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A neural-network emulator for the Lyman-α flux power spectrum

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The Lyman-α forest presents a unique opportunity to study the distribution of matter in the high-redshift universe and extract precise constraints on the nature of dark matter, neutrino masses, and other extensions to the ΛCDM model. However, accurately interpreting this observable requires precise modeling of the thermal and ionization state of the intergalactic medium, which often relies on computationally intensive hydrodynamical simulations. In this study, we introduce the first neural-network emulator capable of rapidly predicting the one-dimensional Lyman-α flux power spectrum (P_{1D}) as a function of cosmological and IGM parameters.
Traditionally, Gaussian processes have been the preferred choice for emulators due to their ability to make robust predictions with fewer training data points. However, this advantage comes at the cost of runtimes that scale cubically with the number of data points. With the continuous growth of training data sets, the need to transition to algorithms such as neural networks becomes increasingly crucial. Unlike other methods, neural networks provide a linear scaling between time and the number of training points. This scalability is particularly advantageous as it allows for efficient processing even with large datasets. Additionally, the use of GPUs further accelerates neural-network computations, enhancing the speed and efficiency of the training process.
Our emulator has been specifically designed to analyze medium-resolution spectra from the Dark Energy Spectroscopic Instrument (DESI) survey, considering scales ranging from $k_{\parallel}$ = 0.1 to 4 Mpc^{-1} and redshifts from z = 2 to z = 4.5. DESI employs a sophisticated instrument equipped with thousands of optical fibers that simultaneously collect spectra from millions of galaxies and quasars. Indeed, DESI started 2 years ago, and it has already doubled the amount of quasar spectra previously obtained.
Our approach involves modeling P_{1D} as a function of the slope and amplitude of the linear matter power spectrum, rather than directly as a function of cosmological parameters. We demonstrate that our emulator achieves sub-percent precision across the entire range of scales. Additionally, the emulator maintains this level of accuracy for three ΛCDM extensions: massive neutrinos, running of the spectral index, and curvature. It also performs at the percent level for thermal histories not present in the training set.
To emulate the probability distribution of P_{1D} at any given k scale, we employ a mixture density network. This allows us to estimate the emulator's uncertainty for each prediction, enabling the rejection of measurements associated with high uncertainty. We have observed that the neural network assigns higher uncertainties to inaccurate emulated P_{1D} values and to training points that lie close to the limits of the convex hull. Furthermore, by emulating the probability distribution of P_{1D}, we can estimate the covariance of the emulated values, providing insights into the correlation at different scales. While further investigations are required to enhance our understanding of P_{1D} measurement covariances, we are pleased to note that, to the best of our knowledge, this study represents the first instance in which a complete emulator covariance is provided for P_{1D} emulators, rather than solely focusing on the diagonal elements.
Given the demonstrated sub-percent precision, robustness to ΛCDM extensions, and the ability to estimate uncertainties, we expect that the developed neural network emulator will play a crucial role in the cosmological analysis of the DESI survey.

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