Generating Black Hole Mergers from Globular Clusters Using Deep Learning

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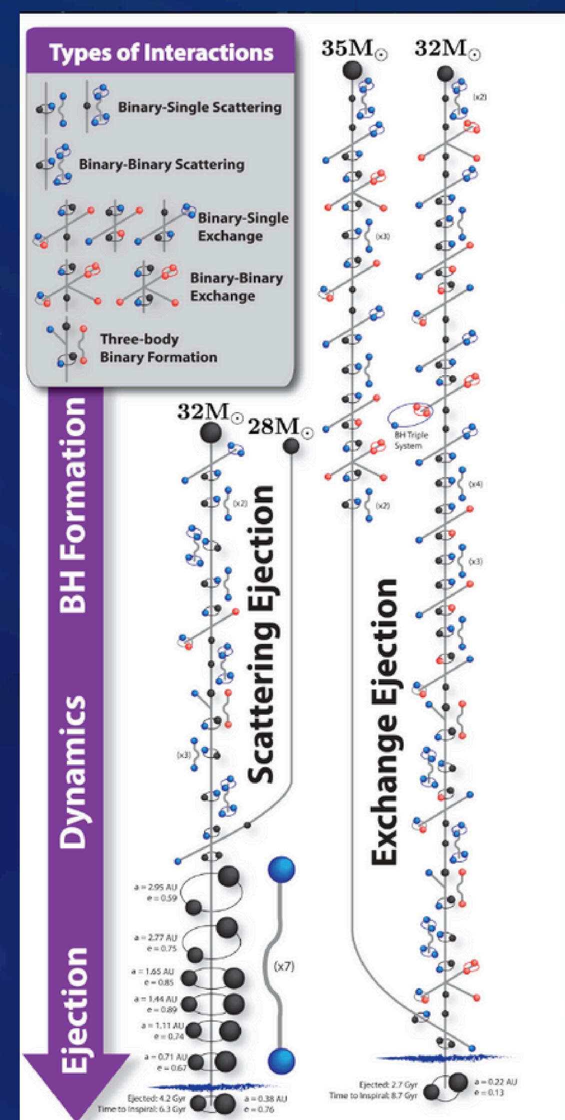
Introduction

Some black hole mergers are believed to originate in the center of Globular Clusters, which are densely packed groups of thousands of stars bound by gravity. The figure at right shows the interactions between stellar objects and black holes within these clusters which over time, create a binary black hole system that merges to produce a gravitational wave event. Many properties of globular clusters that lead to black hole mergers are unknown.



Research Objective & Goals

Traditional N-body simulations help us understand how black hole binaries form and evolve within stellar clusters. However, these simulations—such as those run using the Cluster Monte Carlo (CMC) Code—are computationally intensive, often taking months to simulate a single cluster.

This project aims to develop a generative AI-based emulator using neural networks to approximate the outcomes of astrophysical simulations more efficiently.

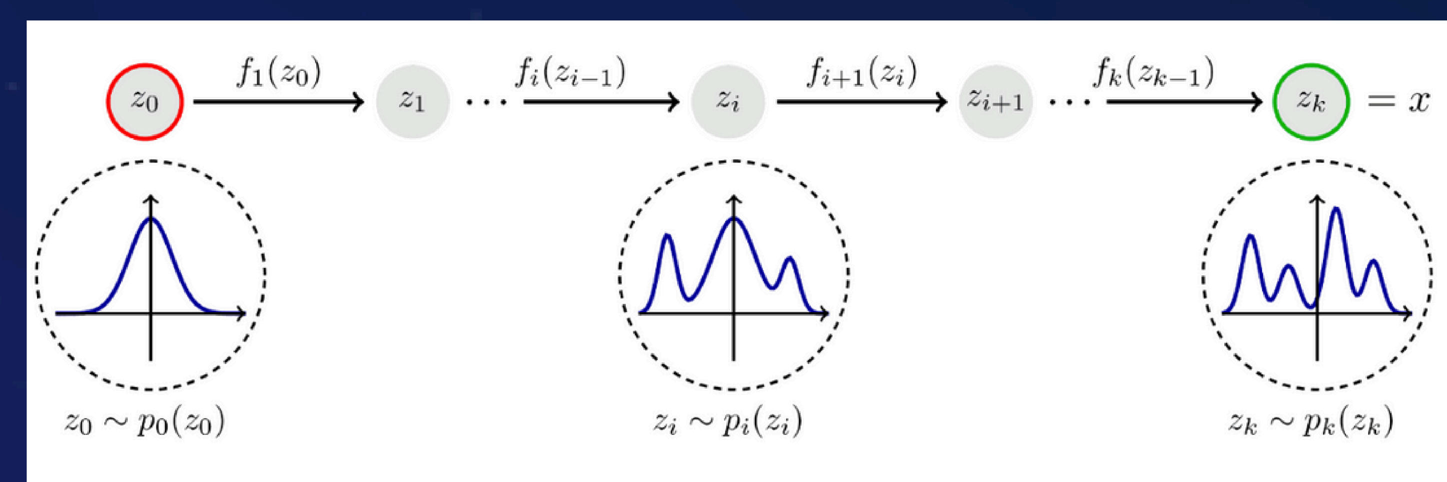
- Data Source: Utilize the Cluster Monte Carlo (CMC) dataset for training. Our data contains around 13,000 black hole mergers spread across different cluster properties.
- Generative Model: Apply Normalizing Flows, a class of generative AI models, to emulate complex astrophysical events with reduced computational demand.

Normalizing Flows

Normalizing flows help model complex distributions of binary black hole properties (like masses, time delay, and merger channels) by transforming a simple, known distribution (e.g., Gaussian) into one that matches the CMC data. This is done through a series of invertible transformations that progressively reshape the base distribution to approximate the true distribution of black hole attributes.

Key Steps

1. Start with a Base Distribution: Begin with a simple probability distribution as a starting point.
2. Apply Transformations: A sequence of transformations reshapes this base distribution to match the complex patterns in black hole distributions.
3. Calculate Probabilities: By applying the change of variables, the model provides exact probability densities for black hole characteristics, making it effective for likelihood estimation and data generation.



Simple Distribution -> Learning Transformations -> Complex Distribution

Properties of the cluster (Input)

- rv = varial radius
- rg = position in galaxy
- Z = metallicity (chemical composition)
- N = Number of stars

Properties of binary black holes (Output)

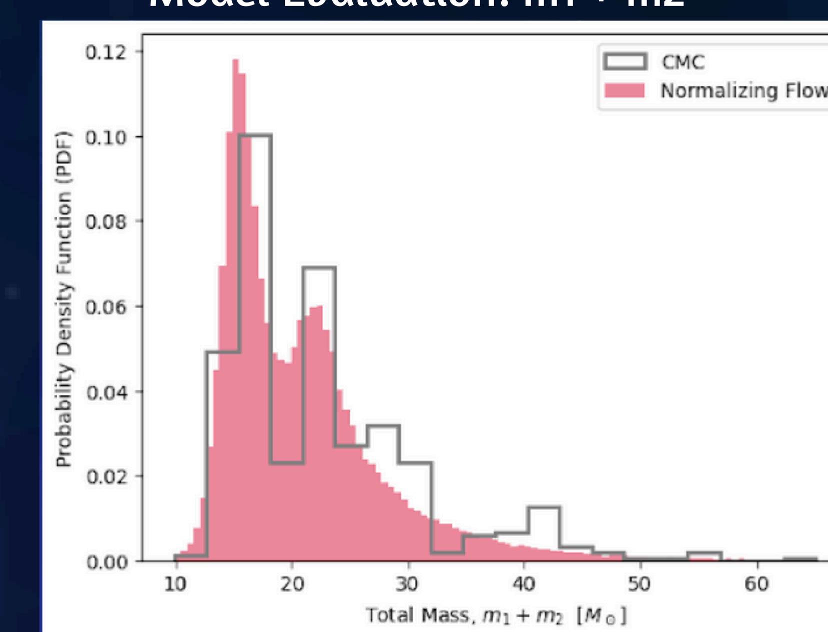
- m1 = mass of heavier black hole
- m2 = mass of lighter black hole
- Merger time = time from the simulation until the black holes merge
- Merger channel = the way/process through which these black holes merge

We trained our model on 136 distinct properties of unique globular clusters, resulting in a dataset of 13,000 black hole mergers. The model architecture consists of 10 layers, each containing 1,024 hidden units. We optimized the training process by maximizing the likelihood of the observed data as we tuned hyperparameters.

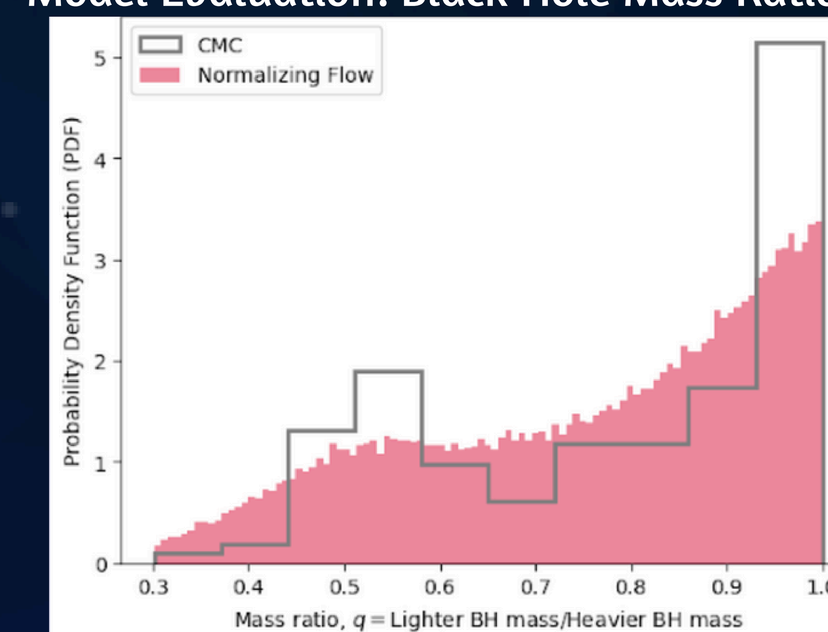
Data Analysis

To illustrate our findings, we present a comparison of binary black hole (BBH) properties between CMC and our network for a globular cluster characterized with rv = 1 pc, rg = 20 pc, Z = 0.02 solar metallicity, N = 32 x 10^5 stars. The results are shown as histograms depicting the following key properties: the sum of black hole masses (m1 + m2), the mass ratio (q), the merger time, and the classifications of the merger channels.

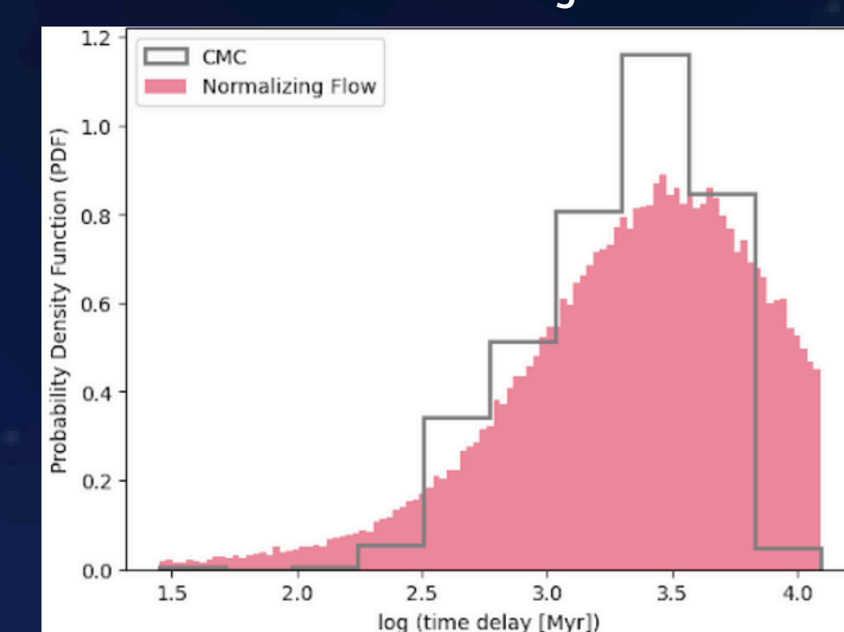
Model Evaluation: m1 + m2



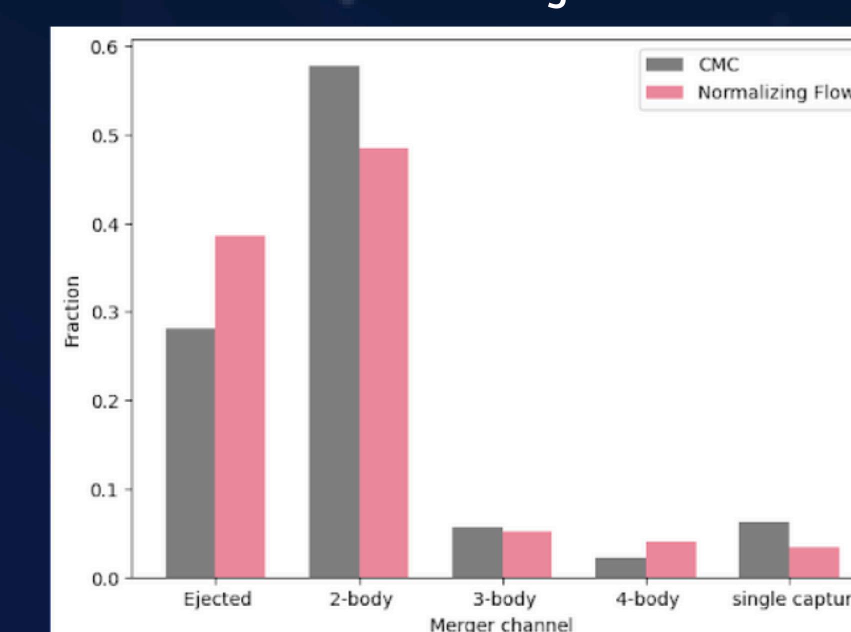
Model Evaluation: Black Hole Mass Ratio (q)



Model Evaluation: Merger Time



Model Evaluation: Merger Channel



Conclusion

- We developed a normalizing flow network to create an accurate simulation model for binary black hole mergers in globular clusters.
- The trained neural networks efficiently generate outputs based on conditional inputs related to globular clusters that host these mergers.
- We have reduced the simulation time for a single cluster from months (using CMC code) to mere seconds with machine learning.
- The Normalizing Flow network directly provides likelihoods that can be applied in Bayesian analysis of globular cluster properties.

Key References

All images, unless indicated by [X] are created by researcher

[1]https://tikz.net/normalizing-flow/
[2]https://clustermontecarlo.github.io/CMC-COSMIC/src/index.html (dataset)
[3]https://medium.com/@jain.sm/normalizing-flows-an-intuitive-explana-13b92dcfe643
[4]https://uvadlc-notebooks.readthedocs.io/en/latest/tutorial_notebooks/tutorial11/NF_image_modeling.html
[5]https://github.com/ikostrikov/pytorch-flows (flows architecture)
[6] https://arxiv.org/pdf/1604.04254.pdf
[7]https://www.sci.news/astronomy/globular-star-clusters-repeated-merging-multiple-black-holes-05906.html