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Interpretable Machine Learning for Constraining Self-Interacting Dark Matter in Galaxy Clusters

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Cold dark matter, the standard cosmological model, faces several challenges on small scales that self-interacting dark matter may help resolve. Traditional methods to constrain the nature of dark matter often rely on summary statistics, which discard much of the available information, or require complex and computationally expensive lensing models. Machine learning (ML) has gained traction in astronomy for its ability to extract features from high-dimensional data, but its black box nature raises concerns for scientific inference.
We present an interpretable ML algorithm for constraining the dark matter cross-section from cosmological simulations of galaxy clusters. Our algorithm embeds weak gravitational lensing maps into a low-dimensional latent space based on their similarity, allowing simulations to cluster based on their physical differences. This latent space provides a way to assess whether a test dataset, such as observations, lies within the training domain using a Bayesian framework, indicating whether any predicted parameter is reliable or requires extrapolation. We enforce one latent dimension to represent the dark matter cross-section, with each galaxy cluster acting as a sample from the simulation's cross-section posterior. By applying ensemble learning, we reduce the predictive uncertainty and tighten the posterior constraints on the cross-section for the test dataset. Our ML algorithm provides accurate parameter recovery alongside a measure of prediction confidence for improved ML trustworthiness.

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