Measurement of general-relativistic precession in a black-hole binary

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Abstract

In Newtonian gravity the angular momentum of each component of a point-particle binary system is conserved: the orbital angular momentum of the binary, and the individual angular momenta of the two objects in orbit. In general relativity this is no longer true; there are spin-orbit and spin-spin couplings between the individual angular momenta of the binary components, and as a result the orbital plane precesses around the direction of the total angular momentum. General relativistic precession has previously been measured in binary pulsars, where the precession frequency was several degrees per year. The effect can be far stronger in binaries consisting of black holes in close orbit. It has long been anticipated that strong-field precession will be measured in gravitational-wave observations of the late inspiral and merger of two black holes. While there is compelling evidence that the binary-black-hole population includes precessing binaries, precession has not been unambiguously measured in any one of the ∼90 LIGO-Virgo-Kagra (LVK) gravitational-wave detections to date. Here we report strong evidence for the measurement of strong-field precession, which we find in the LVK gravitational-wave signal GW200129. The binary's orbit precesses at a rate ten orders of magnitude larger than previously measured from binary pulsars. We also report that the primary black hole is likely highly spinning.

Keywords: black hole physics — gravitational waves — orbital precession

A binary system emits gravitational waves (GWs) that are predominantly directed out of the orbital plane, both above and below the binary. The strength of the GW signal measured from a binary system is dominated by the binary's total mass, orbital frequency and its distance and orientation to an observer. As energy and angular momentum are radiated the two objects will slowly inspiral, and the orbital frequency, and therefore also GW frequency, will increase. The frequency's time evolution depends on the masses and spin angular momenta of the objects, and many of the binary's properties can be measured from the signal's phasing. If the spins are misaligned with the orbital angular momentum, then the individual angular momenta will precess around the direction of the total angular momentum, which is approximately fixed. As the orbital plane precesses the signal's emission direction will vary, and a distant detector will observe modulations in the signal strength. In most binary systems these effects are imperceptibly small, but in a binary of compact objects like black holes or neutron stars, they may become strong enough to measure. Both the slow inspiral *and* geodetic precession have been observed in binary pulsars (e.g., Refs. [1–4]), and, through GW observations, the late inspiral and merger of black holes and neutron stars [5–7]. However, to date orbital precession has not been unambiguously measured in individual GW events, although strong statistical evidence was seen collectively in ensembles of events [8].

In most configurations, particularly for binaries with near equal masses, the precession modulations are weak, and for the binary inclinations that would most strongly enhance the modulations (i.e., edge-on to the mean orbital plane orientation) the signal is much weaker than for face-on binaries, and so less likely to be observed. Current observations of binary-black-hole (BBH) mergers suggest that black-hole spins are typically mis-aligned [9–11], and therefore almost all binaries will undergo some precession, but in GW observations most binaries have been close to equal mass, and the spins low. For these reasons, precession effects are difficult to observe in individual signals [12], and there has been no definitive identification of orbital precession reported in any one of the 84 BBH observations to date [5–7] by the Advanced LIGO and Virgo detectors [13, 14]. Potential measurements of precession have been reported in several signals (GW151226 [15], GW190412 [16–18], and GW190521 [19, 20], along with the more recent events GW191109_010717 and GW200129_065458 [7]), but the evidence in favour of precession has either been weak, or inconclusive due to systematic uncertainties.

We present strong evidence that one of the events in the most recent LIGO-Virgo-Kagra (LVK) data release [7] *does* exhibit general relativistic orbital precession. The event is GW200129_065458, which we refer to throughout this paper as GW200129. We find that, given our astrophysical priors, observational biases, and an assumption of Gaussian noise, the precessing hypothesis is favoured to the non-precessing hypothesis by a factor of at least 30:1. Considering noise effects alone, there is only a 1 in 25,000 chance that the imprint of precession on this signal is entirely due to noise. We also verify that the main features of our results are not explained by noise, by repeating our analysis on a theoretical signal injected into detector data, and on a theoretical signal as it would appear in a noise-free detector network.

GW200129 was reported with a signal-to-noise ratio (SNR) of 26.5 across the three-detector LIGO-Virgo network [7]. This makes it the loudest BBH signal yet observed, slightly louder than the first detection, GW150914, initially reported with a network SNR of 24 [21]. The LVK source properties for GW200129 were based on two analyses. One reported high precession broadly consistent with the results we present here, and the other did not. Ref. [7] gave equal weight to both analyses, leaving the properties of GW200129 unclear. Our work shows that both analyses rely on theoretical gravitational waveform models that may not be sufficiently accurate to measure GW200129. However, a third theoretical model *is* sufficiently accurate and with that model we are able to identify that GW200129 is indeed highly precessing.

Primary mass, m_1 ($M_\odot$)	39^{+6}_{-7}
Secondary mass, m_2 ($M_\odot$)	22^{+8}_{-3}
Total mass, $M = m_1 + m_2$ ($M_\odot$)	62^{+3}_{-3}
Mass ratio, $q = m_2/m_1$	$0.6^{+0.3}_{-0.2}$
Primary spin, a_1/m_1	$0.9^{+0.1}_{-0.5}$
Primary spin tilt angle, θ_{LS_1} (rad)	$1.4^{+0.4}_{-0.5}$
Secondary spin, a_2/m_2	(undetermined)
Binary inclination, θ_{JN} (rad)	$0.5^{+0.3}_{-0.3}$
Luminosity distance, D_L (Mpc)	1000^{+200}_{-200}
Redshift, z	$0.21^{+0.03}_{-0.05}$

Table 1 Source parameter measurements from our analysis of GW200129, with uncertainties at the 90% credible interval.

Our measurements of the binary's properties, with 90% credible intervals, are given in Tab. 16. The details of our parameter-estimation and systematics analysis are given in the Methods section.

The key feature of GW200129 that we focus on in our analysis is the measurement of strong-field general-relativistic orbital and spin precession. Precession was previously measured in binary pulsars, both from the precession of one of the pulsars' spins [2, 4, 22–24], or precession of the binary's orbital plane [25]. In the limit of a point particle orbiting a much larger body, the precession of the test body's spin due to the presence of the larger body is known as de Sitter precession, while the precession of a test body's orbit due to the spin of a larger body is Lense-Thirring precession. In the general case, where the two bodies can be of comparable mass, the two effects can be seen to counteract each other, such that the direction of the total angular momentum of the binary remains constant and the total spin precesses at the same rate as the orbital plane [26–28]. Black-hole mergers are in the strong-field non-linear regime of general relativity well beyond leading-order effects, but one quantity that can be compared across all regimes is the system's precession frequency.

For example, the pulsar PSR B1913+16 was found to have a precession rate of approximately 1.2 degrees per year [2], or 1.1×10^{-10} Hz. Later, the double pulsar PSR J0737-3039 was found to have a precession rate of about 4.8 degrees per year [4], or 4.4×10^{-10} Hz. In contrast, we find GW200129 to have an average precession rate in the LIGO-Virgo band of $\sim$3 Hz, i.e., *ten orders of magnitude higher than previously measured.* Fig. 1 shows the precession frequency Ω_{p} as a function of time. We see that the precession frequency is at least 1 Hz when the signal enters the detector sensitivity band, and rises to over 10 Hz at merger, which is indicated here by $t = 0$, the time of maximum signal amplitude. The binary's orbital plane is inclined to the total angular momentum by $\sim$0.5 rad; this inclination does not change significantly through the late inspiral. We discuss further the subtleties of this measurement in the Methods section.

We now turn to the black hole's spin angular momentum, S. The spin of a black hole with mass m is usually represented in geometric units by the dimensionless quantity $a/m = S/m^2$, which ranges from zero (non-spinning) to one (extremal spin). Fig. 2 shows the posterior distribution of our measurement of the spin of the primary

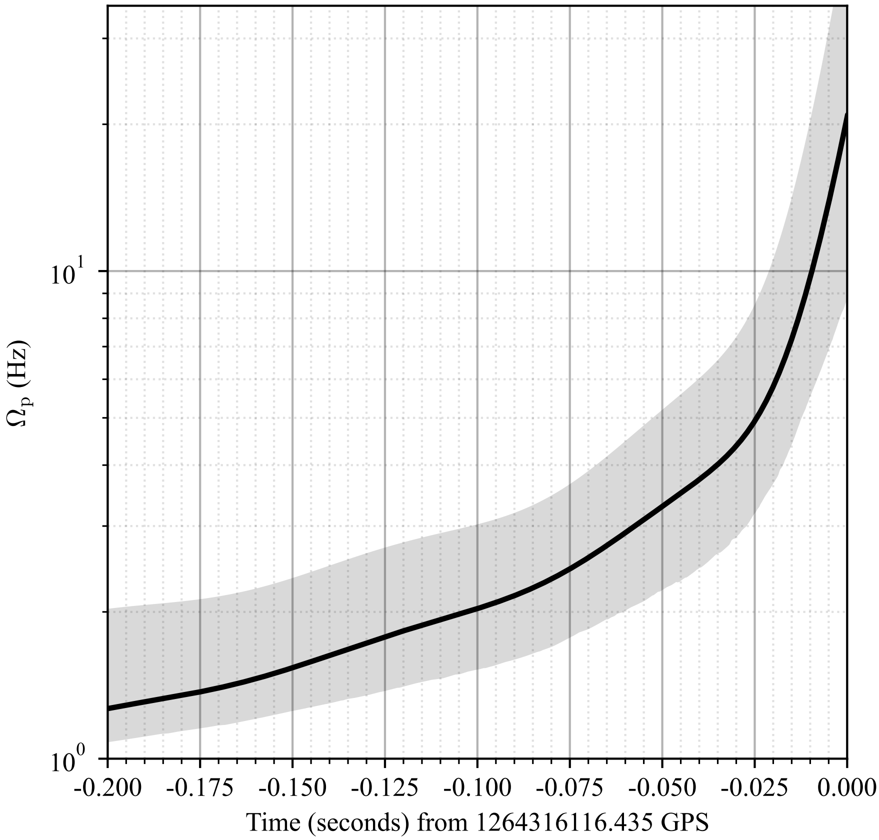

Fig. 1 The precession frequency Ω_p of GW200129 as a function of time, from 0.2s before merger, along with the 90% credible interval.

black hole a_1/m_1, and its angle of misalignment ("tilt") with respect to the orbital angular momentum. The misalignment is close to 90°, and therefore the spin lies almost entirely in the orbital plane; this is the cause of the significant orbital precession. We also find that the primary black hole's spin is larger than ∼0.4, with a strong preference for much higher values, with $a_1/m_1 = 0.9^{+0.1}_{-0.5}$. The signal is not strong enough for the secondary spin to be measured; this is the case in all BBH observations to date, and in general reliable measurements of both spins are not expected for SNRs less than ∼100 [29].

Black-hole spin and orbital precession leave only subtle imprints on the waveform. This is why a high SNR is in general necessary for precession to be measured. Fig. 3 shows the plus polarisation of the theoretical signal preferred by our analysis, over a ∼0.25 s window that roughly corresponds to the roughly half of the duration of data that we analyse. It is possible to make an approximate decomposition of the signal into two non-precessing harmonics, and to recover the mild precession modulations as the beating between these two harmonics [30]. The leading harmonic

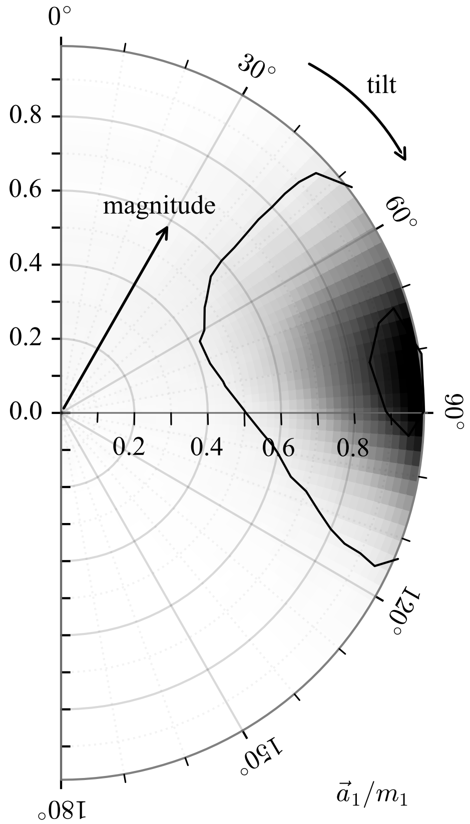

Fig. 2 Two-dimensional posterior probability for our measurement of the dimensionless spin $\vec{a}_1/m_1$ of the primary black hole, and its mis-alignment (tilt) with the direction of the orbital angular momentum. Tilt angles of 90° means that the spin vector lies within the plane of the binary. The colour indicates the posterior probability per pixel. This plot is produced by using histogram bins that are constructed linearly in spin magnitude and the cosine of the tilt angles such that each bin contains identical prior probability. The probabilities are marginalized over the azimuthal angles. Contours represent the 50% and 90% credible intervals.

("harmonic 0") makes up the dominant part of the signal, while the next harmonic ("harmonic 1") provides the power in precession. Fig. 3 also shows these two harmonics. The harmonics are in phase at merger and roughly ninety degrees out of phase 0.2 s earlier, illustrating that the system undergoes roughly one precession cycle while in the detector's sensitivity band from 0.65 s before meger.

Having argued that the signal GW200129 was likely produced by a precessing high-spin binary, we address the question of how it may have formed. A single observation is not informative about the overall binary population. However, GW200129 does tell us that black holes can form with high spins, and can end up in binaries with a large spin misalignment. The 84 LVK BBH observations suggest that black-hole spins are typically low, with half of spin magnitudes less than 0.26 [10], and this

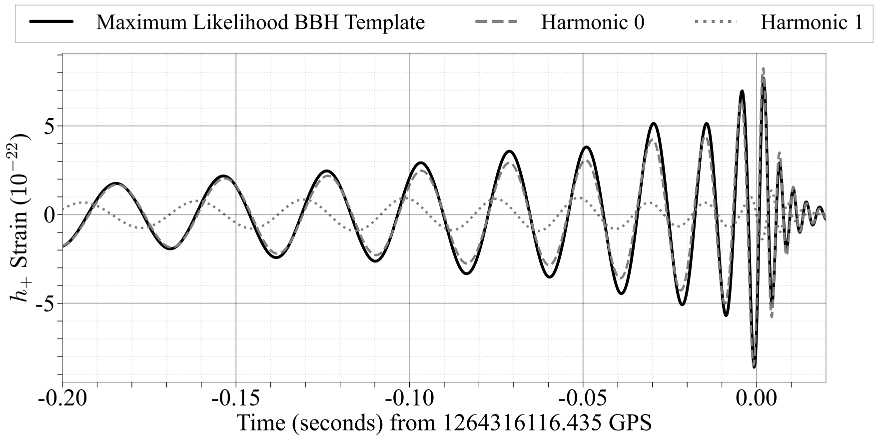

Fig. 3 Anatomy of GW200129. The figure shows the theoretical maximum likelihood waveform from our parameter-estimation analysis (see Methods section), and its approximate decomposition into the two strongest (out of five) non-precessing harmonics [30]. It is the second harmonic that provides the power in precession.

is consistent with the expectation that black holes that form through stellar collapse will not be highly spinning [31].

Although formation of a binary like GW200129 would be rare from the formation mechanisms that are consistent with the currently observed astrophysical population, there are a number of viable routes. One is a hierarchical merger, where successive black-hole mergers could ultimately lead to a binary where one component is highly spinning, and misaligned with the secondary. Hierarchical mergers may have already been identified through gravitational wave observations; see, e.g., Refs. [32–34]. Other options to produce high spins include chemically homogeneous evolution [35] (although this would *not* lead to spin misalignment), formation in AGN [36] (including accretion), and a binary that has formed from a triple-black-hole system [37].

In some of these scenarios, an event such as GW200129 would be extremely rare, and if that is the case, then we do not expect to observe another signal of this type for some time. Alternatively, we note that in the majority of observed BBH signals the SNR has not been high enough for precession to be measured, even if the black-hole spins are large and mis-aligned, and so these may be more common than previously thought. If so, more binaries such as this will be observed during the upcoming LVK observing runs and they will provide clues as to the specific mechanism that produces high-spin, high-misalignment binaries, and how frequently they form.

1 Methods

We analyse public LVK data from the second half of the third observing run (O3b) [7, 38], which ran from November 1, 2019 until March 27, 2020. The signal GW200129 was observed on January 29, 2020, and enters the detector sensitivity band at 20 Hz approximately 0.65s before merger. During that time the binary completes roughly nine orbits. GW200129 was reported by the LVK with SNRs in each of the three operational detectors of 21.2 in Livingston, 14.6 in Hanford and 6.3 in Virgo. The total network SNR is 26.5.

We determine the properties of the signal source by comparing the data against theoretical predictions from general relativity. We calculated predicted signals using the most accurate theoretical waveform model available for configurations consistent with this signal, `NRSur7dq4` [39]: when we analyse the data starting at 20 Hz, the model is appropriate for sources at a redshift of 0.2 with total binary masses above $56.7\,M_\odot$ and where the primary black hole is no more than four times more massive than the secondary. We find that the binary's mass is above $58\,M_\odot$ with 99% confidence, and the mass ratio is less than 1:3 with 99% confidence.

We perform our analysis using the Bayesian Markov-Chain Monte-Carlo (MCMC) code `LALInference` [40] that has been used in LVK analyses since the first GW detection in 2015 [41], and has been rigorously tested and refined since that time. We used the same sampler settings, power spectral densities, and calibration envelopes as those used in LVK GWTC-3 analyses, except for a cut in the prior parameter space to accommodate the `NRSur7dq4` model, i.e., limiting the mass ratio to be less than 1:4 and the total mass to be above $68\,M_\odot$ in the detector frame, which corresponds to $56.7\,M_\odot$ at redshift 0.2.

Our analysis is restricted to the $\ell \leq 3$ multipoles of the signal. The signal power in the $\ell > 3$ multipoles has an SNR of less than 1.0, and does not significantly change the results. There is also some power lost in the $(3, \pm 3)$ multipoles between 20 Hz and 30 Hz for the lowest-mass configurations that are sampled, due to these multipoles starting at a frequency $3/2$ times higher than dominant the $(2, \pm 2)$ multipoles. We have also verified that this missing power is negligible and also does not affect the results. Finally, we performed analyses on both the raw public detector data and the public data that had undergone glitch removal. The "de-glitched" data were used in the official LVK results, and we do the same here. The raw data gave very similar results, with slightly increased support for precession.

We find that the signal power due to precession has an SNR of $\rho_p = 4^{+2}_{-3}$. If precession effects were due to noise, we expect ρ_p to be no higher than around 2 [42]. The ρ_p estimate of power in precession makes use of an approximate two-harmonic decomposition of the signal [30], which becomes less applicable for high-mass signals; however, in these cases it is most likely an *underestimate* of the total power due to precession. We also find, following Ref. [18], that there is only a 1 in 25,000 chance that noise alone would produce the inferred precession SNR that we measure.

Despite the clear measurement of a high in-plane primary spin in Tab. 16 and Fig. 2, we now quantify our statistical confidence that GW200129 was produced by a precessing binary. We compare the marginal likelihood from our parameter-estimation analysis with that from a second analysis, which restricts the in-plane spin components to be zero, i.e., a non-precessing binary. We calculate that the precessing-binary hypothesis is favoured over the non-precessing hypothesis by a factor of 30:1, or a $\log_e$ Bayes factor of 3.4 ($\log_{10}$ Bayes factor of 1.5). This Bayes factor is consistent with the output from independent nested samplers [40, 43, 44].

We estimate the time evolution of the precession frequency, and the opening angle between the orbital and total angular momenta (i.e., the inclination of the orbital plane), from a subset of theoretical waveforms within the 90% credible region of our parameter-estimation results. It is possible to estimate these dynamical properties from the multipole structure of the waveforms [45]. The precession frequency and opening angle calculated from the signal are not identical to those in the binary dynamics, but the differences are smaller than the overall uncertainty in our measurements. The signal-based precession frequency as measured from the theoretical model also contains oscillations that we know are not present in the orbital dynamics, and we filter those out of the results shown in Fig. 1.

There are three potential sources of error in our results. (1) uncertainties in the waveform model have biassed the results, (2) the parameter-estimation code has settled on the wrong source-parameter values, (3) the results are due to noise artifacts. We now discuss each of these in detail.

(1) Waveform model uncertainties. The waveform model was tuned to numerical-relativity simulations between mass ratios of 1:1 and 1:4, and black-hole spins up to 0.8, and is well extrapolated up to extreme spins [39, 46]. All tests reported in the literature, and our own, suggest that the extrapolation to extreme spins is well-behaved, i.e., the properties of the waveforms (changes in phasing, amplitude and precession angles) extend smoothly from zero spin to extreme spin.

The usual measure of the accuracy of a model waveform is the mismatch between the model and a fiducial "true" waveform. The mismatch between two waveforms is calculated from a noise-weighted inner product between the normalised waveforms; the mismatch is the deviation of this quantity from unity, and a value of 0 indicates that the waveforms agree perfectly (up to an overall amplitude rescaling), and a value of 1 that they are completely orthogonal. The mismatch also allows us to estimate the SNR at which two signals would be distinguishable [47]. If the mismatch between two signals is $\mathcal{M}$, then they will be distinguishable at,

$$\mathcal{M} \leq \frac{\chi_k^2(1-p)}{2\rho^2}, \tag{1}$$

where χ_k^2 is calculated from the cumulative distribution function of the χ^2 distribution with k degrees of freedom at probability p. A binary black hole system undergoing non-eccentric inspiral has eight physical parameters (the two masses, and the components of each spin vector); with eight degrees of freedom, two waveforms will be distinguishably at 90% confidence if their mismatch satisfies $\mathcal{M} \leq 6.68/\rho^2$. Given that we do not measure most of the spin components, we might instead consider four degrees of freedom (e.g., the two masses, and the in-plane and aligned spin contributions), which provides a stronger mismatch criteria of $\mathcal{M} \leq 3.89/\rho^2$. For an SNR of 27, we will be able to distinguish signals with a mismatch above 9.2×10^{-3} if we assume eight degrees of freedom. If we apply the more stringent criteria of four degrees of freedom, the mismatch must be above 5.3×10^{-3}.

Within the model's calibration parameter space, the mismatch error between the model and fully general relativistic numerical relativity simulations was less than 4×10^{-3} for 95% of configurations considered in Ref. [39]. This is well within both criteria proposed above, and indicates that the model is well within the accuracy requirements to measure GW200129.

We explicitly test these accuracy statements for signals in the region of parameter space of GW200129, for `NRSur7dq4` and for the two alternative theoretical models that were used in the LVK analysis. These were selected because the total mass and mass-ratio limitations of the `NRSur7dq4` model mean that it cannot be used to measure the properties of binaries with low total mass. Since most of the LVK detections to date were indeed at masses below the model's low-mass limit, the LVK analysis of the O3b data made use of two other independent models, `PhenomXPHM` [48–50] and `SEOBNRv4PHM` [51]. Both models are on average less accurate than `NRSur7dq4` over its calibration region, but have the advantage of being applicable at both higher mass ratios, and lower masses, and their accuracy is sufficient at the SNRs and configurations (in particular, low spins) of most LVK observations. However, they may not meet the accuracy requirements of the high-SNR high-spin merger GW200129. Fig. 4 shows mismatches for the three different models against a set of publicly available numerical-relativity waveforms [52]. All five simulations are at mass-ratio 1:2, and have different magnitudes of in-plane spin on the larger black hole. The simlulations used are SXS:BBH:1128, SXS:BBH:1096, SXS:BBH:0800, SXS:BBH:1097, SXS:BBH:1215, listed in order of increasing in-plane spin. The mismatches are calculated at a binary inclination of $\pi/6$ (close to that recovered for GW200129), a total mass of $73\,M_\odot$ (the maximum likelihood total mass in the detector frame), and are optimised over the template phase, polarization and in-plane spin direction, while SNR-weighted averaging over signal polarization and phase. (More details on the mismatch calculation that we use are given in Ref. [53].) The figure also shows the mismatch accuracy threshold for a signal with SNR 27 with eight and four degrees of freedom. We see that `NRSur7dq4` meets the eight-degrees-of-freedom requirement for high spins, and indeed is the only model that also meets the requirement with four degrees of freedom. For the simulation with the highest in-plane spin of $a_{1\perp}/m_1 = 0.85$, SXS:BBH:1215, we find a mismatch of 2.23×10^{-3}, corrsponding to a distinguisable SNR of $\sim$42 (with four degrees of freedom). We note that this configuration is *outside* the calibration region of the model, since $a_1/m_1 > 0.8$.

In Fig. 5 we show an alternative mismatch-accuracy check. Here we assume that the `NRSur7dq4` model accurately represents binary signals, and calculate the mismatch against that model evaluated at the parameters that yield the maximum likelihood in our parameter-estimation analysis, and instances of the `PhenomXPHM` and `SEOBNRv4PHM` models evaluated at the same parameters, and optimised as in Fig. 4. We also calculate mismatches for model evaluations with the same parameters, but with a range of values of the primary spin magnitude a_1/m_1. We see again that both models do not meet the indistinguishability requirement when the spins are high. We also see that the high-spin mismatches are better for the `PhenomXPHM` model, which is consistent with that model recovering signs of precession in GW200129, while `SEOBNRv4PHM` does not. Note, however, that systematics errors are likely still a problem for `PhenomXPHM`, as discussed in Ref. [54].

A final source of systematic uncertainty is that we assume non-eccentric inspiral. As an example of how this can affect a measurement, the earlier GW observation

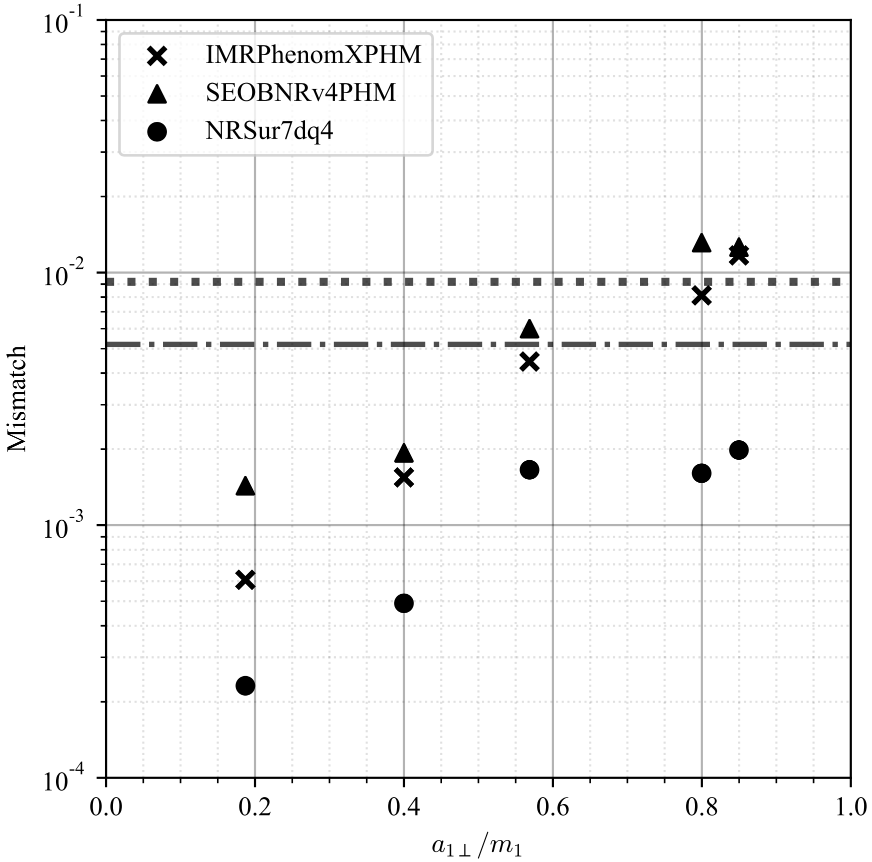

Fig. 4 Mismatches between three waveform models, and five waveforms from numerical-relativity simulations. The simulations were of binaries with mass-ratio 1:2, and varying values of the in-plane spin magnitude on the primary black hole, $a_{1\perp}/m_1$, which is what drives precession. The dotted line shows the accuracy threshold assuming eight degrees of freedom, and the dashed-dotted line the threshold assuming only four degrees of freedom (see text for discussion). Only the `NRSur7dq4` is well within the accuracy thresholds for GW200129.

GW190521 also appears to have a large in-plane spin when analysed with a non-eccentric-binary model [19], but the apparent precession signature may be due to orbital eccentricity [55, 56] or even a head-on collision [57]. The key difference with GW200129 is that the binary has lower mass, and so more GW cycles are detectable, and over this number of cycles it should be possible to distinguish eccentricity from precession; GW200129 undergoes roughly half of a precession cycle in the detectors' sensitivity bands, while eccentricity appears at the orbital timescale. It would nonetheless be interesting to see an analysis that includes eccentricity.

(2) Parameter-estimation uncertainties. The results have several features that at first sight raise concerns. In preliminary parameter-estimation runs the one-dimensional posterior distribution functions for the masses were bi-modal, which is

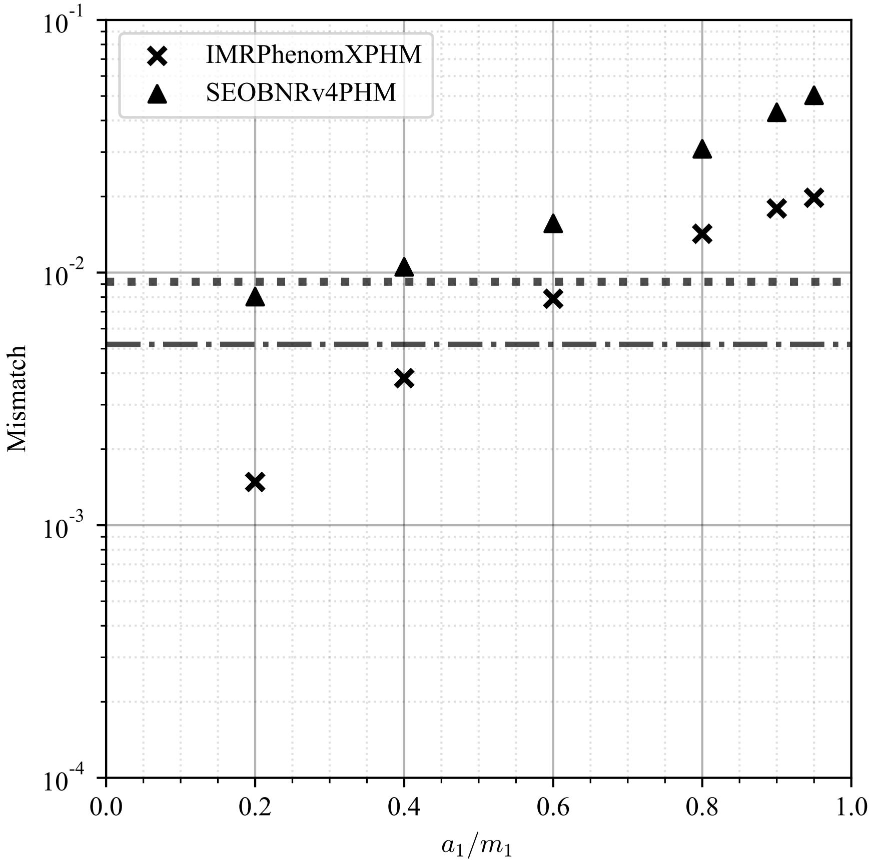

Fig. 5 Mismatches between theoretical signals (calculated using the `NRSur7dq4` model) against the `PhenomXPHM` and `SEOBNRv4PHM` models. The model parameters are those recovered from our analysis of GW200129, but with a range of values of the primary spin magnitude a_1/m_1. We see that neither model meets the accuracy thresholds for GW200129 at high spins, but the better agreement of `PhenomXPHM` is consistent with it recovering results closer to those reported in this work.

often a sign of a noise artefact, or that the MCMC method has not converged, or some other issue. However, we found that the results became much cleaner when the sampler was run for longer, and the final production run produced 1.93×10^5 samples. (By comparison with standard GW applications of the `LALinference` sampler, we would normally consider $\sim 10^4$ samples to be sufficient.) In the final results, the probability distribution for the binary's mass ratio has a tail that extends to equal masses. However, our astrophysical priors have a preference for equal masses, and so this result is not surprising, and, despite this prior preference, over 80% of the samples are at mass ratios above 1:1.35.

Another concern is the apparent "railing" of the spin measurement against extremal spin; this can also be a sign of noise issues. There have also been studies that suggest that the astrophysical prior and observational biases will pull the spin-magnitude measurement down to lower values, even if the source contains a highly spinning black hole [58]. However, in those studies the large spin was aligned with the orbital angular momentum, and the prior on the aligned-spin components has a strong preference for low spin. In our case, the priors on the spin magnitudes are flat.

Finally, we find that if we restrict the analysis to the Livingston and Virgo detectors, then a similar precessing configuration is recovered, but if we restrict to Hanford and Virgo, we recover a configuration closer to equal-mass, and with minimal precession. This suggests that the data in the Livingston and Hanford detectors may not be consistent.

To investigate these effects, we checked whether we would find similar results if the precessing-binary signal matching our preferred parameters were observed in a detector network with zero noise. We performed a parameter-estimation run on an idealised example of a theoretical signal from a binary with our best-estimate parameters (those with the maximum likelihood in our main parameter-estimation results), as it would be observed in a network of detectors with the same frequency-dependent sensitivity, but no noise. For this exercise we compared with an analysis on raw data, and starting at 30 Hz. We recovered parameters consistent with our measurements in real data: the spin-magnitude again “rails” against extreme spins and the mass-ratio measurement has a tail that extends towards equal-mass systems. In addition, we again find that precession is identified in the Livingston and Virgo detectors, but *not* when repeated with only the Hanford and Virgo detectors. This can be explained by the lower SNR in the Hanford detector: the precession SNR will be only $\sim$2.4 in that detector, and so difficult to distinguish from noise.

(3) Noise effects. The LVK analysis noted some noise artifacts near the time of the observation, but mitigation procedures were applied to the data, and these de-glitched data were used for the LVK analysis. We have analysed both the raw and de-glitched data, and find broadly consistent results. However, the support for precession is slightly *higher* in the raw data, and an interesting topic for future work would be to quantify more precisely the effect of the de-glitching procedures on the precession measurement. As a final consistency check, we also perform injections of the preferred waveform into data within 2 s of GW200129, and recovery of these signals also gives consistent results.

Data Availability. The posterior samples from the analyses performed in this work are available on Zenodo at https://zenodo.org/record/6672460. Public documentation is available at https://data.cardiffgravity.org/GW200129-precession/.

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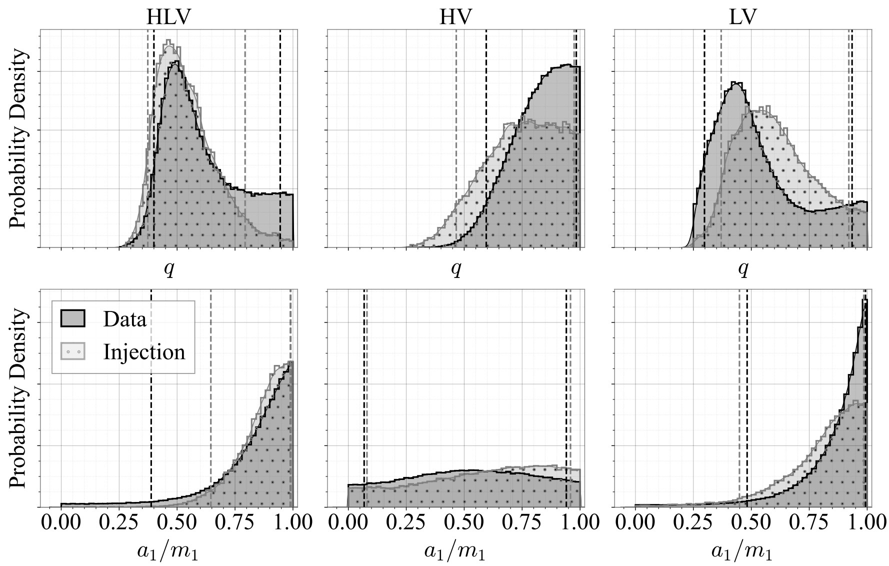

Fig. 6 One-dimensional posterior distributions for the primary black hole's spin, a_1/m_1, and the binary's mass ratio, $q = m_2/m_1 \leq 1$, from a parameter-estimation analysis of GW200129 in raw detector data starting at 30 Hz, and an idealised zero-noise injection. The main results for the three-detector network (left) are broadly consistent between the real data and the injection. We also find in both the real data and the injection that analysis of a Hanford-Virgo-only analysis (middle) prefers equal-mass binaries and much weaker evidence for precession, while a Livingston-Virgo-only analysis (right) identifies an unequal-mass precessing binary; this can be explained by the lower SNR in Hanford (14.6, vs 21.2 in Livingston), which reduces the measurability of precession.

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Plots were prepared with Matplotlib [59], GWpy [60] and PESUMMARY [61]. Parameter estimation was performed with the LALINFERENCE [40] and LALSIMULATION libraries within LALSUITE [62], as well as the BILBY [63, 64] and PBILBY Libraries [43] and the DYNESTY nested sampling package [44]. NUMPY [65], SCIPY [66] and POSITIVE [67, 68] were used during the analysis.

Author contributions

M.H. initiated and lead the study and writing of the text. C.H. and J.T. performed the parameter estimation calculations on the detector data, and the synthetic injections. J.T. performed the mismatch calculations. V.R. and S.F. provided valuable input to the analysis; V.R. verified the PE results and S.F. produced Fig. 3. M.H., C.H., J.T., S.F. and V.R. all contributed to the interpretation of the results and writing the paper. Although they did not directly contribute to the results presented here, the other authors contributed to the LVK's initial understanding of GW200129, which was the foundation of this work.