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Probing Dark Matter Models through Subhalo Populations

The nature of dark matter (DM), which constitutes about 80% of the Universe's matter, remains one of the most profound mysteries in physics. While the cold dark matter (CDM) paradigm successfully explains large-scale structure formation, small-scale tensions motivate the exploration of alternative DM models. These include warm DM, ultralight DM, and interacting DM candidates.

One promising avenue for testing DM models lies in analyzing subhalo populations - gravitationally bound structures within halos. Their abundance and distribution are sensitive to the underlying DM particle model and can be inferred through gravitational lensing observations, such as those provided by the James Webb Space Telescope (JWST). Accurate theoretical predictions for subhalo statistics across a range of redshifts and environments are essential for leveraging these observations.

To address this, we use the semi-analytic Galacticus model to predict subhalo populations and halo assembly histories with high computational efficiency compared to traditional N-body simulations. Galacticus employs merger tree algorithms, which trace the hierarchical growth of halos, allowing us to statistically characterize the formation histories of different DM models. Calibration against the MDPL and Symphony simulations shows initial agreement for progenitor mass functions down to three orders of magnitude below the mass of the main halo, including, for the first time non-CDM models. However, further refinements are required to achieve the precision needed for JWST's observations of massive halos in the range $10^{13} - 10^{14}\ M_{\odot}$.

We optimize Galacticus'"window function," which maps early-Universe DM density perturbations to late-time halo populations, using Markov Chain Monte Carlo techniques. These improvements enhance the accuracy of CDM predictions by an order of magnitude but reveal challenges in non-CDM cases due to noise and insufficient calibration data. Preliminary results suggest that distinct window functions may be necessary to model CDM and non-CDM scenarios. Ongoing efforts focus on refining these optimizations and incorporating additional metrics, such as halo formation times and merger histories, to validate Galacticus predictions.

By advancing the modeling of subhalo populations, this research bridges theoretical predictions with observational capabilities. Our framework will enable robust testing of DM models using data from JWST, LSST, and other forthcoming surveys, offering a path to uncovering the fundamental nature of dark matter and resolving key tensions in cosmology.

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