PHSX 525 Final Project

Search for GW200311_115853 with template bank

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Abstract

We analyze two minutes of data from LIGO Hanford and Livingston surrounding event GW200311_115853. The PSDs for each detector are estimated from strain data before the analysis window using a Welch averaging technique. We construct a two-dimensional template bank over the component masses, using PhenomA to generate waveforms in the frequency-domain. After verifying the coverage of the template bank, we use matched-filtering to construct an SNR time-series in each detector for every template. We find a coincident SNR spike in both detectors with combined $\mathrm{SNR}^2 \sim 230$ and time delay $\Delta\tau = 0.0059\,\mathrm{s}$ between detectors. The time of the coincident spike is near the event time listed by GWOSC. The template that maximizes the SNR has parameters $m_1 = 36.6\,\mathrm{M}_\odot$ and $m_2 = 34.6\,\mathrm{M}_\odot$. Converting to source frame masses, we see good agreement in total and chirp mass between our results and those published by GWOSC.

Template bank construction

We generate our frequency-domain waveforms using PhenomA, with frequency bins defined by $f_{\min} = 20\,\mathrm{Hz}$, $f_{\max} = 2048\,\mathrm{Hz}$, and $N_f = 2^{12} + 1$. We define the inner product between two waveforms, $\boldsymbol{a}$ and $\boldsymbol{b}$, in the frequency-domain as

$$(\boldsymbol{a}|\boldsymbol{b}) = 2\int_0^\infty \frac{\tilde{a}(f)\tilde{b}^*(f) + \tilde{a}^*(f)\tilde{b}(f)}{S_n(f)}df \tag{1}$$

where $S_n(f)$ is the power spectral density (PSD). The PSD is estimated with a Welch average of the data using 32 non-overlapping 8 s segments (taken before the analysis). In the construction of the template bank, we use the joint PSD between the Hanford and Livingston detectors, $S_{\text{joint}} = [\sum_n S_n^{-1}]^{-1}$.

Next we compute the metric tensor over template space, with parameters m_1, m_2, t_0, ϕ_0, and D_L. The template metric has components

$$g_{\mu\nu} = \frac{(h_{,\mu}|h_{,\nu})}{(h|h)} - \frac{(h|h_{,\mu})(h|h_{,\nu})}{(h|h)^2} \tag{2}$$

The partial derivatives are computed with central finite differencing. We use unit normalized templates so the luminosity distance components of the metric are identically zero. The t_0- and ϕ_0-dependence is projected out of the metric to obtain the (projected) metric components, $\tilde{g}_{\mu\nu}$. The only nonzero components of the projected metric are those corresponding to the component masses.

The template bank will be two-dimensional (over the component masses), so we fix $t_0 = \phi_0 = 0$ and $D_L = 100\,\mathrm{Mpc}$. The mis-match between two nearby points in parameter space is approximated by

$$\mathrm{MM} \approx \frac{1}{2}\tilde{g}_{\mu\nu}\Delta\lambda^\mu\Delta\lambda^\nu \tag{3}$$

for small $\Delta\lambda$. All templates in the bank are situated along the $m_2 = m_1 - 2\,\mathrm{M}_\odot$ line. We will show the coverage of this bank is sufficient for our search. We initialize the first template at $m_1 = 27\,\mathrm{M}_\odot$ ($m_2 = 25\,\mathrm{M}_\odot$). This template defines an ellipse in parameter space containing the area where $\mathrm{MM} \lesssim 0.05$. We find the ellipse by iterating along the semi-major and -minor axes, defined by the eigenvectors of the template metric at that point. The iterations are terminated when MM ~ 0.05, and the next template is placed here along the semi-minor axis.

We generate a total of 17 templates along the $m_2 = m_1 - 2\,\mathrm{M}_\odot$ line. The coverage ellipses (with scaled down widths for visualization) are shown in Fig. 1. To test the coverage, we draw $10,000$ random points in parameter space, and compute the minimum mis-match over the template bank. We make a histogram of these samples in Fig. 2.

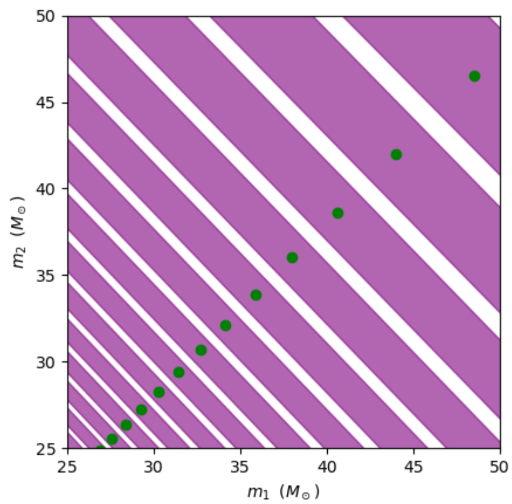

Figure 1: The templates stored in the bank (green dots) and their respective coverage ellipses (scaled down) indicating sufficient coverage of parameter space.

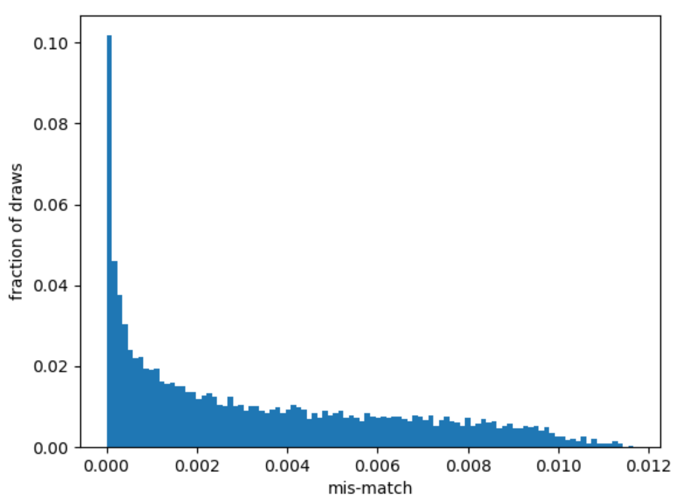

Figure 2: Histogram of minimum mis-match between random draws in parameter space and template bank. The large percentage of small mis-matches indicates our bank sufficiently covers parameter space.

SNR time-series

The SNR time-series is computed by taking the inverse FFT of the z-statistic

$$\tilde{z}(f, m_1, m_2) = 4\frac{\tilde{d}(f)\tilde{p}^*(f, m_1, m_2)}{S_n(f)}\Theta(f) \tag{4}$$

where $\tilde{d}$ and $\tilde{p}$ are the data and template (unit normalized) in the frequency-domain, respectively. $\Theta(f)$ is the Heaviside step function. The data is segmented into 8 s chunks, overlapping 0.5 s of each adjacent segment. We splice the central 7 s of each segment together to make the time-series. The best-fit template is selected to maximize the SNR spike. The time-series is shown in Fig. 3 and appears to have a coincident spike corresponding to the GW event.

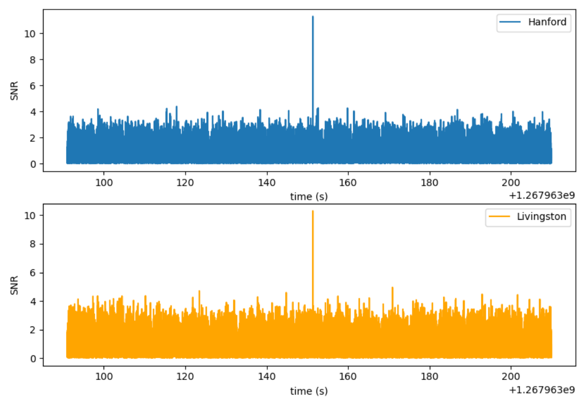

Figure 3: SNR time-series for the Hanford and Livingston detectors. The series is generated with the best-fit template.

Analysis

SNR series analysis

The SNR spikes between detectors are within 10 ms of one another ($\Delta\tau = 0.005859375\,\mathrm{s}$) and the same template ($m_1 = 36.6\,\mathrm{M}_\odot$, $m_2 = 34.6\,\mathrm{M}_\odot$) maximizes the SNR in both detectors, indicating this is a GW candidate! We plot the histogram of SNR values in Fig. 4. Notice the maximum SNR (green line) is significantly higher than 5σ above the mean.

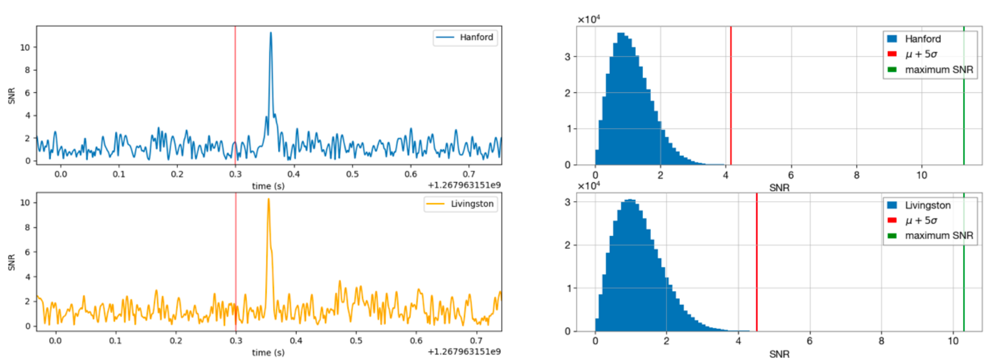

Figure 4: Left: SNR time-series zoomed-in, the red line is event's GWOSC GPS time. Right: histogram of SNR values in each detector.

We also compute the combined SNR^2 between the detectors. For every SNR^2 value in the Hanford series, we add the maximum SNR^2 from the Livingston series within 10 ms, to account for the time-delay between detectors. The series and histogram of SNR^2 values is shown in Fig. 5. The maximum SNR^2 is $\sim 58\sigma$ above the mean!

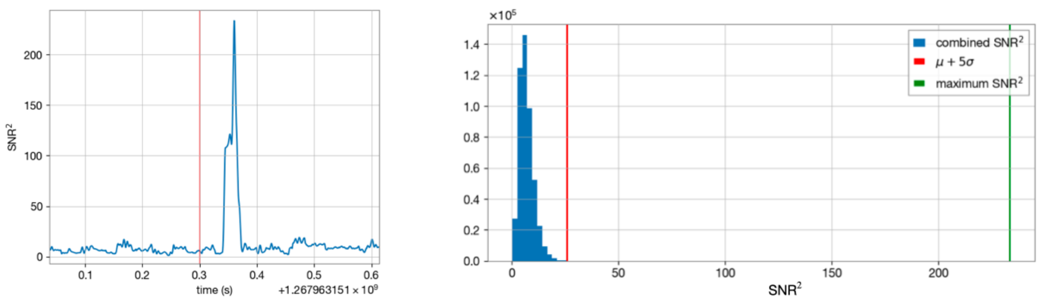

Figure 5: Left: SNR^2 series for combined detectors, the red line shows the event GPS time listed on GWOSC. Right: histogram of SNR^2 values.

Template analysis

The best-fit template has parameters $m_1 = 36.6\,\mathrm{M}_\odot$ and $m_2 = 34.6\,\mathrm{M}_\odot$. According to GWOSC, the parameter-estimation of this event yields $D_L = 1170^{+280}_{-400}$ Mpc. This corresponds to redshift $z \approx 0.23$, using standard cosmological parameters: $H_0 = 69.6$ km/s/Mpc, $\Omega_M = 0.29$, and $\Omega_\Lambda = 0.71$. Then we can compute the best-fit masses in the source frame,

$$m_{1,\mathrm{s}} = (1+z)^{-1} m_{1,\mathrm{d}} \approx 29.7\,\mathrm{M}_\odot\ , \qquad m_{2,\mathrm{s}} = (1+z)^{-1} m_{2,\mathrm{d}} \approx 28.1\,\mathrm{M}_\odot \tag{5}$$

These are quite different from the component masses listed on GWOSC, but our component masses are constrained by choice of template parameters. If we compute the total and chirp mass from the best-fit (bf) template, we find values within the uncertainty of those listed on GWOSC.

$$M_{\mathrm{bf}} = 57.8\,\mathrm{M}_\odot\ , \quad M_{\mathrm{GWOSC}} = 61.9^{+5.3}_{-4.2}\,\mathrm{M}_\odot\ , \quad \mathcal{M}_{\mathrm{bf}} = 25.2\,\mathrm{M}_\odot\ , \quad \mathcal{M}_{\mathrm{GWOSC}} = 26.7^{+4.5}_{-4.4}\,\mathrm{M}_\odot \tag{6}$$

We also compute the phase difference between detectors $\Delta\phi \approx 1.2$ (rad) and an amplitude ratio $A_{\mathrm{H/L}} \approx 1.095$. So the event's significance in each detector is nearly identical, with the edge to Hanford. Lastly in Fig. 6 we plot the whitened template over the whitened and bandpassed data. We minimize the chi-squared (between the data and template) over the reference phase, time, and amplitude before plotting.

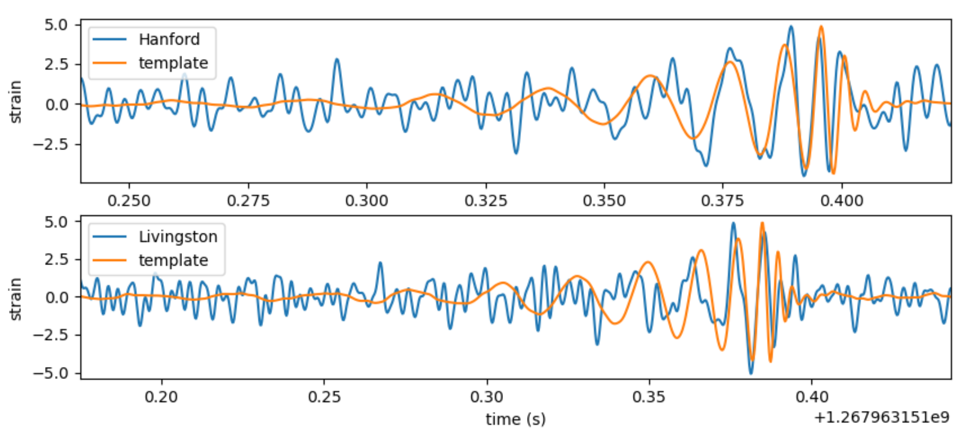

Figure 6: Fit of whitened template to whitened and bandpassed data. The template minimizes the chi-squared over the reference time, phase, and amplitude.