Predicting the Evolution of Dark Matter Halos Using Neural Networks

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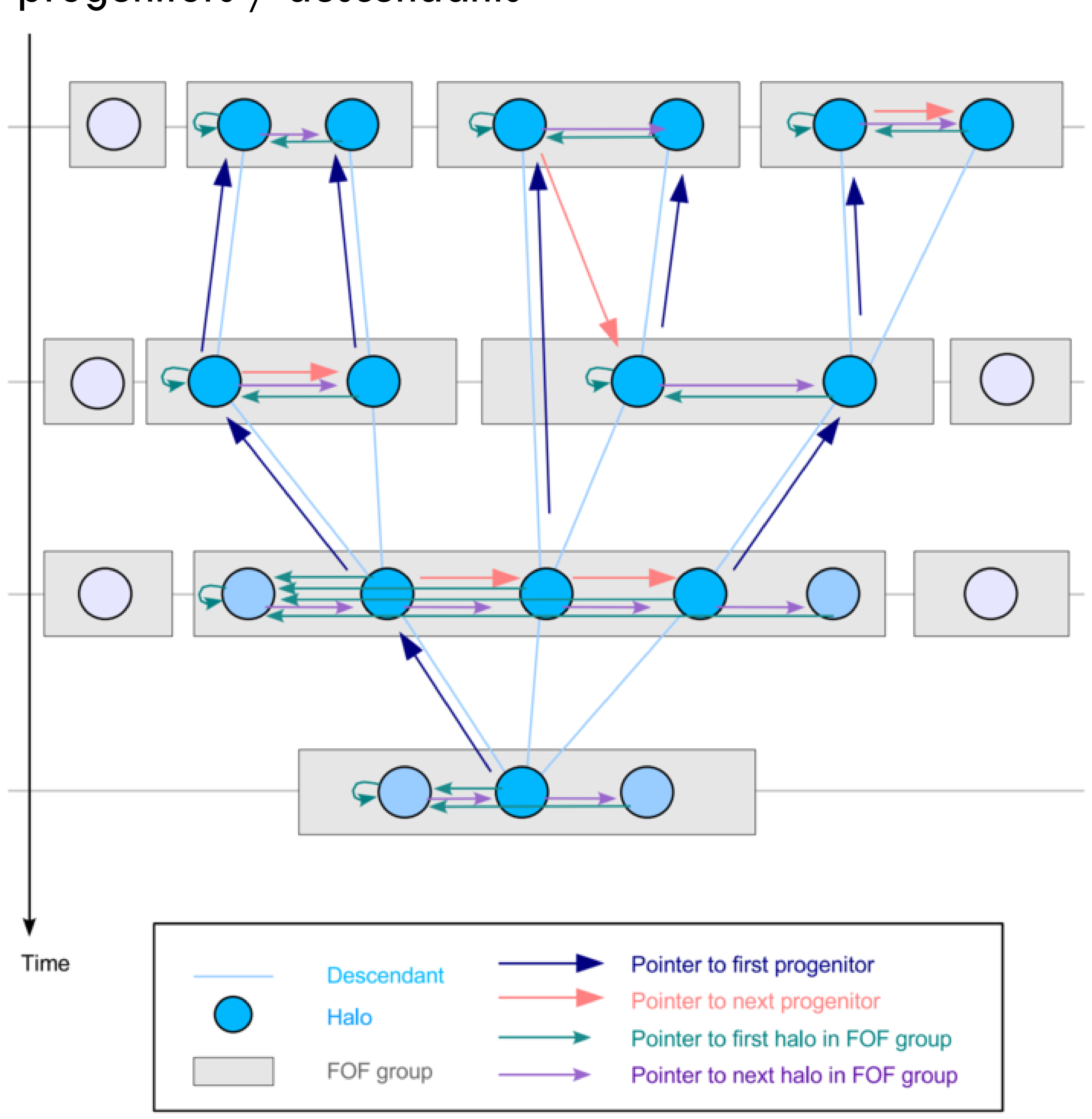
Background

The earliest dark matter halos formed from the collapse of overdense regions in the matter density field. Since they formed by direct collapse, these halo populations contain information about the primordial density field of the universe. This can lead to a better understanding of processes such as inflation and the early matter-dominated era (EMDE).

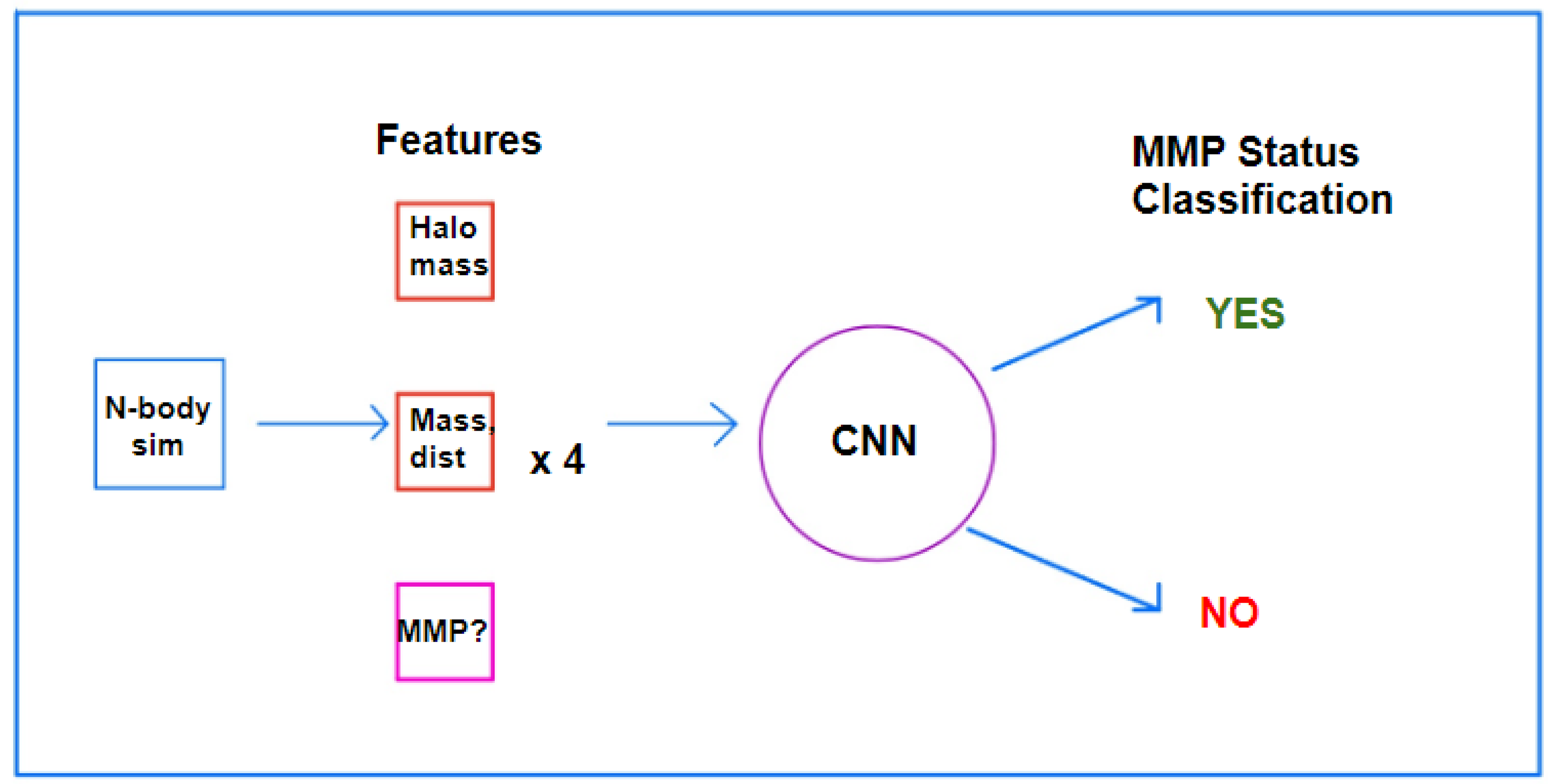
The power spectrum P(k), which quantifies the power in density fluctuations at a wave number k, provides a probe for inflation models and the nature of dark matter. The density profile of a halo is uniquely related to the properties of its density peak, or local maxima in the density field. Overarching goal: predict which density peaks successfully formed halos.

GADGET-4 Simulations

•C++ code for N-body simulations, modified for various cosmologies
•Inputs: initial conditions via power spectrum P(k)
•Results:
- Snapshots: captures the state of the system at a given time
- Group finders: FOF - groups particles of approx overdensity - generates catalogs
- Merger trees: used to trace halo formation using progenitors / descendants



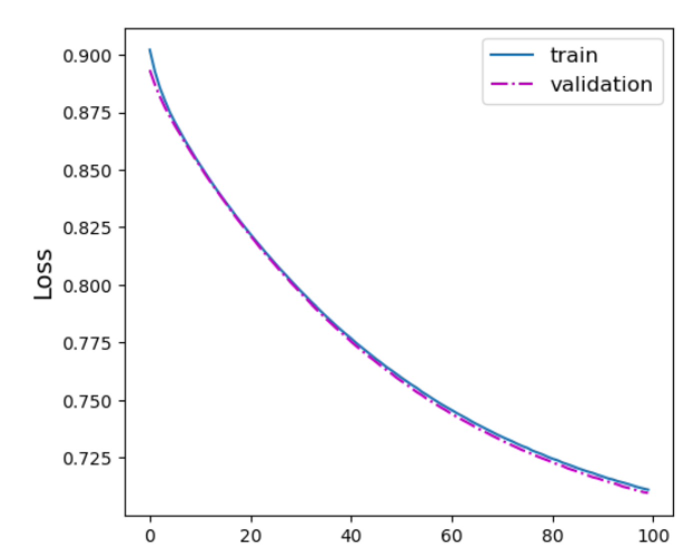
Convolutional Neural Network



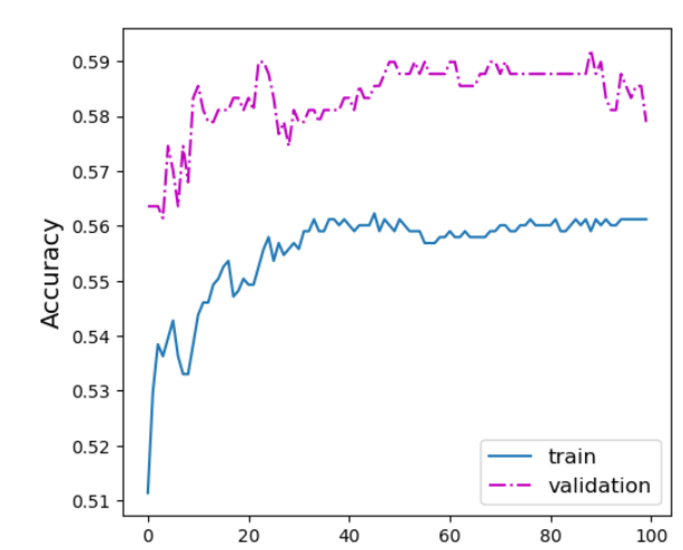
- We construct a convolutional neural network (CNN) which utilizes a binary classifier, 2 fully connected layers, and regularization to reduce overfitting
- Convolutional operations at each stage extract important features and pass output through dense layers for classification
- CNN predicts whether a given halo is a MMP or not based on features about its 4 nearest neighbors

Hyperparameter Optimization

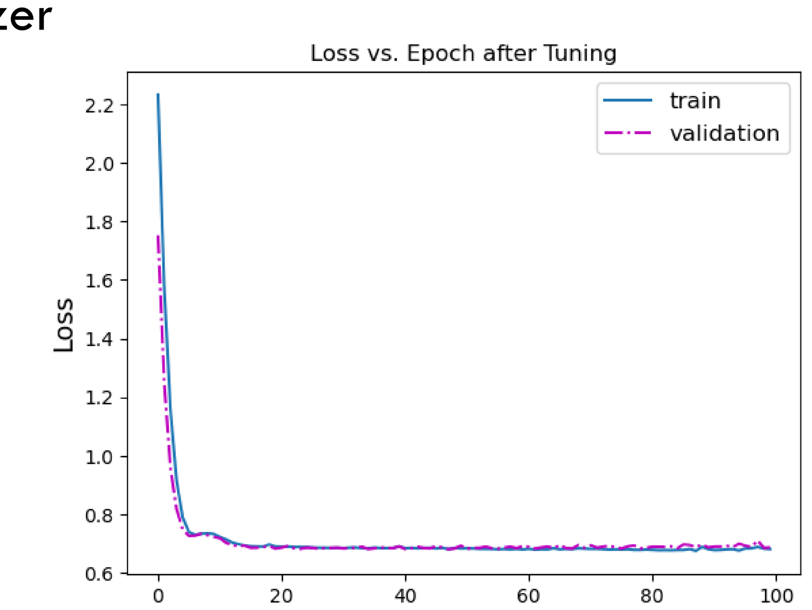
Loss vs. Epoch



Accuracy vs. Epoch

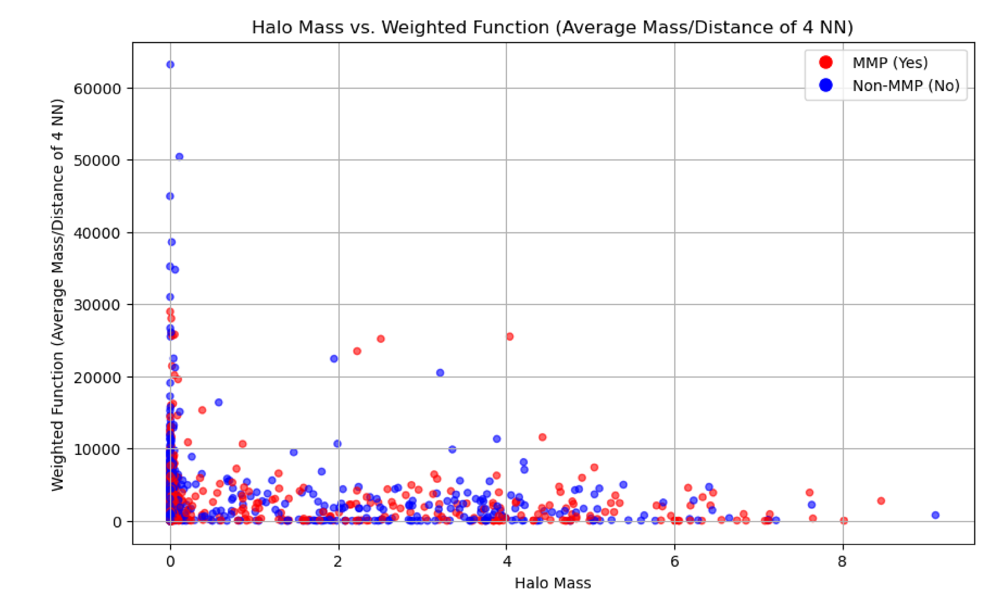


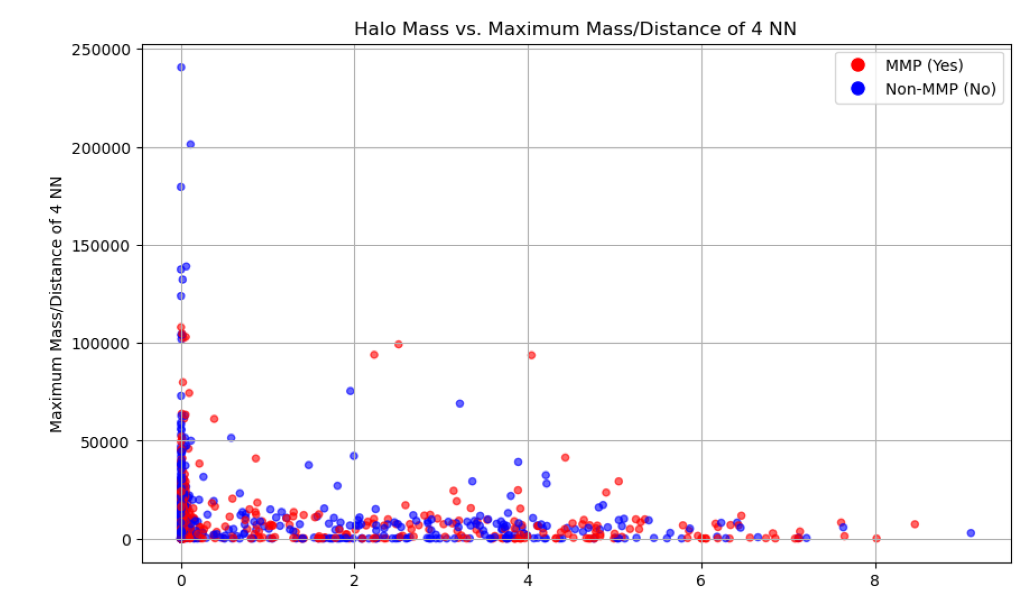
- To improve the performance of training and validation data, we use keras to tune hyperparameters such as the numbers of layers, learning rate, epochs, and choice of optimizer



Results

Nearest Neighbor Information:





False Negatives/False Positives

	Predicted Negative (0)	Predicted Positive (1)
Actual Negative (0)	144	255
Actual Positive (1)	103	323

Overall Accuracy (Training Set): 56.61%

Future Work

- To reduce overfitting, we can increase size of dataset and investigate a variety of power spectra
- We can utilize information about MMP status in order to predict halo evolution without having to run an entire simulation

References

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4. Ramanah (2019). Painting halos from cosmic density fields of dark matter with physically motivated neural networks.
5. Acquaviva (2023). Machine Learning for Physics and Astronomy