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Tracing the Imprint of the Cosmic Web and Tidal Anisotropy on Halo Assembly

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In the ΛCDM framework, the Universe appears homogeneous and isotropic on large scales. However, on scales below $\sim 100\,Mpc$, the matter distribution reveals a hierarchical pattern known as the cosmic web —an interconnected filamentary network that naturally emerges from the anisotropic gravitational collapse of the density field, driven by tidal forces that induce directional deformations. Using \textit{the Next Generation Illustris} (IllustrisTNG300-1) simulation, we investigate how the cosmic web and the local tidal environment regulate halo assembly through the tidal anisotropy parameter α_R, which quantifies the directional deformation of the gravitational field at the scale of dark matter haloes with masses in the range $10^{11} \leq M_h[h^{-1}M_\odot] \leq 10^{14.1}$. Our results reveal a strong dependence between halo formation time (z_H) and local tidal anisotropy. Low-mass haloes in highly anisotropic regions—typically associated with filaments —assemble earlier and show lower satellite richness, whereas haloes in more isotropic environments assemble later and host richer satellite systems. By combining α_R with the relative bias b_r, we find that low-mass haloes with early assembly times are preferentially located in regions of highest clustering and high α_R, highlighting the environmental origin of assembly bias. Meanwhile, the morphological environment type of the cosmic web shows no additional dependence on z_H once the halo mass is controlled. These findings suggest that α_R acts as both a driver and a regulator of structure growth, establishing a physical link between halo assembly, clustering strength, and the morphology of the cosmic web.

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