Letter

Effective-one-body modeling for generic compact binaries with arbitrary orbits

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We present the first unified model for the general relativistic dynamics and gravitational radiation of generic compact binaries. `TEOBResumS-Dalí` is a model based on the effective-one-body framework incorporating tidal interactions, generic spins, multipolar radiation reaction/waveform, and numerical relativity information. It allows the computation of gravitational waves and other dynamical gauge invariants from *generic* binaries (black holes, neutron stars, and neutron star–black hole binaries) evolving along *arbitrary* orbits (quasicircular, eccentric, and nonplanar) through merger and including scattering. The performances of `TEOBResumS-Dalí` in the strong-field regime are showcased by comparisons with a large sample of 1395 high-accuracy numerical relativity simulations. `TEOBResumS-Dalí` allows the computation of faithful waveforms for gravitational wave astronomy, providing at the same time an understanding and a prediction of the strong-field dynamics.

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Introduction. Gravitational waves (GWs) from compact binaries have transformed our understanding of the Universe [1–3]. Current and future observatories [4–9] require accurate waveform models for compact binaries, based on precise solutions of the relativistic two-body problem for generic orbits. The effective-one-body (EOB) formalism provides a powerful framework to model both the dynamics and emitted waveforms [10–12]. Its key elements are a Hamiltonian and a radiation reaction force, which parametrizes energy and angular momentum losses. Both these elements incorporate post-Newtonian (PN), numerical relativity (NR), and gravitational self-force (GSF) (and test mass) information in a resummed way, to make the model predictive in the high-frequency regime. While initially developed for quasicircular nonspinning binary black holes (BBHs) [13–19], the EOB approach has been extended to include spin interactions [20–28], subdominant modes [29–35], tidal interactions [36–48], precessing systems [26,49–55], and arbitrary planar orbits [56–71]. The EOB description of the inspiral-plunge phase is then completed with postmerger models for the vacuum [72] and matter [46,73] cases, thus providing a description of the whole evolution. Despite significant progress, no EOB model incorporates all these effects throughout the entire coalescence, as presented in this work. The availability of a unified EOB model has important consequences on our capabilities to learn additional information from GW data: the incomplete description of GW sources can lead to systematic errors in the estimation of their parameters, limiting the scientific return of observations [74]. This was demonstrated in the analyses of the GW190521 event [75] conducted in Refs. [66,76,77], which, respectively, favored a head-on, highly eccentric or dynamical capture scenario over a quasispherical one, highlighting the importance of models that accurately describe arbitrary orbits to avoid missing key physical insights. Similarly, Bayesian analyses of GW190814 [78] using the previous `TEOBResumS` unified model for BBH and black hole–neutron star (BHNS) have reinforced the decisive evidence for the

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presence of higher modes [46]. Such models can be crucial to infer the presence of a neutron star in the source in future events.

Here, we discuss `TEOBResumS-Dalí`, the first EOB model offering a comprehensive description of generic compact binary dynamics and waveforms. `TEOBResumS-Dalí` allows the precise computation of GWs from BBHs, binary neutron stars (BNSs), and BHNS evolving along any orbit (quasicircular, eccentric, hyperbolic, and nonplanar), from arbitrarily large separations (low frequencies) to merger. The waveform is completed with ringdown for BBH [32,72] and BHNS [46,79], and postmerger emission for BNS [73]. We discuss the model's performance by comparing with a sample of high-accuracy NR simulations: 1183 BBHs, 27 BNSs, and 185 BHNSs. This comparison represents one of the most exhaustive tests of any GW model to date, in terms of variety of configurations and number of NR simulations used. We focus on faithfulness analysis of the GW signal to showcase the global accuracy of the model, and we consider scattering angles for open orbits. We further showcase how EOB can be employed to inform future numerical studies of systems with neutron stars (NSs).

Conventions. We denote the total rest mass of the binary as $M = m_1 + m_2$, the symmetric mass ratio as $\nu = m_1 m_2/M^2$, the mass ratio as $q = m_1/m_2 \geq 1$, the dimensionless spins as $\chi_{1,2} = S_{1,2}/(m_{1,2}^2)$, and the dimensionless precession spin parameter as $\chi_p = \max\left(|\boldsymbol{\chi}_{\mathbf{1},\perp}|, \frac{4+3q}{4q^2+3q}|\boldsymbol{\chi}_{\mathbf{2},\perp}|\right)$ [80]. We also use $p_\varphi \equiv L/(\nu M^2)$, where L is the orbital angular momentum. The quadrupolar dimensionless tidal polarizability parameters for gravitoelectric interactions are indicated as $\Lambda_{1,2}$. The reduced tidal parameter $\tilde{\Lambda} = 16/13(m_1 + 12m_2)m_1^4\Lambda_1/M + (1 \leftrightarrow 2)$ [81] is equivalent to the tidal coupling constant introduced in [37] for equal-mass binaries. The GW polarizations $h_{+,\times}$ are decomposed as $h_+ - ih_\times = \mathcal{D}_L^{-1}\sum_{\ell=2}^{\infty}\sum_{m=-\ell}^{\ell} h_{\ell m}\,{}_{-2}Y_{\ell m}(\iota, \phi_{\rm ref})$, where $\mathcal{D}_L$ is the luminosity distance, ι is the inclination angle, $\phi_{\rm ref}$ is the orbital reference phase, ${}_{-2}Y_{\ell m}$ are the spin-weighted spherical harmonics, and $h_{\ell m} = A_{\ell m}e^{-i\phi_{\ell m}}$ are the GW modes. We use geometric units with $G = c = 1$.

`TEOBResumS-Dalí`. To model BBHs, `TEOBResumS-Dalí` uses a 5PN Hamiltonian with two parameters calibrated to NR quasicircular simulations and a 3^{+3} PN description of all multipoles[1] up to $\ell = 8$ with the exception of the (2,2), taken at full 4PN order [65]. Spin-spin couplings are incorporated using the concept of centrifugal radius [28], r_c, including up to next-to-leading-order PN information.

Predictability in the strong-field regime is obtained by the systematic use of Padé resummations [82]. In particular, the log-terms of the residual amplitudes in the resummed radiation of Ref. [17] are treated as proposed in Ref. [65]. Analytical noncircular corrections for the angular momentum and energy losses are included via a Newtonian prefactor for arbitrary orbits,[2] depending on time derivatives of the orbital frequency and radial separation [57,65] and with a resummed 2PN radial force [34]. The validity of this prescription has also been confirmed in the test-mass limit [83,84], which provides a well-controlled setting for testing analytical prescriptions for comparable-mass EOB models [83–95]. Effects due to spin-induced precession are accounted for via a hybrid PN-EOB scheme [50,52,55], which relies on the timescale separation between the precession and the orbital motion [80,96–99]. The inspiral-plunge waveform is completed with a quasicircular NR-informed ringdown model [72,100]. The smooth transition is aided using NR-informed next-to-quasicircular corrections (NQCs) [13,33] in the quasicircular and mildly eccentric cases. Spin-dependent horizon absorption effects are included to leading order [28].

BNSs are described using similar analytical prescriptions to BBHs but adding tidal interactions. The latter are incorporated in the Hamiltonian by including all the gravitoelectric and gravitomagnetic terms currently known and up to multipolar order $\ell = 8$. These interactions are parametrized by the usual multipolar set of tidal polarizability parameters, and the dominant (gravitoelectric, $\ell = 2$) contribution is parametrized by the reduced tidal parameter $\tilde{\Lambda}$ [37]. Different prescriptions for the tides are available: tidal potentials in PN form [101], an f-mode resonance model [47], and GSF-resummed expressions of the leading-order multipolar terms [102–104]. Comparisons with NR suggest the latter performs best [47,103,104], and it is the default choice in `TEOBResumS-Dalí`. Nonlinear-in-spin interactions dependent on finite-size effects are incorporated up to next-to-next-to-leading order in a PN-resummed fashion using the centrifugal radius and an effective spin variable [42]. The multipolar waveform incorporates known PN coefficients up to 2PN order [47]. A postmerger completion that accounts for the emission from the NS remnant is obtained using NR-informed analytical models `NRPM` [105] or `NRPMw` [73,106]. These models leverage on a quasiuniversal character of BNS postmerger GWs that allows a parametrization of the wave in terms of the same tidal polarizability parameters employed in the EOB Hamiltonian [107]. Therefore, `TEOBResumS-Dalí` delivers a robust representation of the complete BNS spectrum [105], which can be used for inference on extreme matter effects with next-generation observations [108–110].

[1]This notation means that the waveform multipoles contain ν-dependent information up to 3PN order, hybridized with test-mass terms as to reach (formal) 6PN accuracy.

[2]Note that using a radiation reaction force without an explicit eccentricity parametrization, as opposed to what is done in `SEOBNRv5EHM` [70,71], ensures a smooth transition between hyperbolic and elliptic regimes.

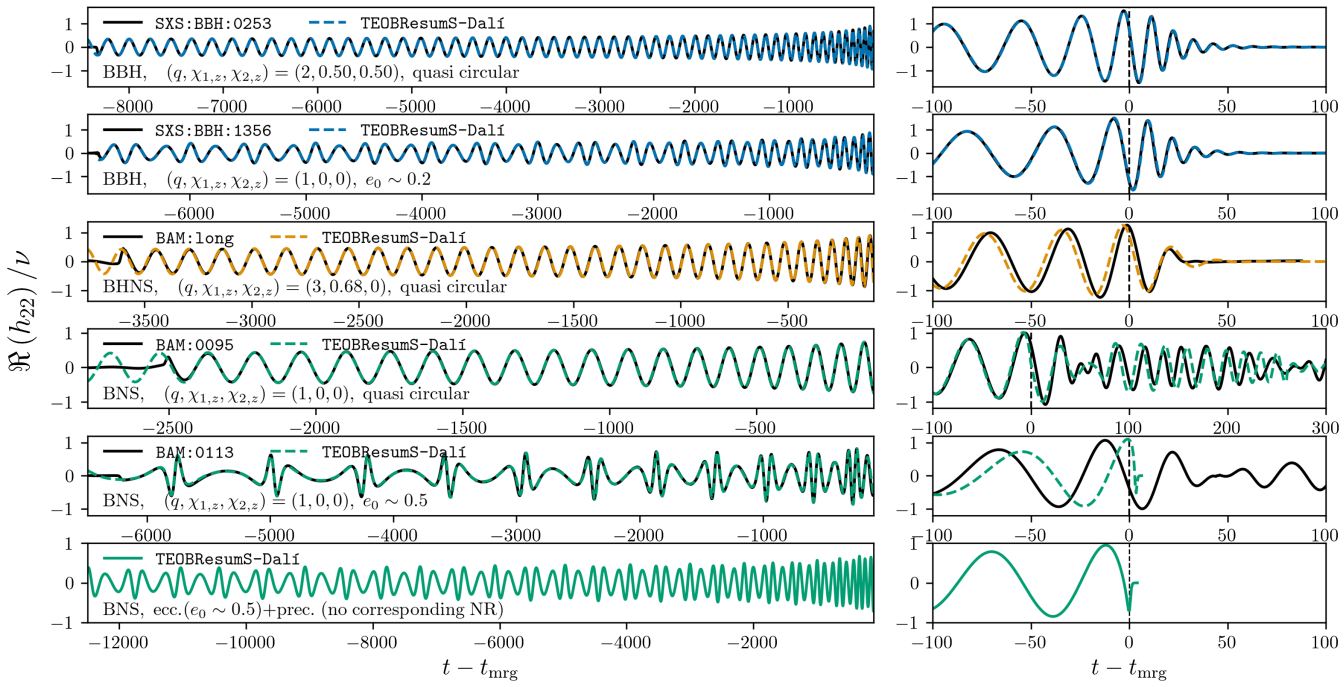


FIG. 1. EOB and NR waveforms for a sample of coalescing binaries: quasicircular and eccentric spin-aligned BBHs (blue) and BNSs (green), and quasicircular BHNS (orange). Waveforms aligned during the inspiral. For the eccentric and precessing BNS, we present only the EOB waveform (green), as no corresponding NR data are currently available.

BHNSs are described by incorporating the same tidal interactions as for BNSs in the Hamiltonian but adopting NQCs and a ringdown model similar to BBHs. Building upon Ref. [46], the new `TEOBResumS-Dalí` implementation improves the multipolar NQCs and the remnant + ringdown model by using new numerical data from CoRe Collaboration [111]. The remnant black hole (BH) from BHNSs can be different from those of BBHs because of the tidal disruption of the NS during merger. Therefore, the remnant's mass and spin are modeled from NR data using an analytical representation that smoothly deforms the BBH case [79]. Similarly, NQCs to the waveform for higher modes up to $\ell = 4$ have been developed from the new simulations together with a smooth deformation of the ringdown model used for BBHs.

Algorithmically, `TEOBResumS-Dalí` inherited from previous `TEOBResumS` models two key analytical acceleration techniques (for quasicircular dynamics): the post-adiabatic approximation for the fast solution of the Hamiltonian equations of motion [112] and the stationary phase approximation for the computation of frequency-domain EOB waveforms [44].

We showcase time-domain waveform comparisons with NR in Fig. 1. From top to bottom we consider a quasicircular nonspinning BBH from the SXS catalog [113], a mildly eccentric BBH, a quasicircular BHNS [111], and a quasicircular and a highly eccentric BNS from the CoRe catalog [114,115]. The last panel shows an EOB waveform for an eccentric and precessing BNS [$e_0^{\rm EOB} = 0.5$, $\chi_1 = (0.1, 0.3, 0.1)$, $\chi_2 = (0.1, 0.0, 0.4)$], which has not been explored so far in NR.

The consistency of both EOB/NR phase and amplitude is maintained over the duration of the entire NR signals. Indeed, the quasicircular spin-aligned BBH in the top row of Fig. 1 yields an excellent phase difference at merger ($\Delta\phi_{22}^{\rm mrg} \simeq 0.057$ rad). For the eccentric BBH we have $\Delta\phi_{22}^{\rm mrg} \simeq 0.073$ rad, a value that is only slightly higher than the one obtained for the standard equal-mass configuration `SXS:BBH:0180` ($\Delta\phi_{22}^{\rm mrg} \simeq 0.036$ rad, not shown in Fig. 1). For the quasicircular BHNS, we get a dephasing of $\Delta\phi_{22}^{\rm mrg} \simeq 0.502$ rad, a value similar to the quasicircular BNS considered here ($\Delta\phi_{22}^{\rm mrg} \simeq 0.579$ rad). However, these dephasings are compatible with NR uncertainties.

Systematic EOB/NR comparisons. We consider a faithfulness analysis with NR data for a systematic accuracy assessment. The EOB/NR mismatch (or unfaithfulness) $\bar{\mathcal{F}}$ is defined as the noise-weighted inner product of the two frequency-domain waveforms, $h_{\rm EOB}$ and $h_{\rm NR}$,

$$\bar{\mathcal{F}} = 1 - \max_{t_{\rm ref}, \phi_{\rm ref}, \theta_a} \mathcal{O}(h_{\rm NR}, h_{\rm EOB}), \tag{1}$$

where $\mathcal{O}$ is the overlap integral[3] with the detector's power spectral density $S_n(f)$,

[3]If subdominant multipoles are employed, we consider the sky-maximized overlap statistic [116].

$$\mathcal{O}(h_{\rm NR}, h_{\rm EOB}) = 4\Re \int_{f_0}^{f_{\rm max}} \frac{\tilde{h}_{\rm NR}\tilde{h}^*_{\rm EOB}}{S_n(f)}\, df. \qquad (2)$$

We use the zero-detuned, high-power noise spectral density of Advanced LIGO [117]. The maximization is performed over a reference time $t_{\rm ref}$ and phase $\phi_{\rm ref}$, and an additional set of parameters θ_a depending on the specific nature of the configuration considered. For instance, following Ref. [118], for quasispherical (spin-precessing) systems, $\theta_a = \{\varphi_{\rm plane}\}$, where $\varphi_{\rm plane}$ is an angle that rotates the in-plane components of the spins at a reference frequency. For eccentric or hyperbolic systems, $\theta_a = \{E^0, p^0_\varphi\}$ are the initial energy and angular momentum, respectively. Then, initial separation is set as a large radius in the unbound case, while it is set to the apastron identified by (E_0, p^0_φ) for bound cases. To compute the mismatches, we use the package PyCBC [119]. In the case of scattering orbits, NR waveforms are typically not yet sufficiently accurate. We have thus also performed an analysis of the scattering angle θ following Ref. [120] and subsequent works [68,121–124].

Binary black holes. We consider NR waveforms from several codes, totaling 1183 configurations. Out of these, 635 are quasicircular (528) or quasispherical (107) simulations from the SXS catalog [113,125–136], 28 are the eccentric public simulations from the same SXS catalog, 338 are eccentric binaries[4] from the RIT catalog [137,138], 128 correspond to highly eccentric configurations of the ICC catalog [67,139], and finally, 54 are dynamical captures and scatterings [68] from CoRe Collaboration performed with GR-Athena++ [140–142] and with initial energy $E_0 \lesssim 1.2M$.

Mismatches are computed with the dominant $(2, \pm 2)$ mode for spin-aligned BBHs and with the $(2, \pm 2)$, $(2, \pm 1), (3, \pm 3)$, and $(4, \pm 4)$ coprecessing modes for precessing systems. For the latter, we consider an inclination of $\pi/3$ and average over the phase and effective polarization angle.

The mismatches that we show have been computed for a reference mass of $100M_\odot$ in the frequency band [10,1024] Hz.

Our results are reported in Fig. 2. The two panels show the same mismatches plotted against the orbital angular momentum of the system, while the two color maps indicate the mass ratio and the effective spin.[5] Of the configurations considered, 86.3% have a mismatch below 0.01, while 97.9% (99.2%) of them are below the 0.03 (0.05) threshold. The largest mismatches are obtained

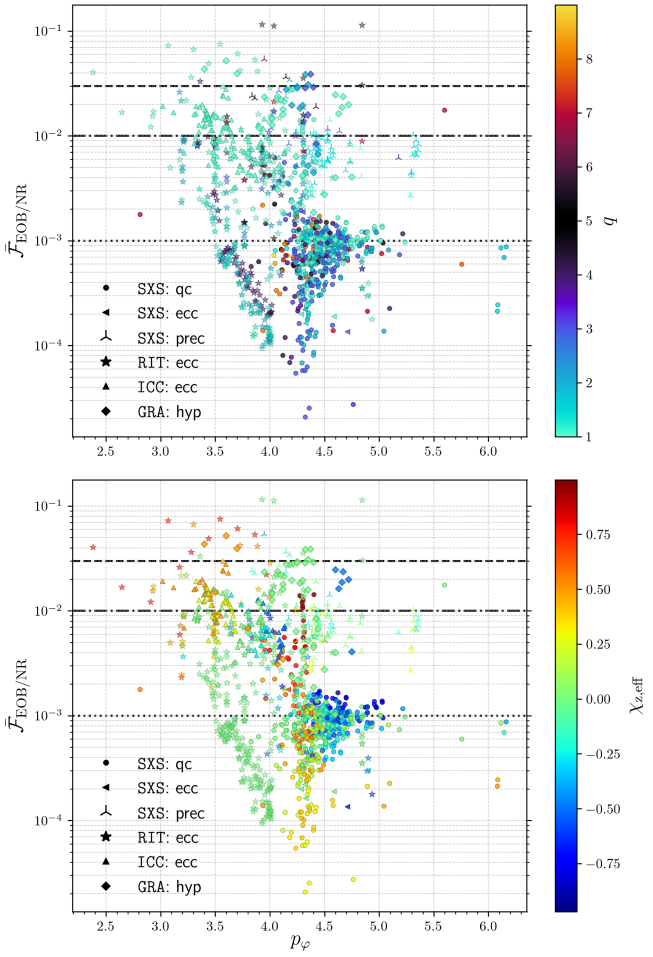


FIG. 2. EOB/NR mismatches for the 1183 BBHs considered in this work. The color maps highlight the mass ratio (upper panel) and the (initial) z-component of the effective spin (lower panel). Horizontal lines mark the 0.1%, 1%, and 3% thresholds.

for configurations with high mass ratio, low angular momentum, and/or large in-plane spins. This is expected, since in these regions the NR data are more sparse and TEOBResumS-Dalí is not NR-informed there. Nonetheless, TEOBResumS-Dalí accurately reproduces the NR waveforms for the vast majority of the configurations considered. Note that mismatches of 10^{-4} graze the numerical uncertainties of the data.

Previous studies showed that TEOBResumS-Dalí accurately models general relativistic dynamics in encounters and scatterings, including the transition between the two regimes [58,68]. We further compare NR scattering orbits using 42 configurations from Ref. [122] and 69 from Ref. [123], finding that TEOBResumS-Dalí agrees with NR results within a few percent for small scattering angles (see Supplemental Material [143]).

Binaries with neutron stars. For BNSs we consider 26 quasicircular (13 of which with residual eccentricity $\lesssim 10^{-4}$) and one eccentric BNS from the CoRe database.

[4]The RIT catalog contains several almost head-on configurations and, therefore, we consider only systems with $p^0_\varphi \geq p^{\rm LSO}_\varphi$, where $p^{\rm LSO}_\varphi$ is the angular momentum that corresponds to the spin and ν-dependent last stable orbit (LSO).

[5]For the precessing cases, the color highlights the initial z-component.

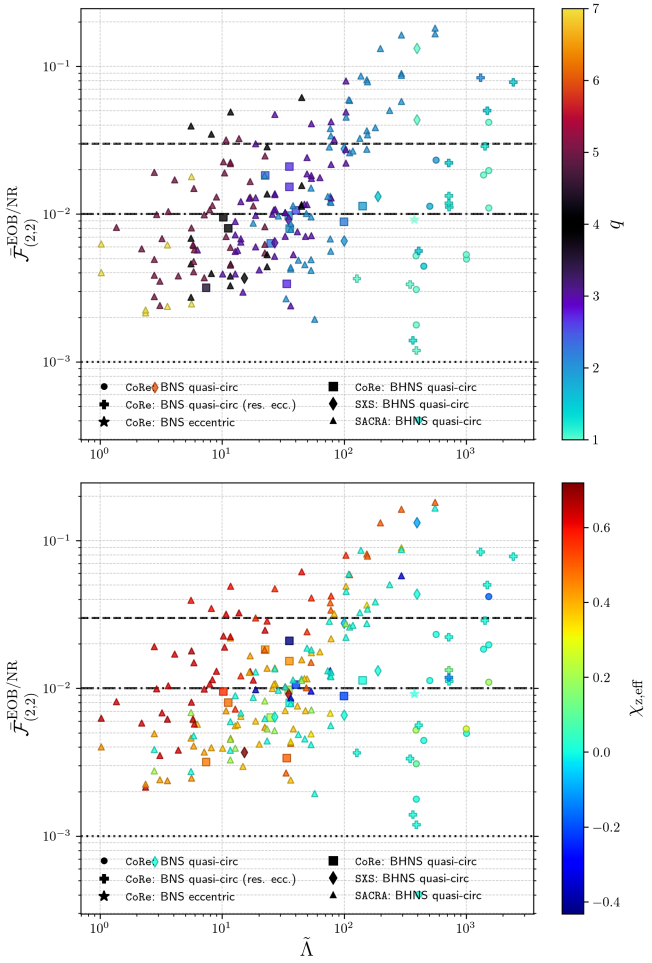


FIG. 3. EOB/NR mismatches computed with the (2,2) mode for BNS and BHNS data from different catalogs. The lines mark the 0.1%, 1%, and 3% thresholds.

The chosen data are representative of the longest and most accurate simulations available to date. We report the corresponding EOB/NR mismatches for the (2,2) mode up to merger in Fig. 3. Note that higher mismatches are found for high values of $\tilde{\Lambda}$, which are incompatible with GW170817 [154]. The eccentric configuration considered corresponds to an initial EOB eccentricity $e_0^{\rm EOB} \sim 0.58$ (see Fig. 1) and yields a mismatch of 0.9%. This highlights the accuracy of `TEOBResumS-Dalí` for eccentric BNSs [47]. BNS waveforms generated with `TEOBResumS-Dalí` can also be completed with the postmerger model `NRPMw`, which has been tested against 102 independent NR simulations not used to design the model [73]. The precision favorably compares against other postmerger models [155] and is compatible with NR uncertainties.

For BHNSs, we consider 162 spin-aligned simulations from the SACRA catalog [156,157], nine from SXS collaboration [158–166], and 13 new simulations from CoRe Collaboration [111]. The mismatches for the inspiral-merger-ringdown (2,2) mode in the frequency band [10,4096] Hz are reported in Fig. 3. As in the BNS case, higher mismatches are obtained for configurations with large $\tilde{\Lambda}$. For the SXS data, the two highest mismatches are obtained for `SXS:BHNS:0005` (13.2%) and `SXS:BHNS:0007` (2.8%), which have spinning NSs. Some high mismatches are also obtained for some SACRA configurations, but it should be noted that these are short simulations and the NR uncertainty is large. Regarding the new BAM BHNS simulations [111], we consider the ones that have at least $500M$ of evolution before the merger. The longest BAM simulation available ($3500M$ before merger), which has $q = 2.7$, a BH with $\chi_z = 0.68$, and nonspinning NS with $\Lambda = 599$, yields a mismatch of ∼0.3%. Overall, the model remains accurate for BHNSs with astrophysically relevant tidal deformabilities. We finally consider an additional precessing $q = 2.5$ BAM configuration, which has a precessing spin $\chi_p = 0.61$, a NS with $\Lambda \simeq 494$, and yields a mismatch of 1.4%.

Binaries with NSs are less investigated in NR due to the higher computational cost and the increased dimensionality of the parameter space compared to BBH systems. `TEOBResumS-Dalí` allows us to identify which regions of the parameter space for these systems should be prioritized for future NR simulations. We perform a greedy search based on a parameter space defined by masses, spins, and $\Lambda_{1,2}$ and using `TEOBResumS-Dalí` with nonprecessing spins. The search aims at finding an optimal waveform basis in the considered parameter space (see Supplemental Material [143]). For BNSs, extrapolating our results, we find that 500 quasicircular configurations may be sufficient to generate a waveform basis for this type of system, which is accurate to $\bar{\mathcal{F}} \lesssim 0.3\%$. The greedy algorithm selects configurations with mass ratios up to 2 and/or tidal deformabilities $\Lambda \in [10, 10 \times 000]$. NR simulations with these parameters are entirely feasible and will be pursued in the future. For BHNSs, a basis of 1000 simulations may be enough to describe all the spin-aligned systems within the ranges considered up to $\bar{\mathcal{F}} \lesssim 3\%$.

Outlook. Being able to describe arbitrary orbits for generic compact binaries, `TEOBResumS-Dalí` presents itself as a milestone in the landscape of waveform models. `TEOBResumS-Dalí` is ready to use for GW inference with current observations, and it can inform science cases for next-generation interferometers, such as Einstein Telescope [6,7], Cosmic Explorer [8], and LISA [9]. It can further support the interpretation of strong-field dynamics, as computed in NR simulations, as, for example, in Refs. [68,120,167,168] (see also Supplemental Material [143] for an example).

Despite reaching a high level of accuracy, much work remains to improve `TEOBResumS-Dalí` across the binary parameter space. In the BBH sector, ongoing work is focused on the development of NQCs for highly elliptic and hyperbolic mergers. A promising approach is to exploit

the universality of the merger structure discovered in Ref. [169]. The ringdown model should also be generalized to arbitrary orbits, possibly including physical effects that are typically unmodeled, such as inspiral-inherited tail effects [64,170–173] and $m = 0$ modes [174]. Absorption fluxes should also be improved in order to capture the BBH phenomenology observed in simulations [175]. The model can currently generate full extreme-mass-ratio inspirals and mergers for nonprecessing spins/planar orbits (not discussed here) using test mass and GSF information [176–181]—extensions to arbitrary orbits are ongoing. Further refinement of BNS and BHNS sectors requires new sets of simulations, such as those indicated in Supplemental Material [143]. For example, a preliminary version of NR-informed tides is investigated in Ref. [48]. Alternative routes to the approach presented here are EOB models relying on post-Minkowskian calculations [121,122,182,183], in particular the Lagrangian EOB approach recently proposed [184].

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Data availability. `TEOBResumS-Dalí` is publicly developed at [186]. A machine readable file with a list of simulations employed for the faithful analysis is distributed along with this paper. Mismatches are computed using PyART, which is available at [187].

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