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Imprints of Axion's Evolution in CMB

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We studied the non-equilibrium dynamics of an axion-like particle (ALP) weakly coupled to a thermal bath and misaligned initial conditions. The ALP's evolution is studied to leading order in the ALP coupling to the bath but to all orders in couplings among the bath's degrees of freedom. Results are obtained using both Langevin equation derived from in-in formalism and quantum master equation, where consistencies and discrepancies of the two methods are identified and discussed. A quantum fluctuation-dissipation relation is revealed in in-in formalism. The solution exhibits damping of the misaligned condensate and thermalization with the bath. It describes a mixed dark matter scenario where the initial (cold) component decays and the thermalized (hot) component grows. ALP-photon coupling is calculated explicitly as a specific example, in which we found an enhancement to ALP's relaxation rate, a potential inverted phase transition, and the requirement of higher order derivative terms. The back reaction of ALP to the photon bath is also investigated. Due to the special coupling form $ga\vec{E}\cdot\vec{B}$, a Chern-Simons condensate is induced by the coherent axion field. Such a condensate will leave observable imprints in both CMB's Stokes parameters and quasi-axions in condense matter physics. In particular, these effects are at the leading order of axion-photon coupling due to the coherence of the axion field.

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