The axino is the fermionic superpartner of the axion. Assuming the axino is the lightest supersymmetric particle and stable due to $R$-parity conservation, we compute the relic axino density from thermal reactions in the early Universe. From the comparison with the WMAP results, we find that thermally produced axinos could provide the dominant part of cold dark matter, for example, for an axino mass of 100 keV and a reheating temperature of $10^6$ GeV.

1 Introduction

If supersymmetry is realized in nature and the strong CP problem is solved by the Peccei-Quinn (PQ) mechanism, the axino $\tilde{a}$ should exist as the fermionic superpartner of the axion. As the interactions of the electrically and color neutral axion supermultiplet are suppressed by the PQ scale $f_a/N \simeq 5 \times 10^9$ GeV, the axino couples only very weakly to the MSSM particles. If the axino is the lightest supersymmetric particle (LSP) and if $R$-parity is conserved, axinos will be stable and exist as dark matter in the Universe. Then, depending on the axino mass $m_{\tilde{a}}$ and the temperature $T$ of the primordial plasma, axinos could play an important role in the cosmos. In particular, they could provide the dominant part of cold dark matter.

In this talk we consider the thermal production of stable axinos in the early Universe. Assuming that inflation has governed the earliest moments, any initial population of axinos has been diluted away by the exponential expansion during the slow-roll phase. The thermal production of axinos starts then after completion of the reheating phase at the reheating temperature $T_R$. We restrict our investigation to $f_a/N \gtrsim T_R \gtrsim 10^4$ GeV, where the $U(1)_{PQ}$ symmetry is broken and axino production from decays of particles out of equilibrium is negligible. Based on our computation of the thermal axino production rate within thermal field theory, we discuss the possibility of stable axinos forming the dominant component of cold dark matter. The results presented are extracted from Ref. 3 where more details can be found.

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2 Relic Axino Abundance from Thermal Production in the Early Universe

We concentrate on the axino-gluino-gluon interactions given by the dimension-5 interaction term

$$\mathcal{L}_{\tilde{a}g\tilde{g}} = i \frac{g^2}{64\pi^2} \frac{f_{a/N}}{N} \, \tilde{a} \gamma_5 \left[ \gamma^\mu, \gamma^\nu \right] \tilde{g}^a G_{\mu\nu}^a,$$

(1)

with the strong coupling $g$, the gluon field strength tensor $G_{\mu\nu}^a$, the gluino $\tilde{g}$, and $N$ being the number of quarks with PQ charge. These interactions govern the thermal axino production at high temperatures. For $f_{a/N} = 10^{11}$ GeV, Rajagopal, Wilczek, and Turner have estimated an axino decoupling temperature of $T_D \approx 10^9$ GeV by comparing the corresponding axino interaction rate with the Hubble parameter $H$ for the early radiation-dominated epoch.

For $T_R \gg T_D$, axinos have been in thermal equilibrium with the primordial plasma. Their abundance is then given by the equilibrium number density of a relativistic Majorana fermion while contributions from axino production and annihilation processes at smaller temperatures are negligible. Thus, the axino yield and the axino density parameter are given respectively by

$$Y_{\tilde{a}}^{\text{eq}} = \frac{n_{\tilde{a}}^{\text{eq}}(T_D)}{s(T_D)} \approx 1.8 \times 10^{-3},$$

(2)

$$\Omega_{\tilde{a}}h^2 = m_{\tilde{a}} Y_{\tilde{a}}^{\text{eq}} s(T_0) h^2 / \rho_c \approx \frac{m_{\tilde{a}}}{2 \text{keV}},$$

(3)

where $n_{\tilde{a}}$ is the axino number density, $s(T) = 2\pi^2 g_* S(T) T^3 / 45$ is the entropy density, $h$ parameterizes the Hubble constant $H_0 = 100$ km/sec/Mpc, $T_0$ is the present temperature of the cosmic photon background radiation, and $\rho_c$ is the critical density so that $\rho_c / [s(T_0) h^2] = 3.6 \times 10^{-9}$ GeV. In $s(T_D)$ we have used the MSSM value $g_* S(T_D) = 228.75$ for the number of effectively massless degrees of freedom being in thermal equilibrium with the primordial plasma at $T_D$.

For $T_R < T_D$, axinos have not been in thermal equilibrium after inflation. Here the evolution of $n_{\tilde{a}}$ with cosmic time $t$ can be described by the Boltzmann equation with a collision term $C_{\tilde{a}}$ accounting for both the axino production and disappearance in thermal reactions in the primordial plasma,

$$\frac{dn_{\tilde{a}}}{dt} + 3H n_{\tilde{a}} = C_{\tilde{a}}.$$

(4)

The disappearance processes can be neglected for $T_R$ sufficiently below $T_D$. The collision term then is given by integrating the thermal axino production rate. We have computed this rate for axinos with $E \gtrsim T$ in SUSY QCD using the Braaten-Yuan prescription and hard thermal loop (HTL) resummation.

A finite result is obtained in a gauge-invariant way, which takes into account Debye screening in the primordial plasma and does not depend on any ad hoc cutoffs. By numerical integration of our result for the axino production rate, we obtain the collision term

$$C_{\tilde{a}}(T) \bigg|_{T_R < T_D} \approx \left( \frac{N_c^2 - 1}{f_{a/N}^2} \right) \frac{\zeta(3)}{4096\pi^4} \left[ \ln \left( \frac{1.380 T^2}{m_{\tilde{a}}^2} \right) (N_c + n_f + 0.4336 n_f) \right],$$

(5)

where $N_c = 3$ is the number of colors, $n_f = 6$ is the number of color triplet and anti-triplet chiral multiplets, $\zeta(3) \approx 1.2021$, and $m_g = gT\sqrt{(N_c + n_f)/6}$ is the thermal gluon mass in SUSY QCD. Assuming conservation of entropy per comoving volume, the Boltzmann equation can be integrated analytically. The resulting axino yield and axino density parameter read respectively

$$Y_{\tilde{a}}(T_0) \approx \frac{C_{\tilde{a}}(T_R)}{s(T_R) H(T_R)} = 2.0 \times 10^{-7} g^2 \ln \left( \frac{1.108 G eV}{g} \right) \left( \frac{10^{11} \text{GeV}}{f_{a/N}} \right)^2 \left( \frac{T_R}{10^4 \text{GeV}} \right),$$

(6)

$$\Omega_{\tilde{a}}h^2 = m_{\tilde{a}} Y_{\tilde{a}}(T_0) s(T_0) h^2 / \rho_c = 5.5 \times 10^{-6} \ln \left( \frac{1.108 G eV}{g} \right) \left( \frac{m_{\tilde{a}}}{0.1 \text{GeV}} \right) \left( \frac{10^{11} \text{GeV}}{f_{a/N}} \right)^2 \left( \frac{T_R}{10^4 \text{GeV}} \right),$$

(7)

where we have used the Hubble parameter describing the radiation-dominated epoch $H(T) = \sqrt{g_*(T)\pi^2/90} \, T^2 / \text{M}_{\text{Pl}}$ with $\text{M}_{\text{Pl}} \approx 2.4 \times 10^{18}$ GeV and $g_*(T_R) = g_* S(T_R) = 228.75.$
In Fig. 1, our result for the relic axino density $\Omega_{\tilde{a}} h^2$ is illustrated as a function of the reheating temperature $T_R$ for a PQ scale of $f_a/N = 10^{11}$ GeV and an axino mass of $m_{\tilde{a}} = 1$ keV (dotted line), 100 keV (dashed line), and 10 MeV (solid line). The 1-loop running of the strong coupling in the MSSM is taken into account by replacing $g$ with $g(T_R) = \left[ g^2(M_Z) + 3 \ln(T_R/M_Z)/(8\pi^2) \right]^{-1/2}$, where the value of the strong coupling at the Z-boson mass $M_Z$, $g^2(M_Z)/(4\pi) = 0.118$, is used as input. For $T_R$ above $T_D \approx 10^9$ GeV, the relic axino density is independent of $T_R$ as shown for $m_{\tilde{a}} = 1$ keV by the horizontal line. There will be a smooth transition instead of a kink once the axino disappearance processes are taken into account. The grey band in Fig. 1 indicates the WMAP result on the cold dark matter density (2$\sigma$ error) $\Omega_{\text{CDM}}^{\text{WMAP}} h^2 = 0.113_{-0.018}^{+0.016}$.

3 Can Axinos Provide the Dominant Component of Cold Dark Matter?

Assuming the axino is the LSP and stable due to R-parity conservation, the first crucial criterion is whether the relic axino abundance matches the observed abundance of cold dark matter. As one can see from Fig. 1, there are certain combinations of $m_{\tilde{a}}$ and $T_R$ for which the relic axino density $\Omega_{\tilde{a}} h^2$ indeed agrees with the WMAP result on the abundance of cold dark matter.

The next question is whether axino dark matter from thermal production is sufficiently cold (i.e. non-relativistic sufficiently long before matter-radiation equality) in order to explain the formation and power spectrum of large-scale structures and the early reionization observed by the WMAP satellite. As the thermal axino production rate shows basically a thermal spectrum, the dark matter classification for particles with thermal spectrum can be adopted. For an axino mass in the range $m_{\tilde{a}} \lesssim 1$ keV, $1$ keV $\lesssim m_{\tilde{a}} \lesssim 100$ keV, and $m_{\tilde{a}} \gtrsim 100$ keV, we refer to hot, warm, and cold axino dark matter, respectively. Thus, axinos could provide the dominant part of cold dark matter for $T_R \lesssim 10^6$ GeV; cf. Fig. 1. While our classification is only an approximate guideline, simulations of early structure formation show that dark matter of particles with mass $m_x \lesssim 10$ keV cannot explain the early reionization observed by the WMAP satellite.
Another important issue is whether the abundance of the primordial light elements (D, $^3$He, $^4$He, Li) remains unaffected by the production of axinos. The increase of the energy density at the time of primordial nucleosynthesis due to the presence of the thermally produced axinos is small and consistent with the observed abundance of the light elements. More model dependent and possibly more severe are the nucleosynthesis constraints concerning the potential destruction of the light primordial elements by photons or hadronic showers from late decays of the NLSP into axinos. Anyhow, the axino LSP is far less problematic than the gravitino LSP as the axino interactions are not as strongly suppressed as the gravitino interactions.

4 Conclusion

The relic axino density (obtained for $f_a/N = 10^{11}$ GeV) agrees with the WMAP result (2σ errors) on the cold dark matter density for the $m_\tilde{a} - T_R$ combinations within the grey band shown in Fig. 1b and, in particular, for $m_\tilde{a} = 100$ keV and $T_R \approx 10^6$ GeV. Although relatively light for being cold dark matter, axinos with $m_\tilde{a} = 100$ keV could still explain large-scale-structure formation, the corresponding power spectrum, and the early reionization observed by WMAP. For larger $m_\tilde{a}$, the matching with the WMAP result does restrict $T_R$ to lower values. Already $T_R \approx 10^6$ GeV is relatively small and excludes some models for inflation and baryogenesis such as thermal leptogenesis. Note that the limits on $T_R$ shown in Fig. 1b are relaxed by one order of magnitude with respect to the ones found in Ref. 2. This difference results from our computation of the thermal production rate, in which we have used the Braaten-Yuan prescription with the HTL-resummed gluon propagator as opposed to the pragmatic cutoff procedure used in Ref. 2. There is no upper limit on $T_R$ for $m_\tilde{a} \lesssim 0.2$ keV. As the axinos have been in thermal equilibrium with the primordial plasma for $T_R \gtrsim 10^3$ GeV, the resulting relic axino density is completely determined by $m_\tilde{a}$ and independent of $T_R$. The agreement with the WMAP result is then achieved for any $T_R \gtrsim 10^3$ GeV as long as $m_\tilde{a} \approx 0.2$ keV, which is the updated version of the Rajagopal-Turner-Wilczek bound. However, axinos with $m_\tilde{a} \lesssim 0.2$ keV are too light for being cold dark matter. As warm or hot dark matter, they alone cannot explain the formation and power-spectrum of large-scale structures and, in particular, the early reionization observed by WMAP. Nevertheless, even such a light axino can have important cosmological implications provided it is the LSP. By destabilizing the other $R$-odd particles including the gravitino, the light axino provides a solution to the gravitino problem so that a reheating temperature of $T_R \gtrsim 10^6$ GeV is no longer problematic. Thus, with the light axino being the LSP, thermal leptogenesis can coexist with SUSY and explain the baryon asymmetry in the Universe. The cold dark matter needed to explain structure formation could then be provided by the axion.

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