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Dark matter and axion dark radiation properties from energy cascade in dark matter flow

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We present a new theory to predict dark matter (DM) particle mass, size, lifetime, and properties of possible dark radiation from DM particle decay. In self-gravitating collisionless dark matter, the existence of inverse mass and energy cascade from small to large scales facilitates the hierarchical structure formation. A scale-independent constant rate of energy cascade $\varepsilon_u \approx -4.6 \times 10^{-7} m^2/s^3$ can be identified. The energy cascade leads to a two-thirds law for pairwise velocity and a four-thirds law for halo density profile. Both scaling laws can be directly confirmed by N-body simulations and galaxy rotation curves. For collisionless dark matter with only gravity involved, scaling laws can be extended down to the smallest scale, where quantum effects become important. Combining ε_u, Planck constant $\hbar$, and gravitational constant G on that scale, we predict DM particles have a mass $m_X = (\varepsilon_u \hbar^5 G^{-4})^{1/9} = 0.9 \times 10^{12}$GeV, a size $l_X = (\varepsilon_u^{-1} \hbar G)^{1/3} = 3 \times 10^{-13}$m, and a lifetime $\tau_X = c^2/\varepsilon_u = 10^{16}$yrs, where c is the speed of light. The energy scale $E_X = (\varepsilon_u^5 \hbar^7 G^{-2})^{1/9} = 10^{-9}$eV strongly suggests a dark "radiation" field to provide a viable energy dissipation mechanism. If existing, the dark "radiation" should be produced by DM decay at early time $t_X = (\varepsilon_u^{-5} \hbar^2 G^2)^{1/9} = 10^{-6}$s (quark epoch) with a mass of 10^{-9}eV such that axion can be a very promising candidate. If axion is the dark "radiation" responsible for the energy dissipation, it should have a mass around 10^{-9}eV with a GUT scale decay constant 10^{16}GeV and an effective axion-photon coupling constant 10^{-18}GeV^{-1}. The dark radiation energy density is around $\Omega_a h^2 \approx 2.6 \times 10^{-7}$, which is about 1 percent of the photon energy in CMB. Parameterized by the increase in the effective number of neutrino, $\Delta N_{eff} = 0.02$ can be obtained. Since the DM particle mass m_X is only weakly dependent on ε_u as $m_X \propto \varepsilon_u^{1/9}$, the estimation of m_X should be pretty robust for a wide range of possible values of ε_u. If gravity is the only interaction and dark matter is fully collisionless, mass of 10^{12}GeV seems required to produce the given rate of energy cascade ε_u. In other words, if DM particle mass has a different value, there must be some new interactions beyond gravity. This work suggests a heavy dark matter scenario with a mass much greater than WIMPs. Potential extension to self-interacting dark matter is also presented. More details can be found at arXiv:2202.07240.

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