Accessing Universal Relations of Binary Neutron Star Waveforms in Massive Scalar-Tensor Theory

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(Received 10 October 2024; revised 19 February 2025; accepted 27 March 2025; published 15 April 2025)

We investigate how the quasiuniversal relations connecting tidal deformability with gravitational waveform characteristics and/or properties of individual neutron stars that were proposed in the literature within general relativity would be influenced in the massive Damour-Esposito-Farese-type scalar-tensor gravity. For this purpose, we systematically perform numerical relativity simulations of ~120 binary neutron-star mergers with varying scalar coupling constants. Although only three neutron-star equations of state are adopted, a clear breach of universality can be observed in the datasets. In addition to presenting difficulties in constructing quasiuniversal relations in alternative gravity theories, we also briefly compare the impacts of non-general-relativity physics on the waveform features and those due to the first order or cross-over quantum chromodynamical phase transition.

DOI: 10.1103/PhysRevLett.134.151402

Introduction—Coalescence of binary neutron stars (BNSs) offers a unique avenue for testing gravity in its strong regime and for probing thermodynamic states of matter at subatomic densities. The gravitational wave (GW) signal originating from such a process was detected for the first time in 2017 by LIGO and VIRGO observatories [1,2], though only in the late-inspiral epoch. This event, GW170817 [3–5], has led to certain constraints on gravitation [6–8] and the equation of state (EOS) of nuclear matter [9–12]. The analysis was conducted assuming general relativity (GR) as the underlying theory of gravity to agnostically bound the deviation of the observation from the prediction of GR. However, tests of a specific alternative theory of gravity require the development of waveform templates within the theory and may entail certain modifications in the data analysis formalism. Although analytic efforts in waveform modeling have been devoted to some theories, e.g., the scalar-tensor theory and the scalar-Gauss-Bonnet theory, a lot remains to be done to establish machinery at the same level of sophistication as that in GR to analyze GWs.

GWs emitted during and in the aftermath of the merger would lie in the frequency band of 2–4 kHz if the system produces a hypermassive neutron star (HMNS) as a transient remnant [13–15]. The current ground-based GW detectors are less sensitive in these bands [16–18]; in fact, even with the design sensitivity of Advanced LIGO, the postmerger waveform of a GW170817-like event might only have a SNR of ~2–3, which can hardly be detected. However, waveforms at a few kHz may be reachable with the next-generation detectors such as the Einstein Telescope [19–21] and the Cosmic Explorer [22–24], for which the sensitivity is by a factor of $\gtrsim 10$ higher than those of current detectors.

Postmerger waveforms are informative of the dynamics of remnant systems. Of particular interest are the mergers that lead to an HMNS temporarily supported by differential rotations [25,26] and high thermal pressure [27–30]. The fluid motions within these remnants will emit a loud GW transient over ~10–20 ms with characteristic frequencies corresponding to the oscillation modes excited in the remnant massive NS [14,26,28,31–35]. The dominant peak in the spectrum can be related to the fundamental mode of the remnant, whose frequency depends sensitively on both the EOS and the underlying gravitational theory [36–38]. Therefore, the measurement of this frequency provides combined information about the nature of gravity and supranuclear matters.

However, to what extent we can learn about the gravitation and the EOS is subject to at least these technical and theoretical challenges: (i) the morphology of the postmerger waveforms is qualitatively different from that of inspiral, requiring different modeling and analysis strategies [39–41], and (ii) the influences of the microphysics and the gravitational aspects of the problem on waveforms

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are strongly degenerate [42], which hinders a clear determination of matter effects and deviations from GR. One of the cogent proposals to address the latter issue appeals to quasiuniversal relations that connect the spectral properties of postmerger waveforms with properties of cold stars in isolation or participating in a coalescing binary.

Within GR, these quasiuniversal relations are leveraged to infer quantities that are not directly observable [43–48], facilitate efficient Bayesian analysis [49–53], and develop phenomenological waveform models by reducing the degrees of freedom of the matter [35,54–56]. In alternative theories, the EOS-insensitive feature of these relations will be useful in disentangling the EOS effects from gravity and, thus, can help to distinguish non-GR imprints from the uncertainties of the EOS. However, this method requires a cautious evaluation of the reliability of these relations in the gravity theory under study to prevent any contamination in the inference. Taking the massive Damour-Esposito-Farese-type (DEF; [57–60]) scalar-tensor theory of gravity as an example, whose action is given as [61–63],

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left[\phi\mathcal{R} - \frac{\omega(\phi)}{\phi}\nabla_a\phi\nabla^a\phi - \frac{2m_\phi^2\varphi^2\phi^2}{B}\right] - S_{\rm matter}, \tag{1}$$

we illustrate in the remainder of this Letter that many (if not all) of the quasiuniversal relations on the market are actually breached, hinting at a strong caveat of using them for Bayesian analysis. Here, $\mathcal{R}$ is the Ricci scalar associated with metric g_{ab}, g is the determinant of the metric, ϕ is the scalar field, $S_{\rm matter}$ is the action for matter, $\omega(\phi)$ is defined via $[\omega(\phi)+3/2]^{-1} = B\ln\phi$ for the scalar coupling constant B, and $\varphi = \sqrt{2\ln\phi}$ is an auxiliary scalar field. The scalar mass has been constrained by pulsar observations [64–66] as $m_\phi > 10^{-15}$ eV [67,68]. In addition, GW170817 can tentatively suggest a lower bound on scalar mass as $m_\phi > 10^{-12}$ eV [62,69]. In this Letter, we will consider $m_\phi = 1.33\times10^{-11}$ eV (Compton wavelength of $\approx$15 km), which suffices to demonstrate the main conclusion: we will emphasize the violation of the quasiuniversal relations, which can only be more profound for smaller m_ϕ.

For the simulations in this Letter, the coupling constants have been chosen such that the non-GR effects can only marginally appear during inspiral, and the scalar effect mainly emerges when coalescing in order to respect the observation of GW170817 in [63]. The radius-mass and tidal deformability-mass relations are shown in Fig. 1 (see Supplemental Material [70] for the equations used to compute tidal deformability in the massive DEF theory, while those for the massless theory can be found in [71–73]). We can see a qualitative difference between the sequence of the H4 EOS and those of the other two EOSs: the scalarized sequence of equilibria of static, spherical stars does not merge into the GR branch in the high-density regime. The steep softening behavior of the H4 EOS at the high density prevents the revealing of a core that features a negative trace of the energy-stress tensor, staving off the conditions for descalarization (see, e.g., the discussion in Sec. III of [74]). The complete catalog of the simulated system is listed in Supplemental Material [70], while the details of numerical schemes and setups can be found in [63] as well as in [74,75]. We also note that the simulations included in this Letter focus on the postmerger evolution, and thus, the initial binary states were prepared at <5 orbits before the merger.

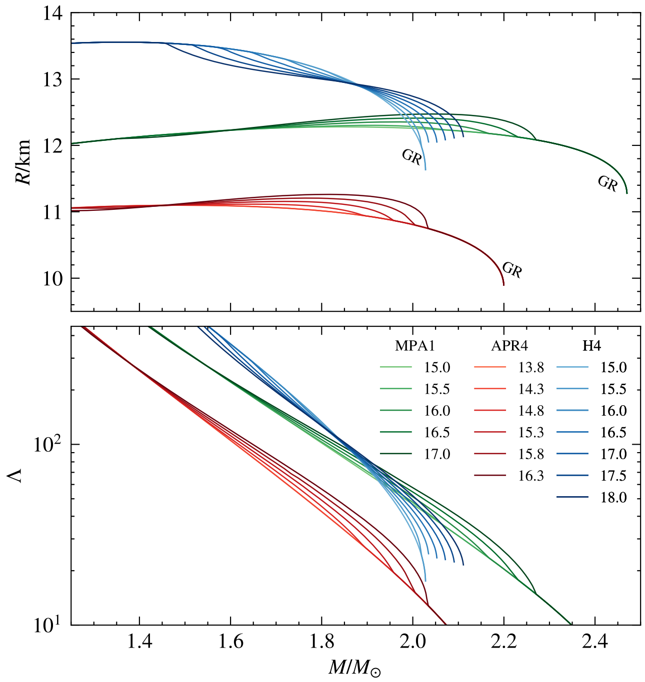

FIG. 1. The radius-mass (top), and the tidal deformability-mass (bottom) relations for the considered theories. The lines labeled "GR" represent the cases identical to those in GR. Three EOSs are considered in the piecewise-polytropic approximation [76]. For each EOS, a variety of scalar coupling constants (labels on the plot) are adopted while fixing the scalar mass as $m_\phi = 1.33\times10^{-11}$ eV.

Throughout, we adopt the geometrical units $c = G = 1$, and denote the ratio between the masses of binary as $q = m_2/m_1 \leq 1$, the instantaneous frequency of GWs at the merger as $f_{\rm peak}$, the GW amplitude at the merger as $h_{\rm peak}$ (here, the merger time is defined as the moment when the GW amplitude reaches the maximal), the threshold mass for prompt collapse to a black hole as $M_{\rm thr}$, and the frequency of the dominant peak in the postmerger waveform as f_2. The numerical results presented here are limited to simulations of equal-mass binaries, including those performed in the recent work [63] using theory-consistent quasiequilibrium states as initial data [62] and some simulations within GR newly performed here.

Correlations between $\tilde{\Lambda}$ and GW characteristics—The main tidal signature in inspiral waveforms depends predominantly on the binary tidal deformability $\tilde{\Lambda} = 16(m_1 + 12m_2)m_1^4\Lambda_1/13M^5 + (1 \leftrightarrow 2)$, where $M = m_1 + m_2$ and the tidal deformability of the individual stars are Λ_1 and Λ_2, respectively [77–81]. The estimate on $\tilde{\Lambda}$ for GW170817 yielded, though loosely, the first constraints on the yet unknown EOS of NSs while assuming GR as the gravitational theory. On the observation front, measurability of $\tilde{\Lambda}$ is within the uncertainty of $\sigma_{\tilde{\Lambda}} \sim 400$ at the 2σ level with current detectors [5,82,83] and is expected to be improved to $\sigma_{\tilde{\Lambda}} \lesssim 50$ at the 1σ level in the fifth observation mission [84,85]. It is owing to this dominant role of $\tilde{\Lambda}$ in affecting the phasing of waveforms that several quasiuniversal relations have been proposed to relate it with GW properties as introduced as follows.

Using numerical simulations, a quasiuniversal relation between $\tilde{\Lambda}$ and $f_{\rm peak}$ is found for $1.35 + 1.35M_\odot$ irrotational binaries [54,86]. The validity of this relation is extended in [35,87,88] to binaries with individual NSs having a mass of 1.2–1.65$M_\odot$ while keeping binaries as symmetric and irrotational. Aside from reading off the numerical results, Bernuzzi *et al.* [54] also discover this universality by inspecting effective-one-body waveform models, where the mass range is further extended to include the mass close to the Tolman–Oppenheimer–Volkoff limit for the respective EOS and includes a small spin up to $|\chi| = 0.1$. The influence of mass ratio on this relation is pointed out later on, which is evidenced by the simulations of asymmetric, irrotational binaries with varying mass ratios between 0.734–1 [89,90]. This motivates Kiuchi *et al.* [89] to generalize the relation to capturing the effect of mass asymmetry, and subsequently, the coefficients of the fitting formula acquire a q dependence.

The top panel of Fig. 2 shows our numerical results (the filled markers denote the GR data; numerical uncertainties in determining the considered characteristic properties are much less than the uncertainties of each fitting formula and, thus, are not shown on Fig. 2. However, we provide some information about the numerical uncertainties in Supplemental Material [70].) (the filled markers denote the GR data) together with the relation established in [89] when setting the coefficients for equal-mass binaries (dashed line). First, we see that the GR data deviates slightly from the fitting formula, but this is within the uncertainty of the fitting formula itself (4%; shaded area). The largest deviation is found as $\lesssim$5.8% in the middle range of $\tilde{\Lambda}$, which is near the low (high) end of our H4 (APR4 and MPA1) samples. We can also notice that the binaries that do not exhibit scalarization before the merger (squares) obey the quasiuniversal relation well with deviations falling below the fitting uncertainties given in the original papers of the associated quasiuniversal relations (grey). This is expected since the inspiral dynamics leading up to the merger are equivalent to in GR for these cases.

On the other hand, the relation tends to underestimate $f_{\rm peak}$ for a given $\tilde{\Lambda}$ for either spontaneously (circles) or

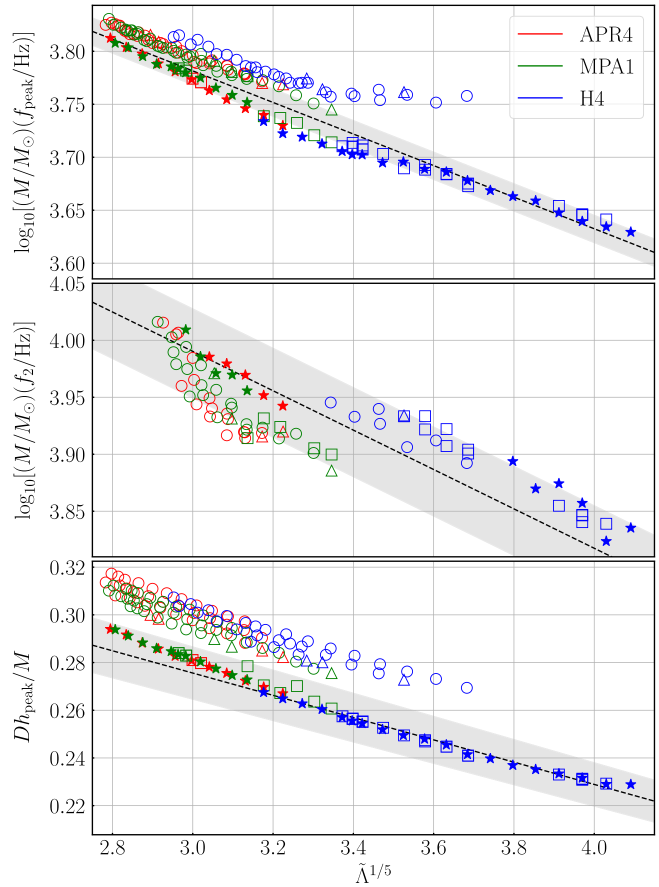

FIG. 2. Relations between binary tidal deformability $\tilde{\Lambda}$ and the frequency of the GW at the moment of merger (top), the frequency of the dominant peak of the postmerger waveform (middle), and the maximal strain of emitted GWs (bottom). The filled stars are the results of our simulations in GR, while open circles, triangles, and squares are for models with spontaneous scalarization, dynamical scalarization, and no scalarization in the inspiral phase, respectively. The dashed lines are the fitting formula proposed in [89].

dynamically (triangles) scalarized mergers, indicating that the orbital frequency right before the merger is systematically enhanced compared to the case with no scalarization. Although the deviation is still within the formula's uncertainty and does not show a decisive violation, the mergers with large $\tilde{\Lambda}$ (i.e., the stiff EOS H4) display a clear disagreement with the formula. In particular, $f_{\rm peak}$ for the EOS H4 is roughly constant for $\tilde{\Lambda}^{1/5} \gtrsim 3.4$ and, thus, differs further from the relation to the right of the plot.

On top of the GW frequency at the merger, Refs. [49,89,91,92] demonstrated that $\tilde{\Lambda}$ can also be quasiuniversally related to f_2 for a quite wide range of mass ratios ($0.67 \le q \le 1$) while commenting on a possible violation of the universality when including spinning and/or magnetized binaries. The relation is also proposed in [35,87], while their simulations were limited to nearly equal-mass binaries. Our data together with the formula in [89] are shown in the middle panel of Fig. 2, where the shaded area presents the fitting uncertainty of 9%. We note that mergers promptly collapsing into a black hole are not shown here since no information of f_2 can be extracted. For the GR cases, data points with the APR4 and MPA1 EOSs lie on the line within a minor deviation of $< 1\%$, while those with the H4 EOS are on the boundary of the fitting uncertainty. In contrast to the $\tilde{\Lambda}$-$Mf_{\rm peak}$ relation, the scalar field is always activated in the aftermath of the merger for the adopted coupling constants. Therefore, f_2 is naturally expected to be different from what would be predicted in GR. Indeed, we observe a systematic reduction in f_2 when $\tilde{\Lambda}^{1/5} \lesssim 3.4$, for the chosen samples with the soft EOSs APR4 and MPA1. However, the cases with the H4 EOS are quite consistent between GR and the considered DEF theories. The qualitatively distinct M-R curves between the H4 EOS and the other two EOSs (cf. Fig. 1) suggest a different trend in the results for the H4 EOS. However, pinpointing the reason is challenging as the f_2 frequency is determined by the interplay between gravity and the EOS in a highly dynamical environment, and this is precisely why numerical relativity is necessary to explore it.

In our simulations with the H4 EOS, the HMNS remnant in GR continuously contracts after formation and eventually collapses into a black hole with monotonically increasing maximum rest mass density throughout the process. By contrast, in the DEF theory, the HMNS undergoes scalarization within the first few milliseconds postmerger when the binaries have similar $\tilde{\Lambda}$, causing a transient decrease in maximum rest mass density before stabilizing in a quasistationary state that persists to the end of the simulation. Despite the qualitatively different evolutions, the resulting f_2 frequency is similar in both cases, exemplifying the degeneracy between gravitational and EOS effects in physical observables—an issue further illustrated by another example below. That said, a difference still exists between the GR and DEF scenarios: a prompt collapse realizes for $\tilde{\Lambda}^{1/5} \lesssim 3.8$ in GR, while an HMNS can still be formed until $\tilde{\Lambda}^{1/5} \lesssim 3.4$ depending on B.

Kiuchi *et al.* [89] further provide relations of $\tilde{\Lambda}$ to $h_{\rm peak}$. Again, we compare our numerical data of $h_{\rm peak}$ with their formula, shown in the bottom panel of Fig. 2. Our GR results progressively exceed the fitting formula for lower $\tilde{\Lambda}$, and the deviation reaches $\lesssim 3.3\%$ to the left side of the plot. In general, cases that are not scalarized in the inspiral epoch, including those in the DEF theory with weak scalar coupling and those in GR, align well with quasiuniversal relations. However, binaries endowed with a scalar cloud during inspiral exhibit a systematic upward shift from this trend.

Correlations between f_2 and properties of individual NSs—On top of the above relations, the frequency of the dominant mode in postmerger waveforms can also be universally connected to the certain properties of a cold spherical neutron star in isolation, e.g., the Love number ($\Lambda_{1.6}$) and radius ($R_{1.6}$) of the $1.6M_\odot$ NSs, assuming no strong phase transitions. In particular, Bauswein *et al.* proposed a f_2-$R_{1.6}$ relation [93,94] (see also [14]) from their simulations of $1.35 + 1.35M_\odot$ binaries while adopting the conformal flatness condition (CFC). The dataset for seeking such a relation has been significantly extended by including different M while keeping $q = 1$ in [95]. In the above work, the authors found different relations for each M and this dependence on M is also found later in [40]. On the other hand, focusing on binaries with similar total binary mass (viz. 2.7 and $2.6M_\odot$) for mass ratios $0.8 \leq q \leq 1$, Refs. [28,96] showed a consistent fitting, while the data spread broader away from the fitting formula as quantified in [89]. This relation is also substantially revised by including the chirp mass as an additional fitting parameter in [97]. In that work, the authors adopted the combined numerical results of equal-mass binary mergers under CFC with individual NS mass ranging from 1.2–$1.9M_\odot$, and the simulations withdrawing CFC of unequal-mass binaries with $q \geq 0.49$ for a mass range of 0.94–$1.94M_\odot$ released in the CORE database [98].

In Fig. 3, we show the comparison with the quasiuniversal relation obtained in [96]. Even in GR, the formula can only approximately describe the cases with the EOS H4, while the systems with the other softer EOSs are significantly below. The relative deviation is depicted in the bottom panel, where we see that the formula tends to overestimate f_2 frequency by $\gtrsim 10\%$ for the APR4 and MPA1 EOSs. Focusing on the numerical data, it can be noticed that $R_{1.6}$ is larger in the DEF theories for the APR4 and MPA1 EOSs, while the trend is reversed for the H4 EOS. The overall reduced value of f_2 in the DEF theories can seemingly be explained by the effective stiffening for the APR4 and MPA1 EOSs. However, such a rationale does

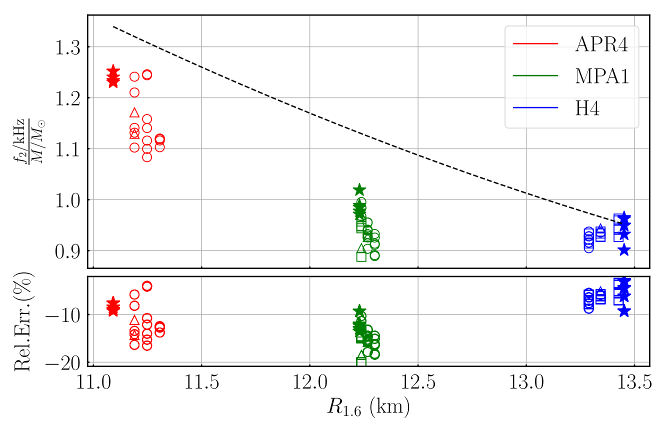

FIG. 3. Correlation between f_2/M and $R_{1.6}$ for the considered EOS (see plot legends) and various of B. The numerical results are denoted in the same manner as in Fig. 2. The quasiuniversal relation proposed in [96] is shown as the dashed curve, while the relative deviation of our numerical results to the formula is given in the bottom panel.

not apply to the H4 EOS, indicating that the interplay between gravity and matter is nontrivial and more investigation is needed to understand their competition in determining the stellar structure.

We have also compared the numerical results with the f_2-$\Lambda_{1.6}$ relation in Lioutas *et al.* [95]. The situation is more or less the same as the comparison with the f_2-$R_{1.6}$ relation, and therefore, we do not present it here.

Degeneracy with QCD phase transition—Certain caveats have already been raised that the tightness of quasiuniversal relations can be broadened by including a wider set of EOSs [99] or violated by either a strong, first-order [85,100–108] or cross-over phase transition [109]. Consequently, an inconsistency between the inference on the EOS from the inspiral and postmerger waveforms is speculated as an indicator of phase transitions occurring during the merger process. In particular, the f_2 peak will have a higher frequency than what would be predicted by the quasiuniversal relations for EOSs with first-order phase transition since matters will be softened when the new degree of freedom emerges. On the other hand, matters will experience a stiffening at 3–4 n_0 followed by a softening at 4–5 n_0 for the cross-over phase transition scenario [110,111], leading to a reduced f_2. Here, $n_0 = 0.16\,\mathrm{fm}^{-3}$ is the nuclear saturation number density.

However, the connection between the violation in the quasiuniversal relations and matter phase transition should be carefully revisited as it can also arise from a modification in the underlying gravitational theory, as shown in this Letter. The similarity between modified gravity and QCD phase transition in terms of postmerger waveforms does not end here. After baryons crush to form exotic particles, the EOS can be stiffened or softened depending on the nature of the QCD phase transition (see above). In turn, the core can become less or more compact thereby adjusting the frequency of fluid oscillation and the associated GWs [102,112]. This process can also manifest in scalarized HMNSs (cf. Fig. 2). In particular, the scalar activity in HMNSs pertaining to H4 can lead to a higher f_2 than the prediction by the quasiuniversal relation (see the deviation in f_2 for $3.3 \lesssim \tilde{\Lambda}^{1/5} \lesssim 3.7$ in Fig. 2), reminiscent of the influence of a first-order nuclear phase transition. On the other hand, the coupling between the scalar field and matter tends to reduce f_2 for the EOSs APR4 and MPA1, mimicking the cross-over phase transition (see the deviation in f_2 for $\tilde{\Lambda}^{1/5} \lesssim 3.4$ in Fig. 2).

There is a distinction between the QCD phase transition and the gravitational transition of states: an interface (e.g., quark hadron) will reveal in the former process, supporting a class of oscillation modes (i mode) that may leave certain imprints in GW signals [113–115]. On the other hand, there is a class of mode linked to the scalar field, i.e., ϕ mode [38,116]. In principle, the quadrupole member of ϕ mode can emit GWs as a result of the entrained fluid motions. Both the i and ϕ modes typically have the frequency of several hundred Hz, and the largely overlapped frequency band makes it nontrivial to tell them apart even if this weak emission could be detected.

Conclusion—We systematically performed numerical simulations of BNS mergers in GR and DEF theories to solve for the waveforms throughout inspiral up to the merger, where the considered scalar coupling constants are summarized in Fig. 1. Based on the numerical data, we examine several quasiuniversal relations connecting the binary tidal deformability to waveform characteristics. For the mergers that scalarization does not realize before merger, the GW's frequency and amplitude at the merger in the DEF theories aligned well with the fitting formula valid in GR (cf. the top and bottom panels of Fig. 2). However, these two relations can be significantly violated if scalarization occurs in the inspiral phase.

Despite considering only three EOSs, our results already suggest a serious caveat in applying GR-based quasiuniversal relations to probe the EOS and gravity in modified theories. In particular, we demonstrated that a gravitational effect like scalarization could also violate these relations, mimicking the similar violation that could be caused by a strong phase transition. Thus, future disagreements between GW signals and quasiuniversal predictions cannot be taken as a smoking gun of either effect. Recent studies [73,117] show that three distinct kinds of finite-size effects are present in the DEF theory attributing to the matter, scalar field, and a mixed type, respectively. The imprint of each of them on the waveform differs in sign and/or the scaling with frequency. Measuring these effects within sufficiently small statistical error with future detectors could help disentangle EOS and gravity effects. In any case, much more investigation remains to be done to further discriminate one effect from the other. Also, thermal effects in postmerger signals still remain to be explored [26,27,91,118–121], warranting a reassessment of quasiuniversal relations even in GR without phase transitions.

Acknowledgments—Numerical computations were performed on the clusters Sakura and Raven at the Max Planck Computing and Data Facility. This work was in part supported by Grant-in-Aid for Scientific Research (Grant No. 20H00158, No. 23H04900, and No. 23H01172) of Japanese MEXT/JSPS.

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