Axion-like particles in the post-inflationary Universe: dark matter and substructure

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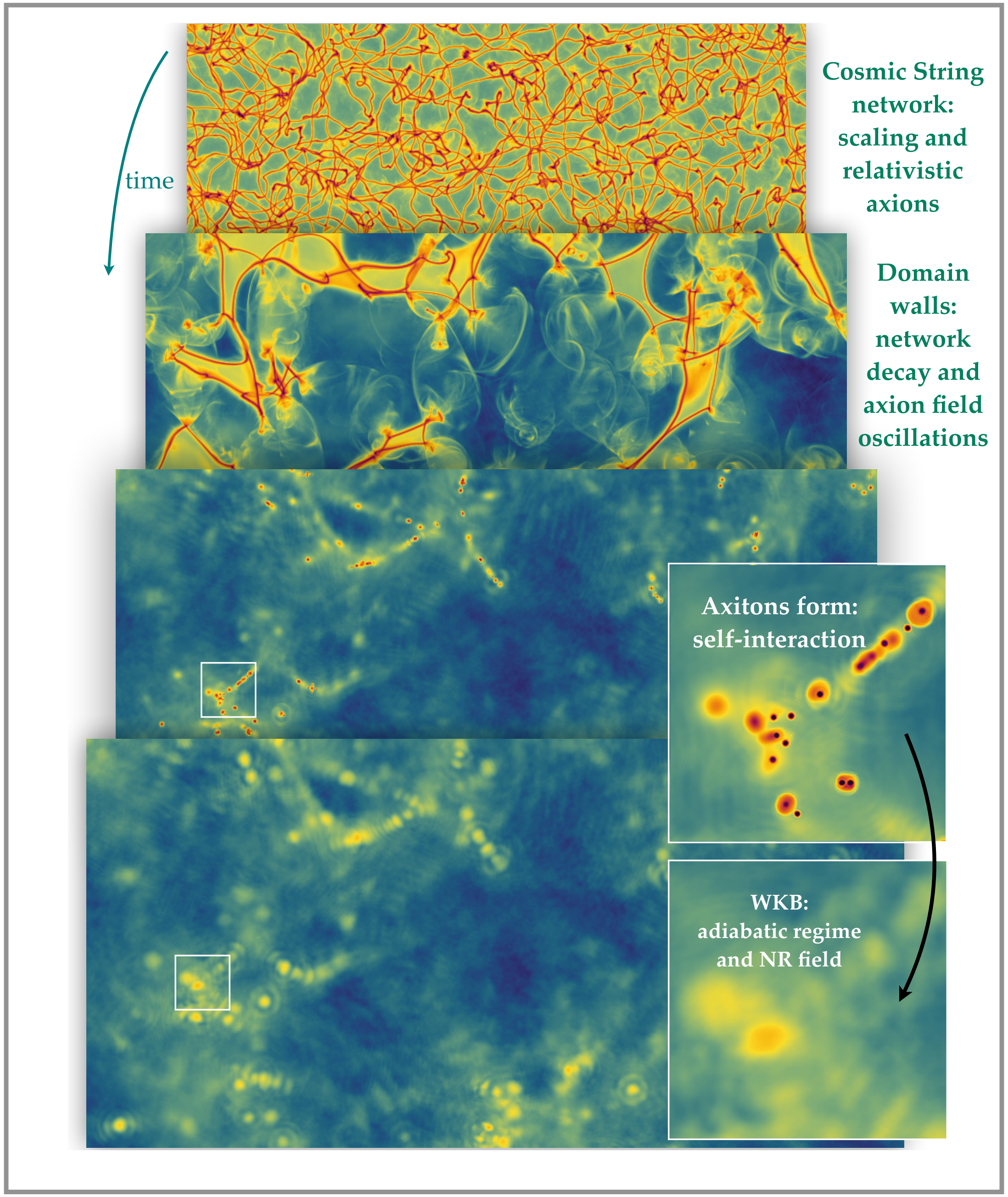

Overview

In the scenario in which the axion is born after inflation, its field develops significant inhomogeneity and evolves in a highly *nonlinear* fashion, demanding a numerical study. Here, we perform a suite of simulations on a periodic lattice for a class of axion-like particles that arise in the spontaneous breaking of a global $U(1)$ symmetry at an energy scale f_a and acquire a mass at a much smaller scale. We solve the equations for a complex field $\phi(x) = |\phi|e^{i\theta}$, under the potential

$$V = \frac{\lambda_\phi}{8}(|\phi|^2 - f_a^2)^2 + m_a^2(T) f_a^2 (1 - \cos\theta), \quad (1)$$

$$m_a^2(T) = m_a^2 \left(\frac{T_\star}{T}\right)^n, \quad (2)$$

and around the epoch where the Hubble scale is comparable to the mass m_a. Focusing on the impact of the parameter $n \in [0, 6]$, we study the complex dynamics of the axion field, including the scaling of cosmic strings and domain walls, the spectrum of non-relativistic axions, the lifetime and internal structure of axitons, and the seeds of miniclusters. We solve the full equation for the field ϕ until strings and walls collapse entirely and the equation for $\theta = a/f_a$ afterwards. After the end of the simulation we apply an adiabatic (WKB) approximation to remove self-interactions and axitons, and study the non-relativistic axion field. We emphasize some of the *highlights*:

* We performed 10 simulations per $n \in [0, 6]$ with a lattice size of 3072^3 uniformly distributed points. This allows us to avoid any unphysical destruction of domain walls and study the axion field deep in the non-relativistic regime.
* We analyse for first time axion-like particles with general mass dependence, including the temperature-independent $n = 0$ case.
* We resolve small scale structure at late times in the simulation, represented by pseudo-breathers known as *axitons*, and statistically analyse their properties.

Main Results

We compute the comoving axion number density n_a, constant in the adiabatic regime, and calculate the axion production efficiency when compared to the misalignment calculation. We study the distribution of density fluctuations in the axion energy ρ_a, through the dimensionless power spectrum Δ_a^2.

* We find that the smaller-n cases are considerably more efficient at producing axions, with the temperature-independent case being the most efficient of all. The presence of topological defects leads to 25% more DM than the misalignment calculation in the $n = 0$ case.
* We observe a coherent trend of increasing density correlations towards smaller scales as we increase n up to QCD values ($n \gtrsim 6.7$). This observation modifies the naive assumption that spatial fluctuations—and subsequently the seeds of miniclusters—occur on scales $\sim L_1$, the latter being the comoving horizon size when $H \sim m_a$.