,

PREPARED FOR SUBMISSION TO JCAP

On the bogus chirp template correlations 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 five gravitational wave (GW) events detected in Hanford(H1), Livingston(L1) and Virgo(V1) detectors by the LIGO[1] collaboration. It is shown that GW170814, GW170817, 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. Normalized Cross Correlation Function(CCF) method is implemented in time domain using short windows, and it is shown that the normalized CCF for GW151226 and GW170104, when correlating H1/L1 and template, is indistinguishable from correlating H1/L1 and bogus chirp templates which are frequency modulated(FM) waveforms which differ significantly from ideal templates. Similar results are shown with LIGO's matched filter, which misfires with high Signal to Noise Ratio(SNR) for bogus chirp templates.

Hence it is argued that the only way to avoid this wrong classification of bogus templates as GW signals, is by correlating H1 with L1, for GW151226 and GW170104. It is also shown that normalized CCF is poor, when correlating H1 and L1, which is indistinguishable from detector noise correlations. Hence it is suggested that GW151226 and GW170104 be questioned as candidates for GW signals. The implications of these results are discussed for GW170814 and GW170817. All the results in this paper are demonstrated using modified versions of LIGO's Python scripts[15].[2]

[1]The Laser Interferometer Gravitational-Wave Observatory

[2]The specific Python script used to generate Fig.1 to Fig.10 in this manuscript, is mentioned in [15].

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, the third signal[3] GW170104, the fourth signal[4] GW170814 and the fifth signal[5] GW170817 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 of less than 1 second (Fig.15, Fig.16, Fig.17, Fig.18, Fig.19).

This raises the important question of whether GW151226 and GW170104 could have been caused by bogus chirp templates, non-GW signals from other sources or non-stationary detector

[1]LIGO detectors have significant impulsive intereference at 60*n Hz and other frequencies, hence they are removed by whitening the signal. Fourth order Butterworth bandpass filters used in frequency range 20-300Hz for GW150914, 43-800Hz for GW170104 and GW151226.

noise. 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 non-GW signals or 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, bogus chirp templates are simulated, which model the ideal template as a frequency modulated signal and then noise is added to the phase. In Sections 3, it will be shown that the LIGO matched filter misfires with high SNR, even for bogus chirp templates added to the detector noise and is indistinguishable from the SNR observed for ideal template, resulting in false coincidence, for GW151226 and GW170104.

In Sections 4, it will be shown that the time domain cross-correlation of bogus chirp templates added to the detector noise vs the template, is indistinguishable from the cross-correlation of H1/L1 vs template, resulting in false coincidence, for GW151226 and GW170104. It is also shown for GW151226 that L1 detector noise vs the template produces high CCF peaks and a bogus chirp template at H1 produces high CCF peaks, which may result in false coincidence.

Hence it is argued that H1 vs L1 cross-correlation test is necessary to avoid this wrong classification of bogus templates as GW signals, irrespective of the source of these bogus templates. In Section 5, using Normalized Cross Correlation Function(CCF) method, it will be shown that the normalized CCF of H1 vs L1, is indistinguishable from detector noise correlations, for GW151226 and GW170104. In Section 6, it will be shown that the normalized CCF of H1 vs L1, is indistinguishable from detector noise correlations, for GW170814 and GW170817.

2 Bogus Chirp Templates

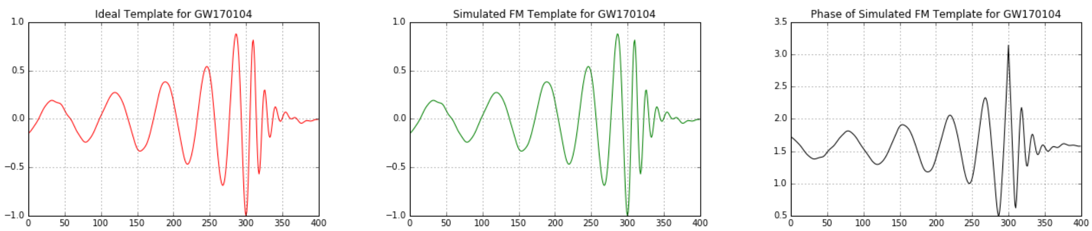

Figure 1. GW170104: Left: Ideal template. Middle: Simulated FM Chirp Template. Right: Phase of Simulated FM Template

Let us consider the ideal template $h(t)$ for GW170104, which is shown in the left panel of Fig.1. We can simulate this ideal template by a frequency modulated(FM) waveform in the middle panel, where $h_s(t) = cos(m(t))$, where $m(t)$ is the phase of FM signal, which is shown in the right panel. This simulated FM signal also is a chirp signal with frequency increasing from the left to the right.

Now we can simulate bogus chirp templates $h_b(t)$, where $h_b(t) = cos(m_b(t))$, $m_b(t) = m(t) + w_m(t)$ and $w_m(t)$ is additive white gaussian noise(AWGN) added to the phase of the FM template.

We will inject these bogus chirp templates to the detector noise and show in the sections below, that LIGO matched filter misfires with high SNR, even for bogus chirp templates. We will show similar results using time domain CCF method.

It is possible that there was **coincident** false detection at H1 and L1, due to a bogus chirp template at one detector and a different bogus chirp template or a noise burst, in the other detector. We do not know the probability of this false coincident detection, due to unknown external factors.

LIGO's false alarm rate calculation is **not** applicable for this case, which pertains only coincident false detection due to detector noise.

Irrespective of the source of these bogus chirp templates, it will be argued that H1 vs L1 cross-correlation test is **necessary** to avoid this wrong classification of bogus templates as GW signals, detailed in Section 5, given the need for high standards for classifying a GW signal.

3 False SNR peaks in LIGO matched filter due to Bogus Chirp Templates

The **core engine** of the LIGO software for identification of GW signals is the matched filter as described in Eq.1-4 in [6], 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.

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

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. The expression for re-weighted SNR is given in Eq.6. in [6].

3.1 False SNR peaks in LIGO matched filter with bogus templates for GW150914.

Let us consider the case where a noisy signal roughly resembling the template but generated by frequency modulation(FM) [3], is observed at L1. This bogus template also produces SNR peaks, when correlated with the template, as in the lower right panel of Fig. 2. This happens more than 50 percent of the time, in Monte-Carlo simulations with white gaussian noise.

The upper left panel in Fig. 2 shows the ideal L1 template of GW150914 and the bogus L1 template. The upper right panel shows the error between the L1 bogus template and the ideal template. The lower left panel in Fig. 2 shows LIGO matched filter reweighted SNR, when correlating L1 with the template of GW150914 and the lower right panel shows SNR peaks obtained by correlating template vs L1 bogus template added to the detector noise. We can see that GW150914 shows SNR peaks **comparable** with SNR peaks corresponding to bogus template correlations.

[2] GSTLAL analysis also uses matched filter search, and as per Page 7 in [6], "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. [13].

[3] The template for GW150914 is represented by a FM signal $h(t) = cos(m(t))$. Bogus template is given by $h_b(t) = cos(m_b(t))$ where $m_b(t) = m(t) + w_m(t)$ and $w_m(t)$ are white gaussian noise.

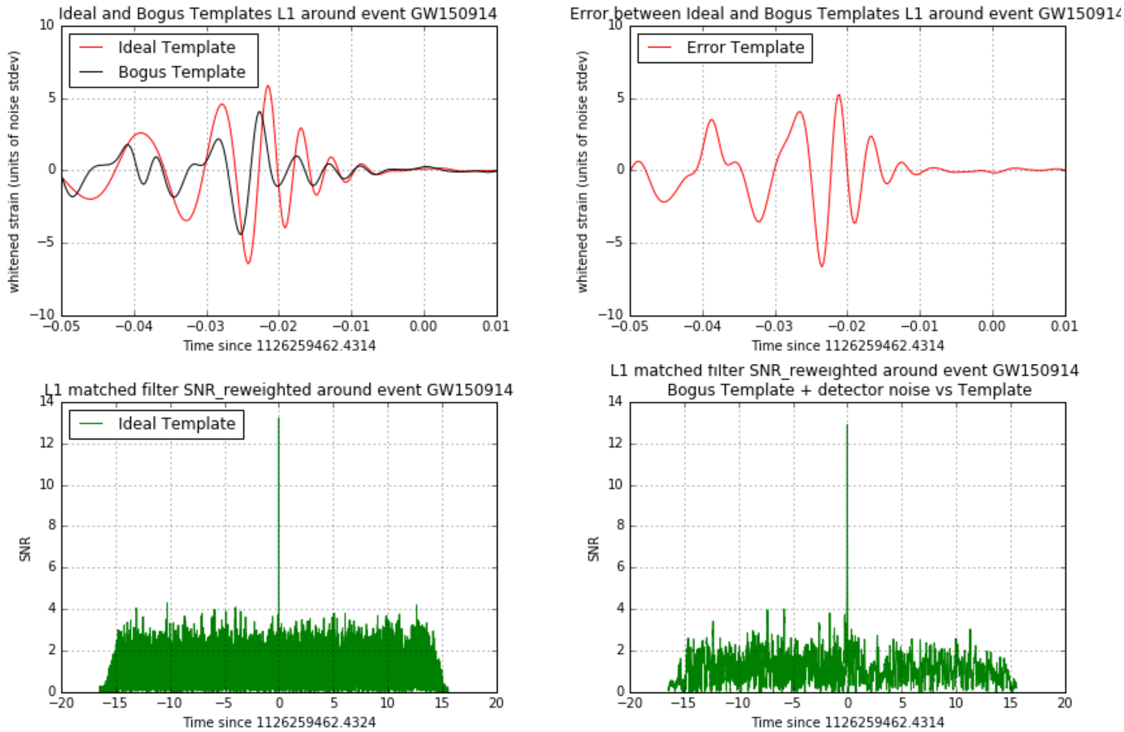

Figure 2. GW150914: Upper Left: Red: Ideal template. Black: Bogus Template. Upper Right: Error between Ideal and Bogus Templates. Lower Left: LIGO matched filter Reweighted SNR for L1 vs Ideal template. Lower Right: LIGO matched filter Reweighted SNR for L1 vs Bogus template.

Given that bogus template can produce comparable correlations with the template, as the observed GW150914 signal, this means that we **cannot be sure** whether the SNR peaks in GW150914 were caused by GW signals or bogus template correlations. Hence H1 vs L1 cross-correlation test is necessary to avoid this wrong classification of bogus templates as GW signals, detailed in Section 5.

3.2 False SNR peaks in LIGO matched filter with bogus templates for GW151226.

Let us consider the case where a noisy signal roughly resembling the template but generated by frequency modulation(FM), is observed at L1. This bogus template $h_b(t)$ also produces SNR peaks, when correlated with the template, as in the lower right panel of Fig. 3.

The upper left panel in Fig. 3 shows the ideal template of GW151226 and the bogus L1 template. The upper right panel shows the error between the L1 bogus template and the ideal template. We can see that the bogus template differs **significantly** from the ideal template, in fact the last 5 cycles in the crucial final chirp portion is **completely absent**. The lower left panel in Fig. 3 shows LIGO matched filter reweighted SNR, when correlating L1 with the template of GW151226 and the lower right panel shows SNR peaks obtained by correlating template vs L1 bogus template added to the detector noise. We can see that the reweighted SNR due to the bogus template is greater than the threshold of 5 and GW151226 shows SNR peaks **comparable** with SNR peaks corresponding to bogus template correlations.

We can also show high SNR peaks with a bogus H1 template, which is different from a bogus L1 template, as in Fig. 12. This may result in false coincidence. In Section 4.3, it is shown that

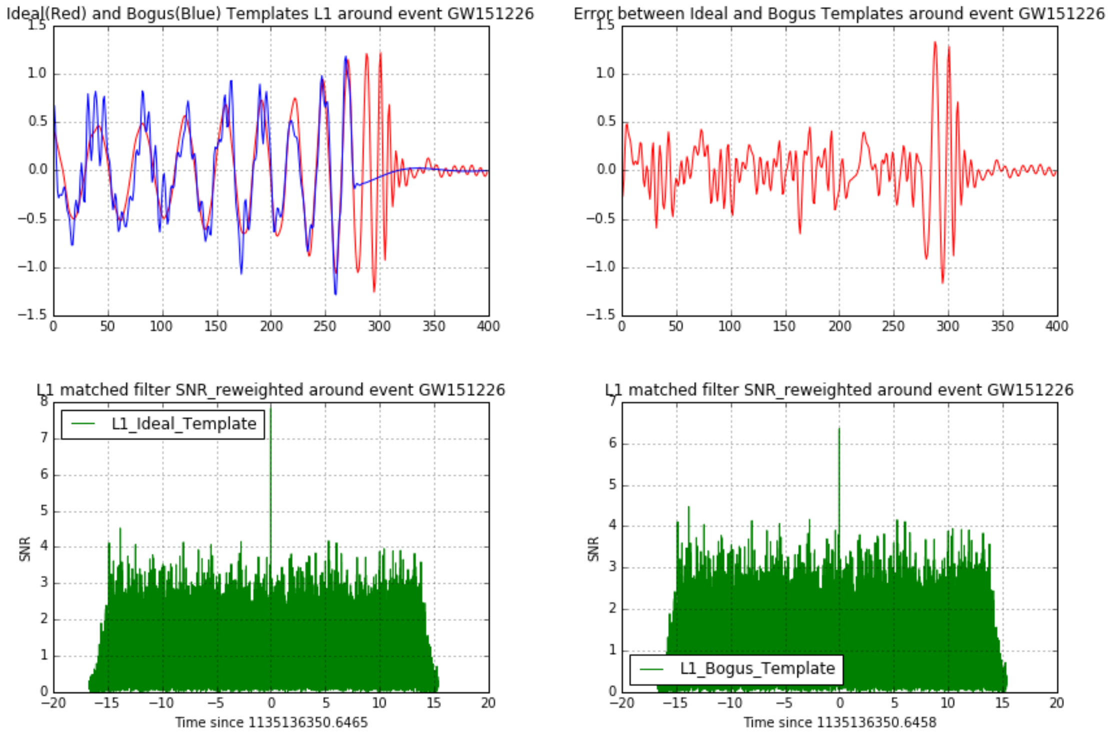

Figure 3. GW151226: Upper Left: Red: Ideal template. Black: Bogus Template. Upper Right: Error between Ideal and Bogus Templates. Lower Left: LIGO matched filter Reweighted SNR for L1 vs Ideal template. Lower Right: LIGO matched filter Reweighted SNR for L1 vs Bogus template.

detector noise itself may produce false cross-correlation peaks in L1, while a bogus template may produce false peaks in H1.

Given that bogus template can produce comparable correlations with the template, as the observed GW151226 signal, this means that we **cannot be sure** whether the SNR peaks in GW151226 were caused by GW signals or bogus template correlations. Hence H1 vs L1 cross-correlation test is necessary to avoid this wrong classification of bogus templates as GW signals, detailed in Section 5.

Hence **GW151226** should be questioned, based on this test alone[Reason 3c].

3.3 False SNR peaks in LIGO matched filter with bogus templates for GW170104.

Let us consider the case where a noisy signal roughly resembling the template but generated by frequency modulation(FM), is observed at L1. This bogus template $h_b(t)$ also produces SNR peaks, when correlated with the template, as in the lower right panel of Fig. 4.

The upper left panel in Fig. 4 shows the ideal template of GW170104 and the bogus L1 template. The upper right panel shows the error between the L1 bogus template and the ideal template. The lower left panel in Fig. 4 shows LIGO matched filter reweighted SNR, when correlating L1 with the template of GW170104 and the lower right panel shows SNR peaks obtained by correlating template vs L1 bogus template added to the detector noise. We can see that the reweighted SNR due to the bogus template is greater than the threshold of 5 and GW170104 shows SNR peaks **comparable** with SNR peaks corresponding to bogus template correlations.

We can also show high SNR peaks with a bogus H1 template, which is different from a bogus L1 template, as in Fig. 11. This may result in false coincidence.

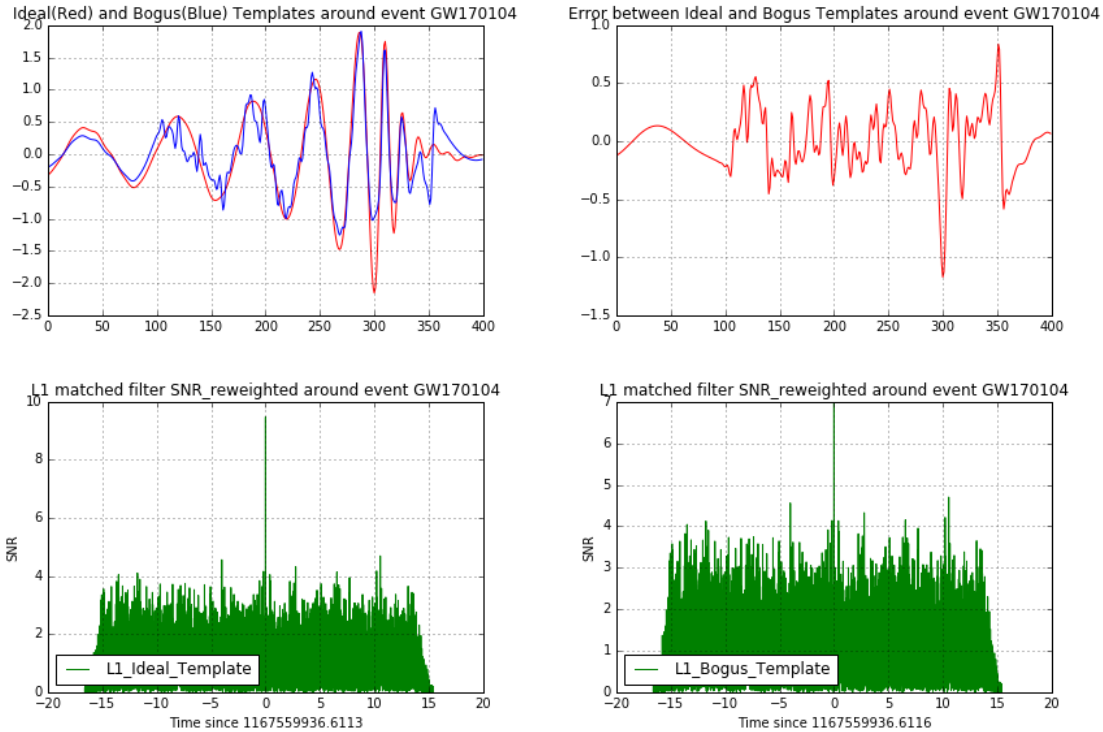

Figure 4. GW170104: Upper Left: Red: Ideal template. Black: Bogus Template. Upper Right: Error between Ideal and Bogus Templates. Lower Left: LIGO matched filter Reweighted SNR for L1 vs Ideal template. Lower Right: LIGO matched filter Reweighted SNR for L1 vs Bogus template.

Given that bogus template can produce comparable correlations with the template, as the observed GW170104 signal, this means that we **cannot be sure** whether the SNR peaks in GW170104 were caused by GW signals or bogus template correlations. Hence H1 vs L1 cross-correlation test is necessary to avoid this wrong classification of bogus templates as GW signals, detailed in Section 5.

Hence **GW170104** should be questioned, based on this test alone[Reason 3b].

4 False peaks in time domain Normalized CCF Method due to Bogus Chirp Templates

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].[4] We will use reference systems as follows.

Normalized CCF of H1/L1 with template is the same as "matched filtering of H1/L1 with template" using short windows in time domain and is an equally sensitive test. It was shown in Section 3 that matched filter in fact does cross-correlation. The tests listed in this section are **new tests** with short windows.

[4]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

In this manuscript, the term "Normalized CCF" is used to describe the cross-correlation of **any two signals**, such as H1/L1 with templates **or** H1 with L1, in time domain, using short windows over which GW event was observed, and the signals are normalized such that CCF of a signal with itself gives a value of unity at zero lag. The term "LIGO matched filter" is used to describe the matched filter implemented in LIGO python script[14], which does matched filtering of H1/L1 and the template, using 32 second windows, implemented in frequency domain.

It is possible that there was **coincident** false detection at H1 and L1, due to a bogus chirp template at one detector and a different bogus chirp template or a noise burst, in the other detector. We do not know the probability of this false coincident detection, due to unknown external factors. LIGO's false alarm rate calculation is **not** applicable for this case, which pertains only coincident false detection due to detector noise.

4.1 False peaks in time domain CCF with bogus templates for L1 for GW151226.

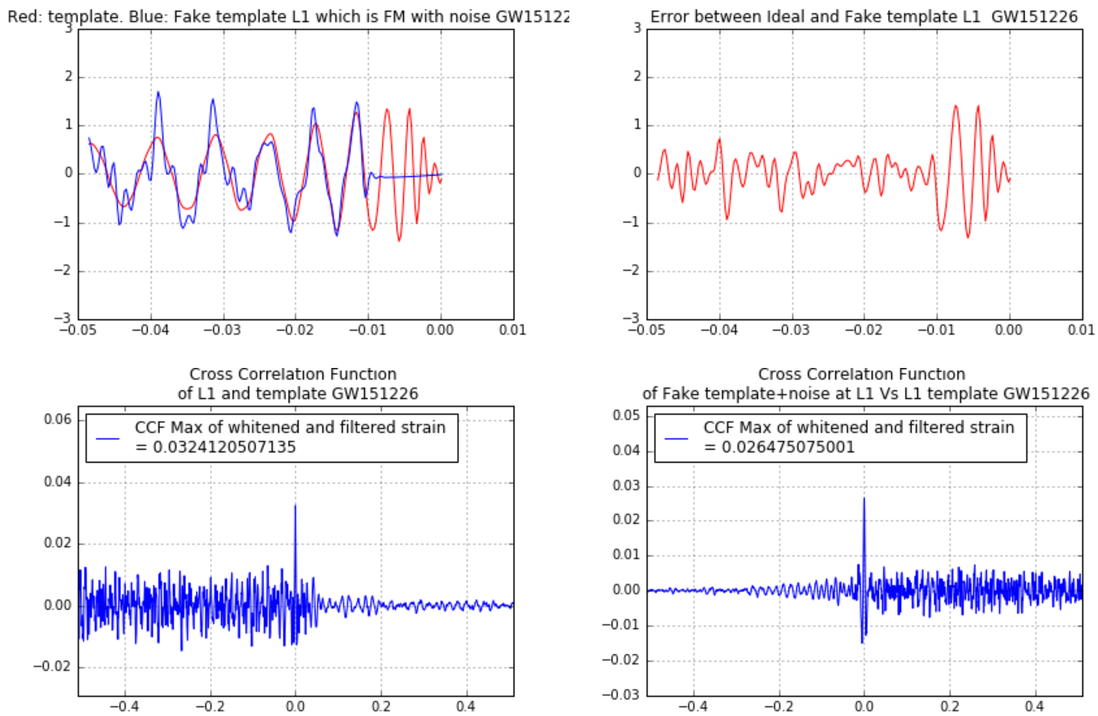

Figure 5. GW151226: Upper Left: Red: Ideal template. Black: Bogus Template. Upper Right: Error between Ideal and Bogus Templates. Lower Left: Normalized CCF in time domain for L1 vs Ideal template. Lower Right: Normalized CCF in time domain for L1 vs Bogus template.

Let us consider the case where a noisy signal roughly resembling the template but generated by frequency modulation(FM), is observed at L1. This bogus template $h_b(t)$ also produces CCF peaks, when correlated with the template, as in the lower right panel of Fig. 5.

The upper left panel in Fig. 5 shows the ideal template of GW151226 and the bogus L1 template. The upper right panel shows the error between the L1 bogus template and the ideal template. The lower left panel in Fig. 5 shows Cross Correlation Function (CCF) done over 1 second duration, when correlating L1 with the template of GW151226 and the lower right panel shows CCF peaks obtained by correlating template vs L1 bogus template added to the detector noise. We can see that GW151226 shows CCF peaks **comparable** with CCF peaks corresponding to bogus template correlations.

We can also show high SNR peaks with a bogus H1 template, which is different from a bogus L1 template, as in Fig. 14. This may result in false coincidence.

Given that bogus template can produce comparable correlations with the template, as the observed GW151226 signal, this means that we **cannot be sure** whether the CCF peaks in GW151226 were caused by GW signals or bogus template correlations. Hence H1 vs L1 cross-correlation test is necessary to avoid this wrong classification of bogus templates as GW signals, detailed in Section 5. Hence **GW151226** should be questioned, based on this test alone[Reason 4a].

4.2 False peaks in time domain CCF with bogus templates for GW170104.

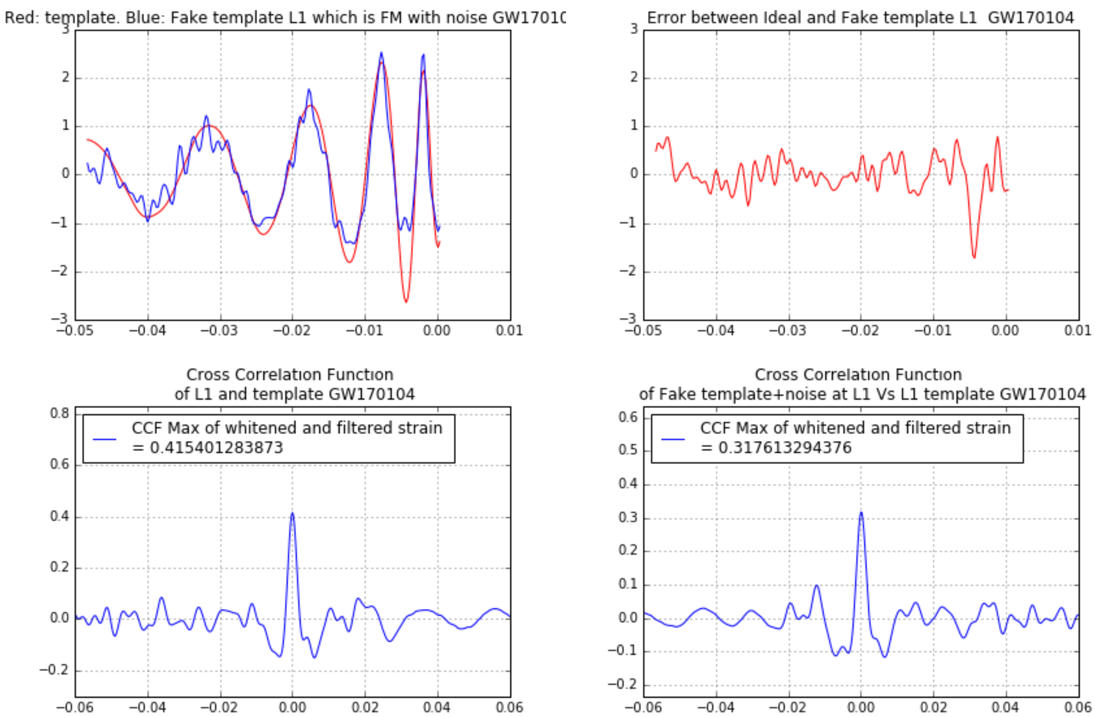

Figure 6. GW170104: Upper Left: Red: Ideal template. Black: Bogus Template. Upper Right: Error between Ideal and Bogus Templates. Lower Left: Normalized CCF in time domain for L1 vs Ideal template. Lower Right: Normalized CCF in time domain for L1 vs Bogus template.

Let us consider the case where a noisy signal roughly resembling the template but generated by frequency modulation(FM), is observed at L1. This bogus template $h_b(t)$ also produces CCF peaks, when correlated with the template, as in the lower right panel of Fig. 6.

The upper left panel in Fig. 6 shows the ideal template of GW170104 and the bogus L1 template. The upper right panel shows the error between the L1 bogus template and the ideal template. The lower left panel in Fig. 6 shows Cross Correlation Function (CCF) done over 0.1 second duration, when correlating L1 with the template of GW170104 and the lower right panel shows CCF peaks obtained by correlating template vs L1 bogus template added to the detector noise. We can see that GW170104 shows CCF peaks **comparable** with CCF peaks corresponding to bogus template correlations.

We can also show high SNR peaks with a bogus H1 template, which is different from a bogus L1 template, as in Fig. 13. This may result in false coincidence.

Given that bogus template can produce comparable correlations with the template, as the observed GW170104 signal, this means that we **cannot be sure** whether the CCF peaks in GW170104 were caused by GW signals or bogus template correlations. Hence H1 vs L1 cross-correlation test is necessary to avoid this wrong classification of bogus templates as GW signals, detailed in Section 5. Hence **GW170104** should be questioned, based on this test alone[Reason 4b].

4.3 False coincidence with L1 detector noise and bogus template at H1, in 4096 second block of data.

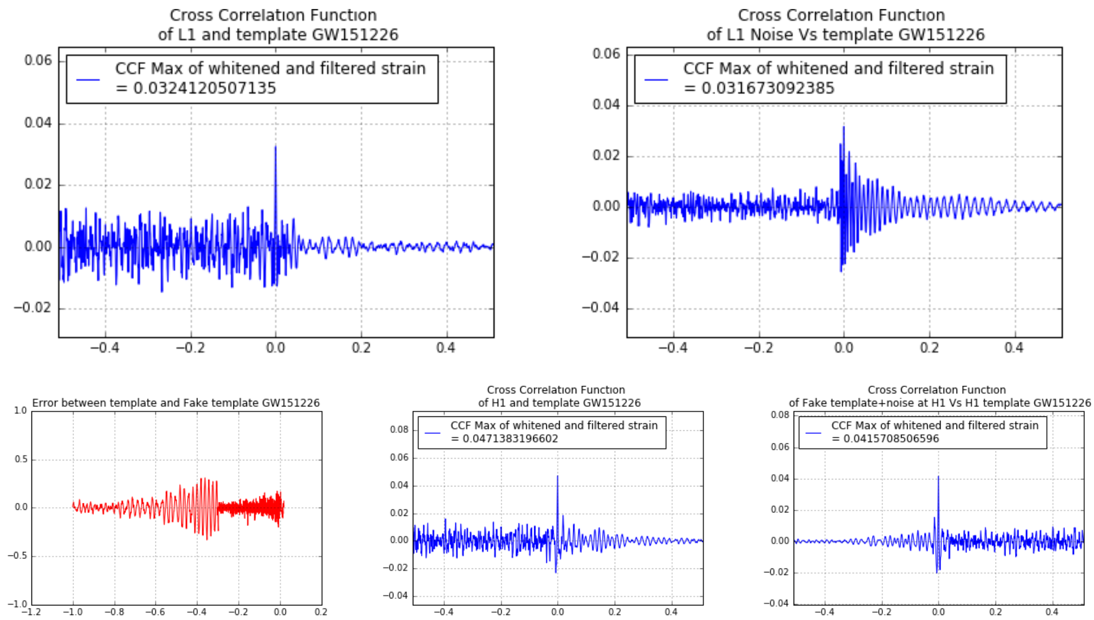

Figure 7. GW151226: CCF Plots done over GW event duration of 1 second, using running windows for the right panels. Upper Left: L1 vs template. Upper Right: L1 Noise vs template. Lower Middle: H1 vs template. Lower Right: (Fake Template+H1 noise) vs template. Lower left: Error between actual and fake template. H1/L1 detector noise obtained from a 4096 second block of data and excluding GW event portions and edges.

The upper left panel in Fig. 7 shows Cross Correlation Function (CCF) done over 1 second duration, when correlating L1 with the template of GW151226 and the upper right panel shows CCF peaks obtained by correlating L1 detector noise with the template, using running windows, over 4096 second block of data, excluding the GW event portions and edges. We can see that GW151226 shows CCF peaks **comparable** with CCF peaks corresponding to detector noise correlations, and **do not** rise well above detector noise correlations.

Given that detector noise can produce comparable correlations with the template, as the observed GW151226 signal, let us consider the case where a) detector noise at L1 produces CCF peaks, when correlated with the template, in 4096 second block of data, as in the upper right panel of Fig. 7, and b) a noisy signal roughly resembling the template but generated by frequency modulation(FM) and amplitude modulation(AM) [5] in the last 0.3 seconds and zero in the first 0.7 seconds, is observed

[5]The template for GW151226 is represented by a FM+AM signal $h(t) = A(t) * cos(2\pi f_0 t + m(t))$ where $f_0 = 56$ Hz. Bogus template is given by $h_b(t) = A_b(t) * cos(2\pi f_0 t + m_b(t))$ where $A_b(t) = A(t) + w_a(t), m_b(t) = m(t) + w_m(t)$

at H1, which also produces CCF peaks, when correlated with the template, as in the lower right panel of Fig. 7.

It is possible that there was **coincident** false detection at H1 and L1, due to a bogus chirp template at one detector and detector noise, in the other detector. We do not know the probability of this false coincident detection, due to unknown external factors. LIGO's false alarm rate calculation is **not** applicable for this case, which pertains only coincident false detection due to detector noise.

This means that we **cannot be sure** whether the CCF peaks in GW151226 were caused by GW signals or detector noise correlations and bogus templates. Similar results hold for the case of GW170104. Hence H1 vs L1 cross-correlation test is necessary to avoid this wrong classification of bogus templates as GW signals, detailed in Section 5. Hence **GW170104** and **GW151226** should be questioned, based on this test alone[Reason 4c].

---

and $w_a(t), w_m(t)$ are white gaussian noise.

5 Need for H1 vs L1 cross-correlation test: Ruling Out False detection of Bogus chirp templates

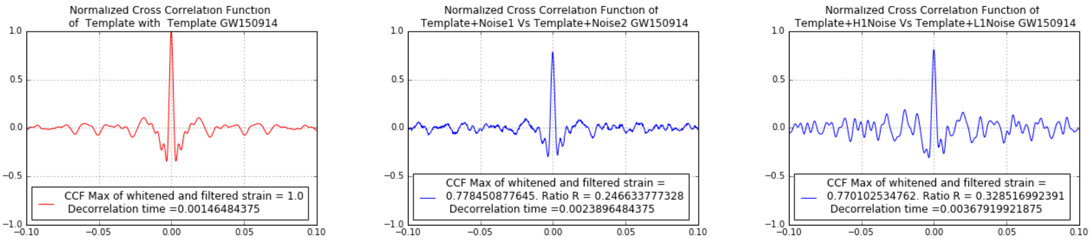

Figure 8. Reference Systems with Normalized CCF over 0.2 second windows for GW150914. Left: Reference System A. Middle: Reference System 1. Right: Reference System 2. If maximum value of CCF is negative, the plot is inverted.

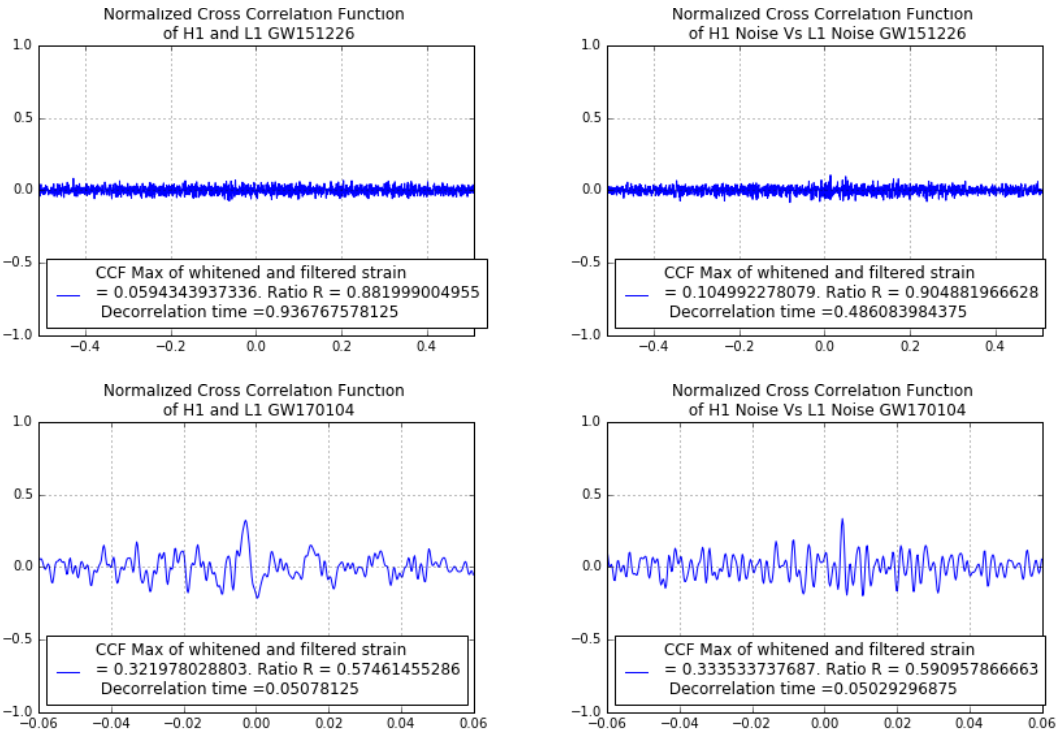

Figure 9. Normalized CCF Plots done over GW event duration. Top Row: GW151226. Bottom Row: GW170104. Left panels: H1 vs L1. Right panels: H1 noise vs L1 noise. H1 and L1 detector noise obtained 1 second after the end of GW151226 and 10 seconds after the end of GW170104.

We do not want to accept above false coincident detection in section 3 and section 4 as a valid GW signal, because they were false coincidences. We can rule out these cases of false coincident detection by correlating H1 with L1, which gives poor CCF peaks, as in the left panel in Fig. 9, which are indistinguishable from detector noise correlations in the right panels.

It is possible that there was **coincident** false detection at H1 and L1, due to any combination of sine wave/noise burst/bogus chirp templates/detector noise, in both detectors. We do not know the probability of this false coincident detection, due to unknown external factors. LIGO's false alarm rate calculation is **not** applicable for this case, which pertains to only coincident false detection due to detector noise.

Given that the same GW signal is expected to be received in both sites, these signals should give a high CCF 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 [10]. 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 or cross-correlation imposes no constraints on the characteristics of the template.

The same template $h(t)$ is used in the right panels CCF plots of Fig. 8, 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. We observe that $R < \frac{1}{e}$. Given that GW signals are assumed to be the sum of an ideal template and detector noise, this comparison is reasonable.

Reference System A: An ideal template for GW151226 or GW170104 $h(t)$ is correlated with itself, after normalization, to give a peaky CCF [6], the maximum value of CCF = 1 at zero lag, as in left panels in Fig. 8.

Reference System 1: Fig. 8 shows this system in the second panel, 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. 8 shows a reference system 2 in the third panel, 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.

Fig. 9 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 **indistinguishable** from CCF peaks

[6]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 $\frac{1}{e} = 0.36$ of the maximum value at zero lag [11]. 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.

corresponding to detector noise in the right column. Hence, we cannot be sure whether detector noise or GW signal caused the CCF peaks.

We can reproduce these results for **longer H1/L1 strains** of GW151226 and GW170104 as well. Figure shows CCF done over 14 second duration, when correlating H1 with L1 for GW151226(top panel) and GW170104(bottom panel). We can see that GW151226 and GW170104 show CCF peaks (left panel) **indistinguishable** from CCF peaks corresponding to detector noise correlations (right panel).

Hence **GW170104** and **GW151226** should be questioned, based on this test alone[Reason 5].

6 H1 vs L1 cross-correlation test fails for GW170814 and GW170817

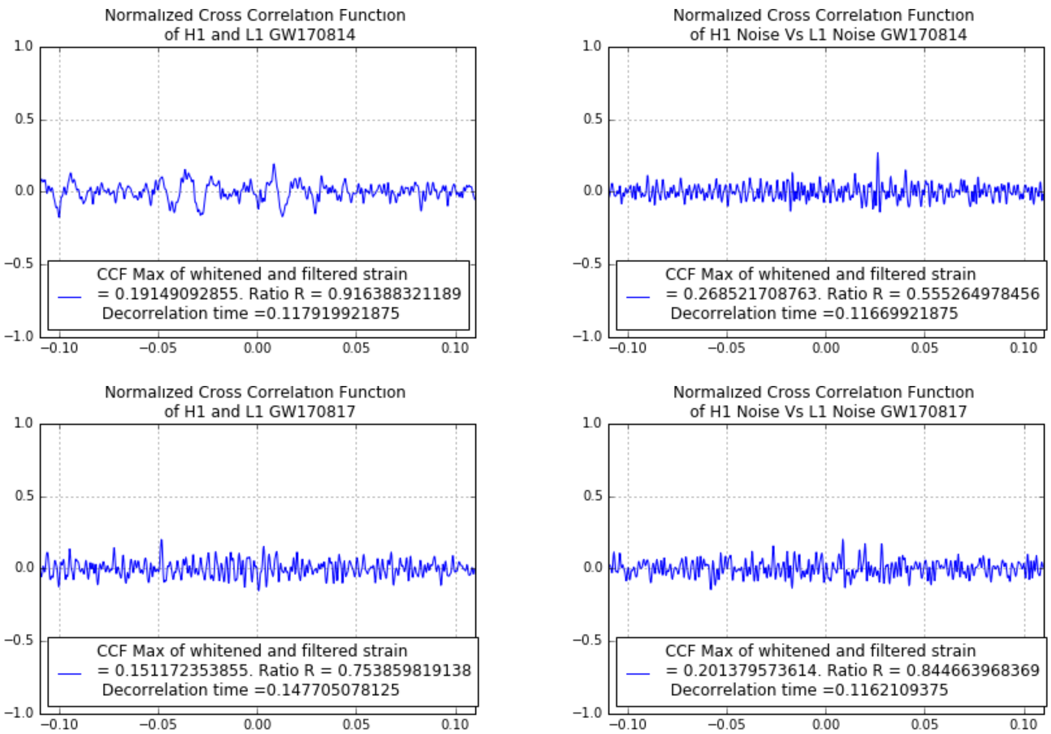

Figure 10. Normalized CCF Plots done over GW event duration of 0.2 seconds. Top Row: GW170814. Bottom Row: GW170817. Left panels: H1 vs L1. Right panels: H1 noise vs L1 noise. H1 and L1 detector noise obtained 10 seconds after the end of GW events.

GW170814 and GW170817 have been observed at three detectors H1, L1 and V1. For the purpose of this section, we will do the correlation test for H1 vs L1 only and this is enough to show that the correlation test fails.

Fig. 10 plots the normalized CCF for GW170814(top row) and GW170817 (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 GW170814 and GW170817 show very poor CCF peaks ($R_3 > \frac{1}{e}$) when correlating H1 with L1, and we can see that CCF peaks are **indistinguishable** from CCF peaks corresponding to detector noise in the right column. Hence, we cannot be sure whether detector noise or GW signal caused the CCF peaks.

Hence **GW170814** and **GW170817** should be questioned, based on this test alone[Reason 6].

7 Case for Questioning of GW151226 and GW170104

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 3,4 and Reason 5 **independently**.

Reason 3 and 4: In Section 3, we observed that LIGO matched filter SNR misfires with high SNR when correlating bogus chirp templates with the ideal template and is indistinguishable from correlating H1/L1 with the template, and produces false coincidence, for GW151226 and GW170104. Similar results were observed using time domain CCF method in Section 4.

Reason 5: In Section 5, we observed in Fig. 9 that the normalized CCF is very poor ($R_3 > \frac{1}{e}$) when correlating H1 and L1, and is indistinguishable from detector noise correlations, for GW151226 and GW170104.

8 Case for Questioning of GW170814 and GW170817

Given the high standards required for declaration of GW signal, it is suggested that GW170814 and GW170817 be questioned, due to Reason 6.

Reason 6: In Section 6, we observed in Fig. 10 that the normalized CCF is very poor ($R_3 > \frac{1}{e}$) when correlating H1 and L1, and is indistinguishable from detector noise correlations, for GW170814 and GW170817.

9 Concluding remarks

Section 7 gives the reasons why weak signals GW151226 and GW170104 should be questioned. Section 8 gives the reasons why weak signals GW170814 and GW170817 should be questioned. It is possible that there was **coincident** false detection at H1 and L1, due to any combination of sine wave/noise burst/bogus chirp templates/detector noise, in both detectors. We do not know the probability of this false coincident detection, due to unknown external factors. LIGO's false alarm rate calculation is **not** applicable for this case, which pertains to only coincident false detection due to detector noise.

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.

Acknowledgments

We are grateful to Andrew D. Jackson, Dr. A. Paulraj, Helmut Bolcskei and John M Cioffi for encouragement, suggestions and discussions. We would like to thank Sebastian Domenico von Hausegger and Arunava Chaudhuri for review of our Python scripts and helpful suggestions. We would like to thank M.A. Srinivas, Hao Liu, James Creswell, Bhavna Antony, Anant Sahai and Kannan Ramachandran for discussions and helpful suggestions. We would like to thank LIGO Open Science Center for making the data and Python scripts available online. We would like to thank LIGO scientists who answered 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.*GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence*, Physical Review Letters, 119, 141101 (2017) Online version of paper.

[5] Abbott, B. P., Abbott, R., Abbott, T. D., et al.*GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral*, Physical Review Letters, 119, 161101 (2017) Online version of paper.

[6] 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.

[7] 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.

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

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

[10] 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

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

[12] LOSC LIGO GW150914 Tutorial

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

[14] LIGO Tutorials

[15] Zip Files of Modified LIGO Tutorials which demonstrate the results in this paper.

.

Fig.1,3,4,5,6,11,12,13,14 LOSC Event tutorial Normalized CCF bogus template GW170104 GW151226.py, LOSC Event tutorial MF bogus template GW170104 GW151226.py
Fig.2: LOSC Event tutorial bogus template GW150914.py
Fig.7 LOSC Event tutorial Normalized CCF H1 template fake.py
Fig.8, 9: LOSC Event tutorial Normalized CCF H1 L1 new.py
Fig.10,18,19: LOSC Event tutorial GW170814 H1 L1.py, LOSC Event tutorial GW170817 H1 L1.py

.

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.

10 Appendix

10.1 False peaks in LIGO matched filter and time domain CCF due to bogus templates at H1, for GW152226, GW170104.

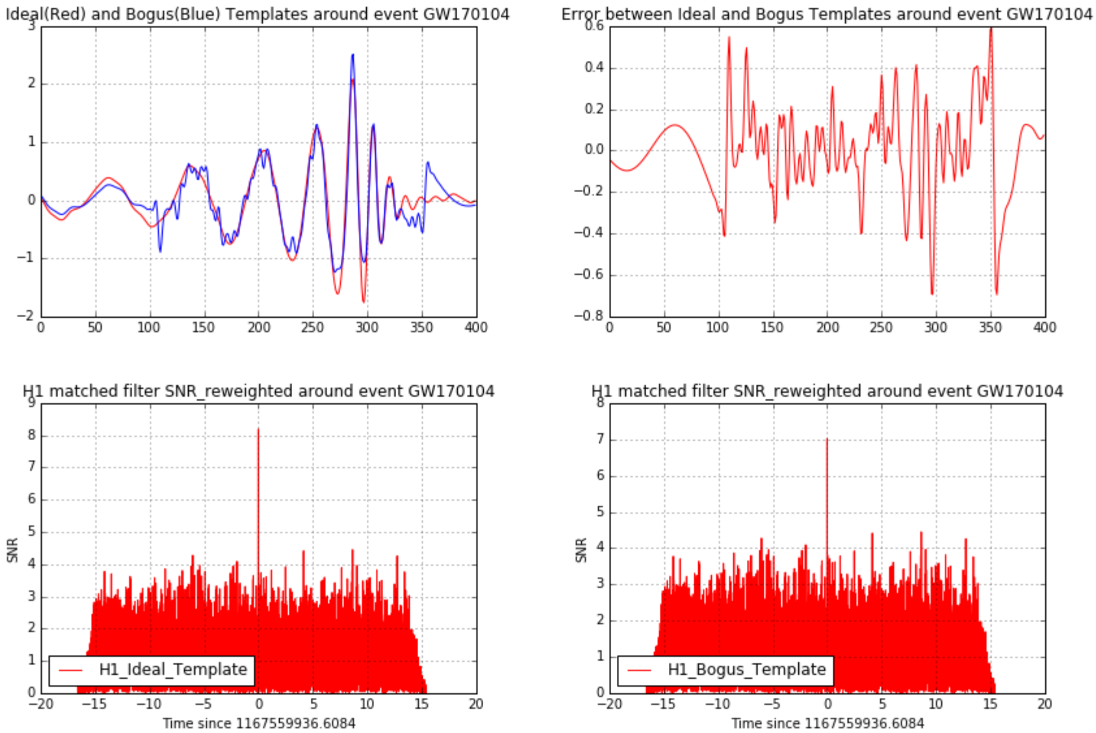

Figure 11. GW170104: Upper Left: Red: Ideal template. Black: Bogus Template. Upper Right: Error between Ideal and Bogus Templates. Lower Left: LIGO matched filter SNR for H1 vs Ideal template. Lower Right: LIGO matched filter SNR for H1 vs Bogus template.

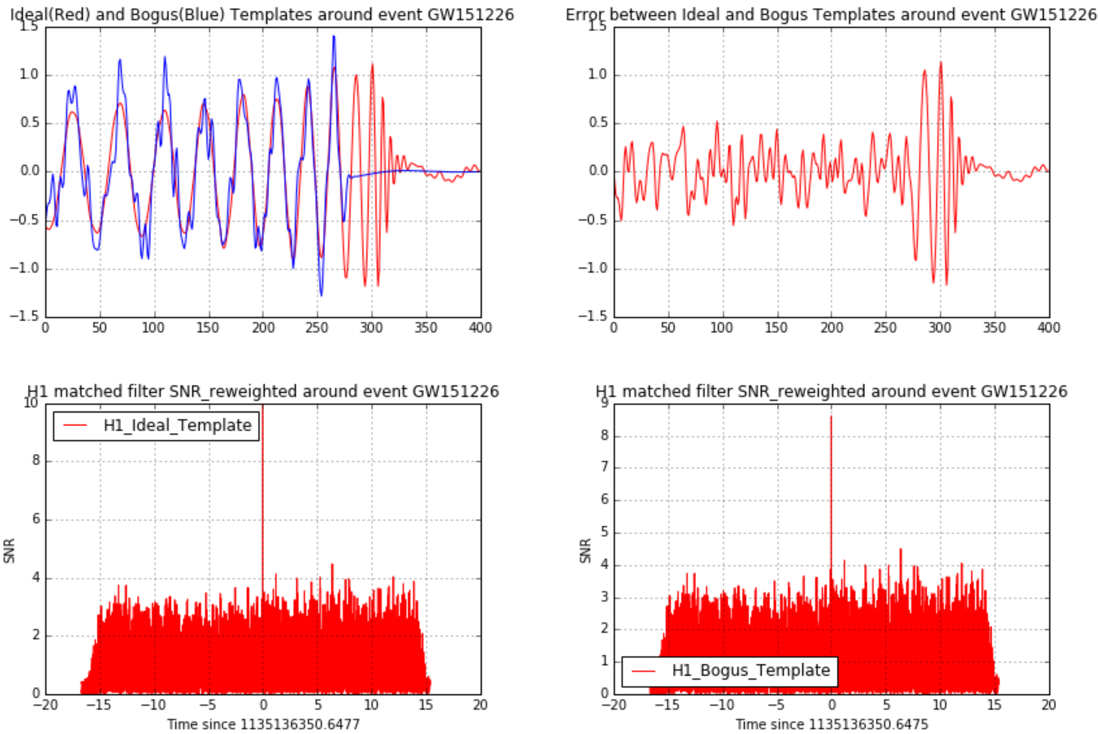

Figure 12. GW151226: Upper Left: Red: Ideal template. Black: Bogus Template. Upper Right: Error between Ideal and Bogus Templates. Lower Left: LIGO matched filter SNR for H1 vs Ideal template. Lower Right: LIGO matched filter SNR for H1 vs Bogus template.

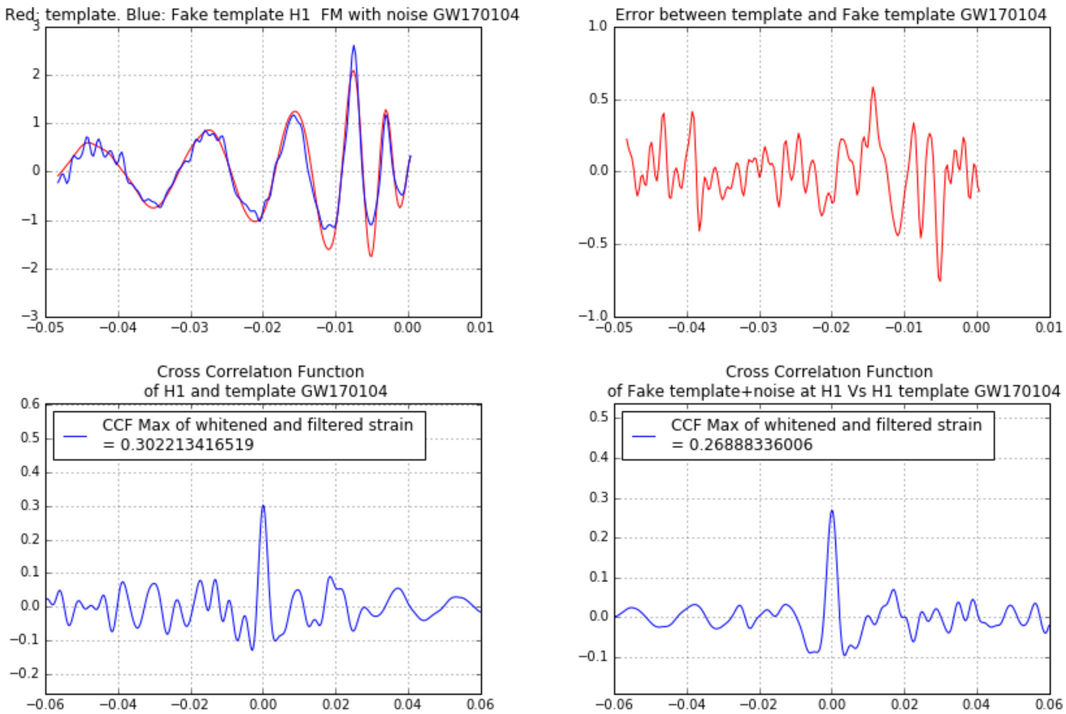

Figure 13. GW170104: Upper Left: Red: Ideal template. Black: Bogus Template. Upper Right: Error between Ideal and Bogus Templates. Lower Left: Normalized CCF in time domain for H1 vs Ideal template. Lower Right: Normalized CCF in time domain for H1 vs Bogus template.

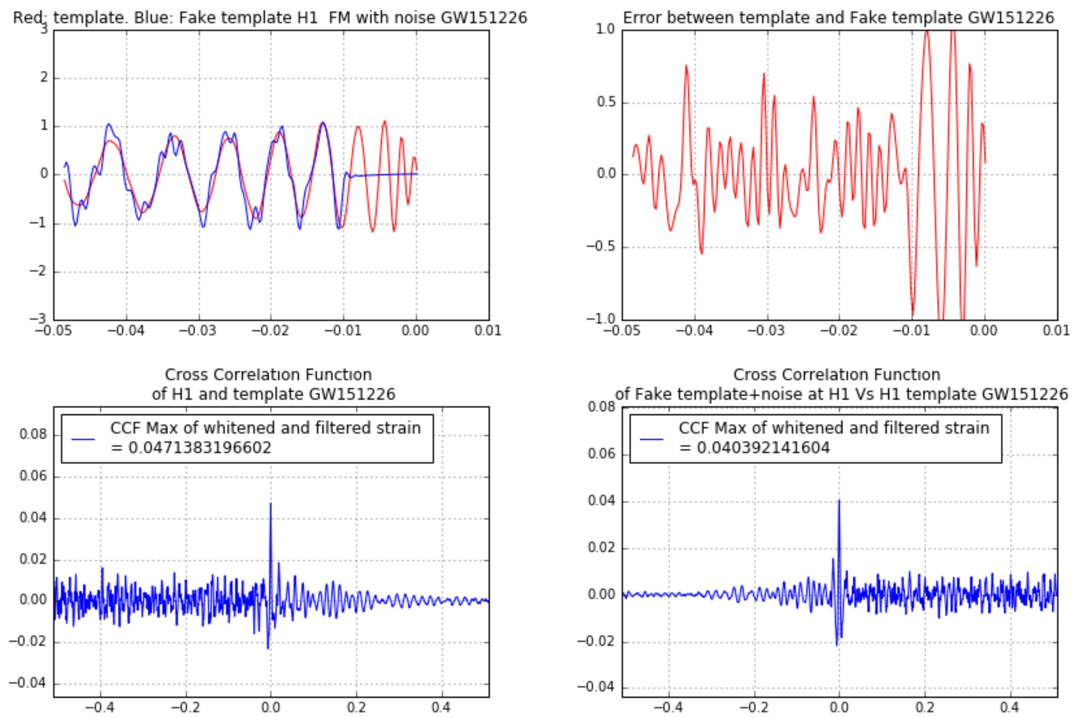

Figure 14. GW151226: Upper Left: Red: Ideal template. Black: Bogus Template. Upper Right: Error between Ideal and Bogus Templates. Lower Left: Normalized CCF in time domain for H1 vs Ideal template. Lower Right: Normalized CCF in time domain for H1 vs Bogus template.

10.2 GW waveforms

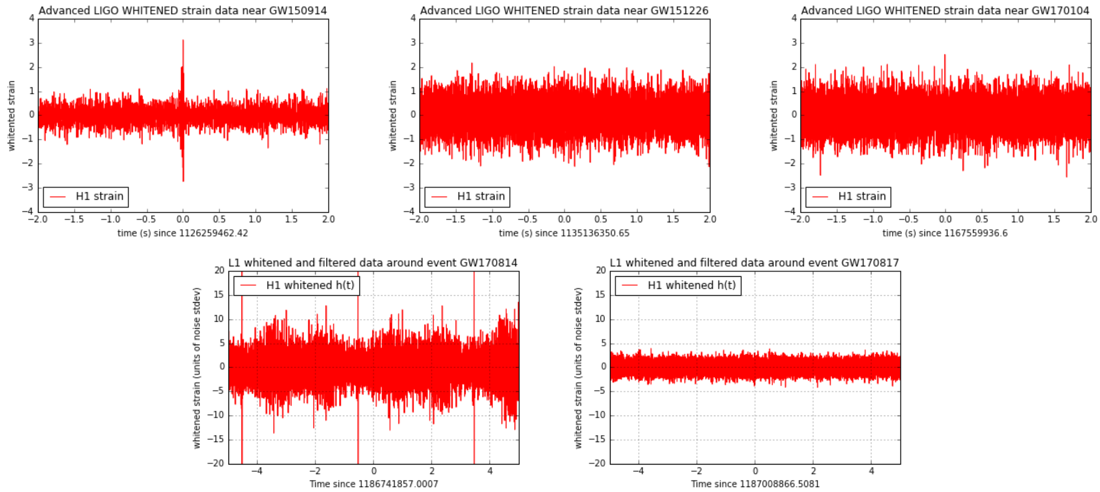

Figure 15. Plots of H1 whitened and filtered strain in GW150914, GW151226, GW170104, GW170814 and GW170817.

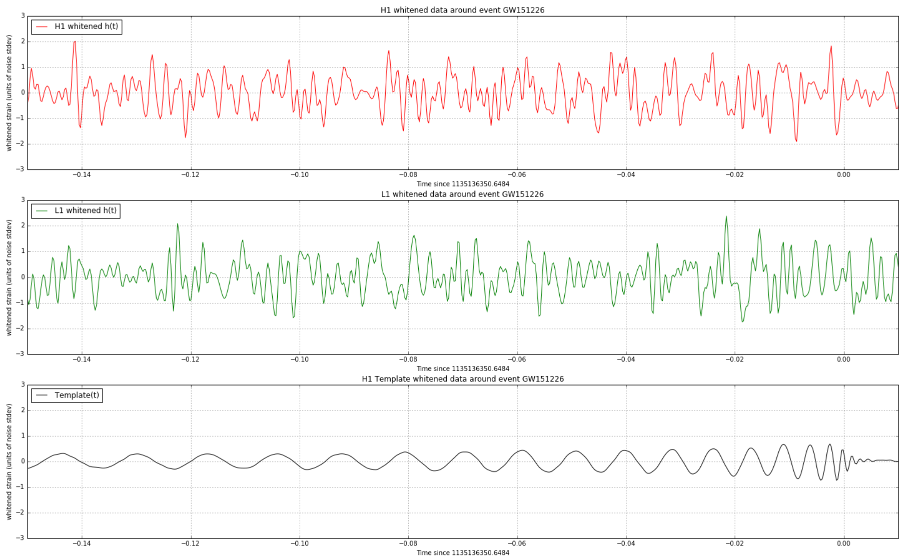

Figure 16. GW151226 whitened and filtered H1 and L1 strain, and the template

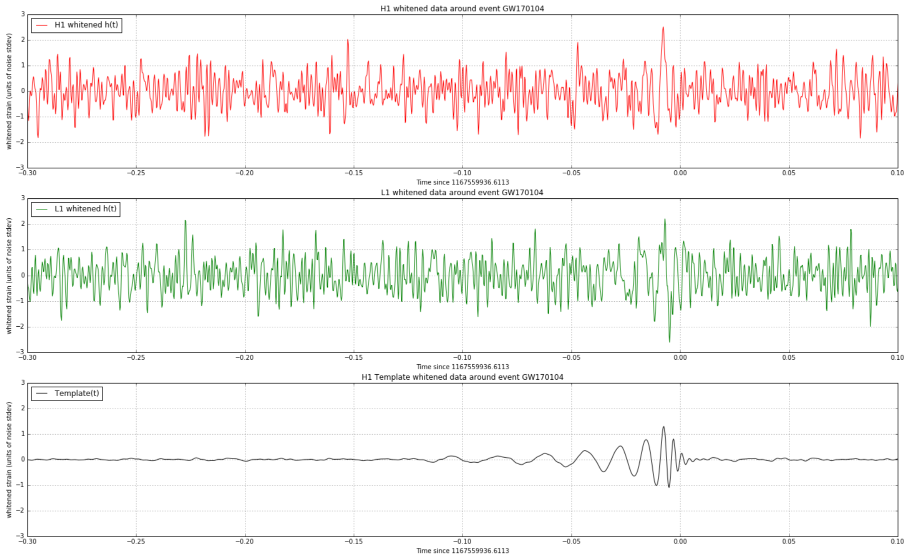

Figure 17. GW170104 whitened and filtered H1 and L1 strain, and the template

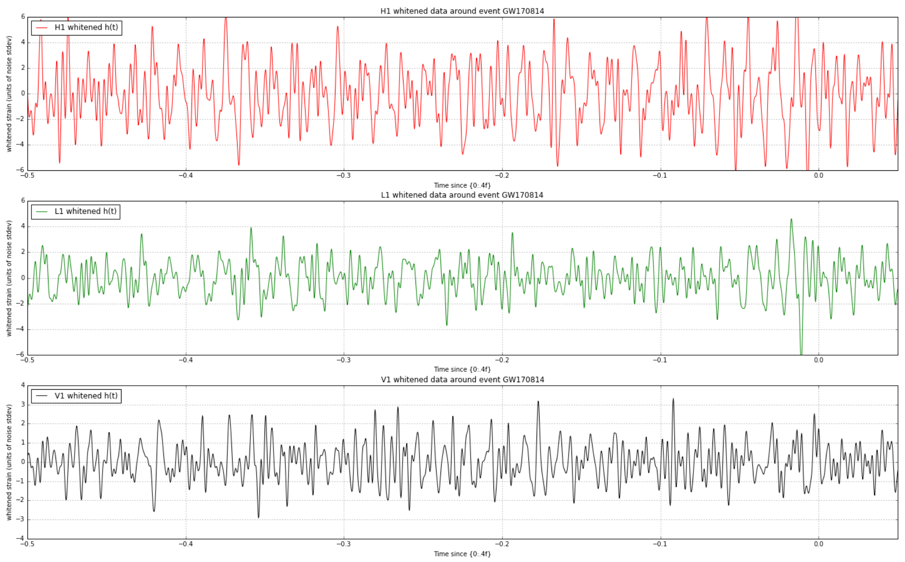

Figure 18. GW170814 whitened and filtered H1, L1 , V1 strain

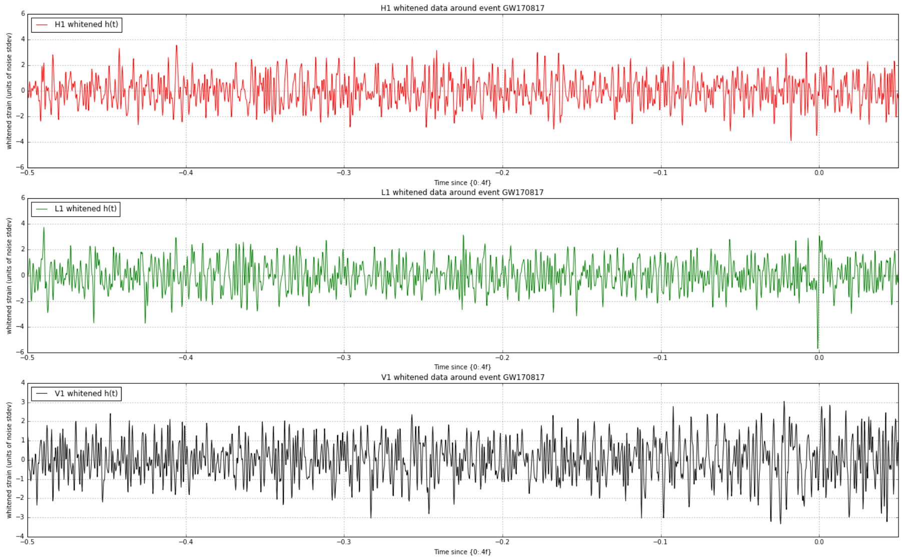

Figure 19. GW170817 whitened and filtered H1, L1 , V1 strain