Determining Frequency Anomalies in Gravitational Waves with LIGO Data

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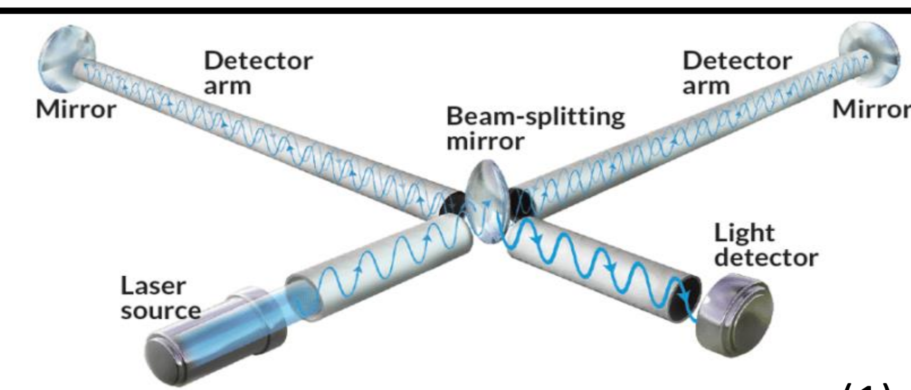
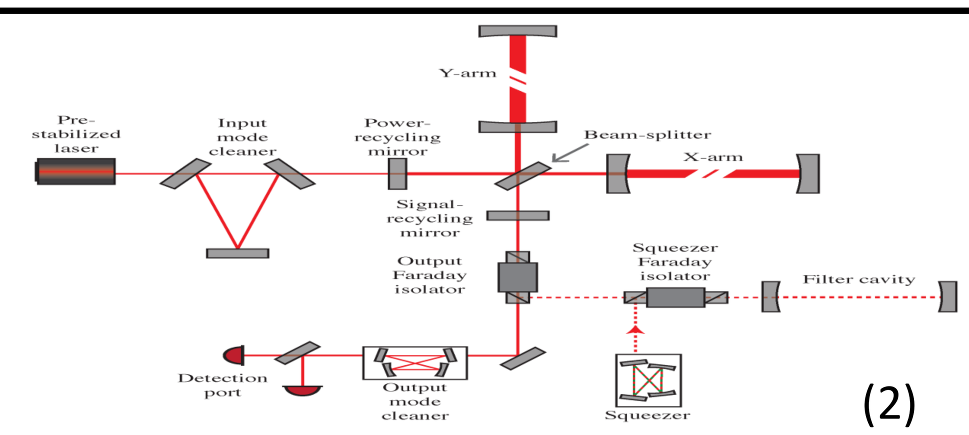
LIGO Introduction & Project Objective

- LIGO (Laser Interferometer Gravitational-Wave Observatory) is an observatory that detects gravitational waves. Using laser interferometry, a laser is split into two beams that travel down 4 km long arms and then bounce back to form an interference pattern. The data collected is called strain, which is analyzed to determine properties of astrophysical events such as binary black hole mergers.
- The first direct observation of such gravitational waves was made on September 14, 2015, by LIGO. Our objective of this project was to analyze raw data from LIGO and filter it through Python to detect a visual of the 2015 black hole merger.



(1)

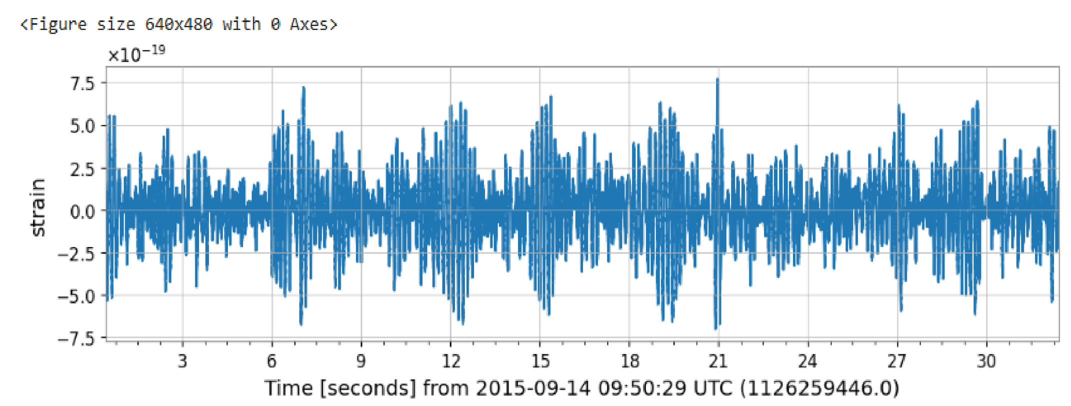


(2)

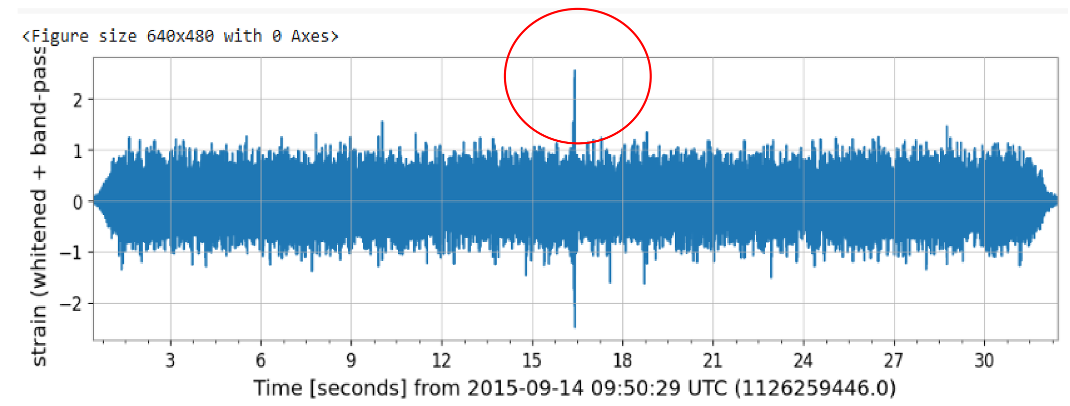
Time-series Filtering

- A Fourier transform breaks down a time-based signal into its component frequencies, showing how much of each frequency is present. LIGO uses Fourier transforms to convert raw strain data into the frequency domain, where gravitational wave signals are easier to detect.
- The strain is filtered using two techniques, whitening and bandpass filtering. Whitening evens out the background noise, making real signals stand out more clearly across all frequencies. Bandpass filters remove irrelevant low and high frequencies by reducing their magnitude, isolating the mid-range where gravitational waves are typically found.
- This is done on Python using the packages matplotlib (graphing) and gwpy (strain processing techniques).

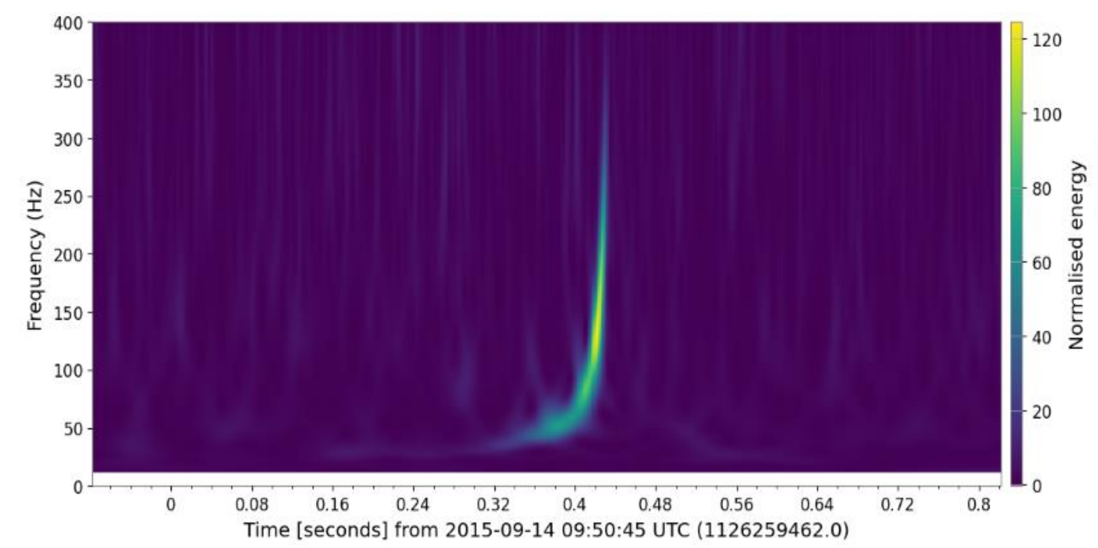
Strain (unfiltered)



Strain (whitened + bandpass)



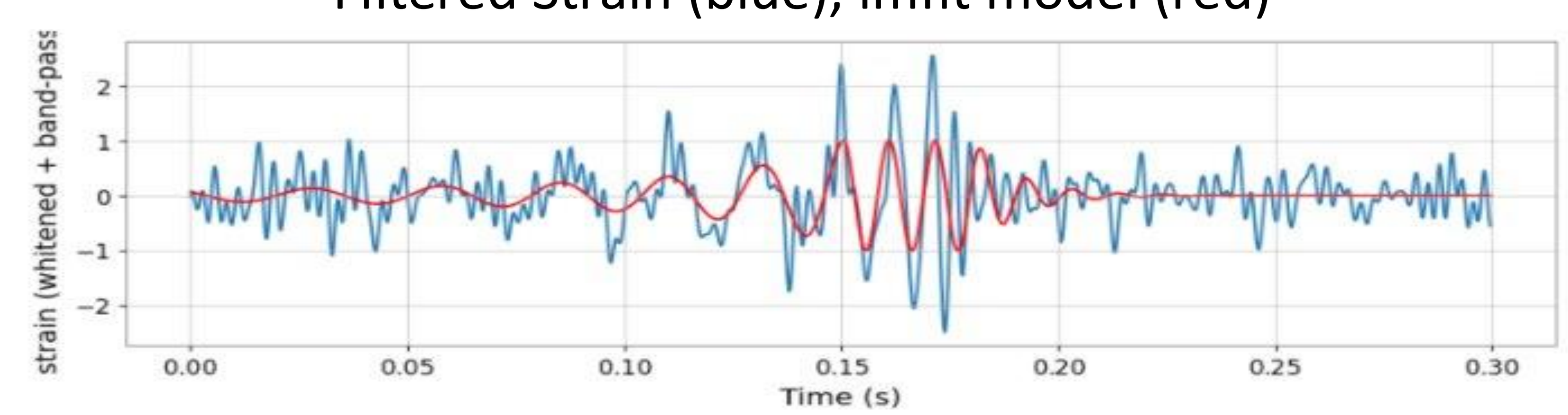
Visualized Data (Q-Transform)



Matched Filtering

- To determine whether filtered data matches an astrophysical event, the filtered data is matched onto a model of such events. This model is derived through physics equations such as Newton's gravitational laws.
- A chi-squared test is used to analyze how well the filtered data matches. To search for events, chi-squared tests are used on small time periods of filtered data across an entire long stretch of time. The strain data can be used to find mergers across large swaths of time.
- To perform matched filtering on Python, the package lmfit is used.

Filtered Strain (blue), lmfit model (red)



Quantum Application: Squeezed Light

- Because LIGO operates on such a small magnitude, quantum fluctuations of light limit its sensitivity.
- To reduce the effects of these fluctuations, LIGO uses a concept known as squeezed light, whose properties stem from the Heisenberg Uncertainty principle.
- Quantum uncertainty is redistributed to reduce noise in the measurement of phase at the expense of amplitude, to make more accurate measurements of strain.

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Image Sources: ScienceNews (1), MDPI (2)