

**INVESTIGATION AND ANALYSIS OF  
GRAVITATIONAL WAVES USING DATA  
FROM THE LVT151012 EVENT**

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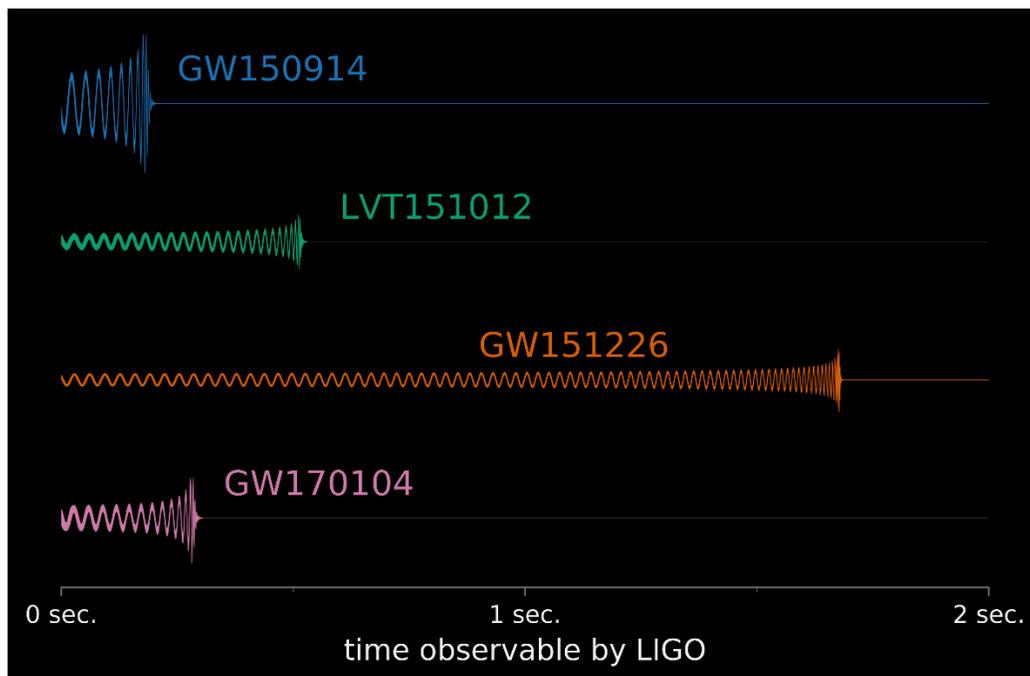
**Mentor: Eric Myers**

## **ABSTRACT**

The LVT151012 event produces numerous questions on its validity due to various factors. In this paper, I investigate this and analyze the LIGO data for this specific event. I will first give background on what gravitational waves are and how they're measured, my methodology in investigating the event, and a conclusion of my results. This paper is targeted at anyone who is interested in learning about gravitational waves and has a basic understanding of physics.

## INTRODUCTION

On October 12th, 2015, LIGO made its second detection of gravitational waves. This event, known as LVT151012, is theorized to be the result of the inspiral of two black holes in a binary system of 23 and 13 solar masses. This isn't confirmed completely yet, which is the reason to why it is given the acronym LVT, meaning "LIGO-Virgo Trigger", and not GW like others, which stands for "Gravitational Wave" [1].



*Figure 1: Comparison of gravitational-wave signals from recent LIGO observations. [2]*

A major difference between this specific detection and others is that the confidence is significantly lower, and it is not enough to make the cut for an official detection. The confidence level is  $1.7\sigma$ , and the official amount that a detection has to be greater than is  $5\sigma$ . LVT151012 also has a much greater distance compared to all other detections, which comes out to be approximately 1000 Mpc.

My goal is to investigate why the confidence level for this detection is lower than others, including investigating multiple variables such as distance, luminosity, and sky localization, and also researching

whether the gravitational waves caused by this event is really the result of inspiraling black holes, or maybe the result of a continuous wave source. But, in order to research this, I must know what exactly are gravitational waves and how are they measured.

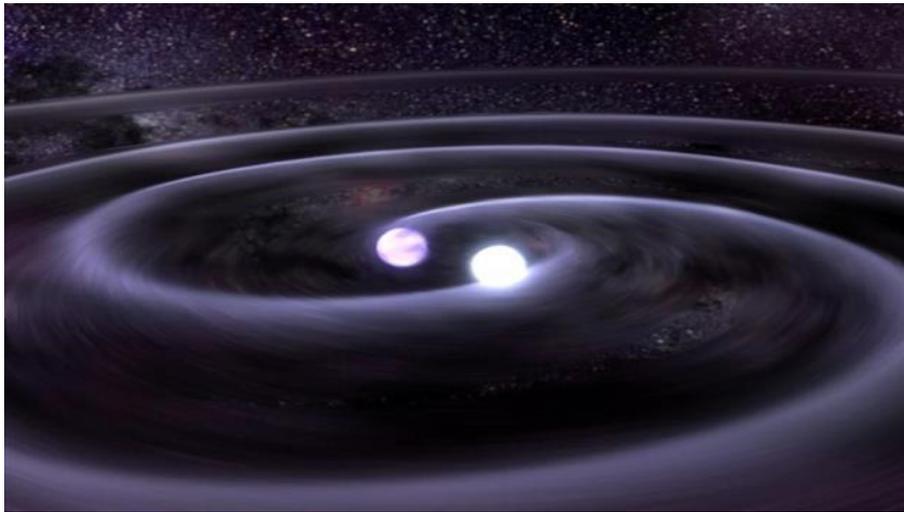
## **BACKGROUND**

As part of his theory of general relativity, Albert Einstein made gravitational waves known to the world in 1916 [3]. Ever since, scientists all over the world have been testing different techniques that would help confirm this theory of gravitational waves. The reason is that these type of waves are a different approach to measuring our universe, besides through electromagnetic waves, which is how astrophysicists observed space up until late 2015. But what are these waves, and why are they essential to understanding the universe? How are they different in comparison to electromagnetic waves? What type of forces produce them, and how can they be detected?

Ever since James Maxwell developed a theory to explain it over 150 years ago, electromagnetic waves have been key to our understanding of our expanding universe [4]. EM waves have two polarizations, horizontal and vertical, and can be generated by a changing dipole charge distribution. This radiation is produced and transmitted by astronomical objects, and from this, whether through the form of light, radio waves, and others, scientists gain information and insight on many celestial bodies. But this can only go so far, and electromagnetic waves have their limits on what they can measure, which leads to the topic of gravitational waves.

Einstein proposed that in General Relativity, gravitation is described as being a property of the geometry of space and time, which we call space-time. Space-time, which can be analogized to a fabric, is malleable in the sense that an object that has mass can bend or distort it. This is what creates what we

know as gravity. Now, when you take two objects that have mass and are oscillating together, this creates a ripple in space-time, or a gravitational wave, as shown in Figure 1 [5]. Examples of two objects that could produce these are neutron stars and black holes. By the detection of these waves, scientists can inspect objects far out deep inside our universe, and learn things never known before.



*Figure 2: An artist's rendition of how gravitational waves are produced, where two large masses are oscillating, creating a curvature in what we call space-time. [5]*

So how do we exactly detect these waves? The first attempt at this was by Joseph Weber, a physicist at the University of Maryland in the 1960s. Weber proposed that that these waves could be seen with the use of large cylinders of ultrapure aluminum (Figure 2), which would vibrate by about a 10 millionth of a nanometer once a gravitational wave travelled through it [6]. This attempt turned out to be unsuccessful in the long run, but Weber is recognized all over the world as the one who started the movement of finding methods to detect gravitational waves, as scientists rushed to develop their own methods of detecting these at the time fictional waves. This hunt soon led to the development of a new technique for detection, which would be known as the Michelson Fabry-Perot Interferometer.



*Figure 3: Photographed here is Joseph Weber and one of his gravitational wave detectors. [6]*

An interferometer is an instrument in which the interference of two beams of light is employed to make precise measurements, and scientists started using these in detecting gravitational waves. The Michelson Interferometer first found its origins in the late 1800s. The Michelson-Morley experiment had used this device to measure a thing called Ether, a medium that light traveled through and was believed to be transparent [7]. The mechanics of the device used in this experiment, the Michelson Interferometer, is what inspired the Fabry-Perot variant. The Michelson interferometer is an instrument that measures small changes in optical path length. As seen in Figure 3, it takes a beam of light and uses a splitter to send this beam into two perpendicular directions. A mirror causes these two beams to reflect and bounce back in the direction they came from, where they will eventually combine and create interference, hence the name “interferometer” [8]. Changes can be observed by how much interference is created by looking at bright or dark “fringes”, or constructive/deconstructive interference.

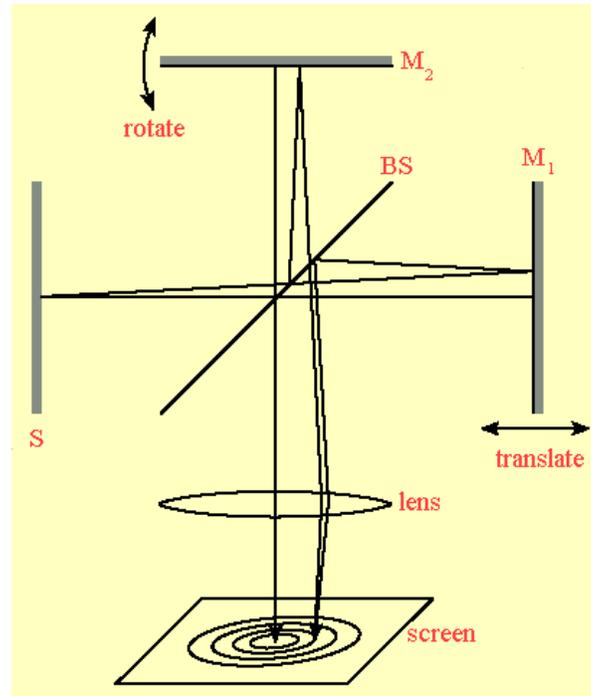


Figure 4: Basic schematic of the technology behind the Michelson Interferometer. [8]

The Fabry-Perot interferometer (Figure 4), developed only a decade later, used the same technology that was constructed in the Michelson variant, except that mirrors are added between the light source and the end mirror, which creates a folding effect. This produces more precision by creating a more elongated beam of light band then reflecting it, which will help scientists see any changes in interference more clearly. The Fabry-Perot interferometer is the basis of the Laser Interferometer Gravitational wave Observatory (LIGO).

LIGO was first pioneered by Rainer Weiss at MIT and Ron Drever at Glasgow in the 1970s. It uses interferometer technology to measure the strain amplitude, or the change in length in the arms of the device over the total length. The change in length will depend on the gravitational wave that passes through, which either will stretch or shrink the light passing through the arm, which will lead to fringes, or interference. In the United States, there are currently two LIGO sites, one based in Livingston Parish, Louisiana, and the other in Hanford, Washington. The reasoning behind having two sites is to be able to

look for a coincident signal, so background noises from either sites can be easily detected. The instruments have arm lengths of 4 kilometers that stretch perpendicular to each other.

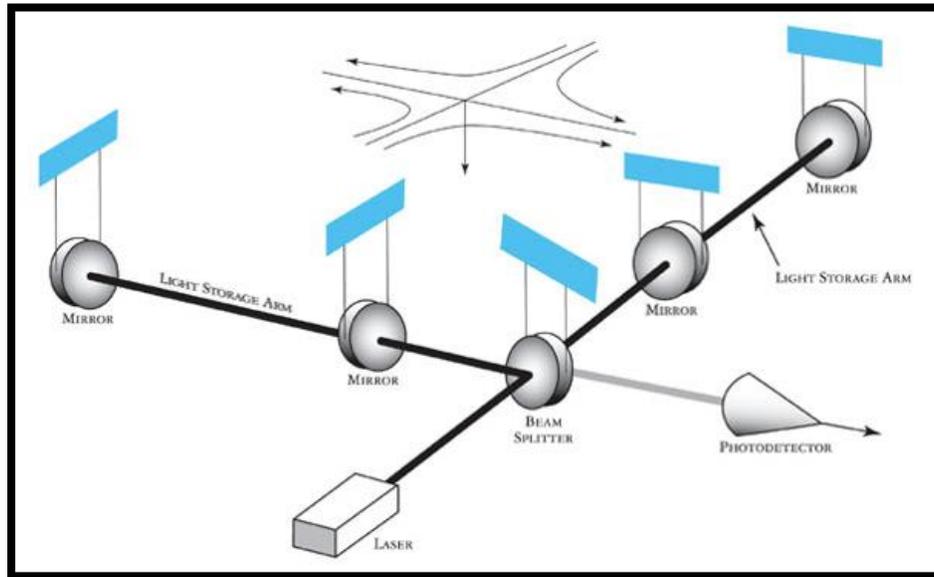


Figure 5: Diagram of LIGO's interferometers with an incoming gravitational wave depicted as arriving from directly above the detector. [9]

LIGO had gone through two renovations, Enhanced LIGO and Advanced LIGO, before it was finally able to detect gravitational waves on September 14, 2015 (Figure 5), only two days after it had been turned on. It would later be published about on February 11, 2016 [10][11]. These detections were from two merging black holes 410 megaparsecs away, or over 1.3 billion light years away! Since then, there have been 2 other LIGO detection candidates, in addition to one trigger event, all from merging black holes.

These detections from LIGO have opened a new branch of astronomy, one that isn't measured through electromagnetic waves, but through gravitational. It has led to multiple gravitational wave detectors going online all over the world, and has even led to plans for producing a detector to put up in space.

There is so much opportunity for this, and we only expect it to all get better.

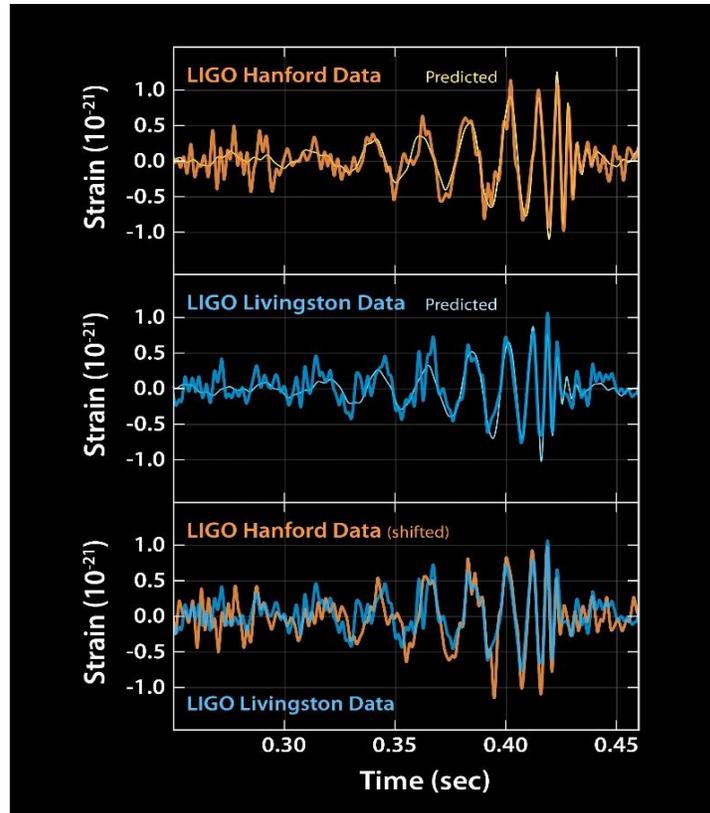


Figure 6: These waveforms, real data from the event, show what two merging black holes should look like according to the equations of Albert Einstein's general theory of relativity, along with the instrument's ever-present noise. Time is plotted on the X-axis and strain on the Y-axis. Strain represents the fractional amount by which distances are distorted. [11]

## METHODOLOGY

I first created a hypothesis on why I think the confidence level for this detection is much lower than its counterparts. As mentioned before, there are multiple factors affecting this, so I wanted to investigate as many factors as I could, and my first goal would be to create a spectrogram for the event that would show the chirp.

So then I went through the Python code in the tutorials on the LIGO Open Science Center (LOSC: <https://losc.ligo.org/about/>) website and analyze the data from the LVT151012 event. While going through the tutorial, I did some research and found a paper that had made their own spectrogram of the

LVT151012 event (Figure 7). I then made it my goal to see if I could reproduce the spectrogram I had found in the research paper.

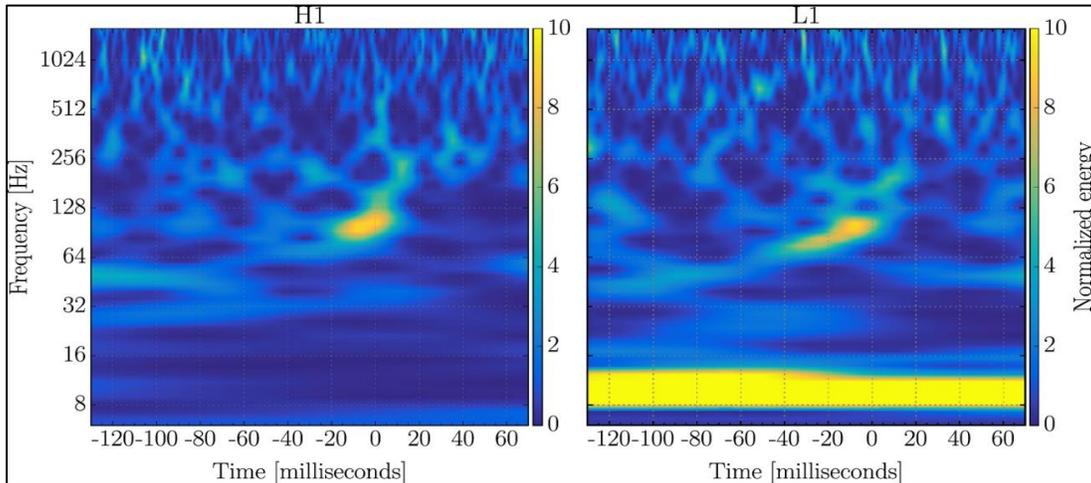


Figure 7: Normalized spectrograms of LVT151012 in LIGO-Hanford (left) and LIGO-Livingston (right). [12]

So after completing the tutorial, the Python code produced a graph of the spectrogram, first one with the raw data from LVT151012 (Figure 8), and one with the whitened data. The graph produced looked completely different than the one shown in the paper, including a different color map and scale. It seems to be that the paper had used the color map “Viridis”, while the LOSC tutorials used “Ocean”.

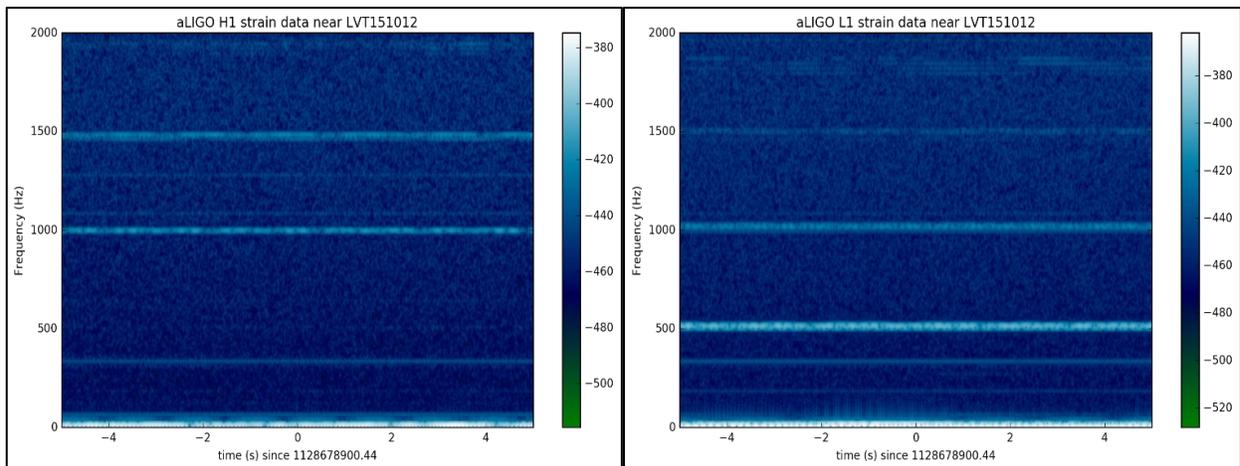


Figure 8: Spectrograms of LVT151012 in LIGO-Hanford (left) and LIGO-Livingston (right) that were produced from the LOSC tutorials. It can be easily seen that the spectrograms shown in the paper were filtered and edited, since in comparison to these, they look nothing alike. [13]

It can also be seen that the paper had used milliseconds for the x-axis, and a logarithmic scale for the y-axis. So in order to try replicating the graph I had found, I edited the code by small increments.

I first changed the color map of the spectrograms I had made by commenting out `spec_cmap='ocean'` and setting it to `spec_cmap='viridis'`. After running through this, I change the time increments on the x-axis to milliseconds by replacing `plt.axis([-deltat, deltat, 0, 2000])` with `plt.axis([-0.120, 0.060, 0, 512])`, also changing the maximum amount on the y-axis. This produced Figure 9, which looks much closer to the graph from the research paper than it had before.

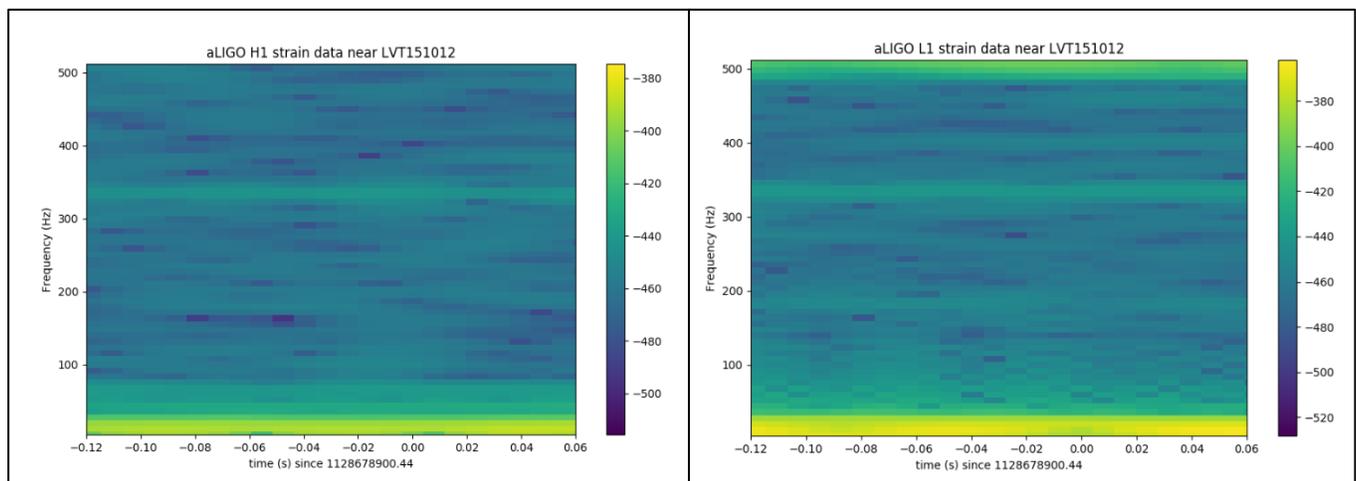


Figure 9: Spectrograms of the LVT151012 raw data after making small changes to the code.

My next step is to try and change the y-axis to an actual logarithmic scale, and also trying to change the resolution of the graphs. In Figure 9, the background is sort of blocked and not as smooth compared to Figure 7, which is the graphs from the paper. I can try this by changing the Fast Fourier Transform (NFFT) time interval from 1/8 to maybe 1/32 or 1/64.

I set the y-axis by making a subplot, and using the code `plot11.axes.set_yscale('log')`, and commented out the previous `plt.axis([-0.120, 0.060, 0, 512])` I had. The x-axis was set with the `xextent=[-deltat, deltat]`, where `deltat` was equal to `0.060`. Lastly, I set `NFFT` to 640. After making these changes, I got two graphs that looked very compared to the previous graphs I had. Although, it wasn't the kind of

smoothness I was wishing to create, as I am trying to model the graphs from the other paper. There also seemed to be a lot of yellow at the bottom of the two graphs, which when comparing to the graphs from the research paper, makes sense for Livingston, but not really for Hanford.

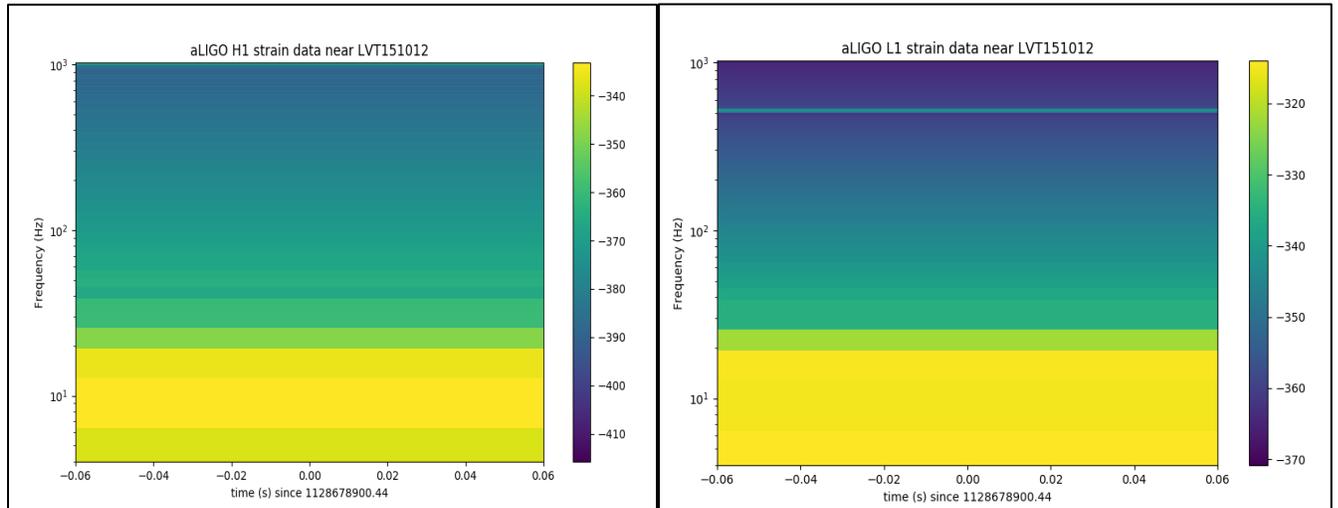


Figure 10: Spectrograms after applying the logarithmic scale and changing the NFFT.

Although, the main problem with these spectrograms is that the chirp still can't be seen, even though the axes are similar to the one in the seen in the research paper.

## **CONCLUSION**

After this investigation, I've concluded that there isn't sufficient information from the research paper or LIGO's LOSC data that would lead me to producing a spectrogram that would show the chirp of this event. I've learned that replicating data from other scientists and researchers could be a grueling task at times, and you won't always leave with results you expected. But this doesn't equal failure, this only means that there is a bigger investigation waiting to be explored. The LVT151012 event is still a mystery, and I hopefully in the near future will be able to analyze the data more, and maybe find a chirp, or even

discover something else extraordinary. I still want to investigate the many factors I mentioned earlier, like the impact of distance and luminosity. I hope to one day see the answer to this investigation.

## **ACKNOWLEDGEMENTS**

I would first like to thank Professor Eric Myers for guiding me through my whole project. If it wasn't for his help and expertise, I wouldn't have been able to expand my knowledge of gravitational waves and create a project surrounding it. I would also like to thank Professor Myers for helping me learn some Python programming and for sparking my interest in it.

I would like to thank LIGO and their LOSC website for letting students like me have access to this data. It's really cool to see what different routes you could take using the data they have provided. My project would literally be impossible without them.

Lastly, I would like to thank Pioneer Academics for giving me this opportunity to do this research. If someone told me a few months ago that I would have this opportunity, I would've laughed and told them that it was impossible. I've learned that I love doing research, because there's always something new that you'll find and something that will surprise you. I know that I'll continue doing research throughout college and hopefully graduate school when I get there. Thank you so much for this opportunity, it will be remembered for a lifetime.

## APPENDIX

The following is the code I had been manipulating in order to analyze the spectrograms. The original code for this is on the LOSC website, under the LVT151012 tutorial. It is section 11, which is the specific section for making the spectrogram.

```
# ## Spectrograms
#
# Now let's plot a short time-frequency spectrogram around our event:

# In[11]:

if make_plots:
    # index into the strain time series for this time interval:
    indxt = np.where((time >= tevent-deltat) & (time < tevent+deltat))

    # pick a shorter FFT time interval, like 1/8 of a second:
    NFFT = 640 #int(fs/20)
    # and with a lot of overlap, to resolve short-time features:
    NOVL = int(NFFT*15./16)
    # and choose a window that minimizes "spectral leakage"
    # (https://en.wikipedia.org/wiki/Spectral_leakage)
    window = np.blackman(NFFT)

    # the right colormap is all-important! See:
    # http://matplotlib.org/examples/color/colormaps_reference.html
    # viridis seems to be the best for our purposes, but it's new;
    # if you don't have it, you can settle for ocean.
    spec_cmap='viridis'
    #spec_cmap='ocean'

    # Plot the H1 spectrogram:
    plt.figure(figsize=(10,6))
    plot11 = plt.subplot(111)
    spec_H1, freqs, bins, im = plt.specgram(strain_H1[indxt], NFFT=NFFT, Fs=fs, window=window,
                                           noverlap=NOVL, mode='magnitude', cmap=spec_cmap,
                                           xextent=[-deltat,deltat])

    plt.xlabel('time (s) since '+str(tevent))
    plt.ylabel('Frequency (Hz)')
    plt.colorbar()
    #plt.axis([-0.120, 0.060, 4, 512])
    plot11.axes.set_yscale('log')
    plot11.axes.set_ylim(4,1024)
    plt.title('aLIGO H1 strain data near '+eventname)
    plt.savefig(eventname+'_H1_spectrogram.'+plottype)

    # Plot the L1 spectrogram:
    plt.figure(figsize=(10,6))
    plot12 = plt.subplot(111)
    spec_H1, freqs, bins, im = plt.specgram(strain_L1[indxt], NFFT=NFFT, Fs=fs, window=window,
                                           noverlap=NOVL, mode='magnitude', cmap=spec_cmap,
                                           xextent=[-deltat,deltat])

    plt.xlabel('time (s) since '+str(tevent))
    plt.ylabel('Frequency (Hz)')
    plt.colorbar()
    #plt.axis([-0.120, 0.060, 4, 512])
    plot12.axes.set_yscale('log')
    plot12.axes.set_ylim(4,1024)
    plt.title('aLIGO L1 strain data near '+eventname)
    plt.savefig(eventname+'_L1_spectrogram.'+plottype)
```

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