# GW190521: A Binary Black Hole Merger with a Total Mass of $150 M_\odot$ - Supplemental Material

The LIGO Scientific Collaboration and the Virgo Collaboration

## SUPPLEMENTAL MATERIAL

### Coherent Wave Burst search

Coherent Wave Burst (CWB) is a search algorithm for detection and reconstruction of gravitational wave (GW) transient signals operating without a specific waveform model. CWB searches for coincident signal power in multiple detectors with duration up to a few seconds. The analysis is performed in the wavelet domain [1] on data normalized by the amplitude spectral density of the detector noise. CWB selects wavelets with amplitudes above the fluctuations of the detector noise and groups them into clusters. For clusters correlated in multiple detectors, CWB identifies coherent events and reconstructs the source sky location and signal waveforms with the constrained maximum likelihood method [2].

The CWB detection statistic is based on the coherent network energy $E_\mathrm{c}$ obtained by cross-correlating data in different detectors; $\sqrt{E_\mathrm{c}}$ is the estimator of the coherent network signal-to-noise ration (SNR) [2]. The agreement between a GW signal and CWB reconstruction is characterized by a reduced chi-squared statistic $\chi^2 = E_\mathrm{n}/N_\mathrm{df}$, where $E_\mathrm{n}$ is the residual energy estimated after the reconstructed waveforms are subtracted from the whitened data, and $N_\mathrm{df}$ is the number of independent wavelet amplitudes describing the event. GW190521 is identified in LIGO data with $\chi^2 = 0.68$, showing no evidence for residual energy inconsistent with Gaussian noise.

To improve the robustness of the algorithm against non-stationary detector noise (glitches) and reduce the rate of false alarms, CWB uses signal-independent vetoes. The primary veto cuts are on the network correlation coefficient $c_\mathrm{c} = E_\mathrm{c}/(E_\mathrm{c} + E_\mathrm{n})$ and the $\chi^2$. For a GW signal the expected values of both statistics are close to unity and candidate events with $c_\mathrm{c} < 0.7$ and $\chi^2 > 2.5$ are rejected as potential glitches. The blip glitches, described in the Data section of the letter, are decimated by a selection cut based on a distinct shape of the glitch waveform. It is best described by a cosine wave in a Gaussian envelope with the standard deviation less than half a cycle. This selection cut starts to affect the detection of intermediate mass black hole (IMBH) binary systems with total redshifted mass $M > 300 M_\odot$, but the loss of detection efficiency is marginal ($< 20\%$) as was tested with simulated numerical relativity waveforms. In addition, the periodic variations of the noise in the frequency band 16-48 Hz, due to scattered light, are corrected with the linear prediction error filter [3].

The CWB searches are performed with two pipeline configurations targeting detection of low mass (binary BH configuration) and high mass (IMBH configuration) binary systems. They use different selection cuts defined a priori to alleviate the large variability of the non-stationary noise in the detectors. The GW190521 event was detected by CWB in its IMBH configuration. To further improve the background the CWB analysis employs additional selection cuts based on the generic properties of IMBH binary signals: (a) the low central frequency $f_\mathrm{c}$ of the GW signal and (b) their large chirp mass. In CWB, the redshifted chirp mass $\mathcal{M}$ of a binary system is estimated by using the time-frequency evolution of the GW signal [4]. To select IMBH systems we require that $|\mathcal{M}| > 10 M_\odot$ and the signal central frequency $f_\mathrm{c}$ is below 80 Hz. Both parameters $\mathcal{M} = 22.6 M_\odot$ and $f_\mathrm{c} = 58$ Hz reconstructed for GW190521 are well within the limits defined by the analysis selection cuts.

To estimate the statistical significance of selected candidates, each event was ranked against a set of background triggers obtained by repeating the analysis on time-shifted data. The time shifts were selected to be much longer ($\geq 1$ s) than the expected signal time delay between the detectors, in order to exclude astrophysical events from the background set. By using multiple time shifts, a set of background events equivalent to 9800 yr of null observation was obtained. The candidate events that survived the selection criteria were then assigned a false-alarm rate given by the rate of background events with the CWB detection statistics greater than the detection statistic of the candidate event.

### GstLAL and PyCBC searches

GstLAL [5–10] and PyCBC [11–16] independently implement search algorithms targeting compact binary mergers with banks of template waveforms and matched filtering. Both algorithms are used for low-latency as well as offline analyses.

All analyses based on GstLAL and PyCBC in O3 to date rely on SEOBNRv4 waveforms [17] as templates for the heavier-mass BH binary systems. These templates neglect several physical effects. First, the spins of the compact objects are assumed to be aligned with the orbital angular momentum, such that the orbital plane does not precess. Second, the orbit is assumed to be quasicircular: its eccentricity is assumed to be negligible when the signal becomes visible in the interferometers. Third, only the quadrupolar radiation multipole moment is included. Fourth, finite-size effects (such as tidal deformability) are neglected. Simulation studies, as well as the published LIGO and Virgo discoveries, demonstrate that the above simplifications reduce the computational cost of the search by at least an order of magnitude without compromising its sensitivity to most detectable signals [18, 19]. Nevertheless, there can be extreme systems for which one or more of the above assumptions are not applicable, implying that the search may detect the system with a reduced significance, or miss it altogether [19–21]. The template banks also necessarily cover a limited range of redshifted masses. In O3, the range of redshifted total masses is $[2, 758]\ M_\odot$ for GstLAL and $[2, 500]\ M_\odot$ for PyCBC [22, 23]; however, the effective high-mass boundary depends on mass ratio and spins. In the bank used by PyCBC, templates with nearly equal mass and small effective spin have a maximum redshifted total mass just above 100 $M_\odot$, while this limit is $\approx 600 M_\odot$ for the bank used by GstLAL.

GstLAL and PyCBC differ in several important technical choices, notably the signal-based vetoes used to reject instrumental transients, the ranking of GW candidates resulting from matched filtering, and the method used to assign false-alarm rates to the ranked GW candidates. These differences can lead to vastly different significances for the same astrophysical signal.

GstLAL uses a likelihood-ratio statistic to rank GW candidates by (i) the matched-filter SNRs, (ii) a signal consistency check based on waveform autocorrelation, (iii) the sensitivities of the detectors, (iv) the time and phase delays observed across the detector network, and (v) a template-dependent factor that describes the probability that a signal from the observed source population is identified by a specific template in our bank. Information from auxiliary channels that monitor the detectors and their environment is also included in the ranking.

GstLAL estimates the search background from triggers not found in coincidence at times when both LIGO interferometers are operating. The background triggers are used to estimate the probability density of noise-like events, and Monte Carlo methods are used to sample the noise probability density and produce a mapping from the likelihood-ratio to a false alarm rate. The significance of GW190521 is estimated with respect to the first half of O3, over which GstLAL analyzed 106.75 days of coincident LHO and LLO data.

The PyCBC-based analyses rank their candidates according to: (i) the matched-filter SNRs, (ii) two signal-based vetoes that quantify how much the data in each detector resembles the template waveform [14, 24], and (iii) the probability for the observed set of inter-detector arrival times, phases and SNRs to be associated with a plane GW from a distant source. The offline analysis additionally accounts for the rate of background triggers in the parameter space region surrounding each candidate.

In order to assign a false-alarm rate to each candidate coincidence, both the online and offline PyCBC analyses use time shifts to construct background samples and measure the cumulative background rate as a function of the ranking statistic. The two pipelines differ in how this process is implemented. The online analysis includes the data from the third interferometer, if available, in the calculation of the false-alarm rate of a coincident candidate. The offline pipeline calculates the background over an amount of data larger by more than an order of magnitude, and can therefore claim correspondingly lower false-alarm rates for events louder than the available background.

Contrary to previously discovered compact binary mergers, PyCBC's $\chi_r^2$ signal-based veto [24] reported a disagreement between the event and the template waveform producing the highest significance in the search [17, 25]. Specifically, $\chi_r^2$, expected to be $\sim 1$ for signals well described by the search templates, resulted in 1.1 (LHO) and 3.2 (LLO) in the offline analysis; the online analysis showed a similar behavior. The large LLO $\chi_r^2$ reflects a deficit of signal power between $\sim 23$ Hz and $\sim 43$ Hz, and similarly for $\gtrsim 68$ Hz, with respect to the template waveform. This effect can be due to a combination of high redshifted total mass, which places GW190521 at the limit of the mass space covered by PyCBC's configuration in O3 [23], and possibly waveform effects not modeled by the templates, such as precession, higher-order multipole moments, or eccentricity.

In order to investigate this point, we recalculated $\chi_r^2$ at LLO using different quasicircular waveform models with parameters that maximize the network SNR, obtaining values between 0.8 and 1.8, which no longer indicate a disagreement. The LHO–LLO network matched-filter SNR correspondingly increases to 14.5–15.0, consistent with the values obtained by CWB and GstLAL. As an additional check, we then added the maximum-likelihood SEOBNRv4 template to the bank used by PyCBC and repeated the offline analysis. The new template was preferred by the ranking over the previous template, increasing the LHO–LLO network SNR to 14.5 and decreasing the LLO $\chi_r^2$ to 1.7. These values are consistent with the other pipelines. However, we only obtained a slightly larger ranking statistic and, correspondingly, a slightly lower false-alarm rate (1 per 1.40 yr). We attribute the lack of a larger improvement to the fact that instrumental transients cause rapid variations of the trigger rate from template to template in the region of the bank with total redshifted mass above $\approx 100 M_\odot$. This variation is difficult to model when the bank is too sparse, which continues to be the case after adding the maximum-likelihood template.

In light of GW190521, an extension and finer coverage of the high-mass region of the bank, and possible further strategies to suppress the effect of instrumental transients, should improve PyCBC's sensitivity to similar events, and will be considered in future iterations of the search.

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