Searching for gravitational waves from the coalescence of high mass black hole binaries

Research Project Proposal

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Abstract

We aim to detect gravitational wave signals from the coalescence (inspiral, merger and final black hole ringdown) of compact binary systems (neutron stars and/or black holes) with data from the advanced detectors (LIGO, Virgo, KAGRA). The merger signal from the coalescence of low-mass systems (binary neutron stars) tends to lie above the LIGO frequency band; for most events, only the inspiral phase is detectable. For higher mass systems (involving black holes, each of mass greater than 5 solar masses), the merger and final ringdown are also detectable. We search for these signals using analysis pipelines which filter all the data, identify triggers of interest, form coincident triggers between multiple detectors in the network, and attempt to optimally separate signal from detector background noise fluctuations. We use simulated signal injections to evaluate the sensitivity of the search pipeline. The analysis pipeline has numerous parameters that can be tuned to improve the sensitivity. In this project, we will run high-statistics simulations to evaluate the search sensitivity as the analysis parameters are tuned, to arrive at optimal settings under different anticipated noise fluctuation conditions.

1 Introduction

1.1 Gravitational waves

The first theoretical prediction of the existence of gravitational waves was made by renowned physicist Albert Einstein in 1916. In his elegant Einstein's field equation, he realized that under the weak field approximation, there exist wave solutions, namely transverse waves of oscillating gravitational field travelling at the speed of light [1]. Under Einstein's theory of general relativity, there are two types of polarization, namely plus + and cross × polarization, which stretch the spacetime into the shapes as shown in Figure 1 [7].

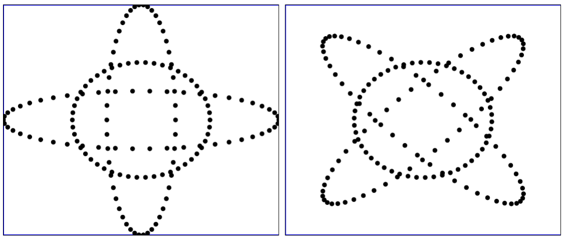

Figure 1: (Left) The effect brought about by plus-polarized gravitational waves to a circular ring. It stretches the ring into an ellipse of equal area horizontally for the first half of a period and stretches the ring into an ellipse vertically for the second half of a period; (Right) The effect brought about by cross-polarized gravitational waves. The effect is similar to that of plus-polarized waves by rotating an angle of $\frac{\pi}{4}$. (Figure taken from [7])

Currently, scientists propose that there are four classes of gravitational waves (GWs), namely continuous GWs from a massive spinning object with imperfection in symmetry (Figure 2); compact binary inspiral GWs from the coalescence of two massive and dense objects, which will be the focus of this study (Figure 3); stochastic GWs from the background, possibly from the big bang (Figure 4); burst GWs, from an unexpected source (Figure 5). In general, the magnitude of gravitational wave is very small, of the order of 10^{-21} to 10^{-28}. This makes the detection of gravitational waves seemingly an impossible mission.

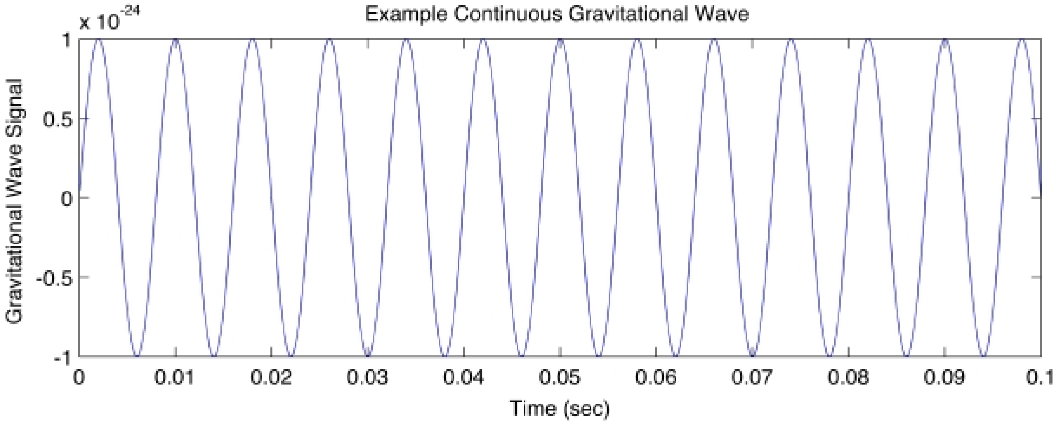

Figure 2: A simulated example of signal of continuous gravitational wave. One can see that the frequency and the amplitude are constant in time. (Figure taken from [3])

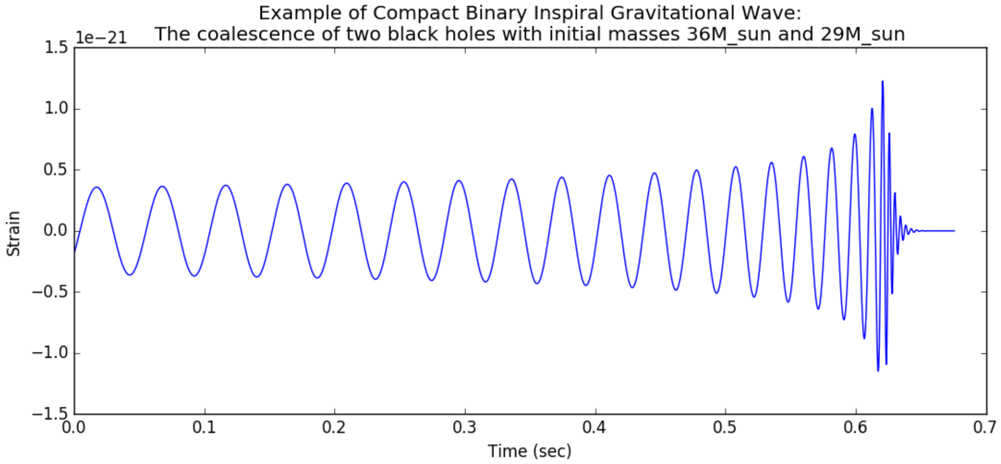

Figure 3: A simulated example of signal of compact binary inspiral gravitational waves. In particular, the signal is generated by the merger of two black holes with initial masses $36M_\odot$ and $29M_\odot$.

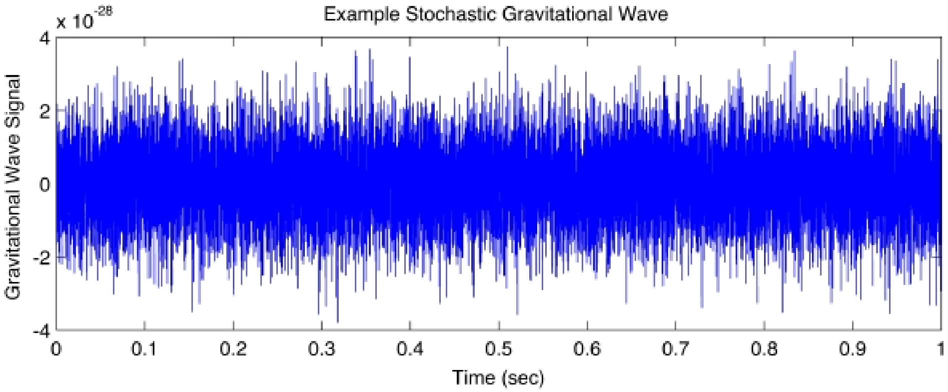

Figure 4: A simulated example of signal of stochastic gravitational waves. (Figure taken from [4])

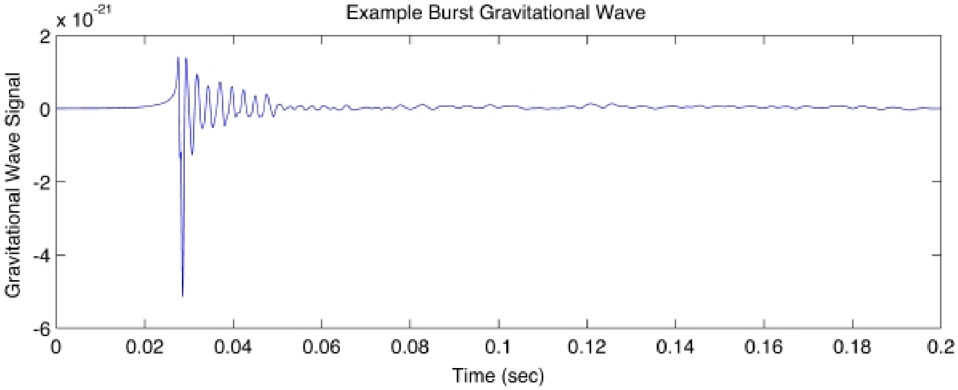

Figure 5: A simulated example of signal of burst gravitational waves. (Figure taken from [2])

1.2 Detections of gravitational waves

The first indirect detection of gravitational waves was made by Russell Hulse and Joe Taylor where PSR B1913+16, a pulsar and a neutron star orbiting around the center of mass of the system lose energy due to the emission of gravitational waves [1]. However, direct detection of gravitational waves was not possible before LIGO, which stands for Laser Interferometer Gravitational-wave Observatory.

A LIGO detector, as shown in Figure 6, is a modified Michelson interferometer consisting of two orthogonal arms with lengths 4 km each. A laser beam passes through a beam splitter and is separated into two beams travelling in two arms respectively. They are then reflected by mirrors on the test masses and eventually rejoin and the signal is recorded by the photo-detector. If the length of the two arms are identical, namely $L = L_X = L_Y$, then destructive interference occurs and the signals from the two arms cancel each other out perfectly. However, if there is a slight difference in length $\Delta L = |L_X - L_Y|$, the two signals will not destructively interfere completely, and thus a signal can be registered by a photo-detector and we can calculate the strain $h = \frac{\Delta L}{L}$.

In reality, LIGO detectors are subject to different types of noises, such as ground vibration, thermal noise, quantum noise and gravity gradient noise [7]. Various efforts, such as installing seismic sensors around the detector and data analysis techniques, have been made to facilitate the observation of gravitational waves and to distinguish gravitational wave signals from noises. These noises limit the sensitivity of the LIGO detectors [1] to observe gravitational waves. Fortunately, some types of signals emitted from a compact binary star system are detectable by the LIGO detectors. Possible combinations of a compact binary star system include:

1. Binary Black Holes system (BBH)
2. Neutron star-Black hole system (NSBH)
3. Binary Neutron Stars system (BNS)

In particular, the signals emitted in the inspiral phase of binary neutron stars system, the inspiral, merger and ring-down phases of the coalescence of compact binary black holes, with each black hole of mass greater than 5 solar mass, lie in the detection band of the LIGO detectors.

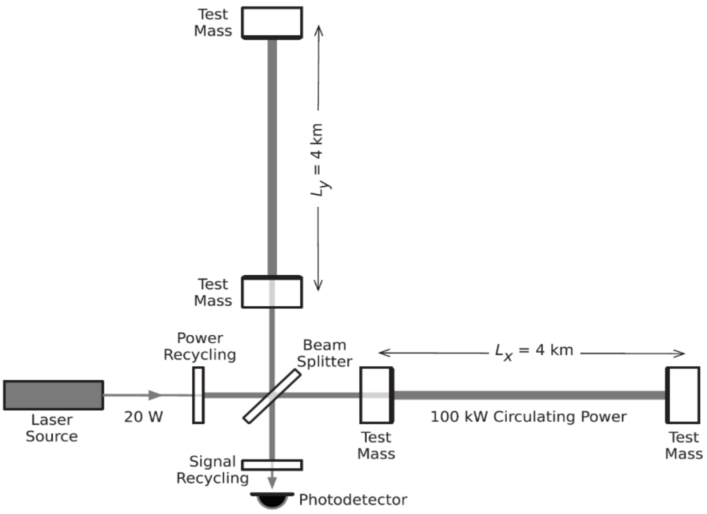

Figure 6: A schematic diagram of a LIGO detector. LIGO detector is more sensitive to plus-polarized GWs than those cross-polarized. (Figure taken from [1])

During the run from 2002-2010, the initial LIGO (iLIGO) was not able to detect any gravitational wave signals. The two detectors in Livingston and Hanford were upgraded to advanced LIGO (aLIGO), with improved sensitivity to different frequencies of signals as shown in Figure 7. Shortly after the upgrade, on 14 September, 2015, LIGO has first directly observed a gravitational wave signal emitted by the coalescence of a binary black hole system with with initial masses $36M_\odot$ and $29M_\odot$, which is also known as GW150914 event. Figure 8 shows the waveform of the signal detected in GW150914. It is worthwhile to mention that the GW150914 event could not be detected by iLIGO because of the insufficient sensitivity. This observation directly proves the existence of gravitational waves and shows the capability of aLIGO detectors to observe gravitational waves. Also, it opens up a new chapter in gravitational-wave astronomy.

Low latency on-line search, which can detect a signal within a few minutes of data acquisition, allows electromagnetic counterparts such as gamma-ray telescopes to observe the binary star system within a short notice and also provides feedback when the search sensitivity has dropped, implying that there might be a problem in the detector [6].

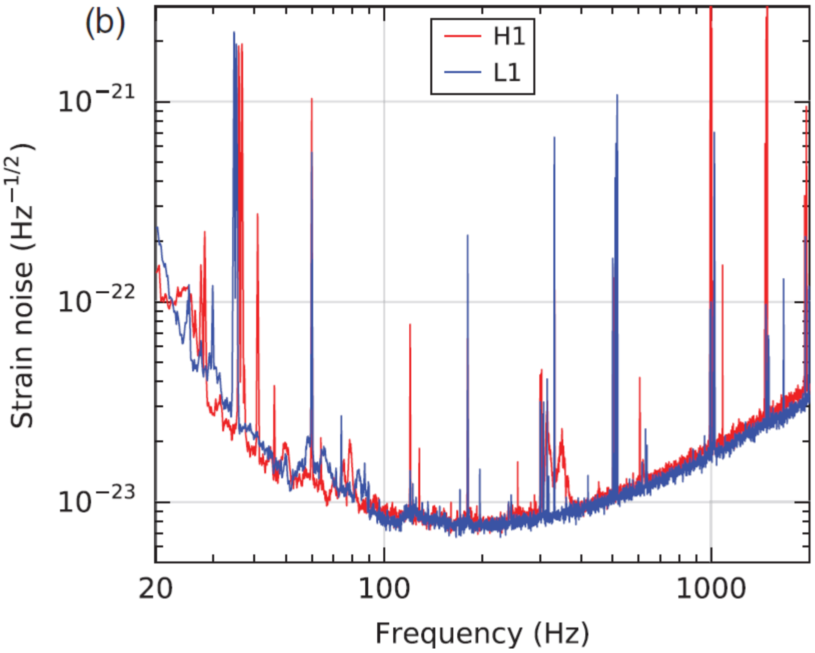

Figure 7: Sensitivity of the LIGO detector to different frequencies of signal. (Figure taken from [1])

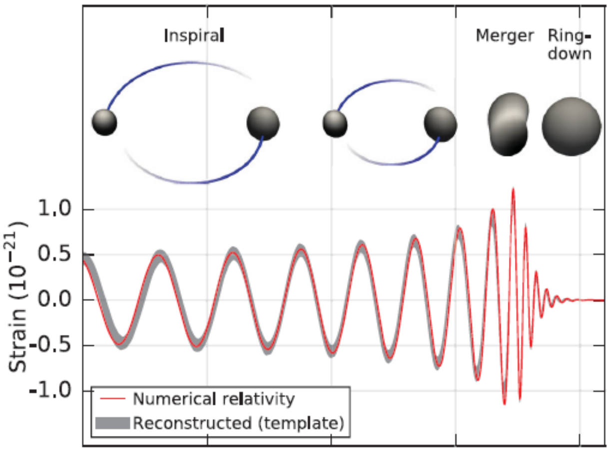

Figure 8: Inspiral, merger and ring-down phases of the coalescence of compact binary star system. In particular, this waveform comes from GW150914. (Figure taken from [1])

1.3 Low latency search pipeline: GstLAL

GstLAL, which is derived from the multi-media library GStreamer and LIGO Algorithm Library [6], is one of the search pipelines for compact binary coalescence (CBC) designed to operate at low latency for rapid EM follow-up. GstLAL looks for the coalescence of compact binary system mentioned above, namely BBH, NSBH and BNS. There is another search pipeline for CBC called pyCBC. However, pyCBC cannot be run in low latency.

2 Objectives

The purpose of this research is to optimize the analysis pipeline GstLAL. By optimizing for both the accuracy and the speed of GstLAL, we can achieve a faster detection for on-line search, as well as a more accurate detection for both on-line and off-line search.

3 Methods

Figure 10 outlines the GstLAL search pipeline. First, the data from Hanford (H1) and Livingston (L1) enters the pipeline. The power spectral density (PSD) is estimated for different portions of time $t_0, t_1, ..., t_N$ and using the results obtained for median PSD estimation. Matched filtering is then performed on the data received against the pre-calculated template bank of gravitational wave waveforms. The template bank used by GstLAL consists of the simulated signals generated by the coalescence of compact binary system with component masses from $1M_\odot$ to 99 $M_\odot$ and total mass of the system $m_1 + m_2$ less than $100M_\odot$. Table 1 lists the parameters in generating the template banks for the search and Figure 9 shows in the parameter space covered by GstLAL. It is also worthwhile to mention that the parameters found by GstLAL may not coincide with the best-fit parameters, in which full parameter estimation analysis will be carried out afterwards, due to the discrete nature of the template bank [5].

Singular Value Decomposition (SVD) is performed on the waveforms in template bank to save computational effort. Signal-to-Noise Ratio (SNR) is then calculated. If a candidate has a SNR value greater than a threshold value $\mathrm{SNR}_{threshold}$, then it is categorized as a “trigger”. Also, the chi-squared χ^2 of the candidate will be calculated to evaluate the statistical significance of the event.

component masses	m_1, m_2
component aligned spins	χ_1, χ_2

Table 1: Parameters in generating the template banks for the search.

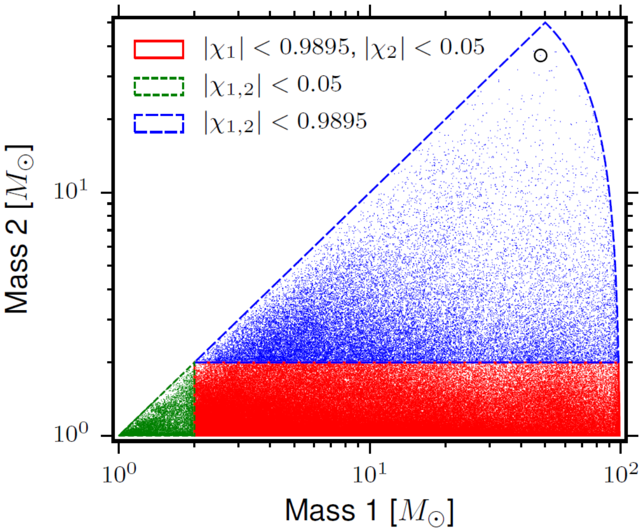

Figure 9: Parameter space covered by GstLAL analysis pipeline. (Figure taken from [5])

We can see that in the GstLAL search pipeline, there are many tunable parameters that one can adjust to improve the speed and accuracy. For instance, we can expand the parameter space covered by GstLAL such as increasing the masses or including the precessing spins. By performing high statistics simulations in which we vary these adjustable parameters, we can seek for a configuration of parameters that will give us the most optimal search result.

4 Schedule

Table 2 shows the tentative schedule for the summer research project.

Date	Task
Pre-arrival to Caltech	
May 15, 2016	**Project Proposal**
May 15, 2016 - June 13, 2016	Learn more about gravitational waves and LIGO detectors
	Review Python, Numpy and Scipy
	Learn more about Linux/Unix environment
Summer research in Caltech	
June 14, 2016	Arrive at Caltech
Week 1 - 3	Learn how to run GstLAL on the LIGO computing cluster, understand the structure of the analysis pipeline, and the inputs, outputs and tunable parameters
July 06, 2016	**First Progress Report**
Week 4 - 6	Explore modifications to the analysis pipeline to improve its sensitivity, efficiency, speed and the quality of its outputs
Week 7 - 8	Perform high-statistics GstLAL runs on simulated noise, real noisy data, and simulated signals, to evaluate the results of the modifications
August 03, 2016	**Second Progress Report**
August 03, 2016	**Abstract**
Week 9 - 10	Compile and document all results; prepare final presentation and paper

Table 2: Summer research schedule

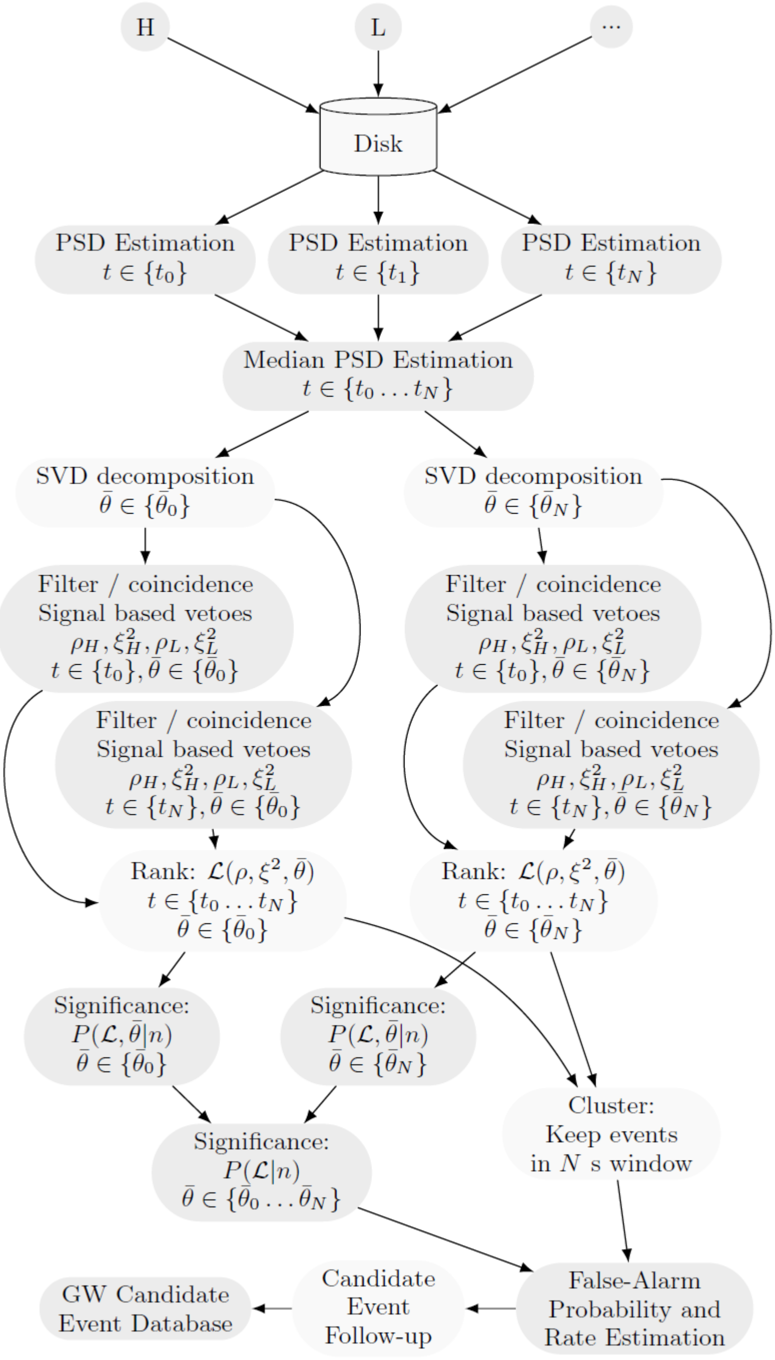

Figure 10: A flow-chart of the GstLAL pipeline. (Figure taken from [6])

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