Searching for Gravitational Waves in Noisy Data

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Introduction

Gravitational waves (GWs) are oscillations in the fabric of spacetime. Generated by motion of bulk masses - for example a system of two black holes orbiting each other and merging into a resultant black hole. First predicted by Einsten's theory of general relativity! They are very useful in multi-messenger astronomy as they can tell us very useful information about the properties of systems that electromagnetic radiation can't see.

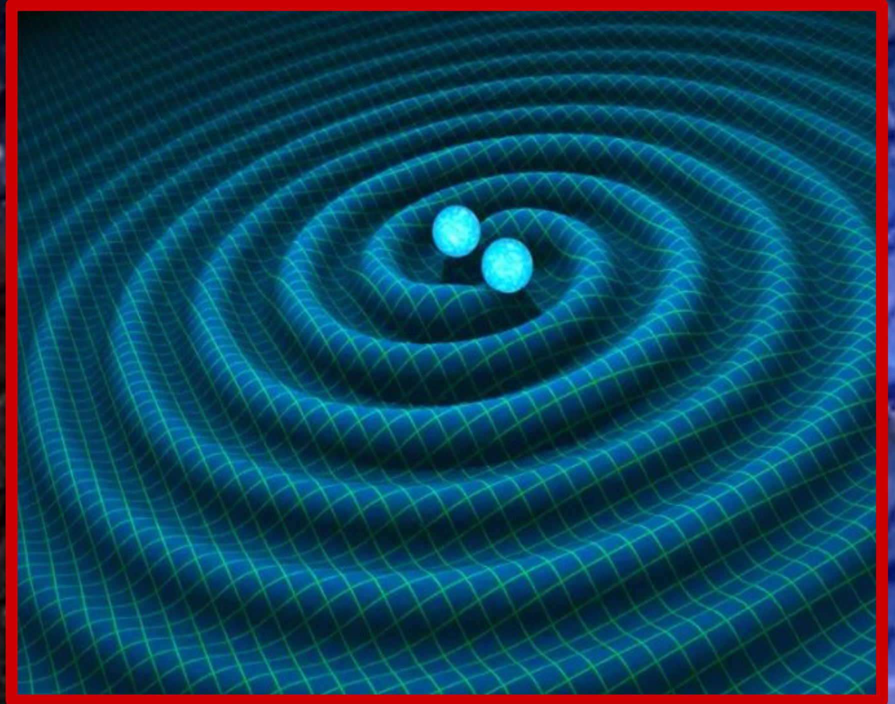

Fig 1: Artist's impression of binary black hole system emitting gravitational waves

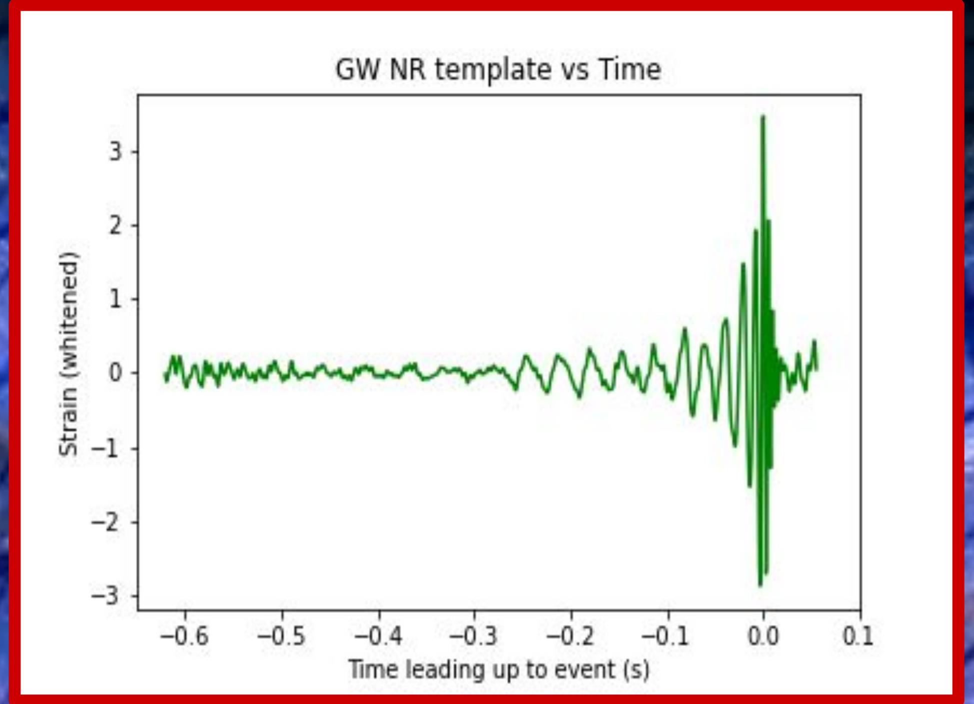

Fig 2: Supercomputer-generated waveform of a GW signal from two merging black holes

Detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO). These are two observatories a distance of 3000km apart that consist of interferometers. They use laser light to measure changes in the stretching of spacetime. Detecting GWs is very difficult; their amplitude is of order 10^{-21} and they are buried in noise! Noise sources include seismic activity, and radiation pressure caused by the lasers reflecting off mirrors.

The Project

The task was to use data from GW150914; the first direct observation of GWs; and show the principles of detecting a signal buried in noise. This allowed estimation of the false alarm rate of the GW signal. The false alarm rate is defined the time it would take for a noise fluctuation of the same size as a genuine GW event to occur. To do so, two statistical methods were used: spectrogram analysis and matched filtering.

Method 1

Spectrogram method; plotting the data of the signal in the form of power as a function of frequency and time. Analysing the noise distribution, to calculate probability of a noise spike with the same power as the GW event.

Method 2

Matched filtering; matching a theoretical GW waveform to the data; a real signal creates a spike in the noise; a better fit to the data creates a larger spike. Analysing the noise distribution allows calculating the probability of the signal-to-noise ratio

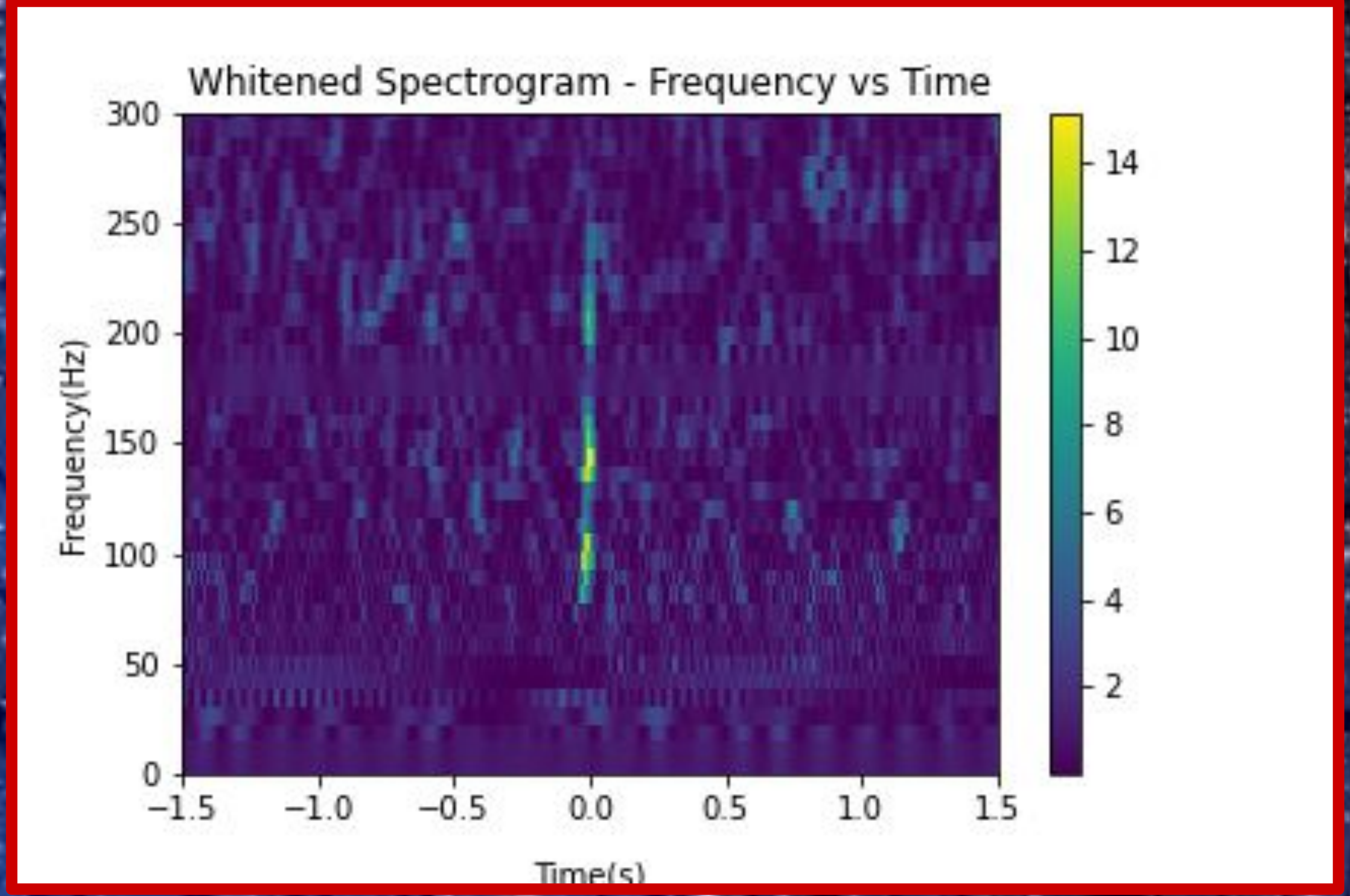

Fig 3: Plot of the spectrogram method. The GW signal can be seen in the middle (the yellow pixels) indicating the power value.

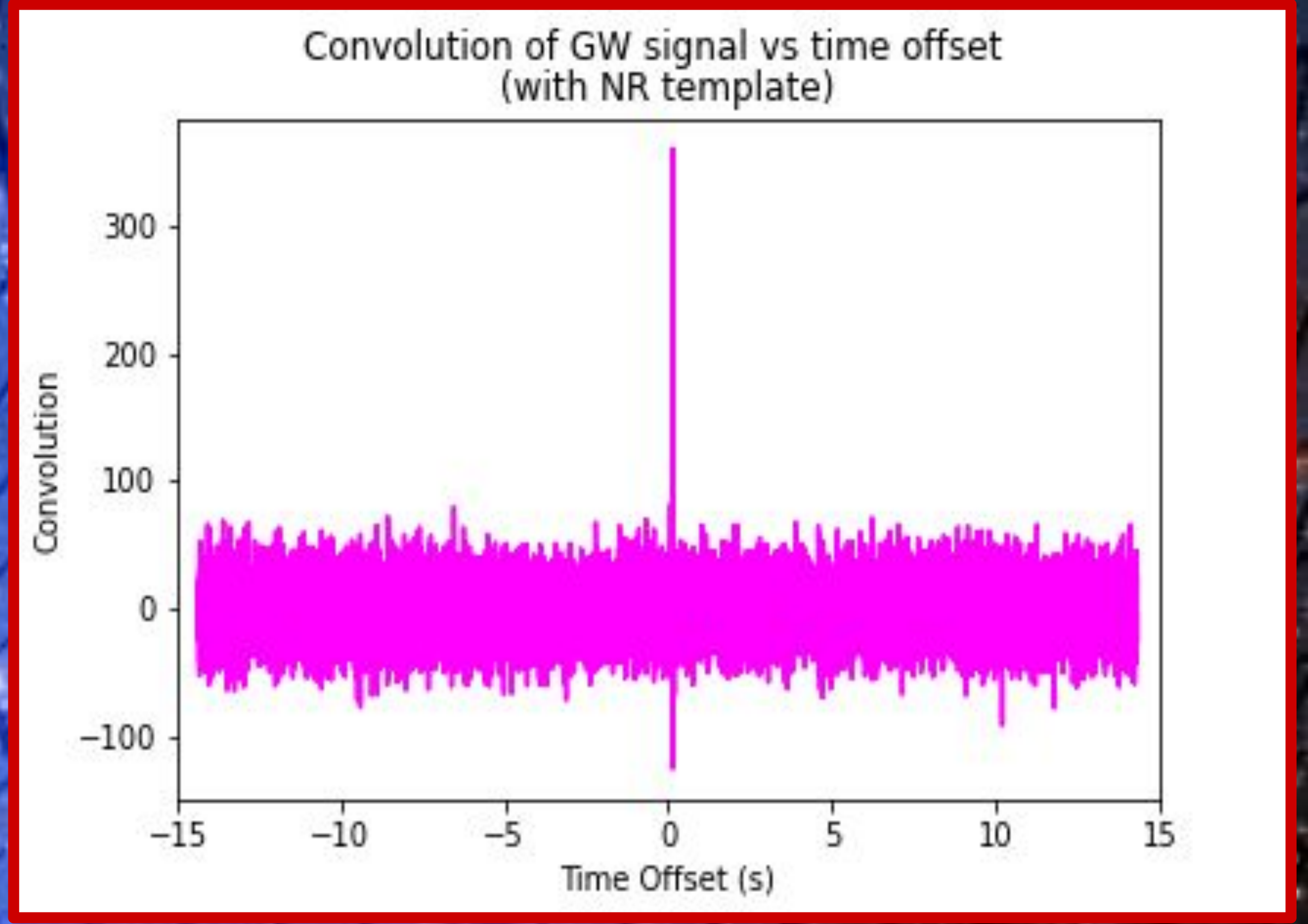

Fig 4: Plot from the matched filtering technique. The spike in the middle indicates the template matching a signal in the data - a real event!

Results

Based on the noise distributions of the two plots (Figures 3 and 4), the corresponding power (3) and signal-to-noise (4) distributions were found; exponential for the spectrogram and Gaussian for the matched filter. The spectrogram gave a false alarm rate of 1 in 13 days. The matched filter gave a false alarm rate of 1 in 10^{62} years.

Conclusion

The matched filtering method produced a more effective false alarm rate - it is the optimal way to detect signals in noisy data. Future research could focus on utilising neural networks to test multiple templates to a set of data to determine the best fit - and hence parameters of the system.

References: Fig 1 - Choi, C. Q. With New Gravitational-Wave Detectors, More Cosmic Mysteries Will Be Solved (Date Accessed 25/03/2022). https : / / www .space . com / gravitational - waves - future -discoveries.html.

Background Image - Tidal forces carry the mathematical signature of gravitational waves (Date Accessed 31/03/2022). https://www.technologyreview.com/2019/12/14/131574/tidal-forces-carry-the-mathematical-signature-of-gravitational-waves/