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Evaluating the origins of the secondary bias based on the correlation of halo properties with the linear density field

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Using two sets of large N-body simulations, we studied the origins of the correlations between halo assembly time ($z_{\rm f}$), concentration ($v_{\rm max}/v_{200}$), and spin (λ) with the large-scale evolved density field at given halo mass, namely, the secondary bias. We find that the secondary bias is a secondary effect resulting from the correlations of halo properties with the linear density estimated at the same comoving scale. Using the linear density on different scales, we find two types of correlations. The internal correlation, which reflects the correlation of halo properties with the mean linear over-density, $\delta_{\rm L}$, within the halo Lagrangian radius, $R_{\rm L}$, is positive for both $z_{\rm f}$ and $v_{\rm max}/v_{200}$, and negative for λ. The external correlation, which describes the correlation of halo properties with linear overdensity at $R > R_{\rm L}$ for a given $\delta_{\rm L}$, shows trends that are contrary to the internal correlation. Both of the external and internal correlations depend only weakly on halo mass, indicating a similar origin for halos of different masses. Our findings offer a transparent perspective on the origins of the secondary bias, which can be largely explained by the competition between the external and internal correlations with the correlation of the linear density field on different scales. The combination of these two types of correlations has the potential to establish the complex halo-mass dependence of the secondary bias observed in the simulations.

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