\Lambda}$ 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 $\tilde{\Lambda} = 340^{+580}_{-240}$ (340^{+490}_{-290}) in [15]. Here, both analyses assume a uniform prior on Λ_1 and Λ_2 and

weighted the posterior for $\tilde{\Lambda}$ by dividing by the prior, effectively imposing a uniform prior in $\tilde{\Lambda}$. 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 $\tilde{\Lambda}$, 90% credible symmetric (HPD) interval on $\tilde{\Lambda}$ is 316^{+504}_{-224} (316^{+367}_{-291}) for restricted TF2 with 5+1PN-order

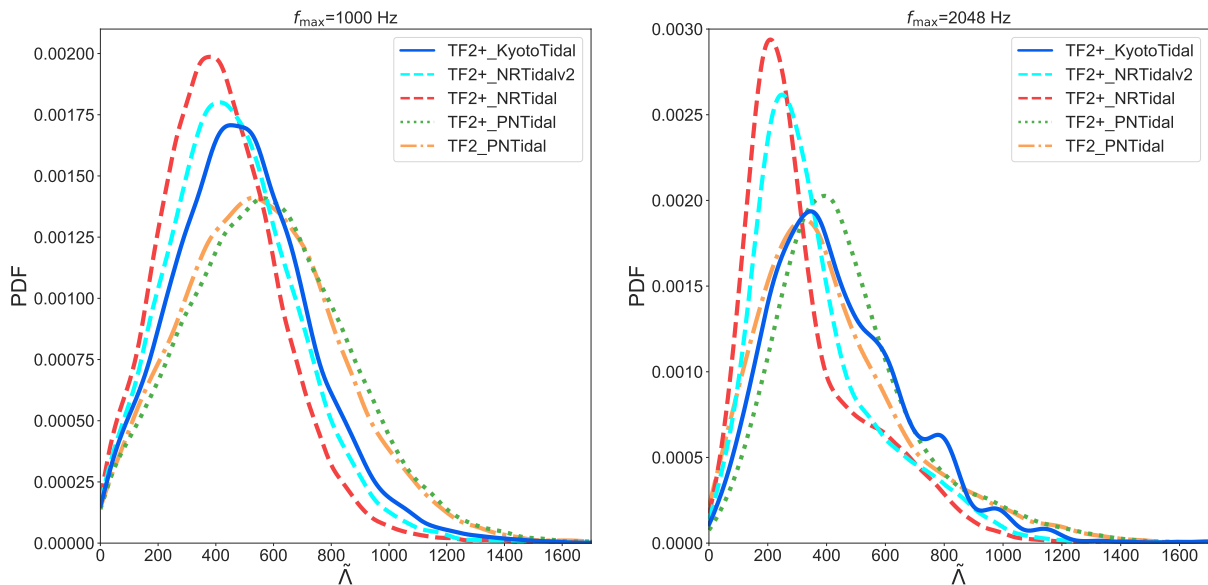


FIG. 3. Marginalized posterior PDFs of binary tidal deformability, $\tilde{\Lambda}$, estimated by different waveform models, for both $f_{\max} = 1000$ Hz (left panel) and 2048 Hz (right panel). The blue, cyan, red, green, and orange curves correspond to the TF2+_KyotoTidal model, the TF2+_NRTidalv2 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.

tidal-part phase.

Figure 3 shows the marginalized posterior PDFs for the binary tidal deformability $\tilde{\Lambda}$ for different waveform models for both $f_{\max} = 1000$ Hz (left panel) and 2048 Hz (right panel). 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 $f_{\max} = 2048$ Hz should be regarded as only a reference.

For $f_{\max} = 1000$ Hz (left panel of Fig. 3), the peak values of $\tilde{\Lambda}$ are 400-500 and the 90% credible intervals do not extend to $\gtrsim 900$ 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 $f_{\max} = 1000$ 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 $f_{\max} = 1000$ Hz.

For $f_{\max} = 2048$ Hz (right panel of Fig. 3), the peak values of $\tilde{\Lambda}$ are 250-400 and the 90% credible intervals do not extend to $\gtrsim 850$ for NR calibrated waveform models. The width of symmetric 90% credible intervals for $f_{\max} = 2048$ Hz are narrower than those for $f_{\max} = 1000$ Hz, by about 7% for the TF2+_KyotoTidal model, 4% for the TF2+_NRTidal model, 5% for the TF2+_NRTidalv2 model, 13% for the TF2+_PNTidal model, and about 5% for the TF2_PNTidal model, as shown in Table III. These decrease in the width of the interval are consistent with the fact that higher-frequency data are more informative to measure $\tilde{\Lambda}$ [34]. The peak values of the posterior PDFs of $\tilde{\Lambda}$ tend to decrease as f_{\max} increases for all waveform models as shown in Fig. 3. The order of peak values of $\tilde{\Lambda}$ for the different waveform models that incorporate the same BBH baseline, TF2+, is not affected by varying f_{\max} as shown in Fig. 3. This is explained by the same reason as that for $f_{\max} = 1000$ Hz. We note that 1400 Hz approximately corresponds to f_{ISCO} for estimated mass

range. The `TF2_PNTidal` model gives slightly smaller peak value than the `TF2+KyotoTidal` 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+PNTidal` and `TF2_PNTidal` models for $f_{\max} = 2048$ Hz is larger than that for $f_{\max} = 1000$ Hz (see Fig. 3 and Table III). 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 III). Here, we use differences in the peak values of the posterior PDFs of $\tilde{\Lambda}$ as an indicator of the systematic error.

For $f_{\max} = 1000$ Hz, there are differences in the peak values of $\tilde{\Lambda}$, by about 40 between NR calibrated waveform models (the `TF2+KyotoTidal` and `TF2+NRTidalv2` models) and by about 110 between NR calibrated waveform and PN waveform models (the `TF2+KyotoTidal` and `TF2+PNTidal` 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+KyotoTidal` model and the `TF2+PNTidal` model can be significant. Comparing the `TF2+KyotoTidal` with `TF2+NRTidalv2` 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+KyotoTidal` and `TF2+NRTidalv2` 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 detec-

tors's sensitivities and verifying how well current waveform models recover the injected values for future work.

$\tilde{\Lambda}$ is indeed determined more precisely for all waveform models in our analysis for $f_{\max} = 2048$ Hz than for $f_{\max} = 1000$ Hz as indicated in Sec. III. However, since the `TF2+KyotoTidal` 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+KyotoTidal` model. The `TF2+KyotoTidal` 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+KyotoTidal` model, the nonlinear effects of the tidal deformability is incorporated. We also reanalyze the event with other waveform models: two PN waveform models (`TF2_PNTidal` and `TF2+PNTidal`), the `TF2+NRTidal` model that is another NR calibrated waveform model, and its upgrade, the `TF2+NRTidalv2` 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 $f_{\max} = 1000$ 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+KyotoTidal` and `TF2+NRTidalv2` 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 $f_{\max} = 2048$ Hz than for $f_{\max} = 1000$ Hz. For the `TF2+KyotoTidal` model, the 90% symmetric interval of $\tilde{\Lambda}$ for $f_{\max} = 2048$ Hz is about 7% narrower than that for $f_{\max} = 1000$ Hz. Though the estimate of $\tilde{\Lambda}$ becomes narrower as the f_{\max} increases, the `TF2+KyotoTidal` model is calibrated only up to 1000 Hz. Since higher frequency data are more informative for $\tilde{\Lambda}$ [34], 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.

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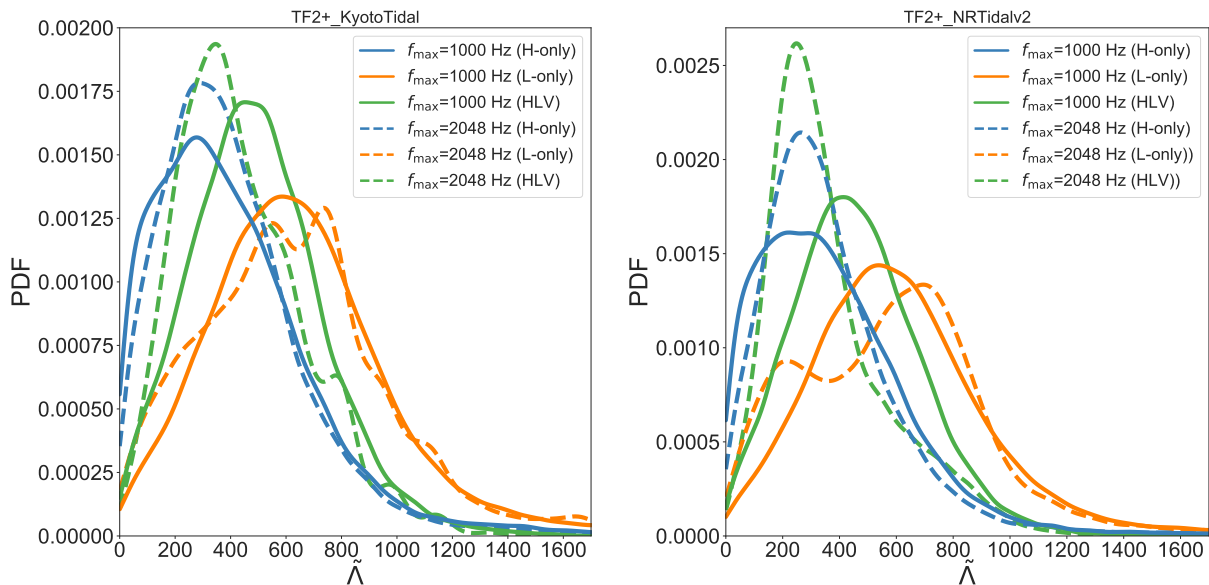


FIG. 4. Marginalized posterior PDFs of binary tidal deformability, $\tilde{\Lambda}$, derived by data of different detector combinations with both $f_{\max} = 1000$ Hz (solid) and 2048 Hz (dashed) for the TF2+_KyotoTidal (left panel) and the TF2+_NRTidalv2 (right panel) models. The distribution derived 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 $f_{\max} = 2048$ Hz, a multimodal (bump) structure at high- $\tilde{\Lambda}$ for the TF2+_KyotoTidal (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 TF2+_KyotoTidal model

and a bump structure for the TF2+_NRTidal and TF2+_NRTidalv2 models for $f_{\max} = 2048$ 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_{\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.

f_{\max}	TF2+ <i>KyotoTidal</i>		TF2+ <i>NRTidalv2</i>	
	Hanford-only	Livingston-only	Hanford-only	Livingston-only
	Symmetric			
1000 Hz	357^{+568}_{-311}	618^{+637}_{-447}	333^{+514}_{-291}	582^{+586}_{-413}
2048 Hz	362^{+514}_{-295}	607^{+658}_{-482}	320^{+481}_{-253}	589^{+549}_{-487}
	HPD			
1000 Hz	357^{+414}_{-357}	618^{+502}_{-523}	333^{+378}_{-333}	582^{+477}_{-484}
2048 Hz	362^{+378}_{-352}	607^{+511}_{-557}	320^{+355}_{-305}	589^{+399}_{-555}

tors. Figure 4 shows marginalized posterior of $\tilde{\Lambda}$ derived by separate analysis for the Hanford and Livingston detectors with both $f_{\max} = 1000$ Hz and 2048 Hz for the TF2+*KyotoTidal* model (left panel) and the TF2+*NRTidalv2* model (right panel). Table IV shows corresponding 90% credible interval of $\tilde{\Lambda}$.

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 $f_{\max} = 2048$ Hz for the HLV combined data is as follows. On the one hand, for the Livingston data, the unimodal distribution for $f_{\max} = 1000$ Hz, whose peak is at about 600, is separated into a bimodal distribution for $f_{\max} = 2048$ 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 $f_{\max} = 1000$ Hz, whose peak is at low- $\tilde{\Lambda}$ region, shrinks for $f_{\max} = 2048$ Hz. As a result, for $f_{\max} = 2048$ 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 $f_{\max} = 2048$ 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 $f_{\max} = 2048$ 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 SEOBNRv4_ROM_NRTidal model in the case of LIGO-Virgo analysis as shown in Fig. 11 in [15], a small high- $\tilde{\Lambda}$ bump at $\tilde{\Lambda} \sim 600$ appears in that with

the TF2+*NRTidal* model presented for $f_{\max} = 2048$ Hz in the right panel of Fig. 3. Here, SEOBNRv4_NRTidal is constructed from the SEOBNRv4 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 Λ_1 and Λ_2 and weighted the posterior for $\tilde{\Lambda}$ by dividing by the prior, effectively imposing a uniform prior in $\tilde{\Lambda}$. Figure 5 shows the dependence of the results on different priors in $\tilde{\Lambda}$, “ $\Lambda_{1,2}$ -flat”, “Weighted”, and “ $\tilde{\Lambda}$ -flat” for the TF2+*NRTidal* model with $f_{\max} = 2048$ Hz. This figure demonstrate that the distribution for “ $\Lambda_{1,2}$ -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_{\max} increases indicate that the Livingston’s high-frequency data are not very useful to determine the tidal deformability for GW170817.

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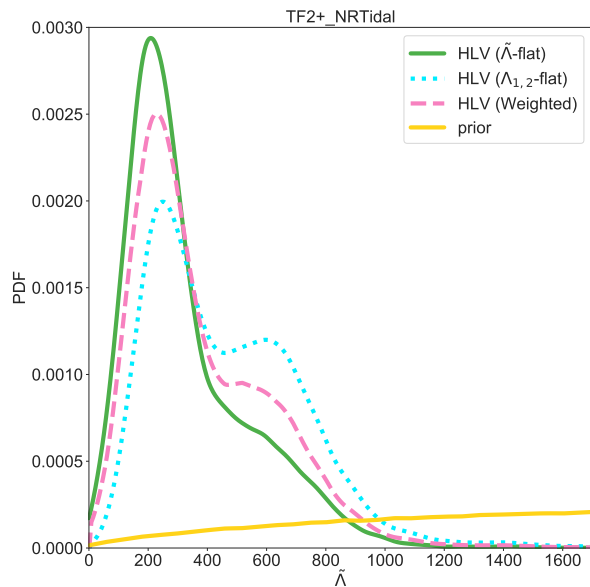


FIG. 5. Dependence of the marginalized posterior PDFs of $\tilde{\Lambda}$ on different priors in $\tilde{\Lambda}$ for the TF2+_{NRTidal} model with $f_{\max} = 2048$ Hz. In addition to PDF of $\tilde{\Lambda}$ for a uniform priors in Λ_1 and Λ_2 (dotted, cyan), we show the PDF for “Weighted”-prior (dashed, magenta), which is weighted by dividing the original prior (also shown by solid yellow curve) and the PDF for a uniform prior in $\tilde{\Lambda}$ (solid, green)

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