

GW231123: Binary black hole merger or cosmic string?Iuliu Cuceu^{1,*}, Marie Anne Bizouard^{1,†}, Nelson Christensen^{1,‡} and Mairi Sakellariadou^{2,1,§}¹*Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Artemis, 06300 Nice, France*²*Theoretical Particle Physics and Cosmology Group, Physics Department, King's College London, University of London, Strand, London WC2R 2LS, United Kingdom*

(Received 29 July 2025; accepted 22 December 2025; published 20 January 2026)

The LIGO-Virgo-KAGRA collaboration recently reported an exceptional gravitational-wave event, GW231123. This gravitational-wave signal was assumed to be generated from the merger of a binary black hole system, with source frame masses of $137^{+22}_{-17}M_{\odot}$ and $103^{+20}_{-52}M_{\odot}$ (90% credible intervals). As seen by the two LIGO detectors, the signal has only ~ 5 cycles, between 30 and 80 Hz, over ~ 10 ms. It is of critical importance to confirm the origin of this signal. Here we present the results of a Bayesian model comparison to test whether the gravitational-wave signal was actually generated by a binary black hole merger, or emitted from cusps or kinks on a cosmic string. We find significant evidence for a binary black hole merger origin versus a cosmic string origin of the signal.

DOI: [10.1103/zd8m-tzxd](https://doi.org/10.1103/zd8m-tzxd)

Introduction. The LIGO [1], Virgo [2], KAGRA [3] collaboration (LVK) has recently announced the detection of an intriguing gravitational-wave event, GW231123 [4]. GW231123 was observed by the two LIGO detectors at 13:54:30.634 UTC on November 23, 2023. Assuming that the signal comes from a compact binary coalescence, the LVK finds that this gravitational-wave event was produced by a binary black hole merger, with source frame masses of $137^{+22}_{-17}M_{\odot}$ and $103^{+20}_{-52}M_{\odot}$ (90% credible intervals). Such a massive binary black hole system poses many questions as to its formation. However, to determine that GW231123 is produced from a binary black hole is made difficult by the fact that only ~ 5 wave cycles are observed. This signal is present between 30 and 80 Hz, lasting ~ 10 ms in the LIGO data [4]. We note that the difficulties for parameter estimation with massive black hole binaries, where the gravitational-wave signal is brief in the detection band, have been addressed in many studies; see, for example, [5–8].

It is probable that in the future there will be other gravitational-wave signals of short duration. More massive binary black hole systems will be observable over shorter times and smaller frequency bands. It will be important to have methods for quantifying the probabilities of different

source models. We do this here, using different cosmic string emission channels, plus a more generic power-law signal emission. Ultimately, other short duration transient models will need to be included in model comparison studies. While the LVK makes the assumption that GW231123 comes from a binary black hole, it acknowledges other possible interpretations for the signal; eccentricity, gravitational lensing, core-collapse supernova, exotic compact objects, or cosmic strings. Since these alternative scenarios are not tested in [4], we investigate here whether a cosmic string could be the source of the GW231123 event.

Cosmic strings are $1+1$ dimensional topological defects, generically predicted in beyond the Standard Model particle physics [9]. Gravitational waves emitted by cosmic strings provide one of their most promising observational signatures accessible by ground-based interferometers [10,11]. Cosmic strings can be either superhorizon (long) or subhorizon (loops). At high frequencies, the gravitational-wave spectrum of an oscillating loop is dominated by bursts emitted by cusps and kinks [12–14]. Cusps are short-lived features on a string loop that briefly travel at the speed of light. The number of cusps per loop has not yet been determined; they are generic features for smooth loops. Kinks are discontinuities in the tangent vector of the string that propagate at the speed of light. Kinks, appearing in pairs, are the result of string intercommutations and therefore exist on long strings as well. Numerical experiments of Nambu-Goto strings (the width is negligible as compared to its size) concluded that kinks accumulate over the cosmological evolution [15–17]. Since long strings also have kinks, they can also emit gravitational waves [18]. Cusps create beamed gravitational waves

*Contact author: icuceu@oca.eu†Contact author: marianne.bizouard@oca.eu‡Contact author: nelson.christensen@oca.eu§Contact author: mairi.sakellariadou@kcl.ac.uk

in the forward direction of the cusp, while kinks produce gravitational waves with fanlike emission. In contrast, kink-kink collisions emit gravitational waves isotropically.

Previously, LIGO and Virgo reported the detection of a gravitational-wave signal, GW190521, which they also stated came from a binary black hole system [19,20]. Model comparison study results were presented, showing that the binary black hole merger scenario was favored over cosmic strings. In what follows, we present a Bayesian model comparison between a binary black hole and a cosmic string as potential sources of the GW231123 event. We conclude that the binary black hole origin of GW231123 is strongly favored over cosmic string.

Method. The data from the two LIGO detectors for the GW231123 event, from which identified noise such as the 60 Hz power mains and its harmonics has been subtracted, is publicly available at the Gravitational Wave Open Science Center [21,22]. We perform a Bayesian study [23] to compare two considered models. We actually compute the noise Bayes factor, comparing the hypothesis of a gravitational wave present in the detector noise ($\mathcal{H}_1$) to the case of only detector noise ($\mathcal{H}_2$),

$$\mathcal{BF} = \frac{\mathcal{Z}(\mathcal{H}_1)}{\mathcal{Z}(\mathcal{H}_2)}, \quad (1)$$

where the evidence $\mathcal{Z}$ is estimated with the nested sampling [24,25] package DYNesty [26,27], within the gravitational wave inference pipeline BILBY [28,29]. The nested sampler is initialized with 1000 live points and utilizes the acceptance-walk sampling method. The evidence is estimated under different hypotheses, outlined below. Given the lack of *a priori* information on the considered models, we assume equal prior odds, so in effect, both a binary black hole merger and a cosmic string origin are equally probable.

We consider a linearly polarized waveform expressed in the frequency domain as

$$h_i = \mathcal{A}_i \Theta(f - f_{\text{low}}) \Theta(f_{\text{high}} - f) e^{-2\pi i f t_A} f^{-q_i}, \quad (2)$$

where $i = \{\text{c, k, kk, pl}\}$ denotes respectively the cusp, kink, kink-kink collision cases, and a generic power law to capture a range of possible sources. The power-law indices q_i depend on the model, with [12–14] $q_c = 4/3$, $q_k = 5/3$, $q_{kk} = 2$, and q_{pl} kept free. The function $\mathcal{A}_i$ stands for amplitude, t_A is the arrival time defined relative to trigger time (1384782888.634 GPS time) in Figs. 1 and 2 below, f denotes the frequency, and Θ is the Heaviside function. The low frequency cutoff f_{low} is fixed at 20 Hz in this analysis to take into account the large rise of the noise at low frequencies. The high frequency cutoff f_{high} is a free parameter that, in the case of the cusp and kink models, is inversely proportional to the cube of the beaming angle,

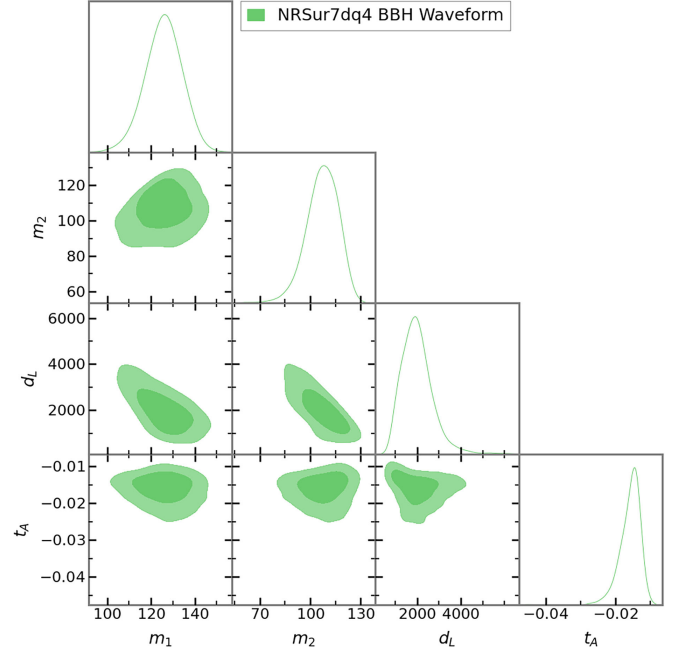


FIG. 1. A subset of source-frame and extrinsic parameters (component masses, luminosity distance, and relative-to-trigger arrival time) under the binary black hole merger event hypothesis with the NRSur7dq4 approximate, with 1- σ and 2- σ contours.

which is defined as the angle between the line of sight and the emission cone axis.

For the cosmic string models, we consider priors inspired from [30]. Specifically, the $\mathcal{A}_i$ samples are drawn from a log-uniform distribution, from 10^{-23} to 10^{-18} and the f_{high} is uniformly distributed starting from 25 to 2000 Hz for all cosmic string cases. The temporal and sky localization priors match [4]. For the arbitrary power-law spectral index, the prior is uniformly distributed between three different choices for the lower bound, to determine the impact of the prior choice on the posterior distribution, and four as the upper bound. We do not vary the priors for the amplitude because, for the range of spectral indices considered here, the lower end of the distribution is below sensitivity, complete noise dominance, and the higher end represents complete signal dominance, $\geq \mathcal{O}(3)$ signal-to-noise ratio (SNR). Similarly, the upper limit on the maximum frequency cutoff is limited by the detector's sensitivity decrease. The rest of the priors are already maximal which is why we do not explore any other prior variation's impact on the Bayes factor outside of the spectral index. The arbitrary specification of priors can influence Bayes factors [31]; prior sensitivity has long been known as one of the chief limitations for the calculation of Bayes factors [32].

For the binary black hole waveform approximant, we take NRSur7dq4 [33], and appropriate for the highly spinning high-mass compact binary coalescence scenario. We note that the LVK study used five different waveforms, but while IMRPhenomXO4a [34] is the approximant recovering the

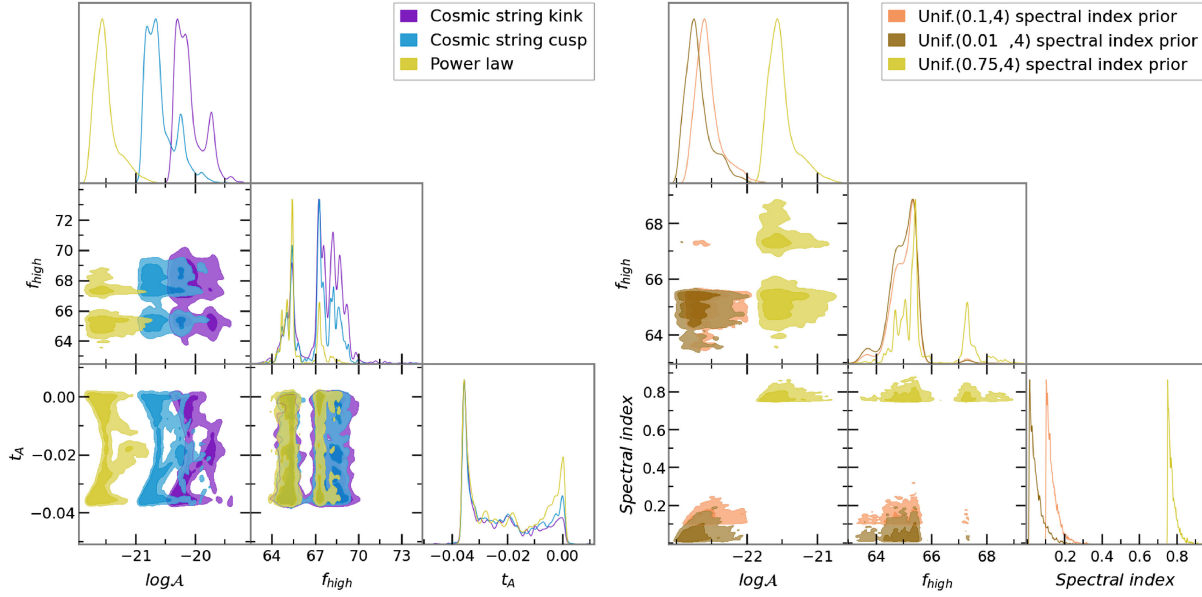


FIG. 2. Corner plots of posterior samples, for three models considered. Left: cosmic string kink (purple), cosmic string cusp (blue), and arbitrary power law (yellow), the log-amplitude, high frequency cutoff, and relative-to-trigger arrival time are shown, with 1- σ and 2- σ contours. The kink-kink model is also considered and consistent with the above posterior, but not shown here for brevity and plot clarity. Right: the arbitrary power law's spectral index is considered with three different uniform priors [starting at 0.01 (orange), 0.1 (brown), and 0.75 (yellow), respectively], the latter coinciding with the power law on the left. The extra freedom allowed with the power law model shows clear prior-dominated posteriors.

highest Bayes factor for GW231123, NRSur7dq4 is known for its accuracy in describing high-mass signals [4]. Although the choice of waveform approximant affects the parameter estimation scheme and subsequent evidence [4], the intramodel variability of binary black hole waveform approximants is insignificant compared to the inter-model variability of gravitational-wave sources in general. Furthermore, for the binary black hole model, we replicate the analysis performed in [4] with the only noteworthy difference being calibration error marginalization, which we do not include here. This affects the recovered SNR, but has a negligible impact on the parameter estimation; the results presented here for the binary black hole hypothesis are fully consistent with those presented by the LVK in [4].

Lastly, in order to illustrate the need for a Bayesian analysis as future, shorter events appear, we also present the results of an injection study. In the data around GW231123 we inject two different binary black hole signals, three seconds before trigger time (1384782885.634 GPS). They are recovered with binary black hole (NRSur7dq4 approximant) and cosmic string cusp hypotheses, using the same power spectral density estimate to facilitate a comparison with GW231123.

Results. Under the binary black hole source hypothesis, using the NRSur7dq4 waveform we recover consistent parameter posteriors with the equivalent waveform analysis of LVK for GW231123 [4], shown in Fig. 1. A binary black hole merger with masses of $m_1 = 125.98^{+13.5}_{-14.6} M_\odot$

and $m_2 = 107.77^{+14.1}_{-17.3} M_\odot$, at a luminosity distance $d_L = 1932^{+1339}_{-952}$ Mpc, provides the highest SNR, as seen in Table I, alongside models' Bayes factors. These binary black hole merger parameter estimates are consistent with the estimates made by the LVK using the NRSur7dq4 waveform alone; $m_1 = 129^{+15}_{-14} M_\odot$, and $m_2 = 111^{+14}_{-17} M_\odot$, $d_L = 1500^{+1500}_{-800}$ Mpc [21].

For cosmic strings, the cusp, kink, and kink-kink collision cases result in high frequency cutoff posteriors, $f_{\text{high,cusp}} = 67.3^{+1.6}_{-2.6}$ Hz, $f_{\text{high,kink}} = 67.6^{+1.6}_{-2.8}$ Hz, and $f_{\text{high,kink-kink}} = 67.9^{+3.2}_{-3.2}$ Hz, respectively. They are shown in Fig. 2 (left panel), consistent with the merger frequency of a $\sim 200 M_\odot$ binary black hole coalescence. This trend is also observed in the power-law posteriors, displayed in

TABLE I. The $\log_{10}$ Bayes factor between the waveform model considered and the noise (no-signal) hypothesis, as well as network matched filtering signal to noise ratios are reported below. The values for the power law correspond to the uniform (0.75, 4) spectral index prior analysis.

Waveform model	$\log \mathcal{BF}$	SNR
Binary black hole	82.13	$21.01^{+0.2}_{-0.3}$
Cusp	38.02	$14.65^{+0.1}_{-0.3}$
Kink	30.91	$13.59^{+0.1}_{-0.3}$
Kink-kink	24.40	$12.41^{+0.2}_{-0.4}$
Power-law	45.23	$16.16^{+0.1}_{-0.3}$

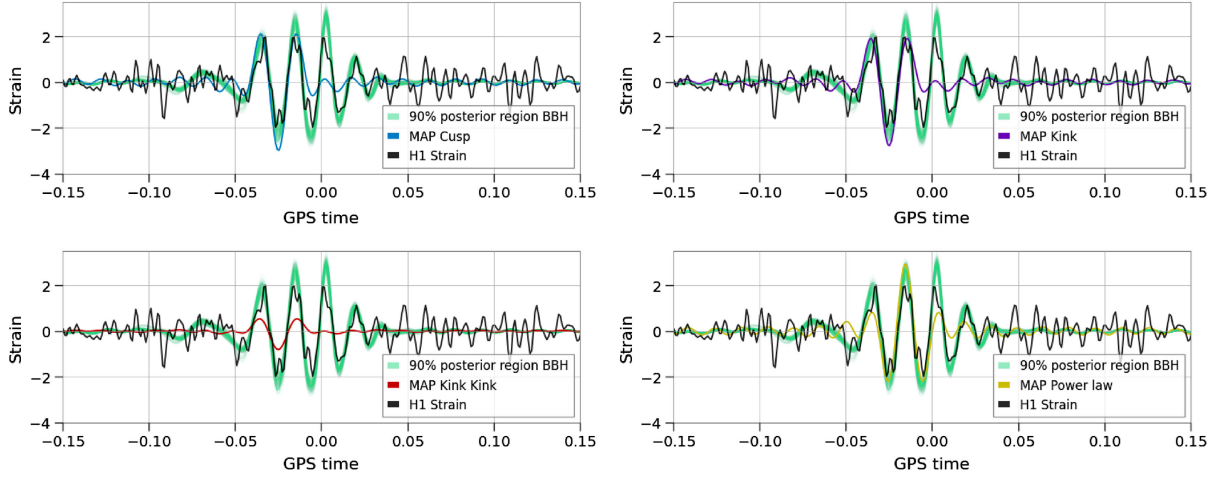


FIG. 3. Best-fitting cosmic string cusp waveform (blue) and the LIGO Hanford detector strain (black) are shown in the upper left plot. The upper right is the same for kink waveform (purple), the lower left is the kink kink waveform (red), and the lower right is the power law with 0.75 lower limit on the spectral index prior (yellow). All data in these plots is whitened with the BayesWave power spectral density [35] and bandpassed between 20–256 Hz. The 90% confidence region of the NRSur7dq4 binary black hole waveform template is superimposed (green). The whitening and spectral leakage (time representation of frequency-domain defined models) are the reasons for the extra oscillations observed in the cosmic string and power law models. The X axis is relative to GW231123 trigger time.

Fig. 2 (right panel). The power-law model leads to the highest Bayes factor for a source different from a binary black hole merger, compared to noise. This is expected, since the extra degree of freedom included, with a clear predilection for lower spectral index values, outweighs the prior space expansion, in comparison with the fixed indices in the cusp, kink, and kink-kink waveforms. Figure 2 (right panel) shows the posteriors for the power-law hypothesis, with different priors for the spectral index. These prior-dominated posteriors, with a preference for the lowest spectral index, explain the inclination of the data for the cusp over the kink case.

The mismatch between cosmic strings' prediction and data is shown in Fig. 3 in the time domain. We present the highest likelihood cosmic string cusp match, against the detector strain and 90% confidence interval for the NRSur7dq4 approximant. The frequency domain power law shape for cosmic strings results in a ~ 3 cycle time domain waveform. These cycles can then be used to fit only around half of the observed strain, which results in a bimodal posterior for the arrival time. This effect is again observed in both cusp and kink cases, to a lesser extent in the latter, as well as in the spectral index-varying generic power law waveform, where it is most prominent. In

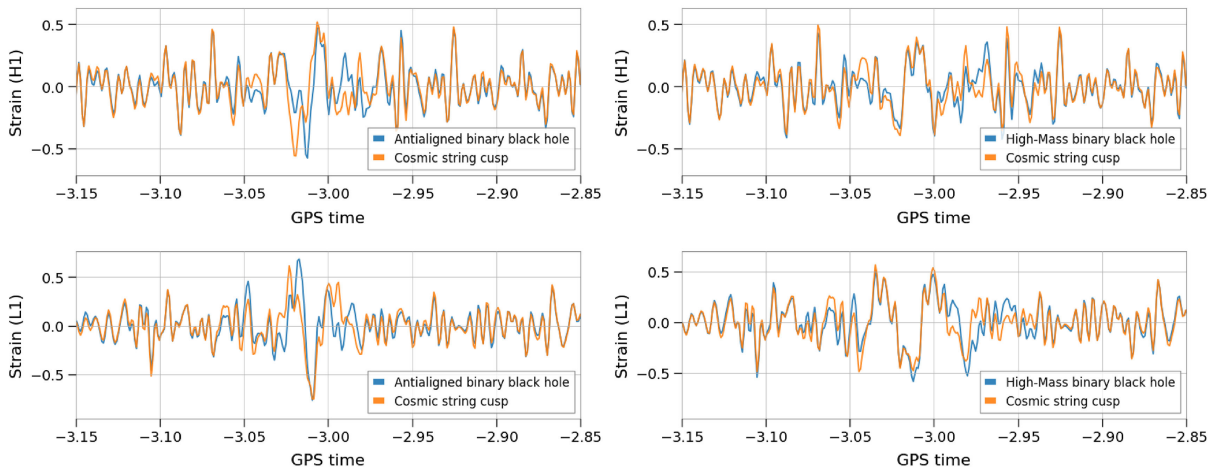


FIG. 4. Representative strains displaying the plausible confusion between signals. On the left, per-detector whitened strains of an antialigned binary black hole (blue) injection ($\theta_1 = 3.12$, $\theta_2 = 3.1$) with the rest of the parameters equivalent to the maximum *a posteriori* (MAP) of GW231123 using NRSur7dq4. On the right, per-detector whitened strains of a higher mass binary black hole system ($\mathcal{M} = 246M_\odot$ and $d_L = 3000$ Mpc), with the rest of the parameters equivalent to MAP of GW231123. Overlaid are some strikingly similar cosmic string models (orange). The X axis is relative to GW231123 trigger time.

contrast, the arrival time bimodality is completely non-existent under the binary black hole merger hypothesis, as shown in Fig. 1.

We note that the cosmic string and power law waveforms considered here do provide an SNR above the ~ 8 threshold, and decisive evidence against the only-noise hypothesis and therefore the existence of “a signal.” However, when compared to the best matching binary black hole waveform, they are in turn decisively disfavored.

Finally, Fig. 4 shows the per-detector whitened strains, for the injection study. The injected binary black hole (blue waveforms) parameters are the maximum *a posteriori* (MAP) of the real data’s Bayesian inference with the NRSur7dq4 waveform, with an exception: on the left, the spins are antialigned ($\theta_1 = 3.12$, $\theta_2 = 3.1$), while on the right the chirp mass is increased ($\mathcal{M} = 246M_\odot$), as well as $d_L = 3000$ Mpc, to maintain comparative SNRs. Both of these changes result in a similar number of cycles in the observed waveform. Overlaid are representative cosmic string cusp waveforms, in orange (left cusp, $\mathcal{A} = 3 \times 10^{-21}$, $f_{\text{high}} = 54$ Hz; right cusp, $\mathcal{A} = 3 \times 10^{-21}$, $f_{\text{high}} = 45$ Hz). After a full Bayesian analysis, the antialigned binary black hole injection results in $\log_{10}$ Bayes factors between the binary black hole and cosmic string cusp hypotheses of 8.4. For the high-mass injection, the corresponding $\log_{10}$ Bayes factor is 8.1.

Conclusions. We have presented a Bayesian model comparison analysis in order to substantiate the source identification of GW231123 as a binary black hole merger [4]. To this end, we have considered the three main emission channels for gravitational waves produced by cosmic strings in addition to the assumed binary black hole compact binary coalescence event. To further facilitate this comparison, inspired by the power-law-like frequency domain representation of all cosmic string waveform models, a freely varying spectral index, generic power law, is also considered. Our analysis is similar to the study of the source of GW190521 [19], where a Bayesian model compared a binary black hole scenario with a cosmic string origin (cusp and kink), showing preference for the binary black hole [20].

For both GW190521 and GW231123, the observed waveform consists of only ~ 5 cycles. Although power-law-like sources, such as cosmic strings, generically produce even fewer cycles, a visual heuristic is not a substitute for a full Bayesian analysis. The apparent cycle count depends on data conditioning (e.g., through whitening) and on moderate, physically plausible shifts of the binary black hole parameters. To illustrate this, we have presented an injection study by varying the binary black

hole spins and masses. In the future, events of even shorter duration could be observed. Likelihood-based model comparison is therefore necessary to adjudicate among all possible source origins. This is a subject of future work.

Acknowledgments. This research has made use of data [22] or software obtained from the Gravitational Wave Open Science Center [36], a service of the LIGO Scientific collaboration, the Virgo collaboration, and KAGRA. This material is based upon work supported by NSF’s LIGO Laboratory which is a major facility fully funded by the National Science Foundation, as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. Virgo is funded, through the European Gravitational Observatory (EGO), by the French Centre National de Recherche Scientifique (CNRS), the Italian Istituto Nazionale di Fisica Nucleare (INFN), and the Dutch Nikhef, with contributions by institutions from Belgium, Germany, Greece, Hungary, Ireland, Japan, Monaco, Poland, Portugal, and Spain. K. A. G. R. A. is supported by Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan Society for the Promotion of Science (JSPS) in Japan; National Research Foundation (NRF) and Ministry of Science and ICT (MSIT) in Korea; Academia Sinica (AS) and National Science and Technology Council (NSTC) in Taiwan. The authors are grateful for computational resources provided by the LIGO Laboratory and supported by the National Science Foundation Grants No. PHY-0757058 and No. PHY-0823459. M. S. acknowledges support from the Science and Technology Facility Council (STFC), UK, under the Research Grant No. ST/X000753/1. This work was supported by the French government through the France 2030 investment plan managed by the National Research Agency (ANR), as part of the Initiative of Excellence of Université Côte d’Azur under Reference No. ANR-15-IDEX-01. This material is based upon work supported by NSF’s LIGO Laboratory which is a major facility fully funded by the National Science Foundation.

This manuscript was assigned LIGO-Document No. LIGO-P2500447.

Data availability. The data that support the findings of this article are openly available [21].

- [1] J. Aasi *et al.* (LIGO Scientific Collaboration), Advanced LIGO, *Classical Quantum Gravity* **32**, 074001 (2015).
- [2] F. Acernese *et al.* (Virgo Collaboration), Advanced Virgo: A second-generation interferometric gravitational wave detector, *Classical Quantum Gravity* **32**, 024001 (2015).
- [3] T. Akutsu *et al.* (KAGRA Collaboration), Overview of KAGRA: Detector design and construction history, *Prog. Theor. Exp. Phys.* **2021**, 05A101 (2021).
- [4] A. G. Abac *et al.* (LIGO Scientific, Virgo, and KAGRA Collaborations), GW231123: A binary black hole merger with total mass $190 - 265 M_{\odot}$, *Astrophys. J. Lett.* **993**, L25 (2025).
- [5] T. B. Littenberg, J. G. Baker, A. Buonanno, and B. J. Kelly, Systematic biases in parameter estimation of binary black-hole mergers, *Phys. Rev. D* **87**, 104003 (2013).
- [6] S. Vitale and M. Evans, Parameter estimation for binary black holes with networks of third generation gravitational-wave detectors, *Phys. Rev. D* **95**, 064052 (2017).
- [7] A. Ramos-Buades, A. Buonanno, and J. Gair, Bayesian inference of binary black holes with inspiral-merger-ring-down waveforms using two eccentric parameters, *Phys. Rev. D* **108**, 124063 (2023).
- [8] S. Biscoveanu, M. Isi, V. Varma, and S. Vitale, Measuring the spins of heavy binary black holes, *Phys. Rev. D* **104**, 103018 (2021).
- [9] R. Jeannerot, J. Rocher, and M. Sakellariadou, How generic is cosmic string formation in SUSY GUTs, *Phys. Rev. D* **68**, 103514 (2003).
- [10] B. P. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), Constraints on cosmic strings using data from the first Advanced LIGO observing run, *Phys. Rev. D* **97**, 102002 (2018).
- [11] R. Abbott *et al.* (LIGO Scientific, Virgo, and KAGRA Collaboration), Constraints on cosmic strings using data from the third Advanced LIGO–Virgo observing run, *Phys. Rev. Lett.* **126**, 241102 (2021).
- [12] T. Damour and A. Vilenkin, Gravitational wave bursts from cosmic strings, *Phys. Rev. Lett.* **85**, 3761 (2000).
- [13] T. Damour and A. Vilenkin, Gravitational wave bursts from cusps and kinks on cosmic strings, *Phys. Rev. D* **64**, 064008 (2001).
- [14] T. Damour and A. Vilenkin, Gravitational radiation from cosmic (super)strings: Bursts, stochastic background, and observational windows, *Phys. Rev. D* **71**, 063510 (2005).
- [15] D. P. Bennett and F. m. c. R. Bouchet, Evidence for a scaling solution in cosmic-string evolution, *Phys. Rev. Lett.* **60**, 257 (1988).
- [16] B. Allen and E. P. S. Shellard, Cosmic-string evolution: A numerical simulation, *Phys. Rev. Lett.* **64**, 119 (1990).
- [17] M. Sakellariadou and A. Vilenkin, Cosmic-string evolution in flat spacetime, *Phys. Rev. D* **42**, 349 (1990).
- [18] M. Sakellariadou, Gravitational waves emitted from infinite strings, *Phys. Rev. D* **42**, 354 (1990); **43**, 4150(E) (1991).
- [19] R. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), GW190521: A binary black hole merger with a total mass of $150 M_{\odot}$, *Phys. Rev. Lett.* **125**, 101102 (2020).
- [20] R. Abbott *et al.* (LIGO Scientific and Virgo Collaboration), Properties and astrophysical implications of the $150 M_{\odot}$ binary black hole merger GW190521, *Astrophys. J. Lett.* **900**, L13 (2020).
- [21] LVK, GWOSC DATA GW231123, [10.7935/anj7-6q40](https://arxiv.org/abs/10.7935/anj7-6q40).
- [22] R. Abbott *et al.* (KAGRA, Virgo, and LIGO Scientific Collaborations), Open data from the third observing run of LIGO, Virgo, KAGRA, and GEO, *Astrophys. J. Suppl. Ser.* **267**, 29 (2023).
- [23] N. Christensen and R. Meyer, Parameter estimation with gravitational waves, *Rev. Mod. Phys.* **94**, 025001 (2022).
- [24] J. Skilling, Nested sampling, *AIP Conf. Proc.* **735**, 395 (2004).
- [25] J. Skilling, Nested sampling for general Bayesian computation, *Bayesian Anal.* **1**, 833 (2006).
- [26] J. S. Speagle, DYNESTY: A dynamic nested sampling package for estimating Bayesian posteriors and evidences, *Mon. Not. R. Astron. Soc.* **493**, 3132 (2020).
- [27] S. Koposov *et al.*, joshspeagle/DYNESTY: v2.1.0, (2023), [10.5281/zenodo.7600689](https://arxiv.org/abs/10.5281/zenodo.7600689).
- [28] G. Ashton *et al.*, BILBY: A user-friendly Bayesian inference library for gravitational-wave astronomy, *Astrophys. J. Suppl. Ser.* **241**, 27 (2019).
- [29] I. M. Romero-Shaw *et al.*, Bayesian inference for compact binary coalescences with BILBY: Validation and application to the first LIGO–Virgo gravitational-wave transient catalogue, *Mon. Not. R. Astron. Soc.* **499**, 3295 (2020).
- [30] A. K. Divakarla, E. Thrane, P. D. Lasky, and B. F. Whiting, Memory effect or cosmic string? Classifying gravitational-wave bursts with Bayesian inference, *Phys. Rev. D* **102**, 023010 (2020).
- [31] A. J. K. Chua and M. Vallisneri, On parametric tests of relativity with false degrees of freedom, [arXiv:2006.08918](https://arxiv.org/abs/2006.08918).
- [32] R. E. Kass and A. E. Raftery, Bayes factors, *J. Am. Stat. Assoc.* **90**, 773 (1995).
- [33] V. Varma, S. E. Field, M. A. Scheel, J. Blackman, D. Gerosa, L. C. Stein, L. E. Kidder, and H. P. Pfeiffer, Surrogate models for precessing binary black hole simulations with unequal masses, *Phys. Rev. Res.* **1**, 033015 (2019).
- [34] J. E. Thompson, E. Hamilton, L. London, S. Ghosh, P. Kolitsidou, C. Hoy, and M. Hannam, PhenomXO4a: A phenomenological gravitational-wave model for precessing black-hole binaries with higher multipoles and asymmetries, *Phys. Rev. D* **109**, 063012 (2024).
- [35] T. Gupta and N. J. Cornish, Bayesian power spectral estimation of gravitational wave detector noise revisited, *Phys. Rev. D* **109**, 064040 (2024).
- [36] <https://gwosc.org/>