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SIDM with an observable $\Delta N_{\rm eff}$ in a $U(1)_D$ framework

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We propose a GeV-scale self-interacting dark matter (SIDM) candidate within a $U(1)_D$ extension of the Standard Model (SM), addressing small-scale structure anomalies in ΛCDM while predicting an observable contribution to $\Delta N_{\rm eff}$. The model introduces a fermionic DM candidate χ and a scalar ϕ, both charged under an unbroken $U(1)_D$ gauge symmetry. The self-interactions of χ are mediated by a light vector boson X^μ, whose mass is generated via the Stueckelberg mechanism. The relic abundance of χ is determined by thermal freeze-out through annihilations into X^μ, supplemented by a non-thermal component from the late decay of ϕ. Crucially, ϕ decays after Big Bang Nucleosynthesis (BBN) but before the Cosmic Microwave Background (CMB) epoch, producing additional χ and a dark radiation species (ν_S). This late-time production compensates for the underabundance from efficient annihilation into light mediators, while remaining consistent with structure formation constraints. The accompanying dark radiation yields a detectable $\Delta N_{\rm eff}$, compatible with Planck 2018 bounds and within reach of next-generation experiments such as SPT-3G, CMB-S4, and CMB-HD.

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