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Dark matter particle properties from nonlinear structure formation and evolution in radiation and matter eras

We studied the formation and evolution of the nonlinear dark matter halo structures in different eras and identified a critical particle mass of 10^{12}GeV. Particles of this mass can have a free streaming mass comparable to the particle mass. Via direct collisions, these particles can form the smallest halo structure as early as 10^{-6}s with a critical density ratio of $32\pi^2$ in the radiation era. The characteristic halo mass follows a power-law scaling $\propto t^{5/2}$ and grows up to $10^8 M_\odot$ at the matter-radiation equality to allow for an early and rapid galaxy formation. In the matter era, the halo mass follows a linear scaling $\propto t$ and grows up to $10^{13} M_\odot$ at the present epoch that matches observations at $z = 0$. Universal scaling laws can be identified for dark matter haloes. On relevant scales r, these include a two-thirds law for the kinetic energy ($v_r^2 \propto \varepsilon_u^{2/3} r^{2/3}$) and a four-thirds law for the halo inner density ($\rho_r \propto \varepsilon_u^{2/3} G^{-1} r^{-4/3}$). Both Illustris simulations and rotation curves can confirm these scaling laws. By extending these scaling down to the smallest structure scale, a critical particle mass $m_X = (\varepsilon_u \hbar^5 G^{-4})^{1/9} = 10^{12}$GeV can be obtained. Here, $\hbar$ is the Planck constant. The associated binding energy $E_X = (\varepsilon_u^5 \hbar^7 G^{-2})^{1/9} = 10^{-9}$eV suggests a dark radiation field associated with the formation and evolution of haloes. If exists, axion-like dark radiation should be produced around $t_X = (\varepsilon_u^{-5} \hbar^2 G^2)^{1/9} = 10^{-6}$s (QCD phase transition) with a mass of $E_X = 10^{-9}$eV, a GUT scale decay constant 10^{16} GeV, or an effective axion-photon coupling 10^{-18}GeV^{-1}. The energy density of dark radiation is estimated to be about 1\% of the CMB photons. This work strongly suggests a heavy dark matter scenario with a critical particle mass of 10^{12}GeV, along with a light axion-like dark radiation associated with structure formation. Superheavy right-handed neutrinos of 10^{12}GeV can be a very promising candidate. The sterile neutrinos of this mass can account for the neutrino oscillations, dark matter, and baryon asymmetry at the same time and potentially stabilize the electroweak vacuum. More details can be found in arXiv:2202.07240.

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