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Article

Using gravitational waves to determine if primordial black holes are sources of dark matter

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SUMMARY
Scientists do not have much information about or evidence of dark matter. Dark matter does not emit electromagnetic radiation and does not interact with normal matter, but some researchers have found evidence of its existence throughout the universe. Scientists have narrowed down to two possible sources of dark matter: Massive Compact Halo Objects (MACHOs) and Weakly Interacting Massive Particles (WIMPs). In our research, we analyzed MACHOs, which are primordial black holes, using gravitational wave data from the LIGO/Virgo collaboration. We hypothesized that MACHOs may be dark matter due to the higher black hole mass formed from binary mergers between primordial black holes, compared to the black hole mass between binary mergers from simulated stellar black holes. Using the data derived from primordial black hole pairs, we used Python to perform Bayesian inference parameter estimation to generate another set of simulated datasets (which are stellar black hole pairs) to compare the final masses of the black hole mergers in the simulated and original gravitational wave datasets. Our results showed that primordial black holes (MACHOs) may not be dark matter, but in the future, based on the research on dark matter, astrophysicists' can further improve understanding of primordial black holes and their effect in the universe.

INTRODUCTION
The universe as known so far makes up only less than five percent of the universe. The rest is hypothesized to be dark matter and dark energy, and the nature of these phenomena are actively studied (1). Dark matter is a phenomenon that was predicted by Vera Rubin and Fritz Zwicky in the 1930s (2). Due to the lack of technology at the time, not much research was done on dark matter, but over time, dark matter has become a highly researched topic. There is indirect evidence of dark matter obtained through galaxy imaging as invisible matter that does not emit any electromagnetic radiation or interact with baryonic matter, (protons and neutrons) (2). One of the most famous images from galaxy observatories is the galaxy cluster 1E0657-56, the Bullet Cluster. This image shows the collision of two different galaxies and through gravitational lensing, scientists were able to determine that there were baryonic matter and dark matter, because of the way the two types of matter dispersed as the galactic collision happened (2). The baryonic matter dispersed and was slowed down by a drag force analogous to air resistance. On the other hand, the dark matter was not slowed down because dark matter does not interact with baryonic matter directly (2). From this analysis, scientists determine that dark matter could possibly be Weakly Interacting Massive Particles (WIMPs) (3).

On the other hand, scientists hypothesize that dark matter could come from black holes formed from the Big Bang. When the universe originated, the dispersion of matter was uneven, resulting in areas with more accumulated matter. Because of the high density of matter in particular areas, the matter collapsed into itself and formed primordial black holes (3). Primordial black holes are also hypothesized to be dark matter because the matter that collapsed into itself to create them was non-baryonic matter, which predated baryonic matter (4). This difference in matter led to another hypothesis that dark matter is Massive Compact Halo Objects (MACHOs) which are primordial black holes (4). Currently, both WIMPs and MACHOs are hypotheses of what dark matter is. Since there is no direct evidence or observation of dark matter, this topic is under debate and there is a need to determine the identity of dark matter to understand its effects on the growth of the universe in the future.

Black holes are the remnants of dead stars that have exploded at the ends of their long lives. Black holes can form from binary stars, which orbit around each other. Usually, one black hole is smaller than the other, which ends up orbiting and eventually merges into the larger black hole due to the immense gravitational pull of the latter. Binary black holes can form in two ways: where the stars go through their lifetime together and form into binary black holes, or black holes can form separately and over time become closer together. The binary black hole system creates powerful gravitational waves as it orbits (5). These waves are produced throughout the time it takes for the smaller black hole to completely orbit until it merges with the larger black hole. As this happens, the gravitational waves travel outwards from where they were created like ripples in a pond. When the waves are first produced, they are very powerful, but their power reduces as they pass through objects like stars and gas (6). Additionally, as gravitational waves travel through space, they can stretch and compress space itself, including any objects in their path, such as Earth.

Scientists have concluded that gravitational waves hold much information on black hole mergers. Hence, scientists measure gravitational waves to study black hole mergers. To record gravitational waves, researchers use laser interferometers, which are 4km tubes assembled in an L shape that have lasers shot through each tube (7). At the end of each tube are mirrors that reflect the lasers back to the detectors at their starting points. When there is no gravitational wave, the waves of the laser would cancel each other due to stagnant waves traveling at the same time in space, which

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causes a destructive interference (8). However, if there is a gravitational wave, the stretching and compressing of Earth causes the photons in the lasers to also move back and forth slightly, creating a constructive interference, that produces data on the gravitational wave (9). Currently there are three laser interferometer observatories on Earth (LIGO in the US, Virgo in Italy, and Kagra in Japan) and they have been collectively recording gravitational wave data since 2015 (10). Using this data, it is possible to study many aspects of black hole mergers such as the masses of both black holes, the mass of the final black hole that is created after they merge, and the distance away from Earth of where it occurred. This is all determined through parameter estimation using Bayesian inferencing which uses probabilities to determine the likely value or a variable, which in this case are the masses of the black holes, the distance away from Earth (10).

With the debate on whether dark matter is MACHOs or WIMPs, we chose to use gravitational waves to determine if primordial black holes could be sources of dark matter. Primordial black holes are hypothesized to have any size from less than a tenth of the mass of the sun to a supermassive black hole (11). On the other hand, stellar black holes (which form from the collapse of stars), must be at least three solar masses because a star must have enough mass, to collapse and form into a black hole (11). We hypothesized that, if primordial black holes were dark matter, we would be able to test this using gravitational waves. For our analysis of gravitational waves, we used gravitational wave data from black hole mergers that had less than three solar masses. The rationale is that dark matter adds extra mass to objects, and if primordial black holes are sources of dark matter, the final mass of a primordial black hole merging with a stellar black hole would result in more mass than a binary merger of two stellar black holes. We found that there was no extra added mass to the final primordial black hole merger, which suggests that primordial black holes may not be sources of dark matter. (12).

RESULTS

To test if primordial black holes are dark matter, we used datasets from the Gravitational Wave Open Science Center (GWOSC) database, which contains datasets of gravitational waves since 2015. To determine which datasets to use, we reasoned that primordial black holes (PBH) can be any size, whereas stellar black holes (SBH) can only be three solar masses or higher (13). Thus, we chose to use datasets with black holes (BH) that are less than three solar masses. This led us to narrow down to six datasets to use in our experimentation and analysis. Each dataset used was a merger system of a stellar and primordial black hole. We studied BHs using parameter estimation with gravitational waves. This method uses Bayes' Theorem, which uses prior variables (known values) to determine posterior variables (unknown values that are being determined) (14). In our study, the prior (known) variables are the masses of both BHs in the merger in the real-time and simulated datasets. The posterior (unknown) variables are the final mass of the black hole produced for both real-time and simulated datasets. Of these properties, we used the masses of each BH (called mass1 and mass2), the final mass (the resulting mass of the black hole created after merging), and the distance away from Earth. To simulate the gravitational waves and estimate the final masses, we used the masses of both black holes and variables called amp (amplitude of the waves of the laser in the interferometer) and tau (duration of time of when the gravitational wave starts and ends), which are necessary values for the simulation. We used the Poisson-Burst Model from the PyCBC Python library and using the masses of both black holes in each dataset, the amp and tau variables, and the distance away from Earth (prior values),

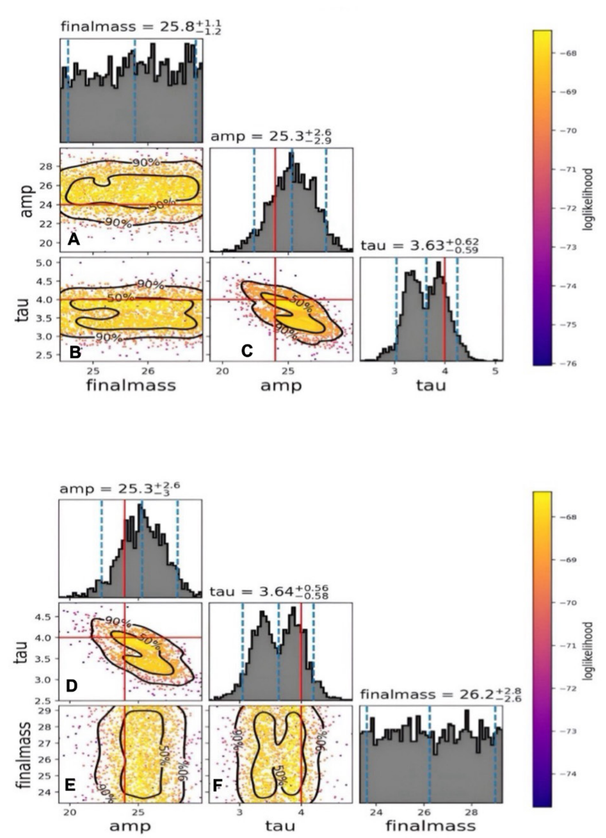

Figure 1: Probability of Amp, Tau, and Finalmass from simulated and real data for GW190814. The gravitational wave simulation was performed with amp = 24.0 and tau = 4.0. Contour plots were created to show the probability of estimated parameters, where the probability and distribution of the points indicate the likelihood of the estimated value of the ints, with the estimated value of each parameter highlighted. (A) and (E) show the relationship between Amp and Finalmass. (B) and (F) show the relationship between Tau and Finalmass. (C) and (D) show the relationship between Amp and Tau. Graphs (A-C) show results from the real-time datasets. Graphs (D), (E), and (F) show results from the simulated datasets. The histogram for Finalmass shows the estimated value of the final mass of the black hole formed from each dataset. For GW190814, the simulated dataset began with merging black hole masses of 23.3 and 2.6 solar masses and created a final mass of 25.8 solar masses. The real-time dataset began with merging black hole masses 23.3 and 3 solar masses and created a final mass of 26.2 solar masses. The likelihood scale was measured by log likelihood of the simulated points created by the real-time and simulated dataset. The simulation was created using the Poisson Burst Gravitational Wave model in PyCBC Python Library. Bottom and Left-horizontal axis represent the inputs of the merging black holes in both simulated and real-time datasets.

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we estimated the final masses of the black holes for each of the six datasets we were using. Since scientists hypothesize that dark matter adds extra mass to existing objects in space, especially in galaxies observed through galaxy imaging of their distribution in mass (more mass in the center, less mass outwards of a galaxy), we used this information to help us set up our experimental design (10). To determine if primordial black holes could be the source of dark matter, we compared the final masses of the black holes created after the merger events with PBH and SBH Holes (**Figures 1-6**). This setup compared a real-time (SBH-PBH merger) and simulated (Stellar-Stellar merger) and determines if the final mass of the real-time dataset has more mass than the simulated dataset because the simulations will have more mass overall than the Stellar-Primordial BH. Additionally, this is confirmed with a t-test and its results (**Figure 7**). Thus, if PBH are sources of dark matter and the real-time datasets have a higher final mass, then that may show that PBH may be sources of dark

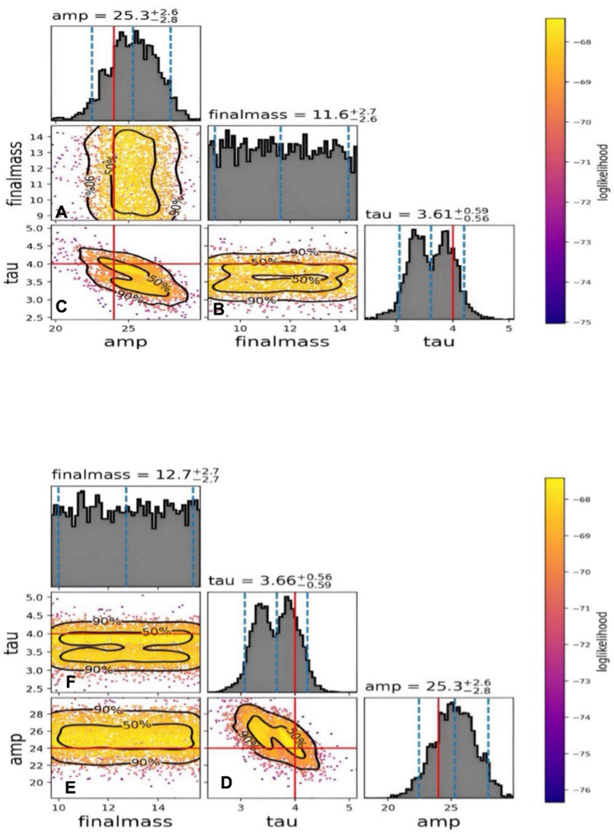

Figure 2: Probability of Amp, Tau, and Finalmass from simulated and real data for GW190917_114630. The gravitational wave simulation was performed with amp = 24.0 and tau = 4.0. Contour plots were created to show the probability of estimated parameters, where the probability and distribution of the points indicate the likelihood of the estimated value of the ints, with the estimated value of each parameter highlighted. (A) and (E) show the relationship between Amp and Finalmass. (B) and (F) show the relationship between Tau and Finalmass. (C) and (D) show the relationship between Amp and Tau. Graphs (A-C) show results from the real-time datasets. Graphs (D), (E), and (F) show results from the simulated datasets. The histogram for Finalmass shows the estimated value of the final mass of the black hole formed from each dataset. For GW190917_114630, the simulated dataset began with merging black hole masses of 9.7 and 2.1 solar masses and created a final mass of 11.6 solar masses. The real-time dataset began with merging black hole masses 9.7 and 3 solar masses and created a final mass of 12.7 solar masses. The likelihood scale was measured by log likelihood of the simulated points created by the real-time and simulated dataset. The simulation was created using the Poisson Burst Gravitational Wave model in PyCBC Python Library. Bottom and Left-horizontal axis represent the inputs of the merging black holes in both simulated and real-time datasets.

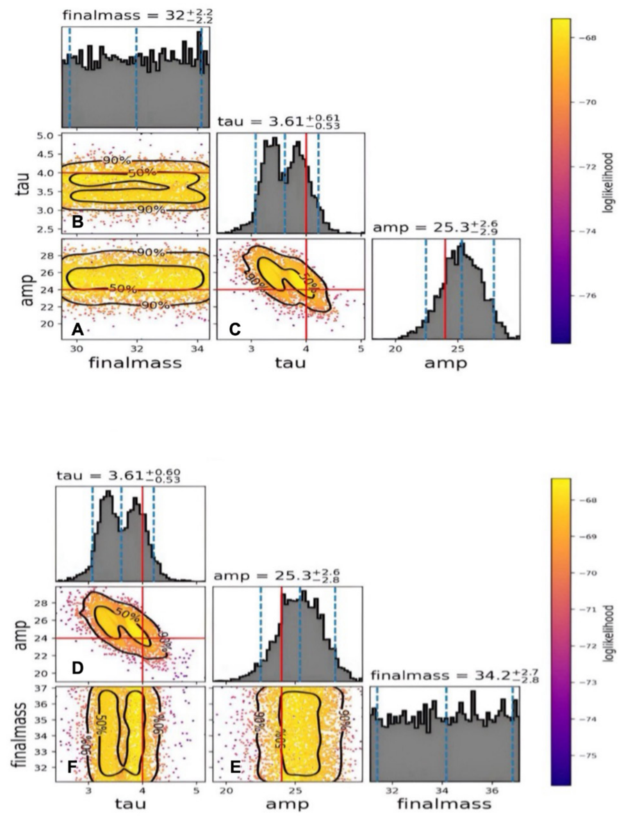

Figure 3: Probability of Amp, Tau, and Finalmass from simulated and real data for GW191219_163120. The gravitational wave simulation was performed with amp = 24.0 and tau = 4.0. Contour plots were created to show the probability of estimated parameters, where the probability and distribution of the points indicate the likelihood of the estimated value of the ints, with the estimated value of each parameter highlighted. (A) and (E) show the relationship between Amp and Finalmass. (B) and (F) show the relationship between Tau and Finalmass. (C) and (D) show the relationship between Amp and Tau. Graphs (A-C) show results from the real-time datasets. Graphs (D), (E), and (F) show results from the simulated datasets. The histogram for Finalmass shows the estimated value of the final mass of the black hole formed from each dataset. For GW191219_163120, the simulated dataset began with merging black hole masses of 31.1 and 1.7 solar masses and created a final mass of 32.0 solar masses. The real-time dataset began with merging black hole masses 31.1 and 3 solar masses and created a final mass of 34.2 solar masses. The likelihood scale was measured by log likelihood of the simulated points created by the real-time and simulated dataset. The simulation was created using the Poisson Burst Gravitational Wave model in PyCBC Python Library. Bottom and Left-horizontal axis represent the inputs of the merging black holes in both simulated and real-time datasets.

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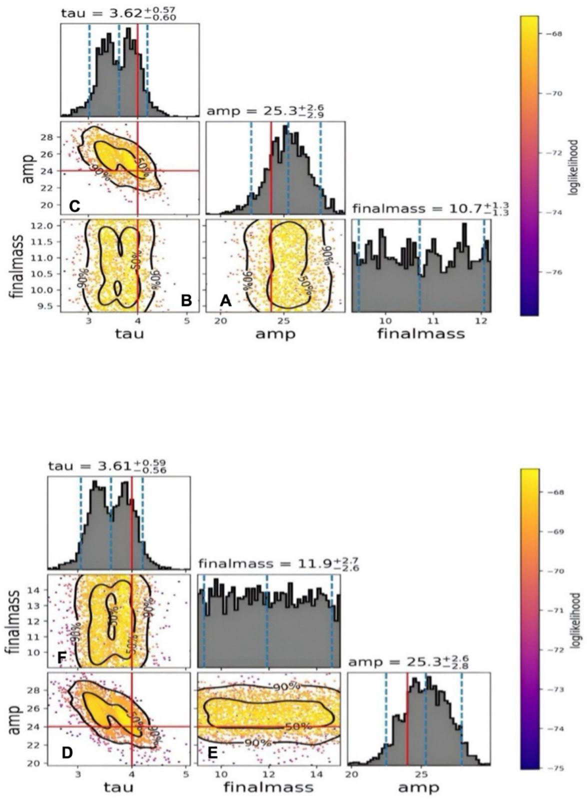

Figure 4: Probability of Amp, Tau, and Finalmass from simulated and real data for GW200105_162426. The gravitational wave simulation was performed with amp = 24.0 and tau = 4.0. Contour plots were created to show the probability of estimated parameters, where the probability and distribution of the points indicate the likelihood of the estimated value of the ints, with the estimated value of each parameter highlighted. (A) and (E) show the relationship between Amp and Finalmass. (B) and (F) show the relationship between Tau and Finalmass. (C) and (D) show the relationship between Amp and Tau. Graphs (A-C) show results from the real-time datasets. Graphs (D), (E), and (F) show results from the simulated datasets. The histogram for Finalmass shows the estimated value of the final mass of the black hole formed from each dataset. For GW200105_162426, the simulated dataset began with merging black hole masses of 9.0 and 1.91 solar masses and created a final mass of 10.7 solar masses. The real-time dataset began with merging black hole masses 9.0 and 3 solar masses and created a final mass of 11.9 solar masses. The likelihood scale was measured by log likelihood of the simulated points created by the real-time and simulated dataset. The simulation was created using the Poisson Burst Gravitational Wave model in PyCBC Python Library. Bottom and Left-horizontal axis represent the inputs of the merging black holes in both simulated and real-time datasets.

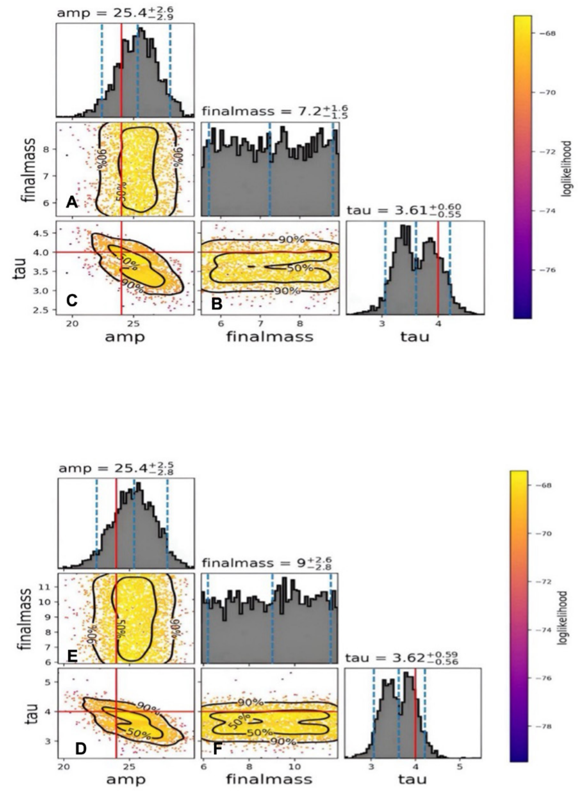

Figure 5: Probability of Amp, Tau, and Finalmass from simulated and real data for GW200105_0422309. The gravitational wave simulation was performed with amp = 24.0 and tau = 4.0. Contour plots were created to show the probability of estimated parameters, where the probability and distribution of the points indicate the likelihood of the estimated value of the ints, with the estimated value of each parameter highlighted. (A) and (E) show the relationship between Amp and Finalmass. (B) and (F) show the relationship between Tau and Finalmass. (C) and (D) show the relationship between Amp and Tau. Graphs (A-C) show results from the real-time datasets. Graphs (D), (E), and (F) show results from the simulated datasets. The histogram for Finalmass shows the estimated value of the final mass of the black hole formed from each dataset. For GW200105_0422309, the simulated dataset began with merging black hole masses of 5.9 and 1.4 solar masses and created a final mass of 7.2 solar masses. The real-time dataset began with merging black hole masses 5.9 and 3 solar masses and created a final mass of 9.0 solar masses. The likelihood scale was measured by log likelihood of the simulated points created by the real-time and simulated dataset. The simulation was created using the Poisson Burst Gravitational Wave model in PyCBC Python Library. Bottom and Left-horizontal axis represent the inputs of the merging black holes in both simulated and real-time datasets.

matter (11).

In all six comparisons between the simulated and real-time datasets, results were similar. All the black holes formed in the simulated datasets were less than the black holes formed in the real-time datasets. In all six figures, the parameters amp = 24.0 and tau = 4.0 and were used to simulate gravitational waves. Additionally, contour plots were made to display the probability of the estimated parameters. Each estimated parameter's value is highlighted, and the probability and point distribution demonstrate how likely it is that the ints will have an estimated value. The link between Amp and Finalmass is depicted in (A) and (E). The link between Tau and Finalmass is depicted in (B) and (F). The link between Amp and Tau is depicted in (C) and (D). The real-time datasets' results are displayed in Graphs (A–C). Graphs (D), (E), and (F) display the outcomes of the datasets that were simulated. The estimated final mass of the black hole created from each dataset is displayed in the Finalmass histogram.

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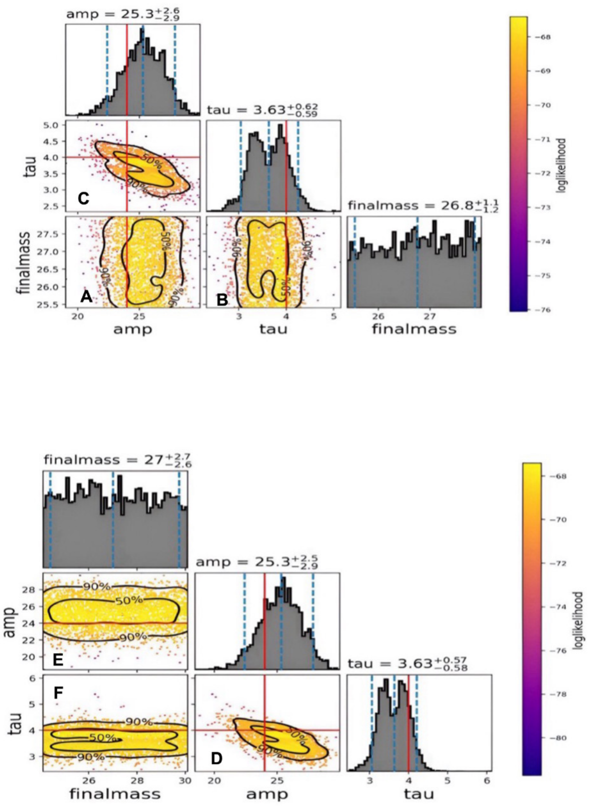

Figure 6: Probability of Amp, Tau, and Finalmass from simulated and real data for GW200210_092254. The gravitational wave simulation was performed with amp = 24.0 and tau = 4.0. Contour plots were created to show the probability of estimated parameters, where the probability and distribution of the points indicate the likelihood of the estimated value of the ints, with the estimated value of each parameter highlighted. (A) and (E) show the relationship between Amp and Finalmass. (B) and (F) show the relationship between Tau and Finalmass. (C) and (D) show the relationship between Amp and Tau. Graphs (A-C) show results from the real-time datasets. Graphs (D), (E), and (F) show results from the simulated datasets. The histogram for Finalmass shows the estimated value of the final mass of the black hole formed from each dataset. For GW200210_092254, the simulated dataset began with merging black hole masses of 24.1 and 2.83 solar masses and created a final mass of 26.8 solar masses. The real-time dataset began with merging black hole masses 24.1 and 3 solar masses and created a final mass of 27.0 solar masses. The likelihood scale was measured by log likelihood of the simulated points created by the real-time and simulated dataset. The simulation was created using the Poisson Burst Gravitational Wave model in PyCBC Python Library. Bottom and Left-horizontal axis represent the inputs of the merging black holes in both simulated and real-time datasets.

In **Figure 1** (GW190814), black hole masses of 23.3 and 2.6 solar masses were combined to give a total mass of 25.8 solar masses for GW190814, according to the simulated dataset. Black hole masses of 23.3 and 3 solar masses were combined at the start of the real-time dataset to produce a final mass of 26.2 solar masses. For **Figure 2** (GW190917_114630), the simulated dataset began with merging black hole masses of 9.7 and 2.1 solar masses and created a final mass of 11.6 solar masses. The real-time dataset began with merging black hole masses 9.7 and 3 solar masses and created a final mass of 12.7 solar masses. For **Figure 3** (GW191219_163120), the simulated dataset began with merging black hole masses of 31.1 and 1.7 solar masses and created a final mass of 32.0 solar masses. The real-time dataset began with merging black hole masses 31.1 and 3 solar masses and created a final mass of 34.2 solar masses. For **Figure 4** (GW200105_162426), the simulated dataset began with merging black hole masses of 9.0 and 1.91 solar masses and created a final mass of 10.7 solar masses. The real-time dataset began with merging black hole masses 9.0 and 3 solar masses and created a final mass of 11.9 solar masses. For **Figure 5** (GW200105_0422309), the simulated dataset began with merging black hole masses of 5.9 and 1.4 solar masses and created a final mass of 7.2 solar masses. The real-time dataset began with merging black hole masses 5.9 and 3 solar masses and created a final mass of 9.0 solar masses. For **Figure 6** (GW200210_092254), the simulated dataset began with merging black hole masses of 24.1 and 2.83 solar masses and created a final mass of 26.8 solar masses. The real-time dataset began with merging black hole masses 24.1 and 3 solar masses and created a final mass of 27.0 solar masses. The log likelihood of the simulated points produced by the real-time and simulated dataset was used to measure the likelihood scale. The Poisson Burst Gravitational Wave model in the PyCBC Python Library was used to produce the simulation. In both the simulated and real-time datasets, the inputs of the merging black holes are represented by the bottom and left horizontal axes. In **Figure 7**, the differences in the black hole final masses for every BH system between the real and simulated datasets are plotted in this graph. Comparison 1: The paired-t test results showed that the difference between Before and After is statistically significant ($t(999) = 741.7$, $p < .001$). Comparison 2: $t(999) = 296.3$, $p < .001$, the results of the paired-t test showed that there is a very substantial difference between Before and After. Comparison 3: The paired-t test results showed a significant substantial difference ($t(999) = 460$, $p < .001$) between Before and After. Comparison 4: The paired-t test results showed a significant substantial difference ($t(999) = 200.8$, $p < .001$) between Before and After. Comparison 5: The paired-t test results showed a significant substantial difference ($t(999) = 297.5$, $p < .001$) between Before and After. Comparison 6: $t(999) = 296.3$, $p < .001$, the results of the paired-t test showed that there is a very substantial difference between Before and After.

The real-time datasets had BH mergers of one greater than three solar masses and the other as less than three solar masses. The simulated datasets had BH mergers of same mass that was greater than three and the other as exactly three solar masses. This was to make sure there were no extra exceptions that needed to be accounted for in the results of the final mass of the BH mergers. In all six comparisons, the results showed that the real-time datasets had a smaller final BH mass than the simulated datasets. This shows that real-time datasets do not have extra mass accounted for when the final BH is created, and therefore primordial black holes may not be sources of dark matter.

Additionally, we did a statistical t-paired test to confirm the results. The null hypothesis is that the masses of the final black holes formed in each comparison of simulated and real-time datasets are the same. The alternate hypothesis is

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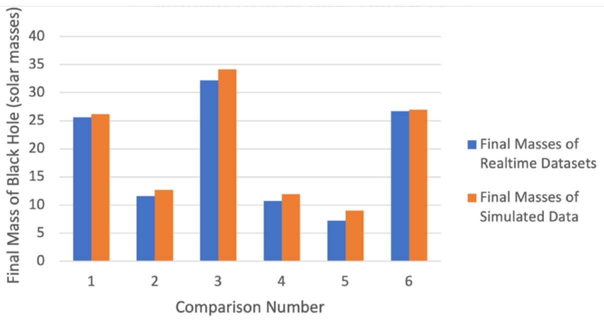

Figure 7: Differences in final masses of black holes from simulated and real time datasets. This graph represents the differences between the final masses of the black holes in each comparison between real and simulated datasets for each BH system. Comparison 1: Results of the paired-t test indicated that there is a significant large difference between Before and After, $t(999) = 741.7$, $p < .001$. Comparison 2: Results of the paired-t test indicated that there is a significant large difference between Before and After, $t(999) = 296.3$, $p < .001$. Comparison 3: Results of the paired-t test indicated that there is a significant large difference between Before and After, $t(999) = 460$, $p < .001$. Comparison 4: Results of the paired-t test indicated that there is a significant large difference between Before and After, $t(999) = 200.8$, $p < .001$. Comparison 5: Results of the paired-t test indicated that there is a significant large difference between Before and After, $t(999) = 297.5$, $p < .001$. Comparison 6: Results of the paired-t test indicated that there is a significant large difference between Before and After, $t(999) = 296.3$, $p < .001$.

that the final mass of the black holes are different in each comparison between the two groups of data. After doing a paired t-test for each comparison, the results are also similar. Analyzing the graph along with the statistical results from doing paired t-tests for each comparison, because all the statistical results for each paired test are significant and show that there is a difference in the final masses of the black holes in each comparison ($t(999) = 741.7$, $p < .001$, $t(999) = 296.3$, $p < .001$, $t(999) = 460$, $p < .001$, $t(999) = 200.8$, $p < .001$, $t(999) = 297.5$, $p < .001$, $t(999) = 296.3$, $p < .001$). This shows that there is a difference in the real time and simulated datasets.

DISCUSSION

In our research, we tested if primordial black holes could be a source of dark matter by using gravitational waves. We analyzed the masses of the final BHs that formed after SBH merger events and stellar-primordial merger events. We found that each trial comparing the original and simulated datasets showed that the original stellar-primordial black hole merger did not show evidence of the presence of dark matter, because its final mass was less than a simulated stellar-stellar black hole merger. Since we found similar results for each of the six trials in our experimental testing, these consistent findings suggest that primordial black holes may not be dark matter. However, since we used only six datasets, more research is needed to truly confirm if primordial black holes are sources of dark matter. Currently, a new laser interferometer is being built by the European Space Agency to detect gravitational waves at a much higher rate and frequency (15). They hope to have the laser interferometer completed in 2037. (15) This more sensitive equipment will facilitate further research using primordial black holes to determine the source of dark matter. Based on the ongoing research on dark matter in recent years, researchers have predicted that dark matter may be WIMPs (16). To advance in the study of dark matter, another aspect could be on focusing the testing to see if WIMPs could instead be a source of dark matter. Ongoing research is being conducted to detect dark matter through the Large Hadron Collider (LHC) and the Super Cryogenic Dark Matter Search (SuperCDMS) (16). Both observatories are currently being used to detect WIMPs particles in chemical elements such as xenon, germanium, and silicon which can help the detection of WIMPs because both research at the LHC and in SuperCDMS are trying to find particles that could be weakly interacting with baryonic matter. Unlike laser interferometry, which determines the possibility of dark matter through estimations of gravitational waves, this method allows for direct investigation, and may thus produce more accurate results.

Since the universe has been discovered to be predominantly dark matter and dark energy, studying dark matter is essential to our understanding of the universe. In the past, scientists believed that the universe was static and would not change in the future. After further research through galaxy imaging and observing red-shifted objects in space, researchers realized that the universe is not static but is rapidly growing (17). Dark matter could contribute to how and why the universe has expanded so fast. Dark matter will also help to understand how galaxies and hot gas move within galaxy clusters. Finally, scientists have determined that without dark matter, there would not be any stars, galaxies, planets, or even signs of life because of its persistence in the natural world from when the universe was formed. Therefore, dark matter acts as an invisible skeletal structure for the universe. With our current and future research on dark matter, we may be able to help scientists create a more accurate model of the universe to understand its future.

MATERIALS AND METHODS

We used publicly available data from a Gravitational Wave Open Science Center (GWOSC) database containing all the gravitational waves that have been detected since 2015. We used six datasets from the GWOSC database (**Table 1**); each dataset is a black hole merger with an SBH and a PBH (15). We were able to identify these datasets that have PBH because previous research concluded that SBH must be at least three solar masses. Hence, we identified datasets that have black holes that are less than three solar masses and labeled them as datasets with PBH (13).

We did all our data analysis on a coding platform called Google Colab, a public free web browser that allows users to do Python programming. Using tutorials available on the GWOSC database, we learned how to use these Python libraries for simulations. We used datasets of Stellar black hole merger events and a Primordial Black Hole. This combination of the black hole merger is essential because this allowed us to compare the final masses of the merger event of real-time data (data sets from the database) and the final masses of the merger of the simulated data.

We used the Python coding language to make our simulations of gravitational waves using Matplotlib (Python library used for making and plotting graphs using data points), NumPy (Python library used for doing higher-level

Binary Black Hole System	Mass 1 (Stellar Black Hole)	Mass 2 (Primordial Black Hole)	Distance (Megaparsecs)	Total Mass	Final Mass
GW190814	23.30	2.60	240.00	25.80	25.60
GW190917_114630	9.70	2.10	720.00	11.80	11.60
GW191219_163120	31.10	1.17	550.00	32.30	32.20
GW200105_162426	9.00	1.91	270.00	11.00	10.70
GW200105_0422309	5.90	1.40	290.00	7.40	7.20
GW200210_092254	24.10	2.83	940.00	27.00	26.70

Table 1: Original raw values for the six studied datasets of PBH-SBH mergers from GWOSC. We studied the following five variables: individual black hole masses, distance of merger away from Earth, total mass of merger, and final mass of merger.

Binary Black Hole System	Mass 1 (Stellar Black Hole)	Mass 2 (Primordial Black Hole)	Distance (Megaparsecs)	Total Mass	Final Mass
GW190814	23.30	3.00	240.00	26.30	26.20
GW190917_114630	9.70	3.00	720.00	12.70	12.70
GW191219_163120	31.10	3.00	550.00	34.10	34.20
GW200105_162426	9.00	3.00	270.00	12.00	11.90
GW200105_0422309	5.90	3.00	290.00	8.90	9.00
GW200210_092254	24.10	3.00	940.00	27.10	27.00

Table 2: Key variables in the simulated datasets. The simulated datasets were used to compare to the real-time datasets from GWOSC. The mass of the smaller black hole in each system was increased to three solar masses, the minimum mass of an SBH. Other variables were kept the same.

calculations), Corner (Python library used for plotting corner plots to do parameter estimation data analysis), and PyCBC (Python library used for parameter estimation using Bayesian Inferencing on gravitational wave data for Compact Binary Coalescences) (11). We used PyCBC to do parameter estimation and create simulated gravitational wave datasets that represent SBH. Along with these necessary data analysis instruments, we used a gravitational wave simulation model called the Poisson Burst Model from the Base Model class in the PyCBC Python library to create the most accurate gravitational wave model for our simulations (12). We used Bayesian Inferencing using the Poisson Burst Model, one of the simulation models in the Base Class in the PyCBC Python library used to simulate gravitational waves (12). This Python library uses the prior variables (the known variables – mass1, mass2, distance away from Earth) to determine the posterior variables (the unknown variables – finalmass) (12). The method of Bayesian Inferencing with Python is that based on the prior variables and the Bayes Theorem, where P(A|B) is probability of A occurring given evidence B has already occurred, P(B|A) is probability of B occurring given evidence A has already occurred, P(A) is the probability of A occurring, and P(B) is the probability of B occurring:

$$P(A|B) = \frac{P(B|A) \cdot P(A)}{P(B)}$$

Using this formula and the prior values the program created with the PyCBC library simulates sample data points for each simulation dataset. As the points are sampled, based on the prior values, the accumulated data points create a probability plot for the final mass of the black hole, which is the parameter that is estimated through Bayesian Inferencing (18).

The original datasets from the GWOSC database are the control group, and the simulated datasets are the experimental group. We cleaned the datasets by filtering them in the database that followed the criteria of the real-time datasets needed (black hole mergers that are a SBH-PBH merger) to compare the control and experimental groups of datasets. We used relevant BH merger variables such as the masses of the merging black holes, distance away from Earth, total mass, and final mass of the black hole merger as prior values to perform the simulation using Bayesian Inferencing (14). Additionally, we used two variables (amp and tau), which are standard variables that we used to simulate the gravitational waves. This is necessary for the type of model we are using for our simulations (Poisson Burst model) (19). These parameters are constant parameters of gravitational waves. Amp represents the amplitude of the waves from the lasers in the laser interferometer when recording the waves, and tau is the duration of time of the waves. This ensures that the gravitational wave simulation resembles actual gravitational waves produced by BH mergers rather than other objects that could produce gravitational waves, such as neutron stars. When running the simulated datasets, we used the same value (3 solar masses) for the black hole that was originally the primordial black hole in the real-time datasets, for all the simulations in each comparison to ensure no exceptions, and these variables were used as part of the prior values for parameter estimation using the Bayes Theorem (20). To create the simulated dataset with SBH, we increased the mass of second SBH (the BH that had less than three solar masses from the real-time datasets) to exactly three solar masses to simulate stellar-stellar black hole datasets to compare with the stellar-primordial black hole datasets.

We made corner plots for the simulated datasets using a Python library called Corner, which creates corner plots for parameter estimation. We made a summary dataset table of the variables for the simulated datasets (**Table 2**). Finally, we compared the final masses of the original and simulated datasets (**Figure 7**).

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