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GW241011 and GW241110: Exploring Binary Formation and Fundamental Physics with Asymmetric, High-spin Black Hole Coalescences

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Abstract

We report the observation of gravitational waves from two binary black hole coalescences during the fourth observing run of the LIGO–Virgo–KAGRA detector network, GW241011 and GW241110. The sources of these two signals are characterized by rapid and precisely measured primary spins, nonnegligible spin–orbit misalignment, and unequal mass ratios between their constituent black holes. These properties are characteristic of binaries in which the more massive object was itself formed from a previous binary black hole merger and suggest that the sources of GW241011 and GW241110 may have formed in dense stellar environments in which repeated mergers can take place. As the third-loudest gravitational-wave event published to date, with a median network signal-to-noise ratio of 36.0, GW241011 furthermore yields stringent constraints on the Kerr nature of black holes, the multipolar structure of gravitational-wave generation, and the existence of ultralight bosons within the mass range 10^{-13}–10^{-12} eV.

[322] Deceased 2024 September.
[323] Deceased 2025 August.

Unified Astronomy Thesaurus concepts: Gravitational wave astronomy (675); Gravitational wave detectors (676); Astrophysical black holes (98); Compact binary stars (283); General relativity (641)

1. Introduction

It has been a decade since the inception of practical gravitational-wave astronomy In the years following the first direct observation of gravitational waves from a binary black hole coalescence in 2015 (B. P. Abbott et al. 2016a), the Advanced LIGO, Advanced Virgo, and KAGRA experiments (J. Aasi et al. 2015; F. Acernese et al. 2015; T. Akutsu et al. 2021) have operated in tandem to regularly identify an ever-increasing number of gravitational-wave signals (R. Abbott et al. 2023a, 2024). The recently released fourth Gravitational-Wave Transient Catalog (GWTC-4.0), including signals discovered through 2024 January, contains hundreds of gravitational-wave signals (A. G. Abac et al. 2025a), and the rate of discoveries continues to accelerate as further upgrades improvement broadband instrumental sensitivity to gravitational waves (F. Acernese et al. 2023; D. Ganapathy et al. 2023; W. Jia et al. 2024; E. Capote et al. 2025; S. Soni et al. 2025; A. G. Abac et al. 2025b). The growing collection of observed gravitational-wave sources includes binary neutron stars (B. P. Abbott et al. 2017a, 2020), one of which was accompanied by transient multimessenger emission seen across the electromagnetic spectrum (e.g., B. P. Abbott et al. 2017b, a; A. Goldstein et al. 2017; D. A. Coulter et al. 2017; G. Hallinan et al. 2017; R. Margutti et al. 2017), as well as likely neutron star–black hole binaries (R. Abbott et al. 2021a, 2023a; A. G. Abac et al. 2024, 2025a). And it includes a growing number of black holes whose masses, whether unexpectedly large, unexpectedly small, or unexpectedly unequal, challenge present understanding of compact binary formation and evolution (B. P. Abbott et al. 2016b; R. Abbott et al. 2020a, 2020b; A. G. Abac et al. 2024, 2025c).

Here, we report a pair of gravitational-wave events discovered in late 2024, GW241011_233834 and GW241110_124123, arising from binary black hole coalescences that each contain at least one rapidly rotating black hole. As illustrated in Figure 1, the primary (more massive) source black hole of GW241011_233834 (hereafter abbreviated GW241011) exhibits one of the most rapid and precisely measured spins observed to date, with $\chi_1 = 0.78^{+0.09}_{-0.09}$. This event provides a larger lower bound on both spin magnitude and $\boldsymbol{\chi}_1 \cdot \hat{L}_{\rm N}$, the spin projected parallel to a binary's Newtonian orbital angular momentum $\boldsymbol{L}_{\rm N}$, than any other binary previously published in GWTC-4.0 (A. G. Abac et al. 2025a). The primary spin of GW241011's source is tilted by ~30 with respect to $\hat{L}_{\rm N}$, and the gravitational-wave signal confidently exhibits relativistic spin–orbit precession. In contrast, the primary component of GW241110_124123 (hereafter GW241110) is measured to be spinning in a direction antiparallel to its orbital angular momentum vector, the most confidently antiparallel spin observed. Despite the opposite character of their spins, the sources of GW241011 and GW241110 possess similar masses. Each is inferred to contain a primary mass between approximately 15 and 20 $M_\odot$ and both favor unequal component black hole masses, with GW241011 in particular requiring an approximately 3:1 mass ratio.

The rapid primary spins, significant spin–orbit misalignment, and unequal mass ratios of GW241011 and GW241110 are in tension with expectations from isolated evolution of massive stellar binaries (V. Kalogera 2000; S. E. de Mink & I. Mandel 2016; P. Marchant et al. 2016; C. L. Rodriguez et al. 2016; K. Belczynski et al. 2016a; T. A. Callister et al. 2021; F. S. Broekgaarden et al. 2022; M. Zevin & S. S. Bavera 2022). The source properties of GW241011 and GW241110 are consistent, however, with those expected from hierarchical mergers in dense stellar clusters. Binary black hole mergers yield remnant black holes that are rapidly rotating, with spin magnitudes of $\chi \approx 0.7$ (F. Pretorius 2005; E. Berti & M. Volonteri 2008; A. Buonanno et al. 2008). Asymmetric gravitational-wave emission can cause these remnant black holes to receive large kicks, with velocities that can reach thousands of kilometers per second (M. J. Fitchett 1983; M. Favata et al. 2004; M. Campanelli et al. 2007; J. A. Gonzalez et al. 2007; J. D. Schnittman & A. Buonanno 2007). In environments with sufficiently high escape velocities, however, remnant black holes may remain gravitationally bound, capture new partners, and participate in subsequent binary mergers (H. M. Lee 1995; R. M. O'Leary et al. 2006; M. Giersz et al. 2015; F. Antonini & F. A. Rasio 2016; M. Fishbach et al. 2017; D. Gerosa & E. Berti 2017; C. L. Rodriguez et al. 2018b; F. Antonini et al. 2019; C. L. Rodriguez et al. 2019; V. Baibhav et al. 2020; G. Fragione & J. Silk 2020; V. Baibhav et al. 2021; Z. Doctor et al. 2021; D. Gerosa & M. Fishbach 2021; C. Kimball et al. 2021; P. Mahapatra et al. 2021; M. Mapelli et al. 2021; G. Fragione et al. 2022; F. Antonini et al. 2023; M. Arca Sedda et al. 2023; D. Chattopadhyay et al. 2023; P. Mahapatra et al. 2025b). Under this hypothesis, the primary black holes of GW241011 and GW241110 may themselves each be a product of a previous binary black hole merger.

The rapid spins and unequal mass ratios of GW241011 and GW241110 furthermore make them prime laboratories with which to test fundamental physics. GW241011, in particular, exhibits both significant relativistic spin precession (T. A. Apostolatos et al. 1994; L. E. Kidder 1995) and gravitational radiation from higher-order multipole moments (K. S. Thorne 1980). By virtue of these features, GW241011 offers one of the most precise confirmations to date of the Kerr nature of spinning black holes (R. P. Kerr 1963; B. Carter 1971; R. O. Hansen 1974) and the multipolar emission pattern of gravitational waves.

The rest of this Letter is organized as follows. In Section 2, we describe the low-latency identification and subsequent validation of GW241011 and GW241110. In Section 3, we discuss the measured properties of these two events. In Section 4, we describe the possible astrophysical interpretation and implications of GW241011 and GW241110, and in Section 5 we present tests of general relativity (GR) using GW241011. We conclude in Section 6. Additional details and results are provided in the Appendices.

2. Detection and Significance

2.1. GW241011

GW241011 passed through the Earth's geocenter on 2024 October 11 at 23:38:34.9 UTC. It was detected in low latency in LIGO Hanford and Virgo data (LIGO Scientific Collaboration et al. 2024a) by the GSTLAL matched-filter search

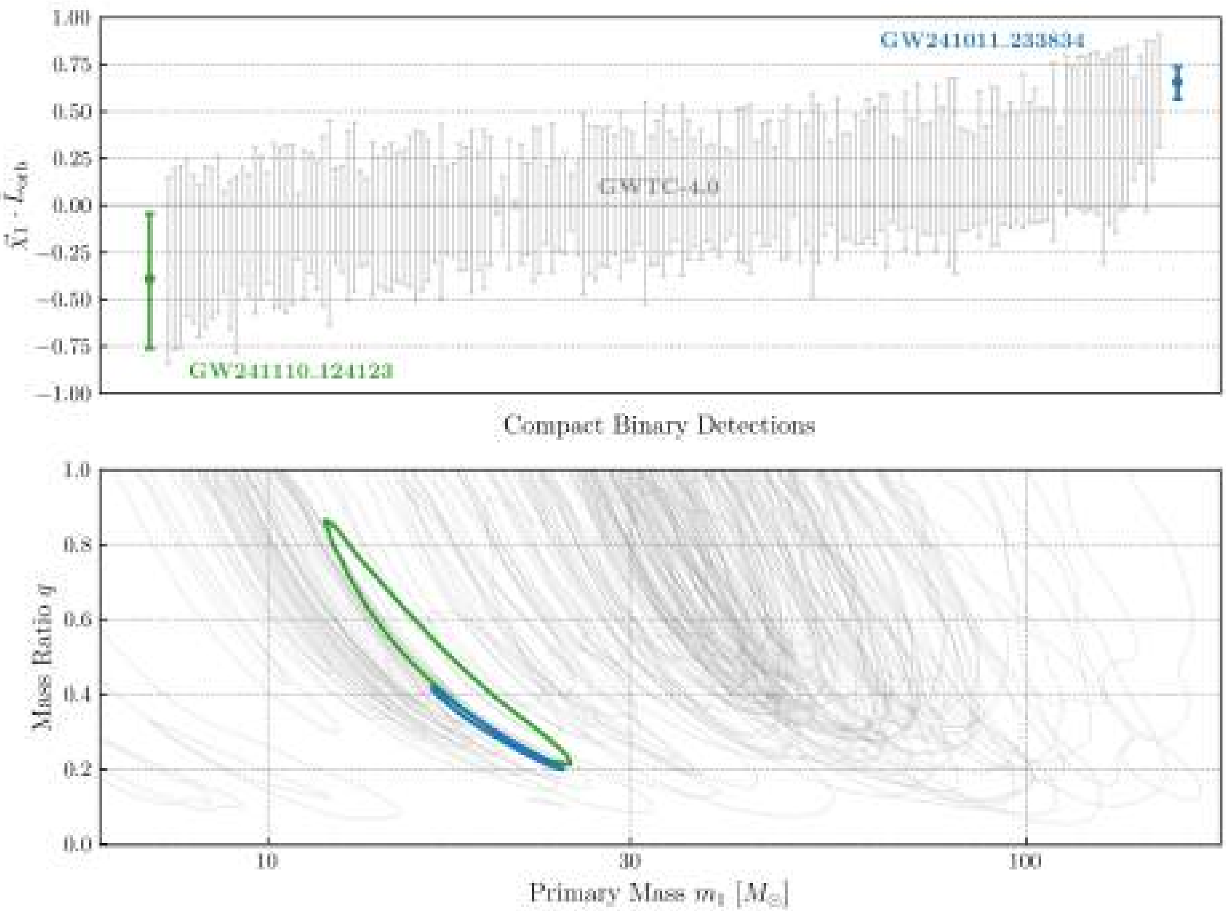

Figure 1. Top: central 90% credible bounds on the dimensionless primary spins $\boldsymbol{\chi}_1$ of GW241011 (blue) and GW241110 (green), projected parallel to the direction $\hat{L}_{\rm N}$ of each binary's Newtonian orbital angular momentum. Shown in gray for comparison are 90% credible bounds on the projected primary spins of previously published compact binary coalescences in the fourth Gravitational-Wave Transient Catalog (GWTC-4.0; A. G. Abac et al. 2025a), sorted by their median posterior values of $\chi_{1,z} \equiv \boldsymbol{\chi}_1 \cdot \hat{L}_{\rm N}$. We specifically show events with false-alarm rates (FARs) below 1 yr^{-1}, consistent with the significance threshold adopted for compact binary population studies in GWTC-3.0 and GWTC-4.0 (R. Abbott et al. 2023b; A. G. Abac et al. 2025d). The source of GW241011 contains one of the most rapidly spinning black holes observed by LIGO–Virgo–KAGRA to date, possessing the largest lower limit on both its primary spin magnitude and projected spin $\chi_{1,z}$. GW241110, conversely, yields the most confident measurement to date of a black hole spinning retrograde with respect to its orbit, with $\chi_{1,z} < 0$ at 97.7% credibility. Bottom: 90% credible posterior bounds on the primary masses and mass ratios of GW241011 and GW241110, together with all binary mergers in GWTC-4.0 with FAR < 1 yr^{-1}. Despite the opposite nature of their spins, GW241011 and GW241110 are likely to have very similar masses, each favoring a primary of 15–20 $M_\odot$ and unequal mass ratios.

pipeline (C. Messick et al. 2017; S. Sachdev et al. 2019; C. Hanna et al. 2020; K. Cannon et al. 2021; A. Ray et al. 2023; L. Tsukada et al. 2023; B. Ewing et al. 2024; S. Sakon et al. 2024; P. Joshi et al. 2025a, 2025b). The signal was measured with optimized signal-to-noise ratios (SNRs) of 35.4 and 9.1 in LIGO Hanford and Virgo, respectively, and a false-alarm rate (FAR) of $<10^{-5}$ yr. LIGO Livingston was not operating at the time of the event. Significant candidates were also identified by the MBTA (T. Adams et al. 2016; F. Aubin et al. 2021; C. Alléné et al. 2025) and PYCBC (B. Allen 2005; B. Allen et al. 2012; S. A. Usman et al. 2016; A. H. Nitz et al. 2017; A. H. Nitz 2018; G. S. Davies et al. 2020; T. Dal Canton et al. 2021) pipelines at the time of GW241011, but fell outside the mass range for which these searches report candidates in low latency seen in only one LIGO instrument (A. G. Abac et al. 2025e). LIGO Hanford and Virgo were each operating normally at the time of detection, with stable angle-averaged binary neutron star inspiral ranges of approximately 160 and 50 Mpc, respectively (L. S. Finn & D. F. Chernoff 1993; H.-Y. Chen et al. 2021). In subsequent high-latency searches, for which more comprehensive data-quality assessment and precise background estimates were available, GSTLAL, MBTA, and PYCBC each detected GW241011 with FARs below 3×10^{-5} yr^{-1}. GW241011's high network SNR makes it the third-loudest gravitational-wave event published to date, behind GW230814_230901 (A. G. Abac et al. 2025a) and GW250114_082203 (A. G. Abac et al. 2025f).

2.2. *GW241110*

GW241110 arrived at Earth on 2024 November 10, at 12:41:23.6 UTC. It was identified in low latency in LIGO Hanford, LIGO Livingston, and Virgo data (LIGO Scientific Collaboration et al. 2024b), assigned FAR $= 0.15$ yr^{-1} by the GSTLAL search pipeline and lower significances by MBTA and PYCBC. At the time of GW241110, the LIGO instruments had angle-averaged binary neutron star inspiral ranges of approximately 160 Mpc, while Virgo's inspiral range was near 50 Mpc. High-latency analyses with the PYCBC, GSTLAL, and MBTA pipelines later reidentified GW241110 with FARs of 6.3×10^{-4} yr^{-1}, 0.099 yr^{-1}, and 0.85 yr^{-1}, respectively.

Table 1
Inferred Source Properties of GW241011 and GW241110

Event	m_1 ($M_\odot$)	m_2 ($M_\odot$)	q	$\mathcal{M}$ [$M_\odot$]	D_L (Mpc)	χ_1	θ_1 (deg)	$\chi_{1,z}$	$\chi_{1,\perp}$	$\chi_{\rm eff}$	χ_p
GW241011	$19.6^{+3.6}_{-2.5}$	$5.9^{+0.8}_{-0.8}$	$0.30^{+0.09}_{-0.08}$	$9.1^{+0.1}_{-0.1}$	214^{+44}_{-48}	$0.78^{+0.09}_{-0.09}$	31^{+11}_{-14}	$0.66^{+0.08}_{-0.09}$	$0.39^{+0.19}_{-0.14}$	$0.49^{+0.06}_{-0.07}$	$0.39^{+0.19}_{-0.14}$
GW241110	$17.2^{+5.0}_{-4.4}$	$7.7^{+2.2}_{-1.5}$	$0.45^{+0.32}_{-0.17}$	$9.8^{+0.5}_{-0.4}$	736^{+270}_{-267}	$0.61^{+0.33}_{-0.40}$	133^{+47}_{-25}	$-0.39^{+0.34}_{-0.37}$	$0.40^{+0.34}_{-0.30}$	$-0.28^{+0.23}_{-0.20}$	$0.42^{+0.33}_{-0.27}$

Note. Shown are each source's primary mass (m_1), secondary mass (m_2), mass ratio (q), chirp mass ($\mathcal{M}$), and luminosity distance D_L, with mass parameters defined in the rest frame of the source binary. We additionally quote a variety of spin measurements: primary dimensionless spin magnitude (χ_1) and spin–orbit misalignment angle (θ_1), primary spin components projected parallel ($\chi_{1,z} = \chi_1 \cos\theta_1$) and perpendicular ($\chi_{1,\perp} = \chi_1 \sin\theta_1$) to the binaries' Newtonian orbital angular momenta, the effective inspiral spin $\chi_{\rm eff}$ (E. Racine 2008; L. Santamaria et al. 2010; P. Ajith et al. 2011), and the effective precessing spin χ_p (M. Hannam et al. 2014; P. Schmidt et al. 2015). We do not obtain informative constraints on the secondary spins of each source; see Appendix A for secondary spin measurements. We follow parameter conventions as defined in Table 3 of A. G. Abac et al. (2025b). For all but one parameter, we quote posterior medians and central 90% credible uncertainties. For θ_1 alone, uncertainties instead correspond to values containing the 90% credible highest posterior density interval for $\cos\theta_1$. This is done to minimize the influence of the uniform-in-$\cos\theta$ priors, which exclude $\theta_1 = 0$. Spin parameters are quoted at infinite binary separation.

For several hours around the arrival time of GW241110, microseismic ground motion near LIGO Livingston was elevated. Elevated microseism is known to increase the rate of scattered-light glitches in detector strain data, particularly below 30 Hz (S. Soni et al. 2020, 2024). Between 0.3 and 2 s after the coalescence time, three noise transients are observed in the data, all below 30 Hz. Two are low-SNR transients, while the third is a high-SNR scattered-light glitch occurring below 15 Hz. Although these transients are not expected to affect the observation and analysis of GW241110 (R. Macas et al. 2022; S. Hourihane & K. Chatziioannou 2025), all further studies of GW241110's properties (see Section 3) use LIGO Livingston data only above 30 Hz.

3. Source Properties

Bayesian parameter estimation is performed on GW241011 and GW241110 following the methodology described in A. G. Abac et al. (2025e). Noise power spectral densities are obtained with the BAYESWAVE algorithm (N. J. Cornish & T. B. Littenberg 2015; T. B. Littenberg & N. J. Cornish 2015; T. B. Littenberg et al. 2016; N. J. Cornish et al. 2021; T. Gupta & N. J. Cornish 2024), and astrophysical parameter inference is performed using the RIFT (C. Pankow et al. 2015; J. Lange et al. 2017; D. Wysocki et al. 2019) and BILBY (G. Ashton et al. 2019; I. M. Romero-Shaw et al. 2020b) code packages, the latter of which invokes the DYNESTY (J. S. Speagle 2020) nested sampler. Analysis of GW241011 includes 32 s of data between 20 and 1792 Hz from LIGO Hanford and Virgo. Analysis of GW241110 incorporates 16 s of data from all three LIGO and Virgo instruments; data between 20 and 1792 Hz are used from LIGO Hanford and Virgo, whereas LIGO Livingston data are used only at frequencies above 30 Hz due to the presence of nonstationary low-frequency noise. We adopt priors that are uniform in detector-frame component masses, uniform and isotropic in component spin magnitudes and orientations, and uniform in comoving volume and source-frame time (A. G. Abac et al. 2025e). Black hole spin orientations evolve over the course of an inspiral due to relativistic spin–orbit precession; we present spin measurements corresponding to the asymptotic values in the limit of infinite binary separation (N. K. Johnson-McDaniel et al. 2022; M. Mould & D. Gerosa 2022; D. Gerosa et al. 2023).

The inferred source properties of GW241011 and GW241110 are summarized in Table 1. Posteriors on the primary black hole's spin vectors of each binary are shown in Figure 2, while posteriors on a subset of other binary parameters appear in Figure 3. These results comprise the union of posterior samples obtained using three different waveform models, SEOBNRV5PHM (A. Ramos-Buades et al. 2023a), IMRPHENOMXPHM-SPINTAYLOR (M. Colleoni et al. 2025), and IMRPHENOMXO4A (J. E. Thompson et al. 2024), that each include the effects of spin–orbit precession and higher-order spherical harmonic modes. Further details about parameter inference, including source properties inferred with each individual waveform model, are presented in Appendix A.

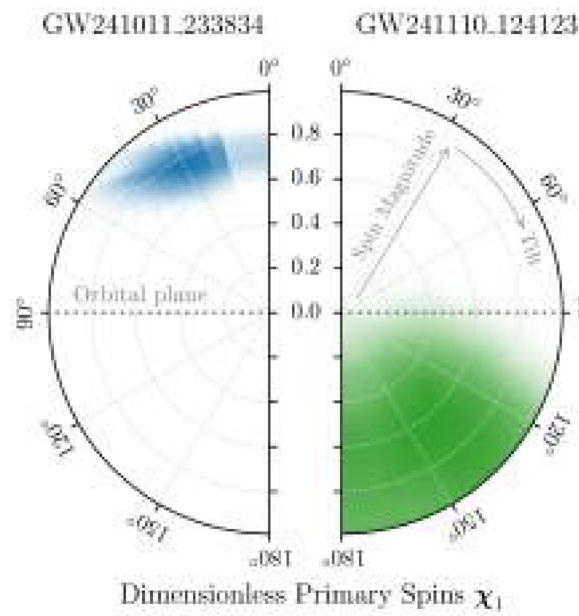

Figure 2. Posterior on the primary spin vector of GW241011 (left) and GW241110 (right). Within each subplot, radial coordinates span the range 0–1 and correspond to dimensionless spin magnitudes. The polar angles, spanning 0 to 180 , correspond to spin–orbit misalignment angles. Color saturation indicates posterior probability as a function of spin magnitude and orientation. Pixels are spaced linearly in spin magnitude and cosine-tilt angle such that they each contain equal prior probability; a completely uninformative spin measurement would therefore yield a uniformly colored disk. GW241011 has a precisely measured spin magnitude of $\chi_1 = 0.78^{+0.09}_{-0.09}$ that is misaligned by 31^{+11}_{-14} deg with respect to its orbital angular momentum. The primary spin of GW241110, in contrast, is constrained to be misaligned by more than 110 from its orbital angular momentum.

3.1. Properties of GW241011

The source of GW241011 is inferred to possess a $19.6^{+3.6}_{-2.5}\,M_\odot$ primary mass and a confidently unequal mass ratio, $q = 0.30^{+0.09}_{-0.08}$. It has a large and precisely measured

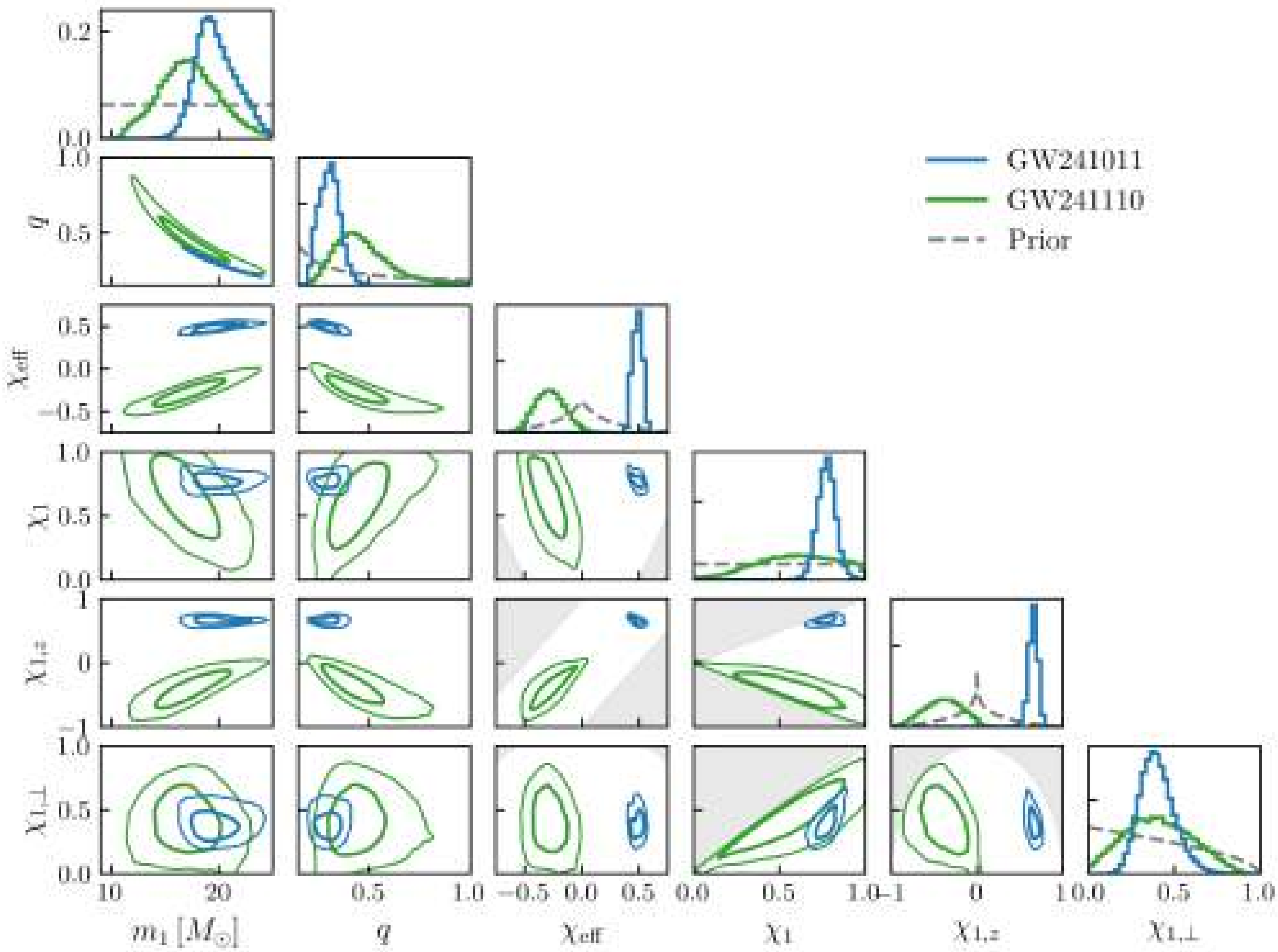

Figure 3. Posterior probabilities on selected properties of GW241011 (blue) and GW241110 (green): their primary masses m_1, mass ratios q, effective inspiral spins $\chi_{\rm eff}$, primary spin magnitudes χ_1, and components of their primary spins projected parallel ($\chi_{1,z}$) and perpendicular ($\chi_{1,\perp}$) to each binary's Newtonian orbital angular momentum. Panels along the diagonal show marginalized posteriors on each parameter; the dashed histograms correspond to the prior probability distributions adopted during parameter estimation. Off-diagonal panels illustrate joint two-dimensional posteriors on each pair of parameters; thick and thin contours denote central 50% and 90% credible bounds. Shaded gray regions indicate to parts of parameter space that the constraint that spin magnitudes be less than or equal to 1. Despite their extreme and opposite spins, GW241011 and GW241110 have consistent component mass measurements, each favoring a 15–20 $M_\odot$ primary and an unequal mass ratio.

primary spin magnitude, $\chi_1 = 0.78^{+0.09}_{-0.09}$, and its primary spin is inferred to be misaligned with respect to its Newtonian orbital angular momentum by $\theta_1 = 31^{+11}_{-14}$ deg. The spin of GW241011's secondary black hole is unconstrained, as expected for an unequal-mass systems in which the primary's spin angular momentum dominates. The inferred geometry of the spin vector of GW241011's primary black hole is depicted in the left-hand side of Figure 2. Within this plot, the radial distance depicts the magnitude of GW241011's primary spin vector, while the polar coordinate denotes its spin–orbit misalignment angle; color saturation indicates posterior probability. GW241011 is, furthermore, probably the closest binary black hole merger observed to date, with a luminosity distance of $D_{\rm L} < 248$ Mpc at 90% credibility.

The primary of GW241011 is among the most rapidly rotating black holes observed to date. At 95% credibility, GW241011 has the largest lower limit obtained thus far on the spin of any merging black hole, with $\chi_1 > 0.69$. Figure 4 compares this primary spin measurement to two signals with similar spin magnitude limits, GW190517 (R. Abbott et al. 2023a) and the recently announced GW231123 (A. G. Abac et al. 2025c), whose sources have $\chi_1 > 0.52$ and $\chi_1 > 0.63$ at 95% credibility, respectively. GW190403_051519 favors similarly rapid spins, but this candidate does not meet the significance threshold adopted for population analyses. Additionally, both the primary aligned spin $\chi_{1,z}$ and the effective inspiral spin of GW241011 (E. Racine 2008; L. Santamaria et al. 2010; P. Ajith et al. 2011), defined as

$$\chi_{\rm eff} = \frac{(m_1 \boldsymbol{\chi}_1 + m_2 \boldsymbol{\chi}_2) \cdot \hat{L}_{\rm N}}{m_1 + m_2}, \tag{1}$$

are bounded higher than any other gravitational-wave source. Among black holes that are confidently rotating, the primary spin magnitude of GW241011 is also the most precisely measured, with a 90% credible region that is half as wide as the next-most-precise measurement, made using GW190412 (R. Abbott et al. 2020c). The binary neutron star source of GW170817 (B. P. Abbott et al. 2017c), the lower mass gap binary source of GW190814 (R. Abbott et al.

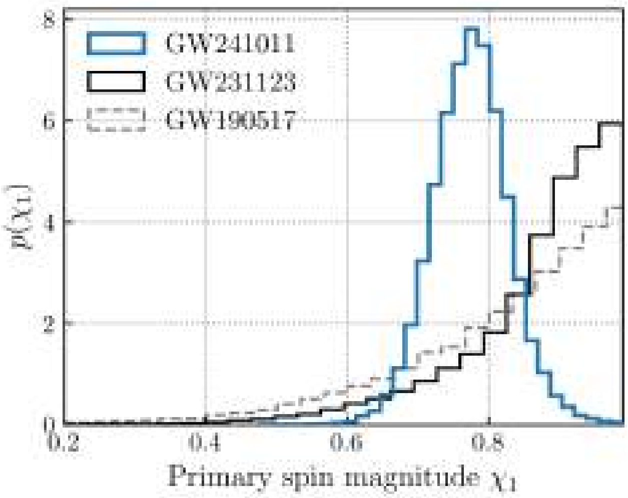

Figure 4. Posterior on the primary spin magnitude of GW241011 (blue). The spin of GW241011's primary black hole has the largest lower bound than that of all other merging compact objects observed to date. We obtain $\chi_1 > 0.69$ at 95% credibility. For comparison, also shown are the primary spin measurements from GW231123 (black; A. G. Abac et al. 2025c) and GW190517 (dashed gray; R. Abbott et al. 2023a), which provide the two next-largest lower limits of $\chi_1 > 0.63$ and $\chi_1 > 0.52$, respectively.

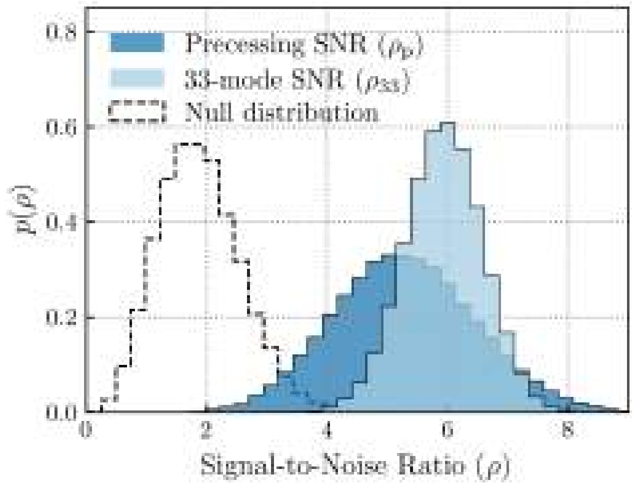

Figure 5. Posterior distribution on GW241011's precession SNR ratio and its SNR in $(\ell, m) = (3, \quad 3)$ spherical harmonic modes. The precession SNR quantifies the observational strength of spin–orbit precession, while $(\ell, m) = (3, \quad 3)$ mode radiation arises from source multipoles beyond the leading-order mass quadrupole. The unequal mass ratio and large, misaligned primary spin of GW241011 together yield $\rho_p = 5.3^{+2.1}_{-1.9}$ and $\rho_{33} = 5.9^{+1.0}_{-1.1}$. For comparison, the dashed histogram illustrates the expected null distribution (a χ-distribution with four degrees of freedom, two per detector active during GW241011) of ρ_p and ρ_{33} in the absence of spin–orbit precession or higher-order radiation modes (R. Prix 2007; I. W. Harry & S. Fairhurst 2011). This null distribution is conservative; in some cases the null distribution may take alternative forms (such as a χ-distribution with fewer degrees of freedom) concentrated toward smaller SNRs (S. Fairhurst et al. 2020b; C. Hoy et al. 2022, 2025).

2020b), and the low-significance neutron star–black hole candidate GW191219_163120 each have more precisely measured spins, but these spins are consistent with zero. GW241011 is therefore the gravitational-wave event that, taken individually, provides the strongest evidence to date that at least some component black holes in merging binaries spin rapidly, with dimensionless spins with magnitudes ∼0.7 or greater.

GW241011 additionally exhibits strong signatures of orbital plane precession and radiation in higher spherical harmonic modes. Orbital plane precession occurs due to relativistic spin–orbit coupling, an effect that is maximized by the large and misaligned primary spin of GW241011. The degree of spin–orbit precession may be parameterized using the effective precessing spin (M. Hannam et al. 2014; P. Schmidt et al. 2015),

$$\chi_p = \mathrm{Max}\left[\chi_1 \sin\theta_1, \frac{3+4q}{4+3q} q\chi_2 \sin\theta_2\right], \quad (2)$$

related to the in-plane spin components $\chi_{i,\perp} = \chi_i \sin\theta_i$. The source of GW241011 has confidently nonzero effective precessing spin, with $\chi_p = 0.39^{+0.19}_{-0.14}$, and we obtain a log-Bayes factor of $\log_{10}\mathcal{B} = 5.4$ in favor of a precessing source over a model in which spins are restricted to be coaligned with their orbit. As Bayes factors may, in general, be sensitive to one's choice of prior, we additionally quantify evidence for precession via the precession SNR ρ_p (S. Fairhurst et al. 2020a, 2020b), the posterior distribution of which is shown in Figure 5. We find $\rho_p = 5.3^{+2.1}_{-1.9}$. In the absence of precession, ρ_p is expected to follow the null distribution indicated in Figure 5. Random draws from GW241011's ρ_p posterior exceed random draws from this null distribution 99.5% of the time.

The significant mass asymmetry of GW241011 also yields significant radiation in higher-order spherical harmonic modes. Whereas gravitational-wave radiation is typically dominated by $(\ell, m) = (2, \quad 2)$ spherical harmonics, subdominant modes, such as $(\ell, m) = (2, \quad 1)$ or $(3, \quad 3)$, become increasingly important for systems with considerable mass asymmetry (K. S. Thorne 1980; E. Berti et al. 2007; L. Blanchet 2014; C. Mills & S. Fairhurst 2021). GW241011 exhibits significant radiation in the $(\ell, m) = (3, \quad 3)$ spherical harmonics, here assuming symmetric contributions from $m = 3$ to -3 modes thus neglecting small asymmetries arising from source precession. We find a log-Bayes factor of $\log_{10}\mathcal{B} = 5.2$ in favor of a signal model including higher-order spherical harmonics, compared to a model including only contributions from $(\ell, m) = (2, \quad 2)$ modes. A posterior distribution on the SNR ρ_{33} measured in higher-order modes is shown in Figure 5, with $\rho_{33} = 5.9^{+1.0}_{-1.1}$. Random draws from the posterior on ρ_{33} exceed draws from the null distribution over 99.9% of the time. No detection is made of other spherical harmonic modes.

3.2. *Properties of GW241110*

GW241110 is inferred to have component masses consistent with those of GW241011, albeit with larger uncertainties due to its lower SNR: the primary mass and mass ratio of GW241110 are measured to be $m_1 = 17.2^{+5.0}_{-4.4}\,M_\odot$ and $q = 0.45^{+0.32}_{-0.17}$ (see Figure 3). Although GW241110 favors unequal component masses, mass ratios of $q \approx 1$ cannot be fully excluded.

In contrast to GW241011, though, GW241110 is measured to have a primary spin that is likely significantly misaligned with respect to its orbital angular momentum. The angle between the binary's orbital angular momentum and the spin vector of its more massive black hole is $\theta_1 = 133^{+47}_{-25}$ deg, with $\theta_1 > 108$ at 90% credibility and $\theta_1 > 90$ at 97.7% credibility. The spin of GW241110's secondary black hole is unconstrained. GW241110 favors negative effective spin, with $\chi_{\rm eff} < 0$ at 98.1% credibility. As illustrated in Figure 3, GW241110 inferred mass ratio is strongly anticorrelated with its inferred $\chi_{\rm eff}$ and $\chi_{1,z}$. This effect arises from a degeneracy in the post-Newtonian expansion of a compact binary's phase evolution (C. Cutler & E. E. Flanagan 1994; E. Poisson & C. M. Will 1995; E. Baird et al. 2013; M. Pürrer et al. 2013; K. K. Y. Ng et al. 2018). Thus, if one requires GW241110 to have positive $\chi_{\rm eff}$ (1.9% probability), it must also be the case that its mass ratio is $q \lesssim 0.3$. If GW241110's mass ratio is above $q = 0.3$, then the event must have negative $\chi_{\rm eff}$ at 99.9% credibility.

GW241110 offers the most significant, although not necessarily conclusive, direct evidence to date that at least some merging black holes have spins antialigned with their orbital angular momentum. A growing number of binary black holes have been observed with large spin–orbit misalignment angles (with, e.g., $\theta \gtrsim 50$ at high credibility). Several detections, including, e.g., GW231230_170116, GW230723_101834, and GW230609_064958, furthermore favor misalignment angles greater than 90 , but only at ∼80% credibilities. (A. G. Abac et al. 2025a). Analysis of the binary black hole GW191109_010717 (GW191109; R. Abbott et al. 2023a) with a numerical-relativity surrogate waveform model, meanwhile, found a negative effective inspiral spin at >99% credibility (T. Islam et al. 2025). The robustness of GW191109's spin measurement is uncertain, however, due to significant contamination by noise transients (R. Abbott et al. 2023a); reanalyses that simultaneously seek to model and subtract these glitches are inconclusive (R. Udall et al. 2025). The spin measurement with GW241110, in contrast, is not believed to be subject to data-quality concerns. Under uniform and isotropic spin priors and standard waveform models, there does remain a 1.9% probability that the source possesses zero or positive effective inspiral spin. The confidence in GW241110's spin antialignment is further bolstered when adopting an astrophysically informed prior (see Appendix C.2), but we cannot completely exclude the possibility that the source has zero or positive primary spin.

3.3. Relationship with the Binary Black Hole Population

Although GW241011 and GW241110 are remarkable for their large and well-measured black hole spins, we do not conclude that they are outliers with respect to the known binary black hole population; see Appendix C for details. These events do, however, individually reinforce conclusions that have been previously drawn only on statistical grounds. Past studies of the binary black hole spin distribution have concluded (i) that merging black holes are usually, but not exclusively, slowly rotating, (ii) that black hole spins are unlikely to be isotropic, statistically favoring spin–orbit alignment and positive effective spins, but that (iii) black hole spins nevertheless exhibit a wide range of spin–orbit misalignment angles, with some component black holes misaligned by nearly or greater than 90 with respect to their orbit (W. M. Farr et al. 2017; B. Farr et al. 2018; B. P. Abbott et al. 2019; J. Roulet & M. Zaldarriaga 2019; S. Miller et al. 2020; R. Abbott et al. 2020c; T. A. Callister et al. 2022; H. Tong et al. 2022; S. Vitale et al. 2022; R. Abbott et al. 2023b; T. A. Callister & W. M. Farr 2024; A. G. Abac et al. 2025d; S. Banagiri et al. 2025). GW241110 offers the strongest confirmation to date of this latter conclusion. The tension between population-level conclusions and the paucity of individual binary black holes favoring antialigned spins can be understood as a confluence of three factors: the large uncertainties typically inherent in spin measurements (M. V. van der Sluys et al. 2008; S. Vitale et al. 2014; A. Ghosh et al. 2016; S. Vitale et al. 2017; K. Chatziioannou et al. 2018; G. Pratten et al. 2020; S. Biscoveanu et al. 2021), a degeneracy between mass ratio and spins that asymmetrically biases $\chi_{\rm eff}$ measurements toward larger positive values (C. Cutler & E. E. Flanagan 1994; E. Poisson & C. M. Will 1995; E. Baird et al. 2013; M. Pürrer et al. 2013; K. K. Y. Ng et al. 2018), and selection effects that cause events with larger, positive $\chi_{\rm eff}$ to be more readily detected and more precisely characterized (E. E. Flanagan & S. A. Hughes 1998; M. Campanelli et al. 2006; K. K. Y. Ng et al. 2018). These effects together have been shown to resolve the apparent inconsistency between individual binary black hole properties and statistical population-level conclusions (E. Payne et al. 2024; C. Hoy et al. 2025).

While we do not conclude that GW241011 and GW241110 are outliers, it is possible that they are members of an emerging subpopulation of binary black holes, characterized by low primary masses, unequal mass ratios, and a wide range of spin–orbit misalignment angles. It remains unknown, however, whether such a subpopulation exists and can be formally characterized. This question will be further explored in future work involving additional observations from LIGO–Virgo–KAGRA's fourth observing run.

4. Astrophysical Interpretation and Implications

4.1. GW241011 and GW241110 through Isolated Binary Evolution

The primary spins of GW241011 and GW241110 are difficult to explain via isolated binary evolution. Efficient angular momentum transport from stellar interiors is predicted to yield black holes that are born slowly rotating (H. C. Spruit 1999, 2002; Y. Qin et al. 2018; J. Fuller & L. Ma 2019), and torques exerted via mass transfer or tides are expected to coalign residual spin with a binary's orbital angular momentum (D. Gerosa et al. 2018; Y. Qin et al. 2018; M. Zaldarriaga et al. 2018; S. S. Bavera et al. 2020, 2021; L. Ma & J. Fuller 2023). The natal spins of black holes do remain highly uncertain, however, with the prediction of small spins due to the Spruit–Tayler dynamo being only one of many possibilities (M. C. Miller & J. M. Miller 2014). Models predicting larger natal spins may better accommodate the observed source properties of GW241011 and GW241110.

Alternative scenarios can also potentially explain the spin properties of GW241011 and GW241110 in the context of isolated binary evolution. Stochastic spin-up of stellar cores immediately preceding core collapse could impart large and misaligned birth spins to black holes (J. Fuller et al. 2014, 2015; A. Gilkis & N. Soker 2016; L. Ma & J. Fuller 2019; L. O. McNeill & B. Müller 2020; A. Antoni & E. Quataert 2022, 2023; V. Baibhav & V. Kalogera 2024). Although black hole progenitors are generally predicted to experience small natal kicks due to near-complete fallback accretion (e.g., C. L. Fryer et al. 2012; M. Zevin et al. 2017; I. Mandel & B. Müller 2020; A. Vigna-Gómez et al. 2024), stronger-than-expected natal kicks and/or asymmetric fallback might misalign spins either by tilting a binary's orbital plane or by torquing of a black hole's spin vector (A. Wongwathanarat et al. 2013; C. Chan et al. 2020; H.-T. Janka et al. 2022; T. M. Tauris 2022; A. Burrows et al. 2025); spin–orbit misalignment among some black hole X-ray binaries may provide evidence for such effects (A. A. Zdziarski et al. 2018; G. Salvesen & S. Pokawanvit 2020; J. Poutanen et al. 2022; A. A. Zdziarski et al. 2023). Finally, the von Zeipel–Lidov–Kozai mechanism (H. von Zeipel 1910; Y. Kozai 1962; M. L. Lidov 1962) due to a tertiary companion can, when coupled to relativistic spin–orbit precession and gravitational-wave emission, tilt the orbital plane as well as component spins to yield a large spin–orbit misalignment (B. Liu & D. Lai 2017; F. Antonini et al. 2018; B. Liu & D. Lai 2018; B. Liu et al. 2019; G. Fragione & B. Kocsis 2020; H. Yu et al. 2020; J. Stegmann & J. Klencki 2025); however, this mechanism does not explain large spin *magnitudes*.

4.2. GW241011 and GW241110 as Hierarchical Mergers

A more natural interpretation for GW241011 and GW241110 is that they involve the mergers of second-generation black holes in dense stellar environments, such as globular, nuclear, and young massive star clusters (S. Portegies Zwart et al. 2010; N. Neumayer et al. 2020). Compact binaries merging within clusters yield remnants that may be retained by the cluster, continue to interact dynamically, and themselves participate in subsequent mergers driven by gravitational-wave emission (e.g., H. M. Lee 2001; R. M. O'Leary et al. 2006; M. C. Miller & V. M. Lauburg 2009; M. Giersz et al. 2015; F. Antonini & F. A. Rasio 2016; C. L. Rodriguez et al. 2019; Z. Doctor et al. 2021; G. Fragione et al. 2022; P. Mahapatra et al. 2021; F. P. Rizzuto et al. 2022; M. Arca Sedda et al. 2023; D. Atallah et al. 2023; P. Mahapatra et al. 2025b). Such second-generation black holes are systematically more massive than their first-generation ancestors and are expected to be rapidly rotating; the spin distribution of remnant black holes is generically and robustly concentrated about $\chi \approx 0.7$ (F. Pretorius 2005; E. Berti & M. Volonteri 2008; A. Buonanno et al. 2008). A remnant black hole's spin arises from the total remaining angular momentum of its ancestral binary at merger, which, for approximately equal-mass mergers, is dominated by the orbital angular momentum. The spin angular momenta of the ancestral black holes do affect the remnant's spin, but their contribution is, in part, countered by the relationship between spin and inspiral duration. Binaries with larger aligned spins undergo longer inspirals and radiate away more orbital angular momentum, while binaries with small or antialigned spins merge more promptly and thus retain more orbital angular momentum (M. Campanelli et al. 2006).

Observationally, mergers involving second-generation objects (often called hierarchical mergers) would distinguish themselves via their large spin magnitudes, statistically isotropic spin orientations, and mass ratios that are typically less than unity. The spin magnitudes, spin–orbit misalignments, and unequal mass ratios of GW241011 and GW241110 therefore make these signals prime candidates for arising from a hierarchical origin. Figure 6, for example, illustrates predictions for the possible primary spin magnitudes (upper row) and mass ratios (lower row) among binary black hole mergers in dense star clusters. Dashed contours indicate predicted properties of mergers in which both components are first-generation black holes, while solid contours correspond to systems in which at least one component is the product of a previous merger. We show data from two models, the Cluster Monte Carlo catalog (CMC; K. Kremer et al. 2020; C. L. Rodriguez et al. 2022) and the clusterBHBdynamics model (cBHBd; F. Antonini & M. Gieles 2020a; F. Antonini et al. 2023); further details regarding both models are provided in Appendix D. The spin magnitude and mass ratio of GW241011, in particular, are inconsistent with the properties predicted of first-generation mergers, but lie within ranges predicted by both models for higher-generation hierarchical mergers. Figure 6 does not, however, convey relative numbers of first-generation and higher-generation mergers; both models predict approximately one higher-generation merger per five first-generation mergers.

Hierarchical black hole mergers are often associated with massive black holes. At subsolar metallicities, black holes masses are thought to be limited by (pulsational)-pair-instability processes (Z. Barkat et al. 1967; S. E. Woosley et al. 2007), preventing the formation of first-generation black holes with masses between $\sim$50 and $\sim$120 $M_\odot$ (e.g., M. Spera & M. Mapelli 2017; S. E. Woosley & A. Heger 2021; D. D. Hendriks et al. 2023). Hierarchical mergers may yield second-generation remnants with masses situated in this range and are therefore a possible evolutionary origin for massive systems like the sources of GW190521 (R. Abbott et al. 2020a) and GW231123_135430 (A. G. Abac et al. 2025c). The sources of GW241011 and GW241110 are, in contrast, relatively light. These masses are not inconsistent with a hierarchical origin, however. The three columns of Figure 6 correspond to predictions for clusters of differing stellar metallicities. At high metallicities, stellar winds increasingly strip massive stars of their envelopes, preventing the formation of massive carbon–oxygen cores and reducing the final masses of black holes (e.g., K. Belczynski et al. 2001; C. L. Fryer et al. 2012; K. Belczynski et al. 2016b; M. Spera et al. 2016). Therefore, although hierarchical mergers in low-metallicity environments predominantly involve high primary masses, clusters with stellar metallicities $Z \approx 0.1\,Z_\odot$ and above are predicted to readily yield hierarchical mergers with $\sim$20 $M_\odot$ primaries, consistent with the sources of GW241011 and GW241110 (C. S. Ye et al. 2025).

4.3. The Ancestors of GW241011 and GW241110

If the primaries of GW241011 and GW241110 are second-generation remnants of previous mergers, we can indirectly constrain the masses, spins, and recoil kicks associated with their first-generation ancestors (e.g., V. Baibhav et al. 2021; O. Barrera & I. Bartos 2022; J. Paynter & E. Thrane 2023; C. Araújo-Álvarez et al. 2024; P. Mahapatra et al. 2024; P. Mahapatra et al. 2025a). We explore this question using two complementary methods. In the first method (the *Forward* approach), we adopt astrophysically informed priors on the ancestral masses and spins of GW241011 and GW241110's hypothesized first-generation ancestors. Priors are chosen to follow closely the results from stellar cluster simulations presented in Figure 6, strongly preferring equal masses and first-generation black hole spins near zero; these priors are described in more detail in Appendix E. We then proceed via a hierarchical Bayesian approach, using observed strain data to obtain posteriors on ancestral properties, marginalized over the source properties of GW241011 and GW241110 (P. Mahapatra et al. 2024). In the second method (the *Backward* approach), we proceed more agnostically. Beginning with the source masses and spins of GW241011 and GW241110's primaries from

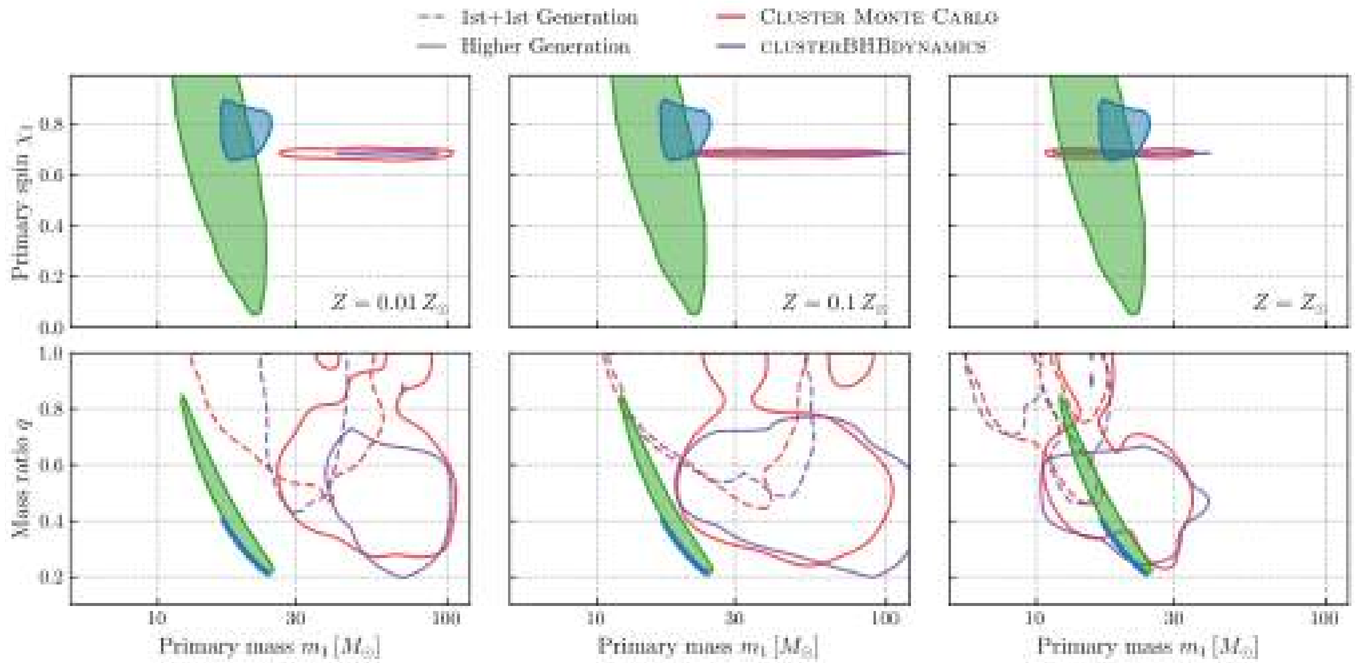

Figure 6. 90% credible bounds on the primary masses, mass ratios, spins of GW241011 (blue) and GW241110 (green), compared to predicted properties of merging black holes in dense star clusters from the Cluster Monte Carlo catalog (K. Kremer et al. 2020; C. L. Rodriguez et al. 2022), and clusterBHBdynamics models (F. Antonini et al. 2023). Dashed contours correspond to merging first-generation black holes, while solid contours correspond to higher-generation binaries containing remnants from previous mergers. Both models assume black holes to be born nonrotating. The three columns correspond to star cluster simulations with stellar populations at three different metallicities: $Z = 0.01\ Z_\odot$, $0.1\ Z_\odot$, and $Z_\odot$. Under the modeling assumptions, the masses of GW241011 and GW241110 appear inconsistent with those predicted in low-metallicity stellar clusters with $Z = 0.01\ Z_\odot$. Their masses and spins may be consistent, though, with those predicted among hierarchical binary black hole mergers that are formed in clusters of moderate or near-solar metallicities.

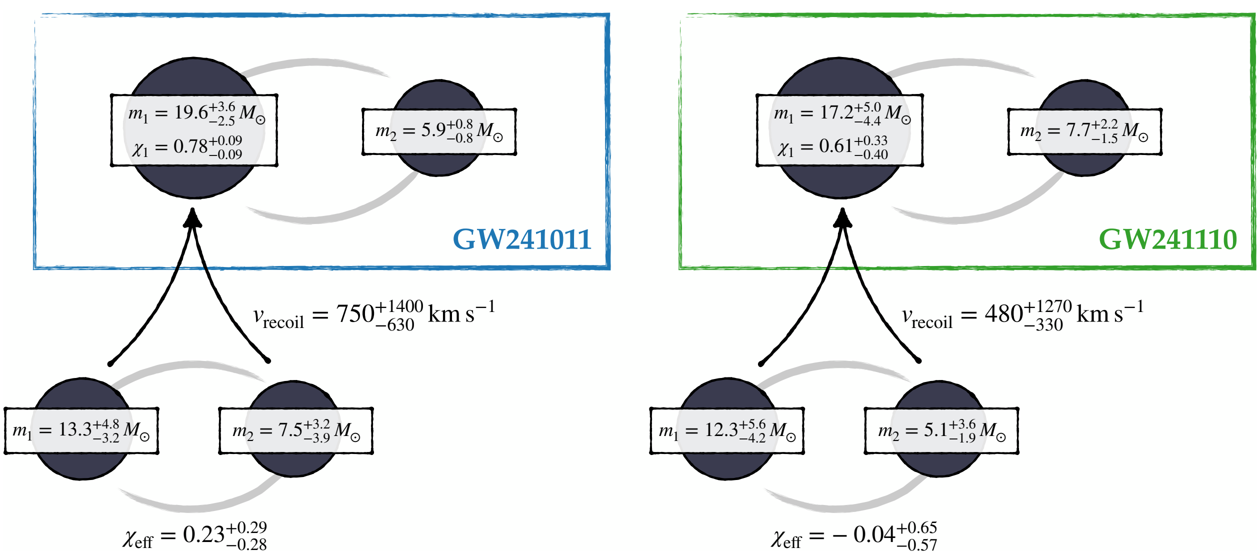

Figure 7. Inferred properties of the first-generation ancestors to the more massive black holes in GW241011 and GW241110, under the hypothesis that these black holes were formed hierarchically from a previous merger. Shown are median and 90% credible bounds inferred on ancestral component masses and effective inspiral spins, as well as the recoil kicks imparted to each remnant black hole due to asymmetric gravitational-wave-emission. We compute ancestral properties in two manners: one (the *Backward* approach) that agnostically retains the same priors and posteriors on GW241011 and GW241110's source properties as presented in Section 3, and one (the *Forward* approach) that adopts an astrophysically informed prior on possible ancestral properties. This figure includes results from the agnostic *Backward* approach; constraints obtained under the astrophysically informed *Forward* approach are described in the text.

Section 3, for each posterior sample we identify an ancestral binary whose remnant mass and spin are consistent, within a small tolerance, with this posterior sample. This approach allows us to construct posteriors on required ancestral properties while preserving the astrophysically agnostic priors and posteriors on the source properties of GW241011 and GW241110 themselves (C. Araújo-Álvarez et al. 2024). In both cases, numerical-relativity simulations are used to map between ancestral binaries and remnant properties (V. Varma et al. 2019).

Figure 7 illustrates the required properties of GW241011 and GW241110's ancestors estimated in the more agnostic *Backward* approach. We infer a first-generation ancestor of

GW241011 to have had masses $13.3^{+4.8}_{-3.2}\,M_\odot$ and $7.5^{+3.2}_{-3.9}\,M_\odot$. A first-generation ancestor to GW241110 likely possessed similar masses: $12.3^{+5.6}_{-4.2}\,M_\odot$ and $5.1^{+3.6}_{-1.9}\,M_\odot$. The effective inspiral spin of GW241011's ancestor is constrained to $\chi_{\rm eff} = 0.23^{+0.29}_{-0.28}$; larger or smaller values would over- or underpredict, respectively, the observed primary spin χ_1. The primary spin of GW241110 is measured less precisely and so allows for a broader range of ancestral effective spins: $\chi_{\rm eff} = -0.04^{+0.65}_{-0.57}$. For both binaries, the remnant recoil kicks are inferred to lie between approximately 100 and 2000 km s^{-1}. Constraints on recoil kicks are, however, almost entirely prior dominated, and it is therefore unclear if they yield meaningful constraints on environmental escape velocities required for successful remnant retention.

In the *Forward* approach, the astrophysically informed yields posteriors favoring more equal-mass ancestors. The ancestor of GW241011 is inferred to have component masses $11.0^{+1.9}_{-1.6}\,M_\odot$ and $9.6^{+1.7}_{-1.8}\,M_\odot$, while GW241110's ancestor is inferred to have masses $9.6^{+3.1}_{-2.0}\,M_\odot$ and $8.0^{+2.1}_{-2.3}\,M_\odot$. The global maximum of the binary black hole mass function is situated at approximately $10\,M_\odot$ (V. Tiwari & S. Fairhurst 2021; A. M. Farah et al. 2023; R. Abbott et al. 2023b; A. G. Abac et al. 2025d); the ancestral black holes of both GW241011 and GW241110 are inferred to lie near this peak. Because the astrophysical prior adopted in the *Forward* approach requires ancestral spins to be near zero, inferred recoil kicks are systematically lower, ranging between approximately 10 and 300 km s^{-1}. As in the *Backward* approach above, this range is a consequence of our prior.

A more detailed presentation of both sets of results and additional methodological detail is provided in Appendix E.

4.4. No Evidence for Eccentricity

Binary black hole coalescences arising dynamically in dense stellar environments may bear unique signatures of orbital eccentricity in their gravitational-wave emission. Gravitational-wave emission rapidly circularizes initially eccentric orbits (P. C. Peters 1964), and binaries evolving in isolation are expected to be nearly perfectly quasi-circular by the time their gravitational-wave emission enters the sensitivity band of ground-based detectors. Following many-body encounters in dense clusters, however, binaries can be placed on nearly hyperbolic trajectories and merge promptly. Several percent of these binaries may retain observable eccentricity in the frequency band of ground-based detectors. In old, metal-poor globular clusters, 5%–10% of binary black hole mergers in the local Universe are predicted to have eccentricities measurable by the LIGO, Virgo, and KAGRA experiments (L. Wen 2003; K. Gultekin et al. 2006; R. M. O'Leary et al. 2006; F. Antonini & H. B. Perets 2012; F. Antonini et al. 2014; J. Samsing & E. Ramirez-Ruiz 2017; J. Samsing et al. 2018; J. Samsing 2018; C. L. Rodriguez et al. 2018a; M. Zevin et al. 2019), although this may decrease by a factor of a couple when assuming higher initial cluster densities (F. Antonini & M. Gieles 2020b). The nonsecular evolution of isolated triple systems may yield $\gtrsim$10% of systems with measurable eccentricities and potentially have a higher merger rate of eccentric sources in the local Universe (A. Dorozsmai et al. 2025). The total merger rate in active galactic nuclei is uncertain with predictions that span multiple orders of magnitude (M. Gröbner et al. 2020), with predictions for measurably eccentric fraction ranging from $\gtrsim$10% (H. Tagawa et al. 2021) up to $\sim$70% (J. Samsing et al. 2022). There exists growing evidence that at least some observed compact binary mergers may possess residual eccentricity (I. M. Romero-Shaw et al. 2020a; V. Gayathri et al. 2022; I. M. Romero-Shaw et al. 2022; R. Gamba et al. 2023; N. Gupte et al. 2024; H. L. Iglesias et al. 2024; G. Morras et al. 2025; M. d. L. Planas et al. 2025; I. Romero-Shaw et al. 2025), possibly indicating binary formation in one or more of these environments.

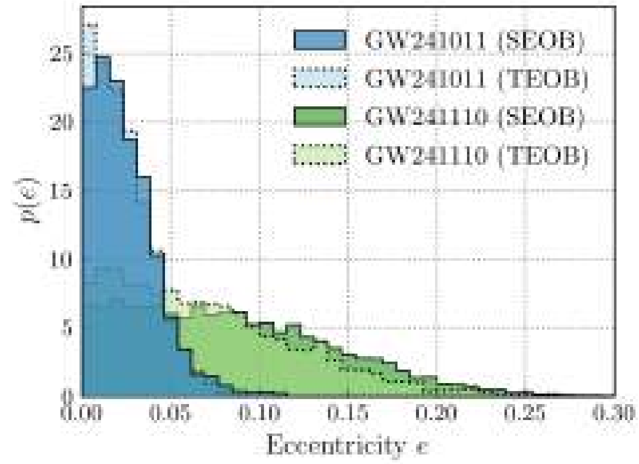

Figure 8. Posteriors on the orbital eccentricity of GW241011 and GW241110. Results are obtained using the SEOBNRv5EHM (A. Gamboa et al. 2025) and TEOBResumS-Dalí (A. Nagar et al. 2024) waveform models, and eccentricities are quoted at a reference frequency of 13.33 Hz, when higher-order spherical harmonic modes first enter the observable frequency band. Neither event exhibits evidence for residual eccentricity. We bound $e < 0.05$ at 90% credibility for GW241011 under both waveform models. GW241110, meanwhile, yields 90% credible upper limits of $e < 0.17$ and $e < 0.14$ under the SEOBNRv5EHM and TEOBResumS-Dalí models, respectively.

If GW241011 and GW241110 evolved dynamically in dense clusters, they may be prime candidates to exhibit measurable eccentricity. We reanalyze GW241011 and GW241110 using a pair of alternative waveform models, SEOBNRv5EHM (A. Gamboa et al. 2025) and TEOBResumS-Dalí (A. Nagar et al. 2024), that describe gravitational-wave emission from eccentric compact binaries through binary inspiral, merger, and ringdown. These waveform models are valid under restricted spin geometries, requiring component spins to be purely parallel or antiparallel to a binary's orbital angular momentum. The gravitational-wave signatures of orbital eccentricity and spin–orbit misalignment are known to be degenerate (e.g., J. Calderón Bustillo et al. 2021; I. M. Romero-Shaw et al. 2020a, 2023; Divyajyoti et al. 2024b; M. d. L. Planas et al. 2025). Degeneracies between spin misalignment and eccentricity are weakest for binaries like GW241011 and GW241110 (I. M. Romero-Shaw et al. 2023; Divyajyoti et al. 2024b) with low chirp masses, which complete many observable cycles. Nevertheless, eccentricity measurements that neglect effects of spin–orbit precession (or, conversely, spin measurements that neglect eccentricity, as in Section 3) may be biased.

Constraints on the orbital eccentricity of GW241011 and GW241110 are presented in Figure 8. Orbital eccentricity is an evolving function of time; results are quoted at the instant when the binaries' orbit-averaged quadrupole emission is observed at 13.33 Hz, corresponding to the time at which $\ell = 3$ spherical harmonic modes enter the observable band at 20 Hz. Neither event possesses measurable eccentricity. Under both waveform models, GW241011 is bounded to have $e < 0.05$ at

90% credibility, while GW241110 has $e < 0.17$ and $e < 0.14$ under the SEOBNRv5EHM and TEOBResumS-DALÍ models, respectively. This is not inconsistent with a dynamical origin; the vast majority of mergers in clusters are expected to have eccentricities $e \lesssim 0.1$ at frequencies accessible to Advanced LIGO, Advanced Virgo, and KAGRA (K. Gultekin et al. 2006; R. M. O'Leary et al. 2006; J. Samsing et al. 2014; L. Gondán et al. 2018; C. L. Rodriguez et al. 2018b; J. Samsing 2018; M. Zevin et al. 2019; M. Dall'Amico et al. 2024). On the basis of eccentricity alone, though, we cannot rule out any individual formation scenarios for GW241011 and GW241110. Further details are presented in Appendix B.

5. Tests of Fundamental Physics

Gravitational waveforms from compact binary coalescences encode detailed information about the nature and internal structure of the merging objects, enabling rigorous tests of general relativity (GR) and fundamental physics. The large primary spin and significant mass asymmetry of GW241011, in particular, makes this event a uniquely powerful probe of the Kerr nature of black holes and the multipolar structure of gravitational-wave emission.

5.1. Black Hole Spin-induced Quadrupole Moment

Within GR, rotating and charge-neutral black holes are uniquely described by the Kerr solution (R. P. Kerr 1963; B. Carter 1971). In Kerr spacetime, the black hole spin-induced quadrupole moment, the leading contribution of spin to a black hole spacetime's multipolar expansion, is given by $Q = -\kappa S^2/(mc^2)$. Here, m is the black hole's mass, S is its spin angular momentum, c is the speed of light, and $\kappa = 1$ exactly (R. O. Hansen 1974). Non-black-hole spacetimes, including neutron stars (W. G. Laarakkers & E. Poisson 1999; G. Pappas & T. A. Apostolatos 2012a, 2012b; I. Harry & T. Hinderer 2018), boson stars (F. D. Ryan 1997; C. A. R. Herdeiro & E. Radu 2014; D. Baumann et al. 2019; H. S. Chia & T. D. P. Edwards 2020), and other exotic compact objects, may in contrast exhibit significantly different values of κ owing to differences in internal structure and composition. Gravitational-wave sources containing rapidly spinning black holes enable direct measurements of the spin-induced quadrupole moment and tests of the Kerr hypothesis (K. G. Arun et al. 2009; C. K. Mishra et al. 2016); any measured deviation from $\kappa = 1$ would strongly suggest the presence of non-black-hole constituents or indicate new physics beyond the predictions of GR.

We define $\kappa_1 = 1 + \delta\kappa_1$ and $\kappa_2 = 1 + \delta\kappa_2$ as the spin-induced quadrupole coefficients of each compact object in GW241011's source binary. We repeat parameter estimation with a modified IMRPhenomXPHM waveform model (G. Pratten et al. 2021), allowing for nonzero $\delta\kappa_1$ and $\delta\kappa_2$ (Divyajyoti et al. 2024a). The resulting posterior is shown in Figure 9. The spin-induced quadrupole coefficient of GW241011's primary deviates from the Kerr prediction by $\delta\kappa_1 = 0.10^{+0.82}_{-0.82}$, consistent with GR (constraints on $\delta\kappa_2$ are uninformative). This is the most stringent constraint to date on the spin-induced quadrupole of a compact object. The constraints offered by GW241011 on $\delta\kappa_1$ are unusual, enabled by the event's high SNR, large primary spin, and unequal mass ratio. Typically, gravitational-wave signals primarily constrain only the symmetric combination $\kappa_s = (\kappa_1 + \kappa_2)/2$ (N. V. Krishnendu et al. 2017, 2019; R. Abbott et al. 2021b; Divyajyoti et al. 2024a). GW241011 constrains this symmetric combination to be within $\delta\kappa_s = 0.10^{+0.09}_{-0.11}$ of the Kerr hypothesis, under the assumption that $\kappa_1 = \kappa_2$. The previous best constraint on κ_s was obtained from the binary black hole GW190412 (Divyajyoti et al. 2024a), which gave $\delta\kappa_s = 0^{+2}_{-91}$. GW241011 improves on this constraint by approximately 3 orders of magnitude. A different implementation for the estimation of the spin-induced quadrupole moment, utilizing the SEOBNRv5HM_ROM (L. Pompili et al. 2023) waveform model, yields consistent results and is discussed in Appendix F.1.

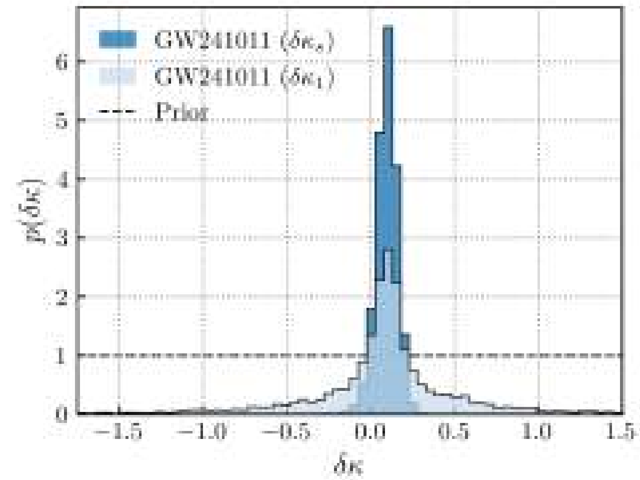

Figure 9. Deviations from the Kerr prediction for the spin-induced quadrupole moment of GW241011's primary black hole, $\delta\kappa_1$, as well as the deviation $\delta\kappa_s$ in the symmetric combination $\kappa_s = (\kappa_1 + \kappa_2)/2$ (N. V. Krishnendu et al. 2017, 2019; R. Abbott et al. 2021b). We bound $\delta\kappa_1 = 0.10^{+0.82}_{-0.82}$ and $\delta\kappa_s = 0.10^{+0.09}_{-0.11}$, consistent with expectations from GR. The next-most-informative event, GW190412 (R. Abbott et al. 2020c), yielded a constraint $\delta\kappa_s = 0^{+2}_{-91}$ (Divyajyoti et al. 2024a).

Measurement of GW241011's spin-induced quadrupole moment may rule out a wide range of exotic compact objects or black hole mimickers. Massive boson star models (F. D. Ryan 1997; C. Pacilio et al. 2020) predict spin-induced quadrupole moment parameters of order ∼10–150 for self-interacting spinning boson stars with quadratic coupling. The measurement of $\delta\kappa_s \leqslant 0.17$ at 90% credibility from GW241011 likely rules out all the massive boson star models described in, e.g., C. Pacilio et al. (2020). Other models, such as minimal boson stars (D. J. Kaup 1968; R. Ruffini & S. Bonazzola 1969; M. Vaglio et al. 2022) and solitonic boson stars (R. Friedberg et al. 1987), remain poorly understood in terms of their spin-induced multipole moments (V. Cardoso et al. 2017; V. Cardoso & P. Pani 2019). Another class of exotic compact objects are the gravastars (E. Mottola 2023), where the spin-induced multipole moments can take negative values due to the prolate deformation induced by their spinning motion. Although spin-induced quadrupole moment values have been predicted for thin-shell gravastar models (N. Uchikata & S. Yoshida 2016), the GW241011 data are insufficient to make definitive conclusions.

5.2. Radiation beyond the Quadrupole Approximation

Gravitational-wave radiation may be generically decomposed into an expansion over spin-weight −2 spherical harmonics, ${}_{-2}Y_{lm}$. The gravitational waves from merging compact binaries are dominated by the $(\ell, m) = (2, 2)$ spherical harmonic, sourced by a binary's mass quadrupole moment. As discussed in Section 3, however, GW241011 exhibits significant radiation in the $(\ell, m) = (3, 3)$ mode

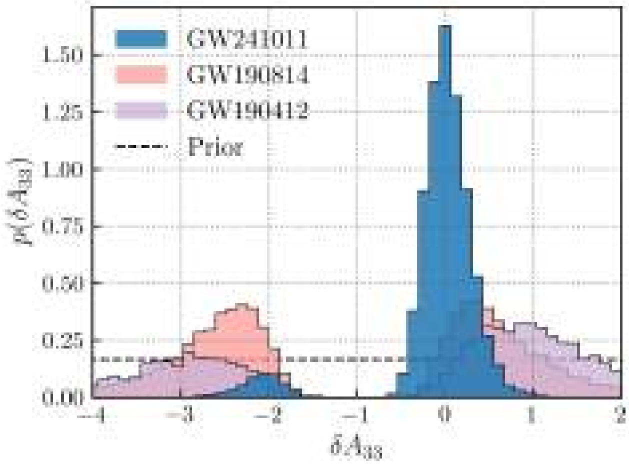

Figure 10. Posterior constraints on the amplitude of GW241011's gravitational radiation in $(\ell, m) = (3, 3)$ spherical harmonic modes, relative to the prediction from GR. GW241011 is consistent with expectation, with deviations from the GR limited to the interval $-1.9 \leqslant \delta A_{33} \leqslant 0.5$ at 90% credibility. Degeneracy with orbital inclination yields a strongly bimodal structure in the posterior for δA_{33}. The dominant mode has $\delta A_{33} = 0.0^{+0.5}_{-0.3}$, consistent with GR, while the subdominant mode has $\delta A_{33} = -2.1^{+0.4}_{-0.5}$. For comparison, also shown are the posteriors obtained from the next-most-informative gravitational-wave events, GW190814 and GW190412 (R. Abbott et al. 2020b, 2017c; A. Puecher et al. 2022; A. G. Abac et al. 2025g, in preparation).

sourced by the current quadrupole and mass octupole moments. General relativity fixes the relative amplitudes of gravitational radiation received in different spherical harmonic modes. The strong detection of multiple modes in a gravitational-wave signal, as in GW241011, offers an opportunity to test these predictions (C. D. Capano & A. H. Nitz 2020; A. Puecher et al. 2022; P. Mahapatra 2024; A. G. Abac et al. 2025g, in preparation).

We repeat inference on the properties of GW241011, but now introduce a parameter δA_{33} that allows for deviations in the signal's $(\ell, m) = (3, 3)$ mode amplitudes, relative to the (2, 2) mode content (A. Puecher et al. 2022; A. G. Abac et al. 2025g, in preparation). Higher-order modes, such as (4, 4) spherical harmonics, are not detected in GW241011, and so are not tested here. The resulting posterior distribution on δA_{33} is shown in Figure 10. Posteriors on δA_{33} are characteristically bimodal, due to degeneracies between a binary's inclination, orbital phase, and expected (3, 3) mode amplitude (C. Mills & S. Fairhurst 2021; A. Puecher et al. 2022). The dominant mode is consistent with GR, with $\delta A_{33} = 0.0^{+0.5}_{-0.3}$, while the subdominant mode has $\delta A_{33} = -2.1^{+0.4}_{-0.5}$. Taking both posterior modes together, we find $-1.9 \leqslant \delta A_{33} \leqslant 0.5$ at 90% credibility. This is the best measurement to date of δA_{33}. Among binaries in GWTC-4, the next-best constraints are provided by GW190814 and GW190412 (R. Abbott et al. 2020b, 2020c; A. Puecher et al. 2022), which give $-3.6 \leqslant \delta A_{33} \leqslant 1.6$ and $-5.3 \leqslant \delta A_{33} \leqslant 4.0$, respectively (A. G. Abac et al. 2025g, in preparation). GW241011 therefore confirms that gravitational waves radiated in (3, 3) spherical harmonic modes have amplitudes consistent with expectations from GR. Further details are elaborated in Appendix F.2.

5.3. Ultralight Bosons

Spinning black holes may prodigiously and spontaneously source particle production through the superradiant instability mechanism (W. H. Press & S. A. Teukolsky 1972; T. Damour et al. 1976; R. Brito et al. 2015a). Ingoing waves may acquire energy as they scatter off a rotating black hole. In the vicinity of a rotating black hole, an oscillating, gravitationally bound fluctuation in a bosonic field may grow exponentially, spontaneously turning an initially small perturbation into a macroscopic boson cloud surrounding the black hole. Cloud growth is powered at the expense of the black hole's rotational energy and may occur on timescales as short as days or minutes. This superradiance instability is specifically relevant for bosons with Compton wavelengths comparable to the black hole's size. If m_b is the boson mass, G is the gravitational constant, and M the black hole's mass, then superradiance requires $m_b \sim \hbar c^2/(GM)$. Thus, the observation of a rapidly rotating black hole of mass M immediately excludes the existence of novel bosons with masses near m_b; if such a particle existed, it should have long since depleted the black hole's spin. Constraints can, in principle, be performed using both electromagnetic and gravitational-wave observations, and for both supermassive and stellar-mass black holes (e.g., A. Arvanitaki et al. 2010; A. Arvanitaki & S. Dubovsky 2011; P. Pani et al. 2012; M. Baryakhtar et al. 2017; N. Fernandez et al. 2019; K. K. Y. Ng et al. 2021a, 2021b; M. J. Stott 2020).

The confidently rapid primary spin of GW241011 excludes the existence of ultralight bosons with masses between approximately 10^{-13} and 3×10^{-12} eV. Figure 11 shows the boson masses excluded by the primary spin measurement of GW241011, as a function of the presumed age of each binary's primary black hole and computed using the SUPERRAD package (N. Siemonsen et al. 2023; T. May et al. 2025); see Appendix F.3 for details. The top and bottom panels correspond to scalar and vector bosons, respectively. The filled contours indicate regions in which the primaries of both binaries should have undergone the superradiance instability, yielding final present-day spins that are inconsistent with observation at 90% credibility. Since all relevant azimuthal modes are included for the black hole ages considered, the narrow exclusion region near 4×10^{-12} eV in the scalar case arises from cloud growth with a higher azimuthal number $m = 3$. Conservatively assuming an age of 10^5 yr for the primary black hole of GW241011, this signal excludes the existence of scalar bosons with masses in the interval $[0.3, 2.6] \times 10^{-12}$ eV. The signal excludes vector bosons, meanwhile, with masses in the $[0.1, 5.3] \times 10^{-12}$ eV interval. Due to its more uncertain spin measurements, GW241110 does not appreciably constrain the existence of ultralight bosons.

GW241011 rules out the existence of bosons at higher masses than those excluded by previous gravitational-wave observations. An analysis considering the population of black holes comprising the LIGO–Virgo–KAGRA GWTC-2 catalog strongly disfavored scalar boson masses between $[2.2, 2.7] \times 10^{-13}$ eV when assuming 10^5 yr old black holes (K. K. Y. Ng et al. 2021b). Under the same age assumption, recent analysis using GW231123 and GW190517 excluded scalar and vector boson masses in the intervals $[0.6, 11] \times 10^{-13}$ and $[0.1, 18] \times 10^{-13}$ eV, respectively, at 90% credibility (P. S. Aswathi et al. 2025). A complementary analysis of GW231123 with a relativistic model for self-interacting scalars excludes axion masses in the interval $[0.6, 5] \times 10^{-13}$ eV with decay constants $\gtrsim 10^{14}$ GeV (A. Caputo et al. 2025).

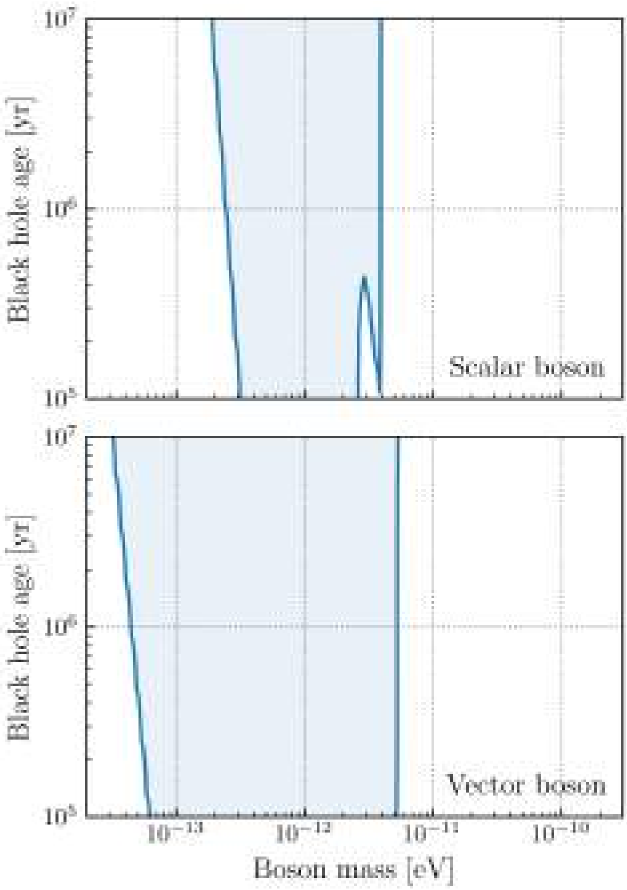

Figure 11. Masses of novel ultralight scalar (top) and vector (bottom) bosons that are excluded at 90% credibility by the nonzero spin measurements of GW241011. If bosons with masses lying in the shaded regions existed, then the primary black hole of GW241011 would have undergone the superradiance instability, spontaneously generating a cloud of bound boson particles and driving the black holes' spins below their observed values. The superradiance instability can deplete a black hole's spin over an astrophysically brief timescale, but this timescale becomes significantly longer outside a narrow range of boson masses. The exclusion curves therefore depend on the presumed age of GW241011's primary black hole.

6. Conclusions

In this Letter, we have presented gravitational-wave signals from two binary black hole coalescences—GW241011 and GW241110—discovered during the second part of the fourth observing run of the LIGO, Virgo, and KAGRA observatories. The measured properties of these events naturally suggest consideration as a pair. The spins of the more massive black holes in GW241011 and GW241110 are respectively situated at either extreme of the binary black hole population. The primary black hole of GW241011 possesses one of the largest and most precisely measured black hole spins observed via gravitational waves, and is spinning in a direction primarily (but not exactly) aligned with its orbital angular momentum. Conversely, the primary black hole of GW241110 is rapidly spinning in a direction confidently antiparallel to its orbit, the first confidently antialigned black hole spin measured to date. At the same time, these two binary black holes exhibit nearly identical masses, with each event favoring a primary mass in the range 15–20 $M_\odot$ and an unequal mass ratio between their component black holes.

Taken together, the mass ratios, large primary spins, and significant spin–orbit misalignment angles of GW241011 and GW241110 are strongly suggestive of hierarchical binary black hole mergers in dense stellar environments, such as globular, nuclear, or young stellar clusters. Under this interpretation, the primary black holes of both binaries are themselves the remnants of past black hole mergers. However, although the properties of GW241011 and GW241110 are in strong tension with predictions from isolated binary evolution, from gravitational-wave data alone we cannot rule out formation by massive stellar binaries (or systems of higher multiplicity). GW241011 and GW241110 nevertheless suggest that at least some merging binary black holes merge dynamically in dense environments, and that these environments are sufficiently massive to retain remnant black holes and foster repeated mergers.

The large and precisely measured primary spin of GW241011 furthermore enables myriad tests of fundamental physics. In particular, we find that this event provides the best measurements to date of a black hole's spin-induced quadrupole moment, confirming the Kerr prediction to within a factor of 2 (or to within 10%, depending on the parameterization used, an improvement in precision by 2 orders of magnitude; see Section 5.1). The nature of this test is independent from and complementary to the ringdown spectroscopy performed on the extremely loud event GW250114; analysis of GW250114's ringdown identified overtones with frequencies constrained to within 30% of their Kerr predictions (A. G. Abac et al. 2025f, 2025h). GW241011's strong radiation in multiple spherical harmonic modes furthermore enables the best constraint to date on the relative amplitudes of $(\ell, m) = (2, 2)$ and $(3, 3)$ modes, confirming the expected structure of gravitational-wave emission beyond the quadrupole approximation. Finally, the large spins of both GW241011 and GW241110 rule out the existence of novel boson particles with masses in the range 10^{-13}–10^{-12} eV.

Growing gravitational-wave catalogs, enabled by the concurrent operation of increasingly sensitive gravitational-wave observatories, continue to yield individually interesting sources that expand our knowledge of the compact binary landscape. Gravitational waves detected during the fourth observing run of the LIGO, Virgo, and KAGRA observatories have thus far enabled novel tests of relativity and gravitational waveform models (A. G. Abac et al. 2025f, 2025h, 2025i) and provided sources in new and unexpected regions of parameter space (A. G. Abac et al. 2024, 2025c). We expect discoveries to continue through the remainder of the fourth LIGO–Virgo–KAGRA observing run and beyond.

Acknowledgments

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Data Availability

Strain data from the LIGO and Virgo observatories associated with GW241011 and GW241110 are available from the Gravitational Wave Open Science Center. Datasets generated as part of this study, including posterior samples on the source properties of both events, are available on Zenodo, together with notebooks reproducing figures in this Letter (LIGO Scientific Collaboration et al. 2025).

Software: Calibration of the LIGO strain data was performed with a GSTLAL-based calibration software pipeline (A. Viets et al. 2018). Data-quality products and event-validation results were computed using the DMT (J. Zweizig 2006), DQR (LIGO Scientific Collaboration & Virgo Collaboration 2018), DQSEGDB (R. P. Fisher et al. 2021), gwdetchar (D. Macleod et al. 2021), hveto (J. R. Smith et al. 2011), iDQ (R. Essick et al. 2020), Omicron (F. Robinet et al. 2020), and PythonVirgoTools (Virgo Collaboration 2021) software packages and contributing software tools. Analyses in this catalog relied on software from the LVK Algorithm Library Suite (LIGO Scientific Collaboration et al. 2018; K. Wette 2020). The detection of the signals and subsequent significance evaluations were performed with the GSTLAL-based inspiral software pipeline (C. Messick et al. 2017; S. Sachdev et al. 2019; C. Hanna et al. 2020; K. Cannon et al. 2021; A. Ray et al. 2023; L. Tsukada et al. 2023; B. Ewing et al. 2024; S. Sakon et al. 2024; P. Joshi et al. 2025a, 2025b), with the MBTA pipeline (T. Adams et al. 2016; F. Aubin et al. 2021; C. Alléné et al. 2025), and with the PYCBC (S. A. Usman et al. 2016; A. H. Nitz et al. 2017; A. H. Nitz 2018; G. S. Davies et al. 2020; T. Dal Canton et al. 2021) packages. Estimates of the noise spectra and glitch models were obtained using BAYESWAVE (N. J. Cornish & T. B. Littenberg 2015; T. B. Littenberg & N. J. Cornish 2015; T. B. Littenberg et al. 2016; N. J. Cornish et al. 2021; T. Gupta & N. J. Cornish 2024). Low-latency source localization was performed using BAYESTAR(L. P. Singer & L. R. Price 2016). Source-parameter estimation was performed with the BILBY library (G. Ashton et al. 2019; I. M. Romero-Shaw et al. 2020b), using the DYNESTY nested sampling package (J. S. Speagle 2020), and the RIFT (C. Pankow et al. 2015; J. Lange et al. 2017; D. Wysocki et al. 2019) package. SEOBNRV5PHM waveforms used in parameter estimation were generated using pySEOBNR (D. P. Mihaylov et al. 2025). PESummary was used to postprocess and collate parameter estimation results (C. Hoy & V. Raymond 2021). The various stages of the parameter estimation analysis were managed with the Asimov library (D. Williams et al. 2023). Population inference was performed with the GWPOPULATION package (C. Talbot et al. 2025). The SUPERRAD package (N. Siemonsen et al. 2023; T. May et al. 2025) was used to characterize superradiance phenomena. Plots were prepared with MATPLOTLIB (J. D. Hunter 2007). NUMPY (C. R. Harris et al. 2020) and SCIPY (P. Virtanen et al. 2020) were used for analyses in the manuscript.

Appendix A
Source Parameter Estimation: Further Results and Details

Results quoted in the main text are given by the union of posterior samples under three different gravitational waveform models: SEOBNRV5PHM (SEOBNR; A. Ramos-Buades et al. 2023a), IMRPHENOMXPHM-SPINTAYLOR (XPHM; G. Pratten et al. 2021; M. Colleoni et al. 2025), and IMRPHENOMXO4A (XO4A; J. E. Thompson et al. 2024). Although all of these models describe quasi-circular precessing binaries and include higher-order multipole moments, they differ in the approach used to model the waveforms. The SEOBNR, XPHM, and XO4A models are each constructed from a combination of analytical and numerical information. They offer a complete description of binary inspiral, merger, and ringdown, and are therefore applicable to systems of any mass. The SEOBNR model computes the signal in the time domain. The XPHM and XO4A models each calculate signals in the frequency domain, but differ in their treatment of spin precession. Whereas the XPHM model numerically solves the post-Newtonian spin-precession dynamics, the XO4A model adopts a phenomenological ansatz that is fit to numerical-relativity simulations, calibrating evolution of precession angles, the coprecessing frame, and modal asymmetries between positive and negative m modes.

The main text presented only primary spin measurements with GW241011 and GW241110. For completeness, in Figure 12 we present posteriors on both the primary and secondary dimensionless spin magnitude of each binary black hole. The magnitude and orientation of the events' secondary spin vectors are unconstrained; neither the secondary spin magnitudes, the secondary spin–orbit misalignment angles, nor the azimuthal angles between component spins constrained away from the boundaries of their respective priors.

In Table 2 and Figure 13, we present posteriors on the source properties of GW241011 obtained independently with each waveform. All models recover nearly identical binary chirp masses. At the same time, they each provide slightly different (although statistically consistent) estimates of the binary's primary mass, mass ratio, and primary spin. Such systematic differences between waveform models are not unexpected; the unequal mass

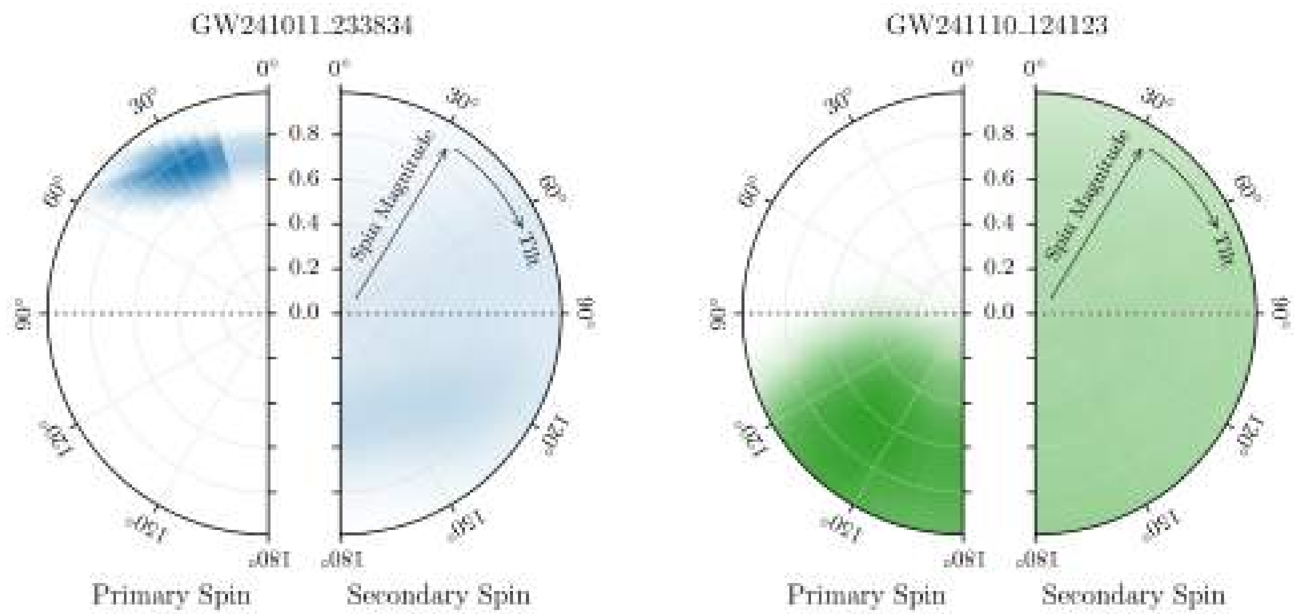

Figure 12. Posterior on both the primary and secondary spin vectors of GW241011 (left) and GW241110 (right). As in Figure 2, radial and polar coordinates correspond to dimensionless spin magnitude vectors and spin–orbit misalignment angles, respectively. Pixels spaced uniformly in spin magnitude and in cosine-tilt angles, such that each pixel contains equal prior probability. For both events, the properties of the secondary spin vectors are unconstrained.

Table 2
Inferred Source Properties of GW241011 under Different Waveform Models

Waveform	m_1 ($M_\odot$)	m_2 ($M_\odot$)	q	$\mathcal{M}$ [$M_\odot$]	D_L (Mpc)	χ_1	θ_1 (deg)	$\chi_{1,z}$	$\chi_{1,\perp}$	$\chi_{\rm eff}$	χ_p
SEOBNRV5PHM	$21.1^{+2.8}_{-3.6}$	$5.5^{+0.9}_{-0.5}$	$0.26^{+0.11}_{-0.05}$	$9.0^{+0.1}_{-0.1}$	225^{+39}_{-40}	$0.79^{+0.09}_{-0.08}$	35^{+11}_{-14}	$0.64^{+0.06}_{-0.08}$	$0.45^{+0.19}_{-0.15}$	$0.50^{+0.05}_{-0.06}$	$0.45^{+0.19}_{-0.15}$
IMRPHENOMXPHM	$19.8^{+2.4}_{-2.4}$	$5.9^{+0.7}_{-0.5}$	$0.30^{+0.08}_{-0.06}$	$9.1^{+0.1}_{-0.1}$	214^{+41}_{-43}	$0.75^{+0.07}_{-0.07}$	31^{+10}_{-12}	$0.64^{+0.06}_{-0.09}$	$0.38^{+0.15}_{-0.13}$	$0.51^{+0.05}_{-0.04}$	$0.38^{+0.15}_{-0.13}$
IMRPHENOMXO4A	$18.6^{+2.1}_{-2.1}$	$6.2^{+0.7}_{-0.5}$	$0.33^{+0.08}_{-0.06}$	$9.1^{+0.1}_{-0.1}$	201^{+44}_{-46}	$0.79^{+0.08}_{-0.10}$	27^{+9}_{-12}	$0.70^{+0.05}_{-0.08}$	$0.35^{+0.17}_{-0.13}$	$0.44^{+0.05}_{-0.04}$	$0.35^{+0.17}_{-0.13}$

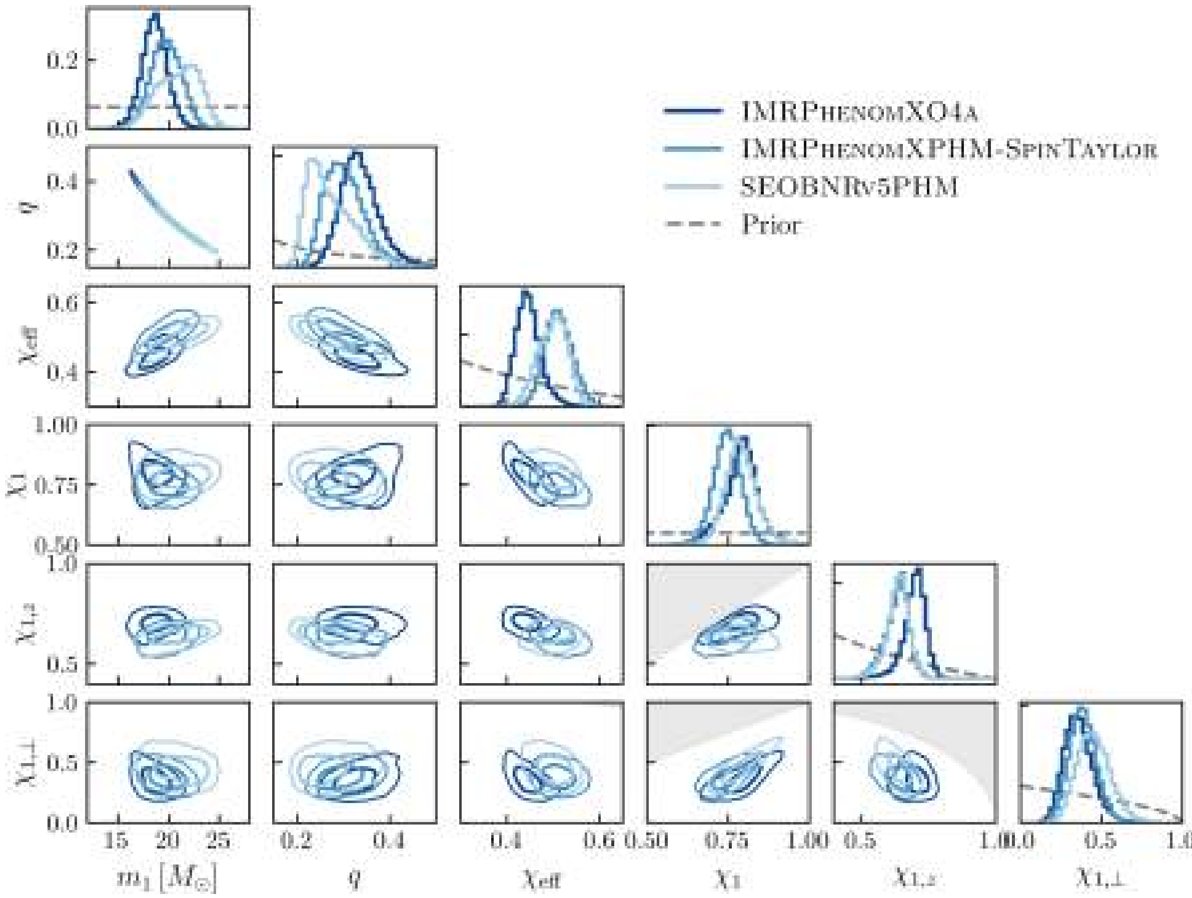

Figure 13. Posterior on the source properties of GW241011 under each individual waveform model considered. Different waveform models yield qualitatively similar conclusions, although waveforms exhibit nonnegligible systematic differences due to the strong precession and unequal masses of the source binary.

Table 3
Inferred Source Properties of GW241110 under Different Waveform Models

Waveform	m_1 ($M_\odot$)	m_2 ($M_\odot$)	q	$\mathcal{M}$ [$M_\odot$]	D_L (Mpc)	χ_1	θ_1 (deg)	$\chi_{1,z}$	$\chi_{1,\perp}$	$\chi_{\rm eff}$	χ_p
SEOBNRv5PHM	$17.4^{+5.1}_{-4.7}$	$7.7^{+2.3}_{-1.5}$	$0.44^{+0.33}_{-0.17}$	$9.8^{+0.5}_{-0.4}$	736^{+277}_{-280}	$0.59^{+0.34}_{-0.39}$	133^{+47}_{-26}	$-0.37^{+0.34}_{-0.38}$	$0.39^{+0.34}_{-0.29}$	$-0.27^{+0.23}_{-0.20}$	$0.40^{+0.33}_{-0.26}$
IMRPhenomXPHM	$17.2^{+5.0}_{-4.5}$	$7.7^{+2.2}_{-1.5}$	$0.45^{+0.33}_{-0.17}$	$9.9^{+0.5}_{-0.4}$	738^{+263}_{-261}	$0.58^{+0.35}_{-0.39}$	132^{+48}_{-26}	$-0.37^{+0.33}_{-0.38}$	$0.39^{+0.34}_{-0.29}$	$-0.27^{+0.22}_{-0.20}$	$0.40^{+0.33}_{-0.26}$
IMRPhenomXO4a	$16.9^{+4.9}_{-4.2}$	$7.8^{+2.1}_{-1.6}$	$0.46^{+0.31}_{-0.17}$	$9.8^{+0.5}_{-0.4}$	731^{+268}_{-260}	$0.65^{+0.30}_{-0.41}$	133^{+47}_{-22}	$-0.43^{+0.35}_{-0.35}$	$0.43^{+0.32}_{-0.32}$	$-0.30^{+0.22}_{-0.20}$	$0.45^{+0.31}_{-0.29}$

ratio, high spin, significant spin precession, and high SNR of this source are likely to exacerbate differences between waveform models (J. Mac Uilliam et al. 2024; S. Akçay et al. 2025; A. Dhani et al. 2025). Table 3 and Figure 14, in turn, shows properties of GW241110 inferred under the previously listed waveform models. We recover good agreement between the different waveforms, with only small differences in the width and mean of the posterior for parameters like the chirp mass and the spin parameters.

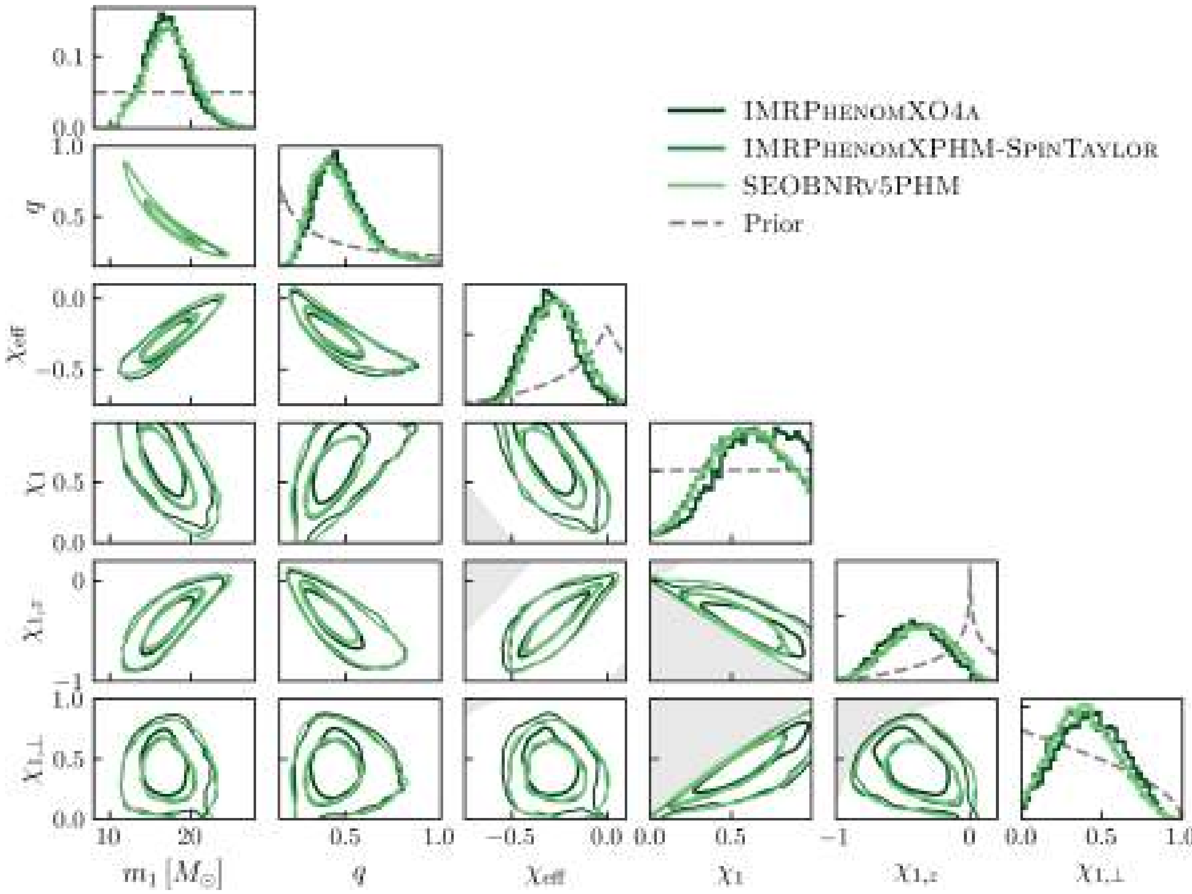

Figure 14. As in Figure 13, but for GW241110.

Appendix B
Eccentricity Measurements: Further Details

Gravitational-wave measurements of orbital eccentricity have long been challenging, as the dynamics of eccentric orbits vary rapidly on short orbital timescales and give rise to complex waveform morphologies. Recently, however, a number of mature models have been developed that describe gravitational-wave emission from eccentric compact binaries through binary inspiral, merger, and ringdown. We study the eccentricity of GW241011 and GW241110 using two waveform models: the SEOBNRv5EHM (A. Gamboa et al. 2025) and TEOBResumS-Dalí (A. Nagar et al. 2024) waveforms. Both models define eccentricity based a Keplerian parameterization of the orbit (C. Darwin 1959), in which the deformation of the orbit is measured by the Keplerian eccentricity e and the relative position of the binary along the orbit at a specific reference frequency is determined by the relativistic anomaly (SEOBNRv5EHM) or mean anomaly (TEOBResumS-Dalí). Each model restricts spin to lie parallel (or antiparallel) to a binary's orbital angular momentum, and therefore neglects precessional effects due to in-plane spin components. We adopt Bayesian priors that are uniform in detector-frame component masses, uniform in comoving volume and detector-frame time, and isotropic in source position and orientation. The prior on aligned-spin components is taken to be the projection of uniform-in-magnitude and isotropic spin priors, consistent with the prior adopted in Section 3. We adopt uniform priors on the relativistic anomaly and on the eccentricity at a reference frequency of 13.33 Hz (A. Ramos-Buades et al. 2023b). Sampling of the SEOBNRv5EHM waveform model is performed using both the BILBY (G. Ashton et al. 2019; I. M. Romero-Shaw et al. 2020b) and RIFT (C. Pankow et al. 2015; J. Lange et al. 2017; D. Wysocki et al. 2019) packages, the former invoking the DYNESTY (J. S. Speagle 2020) nested sampler; posterior samples from each software are combined in equal proportion. Sampling of the SEOBNRv5EHM waveform model is performed with RIFT.

Figure 15 shows more complete posteriors on the source properties of GW241011 and GW241110 using both waveform models. The component masses, effective inspiral spin, and primary aligned spin of both sources are consistent with results presented above using quasi-circular and precessing waveform models, with little correlation between these parameters and orbital eccentricity. This suggests, although does not prove, that eccentricity limits for GW241011 and GW241110 are minimally biased by the lack of precessional effects, and conversely that measurements of spin–orbit precession are likely robust despite neglecting eccentricity.

Care must be taken when comparing eccentricities among waveform families and to predictions from the literature. First, the orbital eccentricity for inspiraling compact binaries is not uniquely defined; different waveform families may adopt distinct, gauge-dependent choices for e. Growing efforts exist to standardize the definition of compact binary eccentricity using waveform-based descriptions to remove gauge ambiguity (M. A. Shaikh et al. 2023; M. A. Shaikh et al. 2025; T. Islam & T. Venumadhav 2025), but in this Letter we have not attempted to unify the SEOBNRV5EHM and

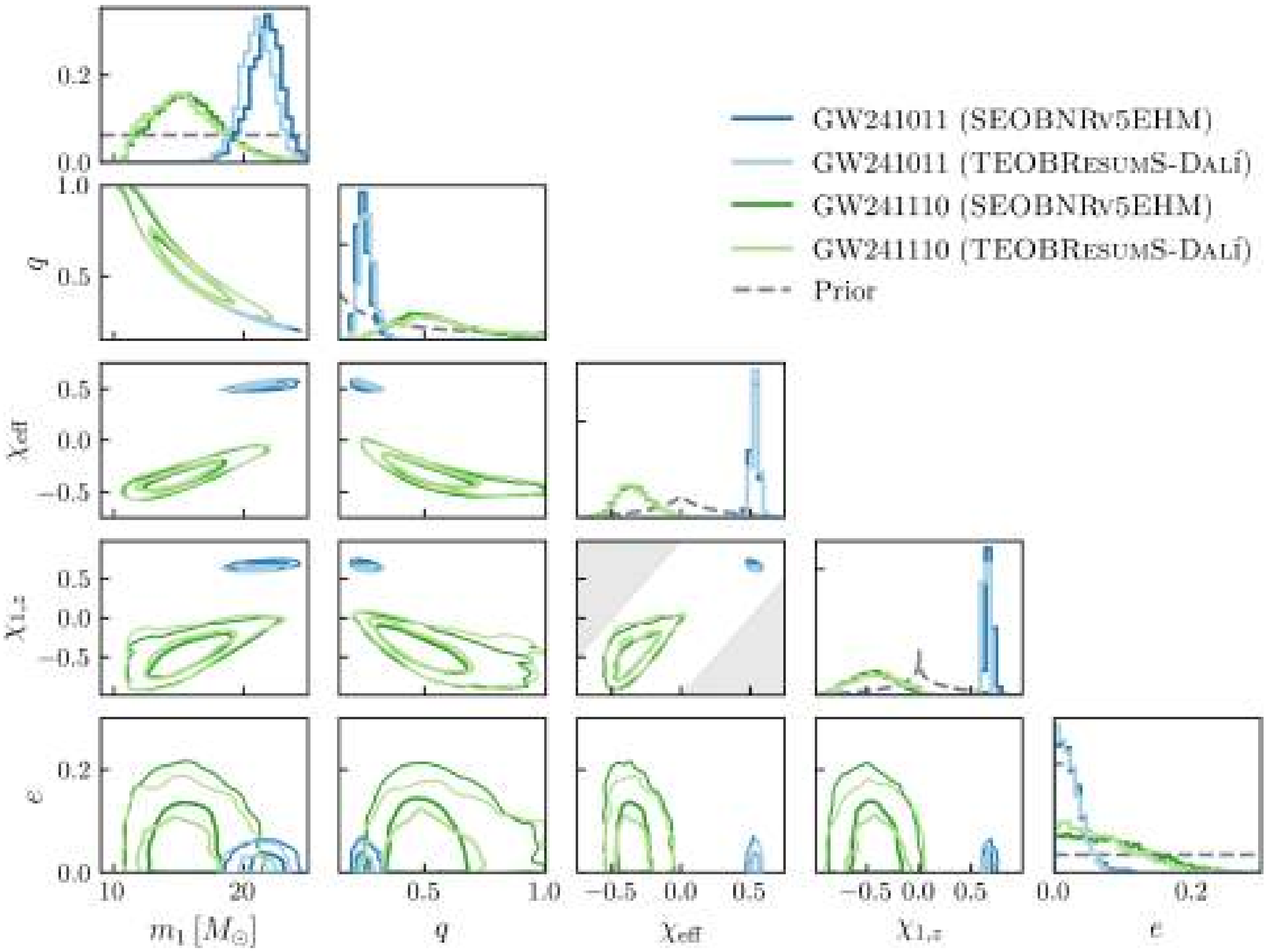

Figure 15. Posteriors on the source properties of GW241011 and GW241110, obtained using the eccentric and spin-aligned SEOBNRv5EHM (A. Gamboa et al. 2025) and TEOBResumS-Dalí (A. Nagar et al. 2024) waveform models. Orbital eccentricities, quoted at a reference frequency of 13.33 Hz, are consistent with $e = 0$, while other source parameters are consistent with estimates obtained elsewhere using quasi-circular and precessing waveform models.

TEOBResumS-Dalí definitions in this fashion. We nevertheless find strong consistency between eccentricity limits placed by both waveform models. Second, orbital eccentricity rapidly evolves under gravitational-wave radiation, and thus must be quoted at a specific time. As in our case above, orbital eccentricity is typically quoted at a fixed gravitational-wave reference frequency, to be taken as a proxy for time. The instantaneous frequency of an eccentric binary inspiral is not monotonic in time, however, and so there exist different conventions with which to define reference frequencies. In this work, we define the reference frequency as the orbit-averaged detector-frame frequency of a binary's $(\ell, m) = (2, 2)$ quadrupole radiation. Astrophysical predictions, in contrast, tend to adopt reference frequencies defined by the frequency of the *instantaneously loudest frequency harmonic* (L. Wen 2003). Eccentricities quoted at numerically identical reference frequencies can, under both prescriptions, correspond to eccentricities at very distinct times in a binary's evolution (A. Vijaykumar et al. 2024).

Appendix C
Binary Black Hole Population Inference with GW241011 and GW241110

In Section 3.3, we noted that GW241011 and GW241110 do not appear to be clear outliers with respect to the population of merging binary black holes. This appendix elaborates on this statement, presenting and discussing updated measurements of the binary black hole population using GW241011 and GW241110.

C.1. The Binary Black Hole Spin Distribution

We hierarchically measure the population properties of binary black holes following the methodology described in A. G. Abac et al. (2025d). We select all binary black holes among GWTC-4.0 (A. G. Abac et al. 2025a), detected with a false-alarm rate below 1 yr^{-1} by at least one search algorithm, and exclude the events GW190814 (R. Abbott et al. 2020b), GW190917_114630 (R. Abbott et al. 2024), and GW230529 (A. G. Abac et al. 2024) that contain low-mass objects of unknown nature. This yields a total of 153 binary black hole coalescences, plus GW241011 and GW241110. Selection biases are estimated using a suite of simulated signals added to data from the first three observing runs (O1, O2, and O3) and the first part of the fourth LIGO–Virgo–KAGRA observing run (O4a; A. G. Abac et al. 2025d; R. Essick et al. 2025). We neglect the additional time–volume surveyed early in the second part of the fourth observing run (O4b), in which GW241011 and GW241110 were detected. This slightly biases our measurements of the binary black hole population, but the short duration and comparable sensitivity

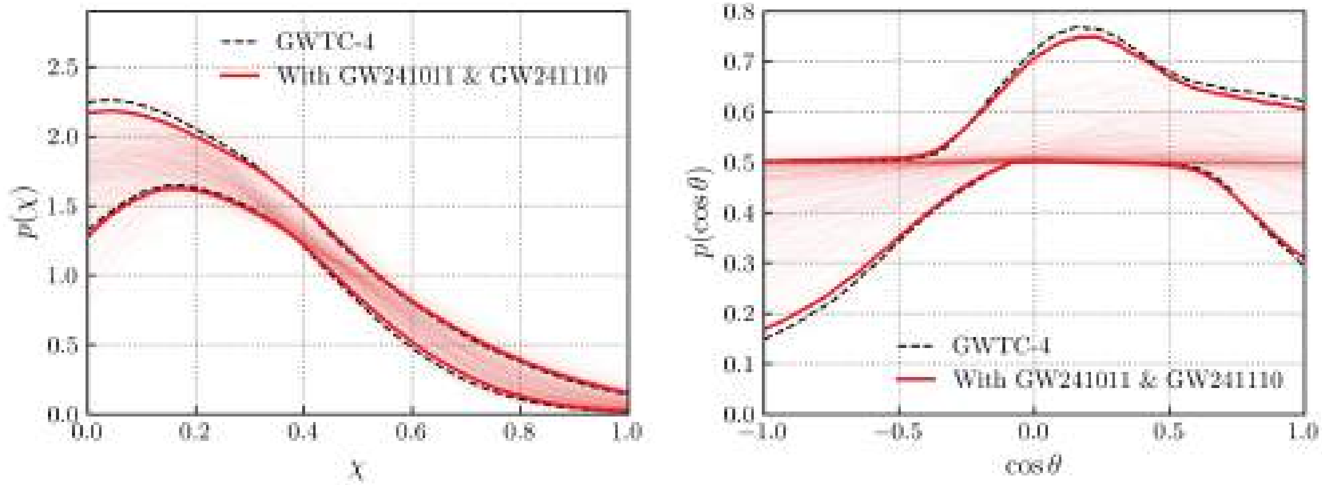

Figure 16. Inferred distribution of component spin magnitudes (left) and cosine spin–orbit misalignment angles (right) of merging binary black holes, with and without GW241011 and GW241110. We use the GAUSSIAN COMPONENT SPIN population model from A. G. Abac et al. (2025d), in which spin magnitudes are Gaussian-distributed, and cosine spin–orbit angles follow a mixture between Gaussian and uniform components. Dashed lines indicate 90% credible bounds on $p(\chi)$ and $p(\cos\theta)$ when using binary black holes from GWTC-4.0 (A. G. Abac et al. 2025a), while the thick red lines indicate updated bounds when additionally including GW241011 and GW241110. The ensemble of thin red lines shows the probability distributions corresponding to individual draws on our population posterior, when including GW241011 and GW241110. The inclusion of GW241011 and GW241110 negligibly affects the inferred spin magnitude and spin–orbit tilt distributions.

of early O4b render this bias negligible. We perform hierarchical inference using the GWPOPULATION package (C. Talbot et al. 2019, 2025) and the DYNESTY nested sampler (J. S. Speagle 2020).

Figure 16 illustrates the inferred distributions of spin magnitudes (left) and spin–orbit misalignment angles (right) among binary black holes, with and without GW241011 and GW241110. We use the GAUSSIAN COMPONENT SPIN model described in A. G. Abac et al. (2025d), in which component spin magnitudes are identically and independently drawn from a truncated normal distribution,

$$p(\chi_1, \chi_2) = N_{[0,1]}(\chi_1|\mu_\chi, \sigma_\chi) N_{[0,1]}(\chi_2|\mu_\chi, \sigma_\chi), \quad \text{(C1)}$$

and cosine spin–orbit tilts are jointly distributed as a mixture between Gaussian and uniform components:

$$\begin{aligned} p(\cos\theta_1, \cos\theta_2) &= \zeta\, N_{[-1,1]}(\cos\theta_1|\mu_t, \sigma_t)\, N_{[-1,1]}(\cos\theta_2|\mu_t, \sigma_t) \\ &\quad + (1-\zeta)\, U_{[-1,1]}(\cos\theta_1)\, U_{[-1,1]}(\cos\theta_2). \end{aligned} \quad \text{(C2)}$$

Here, $N_{[a,b]}$ and $U_{[a,b]}$ represent Gaussian and uniform distributions truncated and normalized on the interval $[a, b]$, and the means μ_χ and μ_t, standard deviations σ_χ and σ_t, and mixing fraction ζ are free parameters inferred from data. We assume that black hole masses and redshifts follow the default distributions adopted in A. G. Abac et al. (2025d) and adopt the same Bayesian priors. We see that the inclusion of events GW241011 and/or GW241110 yields a spin tilt distribution marginally more consistent with isotropy, but that these events otherwise have negligible effects on the inferred spin distributions.

It is possible that the GAUSSIAN COMPONENT SPIN model, with unimodal spin magnitude and tilt distributions, may provide a poor description of events like GW241011 and GW241110. We therefore explore two extensions of this model to further study the implications of GW241011 and GW241110.

1. First, whereas the $\cos\theta$ distribution in Equation (C2) was truncated on the interval $[-1, 1]$, we instead introduce a variable lower truncation bound $\cos(\theta_{\max})$ (S. Galaudage et al. 2021; H. Tong et al. 2022) (i.e., a maximum spin tilt angle $\theta_{\max}$) with a prior uniform on the interval $[-1, 1]$, and ask how extreme spin–orbit misalignment angles must be to accommodate events like GW241110 (the MAX-TILT model),

$$\begin{aligned} p(\cos\theta_1, \cos\theta_2) &= \zeta N_{[\cos(\theta_{\max}),1]}(\cos\theta_1|\mu_t, \sigma_t) N_{[\cos(\theta_{\max}),1]}(\cos\theta_2|\mu_t, \sigma_t) \\ &\quad + (1-\zeta) U_{[\cos(\theta_{\max}),1]}(\cos\theta_1)\, U_{[\cos(\theta_{\max}),1]}(\cos\theta_2). \end{aligned} \quad \text{(C3)}$$

2. Second, we allow for the existence of a distinct subpopulation of rapidly spinning black holes with large χ, designed to explore whether events like GW241011 require a multimodal spin distribution (HIGH-SPIN model). We extend the Equation (C1) model by introducing a high-spin Gaussian,

$$\begin{aligned} p(\chi_1, \chi_2) = &(\xi_\chi N_{[0,1]}(\chi_1|\mu_\chi, \sigma_\chi) \\ &+ (1-\xi_\chi) N_{[0,1]}(\chi_1|\mu_{\chi,\mathrm{high}}, \sigma_{\chi,\mathrm{high}})) \\ &\times (\xi_\chi N_{[0,1]}(\chi_2|\mu_\chi, \sigma_\chi) \\ &+ (1-\xi_\chi) N_{[0,1]}(\chi_2|\mu_{\chi,\mathrm{high}}, \sigma_{\chi,\mathrm{high}})), \end{aligned} \quad \text{(C4)}$$

where $\mu_{\chi,\mathrm{high}}$ is the mean high-spin Gaussian with a prior the uniform on the interval [0.5, 1], $\sigma_{\chi,\mathrm{high}}$ is the width of the high-spin Gaussian with a prior the uniform on the interval [0.005, 1], and finally ξ_χ is the mixing fraction between the low-spin and high-spin Gaussians with a uniform prior on the interval [0, 1].

Figure 17 shows the measured distribution of spin–orbit misalignment angles θ when inferring the maximum misalignment angle $\theta_{\max}$. The left panel shows the posterior on $\cos(\theta_{\max})$. Binary black holes among GWTC-4.0 require maximum spin–orbit misalignment angles of $\theta_{\max} \geqslant 125^\circ$ ($\cos\theta_{\max} \leqslant -0.57$) at 90% credibility. This result is only

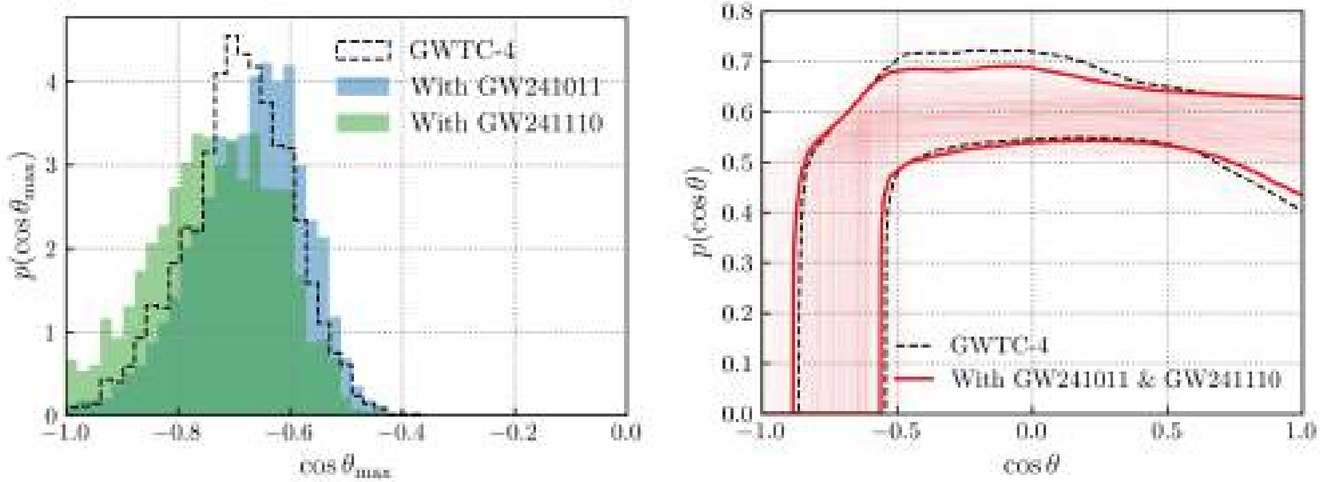

Figure 17. Right: inferred distribution of cosine spin–orbit misalignment angles, when additionally inferring the maximum misalignment angle (minimum $\cos\theta$ value) among the binary black hole population (the MAX-TILT model). As in Figure 16, dashed lines indicate 90% credible bounds using black holes from GWTC-4.0 (A. G. Abac et al. 2025a), thick red lines indicate updated bounds when additionally including GW241011 and GW241110, and thin red lines illustrate individual draws from our updated population posterior. Left: posterior obtained on the minimum value $\cos(\theta_{\max})$ below which the $\cos\theta$ distribution is truncated. The inclusion of GW241011 and GW241110 minimally affects inference of the maximum spin misalignment angle among the binary black hole population. Inference using GWTC-4.0 binary black holes requires $\cos\theta_{\max} < -0.57$ ($\theta_{\max} > 125°$) at 90% credibility. Adding GW241011 and GW241110 gives $\cos(\theta_{\max}) \leqslant -0.55$ and -0.59, respectively.

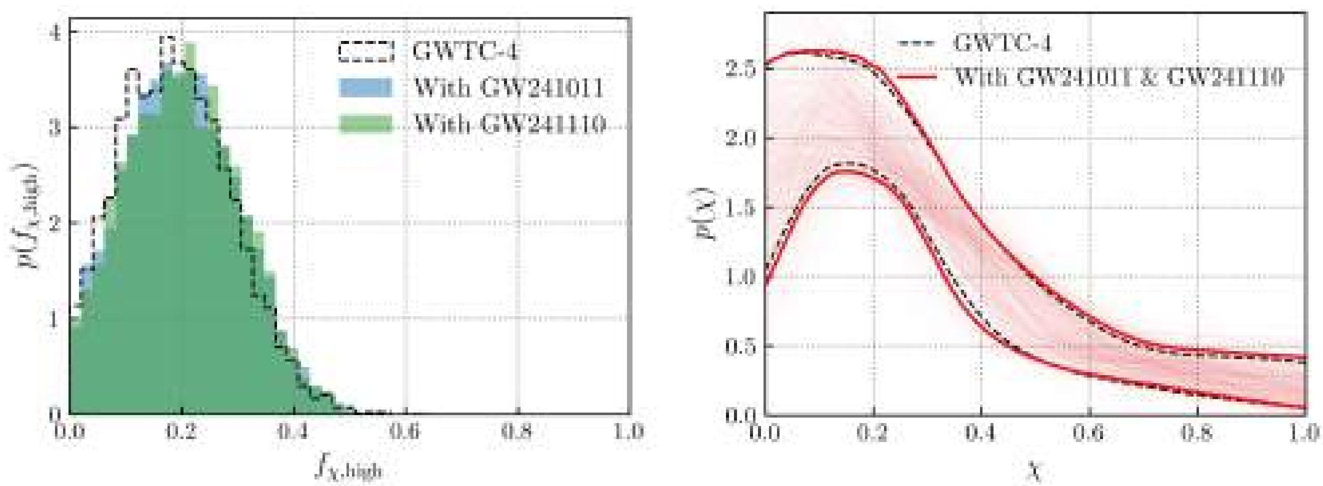

Figure 18. Right: inferred distribution of black hole component spin magnitudes when allowing for a distinct subpopulation of rapidly spinning black holes where one or both black hole components occupy this high-spin region (the HIGH-SPIN model). As above, the dashed lines and filled region span 90% credible bounds with and without GW241011 and GW241110, respectively. Left: inferred fraction of black holes comprising a possible highly spinning subpopulation. As above, results are negligibly affected by the inclusion or exclusion of GW241011 and GW241110. In both cases, current data do not require the existence of a distinct population of events with rapidly spinning components. When including GW241011 and GW241110, we bound $f_{\chi,\mathrm{high}} \leqslant 0.36$ at 90% credibility, consistent with zero.

marginally affected by the inclusion of GW241011 or GW241110, which yield $\theta_{\max} \geqslant 124°$ and 126 , respectively. Figure 18, meanwhile, shows the inferred black hole spin–magnitude distribution when allowing for a distinct subpopulation of rapidly spinning black holes, together with the inferred fraction of events $f_{\chi,\mathrm{high}}$ with one or both components occupying a possible high-spin population. When compared to Figure 16, it is clear that different models yield slight, systematic differences in the measured spin magnitude distribution; the HIGH-SPIN model gives a spin distribution more concentrated at small χ with an extended tail to high-spin magnitudes. However, the addition or exclusion of GW241011 and GW241110 again result in negligible differences. Binary black holes among GWTC-4.0 do not require the existence of a distinct, high-spinning subpopulation, with $f_{\chi,\mathrm{high}} < 0.32$ at 90% credibility. When including GW241011 and GW241110, the high-spin fraction remains consistent with zero, with $f_{\chi,\mathrm{high}} < 0.36$.

Taken together, our results indicate that GW241011 and GW241110 are not evident population outliers, requiring neither greater spin–orbit misalignments nor larger spin magnitudes than already afforded by binary black holes among GWTC-4.0.

C.2. Population Reweighting

We reweight the parameter estimation samples using population-informed mass and spin distributions using the three population models. Reweighted posteriors are obtained

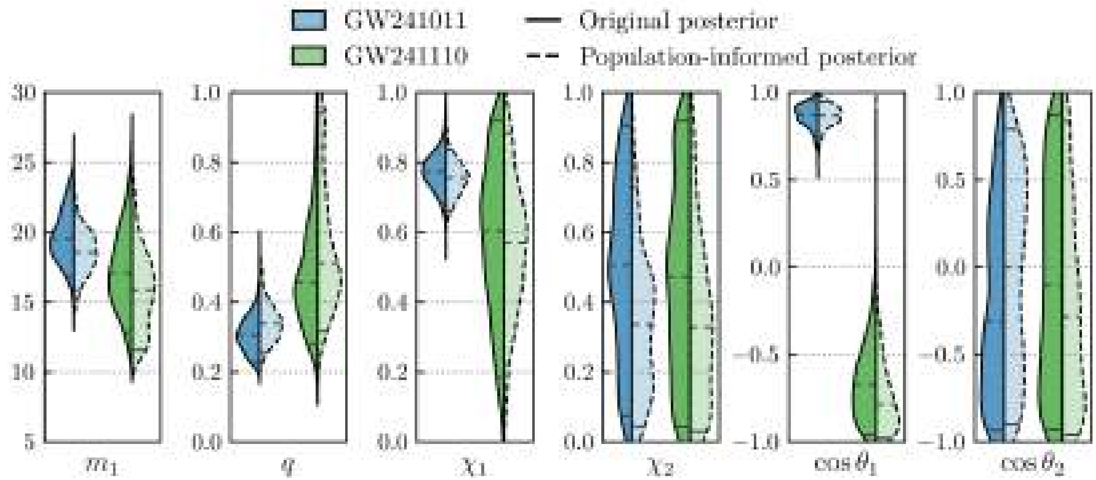

Figure 19. Comparison of original and population-informed (using the GAUSSIAN COMPONENT SPIN population model) posterior distributions for GW241011 and GW241110.

with leave-one-out posterior predictive distributions (S. Galaudage et al. 2020; T. Callister 2021; R. Essick & M. Fishbach 2021), providing astrophysically motivated priors (such reweighting excludes the contribution of the event in question to the population inference, thus avoiding double-counting effects). The resulting posteriors for the GAUSSIAN COMPONENT SPIN population model, for example, are shown in Figure 19.

For the posterior on $\cos(\theta_1)$ of GW241110, reweighted by the population using the GAUSSIAN COMPONENT SPIN, MAX-TILT, and HIGH-SPIN, the upper limit (or minimum misalignment) is given by −0.43, −0.26, and −0.37, respectively, at 90% credibility. The MAX-TILT fit gives the least misaligned result as the model has the flexibility to cut off at values of $\cos(\theta_1) > -1$, whereas the other two models require the fit to end at $\cos(\theta_1) = -1$. For the posterior on χ_1 of GW241011, reweighted by the population using the GAUSSIAN COMPONENT SPIN, MAX-TILT, and HIGH-SPIN, the lower limit (or minimum spin magnitude) is given by 0.68, 0.68, and 0.69, respectively. The lower limit on the spin magnitude is consistent under all three models.

Appendix D
Cluster Models: Further Details

In this appendix, we provide further details regarding the astrophysical population models plotted alongside the properties of GW241011 and GW241110 in Figure 6. For a complete description of the stellar (binary) evolution and cluster dynamics models underlying these results, we direct the reader to K. Kremer et al. (2020), C. L. Rodriguez et al. (2022), and F. Antonini et al. (2023).

The CMC catalog (K. Kremer et al. 2020; C. L. Rodriguez et al. 2022) contains a suite of 148 cluster simulations, primarily comprising a grid of 144 models with varying particle number ($N = \{2, 4, 8, 16\} \times 10^5$), virial radius ($r_v = \{0.5, 1, 2, 4\}$ pc), metallicity ($Z/Z_\odot = \{0.01, 0.1, 1\}$), and Galactocentric distance ($R_{\rm gc} = \{2, 8, 20\}$ kpc). In addition, the CMC catalog include four more massive clusters with $N = 3.2 \times 10^6$ at $R_{\rm gc} = 20$ kpc, spanning two metallicities (0.01 and 1 $Z_\odot$). Compared to earlier CMC model suites (S. Chatterjee et al. 2010, 2013; M. Morscher et al. 2015), this set extends the explored ranges of r_v and Z, and decouples metallicity from Galactocentric distance. Cluster models are evolved dynamically over one Hubble time, and binary black hole mergers are identified as those binaries that successfully coalesce over this timescale. The total numbers of available black hole mergers (both first generation and hierarchical) are provided in Table 4. In Figure 6 we specifically show the direct union of binary black hole mergers obtained across all simulations at each given metallicity, in order to illustrate the range of binary black hole masses, mass ratios, and spins that can be achieved over a broad range of cluster conditions. A more detailed prediction for the merger population expected from clusters, in contrast, would likely adopt a weighted combination corresponding to assumptions about the distribution of cluster masses, metallicities, and formation histories.

The CBHBD code is a semianalytical model that applies cluster dynamics and energy-balance theory to follow the coupled evolution of clusters and their black hole populations, yielding predictions for black hole binary merger rates and properties. We use the CBHBD catalog published in F. Antonini et al. (2023), containing 10^6 cluster models that are sampled uniformly in the mass range $10^2 M_\odot$ to $2 \times 10^7 M_\odot$. We select the subset of models with the same metallicities considered above ($Z/Z_\odot = \{0.01, 0.1, 1\}$) and with initial half-mass densities of $10^5 M_\odot\,{\rm pc}^{-3}$, yielding a sample of 129 cluster models with total masses up to $2 \times 10^6 M_\odot$. The cluster models are evolved over one Hubble time, and Figure 6 contains binary black holes that merge in this time. The total numbers of available mergers are given in Table 4. As with the CMC results above, we take the direct union of binary mergers across all cluster masses, in order to illustrate the range of possible binary properties.

Figure 6 illustrates the range of binary black hole properties predicted under two models of globular cluster evolution. It does not, however, account for observational selection effects, which may alter the range of binary properties that we expect to successfully detect. We verify that the inclusion of selection effects does not significantly affect the content of Figure 6 by using a suite of simulated signals injected into LIGO and Virgo data (A. G. Abac et al. 2025j; R. Essick et al. 2025). We reweight these simulated signals from their original proposal distribution to target distributions defined by the CMC and CBHBD. Selecting only successfully recovered signals then yields the expected

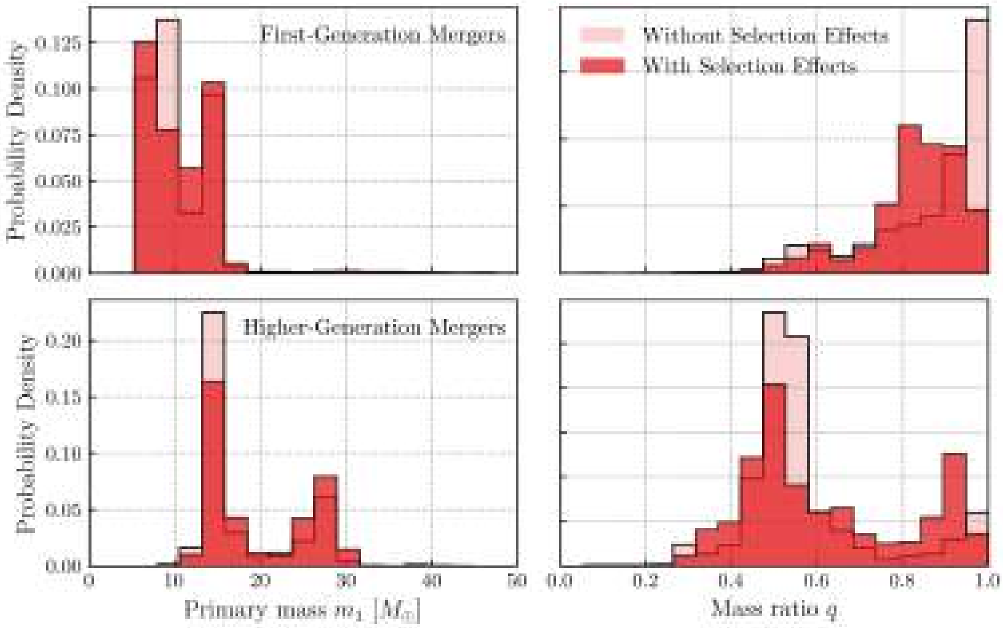

Figure 20. The impact of observational selection effects on the predicted properties of binary black hole mergers in dense stellar clusters. We specifically show the properties predicted in the CMC catalog for clusters of stellar metallicity $Z = Z_\odot$, corresponding to the right column of Figure 6. The upper row corresponds to mergers in which both components are first-generation black holes, and the bottom row to mergers in which one or both components are formed from a previous binary black hole coalescence. Light red distributions correspond to predictions directly from CMC (and shown previously in Figure 6), while dark red distributions have been subjected to an observational selection cut calculated using a campaign of simulated signals injected into LIGO and Virgo data (R. Essick et al. 2025; A. G. Abac et al. 2025j).

Table 4
Number of Binary Black Hole Mergers Included in Datasets from the CMC and CBHBD Catalogs

Model	Generation	$Z = 0.01\ Z_\odot$	$Z = 0.1\ Z_\odot$	$Z = Z_\odot$	Total
Cluster Monte Carlo	First-generation	3681	3566	3758	11005
Cluster Monte Carlo	Higher-generation	660	625	978	2263
clusterBHBdynamics	First-generation	1690	1761	1825	5276
clusterBHBdynamics	Higher-generation	316	351	638	1305

Note. We include the total numbers of first-generation and higher-generation black hole mergers in each catalog, as well as the number of mergers at each stellar metallicity as highlighted in Figure 6.

distribution of detectable binaries arising from stellar clusters. The target distributions are themselves obtained by fitting Gaussian mixture models to CMC and CBHBD predictions at each stellar metallicity; the number of mixture components is determined by minimizing the Akaike information criterion (H. Akaike 1974) on reserved testing data. In order to establish detectability, it is necessary to assume a redshift distribution for binary black hole mergers. We choose a volumetric merger rate that grows with redshift z as $(1 + z)^{2.6}$, following the low-redshift star formation rate of P. Madau & T. Fragos (2017). Our results do not depend strongly on this particular choice, however.

As an example, Figure 20 shows the original range (light red) of properties among first-generation (top row) and higher-generation (bottom row) black hole mergers, as predicted by CMC for a cluster of stellar metallicity $Z = Z_\odot$. Imposing an observational selection cut shifts the distributions of binary masses and mass ratios to higher values, at which expected SNRs are largest. The effect is small, however. The black hole spin distributions predicted by both CMC and CBHBD are sufficiently narrow (nearly delta functions at spin magnitudes of zero or ∼0.7) that they are unaffected by a selection cut. Despite the slight shift to larger mass ratios, mergers at the highest mass ratios are conversely suppressed by observational selection effects. This is due to the fact that binaries with the largest total masses tend to be those with more unequal mass ratios. Thus, although measured SNR is maximized by increasing mass ratio at fixed total mass, in practice we see that large SNRs most commonly occur for massive sources with somewhat unequal mass ratios.

Appendix E
Further Details on Estimating Progenitor Binary Parameters

This appendix provides additional details regarding calculation of GW241011 and GW241110's ancestral binaries, under the hypothesis that these events events contain second-generation black holes born from a previous binary black hole merger. As discussed in the main text, we approach this calculation in two ways. In the *Forward* approach, we adopt a hierarchical Bayesian formalism, placing astrophysically informed priors on the hypothesized ancestral binaries and marginalizing over the source properties of GW241011 and GW241110 to directly obtain posteriors on ancestral properties. In the *Backward* approach, we more agnostically adopt the same uninformative priors on the source properties of GW241011 and GW241110 used in standard parameter estimation. More details about each approach are described in Appendices E.1 and E.2.

E.1. The Forward Approach

Given the gravitational-wave data d due to a binary black hole merger containing a second-generation remnant, we wish to obtain a probability distribution $p(\boldsymbol{\theta}_{1g}|d)$ on the properties $\boldsymbol{\theta}_{1g}$ of that black hole's first-generation ancestors. Rather than repeat Bayesian parameter estimation, we proceed using the results of standard parameter estimation performed directly on GW241011 and GW241110, constructing the posterior (P. Mahapatra et al. 2024)

$$p(\boldsymbol{\theta}_{1g}|d) = \frac{\pi(\boldsymbol{\theta}_{1g})}{\mathcal{Z}_{1g}(d)} \frac{p(\boldsymbol{\theta}_{2g}|d)}{\pi(\boldsymbol{\theta}_{2g})}\Bigg|_{\boldsymbol{\theta}_{2g}=\boldsymbol{F}(\boldsymbol{\theta}_{1g})}. \tag{E1}$$

Here, $\pi(\overrightarrow{\theta}_{1g})$ is the prior distribution on $\boldsymbol{\theta}_{1g}$. The quantity $\boldsymbol{\theta}_{2g}$ denotes parameters of the observed binary merger (i.e., GW241011 and GW241110 themselves); $p(\boldsymbol{\theta}_{2g}|d)$ and $\pi(\boldsymbol{\theta}_{2g})$ are the posterior and prior probability distributions for these events obtained through ordinary parameter estimation. The normalization constant

$$\mathcal{Z}_{1g}(d) \equiv \int \pi(\boldsymbol{\theta}_{1g}) \frac{p(\boldsymbol{\theta}_{2g}|d)}{\pi(\boldsymbol{\theta}_{2g})}\Bigg|_{\boldsymbol{\theta}_{2g}=F(\boldsymbol{\theta}_{1g})} d\boldsymbol{\theta}_{1g} \tag{E2}$$

is the evidence for d under the hierarchical merger hypothesis, while $F(\boldsymbol{\theta}_{1g}) = \boldsymbol{\theta}_{2g}$ is the function mapping the ancestral binary's properties to the final mass and spin of its remnant black hole. We compute $F(\boldsymbol{\theta}_{1g})$ using the the numerical-relativity remnant surrogate model NRSUR7DQ4REMNANT (V. Varma et al. 2019), valid for binary black holes in quasi-circular orbits. In practice, we reconstruct $p(\boldsymbol{\theta}_{2g}|d)$ and $\pi(\boldsymbol{\theta}_{2g})$ using a Gaussian kernel density estimator fit to samples from each distribution. To sample possible ancestral properties from $p(\boldsymbol{\theta}_{1g}|d)$, we employ BILBY (G. Ashton et al. 2019) using the DYNESTY (J. S. Speagle 2020) nested sampler.

We choose a prior distribution $\pi(\boldsymbol{\theta}_{1g}|d)$ that is a close match to the properties of first-generation binary mergers, as predicted in the CMC catalog and shown in Figure 6. Upon combining successful mergers across all simulated clusters, the primary masses of first-generation mergers follow an approximately log-normal distribution, with best-fit mean $\mu_{\ln m_1} = 2.9$ and standard deviation $\sigma_{\ln m_1} = 0.6$, while mass ratios are well described by a power law $p(q) \propto q^{\beta}$, with $\beta = 4.3$. We adopt these distributions as our priors on ancestral primary masses and mass ratios. In the CMC catalog, first-generation black holes are assumed to have identically zero spins. We accordingly limit spins to be small but nonzero, adopting a half-normal prior distribution with a standard deviation of 0.1 on both primary and secondary spin magnitudes.

E.2. The Backward Approach

The above method sets priors on ancestral black hole parameters which, in turn, lead to posterior distributions on the source properties of the observed gravitational waves that are modified with respect to those obtained in standard parameter estimation. As an alternative, the method presented in C. Araújo-Álvarez et al. (2024) preserves the agnostic priors on the source properties of GW241011 and GW241110 themselves, thereby preserving the original posteriors on the observed "child" binaries (provided that all child parameters can be realized with nonnegligible probability from a chosen prior range of ancestral black holes). More precisely, this method yields a joint posterior $p(\boldsymbol{\theta}_{1g}, \boldsymbol{\theta}_{2g}|d)$ that, when marginalized over $\boldsymbol{\theta}_{1g}$, yields a posterior that is proportional to our original posterior $p(\boldsymbol{\theta}|d)$, for all $\boldsymbol{\theta}_{2g}$ satisfying $p(\boldsymbol{\theta}_{2g}|\boldsymbol{\theta}_{1g}) \neq 0$. Equality is achieved when every child parameter is compatible with at least one ancestral configuration under the proposed prior. This method differs from that of Appendix E.1 simply by replacing the term $\pi(\boldsymbol{\theta}_{2g})$ in Equation (E1), which denotes the prior probability on the child parameters set by our original Bayesian parameter estimation, with $\pi(\boldsymbol{\theta}_{1g})$, the prior probability on the child parameters induced by the priors on the ancestral ones.

In practice, we proceed by drawing 2×10^6 random samples from a broad ancestral prior $p(\boldsymbol{\theta}_{1g})$. Ancestral component masses are drawn uniformly from the range $[3M_\odot, 300M_\odot]$, with the mass ratio constrained to lie between $1/6$ and unity, and dimensionless spin magnitudes are sampled uniformly from the range $[0, 0.99]$. Remnant properties and a recoil kick are computed for each sample, yielding the induced prior distribution $p(\boldsymbol{\theta}_{2g})$ on possible remnant properties. For each primary mass and spin posterior sample $\{m_1, \chi_1\}$ obtained from $p(\boldsymbol{\theta}_{2g}|d)$ via the original parameter estimation, we draw random samples from $p(\boldsymbol{\theta}_{2g})$ satisfying $\{m_f, \chi_f\} = \{m_1 \quad \delta m_1, \chi_1 \quad \delta\chi_1\}$. We stress that, depending on the choice of ancestral prior $p(\boldsymbol{\theta}_{1g})$, this will only be possible for a fraction of the posterior samples. The usage of nonzero tolerances δm_1 and $\delta\chi_1$ is motivated by the fact that the discrete nature of our samples for $p(\boldsymbol{\theta}_{1g})$ would naturally prevent us from encountering samples exactly matching the remnant posterior samples. In our case, we choose $(\delta m_1, \delta\chi_1) = (1, 0.05)$, identified in C. Araújo-Álvarez et al. (2024) to yield stable results.

E.3. Progenitor Properties: Additional Results

Table 5 and Figure 21 present the posterior distributions on ancestral properties, as obtained through both the astrophysically motivated *Forward* approach and the agnostic *Backward* approach. Both approaches yield similar estimates for the ancestral primary masses of GW241011 and GW241110. The *Forward* approach, with more stringent priors favoring equal mass ratios, yields more precise estimates of the ancestors' secondary masses. Under an agnostic prior, GW241011 is consistent with an ancestral binary with moderately large, positive effective spin, although both GW241011 and GW241110 are also consistent with nonspinning ancestors. Recoil velocities are almost entirely dominated by spin priors; the low ancestral spins required in the *Forward* approach limit recoil kicks to lower velocities, while the large spins allowed in the *Backward* approach yield more rapid recoils.

Despite recoil velocity posteriors being prior dominated, for self-consistency it is valuable to check that these posteriors are not inconsistent with expected cluster escape velocities. The dashed histograms in Figure 21 show the distribution of cluster escape velocities predicted in the CMC catalog. If the sources of GW241011 and GW241110 are to be consistent with a

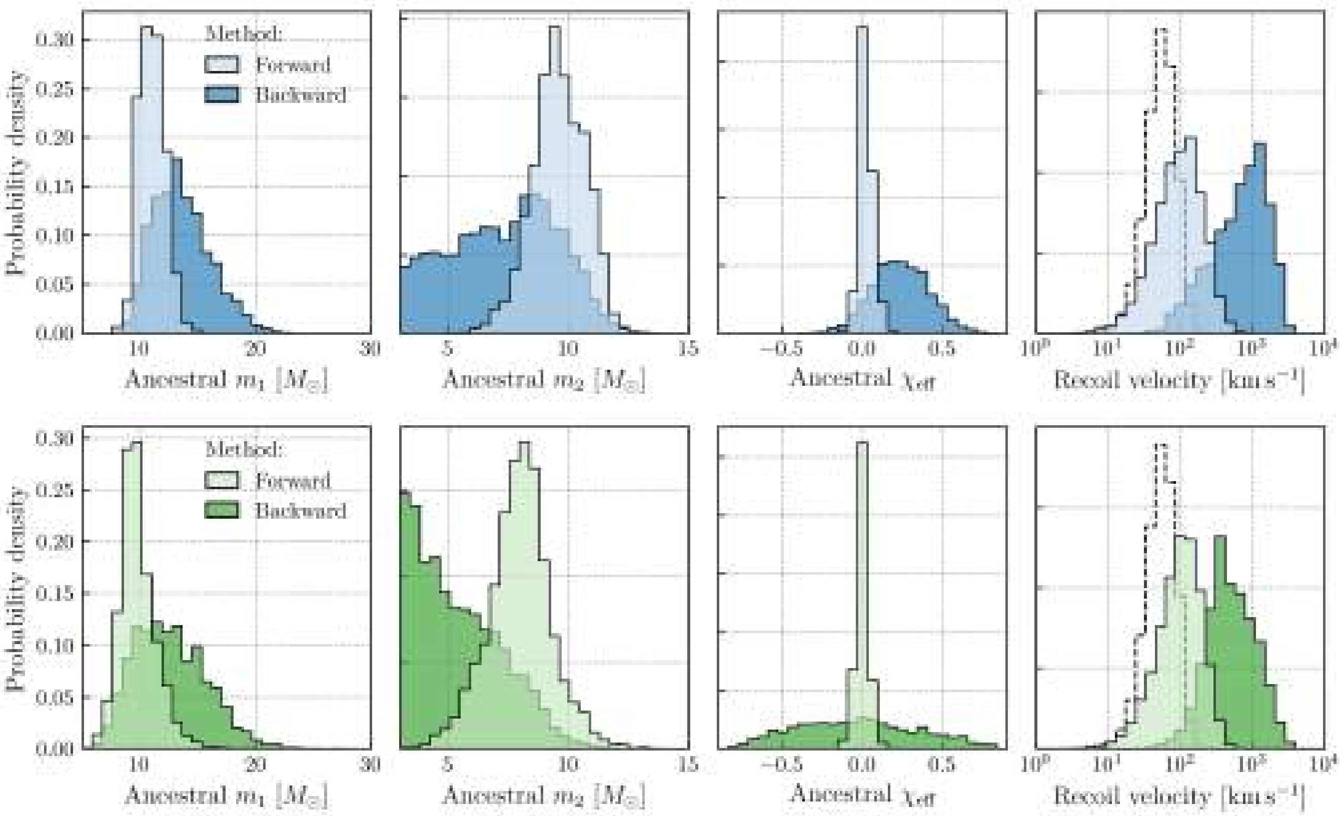

Figure 21. Inferred parameters on the ancestral binary black holes that previously merged to form the primary components of GW241011 (top row) and GW241110 (bottom row), under the hypothesis that each system contains a second-generation primary. We show results obtained under two sets of priors. Darker distributions correspond to an agnostic approach that leaves the priors on GW241011 and GW241110's source properties unchanged, relative to standard parameter estimation. Lighter distributions correspond to an astrophysically motivated approach, in which priors are placed on the ancestral binaries, inducing priors on GW241011 and GW241110's primary masses and spins consistent with their hypothesized hierarchical origin. For comparison, the dashed histograms illustrate the distribution of cluster escape velocities predicted by CMC. In order for the sources of GW241011 and GW241110 to remain consistent with a hierarchical origin in globular clusters, their ancestral recoil velocities should not exceed these escape velocities.

Table 5
Properties of the Ancestral Binary Black Holes of GW241011 and GW241110, under the Hypothesis that the Primary Mass of Each Observed Merger Is Itself a Remnant from a Previous Merger

Event	Method	Ancestral m_1 ($M_\odot$)	Ancestral m_2 ($M_\odot$)	Ancestral $\chi_{\rm eff}$	$v_{\rm recoil}$ (km s^{-1})
GW241011	*Forward*	$11.0^{+1.9}_{-1.6}$	$9.6^{+1.7}_{-1.8}$	$0.02^{+0.08}_{-0.06}$	100^{+190}_{-70}
GW241011	*Backward*	$13.3^{+4.8}_{-3.2}$	$7.5^{+3.2}_{-3.9}$	$0.23^{+0.29}_{-0.28}$	750^{+1400}_{-630}
GW241110	*Forward*	$9.6^{+3.1}_{-2.0}$	$8.0^{+2.1}_{-2.3}$	$-0.00^{+0.06}_{-0.06}$	100^{+160}_{-80}
GW241110	*Backward*	$12.3^{+5.6}_{-4.2}$	$5.1^{+3.6}_{-1.9}$	$-0.04^{+0.65}_{-0.57}$	480^{+1270}_{-330}

Note. Specifically, we include constraints on the primary and secondary masses of the hypothesized ancestors, the ancestors' effective inspiral spins, and the recoil velocity experienced by the remnants following each merger. For each event, we show ancestral properties inferred under two different approaches. In the *Forward* approach, we place astrophysically informed priors directly on the ancestral properties GW241011 and GW241110. In the *Backward* approach, we agnostically maintain the source parameters of GW241011 and GW241110 inferred in standard parameter estimation and identify ancestral binaries compatible with these measured parameters.

hierarchical origin in dense clusters (or at least clusters with masses similar to those explored in the CMC catalog), their inferred ancestral recoil velocities must not be larger than these predicted escape velocities. The *Forward* approach yields recoil velocity posteriors consistent with the distribution of expected escape velocities. The *Backward* approach yields a posterior with support in the range of expected escape velocities, although the posterior also extends to much higher recoil velocities; this is expected, due to the deliberately agnostic prior allowing for rapidly spinning ancestors.

Appendix F
Tests of Fundamental Physics: Further Details

F.1. Spin-induced Quadrupole Moment

In this appendix we provide further detail regarding constraints on GW241011's spin-induced quadrupole moment, discussed in Section 5.1.

When testing for the spin-induced quadrupole moment, corrections are added to the inspiral phase of the gravitational waveform, with uniform priors adopted on the correction parameters. In addition to the results shown in Figure 9, based on corrections to the IMRPhenomXPHM waveform model (G. Pratten et al. 2021; Divyajyoti et al. 2024a), we additionally explored results using corrections to the SEOBNRv5HM_ROM (L. Pompili et al. 2023) waveform model under the Flexible Theory-Independent framework (A. K. Mehta et al. 2023). Besides relying on different base waveform models, these two approaches differ in the treatment of the binary's evolution from inspiral to merger and ringdown. Additionally, the IMRPhenomXPHM includes spin precession while SEOBNRv5HM_ROM assumes spin-aligned binaries. Given the significant spin-precession effects in GW241011, the IMRPhenomXPHM-based results from Figure 9 should therefore be taken as the most physically meaningful constraints on the spin-induced quadrupole, but the SEOBNRv5HM_ROM results are helpful in quantifying the degree of systematic uncertainties arising from missing waveform physics.

The SEOBNRv5HM_ROM-based test gives $\delta\kappa_1 = -0.44^{+1.66}_{-2.01}$ and $\delta\kappa_s = -0.45^{+0.39}_{-1.01}$. While $\delta\kappa_1$ is consistent with a Kerr black hole in GR, $\delta\kappa_s$ is shifted slightly toward negative values, with the Kerr value lying beyond the 95% credible interval. This bias, as well as the broadened posteriors relative to IMRPhenomXPHM results, is due to the absence of relativistic spin–orbit precession noted previously (Divyajyoti et al. 2024a; Z. Lyu et al. 2024). To verify this, we analyzed simulated signals with source parameters consistent with those of GW241011. We considered both signals with misaligned precessing spins and with aligned-spin configurations. When analyzing simulated aligned-spin signals with SEOBNRv5HM_ROM, posteriors are unbiased and peak near zero. When instead analyzing simulated precessing signals, posteriors are instead biased toward negative values, as in the case of GW241011.

F.2. Subdominant Mode Amplitude Consistency

The gravitational-wave strain emitted by compact binary mergers can be decomposed into spin-weighted spherical harmonics of weight -2 as

$$h(t,\theta_{JN},\boldsymbol{\lambda}) = \sum_{\ell\geqslant 2}\sum_{m=-\ell}^{\ell} h_{\ell m}(t,\boldsymbol{\lambda})\,{}_{-2}Y_{\ell m}(\theta_{JN},\phi_0), \tag{F1}$$

where (θ_{JN}, ϕ_0) specify the observer's orientation in the source frame and $\boldsymbol{\lambda}$ encodes intrinsic parameters such as masses and spins. Following common practice, we fix $\phi_0 = 0$ so that θ_{JN} denotes the angle between the binary's total angular momentum vector and the observer's line of sight (G. Pratten et al. 2021).

Typically, gravitational-wave signals are dominated by the quadrupole $(\ell, m) = (2, 2)$ multipole. However, higher-order multipoles such as $(2, 1)$ and $(3, 3)$ become increasingly relevant for systems with unequal masses or for viewing angles away from face-on ($\theta_{JN} \neq 0$). To quantify potential deviations of these subdominant multipoles from GR, the subdominant multipole amplitude (SMA) test (A. Puecher et al. 2022) introduces amplitude deviations $\delta A_{\ell m}$ explicitly into the $(2, 1)$ and the $(3, 3)$ multipoles in the XPHM waveform model:

$$\begin{aligned} h(t,\theta_{JN},\boldsymbol{\lambda}) = &\sum_{m=\pm 2} h_{2m}(t,\boldsymbol{\lambda})\,{}_{-2}Y_{2m}(\theta_{JN},0)\\ &+\sum_{m=\pm 1}(1+\delta A_{21})\,h_{2m}(t,\boldsymbol{\lambda})\,{}_{-2}Y_{2m}(\theta_{JN},0)\\ &+\sum_{m=\pm 3}(1+\delta A_{33})\,h_{3m}(t,\boldsymbol{\lambda})\,{}_{-2}Y_{3m}(\theta_{JN},0)\\ &+\sum_{\text{other HOM}} h_{\ell m}(t,\boldsymbol{\lambda})\,{}_{-2}Y_{\ell m}(\theta_{JN},0). \end{aligned} \tag{F2}$$

The application of the SMA test requires sufficient SNR in the multipole of interest. For each (ℓ, m) mode, the mode-specific SNR, $\rho_{\ell m}$, is computed by projecting $h_{\ell m}$ onto the subspace orthogonal to the dominant $(2, 2)$ mode and evaluating the optimal SNR of the residual (C. Mills & S. Fairhurst 2021). In the absence of the (ℓ, m) multipole in signal, $\rho_{\ell m}$ follows a χ-distribution with two degrees of freedom in Gaussian noise, portrayed as the null distribution in Figure 5. To ensure sufficient mode content, we adopt a conservative selection threshold: a given mode for an event is included in the SMA analysis only if the lower bound of the 68% credible interval of its $\rho_{\ell m}$ distribution exceeds 2.145, corresponding to the 90th percentile of the null distribution. Among the two considered events, only the $(3, 3)$ mode in GW241011 satisfies this criterion. Accordingly, we perform parameter estimation for this mode with a uniform prior on δA_{33} in the range $[-10, 10]$.

F.3. Constraining Ultralight Bosons through Superradiance

In the presence of an ultralight scalar or vector field, a spinning black hole is unstable to the superradiant instability (R. Brito et al. 2015a). Oscillating bosonic modes that satisfy the superradiant condition, $\omega_R < m\Omega_{\rm BH}$, grow exponentially with time at the expense of the black hole's rotational energy. Here $\omega_R \sim m_b c^2/\hbar$ is the angular frequency, m is the azimuthal number, and $\Omega_{\rm BH}$ is the horizon frequency of the black hole. The growth of a mode and spindown of the black hole persist until the superradiant condition is saturated (A. Arvanitaki et al. 2010; R. Brito et al. 2015b; W. E. East & F. Pretorius 2017; W. E. East 2018). Typically, the lowest m mode that is superradiant grows the fastest, but with sufficient time multiple modes can grow and saturate, reducing the black hole's spin to ever smaller values. The vector boson instability rate is parametrically faster than the scalar rate, such that vector bosons spin down a black hole to lower values in a fixed time. For example, adopting the median mass and spin values for the primary black hole in GW241011 (Table 1), the shortest e-folding time for mass growth of a boson cloud is $\sim$8 s for a vector boson and 9 hr for a scalar. This assumes a boson mass optimally matched to the black hole; for smaller boson masses the instability timescales lengthen—roughly as $\propto m_b^{-7}$ and $\propto m_b^{-9}$ for vector and scalar modes, respectively (M. Baryakhtar et al. 2017).

Given a boson mass and a time since black hole formation (or the time since the black hole gained angular momentum), there will be excluded regions of the black hole's mass–spin parameter space where the superradiant instability should have reduced the black hole's spin to lower values. We calculate this excluded region using the SuperRad package (N. Siemonsen et al. 2023; T. May et al. 2025), based on the linear superradiantly unstable modes and including all relevant azimuthal number modes, for both vectors and scalars. For the dominant modes, with $m \leqslant 2$, we use the relativistic frequencies and instability rates. For higher azimuthal modes, we use a nonrelativistic approximation, which in general underestimates the instability rate and is thus conservative.

Using the posteriors for the source primary masses and spins of GW241011 and GW241110, we determine the fraction P of each event's posterior samples lying in the region permitted by the given boson mass and black hole age (P. S. Aswathi et al. 2025). Sufficiently small P would disfavor this mass–age combination. It is important, however, to guard against prior effects; it is possible for uninformative data, with spin magnitude samples drawn randomly from a uniform prior, to yield small P for specific ultralight boson masses. Following P. S. Aswathi et al. (2025), we therefore also calculate a prior fraction P', obtained by replacing the black hole spin posterior with samples drawn from a uniform distribution [0, 1). The exclusion regions shown in Figure 11 correspond to the requirement that $P < 0.1\,P'$; this corresponds to a 90% or better credible bound while also ensuring that constraints are strongly likelihood driven.

This analysis assumes only a minimally coupled boson with gravitational interactions, but will also apply to scalar or vector bosons with sufficiently weak interactions so as to not disrupt the black hole spindown. We also neglect the impact of gravitational effects from the binary companion on the superradiant growth of the boson cloud, implicitly assuming the growth would occur at large enough separation for this to be negligible.

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