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Ensemble-Averaged Axion–Photon Conversion in Turbulent Galaxy Clusters

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Axion-like particles (ALPs) coupled to photons can modify electromagnetic spectra through conversion in astrophysical magnetic fields. In galaxy clusters, turbulence makes this effect stochastic and strongly dependent on the magnetic-field realisation for individual sightlines. Recent work showed that averaging over ensembles of background active galactic nuclei transforms these fluctuations into a smooth, universal absorption-like feature, enhancing the sensitivity of cluster ALP searches [1,2]. We develop an analytic description of this ensemble-averaged signal and establish the connection between physical turbulence spectra and the domain models commonly used in numerical simulations.

Turbulent fields are often represented by uniform domains with sizes distributed as $p(\Delta) \propto \Delta^{\beta-1}$, while a physical turbulent field is characterised by $\langle |B_k|^2 \rangle \propto k^{-a-2}$, corresponding to an energy spectrum $\propto k^{-a}$ and $a = 5/3$ for Kolmogorov turbulence. In the perturbative regime, the ensemble-averaged conversion probability is determined by the one-dimensional power spectrum of the transverse field along the line of sight [3]. Matching the exact domain-model correlator to the turbulent structure function gives $\beta = a - 2$ for $1 < a < 2$. Consequently, Kolmogorov turbulence corresponds to $\beta = -1/3$, i.e. $p(\Delta) \propto \Delta^{-4/3}$, rather than $\beta = 2/3$ as used in [4]. We also show that $\beta > 0$ universally produces an effective k^{-2} spectrum because of the discontinuities at domain boundaries, while spectra with $a > 2$ cannot be reproduced by this class of models.

Using this correspondence, we derive the ensemble-averaged conversion probability in closed form for arbitrary $\Delta_{\min}/\Delta_{\max}$ and obtain a simple two-power-law approximation. The resulting feature starts at $\omega_c \sim m_a^2 \Delta_{\max}/2$, rises approximately as ω^a, and saturates at high energies with an amplitude controlled by the magnetic-field correlation length. Thus, the inertial-range turbulence fixes the spectral shape, while the high-energy plateau retains an $\mathcal{O}(1)$ sensitivity to the modelling of the largest field scales.

Our results provide an analytic dictionary between turbulent spectra and domain-size prescriptions, removing an ad hoc parameter from cluster ALP simulations. They also provide an analytic alternative to Monte-Carlo averaging over magnetic-field realisations, offering a practical framework for interpreting existing ensemble searches and constructing efficient templates for future observations [1,2].

References:
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