Current observations are insufficient to confidently associate the binary black hole merger GW190521 with AGN J124942.3 + 344929

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Abstract
Recently, Graham et al (2020 arXiv:2006.14122) identified ZTF19abanrhrr as a candidate electromagnetic counterpart to the binary black hole merger GW190521. The authors argue that the observations are consistent with a kicked binary black hole interacting with the accretion disk of the active galactic nucleus AGN J124942.3 + 344929. If a real association (rather than happenstance), this has implications for the sources of LIGO/Virgo binary mergers, future prospects for electromagnetic counterparts, and measurements of the expansion rate of the Universe. In this work, we provide an analysis of the multi-messenger coincident-significance based on the localisation overlap and find that, under optimistic assumptions, the odds of a common source for GW190521 and ZTF19abanrhrr range between 1 and 12. These odds are strongly dependent on the waveform model and, with current models, are unable to consistently capture both the effects of precession and orbital eccentricity. We consider this insufficient evidence to warrant confidently associating GW190521 with ZTF19abanrhrr and hence caution against any astrophysical conclusions based on the association.

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(Some figures may appear in colour only in the online journal)

1. Introduction

GW190521 is a high-mass binary black hole merger observed by the LIGO [1] and Virgo [6] gravitational wave detectors [4]. First announced as the public trigger S190521g, this event is exceptional due to its large mass and signatures of precession and eccentricity [4, 20, 36]. The public alert allowed the rapid follow-up of the candidate by optical telescopes; of these, ZTF, the Zwicky transient facility [10, 24] reports a candidate counterpart, ZTF19abanrhr. The counterpart is confirmed to be a flare from the active galactic nuclei (AGN) J124942.3 + 344929. The flare, which begins approximately 26 days after the merger of GW190521, is argued to be caused by the remnant black hole, kicked through the accretion disk of the AGN [27].

If GW190521 can be confidently associated with ZTF19abanrhr, this would be the first association of an electromagnetic counterpart to a binary black hole merger [33]; although a weak, short electromagnetic transient was observed 0.4 s after GW150914 [17]. This has significant implications: the identification of the host AGN, which has a well-measured spectroscopic redshift $z = 0.438 \pm 0.00003$ allows a new standard-candle measurement of the Hubble constant [15, 19, 21, 28, 44] comparable to that of GW170817 [2]. In addition, it has implications for the study of the gaseous accretion disk surrounding the AGN and the population properties of the compact binary systems observed by LIGO/Virgo [27, 43]. But, these implications depend on confidently associating ZTF19abanrhr with GW190521.

In this work, we quantify the association. We calculate the probability of a common-source hypothesis (i.e. a binary black hole merger followed by an AGN flare due to the McKernan et al [27] mechanism) between GW190521 and ZTF19abanrhr based on the source luminosity and sky localisation. Our study is limited by the availability of models (see section 4). Nevertheless, given the scientific impact of the putative association, we seek to quantify the odds with the available information. Ultimately, the question of whether the observations are due to a common source will best be answered by future observations; Graham et al [23] make a verifiable prediction of a repeat flare within the next few years. Nevertheless, we hereby aim to make a statement based solely on the initial observations themselves as to whether the two can be confidently associated. We review the Bayesian coincident detection significance method [7] in section 2, provide results in section 3 before concluding in section 4.

2. Method

GW190521 and ZTF19abanrhr are individually confident detections. But, what is the probability they have a common source compared to the probability that they amount to a random coincidence? Answering this question, in general, depends on two aspects. First, the physics,
how plausible are models which predict an AGN flare due to a kicked binary black hole and what are the rates of those compared with other phenomena which could also explain the data? Second, does the data support the notion that they arise from a common source? To answer the second question, Graham et al [23] applied a p-value approach common in the literature to multi-messenger significance see, e.g. [3]. They estimate the probability that the event is a random coincidence alone. Here, we instead apply a Bayesian approach based on Ashton et al [7] which seeks to compare the probability that they do have a common source to the probability that they are a random coincidence (see Budavári [11], Budavári and Loredo [12], Budavári and Szalay [13], Naylor et al [29] for other similar approaches). We will not attempt to address the first question, the physical plausibility of the model, but instead, focus only on whether the observations have a common source.

We define two hypotheses. First, a common-source hypothesis, $C$ in which the binary black hole merger and the remnant causes the AGN flare; second, a random coincidence hypothesis, $R$, in which the binary black hole merger and AGN flare are entirely separate events. The ratio of the probabilities comparing these two hypotheses is then given in the usual way see, e.g. [39] by the odds:

$$O_{C/R} \equiv \frac{\pi(C|d_{GW}, d_{EM}, I)}{\pi(R|d_{GW}, d_{EM}, I)} \frac{\pi_C}{\pi_R}.$$  \hfill (1)

The first factor here, is the Bayes factor; the ratio of probabilities for the two hypotheses conditional on the two gravitational-wave and electromagnetic data sets $d_{GW}$ and $d_{EM}$ and any cogent prior information $I$. The second factor is the prior-odds, $\pi_{C/R} \equiv \pi(C|I)/\pi(R|I)$: the ratio or probabilities for the two hypotheses based solely on the prior information.

The prior odds are subjective and depend on arguments as to the plausibility of the proposed mechanisms by which a binary black hole merger can produce an electromagnetic counterpart. Later, in section 3, we estimate the prior odds using the simulation studies performed by Graham et al [23]; we will then discuss the sensitivity of our conclusions to this prior choice in section 4.

Binary black hole merger models and the McKernan et al [27] AGN flare model share a set of common parameters which we use to calculate the Bayes factor comparing a common-source with a random coincidence hypothesis. If the two observations arise from a common source, they should have a common luminosity distance $D_L$ and sky location $\Omega$ (specifically, we define $\Omega$ in coordinates of right ascension and declination). Intuitively then, we want to quantify how well the posterior distributions for these i.e.figure 1 of reference [23] agree. We use this set of common-model parameters $D_L$ and $\Omega$ to quantify the Bayes factor.

The odds are then calculated from

$$O_{C/R} = \pi_{C/R} I_{D_L, \Omega} \approx \pi_{C/R} I_{D_L} I_{\Omega},$$  \hfill (2)

where $I_{D_L, \Omega}$ is the combined, while $I_{D_L}$ and $I_{\Omega}$ are the separate posterior overlap integrals [7]. Defining $\theta = \{D_L, \Omega\}$ to be the set of common model parameters used in this analysis, the posterior overlap integral is given by

$$I_\theta = \int \frac{p(\theta|d_{GW}, C)p(\theta|d_{EM}, C)}{\pi(\theta|C)} d\theta,$$  \hfill (3)

where the numerator is the product of the two posterior distributions while $\pi(\theta|C)$ is the common-source hypothesis prior (for this analyses, we set $\pi(\theta|C)$ to the astrophysical prior distribution used in the original analysis [5]).
The factorisation in equation (2) into separate sky and distance components effectively discards information from the coincidence calculation about any correlations between \( \Omega \) and \( D_L \). These parameters are not believed to be strongly correlated, so this is likely a robust approximation, an assumption we validate in section 3.4.

ZTF19abanrhr is localized significantly better than the gravitational-wave source; the right ascension, declination of ZTF19abanrhr and the redshift of the AGN have sub-percentile relative uncertainties. If we treat the posterior distribution condition on \( d_{EM} \) as a delta-function at the transient sky location \( \Omega' \) and AGN luminosity distance \( D'_L \) and assume a fixed cosmology, then the odds simplifies to

\[
O_{C/R} = \pi_{C/R} \frac{p(D_L', \Omega|d_{GW}, C)}{\pi(D'_L, \Omega'|C)} = \pi_{C/R} I_{D_L, \Omega} \tag{4}
\]

\[
\approx \pi_{C/R} \frac{p(D_L'|d_{GW}, C) p(\Omega'|d_{GW}, C)}{\pi(\Omega'|C)} = \pi_{C/R} I_{D_L} I_{\Omega}. \tag{5}
\]

In section 3, we provide details of how each term is calculated and validate the assumption made in deriving equation (5).

Within the framework we use [7], it is simple to include additional common-model parameters (e.g. additional multiplicative terms for the temporal coincidence between the merger and flare, \( I_t \), or the remnant kick velocity, \( I_k \) could be included in equation (5)). The amount by which these terms change the overall odds is proportional to how well the joint data constrains the parameters relative to their prior uncertainty. The remnant kick velocity is poorly constrained by the gravitational-wave data [5] and the uncertainty is not qualified by the modelling of the AGN kick model [23]. Given these considerations, we expect that \( I_k \sim 1 \), though a detailed model, including the uncertainty on the kick velocity, is required to quantify this. Similarly, the temporal coincidence \( I_t \) between GW190521 and ZTF19abanrhr does not provide meaningful insight. In Ashton et al [7], it was shown that \( I_t \) is the ratio of the time between the events and the maximum believable time window in which the two events could be considered ‘coincident’. McKernan et al [27] and Graham et al [23] predict timescales of between days to weeks between the merger and flare while the actual time between the events was 26 d. As such, the temporal overlap factor is \( I_t \sim 1 \). As long as the model makes broad predictions (which are consistent with the data), the temporal coincidence and the information available from the kick velocity will remain inconclusive. Hence, we neglect the temporal association and information about the kick velocity from our overall odds and base our calculation solely on the sky-localisation and luminosity distance.

We calculate the odds using both the combined and separated overlap integral methods in section 3 in order to compare results and establish the component that dominates the odds. The gravitational-wave posterior distributions are provided in Abbott et al [4] as a set of posterior samples; we use a Kernel density estimate (KDE) method to interpolate these samples when evaluating equation (5). The program to reproduce our results (both for the combined and separate overlap integrals) is provided in appendix A.

3. Results

In Abbott et al [4], three waveform models were used to analyse the data: NRSur7dq4 [41], SEOBNRv4PHM [9, 32] and IMRPhenomPv3HM [26]. Using a variety of waveforms allows a study of the systematic uncertainty due to the differing model assumptions: for GW190521, the three waveforms give different estimates of the posterior distribution, though the overall conclusions are broadly consistent [5]. However, all three waveforms neglect the effects of
Table 1. Odds and constituent elements, see equations (2) and (5), for the three waveform models used in analysing GW190521 assuming distance and sky-localization are separable. We also include the odds for the equal-weighted combined results from all three waveforms. Values greater than 1 indicate support for the common-source hypothesis \( C \), while values less than 1 indicate support for the random-coincidence hypothesis \( R \). We estimate the odds are subject to statistical errors from the numerical evidence estimates and reweighting procedure totalling a few percent.

| Waveform model     | \( \pi_{C/R} \) | \( I_D \) | \( I_\Omega \) | \( I_D I_\Omega \) | \( O_{C/R} \) |
|--------------------|----------------|
| NRSur7dq4          | 1/13           | 1.8     | 29     | 52     | 4.0 |
| SEOBNRv4PHM        | 1/13           | 3.6     | 41     | 150    | 12  |
| IMRPhenomPv3HM     | 1/13           | 1.2     | 22     | 26     | 2.0 |
| Combined           | 1/13           | 2.0     | 34     | 68     | 5.2 |

orbital eccentricity, while including precession. It has been shown that GW190521 is also consistent with an eccentric merger [20, 36]. At this time, no model is available which combines both effects, so we are unable to infer the properties of GW190521 under a complete model. In this section, we analyse coincidence for the set of three precessing models individually, then discuss the impact of eccentric models in section 4. We also analyse the coincidence for a combined set of samples taking an equal-weighted mixture of all three waveform models.

In table 1, we calculate the odds and constituent elements from equation (5), using the posterior distributions for each waveform model and the three models combined. Comparing between these waveform models allows us to estimate the uncertainty in the odds due to the inherent uncertainty of the waveform model (neglecting the effects of eccentricity). In the following, we describe how each constituent element of table 1 is calculated, then discuss the overall conclusion in section 4.

3.1. Prior odds

The prior-odds, \( \pi_{C/R} \), quantify the prior probability of the common-source hypothesis (i.e. a binary black hole and AGN flare consistent with the McKernan et al [27] model) compared to a random coincidence hypothesis in which the AGN flare is not related to the gravitational-wave observation of a binary black hole merger. To estimate the prior odds, we apply the approach taken in Ashton et al [7] assuming a Poisson point process produces events detectable via either (or both) their gravitational-wave or electromagnetic emission (in this instance, EM indicates an AGN flare). It was found that observing for a time \( T \), the prior-odds are given by

\[
\pi_{C/R} = \frac{R_{GW,EM}}{TR_{GW}R_{EM}},
\]

where \( R_{GW,EM} \) is the rate of coincident events within the volume searched, while \( R_{GW} \) and \( R_{EM} \) are the rates of gravitational-wave-only and electromagnetic-only observations. However, these rates are poorly understood as is usually the case when we have observed only one event. So, as in Ashton et al [7], we take the special case \( R_{GW} \approx R_{GW,EM} \ll R_{EM} \). That is, we assume that the rate of AGN flares associated with high-mass binary black hole mergers (such as GW190521) is approximately the same as the rate of high-mass binary black hole mergers, but that these are both less than the rate of AGN flares not associated with merger events. This produces a conservative upper limit in the sense that we instead expect \( R_{GW,EM} \lesssim R_{GW} \) (since we have seen several high-mass black hole events without a counterpart) producing correspondingly smaller
prior odds. Under this assumption, the prior odds reduce to

$$\pi_{CR} \approx \frac{1}{TR_{EM}}$$  \hspace{1cm} (7)

We can approximate $TR_{EM}$ by $N$ the number of AGN flares which could conceivably be classified as consistent with the common-source hypothesis observed during time $T$, but which did not have a gravitational wave counterpart. Graham et al [23] found 13 events similar to ZTF19abanhr in the ZTF alert stream over the given observing epoch; therefore we approximate the prior odds by $\pi_{CR} \approx 1/13$. This approximation has the intuitive implication that if $N$ events could be consistent with a common-source hypothesis, the Bayes factor needs to be larger than $1/N$ in order to make a confident association. We note these odds are conservative (in the sense of favouring the common-source hypothesis) but assume the physical plausibility of the model itself.

The prior odds are necessarily subjective. Here we choose a conservative value $\pi_{CR} = 1/13$ based on the analysis of Graham et al [23] which is conservative in the sense that it avoids penalising too harshly a possible association and therefore favours the common-source hypothesis. We consider these priors odds to be as large as they can be while remaining plausible (values larger than one would imply a prior preference for the association which we think to be unreasonable). Values smaller than this would also be plausible, but could reasonably be criticised for penalising the association too harshly.

### 3.2. Luminosity distance

The luminosity distance distribution of the three waveforms and the equal-weights combined samples, along with the position of the AGN are given in figure 1. The initial analysis of GW190521 applied a prior uniform in the square of the luminosity distance ($D_L$), i.e. $\pi(D_L | C) \propto D_L^2$. Beyond a redshift of 1, for which GW190521 shows some support, cosmological effects become important. To improve the physical plausibility of the common-source prior, we re-weight the Abbott et al [4] posterior distributions to the uniform in source-frame prior [37], with identical bounds. Subsequently, we estimate $I_{D_L}$ by evaluating a KDE of the posterior distribution at $D_L^*$, the location of AGN J124942.3 + 344929. In table 1, across all three waveforms, $I_{D_L}$ provides fairly weak evidence for the association. Visually, the location of the AGN in figure 1 sits in the bulk of the posterior, but the posterior is wide; $I_{D_L}$ is the ratio of the posterior to the prior at the same point.

In converting from the median redshift to the luminosity distance of AGN J124942.3 + 344929, we assumed the ‘Plank15’ cosmology (cf the TT, TE, EE + lowP + lensing model in table 4 of Planck Collaboration et al [34]). As such, we neglect the uncertainty in redshift measurement, the cosmological model and between cosmological models. This will result in an underestimate of the uncertainty in the final odds. Of the three neglected uncertainties, the difference between cosmologies dominates. To estimate the size of the neglected uncertainties, we reanalyse the data using the ‘Plank18’ cosmology (cf the TT TE, EE + lowE + lensing + BAO model in table 2 of Planck Collaboration et al [35]). We find that $D_L^*$ changes by 0.05% while $I_{D_L}$ varies by less than 10% for each waveform. Meanwhile, the differences in $I_{D_L}$ between waveforms (cf table 1) is greater than 100%. We conclude that the uncertainty due to the choice of cosmology is subdominant. Neglecting these uncertainties, as we do in this work, will lead to an underestimate of the uncertainty, but does not change the overall conclusion of this work.
3.3. Sky position

The spatial overlap of GW190521 and ZTF19abanrhc can be seen in figure 1 of Graham et al [23] which used the initial skymap produced by LIGO/Virgo. Updated skymaps, based on improved waveform models and better-calibrated data, can be found in Abbott et al [5], but are broadly consistent with the initial skymap: the candidate lies within the 90% credible interval. Using these HEALPix skymaps [22] and creating a skymap for the AGN using its sky coordinate, we calculate $I_{\Omega}$ (see appendix A). We use the method developed for RAVEN [16], a low-latency pipeline that searches for gamma-ray or neutrino bursts coincidences with LIGO/Virgo/Kagra gravitational wave events. The results of this method are found in table 1. Across all three waveforms, $I_{\Omega}$ provides moderate evidence for the common-source hypothesis which matches up to the visual inspection in Graham et al [23]. Taking the product of the prior odds and the individual posterior overlap integrals, $I_{DL}$ and $I_{\Omega}$, we calculate the overall odds $O_{C/R}$ for each of the three waveform models in table 1.

3.4. Luminosity distance and sky position

Separating the analysis into contributions from the sky-position and distance allows us to understand each separately. In table 1, the luminosity distance provides weak evidence for the association, with the sky-localisation dominating the combined Bayes factor. We note that $I_{DL}$ is sensitive to the arbitrary upper bound of the prior luminosity distance prior. We use the value 10 Gpc chosen in the original analysis; varying this upper bound within a reasonable range of values does not change the overall conclusion. This verifies that our results are robust to the distance-prior sensitivity.

We also repeat our analysis without assuming that the luminosity distance and sky-location are independent of each other and separate (see equation (2)). We approximate the three-dimensional posterior on luminosity distance and sky-location using the clustered KDE routines available within ligo.skymap [38]. We then use a three-dimensional KDE to compute the overlap integral $I_{DL_{\Omega}}$ for each waveform model (see appendix A for details). We show the results for the odds and the overlap integral in table 2. The significance for the coincidence is reduced by a factor of 1.3–2 depending on the waveform model that is used compared to...
Table 2. Odds and constituent elements for the three waveform models used in analysing GW190521 without separating distance and sky-location. We also include the odds for the equal-weighted combined results from all three waveforms. The value of $I_{DL,\Omega}$ is computed using a three-dimensional clustered KDE in order to fully take into account any correlations between the luminosity distance and sky-location. We estimate the odds are subject to statistical errors from the numerical evidence estimates and reweighting procedure totalling a few percent.

| Waveform model       | $\pi_{C/R}$ | $I_{DL,\Omega}$ | $O_{C/R}$ |
|----------------------|-------------|-----------------|-----------|
| NRSur7dq4            | 1/13        | 31              | 2.4       |
| SEOBNRv4PHM          | 1/13        | 120             | 9.2       |
| IMRPhenomPv3HM       | 1/13        | 14              | 1.1       |
| Combined             | 1/13        | 44              | 3.4       |

the results in table 1. This small difference can be attributed to the correlations between the luminosity distance and sky position which do not favour the association. We note that the three-dimensional analysis is more complete than the simpler analysis presented in table 1, but the latter is preferable for understanding the constituent elements.

4. Discussion and conclusion

When combining the prior odds, the contribution from the distance, and the contribution from the sky-location, across all three waveforms, the odds range from 2 to 12 (1 to 10 when including correlations between luminosity distance and sky-location). While these odds constitute evidence in favour of associating GW190521 with the transient ZTF19abanrhr, we do not consider it rises to the level needed to confidently associate the events. In particular, we have made assumptions throughout which tend to favour the association (e.g. in the choice of prior odds and neglect of the physical model plausibility). Even under this assumptions and taking the most optimistic waveform model, the odds are $\sim$10:1 in favour; tentative support, but not enough to confidently state the two events have a common source. As such, we caution against drawing astrophysical conclusions based on the association (e.g. about the expansion of the Universe) which use the association.

For comparison, Ashton et al [7] found an odds in excess of $10^6$ for the association between GW170817 and GRB 170817A. Comparing the constituent parts of the calculation where possible,$^8$ the dominant reason GW170817 and GRB GW170817A can be confidently associated while GW190521 and ZTF19abanrhr cannot is the temporal coincidence. For the former, this alone provides an odds in excess of $10^4$, while for GW190521 and ZTF19abanrhr, as discussed in section 2, $I_{\Omega} \sim 1$.

The assumptions underlying the prior odds $\pi_{C/R} \approx 1/13$ used in this calculation are conservative in the sense of favouring the common-source hypothesis. Specifically, we assume that the rate of binary black hole mergers which also produce AGN flares is similar to the rate of binary black hole mergers without AGN flares: $R_{GW,EM} \approx R_{GW}$. But in practice we expect $R_{GW,EM} \ll R_{GW}$, leading to a reduction in $\pi_{C/R}$ and hence the overall odds. We also remind the reader that the prior odds do not consider the physical plausibility of the model itself. Taking these two considerations into account, we find that our conclusion, that the overall odds do not

$^8$ For GW170817-GRB 170817A $I_{\Omega}$ is not calculated as Fermi-GBM does not produce a posterior estimate for the distance, meanwhile $I_{\Omega}$ can be calculated and provides a similar value.
rise to the level needed to confidently associate the events, is robust to the choice of prior odds. A more refined analysis of the prior odds addressing the omissions above would only serve to reduce them, leading to a reduction in the overall odds.

The odds calculated herein are subject to uncertainty dominated by the waveform model (responsible for the range of odds from 2 to 12). We neglected subdominant forms of uncertainty in the position of ZTF19abanrhr and cosmological model. Including these uncertainties will broaden the range of feasible odds, but not change the overall conclusion: that the significance is insufficient to warrant a confident association.

In this work, we have analysed the coincidence for three precessing quasi-circular models, which we find to spread the range of odds by one order of magnitude. However, work has shown that the observation is also consistent with non-circular (i.e. eccentric) mergers of black holes [20, 36]. Under these models, the measured luminosity distance of the merger is smaller (relative to the precessing quasi-circular waveforms considered in figure 1), improving the posterior agreement with the luminosity distance of AGN J124942.3 + 344929. Posterior samples for both these analyses have not been released so we are unable to calculate the odds directly. But, we can estimate $I_D$: dividing $0.4$, the posterior density of the eccentric posterior in figure 1 of Gayathri et al [21] at ZTF19abanrhr by the prior density we have that $I_D^{EC} \sim 4.9$. This improves support for the association by about a factor of 1.4 relative to the SEOBNRv4PHM waveform (cf table 1). However, this is an overestimate as the results of Gayathri et al [20] assume the fixed sky location of ZTF19abanrhr. Nevertheless, it confirms that, even for eccentric waveforms, $I_D$ provides only a weak preference for the association. GW190521 has also been found to be consistent with the head-on collision of horizonless vector boson stars [14] and extended studies suggest the source could have a more extreme mass ratio than initially thought [18, 30]. In both cases the inferred luminosity distance is smaller relative to the waveforms analysed in this work\(^9\), but, the uncertainty on the distance remains large such that we cannot confidently associate the two events. For $I_D$ to be greater than 100, and hence provide strong support for the association, the standard deviation of the luminosity distance posterior would need to reduce by a factor of $\sim 100$.

Given either a precessing or eccentric model, we do not find strong evidence for an association. However, a complete analysis of this coincidence requires a waveform including both the effects of precession and eccentricity. No model is yet available which combines the two so it is impossible to disentangle the effects. This should provide strong motivation for the development of waveform models which include both effects, enabling a complete analysis.

We conclude that the current evidence is insufficient to confidently associate the events and hence use the astrophysical implications based on the association. Nevertheless, the tentative association of ZTF19abanrhr with GW190521 represents an exciting development in gravitational-wave astronomy. While we do not find sufficient evidence to confidently associate the events, this should motivate electromagnetic observers to pursue follow-up of future binary black hole events which may shed light on the phenomena. Future observations, with improved sensitivity from detector improvements, may be better localized and hence result in a confident association of a high-mass binary black hole with an AGN, hence validating the McKernan et al [27] model. On the other hand, the repeat flare predicted by Graham et al [23] may be observed resulting in a more confident association.

\(^9\) These extreme mass ratio modes produce similar shifts in the luminosity distance posterior to that of eccentric models, resulting in a similar variation in the overall odds.
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Data availability

No new data were created or analysed in this study.

Appendix A. Program to evaluate the odds and reproduce the results of tables 1 and 2

The Python3 software packages required to run the program below can be installed with the command

```
$ pip install bilby gwcelery ligo.skymap ligo-raven hifpy
```

The data required to run this program (GW190521_posterior_samples.h5 and GW190521_Implications_figure_data.tgz, which needs to be decompressed) are available from https://dcc.ligo.org/LIGO-P2000158/public. The program below assumes the h5 and fits files are copied to the directory in which the program is run. The results obtained herein used results from LIGO-P2000158-v4.
```python
import numpy as np
from scipy.stats import gaussian_kde
from scipy.stats import Uniform, PowerLaw
from numpy.random import uniform, seed
import matplotlib.pyplot as plt

# Fix seed for reproducibility
seed(123)

ra_em_deg, dec_em_deg = 192.424139, 34.624715

# Advanced LIGO
[1] Aasi J, Abbott B P, Abbott R, Abbott T, Abernathy M R, Ackley K, Adams C, Adams T and Addesso P 2015 Advanced LIGO Class. Quantum Grav. 32 074001

# gravitational-wave standard siren measurement of the Hubble constant
[2] Abbott B P et al 2017a A gravitational-wave standard siren measurement of the Hubble constant Nature 551 85–8
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