Parameter Estimation of Binary Black Hole Coalescence Using LSTM Neural Networks

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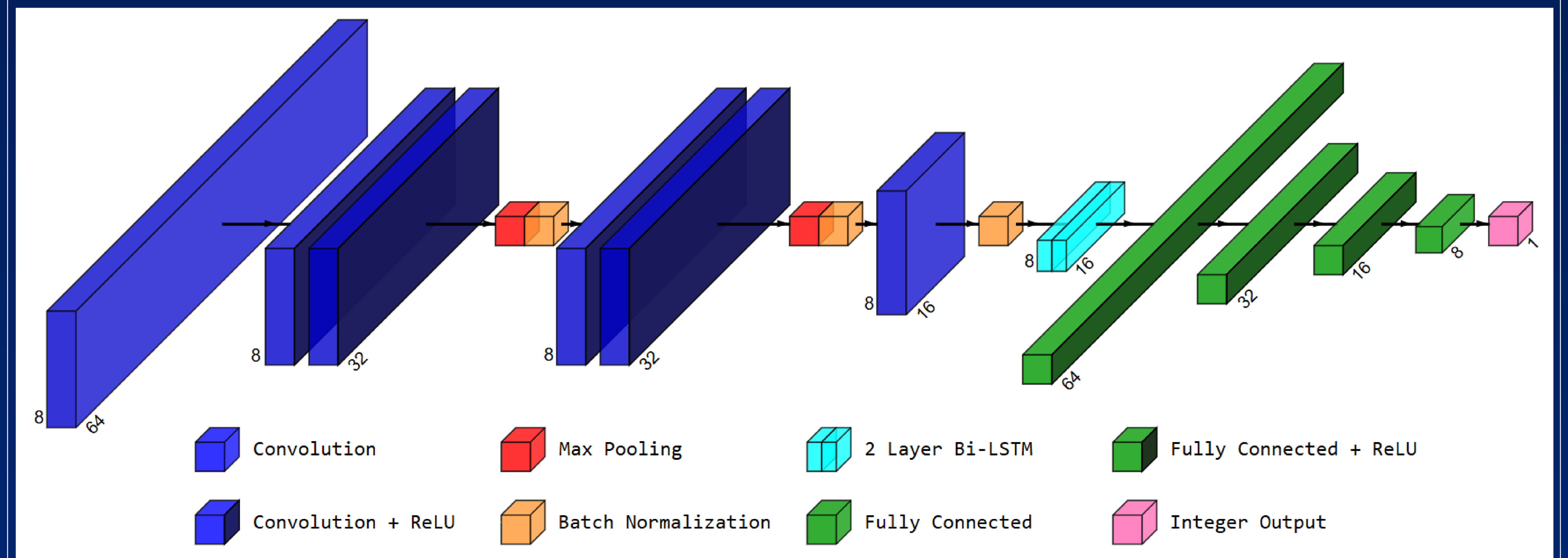
Abstract

Rapid gravitational wave (GW) data analysis is essential for scientific progress, but traditional data analysis methods are computationally intensive and limited in accuracy. With increasing detection rates, there is a pressing need for more efficient analysis techniques. Recently, machine learning has shown promise in these improvements. ***This research presents a neural network capable of directly analyzing raw, noisy gravitational wave signals to accurately estimate the chirp mass of binary black hole systems***. By circumventing extensive preprocessing, this approach enhances computational efficiency and is capable of more accurate parameter estimation than traditional techniques, ***advancing the field of gravitational wave astronomy.***

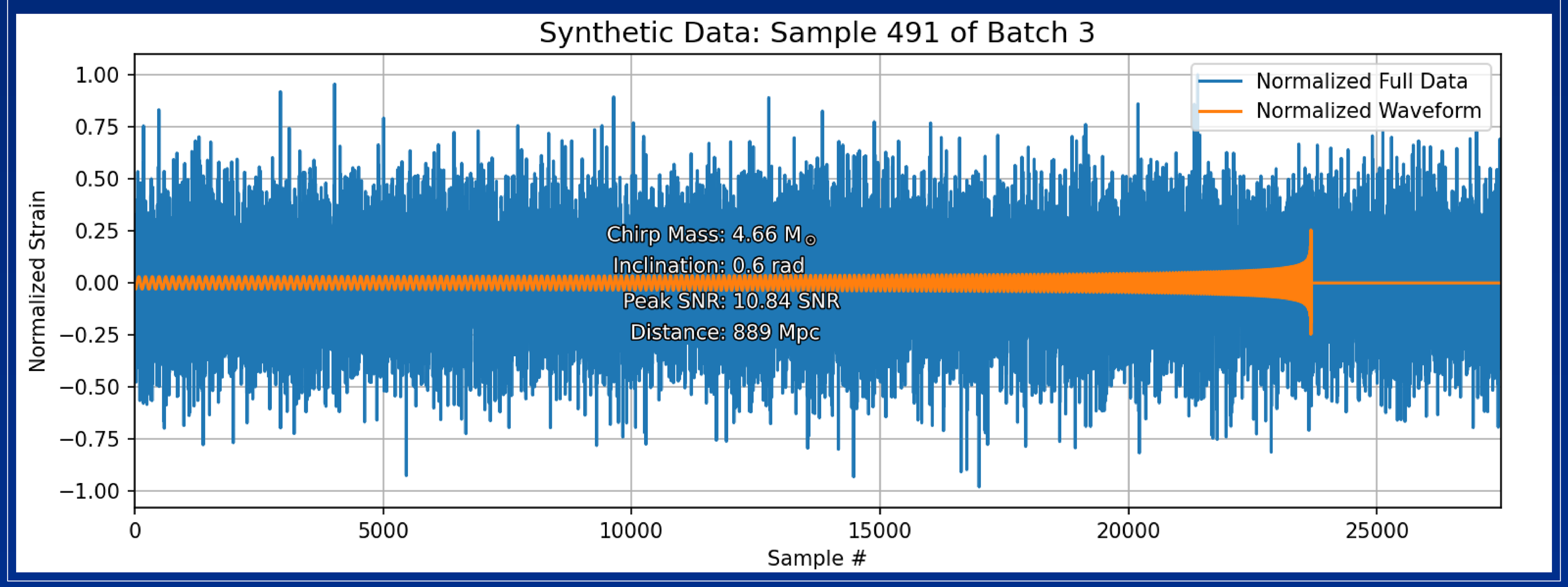
The Neural Network

- A ***hybrid neural network*** structure containing ***Convolution, LSTM, and Dense*** layers
- Optimized via ***random search of hyperparameter space*** with Optuna package
- The model contains ***18,009*** total tunable parameters requiring ***89.9 KB of storage***



Synthetic Data

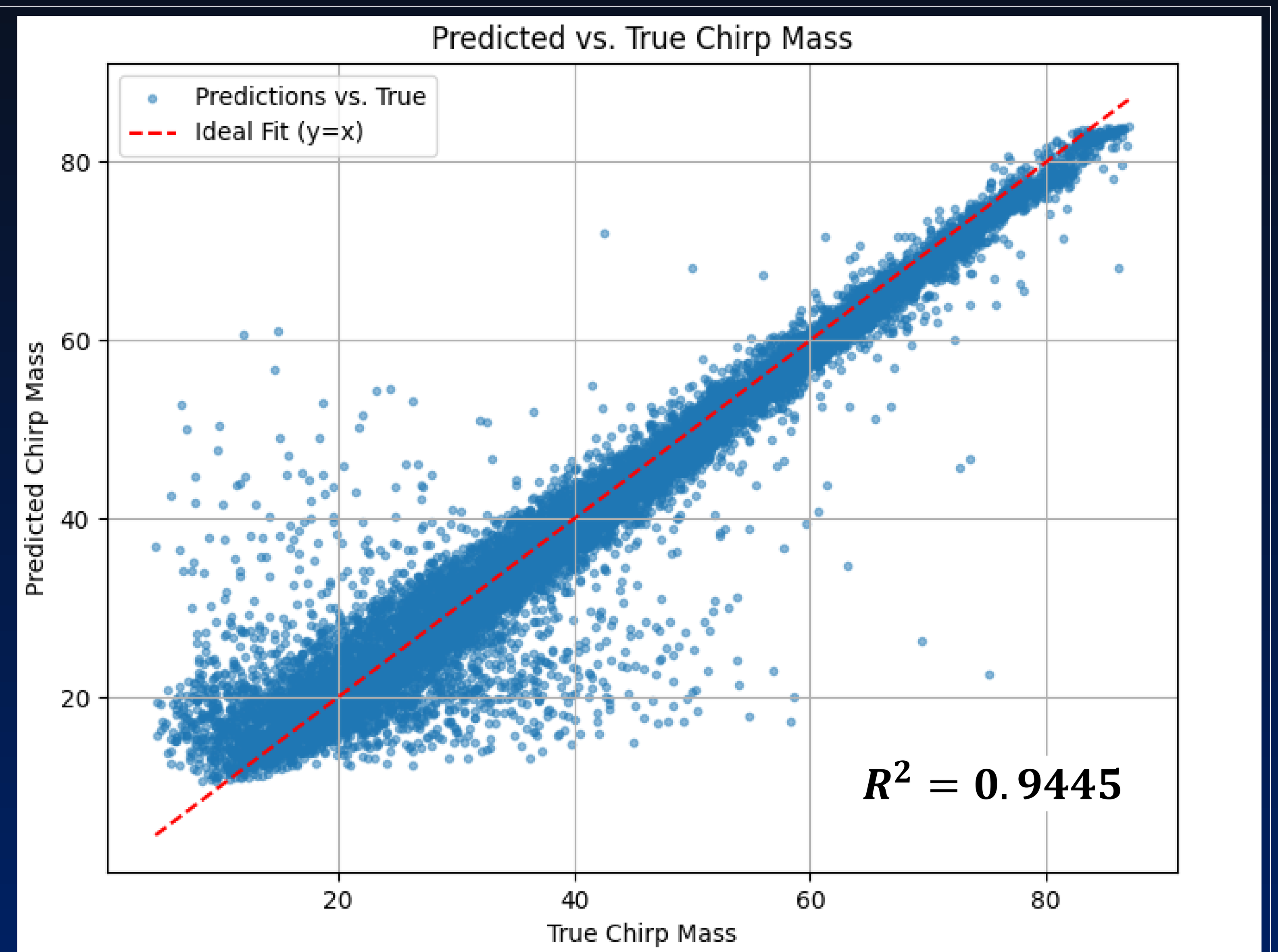
- Produced a total of ***1.3E+5 samples*** of data to train and evaluate the neural network
- Synthetic Observations, Pure Signal, Pure Noise, SNR Regimes ***using PyCBC***
- System ***parameters randomly sampled*** from uniform probability distributions



Results and Impact

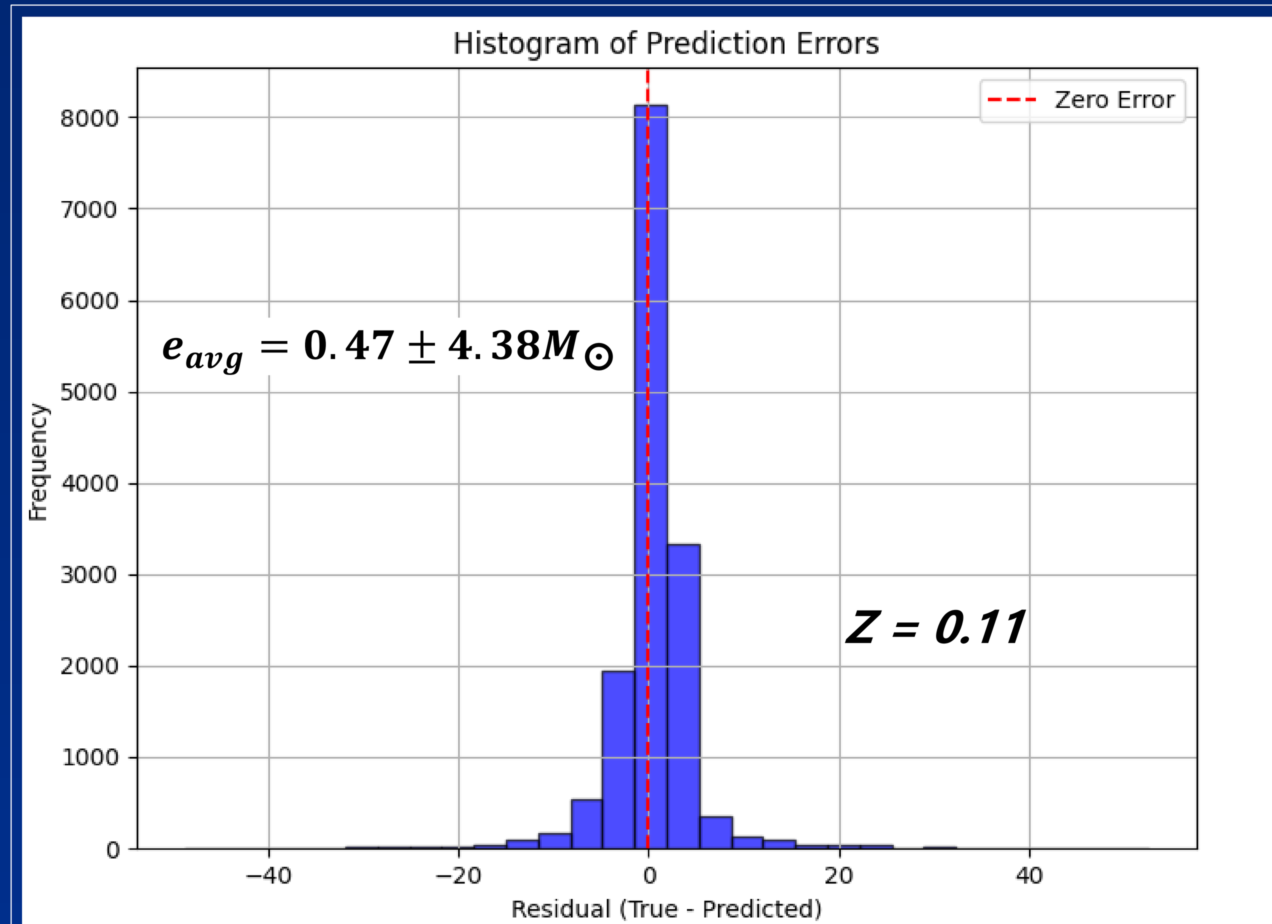
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

- ***Chirp Mass*** can be ***accurately estimated*** from a noisy strain timeseries without the need for preprocessing
- Neural Network performance suffers in low SNR regimes, but ***LIGO's detection threshold*** is currently an SNR of 8
- Machine Learning solutions can perform parameter estimation ***near instantaneously***
- ***Initially trying to estimate 4 parameters***, this network architecture could only ***reliably track 1 parameter***
- This neural network ***struggles to accurately estimate*** chirp masses at the ***extremes of the parameter space***.
- There is a ***definitive linear correlation between true and predicted*** chirp masses evidenced by ***R^2 > 0.99***
- ***Residual plots exhibit more order*** as SNR decreases, implying some sort of ***inherent bias in the model***



Peak SNR Range	R^2 Value	Mean Residual	Std. Dev. of Residual
$0 < SNR < 5$	0.417	1.443	9.241
$5 < SNR < 20$	0.959	0.092	3.558
$20 < SNR < 35$	0.990	0.629	1.594
$35 < SNR < 50$	0.993	0.509	1.336
$50 < SNR < 65$	0.993	0.601	1.220
$65 < SNR < 80$	0.993	0.620	1.092
$80 < SNR$	0.992	0.859	0.837

Conclusion and Future Work



- Neural Networks can indeed ***extract astrophysical parameters*** from ***minimally processed*** interferometer-like data. Extensions of this work should aim to ***estimate multiple system parameters*** simultaneously.
- When ***paired with other light-weight neural networks*** capable of flagging and trimming detections out of continuous data streams, this model could ***work as part of a real-time data analysis stack***.
- Evaluation of this model revealed ***inherent biases and edge effects*** in its ***predictions***, particularly at the extremes of the parameter space. These phenomena should ***attempt to be resolved in future work***.
- Parameter estimation without ***robust uncertainty measurements*** is ***scientifically incomplete***. Continued efforts should prioritize the integration of uncertainty quantification ***for individual estimates***.

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