# Searching for Cosmic String Cusp Events in LIGO's Gravitational Wave Data

SUNY New Paltz Physics Senior Project

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## Abstract

A model of the gravitational wave bursts caused by the theoretical event known as a Cosmic String Cusp is used to create a search process for these events in LIGO's gravitational wave data. The search process is not complete and no new events are found, but the investigation illuminates and describes the challenges of trying to detect the gravitational wave signals from cusp events, and distinguishing them from events with similar signals.

## I Introduction

Since the first direct detection of gravitational waves in 2015 by the network of Laser Interferometer Gravitational Wave Observatories (LIGO), it has become a central question to determine what new information we can learn about the universe using this new paradigm of observational astronomy [1]. One event that is believed to be possible to detect using the LIGO network of detectors is a Cosmic String Cusp event[2]. Detecting such an event with a significant level of confidence would confirm the existence of the theoretical objects known as Cosmic Strings. This would be an incredible discovery that would have implications for the field of cosmology, observational astronomy, and theoretical physics. It would also be a significant achievement for the network of LIGO instruments because thus far they have only detected one type of event, known generally as a Compact Binary Coalescence (CBC). The term CBC describes any merger of two massive objects such as a black hole and or neutron star, an event which produces significant gravitational waves.

Cosmic strings have never been proven to exist or observed, but detecting gravitational waves from an event known as a cosmic string cusp is one of the most promising methods of confirming their existence. These objects were proposed by Tom Kibble in his seminal paper titled "Cosmic Strings"[4]. They are described as one-dimensional topological defects in space-time that would have formed in the very early universe due to a symmetry-breaking phase transition. Many separated areas of theoretical physics describe these defects forming in systems that experience a symmetry-breaking phase transition, but this phenomena occurring in the early universe has never been proven. Predictions made assuming these objects exist is that the strings would form loops if they were to ever meet in space. These loops would oscillate and lose energy in the form of gravitational waves[2][3]. It is predicted that particularly violent oscillations would lead to the formation of cusps and kinks of the string. These cusps would produce a burst of gravitational waves[5]. A few models have been created to predict what the gravitational wave form would be for a Cosmic String Cusp event[2].

Using one of these models as a basis, a program is constructed to generate templates of these gravitational wave signals. A template is the expected form of a gravitational wave signal for a particular event that is used when trying to detect signals within LIGO data. The template is usually in the form of strain value as a function of frequency or as a function of time. Strain ($h$) is the quantity that the LIGO instrument uses to measure the expansion and contraction of space-time as a gravitational wave passes the interferometer. It is defined as :

$$h = \frac{\Delta L}{L} \tag{1}$$

Where $\Delta L$ is the change in path length measured by the interferometer, and the $L$ is the path length itself. These templates are tested on LIGO's gravitational wave data that is made available to the public through the Gravitational Wave Open Science Center(GWOSC)[6]. To begin testing this model it was first used to try and recover Cosmic String cusp events signals that were injected into the LIGO data during their fifth Science Run (S5) in 2006 [6]. These injections are signals put into the strain data by LIGO to test both their ability to detect signals buried in noise, as well as test the instrument itself. After the model was successfully able to recover these injections, it was used on the data from LIGO's official discoveries (confirmed events).

# II Methods

## II.I Model for Cosmic String Cusp Events

The program for creating a gravitational wave signal template was based upon the model of the predicted gravitational wave burst created by a Cosmic String cusp described in the paper: "Gravitational wave bursts from cosmic (super)strings: Quantitative analysis and constraints" [2]. This model considers the predicted signal. The code structure for the program was based upon a similar program for creating templates of gravitational wave signals caused by CBC events which was created by Ashley Disbrow, a student researcher at Caltech[7]. The model describes a strain function in the frequency domain. Their model is given as :

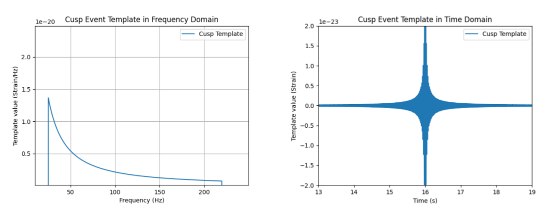
$$H(f) = A|f|\Theta(f_h - f)\Theta(f - f_l) \tag{2}$$

The amplitude factor is defined as :

$$A \ \frac{G\mu L^{\frac{2}{3}}}{r} \tag{3}$$

The $G$ is Newton's constant, $mu$ is the mass per unit length of the string, $L$ is the length of the feature producing the cusp, and $r$ is the effective distance between the cusp and the observation [2]. However since the amplitude is only an overall scale factor, it does not effect the signal morphology and our ability to recover signals. For all templates produced in this project the amplitude was set to a constant $1e-18$, to best match the signal amplitude scale of CBC events and injections[2]. The $f_l$ and $f_h$ term are for the low and high frequency cutoff respectively. The low frequency cutoff is generally limited to the lower limit of sensitivity of the detector, which is 25Hz [5]. The high frequency parameter can be adjusted, which will change the template. This variation and its effect on the results will be discussed more thoroughly in analysis. An example of the template as a function of both frequency and time are shown in Figure [1a] and Figure [1b] respectively.

Figure 1




(a) Frequency domain template for a Cosmic String Cusp event with a low frequency cutoff of 25Hz and a high frequency cutoff of 220Hz

(b) Time domain template for a Cosmic String Cusp event with a low frequency cutoff of 25Hz and a high frequency cutoff of 220Hz

In order to create a time domain template, the Inverse Fast Fourier Transform (IFFT) on the frequency template must be performed. This is a method of taking a noncontinuous function of some variable, and translating it into the associated function of the inverse variable.

## II.II Data Collection

GWOSC offers downloadable files of LIGO's strain data in a HDF5 file format. These data files are organized by GPS time and along with other useful information, they contains strain values over time. GWOSC offers many ways to collect this data and check for particular qualities for a given time. However, the data for this project was downloaded directly from their portal for a specific GPS time. A certain GPS time will fall somewhere within a 4096 second interval that the data files are broken up into. For this project, only files with 100% data quality were chosen. This is a rating system created by GWOSC that states the percentage of the 4096 second interval, at a sampling frequency of 16384Hz, that has complete data with no glitches or breaks [6].To locate the specific section of data, the event portal and injection tables offered by GWOSC were used to retrieve GPS times of events and injections. After the associated file for that GPS time was downloaded, a 64 second segment was taken from that data that began 32 seconds before the event time and ended 32 seconds after.

Only data from LIGO- Hanford and LIGO - Livingston were collected for the entirety of this project. Specifically for data that contained injections, only LIGO- Hanford data was collected.

One interesting finding during the data collection process was the absence of any burst injection flags during the series of burst injections in S5. The flag system is created and maintained by LIGO as a means of easily checking if a data segment has an injection somewhere within the file.The information of what flags are marked at a given time is kept within the HDF5 file. In every file for any of the CBC injections used in the testing process that were also from S5, there was always a specified flag at the time of injection.

## II.III Optimal Matched Filtering

Once a data segment had been collected, and a template for the data had been created, a search process must be completed to try and detect that template's signal buried within the noise of data. The noise comes from imperfections in the instrument's process to account for all external sources of vibration while it is making measurements of strain. The method for detecting the signal in the noise that was used for this project is known as Optimal Matched Filtering (OMF). This method is similar to a cross correlation function but for the frequency domain. The advantage of this method as opposed to using a cross correlation function is that OMF considers the varying amount of noise that is present in a bin of frequencies. It is performing a cross correlation between the template and the data, but weighting each frequency bin by the inverse of the noise power.This method requires both a template and a segment of data to be functions of frequency, so a Fast Fourier Transform (FFT) was performed on the data segment. The data however was not a continuous function, and there were non periodic boundary conditions at the start and end of all of our data segments. So in order to perform the FFT, the data was first windowed with a Blackman window. This is a standard process for transforming noncontinuous data with non periodic boundary conditions [8]. The figure of merit for this method is Signal to Noise ratio. This is the ratio between the power of the signal that is being searched for, and the power of the noise that the signal is buried in. The implementation of this method offered by GWOSC was utilized for this project.

# III Data and Analysis

## III.I Testing on S5 Burst Injections

LIGO performed a series of burst injections during their S5 run in 2006. One of these burst was a signal titled 'wfcusp220'. Their burst injection information page reveals this was an injection to test gravitational wave signals from cosmic string cusp events[6]. To test the effectiveness of this model, these injections were very valuable for the first matched filer analysis. The data file corresponding to the GPS time of 822963758 is a sample of strain data that contains six burst injections within a 64 second sample centered on the GPS time 822963758. The model successfully recovers all six burst injections with a significant signal to noise ratio(SNR).

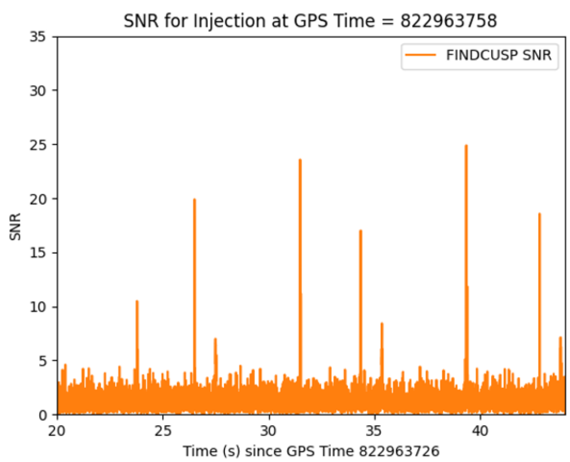



Figure 2: Optimal Matched Filter analysis of a segment of data containing 6 cusp event burst injections, the greatest peaks of SNR corresponding to exact injection times.

The largest six peaks of SNR, in figure (2) correspond to the exact times of the 'wfcusp220' injections. The other and less significant peaks of SNR are attributed to other burst injections in this segment that must have a similar frequency profile when compared to the Cusp template. The LIGO research community practices a high level of scientific scrutiny for all of their work and presumably the templates they used would have the most detailed and accurate models of the time for their injections. Considering their injections as a standard, the significant SNR produced during the optimal matched filtering analysis using our template can be considered a great success for this model. To further increase the ability of the template to produce significant SNR, it was repeatedly tested on injections with a varying inputs for the high frequency cutoff, $f_l$. Figure (3) shows one example of repeatedly changing the high frequency cutoff of a template being tested on an injection. Changing this parameter, changes the signal morphology, and produces a different SNR. The value of approximately 220Hz is what nearly always produced the highest SNR for a given injection that was being tested. The value of 220Hz was set as the high frequency cutoff parameter for all of the matched filtering analysis of real events.

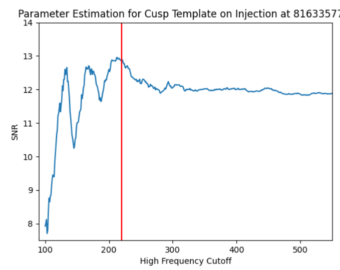



Figure 3: The varying high frequency values used for the template effect the SNR

After recovering all of the cusp event burst injections, there was a reasonable amount of confidence in the templates ability to be tested against CBC templates on real events.

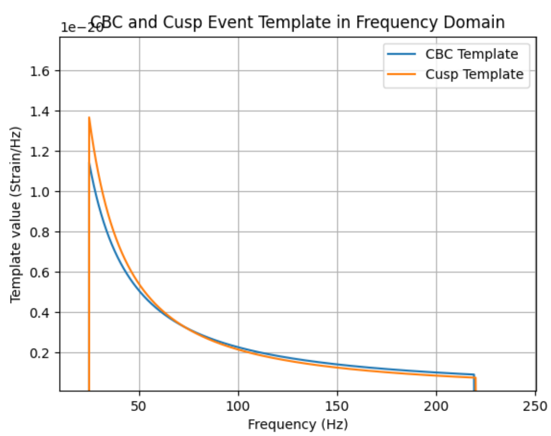


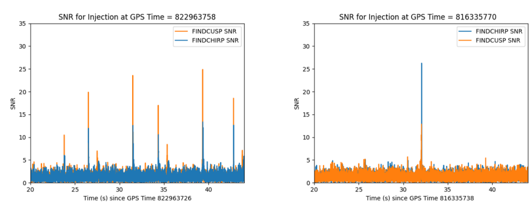

Figure 4: Frequency domain template for a Cosmic String cusp event produced by the program, overlapped with an example frequency domain template produced by the program created by Ashley Disbrow [7]

## III.II Testing on Data from Confirmed Events

As seen in Figure 4, the two templates overlapped in the frequency domain reveals their evident similarity. This similarity is concerning given the fact that the most effective method for detecting signal buried in noise, optimal matched filtering analysis, uses the frequency domain templates.

These templates are so similar, that when there is an injection for either a Cusp or CBC event, both templates are able to recover the signal. Figure (5a) shows the result of using both templates on a matched filter analysis of the cusp injections, and Figure (5b) similarly shows the results for a CBC injection. Despite both always producing a SNR peak, the template that matches the injection type always produces a greater signal to noise ratio. This is expected, as the signal that is injected is likely very close the signal of these templates. However, for a real event, the same can not be said. In a discovery there is no specific expected waveform, and there has to be extensive testing of many different templates to find what type of event is suspected to have a signal that matches best.

Figure 5

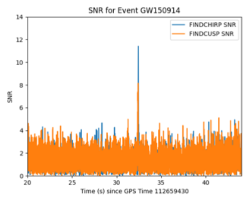



(a) Both templates tested on cusp event injections. (b) Both templates tested on CBC event injections.

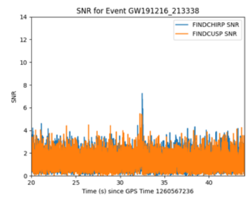
Taking a look at three confirmed discoveries made by LIGO with both templates reveals the complications that arise from these two templates of different events being similar. To create the CBC template for each event, the masses that were published in their discovery announcements were used. For the Cusp templates, a constant $f_h$ of 220Hz was chosen as it had previously been found to produce the highest SNR for all tests.

The last event, known as GW200224_222234, produces a significantly larger SNR peak for the matched filter analysis of the cusp event template. At first this is largely concerning, and raises the question of whether or not this event was actually one of the first observed cusp event that was wrongly classified as a CBC event. However, this is nearly certainly not the case. LIGO performs a much more extensive and exhaustive testing process that can use hundreds of thousands of templates of varying parameters and models, that is far more significant than the testing process in this project. The similarity between

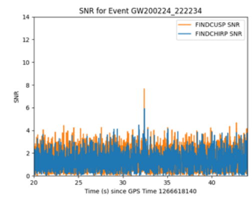
Figure 6: Matched filtering analysis for three confirmed events with both the CBC and Cusp event templates.




(a) Event GW150914




(b) Event GW191216_213338




(c) Event GW200224_222234

| Event Name: | Cusp Template SNR | CBC Template SNR | Reported SNR |
|---|---|---|---|
| Event GW150914 | 8.17 | 11.8 | 24.4 |
| Event GW191216_213338 | 5.57 | 7.4 | 18.6 |
| Event GW200224_222234 | 7.67 | 5.39 | 20 |

Figure 7: A table of peak SNR values of the templates for each event.

these events should still be considered, if not only as motivation to create more advanced models of cosmic string cusps as to further distinguish these event's gravitational wave signature.

# IV Summary

An optimal matched filter analysis using a theoretical model of the gravitational wave form of cosmic string cusp events can be detected in the gravitational wave signals from cosmic string cusps simulated in LIGO-Hanford data. The waveform is similar enough to a basic model of CBC gravitational wave forms that using this model on confirmed events will also produce a significant signal to noise ratio. In the discovery event known as GW200224_222234, the signal to noise ratio using the cusp event model was greater than that of the CBC model. This can be attributed to the simplification of the cusp model, and the CBC model being outdated with only two parameters considered. The complications that arise from the models of these events producing similar gravitational wave signals, should be an incentive for future models of cosmic strings and cusp events to be more evolved so that the process of distinguishing these signals becomes easier.

# V Acknowledgements

- The Gravitational Wave Open Science center offered a number of incredible resources that made this project possible. Resources such as there implementation of the Optimal Matched Filtering method, their example code for downloading and segmenting their files, as well as tips on creating visualizations of the data were all incorporated into this project.

- Dr. Eric Myers was a thoroughly helpful and informative research mentor. Many thanks to him for all of his input and guidance throughout this project.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