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Abbott, R.; LIGO Scientific Collaboration and Virgo Collaboration

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GW190521: A Binary Black Hole Merger with a Total Mass of 150 $M_\odot$

R. Abbott et al.*
(LIGO Scientific Collaboration and Virgo Collaboration)

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On May 21, 2019 at 03:02:29 UTC Advanced LIGO and Advanced Virgo observed a short duration gravitational-wave signal, GW190521, with a three-detector network signal-to-noise ratio of 14.7, and an estimated false-alarm rate of 1 in 4900 yr using a search sensitive to generic transients. If GW190521 is from a quasicircular binary inspiral, then the detected signal is consistent with the merger of two black holes with masses of $85_{-12}^{+14}$ $M_\odot$ and $66_{-18}^{+17}$ $M_\odot$ (90% credible intervals). We infer that the primary black hole mass lies within the gap produced by (pulsational) pair-instability supernova processes, with only a 0.32% probability of being below $65$ $M_\odot$. We calculate the mass of the remnant to be $142_{-16}^{+28}$ $M_\odot$, which can be considered an intermediate mass black hole (IMBH). The luminosity distance of the source is $5.3_{-2.6}^{+2.4}$ Gpc, corresponding to a redshift of $0.82_{-0.28}^{+0.34}$. The inferred rate of mergers similar to GW190521 is $0.13_{-0.11}^{+0.30}$ Gpc$^{-3}$ yr$^{-1}$.

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Introduction.—Advanced LIGO [1] and Advanced Virgo [2] have demonstrated a new means to observe the Universe through the detection of gravitational waves (GWs). In their first two observing runs (O1 and O2), the LIGO Scientific Collaboration and the Virgo Collaboration (LVC) have reported the detection of GWs from 10 binary black hole (BH) mergers, and a binary neutron star inspiral [3,4]. The third observing run (O3) started on April 1, 2019, and was suspended on March 27, 2020; numerous public alerts pertaining to possible detections have been sent to the astronomical community [5], with three confirmed detections [6–8].

The discovery of GW150914 [9] and subsequent events has revealed a population of binary BHs with total masses between ~19 and 84 $M_\odot$, with component masses ranging from ~8 to 50 $M_\odot$ [3]. Signals consistent with heavier BHs (e.g., $170817 + 03:02:46$UTC) have also been reported in [10–12], albeit with a non-negligible chance of having an instrumental origin. For the parametrized population models considered in [13] it was inferred that no more than 1% of primary BH masses in merging binaries are greater than 45 $M_\odot$.

In this Letter we expand this mass range with the confident detection of GW190521, a GW signal consistent with a binary BH merger of total mass $\sim 150$ $M_\odot$, leaving behind a $\sim 140$ $M_\odot$ remnant. Waveform models for quasicircular binary BHs indicate that a precessing orbital plane is slightly favored over a fixed plane. The observation of the ringdown signal from the remnant BH provides estimates for the final mass and spin that are consistent with those from the full waveform analysis.

It is predicted that stars with a helium core mass in the range of $\sim 32–64$ $M_\odot$ are subject to pulsational pair instability, leaving behind remnants with mass less than $\sim 65$ $M_\odot$. Stars with helium core mass in the range $\sim 64–135$ $M_\odot$ would be susceptible to pair instability and leave no compact remnant, while stars with helium mass $\gtrsim 135$ $M_\odot$ are thought to directly collapse to intermediate-mass BHs (IMBHs) [14–19]. The LVC O1-O2 observations are consistent with the prevention of heavy BH formation by pair-instability supernova (PISN) [13]. For GW190521, the mass of the heavier binary component has a high probability to be within the PISN mass gap [17,20–22]. In dense stellar systems or active galactic nuclei disks, BHs with mass in the PISN gap might form via hierarchical coalescence of smaller BHs [23–28], or via direct collapse of a stellar merger between an evolved star and a main sequence companion [29,30].

BHs of mass $10^2–10^5$ $M_\odot$, more massive than stellar mass BHs and lighter than supermassive BHs (SMBHs), are traditionally designated IMBHs [31–33]. A conclusive observation of these objects has thus far remained elusive, despite indirect evidence. These include observations of central BHs in galaxies, kinematical measurements of massive star clusters, scaling relations between the mass of the central SMBH and their host galaxies, and the mass range of globular clusters [34]. The LVC has also previously searched for binaries of IMBHs explicitly in their GW data, for example [35–37], obtaining null results and establishing an upper limit of 0.2 Gpc$^{-3}$ yr$^{-1}$ on their

*Full author list given at the end of the Letter.

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coalescence rate [38]. The remnant of GW190521 fulfills the above definition of an IMBH.

GW190521 was detected by searches for quasicircular binary coalescences, and there is no evidence in the data for significant departures from such a signal model. However, for any transient with high inferred masses, there are few cycles observable in ground-based detectors, and therefore alternative signal models may also fit the data. This is further addressed in the companion paper [39] that also provides details about physical parameter estimation, and the astrophysical implications of the observation of GWs from this massive system.

**Observation.**—On May 21, 2019 at 03:02:29 UTC, the LIGO Hanford (LHO), LIGO Livingston (LLO), and Virgo observatories detected a coincident transient signal. A matched-filter search for compact binary mergers, PyCBC LIVE [40,41,42], reported the transient with a network signal-to-noise ratio (SNR) of 14.5 and a false-alarm rate of 1 in 8 yr, triggering the initial alert. A weakly modeled transient search based on coherent wave burst (CWB) [43] in its IMBH search configuration [35] reported a signal with a network SNR of 15.0 and a false-alarm rate lower than 1 in 28 yr. Two other matched-filter pipelines, SPIIR [44] and GstLAL [45], found consistent candidates albeit with higher false-alarm rates. The identification, localization, and classification of the transient as a binary BH merger were reported publicly within ≈6 min, with the candidate name S190521g [46,47].

A second significant GW trigger occurred on the same day at 07:43:59 UTC, S190521r [48]. Despite the short time separation, the inferred sky positions of GW190521 and S190521r are disjointed at high confidence, and so the events are not related by gravitational lensing. Further discussions pertaining to gravitational lensing and GW190521 are presented in the companion paper [39].

GW190521, shown in Fig. 1, is a short transient signal with a duration of approximately 0.1 s and around four cycles in the frequency band 30–80 Hz. A frequency of 60 Hz at the signal peak and the assumption that the source is a compact binary merger imply a massive system.

**Data.**—The LIGO and Virgo strain data are conditioned prior to their use in search pipelines and parameter estimation analyses. During online calibration of the data [53], narrow spectral features (lines) are subtracted using auxiliary witness sensors. Specifically, we remove from the data the 60 Hz U.S. mains power signature (LIGO), as well as calibration lines (LIGO and Virgo) that are intentionally injected into the detectors to measure the instruments’ responses. During online calibration of Virgo data, broadband noise in the 40–1000 Hz frequency range is subtracted from the data [54]. The noise-subtracted data produced by the online calibration pipelines are used by online search pipelines and initial parameter estimation analyses.

Subsequent to the subtraction conducted within the online calibration pipeline, we perform a secondary offline subtraction [55] on the LIGO data with the goal of

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**FIG. 1.** The GW event GW190521 observed by the LIGO Hanford (left), LIGO Livingston (middle), and Virgo (right) detectors. Times are shown relative to May 21, 2019 at 03:02:29 UTC. The top row displays the time-domain detector data after whitening by each instrument’s noise amplitude spectral density (light blue lines); the point estimate waveform from the CWB search [43] (black lines); the 90% credible intervals from the posterior probability density functions of the waveform time series, obtained via Bayesian inference (LALInference [49]) with the NRSur7dq4 binary BH waveform model [50] (orange bands), and with a generic wavelet model (BayesWave [51], purple bands). The ordinate axes are in units of noise standard deviations. The bottom row displays the time-frequency representation of the whitened data using the Q transform [52].

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removing nonlinear sidebands around the U.S. mains power frequency, caused by low frequency modulation of the 60 Hz noise coupling. Since the subtraction of these sidebands is not expected to significantly improve the sensitivity of search algorithms, it is only used in offline parameter estimation of GW190521. Although GW190521 demonstrates a peak frequency of about 60 Hz, there is no evidence that the power mains contribute coherent power to the recovered signal. Voltage monitors and magnetometers installed at each LIGO site show no evidence of significant power fluctuations at the time of the event. These sensors are more sensitive to mains voltage transients than the interferometers are, detecting voltage fluctuations that are much smaller than those that produce transient noise in the strain data.

At the time of GW190521, the LHO, LLO, and Virgo detectors were observing in their nominal operational O3 state. Low-latency data quality checks [56] did not indicate any transient noise in the vicinity of this event. Four minutes after GW190521, LHO microphones recorded the sound of a nearby helicopter, which also affected the GW strain data. This noise does not impact the confidence of the detection and the affected data are not used for parameter estimation. More thorough analyses performed at higher latency [3,56] find no evidence that GW190521 is due to, or influenced by, instrumental or environmental noise.

To further confirm that GW190521 is not a noise artifact, we followed the treatment in [3,56] and investigated potential sources of nonstationary noise typically found in the same frequency band measured for GW190521. The false-alarm rates calculated by the search pipelines estimate the rate of random coincidences of all glitches from the analysis period. Subsequent evaluation of the background noise relevant to an event does not change its calculated false-alarm rate, but serves solely as an event validation procedure. During local daytime hours, the LLO detector exhibits nonstationary noise that is consistent with scattered light due to excess ground motion in the 1–10 Hz band [3]. It produces a variation of the detector noise below 50 Hz, appearing as a periodic sequence of short duration transients. A similar type of noise is also observed in the LHO detector but at significantly lower rate. GW190521 was detected at 03:02:29 UTC, at which time the 1–10 Hz ground motion was low and the GW strain data are not exhibiting the characteristic nonstationarity associated with excessive scattered light. Both detectors also exhibit populations of short duration, band-limited transients (blip glitches) [57,58], which often demonstrate a characteristic frequency of ~50 Hz. These transients are not found in coincidence between the LHO and LLO detectors (except by random occurrence) and GW190521 does not demonstrate the typical frequency-domain power distribution of blip glitches.

Detection significance.—After the identification by the low-latency analyses described above, GW190521 was also identified by offline analyses. These analyze strain data with improved calibration and updated data-quality vetoes, which are not available in low latency and hence update the low-latency results. The offline analyses use the CWB [43,59,60], GstLAL [45,61–65], and PyCBC [40,66–71] pipelines. CWB searches for short transient signals with minimal assumptions on their waveform. GstLAL and PyCBC search for coalescences of compact objects using matched filtering with banks of quasicircular, quadrupolar-mode-only, nonprecessing templates [72–78].

We performed the offline CWB analyses (see the Supplemental Material [79]) using two detector configurations: one restricted to the LIGO detectors, and one including Virgo as well. These two analyses identified GW190521 with network SNRs of 14.4 and 14.7, respectively, and with event parameters well within the limits defined by the analysis selection cuts. The LIGO-only analysis was used to establish the false-alarm rate for GW190521. The analysis including Virgo produced the waveform reconstruction. The GW190521 false-alarm rate was estimated from the analysis of time-shifted LIGO data. The background is equivalent to 9800 yr of observation and contains only two events ranked higher than GW190521, both consistent with random coincidences of short duration (~1 cycle) glitches observed in the LIGO frequency band 20–100 Hz. The estimated background results in a false-alarm rate of 1 in 4900 yr for GW190521, which constitutes a confident detection of a GW transient.

The offline analysis conducted by GstLAL (see the Supplemental Material [79]) identified GW190521 with a network matched-filter SNR of 14.7 and a false-alarm rate of 1 in 829 yr. The large difference in GstLAL significance reported by its online and offline configurations is due to an improvement in the template bank during O3 that greatly enhanced GstLAL’s sensitivity to mergers of high-mass compact objects.

The offline analysis performed by PyCBC (see Supplemental Material [79]) identified GW190521 with a network matched-filter SNR of 12.6 and a false-alarm rate of 1 in 0.94 yr. The smaller SNR and relatively high false-alarm rate are due to the sparseness of PyCBC’s template bank in the parameter region of GW190521, coupled with the fact that instrumental transients cause different high-mass templates to produce very different rates of high-SNR triggers. The Supplemental Material [79] describes PyCBC’s response to GW190521 in greater detail.

The most massive binary BH merger previously reported by the LVC, GW170729, had the same ordering of significances in CWB, GstLAL, and PyCBC as GW190521, and a simulation campaign showed that larger significances in CWB for such heavy BH mergers are not uncommon [3]. Matched-filter searches based on quasicircular nonprecessing templates and CWB have also been
compared using broader simulations of heavy BH mergers, including precession and higher-order multipole moments, also concluding that CWB is often more sensitive [80,81]. We performed a similar simulation campaign for GW190521 in order to further understand the different significances. We simulated thousands of signals compatible with the parameters inferred for the event under the assumption of a quasicircular BH merger, using the NRSur7dq4 waveform model described in the next section, which includes precession and higher-order multipole moments. The simulated sources have merger times distributed uniformly over several days surrounding GW190521, so as to sample many different realizations of the detector noise. The right ascensions have been correspondingly corrected in order to cancel the effect of Earth’s rotation, which would lead to different projections of the strain polarizations on the detectors. We added the signals into the data surrounding the event, reran the search pipelines with the same configuration used for the offline analysis, and counted the number of signals recovered by each pipeline. CWB, GstLAL, and PyCBC recovered, respectively, 36%, 45%, and 11% of the simulated signals at a false-alarm rate better than 1 in 4900 yr. The fraction of signals found at a false-alarm rate in CWB better than 1 in 4900 yr and a false-alarm rate in PyCBC worse than 1 in 0.94 yr is 2.7%, which is small but not negligible. The fraction found at a false-alarm rate in CWB better than 1 in 4900 yr and a false-alarm rate in GstLAL worse than 1 in 829 yr is 7.8%.

We conclude that the outputs of CWB, GstLAL, and PyCBC are fully consistent with expectations for a quasicircular binary merger signal with the parameters of GW190521. The reported false-alarm rates do not include a trials factor for the number of analyses performed. If one were to choose a single representative false-alarm rate, one should use the CWB rate multiplied by a trials factor of 3, resulting from the conservative assumption [37,38] that CWB, GstLAL, and PyCBC are equally sensitive and statistically independent. The resulting rate would still point to a significant detection.

**Astrophysical source.**—GW190521 is qualitatively different from previous detections [3,6–8] due to the small number of cycles and maximum frequency in the sensitive band of the detectors. Hence, its astrophysical interpretation as a quasicircular compact binary merger warrants more discussion than previous events. Alternative scenarios, such as an eccentric collision [82], become more relevant and are discussed in the companion paper [39]. Nevertheless, the quasicircular BH merger scenario remains the most plausible and we will proceed under this assumption in the rest of this Letter.

We performed Bayesian parameter inference on GW190521 using three waveform models for quasicircular binary BHs including the effects of higher order multipole moments and precession. These are the numerical relativity surrogate model NRSur7dq4 [50], the effective-one-body model SEOBNRv4PHM [83,84], and the phenomenological model IMRPhenomPv3HM [85]. To compute the evidence for the presence of higher-order modes, orbital precession and nonzero spin, we also compared the data with the aforementioned models after removing these effects from the models. We analyzed 8 s of data around the time of GW190521. We impose uniform priors on the redshifted component masses, on the individual spin magnitudes and on the square of the luminosity distance. We have checked that imposing an uniform-in-co-moving-volume prior changes the results by less than 1%. We impose an isotropic prior on the source and the spin orientations. We produce posterior distributions marginalized over calibration uncertainties. For the NRSur7dq4 and IMRPhenomPHM runs, we made use of the LALINFERENCe software package [49] while the SEOBNRv4PHM runs were done using the RIFT algorithm [86]. We find that despite differences in how these waveform models are computed, and the fact that we needed to sample over parameters outside their calibration regions [87], all yield broadly consistent results [39]. In addition, direct comparison of the data to numerical relativity simulations [88–90], using the RIFT algorithm, yields consistent results. In the following we quote results obtained using the NRSur7dq4 model. This choice is motivated by this being the only model that has been calibrated to numerical simulations of precessing BH

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Median Value</th>
<th>90% Credible Intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary mass</td>
<td>$85^{+21}<em>{-14}$ $M</em>\odot$</td>
<td></td>
</tr>
<tr>
<td>Secondary mass</td>
<td>$66^{+18}<em>{-17} M</em>\odot$</td>
<td></td>
</tr>
<tr>
<td>Primary spin magnitude</td>
<td>$0.69^{+0.37}_{-0.27}$</td>
<td></td>
</tr>
<tr>
<td>Secondary spin magnitude</td>
<td>$0.73^{+0.24}_{-0.36}$</td>
<td></td>
</tr>
<tr>
<td>Total mass</td>
<td>$150^{+29}<em>{-17} M</em>\odot$</td>
<td></td>
</tr>
<tr>
<td>Mass ratio ($m_2/m_1 \leq 1$)</td>
<td>$0.79^{+0.27}_{-0.29}$</td>
<td></td>
</tr>
<tr>
<td>Effective inspiral spin parameter ($\chi_{\text{eff}}$)</td>
<td>$0.08^{+0.36}_{-0.27}$</td>
<td></td>
</tr>
<tr>
<td>Effective precession spin parameter ($\chi_p$)</td>
<td>$0.68^{+0.37}_{-0.25}$</td>
<td></td>
</tr>
<tr>
<td>Luminosity Distance</td>
<td>$5.3^{+2.4}_{-2.6}$ Gpc</td>
<td></td>
</tr>
<tr>
<td>Redshift</td>
<td>$0.82^{+0.34}_{-0.28}$</td>
<td></td>
</tr>
<tr>
<td>Final mass</td>
<td>$142^{+28}<em>{-16} M</em>\odot$</td>
<td></td>
</tr>
<tr>
<td>Final spin</td>
<td>$0.72^{+0.12}_{-0.09}$</td>
<td></td>
</tr>
<tr>
<td>$P (m_1 &lt; 65 M_\odot)$</td>
<td>$0.32%$</td>
<td></td>
</tr>
<tr>
<td>log_{10} Bayes factor for orbital precession</td>
<td>$1.06^{+0.06}_{-0.06}$</td>
<td></td>
</tr>
<tr>
<td>log_{10} Bayes factor for nonzero spins</td>
<td>$0.92^{+0.06}_{-0.06}$</td>
<td></td>
</tr>
<tr>
<td>log_{10} Bayes factor for higher harmonics</td>
<td>$-0.38^{+0.06}_{-0.06}$</td>
<td></td>
</tr>
</tbody>
</table>
binaries. The NRSur7dq4 results are summarized in Table I. Results for all three models are presented in the companion paper [39].

Figure 2 shows our estimated 90% credible regions for the individual masses of GW190521. We estimate individual components with \((m_1, m_2) = (85^{+21}_{-14}, 66^{+17}_{-18}) M_\odot\) and a total mass \(150^{+29}_{-17} M_\odot\). This makes GW190521 the most massive binary BH observed to date, as expected from its short duration and low peak frequency. To quantify compatibility with the PISN mass gap, we find the probability of the primary component being below \(65 M_\odot\) to be 0.32%. The estimated mass and dimensionless spin magnitude of the remnant object are \(M_f = 142^{+28}_{-16} M_\odot\) and \(\chi_f = 0.72^{+0.09}_{-0.12}\) respectively. The posterior for \(M_f\) shows no support below \(100 M_\odot\), making the remnant the first conclusive direct observation of an IMBH.

The left panel of Fig. 3 shows the posterior distributions for the magnitude and tilt angle of the individual spins, measured at a reference frequency of 11 Hz. All pixels in this plot have equal prior probability. While we obtain posteriors with strong support at the \(\chi = 1\) limit imposed by cosmic censorship [91], these also show non-negligible support for zero spin magnitudes. In addition, the maximum posterior probability corresponds to large angles between the spins and the orbital angular momentum. Large spin magnitudes and tilt angles would lead to a strong spin-orbit coupling, causing the orbital plane to
The right panel of Fig. 3 shows the corresponding posterior distributions. We estimate $\chi_{\text{eff}} = 0.08^{+0.27}_{-0.36}$ and $\chi_p = 0.68^{+0.25}_{-0.37}$.

We evaluated the Bayesian evidence for both a precessing orbital plane and nonzero spin magnitudes by performing model selection with models omitting precession and spins. We obtain a log$_{10}$ Bayes factor of $1.06^{+0.06}_{-0.06}$ in favor of precessing versus nonprecessing spins and $0.92^{+0.06}_{-0.06}$ in favor of nonzero spin magnitudes versus zero magnitudes. This indicates a weak preference for both a spinning BBH and a precessing orbital plane, consistent with the large uncertainty in the spin parameters and the fact that the final spin, $\chi_f = 0.72^{+0.09}_{-0.12}$, is consistent with a nonspinning BBH [3]. Future analyses of GW190521 with improved wave-form models and more informed population priors may well shift the maximum probability to other regions of the spin parameter space.

We estimate the luminosity distance of GW190521 to be $5.3^{+2.4}_{-1.8}$ Gpc, corresponding to a redshift of $0.82^{+0.34}_{-0.34}$, assuming a $\Lambda$CDM cosmology with Hubble parameter $H_0 = 67.9$ km s$^{-1}$ Mpc$^{-1}$ [100]. Figure 4 shows the joint posterior distribution for the luminosity distance and the inclination angle between the total angular momentum of the binary and the line of sight, $\theta_{\text{PN}}$. We constrain $\sin(\theta_{\text{PN}}) < 0.79$ at the 90% credible level. Signals emitted at such inclinations are dominated by the quadrupolar $(2, \pm 2)$ modes [101–104]. Indeed, we obtain a log$_{10}$ Bayes factor of $-0.38^{+0.06}_{-0.06}$ disfavoring the presence of higher order multipole moments in the data. Despite this fact, as described in [105], models that include higher modes still lead to more precise estimates of the distance and inclination of the source. The reason is that higher modes are more prominent in signals with large inclination angles, especially when the signal is dominated by the merger and ringdown portions, thereby allowing us to discard those angles [103,104,106,107].

Given that GW190521 has only a few observable cycles, a barely observable inspiral, and shows no evidence for higher-order modes, we investigate what aspects of the signal can lead to a slight evidence for nonzero spins and a precessing orbital plane. To do this, we compare the posterior sample waveforms obtained by the analyses including and omitting precession. We find that the most prominent effect of precession is a slight amplitude suppression of the lowest-frequency part of the waveform, consistent with the amplitude modulation typically associated with precession [82,108,109]. Meanwhile, the spin degrees of freedom that most affect $\chi_f$ are encapsulated in $\chi_{\text{eff}}$ and not $\chi_p$ [110,111], so it is unlikely that our measurement of the final mass and spin informs $\chi_p$. Hence, the shift of the posteriors towards large spin magnitudes and tilt angles is more likely caused by the dynamics immediately prior to the merger, rather than postmerger features in the data.

Similarly, we have investigated how information about the mass ratio is being retrieved. We partially attribute this to the measurement of the remnant spin $\chi_f$ from information in the ringdown phase. This constrains the possible values of $q$ that can give rise to the measured $\chi_f$. In addition, the frequency at the signal peak amplitude [112,113], and the phase and amplitude evolution of the (suppressed) premerger signal can further constrain the measurement.

With only one such system so far confirmed, uncertainties on the formation channel and corresponding merger rate are necessarily very large. Under the simplifying assumption that the component masses and spins of GW190521 are representative of a population of merging binaries, we estimate a merger rate $0.13^{+0.30}_{-0.11}$ Gpc$^{-3}$ yr$^{-1}$ [39], consistent with the prior upper bounds set in [38].

Waveform reconstruction—GW190521 waveform reconstructions are obtained through a templated LALINFERE analysis [49], and two signal-agnostic analyses, CWB [43,114], and BayesWave [51,115]. Both signal-agnostic analyses reconstruct signal waveforms as a linear combination of wavelets: CWB obtains point estimate waveforms with the constrained maximum likelihood

![FIG. 4. Posterior distributions for the luminosity distance and the inclination angle of GW190521, according to the NRSur7dq4 waveform model. The inclination angle indicates the angle between the line-of-sight and the total angular momentum of the binary. For nonprecessing binaries, this is equal to the angle between the orbital angular momentum and the line of sight. We find the total angular momentum is likely to be closer to the line of sight than to the orthogonal direction. The solid lines and the central contour denote 90% credible regions.](image-url)
method while BayesWave reconstructs waveforms by drawing posterior samples from an unmodeled Bayesian analysis. Figure 1 shows broad agreement between the waveform reconstructions.

For a quantitative comparison of the CBW point estimate waveform \( w \) and the template \( h \), we calculate the overlap, or match \( \langle w|h \rangle/\sqrt{\langle w|w \rangle \langle h|h \rangle} \), where \( \langle w|h \rangle \) denotes the noise-weighted network inner product [116]. We randomly draw signals from the templated inference analysis, inject these into data surrounding GW190521, and reconstruct the injections with CBW. The overlaps between the simulated signals and the corresponding CBW reconstructions define the null distribution, which takes into account the waveform reconstruction errors and fluctuations of the detector noise. The median and 90% confidence interval for the null distribution are 0.93±0.03. The overlap between the CBW point estimate for GW190521 and the maximum-likelihood NRSur7dq4 template is 0.89 and is consistent with the null distribution.

The overlap [115] between the median BayesWave waveform and the maximum likelihood NRSur7dq4 template is 0.93. A signal residual test is performed by subtracting the maximum likelihood NRSur7dq4 template from the data and then searching for a residual signal using BayesWave [117]. The residual search result is compared to the distribution found from the analysis of the off-source data surrounding the event. This comparison results in a \( p \) value (as first described in [118]) of 0.4, indicating that the residual is fully consistent with noise.

**Black hole ringdown.**—We analyzed the ringdown portion of GW190521 using a damped sinusoid to fit the least-damped ringdown mode [119,120]. Starting 12.7 ms after the peak of the complex strain [corresponding to \( t_{\text{peak}} + 10G(1+z)M_t/c^3 \) in units of the redshifted remnant mass \( (1+z)M_t \) [121], using median values from the NRSur7dq4 approximant], the analysis estimates a frequency \( f = 66_{-3}^{+4} \) Hz and damping time \( \tau = 19_{-9}^{+9} \) ms, with a Bayes factor between signal and noise of \( \log_{10}(B_{s/n}) = 25.45 \pm 0.02 \). By imposing predictions of perturbation theory on the frequency of the GW emission [122] we infer the final redshifted mass and dimensionless spin to be \( (1+z)M_t = 252_{-64}^{+63} M_\odot \) and \( \chi_f = 0.65_{-0.48}^{+0.22} \). All quoted values correspond to median and 90% credible intervals. The grey contour in Fig. 5 shows the corresponding posterior two-dimensional 90% credible region. Accounting for redshift, these results are consistent with the full-waveform analysis when using NR fits to predict the remnant quantities [50,110,122–125]. The corresponding 90% credible region is shown in blue in the same Fig. 5. Additional detailed investigations are reported in the companion paper [39].

**Summary.**—GW190521 is a short duration signal consistent with a binary BH merger. According to state of the art models for quasicircular binaries, the progenitor BHs show mild evidence for nonzero spins and a precessing orbit, and the heavier component mass \( 85_{-14}^{+21} M_\odot \) sits in the PISN mass gap. The merger left behind a remnant with a final mass of \( 142_{-16}^{+28} M_\odot \), making this a direct observation of the formation of an IMBH. The large individual and total masses of GW190521, and the low likelihood that the primary originated from a stellar collapse given theoretical constraints on supernova physics, strongly suggest a different formation channel from BH binaries previously reported. The remnant ringdown signal is compatible with the full waveform analysis and general relativity. The short duration of GW190521 also invites other interpretations for the source. Further details on the properties of GW190521 are discussed in the companion paper, together with its astrophysical implications and possible formation channels [39]. As the low frequency sensitivity improves for Advanced LIGO and Advanced Virgo [126] further massive binary BH events should be observed. Third-generation ground-based GW detectors [127–129] and LISA [130] will be important instruments to study these systems. An event like GW190521 may be observable by both LISA and ground-based detectors, and observing the earlier inspiral is essential to improve our understanding of the source [131–134].
Strain data from the LIGO and Virgo detectors associated with GW190521, and supporting data for this Letter, can be found at [135].

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Note added.—Recently, a candidate optical counterpart to GW190521 was reported [138].

University of Białystok, 15-424 Białystok, Poland
King’s College London, University of London, London WC2R 2LS, United Kingdom
University of Southampton, Southampton SO17 1BJ, United Kingdom
University of Washington Bothell, Bothell, Washington 98011, USA
Institute of Applied Physics, Nizhny Novgorod, 603950, Russia
Ewha Womans University, Seoul 03760, South Korea
Inje University Gimhae, South Gyeongsang 50834, South Korea
National Institute for Mathematical Sciences, Daejeon 34047, South Korea
Ulsan National Institute of Science and Technology, Ulsan 44919, South Korea
Bard College, 30 Campus Rd, Annandale-On-Hudson, New York 12504, USA
Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland
Cornell University, Ithaca, New York 14850, USA
Université de Montréal/Polytechnique, Montreal, Quebec H3T 1J4, Canada
Lagrange, Université Côte d’Azur, Observatoire Côte d’Azur, CNRS, CS 34229, F-06304 Nice Cedex 4, France
Hillsdale College, Hillsdale, Michigan 49242, USA
Korea Astronomy and Space Science Institute, Daejeon 34055, South Korea
Institute for High-Energy Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands
NASA Marshall Space Flight Center, Huntsville, Alabama 35811, USA
University of Washington, Seattle, Washington 98195, USA
INFN, Sezione di Roma Tre, I-00146 Roma, Italy
ESPCI, CNRS, F-75005 Paris, France
Center for Phononics and Thermal Energy Science, School of Physics Science and Engineering, Tongji University, 200092 Shanghai, People’s Republic of China
Southern University and A&M College, Baton Rouge, Louisiana 70813, USA
Department of Physics, University of Texas, Austin, Texas 78712, USA
Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy
Centre Scientifique de Monaco, 8 quai Antoine Ier, MC-98000, Monaco
Indian Institute of Technology Madras, Chennai 600036, India
Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
INAF, Osservatorio Astronomico di Brera sede di Merate, I-23807 Merate, Lecco, Italy
Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, Netherlands
Kenyon College, Gambier, Ohio 43022, USA
Whitman College, 345 Boyer Avenue, Walla Walla, Washington 99362 USA
Hobart and William Smith Colleges, Geneva, New York 14456, USA
Department of Physics, Lancaster University, Lancaster, LA1 4YB, United Kingdom
OzGrav, Swinburne University of Technology, Hawthorn VIC 3122, Australia
Trinity University, San Antonio, Texas 78212, USA
Dipartimento di Fisica, Università degli Studi di Torino, I-10125 Torino, Italy
Indian Institute of Technology, Gandhinagar Ahmedabad Gujarat 382424, India
INAF, Osservatorio Astronomico di Brera sede di Merate, I-23807 Merate, Lecco, Italy
Centro de Astrofísica e Gravitação (CENTRA), Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal
Marquette University, 11420 West Clybourn Street, Milwaukee, Wisconsin 53233, USA
Indian Institute of Technology Hyderabad, Sangareddy, Khandi, Telangana 502285, India
INAF, Osservatorio di Astrofisica e Scienza dello Spazio, I-40129 Bologna, Italy
International Institute of Physics, Universidade Federal do Rio Grande do Norte, Natal RN 59078-970, Brazil
Villanova University, 800 Lancaster Avenue, Villanova, Pennsylvania 19085, USA
Andrews University, Berrien Springs, Michigan 49104, USA
Carleton College, Northfield, Minnesota 55057, USA
Department of Physics, Utrecht University, 3584CC Utrecht, Netherlands
Concordia University Wisconsin, 2800 North Lake Shore Drive, Mequon, Wisconsin 53097, USA