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Impact of Adiabatic Fluctuations on Axion Minicluster Formation in Pre-Inflationary Scenarios

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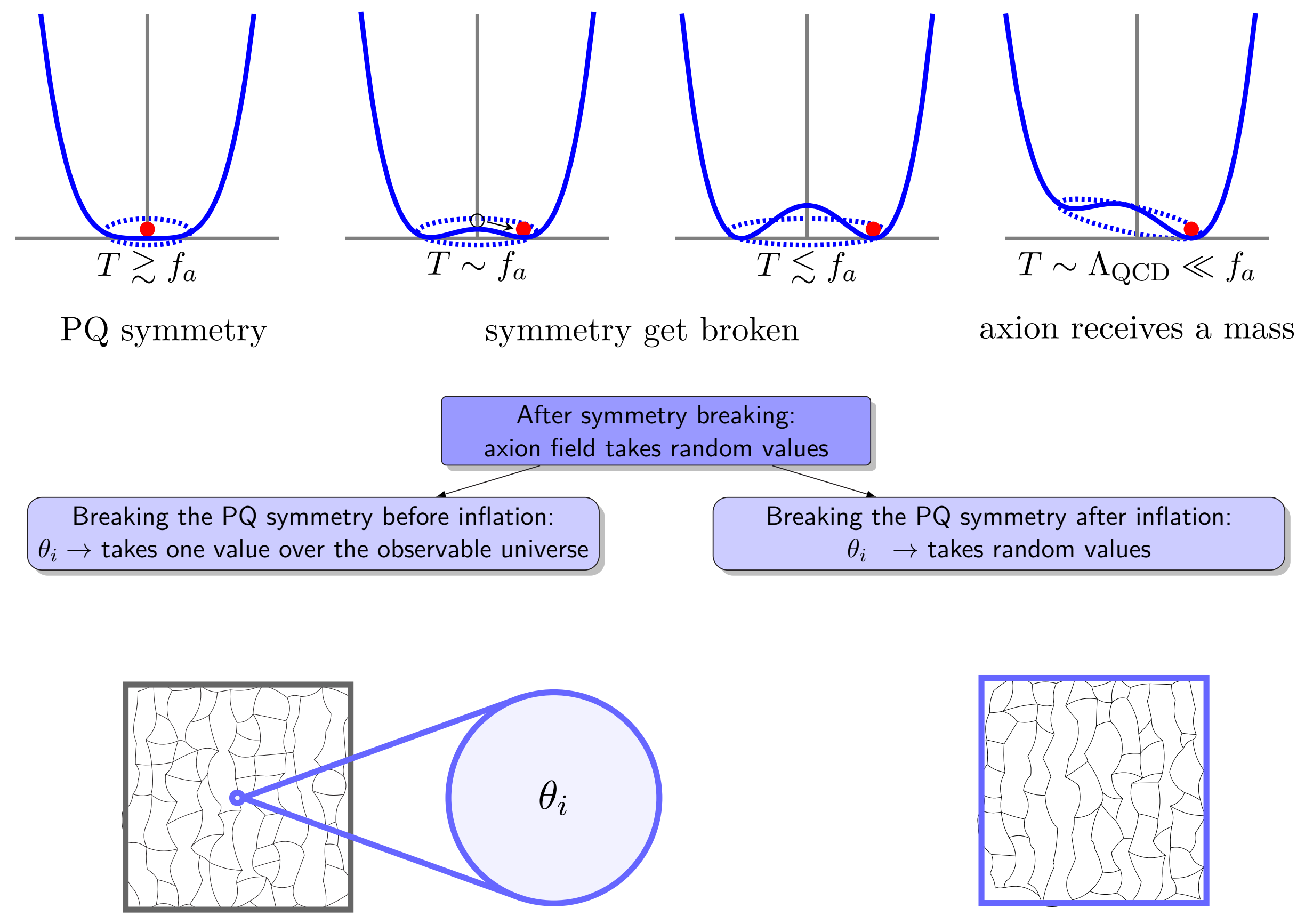
Strong-interaction matter under extreme conditions

Abstract

This study explores the crucial role of adiabatic fluctuations in the formation of axion miniclusters (AMC) and their implications the axion as a potential dark matter candidate in scenarios where the Peccei-Quinn symmetry is spontaneously broken before the end of inflation. We investigate the distribution of energy density and power spectrum of axion density fluctuations, accounting for both quantum and adiabatic fluctuations. Our analysis reveals a significant impact of adiabatic fluctuations, especially on large scales, which alters the formation of AMC and shapes the power spectrum distribution. This highlights the importance of considering adiabatic fluctuations for a comprehensive understanding of axions and their cosmological significance, particularly in the context of low-energy inflation models.

Introduction

- Axions are cold dark matter candidates, with their relic abundance determined by various production mechanisms. AMC formation, influenced by perturbations post-inflation, is pivotal. We investigate AMC formation pre-inflation, focusing on adiabatic fluctuations' impact. Debate centers on whether AMC detection can distinguish pre- vs. post-inflation axion origin.



After symmetry breaking:
axion field takes random values

Breaking the PQ symmetry before inflation:
$\theta_i \rightarrow$ takes one value over the observable universe

Breaking the PQ symmetry after inflation:
$\theta_i \rightarrow$ takes random values

Inhomogeneous Dynamics of Axion Field

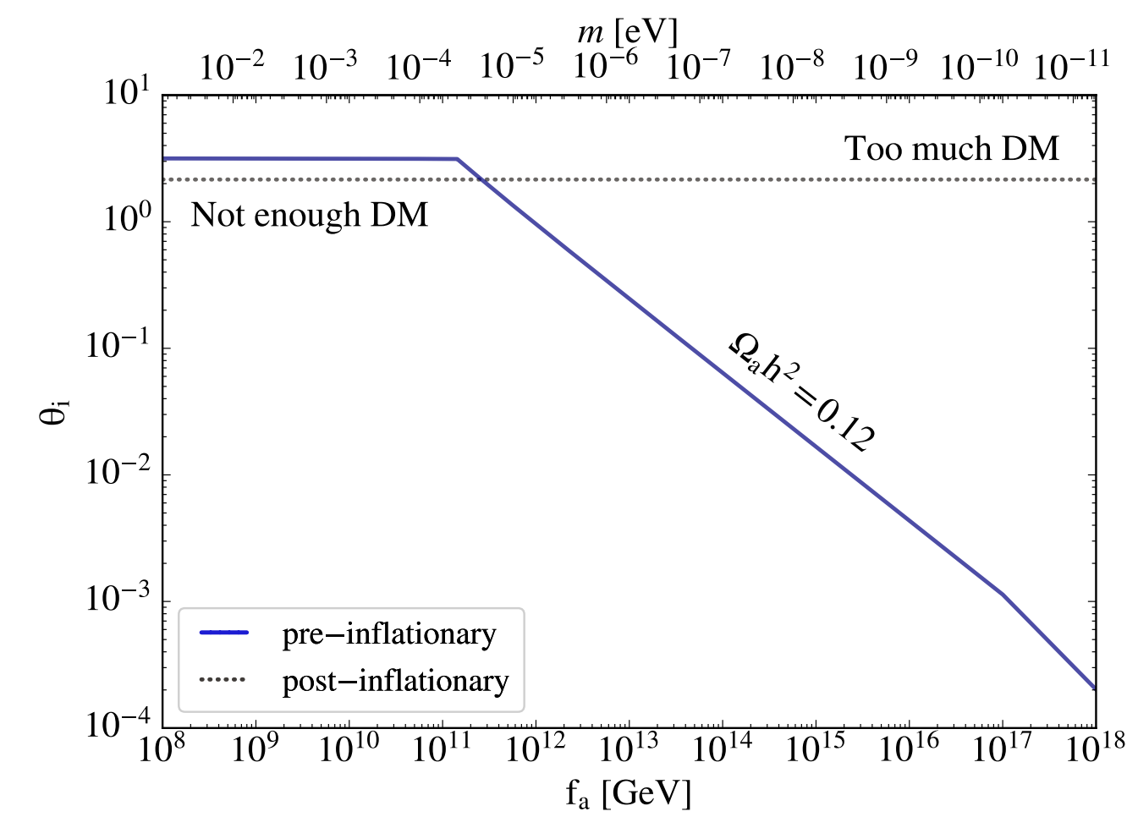
- The axion field starts to oscillate when the axion mass becomes comparable to the Hubble scale at $T_{\rm osc}$.
- Introducing fluctuations in both the axion field, $\vartheta(\mathbf{k},T) = \bar\vartheta(T) + \delta\vartheta(\mathbf{k},T)$, and temperature, $T(\mathbf{k}) = \bar T + \delta T(\mathbf{k},\bar T)$, the axion equation of motion decouples into homogeneous and inhomogeneous components:

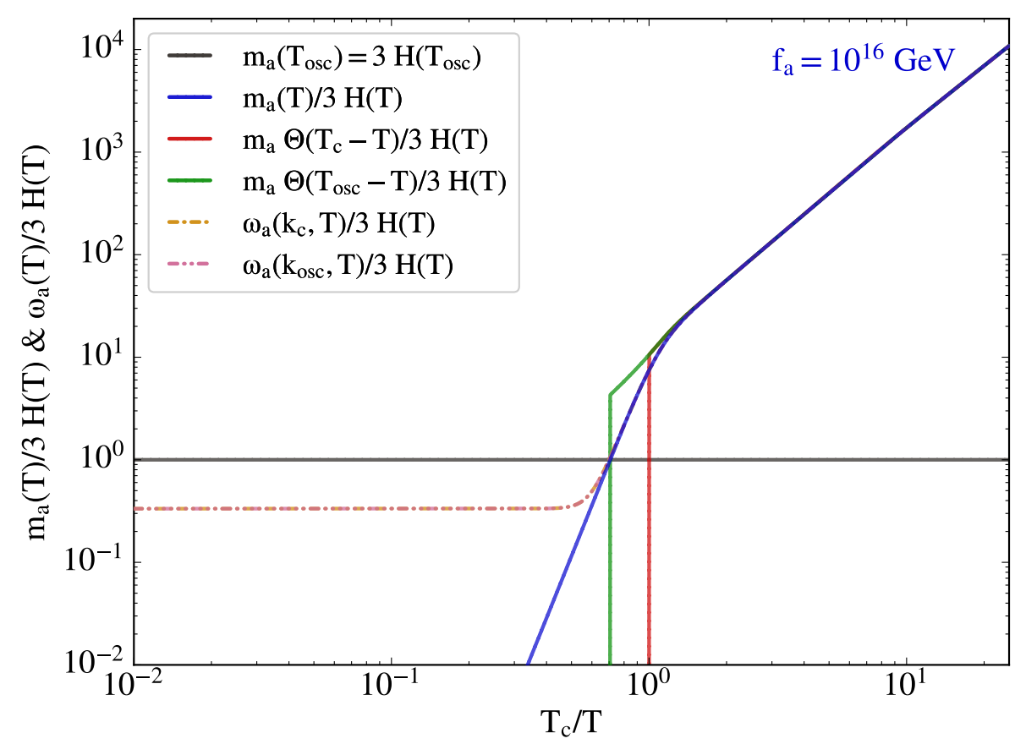
$$\frac{d^2\bar\vartheta}{dT^2} + \left(3H(\bar T)\frac{dt}{dT} - \frac{d^2t}{dT^2}\Big/\frac{dt}{dT}\right)\frac{d\bar\vartheta}{dT} + m_a^2(\bar T)\left(\frac{dt}{dT}\right)^2\bar\vartheta = 0\,,$$

$$\frac{d^2\delta\vartheta}{dT^2} + \left(3H(\bar T)\frac{dt}{dT} - \frac{d^2t}{dT^2}\Big/\frac{dt}{dT}\right)\frac{d\delta\vartheta}{dT} + \left(\frac{k^2}{R^2(\bar T)} + m_a^2(\bar T)\right)\left(\frac{dt}{dT}\right)^2\delta\vartheta = -\frac{\partial m_a^2(\bar T)}{\partial\bar T}\bar\vartheta\delta T\,.$$

- Assuming that axions suddenly acquire their masses at $T_{\rm osc}$, the perturbed equation can be reduced to a simpler form with the right-hand side equal to zero and the following initial conditions:

$$\delta\vartheta(\mathbf{k},T_{\rm osc}) = 0, \quad \delta\dot\vartheta(\mathbf{k},T_{\rm osc}) = m_a^2\bar\vartheta(\bar T_{\rm osc})\frac{1}{3c_s^2(\bar T_{\rm osc})}\frac{1}{H(\bar T_{\rm osc})}A_k\cos\big(c_s k\tau(\bar T_{\rm osc})\big)\,.$$

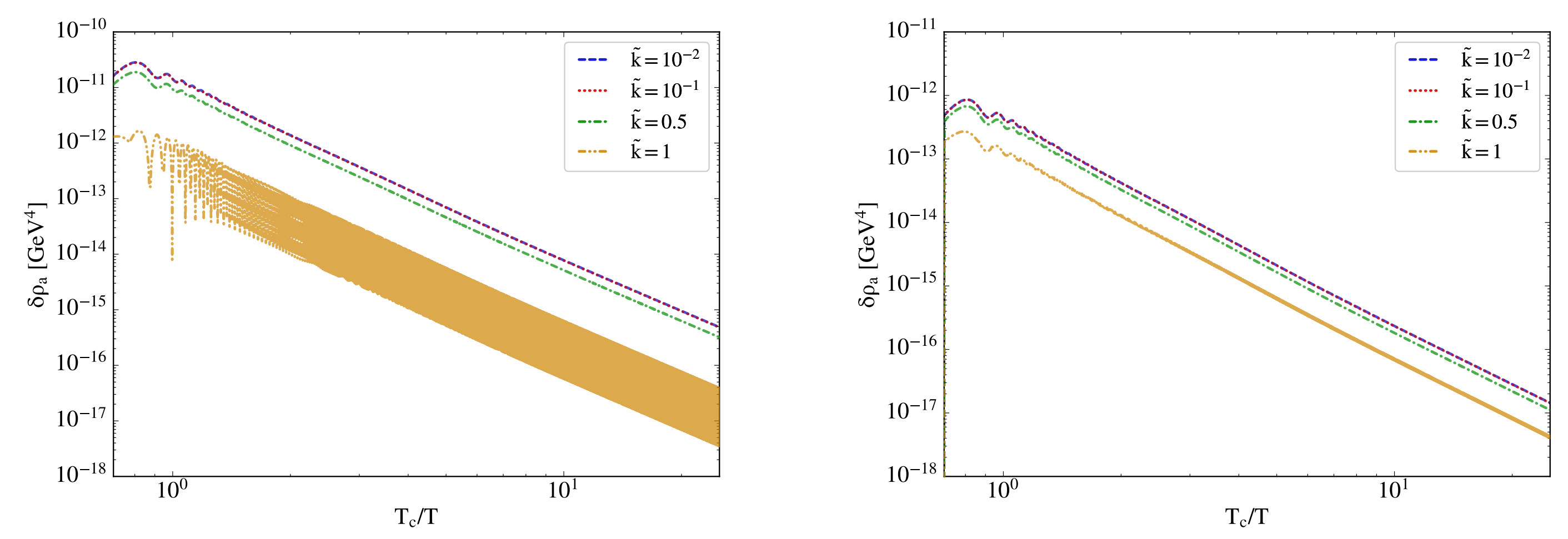




Axion Energy Density Distribution

- The axion background energy density, $\bar\rho_a$, and the contribution of each k mode to the energy density perturbation, $\delta\rho_a(k)$, are

$$\bar\rho_a = f_a^2\left(\tfrac{1}{2}\dot{\bar\vartheta}^2 + \tfrac{1}{2}m_a^2\bar\vartheta^2\right)\;;\quad \delta\rho_a(k) = f_a^2\left(\dot{\bar\vartheta}\delta\dot\vartheta(k) + m_a^2\bar\vartheta\delta\vartheta(k)\right)\,.$$



Density perturbation for different k modes with quantum field fluctuations (left) and induced by temperature fluctuations (right), $f_a = 10^{16}$ GeV, $\tilde k \equiv k/k_{\rm osc}$.

Power Spectrum of the Density Fluctuations

- The fluctuation in the axion energy density, $\delta_a(\mathbf{x})$, relative to the background density characterizes density perturbations

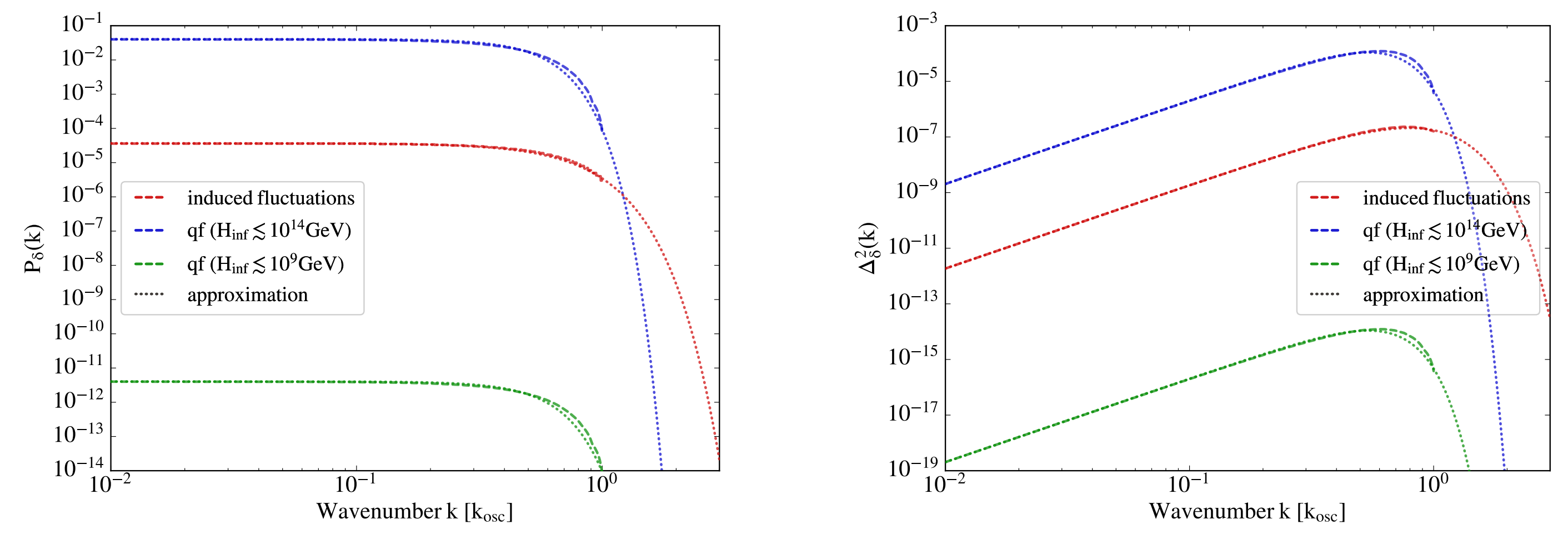
$$\delta_a(\mathbf{x}) = \frac{\delta\rho_a(\mathbf{x})}{\bar\rho_a}\,.$$

- We estimate the power spectrum, $P(\mathbf{k})$, which can be fitted by exponential suppression at large k

$$P(\mathbf{k}) \propto \left(\frac{|\delta\vartheta|}{|\bar\vartheta|}\right)^2 \quad \text{and} \quad P(\mathbf{k}) \simeq \frac{1}{(2\pi)^3}\exp\left(-\frac{k}{K}\right)\left(\frac{|\delta\vartheta_i|}{|\bar\vartheta_i|}\right)^2\,.$$

- We also employ the dimensionless power spectrum, $\Delta^2(\mathbf{k})$,

$$\Delta^2(\mathbf{k}) = \frac{k^3}{2\pi^2}\,P(\mathbf{k})\,.$$



Power spectrum (left) and dimensionless power spectrum (right) from quantum field fluctuations and induced by temperature fluctuations (dashed), with fitted approximation (dotted).

Summary and Outlook

- In conclusion, our analysis highlights the significant influence of adiabatic fluctuations on axion density perturbations, surpassing quantum fluctuations by a few orders of magnitude in low-energy inflation models.
- By examining the power spectrum and dimensionless power spectrum, we underscore the necessity of considering both types of fluctuations for a comprehensive understanding of axion density dynamics, especially concerning AMC formations.
- Our findings emphasize the importance of further research to elucidate the intricate relationship between inflationary dynamics, pre-inflationary mechanisms, and AMC formation, crucial for deciphering the true origin of axion dark matter in the Universe. Addressing these complexities will advance our understanding of axions and their cosmological implications, offering insights into the cold dark matter puzzle.

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