Constraint on Cosmic Density of the String Moduli Field in Gauge-Mediated Supersymmetry-Breaking Theories

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Abstract

We derive a constraint on the cosmic density of string moduli fields in gauge-mediated supersymmetry-breaking theories by requiring that photons emitted from the unstable moduli fields should not exceed the observed X-ray backgrounds. Since mass of the moduli field lies in the range between $O(0.1)\text{keV}$ and $O(1)\text{MeV}$ and the decay occurs through a gravitational interaction, the lifetime of the moduli field is much longer than the age of the present universe. The obtained upperbound on their cosmic density becomes more stringent than that from the unclosure condition for the present universe for the mass greater than about $100\text{keV}$.

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1 Introduction

Massless moduli fields $\phi$ exist in all known superstring theories which parameterize continuous vacuum-state degeneracies [1]. They are expected to get their masses from nonperturbative dynamics which breaks the supersymmetry (SUSY) and a generic argument [2] shows that their masses are comparable to the gravitino mass $m_{3/2}$. In hidden sector models of SUSY breaking the moduli fields have the masses at the electroweak scale. On the other hand, their masses lie in the keV range in gauge-mediated SUSY-breaking models [3, 4, 5]. In the latter models the lifetimes of the moduli fields are much longer than the age of the present universe and energy densities of their coherent oscillations easily exceed the critical density of the universe. Thus the gauge-mediated SUSY-breaking models looks to contradict the superstring theories as long as the light moduli fields exist in the keV region.

In a recent paper [5], Gouvêa, Moroi and Murayama have pointed out that the above moduli problem may be solved if a late-time thermal inflation takes place. In this letter we show that a stringent constraint on the cosmic density of the moduli fields is derived from the experimental upperbounds on the cosmic X-ray backgrounds. The basic assumption in the present analysis is that the main decay mode of the moduli field $\phi$ is a two-photon process, $\phi \to 2\gamma$. This assumption is quite reasonable since the decay mode to two neutrinos, $\phi \to \nu_L + \bar{\nu}_L$, has a chirality suppression and vanishes for massless neutrinos.

2 Constraint from X-ray Background

Here we perform a model-independent analysis taking the mass $m_\phi$, the lifetime $\tau_\phi$ and the energy density $\rho_\phi$ of the moduli field as free parameters. We consider the mass region between $\sim 0.2$keV and $\sim 4$MeV.

1If some string dynamics gives rise to large SUSY-invariant masses for the moduli fields, there is no contradiction between gauge-mediated SUSY-breaking and superstring theories. However, no compelling model has been found so far.

2The process, $\phi \to \nu_L + \bar{\nu}_L$, breaks the electroweak gauge symmetry and hence it has an extra suppression.
First we summarize the observational fluxes $F_{\gamma, \text{obs}}$ of the cosmic X-ray backgrounds in the corresponding photon energy region $E_{\gamma} \simeq 0.1 \text{keV} \sim 2 \text{MeV}$. The ASCA satellite experiment measures the flux $F_{\gamma}$ for $0.1 \text{keV} \leq E_{\gamma} \leq 7 \text{keV}$ [6]. For higher photon energies, HEAO satellite gives useful data [7]. We can fit these observational data by simple three power-low spectra for $0.1 \text{keV} < E_{\gamma} < 7 \text{keV}$:

$$ F_{\gamma, \text{obs}}(E_{\gamma}) \simeq 8(E_{\gamma}/\text{keV})^{-0.4} \quad 0.1 \text{keV} \lesssim E_{\gamma} \lesssim 25 \text{keV}, \quad (1) $$

$$ \simeq 380(E_{\gamma}/\text{keV})^{-1.6} \quad 25 \text{keV} \lesssim E_{\gamma} \lesssim 350 \text{keV}, \quad (2) $$

$$ \simeq 2(E_{\gamma}/\text{keV})^{-0.7} \quad 350 \text{keV} \lesssim E_{\gamma} \lesssim 2 \text{MeV}, \quad (3) $$

where $F_{\gamma, \text{obs}}$ is measured in units of $(\text{cm}^2 \text{ sr sec})^{-1}$. (The fit is not good for $E_{\gamma} \gtrsim 1 \text{MeV}$ since data scatter very much.)

Next let us estimate the photon flux from decaying moduli field. The present cosmic number density $n_\phi$ of the moduli field is given by its mass $m_\phi$ and density $\rho_\phi$ as

$$ n_\phi = 10.54 \text{cm}^{-3}(m_\phi/\text{keV})^{-1}(\Omega_\phi h^2), \quad (4) $$

where $\Omega_\phi \equiv \rho_\phi/\rho_c$ ($\rho_c$: critical density of the universe) and $h$ is the present Hubble constant in units of $100 \text{ km/sec/Mpc}$. Since two monochromatic photons with energy $m_\phi/2$ are produced in the decay, the flux from the moduli fields is estimated as

$$ F_{\gamma}(E_{\gamma}) = \frac{E_{\gamma}}{4\pi} \int_0^{t_0} dt' \frac{1}{\tau_\phi} n_\phi(1+z)2\delta(E_{\gamma}(1+z)-m_\phi/2), $$

$$ = \frac{\sqrt{2n_\phi E_{\gamma}^{3/2}}}{\pi \tau_\phi H_0 m_\phi^{3/2}}[\Omega_0 + (1 - \Omega_0 - \Omega_\Lambda)(2E_{\gamma}/m_\phi) + \Omega_\Lambda](2E_{\gamma}/m_\phi)^3]^{-1/2}, \quad (5) $$

where $t_0$ is the present time, $z$ is the redshift, $H_0$ is the present Hubble constant, $\Omega_0$ is the present (total) density parameter and $\Omega_\Lambda$ is the density parameter of the cosmological constant. The flux $F_{\gamma}$ takes a maximum value $F_{\gamma, \text{max}}$ at $E_{\gamma} = m_\phi/2$. From eqs. (4) and (5) $F_{\gamma, \text{max}}$ is given by

$$ F_{\gamma, \text{max}} = 1.55 \times 10^3(\text{cm}^2 \text{ str sec})^{-1} \left(\frac{m_\phi}{\text{keV}}\right)^{-1} \left(\frac{\tau_\phi}{10^{25} \text{sec}}\right)^{-1} (\Omega_\phi h). \quad (6) $$

By requiring that $F_{\gamma, \text{max}}$ should be less than the observed X-ray background fluxes $F_{\gamma, \text{obs}}$ (eqs. (1) – (3)), we can obtain the constraint on $\Omega_\phi$ using eqs. (1)–(3):

$$ \Omega_\phi h \lesssim 7 \times 10^{-3} \left(\frac{\tau_\phi}{10^{25} \text{sec}}\right) \left(\frac{m_\phi}{\text{keV}}\right)^{0.6} \quad 0.2 \text{keV} \lesssim m_\phi \lesssim 50 \text{keV}, \quad (7) $$
\[ 7 \times 10^{-1} \left( \frac{\tau_{\phi}}{10^{25} \text{sec}} \right) \left( \frac{m_{\phi}}{\text{keV}} \right)^{-0.6} \quad 50 \text{keV} \lesssim m_{\phi} \lesssim 0.7 \text{MeV}, \quad (8) \]

\[ 2 \times 10^{-3} \left( \frac{\tau_{\phi}}{10^{25} \text{sec}} \right) \left( \frac{m_{\phi}}{\text{keV}} \right)^{0.3} \quad 0.7 \text{MeV} \lesssim m_{\phi} \lesssim 2 \text{MeV}. \quad (9) \]

This constraint is shown in Fig. 1 by the dashed line. The use of the simple power-low spectra (1)–(3) is convenient to get the analytic expression for the upperbound on \( \Omega_{\phi} \). However, a more precise constraint is obtained by using a smooth curve which gives better fit to observational data and the resultant constraint on \( \Omega_{\phi}/\tau_{\phi} \) is shown in Fig. 1 by solid curve.

### 3 Gravitational Decay of the String Moduli Field

The constraint obtained above is general in the sense that it applies to any unstable particles which decay mainly into photons with lifetime much longer than the age of the universe. We now apply this model-independent constraint to the string moduli field which decays into photons only through a gravitational interaction.

The lifetime of the moduli field \( \tau_{\phi} \) is related to its mass \( m_{\phi} \) by\(^3\)

\[
\tau_{\phi} \simeq \frac{M_p^2}{m_{\phi}^3} \simeq 10^{32} \text{sec} \left( \frac{m_{\phi}}{\text{keV}} \right)^{-3},
\]

where \( M_p \) is the Planck mass. With this relation, the maximum flux \( F_{\gamma,\text{max}} \) is given by

\[
F_{\gamma,\text{max}} = 1.55 \times 10^{-4} \left( \text{cm}^2 \text{ str sec} \right)^{-1} \left( \frac{m_{\phi}}{\text{keV}} \right)^2 \left( \Omega_{\phi} h \right).
\]

Then, in the same way as in the previous section, we can obtain the constraint on \( \Omega_{\phi} \) which is shown in Fig. 2. From the figure it is seen that the upperbound on \( \Omega_{\phi} \) is less than 1 for \( m_{\phi} \gtrsim 100 \text{keV} \). Thus, for the moduli field with such masses the constraint from the X-ray backgrounds is much more stringent than that from the critical density (i.e. \( \Omega_{\phi} \lesssim 1 \))\(^4\)

\(^3\)The decay rate \( \Gamma_{\phi} \) of the moduli field has an unknown parameter \( h \) of order 1 as \( \Gamma_{\phi} \simeq h m_{\phi}^3/M_p^2 \). If one uses smaller values of \( h \), \( h < 1 \), the obtained constraint becomes weaker.

\(^4\)Here we assume that the density of the moduli fields are homogeneously in the universe. However, if the moduli fields concentrates in the halo of our galaxy, one may obtain the more stringent constraint.
In order to satisfy the constraint on $\Omega_\phi$ it is necessary to dilute the density of moduli fields by some large entropy production such as thermal inflation [8, 5]. However, the entropy production cannot be too large since it also dilutes the baryon number in the universe. For example, in ref. [5] it has been shown that the Affleck-Dine baryogenesis can generate the baryon asymmetry given by

$$\frac{n_B}{s} \lesssim 4 \times 10^{-5}(\Omega_\phi h^2)^{-1},$$

where $n_B$ is the baryon number density and $s$ the entropy density. Requiring $n_B/s \simeq 4 \times 10^{-11}$, we obtain the lower limit on $\Omega_\phi$:

$$\Omega_\phi h^2 \gtrsim 10^{-6}\left(\frac{m_\phi}{100\text{keV}}\right),$$

where we assume $m_\phi \simeq m_{3/2}$. This, together with the X-ray background constraint, leads to $m_\phi \lesssim 2\text{MeV}$ (see Fig. 2).

4 Conclusion

We have shown that a stringent constraint on the density of the string moduli fields in gauge-mediated SUSY-breaking theories is obtained by requiring that the photons emitted from the unstable moduli field should not exceed the observed X-ray backgrounds. In particular, if the decay occurs through the gravitational interaction, the lifetime of the moduli field is estimated as a function of its mass and the constraint on $\Omega_\phi$ is more stringent than that from the unclosure condition for the present universe for $m_\phi \gtrsim 100\text{keV}$.

The observed X-ray backgrounds are usually explained by the emission from active galactic nuclei and Type I supernova. However it is known that there may be a hump [8] in the spectrum at a few MeV which cannot be explained by usual sources. It is very much intriguing that the unstable moduli fields with mass about 1MeV are indeed the source of the hump. However the recent COMPTEL observation [9] has not confirmed the existence of the hump. Thus the precise measurement of the spectrum at $O(1)$MeV energies by future experiments are highly required.
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Figure Captions

Fig.1 Upperbound on $\Omega_\phi/\tau_\phi$ from the X-ray background radiation (solid curve). The dashed line represents the constraint obtained by using the simple fitting spectrum of the X-ray background.

Fig.2 Upperbound on $\Omega_\phi$ from the X-ray background (solid curve). The lowerbound from the baryogenesis (proposed in ref.[5]) is denoted by the dashed line.
