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GW240925 and GW250207 are two loud gravitational-wave signals from binary black hole coalescences observed with network signal-to-noise ratios ~ 32 and ~ 69, respectively, by the LIGO Hanford–LIGO Livingston–Virgo network. Gravitational-wave signals from coalescing binaries have characteristic phase and amplitude evolution predicted by general relativity. These signal waveforms, together with measured instrumental calibration uncertainties, are used to infer source parameters. However, for sufficiently loud detections it is possible to constrain the calibration of the detectors directly using the signals themselves. We present the first informative astrophysical measurements of gravitational-wave detector calibration. For GW240925, we verify the inference of Hanford calibration from the astrophysical signal through cross-checks with known calibration errors obtained from in-situ measurements. At the time of GW250207, the Hanford detector was not fully stabilized, leading to elevated calibration uncertainties; thus, astrophysical calibration is essential to obtain accurate data and to enable source localization. These well-localized, high signal-to-noise observations have the potential to offer precise measurements of source properties, stringent tests of general relativity, and informative dark siren measurements, provided that calibration uncertainties are properly incorporated. As detector sensitivity improves, astrophysical calibration will become an increasingly valuable complement to in-situ calibration measurements. Obtaining accurate calibration will be essential for precision gravitational-wave science.

Introduction— We report the discovery of GW240925_005809 and GW250207_115645 (hereafter, GW240925 and GW250207), two loud gravitational-wave (GW) signals detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO) Hanford, LIGO Livingston and Virgo during their fourth observing run (O4). Since the first direct observation of GWs in 2015 [1], the LIGO–Virgo–KAGRA (LVK) network [2–4] has undergone substantial upgrades, achieving a roughly tenfold increase in detection rate and facilitating high signal-to-noise ratio (SNR) observations of compact binary coalescences (CBCs) [5–10]. These advances mark a transition from an era of initial discoveries to one of precision GW astronomy. High-SNR observations enable precise measurements of signal properties [11–13], advancing our understanding of source astrophysics, the nature of gravity, and cosmology.

Interpreting GW signals requires accurate understanding of detector behavior [13]. GW240925 and GW250207 both coincide with times where the LIGO Hanford detector was not in its usual observational state with well-characterized calibration. The calibration process typically reconstructs the raw digitized output of each interferometer into an accurate and reliable measure of the dimensionless strain [14–17]. Its accuracy directly impacts signal-parameter estimation [18, 19]; miscalibrations can bias inferred source properties [20, 21], affect cosmological measurements [22] and even mimic or obscure deviations from general relativity (GR) [23, 24]. To take advantage of the small statistical uncertainties offered by high SNRs, we must ensure small systematic uncertainties.

Fortunately, GW signals can be used to constrain the detector response directly. This *astrophysical* calibration approach leverages accurate modeling of GW waveforms, allowing the astrophysical signal to serve as an independent reference for the frequency-dependent detector calibration [5, 25, 26]. Astrophysical calibration may be performed in a variety of ways: using the frequency and amplitude evolution of the (predicted) signal to infer calibration parameters together with source parameters [26–28]; using an electromagnetic counterpart (and assumed cosmology) to establish the distance to a source [29], which provides more information than using the GW signal alone [26]; combining data from multiple detectors so the signals should cancel out if the data are correctly calibrated [30], or using the population of detections to constrain the relative sensitivity of the detectors [31]. The sensitivity of the first years of observations was insufficient for astrophysical measurements to be informative compared to in-situ results [26–28], but with the improvements of the detector network, astrophysical calibration is now becoming feasible.

We present the first astrophysical calibrations of a GW detector used to enhance our understanding of the state of the instrument. We perform a coherent analysis of data from Hanford, Livingston and Virgo for GW240925 and GW250207, inferring calibration properties for Hanford at the times of the two observations using the GW signals.

For GW240925, there was a significant frequency-dependent calibration systematic error for Hanford at the time of the observation. The frequency-dependent error can be inferred using the signal, and cross-checked with the in-situ measurements. Agreement between results validates the GW-informed calibration measurements and demonstrates the utility of inferring calibration from an astrophysical signal.

At the time of GW250207, the Hanford detector response had not yet fully stabilized, leading to larger calibration uncertainties. Lacking in-situ measurements of the calibration, astrophysical calibration was essential to ensure the reliability of the Hanford data and accurate inference of source properties such as localization.

These results establish astrophysical calibration as a complementary cross-check and, when required, a critical input to GW analysis. While not yet as precise as typical in-situ measurements, astrophysical calibration will improve as detector sensitivity continues to be enhanced.

Detector calibration— GW detectors like LIGO [2], Virgo [3] and KAGRA [4] are enhanced Michelson interferometers that measure spacetime strain by detecting changes in light-travel time between their orthogonal arms [32, 33]. The detector output strain data d are defined as the free (uncontrolled) differential change in arm length ΔL_{free} divided by arm length L, i.e., $d \equiv \Delta L_{\mathrm{free}}/L$; however, ΔL_{free} is not directly measurable, as the detector actively suppresses differential motion via feedback control. A detailed *calibration* procedure is therefore required to convert the raw digitized electrical output of the detector into the reconstructed strain data [14–16, 34, 35].

To reconstruct the strain, we need the frequency-dependent and time-varying detector response function $R(f;t)$ (detailed in the Supplemental Material [36]); however, in the calibration procedure, the true response function is not perfectly known. The strain data are reconstructed using a *modeled* response function $R^{(\mathrm{model})}(f;t)$ [14–16]. Calibration systematic errors arise from discrepancies between the true and modeled response functions; these errors and associated statistical uncertainties directly translate into the errors and uncertainties in the reconstructed d. In the absence of configuration changes (which are typically associated with updates to $R^{(\mathrm{model})}$), $R(f;t)$ remains approximately stable, but can vary on hour timescales during periods of evolving detector state, e.g., at the beginning of a lock stretch (see discussion of thermal lens below) [37]. For LIGO, we quantify calibration errors using a complex correction factor $\eta(f;t)$ [16, 38]:

$$\eta(f;t) = \frac{R(f;t)}{R^{(\mathrm{model})}(f;t)} = \left[1 + \delta\mathcal{A}(f;t)\right]\exp\left[i\delta\phi(f;t)\right], \quad (1)$$

where $\delta\mathcal{A}(f;t)$ and $\delta\phi(f;t)$ denote amplitude and phase errors, respectively. A more accurate estimate of the true strain is obtained by multiplying the (frequency-domain) detector strain data by the correction factor η,

$$d^{(\mathrm{corr})} = \eta d. \quad (2)$$

The probability distribution of $\eta(f;t)$ is evaluated using in-situ calibration measurements, primarily through excitations via photon calibrators [39–42] and quadruple-pendulum actuators [16, 43], and is used to construct the calibration prior for signal parameter estimation [44] (see Supplemental Material [36]).

The low-latency, online calibrated (C00) strain data produced during observing runs may contain systematic errors due to model inaccuracies that are not identified or corrected in real time. In previous observing runs, offline calibrated data (C01) were produced for the LIGO detectors as the standard final data product, incorporating all known corrections [14–16]. In O4, the photon calibrators were used to monitor the calibration accuracy at a discrete set of frequencies in real time [17, 43], and C01 data were generated when necessary, e.g., when the calibration error was known to exceed $\sim 10\%$ in amplitude or ~ 10 deg in phase (68% probability).

At the times of GW240925 and GW250207, Livingston and Virgo were observing normally, but the Hanford detector was either miscalibrated or still stabilizing, with a response deviating from the modeled behavior. KAGRA was not observing over this period of O4 [5]. Detailed real-time calibration monitoring measurements [43] at the Hanford detector around the times of these two observations are provided in the Supplemental Material [36]. The Livingston and Virgo detectors had reliable calibration: in the most sensitive frequency band 20–2000 Hz, their frequency-dependent uncertainties (68% probability) were constrained to $\lesssim 2\%$ in amplitude and $\lesssim 2$ deg in phase for Livingston, and $\lesssim 2.5\%$ in amplitude and $\lesssim 6$ deg ($\lesssim 3$ deg below 500 Hz) in phase for Virgo [45].

For GW240925, a procedural inconsistency at Hanford resulted in a temporary mismatch between a calibration parameter used in the interferometer control system and the corresponding value adopted in the calibration model. The mismatch led to a mischaracterization of the detector response, introducing a frequency-dependent systematic error in the reconstructed strain data. The error reached up to $\sim 20\%$ in amplitude and ~ 12 deg in phase across the sensitive frequency band [46]. This large error in the C00 calibration, combined with GW240925's high SNR, provided a unique opportunity to cross-check signal-informed astrophysical calibration with in-situ measurements. C01 data were later generated around the time of GW240925, correcting the miscalibration.

For GW250207, the Hanford detector had just reached its low-noise operational state but had not yet formally entered observing mode [46]. The detector was still settling; in particular, the changing thermal lens of the test masses affected the low-frequency response [10]. While real-time calibration monitoring can provide valuable information about the evolution of systematic errors during such transient periods [43], the monitoring lines had not yet stabilized, and several were not yet recording measurements. As a result, no reliable measurement of the real-time detector response is available for this period, and the associated calibration systematic errors and uncertainties in the Hanford strain data cannot be robustly quantified using in-situ measurements. Astrophysical calibration is essential to analyze Hanford data.

Detection— GW240925 and GW250207 were observed by the three-detector Hanford–Livingston–Virgo network. Time–frequency spectrograms of the data around the two signals are shown in Fig. 1. The characteristic chirps of CBC signals are visible sweeping up from low frequencies.

GW240925 was observed at 00:58:09 Coordinated Universal Time (UTC) on September 25, 2024 during the second part of O4 (O4b). It was identified in low latency in Hanford and Livingston data by the minimally modeled cWB [48–51] pipeline as well as the GstLAL [52–60], MBTA [61–63] and SPIIR [64] matched-filtering pipelines. The candidate was identified with SNRs of 17.3 and 25.8 in Hanford and Livingston, respectively, and a false alarm rate (FAR) of $< 1 \times 10^{-5}\ \mathrm{yr}^{-1}$. The Virgo detector was operating at the time, but the candidate's SNR of 2.7 was too small to contribute to the coincident detection. Nevertheless, the Virgo SNR time series was analyzed by BAYESTAR [65, 66] to infer the location. General Coordinate Network (GCN) Notices and Circu-

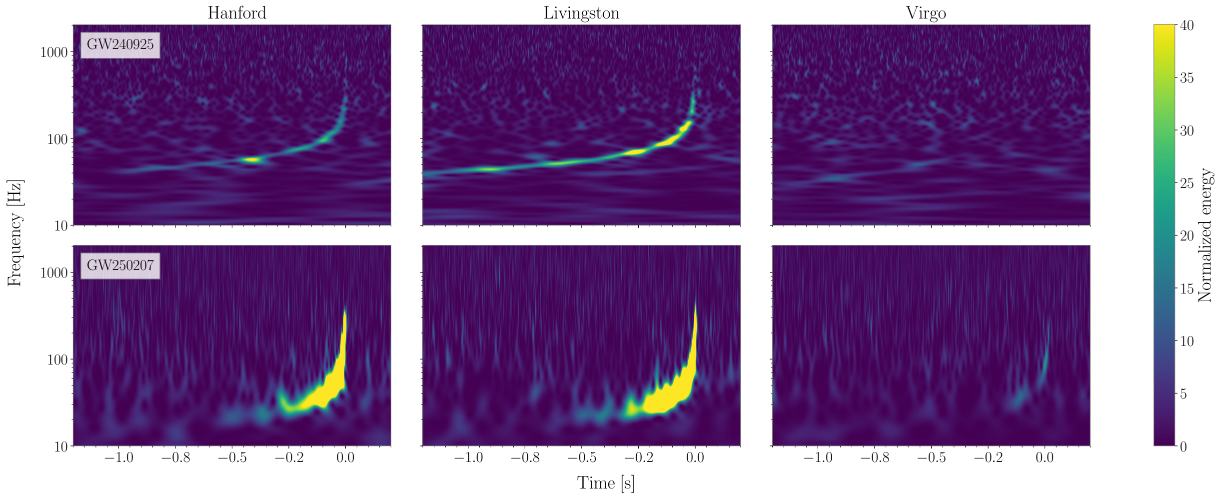

FIG. 1. Time–frequency spectrograms [47] showing data from LIGO Hanford (left), LIGO Livingston (middle) and Virgo (right) for GW240925 (top) and GW250207 (bottom). Times are relative to the times reported from the search algorithms for the two detections. We use C00 LIGO data. The data are whitened [13], and the scale bar shows the normalized energy.

lars about the detection were shared in low latency.[1]

Data quality (DQ) was scrutinized around GW240925 following established procedures [67]. We identified a burst of non-Gaussian noise (a *glitch* [68, 69]) in Livingston data, but this occurred sufficiently after the signal to not require mitigation [70]. No DQ issues impacting the analysis were found.

GW250207 was observed at 11:56:45 UTC on February 7, 2025 during the third part of O4 (O4c). It was identified in low latency in Livingston and Virgo data by the GstLAL and SPIIR search pipelines. The signal was measured with SNRs of 48.3 and 8.1 in the Livingston and Virgo detectors, respectively, and a FAR of $< 1 \times 10^{-5}$ yr^{-1}. DQ checks [67] revealed no issues impacting the detection. As Hanford was not in observing mode, its data were not used in low-latency, but were later determined to be of good quality [46]. GCN Notices and Circulars were again shared in low latency.[2]

Further DQ and search-analysis results for both detections are given in the Supplemental Material [36].

Inference of calibration errors and source properties— We analyze the detector data for each signal using Bilby [71, 72] to obtain posterior probability distributions on the parameters $\boldsymbol{\theta}$ characterizing the source binary and those describing the calibration of each detector [44]. We assume that a GR waveform $h(\boldsymbol{\theta})$ accurately describes the signal. To account for calibration uncertainty, the reciprocal of the correction factor $(1/\eta)$ is applied to the waveform. This reciprocal factor is parametrized using amplitude and phase deviations, derived from their counterparts in Eq. (1) [44, 73], which are modeled using splines and inferred from the data [44, 74, 75]. Further details on inferences are given in the Supplemental Material [36].

[1] GCN Circular archive for S240925n.
[2] GCN Circular archive for S250207bg.

The consistency of the signal across frequencies and between detectors provides information about the detector calibration. Typically, we use the in-situ measured calibration-uncertainty estimates from the time closest to the signal as priors in the analysis. As these are usually well constrained, the GW signal adds little information [6, 26]. However, for higher SNR signals or cases where calibration errors are significant, astrophysical calibration is expected to become informative.

We first demonstrate the measurement of the Hanford calibration error with GW240925, performing three analyses. For each, we use the usual calibration priors informed by in-situ measurements for Livingston and Virgo. We analyze LIGO C00 data, which contains the large Hanford calibration error, assuming two different priors for the Hanford calibration: one narrow, informed by in-situ measurements, and one wide across all frequencies. As the cause of the calibration error can be identified, we can directly compare the in-situ measured calibration error to the calibration independently inferred from the signal. We also analyze LIGO C01 data, where the calibration error has been corrected, assuming a narrow in-situ calibration prior.

In Fig. 2 (left), we plot the Hanford calibration parameters for GW240925 as a function of frequency. With the wide prior, the posterior provides the tightest constraints at frequencies where the signal is loud (below the peak of the dominant $\ell = |m| = 2$ multipole at a frequency $f_{22}^{\rm peak}$ of $\sim$ 680 Hz), and tends towards the prior at higher frequencies where there is no signal to constrain the calibration (the oscillations reflect the discrete placement of spline nodes). To quantify the difference between the wide prior and the corresponding posterior, we use the Jensen–Shannon divergences (JSDs) [76] between the distributions, finding $0.06^{+0.09}_{-0.05}$ nat for amplitude and $0.05^{+0.13}_{-0.05}$ nat for phase, quoting the median and 90% range across the frequency nodes, where JSD $\lesssim 0.002$ nat is consid-

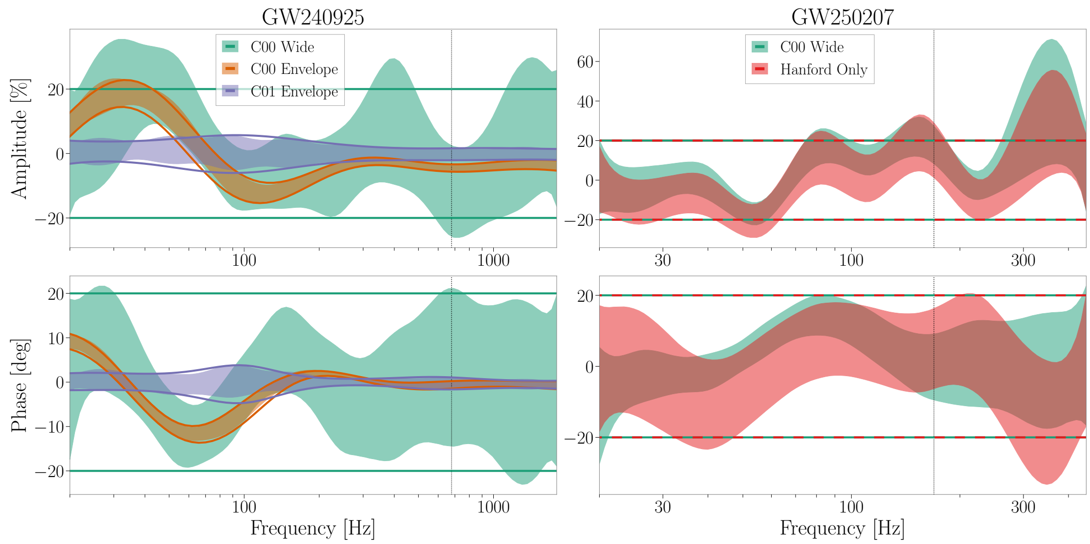

FIG. 2. LIGO Hanford calibration as a function of frequency over the analysis band for each signal. The top and bottom panels show the frequency-dependent amplitude error $\delta\mathcal{A}$, and phase error $\delta\phi$, respectively. Shaded regions indicate the 68% credible intervals of the posteriors, and the lines denote the 68% probability envelopes from which the priors are derived (see Supplemental Material [36]). GW240925 results (left) are from three analyses: one using a wide, uninformative prior on the miscalibrated C00 data (green), one using a narrow prior envelope based upon in-situ measurements on the same data (orange), and one using a narrow in-situ measured prior envelope for the recalibrated C01 data (purple). GW250207 results (right) are from two analyses, both using the same wide priors on the miscalibrated Hanford C00 data: one using data from all three detectors (green), with the in-situ priors applied to Livingston and Virgo data, and one using only Hanford data (red). Results are more informative for frequencies where there is more signal power (Fig. 1), and the dotted vertical lines indicate the approximate peak frequencies $f_{22}^{\rm peak}$ for the $\ell = |m| = 2$ multipole of the signals.

ered a negligible difference [72]. This indicates that the posterior is informed by the signal at various frequencies. The posterior obtained with the wide, uninformative prior agrees well with the results informed by the in-situ measurements, demonstrating that detector calibration can be inferred from an astrophysical signal. Although the signal-informed calibration is less constrained than the in-situ measurements, it provides an independent cross-check and a valuable diagnostic for uncovering analysis inconsistencies. In this case, the direct comparison between constraints revealed (and led to the correction of) a long-standing convention mismatch in the analysis procedure for incorporating calibration uncertainties, which had only had a minor effect prior to O4 [44, 73]. Results from the C01 data for both LIGO detectors and Virgo are consistent with zero error, as expected after calibration correction.

We find that inferred source parameters are typically consistent between analyses. We adopt the C01 results as our default for interpretation, with medians and 90% symmetric credible intervals for the parameters listed in Table I.

The sky localization is illustrated in Fig. 3. Calibration uncertainty can have a significant impact on source localization [20, 27, 77], and using the wider calibration prior increases the localization area. Also shown in Fig. 3 is a medium-latency localization [78]; this did not use Hanford data because of the miscalibration. To leading order, the sky localization depends upon the time delay observed between detectors, and adding a third detector enables triangulation of the source [79–81]. The inclusion of the Hanford data significantly changes the inferred localization (the 90% localization volume shrinks from $\sim 1 \times 10^7$ Mpc^3 to $\sim 2 \times 10^5$ Mpc^3), as further discussed in the Supplemental Material [36], demonstrating the importance of using data from all detectors.

GW240925's source is inferred to be a low-mass binary black hole (BBH). The binary has a total mass of $M = 16.1^{+0.7}_{-0.4} M_\odot$ (median and 90% symmetric credible interval) and has support for equal-mass components, with mass ratio $q > 0.57$ (90% probability). The masses are consistent with the peak of the BBH mass distribution [84] and the masses of black holes in X-ray binaries [85–90]. The source is inferred to not have high spins ($\chi_1 < 0.53$ and $\chi_2 < 0.69$); the effective inspiral spin $\chi_{\rm eff}$ [91, 92] is small ($|\chi_{\rm eff}| < 0.08$), with positive values preferred, indicating a probable net alignment of the component spins with the orbital angular momentum.

Having demonstrated the efficacy of astrophysical calibration with GW240925, we turn to GW250207, where we must rely on signal-based inference to constrain the Hanford calibration. We analyze the C00 data using a wide prior across all frequencies for the Hanford calibration parameters, and in-situ measured priors for Livingston and Virgo. For comparison we also perform (i) an analysis using only Hanford data, to show what can be inferred without constraints from other detectors, and (ii) an analysis assuming that the data from all three detectors are perfectly calibrated, to investigate the impact of neglecting calibration uncertainties.

The results in Fig. 2 (right) show that the astrophysical cal-

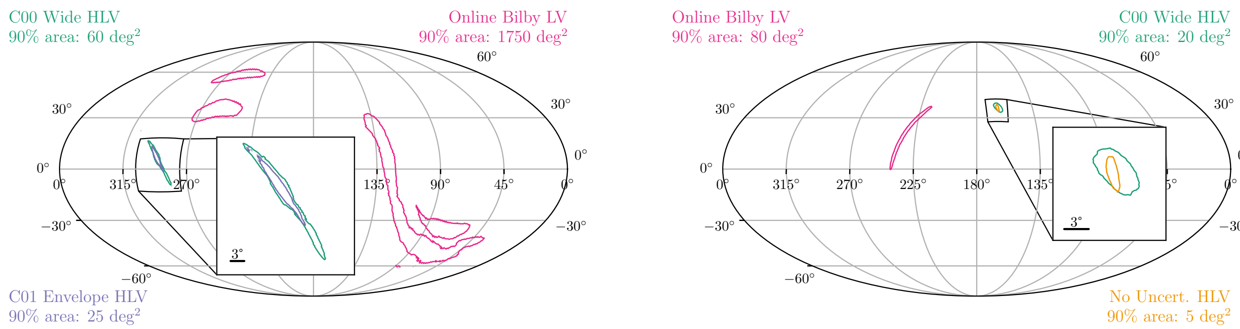

FIG. 3. Sky localization for GW240925 (left) and GW250207 (right) from analyses using data from all three detectors (HLV) and just Livingston and Virgo (LV). The contours show 90% credible areas. We show results using the wide calibration prior for Hanford (green), plus the result using the in-situ measured prior for GW240925 (purple) and the result neglecting calibration uncertainty for GW250207 (yellow). The medium-latency Online Bilby (magenta) analyses only used Livingston and Virgo data for both signals [78, 83]. Inclusion of the Hanford data, enabled by the simultaneous estimation of the calibration parameters, has a significant impact on both localizations.

TABLE I. Inferred source properties [5] for GW240925 and GW250207. We report median values with 90% symmetric credible intervals. GW240925 results use C01 data and calibration uncertainties based upon in-situ measurements. GW250207 results use a wide prior for the Hanford calibration uncertainty, and a prior based upon in-situ measurements for Livingston and Virgo calibration. Quantities that evolve throughout the inspiral are quoted at a reference frequency of 20 Hz. Results are computed assuming a standard cosmology with $H_0 = 67.9\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ [44, 82].

Parameter	GW240925	GW250207
Primary mass $m_1/M_\odot$	$9.0^{+2.0}_{-1.0}$	$35.2^{+1.7}_{-1.7}$
Secondary mass $m_2/M_\odot$	$7.0^{+0.8}_{-1.3}$	$30.6^{+1.5}_{-1.8}$
Total mass $M/M_\odot$	$16.1^{+0.7}_{-0.4}$	$65.9^{+1.0}_{-1.7}$
Chirp mass $\mathcal{M}/M_\odot$	$6.85^{+0.22}_{-0.08}$	$28.57^{+0.44}_{-0.77}$
Final mass $M_\mathrm{f}/M_\odot$	$15.3^{+0.7}_{-0.4}$	$62.7^{+1.0}_{-1.6}$
Effective inspiral spin χ_eff	$0.02^{+0.08}_{-0.02}$	$0.00^{+0.03}_{-0.04}$
Effective precession spin χ_p	$0.25^{+0.37}_{-0.20}$	$0.06^{+0.15}_{-0.05}$
Final spin χ_f	$0.69^{+0.02}_{-0.03}$	$0.69^{+0.01}_{-0.01}$
Luminosity distance $D_\mathrm{L}/\mathrm{Mpc}$	356^{+61}_{-162}	187^{+121}_{-52}
Redshift z	$0.08^{+0.01}_{-0.03}$	$0.04^{+0.03}_{-0.01}$
Network SNR ρ	$31.96^{+0.11}_{-0.15}$	$68.91^{+0.08}_{-0.11}$

ibration posterior is informative and distinct from the prior across the frequency range of the signal (f_{22}^{peak} is ~ 170 Hz), similar to results for GW240925. For GW250207, we obtain JSDs between the posterior and prior of $0.15^{+0.11}_{-0.15}$ nat for amplitude and $0.14^{+0.13}_{-0.14}$ nat for phase. Some of the frequency-dependent structure reflects the discrete placement of spline nodes. The amplitude error near the 317.1 Hz node is only weakly constrained (likely by contributions from higher-order multipole moments); although the inferred error appears large, the posterior distribution is skewed and is still consistent with zero, with $\delta\mathcal{A} = 26^{+69}_{-32}\%$ (90% credible interval). The calibration is best constrained when using the in-situ measured priors for Livingston and Virgo, but the Hanford data alone remain informative. In the Hanford-only analysis, the overall (frequency-independent) calibration amplitude scale is fully degenerate with the source distance, since $h(\boldsymbol{\theta})$ scales inversely with distance, and the overall calibration phase scale is fully degenerate with the signal's reference phase. Therefore, the absolute scales of the Hanford-only constraints shown in Fig. 2 are prior driven: the prior favors $\delta\mathcal{A} \sim 0$ and $\delta\phi \sim 0$ deg. However, the *frequency-dependent* evolution of the calibration parameters can still be constrained using the signal morphology in the Hanford data alone.

Measurements of key astrophysical parameters for GW250207 are given in Table I. GW250207's source is similar to GW150914's [75, 93]. The BBH source has total mass of $M = 65.9^{+1.0}_{-1.7} M_\odot$ and a well-measured mass ratio of $q = 0.87^{+0.08}_{-0.08}$. The individual spins are small, with $\chi_1 < 0.15$ and $\chi_2 < 0.19$. These properties are consistent with the inferred BBH population, with component masses near the feature in the mass distribution at $\sim 35 M_\odot$ which contributes many observed binaries [84, 94]. With the inclusion of Hanford data, GW250207 has the second-highest network SNR published to date (after GW250114_082203 [7]), and its source is probably the closest BBH observed with $D_\mathrm{L} = 187^{+121}_{-52}$ Mpc [6, 93, 95, 96]. Such a high SNR facilitates more precise parameter estimation than for typical GW observations [6, 11].

GWs can be decomposed into spherical harmonics [97–100]. The $\ell = |m| = 2$ multipole moment dominates the signal. However, the high SNR of GW250207 means that other moments are observable; the signal probably has the highest $\ell = |m| = 4$ SNR found to date, $\rho_{44} = 5.1^{+0.5}_{-1.9}$ [6, 7, 101].

Comparing analysis results, we see that erroneously assuming perfect calibration for all detectors leads to narrower and, in some cases, biased posteriors for source parameters. The inferred distance becomes $D_\mathrm{L} = 175^{+42}_{-28}$ Mpc. The miscalibration at frequencies between $\sim$ 40–60 Hz is mistaken for a signature of spin precession: the constraint on the effective precession spin shifts from $\chi_\mathrm{p} = 0.06^{+0.15}_{-0.05}$, corresponding to a precessing SNR [102, 103] of $\rho_{\rm p} = 2.4^{+4.8}_{-1.9}$ (using the wide prior for Hanford and in-situ priors for Livingston and Virgo) to $\chi_{\rm p} = 0.13^{+0.17}_{-0.07}$, $\rho_{\rm p} = 5.8^{+6.8}_{-3.1}$ (neglecting calibration uncertainties). This demonstrates how miscalibration can mimic physical effects and impact astrophysical inferences.

The sky localization is shown in Fig. 3. Again, neglecting calibration uncertainty leads to narrower posteriors. As for GW240925, and discussed in the Supplemental Material [36], the inclusion of Hanford data shifts the sky-position posterior such that it lies outside of the two-detector 90% area [83]. This type of shift can happen in (infrequent) cases where the third detector adds information that strongly disfavours locations in the two-detector 90% area [104, 105]. The inclusion of the Hanford data reduces the volume localization from $\sim 2 \times 10^6$ Mpc^3 to $\sim 5 \times 10^4$ Mpc^3. Without using Hanford data and accounting for its uncertain calibration, it would be difficult to locate the source.

These results for GW240925 and GW250207 demonstrate that astrophysical signals can be used to infer detector calibration, providing both a practical fallback when in-situ measured calibration is incomplete or uncertain and a valuable cross-check of analysis procedures. Further results are provided in the Supplemental Material [36].

Potential for dark siren cosmology— CBCs act as dark sirens providing constraints on their source distances; cross-referencing the inferred localization volume with galaxy catalogs that provide redshift information then enables inference of the Hubble constant [25, 106, 107]. Localization of GW sources is best for high-SNR signals observed with at least three detectors [81, 105, 108–110].

Since the two signals have well-localized sources, they could be considered as potentially useful dark sirens. Unfortunately, GW240925 will not provide significant cosmological information from its localization as it is hidden by the Milky Way plane. However, GW250207 has a localization volume of $\sim 5 \times 10^4$ Mpc^3, similar to that of GW190814 ($\sim 5 \times 10^4$ Mpc^3 [93, 111]), far from the Milky Way plane, making it well suited for a dark siren cosmological analysis. The host galaxy of GW250207 has an estimated probability $\sim 74\%$ to be present in the extended version of the Galaxy List for the Advanced Detector Era (GLADE+) catalog [112, 113]. This probability is based on the K-band luminosity, assumes that the likelihood of hosting a CBC is proportional to the galaxy luminosity, and adopts a flat cosmological model with $H_0 = 67.9$ km s^{-1} Mpc^{-1} and $\Omega_{\rm m} = 0.3065$ [44, 82]. Both signals will be included in a comprehensive analysis of all detections up to the end of O4, which will be presented with a future version of the Gravitational-Wave Transient Catalog (GWTC), similar to the analysis for GWTC-4.0 [107]. This population analysis will allow information from multiple detections to be combined with a proper computation of selection effects across observing runs.

Consistency tests— We perform a suite of verification tests using the two observations, including general residual analyses, tests that constrain deviations of post-Newtonian (PN) parameters from the expected GR values, and quasinormal mode (QNM) spectroscopy tests of the remnant. These tests are often framed as tests of GR, but are also sensitive to a variety of assumptions about the data. Failing to incorporate the calibration systematics in these analyses can lead to biased results, potentially mimicking or obscuring deviations from GR predictions [18, 23]. Here, we summarize results and provide additional details in the Supplemental Material [36].

The residuals test evaluates the agreement between the data and the best-fit GR waveform by searching for excess coherent power remaining after subtracting the signal [114–116]. Residual power may indicate the presence of calibration errors, instrumental artifacts or waveform-modeling errors. We find no evidence of residual power.

The FTI [117], TIGER [118–121] and PCA [122, 123] analyses explore deviations of the PN coefficients from the GR value in the inspiral signal. TIGER also allows for deviations in the phenomenological coefficients of the post-inspiral signal [121]. All analyses incorporate calibration uncertainties, like in the analyses to infer source properties, but now using waveform models that include the modeled deviations from GR. We find that neglecting calibration uncertainties can introduce mild biases in the inferred deviations, even though the results remain statistically consistent with GR. Using the wide, uninformative calibration priors mitigates the risk of falsely identifying GR violations. The GW250207 analyses for the PN deviation parameters give the tightest upper limits to date on the 2PN and higher-PN deviation parameters, surpassing GW250114_082203 [124]; at −1PN and 0.5PN, the constraints from GW170817 remain the best [125, 126].

For the ringdown signal, we use the pSEOBNR [127–131], QNMRF [132–135], and RINGDOWN [136–138] pipelines to perform QNM analyses. pSEOBNR can include calibration uncertainty with its parametrized waveform, but QNMRF and RINGDOWN do not currently support calibration marginalization and instead analyze Hanford and Livingston data separately to assess potential systematic errors. Figure 4 presents results from these analyses. These consistently show that neglecting calibration errors at Hanford leads to biased estimates for the $(2, 2, 0)$ QNM frequency and damping time relative to those inferred from the full inspiral–merger–ringdown (IMR) waveform. The 90% credible intervals on the $(2, 2, 0)$ QNM are compatible with GW230814_230901 [101], GW250114_082203 [7, 124], and other signals included in the GWTC-4.0 analysis [139].

Conclusion— Using the high-SNR BBH signals GW240925 and GW250207, observed during times of elevated calibration uncertainty, we have demonstrated that the information encoded within CBC signals can enable astrophysical calibration of GW detectors. With loud GW observations, we may cross-check in-situ calibration measurements. Furthermore, when we lack a complete set of calibration measurements, GW signals may be used to infer calibration properties: in such cases, signal-informed calibration is necessary and required to obtain precise and accurate source localization for multi-messenger follow-up and cosmological measurements, along with unbiased tests of

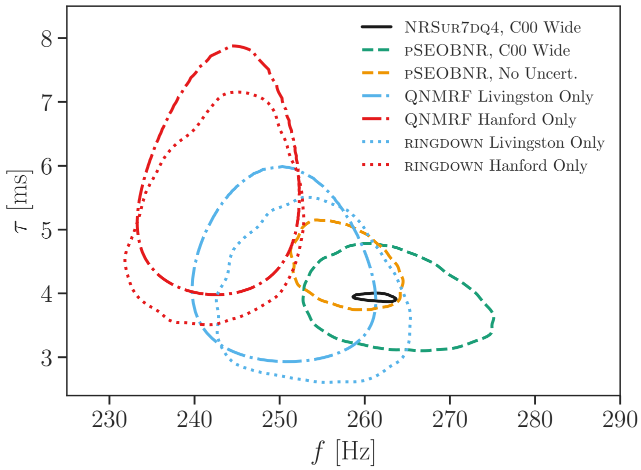

FIG. 4. Inferred (2, 2, 0) QNM frequency and damping time from analyses of GW250207. The full IMR GR result, incorporating a wide prior for Hanford calibration, is indicated by the solid line. The pSEOBNR analysis (dashed) compares results obtained by either neglecting calibration uncertainties (yellow) or incorporating a wide prior for Hanford to marginalize over them (green). The QNMRF (dot–dashed) and ringdown (dotted) analyses analyze Hanford (red) and Livingston (light blue) data separately without calibration uncertainty to assess potential systematic errors. QNMRF and ringdown analyze the signal starting at $8t_{M_f}$ after the peak of the strain, where time is in units of the remnant mass in the detector frame (the maximum-likelihood estimate from the IMR analysis using the NRSur7dq4 waveform [140] and the wide calibration prior).

GR. Although astrophysical calibration has long been proposed as possible [19, 26, 29, 30], the groundbreaking higher SNRs found during O4 are now making it practical [26–28].

GW240925 and GW250207 were fortunately detected while multiple detectors were observing, allowing for a coherent analysis across the network. Having multiple observatories increases the probability of detection, improves source localization, and mitigates any adverse effects of detector noise on interpretation. Good source localization of GW250207 is only possible with the addition of LIGO Hanford data and the astrophysical inference of its calibration. Further expansion of the network [5, 81] with increasing sensitivity for KAGRA and the construction of LIGO India will enhance the opportunities for GW discovery and mitigate against cases where one observatory is adversely impacted by an instrumental problem, a glitch or a calibration issue. With a global observatory network, we are best prepared to fulfill the potential of GW astronomy and to make discoveries that advance our understanding of the Universe.

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Calibration of the LIGO strain data was performed with GstLAL-based calibration software pipeline [34], and calibration of the Virgo strain data is performed with C-based software [17]. DQ products and event-validation results were computed using the BRiSTOL [141], DMT [142], DQR [143], DQSEGDB [144], Glitchfind [145], GSpyNetTree [146], gwdetchar [147], Hveto [148], iDQ [149], LigoDV-web [150], OmegaOverlap [151], Omicron [152], PEMcheck [153], PythonVirgoTools [154] and Stationarity [155] software packages and contributing software tools. Analyses relied upon the LALSuite software library [156, 157]. The detection of the signals and subsequent significance evaluations were performed with the GstLAL-based inspiral software pipeline [52–55], with the MBTA pipeline [61, 62], the PyCBC package [158–160] and the cWB packages [50, 51, 161–163]. Estimates of the noise spectra and glitch models, as well as tests of residuals, were obtained using BayesWave [164–166]. Signal parameter estimation was performed with the Bilby library [71, 72] using the Dynesty nested-sampling package [167]. SEOBNRv5PHM waveforms used in parameter estimation were generated using pySEOBNR [168]. PESummary was used to postprocess and collate parameter-estimation results [169]. Tests of GR were performed with the FTI [117], TIGER [119–121] and pSEOBNR [127–131] tests implemented in BilbyTGR [170], as well as with the QNMRF [132–135] and ringdown [136–138] pipelines. Cosmological inference was performed with the gwcosmo [171–173] and icarogw [174, 175] codes. Some of the parameter-estimation analysis were managed with the Asimov library [176]. Plots were prepared with Matplotlib [177], seaborn [178] and GWpy [179]. NumPy [180] and SciPy [181] were used in the preparation of the manuscript.

C01 strain data for GW240925 and C00 strain data for GW250207 analysed as part of this study are publicly available through Gravitational Wave Open Science Center (GWOSC) [182]; the (miscalibrated) C00 strain data for GW240925 are available in a supplemental release from Zenodo. Data releases of inference results, together with example scripts, are available from Zenodo [183].

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