

Plunge-merger-ringdown tests of general relativity with GW250114

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The binary black hole signal GW250114, the clearest gravitational wave detected to date, offers a unique opportunity to test general relativity in the relativistic strong-gravity regime. How well does GW250114 agree with Einstein's predictions in the plunge-merger-ringdown stage? To address this point, we constrain deviations from general relativity across the plunge-merger-ringdown stage of spin-precessing binaries with a parametrized waveform model within the effective-one-body formalism. We find that deviations from the peak gravitational-wave amplitude and instantaneous frequency of the $(\ell, |m|) = (2, 2)$ mode are constrained to about 10% and 4%, respectively, at 90% credible level. These constraints are, respectively, 2 and 4 times more stringent than those obtained by analyzing GW150914. We also constrain, for the first time, the instantaneous frequency of the $(\ell, |m|) = (4, 4)$ mode at merger to about 6% and the time at which the gravitational-wave amplitude peaks to about 5 ms. These results provide exquisitely precise tests of general relativity in the strong-gravity regime and can be employed to constrain extensions of Einstein's theory.

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Introduction. On January 14, 2025, the clearest gravitational-wave (GW) signal to date, GW250114_082203 (hereafter GW250114) [1], was observed by the LIGO detectors [2]. Its high network signal-to-noise ratio (SNR) of 76 allows for testing Einstein's general relativity (GR) with unprecedented accuracy [3]. Together with other signals in the fourth Gravitational-Wave Transient Catalog [4], which includes events up to the first part of the fourth observing run of the LIGO-Virgo-KAGRA (LVK) detectors [2,5,6], GW250114 underpins the current state of the art in strong-field tests of GR [7–10].

Black holes (BHs) in binary configurations in vacuum lose energy via emission of gravitational radiation and spiral toward each other until they merge [11–13]. During the final orbits, the binary reaches relativistic velocities and highly dynamical gravitational fields, causing the two objects to rapidly coalesce, producing a short but intense burst of GWs that marks the merger. The remnant, a highly distorted BH, settles down to a stationary configuration by

emitting GWs in the ringdown [14–18]. This stage can be modeled as a superposition of damped sinusoids whose frequencies and decay times, called quasinormal modes (QNMs), depend solely on the remnant BH mass and spin [19,20] in GR. Several studies in the last years have investigated possible signatures of beyond-GR physics in the dynamical and nonlinear regime [21–27] and the presence of QNMs in GW data [28–38].

Current analyses of GW250114 [1,3] included ringdown tests of the remnant, constraints to parametrized deviations to the post-Newtonian (PN) coefficients in the inspiral phase (both single- [26,39–41] and multiparameter tests using principal component analysis [42,43]), consistency tests between the inspiral and merger-ringdown portions of the waveform [44,45], and residual tests [9]. Notably, post-merger analyses of GW250114 reported the consistency of the data with the dominant quadrupolar ($\ell = |m| = 2$) mode of a Kerr BH and its first overtone [1,3]. By fitting a parametrized inspiral-merger-ringdown (IMR) waveform model [35], these studies have also constrained the fundamental $\ell = |m| = 4$ mode frequency for the first time [3].

In this Letter, we extend these analyses by constraining deviations from the GR predictions throughout the plunge-merger-ringdown stage, focusing on theory-independent tests. We employ the parametrized waveform model pSEOBNRv5PHM (hereafter pSEOBNR) [24,28,31,35,46], a state-of-the-art, multipolar, spin-precessing effective-one-body

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(EOB) waveform model for binary BHs (BBHs) in quasicircular orbits [47–50]. pSEOBNR is a complete IMR waveform that introduces fractional deviations to the numerical-relativity- (NR) informed input values for the peak amplitude and frequency, and the peak time itself, as well as the frequency and decay time of the fundamental QNMs in the ringdown to perform tests of GR with GWs. Using this model, we place the most stringent constraints to date on deviations in the peak GW amplitude and instantaneous frequency of the $(\ell, |m|) = (2, 2)$ mode, together with the first constraints on deviations to the instantaneous frequency of the $(\ell, |m|) = (4, 4)$ mode at merger and the time at which the GW (2,2) mode amplitude peaks. All tests yield results consistent with GR.

NR simulations of theories beyond GR and exotic compact objects, as well as gravitational self-force calculations, have explored potential signatures of new physics in the merger stage [21, 51–67]. Given the predictions for these corrections, results from theory-independent tests can be translated into constraints on the additional degrees of freedom of modified theories of gravity.

For tests of GR that use the full IMR signal, such as the pSEOBNR approach, waveform systematics could lead to false indications of deviations from GR already for SNRs of $\mathcal{O}(100)$ [24, 46, 68–70]. Given the network SNR of GW250114, particular attention is required when interpreting the results, as they may be subject to such systematic errors. In Supplemental Material [71], we perform injection studies to assess the impact of noise and waveform systematics on our results.

GW250114. Using the IMR NRSur7dq4 model [77] for quasicircular and spin-precessing binaries, Abac *et al.* [1] found that the wave morphology is consistent with a BBH with component masses $m_1 = 33.6^{+1.2}_{-0.8} M_\odot$ and $m_2 = 32.2^{+0.8}_{-1.3} M_\odot$ and dimensionless spin magnitudes $\chi_1 \leq 0.24$ and $\chi_2 \leq 0.26$ at 90% credible intervals. The results with other models [47–50, 78–80] are consistent with each other. The eccentricity is constrained to $e \leq 0.03$ at a reference frequency of 13.33 Hz, using eccentric aligned-spin models [1]. We confirm the eccentricity constraint by repeating the analysis using the SEOBNRv5EHM model [81] (see Supplemental Material [71] for details) and conclude that eccentricity effects can be neglected when performing tests of GR with GW250114.

The waveform model. pSEOBNR [24, 28, 31, 35, 46] is a parametrized waveform model for spin-precessing BBHs in quasicircular orbits, built within the EOB formalism [82, 83] and calibrated to NR simulations. It includes the subdominant modes $(\ell, |m|) = (2, 1), (3, 3), (3, 2), (4, 4), (4, 3)$, and (5,5) in addition to the dominant (2,2) mode. It extends the SEOBNRv5PHM model [47–50] by introducing free parameters that encode potential deviations across the different stages of the coalescence. In the ringdown stage,

it includes fractional deviations to the frequency and damping time of the fundamental QNMs [28, 31]. In the plunge-merger stage, it allows for fractional deviations to the NR-calibrated merger amplitude and frequency of each waveform mode, as well as the instant at which the (2,2) mode amplitude peaks [24], which, in the rest of the Letter, we associate with the merger. Additional parametrized corrections are incorporated in the NR-calibration parameters of the model in the inspiral stage [35].

The GW polarizations can be written in the observer’s frame as

$$h_+ - ih_\times = \sum_{\ell, m} {}_{-2}Y_{\ell m}(\varphi, \iota) h_{\ell m}(t), \quad (1)$$

where ${}_{-2}Y_{\ell m}(\varphi, \iota)$ are the -2 spin-weighted spherical harmonics, with φ and ι being the azimuthal and polar angles to the observer. The SEOBNRv5PHM model describes waveforms from spin-precessing binaries by a suitable time-dependent rotation of approximately aligned-spin waveforms in a coprecessing frame, which tracks the instantaneous direction of the orbital plane [84–89]. The GW modes in the coprecessing frame are decomposed as

$$h_{\ell m}(t) = h_{\ell m}(t)^{\text{insp-plunge}} \theta(t_{\text{match}}^{\ell m} - t) + h_{\ell m}(t)^{\text{merger-RD}} \theta(t - t_{\text{match}}^{\ell m}), \quad (2)$$

where $\theta(t)$ is the Heaviside step function, $h_{\ell m}^{\text{insp-plunge}}$ and $h_{\ell m}^{\text{merger-RD}}$ are the inspiral-plunge and merger-ringdown parts of the waveform, respectively. The matching time $t_{\text{match}}^{\ell m}$ is chosen as the peak of the (2,2) mode amplitude for all (ℓ, m) modes except (5,5), for which it is taken as the peak of the (2,2) harmonic minus $10M$ [47].

The peak-time of the (2,2) mode, t_{peak}^{22} is defined as

$$t_{\text{peak}}^{22} = t_{\text{ISCO}} + \Delta t_{\text{NR}}, \quad (3)$$

where t_{ISCO} is the time at which $r = r_{\text{ISCO}}$, and r_{ISCO} is the radius of the innermost-stable circular orbit (ISCO) [90] of a Kerr BH with the remnant mass and spin [91, 92]. The parameter Δt_{NR} is a free parameter calibrated to aligned-spin NR waveforms [47].

The inspiral-plunge waveform $h_{\ell m}^{\text{insp-plunge}}$ is constructed on a factorization of the PN GW modes [93–95], evaluated on the dynamics obtained from the EOB equations of motion [83]. Nonquasicircular corrections enforce that the modes’ amplitude and first two derivatives, and their frequency and first derivative, match “input values” extracted from NR simulations at $t_{\text{match}}^{\ell m}$. The model has two calibration parameters in the EOB Hamiltonian, namely, a_6 , which is a 5PN parameter that enters the nonspinning potential, and d_{SO} , which is a 4.5PN spin-orbit parameter.

For all harmonics, except for $(\ell, |m|) = (3, 2)$ and (4,3), the merger-ringdown waveform employs the following ansatz,

$$h_{\ell m}^{\text{merger-RD}}(t) = \nu \tilde{A}_{\ell m}(t) e^{i\tilde{\phi}_{\ell m}(t)} e^{-i\sigma_{\ell m 0}^{\text{CP}}(t - t_{\text{match}}^{\ell m})}, \quad (4)$$

where $\nu = m_1 m_2 / M^2$ is the symmetric mass ratio, $M = m_1 + m_2$ is the total mass, $\tilde{A}_{\ell m}$ and $\tilde{\phi}_{\ell m}$ are time-dependent amplitude and phase functions, and $\sigma_{\ell m 0}^{\text{CP}}$ is the complex frequency of the least-damped QNM of the remnant BH in the coprecessing frame. The QNM frequencies obtained from BH perturbation theory are formally valid in the $\mathbf{J}_f$ frame, where the z axis is aligned with the spin of the final BH. The $\mathbf{J}_f$ frame QNMs, $\sigma_{\ell m 0}$, are related to the coprecessing frame QNMs by Eq. (35) of Ref. [96].

The real and imaginary parts of $\sigma_{\ell m 0}$ are related to the QNM oscillation frequency and damping time as follows:

$$f_{\ell m 0} = \frac{1}{2\pi} \text{Re}(\sigma_{\ell m 0}), \quad \tau_{\ell m 0} = -\frac{1}{\text{Im}(\sigma_{\ell m 0})}. \quad (5)$$

Fractional deviations to the frequency and decay time of the fundamental QNMs in the $\mathbf{J}_f$ frame are introduced as

$$f_{\ell m 0} = f_{\ell m 0}^{\text{GR}}(1 + \delta f_{\ell m 0}), \quad \tau_{\ell m 0} = \tau_{\ell m 0}^{\text{GR}}(1 + \delta \tau_{\ell m 0}), \quad (6)$$

where the GR predictions for these quantities ($f_{\ell m 0}^{\text{GR}}$ and $\tau_{\ell m 0}^{\text{GR}}$) are obtained from the mass and spin of the remnant BH, estimated using NR fits on the measured component masses and spins [91,92].

Fractional deviations to the NR-informed input values for the coprecessing frame modes' amplitude and frequency at $t = t_{\text{match}}^{\ell m}$ are introduced as

$$|h_{\ell m}| = |h_{\ell m}^{\text{NR}}|(1 + \delta A_{\ell m}), \quad \omega_{\ell m} = \omega_{\ell m}^{\text{NR}}(1 + \delta \omega_{\ell m}), \quad (7)$$

where $|h_{\ell m}^{\text{NR}}|$ and $\omega_{\ell m}^{\text{NR}}$ are calibrated to NR simulations at the matching point $t_{\text{match}}^{\ell m}$ (see Sec. III A of Ref. [47] for details).

The model also allows for changes to $t_{\text{match}}^{\ell m}$ by modifying the time shift parameter Δt_{NR} as

$$\Delta t_{\text{NR}} \rightarrow \Delta t_{\text{NR}} - \delta \Delta t. \quad (8)$$

The deviation parameter $\delta \Delta t$ has, by definition, a lower bound. Indeed, if this parameter is too negative, $t_{\text{match}}^{\ell m}$ can overshoot the end of the BBH dynamics [47].

Additive deviations to the EOB calibration parameters a_6 and d_{SO} are introduced as follows:

$$a_6 \rightarrow a_6 + \delta a_6, \quad d_{\text{SO}} \rightarrow d_{\text{SO}} + \delta d_{\text{SO}}. \quad (9)$$

Prior choices. We assume prior distributions on the GR parameters consistent with Ref. [97]. Specifically, we sample the masses using the chirp mass ($\mathcal{M} = \nu^{3/5} M$) and mass ratio ($q = m_2/m_1$), with uniform priors in component masses. The priors on the dimensionless spin vectors are uniform in magnitude $\chi_i \in [0, 0.99]$ and isotropically distributed in the unit sphere for the spin

directions. For the distance, we employ a uniform prior in the comoving frame of the source.

The fractional deviations are, by definition, larger than -1 . For them, we assume uniform priors with a lower limit set to be -0.8 , to avoid anomalies near -1 , and an upper limit of 1 , with the only exception of δA_{44} which has an upper limit extended to 4 . The time shift deviation $\delta \Delta t$, instead, has a lower limit incorporated in the pSEOBNR model to ensure that $t_{\text{match}}^{\ell m}$ is not after the last point of the BBH dynamics. The upper limit on its uniform prior is set to $50M$. For δa_6 and δd_{SO} , we set a uniform prior between -100 and 100 .

We use Bilby [98,99] with the DYNesty nested sampler [100] to sample the posterior distributions of the GR and deviation parameters.

The GW250114 analysis. We first analyze GW250114 by allowing for deviations to the merger amplitude and frequency of the dominant (2,2) mode, as well as the ringdown (2,2,0) QNM. The results are shown in Fig. 1, where the frequency and damping time of the (2,2,0) QNM are consistent with the LVK analysis in Ref. [3]. The merger amplitude and frequency of the (2,2) mode are consistent with the predictions of GR and are exceptionally well constrained, with $\delta \omega_{22} = 0.01_{-0.04}^{+0.04}$ and $\delta A_{22} = 0.06_{-0.11}^{+0.13}$ at 90% credible intervals. The constraint on the merger amplitude is roughly twice as stringent as the one obtained from the analysis of GW150914 [24,101], while the constraint on the merger frequency is about 4 times tighter. For comparison, the GW150914 analysis yielded $\delta \omega_{22} = 0.00_{-0.12}^{+0.17}$ and $\delta A_{22} = -0.01_{-0.19}^{+0.27}$. The remarkable improvement of the GR constraints at merger is explained by the larger SNR of the event, of a factor of 3 with respect to GW150914.

When interpreting our inference on these parameters, it is important to note that in the SEOBNRv5PHM model they are calibrated to NR simulations of aligned-spin binaries. The model extends these fits to spin-precessing systems by evaluating them for the spin components perpendicular to the orbital plane at the matching time. Because GW250114 is consistent with a binary with negligible spin precession, the error introduced by approximating the input values with approximately aligned-spin fits is subdominant relative to the statistical uncertainties. We compare the merger amplitude and frequency predicted by SEOBNRv5PHM and NRSur7dq4 for the posterior samples of GW250114 with NRSur7dq4, finding average differences of around 1%, smaller than the statistical uncertainty of our analysis ($\gtrsim 4\%$).

As a further step, we extend the analysis of GW250114 to probe the (4,4) mode. We perform analyses including only the merger parameters and both merger and ringdown parameter deviations. We find that their results agree with each other, and the results for the (2,2,0) and (4,4,0) QNMs are compatible with those of the LVK analysis [3]. Quite notably, this shows that the constraints on the (4,4,0)

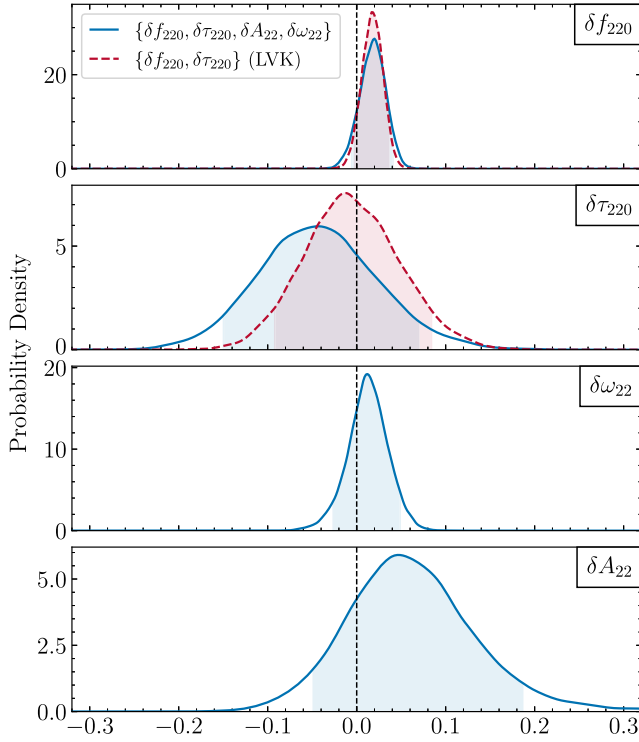


FIG. 1. The one-dimensional posterior distributions on the merger-ringdown deviation parameters for our analysis (blue lines) and the LVK analysis [3] (red lines), which included only ringdown deviations. Both analyses were performed using the pSEOBNRv5PHM waveform model where the shaded areas indicate 90% credible intervals. The vertical lines mark the null GR expectation. The inferred values of δA_{22} and $\delta \omega_{22}$ are consistent with GR.

QNM are a robust result, since they do not change when allowing for the merger amplitude and frequency to deviate from their GR predictions (see Supplemental Material [71] for a more detailed discussion).

Since the analyses agree with each other, in the following we present the one with deviations to the merger parameters δA_{22} , $\delta \omega_{22}$, δA_{44} , and $\delta \omega_{44}$. The results are summarized in Fig. 2. Remarkably, we constrain, for the first time, the merger frequency of the subdominant (4,4) mode, obtaining $\delta \omega_{44} = -0.06^{+0.06}_{-0.06}$, which is marginally compatible with GR. The amplitude of this mode remains unconstrained.

To better understand why the posterior distribution of δA_{44} remains unconstrained and rails against the upper bound of the prior range, we perform several injection studies (see Supplemental Material [71] for details). First, we find a correlation between the posterior samples with large δA_{44} and the inclination angle ι . This causes the posterior distribution on ι to shift away from the GR parameter estimation (see Fig. 5 in Supplemental Material [71]). Since the inclination angle correlates with the luminosity distance D_L , we also find a bias with the GR recovery for this parameter. We perform zero-noise injections with SEOBNRv5PHM and NRSur7dq4 waveforms and

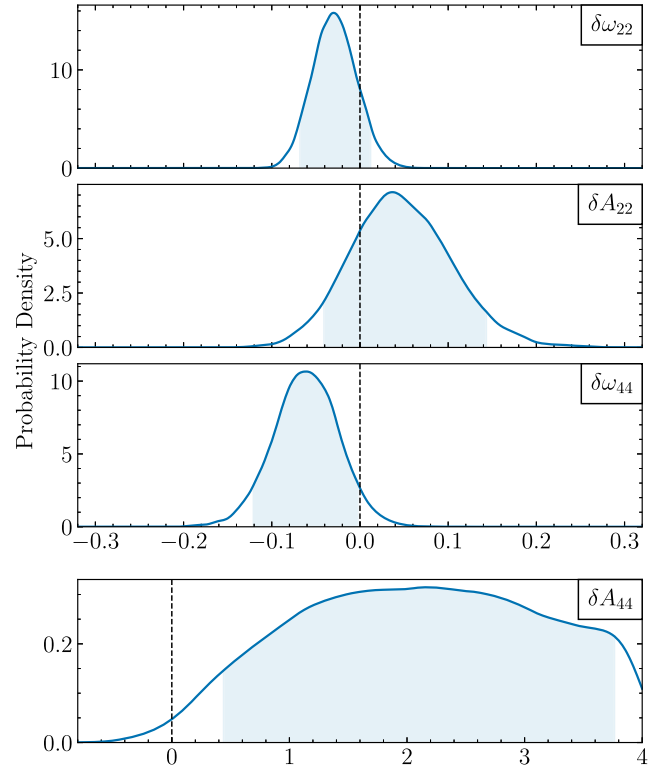


FIG. 2. The one-dimensional posterior distributions on the merger parameters for GW250114, where the shaded areas indicate 90% credible intervals. The vertical lines mark the null GR expectation. The inferred values of δA_{22} and $\delta \omega_{22}$ are consistent with GR, while $\delta \omega_{44}$ is marginally consistent with GR. The posterior distribution on δA_{44} is unconstrained and rails against the upper bound (note the different scale with respect to the other parameters).

recover δA_{44} with wide and uninformative posteriors that no longer rail against the upper limit of the prior (see Fig. 6 in Supplemental Material [71]). This result excludes the possibility that waveform systematics can be responsible for the railing of the δA_{44} posterior. We then inject the SEOBNRv5PHM waveform in ten different Gaussian-noise realizations and find that one of them can induce the railing observed in the real data (see the thick other line in Fig. 6 in Supplemental Material [71]). We conclude that the correlation between δA_{44} and ι causes the posterior on the first parameter to have a long tail, while the specific noise realization of the event produces a shift away from GR, causing it to rail against the upper bound. The interplay between the low SNR of the (4,4) mode, the correlation with the inclination angle, and the noise make the measurement of δA_{44} particularly difficult for this specific event.

We also notice the presence of a mild correlation between $\delta \omega_{22}$ and $\delta \omega_{44}$. Indeed, the posterior distribution on $\delta \omega_{22}$ is shifted toward negative values with respect to the analysis with merger deviations only to the (2,2) mode. By injecting SEOBNRv5PHM and NRSur7dq4 waveforms in zero noise, we find that the correlation between $\delta \omega_{22}$ and

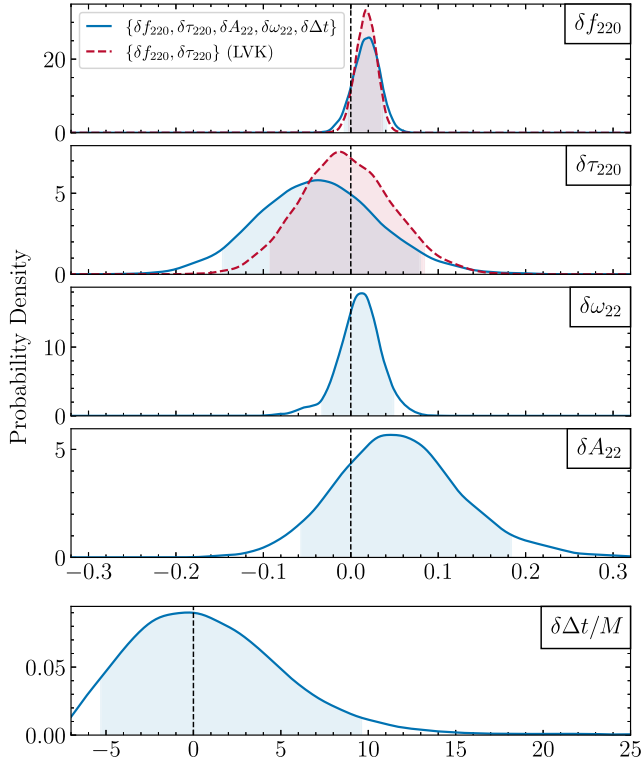


FIG. 3. The one-dimensional posterior distributions on the merger-ringdown deviation parameters for our analysis (blue lines) and the LVK analysis [3] (red lines), which included only ringdown deviations. Both analyses were performed using the pSEOBNRv5PHM waveform model. The shaded areas indicate 90% credible intervals. The vertical lines mark the null GR expectation. We constrain for the first time the merger time shift to be consistent with GR.

$\delta\omega_{44}$ is already present. The introduction of the Gaussian noise can accentuate the shifts on $\delta\omega_{44}$, making it marginally compatible with GR. We conclude that the correlation between $\delta\omega_{22}$ and $\delta\omega_{44}$ is genuine and does not depend on waveform systematics. The shift of $\delta\omega_{44}$ is instead explained by the interplay between the correlation with $\delta\omega_{22}$ and the specific noise realization of the event. More details are presented in Supplemental Material [71].

Finally, we perform an analysis of GW250114 allowing for deviations in the merger amplitude, frequency, and peak time of the (2,2) mode, as well as the (2,2,0) QNM. The results are summarized in Fig. 3. We constrain, for the first time to the best of our knowledge, the merger time shift to $\delta\Delta t = 0.5^{+9.1}_{-5.8}M$. The 90% credible interval corresponds to about 5 ms, to be compared with the signal length of about 550 ms. This finding is consistent with the injection studies in Ref. [24] with $\text{SNR} \sim 100$ (note that a different parametrization on the time shift parameter was used).

We also analyzed GW250114 by allowing for parametrized deviations to the inspiral calibration parameters a_6 and d_{SO} ; however, the analyses returned uninformative posteriors. This result can be explained by the fact that d_{SO}

has a prefactor proportional to the effective spin χ_{eff} in the EOB Hamiltonian. Since for this event χ_{eff} is well measured to be small, d_{SO} is hard to constrain. Moreover a_6 , which is a 5PN correction to the EOB Hamiltonian, likely needs higher SNR and longer signals to be constrained.

Overall, the stringent pSEOBNR results can improve current constraints on gravity theories beyond GR and exotic compact objects, provided model predictions for beyond-GR modifications to merger observables are available. While accurate merger amplitudes and frequencies require NR calibration, and sufficiently accurate NR simulations for beyond-GR theories are not yet available, we can nonetheless perform an illustrative mapping for the time at which the GW amplitude peaks. As an example, we map the observational bound of $\delta\Delta t$ to Einstein-dilaton-Gauss-Bonnet (EdGB) gravity using the SEOBNR-EdGB model of Ref. [102]. In this model, the merger time shifts because EdGB corrections modify the ISCO location, generally leading to an earlier merger than in GR. One can therefore determine the largest coupling compatible with the inferred bound from the analysis of GW250114. Using the maximum-likelihood NRSur7dq4 parameters, we find that a coupling of $\sqrt{\alpha_{\text{GB}}} \simeq 5.8$ km yields a peak-time shift of $\sim 9M$ relative to GR at the upper edge of the 90% credible interval. Although this constraint is weaker than the tightest existing bounds (i.e., $\sqrt{\alpha_{\text{GB}}} \lesssim 0.3$ km [102,103]), largely because the source is near equal mass and relatively massive, it illustrates how agnostic merger-deviation parameters can be approximately mapped to specific beyond-GR theories. A fully robust interpretation of this mapping would ultimately require NR-calibrated predictions for this parameter, as done in GR.

Conclusions. We tested GR in the plunge-merger-ringdown stage of GW250114, the clearest event to date. We found that the (2,2) mode peak amplitude and instantaneous frequency are constrained to about 10% and 4%, respectively, at 90% credible level. These results are, respectively, 2 and 4 times more stringent than the ones obtained for GW150914. We also constrained, for the first time to the best of our knowledge, the instantaneous frequency of the (4,4) mode at merger to about 6% and the time at which the GW (2,2) mode amplitude peaks to about 5 ms. Thanks to the high SNR of this event, these results offer exceptionally accurate tests of GR in the strong-gravity regime and mark a significant improvement over previous analyses, heralding a new era of precision tests of GR.

We performed injection studies in zero and Gaussian noise to assess the correlations between the binary parameters and the parametrized deviations from GR. Our results confirm that waveform systematics does not affect the GW250114 analyses, while the specific noise realization of the event can slightly affect the parameter estimation.

The analyses did not constrain the (4,4) mode amplitude at merger, as the posterior distribution on this parameter is

wide and rails against the upper bound of its prior range. This behavior can be explained by the correlation with the inclination angle and the specific noise realization of the event, which make the measurement of δA_{44} particularly difficult in this specific case. The lack of a meaningful constraint on deviations in the (4,4) mode amplitude at merger is consistent with the findings of Refs. [104,105], which considered a global deviation to the (4,4) mode amplitude and similarly found no significant constraint for GW250114, with the posterior showing little support near zero.

We have shown that the constraints on the (2,2,0) and (4,4,0) QNMs do not depend on the assumptions that are made for the amplitudes and the exact point at which inspiral and merger ringdown are attached. These results provide evidence for the robustness of the QNM constraints found by the LVK Collaboration [3].

The tests performed in this work can be applied to future high-SNR events, potentially increasing precision by combining the resulting constraints. The fact that the source of GW250114 is a binary with nearly equal masses limits the ability to place constraints on modified-gravity theories such as EdGB and dynamical Chern-Simons gravity [106]. In the future, signals from binaries with different mass ratios and nonzero spins will allow us to test beyond-GR theories more effectively.

Note added. Recently, we became aware of an independent study, Chandra *et al.* [105], that constrains the GW250114 merger’s amplitude of the (2,2) mode using pTEOBResumS-Dali.

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Data availability. The data that support the findings of this article are openly available [108].

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