Searching for gravitational wave echoes in GWTC-1 and O3 events

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Gravitational wave (GW) echoes, if they exist, would be a probe to the near-horizon physics of black hole. In this brief report, we performed the Monte Carlo Markov Chain analysis to search for echo signal in all GWTC-1 and O3 GW events. We focus on the Inspiral-Merger-Ringdown-Echo (IMRE) waveform, and apply the Bayesian model selection to compare the IMRE result with IMR’s (no echo). We find no statistically significant ($< 1\sigma$ combined) evidence for the GW echoes and only individual GW events with the echoes at $1 \sim 2\sigma$ significance.

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\section{I. INTRODUCTION}

Over the past several years, the network of Advanced LIGO [1] and Virgo [2] observatories have demonstrated that the detection of gravitational wave (GW) has become a significant method to observe the universe. LIGO and Virgo collaboration have reported 15 GW events till now [3–8].

The corresponding GW events are compatible with the binary black holes (BHs) coalescences predicted by General Relativity (GR) [9–12]. However, it is still possible that the new physics might emerge near the horizon e.g.[13, 14]. The GW signal of binary BHs coalescences consists of the inspiral phase, the merger phase and the ringdown phase, see [15, 16] for a review. It has been showed in Refs.[17–19] that if certain physics (surface or barrier) near horizon reflects GW, the ringdown waveform of post-merger object will show itself a series of “echoes” at late-time. The GW echoes, regarded as the probes of new physics at the near-horizon regime, have motivated the searching for the corresponding signals in GW data [19, 20], see also [21–24].

The property of echo encodes the distinct physics of post-merger BH or compact object [25–41]. The echo interval might be not constant. It has been pointed out that if the post-merger object is a wormhole that is slowly pinching off and eventually collapsing into a BH, the ringdown waveform will exhibit a series of echoes with increasing intervals [27], see also primordial compact object [29]. In particular, if the near-horizon regime of BH is modelled as a multiple-barriers filter, the mixing of echoes, even the superpositions, will be also inevitably present [34]. These studies not only enriched the echo phenomenology, but also helped to the searching for the echo signals [21].

In this brief report, we will perform the MCMC analysis to search for GW echo signal in all GWTC-1 and O3 events. We focus on the full Inspiral-Merger-Ringdown-Echo (IMRE) waveform, and apply the Bayesian model selection to compare the IMRE result with IMR’s (no echo). In addition, we also consider the possibility of the unequal interval echo [21, 27].

\section{II. METHOD AND RESULTS}

Here, it is sufficient to consider a simple phenomenological waveform
\begin{equation}
\Psi_{IMRE}(t) = \Psi_{IMR}(t) + \Psi^{echo}(t),
\end{equation}
where
\begin{equation}
\Psi^{echo}(t) = \sum_{n=1}^\infty (-1)^n A_n e^{-\frac{t^2}{\beta^2}} \cos \left[ 2\pi f_n \left( t - t_{echo} - \left( n + \frac{n(n+1)}{2} \right) \Delta t_{echo} \right) \right],
\end{equation}
and $\Psi_{IMR}(t)$ corresponds to the IMR (each GW event have different IMR waveform).

We, for simplicity, set $A_n \sim A A/(3+n)$ with $A$ being the ratio of the first echo amplitude to the ringdown peak $A$ and the increment of echo intervals monotonical and proportional to $\Delta t_{echo}$: $\delta t = r \Delta t_{echo}$. As suggested in Refs.[27, 29], $r \neq 0$ will be a hint of wormhole or specific cosmological scenarios.

We performed the MCMC analysis with the MGWB (Modified GWBinning code package)\textsuperscript{[42]} and emcee\textsuperscript{3.0.2} package \textsuperscript{[43]} on the parameter set
\begin{equation}
\{(\text{IMR parameters}), A, \beta, r, t_{echo}, \Delta t_{echo} \}
\end{equation}
of (1) for all GWTC-1 and O3 events, see e.g.Fig.2 for the GW190425. However, the corresponding results should be assessed with the Bayesian model selection.

Regarding the IMR and IMRE as hypothesis $\mathcal{H}_0$ and $\mathcal{H}_1$, respectively, we have the logarithm of Bayes factor $\ln B_{01} = \ln \frac{p(d|\mathcal{H}_1, I)}{p(d|\mathcal{H}_0, I)}$, which reflects the preference of
TABLE I: Log Bayes factors and statistical significances of IMRE compared with IMR for the GWTC-1 events.

| Event           | $\ln B$ | $\sigma$ | $\Psi_{IMR}$     |
|-----------------|---------|----------|------------------|
| GW150914        | -1.94   | 0.06     | IMRPhenomD       |
| GW151012        | 1.96    | 1.84     | IMRPhenomD       |
| GW151226        | -0.57   | 0.46     | IMRPhenomD       |
| GW170104        | 0.09    | 0.82     | IMRPhenomD       |
| GW170608        | -0.01   | 0.76     | IMRPhenomD       |
| GW170729        | -2.16   | 0.04     | SEOBNRv4         |
| GW170809        | 0.05    | 0.80     | IMRPhenomD       |
| GW170814        | -0.83   | 0.35     | IMRPhenomD       |
| GW170817        | 0.55    | 1.00     | IMRPhenomD       |
| GW170818        | 0.27    | 0.93     | IMRPhenomD       |
| GW170823        | 0.55    | 1.10     | IMRPhenomD       |
| Combined        | -1.49   | 0.14     |                  |

TABLE II: Log Bayes factors and statistical significance of IMRE compared with IMR for the O3 GW events.

| Event           | $\ln B$ | $\sigma$ | $\Psi_{IMR}$     |
|-----------------|---------|----------|------------------|
| GW190814        | -0.34   | 0.58     | IMRPhenomD       |
| GW190521        | -1.29   | 0.19     | NRSur7dq4        |
| GW190425        | -0.18   | 0.60     | IMRPhenomDNRtidal|
| GW190412        | 0.72    | 1.21     | IMRPhenomPV3HM   |
| Combined        | -1.08   | 0.26     |                  |

We apply the Bayesian model selection to, for the first time, compare the IMRE result with IMR’s (no echo). Though the echo waveform we consider is quite simplified, our method is actually independent of the waveform model used, and can be applicable for other echo waveforms motivated by BH physics.

Through the Bayesian model selection, we found that all GW events reported in GWTC-1 and O3 so far have no preference for the IMRE, which suggests no statistically significant (only $<1\sigma$ combined) evidence for the GW echoes. However, individual GW events seem have the slightly positive results, so it might be expected that with higher sensitivity of aLIGO O5 or ET, the GW echo signal would be detectable.

III. DISCUSSION

We reported the results of searching for GW echo in all GWTC-1 and O3 events, see Tabs. I and II, and Fig.1.

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FIG. 2: Posterior distributions for GW190425, with contours corresponding to the 68% and 95% regions.
