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Simulation-based inference of dark matter properties in strong gravitational lenses

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Precision analysis of strong gravitational lensing images can in principle characterize the population of small-scale dark halos and consequentially constrain the fundamental properties of dark matter (DM). In reality, this analysis is extremely challenging, because the signal we are interested in has a sub-percent level influence on high-variance data dominated by statistical noise.
Robustly inferring collective substructure properties from gravitational lensing images requires marginalizing over all source, lens, and numerous subhalos and line-of-sight halos parameters. Thus, conventional likelihood-based methods would be extremely time-consuming, necessitating the exploration of a very high-dimensional parameter space, which is often intractable. Instead, we use a likelihood-free simulation-based inference (SBI) method called truncated marginal neural ratio estimation (TMNRE) that leverages neural networks to directly obtain low-dimensional marginal posteriors from observations.
We present a new multi-stage method that combines parametric lensing models and TMNRE to constrain the DM halo mass function cutoff scale. We apply our proof-of-concept pipeline to realistic, high-resolution, mock observations, showing that it enables robust inference through marginalization over source and lens parameters, and large populations of realistic substructures that would be undetectable on their own. These first results demonstrate that this method is imminently applicable to existing lensing data and to the large sample of very high-quality observational data that will be delivered by near-future telescopes.

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