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Cosmological bounds on three scenarios of axion-like particles and condensates from non-equilibrium QFT

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We derive and review cosmological constraints on axion-like particles (ALPs), produced thermally via freeze-in through their interaction with gluons, photons and Standard Model (SM) fermions and non-thermally through the misalignment mechanism and decay of topological defects. In particular, we discuss the QCD, the photophilic and the photophobic ALP scenarios where the ALPs couple respectively to gluons and a hidden gauge sector generating a mass $m_{a,0}$ for the particle [1], couple primarily to photons and primarily to SM fermions [2].

We develop our calculations with a Liouville-Von Neumann equation, as in Ref. [3], and an approach through a Boltzmann transport equation, calculated through the 2PI effective action, as in Ref. [4]. We apply our results to evaluate the decay of condensates of the ALP field to free ALPs, gravitational waves, gluons, photons and SM fermions. Furthermore, we evaluate the production of thermal ALPs in the presence of ALP condensates. Finally, we study the resulting cosmological constraints in the parameter space $(m_a, g_{a\gamma\gamma})$, coming from the observational bounds on the birefringence of the CMB, the ALP contribution to the effective number of ultrarelativistic species ΔN_{eff} and from other known bounds on ALPs.

[1] A.Lella, E. Ravensburg, P. Carenza and M.C.D.Marsh, Supernova limits on ‘QCD axion-like particles’, arXiv:2405.00153 [hep-ph].

[2] S. Baumholzer, V.Brdar and E.Morgante, Structure Formation Limits on Axion-Like Dark Matter, JCAP 05 (2021), 004.

[3] S. Cao and D. Boyanovsky, Nonequilibrium dynamics of axionlike particles: The quantum master equation, Phys. Rev. D 107, 063518 (2023).

[4] Ai, WY., Beniwal, A., Maggi, A. et al. From QFT to Boltzmann: freeze-in in the presence of oscillating condensates. J. High Energ. Phys. 2024, 122 (2024).

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