Production and Evolution of Dark Matter Axions in the Early Universe

Ken'ichi Saikawa[1], *Takashi Hiramatsu*[2], *Masahiro Kawasaki*[3,4], *Toshifumi Noumi*[5], *Ryosuke Sato*[6], *Toyokazu Sekiguchi*[7], *Masahide Yamaguchi*[1]

[1]Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[2]Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto, Japan
[3]Institute for Cosmic Ray Research, The University of Tokyo, Chiba, Japan
[4]Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, The University of Tokyo, Chiba, Japan
[5]Mathematical Physics Laboratory, RIKEN Nishina Center, Saitama, Japan
[6]Theory Center, High Energy Accelerator Research Organization (KEK), Ibaraki, Japan
[7]Helsinki Institute of Physics, University of Helsinki, Finland

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Production mechanisms and interaction properties of dark matter axions are investigated. The decay of string-wall systems gives an additional contribution to the dark matter abundance, which implies that the axion becomes dark matter in the high mass range of $\mathcal{O}(10^{-4}\text{–}10^{-2})$eV. The structure of gravitational self-interactions of coherently oscillating axions is also evaluated, and it turns out that their self-interaction rate can be relevant in their late time evolution.

1 Introduction

The axion [1, 2] is a hypothetical particle predicted by the Peccei-Quinn (PQ) mechanism as a solution of the strong CP problem of quantum chromodynamics (QCD) [3, 4]. Since it has tiny couplings with ordinary matter and it is highly non-relativistic at the time when it was produced, it can be a good candidate of the cold dark matter of the universe. Identifying the cosmological behavior of the dark matter axions is important not only to understand the early history of the universe, but also to distinguish them from other dark matter candidates.

In this work, we investigate the production and evolution of the axions in the early universe. For the cold dark matter axions, there are three major production mechanisms: One is the misalignment mechanism [5, 6, 7], which induces the coherent oscillation of the axion field. The second is the production from global strings [8], which occurs during the epoch between the PQ phase transition and the QCD phase transition. The last one is the production from the string-wall systems [9, 10], which occurs after the QCD phase transition. The latter two become relevant only if the PQ symmetry is broken after inflation. In the following sections, we first discuss the recent development on the estimation of the abundance of axions produced from the string-wall systems. After that, we switch our attention to the evolution of axions, and address the question whether they form a Bose-Einstein condensate (BEC).

2 Axion production from topological defects

In the invisible axion models [11], we must introduce an additional $SU(2)_L \times U(1)_Y$ singlet scalar field Φ. Let us call this field the PQ field. This field is charged under the global $U(1)_{\mathrm{PQ}}$ symmetry, which is spontaneously broken due to the potential of the form $V(\Phi) = \frac{\lambda}{4}(|\Phi|^2 - \eta^2)^2$. This occurs when the temperature of the universe becomes less than the scale η, and at that time the line-like objects called strings are formed. Then, the axion field $a(x)$ can be identified as the phase direction of the PQ field: $\Phi = |\Phi|e^{ia(x)/\eta}$.

The axion acquires a mass m_a due to the non-perturbative effect of QCD when the temperature of the universe becomes $T \lesssim \mathcal{O}(1)$GeV. We can model this effect by considering the following potential for the axion field:

$$V(a) = \frac{m_a^2\eta^2}{N_{\mathrm{DW}}^2}\left(1 - \cos\left(N_{\mathrm{DW}}\frac{a}{\eta}\right)\right), \tag{1}$$

where N_{DW} is an integer number called the domain wall number. There are N_{DW} degenerate vacua, and N_{DW} domain walls are formed around the boundary of different vacua [12]. Since the field a is the phase direction of Φ, these domain walls are attached to strings. We call such configurations the string-wall systems.

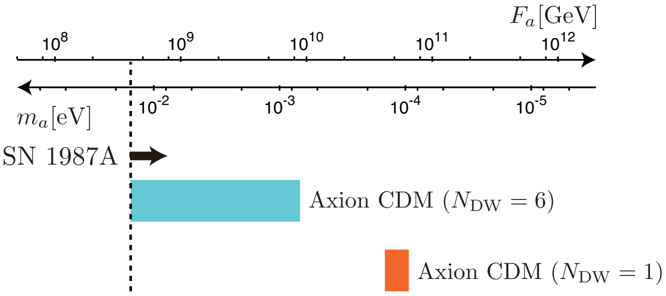

Figure 1: The mass ranges where the QCD axion explains the cold dark matter for the models with $N_{\mathrm{DW}} = 1$ (orange interval) and $N_{\mathrm{DW}} = 6$ (light blue interval).

The subsequent history after the QCD phase transition is different according to the value of the domain wall number. If $N_{\mathrm{DW}} = 1$, the string-wall systems are unstable, and they decay immediately after the formation. On the other hand, if $N_{\mathrm{DW}} > 1$, they are stable and come to overclose the universe, causing a problem in the standard cosmology [13]. This problem can be avoided by introducing an explicit symmetry breaking term in the potential of the PQ field [12], which induces the annihilation of domain walls at a late time.

We investigate these scenarios based on the lattice simulations of the PQ field. The simulations are executed by solving the classical field equation of Φ in the expanding universe. Using the results of the simulations, we estimate the spectrum of axions radiated from the string-wall systems. In the models with $N_{\mathrm{DW}} = 1$, the inclusion of the wall decay contribution [9] leads to the upper bound on the axion decay constant $F_a \lesssim (4.2\text{–}6.5) \times 10^{10}$GeV [14], which corresponds to the lower bound on the axion mass: $m_a \gtrsim (0.9\text{–}1.4) \times 10^{-4}$eV. The constraint becomes more severe for the models with $N_{\mathrm{DW}} > 1$, but there still exists a loophole if we allow a mild tuning of a theoretical parameter [10]. We note that there is a large systematic uncertainty on the determination of the lifetime of the domain walls in the models with $N_{\mathrm{DW}} > 1$ [15]. This kind of uncertainty is not reduced straightforwardly even in the recent numerical simulations with improved dynamical ranges [14].

In Fig. 1, we show the parameter range in which the axion can be dominant component of the cold dark matter for the models with $N_{\mathrm{DW}} = 1$ and $N_{\mathrm{DW}} = 6$. Here, we also show the lower bound on the axion decay constant $F_a > 4 \times 10^8$GeV obtained from the observation of the supernova (SN) 1987A [16]. Since the decay of the string-wall systems amplifies the energy density of dark matter axions, they explain the cold dark matter in the higher mass range [$m_a \approx \mathcal{O}(10^{-4}$–$10^{-2})$eV]. More extensive studies will be required to reduce the uncertainties of these theoretical predictions.

3 Evolution of axion dark matter in the condensed regime

Next, let us turn our attention to the evolution of the cold dark matter axions. Although their mass is as small as $\mathcal{O}(10^{-4}$–$10^{-2})$eV, they have an extremely small velocity dispersion because of the non-thermal production mechanisms. The smallness of the velocity dispersion implies that they have a large occupation number in the phase space. Regarding this fact, the authors of Refs. [17, 18] claimed that the axions exist in the form of a BEC. The point in Ref. [18] was that the BEC is defined in the thermal equilibrium state and that the system of dark matter axions can reach the thermal equilibrium due to the gravitational self-interactions. This phenomenon might lead to some observable signatures such as effects on the phase space structure of galactic halos [19] and those on the cosmological parameters [20].

Our aim here is to discuss the above issues more carefully. At this stage, we just expect that the system of dark matter axions develops toward the thermal equilibrium when the transition rate Γ between different momentum states exceeds the cosmic expansion rate H. The rate Γ can be estimated in terms of the time derivative of the expectation value of the operator $\mathcal{N}_{\mathbf{p}}$ corresponding to the occupation number of axions with the three-momentum $\mathbf{p}$. As a result of the calculation in the second quantized field theory, we obtain the following expression [21]:

$$\Gamma \simeq \frac{4\pi G m_a^2 n_a}{(\delta p)^2}, \tag{2}$$

where G is the Newton's constant, n_a is the number density of axions, and δp is their typical momentum dispersion. This rate indeed exceeds the expansion rate when the temperature of the universe becomes $T \sim$ keV [18, 21]. Although the above result was obtained for the Newtonian approximation for the gravitational interactions, we can obtain the similar result when we take account of the general relativistic corrections [22].

We note that the estimation given by Eq. (2) holds only if the initial state is given by the coherent state [21]. With the assumption that the axion field produced by the misalignment mechanism is described as the coherent state, we conclude that the gravitational self-interaction is relevant only for the misalignment axions. This result implies that the misalignment axions evolve differently from those produced by strings and domain walls, and it will be important to see how this difference affects the dynamics of Large Scale Structure [23].

4 Summary

We have investigated the production and evolution of axions in the early universe. Their total abundance is given by the sum of three contributions: axions produced from the misalignment mechanism, the decay of strings, and the decay of string-wall systems. We showed that the contribution from the decay of string-wall systems can be considerable and that the axion can be responsible for dark matter in the high mass range. We also showed that the gravitational self-interaction of the misalignment axions becomes relevant in their late time evolution. Further studies are needed to evaluate the observational consequences of these results.

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