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Parameter estimation and statistical significance of echoes following black hole signals in the first Advanced LIGO observing run

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Searching for black hole echo signals with gravitational waves provides a means of probing the near-horizon regime of these objects. We demonstrate a pipeline to efficiently search for these signals in gravitational wave data and calculate model selection probabilities between signal and no-signal hypotheses. As an example of its use we calculate Bayes factors for the Abedi-Dykaar-Afshordi (ADA) model on events in LIGO’s first observing run and compare to existing results in the literature. We discuss the benefits of using a full likelihood exploration over existing search methods that used template banks and calculated p-values. We use the waveforms of ADA, although the method is easily extendable to other waveforms. With these waveforms we are able to demonstrate a range of echo amplitudes that is already ruled out by the data.

I. INTRODUCTION

Black holes are defined by their horizons [1]. Although a large amount of astrophysical data is compatible with the existence of black holes [2], a number of theoretical models still predict dark compact objects without horizons or for which the horizon structure is significantly modified from classical vacuum general relativity [3–8]. These models are typically motivated by quantum effects or attempts to address issues related to black hole information and evaporation [9]. One possible observational signature of such structure is that infalling waves would not be entirely absorbed by the horizon as is generally expected in general relativity, but instead some amount of the infalling wave would be reflected [4]. Similar signals have been studied for stars for a long time [10, 11].

Recent observations of gravitational waves from coalescences of binary black holes [12–17] by the LIGO [18] and Virgo [19] detectors have allowed for a number of new tests of the near horizon structure of black holes [20–22]. One such test involves searching for echo signals that could potentially be caused by reflective structure forming at or near the location of the black-hole horizon. A number of groups have searched for such signals in gravitational wave data with contrasting conclusions [23–25], ranging from “tentative evidence” in [23] to “low significance” in [24].

Here we propose a new method to search for these echo signals that provides an explicit probability for the compatibility of the data with the echoes model relative to a noise hypothesis. We demonstrate this method on the binary black hole events detected during the first observing run of the Advanced LIGO detectors; these events are

the same events that were the subject of previous studies [23–25].

The general physical picture of echoes is that infalling radiation is reflected due to some mechanism near the putative horizon location. This radiation is then partially trapped between the near-horizon structure and the angular momentum light-ring barrier [4]. Some of the energy is transmitted away from the system by successive bounces, thereby forming a series of echoes. Generic parameters in the physical models are the amount of wave reflected by the boundary and the effective location where this reflection occurs. These in turn are related to the amplitude of the reflected echo signals and the time separation between the successive echoes. Bounds on the amplitude and time separation of echo signals derived from the data can thus be translated into bounds on the reflectivity and location of the near-horizon structure.

For illustrative purposes here, we focus on the explicit model of Abedi-Dykaar-Afshordi (ADA) [23], which has been the subject of discussion in the literature [24, 26–28]. However, we note that our methodology can just as well be applied to other, more detailed models with explicit waveforms, including those recently proposed in the literature [29, 30]. Efforts to search for echo templates using Bayesian model selection have been developed with LALInference [31] in parallel to our own work, and published concurrently with our own [32]. Other, model-agnostic searches [33], have also been ongoing, along with different techniques to constrain horizonless objects through their impact on the stochastic background [34].

The primary result of [23] is a p-value, calculated as the probability of observing a signal-to-noise ratio (SNR) in noise (assumed to be free of signal) at least as significant as that observed in the on-source data that potentially contains the signal. This by itself does not indicate the probability that the on-source data contains a signal.

A probability that the data contains a signal can how-

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ever be obtained using Bayes' theorem:

$$P(\text{signal}|\text{data}) = \frac{P(\text{data}|\text{signal})P(\text{signal})}{P(\text{data})}. \quad (1)$$

It is most convenient to compare this probability to an alternative hypothesis, for example that the data contains pure noise:

$$\frac{P(\text{signal}|\text{data})}{P(\text{noise}|\text{data})} = \frac{P(\text{data}|\text{signal})}{P(\text{data}|\text{noise})} \frac{P(\text{signal})}{P(\text{noise})}. \quad (2)$$

In the above, the first factor on the right hand side is the likelihood ratio, or Bayes factor, and the second factor is the prior odds. Evaluating the prior odds is difficult without prior data (and in the case of a signal model that violates standard physics, might well be a very small factor). The likelihood ratio, on the other hand, can be calculated by exploring the likelihood function over the model parameters using a stochastic sampling algorithm, such as a Markov chain Monte Carlo (MCMC). In addition to the prior probability of hypotheses, a hypothesis itself may have a number of free parameters, each of which will have its own prior probability distribution. To obtain a final Bayes factor, the model parameters must be marginalized over using their respective prior distributions.

The data of gravitational wave detectors is known to be non-Gaussian [35], so a comparison with a Gaussian noise hypothesis does not exhaust the list of possible explanations for the data. However, for sufficiently short periods of time (of the order a few seconds) around the events discussed here, the noise can be well approximated as Gaussian and any signal hypothesis that is disfavoured relative to Gaussian noise is unlikely to be favoured relative to a more accurate noise hypothesis. If the signal hypothesis is favoured over Gaussian noise, then further analysis would be warranted.

To establish that our method can correctly identify echo signals in the data, we test it on simulated echo signals with a variety of different amplitudes. These simulations are added to real detector data, which is made available by the Gravitational Wave Open Science Center (GWOOSC) [36, 37]. We choose to inject simulated signals 100 seconds after GW150914. This 100-second delay makes it unlikely that the data at that time is contaminated by a real astrophysical signal [38]. These injections allow us to estimate the sensitivity of our method and establish a signal amplitude that would be unambiguously identified by our method.

We then apply our method directly to the three binary black hole events in O1: GW150914, GW151012 and GW151226. We find that the data for GW150914 favours Gaussian noise over the echoes hypothesis. The other two events show a marginal preference for echoes, but this is again consistent with noise. Finally, we discuss how our results can be used to place bounds on the reflectivity of structure that has formed a given distance from the location of the would-be horizon. Although our

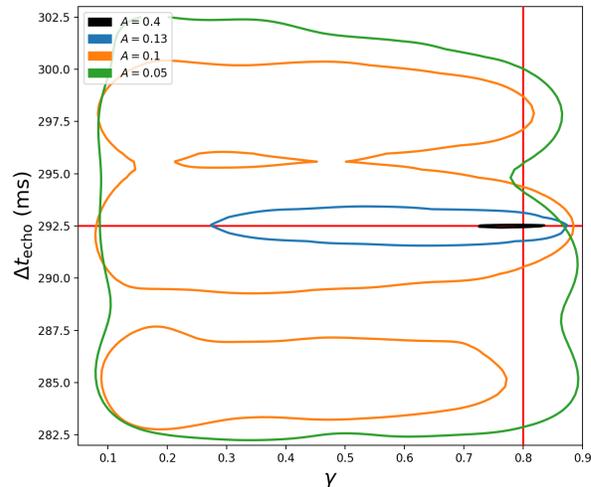


FIG. 1. The 90% credible regions of the 2D marginal posteriors of Δt_{echo} and γ for GW150914-like simulated signals. Shown are a range of echo amplitudes (relative to the peak amplitude of the original signal) A . The injected values are given by the horizontal and vertical red lines. For small values of A , the 90% contour covers most of the prior range, whereas for larger amplitudes the contours narrow down onto the injected values.

conservative bounds cannot conclusively exclude the signal amplitudes claimed in [23], we show that they are consistent with being noise, having amplitudes below the level that can be reliably estimated and Bayes factors not uncommon in off-source times. Future runs with more sensitive detectors and louder events are likely to lower the level of amplitudes that can be reliably estimated and rule definitively on the generic claims of [23].

II. METHODOLOGY AND ANALYSIS PIPELINE

The example signal hypothesis we consider here is based on that of ADA [23]; we refer the reader to that work for more detail on the model and the meaning of the various model parameters. The most important of these parameters are the overall amplitude of the echoes relative to the original signal's peak A , the relative amplitude between successive echoes γ , and the time separation between successive echoes Δt_{echo} ; these and the other parameters t_{echo} and t_0 trunc. are explained more fully in [23]. Table II gives the prior ranges employed here for the relevant parameters. These are adapted for our purposes from the template bank search performed in [23].

In the ADA model the range for Δt_{echo} is inferred from the published parameters of GW150914 [14], using 50% ranges, and assuming Gaussian distributions for the er-

Echo param.	Prior range	GW150914 range	Injected value
Δt_{echo}	inferred	0.2825 to 0.3025 s	0.2925 s
t_{echo}	$\Delta t_{\text{echo}} \pm 1\%$	0.2795 to 0.3055 s	0.2925 s
t_0 trunc.	$(-0.1 \text{ to } 0)\Delta t_{\text{echo}}$	-0.02925 to 0 s	-0.02457 s
γ	0.1 to 0.9	0.1 to 0.9	0.8
A	unconstrained	0.00001 to 0.9	varying

TABLE I. Table of prior ranges for echoes’ parameters along with the values used here for injection studies. The ranges are adopted from [23]. The injection values are chosen to lie close to the parameter values found in that work, except for γ and t_0 trunc. which are chosen to lie within the prior range rather than at the boundary.

ror. The Kerr metric formula is used for the light travel time between the light ring and a perfectly reflecting surface. This surface is assumed to be at a proper distance one Planck length along Boyer-Lindquist time slices from the Kerr metric event horizon. The parameter γ was chosen to reflect the physical expectation that the amplitude of successive echoes should decrease due to energy loss through one or both of the boundaries. We allow the parameter t_{echo} to vary independently from Δt_{echo} within 1% of its maximum values, and choose an explicit prior for the relative amplitude.

Since the value of the amplitude will have a direct influence on the signal strength, and hence the signal likelihood, its prior range is of central importance to our results. In the template bank search of [23] a prior for the amplitude is not explicitly given. Instead, it is maximised over the template bank. To replicate as closely as possible the method of [23] we choose a flat amplitude prior from 10^{-5} to 0.9. This ensures we are sensitive to relatively quiet amplitude signals, although not arbitrarily quiet, and implements the reasonable assumption that the first echo should not be louder than the main signal.

For simplicity we choose to fix the number of echoes to 30. In principle this could be allowed to vary, but for values of γ less than 0.9, 30 echoes capture the main part of the signal that influences the SNR. In testing, we found that varying this number did not change the results substantially.

The pipeline we use is based on `pycbc_inference` [39]. It employs a parallel-tempered MCMC algorithm, `emcee_pt` [40, 41], to sample the likelihood function for a hypothesis based on the existence of a signal in the data. The likelihood function is chosen to be compatible with the assumption that the underlying noise is Gaussian with a given power spectral density. Once the likelihood has been mapped, the marginalization over the model parameters is performed using thermodynamic integration to obtain a probability for the hypothesis given the data. Although it is known that LIGO data is not Gaussian over long periods of time, over shorter periods it is approximately Gaussian [35, 38]. To account for the non-Gaussianities without a model hypothesis for them, it is

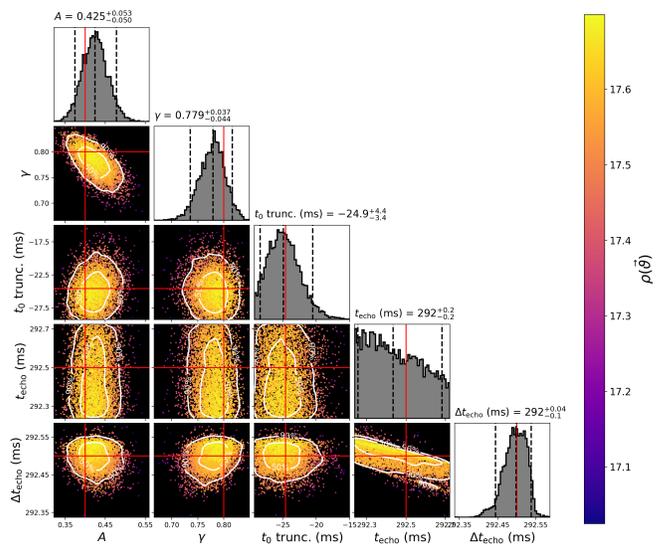


FIG. 2. Posterior on the echo parameters for a loud ($\text{SNR} \sim 18$) simulated signal. The signal has GW150914-like parameters at a fiducial distance of 400 Mpc. An amplitude factor of 0.4 is used for the echoes. Off-diagonal plots show 2D marginal posteriors; the white contours show the 50% and 90% credible regions. Each point represents a random draw from the posterior, colored by the SNR (ρ) at those parameters. The diagonal plots show the 1D marginal posteriors, with the median and 90% credible intervals indicated by the dashed lines. The reported values are the median of the 1D marginal posterior plus/minus the 5/95 percentiles. The injected parameter values, shown by the red lines, are all within the 90% credible intervals. The log Bayes factor for this signal is 140.57.

possible to sample the Gaussian Bayes factor over many realisations of the true detector noise.

In the results presented here we used 100 Markov chains to sample the likelihood. We require that each chain run for at least five auto-correlation lengths (ACL) beyond 1000 iterations of the sampler. The ACL is measured by averaging parameter samples over all chains, then taking the maximum ACL over all parameters. For the thermodynamic integration of the likelihood function, care has to be taken that it is sufficiently sampled both near its peak, but also at lower values of the likelihood. In tests we found that using 16 different temperatures, each placed by inspection, was sufficient to guarantee a consistent value of the Bayes factor. Convergence of this result was checked by running with double the number of temperatures and ensuring that the results were consistent. The posterior distributions are constructed from the coldest temperature chain.

III. INJECTIONS BASED ON GW150914

To test our method we choose to examine simulated echo signals based on GW150914. This is, to date, the

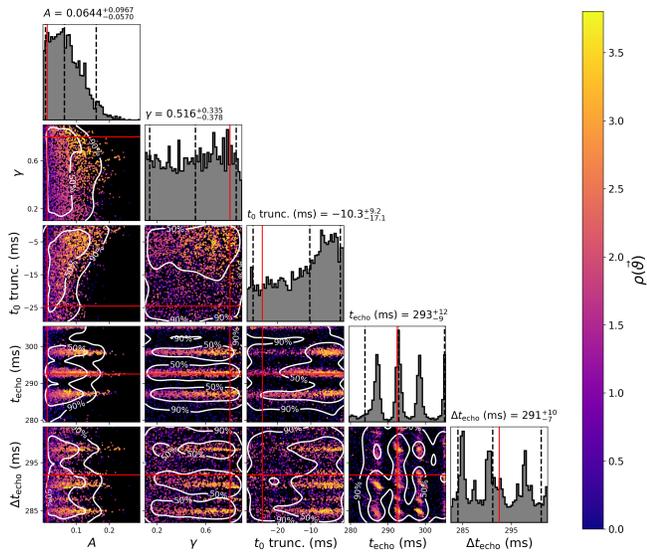


FIG. 3. Posterior on the echo parameters for a quiet (SNR ~ 4) simulated signal. The signal has GW150914-like parameters at a fiducial distance of 400 Mpc. An amplitude factor of 0.0125 is used for the echoes. Again, the injected values are shown by the red lines, while points are colored by the SNR at that point in the parameter space. The log Bayes factor for this injection is -1.55 , indicating what to expect when the signal is indistinguishable from noise. The prior ranges are largely saturated and lines appear in the 1D marginal posterior for t_{echo} .

loudest binary black hole signal that has been observed via gravitational waves, and should play a central role in constraints derived from the data. While we focus here on GW150914, we expect similar results will apply to echo signals of other events when suitably scaled in amplitude.

Following ADA for simplicity, we choose to fix the base inspiral-merger-ringdown (IMR) waveform to be echoed for both injections and for the search templates. The parameters for these base IMR waveforms are given in the appendix and are obtained from the maximum likelihood results of [39]. The waveforms are constructed using the phenomenological IMR waveform family IMR-PhenomPv2 [42, 43] which is freely available as part of LALSuite [44]. These IMR signals are then used to produce echo signals with echo parameters given in Table II. The simulated echo injections are added linearly at varying amplitudes to real detector noise (chosen to be 100 seconds after GW150914, far enough away to be uncontaminated by echo signals or any pre-merger signal). We then attempt to recover them with our analysis pipeline. Example results are shown in Figs 2 and 3.

Figure 2 shows a very loud injection with a relative amplitude of 0.4 and a maximum likelihood SNR of ~ 17.7 . The log Bayes factor for this injection is 140.57, showing a strong preference for the echoes hypothesis over the pure Gaussian noise hypothesis. In this case the echo parameters are well recovered, with the injected values ly-

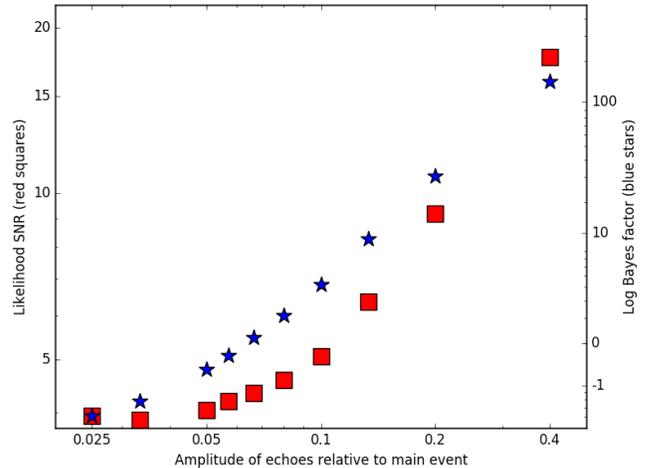


FIG. 4. Values of the maximum likelihood SNR and log Bayes factors for GW150914-based injections with amplitudes from 0.025 to 0.4 at a distance of 400 Mpc. A linear fit is possible through the SNR points down to an amplitude around 0.1. The log Bayes factor is negative for amplitude values below ~ 0.07 (indicating formal preference for Gaussian noise over the echoes hypothesis).

ing within the 90% credible intervals of the marginalised one-dimensional posterior distributions.

Figure 3 shows a much quieter injection with a relative amplitude of 0.0125 and a maximum likelihood SNR of only 3.8. The log Bayes factor for this injection is -1.55 showing a preference for the pure Gaussian noise hypothesis. In this case most echo parameters are not well recovered and their posterior distributions are close to the original prior distributions.

Figure 1 shows the recovery of γ and Δt_{echo} for a range of different injection amplitudes. As the amplitude is increased, the recovered value is increasingly constrained to the injected value.

The log Bayes factor and likelihood SNR for injected signals with different amplitudes is shown in Fig. 4. Here we find that below an injected amplitude of ~ 0.1 the recovered maximum likelihood SNR no longer falls off linearly, and flattens out to an approximately constant value of ~ 4 , independently of the signal injected. At amplitudes below ~ 0.07 the log Bayes factor becomes negative.

A plot of the recovered amplitudes versus injected amplitudes is shown in Fig. 5. This figure can be compared with Fig. 4 of [24], which also shows recovered amplitudes relative to injected amplitudes for a template bank search. In that work it was found that below a certain injection strength, the recovered echo amplitude was no longer reliable using the template bank method. Our results here are consistent with that finding. This gives a clear sense of the amplitude of signals which it is possible to reliably recover, relative to the detector noise level. Signals below this level, such as the one claimed in [23], cannot be clearly distinguished from noise.

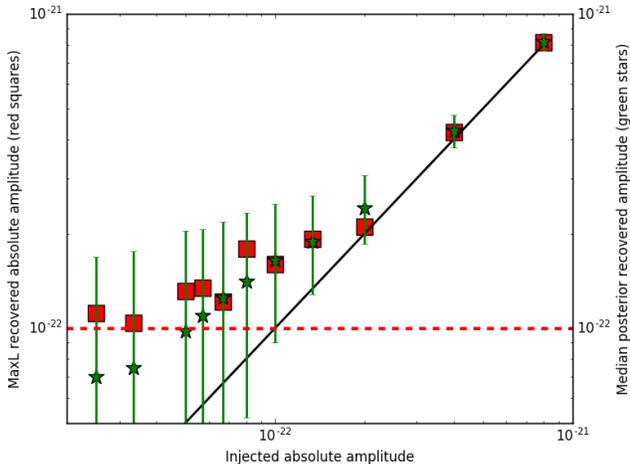


FIG. 5. Injected versus recovered amplitudes expressed in terms of strain values for GW150914-based injections. At lower injected amplitude values the recovered amplitude and hence the recovered SNR, saturate around an amplitude value of 10^{-22} . Median posterior values are given by the green stars with 90% credible intervals given by the green bars. The amplitudes of the maximum likelihood waveforms are given by the red boxes. The red dashed line is the approximate amplitude of the signal claimed in [23].

IV. EVENTS IN THE FIRST OBSERVING RUN

The developed pipeline can be run directly on data immediately after the observed GW events (without injections). We show results for the three events of the first LIGO observing run in Table II. This shows that Gaussian noise is favoured over the echoes hypothesis for GW150914 with a log Bayes factor of ~ -1.81 . GW150914 is the loudest binary black hole merger yet detected. A corner plot for the posterior distributions for the echo parameters for GW150914 is shown in Fig. 6. The 90% credible interval for the marginalised posterior of the parameter γ is almost as wide as the prior range. The posterior of the amplitude, A , prefers lower values of the amplitude. The posterior for t_{echo} shows distinct lines at certain values of time. These lines are unlikely to be associated with an astrophysical signal and are also seen in tests on simulated Gaussian noise with the same pipeline.

As seen in Table II, both GW151226 and GW151012 prefer the echoes hypothesis over Gaussian noise, but only marginally. The log Bayes factor for GW151012 is ~ 1.25 , indicating that the echoes hypothesis is ~ 3.5 times more likely than the Gaussian noise hypothesis. As mentioned earlier, the detector noise is known not to be truly Gaussian for the LIGO detectors [35]. To estimate how likely the GW151012 Bayes factor is in true detector noise, we performed 20 background tests on off-source data that lies before or after the time of GW151012 at intervals of 50 seconds. Each of these tests is sufficiently separated in time from the others that it will not be

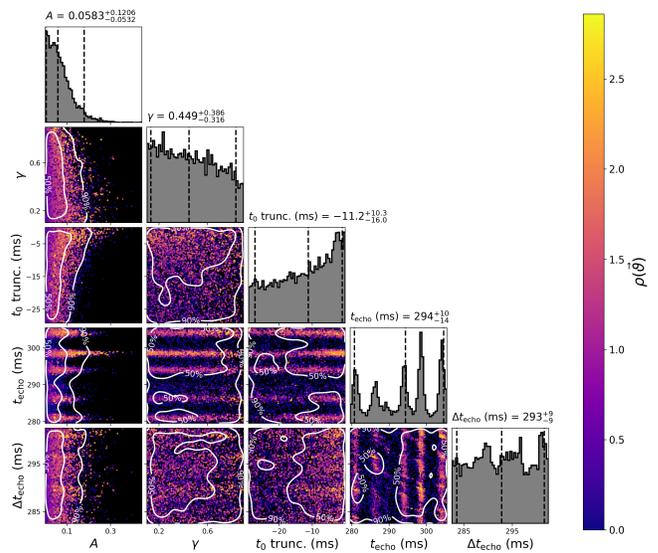


FIG. 6. Corner plot for ADA echoes templates in data just after the merger of GW150914. The log Bayes factor for this data is -1.81 , indicating a preference for the Gaussian noise hypothesis over the Echoes hypothesis. Lines are visible in the t_{echo} subplots, but the SNR associated with these is still not high. These lines are also seen in quiet injections into noise Fig. 3 and even tests of the pipeline on simulated Gaussian noise (not shown).

contaminated by a common signal. In these background tests, two examples were found with a Bayes factor larger than the result for GW151012 shown in Table II. A total of four intervals returned Bayes factors that favoured the echo hypothesis over Gaussian noise. Backgrounds for similar (but not identical) echoes hypotheses were also studied in [32] which found evidence for significant tails in the distribution of Bayes factors in real detector noise versus simulated Gaussian noise.

While it is interesting to speculate whether a signal model could be developed that postdicts echo signals for certain events, such as GW151012, but not for others, such as GW150914, we do not pursue that here. The argument that GW151012 should be accepted as a genuine binary black hole merger was given recently in [46], however we do not feel that the echoes data for GW151012 is sufficiently strong to seriously entertain a model where GW15012-like events display echoes, but GW150914-like events do not.

The SNR values found for the maximum likelihood templates in Table II are comparable, although not identical to those found in [23] and [24]. The finite template spacing in the template banks of [23] and [24] causes a minor difference in recovered SNR values. The main differences are the different base IMR waveform employed and the different power spectral density (PSD) used to calculate the matches. Here we have used a PSD computed using standard `pycbc` [47, 48] routines based on Welch's method. We estimate the PSD by taking the

Event	Log Bayes factor	Max SNR
GW150914	-1.8056	2.86
GW151012	1.2499	5.57
GW151226	0.4186	4.07

TABLE II. Table of Bayes factor results. Negative values indicate that the Gaussian noise hypothesis is preferred. Positive values indicate that the echoes hypothesis is preferred after marginalization over parameters. For an approximate indication of scale, log Bayes values with magnitude < 1 are “not worth more than a bare mention” in the nomenclature of [45].

median value over 64 8 second-long segments (each overlapped by 4 seconds), centered on the main event. A different routine was used in [23] and [24] based on examples provided at [36].

With the simplistic hypothesis that all three binary black hole events should show evidence for echo signals in the range of parameters assumed, we can simply add the log Bayes factor together to obtain an overall log Bayes factor for this model relative to Gaussian noise of $-1.81 + 1.25 + 0.42 = -0.14$. This is negative, indicating a preference for Gaussian noise, but not by much. It is worth noting that this simplistic combination assumes that the values for the echo parameters can lie anywhere in their prior ranges for any of the three events. This is slightly different from the hypothesis of [23] that assumes certain echo parameters should have the same value in all three events. With a hypothesis that fixes the values of certain echo parameters to be the same in all cases, it is possible that the overall Bayes factor would be different from our result. But this issue also raises the question of how these common parameters should be fixed; a simple maximization of the sum of the squares of the template SNRs as in [23], or as a maximization or marginalization of the likelihood function introduced here. The two events, GW151012 and GW151226, have lower amplitudes for the main signal than for GW150914 and thus echoes signals with the same relative amplitude would have a lower absolute amplitude relative to the ambient noise [24]. We defer investigation of these subtle issues to future work.

V. DISCUSSION AND CONCLUSIONS

With knowledge of how sensitive our pipeline is from the injection test runs of Sec. III we can determine the amplitude of echoes that would have been detectable had they been present in the data. This allows us to place a bound on the amplitude of echoes emitted from the events considered here. We remind the reader that bounds from our search only relate to the family of echo waveforms considered here. These are based on the waveform model assumed in [23] and adopting the prior ranges

of Table II.

As shown in Fig. 6, the posterior amplitude recovery for GW150914 has a 90% confidence interval from 0.0051 to 0.1789. For this realization of the noise, amplitudes above 0.1789 are ruled out at 90% confidence. This is consistent with the injection studies depicted in Fig. 4 which show that (for noise at a different time, 100 seconds after the main event) echo signals with amplitudes $\gtrsim 0.15$ would have been unambiguously identified in the data.

Echo signals of amplitude 0.1 relative to GW150914 would correspond to approximately 0.1 solar masses of energy being reflected from near the black horizon [26]. Although this value of the amplitude is not conclusively ruled out with the current data, an amplitude as high as 0.2 is conclusively ruled out by our results.

For numerical simulations of systems similar to GW150914 within general relativity, it is conservatively estimated that ~ 2 solar masses of gravitational energy flows across the horizon [49]. Our constraints here on the amplitude of echoes within the model of [23] suggest that at most 20% of this energy is being reflected by near-horizon structure and re-emitted as echoes. In the context of this specific model, it implies that a significant amount of energy is still being lost into the black hole. Our results in this context are qualitatively similar to those in [50], although an exact quantitative comparison is not possible because of the different models assumed.

We have seen that Gaussian noise is preferred over ADA echo-like signals in the data of GW150914. Although there is some evidence of echoes in GW151012 and GW151226, as both show positive log Bayes factors, this evidence is not very strong. Sampling the true detector noise by running over off-source times, shows that the log Bayes factor found for GW151012 is not unusual, and contrarily to [23], cannot be reliably distinguished from pure noise. A number of improved echo waveform models have been proposed; we defer running with these on further events to future work.

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Appendix: Fiducial IMR waveform parameters

We list here the parameters of the base IMR waveforms used to construct the echo templates both for injections and for the searches. These values are obtained from the maximum likelihood values of [39].

Parameter	GW150914	GW151012	GW151226
mass1	39.03	22.87	18.80
mass2	32.06	18.67	6.92
spin1x	-0.87	0.12	0.44
spin1y	-0.43	0.19	0.59
spin1z	-0.06	-0.20	0.33
spin2x	-0.11	0.018	0.00
spin2y	-0.03	-0.019	-0.017
spin2z	-0.15	0.062	0.0033
distance	477	751	315
ra	1.57	0.65	2.23
dec	-1.27	0.069	0.98
tc	1126259462.42	1128678900.46	1135136350.66
polarization	5.99	5.64	1.43
inclination	2.91	2.32	0.68
coa_phase	0.69	4.44	1.64
phase_shift	-0.92	-0.91	1.86