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An universal equation to predict $\Omega_{\rm m}$ from halo and galaxy catalogues

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We present analytic equations that can infer $\Omega_{\rm m}$ from the positions and velocity modulus fields of dark matter halos and galaxies. We first train a graph neural network with a sparse latent space on halo catalogues from Gadget N-body simulations to perform field-level likelihood-free inference of $\Omega_{\rm m}$. The network is trained using the relative positions and velocity modulus of halos and is able to infer the value of $\Omega_{\rm m}$ a mean relative error of $\sim 6\%$. We then extract analytic equations that can approximate this learned model using symbolic regression and find that the equations preserve the accuracy with mean relative error of $\sim 7\%$. We find that model is extracting information on small scales of $\leq 1.35\ h^{-1}$Mpc. Additionally, we find that the equations also preserve the model robustness as they achieve comparable accuracy for predictions of $\Omega_{\rm m}$ for halo catalogues from thousands of N-body simulations run with five different N-body codes: Abacus, CUBEP^{3}M, Enzo, PKDGrav3, and Ramses. Similarly, they also also work when tested on thousands of state-of-the-art CAMELS hydrodynamic simulations run with four different codes and subgrid physics implementations. This demonstrates the abundance of robust information embedded in phase space distribution of cosmological structures. Moreover, in some cases the found analytic equations can extrapolate even better than the GNN when presented with data points that exist outside the range of previously encountered data. Our results illustrate the effectiveness of using symbolic regression to approximate sparse representations in GNNs to discover novel physical relations for field-level cosmological inference. We speculate that the found relations take advantage of the initial cosmic velocity fields which might be insensitive to baryonic effects on the considered scales where the linear Zel'dovich approximation dominates.

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