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Exploring the Relationships Between Binary Black Hole Parameters and Gravitational-Wave Signal Characteristics

By Zixuan Chen

AUTHOR BIOGRAPHY

Zixuan Chen is a senior at Cypress Ranch High School, passionate about physics, cosmology, and data science. Her research explores how binary black hole properties influence gravitational-wave signals through statistical analysis and computational methods.

ABSTRACT

This study sought to investigate how Binary Black Hole (BBH) parameters—chirp mass, mass ratio, and luminosity distance—influence key Gravitational Wave (GW) signal features maximum frequency, and signal-to-noise ratio (SNR). Examining GWs enables the study of the dynamics of BBH systems as their physical properties can reflect observable signal characteristics. A quantitative research is conducted utilizing a set of 16 high-SNR events from the Gravitational-Wave Transient Catalogs. For each event, physical parameters were extracted from catalog data, and maximum frequencies were obtained from previous discovery papers or estimated through Q-transform visualizations of strain time-series. With these data, five parameter pairs—chirp mass vs. maximum frequency, mass ratio vs. maximum frequency, distance vs. maximum frequency, chirp mass vs. SNR, mass ratio vs. SNR—are analyzed by Pearson and Spearman correlations. Analyses revealed generally weak relationships between BBH parameters and GW signal characteristics, suggesting the subtle influence of BBH parameters on GW signal features and the potential role of untested variables, like spin, orbital orientation. Future work should focus on strengthening the precision of GW data analysis by incorporating methods such as bootstrapping, expanding the range of examined signal characteristics, and improved signal-extraction tools. This research can help deepen the understanding of how fundamental black hole properties impact the signals we observe.

Keywords: *Binary Black Hole (BBH), Gravitational Waves, Chirp Mass, Mass Ratio, Luminosity Distance, Signal-to-Noise Ratio (SNR), Maximum Frequency, Correlation Analysis, Bootstrapping, Time-Frequency Denoising, Black Hole Spin, Orbital Orientation.*

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INTRODUCTION

Black holes are a key factor in shaping the evolution of galaxies over cosmic time. Their growth releases vast amounts of energy that powers quasars and other weaker active galactic nuclei, regulating the cooling of gas and thus controlling star formation (Cattaneo et al., 2009). While studying black holes is important, gravitational waves (GWs), ripples in space-time generated by highly energetic events such as binary black hole mergers, provide a unique pathway that amplifies black hole dynamics.

The existence of GWs was first predicted by Einstein in 1916, while working on the weak field linearized approximation of his general theory of relativity, Einstein realized that there is a small disturbance propagating in a flat space-time, just like electromagnetic waves emitted by accelerated charges (Weinstein, 2016). Later in 2015, the field of GW astronomy experienced a breakthrough when the Laser Interferometer Gravitational-Wave Observatory (LIGO) achieved the first direct detection, matching predictions from Einstein's general relativity for two inspiraling and merging black holes (The LIGO Scientific Collaboration & the Virgo Collaboration, 2016). Since then, an increasing number of GW events have been observed and GW astronomy has rapidly evolved. Among all the observations, high-signal-to-noise (SNR) ratio signals are particularly valuable, as they provide particularly powerful constraints on their source parameters and play an important role in extracting astrophysics from gravitational wave sources (Chen & Holz, 2014).

GW signals are shaped by physical parameters such as chirp mass, mass ratio, aligned and in-plane spins and extrinsic parameters, which determine key characteristics including frequency (Roulet & Venumadhav, 2024). Previous research has proved some relationships between parameters of black holes and the observed signals. For instance, a model was created to predict the peak gravitational-wave frequency directly from the system's total mass, symmetric mass ratio, and effective spin. This model demonstrates a clear, inverse relationship between the total mass of the system and the frequency of the emitted radiation (Carullo, Riemenschneider, Tsang, Nagar, & Del Pozzo, 2019). Furthermore, a "rule of thumb" was developed, relating the energy emitted in gravitational waves for a narrowband source and the distance to which that emission can be detected by a single detector. It also shows that the same energy emitted at a frequency where detectors are least sensitive yields low SNR (Sutton, 2013). These studies illustrate how black hole properties are reflected in signal characteristics, including max frequency and SNR, and reinforce the need to establish their linkage.

In light of previous insights, this research investigates how BBH physical parameters (mass ratio, chirp mass and luminosity distance) influence both maximum frequency and SNR in high-SNR BBH gravitational waves. The analysis assesses the following simple correlations:

- Chirp mass vs. maximum frequency
- Mass ratio vs. maximum frequency

- Distance vs. maximum frequency
- Chirp mass vs. SNR.
- Mass ratio vs. SNR.

Quantifying these relationships with statistical measures offers a deeper understanding of how physical parameters shape both the highest oscillation rate of spacetime distortions and the observability of BBH signals. Overall, this research aims to enhance the understanding of GW signals, and this potentially sparks new techniques in investigating GW astronomy.

METHODS

To investigate the relationships between BBH physical parameters and the characteristics of their GW signals, this study used correlation techniques to analyze publicly available data. Parameters, including chirp mass, mass ratio, luminosity distance, and signal-to-noise ratio (SNR), were extracted from existing Gravitational-Wave Transient Catalogs (GWTCs). Signal characteristics and maximum frequency were captured either from published discovery papers and fact sheets or through data analysis by visualizing strain time-series by performing Q-transform diagrams of strain time-series in Python. Linear (Pearson) and monotonic (Spearman) correlations were used to quantify potential relationships between physical parameters—chirp mass, mass ratio, luminosity distance—and signal characteristics—max frequency and SNR. This combination of data extraction and statistical analysis provide a comprehensive evaluation that reveals both linear and non-linear correlation patterns, allowing a thorough understanding of how physical properties of BBH mergers associate with their signals.

Physical Parameter Extraction

This study used publicly available data from GWTCs: GWTC-1, GWTC-2.1, GWTC-3, and GWTC-4.0 (Abbott et al., 2019; The LIGO Scientific Collaboration & the Virgo Collaboration, 2024; The LIGO Scientific Collaboration, Virgo Collaboration, & KAGRA Collaboration, 2023; The LIGO Scientific Collaboration, Virgo Collaboration, & KAGRA Collaboration, 2025), and a set of 16 confirmed BBH merger events with high SNR (SNR $\geq$ 12.8) were selected. Mass ratio, chirp mass, and luminosity distance were extracted directly from tables in the corresponding GWTCs.

Signal Characteristic Extraction

The signal characteristic maximum frequency was obtained from discovery papers and fact sheets in LIGO Document Control Center portals when explicitly reported (The LIGO Scientific Collaboration & the Virgo Collaboration, 2016b, 2016a, 2019a, 2019b, 2020b). For events lacking explicit reports, data was

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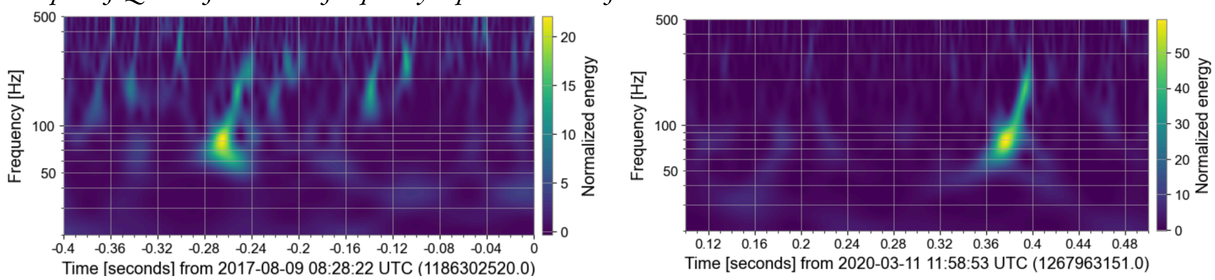
processed and analyzed using Python within Jupyter Notebook. Q-transforms and a time-frequency analysis were applied to the strain time-series to generate high-resolution spectrograms, visually estimating maximum frequencies (Macleod, 2024).

Strain data were accessed from the Gravitational Wave Open Science Center (GWOSC), prioritizing H1detector data when available, and otherwise using L1 or V1 data. Event GPS times and Timeline Queries are used to identify the time segment shown in the Q-transforms, allowing estimation of max frequencies, which is not always reported, ensuring a full dataset across all selected events. Figure 1 shows two examples of Q-transform spectrograms containing their prominent transients, showing how maximum frequencies were visually estimated.

Figure 1

Examples of Q-transform time-frequency representation of GW strain data



(a) Event GW170809 (b) Event GW200311

Note. The diagrams show normalized signal energy as a function of time and frequency. Left: H1 data has a prominent transient near ~60 Hz around -0.27 s. Right: H1 data has a prominent transient near ~80 Hz around -0.38 s with a clearer pattern and minimal background noises. These features were used to estimate the maximum frequency of the GW signal.

DATA ANALYSIS

Five pairs of physical parameters and signal characteristics were analyzed:

- Chirp mass vs. maximum frequency
- Mass ratio vs. maximum frequency
- Distance vs. maximum frequency
- Chirp mass vs. SNR
- Mass ratio vs. SNR.

These pairs were chosen to examine how common physical parameters relate to maximum frequency, the highest oscillation rate of a GW signal, and SNR, the strength of a GW signal relative to the background noise in the detector. Altogether, they provide insights into BBH dynamics and GW signal detectability.

For each pair, scatter plots were generated to visualize trends. Pearson correlation coefficients were calculated to quantify linear relationships between variables and Spearman correlation coefficients were used to quantify monotonic relationships. Corresponding p-values that evaluate the statistical significance of these correlations, helping determine whether the trends reflect true associations instead of random variations. All resulting values were subsequently organized into tables, sorted in descending order of their absolute values, displaying a clear overview of the data and helping identify the most meaningful associations between BBH physical parameters and the characteristics of their GW signals.

RESULTS

This analysis produced three values for each pair of GW property and signal characteristic—Pearson correlation coefficients, Spearman correlation coefficients, and corresponding p-values that evaluate the statistical significance of these correlations. These analyses are used to examine how BBH physical parameters relate to the characteristics of their GW signals. Correlation tests using Pearson and Spearman coefficients were performed to assess the strength of relationships among five parameter pairs, detecting how mass and distance properties might influence frequency behavior and signal detectability.

According to the conventional statistical interpretation, the results indicated that relationships between BBH physical parameters (chirp mass, mass ratio, and distance) and GW signal characteristics (maximum frequency and SNR) were generally weak, with most correlation coefficients about 0.3 and none of the correlations reaching conventional levels of statistical significance ($p < 0.05$; Cohen, 1988, pp. 3, 83). These relationships are illustrated in Figures 2, and a summary of parameter pairs and their correlation statistics is provided in Tables 1 and 2.

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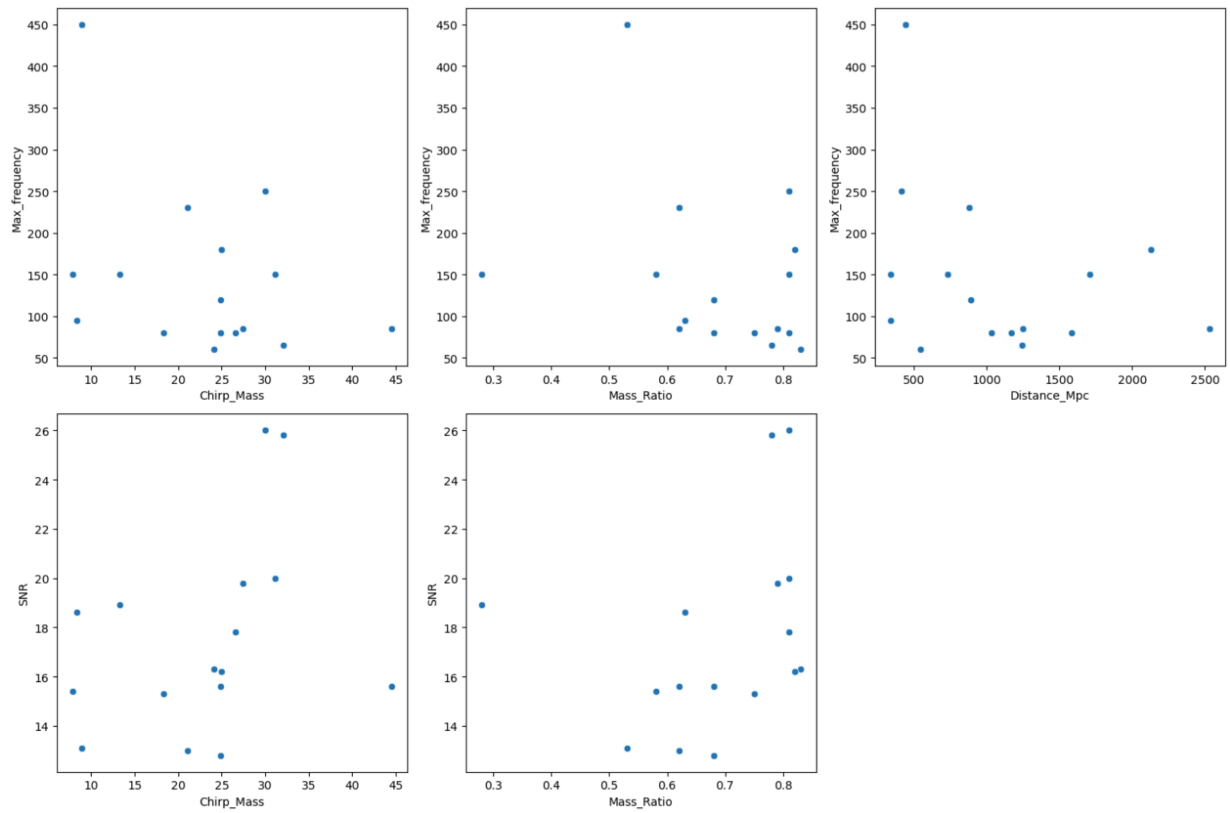
Figure 2

Visual comparison between BBH parameters and GW signal characteristics



Note. Each scatter plot shows how one GW signal characteristic varies with a BBH parameter.

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Table 1

Ranked Pearson correlations between binary black hole parameters and gravitational-wave signal characteristics

Pair	r	p
Chirp Mass vs Max frequency	0.371	0.158
Chirp Mass vs SNR	0.326	0.218
Distance vs Max frequency	-0.314	0.237
Mass Ratio vs Max frequency	-0.312	0.239
Mass Ratio vs SNR	0.306	0.248

Note. Correlations are ranked by absolute value of r.

Table 2

Ranked Spearman correlations between binary black hole parameters and gravitational-wave signal characteristics

Pair	ρ	p
Chirp Mass vs SNR	0.488	0.055
Mass Ratio vs SNR	0.445	0.084
Mass Ratio vs Max frequency	-0.338	0.200
Distance vs Max frequency	-0.286	0.283
Chirp Mass vs Max frequency	-0.239	0.374

Note. Correlations are ranked by absolute value of ρ.

Based on conventional standards, results of Pearson correlations showed weak linear relationships for all tested pairs. The largest coefficient was observed between chirp mass and maximum frequency ($r = -0.371$, $p = 0.158$), which falls on the lower end of the moderate range for a correlation coefficient value and was not statistically significant. Similarly, the results of Spearman correlations revealed somewhat stronger trends. The strongest observed relationship was between chirp mass and SNR ($\rho = 0.488$, $p = 0.055$), indicating a positive, almost strong, monotonic association. A relatively strong moderate positive correlation was also found between mass ratio and SNR ($\rho = 0.44$, $p = 0.084$). In contrast, correlations involving maximum frequency were relatively weak and nonsignificant.

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This data reveals that most relationships in this study fall within the weak-to-moderate range and do not meet conventional significance levels. The weak correlations with maximum frequency imply that the max frequency is not strongly determined by mass or distance alone. In comparison, the relatively stronger correlations between chirp mass or mass ratio and SNR indicate that systems with greater mass tend to produce slightly stronger signals. On the whole, these patterns highlight the complexity of how BBH properties influence GW signals.

While individual correlations vary in strength, the overall pattern shows that the influence of BBH physical parameters examined in this study (chirp mass, mass ratio, distance) have only subtle influence on max frequency and SNR within this dataset, with only a few moderate trends observed with some evidence underscoring that although these parameters somehow affect max frequency and SNR observed in signals, some other parameters should be taken into consideration when studying GW and their signals.

DISCUSSION

The study provided insights of how physical parameters of BBH systems influence the characteristics of high-SNR GWs. According to the results, correlations between the selected physical parameters and GWs appear weak in the limited dataset.

Although most relationships were weak, these results remain informative regarding previous findings. The correlation coefficients between maximum frequency and physical parameters are especially low. Still, the negative value that represents how maximum frequency depends on mass terms, chirp mass and mass ratio, reflects true astrophysical concepts. According to Kepler's third law, the orbital period of a binary system increases with the size of the orbit and the total mass, so more massive systems have larger orbits and longer periods, causing slower orbital motion and lower-frequency gravitational waves (Vijaya, 2019). This inverse relationship between mass and frequency is also confirmed by observations of BBH mergers. For instance, the report of the first direct observation of GW clearly states that the signal increased in frequency and amplitude from 35 to 150 Hz over 0.2 s, the estimated chirp mass of $\sim 30\,M_\odot$ implied a total mass $\gtrsim 70\,M_\odot$, bounding the sum of Schwarzschild radii to $\gtrsim 210\,\text{km}$, and the observed peak frequency corresponds to a very compact binary (The LIGO Scientific Collaboration & the Virgo Collaboration, 2016). These observations align with the patterns identified in this analysis, supporting the idea that more massive BBH systems produce lower-frequency GW signals. As only black holes are compact and massive enough to produce the observed signal, the identification of the merger is validated as a BBH event.

Additionally, the weak relationships observed between BBH physical parameters (chirp mass, mass ratio, and distance) and gravitational wave signal characteristics (maximum frequency and SNR) suggest that these parameters alone do not fully determine signal features. Other factors, such as spin or orbital orientation,

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may play more critical roles in shaping signals (Abbott et al., 2019). Understanding this nature is important for guiding more comprehensive analyses for GW data and future work.

Future work should focus on some improvements to strengthen GW data analyses. First, bootstrapping methods, which was introduced by Efron, can be used to better assess the reliability of correlations between BBH physical parameters and GW signal characteristics (Efron, 1979). When extracting data from GW catalogs, median values are used, disregarding the full uncertainty range. This means the observed correlations are influenced by these measurement errors, potentially underestimating stronger underlying relationships, as chirp mass, mass ratio, and maximum frequency all have non-negligible confidence intervals due to detector noise and the methods used to infer source properties. This simplification may distort real relationships as it failed to account for variability. By repeatedly resampling the dataset and recalculating correlation coefficients, a distribution of values can be generated to estimate confidence intervals, providing a more accurate measure of uncertainty in correlation coefficients, slopes, and intercepts and helps determine whether weak or moderate correlations reflect true trends (Singh, K., & Xie, M., 2010). In this study, applying bootstrapping would help determine whether the weak-to moderate correlations are simply the result of limitations such as sample size and measurement uncertainties, increasing confidence in the conclusions drawn from the data. Ultimately, bootstrapping creates more informative inferences and reduces overconfidence in observed relationships.

Second, exploring additional signal characteristics may reveal stronger or broader relationships with physical parameters. For instance, studying duration may help learn the parameter of mass ratio, as decreasing the mass ratio may lead to longer signals. This inverse relationship between mass ratio and signal duration was once verified under a waveform-based approach (Kang, Miller, Chatziioannou, & Ferguson, 2025). The amplitude of GW signal also can be taken into consideration, while it is suggested to be inversely proportional to the distance from the source (Shawhan, 2017).

Finally, developing a precise extraction tool for GW signal characteristics will efficiently reduce systematic errors and enable more efficient analysis. This study's method relies on visually estimating maximum frequency from Q-transforms. A more dedicated method can be designed by feature-detection algorithms and signal denoising techniques. One possibility is Time-frequency denoising, which removes noise from nonstationary signals by transforming them into the time-frequency domain, thresholding small-magnitude coefficients while keeping large ones and reconstructing the signal with the inverse transform (Aburakhia, Shami, & Karagiannidis, 2024). This approach effectively removes noise while preserving the evolving frequencies of signals. Obtaining cleaner, more accurate data enhances the reliability of correlation analyses between BBH physical parameters and GW signal characteristics.

In summary, while correlations in this high-SNR dataset are weak, the observed trends are consistent with theoretical expectations, and careful treatment of uncertainties is essential for understanding how BBH properties shape the characteristics of gravitational-wave signals. Ultimately, this study helps clarify how fundamental properties of black holes are related to GW signal characteristics, paving the way for more precise astrophysical and cosmological investigations.

CONCLUSION

This study examined the relationships between BBH physical parameters (chirp mass, mass ratio, and distance) and key GW signal characteristics (max frequency and SNR) through a set of 16 high-SNR events. Using Pearson and Spearman correlation analyses, linear and monotonic trends were quantified and their statistical significance are evaluated. Overall, correlations were weak, with evidence that only higher chirp mass and mass ratio may be associated with stronger signals. This result suggests that the influence of BBH parameters on observable GW features is subtle, as it potentially intertwines with other factors such as spin, orbital orientation, or due to measurement uncertainty.

Understanding these relationships is crucial for interpreting GW detections, improving waveform models, and refining astrophysical inferences. By combining high-SNR data analysis with physical interpretation, this research helps advance current understandings of BBH mergers and their observable signals. Future work incorporating reinforced uncertainty estimation, additional signal features, and automated extraction tools will continue to improve the accuracy of analyses.

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