Simulating Continuous Gravitational Waves

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INTRODUCTION

- Gravitational Waves (GWs) are ripples in spacetime produced by accelerated massive objects in the universe. Albert Einstein predicted GWs in his theory of General Relativity in 1916 [1].
- GWs were detected in 2015 by the Laser Interferometer Gravitational-Wave Observatory (LIGO), shown as a computational simulation in Fig.1, when two massive black holes merged into one.

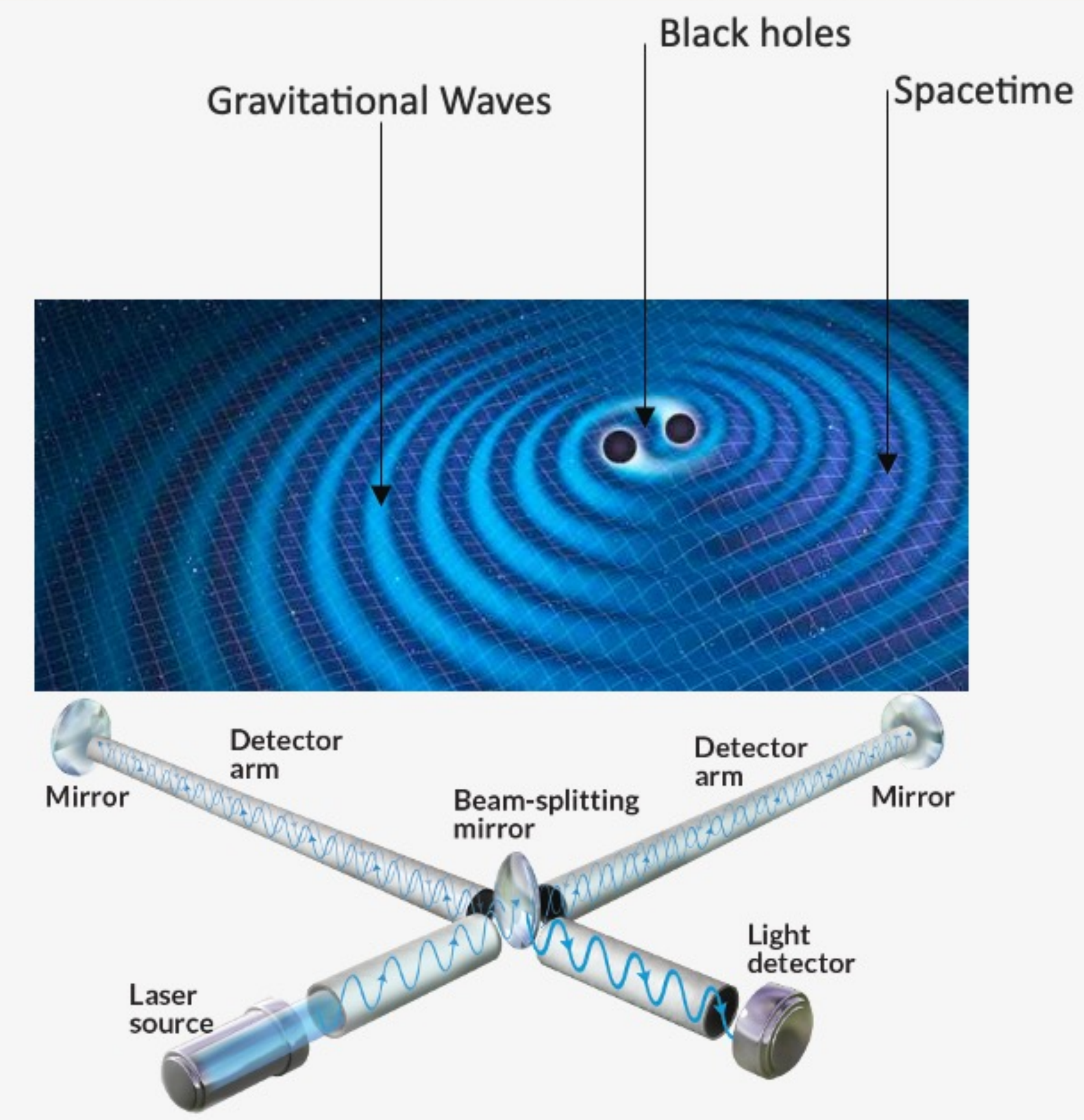

Fig.1: Top: artist rendition of a binary system, where two black holes are orbiting each other [2]. Bottom: sketch of how LIGO would detect GWs interference.

- Currently, scientists are trying to detect *Continuous* GWs (CWs). Although simulations of CWs have been done, so far there has not been experimental detections. The challenges to measure CWs are not only technological, but also due to three major reasons:
  1) Mass accretion from the companion star in a binary system shown in Fig.2.
  2) Energy loss by the star as it spins on its axis shown in Fig.3
  3) Rotation of the earth with respect to the star.

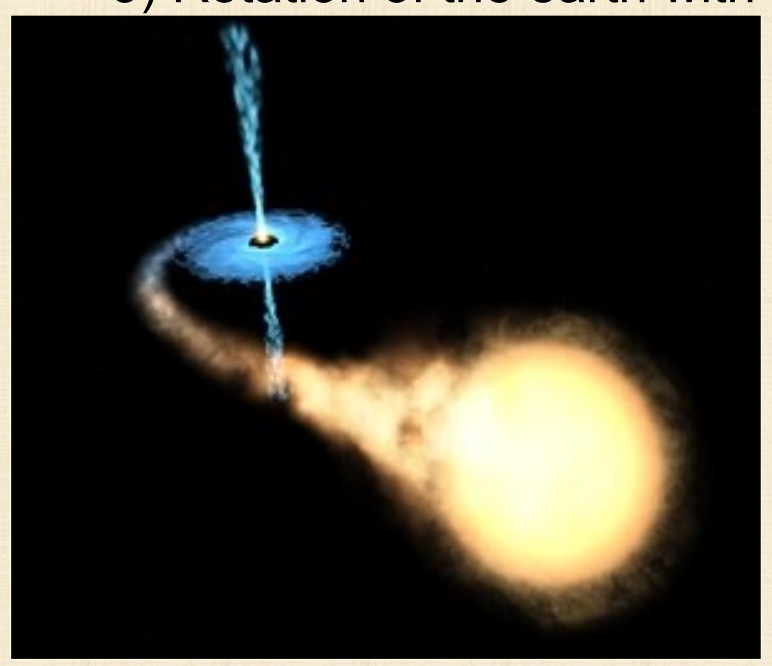

Fig.2: Artist rendition of a neutron star accreting matter from a companion star in a binary system.

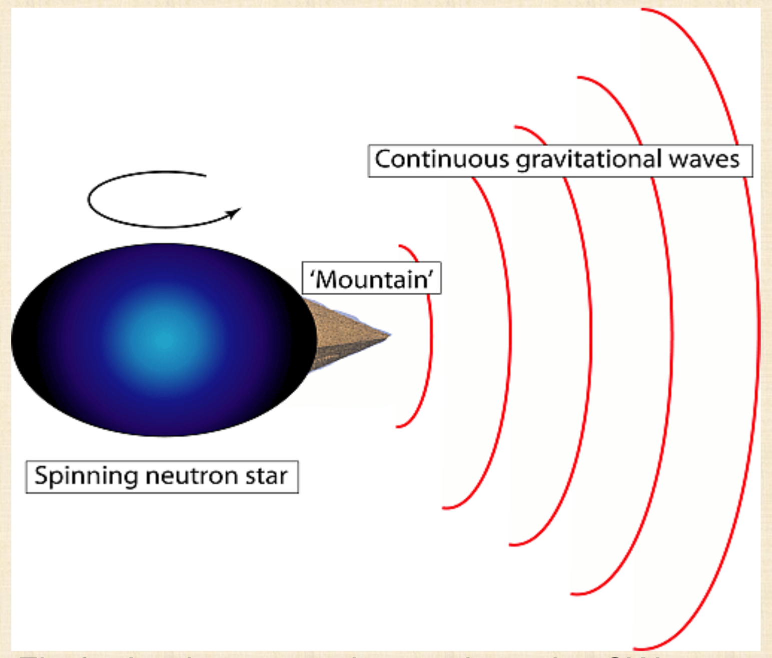

Fig.3: As the star spins on its axis, CWs are generated due to the presence of a "mountain."

OUR SIMULATION STUDIES

- In our study, we use sound to simulate gravitational disturbance, and we replicate LIGO arrangement by using the Michelson Interferometer (MI). Our study closely follows Ref. [3] unless stated differently.
- Fig.4 shows a schematic of the apparatus we use in our lab. Notice that we placed a speaker on the back of M2, where we inject a sinusoidal audio signal, as shown in Fig.7, emulating the disturbance of CWs.
- Small changes in the distance of one of the arms of the MI produces a shift in the interference pattern known as fringes. The motion of M2 due to audio signals from the speaker allows the motion of the fringes.

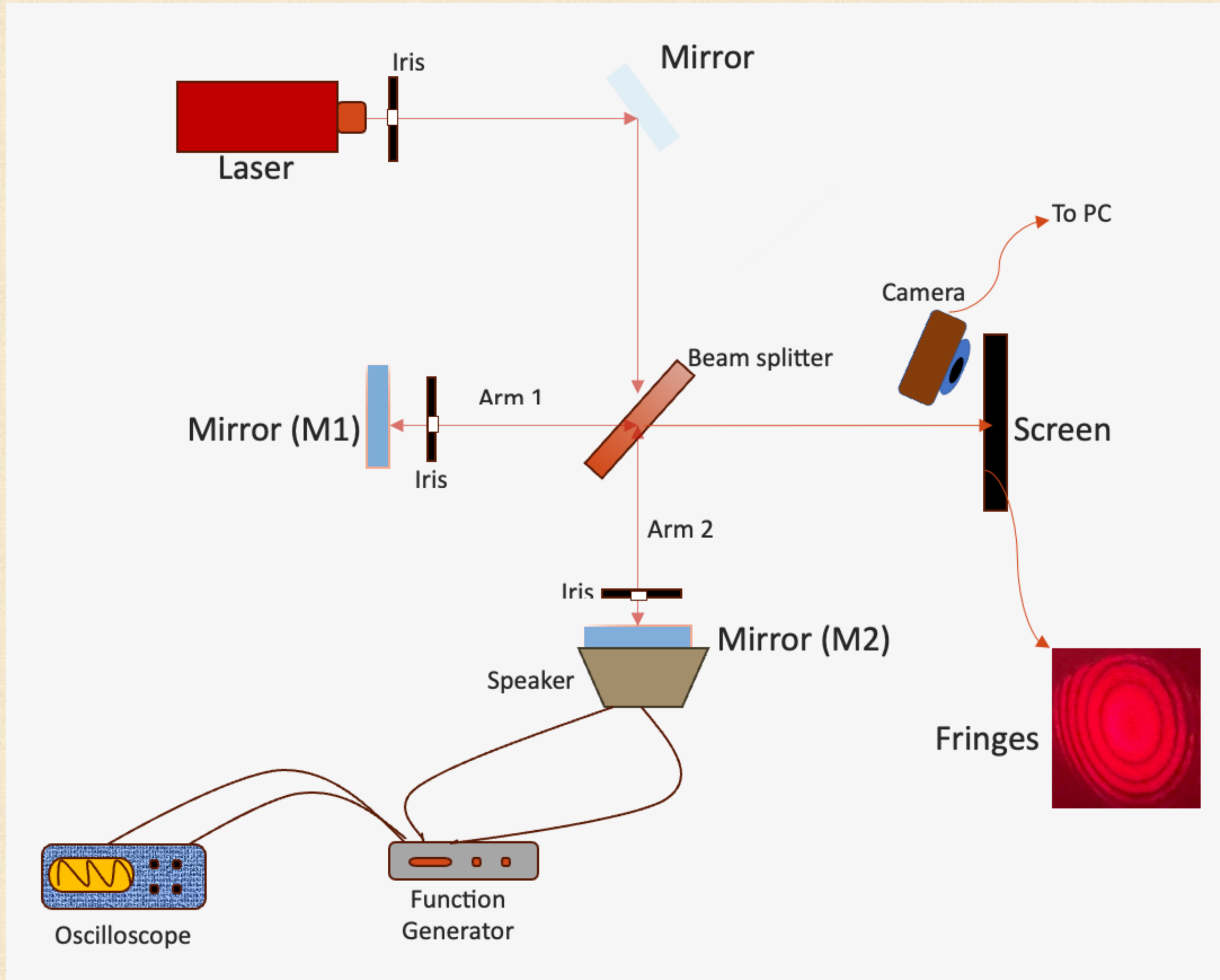

Fig.4: Michelson Interferometer apparatus setup in our studies.

- We played a sinusoidal tone with a frequency of 5.6 Hz through the speaker for more than one minute. We then recovered the injected signal using the program Python, which allows us to perform the mathematics of the Fourier Transform (FT) as a method of detecting the injected signal. The spike shown in Fig. 5 would then represent a CW at 5.6 Hz.

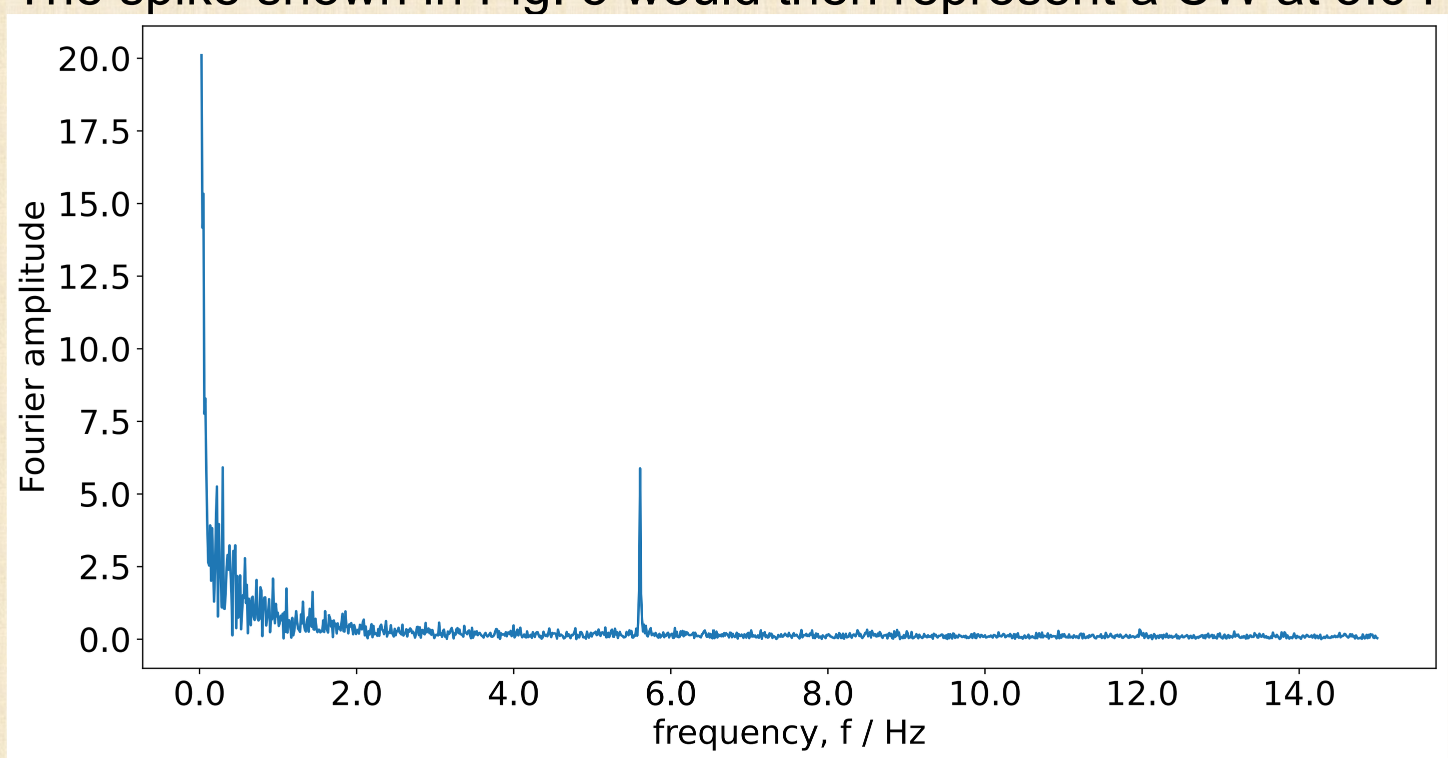

Fig.5: Spectrum of recovered signal in this study. A maximum amplitude is observed at 5.6Hz. The appearance of noise near zero is currently under investigation.

CONTINUOUS GRAVITATIONAL WAVES

- Over the period of observation of CWs ~ months to years~ the frequency of the signal can drift unexpectedly, and randomly (i.e., wandering). The Hidden Markov Model (HMM) along with the Viterbi algorithm are used to track the wandering signal.
- Fig.6 & Fig.7 show representations of wandering CWs and CWs, respectively.

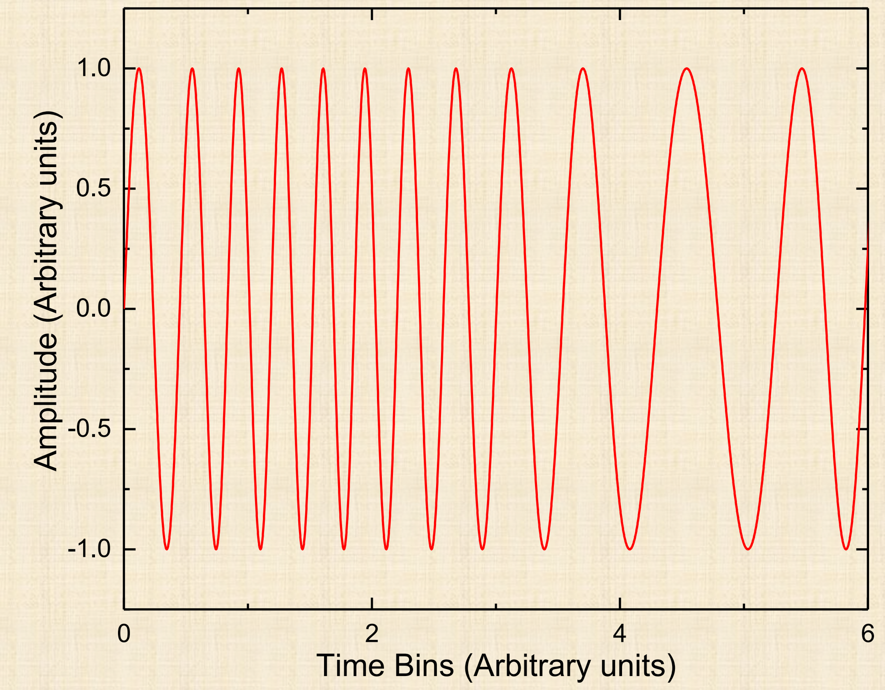

Fig.6: Simulation of wandering Continuous Gravitational Waves signal.

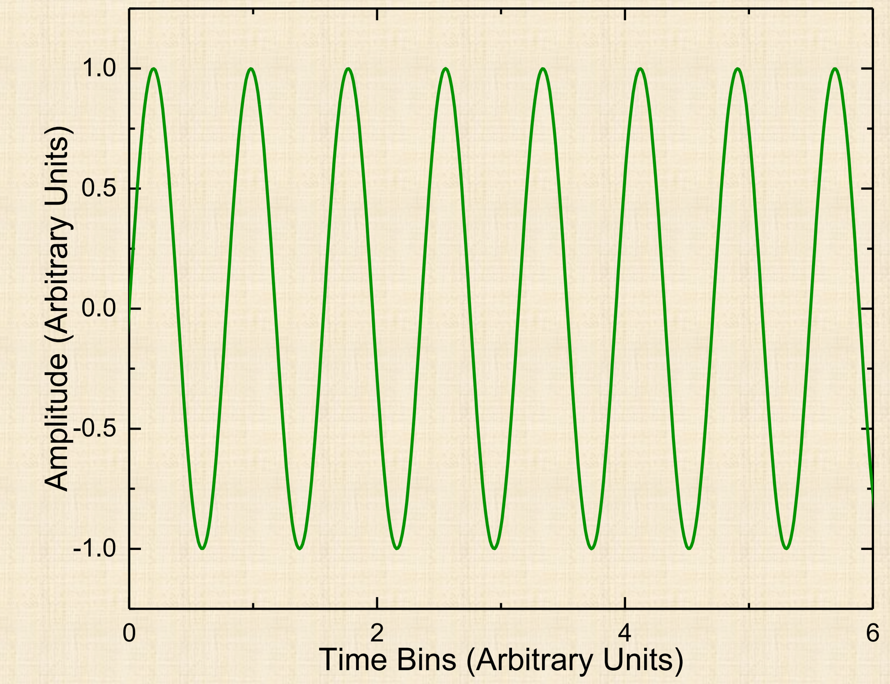

Fig.7: Simulation of Continuous Gravitational Waves signal. Fig. 5 represents an example of this type of retrieved GWs.

FUTURE STUDIES

- In an HMM, the state (i.e., frequency) is unknown and can undergo transitions at discrete times. The Viterbi algorithm is a computational tool that can search for signals that have an unknown frequency evolution, as shown in Fig.8. For our future studies, we will implement these two methods together to ultimately track a Wandering Continuous Gravitational Wave.

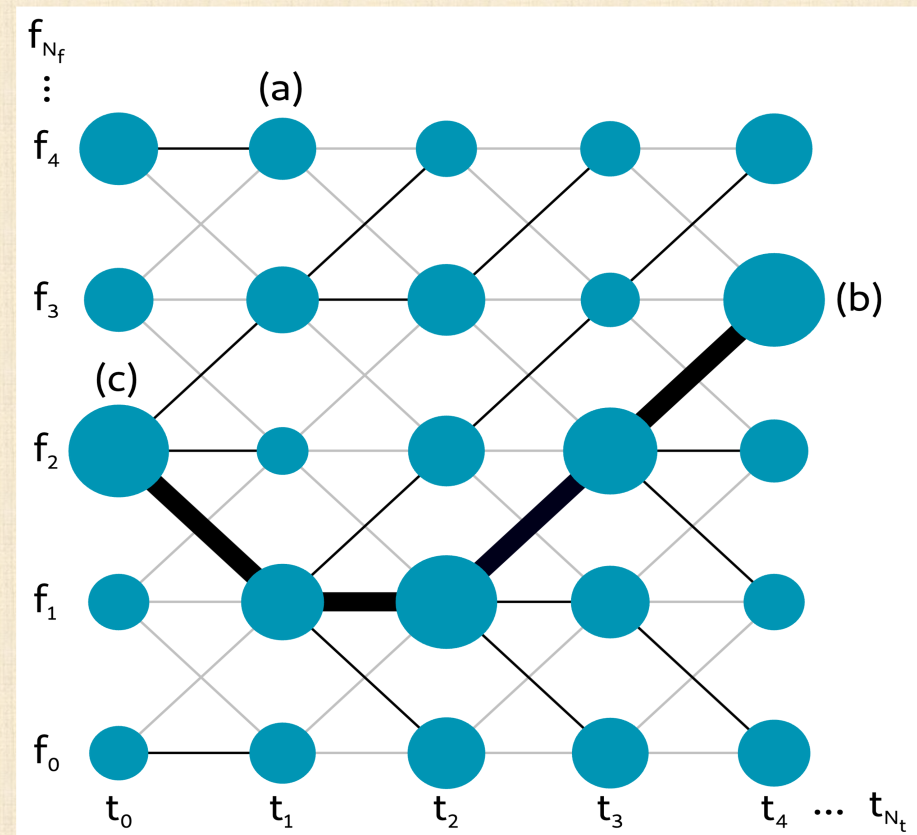

Fig.8: This diagram represents the Viterbi Algorithm. Along the x-axis we have the time bins, and along the y-axis we have the frequency bins. The sizes of the nodes represents the likelihood of the signal being present in each time-frequency bin. The smaller the size of the node the less likely the signal, and vice versa. The black line follows the most optimal path through each node and what will ultimately give us the desired signal.

REFERENCES

[1] Albert Einstein "Approximative Integration of the Field Equations of Gravitation", Sitzungsber. Preuss. Akad. Wiss. Berlin, June 22, 1916.
[2] Credit: Mark Garlick/Science Photo Library via Getty Images
[3] Continuous gravitational waves in the lab: recovering audio signals with a table-top optical microphone (James W. Gardner, *et al.*; Am. J. Phys., Vol. 90, No. 4, April 2022).

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