Prepared for submission to JCAP

On the matched filter Signal to Noise Ratio in LIGO signals

Akhila Raman[a]

[a]University of California at Berkeley

E-mail: akhila.raman@berkeley.edu

Abstract. This article analyzes the data for the three gravitational wave (GW) events detected in both Hanford(H1) and Livingston(L1) detectors by the LIGO[1] collaboration. It is shown that GW151226 and GW170104 are very weak signals whose amplitude does not rise significantly during the GW event, and they are indistinguishable from non-stationary detector noise. Using LIGO's matched filter to correlate H1 strain data with L1 strain data, it is shown that the matched filter Signal to Noise Ratio(SNR) does not show expected peaky behaviour for GW151226, GW170104 and GW150914, as observed when correlating H1 strain data with the H1 template. It is also shown that LIGO's whitening code does not sufficiently remove strong impulsive interference present in the strain signals and that this may affect the performance of the matched filter. Normalized Cross Correlation Function(CCF) method is implemented, and it is shown that the normalized CCF is poor for GW151226 and GW170104, when correlating H1 and L1. Hence it is suggested that GW151226 and GW170104 be questioned as candidates for GW signals. It is shown that LIGO's matched filter misfires with high SNR, even when correlating a sine wave with the template. The implication of these results for GW150914 is also examined. All the results in this paper are demonstrated using modified versions of LIGO's Python scripts[13].[2]

---

[1]The Laser Interferometer Gravitational-Wave Observatory

[2]The specific Python script used to generate Fig.1 to Fig.11 in this manuscript, is mentioned in [13].

Contents

1 Introduction

The first GW signal observed was GW150914 [1] which was a relatively strong signal whose amplitude, after whitening and filtering[1], rose significantly, well over detector noise level, during the 0.2 second GW event duration. In comparison, the second signal[2] GW151226[Fig. 2] and the third signal[3] GW170104[Fig. 3] were very weak signals, which look like noise after whitening and filtering and whose signal amplitude does not rise above the detector noise level during the GW event of duration 1 and 0.12 seconds, respectively.(Fig. 1)

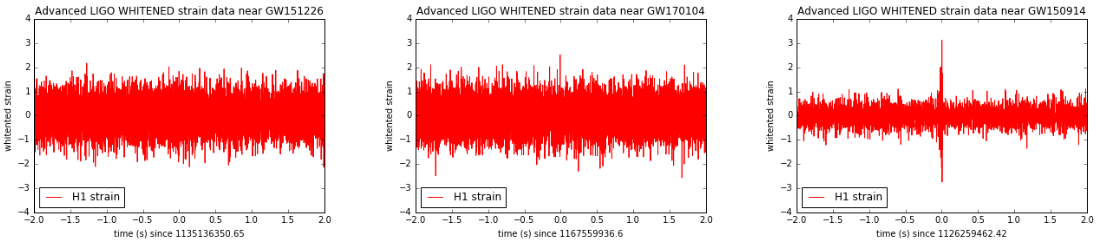

Figure 1. Plots of H1 whitened and filtered strain in GW151226, GW170104 and GW150914.

This raises the important question of whether GW151226 and GW170104 could have been caused by non-stationary detector noise. Creswell et al.[5] have reported correlations in the detector

[1]Fourth order Butterworth bandpass filters used in frequency range 20-300Hz for GW150914, 43-800Hz for GW170104 and GW151226.

noise which, at the time of the event, happen to be maximized for the same time lag as that found for the GW event itself.

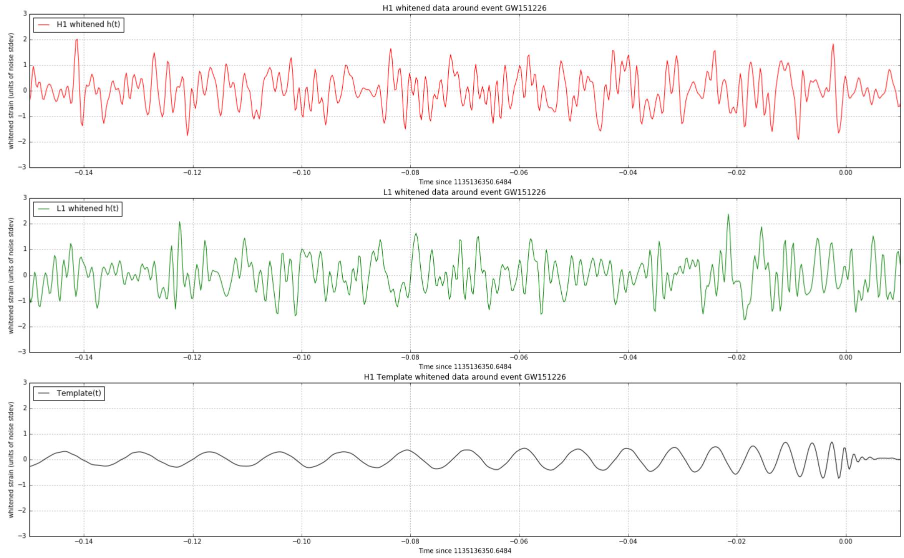

Figure 2. GW151226 whitened and filtered H1 and L1 strain, and the template

Because we are more often likely to observe weak signals which look like noise and whose amplitude does not rise during assumed GW event, it is of paramount importance that we should not classify noise as GW events. We must insist on high standards before classifying an observed time series as a GW signal.

The organization of this paper is as follows. In Section 2 we consider the effect of non-stationarity of detector noise on the false alarm rate computation and argue that brief bursts in detector noise coincident at both detectors could produce a high SNR in the matched filter, even though the amplitude of the whitened signal does not rise significantly over detector noise level in the time domain. Such bursts could be mistaken for GW events, particularly for GW151226 and GW170104.

In Section 3, we examine the theory and implementation of LIGO's matched filter which is the **core engine** driving the two independent analyses, PYCBC and GSTLAL. It will be shown that the matched filter SNR is very poor when correlating H1 and L1 whitened strain signals for GW151226 and GW170104 and also for GW150914. Using Normalized Cross Correlation Function(CCF) method, it will be shown that the normalized CCF is very poor, when correlating whitened and filtered H1 and L1 strain signals for GW151226 and GW170104.

In Section 4, LIGO's matched filter SNR performance is tested with a sine wave added to the detector noise and it will be shown that it misfires with high SNR, when correlated with the template. In Section 5, it is shown that H1 and L1 strains still show significant impulsive interference even after following LIGO's whitening procedure. In Section 6, the case is presented for questioning

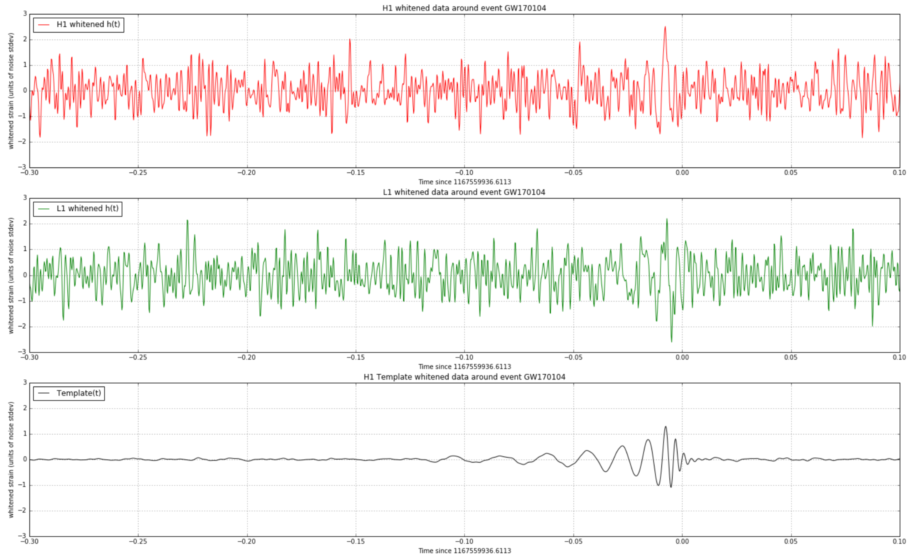

Figure 3. GW170104 whitened and filtered H1 and L1 strain, and the template

GW151226 and GW170104 as candidates for GW signals. In Section 7, a case for questioning GW150914 is presented, despite its relatively strong signal amplitude during the GW event window.

2 Non-stationary Detector Noise and its effect on False Alarm Rate

LIGO detector noise is non-stationary and non-Gaussian and has no analytical model. The number of background noise events which cross a specified SNR threshold, at the output of the matched filter, is determined empirically [4]. Creswell et al.[5] have pointed out that the sources of non-stationary and non-Gaussian detector noise need to be identified and eliminated to ensure reliable GW detection and that analysis methods for stationary noise cannot be used for non-stationary noise in LIGO detectors. It has been pointed out that, LIGO does not assume the noise is Gaussian and stationary for the observation of compact binary mergers.

It should be noted that, when LIGO papers claim high SNR for the three GW events [1–3], they mean SNR observed at the output of the matched filter. This does not necessarily mean that the signal amplitude during the GW event is significantly higher than the background noise amplitude. Let us define Signal Power Ratio (**SPR**) which is defined as the ratio of signal power during the GW event to the signal power outside the GW event (background detector noise). We can see in Fig. 1 that SPR is close to unity for weak signals GW151226(SPR=1.29) and GW170104(SPR=1.08), while GW150914 has relatively higher SPR=4.122. When SPR is close to unity or less than unity for weak signals, assumed GW template is buried in the detector noise, and the probability that non-stationary detector noise simulates the template becomes higher.

LIGO's search software uses two independent analyses, PYCBC and GSTLAL, and false alarm rate computations in Eq.8 and Eq.12 in [4] estimate empirically the number of coincident events above a certain threshold. For example, in the PYCBC analysis, the false alarm rate is given by the equation below, where T is the observation time of the search, T_b is the background time, $n_b(\hat{\rho}_c)$ is the number of background noise events that cross the candidate event's re-weighted SNR threshold.

$$F(\hat{\rho}_c) = 1 - e^{\frac{-T}{T_b}(1+n_b(\hat{\rho}_c))} \tag{2.1}$$

We may not observe high coincident SNR during 8 days of observation, but during next several months, by **definition** of non-stationarity, there is a possibility that the mean and variance of detector noise **may** change unpredictably and simultaneously in both sites, producing high coincident SNR in the output of the matched filter, even though the signal amplitude does not rise during the GW event, as is the case for GW151226 and GW170104 (Fig. 1). This will result in the estimate of the false alarm rate not applicable, particularly for weak signals GW151226 and 170104.

Hence, 5.1σ significance associated with the false alarm rate computation may be true for stationary white gaussian noise, but **not** necessarily for LIGO's non-stationary detector noise, which by definition, may change unexpectedly. We cannot be sure that the high SNR is produced by the GW template and **not** by non-stationary detector noise changing unexpectedly. For this reason alone[Reason 1], **independent** of other reasons, GW151226 and GW170104 should be questioned.

This point is illustrated by the signal $w_d(t)+a(t)$, where $w_d(t)$ is the L1 detector noise, obtained from a 32 second block of data which does not contain the GW signal, and $a(t)$ is Additive White Gaussian Noise(AWGN) of duration 1 second, scaled so that the standard deviation of $a(t)$ is 10 times lower than standard deviation of $w_d(t)$. Then we correlate $w_d(t) + a(t)$ with the GW151226 template $h(t)$ in the LIGO matched filter. Fig. 4 shows the results, and we can see from the right plot that, even white gaussian noise added to the detector noise can produce high SNR in LIGO's matched filter, similar to what actual GW151226 produces in the middle plot. Similar results are observed for GW170104.

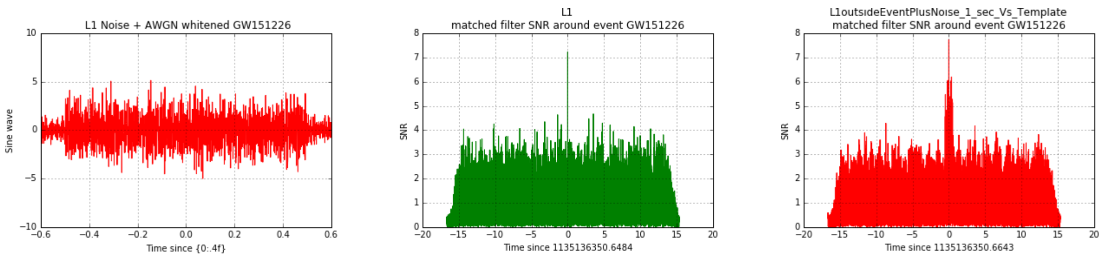

Figure 4. GW151226: Left panel: AWGN added to detector noise and then whitened and filtered. Middle Panel: LIGO matched filter SNR for L1 vs Template. Right Panel: LIGO matched filter SNR for AWGN + detector noise vs template.

3 LIGO Matched Filter Implementation

The **core engine** of the LIGO software for identification of GW signals is the matched filter as described in Eq.1-4 in [4], which is used in two independent search methods, PYCBC and GSTLAL analysis[2]. For the case of PYCBC analysis, matched filter SNR(MF-SNR) $\rho^2(t)$ is given as follows.

[2] GSTLAL analysis also uses matched filter search, and as per Page 7 in [4], "the data s(t) and templates h(t) are each whitened in the frequency domain by dividing them by an estimate of the power spectral density of the detector noise." and also "By the convolution theorem, $\rho(t)$ obtained in this manner is the same as the $\rho(t)$ obtained by frequency domain filtering in Eq. (1)."[in PYCBC analysis]. These equations are implemented in lines 662-740 in the matched filter section of LIGO's tutorial python script. [11].

$$
\begin{aligned}
\rho^2(t) &= \frac{1}{|\langle h|h\rangle|}|\langle s|h\rangle(t)|^2 \\
\langle s|h\rangle(t) &= 4\int_0^\infty \frac{\widehat{s}(f)\widehat{h}^*(f)}{S_n(f)}e^{i2\pi ft}df
\end{aligned}
\tag{3.1}
$$

where $s(t)$ and $h(t)$ are the strain signal and the template respectively and $\widehat{s}(f)$ and $\widehat{h}^*(f)$ are the Fourier Transforms of $s(t)$ and $h^*(-t)$ respectively and $S_n(f)$ is the power spectral density of the detector noise. In the time domain, this is equivalent to the convolution of whitened version of $s(t)$ with real $h(-t)$, which is equivalent to the Cross-Correlation Function(CCF) of the whitened strain signal $s(t)$ and the template $h(t)$, with a normalization scale factor as follows.

$$
\langle h|h\rangle = 4\int_0^\infty \frac{\widehat{h}(f)\widehat{h}^*(f)}{S_n(f)}df \tag{3.2}
$$

It is noted that the above CCF is **not** normalized to give MF-SNR =1 for an ideal template correlated with itself. Hence we will use reference systems as follows.

Reference System A: An ideal template for GW150914 $h(t)$ is correlated with itself, after normalization, to give the maximum value of CCF = 1 at zero lag.

Reference System 1: Each strain signal H1 and L1 is replaced by $s^{'}(t) = h(t) + w(t)$, where $h(t)$ is the ideal template for GW150914 and $w(t)$ is Additive White Gaussian Noise(AWGN) simulated in software, with power comparable to the background detector noise power.

Reference System 2: Each strain signal is replaced by $s^{'}(t) = h(t) + w_d(t)$, where $h(t)$ is the ideal template for GW150914 and $w_d(t)$ is the actual non-stationary detector noise outside the GW events. Then we can compare how the MF-SNR of the practical system compares with the reference systems 1 and 2.

Given that GW signals are assumed to be the sum of an ideal template and detector noise, this comparison is reasonable.

3.1 Test 3a: LIGO matched filter SNR by Correlating H1 with L1

The first step is to cross-correlate the strain signal H1 with L1 and test whether LIGO's matched filter SNR shows the peaky behaviour observed in the reference plots in the top row of Fig. 5. Given that the same GW signal is expected to be received in both sites, these signals should give a high SNR at the matched filter output when correlated with each other. This is a **crucial** test which must be performed.

We **can** cross-correlate two noisy signals and expect a peaky CCF, if the signals are correlated. In fact, wireless communication with sensors routinely use cross-correlation of two noisy signals [8]. We wish to correlate two noisy signals $s(t) = h_H(t) + w_H(t)$[H1] and $h^{'}(t) = h_L(t) + w_L(t)$[L1] where $w_H(t)$ and $w_L(t)$ represent the detector noise, and $h_H(t)$ and $h_L(t)$ represent the templates of H1 and L1. This is equivalent to correlating $s(t) = h^{'}(t) + (w_H(t) - w_L(t)) + (h_H(t) - h_L(t))$ and $h^{'}(t)$ and hence correlating $s(t) = h^{'}(t) + w(t)$ and $h^{'}(t)$, where $w(t) = (w_H(t) - w_L(t)) + (h_H(t) - h_L(t))$. $h^{'}(t)$ is the noisy template. The theory of matched filter imposes no constraints on the characteristics of the template.

The same template $h(t)$ is used in the top row CCF plots of Fig. 5, because the templates received at H1 and L1 detectors are nearly identical, which differ only by a time shift and a scale factor, and this does not matter for the ratio R, in the the normalized CCF plots.

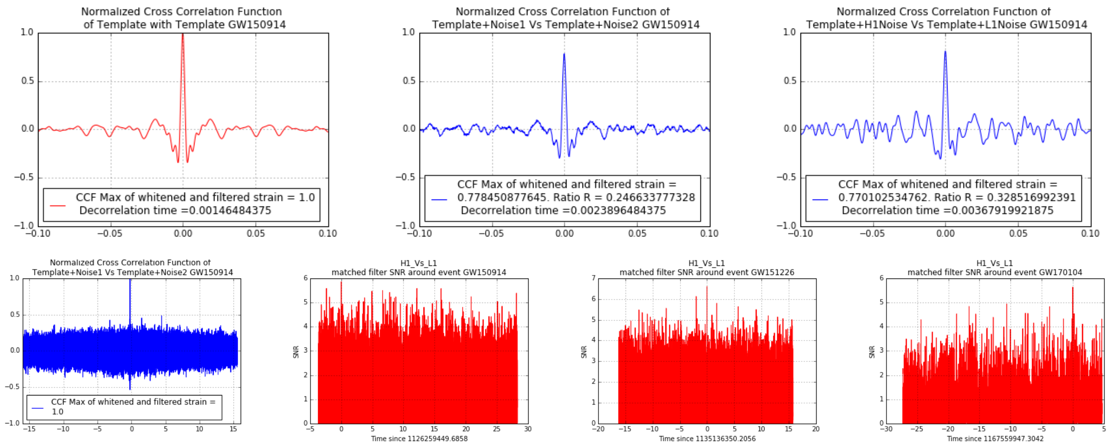

Figure 5. Bottom Row: Last 3 plots: Plots of H1 vs L1 LIGO matched filter SNR for GW150914, GW151226 and GW170104. Left plot: LIGO matched filter SNR for Template+AWGN vs Template+AWGN for GW150914. 32 second windows used by LIGO's original script for both H1/L1 and the template. Top Row: Reference Systems with Normalized CCF over 0.2 second windows for GW150914. Top left: Reference System A. Top Middle : Reference System 1. Top Right: Reference System 2. If maximum value of CCF is negative, the plot is inverted.

By peaky CCF, we mean that the ratio, R, of the the absolute value of CCF for any lag greater than the decorrelation time of the template, to the absolute maximum value of CCF, should be less than a certain threshold. Decorrelation time of the template τ_0 is defined as the time taken for the autocorrelation of the template to fall to $\frac{1}{e}$ of the maximum value at zero lag [9] and $\tau_0 = 0.001464$ seconds for the template of GW150914. If we look at the reference plots in the top row of Fig. 5, we observe that $R < \frac{1}{e}(\frac{1}{e} = 0.36)$.

Reference System 1: Fig. 5 shows this system in the second plot in top row, which correlates two noisy signals, $s(t)$ and $h^{'}(t)$, where $s(t)$ is the sum of the template for GW150914 and AWGN, and $h^{'}(t)$ is the sum of the same template and an independent AWGN. Then it computes the normalized $CCF(t) = \int_{-T}^{T} s(\tau)h^{'}(t-\tau)d\tau$. We can see that the CCF shows strong peaky behaviour. Average decorrelation time for this system is $\tau_1 = 0.0024$ seconds.

Reference System 2: Fig. 5 shows a reference system 2 in the third plot in top row, which correlates two noisy signals, $s(t)$ and $h^{'}(t)$, where $s(t)$ is the sum of the template for GW150914 and H1 detector noise outside the GW event, and $h^{'}(t)$ is the sum of the same template and and L1 detector noise outside the GW event, and computes the normalized CCF. We can see that the CCF shows strong peaky behaviour. Average decorrelation time for this system is $\tau_2 = 0.0037$ seconds.

Reference systems 1 and 2 are shown only for the purpose of demonstrating the fact that we can cross-correlate two noisy signals and expect a peaky CCF. Given the need for high standards required in classifying GW signals, we will use only the decorrelation time τ_0 of the reference system A, which correlates the template of each GW signal with itself, when we compare the decorrelation times and the ratio R, of the three GW signals. We will use the ratio R_3, which is the ratio of the absolute value of CCF at any lag greater than $\tau_0 * 3$ to the absolute maximum value of CCF, and test whether $R_3 < \frac{1}{e}$. Lag greater than $\tau_0 * 3$ is taken to allow for some cushion.

The last three plots in the lower left panel in Fig. 5 show the results for correlating H1 with L1 in LIGO's matched filter for the three GW signals, GW150914, GW151226 and GW170104. We can see clearly that the three GW signals **do not** show peaky correlations ($R_3 > \frac{1}{e}$), comparable to the reference plots in the top row of Fig. 5 ($R_3 < \frac{1}{e}$).

This result is **surprising** for GW150914 because it shows very good visual correlations. The top right panel in Fig. 6 shows very good CCF peaks for GW150914, when using normalized CCF using 0.2 second windows for correlating H1 and L1 ($R_3 < \frac{1}{e}$).

It is possible that LIGO's matched filter SNR correlation over 32 second windows, is too long to bury the correlations in the presence of detector noise at both sites, for GW150914. Normalized CCF in the plots of Fig. 6 is performed over 0.2 second window over which GW150914 was observed and hence the short window may have captured the correlation between H1 and L1 in GW150914.

It is worthwhile to note that the first plot in the lower left panel in Fig. 5 shows good correlation peaks in normalized CCF over 32 second windows, correlating x(t) with y(t), where x(t) is the sum of GW150914 template and AWGN and y(t) is the sum of the same template and independent AWGN, with power of AWGN comparable to the background detector noise power. This suggests the correlations between H1 and L1 in GW150914 are poorer [Reason 2].

3.2 Test 3b: Normalized CCF Method

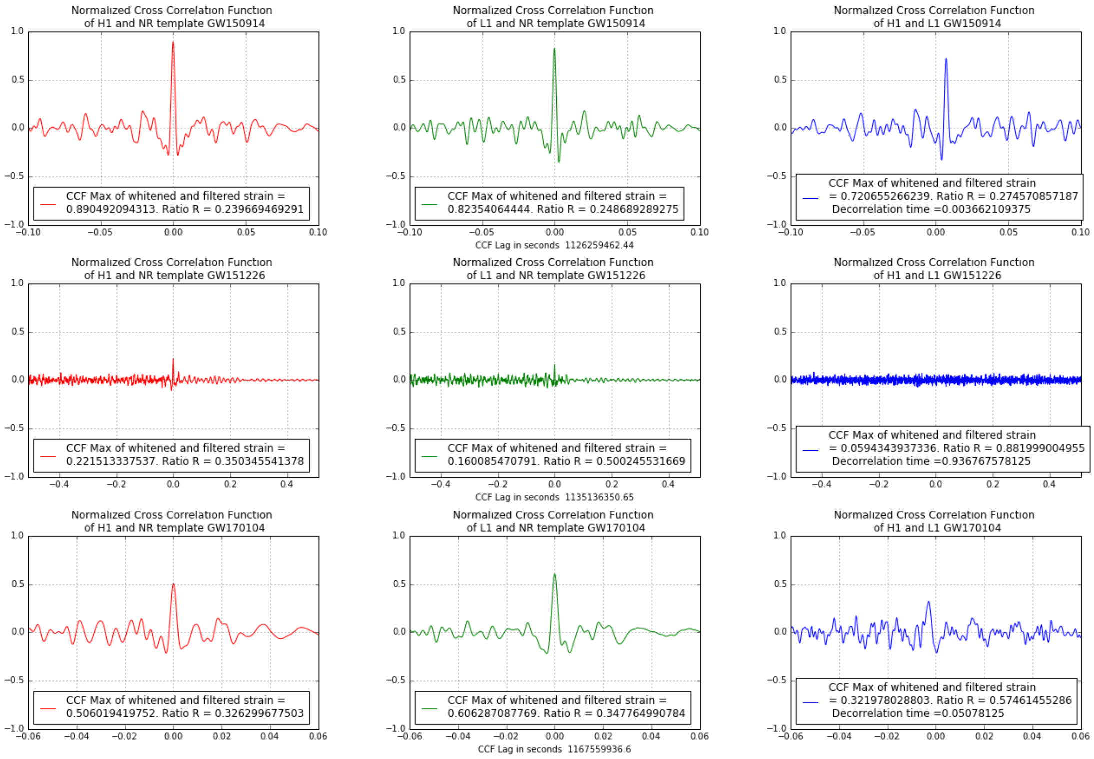

Figure 6. Normalized CCF for GW150914, GW151226 and GW170104 done over GW event duration of 0.2, 1 and 0.12 seconds respectively. If maximum value of CCF is negative, the plot is inverted. Ratio $R = R_3$

.

Let us consider a normalized Cross Correlation Function(CCF) $CCF(t) = \int_{-T}^{T} s(\tau)h(t-\tau)d\tau$, where both $s(t)$ and $h(t)$ are normalized over the time window [-T,T] during which GW signal was observed, such that CCF of each signal with itself gives a result of unity for zero lag. GW150914 was observed in the window of duration 0.2 seconds, GW151226 in a duration of 1 second and GW170104 in a duration of 0.12 seconds[1–3].[3]

[3]Normalized CCF using running windows method using, say 32 seconds of H1 and 0.2 seconds of L1, gives similar results as this method using short windows for both H1 and L1. See the file LOSC Event tutorial Normalized CCF v1.py

GW signal	R_3 H1 vs template	R_3 L1 vs template	R_3 H1 vs L1
GW150914	0.2396	0.2486	0.2745
GW151226	0.35	0.50	0.88
GW170104	0.3262	0.3477	0.5746

Table 1. Normalized CCF Ratio for GW150914, GW151226 and GW170104. R_3 = Ratio of the absolute value of CCF at any lag greater than $\tau_0 * 3$ to the absolute maximum value of CCF. τ_0 is the decorrelation time of the template. Lag greater than $\tau_0 * 3$ is taken to allow for some cushion.

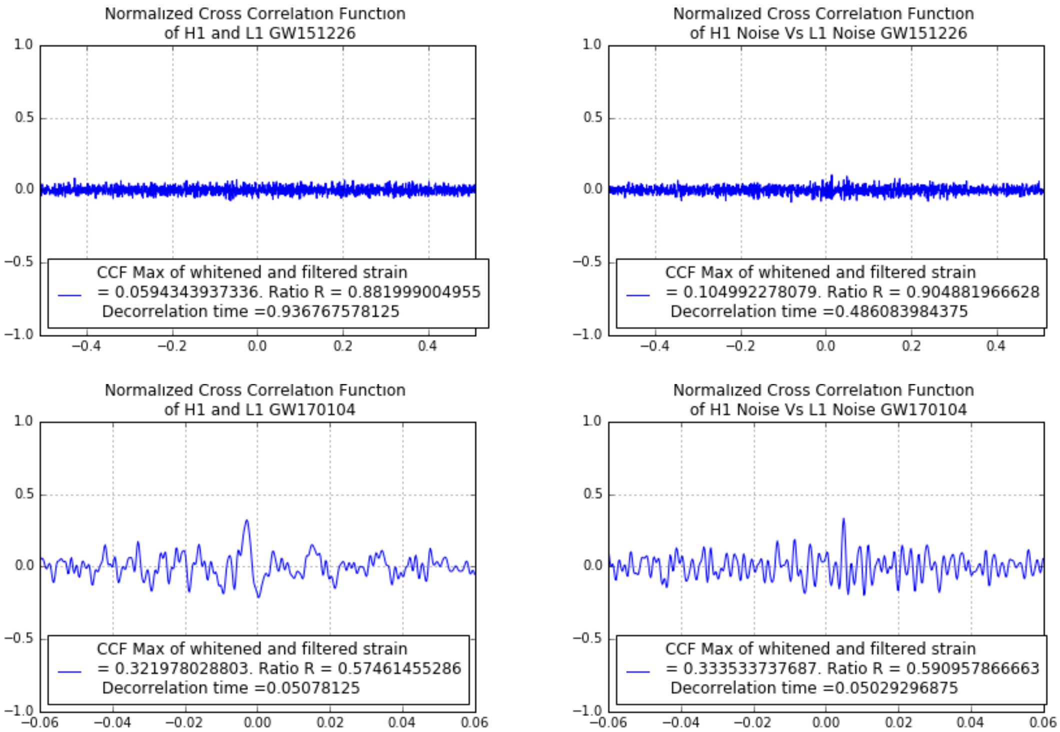

Figure 7. Normalized CCF Plots done over GW event duration. Top Row: GW151226. Bottom Row: GW170104. Left panels: H1 vs L1. Right panels: H1 noise vs L1 noise. H1 and L1 detector noise obtained 1 second after the end of GW151226 and 10 seconds after the end of GW170104.

We observed in the top row of Fig. 5 that the normalized CCF of the template with itself, gives a maximum value of 1 at zero lag and has a decorrelation time $\tau_0 = 0.001464$ seconds. The two reference systems 1 and 2, also have normalized CCF with the ratio $R_3 < \frac{1}{e} = 0.36$. It is reasonable to expect a similar ratio $R_3 < \frac{1}{e}$ from GW150914, GW151226 and GW170104, when correlating H1 with L1.

Fig. 6 plots the normalized CCF for GW150914(top row), GW151226(middle row) and GW170104 (bottom row) by correlating H1 with the template, L1 with the template and H1 with L1. We can see from the rightmost 3 plots that GW151226 and GW170104 show very poor CCF peaks ($R_3 > \frac{1}{e}$) when correlating H1 with L1, while GW150914 shows relatively higher CCF peak. We can also see from the middle row in Fig. 6 that GW151226 shows very poor CCF peaks ($R_3 > \frac{1}{e}$) when correlating L1 with the template[4].

[4]In Fig. 6, we use whitened and filtered versions of H1, L1 strains and the templates, for the 3 GW signals. In LIGO

Table 1 summarizes the ratio, R_3, of the absolute value of CCF at any lag greater than $\tau_0 * 3$ to the absolute maximum value of CCF, for the three GW signals, where τ_0 is the decorrelation time of the template. GW151226 has $R_3 > \frac{1}{e}$ when correlating L1 with the template. GW151226 and GW170104 have $R_3 > \frac{1}{e}$ when correlating H1 with L1.

Fig. 7 plots the normalized CCF for GW151226(top row) and GW170104 (bottom row) by correlating H1 with L1 in the left column and correlating H1 detector noise with L1 detector noise in the right column. We can see that GW151226 and GW170104 show very poor CCF peaks ($R_3 > \frac{1}{e}$) when correlating H1 with L1, and we can see that CCF peaks are **comparable** with CCF peaks corresponding to detector noise in the right column.

For this reason alone[Reason 3], **independent** of other reasons, GW151226 and GW170104 should be questioned.

4 LIGO's Matched Filter Misfires for Sine Wave

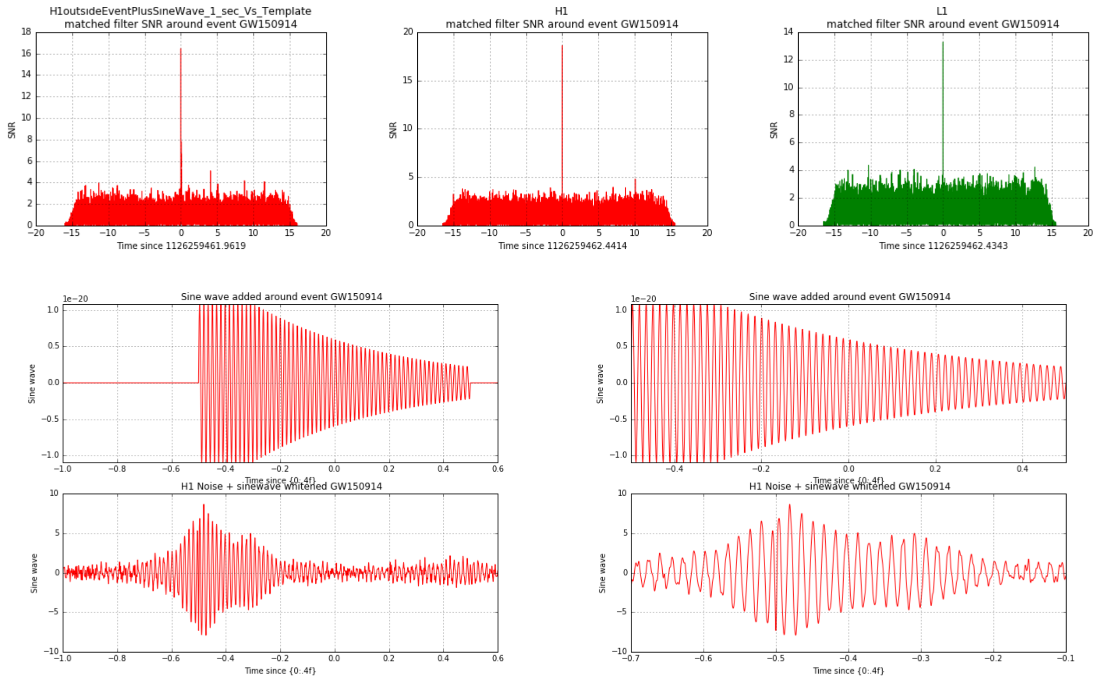

Figure 8. Top Left Panel: LIGO matched filter SNR for Sinewave + detector noise vs template. Bottom row: whitened and filtered signal in the time domain.

In this section, we will examine whether LIGO's matched filter fires with high SNR, if it is fed with a signal other than the template. Let us test it by replacing the GW150914 signal with the signal $w_d(t) + a(t)$, where $w_d(t)$ is the H1 detector noise, obtained from a 32 second block of data which does not contain the GW signal, and $a(t)$ is a sine wave of duration 1 second and frequency 60 Hz, scaled so that the standard deviation of $a(t)$ is 10 times lower than standard deviation of $w_d(t)$ and has an exponential decay. Then we correlate $w_d(t) + a(t)$ with the template $h(t)$ in the LIGO matched filter.

tutorial file LOSC Event Tutorial.py, the variables "strain H1 whitenbp" and "strain L1 whitenbp", "template match" are used.

Fig. 8 shows the results, and we can see from the top left plot that even a sine wave added to the detector noise can produce strong peaky CCF in LIGO's matched filter, similar to what actual GW150914 produces in the top right plots. This result is not unique to any specific sine wave frequency, but similar results are observed for other frequencies as well and also for GW151226 and GW170104.

This means that either the template or a sine wave of any frequency could have produced peaky CCF in LIGO's matched filter, and we **cannot be sure** that GW150914 was caused by an astrophysical event. It should be noted that we do not claim that a sine wave produced high SNR in the matched filter for GW150914. In the case of weak signals GW151226 and GW170104, where the template is assumed to be buried in noise, buried sine wave can also produce high SNR in the matched filter.

It is clear that LIGO's matched filter may have problems that need to be fixed, and given the fact that LIGO's matched filter SNR is the core engine used in PYCBC and GSTLAL analyses and estimation of false alarm rates, this calls into question results for GW150914, GW151226 and GW170104.

For this reason alone[Reason 4], **independent** of other reasons, GW151226, GW170104 and GW150914 should be questioned.

5 Problems in the LIGO Whitening Code

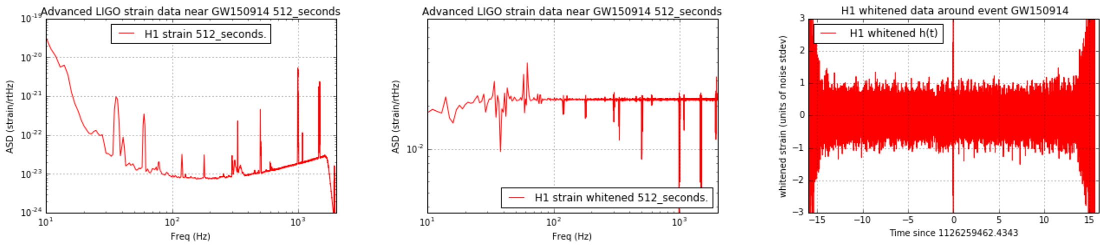

Figure 9. First 2 panels: Amplitude Spectral Density(ASD) Plots of H1 strain, H1 whitened and filtered strain, in GW150914. Third panel: H1 whitened and filtered strain 32 seconds, in time domain

LIGO detectors have very strong impulsive interference in 60Hz and harmonics and also in 300Hz-2000Hz range. Creswell et al.[5] have pointed out that the whitening section of LIGO's matched filter does not remove the narrow resonances in the strain signals well enough.

The first 2 plots in Fig. 9 shows the Amplitude Spectral Density(ASD) for 512 seconds of H1 strain data and H1 strain whitened and filtered. We can see that LIGO's whitening code does not remove impulsive interference well enough. The third panel shows the full 32 second whitened and filtered H1 strain data and we can see that the whitening code which operates in the frequency domain has edge effects. This may affect the performance of LIGO's matched filter.

It is important to clean up the impulsive interference in the detectors, so when we compute the matched filter SNR by correlating H1 and L1 signals, it can give high values for valid GW signals.

6 Case for Questioning of GW151226 and GW170104

GW151226 and GW170104 belong to a class of signals with Signal Power Ratio(SPR) around unity. We need to have much higher standards for classifying such signals as GW signals, than signals like GW150914 which have $SPR > 4$.

Given the high standards required for declaration of GW signal, it is suggested that GW151226 and GW170104 be questioned, due to each of the following Reason 1, 3 and Reason 4 **independently**.

Reason 1: Being weak signals, non-stationary and non-Gaussian detector noise at the two sites could have caused the weak GW signal. When high SNR is observed at the matched filter during the GW event, while signal amplitude does not rise significantly, as is the case for GW151226 and GW170104, it may be due to non-stationary detector noise having high SNR at the output of the matched filter briefly at both sites as well.

Reason 3: In Section 3, we observed in Table 1 and Fig. 6 and Fig. 7 that the normalized CCF is very poor ($R_3 > \frac{1}{e}$) when correlating H1 and L1, for GW151226 and GW170104.

Reason 4: In Section 4, we observed in Fig. 8 that LIGO's matched filter misfiring for a sine wave, may have problems for GW151226 and GW170104.

7 Implications of Results for GW150914

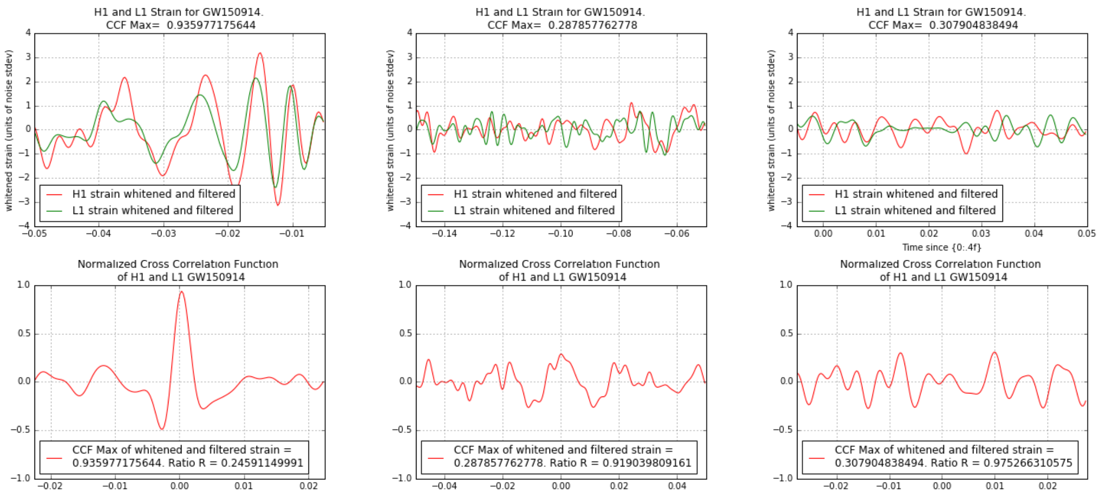

Figure 10. GW150914 whitened and filtered strains: Top Row: Plots of H1 vs L1. Bottom Row: Normalized CCF of H1 vs L1. 3 time windows: [-0.05,-0.005], [-0.15,-0.05] and [-0.005,0.05] seconds.

Fig. 10 shows the visual correlations of whitened and filtered H1 and L1 strains over the 3 windows and we can see that the correlations are satisfyingly strong only in a short 0.05 second window in the first plot. Correlations in the second and third windows in the rest of $0.2 - 0.05 = 0.15$ seconds are not convincing.

This agrees with the maximum values of the normalized CCF, given by CCF_{max} computed for these 3 windows. We can see that $CCF_{max} > 0.9$ for the short 0.05 second window in the first plot, but $CCF_{max} < 0.31$ for the other 2 windows and the Ratio $R_3 > \frac{1}{e}$.[Reason 5]. This is attributed to the high levels of detector noise which is comparable to the template power in these 2 windows. So, we **cannot be sure** if template is present in these 2 windows for GW150914[Reason 5]. This problem can be resolved only by reducing detector noise in future.

7.1 Effect of removal of 20-300Hz Bandpass filter

Fourth order butterworth bandpass filters are used in the frequency range 20-300 Hz in plotting whitened and filtered H1 and L1 strains for GW150914 in Fig. 10. The template for GW150914 has 86 percent of its energy in this 20-300 Hz range and **14 percent** of energy in the remainder of

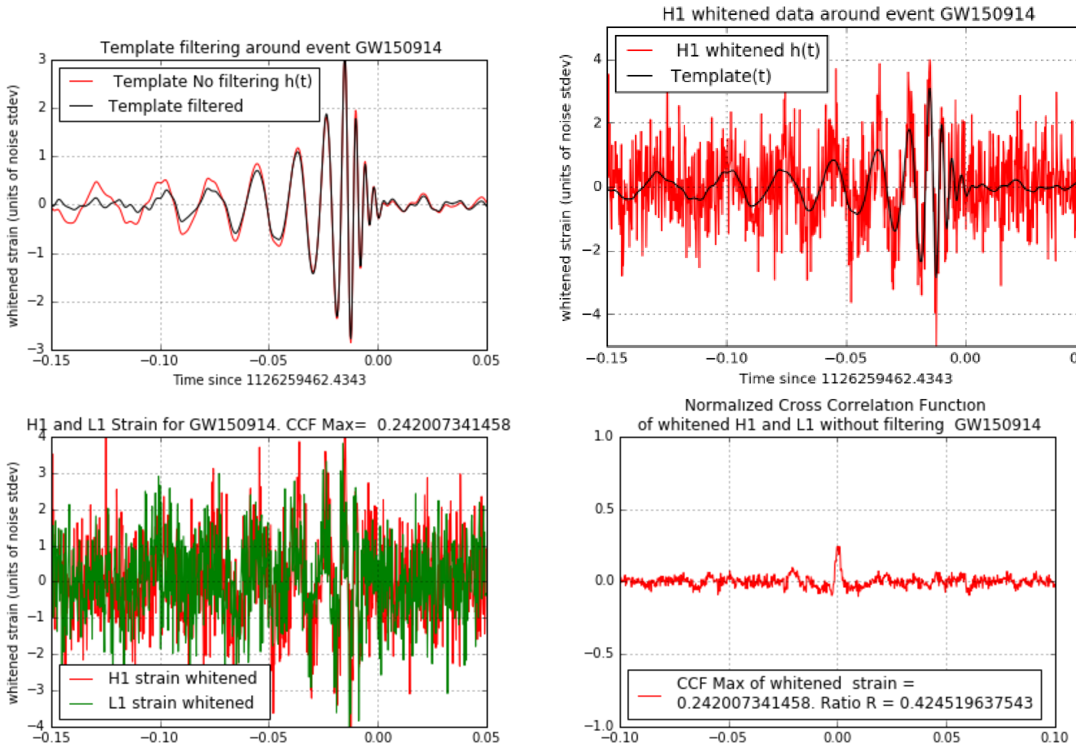

Figure 11. Top Left: Plots of templates with and without filtering. Top Right: Plots of whitened H1 vs template without filtering. Lower Left:Plots of H1 vs L1 whitened strain in GW150914 without filtering. Lower Right: Normalized CCF of H1 vs L1 whitened strain in GW150914 without filtering

the total frequency range of 0-2048 Hz, with sampling frequency of 4096 Hz. The upper left panel in Fig. 11 compares the templates inside 20-300 Hz band and the total range of 0-2048 Hz.

The upper right panel in Fig. 11 compares the whitened H1 strain without filtering and compares it with the unfiltered template. The lower left panel in Fig. 11 compares the whitened H1 and L1 strains without filtering. The lower right panel in Fig. 11 compares the Normalized CCF of whitened H1 and L1 strains without filtering. We can see that visual correlations and the normalized CCF values become much poorer if we do not filter the strains with 20-300 Hz filter, so that we can capture the **14 percent** template energy outside 20-300 Hz. We see that the maximum value of CCF falls from 0.72 in the upper right panel in Fig. 6, to 0.24 in the lower right panel in Fig. 11 and also that the Normalized CCF Ratio $R_3 > 1/e$[Reason 6]. This problem can be resolved only by reducing detector noise in future.

7.2 Summary of results

Given the high standards required for declaration of GW signal, it is suggested that GW150914 be questioned, due to each of the following Reason 4, Reason 5 and Reason 6 **independently**.

Reason 4: In Section 4, we observed in Fig. 8 that LIGO's matched filter misfires for sine wave input with high SNR and hence we cannot be sure if GW150914 template was received.

Reason 5: We observed in Fig. 10 that the normalized CCF is high only for a short 0.05 second window when correlating H1 and L1, for GW150914. It is poor for the other 2 windows ($R_3 > 1/e$).

Reason 6: We observed in Fig. 11 that the normalized CCF is poor and the Normalized CCF Ratio $R_3 > 1/e$, when correlating H1 and L1, for GW150914, without using 20-300 Hz filter, so that we can capture the 14 percent template energy outside 20-300 Hz.

8 Concluding remarks

Section 6 gives the reasons why weak signals GW151226 and GW170104 should be questioned. Section 7 gives the reasons why GW150914 should be questioned. Reiterating the point made earlier, because we are more often likely to observe weak signals which look like noise and whose amplitude does not rise during assumed GW event, it is of paramount importance that we should not classify noise as GW events. We need **high** standards to classify an observed time series as a GW signal. LIGO detectors have very strong impulsive interference in 60Hz and harmonics and also in 300Hz-2000Hz range. This may affect the performance of the matched filter. It is very important to clean up the impulsive interference in the detectors.

Acknowledgments

I am grateful to Andrew D. Jackson of Niels Bohr International Academy for his encouragement, suggestions, discussions and review of this manuscript. I would like to thank Sebastian Domenico von Hausegger and Arunava Chaudhuri for review of my Python scripts and helpful suggestions. I would like to thank M.A. Srinivas for discussions and helpful suggestions. I would like to thank LIGO Open Science Center for making the data and Python scripts available online. I would like to thank LIGO scientists who answered my many questions in detail.

References

[1] Abbott, B. P., Abbott, R., Abbott, T. D., et al., *Observation of Gravitational Waves from a Binary Black Hole Merger*, Physical Review Letters, 116, 061102 (2016) Online version of paper.

[2] Abbott, B. P., Abbott, R., Abbott, T. D., et al., *GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence*, Physical Review Letters, 116, 241103(2016) Online version of paper.

[3] Abbott, B. P., Abbott, R., Abbott, T. D., et al.*GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2*, Physical Review Letters, 118, 221101 (2017) Online version of paper.

[4] Abbott, B. P., Abbott, R., Abbott, T. D., et al., *GW150914: First Results from the Search for Binary Black Hole Coalescence with Advanced LIGO*, Phys. Rev. D 93, 122003 (2016) [see pp.4-9] Arxiv copy of paper. see pp.8-13.

[5] Creswell, J., Hausegger,S., Jackson, A. D., Liu,H., Naselsky, P., *On the time lags of the LIGO signals*, 2017, arxiv:1706.04191 Arxiv copy of paper.

[6] Naselsky, P., Jackson, A. D., & Liu, H., *Understanding the LIGO GW150914 event*, Journal of Cosmology and Astroparticle Physics, 8, 029 (2016)

[7] Liu, H., & Jackson, A. D., *Possible associated signal with GW150914 in the LIGO data*, Journal of Cosmology and Astroparticle Physics, 10, 014 (2016)

[8] Garnier, J., Papanicolaou,G., *Passive Sensor Imaging Using Cross Correlations of Noisy Signals in a Scattering Medium*, SIAM J. Imaging Sci., 2(2), 396437.(2009). Online version of paper

[9] Kenneth Y. Jo, Satellite Communications Network Design and Analysis, Page 415.

[10] LOSC LIGO GW150914 Tutorial

[11] LOSC LIGO GW151226 Tutorial matched filter equations are implemented in the section ”matched filtering to find the signal”

[12] LIGO Tutorials

[13] Zip Files of Modified LIGO Tutorials which demonstrate the results in this paper. Matched Filter SNR results are demonstrated with 32 second block of data, used in the original LIGO tutorial scripts. Results hold for 512 second block of data also.
Fig.1, Fig.2 , Fig.3: LOSC Event tutorial zoom.py
Fig.4: LOSC Event tutorial MF noise test.py
Fig.5: Lower Panel: LOSC Event tutorial H1 L1 No Correlations v1.py.
Upper panel:LOSC Event tutorial Normalized CCF.py
Fig.6: LOSC Event tutorial Normalized CCF.py
Fig.7: LOSC Event tutorial Normalized CCF v2.py
Fig.8: LOSC Event tutorial MF sinewave test.py
Fig.9: GW150914 tutorial GW150194 PSD 512.py, LOSC Event tutorial edge effect.py
Fig.10, Fig.11: LOSC Event tutorial Normalized CCF.py

8.1 Appendix A

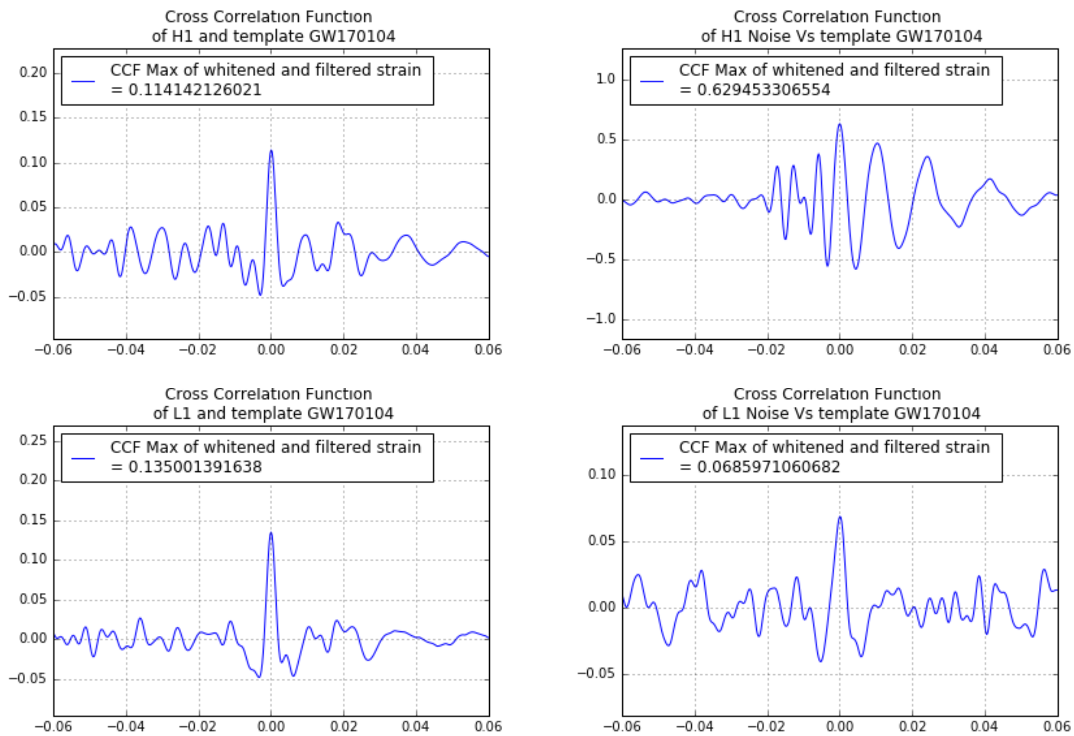

Figure 12. GW170104: CCF Plots done over GW event duration, using running windows for the right panels. Top Left: H1 vs template. Top Right: H1 Noise vs template. Lower Left: L1 vs template. Lower Right: L1 Noise vs template. H1 and L1 detector noise obtained from the vicinity of GW170104, 10 seconds before and after the GW event, in a 4096 second block of data..

Fig. 12 plots the CCF for GW170104, by correlating H1 with the template in the upper left panel and correlating H1 detector noise with the template in the upper right panel. We can see that GW170104 shows **comparable** CCF peaks, when correlating H1 with the template, which are

indistinguishable from the CCF peaks corresponding to detector noise in the upper right panel. Similar results are observed in the lower panel, by correlating L1 with the template. This behaviour is observed just in 4096 seconds of detector noise. If we observed detector noise for months, we are likely to get higher CCF peaks.

For this reason alone[Reason 3], **independent** of other reasons, GW170104 should be questioned.

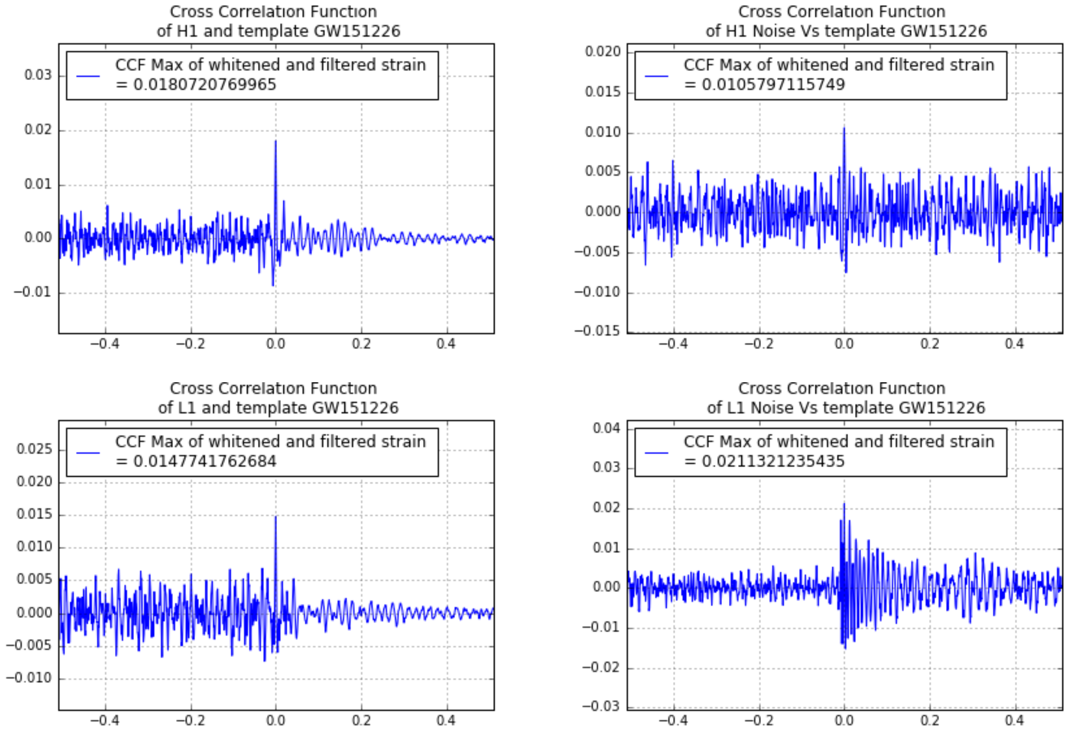

Figure 13. GW151226: CCF Plots done over GW event duration, using running windows for the right panels. Top Left: H1 vs template. Top Right: H1 Noise vs template. Lower Left: L1 vs template. Lower Right: L1 Noise vs template. H1 and L1 detector noise obtained from the vicinity of GW151226, 10 seconds before and after the GW event, in a 4096 second block of data.

Fig. 13 plots the CCF for GW151226, by correlating H1 with the template in the upper left panel and correlating H1 detector noise with the template in the upper right panel. We can see that GW151226 shows **comparable** CCF peaks, when correlating H1 with the template,which are **indistinguishable** from the CCF peaks corresponding to detector noise in the upper right panel. Similar results are observed in the lower panel, by correlating L1 with the template. This behaviour is observed just in 4096 seconds of detector noise. If we observed detector noise for months, we are likely to get higher CCF peaks.

For this reason alone[Reason 3], **independent** of other reasons, GW151226 should be questioned.

8.2 Appendix B

Fig. 14 shows the signal $w_d(t) + a(t)$, where $w_d(t)$ is the H1 detector noise, obtained from a 32 second block of data which does not contain the GW signal, and $a(t) = a_1(t) + a_2(t)$ and $a_1(t)$ is a fake template, which equals ideal template for GW170104 in the window [-0.02,-0.005] seconds and

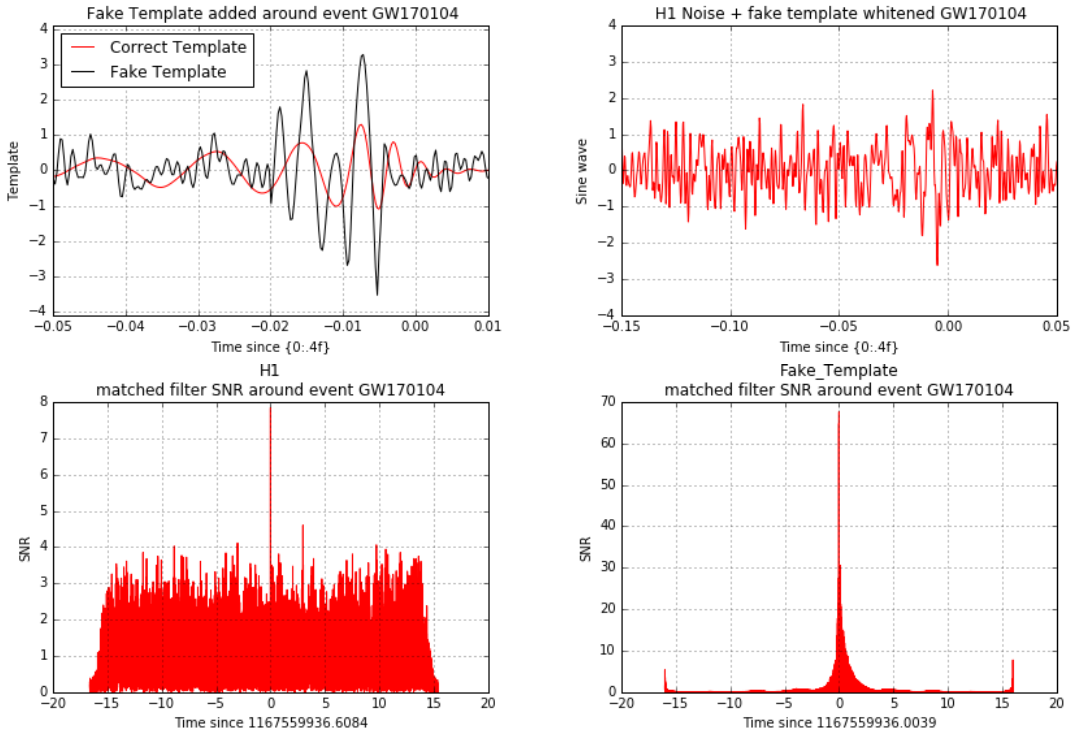

Figure 14. GW170104: Top Left: Real Template vs Fake Template. Top Right: H1 Noise + Fake Template whitened. Lower Panels: LIGO matched filter SNR Plots. Left: H1 vs template. Right: H1 Noise + Fake template vs correct template.

is zero outside this window. $a_2(t)$ is the sum of a sine wave of frequency 256 Hz and duration 1.5 msec and Additive White Gaussian Noise(AWGN) of duration 0.2 seconds, which is scaled so that the standard deviation of $a(t)$ is half of maximum value of the template. Then we correlate $w_d(t) + a(t)$ with the GW170104 template $h(t)$ in the LIGO matched filter. Fig. 14 shows the results, and we can see from the right plot that, even white gaussian noise added to the detector noise can produce high SNR in LIGO's matched filter, similar to what actual GW170104 produces in the middle plot.

Fig. 15 shows the signal $w_d(t) + a(t)$, where $w_d(t)$ is the H1 detector noise, obtained from a 32 second block of data which does not contain the GW signal, and $a(t) = a_1(t) + a_2(t)$ and $a_1(t)$ is a fake template, which equals ideal template for GW151226 in the window [-0.02,-0.005] seconds and is zero outside this window. $a_2(t)$ is the sum of a sine wave of frequency 256 Hz and duration 1.5 msec and Additive White Gaussian Noise(AWGN) of duration 0.2 seconds, which is scaled so that the standard deviation of $a(t)$ is half of maximum value of the template. Then we correlate $w_d(t) + a(t)$ with the GW151226 template $h(t)$ in the LIGO matched filter. Fig. 15 shows the results, and we can see from the right plot that, even white gaussian noise added to the detector noise can produce high SNR in LIGO's matched filter, similar to what actual GW151226 produces in the middle plot.

Fig. 16 shows the signal $w_d(t) + a(t)$, where $w_d(t)$ is the H1 detector noise, obtained from a 32 second block of data which does not contain the GW signal, and $a(t) = a_1(t) + a_2(t)$ and $a_1(t)$ is a fake template, which equals ideal template for GW150914 in the window [-0.05,-0.005] seconds and is zero outside this window. $a_2(t)$ is Additive White Gaussian Noise(AWGN) of duration 0.2 seconds, which is scaled so that the standard deviation of $a(t)$ is half of maximum value of the template. Then we correlate $w_d(t) + a(t)$ with the GW150914 template $h(t)$ in the LIGO matched filter. Fig. 16

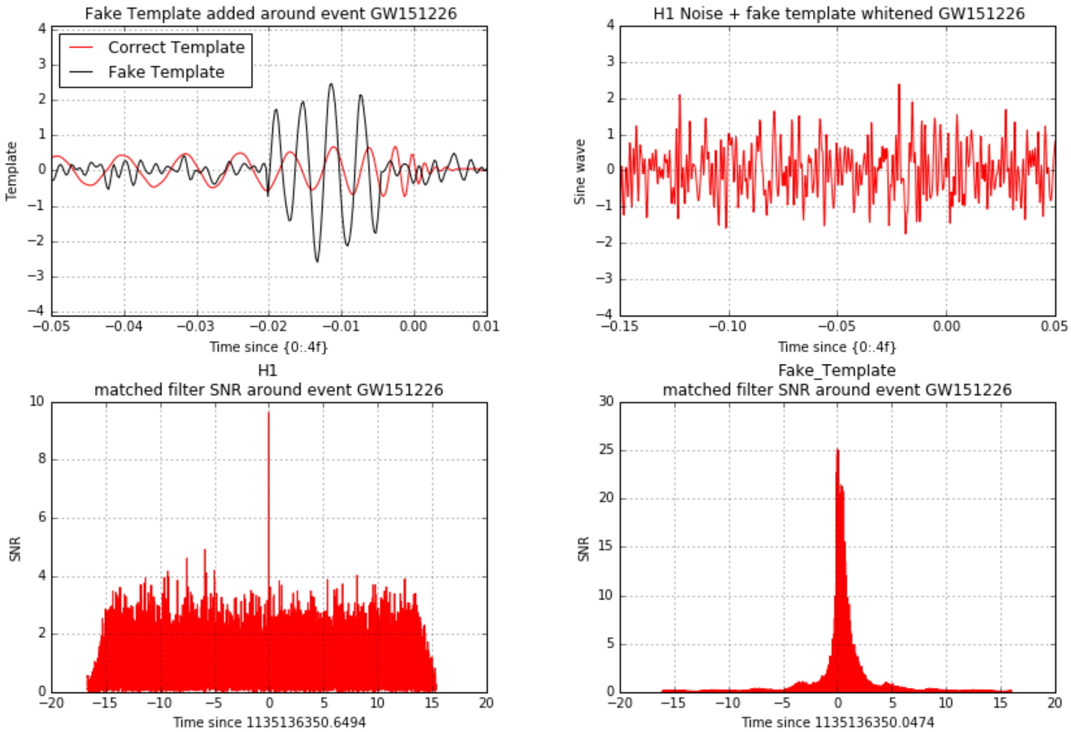

Figure 15. GW151226: Top Left: Real Template vs Fake Template. Top Right: H1 Noise + Fake Template whitened. Lower Panels: LIGO matched filter SNR Plots. Left: H1 vs template. Right: H1 Noise + Fake template vs correct template.

shows the results, and we can see from the right plot that, even white gaussian noise added to the detector noise can produce high SNR in LIGO's matched filter, similar to what actual GW150914 produces in the middle plot.

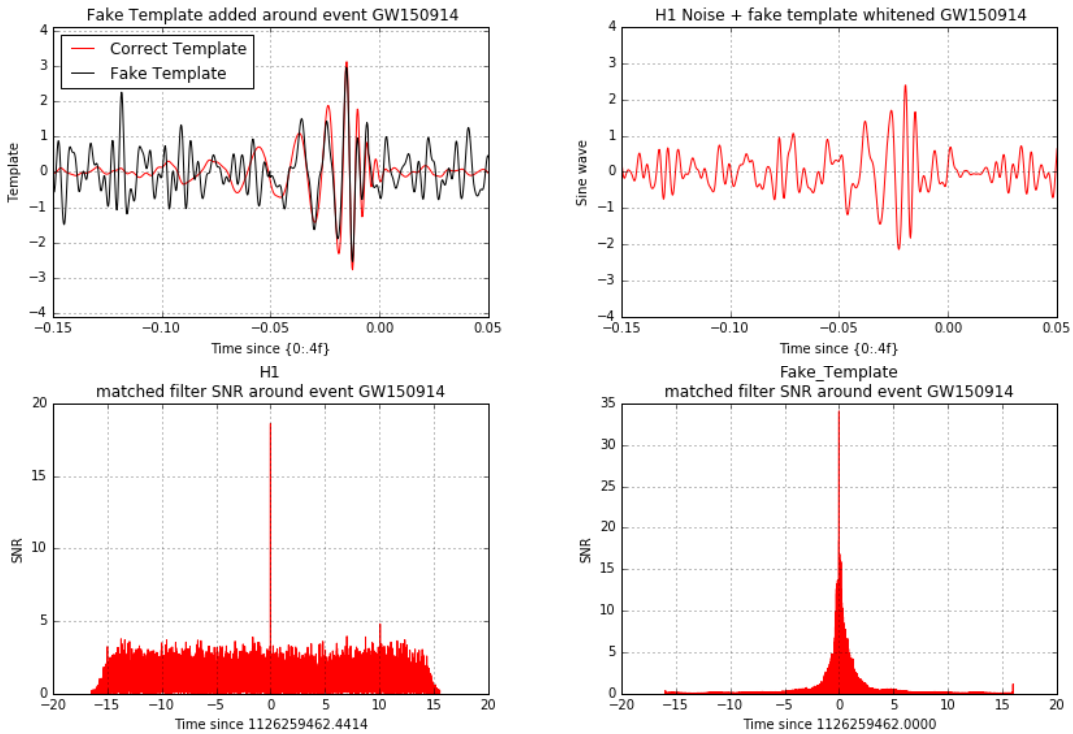

Figure 16. GW150914: Top Left: Real Template vs Fake Template. Top Right: H1 Noise + Fake Template whitened. Lower Panels: LIGO matched filter SNR Plots. Left: H1 vs template. Right: H1 Noise + Fake template vs correct template.