Gravitino Overproduction through Moduli Decay

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We derive cosmological constraints on the masses of generic scalar fields which decay only through gravitationally suppressed interactions into unstable gravitinos and ordinary particles in the supersymmetric standard model. For the gravitino mass 100 GeV–1 TeV, the scalar masses should be larger than 100 TeV to insure the validity of big-bang nucleosynthesis if no late-time entropy production dilutes the gravitino density.

§1. Introduction

Superstring theories have infinitely degenerate supersymmetric vacua which are continuously connected by massless scalar fields, called moduli. These moduli fields are generally expected to acquire masses m_φ on the order of the gravitino mass $m_{3/2}$ when supersymmetry breaking effects are included. The moduli decay into two gravitinos if the masses of moduli are larger than $2m_{3/2}$.

In this paper, we consider the decay of the moduli into two gravitinos and discuss the cosmological consequences of this decay. It is known[1],[2] that a gravitino with mass $100 \text{ GeV} - 1 \text{ TeV}$ decays soon after nucleosynthesis and that the decay product destroys light nuclei produced in the early universe. We see that the moduli decay tends to produce too many gravitinos to insure the validity of big-bang nucleosynthesis. We derive stringent constraints on the moduli masses to avoid this disaster, such as $m_\varphi \gtrsim 100 \text{ TeV}$.

We stress that this constraint is applicable to generic scalar fields that decay only through gravitationally suppressed interactions, as long as their masses are larger than the threshold of the two-gravitino decay channel.

§2. The interaction

We assume one modulus field throughout the paper, though the generalization to the case of many moduli is straightforward. We set the gravitational scale 2.4×10^{18} GeV equal to unity.

The relevant terms in the supergravity Lagrangian[3] which describe the decay of a modulus φ into gravitinos χ are given by

$$\mathcal{L} = \epsilon^{klmn} \bar{\chi}_k \bar{\sigma}_l \frac{1}{4} (K_\varphi \partial_m \varphi - K_{\varphi^*} \partial_m \varphi^*) \chi_n - e^{\frac{K}{2}} (W^* \chi_a \sigma^{ab} \chi_b + W \bar{\chi}_a \bar{\sigma}^{ab} \bar{\chi}_b), \quad (1)$$

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where W denotes the superpotential, and we choose the field φ so that its vacuum expectation value vanishes: $\langle \varphi \rangle = 0$. With our definition of φ, the Kähler potential K generically contains linear terms, $K = c\varphi + c^*\varphi^* + \varphi\varphi^* + \cdots$, where the coefficient c is of order one.

§3. The decay

Let us begin by discussing the decay rate of the modulus. When $m_\varphi \gg 2m_{3/2}$, the order of the decay width of φ into gravitinos is given by

$$\Gamma(\varphi \to \text{gravitinos}) \sim |c|^2 m_{3/2}^2 m_\varphi, \tag{2}$$

where c denotes the coefficient of the φ term in the Kähler potential. Here, we have used Eq. (1), the gravitino equation of motion, and $\langle e^{K/2}W \rangle = m_{3/2}$.

On the other hand, the order of the decay width of φ into radiation is given by

$$\Gamma(\varphi \to \text{radiation}) \sim Nm_\varphi^3, \tag{3}$$

where N is the number of decay channels. Hence the branching ratio of the decay into gravitinos turns out to be

$$B_\chi \sim \frac{|c|^2}{N}\left(\frac{m_{3/2}}{m_\varphi}\right)^2. \tag{4}$$

The modulus φ begins to undergo damped oscillation when the Hubble scale H becomes comparable to its mass, m_φ. The initial amplitude of the coherent oscillation is expected to be of order one in Planck units. Then the modulus density ρ_φ dominates the universe at the decay time, since $\Gamma_\varphi \ll H \sim m_\varphi$. The reheat temperature after the modulus decay is given by

$$T_R \sim N_*^{-\frac{1}{4}}\sqrt{\Gamma_\varphi}, \tag{5}$$

where N_* denotes the degrees of freedom at temperature T_R.

This implies that the gravitino number density $n_{3/2}$ produced through the modulus decay at the decay time is given by

$$\frac{n_{3/2}}{s} \sim \frac{|c|^2 N_*^{-\frac{1}{4}}}{\sqrt{N}}\frac{m_{3/2}^2}{m_\varphi^{\frac{3}{2}}}, \tag{6}$$

where s denotes the entropy density and we have used

$$B_\chi\rho_\varphi \sim m_\varphi n_{3/2}, \quad \rho_\varphi \sim N_* T_R^4, \quad s \sim N_* T_R^3. \tag{7}$$

Namely, the modulus mass is given by

$$m_\varphi \sim \left(\frac{|c|^2 N_*^{-\frac{1}{4}}}{\sqrt{N}}\frac{m_{3/2}^2}{y_{3/2}}\right)^{\frac{2}{3}}, \tag{8}$$

where $y_{3/2} = n_{3/2}/s$.

Gravitinos are also produced by the scattering processes caused by thermal radiation after the modulus decay. The contribution to the gravitino number density is given by [2]

$$\frac{n'_{3/2}}{s} \sim 10^{-3} T_R \sim 10^{-3} N_*^{-\frac{1}{4}} \sqrt{N} m_\varphi^{\frac{3}{2}}. \tag{9}$$

§4. The bound

In the previous section, we estimated $y_{3/2} = n_{3/2}/s$ at the decay time of the modulus φ. We may derive cosmological constraints on $y_{3/2}$ from observation of the present universe, since the estimated value $y_{3/2}$ itself yields the value of $n_{3/2}/s$ at the time of the gravitino decay.

Stringent constraints are implemented to maintain the successful predictions of the big-bang nucleosynthesis provided that the gravitino with mass $100\,\text{GeV} - 1\,\text{TeV}$ decays mainly into a photon and a photino: [2]

$$y_{3/2} \lesssim 10^{-15} - 10^{-13}. \tag{10}$$

By means of Eq. (8), we obtain

$$m_\varphi \gtrsim 100\,\text{TeV}. \tag{11}$$

On the other hand, the constraints due to gravitinos produced by the scattering processes caused by thermal radiation read as follows:

$$m_\varphi \lesssim (10^7 - 10^9)\,\text{TeV}, \tag{12}$$

where we have used Eq. (9).

§5. Conclusion

We have derived the constraint $100\,\text{TeV} \lesssim m_\varphi \lesssim 10^9\,\text{TeV}$ on the moduli masses m_φ in the case of an unstable gravitino[*] with mass $100\,\text{GeV} - 1\,\text{TeV}$. This may have obvious implications for mechanisms of moduli stabilization. Here, the moduli may be regarded as generic scalar fields that decay only through gravitationally suppressed interactions as long as their masses are larger than the threshold of the two-gravitino decay channel.

In the course of the analysis, we have assumed that no entropy production has diluted the modulus and gravitino densities, since the modulus density once dominated the universe. In fact, entropy production may evade the constraints. New inflation and thermal inflation are possible candidates of sufficient entropy production. Without such inflationary dilution, the moduli masses are severely constrained. On the other hand, if the moduli masses lie in the region $100\,\text{TeV} \lesssim m_\varphi \lesssim 10^9\,\text{TeV}$, the reheat temperature of the cosmological inflation could be very high, since the

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[*] On the other hand, no stringent constraint on the moduli masses can be derived from the moduli decay in the case of the lighter gravitino with $m_{3/2} \lesssim 10\,\text{GeV}$. [4]

density of gravitinos produced just after the inflation is diluted substantially by the decay of moduli.

Acknowledgements

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