Constraining Astrophysical Parameter Bias due to Glitches in Third-Generation Gravitational-Wave Detectors

Interim Report #1

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Transient detector noise or "glitches" which coincide in time and frequency with gravitational wave signals have been demonstrated to significantly bias inference of astrophysical parameters. We investigate how the effect of glitches on parameter bias will change with increased detector sensitivity, particularly in the case of LIGO A♯ and Cosmic Explorer (CE). The impact of glitches on these detectors is unknown: improved sensitivity may reduce their effects, or they may still contribute to significant parameter bias. We generate simulated data with various combinations of glitch and CBC injections, considering two glitch-scaling scenarios relative to current glitch properties. In one case, we assume that the glitch amplitude remains constant relative to glitches in current detectors. In the other, we instead assume that the glitch SNR remains constant relative to glitches in current detectors. We present simulated data generated in each of these cases and discuss initial parameter estimation results and validation tests.

I. INTRODUCTION

Gravitational waves (GWs) are traveling-wave perturbations of spacetime generated by an accelerating mass-energy quadrupole moment. Since 2015, the Laser Interferometer Gravitational-Wave Observatory (LIGO) has detected over 200 gravitational-wave events from binary black hole (BBH) mergers and binary neutron star (BNS) mergers to date, with many more observations still to come from the most recent observing run [1].

Using GW waveform models and Bayesian inference, the characteristics of the astrophysical event can be inferred from the GW signal, a process known as parameter estimation. For BBH mergers, these parameters include the masses of the black holes, their spins, the sky position, and the distance to the source, among other parameters. Accurate parameter estimation is crucial to identifying the source of the GWs and localizing the signal's sky position, which has enabled important scientific advances in gravitational-wave physics, tests of general relativity, and broader astrophysical studies [2]. The spins of the black holes are of particular interest, as they give insight into the origin and evolution of the binary system, which could help address open questions regarding binary stellar evolution and the existence of BBH subpopulations [3–5].

The broad characteristics of the BH spins are encoded in two parameters, $\chi_{\rm eff}$ and $\chi_{\rm p}$, which describe the BH spin aligned with the orbital angular momentum and the BH spin parallel to the orbital plane, respectively. Previous observations (GW191109_010717 and GW200129_065458) have exhibited spins not aligned with the angular momentum of the orbital system, or spins in the plane of the binary [6, 7]. This suggests that the systems could have been formed through dynamical interactions rather than through isolated binary evolution, where the progenitor stars are born and evolve together as a binary system [5].

However, these conclusions may be biased by transient noise, known as "glitches." Typically, the process of parameter estimation assumes as a baseline a transient signal and stationary Gaussian noise [8]. If a glitch is suspected, one method is to model it as a separate component of the data and subtract the best fitting estimate before proceeding with analysis [9]. A more robust approach is joint compact binary coalescence (CBC)-glitch inference, in which the properties of the compact-binary signal and the glitch are inferred simultaneously. This allows the analysis to marginalize over multiple possible glitch realizations rather than relying on a single best-fit subtraction [10]. Despite these mitigation strategies, Udall *et al.* [11] showed that glitches can still significantly bias spin parameter estimates, even for glitches with signal-to-noise ratio (SNR) below the threshold of detectability. Figure 1 illustrates this bias in the case of a simulated waveform, demonstrating that even using various subtraction and joint CBC-glitch inference methods, the effective spin parameters remain substantially biased.

This project focuses on how the issue of glitch mitigation and parameter bias will evolve with third-generation detectors. The upcoming detectors Cosmic Explorer (CE) and Einstein Telescope (ET) [12, 13] will be able to detect an unprecedented number of gravitational-wave signals. CE in particular is expected to observe 10^5 BBH mergers (one every 5 minutes) and 3×10^5 BNS mergers (one every 100 seconds) per year of observation [14]. In the transition toward these next-generation observatories, planned sensitivity upgrades to current LIGO detectors, known as LIGO A♯, will provide an intermediate step toward improved detector performance.

Currently, parameter estimation for a single source can take days, or longer if a glitch overlaps with the sig-

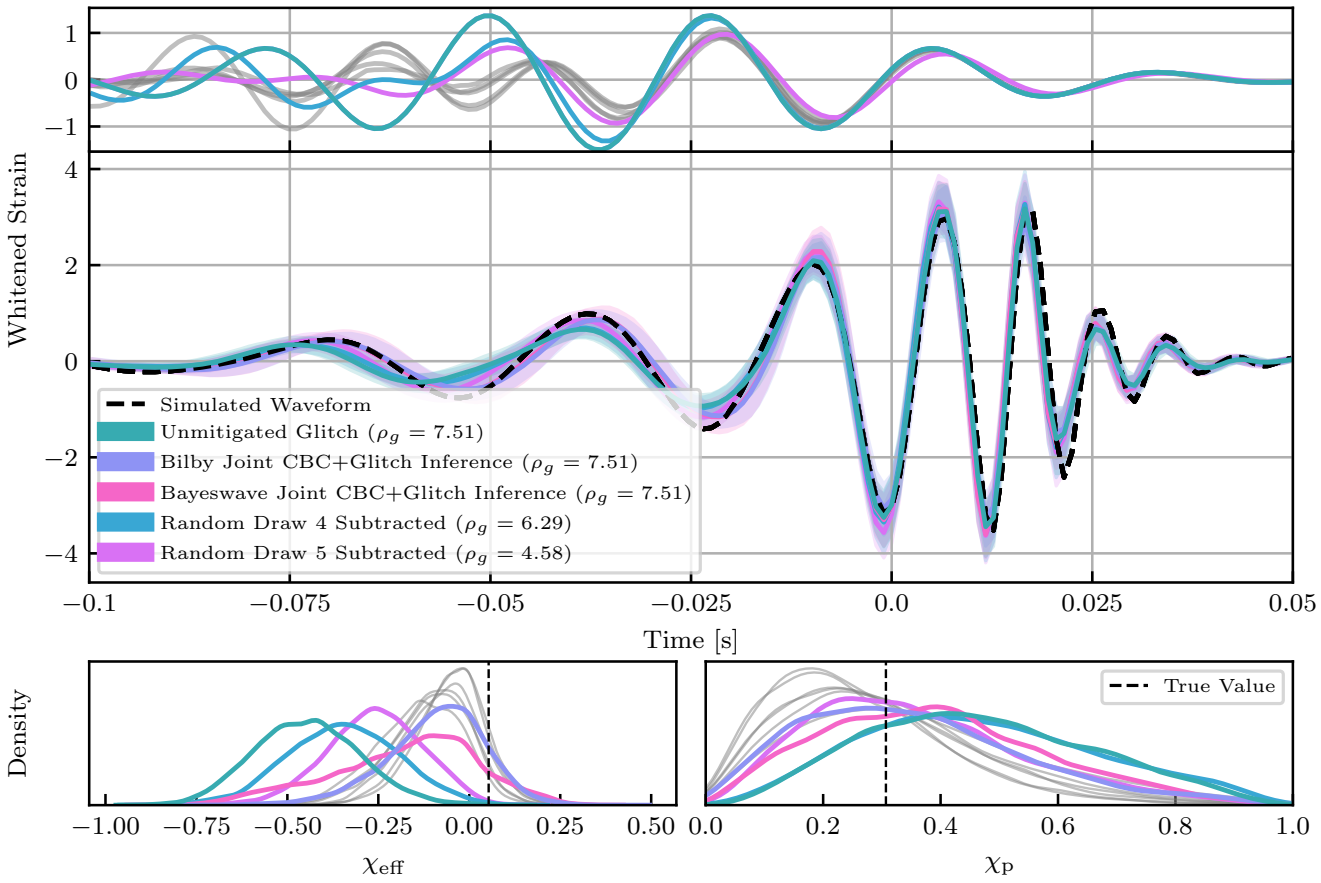


FIG. 1: Reproduced from Figure 7 of [11]. Results of the inference-subtraction procedure for a simulated glitch overlapping with a CBC signal, comparing the performance of various glitch mitigation strategies on spin parameter recovery. Glitch parameters were inferred only in the presence of Gaussian noise (before CBC injection) for the point estimate cases, and inferred jointly with the CBC in the other cases. Notable cases are highlighted in color. The top panel shows the glitch residuals after subtraction in the point estimate cases, as well as the full glitch in the unmitigated case. The middle panel displays the posterior CBC reconstructions for each of the cases, with the true waveform illustrated in black dashes. The bottom panels show the posteriors of both $\chi_{\rm eff}$ and $\chi_{\rm p}$ resulting from each of the methods, with the true value indicated by a black dashed line. The parameters are significantly biased when the glitch is unmitigated or subtracted, whereas this bias is improved with joint inference methods.

nal (which occurs in about 10% of cases). Moreover, the process of joint BBH-glitch inference is not fully automated and must be manually assessed at each step. With the increased detection rates of third-generation detectors, it will no longer be practical to treat every glitch-contaminated event with the same level of manual intervention. It is therefore crucial to understand how glitches scale with detector sensitivity in order to identify when full joint BBH-glitch inference will be necessary, and to develop scalable glitch mitigation pipelines to ensure accurate parameter estimates across a high volume of events.

We aim to simulate increased sensitivity of GW detectors in order to extend past studies of glitch-induced parameter bias such as [11]. In doing so, we hope to clarify whether glitches are expected to continue to pose a significant problem in producing accurate parameter estimates with third-generation detectors.

II. BACKGROUND

A. Expressing Detector Sensitivity

The sensitivity of a GW detector is reflected in its power spectral density (PSD) or amplitude spectral density (ASD) function, where the ASD is the square root of the PSD. The PSD and ASD are functions of frequency and are measured in units of Hz^{-1} and $\mathrm{Hz}^{-1/2}$ respectively, with lower values indicating greater sensitivity. Figure 2 illustrates the ASD for current LIGO detectors and the projected ASD for LIGO A♯ detectors and CE.

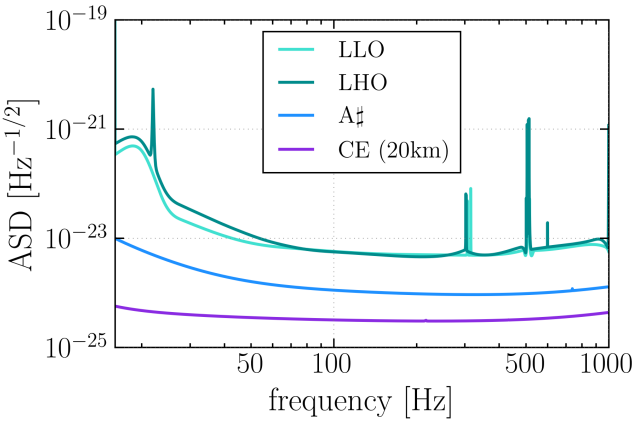


FIG. 2: Amplitude spectral density (ASD) as a function of frequency for the LIGO Livingston Observatory (LLO) and LIGO Hanford Observatory (LHO) during the third observing run (O3), shown in green and teal respectively, along with the projected sensitivities of LIGO A♯ (blue) and the 20 km Cosmic Explorer (CE) detector (purple).

In order to simulate increased sensitivity of the detector, we vary the PSD throughout our analysis.

The PSD also defines the relationship between "colored" and "whitened" strain data. Colored strain refers to the detector strain before whitening, in which the frequency content is shaped by the detector's frequency-dependent noise. Whitening divides out this frequency dependence through the relation

$$\tilde{h}_{\rm white}(f) = \frac{\tilde{h}(f)}{\sqrt{S_n(f)}}, \tag{1}$$

where $\tilde{h}(f)$ is the Fourier transform of the colored strain and $S_n(f)$ is the PSD. This suppresses frequency components in regions of high detector noise and emphasizes those in regions of low detector noise.

B. Scaling Glitch Properties

The GW strain amplitude is fixed by the physics of the source, but with increased CE detector sensitivity, we expect the noise to decrease, thus increasing the signal SNR. However, it is unclear how the glitches will be impacted. In this project, we will consider two limiting cases: 1) the glitch amplitude remains constant and 2) the glitch SNR remains constant (relative to glitches observed in current detectors). Based on simple scaling arguments outlined in Udall *et al.* [11], we expect these cases to affect parameter estimation differently. Our simulations aim to test whether these expectations hold.

For the first case, the absolute BBH parameter bias is expected to remain approximately comparable to the bias at current detector sensitivity, while the posterior widths are expected to decrease as detector sensitivity improves, resulting in a greater statistical deviation between the true and measured value. For the second case, we expect the absolute bias to decrease with respect to the bias at current detector sensitivities, but predict that the standard deviation from the true value will remain similar.

Glitches will be modeled as Morlet-Gabor wavelets, given by the expression

$$\Psi(t) = Ae^{-(t-t_0)^2/\tau^2}\cos(2\pi f_0(t-t_0)+\phi_0), \tag{2}$$

where $\tau = Q/(2\pi f_0)$ and A is the amplitude, Q is the quality factor, t_0 and f_0 are the central time and frequency, and ϕ_0 is the phase offset [15].

For the fixed amplitude case, the glitch form will be modeled identically between current and third-generation detectors. For the fixed SNR case, the amplitude of the glitch must be scaled accordingly. Here, we derive the amplitude scaling relation used to fix the SNR of a glitch.

The SNR of an arbitrary GW strain time series $h(t)$ is defined as

$$\rho = \left[4\int_0^\infty \frac{|\tilde{h}(f)|^2}{S_n(f)}\,df\right]^{1/2}, \tag{3}$$

where $\tilde{h}(f)$ is the Fourier transform of $h(t)$, and $S_n(f)$ is the PSD of the detector. The Fourier transform of Equation (2) is given by

$$\tilde{\Psi}(f) = \frac{\sqrt{\pi}A\tau}{2}e^{-\pi^2\tau^2(f-f_0)^2} \times \left(e^{i(\phi_0+2\pi(f-f_0)t_0)} + e^{-i(\phi_0+2\pi(f+f_0)t_0)}e^{-Q^2f/f_0}\right) \tag{4}$$

For glitch modeling purposes, we take $Q > 1$, thus $e^{-Q^2f/f_0} << 1$ and we can neglect the last term in the equation. Assuming a narrow wavelet, we can take $S_n(f) \approx S_n(f_0)$ over the width of the glitch. Equation (3) then becomes

$$\rho^2 \approx \frac{4}{S_n(f_0)}\int_0^\infty e^{-2\pi^2\tau^2(f-f_0)^2}\,df. \tag{5}$$

Evaluating the Gaussian integral and simplifying yields the SNR approximation for a Morlet-Gabor wavelet:

$$\boxed{\rho \approx \frac{A\sqrt{Q}}{\sqrt{2\sqrt{2\pi}f_0S_n(f_0)}}.} \tag{6}$$

Thus, to maintain a constant glitch SNR, we rescale the glitch amplitude following

$$A' = A\sqrt{\frac{S_n'(f_0)}{S_n(f_0)}}, \tag{7}$$

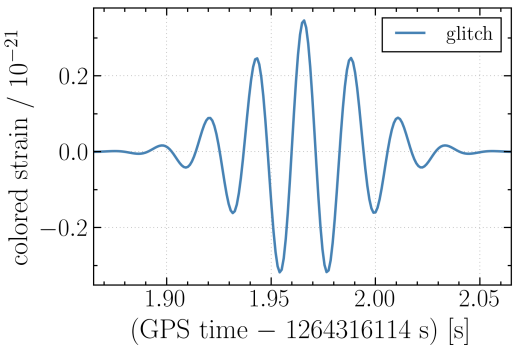


FIG. 3: Morlet-Gabor wavelet glitch, as injected into the colored strain data. The analytical form of the glitch is given by Equation (2).

where primed quantities denote the modified glitch amplitude and PSD, while all other waveform parameters remain fixed.

III. APPROACH

We study three detector configurations, LIGO O3, LIGO A♯, and CE, whose varied ASDs are pictured in Figure 2. As the future site of CE has not yet been chosen, we assume the location of two 20km CE detectors to be at the present sites of LIGO Livingston Observatory (LLO) and LIGO Hanford Observatory (LHO). Thus, all three configurations are identical in location and orientation, isolating the effect of varied sensitivity.

To generate data, we simulate stationary Gaussian noise based on the PSD of the chosen detector. Then, we inject a CBC signal using the waveform model IMRPhenomXPHM [16] with injection parameters from the BBH merger event GW200129 [6]. For the detector located at the LLO site, we inject a Morlet-Gabor wavelet glitch, pictured in Figure 3. The glitch parameters for the LIGO O3 configuration are preset to $A = 3.467 \times 10^{-22}$ and the glitch SNR to $\rho \approx 7.96$. For the other configurations, these parameters vary according to whether we are modeling fixed glitch amplitude or fixed glitch SNR. In the case of fixed glitch SNR, the amplitude is scaled with Equation (7), otherwise, the glitch form is not modified and the SNR scales accordingly as the detector noise decreases.

The simulated data frames are then passed to Bilby to perform parameter estimation (PE). Bilby is a Python library designed to perform GW data analysis using Bayesian inference [17]. Probability distributions for the values of each BBH parameter, known as "posteriors," are produced from these PE runs. Increased sensitivity will cause the width of the posteriors, or the uncertainty of the parameter measurement, to decrease. We aim to investigate how increased detector sensitivity affects deviations of the recovered parameters from their known injection values, focusing on changes in both the absolute numerical offset and the location of the injected values relative to the posterior standard deviations.

	Fixed amplitude		Fixed SNR	
Detector	Amplitude	SNR	Amplitude	SNR
LIGO O3	3.47	7.96	3.47	7.96
LIGO A♯	3.47	42.24	0.65	7.95
CE	3.47	212.84	0.13	7.95

TABLE I: Glitch parameters across detector configurations under two scenarios: amplitude held fixed at the LIGO O3 value, versus SNR held fixed at the LIGO O3 value. Amplitude in units of $\times 10^{-22}$. SNR values shift slightly due to the SNR approximation (6) used in amplitude scaling.

IV. INITIAL RESULTS

The current analysis has focused on validating the simulated data generation pipeline and establishing the expected behavior of the two glitch-scaling scenarios before performing the full PE analysis. First, we examined the simulated strain data to visualize how detector sensitivity and glitch scaling affect the prominence of the signal. Figure 4 illustrates the whitened simulated strain data for all three detector configurations, with the relative contribution of the injected CBC waveform increasing as detector sensitivity improves. Note that the figure displays whitened data, in which the noise variance is normalized to approximately unity. The apparent amplitude of the CBC waveform increases in the whitened representation; however, the physical waveform amplitude is fixed by the source. This change in scale simply reflects the increasing prominence of the signal arising from the reduction in detector noise with improved sensitivity.

Next, we injected various glitches into the detector data at the LLO site to examine how the strain was affected in both glitch scaling cases. The glitch amplitudes and SNRs for each case are listed in Table I, calculated with Equations (6) and (7). With increased detector sensitivity, fixing the glitch amplitude increases the glitch SNR, while fixing the glitch SNR decreases the glitch amplitude. This difference in scaling ultimately has a substantial impact on the strain data produced after glitch injection, as demonstrated in Figure 5. The fixed-amplitude glitches produce substantially larger distortions in the whitened strain data, whereas the glitches with fixed SNR have an almost negligible impact with decreased amplitude.

PE runs with Bilby can take several days to complete. Thus far, our only completed run has been with the LIGO O3 PSD, whose results are known. An initial corner plot showing our resultant posterior distributions for $\chi_{\rm eff}$ and $\chi_{\rm p}$ is displayed in Figure 6. The no-glitch posteriors show

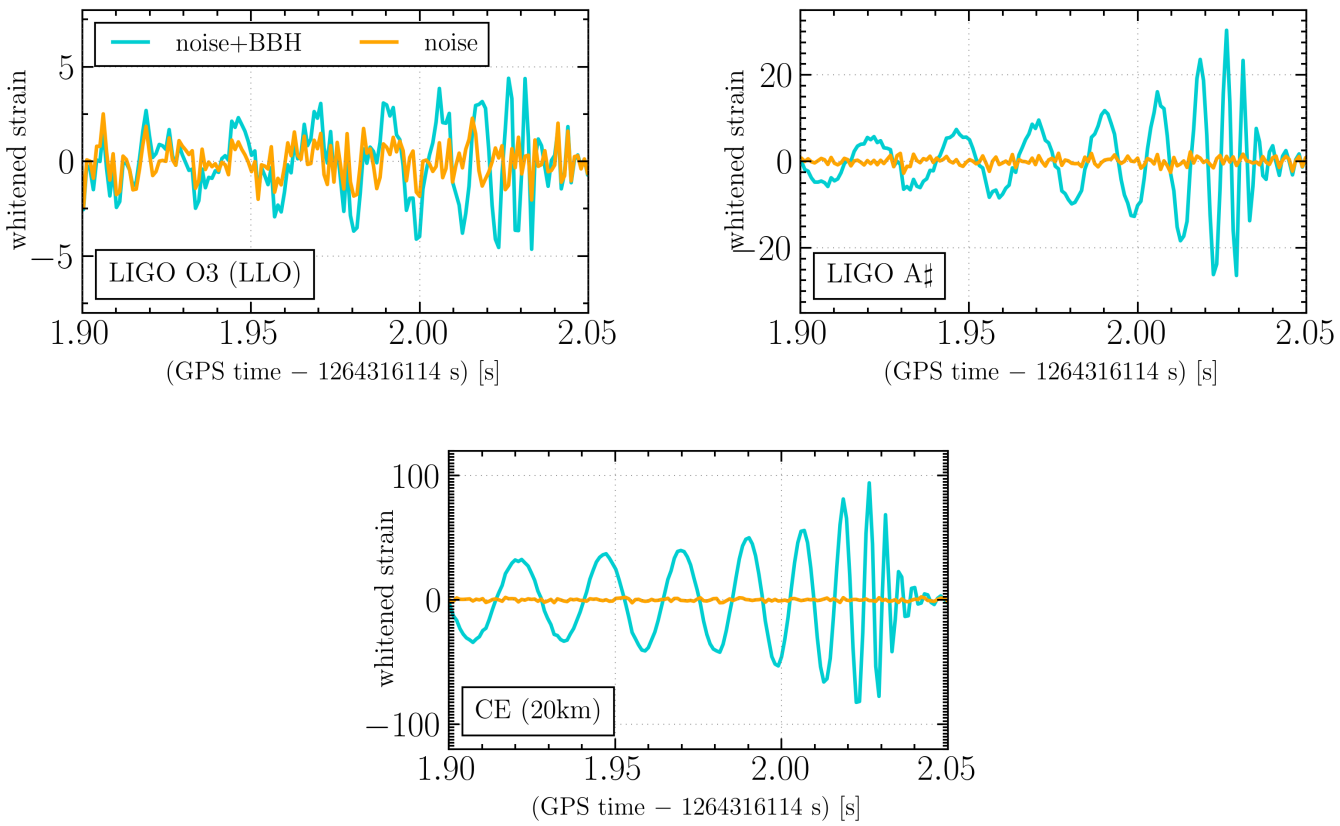


FIG. 4: Whitened strain for simulated Gaussian noise (orange) and the same noise with an injected CBC waveform (blue) for the LIGO O3 (LLO), LIGO A♯, and CE PSDs (clockwise from left). The waveform was generated with the IMRPhenomXPHM model using injection parameters from the event GW200129.

partial agreement with the injected values; however, the recovered distributions are not centered on the expected injection parameters, particularly for $\chi_{\rm eff}$. Since the no-glitch case serves as a validation test of the data generation and PE pipeline, this discrepancy indicates that further investigation of the simulation or PE configuration is required before interpreting glitch-induced biases.

V. FUTURE WORK

We await the results of the LIGO A♯ and CE parameter estimation runs. Upon receiving these results, we will confirm that the no-glitch runs, which act as a control to ensure the data and analysis is calibrated properly, align with the injection parameters we expect to recover.

After resolving any discrepancies, we will begin with analyzing how increasing detector sensitivity impacts parameter bias in the case of fixed glitch SNR, followed by the case of fixed glitch amplitude. We will quantify parameter bias using statistical metrics, namely the credibility of the injected value within the recovered posterior distribution.

Once we have analyzed the results of the PE runs, we plan to test several glitch mitigation strategies on the simulated data in order to infer their effectiveness with next-generation detectors. To do this, we will use the model BayesWave [15] to perform joint CBC-glitch inference, among other glitch mitigation methods.

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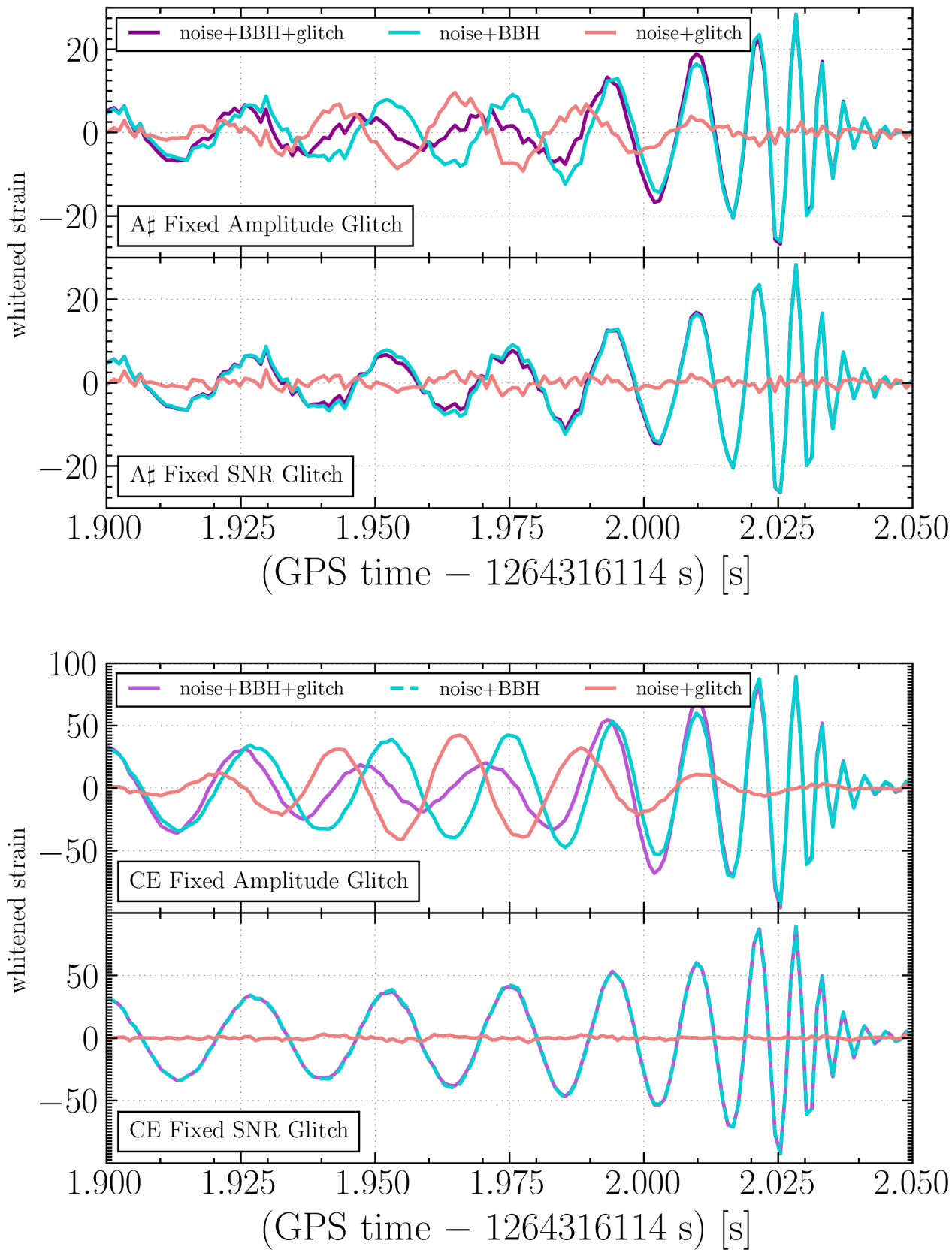


FIG. 5: Whitened strain data including glitch and CBC injections. Each panel shows the glitch and CBC injection in purple, the CBC-only injection in blue, and the glitch-only injection in coral. The top two panels correspond to simulated LIGO A♯ sensitivity, the uppermost showing the fixed glitch amplitude case and the panel below showing the fixed glitch SNR case. The bottom two panels display the corresponding data simulated with CE sensitivity. The lowermost blue line is dashed to illustrate its overlap with the purple line.

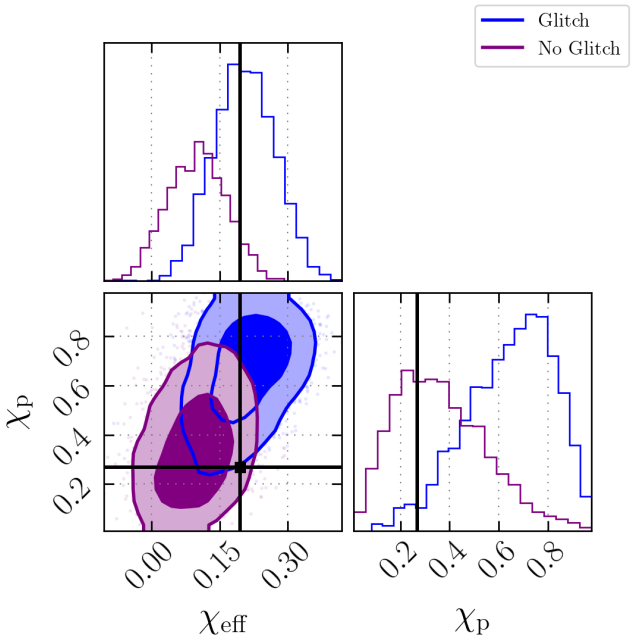


FIG. 6: Initial corner plot of the posterior distribution for $\chi_{\rm eff}$ and $\chi_{\rm p}$ with an injected glitch (blue) and with no glitch (purple) from the BILBY PE analysis for the LIGO O3 detector configuration. The known injection parameters of the CBC are indicated in black.