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Learning the Reionization History from High-z Quasar Damping Wings with Simulation-based Inference

The damping wing signature of high-redshift quasars in the intergalactic medium (IGM) provides a unique way of probing the history of reionization. Next-generation surveys will collect a multitude of spectra that call for powerful statistical methods to constrain the underlying astrophysical parameters such as the global IGM neutral fraction as tightly as possible. Inferring these parameters from the observed spectra is challenging because non-Gaussian processes such as IGM transmission causing the damping wing imprint make it impossible to write down the correct likelihood of the spectra.

We will present a tractable Gaussian approximation of the likelihood that forms the basis of a fully differentiable Hamiltonian Monte-Carlo inference scheme implemented in JAX. Our scheme can be readily applied to real observational data and is based on realistic forward-modelling of high-redshift quasar spectra including IGM transmission and heteroscedastic observational noise. In contrast to most previous approaches, we do not only use the smooth part of the spectrum redward of the Lyman-alpha line to infer the quasar continuum but also the information encoded in the Lyman-alpha forest, taking into account the full covariance between the red and the blue part of the spectrum.

We improve upon our Gaussian likelihood approximation by learning the true likelihood with a simulation-based version of the inference scheme. To this end, we train a normalizing flow as neural likelihood estimator as well as a binary classifier as likelihood ratio estimator and incorporate them into our inference pipeline.

We provide a full reionization forecast for Euclid by applying our procedure to a set of realistic mock observational spectra resembling the distribution of Euclid quasars and realistic spectral noise. By inferring the IGM neutral fraction as a function of redshift, we show that our method applied to upcoming observational data can robustly constrain its evolution up to ˜5% at all redshifts between $6 < z < 11$.

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