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Detecting Ultralight Dark Matter with Matter Effect

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Ultralight particles, with a mass below the electronvolt scale, exhibit wave-like behavior and have arisen as a compelling dark matter candidate. A particularly intriguing subclass is scalar dark matter, which induces variations in fundamental physical constants. However, detecting such particles becomes highly challenging in the mass range above 10^{-6} eV, as traditional experiments face severe limitations in response time. In contrast, the matter effect becomes significant in a vast and unexplored parameter space. These effects include (i) a force arising from scattering between ordinary matter and the dark matter wind and (ii) a fifth force between ordinary matter induced by the dark matter background. Using the repulsive quadratic scalar-photon interaction as a case study, we develop a unified framework based on quantum mechanical scattering theory to systematically investigate these phenomena across both perturbative and non-perturbative regimes. Our approach not only reproduces prior results obtained through other methodologies but also covers novel regimes with nontrivial features, such as decoherence effects, screening effects, and their combinations. In particular, we highlight one finding related to both scattering and background-induced forces: the descreening effect observed in the non-perturbative region with large incident momentum, which alleviates the decoherence suppression. Furthermore, we discuss current and proposed experiments, including inverse-square-law tests, equivalence principle tests, and deep-space acceleration measurements. Notably, we go beyond the spherical approximation and revisit the MICROSCOPE constraint on the background-induced force in the large-momentum regime, where the decoherence and screening effects interplay.

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