Classical Machine Learning **significantly outperforms** linear regression when predicting the properties of **Quasi-Periodic Oscillations** in Black Holes.

Leveraging Machine Learning and Game Theory to Detect and Characterize Quasi-Periodic Oscillations in X-ray Binaries

Introduction

Almost all X-ray Binaries are transient systems which vary in measurable ways (including their luminosity, disk temperature, hardness, etc.) over the course of their outbursts. The values of these parameters, as well as the presence and properties of Quasi-Periodic Oscillations (QPOs) are used to classify their accretion states.

QPOs are rapid flickers in the X-ray light from X-ray binaries that are revealed in a source's Power-Density Spectra. Although they correlate with different outburst properties, no conclusive explanation has been agreed upon for the origin. Nevertheless, understanding QPOs is a crucial priority in Astronomy because they test the predictions of generality relativity in the strong gravity regions around Neutron Stars and Black Holes.

Methods

We evaluated our approach on 555 energy spectra and power-density spectra observations of the black hole GRS 1915+105 using archival data from the Rossi X-ray Timing Explorer (RXTE) telescope, and 270 observations of the black hole MAXI J1535-571 from the NICER space telescope.

After using repeated k-fold validation for hyperparameter tuning, we trained a linear regressor and four tree-based classical machine learning models to predict the number of QPOs present based on either raw energy spectra data or processed and physically-motivated features derived from the XSPEC modeling suite. We also trained these models to predict the properties of present QPOs as parameterized by Lorentzian distributions.

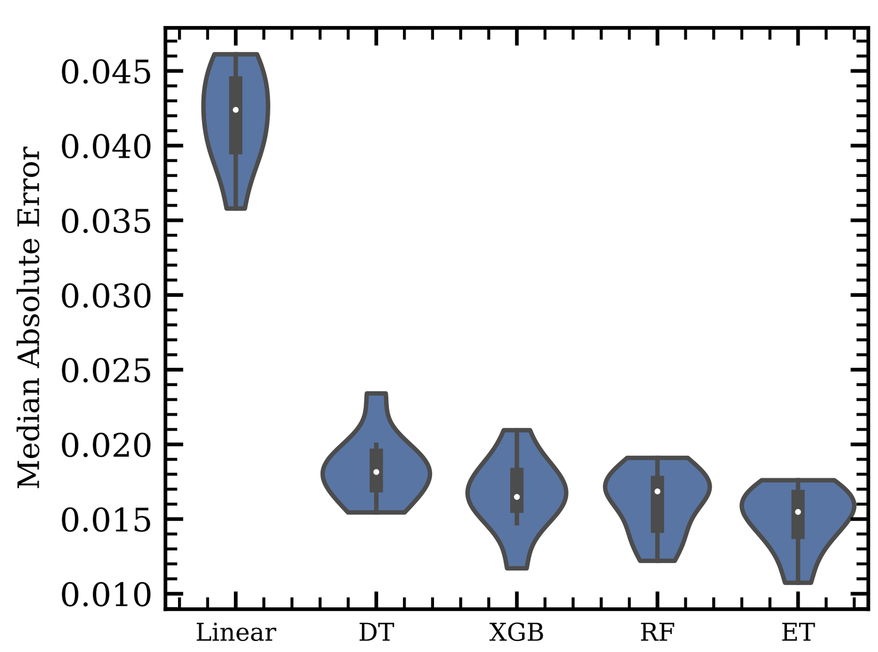
To avoid issues associated with default or permutation based feature importances, we employed the game theoretic and computationally optimized `TreeSHAP` algorithm to determine SHapley Additive exPlanation (SHAP) feature importances for each machine learning model.

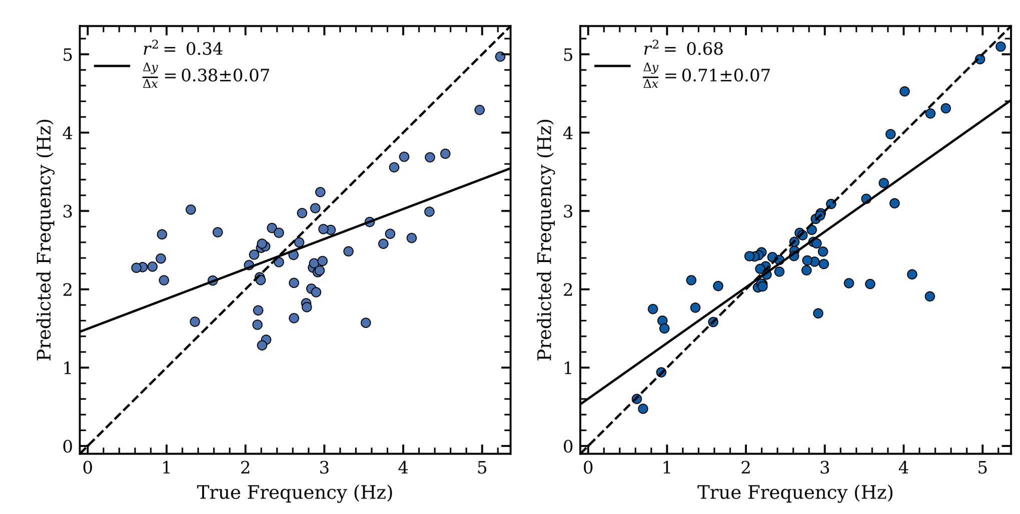
Results

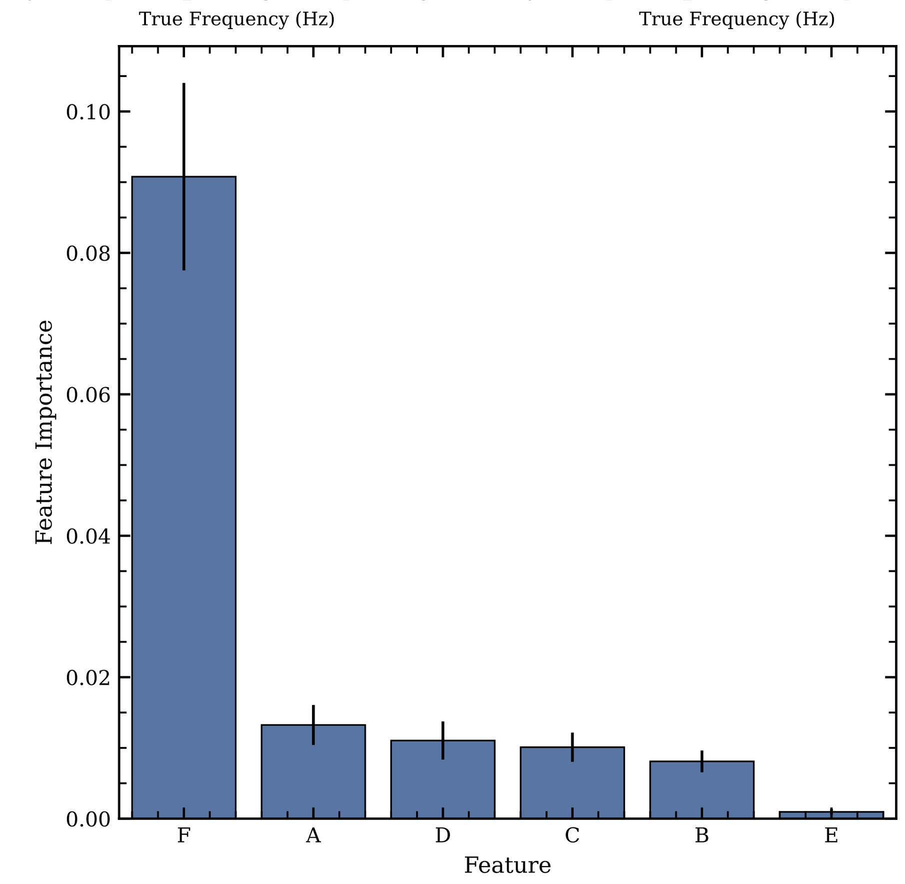
All tested regression models yielded significantly better results on MAXI 1535-571 versus GRS 1915+105 data (as determined by Diebold-Mariano corrected paired t-tests and Benavoli Bayesian comparisons), despite the latter having 6x more data with QPOs and no issue with QPO absent observations. We attributed this to the multitude of unusual variability classes unique to GRS 1915+105.

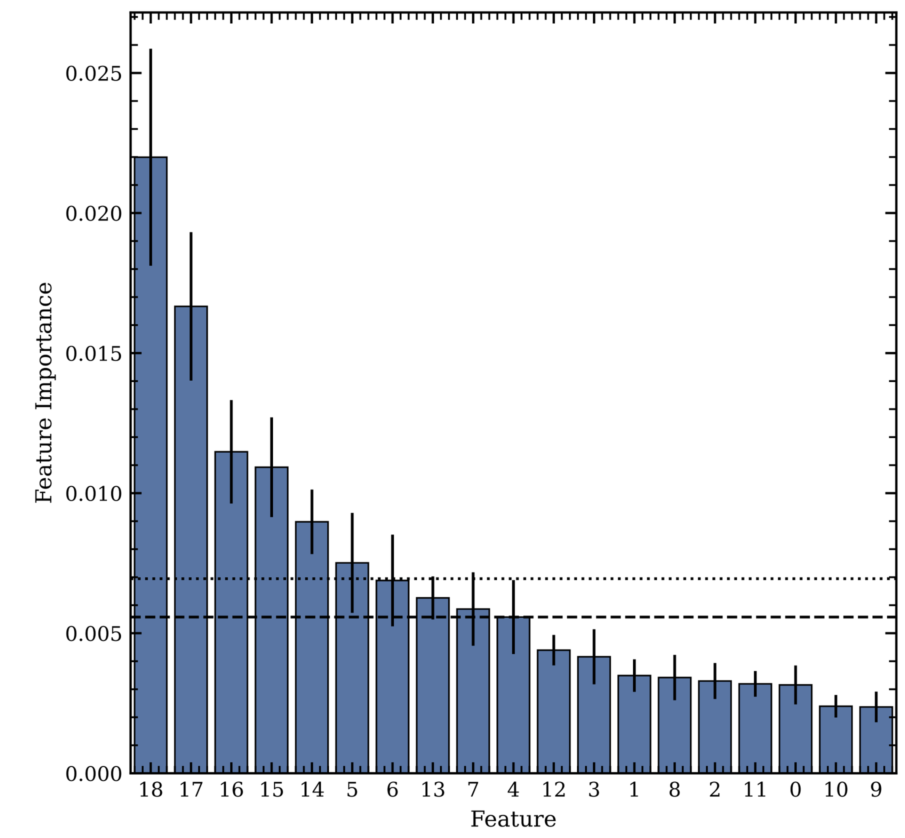
Using rebinned raw spectral data as opposed to XSPEC derived features resulted in significantly worse performance for regression, binary classification, and multiclass classification on MAXI J1535-571 observations.

The most significant features for GRS 1915+105 were net count rate and hardness ratio, whereas the same models predicting for MAXI J1535-571 found diskbb normalization most important, which suggests a dependence on physical inner disk radius.









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