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Effective multi-axion cosmology and constraints from black hole superradiance

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Consistent string theory frameworks of quantum gravity often predict the existence of a plethora of ultralight pseudoscalar degrees of freedom forming the phenomenological landscape of the string axiverse. The complexity of the extra-dimensional compactification manifold and vacua in these models indicate these fields may well possess parameters spanning many decades, covering cosmologically significant scales. If the fields phenomenologically defining parameters, the axion mass, m_a, and (effective) decay constant, f_a, fall in specific ranges, then they may contribute to the cosmological dark sector as either dark matter or an effective cosmological constant. It is important therefore, to quantify the statistical properties for such fields under the assumption of a multifarious scalar component in the low energy spectrum and the viability these ubiquitous elements of string models provide correct theoretic solutions to cosmological paradigms. The powerful asymptotic nature of the limiting spectral distributions of large random matrices has incorporated itself into various areas associated to multi-field axion cosmology. These include models of inflation, quintessence, dark sector cosmology and explicit forms of the superpotential Hessian. The complexities of dealing with the complete UV theory space is often reduced by considering a series of simple yet very powerful nomothetic principles. These considerations see the theoretic conjecture of the string axiverse modelled as an effective field theory which encodes the theoretical uncertainty from the UV limit in the high-dimensional matrices present in the effective Lagrangian, greatly reducing the potential dimensionality of the model parameter space. In order to realise these objectives we will introduce a series of random matrix theory (RMT) inspired models based on axion field alignment and multivariate analysis considerations. We will also present an overview of an effective approach to the spectrum arising from the superpotential in explicit realisations of the string axiverse in G_2 compactified M-theory, which take universal forms at the level of an effective description using stochastic model parameters. Such models can be used to test the viability of axion contributions to the cosmic history using hierarchical Bayesian inference models on the simplified parameter space, along with possessing a susceptibility to machine learning techniques to draw conclusions on the validity of the existence of a string axiverse in the ultralight sector of cosmology. We will also demonstrate how these models can be used to draw inferences on the axion parameter space, using astrophysical spin measurements of stellar binary and supermassive black hole systems, which can exclude the existence of fields spanning a large portion of the ultralight bosonic mass parameter space, via the superradiance phenomenon. We will explore how these measurements are used to constrain properties of the universal statistical distributions in effective axiverse models, specifically the mass ranges and allowed numbers of fields present in the spectrum. Such a methodology generally excludes $N \geq 30$ axion-like fields with a range of mass distribution widths and central values spanning many orders of magnitude, covering axion phenomenologies important to the dark sector of cosmology and grand unified theories.

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