

Cosmology of Supersymmetric Axion Models

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Abstract

We derive general cosmological constraints on supersymmetric extension of axion models, in particular paying careful attention to the cosmological effects of saxion. It is found that for every mass range of the saxion from $O(1)$ keV to $O(10)$ TeV, severe constraints on the energy density of the saxion are imposed. Together with constraints from axino, we obtain stringent upper bounds on the reheating temperature.

1 Introduction

Although the standard model in particle physics has achieved great successes, there still remain some theoretical problems. One is the strong CP problem, and another is the gauge hierarchy problem. In other words, these problems indicate the existence of the physics beyond the standard model.

A promising solution to the strong CP problem was proposed in the 1970's by Peccei and Quinn [1]. They introduced an anomalous $U(1)$ symmetry, called PQ symmetry, which is spontaneously broken at some energy scale F_a . From astrophysical and cosmological arguments, F_a is constrained as 10^{10} GeV $\lesssim F_a \lesssim 10^{12}$ GeV. A coherent oscillation of the axion, which is a pseudo-Nambu-Goldstone boson associated with spontaneous breaking of PQ symmetry, can be the cold dark matter of the universe for $F_a \sim 10^{12}$ GeV.

On the other hand, supersymmetry (SUSY) is also well-motivated from particle physics point of view. First, SUSY provides a solution to the gauge hierarchy problem. Due to the symmetry between a scalar and fermion, radiative corrections to the Higgs scalar mass squared are canceled and quadratic divergent quantity disappears. Thus the weak scale becomes stabilized against the radiative correction, which explains why the Higgs mass should be around 100 GeV, as indicated by electroweak precision measurements at LEP. Next, the running of the gauge coupling constants are modified in SUSY, which realizes the gauge coupling unification at the energy scale $\sim 2 \times 10^{16}$ GeV. Thus Grand Unified Theory (GUT) is naturally realized in the framework of SUSY.

Therefore the combination these two paradigms, the SUSY axion model, has many attractive features. However, cosmology of SUSY axion model is highly non-trivial. In SUSY axion model, the axion forms a supermultiplet, which contains a scalar partner called *saxion* and fermionic superpartner, called *axino* [2]. Their interaction is suppressed by the PQ scale, and hence they are long-lived particles (or become stable for the axino). Such a long-lived particle has a potential to affect the cosmological evolution scenario like the gravitino [3]. In the present work, we have studied the cosmology of SUSY axion models, in particular paying careful attention to the effects of the saxion (see Ref. [4] for a detail).

2 Properties of Saxion

The saxion corresponds to a flat direction which does not feel the scalar potential, which is preserved by $U(1)_{\text{PQ}}$ symmetry and the holomorphic property of the superpotential in SUSY limit. Thus the saxion obtains a mass only from SUSY breaking effects, and hence the saxion mass (m_s) is naturally expected to be of order of the gravitino mass ($m_{3/2}$). The gravitino mass ranges from $O(1)$ keV to $O(10)$ TeV depending on SUSY breaking models, such as gauge-, gravity- or anomaly-mediated SUSY breaking models. Here we regard the saxion (gravitino) mass as a free parameter within the above range.

Now we turn to the cosmological effects of the saxion. For cosmological arguments, it is important to know the production mechanism and decay modes.

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Saxions are produced in the early universe in two ways. One is thermal production, where scattering processes of particles in thermal bath produce saxion. The other is the coherent oscillation. Because the saxion is a scalar field, it has large energy density with an initial amplitude s_i in the form of Bose-Einstein condensate. The former contribution, in terms of the saxion-to-entropy ratio, is given by

$$\left(\frac{\rho_s}{s}\right)^{(\text{TP})} \sim 1.0 \times 10^{-9} \text{ GeV} \left(\frac{m_s}{1 \text{ GeV}}\right) \left(\frac{T_R}{10^5 \text{ GeV}}\right) \left(\frac{10^{12} \text{ GeV}}{F_a}\right)^2 \quad (1)$$

for $T_R \lesssim T_D \sim 10^9 \text{ GeV} (F_a/10^{11} \text{ GeV})^2$, where T_R denotes the reheating temperature of the universe after inflation. For $T_R \gtrsim T_D$, saxions are thermalized and its abundance is given by $(\rho_s/s)^{(\text{TP})} \sim 1.0 \times 10^{-3} \text{ GeV}(m_s/1 \text{ GeV})$. The coherent oscillation contribution is estimated as

$$\left(\frac{\rho_s}{s}\right)^{(\text{C})} = \frac{1}{8} T_R \left(\frac{s_i}{M_P}\right)^2 \simeq 2.1 \times 10^{-9} \text{ GeV} \left(\frac{T_R}{10^5 \text{ GeV}}\right) \left(\frac{F_a}{10^{12} \text{ GeV}}\right)^2 \left(\frac{s_i}{F_a}\right)^2 \quad (2)$$

for $\Gamma_I < m_s$ where Γ_I denotes the decay rate of the inflaton. For $\Gamma_I > m_s$, T_R in the above formula should be replaced with T_{osc} , which is the temperature at which the saxion oscillation begins. Importantly, both contributions are proportional to T_R for wide parameter regions, and hence cosmological constraints on the saxion abundance are rephrased by the upper bound on T_R .

Next let us investigate the saxion decay modes. First, the saxion can decay into two axions ($s \rightarrow 2a$). We can estimate the decay rate of the saxion into axions as

$$\Gamma(s \rightarrow 2a) \simeq \frac{f^2}{64\pi} \frac{m_s^3}{F_a^2}, \quad (3)$$

where $f = \sum_i q_i^3 v_i^2 / F_a^2$ with the VEV of the i -th PQ scalar field v_i and its PQ charge q_i . If $f \sim 1$ as in many cases including the case with only one PQ scalar, this is the dominant decay mode of the saxion [5]. Then the lifetime is given by

$$\tau_s \simeq 1.3 \times 10^2 f^{-2} \text{ sec} \left(\frac{1 \text{ GeV}}{m_s}\right)^3 \left(\frac{F_a}{10^{12} \text{ GeV}}\right)^2. \quad (4)$$

As for the cosmological arguments, it is important to know whether the main saxion decay mode is into axions ($f \sim 1$) or not ($f \sim 0$), because such a decay mode does not affect BBN or CMB.

On the other hand, the saxion also decays into ordinary particles. For the KSVZ axion model, the saxion decays into two gluons through one-loop process with a decay rate given by

$$\Gamma(s \rightarrow 2g) \simeq \frac{\alpha_s^2}{64\pi^3} \frac{m_s^3}{F_a^2}, \quad (5)$$

for $m_s \gtrsim 1 \text{ GeV}$. The decay rate into two photons is given by

$$\Gamma(s \rightarrow 2\gamma) \simeq \frac{\kappa^2 \alpha_{\text{EM}}^2}{512\pi^3} \frac{m_s^3}{F_a^2}, \quad (6)$$

where κ is a model dependent constant of $O(1)$.

For the DFSZ axion model, the saxion decays into fermion-anti-fermion pair. The decay rate into down-type quarks d_i ($i = 1, 2, 3$) is represented as

$$\Gamma(s \rightarrow d_i \bar{d}_i) = \frac{3}{8\pi} \left(\frac{2x}{x+x^{-1}}\right)^2 m_s \left(\frac{m_{di}}{F_a}\right)^2 \left(1 - \frac{4m_{di}^2}{m_s^2}\right)^{3/2}, \quad (7)$$

where $x = \tan \beta = \langle H_u \rangle / \langle H_d \rangle$. Decay rate into up-type quarks u_i ($i = 1, 2, 3$) is similar,

$$\Gamma(s \rightarrow u_i \bar{u}_i) = \frac{3}{8\pi} \left(\frac{2x^{-1}}{x+x^{-1}}\right)^2 m_s \left(\frac{m_{ui}}{F_a}\right)^2 \left(1 - \frac{4m_{ui}^2}{m_s^2}\right)^{3/2}. \quad (8)$$

Although those decay modes into ordinary particles may be sub-dominant if $f \sim 1$, only such a small fraction of the saxion decay may significantly affect cosmology, as we will see in the next section.

3 Cosmological Constraints

Now we briefly summarize various cosmological constraints on the saxion abundance.

Effective number of neutrinos : Decay products of the saxion increase the radiation energy density of the universe. Such extra radiation contributions accelerate the Hubble expansion and changes the predictions of BBN, CMB anisotropy and structure formation etc. In terms of the effective number of neutrino species, $\Delta N_\nu \lesssim 1$ must hold. Note that this constraint is relevant for the decay mode $s \rightarrow 2a$ [6], even if $\tau_s \ll 1$ sec.

Big-Bang nucleosynthesis : Decay produced photons or hadrons may significantly affect BBN for $\tau_s \gtrsim 10^{-2}$ sec [7]. For 10^{-2} sec $\lesssim \tau_s \lesssim 10^2$ sec, the main effect is $p \leftrightarrow n$ conversion due to injected pions, which results in ${}^4\text{He}$ overproduction. For later injection, the main effect is photo (hadro)-dissociation of light elements, for radiative (hadronic) decay modes.

Cosmic microwave background : For $\tau_s \gtrsim 10^6$ sec, injected radiations can not reach chemical equilibrium because double-Compton scattering processes are ineffective. Then the extra radiations distort the blackbody spectrum of CMB. The distortion is characterized by a chemical potential μ or Compton- y parameter, which is constrained by the COBE FIRAS measurement [8].

Diffuse X(γ)-ray background : For $\tau_s \gtrsim 10^{13}$ sec, the decay produced photons contribute to diffuse X(γ)-ray background [9]. But such a contributions are constrained from the observations of ASCA, HEAO1, COMPTEL, EGRET. This gives a stringent bound on the saxion abundance.

Reionization : For $\tau_s \gtrsim 10^{13}$ sec, depending on the photon energy and decay epoch, the decay-produced photon may escape the “transparency window”, where photons can freely propagate the universe without interacting with intergalactic medium (IGM) [10]. If this is the case, decay-produced photons ionize the IGM and change the reionization history of the universe which results in too large optical depth to the last scattering surface to be consistent with the WMAP three year observaton.

Present matter density limit : If the saxion lifetime exceeds the present age of the universe, the energy density of the saxion itself contributes to the total matter density of the universe, $\Omega_m h^2$.

LSP overproduction : If the saxion is heavy enough to decay into SUSY particles, the non-thermally produced LSPs emitted by the saxion decay must not be overproduced [11]. Otherwise the LSPs give too large contribution to the matter density of the universe. Here we assume for $m_s \gtrsim 1$ TeV, such decay modes are open, and also the annihilation cross section of the LSP is small so that they do not annihilate with each other after the non-thermal production.

Gravitino and Axino overproduction : As is well known, gravitinos are produced through scattering of particles in thermal bath. The resulting abundance is proportional to the reheating temperature T_R [12]. For $m_{3/2} \lesssim 100$ GeV, the gravitino is stable and it contributes to the matter density of the universe. Similarly, axinos are also produced efficiently. Its abundance is also proportional to T_R [13]. (Here we assume the axino mass $m_{\tilde{a}}$ is equal to the gravitino mass.) Thus both set the upper bound on T_R .

In Fig. 1 we summarize the upper bound on the reheating temperature including all the above mentioned constraints. Four panels correspond to different models. Upper left : KSVZ with $f = 1$, upper right : KSVZ with $f = 0$, lower left : DFSZ with $f = 1$, lower right : DFSZ with $f = 0$. We can see that for almost all the saxion mass, the reheating temperature is severely constrained.

4 Summary

In this work, we have derived general cosmological constraints on SUSY axion models. It is found that the reheating temperature is severely constrained, compared with the bound from usual gravitino problem.

This has some implications on SUSY axion models. Because the reheating temperature is severely constrained, it is rather difficult to produce the correct amount of baryon asymmetry. In particular, thermal leptogenesis using right-handed neutrinos suffers from the low-reheating temperature. One possibility to generate baryon asymmetry is using Affleck-Dine mechanism. In fact, it can create a correct amount of baryon asymmetry even for such a low-reheating temperature [14]. Also, the present dark matter can be accounted for by the axion condensate or the axino. For an unstable axino, the neutralino LSP produced either thermally or non-thermally may also be the dark matter candidate.

As a final remark, the axion induces an isocurvature fluctuation with an amplitude proportional to the inflation scale. Hence a low-scale inflation model such as new inflation should be assumed [15].

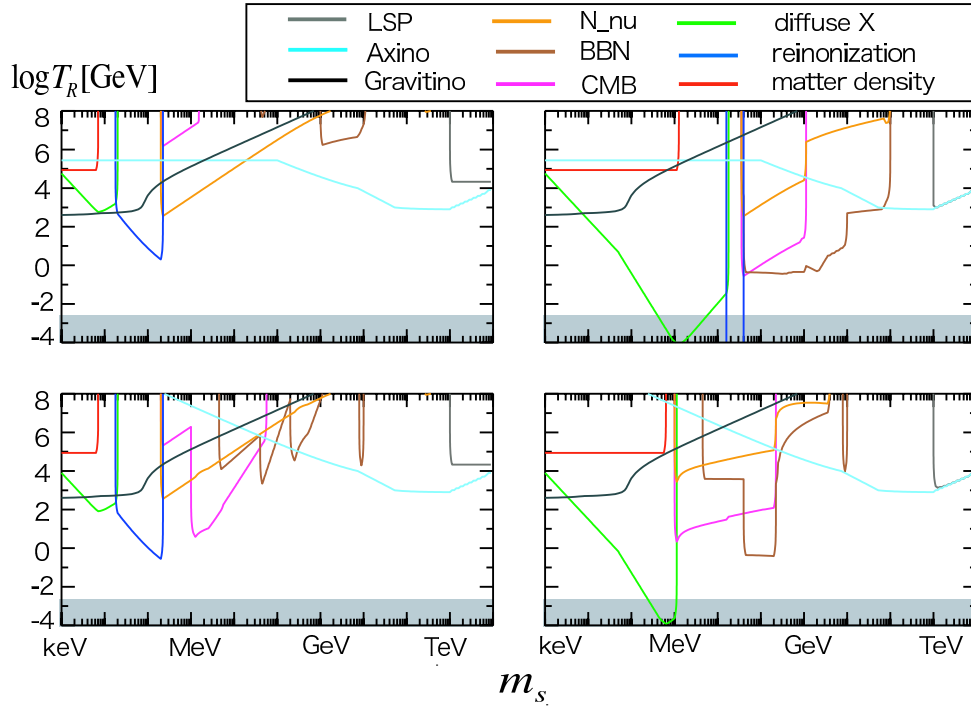


Figure 1: Upper bounds on the reheating temperature T_R for each model with $F_a = 10^{12}$ GeV [4]. The initial amplitude of the saxion is assumed to be $s_i \sim F_a$.

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