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Reconciling Cosmological Tensions with Inelastic Dark Matter and Dark Radiation in a $U(1)_D$ Framework

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We propose a novel and comprehensive particle physics framework that addresses multiple cosmological tensions observed in recent measurements of the Hubble parameter, S_8, and Lyman-α forest data. Our model, termed ‘{\bf SIDR+z_t}’ (Self Interacting Dark Radiation with transition redshift), is based on an inelastic dark matter (IDM) scenario coupled with dark radiation, governed by a $U(1)_D$ gauge symmetry. This framework naturally incorporates cold dark matter (DM), strongly interacting dark radiation (SIDR), and the interactions between these components. The fluid-like behavior of the dark radiation component which originates from the self-quartic coupling of the $U(1)_D$ breaking scalar, effectively mitigates both the Hubble and S_8 tensions by suppressing free-streaming effects. Simultaneously, the interacting DM-DR system attenuates the matter power spectrum at small scales, potentially reconciling discrepancies in Lyman-α (Ly-α) observations. The inelastic nature of DM provides a distinct temperature dependence for the DM-DR interaction rate determined by the mass-splitting between the inelastic dark fermions which is crucial for resolving the Ly-α discrepancies. We present a cosmologically consistent analysis of the model by solving the relevant Boltzmann equations to obtain the energy density and number density evolution of different species of the model. The DR undergoes two “steps” of increased energy density when the heavier dark species freeze out and become non-relativistic, transferring their entropy to the dark radiation and enhancing $\Delta N_{\rm eff}$. The analysis showcases the model’s potential to uphold the Big Bang Nucleosynthesis (BBN) prediction of $\Delta N_{\rm eff}$ but dominantly producing additional contributions prior to recombination, while simultaneously achieving correct relic density of DM though an hybrid of freeze-in and non-thermal production.

Authors: Dr CHOI, Ki-Young (Sungkyunkwan University); MAHAPATRA, Satyabrata (Sungkyunkwan University); Mr CHO, Wonsub (Sungkyunkwan University)

Presenter: MAHAPATRA, Satyabrata (Sungkyunkwan University)

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