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Black Hole Spectroscopy and Tests of General Relativity with GW250114

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The binary black hole signal GW250114, the loudest gravitational wave detected to date, offers a unique opportunity to test Einstein's general relativity (GR) in the high-velocity, strong-gravity regime and probe whether the remnant conforms to the Kerr metric. Upon perturbation, black holes emit a spectrum of damped sinusoids with specific, complex frequencies. Our analysis of the postmerger signal shows that at least two quasinormal modes are required to explain the data, with the most damped remaining statistically significant for about one cycle. We probe the remnant's Kerr nature by constraining the spectroscopic pattern of the dominant quadrupolar ($\ell = m = 2$) mode and its first overtone to match the Kerr prediction to tens of percent at multiple postpeak times. The measured mode amplitudes and phases agree with a numerical-relativity simulation having parameters close to GW250114. By fitting a parametrized waveform that incorporates the full inspiral-merger-ringdown sequence, we constrain the fundamental ($\ell = m = 4$) mode to tens of percent and bound the quadrupolar frequency to within a few percent of the GR prediction. We perform a suite of tests—spanning inspiral, merger, and ringdown—finding constraints that are comparable to, and in some cases 2–3 times more stringent than those obtained by combining dozens of events in the fourth Gravitational-Wave Transient Catalog. These results constitute the most stringent single-event verification of GR and the Kerr nature of black holes to date, and outline the power of black-hole spectroscopy for future gravitational-wave observations.

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Introduction—On January 14, 2025, the LIGO detectors [1] recorded the loudest gravitational-wave (GW) signal to date, GW250114_082203 (hereafter GW250114) [2]. The Virgo [3] and KAGRA [4] interferometers were offline at the time. The high network signal-to-noise ratio (SNR) of 76 makes GW250114 an especially powerful probe of whether Einstein's theory of general relativity (GR) [5], and, in particular, its rotating vacuum black hole (BH) solution [6], accurately describe the observed gravitational radiation.

The nonlinearity of Einstein's field equations, coupled with the interdependence of metric and matter, the inherent gauge freedom, and the complexity of the initial-value problem [7,8] have made solving these equations notoriously challenging. Following the spherically symmetric solution [9] in 1916, the search for an exact rotating axisymmetric solution in vacuum spanned nearly 50 years, until the Kerr metric breakthrough [6]. This was followed by efforts to establish the uniqueness of static and stationary solutions, including their full characterization by conserved quantities, such as mass, spin, and charge [10–15]. The Kerr metric's simplicity has enabled the derivation of unexpected properties, including integrability for geodesic motion [16], the Penrose process [17,18], and the four laws of BH mechanics [19]. The solution's application to rotating BHs has had a profound impact on astrophysics, particularly once quasars were discovered [20]. The Kerr solution underpins waveform models used to detect GWs and infer properties of dark objects. Thus, finding that these objects do not conform to Kerr BHs would have far-reaching implications for both astrophysics and fundamental physics.

From shortly after its inception, the theory of GR has withstood a broad array of experimental probes. Nevertheless, there are open questions associated to BHs, such as their stability [21–24], the existence of singularities inside their event horizon [25], and Hawking's information-loss paradox [26,27]. Furthermore, GR is known to be incomplete in the quantum domain and requires a dark sector (dark matter and dark energy) to explain cosmological observations, motivating continued searches for possible deviations and viable extensions of the theory [28]. Some gravity theories alternative to GR admit the Kerr metric as a solution [29,30], thus tests of GR and tests of Kerr spacetime are complementary.

In the last ten years, GW observations from binary black hole (BBH) coalescences [31,32] (as well as, from binary neutron stars and mixed binaries) have provided a unique laboratory for testing GR in the strong-gravity, dynamical,

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and high-velocity regime, where potential departures from GR are expected to be most pronounced [28–30,33]. Since the first detection of a BBH coalescence [34,35], the growing catalog of GW events [32,36–39] has enabled increasingly stringent bounds of the inspiral, merger, and ringdown phases [40–43]. These results complement other GR investigations—Solar System tests, binary-pulsar experiments, observations of massive BHs at galactic centers, and cosmological measurements [28,44–49]—which span low-velocity, quasistatic, weak-field regimes and, in some cases, strong-field environments with self-gravitating bodies.

In vacuum, BHs in binaries adiabatically and steadily approach each other during the inspiral until they merge, driven by GW emission, a purely tensorial radiation in GR, dominated by the quadrupolar multipole [50]. According to GR, after the two BHs merge, a highly distorted remnant BH is formed, which equilibrates by emitting gravitational radiation [51–53]. In the 1970s, Vishveshwara and Press [54,55], using results from Regge, Wheeler, and Zerilli [56,57], made a significant discovery. In response to an incoming pulse of radiation, BHs ring the spacetime, emitting a superposition of damped sinusoids with discrete frequencies and decay times, depending solely on the intrinsic properties of the BH, notably its mass and spin. This follows from the no-hair theorem [6,10–15], which states that in four-dimensional vacuum GR, a stationary BH that is nonsingular outside the horizon is fully characterized by its mass and spin. Since those pioneering works [54,55], using sophisticated analytical and numerical methods in BH perturbation theory [58–62], the full first-order BH spectrum has been computed for rotating BHs, revealing also the presence of GW tails [63,64] at late times. It was also noted [61] that with the advent of GW astronomy, detecting BH's quasinormal mode (QNM) frequencies could confirm their existence with a certainty comparable to the way the 21 cm line unequivocally identifies interstellar hydrogen. This started the BH-spectroscopy program [61,65–72]. A measurement of the frequency and damping rate of a single mode suffices to constrain the final-state mass and spin. Measurements of multiple mode frequencies and damping times enable a test of the no-hair theorem [17,73–75] through the consistency of the modes' properties with the Kerr prediction [6]. In principle, the QNMs are affected by electromagnetic charges, but we expect the latter to be negligible for astrophysical BHs [76–79]. Several studies in the last few years have investigated the presence of QNMs in GW data claiming different levels of significance [35,43,80–85].

In this Letter, we perform several studies of GW250114, aimed at constraining deviations from the GR predictions throughout the inspiral, merger, and ringdown; the Kerr nature of the components in the binary; and of the remnant via BH spectroscopy. Extending the recent work in Abac *et al.* [2], we investigate the postmerger stage with different ringdown models and methods. We corroborate our findings for the amplitudes and phases of the quadrupolar QNMs with results of a numerical-relativity (NR) simulation having parameters close to GW250114. We bound the spectroscopic pattern of the dominant quadrupolar mode and its first overtone to match the Kerr prediction at multiple postpeak times, while constraining, for the first time, the hexadecapolar fundamental-mode frequency using a parametrized waveform model for the full signal. We use waveform models with parametrized deviations from GR to set the most stringent bounds on the post-Newtonian (PN) parameters determining the GW phasing during the inspiral, perform signal consistency tests, and use them to assess the increase of the BHs area from the inspiral to the ringdown at high credibility. Overall, GR and the Kerr metric once again remain empirically unshaken.

GW250114—Using the inspiral-merger-ringdown (IMR) quasicircular, spin-precessing NRSur7dq4 model [86], Abac *et al.* [2] found that the wave morphology is consistent with a BBH with component masses $33.6^{+1.2}_{-0.8} M_\odot$ and $32.2^{+0.8}_{-1.3} M_\odot$ and dimensionless spin magnitudes ≤ 0.24 and ≤ 0.26 (90% credible intervals). Its eccentricity is constrained to $e \leq 0.03$ at a reference frequency of 13.33 Hz, using eccentric aligned-spin models [87,88].

BH spectroscopy of the remnant alone—In GR, after a dynamical phase surrounding a BBH merger, the postmerger signal is dominated by a superposition of exponentially damped sinusoids corresponding to QNMs of the final Kerr remnant with redshifted mass $M_\mathrm{f}(1+z)$, where z is the cosmological redshift, and dimensionless spin χ_f [51–53].

While the prompt response [65,89,90], dynamical effects [91–93], higher-order perturbative terms [94–97], and other noninearities [51] are expected to contribute to the early postmerger signal, they are subdominant to the QNMs at sufficiently late times [98,99]. Gravitational-wave tails [63,64,100–103] dominate at much later times. Here, because of some theoretical modeling uncertainties, we neglect these other contributions, focusing on the exponentially decaying sinusoidal QNM component and assume that the plus and cross polarizations of the postmerger signal at the detectors take the form [35]

$$h_+ - ih_\times = \sum_{\substack{\ell\geq 2\\ 0\leq m\leq \ell\\ n\geq 0}} e^{-t/\tau_{\ell mn}}\left(A^\mathrm{R}_{\ell mn} e^{-2\pi i f_{\ell mn} t} + A^\mathrm{L}_{\ell mn} e^{2\pi i f_{\ell mn} t}\right), \tag{1}$$

where the complex numbers $A^\mathrm{R}_{\ell mn}$ and $A^\mathrm{L}_{\ell mn}$ encode the amplitudes and phases of the right- and left-circularly polarized components of the mode, and depend on the excitations imprinted on the spacetime by the progenitors' dynamics [104–109]. The frequency $f_{\ell mn}$ and the damping time $\tau_{\ell mn}$ correspond to the Kerr QNM frequencies and damping times, and are indexed by the angular-mode numbers ℓ and m, and the radial-overtone number n [58–60]. The amplitude of the elliptically polarized mode at time $t = 0$, which we take to be the starting time of fits of Eq. (1) to GW250114, is $A_{\ell mn} = |A^{\mathrm{R}}_{\ell mn}| + |A^{\mathrm{L}}_{\ell mn}|$ [110]. Given GW250114's properties, in Eq. (1) we have neglected retrograde modes, which are known to be less excited and less important than prograde modes for this type of system [106,111,112].

We employ RINGDOWN [81,110] and pyRing [80,113] to fit Kerr models of the form Eq. (1), as well as models with agnostic complex frequencies, to the postpeak signal from GW250114, starting at a range of times, $t_>$, after t_{peak}: the time at which NRSur7dq4's maximum likelihood strain magnitude over the two-sphere achieves its maximum [2,80,81,86,110,114]. We adopt the reference peak time, mass, and sky location from the ringdown fits in Abac *et al.* [2], with $t_{M_\mathrm{f}} = (1+z)GM_\mathrm{f}/c^3 = 0.337$ ms. Henceforth, we refer to the Kerr modes in Eq. (1) as ℓmn, and a sum of multiple modes is denoted as $\ell mn + \ell' m' n'$. The RINGDOWN and pyRing codes have different native priors and run settings, and therefore produce results for this analysis that differ [2]. The results from both codes are sufficiently qualitatively similar; however, in most cases we show results from only one or the other code throughout.

As shown in Abac *et al.* [2], the postpeak data of GW250114 is consistent with the 220 and 221 QNMs. Here, we further motivate this identification, extend this Lette using other ringdown models and methods, and test the remnant's Kerr nature at different postpeak times. In the Supplemental Material [115], we also validate the use of Eq. (1) at the times at which we apply our QNM models by comparing to NR waveforms. We start by adopting an agnostic sum of two damped sinusoids (2DS) whose complex amplitudes, frequencies, and damping times are arbitrary [35,42,43]. In the top panel of Fig. 1, we show that the amplitude of the more rapidly decaying damped sinusoid at various fit start times $t_>$ is bounded away from zero at $>3\sigma$ until $t_> > 9t_{M_\mathrm{f}}$, and it is nonzero at 3.5σ at $t_> = 6t_{M_\mathrm{f}}$. By examining the frequencies and damping times of the two damped sinusoids shown by the red contours in Fig. 2 (the other contours will be discussed later), we find that they are broadly consistent with the 220 and 221 QNMs predicted from the remnant mass and spin inferred from the IMR analysis of GW250114 in GR. This motivates fitting GW250114 with the $220 + 221$ model. In the bottom panel of Fig. 1, which shows the amplitude of the 221 QNM at various fit start times, we see that for the $220 + 221$ model the 221 QNM's amplitude is not only bounded away from zero, but is consistent with the exponential decay expected within the error bounds of the 221 QNM fit at $t_> = 6t_{M_\mathrm{f}}$ for $t_> \geq 6t_{M_\mathrm{f}}$. At earlier times, the amplitude deviates from its expected value, suggesting a breakdown of the $220 + 221$ model. Motivated by analysis of NR simulations [116], we find that if the 222 QNM is added to the

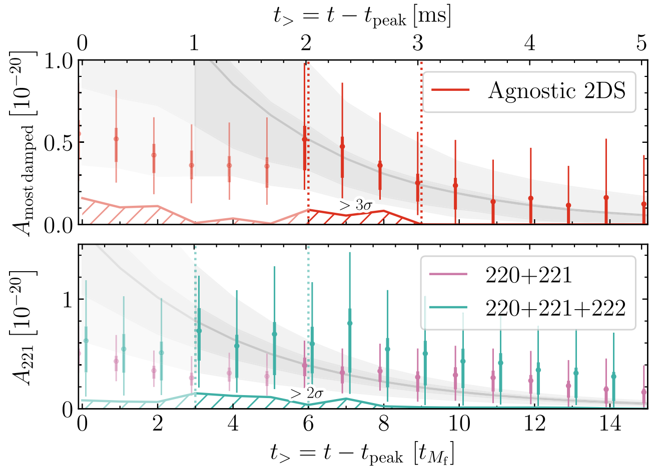

FIG. 1. Consistency of postmerger data with two QNMs. Top: the inferred amplitude of the most rapidly decaying damped sinusoid for the 2DS model at different fit times as measured by RINGDOWN. The dots indicate posterior medians, while the thick (thin) bars indicate the 50% (90%) credible interval; for each time, they have been offset slightly for clarity. The gray bands predict the median, 50%, and 90% credible ranges of amplitudes over time from the $t_> = 6t_{M_\mathrm{f}}$ fit, marked by the first dotted line. The second dotted line at $t_> = 9t_{M_\mathrm{f}}$ indicates the latest time that the 90% credible range of the amplitude is distinct from zero. The hatched region shows the greater than 3σ-equivalent credible region for the amplitude being strictly positive. Bottom: the inferred amplitude of the 221 mode for the $220 + 221$ (pink) and $220 + 221 + 222$ (green) models as measured by pyRing. The first dotted line indicates $t_> = 3t_{M_\mathrm{f}}$, beyond which $220 + 221 + 222$ fits yield 221 amplitudes consistent with that at $t_> = 6t_{M_\mathrm{f}}$. The second dotted line indicates $t_> = 6t_{M_\mathrm{f}}$. The hatched curve shows the $> 2\sigma$-equivalent credible region.

fit, then consistency at the 90% level with the amplitude at $t_> = 6t_{M_\mathrm{f}}$ is obtained until $t_> \geq 3t_{M_\mathrm{f}}$, even though the amplitude of the 222 QNM is never confidently measured away from zero in these fits. These findings suggest that the data is indeed consistent with the 220 and 221 QNMs over a range of times.

In the Supplemental Material [115], we corroborate these results using a NR simulation in GR. Specifically, we demonstrate that the results in Fig. 1 are broadly consistent with that of a simulated signal of a NR simulation with parameters close to GW250114; we show that the relative amplitudes and phases of GW250114's 220 and 221 QNMs are consistent with those of the NR simulation at the $\geq 38\%$ credible level for $t_> \in [3, 9]t_{M_\mathrm{f}}$. Separately, using GW250114 we also find consistency among the final mass and spin computed with the IMR analysis and the various QNM models we fit.

In Fig. 2, we probe the Kerr nature of the remnant. We examine the fit to the postpeak data of GW250114 with a $220 + \delta 221$ model whose 221 QNM's frequency and damping time (f_{221} and τ_{221}) are allowed to vary from their Kerr values ($f_{221,\mathrm{Kerr}}$ and $\tau_{221,\mathrm{Kerr}}$) by

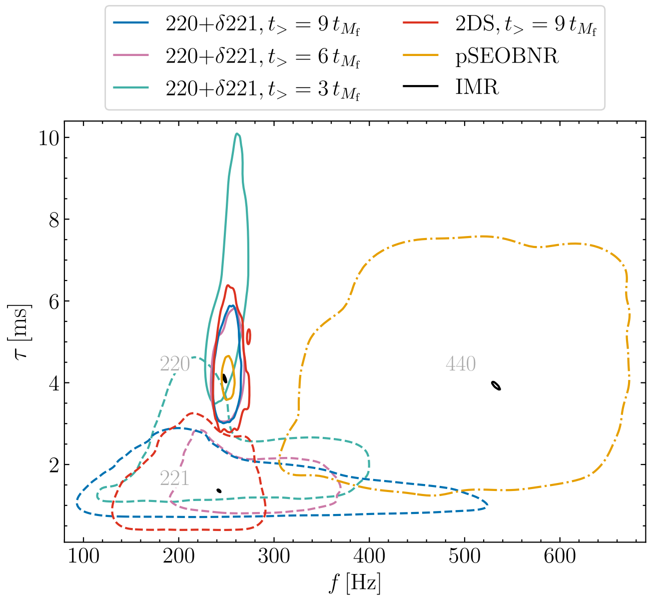

FIG. 2. BH spectroscopy with different QNMs. The 90% credible regions for the 220 (solid) and 221 (dashed) QNM frequencies and damping times as measured when fitting the $220 + \delta 221$ model at $t_> \in \{3, 6, 9\} t_{M_f}$ (green, pink, blue) and the 2DS model at $t_> = 9t_{M_f}$ (red). In orange, the constraints from the pSEOBNR analysis for the 220 (solid) and 440 (dot-dashed) QNMs. Black curves indicate the 220, 221, and 440 frequencies and damping times inferred from the IMR remnant mass and spin posteriors.

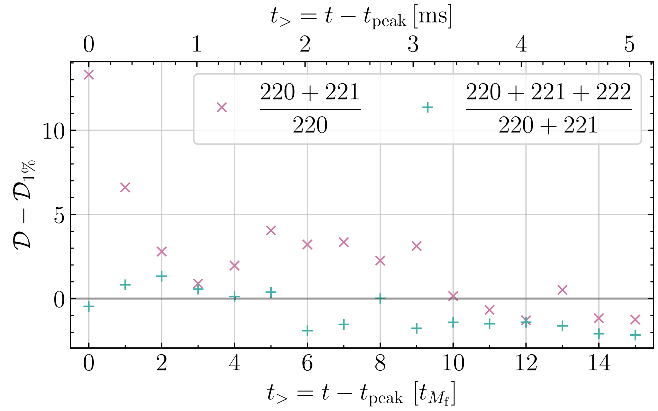

FIG. 3. Filtering out two QNMs in the postmerger data. Detection statistics for the QNMRF analysis with varying mode content relative to the 1% FAP threshold over time [121]. At times $t_> \leq 10t_{M_f}$, the QNMRF finds strong support for the $220 + 221$ model over the single-mode 220 model. The $220 + 221 + 222$ model is weakly preferred over the $220 + 221$ model from $t_< = 1t_{M_f}$ to $t_< = 5t_{M_f}$.

$\delta\hat{f}_{221} = \ln(f_{221}/f_{221,\mathrm{Kerr}})$ and $\delta\hat{\tau}_{221} = \ln(\tau_{221}/\tau_{221,\mathrm{Kerr}})$. As suggested by the 2DS fit, the data are particularly consistent with the 220 and 221 QNMs predicted by the remnant mass and spin inferred by the full IMR analysis. More specifically, we constrain $\delta\hat{f}_{221} = -0.13^{+0.61}_{-0.16}$ at $t_> = 3t_{M_f}$, $\delta\hat{f}_{221} = 0.09^{+0.29}_{-0.30}$ [2] at $t_> = 6t_{M_f}$, and $\delta\hat{f}_{221} = -0.07^{+0.72}_{-0.53}$ at $t_> = 9t_{M_f}$, all at the 90% credible level. However, the recovered amplitude of the 221 QNM is not consistent with values at later times in the $3t_{M_f}$ fit, indicating that the model may be fitting other content at these times. Previously, analysis using the third Gravitational-Wave Transient Catalog (GWTC-3.0) [43] set $\delta\hat{f}_{221} = 0.01^{+0.27}_{-0.28}$ by analyzing the data from the peak onward using pyRing, and hierarchically combining results from 21 events [117]. In the following section, we will return to this figure to discuss the pSEOBNR analysis.

Additionally, we perform an analysis that does not measure the mode amplitudes, but filters out successive Kerr QNMs from the data in the frequency domain: the QNM rational filter (QNMRF) [118–120]. We adopt a hybrid Bayesian-like approach, with a detection statistic $\mathcal{D}$ that is analogous to a logarithmic Bayes factor, yet differs from the Bayes factors used in other time-domain ringdown analyses (see details in Supplemental Material [115]). Figure 3 shows the difference between the QNMRF detection statistic and the detection statistic corresponding to a 1% false-alarm probability (FAP) for the $220 + 221$ and $220 + 221 + 222$ models. Like the other analyses, the QNMRF finds strong support for the $220 + 221$ model over the single-mode 220 model for times $t_> \leq 10t_{M_f}$. Additionally, the three-mode $220 + 221 + 222$ model is more weakly preferred over the $220 + 221$ model from $t_< = 1t_{M_f}$ to $t_< = 5t_{M_f}$. This provides independent evidence that GW250114 is consistent with the 220 and 221 QNMs.

BH spectroscopy with full signal—So far, we have treated the complex amplitudes of the QNMs in Eq. (1) as free parameters, and directly constrained them from the data using only the postpeak signal. When these amplitudes are instead predicted from the binary's properties using NR simulations in GR, consistency tests are feasible even with a single mode [43,85,122]. This results in a more stringent test of GR, at the cost of stronger assumptions about the emission process: most existing amplitude models assume the perturbed BH originates from a binary merger, and are restricted to quasicircular orbits [104–109].

Including additional premerger information, one can test for deviations in QNM frequencies by analyzing a full IMR waveform calibrated to NR simulations. The pSEOBNR analysis [122–125] introduces fractional deviations $(\delta\hat{f}_{\ell m0}, \delta\hat{\tau}_{\ell m0})$ to the frequency and decay time of the fundamental QNMs in the ringdown description of SEOBNRv5PHM [126,127] as

$$f_{\ell m0} = f^{\mathrm{GR}}_{\ell m0}(1 + \delta\hat{f}_{\ell m0}), \qquad \tau_{\ell m0} = \tau^{\mathrm{GR}}_{\ell m0}(1 + \delta\hat{\tau}_{\ell m0}). \tag{2}$$

The GR predictions for these quantities are obtained using the final mass and spin of the remnant BH, estimated using NR fits based on the measured component masses and spins [128,129]. Rather than isolating the post-merger stage, excluding the inspiral and merger phases, the analysis uses the full IMR signal, assuming GR holds up to the merger. The merger-ringdown model is based on a factorized ansatz: the contributions of the fundamental QNMs, modified via the parametrization in Eq. (2), are multiplied by phenomenological, time-dependent amplitudes calibrated to NR [127,130,131]. These amplitudes aim to capture the ringdown prompt response [65,89,90] and dynamical phase [91–93]. As for now, this approach enables constraints on fundamental QNMs, but not on overtones, whose effects are implicitly absorbed by the time-dependent amplitudes rather than being parametrized explicitly.

We first perform an analysis allowing for deviations in the dominant 220 QNM only, which has been the focus of previous constraints [42,43,123,125]. Owing to GW250114 's high SNR (∼65 up to merger and ∼40 postmerger), we also extend the analysis to probe higher fundamental QNMs. The nearly equal masses and low spins of the binary's components imply that multipoles with odd m are suppressed due to rotational symmetry, while even-m multipoles are expected to be more prominent [99,132,133]. The inclination ($\Theta = 0.78^{+0.19}_{-0.23}$ rad [2] at a reference frequency of 20 Hz, when folded to $[0, \pi/2]$) and azimuthal phase inferred from GW250114 favor the excitation of the $(\ell, |m|) = (4, 4)$ multipoles [2,133], which contribute an SNR of $3.6^{+1.4}_{-1.5}$ to the full IMR signal [134]. Therefore, we perform an analysis including deviations in both the 220 and 440 QNMs. We find minimal correlation between the deviation parameters of the two modes, and in the following we report constraints on $(\delta\hat{f}_{220}, \delta\hat{\tau}_{220})$ from the joint fit.

The results are summarized in Fig. 4. The frequencies and damping times of both modes are consistent with the predictions of GR, based on the Kerr remnant parameters inferred from the inspiral. The dominant 220 QNM is especially well constrained, with $\delta\hat{f}_{220} = 0.02^{+0.02}_{-0.02}$ and $\delta\hat{\tau}_{220} = -0.01^{+0.10}_{-0.09}$. Owing to the exceptional SNR of this signal, these constraints are roughly twice as stringent as those obtained by hierarchically combining [117,135] results from 17 events in the fourth Gravitational-Wave Transient Catalog (GWTC-4.0) [136], which have SNR above 8 in the inspiral and postinspiral stages. That analysis yielded $\delta\hat{f}_{220} = 0.00^{+0.06}_{-0.06}$ and $\delta\hat{\tau}_{220} = 0.16^{+0.18}_{-0.16}$. A measure of consistency with GR is provided by the GR quantile $\mathcal{Q}_{\rm GR}$ [42], which corresponds to the cumulative posterior probability enclosed by the isoprobability surface passing through the GR prediction. A lower (higher) value of $\mathcal{Q}_{\rm GR}$ indicates better (worse) consistency with GR. For GW250114, the GR quantile is 54.2%, lower than for the combined constraints from GWTC-4.0 [136], 85.1%. The GWTC-4.0 results show a mild tension with GR [136], potentially due to non-Gaussian or nonstationary noise [42,125], parameter correlations amplified by unrealistic astrophysical priors [43,137], intrinsic variance due to the limited number of events in the catalog [138], or unmodeled selection effects that could systematically influence which signals are included in the analysis.

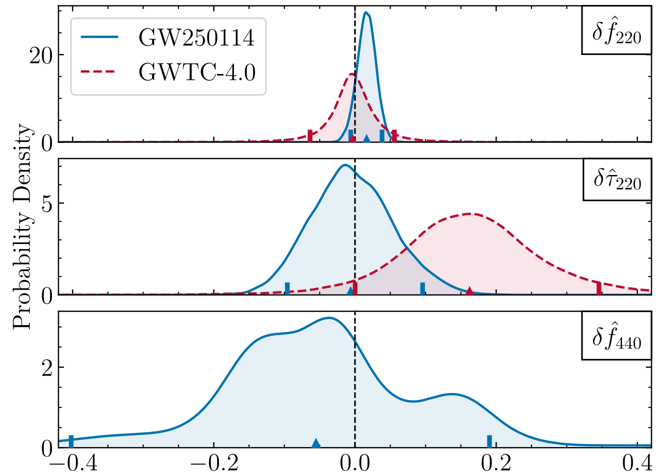

FIG. 4. Constraining the 220 and 440 QNMs using the full signal. Marginalized posterior distributions for fractional deviations in the frequency and damping time of the 220 QNM $(\delta\hat{f}_{220}, \delta\hat{\tau}_{220})$, and in the frequency of the 440 QNM $(\delta\hat{f}_{440})$, from the pSEOBNR analysis of GW250114. Hierarchically combined results from GWTC-4.0 [136] are also shown. Triangles mark the median values and vertical bars the symmetric 90% credible interval.

We also constrain, for the first time, the frequency of the subdominant 440 QNM, obtaining $\delta\hat{f}_{440} = -0.06^{+0.25}_{-0.35}$. The damping time remains weakly constrained, with $\delta\hat{\tau}_{440} = 0.20^{+0.53}_{-0.69}$. Since the pSEOBNR method employs the entire IMR signal, it enforces continuity across the waveform and does not allow the mode amplitudes to vanish. As a result, the analysis cannot by itself establish whether the 440 QNM is present in the data. However, similar constraints do not appear in simulated signals that exclude this mode or in lower-SNR events (see details in the Supplemental Material [115]), lending support to the interpretation that the constraint is driven by the presence of the 440 QNM in the ringdown signal of GW250114.

Beyond testing whether each mode is individually consistent with GR, one can also test whether both are consistent with originating from the same Kerr remnant, as in classical no-hair-theorem tests [61,65–68,70]. In the pSEOBNR framework, this is done by reconstructing the complex frequencies of the two modes from Eq. (2), giving $f_{220} = 251.7^{+5.1}_{-5.0}$ Hz, $\tau_{220} = 4.09^{+0.42}_{-0.38}$ ms, $f_{440} = 503^{+130}_{-185}$ Hz, and $\tau_{440} = 4.7^{+2.1}_{-2.7}$ ms. Their 90% credible regions are shown as the orange solid and dot-dashed curves in Fig. 2. These are then inverted to obtain two separate estimates of the remnant's mass and spin using fitting formulas [68], shown in Fig. S3 in the Supplemental Material [115]. We find that the estimates are mutually consistent, and agree with both the IMR-inferred values and with results from ringdown remnant-alone analyses.

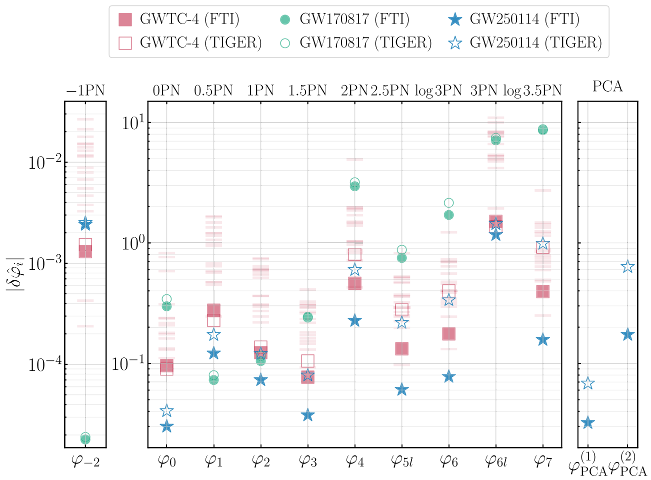

FIG. 5. Constraints on the inspiral phase from GW250114. The 90% upper bounds on the magnitude $|\delta\hat{\varphi}_i|$ of the PN inspiral deviation coefficients from −1 PN to 3.5 PN and the first two leading PCA parameters. For GW250114, blue filled (unfilled) stars are for FTI (TIGER). The horizontal red stripes mark the results from individual events from GWTC-4.0 using FTI. Bounds obtained by hierarchically combining the results from GWTC-4.0 are shown in the filled (unfilled) red squares for FTI (TIGER) [136]. The right panel shows constraints on the two leading PCA parameters that capture the dominant modes of deviation across the 1.5–3.5 PN parameter space.

The presence of the (4,4) multipole is independently supported by isolating the post-peak data in time domain, with the KerrPostmerger model in pyRing [85]. This model has also amplitudes calibrated to NR simulations at merger [131,139,140]. Including the (4,4) mode is mildly favored by a $\log_{10}$ Bayes factor of $0.54^{+0.18}_{-0.18}$ compared to a model with only the dominant (2,2) mode. Allowing for deviations from GR with the parametrization in Eq. (2), we constrain the 220 QNM as $\delta\hat{f}_{220} = 0.09^{+0.34}_{-0.22}$ and $\delta\hat{\tau}_{220} = -0.14^{+0.25}_{-0.23}$, while the 440 mode remains unconstrained. While less stringent than pSEOBNR, this analysis quantifies the constraints achievable when isolating the remnant's relaxation.

The stringent pSEOBNR results can improve current constraints on gravity theories beyond GR [141–145], and constrain properties of exotic compact objects [146,147]. As a concrete example, we consider dynamical Chern-Simons (dCS) gravity [148], a parity-violating extension of GR in which the QNM spectrum receives corrections controlled by a coupling length $\sqrt{\alpha_{\rm dCS}}$ [149]. Mapping the bound on the 220 QNM frequency to the predicted dCS correction yields an approximate constraint on the dCS coupling length of $\sqrt{\alpha_{\rm dCS}} < 32.2(40.1)$ km, assuming purely axial (polar) perturbations [149] (using the conventions therein). Differently from GR, dCS gravity breaks isospectrality [148]. These single-event bounds are competitive with recent ringdown-only analyses of GW150914, GW190521_074359, and GW200129_065458 [145]. The estimate is based on the posteriors for $\delta\hat{f}_{220}$ and remnant mass and spin from the pSEOBNR analysis, reweighted to a prior uniform in the dCS coupling length. More robust constraints could be obtained from a Bayesian analysis that directly uses waveform predictions in dCS gravity [143,145].

Bounding post-Newtonian inspiral parameters—The inspiral regime can be treated perturbatively within the PN framework [150], an expansion in powers of v/c where the nPN order corresponds to $\mathcal{O}([v/c]^{2n})$. As the intrinsic parameters of the binary uniquely determine the PN coefficients φ_i in the GW phase at each order, we can construct a consistency test of GR by introducing deformation parameters at each PN order [151–157]. We only consider variations in the individual PN coefficients independently, treating them as free coefficients that constrain the degree to which deviations from GR agree with the data. The inspiral deviations are constructed so as to represent a shift to the nonspinning PN coefficient, i.e., $\varphi_i \to (1+\delta\hat{\varphi}_i)\varphi_i^{\rm NS} + \varphi_i^{\rm S}$, where $\varphi_i^{\rm NS}$ denotes the nonspinning coefficient and $\varphi_i^{\rm S}$ is the spin-dependent part of the PN coefficient. In GR, the coefficients at −1 PN and 0.5 PN are explicitly zero and should be interpreted as absolute deviations, while the other coefficients are expressed as fractional deviations.

As in the GWTC-4.0 analysis [136], we use two independent pipelines: Flexible Theory Independent (FTI) [40,158] and Test Infrastructure for General Relativity (TIGER) [159–161]. The pipelines have several methodological differences, including the cutoff frequency at which corrections are turned off and choice of waveform models used. The FTI pipeline employs the SEOBNRv5HM_ROM model [127], which is restricted to aligned-spin configurations, whereas TIGER utilizes the precessing-spin waveform model IMRPhenomXPHM_SpinTaylor [162,163]. Because of technical changes in the pipelines, only events first reported in GWTC-4.0 that meet the FTI or TIGER selection criteria are analyzed [136]. For FTI, we use 18 events and for TIGER, we use 22 events.

The results are summarized in Fig. 5. Due to the significantly higher SNR of GW250114 during the inspiral phase compared to the rest of the observed BBH population, the FTI analysis of GW250114 provides constraints on a subset of deviations that are 2–3 times more stringent than the joint constraints derived from a hierarchical analysis [117,135] of the GWTC-4.0 results [136]. The bounding fractional deviations to the leading-order PN and 1.5PN coefficients are $\delta\hat{\varphi}_0 = 0.00^{+0.03}_{-0.03}$ and $\delta\hat{\varphi}_3 = -0.01^{+0.03}_{-0.02}$ for GW250114 compared to $\delta\hat{\varphi}_0 = -0.00^{+0.09}_{-0.09}$ and $\delta\hat{\varphi}_3 = 0.00^{+0.07}_{-0.07}$ for GWTC-4.0. GW250114 being a shorter signal, we do not place competitive constraints on the dipole φ_{-2} compared to those obtained from GW170817 [40]. Overall, the TIGER pipeline yields constraints that are less stringent than the combined GWTC-4.0 results [136], likely due to the differing treatment of the cutoff frequency and transition to merger-ringdown between the pipelines [136], and the inclusion of spin-precession in the TIGER analysis.

To address the limitation of varying individual PN coefficients independently, we perform a principal-component analysis (PCA) to probe correlated deviations across multiple PN orders [164–167], focusing on the 1.5 to 3PN coefficients [166,167].

The PCA analysis identifies the principal directions of parameter covariance, with the leading component corresponding to the linear combination of PN coefficients that is best constrained by the data. The leading PCA component can therefore yield tighter bounds than the individual PN coefficients, while the sub-leading component, being orthogonal to this optimal direction, can have weaker constraints than the best measured PN coefficients. We find that the FTI pipeline constrains the leading PCA component to $\delta\hat{\varphi}^{(1)}_{\rm PCA} = -0.01^{+0.02}_{-0.02}$ (slightly better constrained than $\delta\hat{\varphi}_3 = -0.01^{+0.03}_{-0.02}$) and the subleading component to $\delta\hat{\varphi}^{(2)}_{\rm PCA} = 0.04^{+0.14}_{-0.15}$, consistent with GR (see Fig. 5). A comparison of the PCA results to GWTC-4.0 is technically challenging as the PCA components correspond to different linear combinations of PN parameters for each event. This means that hierarchical inference requires modeling the joint distribution across all six PN coefficients [167]. Further details are presented in the Supplemental Material [115].

Signal consistency tests—We now construct an analysis complementary to the other tests, focusing on the consistency between different portions of the signal, by employing dimensionless deviation parameters that quantify the fractional difference between the remnant mass $M_{\rm f}$ and spin $\chi_{\rm f}$ inferred from the low- ($f < f_{\rm c}^{\rm IMR}$) and high-frequency ($f > f_{\rm c}^{\rm IMR}$) portions of the GW signal [168–170]. The cutoff $f_{\rm c}^{\rm IMR}$ is taken to be the GW frequency of the (2,2) mode at the innermost circular orbit of the remnant Kerr BH [171]. Ideally, the determination of whether a violation has occurred should be independent on the selected cutoff frequency. However, the stringency and sensitivity of the test may exhibit some dependence on this choice. The remnant properties are calculated using NR-calibrated fits for the final state [129,172,173] applied to the median values of the redshifted component masses, spin magnitudes, and spin angles as inferred from the full IMR analysis [41–43]. Inference is performed in each of the frequency regimes using IMRPhenomXPHM_SpinTaylor [162,163], with priors that are uniform in component mass and spin magnitude, and isotropic in the spin orientation. This choice of priors leads to highly nonuniform priors on the deviation parameters, and we therefore reweight the posteriors to impose uniform priors on them [42,43].

If GR is valid, and our waveform models are sufficiently accurate, the analysis in each of these regimes should yield consistent results. Thus, we have $\Delta M_{\rm f}/\bar{M}_{\rm f} = 2(M_{\rm f}^{\rm insp} - M_{\rm f}^{\rm postinsp})/(M_{\rm f}^{\rm insp} + M_{\rm f}^{\rm postinsp})$ and $\Delta\chi_{\rm f}/\bar{\chi}_{\rm f} = 2(\chi_{\rm f}^{\rm insp} - \chi_{\rm f}^{\rm postinsp})/(\chi_{\rm f}^{\rm insp} + \chi_{\rm f}^{\rm postinsp})$, such that the GR limit is given by $\Delta M_{\rm f}/\bar{M}_{\rm f} = \Delta\chi_{\rm f}/\bar{\chi}_{\rm f} = 0$. The core results are summarized in Fig. 6. We infer $\Delta M_{\rm f}/\bar{M}_{\rm f} = 0.02^{+0.07}_{-0.06}$ and $\Delta\chi_{\rm f}/\bar{\chi}_{\rm f} = -0.01^{+0.11}_{-0.11}$ from GW250114. We compare these results with the ones obtained by hierarchically combining the 12 events first reported in GWTC-4.0, yielding $\Delta M_{\rm f}/\bar{M}_{\rm f} = 0.03^{+0.13}_{-0.11}$ and $\Delta\chi_{\rm f}/\bar{\chi}_{\rm f} = -0.01^{+0.13}_{-0.13}$. Remarkably, the constraints derived from GW250114 alone yield a consistency test of comparable stringency to the combined analysis of GWTC-4.0 [136]. The GR quantile for the two-dimensional posteriors from GW250114 is 49.5%, compared to 19.5% for the GWTC-4.0 analysis [136].

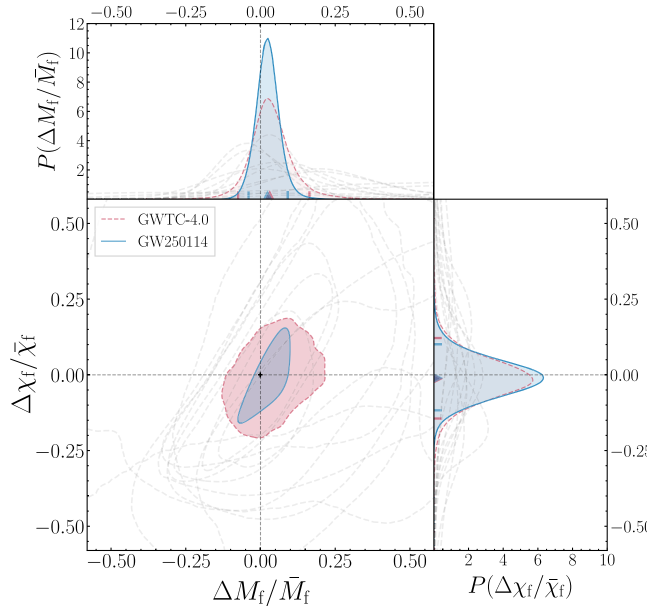

FIG. 6. Consistency of GW250114 with a BBH in GR using data from the inspiral and merger–ringdown. The 90% credible regions of the two-dimensional posteriors on $\Delta M_{\rm f}/\bar{M}_{\rm f}$ and $\Delta\chi_{\rm f}/\bar{\chi}_{\rm f}$ for GW250114 (filled blue), with (0, 0) being the expected value for GR. The side panels show the marginalized posteriors. The gray two-dimensional posteriors show the results from individual events in GWTC-4.0 [136], while the red shaded posteriors denote constraints derived from a hierarchical inference on these events. Triangles mark the median values and vertical bars the symmetric 90% credible interval.

We also exploit the results of the consistency test to determine at what statistical significance the Hawking area theorem [174], a fundamental consequence of the second law of BH mechanics, holds. This theorem states that the horizon area of a BH cannot decrease over time. Our analysis yields a credibility of $4.8\sigma_{\rm IMRCT}$, representing the statistical significance in standard deviations of the difference between the mean total area of the initial BHs and the mean final BH's area. This test differs from the more agnostic strategy followed in Abac *et al.* [2], where the initial and final areas of the objects are computed excluding the GW data around the merger signal. In addition, the test performed here splits the data in the frequency domain, which is not equivalent to the time-domain analysis in Abac *et al.* [2]. See the Fig. S6 in the Supplemental Material [115] for the main results and further details.

Finally, in the Supplemental Material [115] we also report the results of a residuals test [35,175,176], which looks for excess coherent power in the detector network after the maximum-likelihood waveform has been subtracted from the data. The upper limit for the residual network SNR is 6.86 at 90% credibility (p-value 0.34, see Supplemental Material [115]). Thus, we do not find any statistically significant coherent power beyond what is expected from the noise background.

Conclusion—The outstanding improvement of the LIGO detectors in the last decade [177–179] has enabled unprecedented observations [32,180]. In particular, GW250114 was observed with the largest SNR to date (65 up to merger and 40 postmerger) [2], approximately three times that of the similar event GW150914 [181]. We have performed the most stringent suite of tests of GR and the Kerr nature for a BBH coalescence to date. Probing the inspiral, merger and ringdown stages, we have set constraints comparable, and in some cases 2–3 times more stringent, than the ones obtained combining tens loudest events of GWTC-4.0 [136]. At least three QNMs have been identified or constrained with several methods and models: the quadrupolar 220 fundamental and first overtone 221, and the hexadecapolar 440 mode. We have found that their spectroscopic pattern [61,65–68,70] aligns with the Kerr metric prediction, and their amplitudes are consistent with those measured in a NR simulation of GW250114-like systems in GR. In summary, the single, loud event GW250114 has yielded the scientific return of dozens of previous detections, offering a preview of the unprecedented science that upcoming LIGO-Virgo-KAGRA observing runs [182] will unlock.

Strain data from the LIGO detectors for GW250114 are available from the Gravitational Wave Open Science Center [183]. All the material required for reproducing the figures, including scripts and posterior distributions from the analyses, is available in the data release [184].

This Letter made use of the following software, listed in alphabetical order: ARVIZ [185], Asimov [186], Astropy [187–189], BayesWave [190], Bilby [191,192], Bilby_TGR [193], CPNest [194], DYNESTY [195], GWpy [196,197], H5PY [198], IMRPhenomXPHM_SpinTaylor [162,163], Jupyter and IPython [199–201], LALSuite [202,203], Matplotlib [204,205], NRSur7dq4 [86], NumPy [206], PANDAS [207,208], PESummary [209], pyRing [80,113], pySEOBNR [210], Python [211], QNM [212], RINGDOWN [110,213], SciPy [214,215], SEABORN [216], SEOBNRv5PHM and SEOBNRv5HM_ROM [126,127,217,218], SXS [219], and TQDM [220].

Note added—Recently an error in the likelihood function used in the Bilby inference code was discovered, leading to an overly constrained likelihood [221]. The impact of this error is discussed in detail in the GWTC-4.0 methods paper [222]. Following from investigations presented therein, we expect differences in the inferred posterior distributions due to this error to be small. Results for pSEOBNR, FTI, TIGER, the PCA analysis, and the IMR consistency test have been corrected. Other analyses are unaffected by this error.

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Data availability—The data that support the findings of this article are openly available [183].

[1] J. Aasi *et al.* (LIGO Scientific Collaboration), Advanced LIGO, Classical Quantum Gravity **32**, 074001 (2015).

[2] A. G. Abac *et al.*, GW250114: Testing Hawking's area law and the Kerr nature of black holes, arXiv:2509.0000.

[3] F. Acernese *et al.* (Virgo Collaboration), Advanced Virgo: A second-generation interferometric gravitational wave detector, Classical Quantum Gravity **32**, 024001 (2015).

[4] T. Akutsu *et al.* (KAGRA Collaboration), Overview of KAGRA: Detector design and construction history, Prog. Theor. Exp. Phys. **2021**, 05A101 (2021).

[5] A. Einstein, On the general thoery of relativity, Sitzungsber. K. Preuss. Akad. Wiss. **49**, 778 (1915), https://ui.adsabs.harvard.edu/abs/1915SPAW.......778E/abstract.

[6] R. P. Kerr, Gravitational field of a spinning mass as an example of algebraically special metrics, Phys. Rev. Lett. **11**, 237 (1963).

[7] R. L. Arnowitt, S. Deser, and C. W. Misner, The dynamics of general relativity, Gen. Relativ. Gravit. **40**, 1997 (2008).

[8] Y. Foures-Bruhat, Theoreme d'existence pour certains systemes derivees partielles non lineaires, Acta Math. **88**, 141 (1952).

[9] K. Schwarzschild, On the gravitational field of a mass point according to Einstein's theory, Sitzungsber. Preuss. Akad. Wiss. Berlin (Math. Phys.) **1916**, 189 (1916).

[10] E. T. Newman, E. Couch, K. Chinnapared, A. Exton, A. Prakash, and R. Torrence, Metric of a rotating, charged mass, J. Math. Phys. (N.Y.) **6**, 918 (1965).

[11] W. Israel, Event horizons in static electrovac space-times, Commun. Math. Phys. **8**, 245 (1968).

[12] B. Carter, Axisymmetric black hole has only two degrees of freedom, Phys. Rev. Lett. **26**, 331 (1971).

[13] S. W. Hawking, Black holes in general relativity, Commun. Math. Phys. **25**, 152 (1972).

[14] D. C. Robinson, Uniqueness of the Kerr black hole, Phys. Rev. Lett. **34**, 905 (1975).

[15] P. O. Mazur, Proof of uniqueness of the Kerr-Newman black hole solution, J. Phys. A **15**, 3173 (1982).

[16] B. Carter, Global structure of the Kerr family of gravitational fields, Phys. Rev. **174**, 1559 (1968).

[17] R. Penrose, Gravitational collapse: The role of general relativity, Riv. Nuovo Cimento **1**, 252 (1969).

[18] R. Penrose and R. M. Floyd, Extraction of rotational energy from a black hole, Nat. Phys. Sci. **229**, 177 (1971).

[19] J. M. Bardeen, B. Carter, and S. W. Hawking, The four laws of black hole mechanics, Commun. Math. Phys. **31**, 161 (1973).

[20] M. Schmidt, 3C 273: A star-like object with large red-shift, Nature (London) **197**, 1040 (1963).

[21] M. Dafermos, G. Holzegel, and I. Rodnianski, The linear stability of the Schwarzschild solution to gravitational perturbations, Acta Math. **222**, 1 (2019).

[22] R. Teixeira da Costa, Mode stability for the Teukolsky equation on extremal and subextremal Kerr spacetimes, Commun. Math. Phys. **378**, 705 (2020).

[23] S. Klainerman and J. Szeftel, Kerr stability for small angular momentum, Pure Appl. Math. Q. **19**, 791 (2023).

[24] M. Dafermos, G. Holzegel, I. Rodnianski, and M. Taylor, The non-linear stability of the Schwarzschild family of black holes, arXiv:2104.08222.

[25] S. W. Hawking and R. Penrose, The singularities of gravitational collapse and cosmology, Proc. R. Soc. A **314**, 529 (1970).

[26] A. Almheiri, T. Hartman, J. Maldacena, E. Shaghoulian, and A. Tajdini, The entropy of Hawking radiation, Rev. Mod. Phys. **93**, 035002 (2021).

[27] S. Raju, Lessons from the information paradox, Phys. Rep. **943**, 1 (2022).

[28] C. M. Will, The confrontation between general relativity and experiment, Living Rev. Relativity **17**, 4 (2014).

[29] E. Berti *et al.*, Testing general relativity with present and future astrophysical observations, Classical Quantum Gravity **32**, 243001 (2015).

[30] N. Yunes, X. Siemens, and K. Yagi, Gravitational-wave tests of general relativity with ground-based detectors and pulsar-timing arrays, Living Rev. Relativity **28**, 3 (2025).

[31] A. G. Abac *et al.* (LIGO Scientific, Virgo, and KAGRA Collaborations), GWTC-4.0: An introduction to version 4.0 of the gravitational-wave transient catalog, arXiv:2508.18080.

[32] A. G. Abac *et al.* (LIGO Scientific, Virgo, and KAGRA Collaborations), GWTC-4.0: Updating the gravitational-wave transient catalog with observations from the first part of the fourth LIGO-Virgo-KAGRA observing run, arXiv:2508.18082.

[33] L. Blanchet and B. S. Sathyaprakash, Detecting a tail effect in gravitational-wave experiments, Phys. Rev. Lett. **74**, 1067 (1995).

[34] B. P. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), Observation of gravitational waves from a binary black hole merger, Phys. Rev. Lett. **116**, 061102 (2016).

[35] B. P. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), Tests of general relativity with GW150914, Phys. Rev. Lett. **116**, 221101 (2016); **121**, 129902(E) (2018).

[36] B. P. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), GWTC-1: A gravitational-wave transient catalog of compact binary mergers observed by LIGO and Virgo during the first and second observing runs, Phys. Rev. X **9**, 031040 (2019).

[37] R. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), GWTC-2: Compact binary coalescences observed by LIGO and Virgo during the first half of the third observing run, Phys. Rev. X **11**, 021053 (2021).

[38] R. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), GWTC-2.1: Deep extended catalog of compact binary coalescences observed by LIGO and Virgo during the first half of the third observing run, Phys. Rev. D **109**, 022001 (2024).

[39] R. Abbott *et al.* (KAGRA, Virgo, and LIGO Scientific Collaborations), GWTC-3: Compact binary coalescences observed by LIGO and Virgo during the second part of the third observing run, Phys. Rev. X **13**, 041039 (2023).

[40] B. P. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), Tests of general relativity with GW170817, Phys. Rev. Lett. **123**, 011102 (2019).

[41] B. P. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), Tests of general relativity with the binary black hole signals from the LIGO-Virgo catalog GWTC-1, Phys. Rev. D **100**, 104036 (2019).

[42] R. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), Tests of general relativity with binary black holes from the second LIGO-Virgo gravitational-wave transient catalog, Phys. Rev. D **103**, 122002 (2021).

[43] R. Abbott *et al.* (LIGO Scientific,, and KAGRA Collaborations), Tests of general relativity with GWTC-3, Phys. Rev. D **112**, 084080 (2025).

[44] P. C. C. Freire, N. Wex, G. Esposito-Farese, J. P. W. Verbiest, M. Bailes, B. A. Jacoby, M. Kramer, I. H. Stairs, J. Antoniadis, and G. H. Janssen, The relativistic pulsar-white dwarf binary PSR J1738 + 0333 II. The most stringent test of scalar-tensor gravity, Mon. Not. R. Astron. Soc. **423**, 3328 (2012).

[45] M. Kramer *et al.*, Strong-field gravity tests with the double pulsar, Phys. Rev. X **11**, 041050 (2021).

[46] R. Abuter *et al.* (GRAVITY Collaboration), Detection of the gravitational redshift in the orbit of the star S2 near the Galactic centre massive black hole, Astron. Astrophys. **615**, L15 (2018).

[47] T. Do *et al.*, Relativistic redshift of the star S0-2 orbiting the Galactic center supermassive black hole, Science **365**, 664 (2019).

[48] K. Akiyama *et al.* (Event Horizon Telescope Collaboration), First M87 Event Horizon Telescope results. I. The shadow of the supermassive black hole, Astrophys. J. Lett. **875**, L1 (2019).

[49] T. Clifton, P. G. Ferreira, A. Padilla, and C. Skordis, Modified gravity and cosmology, Phys. Rep. **513**, 1 (2012).

[50] A. Einstein, Über Gravitationswellen, Sitzungsber. Preuss. Akad. Wiss. Berlin (Math. Phys.) **1918**, 154 (1918), https://ui.adsabs.harvard.edu/abs/1918SPAW.......154E/abstract.

[51] F. Pretorius, Evolution of binary black hole spacetimes, Phys. Rev. Lett. **95**, 121101 (2005).

[52] M. Campanelli, C. O. Lousto, Y. Zlochower, B. Krishnan, and D. Merritt, Spin flips and precession in black-hole-binary mergers, Phys. Rev. D **75**, 064030 (2007).

[53] J. G. Baker, J. Centrella, D.-I. Choi, M. Koppitz, and J. van Meter, Gravitational wave extraction from an inspiraling configuration of merging black holes, Phys. Rev. Lett. **96**, 111102 (2006).

[54] C. V. Vishveshwara, Scattering of gravitational radiation by a Schwarzschild black-hole, Nature (London) **227**, 936 (1970).

[55] W. H. Press, Long wave trains of gravitational waves from a vibrating black hole, Astrophys. J. **170**, L105 (1971).

[56] T. Regge, Stability of a Schwarzschild singularity, Phys. Rev. **108**, 1063 (1957).

[57] F. J. Zerilli, Effective potential for even parity Regge-Wheeler gravitational perturbation equations, Phys. Rev. Lett. **24**, 737 (1970).

[58] S. A. Teukolsky, Perturbations of a rotating black hole. 1. Fundamental equations for gravitational electromagnetic and neutrino field perturbations, Astrophys. J. **185**, 635 (1973).

[59] S. Chandrasekhar and S. L. Detweiler, The quasi-normal modes of the Schwarzschild black hole, Proc. R. Soc. A **344**, 441 (1975).

[60] S. L. Detweiler, Resonant oscillations of a rapidly rotating black hole, Proc. R. Soc. A **352**, 381 (1977).

[61] S. L. Detweiler, Black holes and gravitational waves. III. The resonant frequencies of rotating holes, Astrophys. J. **239**, 292 (1980).

[62] E. W. Leaver, An analytic representation for the quasi-normal modes of Kerr black holes, Proc. R. Soc. A **402**, 285 (1985).

[63] R. H. Price, Nonspherical perturbations of relativistic gravitational collapse. 1. Scalar and gravitational perturbations, Phys. Rev. D **5**, 2419 (1972).

[64] R. H. Price, Nonspherical perturbations of relativistic gravitational collapse. II. Integer-spin, zero-rest-mass fields, Phys. Rev. D **5**, 2439 (1972).
[65] H.-P. Nollert, Topical review: Quasinormal modes: The characteristic "sound" of black holes and neutron stars, Classical Quantum Gravity **16**, R159 (1999).
[66] K. D. Kokkotas and B. G. Schmidt, Quasinormal modes of stars and black holes, Living Rev. Relativity **2**, 2 (1999).
[67] O. Dreyer, B. J. Kelly, B. Krishnan, L. S. Finn, D. Garrison, and R. Lopez-Aleman, Black hole spectroscopy: Testing general relativity through gravitational wave observations, Classical Quantum Gravity **21**, 787 (2004).
[68] E. Berti, V. Cardoso, and C. M. Will, On gravitational-wave spectroscopy of massive black holes with the space interferometer LISA, Phys. Rev. D **73**, 064030 (2006).
[69] E. Berti, V. Cardoso, and A. O. Starinets, Quasinormal modes of black holes and black branes, Classical Quantum Gravity **26**, 163001 (2009).
[70] S. Gossan, J. Veitch, and B. S. Sathyaprakash, Bayesian model selection for testing the no-hair theorem with black hole ringdowns, Phys. Rev. D **85**, 124056 (2012).
[71] J. Meidam, M. Agathos, C. Van Den Broeck, J. Veitch, and B. S. Sathyaprakash, Testing the no-hair theorem with black hole ringdowns using TIGER, Phys. Rev. D **90**, 064009 (2014).
[72] E. Berti, V. Cardoso, G. Carullo *et al.*, Black hole spectroscopy: From theory to experiment, arXiv:2505.23895.
[73] R. Penrose, "Golden Oldie": Gravitational collapse: The role of general relativity, Gen. Relativ. Gravit. **34**, 1141 (2002).
[74] S. Klainerman, Mathematical challenges of general relativity, in *The Ninth Marcel Grossmann Meeting*, edited by V. G. Gurzadyan, R. T. Jantzen, and R. Ruffini (2002), pp. 28–43.
[75] P. T. Chruściel, J. Lopes Costa, and M. Heusler, Stationary black holes: Uniqueness and beyond, Living Rev. Relativity **15**, 7 (2012).
[76] G. W. Gibbons, Vacuum polarization and the spontaneous loss of charge by black holes, Commun. Math. Phys. **44**, 245 (1975).
[77] R. D. Blandford and R. L. Znajek, Electromagnetic extractions of energy from Kerr black holes, Mon. Not. R. Astron. Soc. **179**, 433 (1977).
[78] R. S. Hanni, Limits on the charge of a collapsed object, Phys. Rev. D **25**, 2509 (1982).
[79] G. Carullo, D. Laghi, N. K. Johnson-McDaniel, W. Del Pozzo, O. J. C. Dias, M. Godazgar, and J. E. Santos, Constraints on Kerr-Newman black holes from merger-ringdown gravitational-wave observations, Phys. Rev. D **105**, 062009 (2022).
[80] G. Carullo, W. Del Pozzo, and J. Veitch, Observational black hole spectroscopy: A time-domain multimode analysis of GW150914, Phys. Rev. D **99**, 123029 (2019); **100**, 089903(E) (2019).
[81] M. Isi, M. Giesler, W. M. Farr, M. A. Scheel, and S. A. Teukolsky, Testing the no-hair theorem with GW150914, Phys. Rev. Lett. **123**, 111102 (2019).
[82] C. D. Capano, M. Cabero, J. Westerweck, J. Abedi, S. Kastha, A. H. Nitz, A. B. Nielsen, and B. Krishnan, Observation of a multimode quasi-normal spectrum from a perturbed black hole, Phys. Rev. Lett. **131**, 221402 (2023).
[83] R. Cotesta, G. Carullo, E. Berti, and V. Cardoso, Analysis of ringdown overtones in GW150914, Phys. Rev. Lett. **129**, 111102 (2022).
[84] H. Siegel, M. Isi, and W. M. Farr, Ringdown of GW190521: Hints of multiple quasinormal modes with a precessional interpretation, Phys. Rev. D **108**, 064008 (2023).
[85] V. Gennari, G. Carullo, and W. Del Pozzo, Searching for ringdown higher modes with a numerical relativity-informed post-merger model, Eur. Phys. J. C **84**, 233 (2024).
[86] V. Varma, S. E. Field, M. A. Scheel, J. Blackman, D. Gerosa, L. C. Stein, L. E. Kidder, and H. P. Pfeiffer, Surrogate models for precessing binary black hole simulations with unequal masses, Phys. Rev. Res. **1**, 033015 (2019).
[87] A. Gamboa *et al.*, Accurate waveforms for eccentric, aligned-spin binary black holes: The multipolar effective-one-body model SEOBNRv5EHM, Phys. Rev. D **112**, 044038 (2025).
[88] A. Nagar, R. Gamba, P. Rettegno, V. Fantini, and S. Bernuzzi, Effective-one-body waveform model for non-circularized, planar, coalescing black hole binaries: The importance of radiation reaction, Phys. Rev. D **110**, 084001 (2024).
[89] E. W. Leaver, Spectral decomposition of the perturbation response of the Schwarzschild geometry, Phys. Rev. D **34**, 384 (1986).
[90] N. Andersson, Evolving test fields in a black hole geometry, Phys. Rev. D **55**, 468 (1997).
[91] H. Zhu *et al.*, Imprints of changing mass and spin on black hole ringdown, Phys. Rev. D **110**, 124028 (2024).
[92] A. Chavda, M. Lagos, and L. Hui, The impact of initial conditions on quasi-normal modes, J. Cosmol. Astropart. Phys. 07 (2025) 084.
[93] M. De Amicis, E. Cannizzaro, G. Carullo, and L. Sberna, Dynamical quasinormal mode excitation, arXiv:2506.21668.
[94] L. London, D. Shoemaker, and J. Healy, Modeling ringdown: Beyond the fundamental quasinormal modes, Phys. Rev. D **90**, 124032 (2014); **94**, 069902(E) (2016).
[95] K. Mitman *et al.*, Nonlinearities in black hole ringdowns, Phys. Rev. Lett. **130**, 081402 (2023).
[96] M. H.-Y. Cheung *et al.*, Nonlinear effects in black hole ringdown, Phys. Rev. Lett. **130**, 081401 (2023).
[97] S. Ma and H. Yang, Excitation of quadratic quasinormal modes for Kerr black holes, Phys. Rev. D **109**, 104070 (2024).
[98] A. Buonanno, G. B. Cook, and F. Pretorius, Inspiral, merger and ring-down of equal-mass black-hole binaries, Phys. Rev. D **75**, 124018 (2007).
[99] E. Berti, V. Cardoso, J. A. Gonzalez, U. Sperhake, M. Hannam, S. Husa, and B. Brügmann, Inspiral, merger and ringdown of unequal mass black hole binaries: A multipolar analysis, Phys. Rev. D **76**, 064034 (2007).
[100] E. S. C. Ching, P. T. Leung, W. M. Suen, and K. Young, Wave propagation in gravitational systems: Late time behavior, Phys. Rev. D **52**, 2118 (1995).

[101] S. Ma, M. A. Scheel, J. Moxon, K. C. Nelli, N. Deppe, L. E. Kidder, W. Throwe, and N. L. Vu, Merging black holes with Cauchy-characteristic matching: Computation of late-time tails, Phys. Rev. D **112**, 024003 (2025).
[102] M. De Amicis, S. Albanesi, and G. Carullo, Inspiral-inherited ringdown tails, Phys. Rev. D **110**, 104005 (2024).
[103] M. De Amicis *et al.*, Late-time tails in nonlinear evolutions of merging black holes, Phys. Rev. Lett. **135**, 171401 (2025).
[104] I. Kamaretsos, M. Hannam, and B. Sathyaprakash, Is black-hole ringdown a memory of its progenitor?, Phys. Rev. Lett. **109**, 141102 (2012).
[105] L. T. London, Modeling ringdown. II. Aligned-spin binary black holes, implications for data analysis and fundamental theory, Phys. Rev. D **102**, 084052 (2020).
[106] X. Jiménez Forteza, S. Bhagwat, P. Pani, and V. Ferrari, Spectroscopy of binary black hole ringdown using overtones and angular modes, Phys. Rev. D **102**, 044053 (2020).
[107] M. H.-Y. Cheung, E. Berti, V. Baibhav, and R. Cotesta, Extracting linear and nonlinear quasinormal modes from black hole merger simulations, Phys. Rev. D **109**, 044069 (2024); **110**, 049902(E) (2024).
[108] L. Magaña Zertuche *et al.*, High-precision ringdown surrogate model for non-precessing binary black holes, Phys. Rev. D **112**, 024077 (2025).
[109] F. Nobili, S. Bhagwat, C. Pacilio, and D. Gerosa, Ringdown mode amplitudes of precessing binary black holes, Phys. Rev. D **112**, 044058 (2025).
[110] M. Isi and W. M. Farr, Analyzing black-hole ringdowns, arXiv:2107.05609.
[111] A. Dhani, Importance of mirror modes in binary black hole ringdown waveform, Phys. Rev. D **103**, 104048 (2021).
[112] X. Li, L. Sun, R. K. L. Lo, E. Payne, and Y. Chen, Angular emission patterns of remnant black holes, Phys. Rev. D **105**, 024016 (2022).
[113] G. Carullo, W. Del Pozzo, and J. Veitch, pyRing: A time-domain ringdown analysis Python package, https://git.ligo.org/lscsoft/pyring (2023).
[114] G. Carullo *et al.*, Empirical tests of the black hole no-hair conjecture using gravitational-wave observations, Phys. Rev. D **98**, 104020 (2018).
[115] See Supplemental Material at http://link.aps.org/supplemental/10.1103/6c61-fm1n for additional details regarding the assumptions and analyses that have been presented.
[116] M. Giesler *et al.*, Overtones and nonlinearities in binary black hole ringdowns, Phys. Rev. D **111**, 084041 (2025).
[117] M. Isi, K. Chatziioannou, and W. M. Farr, Hierarchical test of general relativity with gravitational waves, Phys. Rev. Lett. **123**, 121101 (2019).
[118] S. Ma, K. Mitman, L. Sun, N. Deppe, F. Hébert, L. E. Kidder, J. Moxon, W. Throwe, N. L. Vu, and Y. Chen, Quasinormal-mode filters: A new approach to analyze the gravitational-wave ringdown of binary black-hole mergers, Phys. Rev. D **106**, 084036 (2022).
[119] S. Ma, L. Sun, and Y. Chen, Black hole spectroscopy by mode cleaning, Phys. Rev. Lett. **130**, 141401 (2023).
[120] S. Ma, L. Sun, and Y. Chen, Using rational filters to uncover the first ringdown overtone in GW150914, Phys. Rev. D **107**, 084010 (2023).
[121] N. Lu, S. Ma, O. J. Piccinni, L. Sun, and E. Finch, Statistical identification of ringdown modes with rational filters, Phys. Rev. D **112**, 064047 (2025).
[122] R. Brito, A. Buonanno, and V. Raymond, Black-hole spectroscopy by making full use of gravitational-wave modeling, Phys. Rev. D **98**, 084038 (2018).
[123] L. Pompili, E. Maggio, H. O. Silva, and A. Buonanno, Parametrized spin-precessing inspiral-merger-ringdown waveform model for tests of general relativity, Phys. Rev. D **111**, 124040 (2025).
[124] E. Maggio, H. O. Silva, A. Buonanno, and A. Ghosh, Tests of general relativity in the nonlinear regime: A parametrized plunge-merger-ringdown gravitational waveform model, Phys. Rev. D **108**, 024043 (2023).
[125] A. Ghosh, R. Brito, and A. Buonanno, Constraints on quasinormal-mode frequencies with LIGO-Virgo binary–black-hole observations, Phys. Rev. D **103**, 124041 (2021).
[126] A. Ramos-Buades, A. Buonanno, H. Estellés, M. Khalil, D. P. Mihaylov, S. Ossokine, L. Pompili, and M. Shiferaw, Next generation of accurate and efficient multipolar precessing-spin effective-one-body waveforms for binary black holes, Phys. Rev. D **108**, 124037 (2023).
[127] L. Pompili *et al.*, Laying the foundation of the effective-one-body waveform models SEOBNRv5: Improved accuracy and efficiency for spinning nonprecessing binary black holes, Phys. Rev. D **108**, 124035 (2023).
[128] X. Jiménez-Forteza, D. Keitel, S. Husa, M. Hannam, S. Khan, and M. Pürrer, Hierarchical data-driven approach to fitting numerical relativity data for nonprecessing binary black holes with an application to final spin and radiated energy, Phys. Rev. D **95**, 064024 (2017).
[129] F. Hofmann, E. Barausse, and L. Rezzolla, The final spin from binary black holes in quasi-circular orbits, Astrophys. J. Lett. **825**, L19 (2016).
[130] J. G. Baker, W. D. Boggs, J. Centrella, B. J. Kelly, S. T. McWilliams, and J. R. van Meter, Mergers of non-spinning black-hole binaries: Gravitational radiation characteristics, Phys. Rev. D **78**, 044046 (2008).
[131] T. Damour and A. Nagar, A new analytic representation of the ringdown waveform of coalescing spinning black hole binaries, Phys. Rev. D **90**, 024054 (2014).
[132] L. Blanchet, Post-Newtonian theory for gravitational waves, Living Rev. Relativity **27**, 4 (2024).
[133] R. Cotesta, A. Buonanno, A. Bohé, A. Taracchini, I. Hinder, and S. Ossokine, Enriching the symphony of gravitational waves from binary black holes by tuning higher harmonics, Phys. Rev. D **98**, 084028 (2018).
[134] C. Mills and S. Fairhurst, Measuring gravitational-wave higher-order multipoles, Phys. Rev. D **103**, 024042 (2021).
[135] H. Zhong, M. Isi, K. Chatziioannou, and W. M. Farr, Multidimensional hierarchical tests of general relativity with gravitational waves, Phys. Rev. D **110**, 044053 (2024).
[136] A. G. Abac *et al.*, GWTC-4.0: Tests of general relativity, arXiv:2509.0000.

[137] E. Payne, M. Isi, K. Chatziioannou, and W. M. Farr, Fortifying gravitational-wave tests of general relativity against astrophysical assumptions, Phys. Rev. D **108**, 124060 (2023).

[138] C. Pacilio, D. Gerosa, and S. Bhagwat, Catalog variance of testing general relativity with gravitational-wave data, Phys. Rev. D **109**, L081302 (2024).

[139] W. Del Pozzo and A. Nagar, Analytic family of post-merger template waveforms, Phys. Rev. D **95**, 124034 (2017).

[140] A. Nagar, G. Riemenschneider, G. Pratten, P. Rettegno, and F. Messina, Multipolar effective one body waveform model for spin-aligned black hole binaries, Phys. Rev. D **102**, 024077 (2020).

[141] N. Yunes, K. Yagi, and F. Pretorius, Theoretical physics implications of the binary black-hole mergers GW150914 and GW151226, Phys. Rev. D **94**, 084002 (2016).

[142] A. Maselli, P. Pani, L. Gualtieri, and E. Berti, Parametrized ringdown spin expansion coefficients: A data-analysis framework for black-hole spectroscopy with multiple events, Phys. Rev. D **101**, 024043 (2020).

[143] H. O. Silva, A. Ghosh, and A. Buonanno, Black-hole ringdown as a probe of higher-curvature gravity theories, Phys. Rev. D **107**, 044030 (2023).

[144] E. M. Sänger *et al.*, Tests of general relativity with GW230529: A neutron star merging with a lower mass-gap compact object, arXiv:2406.03568.

[145] A. K.-W. Chung and N. Yunes, Probing quadratic gravity with black-hole ringdown gravitational waves measured by LIGO-Virgo-KAGRA detectors, arXiv:2506.14695.

[146] V. Cardoso, S. Hopper, C. F. B. Macedo, C. Palenzuela, and P. Pani, Gravitational-wave signatures of exotic compact objects and of quantum corrections at the horizon scale, Phys. Rev. D **94**, 084031 (2016).

[147] E. Maggio, L. Buoninfante, A. Mazumdar, and P. Pani, How does a dark compact object ringdown?, Phys. Rev. D **102**, 064053 (2020).

[148] S. Alexander and N. Yunes, Chern-Simons modified general relativity, Phys. Rep. **480**, 1 (2009).

[149] A. K.-W. Chung, K. K.-H. Lam, and N. Yunes, Quasinormal mode frequencies and gravitational perturbations of spinning black holes in modified gravity through METRICS: The dynamical Chern-Simons gravity case, Phys. Rev. D **111**, 124052 (2025).

[150] L. Blanchet, Gravitational radiation from post-Newtonian sources and inspiralling compact binaries, Living Rev. Relativity **17**, 2 (2014).

[151] L. Blanchet and B. S. Sathyaprakash, Detecting the tail effect in gravitational wave experiments, Phys. Rev. Lett. **74**, 1067 (1995).

[152] L. Blanchet and B. S. Sathyaprakash, Signal analysis of gravitational wave tails, Classical Quantum Gravity **11**, 2807 (1994).

[153] K. G. Arun, B. R. Iyer, M. S. S. Qusailah, and B. S. Sathyaprakash, Probing the non-linear structure of general relativity with black hole binaries, Phys. Rev. D **74**, 024006 (2006).

[154] N. Yunes and F. Pretorius, Fundamental theoretical bias in gravitational wave astrophysics and the parameterized post-Einsteinian framework, Phys. Rev. D **80**, 122003 (2009).

[155] C. K. Mishra, K. G. Arun, B. R. Iyer, and B. S. Sathyaprakash, Parametrized tests of post-Newtonian theory using Advanced LIGO and Einstein Telescope, Phys. Rev. D **82**, 064010 (2010).

[156] T. G. F. Li, W. Del Pozzo, S. Vitale, C. Van Den Broeck, M. Agathos, J. Veitch, K. Grover, T. Sidery, R. Sturani, and A. Vecchio, Towards a generic test of the strong field dynamics of general relativity using compact binary coalescence, Phys. Rev. D **85**, 082003 (2012).

[157] M. Agathos, W. Del Pozzo, T. G. F. Li, C. Van Den Broeck, J. Veitch, and S. Vitale, TIGER: A data analysis pipeline for testing the strong-field dynamics of general relativity with gravitational wave signals from coalescing compact binaries, Phys. Rev. D **89**, 082001 (2014).

[158] A. K. Mehta, A. Buonanno, R. Cotesta, A. Ghosh, N. Sennett, and J. Steinhoff, Tests of general relativity with gravitational-wave observations using a flexible theory-independent method, Phys. Rev. D **107**, 044020 (2023).

[159] M. Agathos, W. Del Pozzo, T. G. F. Li, C. Van Den Broeck, J. Veitch, and S. Vitale, TIGER: A data analysis pipeline for testing the strong-field dynamics of general relativity with gravitational wave signals from coalescing compact binaries, Phys. Rev. D **89**, 082001 (2014).

[160] J. Meidam *et al.*, Parametrized tests of the strong-field dynamics of general relativity using gravitational wave signals from coalescing binary black holes: Fast likelihood calculations and sensitivity of the method, Phys. Rev. D **97**, 044033 (2018).

[161] S. Roy, M. Haney, G. Pratten, P. T. H. Pang, and C. Van Den Broeck, An improved parametrized test of general relativity using the IMRPhenomX waveform family: Including higher harmonics and precession, arXiv:2504.21147.

[162] G. Pratten *et al.*, Computationally efficient models for the dominant and subdominant harmonic modes of precessing binary black holes, Phys. Rev. D **103**, 104056 (2021).

[163] M. Colleoni, F. A. R. Vidal, C. García-Quirós, S. Akçay, and S. Bera, Fast frequency-domain gravitational waveforms for precessing binaries with a new twist, Phys. Rev. D **111**, 104019 (2025).

[164] A. Pai and K. G. Arun, Singular value decomposition in parametrised tests of post-Newtonian theory, Classical Quantum Gravity **30**, 025011 (2013).

[165] A. A. Shoom, P. K. Gupta, B. Krishnan, A. B. Nielsen, and C. D. Capano, Testing the post-Newtonian expansion with GW170817, Gen. Relativ. Gravit. **55**, 55 (2023).

[166] M. Saleem, S. Datta, K. G. Arun, and B. S. Sathyaprakash, Parametrized tests of post-Newtonian theory using principal component analysis, Phys. Rev. D **105**, 084062 (2022).

[167] P. Mahapatra *et al.*, Confronting general relativity with principal component analysis: Simulations and results from GWTC-3 events, Phys. Rev. D **112**, 104007 (2025).

[168] S. A. Hughes and K. Menou, Golden binaries for LISA: Robust probes of strong-field gravity, Astrophys. J. **623**, 689 (2005).

[169] A. Ghosh *et al.*, Testing general relativity using golden black-hole binaries, Phys. Rev. D **94**, 021101(R) (2016).

[170] A. Ghosh, N. K. Johnson-McDaniel, A. Ghosh, C. K. Mishra, P. Ajith, W. Del Pozzo, C. P. L. Berry, A. B.

Nielsen, and L. London, Testing general relativity using gravitational wave signals from the inspiral, merger and ringdown of binary black holes, Classical Quantum Gravity **35**, 014002 (2018).
[171] J. M. Bardeen, W. H. Press, and S. A. Teukolsky, Rotating black holes: Locally nonrotating frames, energy extraction, and scalar synchrotron radiation, Astrophys. J. **178**, 347 (1972).
[172] J. Healy and C. O. Lousto, Remnant of binary black-hole mergers: New simulations and peak luminosity studies, Phys. Rev. D **95**, 024037 (2017).
[173] X. Jiménez-Forteza, D. Keitel, S. Husa, M. Hannam, S. Khan, and M. Pürrer, Hierarchical data-driven approach to fitting numerical relativity data for nonprecessing binary black holes with an application to final spin and radiated energy, Phys. Rev. D **95**, 064024 (2017).
[174] S. W. Hawking, Gravitational radiation from colliding black holes, Phys. Rev. Lett. **26**, 1344 (1971).
[175] N. Cornish, L. Sampson, N. Yunes, and F. Pretorius, Gravitational wave tests of general relativity with the parameterized post-Einsteinian framework, Phys. Rev. D **84**, 062003 (2011).
[176] M. Vallisneri, Testing general relativity with gravitational waves: A reality check, Phys. Rev. D **86**, 082001 (2012).
[177] W. Jia *et al.* (Members of the LIGO Scientific Collaboration), Squeezing the quantum noise of a gravitational-wave detector below the standard quantum limit, Science **385**, 1318 (2024).
[178] D. Ganapathy, V. Xu, W. Jia, C. Whittle, M. Tse, L. Barsotti, M. Evans, and L. McCuller, Probing squeezing for gravitational-wave detectors with an audio-band field, Phys. Rev. D **105**, 122005 (2022).
[179] E. Capote *et al.*, Advanced LIGO detector performance in the fourth observing run, Phys. Rev. D **111**, 062002 (2025).
[180] LIGO Scientific, Virgo, and KAGRA Collaborations, GWTC-4.0: Population properties of merging compact binaries, arXiv:2508.18083.
[181] B. P. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), Observation of gravitational waves from a binary black hole merger, Phys. Rev. Lett. **116**, 061102 (2016).
[182] B. P. Abbott *et al.* (KAGRA, LIGO Scientific, and Virgo Collaborations), Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA, Living Rev. Relativity **23**, 3 (2020).
[183] LIGO Scientific, Virgo, and KAGRA Collaborations, GW250114 GWOSC page (2025), https://gwosc.org/eventapi/html/O4_Discovery_Papers/GW250114_082203/v1/.
[184] LIGO Scientific, Virgo, and KAGRA Collaborations, Black hole spectroscopy and tests of general relativity with GW250114: Data release (2025), https://zenodo.org/records/17018009.
[185] R. Kumar, C. Carroll, A. Hartikainen, and O. Martin, ARVIZ a unified library for exploratory analysis of Bayesian models in Python, J. Open Source Software **4**, 1143 (2019).
[186] D. Williams, J. Veitch, M. L. Chiofalo, P. Schmidt, R. P. Udall, A. Vajpeji, and C. Hoy, Asimov: A framework for coordinating parameter estimation workflows, J. Open Source Software **8**, 4170 (2023).
[187] T. P. Robitaille *et al.* (Astropy Collaboration), Astropy: A community Python package for astronomy, Astron. Astrophys. **558**, A33 (2013).
[188] A. M. Price-Whelan *et al.* (Astropy Collaboration), The Astropy project: Building an open-science project and status of the v2.0 core package, Astron. J. **156**, 123 (2018).
[189] A. M. Price-Whelan *et al.* (Astropy Collaboration), The Astropy project: Sustaining and growing a community-oriented open-source project and the latest major release (v5.0) of the core package, Astrophys. J. **935**, 167 (2022).
[190] N. J. Cornish, T. B. Littenberg, B. Bécsy, K. Chatziioannou, J. A. Clark, S. Ghonge, and M. Millhouse, BayesWave analysis pipeline in the era of gravitational wave observations, Phys. Rev. D **103**, 044006 (2021).
[191] G. Ashton *et al.*, Bilby: A user-friendly Bayesian inference library for gravitational-wave astronomy, Astrophys. J. Suppl. Ser. **241**, 27 (2019).
[192] I. M. Romero-Shaw *et al.*, Bayesian inference for compact binary coalescences with Bilby: Validation and application to the first LIGO–Virgo gravitational-wave transient catalogue, Mon. Not. R. Astron. Soc. **499**, 3295 (2020).
[193] G. Ashton, C. Talbot, S. Roy, G. Pratten, T.-H. Pang, M. Agathos, T. Baka, E. Sänger, A. Mehta, J. Steinhoff, E. Maggio, A. Ghosh, A. Vijaykumar, R. Enficiaud, and L. Pompili, Bilby_TGR (2025), https://zenodo.org/records/15676285.
[194] W. Del Pozzo and J. Veitch, CPNest: An efficient Python parallelizable nested sampling algorithm, https://github.com/johnveitch/cpnest (2025).
[195] J. S. Speagle, DYNESTY: A dynamic nested sampling package for estimating Bayesian posteriors and evidences, Mon. Not. R. Astron. Soc. **493**, 3132 (2020).
[196] D. M. Macleod, J. S. Areeda, S. B. Coughlin, T. J. Massinger, and A. L. Urban, GWpy: A Python package for gravitational-wave astrophysics, SoftwareX **13**, 100657 (2021).
[197] D. Macleod, S. Coughlin, A. Southgate, D. Davis, M. Pitkin, J. Areeda, R. N. George, P. Altin, P. Godwin, L. Singer *et al.*, GWpy/GWpy: GWpy 3.0.9 (2024), https://zenodo.org/records/12734623.
[198] A. Collette, *Python and HDF5* (O'Reilly, 2013), https://www.oreilly.com/library/view/python-and-hdf5/9781491944981/.
[199] F. Perez and B. E. Granger, IPython: A system for interactive scientific computing, Comput. Sci. Eng. **9**, 21 (2007).
[200] T. Kluyver *et al.* (Jupyter Development Team), *Jupyter Notebooks—A Publishing Format for Reproducible Computational Workflows* (IOS Press, 2016), pp. 87–90, https://ebooks.iospress.nl/publication/42900.
[201] M. Beg, J. Taka, T. Kluyver, A. Konovalov, M. Ragan-Kelley, N. M. Thiéry, and H. Fangohr, Using Jupyter for reproducible scientific workflows, Comput. Sci. Eng. **23**, 36 (2021).
[202] LIGO Scientific, Virgo, and KAGRA Collaborations, LVK Algorithm Library—LALSuite, Free software (GPL) (2018), https://git.ligo.org/lscsoft/lalsuite.
[203] K. Wette, SWIGLAL: Python and octave interfaces to the LALSuite gravitational-wave data analysis libraries, SoftwareX **12**, 100634 (2020).

[204] T. A. Caswell, E. S. de Andrade, A. Lee, M. Droettboom, T. Hoffmann, J. Klymak, J. Hunter, E. Firing, D. Stansby, N. Varoquaux *et al.*, Matplotlib/Matplotlib: Rel: v3.7.3 (2023), https://zenodo.org/records/8336761.

[205] J. D. Hunter, Matplotlib: A 2d graphics environment, Comput. Sci. Eng. **9**, 90 (2007).

[206] C. R. Harris, K. J. Millman, S. J. van der Walt, R. Gommers, P. Virtanen, D. Cournapeau, E. Wieser, J. Taylor, S. Berg, N. J. Smith *et al.*, Array programming with NumPy, Nature (London) **585**, 357 (2020).

[207] W. McKinney, Data structures for statistical computing in Python, in *Proceedings of the 9th Python in Science Conference*, edited by Stéfan van der Walt and Jarrod Millman (2010), pp. 56–61.

[208] The Pandas Development Team, PANDAS-DEV/PANDAS: PANDAS (2024), https://zenodo.org/records/13819579.

[209] C. Hoy and V. Raymond, PESummary: The code agnostic parameter estimation summary page builder, SoftwareX **15**, 100765 (2021).

[210] D. P. Mihaylov, S. Ossokine, A. Buonanno, H. Estelles, L. Pompili, M. Pürrer, and A. Ramos-Buades, pySEOBNR: A software package for the next generation of effective-one-body multipolar waveform models, SoftwareX **30**, 102080 (2025).

[211] G. Van Rossum and F. L. Drake, *Python 3 Reference Manual* (CreateSpace, Scotts Valley, CA, 2009).

[212] L. C. Stein, QNM: A Python package for calculating Kerr quasinormal modes, separation constants, and spherical-spheroidal mixing coefficients, J. Open Source Software **4**, 1683 (2019).

[213] M. Isi and W. M. Farr, RINGDOWN package, https://ringdown.readthedocs.io/en/latest/ (2024).

[214] P. Virtanen *et al.* (SciPy 1.0 Contributors), SciPy 1.0: Fundamental algorithms for scientific computing in Python, Nat. Methods **17**, 261 (2020).

[215] R. Gommers, P. Virtanen, M. Haberland, E. Burovski, W. Weckesser, T. Reddy, T. E. Oliphant, D. Cournapeau, A. Nelson *et al.*, SciPy/SciPy: SciPy 1.12.0 (2024), https://zenodo.org/records/10543017.

[216] M. L. Waskom, SEABORN: Statistical data visualization, J. Open Source Software **6**, 3021 (2021).

[217] M. Khalil, A. Buonanno, H. Estelles, D. P. Mihaylov, S. Ossokine, L. Pompili, and A. Ramos-Buades, Theoretical groundwork supporting the precessing-spin two-body dynamics of the effective-one-body waveform models SEOBNRv5, Phys. Rev. D **108**, 124036 (2023).

[218] M. van de Meent, A. Buonanno, D. P. Mihaylov, S. Ossokine, L. Pompili, N. Warburton, A. Pound, B. Wardell, L. Durkan, and J. Miller, Enhancing the SEOBNRv5 effective-one-body waveform model with second-order gravitational self-force fluxes, Phys. Rev. D **108**, 124038 (2023).

[219] M. Boyle, K. Mitman, M. Scheel, and L. Stein, The SXS package (2025), https://zenodo.org/records/16277847.

[220] C. da Costa-Luis, S. K. Larroque, K. Altendorf, H. Mary, R. Sheridan, M. Korobov, N. Yorav-Raphael, I. Ivanov, M. Bargull, N. Rodrigues *et al.*, TQDM: A fast, extensible progress bar for Python and CLI (2024), https://zenodo.org/records/14002015.

[221] C. Talbot *et al.*, Inference with finite time series II: The window strikes back, arXiv:2508.11091.

[222] A. G. Abac *et al.* (LIGO Scientific, Virgo, and KAGRA Collaborations), GWTC-4.0: Methods for identifying and characterizing gravitational-wave transients, arXiv:2508.18081.

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