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GW250114: Testing Hawking's Area Law and the Kerr Nature of Black Holes

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(Received 13 August 2025; revised 25 August 2025; accepted 26 August 2025; published 10 September 2025)

The gravitational-wave signal GW250114 was observed by the two LIGO detectors with a network matched-filter signal-to-noise ratio of 80. The signal was emitted by the coalescence of two black holes with near-equal masses $m_1 = 33.6^{+1.2}_{-0.8} M_\odot$ and $m_2 = 32.2^{+0.8}_{-1.3} M_\odot$, and small spins $\chi_{1,2} \leq 0.26$ (90% credibility) and negligible eccentricity $e \leq 0.03$. Postmerger data excluding the peak region are consistent with the dominant quadrupolar $(\ell = |m| = 2)$ mode of a Kerr black hole and its first overtone. We constrain the modes' frequencies to $\pm 30\%$ of the Kerr spectrum, providing a test of the remnant's Kerr nature. We also examine Hawking's area law, also known as the second law of black hole mechanics, which states that the total area of the black hole event horizons cannot decrease with time. A range of analyses that exclude up to five of the strongest merger cycles confirm that the remnant area is larger than the sum of the initial areas to high credibility.

DOI: 10.1103/kw5g-d732

Introduction—Ten years after the detection of GW150914 [1] by the LIGO detectors [2], gravitational-wave astronomy is thriving. Advances in detector performance [3], including breakthroughs in quantum precision measurement [4–6], have led the field from the first glimpse of merging black holes [7,8] to an expanding catalog of hundreds of detections [9–18]. Here, we report the observation of GW250114_082203, henceforth GW250114, shown in Fig. 1. With similar parameters to GW150914, GW250114 reaches a similar strain amplitude of $\sim 10^{-21}$. Yet, thanks to the LIGO detectors now operating near their design sensitivity [3], it registers at a signal-to-noise ratio of 80, as opposed to 26 for GW150914 a decade ago. This makes GW250114 the most clearly recorded signal to date, broadening the scope of fundamental tests of strong-field gravity and black holes.

From a theoretical standpoint, black holes are expected to be remarkably simple objects [22–30]. According to Einstein's theory of general relativity and under suitable regularity assumptions, isolated stationary black holes can be fully characterized by just three parameters: mass, spin, and electromagnetic charge. For neutral black holes, this implies that mass and spin determine the system through the Kerr metric [31], the unique axisymmetric, neutral solution to Einstein's equations [26]. This uniqueness is closely tied to key conjectures in classical gravitation, including weak cosmic censorship [32] and the stability of rotating black holes [33–39], both of which remain unproven.

The uniqueness and implied featurelessness of black holes gives rise to paradoxes in the context of quantum mechanics and thermodynamics [40]. The laws of black hole mechanics, originally suspected to be only coincidentally reminiscent of statistical mechanics [41], establish black holes as true thermodynamic systems [40,42,43]: the role of the entropy is assigned to the area of the event horizon [44,45], while black holes radiate due to quantum effects as a black body with a temperature related to their surface gravity [46]. Black hole thermodynamics plays a key role in the quest to reconcile gravity with the rest of physics [47], through concepts such as information loss [48], holographic gravity [49,50], or the microscopic interpretation of black hole entropy [44,51,52].

Black holes are not just mathematical idealizations. They play a central role in the phenomenology and evolution of the Universe, displaying rich and complex behaviors from stellar to galactic scales [53–63]. Astrophysical black holes are expected to not be significantly charged [64–66], thus conforming to the Kerr metric—yet, the extent to which they do so is an open question. Gravitational waves can inform this by observationally probing the Kerr nature of black holes.

Although black hole coalescences feature some of the strongest and most dynamical gravitational fields, their initial and final states are simple. A coalescence begins with a long inspiral, during which two black holes orbit and approach each other as the system loses energy and angular momentum to gravitational radiation [67–69]. After the merger, the remnant black hole "rings" [70] as it settles into a quiescent Kerr state [71–73]. In this context, assuming a

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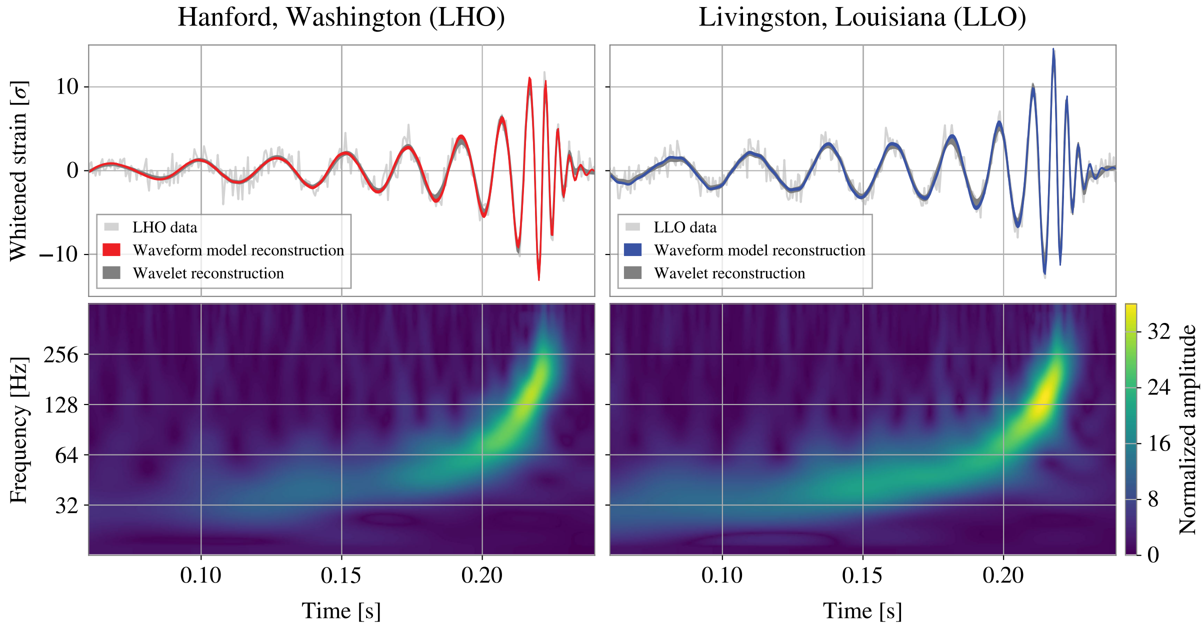

FIG. 1. Data from LIGO Hanford (left) and LIGO Livingston (right) and GW250114 signal reconstruction. Times are relative to January 14, 2025, 08:22:03 UTC. The top panels show whitened data versus time and signal reconstructions (90% credible regions), either with a waveform model for black hole binaries in general relativity [19] or via a model-agnostic wavelet-based approach [20,21]. Data and models have been downsampled to 2048 Hz, whitened (effectively, divided) by the detector noise amplitude spectral density, and finally bandpassed to [20, 896] Hz. The bottom panels show a time-frequency spectrogram of the data. The signal reaches $> 10\sigma$ above the noise.

Kerr remnant implies a specific ringdown spectrum (frequencies and damping rates) which is a known function of the black hole mass and spin [74]. In parallel, the second law of black hole mechanics, also known as Hawking's area law, requires a net increase in the total event horizon area throughout the coalescence [75].

GW250114 enables precise tests of both Hawking's area law and the Kerr nature of black holes. Excluding the neighborhood of the signal peak, we establish that the postmerger data contain at least two distinct ringing modes of the remnant at the 4.1σ credible level. These modes are consistent with the fundamental and first overtone of the quadrupolar ($\ell = |m| = 2$) spectrum of a Kerr black hole; deviations in the mode frequencies are constrained to $\pm 30\%$. To test the area law, we infer the initial black hole areas using premerger data that exclude up to five merger signal cycles and the final black hole area using postmerger data with one-mode or two-mode models at their earliest time of applicability. In all cases, the remnant's event horizon area exceeds the total initial area at high credibility, in agreement with Hawking's law. Thanks to the strength of GW250114, this test is possible even when excising the loudest portion of the signal where gravity is at its strongest and most dynamical.

Observation of GW250114—GW250114 arrived at 08:22:03 UTC on January 14, 2025, while the LIGO Hanford and LIGO Livingston detectors [2] were operating nominally, Virgo [76] was undergoing routine maintenance, and KAGRA [77] was not taking data. No significant data-quality issues were identified at the time [78]. GW250114 was detected with high significance by all search pipelines operating at the time; GstLAL [79–90], MLy [91], SPIIR [92], MBTA [93,94], PyCBC [95], and cWB [96,97], with a network matched-filter signal-to-noise ratio, henceforth SNR [98,99], ranging between 77 and 80. This is the highest reported SNR to date, surpassing GW230814_230901 which had SNR 42 [18,100]. GW250114's record extends to the individual detectors, with SNRs of 53 and 60 at LIGO Hanford and LIGO Livingston, respectively. The combination of the two LIGO detectors at comparable sensitivity enables the measurement precision reported here.

We infer the source properties following standard procedures [101]. Here, we quote selected results obtained with the `NRSur7dq4` waveform model [19], a surrogate of vacuum numerical-relativity simulations of spin-precessing, quasicircular systems. We obtain consistent results with other models [102–111], presented with further technical details in Supplemental Material [112]. The source of GW250114 has a binary total mass $M = 65.8^{+1.1}_{-1.2} M_\odot$ and mass ratio $q \geq 0.91$. Above and throughout, all quantities are quoted at the 90% credible level unless stated otherwise. We constrain the component masses to within $\sim 2M_\odot$, a factor of 3–4 improvement compared to GW150914 [1], at $m_1 = 33.6^{+1.2}_{-0.8} M_\odot$, $m_2 = 32.2^{+0.8}_{-1.3} M_\odot$; see Fig. 2. The black hole dimensionless spins, $\chi \equiv Sc/(Gm^2)$ where S is the spin

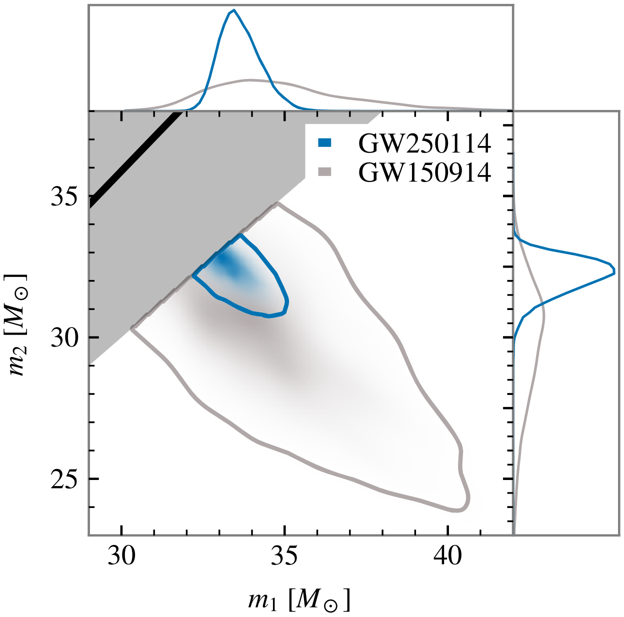

FIG. 2. Posterior distribution for the source-frame component masses of GW250114, under the definition $m_1 \geq m_2$ (marginals and 90%-credible contours). For comparison we also show results for GW150914 [11,132].

angular momentum, are both small, $\chi_1 \leq 0.24$, $\chi_2 \leq 0.26$, with no evidence for precession. The remnant black hole has a mass of $M_\mathrm{f} = 62.7^{+1.0}_{-1.1} M_\odot$ and a spin of $\chi_\mathrm{f} = 0.68^{+0.01}_{-0.01}$. Furthermore, there is support for the $\ell = |m| = 4$ radiation multipole with a network SNR of $3.6^{+1.4}_{-1.5}$. The source parameters are consistent with GW150914 and the wider population of binary black hole mergers [14,128], which contains an overdensity of observed black holes in the $30-40 M_\odot$ mass range and small spins [128,129]. The model-based signal reconstruction is consistent with a model-agnostic, wavelet-based approach [20], to within their statistical uncertainties, see Fig. 1. Their noise-weighted overlap [130,131] is 0.995.

A complementary analysis with models that allow for eccentric orbits but nonprecessing spins [110,111] finds that the eccentricity is constrained to $e \leq 0.03$ at a gravitational-wave frequency of 13.33 Hz.

The ringing of the remnant black hole—

Background: The merger process gives rise to a distorted black hole that rings down into quiescence [31,70–73,133]. Modeling this ringdown signal is a key ingredient of probes of the Kerr nature of the remnant and the area law. Within the framework of perturbation theory, the remnant signal is dominated by a superposition of quasinormal modes of the form $h \sim \exp(-2\pi i f t - \gamma t)$ [33,134–137]. Each mode's frequency f and damping rate γ are determined by the asymptotic Kerr mass M_f and spin χ_f, while its amplitude and phase depend on the details of the coalescence. Since the only relevant scale is the black hole mass, heavier black holes ring at lower frequencies and for a longer time; for a given mass, spin generally increases the damping time. While the spectrum depends on the assumptions of general relativity and a Kerr metric (with ingoing and outgoing boundary conditions at the black hole and infinity, respectively), quasinormal modes arise generically also in alternative frameworks [138–149]. Detected frequencies and times are scaled by a cosmological redshift factor, and the corresponding redshifted timescale is $t_{M_\mathrm{f}} = (1+z) G M_\mathrm{f}/c^3$.

Individual modes are indexed by angular numbers (ℓ, m) and an overtone number n. For a fixed (ℓ, m), modes with a higher n typically have higher damping rates [150]. The quadrupolar geometry of the binary and the fact that gravitational radiation is leading-order quadrupolar [151–153] mean that in equal-mass, nonprecessing, quasicircular binaries similar to GW250114, prograde modes with $\ell = |m| = 2$ dominate the signal. The longest-lived, fundamental, $n = 0$ mode is the main contributor at late times. Fits to numerical-relativity simulations of similar systems additionally suggest that the next strongest mode is $n = 1$, and that it decays below the fundamental around $10 t_{M_\mathrm{f}}$ after the merger [154–161].

Method: We model the postmerger signal from GW250114 using black hole perturbation theory, representing it as a superposition of generically polarized damped sinusoids [162,163]. This analysis is distinct from the full inspiral-merger-ringdown treatment described earlier, which incorporates numerical relativity to capture the complex merger dynamics. Our objective here is to directly test the predictions of first-order perturbation theory against the data.

We choose a reference timescale and merger time consistent with the full-signal analysis. We adopt a reference timescale of $t_{M_\mathrm{f}} = 0.337$ ms. The reference time t_peak is defined via the peak of the inferred strain amplitude [19] and is measured to within $\pm 0.4 t_{M_\mathrm{f}}$ at each detector. Both t_{M_f} and t_peak are only reference points and not a true dependence of the analysis. Using the time-domain RINGDOWN [162] and PYRING [164] inference packages, we model the data after some start time $t_>$ with different mode combinations and obtain posteriors for their parameters. The start time $t_>$ is reported relative to t_peak. See Supplemental Material for details [112].

Modes in GW250114: Since perturbation theory refers to the asymptotic spacetime, we start by analyzing the data from late times and seek the earliest time after which the signal can be described by a single mode; see Fig. 3, blue. The mode frequency and damping rate are parametrized in terms of a Kerr black hole mass and spin; this is equivalent to directly parametrizing in terms of frequency and damping rate as in Ref. [7] up to the choice of priors [162]. We find that data at late times are consistent with a single damped sinusoid, whose amplitude is confidently constrained away from zero at $> 7\sigma$ credibility for start times as late as $t_> = 20 t_{M_\mathrm{f}}$. The mode decays away, falling below 3σ credibility at $t_> = 27.0 t_{M_\mathrm{f}}$. The inferred mode amplitude

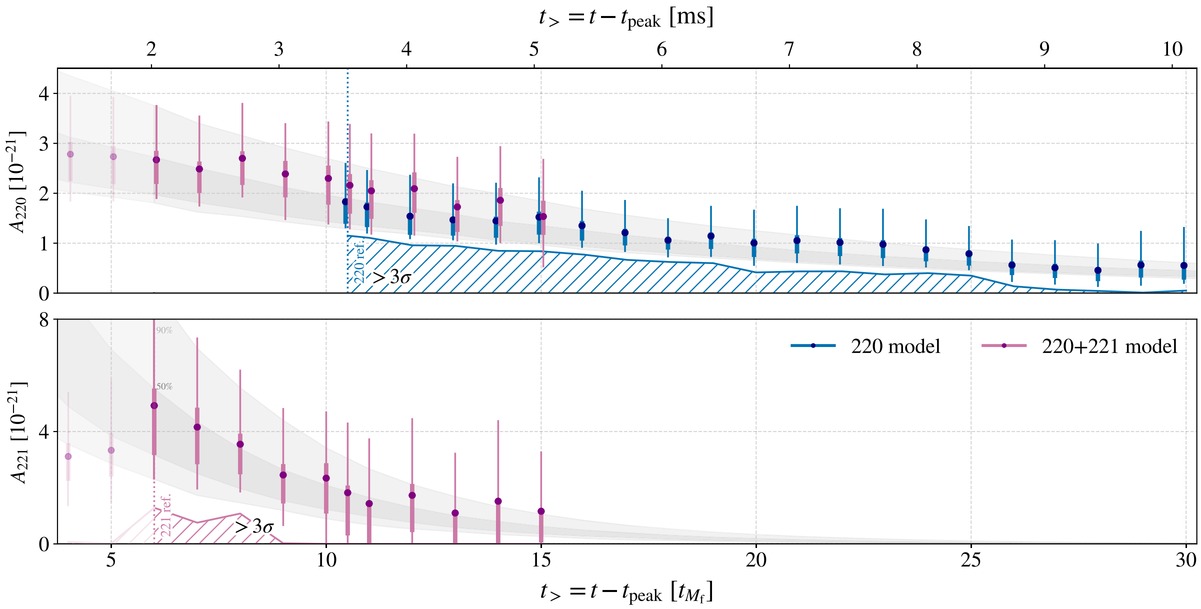

FIG. 3. Strain amplitudes of the fundamental mode A_{220} (top) and first overtone A_{221} (bottom) reported at the start of each analysis, $t_> = t - t_{peak}$, in units of t_{M_f} (bottom x axis) and milliseconds (top x axis). Bars mark 90% (thin) and 50% (thick) credible intervals around the median (circle), when modeling the data with one (blue) or two (pink) modes. Gray shading shows the expected amplitude decay as inferred from $t_> = 10.5t_{M_f}$ for the single-mode analysis (top; 220 ref), and $t_> = 6t_{M_f}$ for the two-mode analysis (bottom; 221 ref). Single-mode results are shown only after $10.5t_{M_f}$ (top), where support for a second mode is $< 1\sigma$. Overtone results are shown up to $15t_{M_f}$, by which time support for a second mode has completely vanished. Results pre-$6t_{M_f}$ are given lower opacity as the overtone decay does not follow the expected trend. Hatched regions are excluded to at least 3σ; higher significance regions are contained within it. We plot RINGDOWN results but obtain qualitatively consistent results with PYRING Mode frequencies, damping rates, and SNRs are plotted in Supplemental Material [112].

evolves consistently with a damped sinusoid in noise (gray shading). As discussed above, symmetry and late-time arguments suggest that this mode is the fundamental ($\ell = |m| = 2, n = 0$) mode of the remnant black hole, without any quantitative comparison to the full-signal analysis (e.g., Ref. [7])—we label the mode as such in the top panel of Fig. 3. Starting at $t_> = 10.5t_{M_f}$, this model recovers a SNR of 21 (Fig. 7 in Supplemental Material [112]) and infers the mode's (redshifted) frequency and damping rate to be $f_{220} = 247^{+6}_{-6}$ Hz and $\gamma_{220} = 221^{+39}_{-32}$ Hz, respectively.

Pushing $t_>$ earlier in time and toward the merger increases the SNR, but risks contamination from other modes, linear effects beyond exponentially damped sinusoids, or nonlinear effects [155,165–169]. The nonorthogonality of damped sinusoids further means that a model with additional modes does not necessarily lead to more faithful inference. We therefore again start from late times and seek (i) the time a second mode is required and (ii) the earliest time after which the data agree with two modes whose amplitudes decay self-consistently. Given the identification of a single damped sinusoid at late times, we expect any additional modes to be short-lived. Following Refs. [153,170–179] and expectations for GW250114-like systems [158,161,180], we enhance the model with the first overtone ($\ell = |m| = 2, n = 1$), and parametrize the frequencies and damping rates of both modes as a function of a single mass and spin.

Figure 3 shows two-mode results in pink. In the bottom panel, we confidently extract the overtone for a range of start times. Its amplitude is nonzero at 4.1σ credibility for $t_> = 6t_{M_f}$ and remains above 3σ until $t_> = 9.0t_{M_f}$. The significance drops below 1σ past $t_> = 10.5t_{M_f}$, when the data become consistent with a single damped sinusoid. Additionally, $t_> = 6t_{M_f}$ emerges as an inflection point in the amplitude trend (gray shading): for later start times, the recovered amplitudes decay consistently with the expected exponential decay. The divergence between the inferred overtone amplitude and the expected decay for $t_> < 6t_{M_f}$ hints at unmodeled features in the data, further explored in a forthcoming paper with extended models [181]. At $t_> = 6t_{M_f}$, the two-mode SNR is 26, and the (redshifted) frequency and damping rate of the overtone are $f_{221} = 249^{+8}_{-9}$ Hz and $\gamma_{221} = 708^{+116}_{-107}$ Hz, respectively. The GW250114 postmerger signal after $t_> = 6t_{M_f}$ has the same SNR as GW150914 in its entirety.

The Kerr nature of the remnant—Identification of two modes in the data can be used to test the Kerr nature of the merger remnant. Consistency with Kerr amounts to the four observables (the frequency and damping rate of each mode)

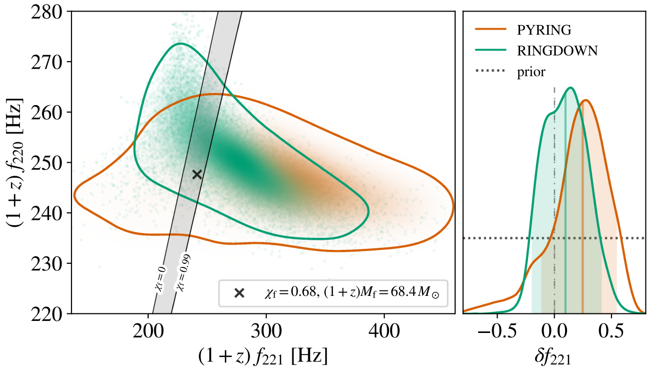

FIG. 4. Spectroscopic test of the Kerr nature of the remnant black hole for $t_> = 6t_{M_f}$. Left: 90% posterior for the observed fundamental and overtone frequencies, compared to the range allowed by the Kerr spectrum (black shaded region) for any black hole mass (vertical span) and spin (horizontal span). The cross marks reference values from the full-signal analysis. Right: posterior on the deviation δf_{221} of the frequency of the first overtone from the Kerr spectrum, with shading and a line showing the 90% credible region and the median respectively, a vertical line showing the Kerr prediction of $\delta f_{221} = 0$, and a horizontal line showing the prior. The pyRing analysis (orange) starts $\sim 0.5 t_{M_f}$ after ringdown (green), which is why the posteriors are not identical, see Supplemental Material [112]. The observed spectrum is consistent with Kerr to ±30%.

agreeing with the Kerr spectrum for some mass and spin. Black hole spectroscopy [182–184] started in earnest with searches for $\ell = |m| = 2$ modes in GW150914 [7,164,170,172–178,185] and has since been extended to further events and modes [100,153,179,186–191]. To constrain deviations away from the Kerr spectrum, we enhance our model with two additional parameters that allow for deviations in the frequency and damping rate of the overtone, respectively: $f_{221} = f_{221}^{(\mathrm{Kerr})}(M_f, \chi_f)\exp(\delta f_{221})$ and $\gamma_{221} = \gamma_{221}^{(\mathrm{Kerr})}(M_f, \chi_f)\exp(\delta\gamma_{221})$. The frequencies and damping rates of both modes are now parametrized via the remnant mass and spin, M_f and χ_f, and the deviations, δf_{221} and $\delta\gamma_{221}$. The Kerr spectrum is recovered for $\delta f_{221} = \delta\gamma_{221} = 0$.

With this setup, we constrain deviations from the Kerr spectrum at $t_> = 6t_M$ to be $\delta f_{221} = 0.1^{+0.3}_{-0.3}$, as seen in Fig. 4, while $\delta\gamma_{221}$ remains uninformative within its prior. This bolsters confidence in the identification of this mode as the overtone, and establishes consistency with Kerr frequencies to ±30%. Results for a variety of start times are presented in a forthcoming paper [181]. This is the first constraint of this kind derived from data confidently removed from the signal peak [153,170,179].

Hawking's area law—

Background: The second law of black hole mechanics, originally proven by Hawking [75] (but previously explored as irreducible mass by Christodoulou [192], Christodoulou and Ruffini [193], and stated by Penrose and Floyd [194]), states that the black hole horizon area cannot decrease in time. A direct consequence is an upper limit of 50% on the efficiency of gravitationally radiating processes in systems with initially vanishing binding energy; this is further limited to ∼29% for nonspinning black holes [75].

The area law relies on three conditions. The first is the null-energy condition, a restriction on the properties of matter. It is violated, for example, by Hawking radiation which extracts energy from a black hole and causes its horizon to shrink [46]—in this case, the area law is superseded by a generalized law that considers both the entropy of the black hole and that of the radiation [45,195]. The second is the premise that the observed objects are black holes and weak cosmic censorship holds, i.e., no naked singularities. Alternative compact objects [196–199] have modified entropy and violate the null-energy condition; their interactions could violate the area law. The third is general relativity; the area law can be violated in alternative theories [142,145,200–202]. Testing the area law thus amounts to testing for physical behavior that violates at least one of these conditions.

In the context of a binary merger, the area law imposes an increase in the horizon area of the remnant with respect to the total area of the initial black holes [75], providing a testable prediction [203–207]. However, since black hole areas are not direct observables, extracting them hinges on certain assumptions: (i) GW250114 originated from a quasicircular merging binary, (ii) general relativity is a good approximation away from highly dynamical regions, and (iii) the black holes are well described by the Kerr metric. The latter guides the black hole states we probe: the initial black holes are considered at wide separations, while the final black hole is considered in its asymptotic state. We thus adopt the Kerr area formula [41],

$$\mathcal{A}(m,\chi) = 8\pi\left(\frac{Gm}{c^2}\right)^2\left(1+\sqrt{1-\chi^2}\right), \qquad (1)$$

for a black hole of mass m and spin χ. This need not hold beyond vacuum general relativity [142,145,208,209].

Method: We extract the properties of the initial and final black holes independently from the premerger and postmerger signal respectively, discarding data in between. Our test, therefore, probes for violations during the most nonlinear and dynamical portion of the signal, which it excludes. It is sensitive to any nonstandard process that may alter the radiated energy or momentum, or any physics that modifies the ringdown spectrum sufficiently to bias the inferred remnant mass and spin, e.g., electromagnetic charge or other deviations from Kerr. Most generally, it is sensitive to physics that breaks any of the premises above and leads the inspiral and ringdown regimes to be better described independently than coherently [205]. Comparing the inspiral to the ringdown in this fashion can provide complementary constraints to those derived from the ringdown alone [210–216]. We truncate the data in the time domain [162,204,205,217,218] rather than the frequency domain [219,220], as there is no exact one-to-one correspondence between signal time and Fourier frequency beyond the adiabatic inspiral [98,221].

The initial horizon area: The initial black holes are considered at wide separations, where they obey the Kerr metric and the total area is the sum of the individual areas. The quantities reported in data analysis differ by the amount of energy and angular momentum absorbed by the black holes throughout the binary evolution, which is negligible for comparable-mass systems [222,223]. We therefore infer the black hole properties from the inspiral signal and interpret them directly as the infinite-separation quantities. Assuming that general relativity describes the inspiral [7,153,179,224–226] and the binary orbit is quasicircular [227], we model the signal with `NRSur7dq4`, up to a preselected time, $t_<$, that is quoted in units of the total mass from the full-signal analysis, $t_M \equiv (1+z)GM/c^3 = 0.354$ ms. We then infer (among other parameters) the masses and spins of the initial black holes, informed only by data before $t_<$ using the TDINF inference package [205,217,218], and from them the initial area $\mathcal{A}_i = \mathcal{A}_1 + \mathcal{A}_2$. See Supplemental Material for details [112].

To interpret the premerger truncation times, we use the gravitational-wave luminosity to proxy how relativistic the system is [68]. Based on the full-signal analysis, in Supplemental Material [112] we show that the luminosity is sharply peaked at merger and drops to 10% of its maximum at $-36t_M$ before $t_{\rm peak}$ [112]. We present results for an array of $t_<$ in Fig. 5 and further highlight $t_< = -40t_M$, a choice that excludes the two loudest signal cycles. For reference, the total SNR before $t_< = -40t_M$ is 55; even truncated, GW250114 has a higher SNR than any other signal to date [18].

The final horizon area: The mass and spin of the remnant are inferred through the postmerger signal. Picking an analysis start time requires balancing: (i) independence from the full-signal analysis that assumes the area law, (ii) maximizing the amount of data and thus the SNR, and (iii) using a model within its regime of validity. Since modes are not orthogonal, the more complex two-mode model is not universally preferable, as the overtone may degrade the inference especially if it is not detectable. Therefore, we adopt the most parsimonious model (single $\ell = |m| = 2$, $n = 0$ mode) at its earliest time of applicability (conservatively, $t_> = 10.5t_{M_{\rm f}}$ when the overtone significance is $< 1\sigma$) thus minimizing potential contamination [228]. We then use the mode's inferred frequency and damping rate to calculate the mass and spin of the final Kerr black hole and hence its area, $\mathcal{A}_f$.

Results: Figure 5 shows the fractional difference between the final and initial areas, $(\mathcal{A}_f - \mathcal{A}_i)/\mathcal{A}_i$, where

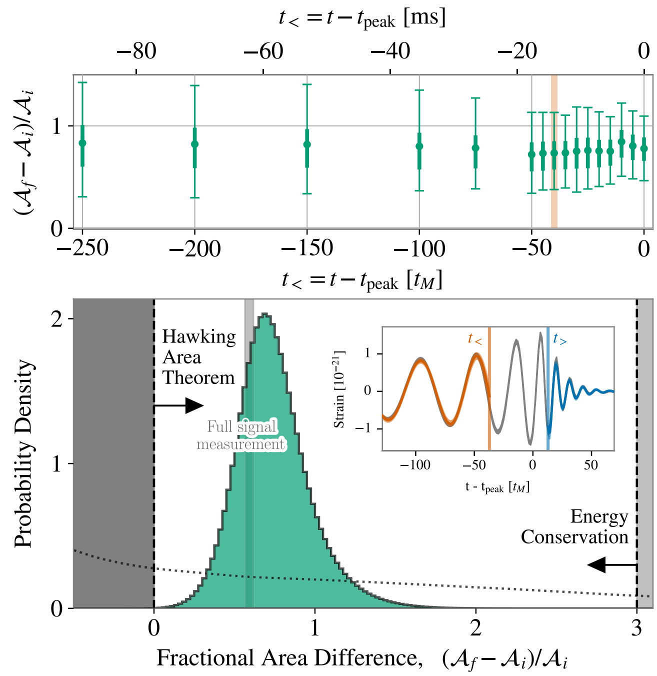

FIG. 5. Fractional difference between the area of the final black hole, $\mathcal{A}_f$, and the initial black holes, $\mathcal{A}_i$. Top: posterior as a function of the premerger truncation time, $t_< = t - t_{\rm peak}$. Bars represent 90% (thin line) and 50% (thick line) credible intervals around the median (circle). The vertical orange band denotes $t_< = -40t_M$, when the gravitational-wave luminosity is at 10% of its maximum. Bottom: posterior (histogram) and prior (dotted line) for $t_< = -40t_M$. The histogram is produced from all pairwise combinations of RINGDOWN and PYRING postmerger samples with TDINF premerger samples. The shading on the right highlights configurations that would violate energy conservation $M_f \leq m_1 + m_2$, a bound saturated for maximally spinning initial black holes that merge into a nonspinning remnant [75,229,230]. The shading on the left highlights configurations that would violate the area law, $(\mathcal{A}_f - \mathcal{A}_i)/\mathcal{A}_i < 0$. The vertical gray band is the 90% credible interval from the full-signal analysis used in Fig. 2, i.e., the general relativity expectation for GW250114. The inset illustrates the analysis via the signal reconstruction in LIGO Livingston from the full signal (gray), and when split into the premerger (orange) and postmerger (blue) stages; the merger phase is included in neither analysis. We find that $\mathcal{A}_f > \mathcal{A}_i$ to high credibility, indicating that GW250114 obeys Hawking's area law.

cosmological redshift factors cancel out because the area is proportional to the mass squared. For $t_< = -40t_M$, $\mathcal{A}_f > \mathcal{A}_i$ at the 4.4σ level, computed as described in Supplemental Material [112]. We find consistency with an increase in the area to at least 3.4σ for all times $t_< > -250t_M$, exceeding 5σ for $t_< \geq -10t_M$. In Supplemental Material we present results for more times and models [112]; the two-mode model at its earliest time of applicability, $t_> = 6t_{M_{\rm f}}$, also agrees with the area law at 3.6σ. All results are further consistent with the general relativity expectation for GW250114, obtained from the full-signal analysis with NRSur7dq4 used in Fig. 2, which considers the entire signal coherently and obeys the area law *a priori*. The strength of GW250114 enables such tests even while excluding the loudest portions of the signal and without any modeling of the nonlinear merger dynamics through numerical relativity, cf. inset of Fig. 5. Similar analyses of GW150914 [205,206] yielded $\sim 2\sigma$ results, albeit with less conservative assumptions: a premerger analysis that extended to the waveform peak and a quasinormal mode model that presumed circular polarization.

Conclusion—The gravitational-wave signal GW250114 is a milestone in the decade-long history of gravitational-wave science. With its high SNR, GW250114 offers an exquisitely clear view of the highly dynamical process by which two black holes merge to give rise to a remnant black hole. Data from LIGO Hanford and LIGO Livingston are consistent with multiple quasinormal modes of a remnant Kerr black hole and with Hawking's area law. Further precision tests of general relativity and the ringdown are presented in a forthcoming publication [181]. Our results suggest that astrophysical black holes are indeed extremely simple objects that follow general relativity and the Kerr description. The strongly perturbed merger remnant settles into a higher-entropy, quiescent state within a few dynamical timescales. The next decade of gravitational-wave science is bound to enhance our view of these highly dynamical, relativistic systems.

Strain data from the LIGO detectors for GW250114 are available from the Gravitational Wave Open Science Center [231].

This Letter made use of the following software, listed in alphabetical order: ARVIZ [233], ASIMOV [234], ASTROPY [235–237], BAYESWAVE [20], BILBY [238,239], CMASHER [240], CPNEST [241], CWB [96,97], DYNESTY [242], EMCEE [243], GST-LAL [79–90], GWPY [244,245], H5PY [246], PhenomXPHM [102,103], PhenomXO4a [108,109], JAX [247], JUPYTER and IPYTHON [248–250], LALSUITE [251], SWIGLAL [252], MATPLOTLIB [253,254], MBTA [93,94], MLY [91], NRSur7dq4 [19], NUMPY [255], NUMPYRO [256,257], PANDAS [258,259], PESUMMARY [260], PYCBC [95], PYRING [164,261], PY-SEOBNR [262], PYTHON [263], QNM [264,265], RIFT [266–268], RINGDOWN [162,269], SCIPY [270,271], SEABORN [272], SEOBNRv5PHM [104–107], SEOBNRv5EHM [110], TEOBResumS-DALI [111], SPIIR [92], TDINF [217,218,273], TQDM [274], software citation information was aggregated using The Software Citation Station [275,276].

Acknowledgments—This material is based upon work supported by NSF's LIGO Laboratory, which is a major facility fully funded by the National Science Foundation. The authors also gratefully acknowledge the support of the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen, Germany, for support of the construction of Advanced LIGO and construction and operation of the GEO 600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors gratefully acknowledge the Italian Istituto Nazionale di Fisica Nucleare (INFN), the French Centre National de la Recherche Scientifique (CNRS), and the Netherlands Organization for Scientific Research (NWO) for the construction and operation of the Virgo detector and the creation and support of the EGO consortium. The authors also gratefully acknowledge research support from these agencies as well as by the Council of Scientific and Industrial Research of India, the Department of Science and Technology, India, the Science & Engineering Research Board (SERB), India, the Ministry of Human Resource Development, India, the Spanish Agencia Estatal de Investigación (AEI), the Spanish Ministerio de Ciencia, Innovación y Universidades, the European Union NextGenerationEU/PRTR (PRTR-C17.I1), the Italian Center for Super Computing–CentroNazionale di Ricerca in High Performance Computing, Big Data and Quantum Computing, funded by the European Union NextGenerationEU, the Comunitat Autonòma de les Illes Balears through the Conselleria d'Educació i Universitats, the Conselleria d'Innovació, Universitats, Ciència i Societat Digital de la Generalitat Valenciana and the CERCA Programme Generalitat de Catalunya, Spain, the Polish National Agency for Academic Exchange, the National Science Centre of Poland and the European Union–European Regional Development Fund; the Foundation for Polish Science (FNP), the Polish Ministry of Science and Higher Education, the Swiss National Science Foundation (SNSF), the Russian Science Foundation, the European Commission, the European Social Funds (ESF), the European Regional Development Funds (ERDF), the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the Hungarian Scientific Research Fund (OTKA), the French Lyon Institute of Origins (LIO), the Belgian Fonds de la Recherche Scientifique (FRS-FNRS), Actions de Recherche Concertées (ARC) and Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO), Belgium, the Paris Île-de-France Region, the National Research, Development and Innovation Office of Hungary (NKFIH), the National Research Foundation of Korea, the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canadian Foundation for Innovation (CFI), the Brazilian Ministry of Science, Technology, and Innovations, the International Center for Theoretical Physics South American Institute for Fundamental Research (ICTP-SAIFR), the Research Grants Council of Hong Kong, the National Natural Science Foundation of China (NSFC), the Israel Science Foundation (ISF), the U.S.-Israel Binational

Science Fund (BSF), the Leverhulme Trust, the Research Corporation, the National Science and Technology Council (NSTC), Taiwan, the United States Department of Energy, and the Kavli Foundation. The authors gratefully acknowledge the support of the NSF, STFC, INFN, and CNRS for provision of computational resources. This work was supported by MEXT, the JSPS Leading-edge Research Infrastructure Program, JSPS Grant-in-Aid for Specially Promoted Research 26000005, JSPS Grant-in-Aid for Scientific Research on Innovative Areas 2402: 24103006, 24103005, and 2905: JP17H06358, JP17H06361, and JP17H06364, JSPS Core-to-Core Program A. Advanced Research Networks, JSPS Grants-in-Aid for Scientific Research (S) 17H06133 and 20H05639, JSPS Grant-in-Aid for Transformative Research Areas (A) 20A203: JP20H05854, the joint research program of the Institute for Cosmic Ray Research, University of Tokyo, the National Research Foundation (NRF), the Computing Infrastructure Project of the Global Science experimental Data hub Center (GSDC) at KISTI, the Korea Astronomy and Space Science Institute (KASI), the Ministry of Science and ICT (MSIT) in Korea, Academia Sinica (AS), the AS Grid Center (ASGC) and the National Science and Technology Council (NSTC) in Taiwan under grants including the Science Vanguard Research Program, the Advanced Technology Center (ATC) of NAOJ, and the Mechanical Engineering Center of KEK. Additional acknowledgements for support of individual authors may be found in [277].

Data availability—The data that support the findings of this Letter are openly available [232], embargo periods may apply.

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