Mainly axion cold dark matter in the minimal supergravity model

Howard Baer[a], **Andrew D. Box**[a] **and Heaya Summy**[a]

[a] *Dept. of Physics and Astronomy, University of Oklahoma, Norman, OK 73019, USA*
E-mail: baer@nhn.ou.edu, box@nhn.ou.edu,heaya@nhn.ou.edu

Abstract: We examine the minimal supergravity (mSUGRA) model under the assumption that the strong CP problem is solved by the Peccei-Quinn mechanism. In this case, the relic dark matter (DM) abundance consists of three components: *i*). cold axions, *ii*). warm axinos from neutralino decay, and *iii*). cold or warm thermally produced axinos. To sustain a high enough re-heat temperature ($T_R \gtrsim 10^6$ GeV) for many baryogenesis mechanisms to function, we find that the bulk of DM should consist of cold axions, while the admixture of cold and warm axinos should be rather slight, with a very light axino of mass ~ 100 keV. For mSUGRA with mainly axion cold DM (CDM), the most DM-preferred parameter space regions are precisely those which are least preferred in the case of neutralino DM. Thus, rather different SUSY signatures are expected at the LHC in the case of mSUGRA with mainly axion CDM, as compared to mSUGRA with neutralino CDM.

Keywords: Supersymmetry Phenomenology, Supersymmetric Standard Model, Dark Matter.

1. Introduction

The cosmic abundance of cold dark matter (CDM) has been recently measured to high precision by the WMAP collaboration[1], which lately finds

$$\Omega_{CDM}h^2 = 0.110 \pm 0.006, \tag{1.1}$$

where $\Omega = \rho/\rho_c$ is the dark matter density relative to the closure density, and h is the scaled Hubble constant. No particle present in the Standard Model (SM) of particle physics has exactly the right properties to constitute CDM. However, CDM does emerge naturally from two compelling solutions to longstanding problems in particle physics.

The first problem is the strong CP problem[2], for which an elegant solution was proposed by Peccei and Quinn many years ago[3], and which naturally predicts the existence of a new particle[4]: the axion a. The axion turns out to be an excellent candidate particle for CDM in the universe[5].

The second problem– the gauge hierarchy problem– arises due to quadratic divergences in the scalar sector of the SM. The quadratic divergences lead to scalar masses blowing up to the highest scale in the theory (*e.g.* in grand unified theories (GUTS), the GUT scale $M_{GUT} \simeq 2 \times 10^{16}$ GeV), unless exquisite fine-tuning of parameters is invoked. The gauge hierarchy problem is naturally solved by introducing supersymmetry (SUSY) into the theory. By including softly broken SUSY, quadratic divergences cancel between fermion and boson loops, and only log divergences remain. The log divergence is soft enough that vastly different scales remain stable within a single effective theory. In SUSY theories, the lightest neutralino emerges as an excellent WIMP CDM candidate. The gravitino of SUSY theories is also a good super-WIMP CDM candidate[6]. Gravity-mediated SUSY breaking models include gravitinos with weak-scale masses. These models experience tension due to possible overproduction of gravitinos in the early universe. In addition, late decaying gravitinos may disrupt calculations of light element abundances produced by Big Bang nucleosynthesis (BBN). This tension is known as the *gravitino problem*.

Of course, it is highly desirable to simultaneously account for *both* the strong CP problem and the gauge hierarchy problem. In this case, it is useful to invoke supersymmetric models which include the PQ solution to the strong CP problem[7]. In a SUSY context, the axion field is just one element of an *axion supermultiplet*. The axion supermultiplet contains a complex scalar field, whose real part is the R-parity even saxion field $s(x)$, and whose imaginary part is the axion field $a(x)$. The supermultiplet also contains an R-parity odd spin-$\frac{1}{2}$ Majorana field, the axino $\tilde{a}$[8]. The saxion, while being an R-parity even field, nonethless receives a SUSY breaking mass likely of order the weak scale. The axion mass is constrained by cosmology and astrophysics to lie in a favored range 10^{-2} eV$> m_a > 10^{-5}$ eV. The axino mass is very model dependent[9], and is expected to lie in the general range of keV to GeV. An axino in this mass range would likely serve as the lightest SUSY particle (LSP), and is also a good candidate particle for cold dark matter[10].

In this paper, we investigate supersymmetric models wherein the PQ solution to the strong CP problem is also invoked. For definiteness, we will restrict ourselves to examining the paradigm minimal supergravity (mSUGRA or CMSSM) model[11]. We will restrict our work to cases where the lightest neutralino $\tilde{\chi}_1^0$ is the next-to-lightest SUSY particle (NLSP); the case with a stau NLSP has recently been examined in Ref. [12]. Related previous work on axino DM in mSUGRA can be found in Ref. [14].

We will be guided in our analysis also by considering the possibility of including a viable mechanism for baryogenesis in the early universe. In order to do so, we will need to allow for re-heat temperatures after the inflationary epoch to reach values $T_R \gtrsim 10^6$ GeV. We will find that in order to sustain such high re-heat temperatures, as well as generating predominantly *cold* dark matter, we will be pushed into mSUGRA parameter space regions that are very different from those allowed by the case of thermally produced neutralino dark matter. In addition, we find that very high values of the PQ breaking scale f_a/N of order $10^{11}-10^{12}$ GeV are needed, leading to the mSUGRA model with *mainly axion cold dark matter*, but also with a small admixture of thermally produced axinos, and an even smaller component of warm axino dark matter arising from neutralino decays. The favored axino mass value is of order 100 keV. We note here recent work on models with dominant axion CDM explore the possibility that axions form a cosmic Bose-Einstein condensate, which can allow for the solution of several problems associated with large scale structure and the cosmic background radiation[15].

The remainder of this paper is organized as follows. In Sec. 2, we first discuss the gravitino problem, and then examine several possible baryogenesis mechanisms: thermal and non-thermal leptogenesis and Affleck-Dine leptogenesis. We then examine production mechanisms for axion and thermally and non-thermally produced axino dark matter. In Sec. 3, we confront the mSUGRA model with the possibility of mixed axion and axino cold and warm dark matter. We plot out contours of re-heat temperature T_R, and find that parameter space regions with large enough T_R to sustain at least non-thermal leptogenesis favor a sparticle mass spectrum which is actually most disfavored by mSUGRA with neutralino cold dark matter. Likewise, the regions of mSUGRA space most favored by neutralino CDM are least favored by mixed axion/axino dark matter. This has a large impact on the sort of SUSY signatures to be expected at LHC. The requirement of mainly axion CDM with $T_R \gtrsim 10^6$ GeV favors rather heavy squarks and sleptons. Thus, we expect in this case that LHC signatures will be dominated by gluino pair production followed by 3-body gluino decays to charginos and neutralinos. In Sec. 4, we present a summary and conclusions.

2. The gravitino problem, leptogenesis and mixed axion/axino dark matter

We adopt the mSUGRA model[11] as a template model for examining the role of mixed axion/axino dark matter in gravity-mediated SUSY breaking models. The mSUGRA parameter space is given by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu), \tag{2.1}$$

where m_0 is the unified soft SUSY breaking (SSB) scalar mass at the GUT scale, $m_{1/2}$ is the unified gaugino mass at M_{GUT}, A_0 is the unified trilinear SSB term at M_{GUT} and

$\tan\beta \equiv v_u/v_d$ is the ratio of Higgs field vevs at the weak scale. The GUT scale gauge and Yukawa couplings, and the SSB terms are evolved using renormalization group equations (RGEs) from M_{GUT} to m_{weak}, at which point electroweak symmetry is broken radiatively, owing to the large top quark Yukawa coupling. At m_{weak}, the various sparticle and Higgs boson mass matrices are diagonalized to find the physical sparticle and Higgs boson masses. The magnitude, but not the sign, of the superpotential μ parameter is determined by the EWSB minimization conditions. We adopt the Isasugra subprogram of Isajet for spectra generation[16].

2.1 Gravitino problem

In supergravity models, supersymmetry is broken via the superHiggs mechanism. The common scenario is to postulate the existence of a hidden sector which is uncoupled to the MSSM sector except via gravity. The superpotential of the hidden sector is chosen such that supergravity is broken, which causes the gravitino (which serves as the gauge particle for the superHiggs mechanism) to develop a mass $m_{3/2} \sim m^2/M_{Pl} \sim m_{weak}$. Here, m is a hidden sector parameter assumed to be of order 10^{11} GeV. [1] In addition to a mass for the gravitino, SSB masses of order m_{weak} are generated for all scalar, gaugino, trilinear and bilinear SSB terms. Here, we will assume that $m_{3/2}$ is larger than the lightest MSSM mass eigenstate, so that the gravitino essentially decouples from all collider phenomenology.

In all SUGRA scenarios, a potential problem arises for weak-scale gravitinos: the gravitino problem. In this case, gravitinos $\tilde{G}$ can be produced thermally in the early universe (even though the gravitinos are too weakly coupled to be in thermal equilibrium) at a rate which depends on the re-heat temperature T_R of the universe. The produced $\tilde{G}$ can then decay to various sparticle-particle combinations, with a long lifetime of order $1-10^5$ sec (due to the Planck suppressed gravitino coupling constant). The late gravitino decays occur during or after BBN, and their energy injection into the cosmic soup threatens to destroy the successful BBN predictions of the light element abundances. The precise constraints of BBN on the gravitino mass and T_R are presented recently in Ref. [18]. One way to avoid the gravitino problem in the case where $m_{3/2} \lesssim 5$ TeV is to maintain a value of $T_R \lesssim 10^5$ GeV. Such a low value of T_R rules out many attractive baryogenesis mechanisms, and so here instead we assume that $m_{3/2} \gtrsim 5$ TeV. In this case, the $\tilde{G}$ is so heavy that its lifetime is of order 1 sec or less, and the $\tilde{G}$ decays near the onset of BBN. In this case, values of T_R as large as 10^9 GeV are allowed.

In the simplest SUGRA models, one typically finds $m_0 = m_{3/2}$. For more general SUGRA models, the scalar masses are in general non-degenerate and only of order $m_{3/2}$[19]. Here for simplicity, we will assume degeneracy of scalar masses, but with $m_0 \ll m_{3/2}$.

2.2 Leptogenesis

One possible baryogenesis mechanism that requires relatively low $T_R \sim m_{weak}$ is electroweak baryogenesis. However, calculations of successful electroweak baryogenesis within the MSSM context seem to require sparticle mass spectra with $m_h \lesssim 120$ GeV, and

[1]In Ref. [17], a link is suggested between hidden sector parameters and the PQ breaking scale f_a.

$m_{\tilde{t}_1} \lesssim 125$ GeV[20]. The latter requirement is difficult (though not impossible) to achieve in the MSSM, and is also partially excluded by collider searches for light top squarks[21]. We will not consider this possibility further.

An alternative attractive mechanism– especially in light of recent evidence for neutrino mass– is thermal leptogenesis[23]. In this scenario, heavy right-handed neutrino states N_i $(i = 1-3)$ decay asymmetrically to leptons versus anti-leptons in the early universe. The lepton-antilepton asymmetry is converted to a baryon-antibaryon asymmetry via sphaleron effects. The measured baryon abundance can be achieved provided the re-heat temperature T_R exceeds $\sim 10^9$ GeV[24]. The high T_R value needed here apparently puts this mechanism into conflict with the gravitino problem in SUGRA theories.

A related leptogenesis mechanism called non-thermal leptogenesis invokes an alternative to thermal production of heavy neutrinos in the early universe. In non-thermal leptogenesis[25], it is possible to have lower reheat temperatures, since the N_i may be generated via inflaton decay. The Boltzmann equations for the $B-L$ asymmetry have been solved numerically in Ref. [26]. The $B-L$ asymmetry is then converted to a baryon asymmetry via sphaleron effects as usual. The baryon-to-entropy ratio is calculated in [26], where it is found

$$\frac{n_B}{s} \simeq 8.2\times 10^{-11}\times\left(\frac{T_R}{10^6\ \mathrm{GeV}}\right)\left(\frac{2M_{N_1}}{m_\phi}\right)\left(\frac{m_{\nu_3}}{0.05\ \mathrm{eV}}\right)\delta_{eff}, \tag{2.2}$$

where m_ϕ is the inflaton mass and δ_{eff} is an effective CP violating phase which may be of order 1. Comparing calculation with data (the measured value of $n_B/s \simeq 0.9\times 10^{-10}$), a lower bound $T_R \gtrsim 10^6$ GeV may be inferred for viable non-thermal leptogenesis via inflaton decay.

A fourth mechanism for baryogenesis is Affleck-Dine[27] leptogenesis[28]. In this approach, a flat direction $\phi_i = (2H\ell_i)^{1/2}$ is identified in the scalar potential, which may have a large field value in the early universe. When the expansion rate becomes comparable to the SSB terms, the field oscillates, and since the field carries lepton number, coherent oscillations about the potential minimum will develop a lepton number asymmetry. The lepton number asymmetry is then converted to a baryon number asymmetry by sphalerons as usual. Detailed calculations[28] find that the baryon-to-entropy ratio is given by

$$\frac{n_B}{s} \simeq \frac{1}{23}\frac{|\langle H\rangle|^2 T_R}{m_\nu M_{Pl}^2} \tag{2.3}$$

where $\langle H\rangle$ is the Higgs field vev, m_ν is the mass of the lightest neutrino and M_{Pl} is the Planck scale. To obtain the observed value of n_B/s, values of $T_R \sim 10^6 - 10^8$ are allowed for $m_\nu \sim 10^{-9} - 10^{-7}$ eV.

Thus, to maintain accord with either non-thermal or Affleck-Dine leptogenesis, along with constraints from the gravitino problem, we will aim for axion/axino DM scenarios with $T_R \sim 10^6 - 10^8$ GeV.

2.3 Mixed axion/axino dark matter

2.3.1 Relic axions

Axions can be produced via various mechanisms in the early universe. Since their lifetime (they decay via $a \to \gamma\gamma$) turns out to be longer than the age of the universe, they can be a good candidate for dark matter. Since we will be concerned here with re-heat temperatures $T_R \lesssim 10^9$ GeV $< f_a/N$ (to avoid overproducing gravitinos in the early universe), the axion production mechanism relevant for us here is just one: production via vacuum mis-alignment[5]. In this mechanism, the axion field $a(x)$ can have any value $\sim f_a$ at temperatures $T \gg \Lambda_{QCD}$. As the temperature of the universe drops, the potential turns on, and the axion field oscillates and settles to its minimum at $-\bar{\theta} f_a/N$ (where $\bar{\theta} = \theta + arg(det\ m_q)$, θ is the fundamental strong CP violating Lagrangian parameter and m_q is the quark mass matrix). The difference in axion field before and after potential turn-on corresponds to the vacuum mis-alignment: it produces an axion number density

$$n_a(t) \sim \frac{1}{2} m_a(t) \langle a^2(t) \rangle, \tag{2.4}$$

where t is the time near the QCD phase transition. Relating the number density to the entropy density allows one to determine the axion relic density today[5]:

$$\Omega_a h^2 \simeq \frac{1}{4} \left(\frac{6 \times 10^{-6}\ \text{eV}}{m_a} \right)^{7/6}. \tag{2.5}$$

An error estimate of the axion relic density from vacuum mis-alignment is plus-or-minus a factor of three. Axions produced via vacuum mis-alignment would constititute *cold* dark matter. However, in the event that $\langle a^2(t) \rangle$ is inadvertently small, then much lower values of axion relic density could be allowed. Additional entropy production at $t > t_{QCD}$ can also lower the axion relic abundance. Taking the value of Eq. (2.5) literally, and comparing to the WMAP5 measured abundance of CDM in the universe, one gets an upper bound $f_a/N \lesssim 5 \times 10^{11}$ GeV, or a lower bound $m_a \gtrsim 10^{-5}$ eV. If we take the axion relic density a factor of three lower, then the bounds change to $f_a/N \lesssim 1.2 \times 10^{12}$ GeV, and $m_a \gtrsim 4 \times 10^{-6}$ eV.

2.3.2 Axinos from neutralino decay

If the $\tilde{a}$ is the lightest SUSY particle, then the $\tilde{\chi}_1^0$ will no longer be stable, and can decay via $\tilde{\chi}_1^0 \to \tilde{a}\gamma$. The relic abundance of axinos from neutralino decay (non-thermal production, or NTP) is given simply by

$$\Omega_{\tilde{a}}^{NTP} h^2 = \frac{m_{\tilde{a}}}{m_{\tilde{\chi}_1^0}} \Omega_{\tilde{\chi}_1^0} h^2, \tag{2.6}$$

since in this case the axinos inherit the thermally produced neutralino number density. The neutralino-to-axino decay offers a mechanism to shed large factors of relic density. For a case where $m_{\tilde{\chi}_1^0} \sim 100$ GeV and $\Omega_{\tilde{\chi}_1^0} h^2 \sim 10$ (as can occur in the mSUGRA model at large m_0 values) an axino mass of less than 1 GeV reduces the DM abundance to below WMAP-measured levels.

The lifetime for these decays has been calculated, and it is typically in the range of $\tau(\tilde{\chi}_1^0 \to \tilde{a}\gamma) \sim 0.01 - 1$ sec[29]. The photon energy injection from $\tilde{\chi}_1^0 \to \tilde{a}\gamma$ decay into the cosmic soup occurs typically before BBN, thus avoiding the constraints that plague the case of a gravitino LSP[18]. The axino DM arising from neutralino decay is generally considered warm or even hot dark matter for cases with $m_{\tilde{a}} \lesssim 1-10$ GeV[30]. Thus, in the mSUGRA scenario considered here, where $m_{\tilde{a}} \lesssim 1-10$ GeV, we usually get *warm* axino DM from neutralino decay.

2.3.3 Thermal production of axinos

Even though axinos may not be in thermal equilibrium in the early universe, they can still be produced thermally via scattering and decay processes in the cosmic soup. The axino thermally produced (TP) relic abundance has been calculated in Ref. [29, 31], and is given in Ref. [31] using hard thermal loop resummation as

$$\Omega_{\tilde{a}}^{TP} h^2 \simeq 5.5 g_s^6 \ln\left(\frac{1.108}{g_s}\right)\left(\frac{10^{11}\text{ GeV}}{f_a/N}\right)^2\left(\frac{m_{\tilde{a}}}{0.1\text{ GeV}}\right)\left(\frac{T_R}{10^4\text{ GeV}}\right) \tag{2.7}$$

where g_s is the strong coupling evaluated at $Q = T_R$ and N is the model dependent color anomaly of the PQ symmetry, of order 1. We take *e.g.* $g_s(T_R = 10^6\text{ GeV}) = 0.915$. The thermally produced axinos qualify as *cold* dark matter as long as $m_{\tilde{a}} \gtrsim 0.1$ MeV[29, 31].

In Fig. 1, we plot the re-heat temperature needed to thermally produce various abundances of axinos versus the Peccei-Quinn scale f_a/N. We plot values of $\Omega_{\tilde{a}}^{TP} h^2 = 0.001$ (solid), 0.01 (dashed) and 0.1 (dot-dashed), assuming values of $m_{\tilde{a}} = 10^{-4}$ (purple), 10^{-2} (green) and 1 GeV (maroon). We see from the curves that in order to achieve T_R values $\gtrsim 10^6$ GeV, we will need values of f_a/N on the large side: $\sim 10^{11} - 10^{12}$ GeV. We also see that the purple curves– with lowest values of $m_{\tilde{a}} \sim 100$ keV– give the largest T_R values. Of course, from the preceeding discussion, large values of f_a/N also give more *axion* dark matter, independent of any other parameters. Thus, to achieve high values of T_R, we will likely need to examine scenarios with mostly axion CDM, combined with smaller amounts of cold and warm axinos.

3. Preferred mSUGRA parameters with mainly axion CDM

In this section, we generate sparticle mass spectra using the Isasugra subprogram of the event generator Isajet[16]. Isasugra performs an iterative solution of the MSSM two-loop RGEs, and includes an RG-improved one-loop effective potential evaluation at an optimized scale, which accounts for leading two-loop effects[32]. Complete one-loop mass corrections for all sparticles and Higgs boson masses are included[33].[2]

Our first results are shown in Fig. 2, where we examine the mSUGRA point with $(m_0, m_{1/2}, A_0, \tan\beta, sgn(\mu)) = (1000, 300, 0, 10, +1)$ (where all mass parameters are in GeV units). We also take $m_t = 172.6$ GeV. For this point, the neutralino relic density computed by IsaReD[34] is $\Omega_{\tilde{\chi}_1^0} h^2 = 8.9$, so the point would be excluded under the assumption that thermal neutralinos make up the dark matter. In frame *a*)., we plot the values of $\Omega_a h^2$, $\Omega_{\tilde{a}}^{TP} h^2$ and $\Omega_{\tilde{a}}^{NTP} h^2$ versus f_a/N under the assumption that $T_R = 10^6$ (dashes), 10^7 (solid)

[2]The case of $m_{\tilde{\tau}_1} < m_{\tilde{\chi}_1^0}$ was recently examined in Ref. [12]. In their results, they always take $\Omega_a h^2 \sim 0$. We have checked using the Micromegas program[13] (to calculate the stau relic density, which is not handled by IsaReD) that the value of T_R generated in the stau NLSP region is always less than the corresponding values generated in the neutralino NLSP regions for the cases considered in this section.

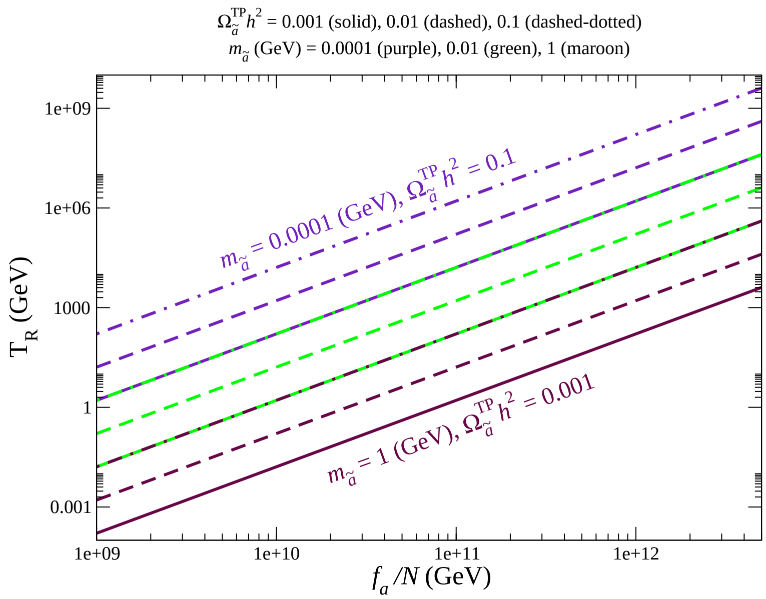

Figure 1: A plot of the expected re-heat temperature of the universe T_R versus PQ breaking scale f_a/N for $\Omega_{\tilde{a}}^{TP}h^2 = 0.001$ (solid), 0.01 (dashed) and 0.1 (dot-dashed), and with $m_{\tilde{a}} = 10^{-4}$ (purple), 10^{-2} (green) and 1 GeV (maroon). (The solid purple and dot-dashed green, and also the solid green and dot-dashed maroon lines coincide.)

and 10^8 GeV (dot-dashed). We assume the axion relic density is as given by the central value of Eq. 2.5. We require as well that the sum $\Omega_a h^2 + \Omega_{\tilde{a}}^{TP}h^2 + \Omega_{\tilde{a}}^{NTP}h^2 = 0.11$, *i.e.* that the combination of three components of axion and axino DM saturate the WMAP central value. For each value of f_a/N, the value of $m_{\tilde{a}}$ needed to saturate the measured DM abundance is calculated, and listed in frame *b*). in GeV units, along with m_a in eV units. The axion abundance is of course independent of T_R. The abundance of $\Omega_{\tilde{a}}^{TP}h^2$ is fixed mainly by requiring the total relic abundance saturate the measured central value, and since T_R is fixed, this means we can compute the needed value of $m_{\tilde{a}}$. For low values of $f_a/N \lesssim 10^{11}$ GeV, the DM abundance is dominated by $\Omega_{\tilde{a}}^{TP}h^2$. (the curves for $\Omega_{\tilde{a}}^{TP}h^2$ for all three cases of T_R overlap to within the line resolution). But comparing with frame *b*)., we see for almost all of this range, $m_{\tilde{a}} < 100$ keV, meaning the bulk of axino DM is actually *warm*, in contradiction to what is needed to generate large scale structure in the universe. An exception occurs in the case of $T_R = 10^6$ GeV (barely enough for non-thermal leptogenesis), where $m_{\tilde{a}}$ moves to values higher than 100 keV. At the highest $f_a/N \gtrsim 3 \times 10^{11}$ GeV, axion CDM dominates the relic abundance. In this case, $m_{\tilde{a}}$ must drop precipitously so that $\Omega_{\tilde{a}}^{TP}h^2$, which wants to rise with increasing f_a/N, instead sharply drops. The region with mainly axion CDM is robust in that it gives rise to a consistent cosmology for all choices of T_R: for this case, the axino mass can drop below 100 keV into the warm DM region, since now axinos will only be a small component of the DM density.

In Fig. 3, we plot again the same quantities as in Fig. 2, but this time we keep $m_{\tilde{a}}$ fixed to a value of 100 keV (solid) and 1 MeV (dashed), and we allow T_R to vary in order

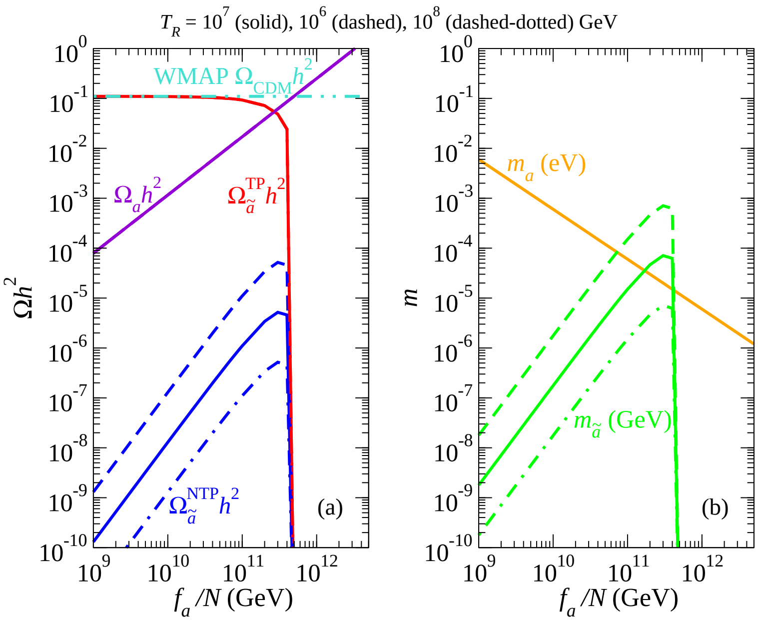

Figure 2: Axion and TP and NTP axino contributions to dark matter density for $T_R = 10^6$ GeV, 10^7 GeV and 10^8 GeV versus PQ breaking scale f_a/N.

to maintain the WMAP measured abundance of CDM. Frame *a*). shows the relic density of all three components of axion/axino dark matter, while frame *b*). shows the value of T_R needed for each value of f_a/N. We see that for low values of f_a/N, the value of T_R is well below the 10^6 GeV regime, and in fact doesn't even exceed 10^6 GeV for the case of $m_{\tilde{a}} = 1$ MeV. In the case of $m_{\tilde{a}} = 100$ keV, T_R exceeds 10^6 GeV for $f_a/N \gtrsim 10^{11}$ GeV, and approaches a maximum for the case of mainly axion dark matter.

Next, we explore the mSUGRA m_0 *vs.* $m_{1/2}$ plane for the presence of solutions with $T_R \gtrsim 10^6$ GeV so they yield consistent baryogenesis mechanisms. In our first try, we set $f_a/N = 1.2\times 10^{12}$ GeV so that the measured dark matter density is saturated by cold axions (we assume the factor of three downward fluctuation in $\Omega_a h^2$, which allows for an increased value of f_a/N). We will assume equal portions of TP and NTP axinos, which saturate the $1-\sigma$ error bars on the WMAP measured $\Omega_{CDM}h^2$ value: $\Omega_{\tilde{a}}^{TP}h^2 = \Omega_{\tilde{a}}^{NTP}h^2 = 0.003$. We also adopt mSUGRA parameters $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$. Using these values, we calculate the sparticle mass spectrum, $\Omega_{\tilde{\chi}_1^0}h^2$ and $m_{\tilde{\chi}_1^0}$ at each point in mSUGRA space. We then determine the necessary value of $m_{\tilde{a}}$ (from $\Omega_{\tilde{\chi}_1^0}^{NTP}h^2$), and then calculate the required value of T_R (from $\Omega_{\tilde{a}}^{TP}h^2$). We plot in Fig. 4 the color-coded regions of T_R values, along with contours of $\log_{10} T_R$. The lower right red region is excluded due to lack of appropriate EWSB, while the left-side red region yields a stau NLSP. The gray region is excluded by LEP2 limits on the chargino mass.

From Fig. 4 we see that the usual regions preferred for neutralino cold dark matter actually give the lowest values of T_R: we find $T_R \sim 1-10$ GeV in the stau co-annihilation region and in the hyperbolic branch/focus point (HB/FP) region.[3] These values are far

[3]The calculation of $\Omega_{\tilde{a}}^{TP}h^2$ is valid perturbatively only for $T_R \gtrsim 10^4$ GeV. In the case of lower T_R, high

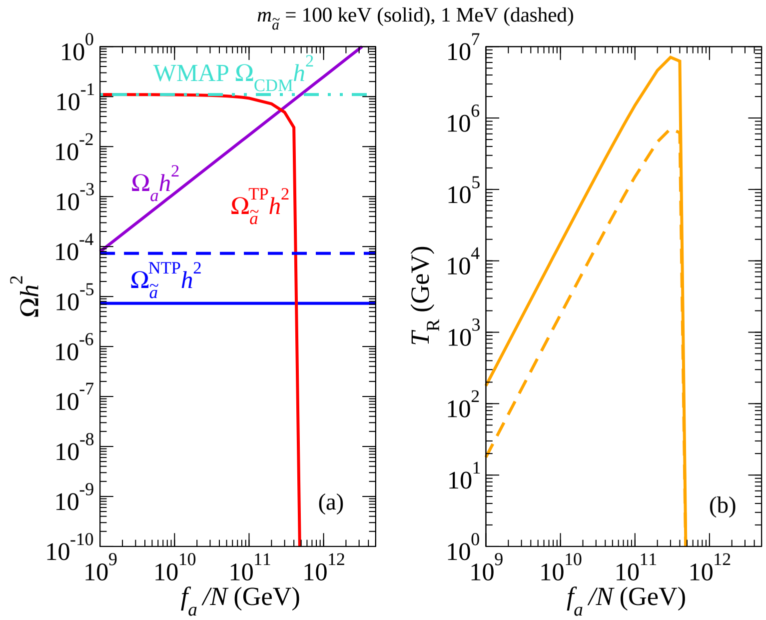

Figure 3: Axion and TP and NTP axino contributions to dark matter density for $m_{\tilde{a}} = 100$ keV versus PQ breaking scale f_a/N.

too small even to sustain electroweak baryogenesis. The central blue regions of the plot accommodate the largest values of $T_R \gtrsim 10^4$ GeV. While yielding a much higher T_R value than the stau and HB/FP regions, even these regions do not yield a high enough T_R value to sustain non-thermal leptogenesis.

Fig. 5 shows the corresponding contours of $m_{\tilde{a}}$. The values range from $m_{\tilde{a}} \sim 100$ (600) GeV in the stau (HB/FP) regions to values of $m_{\tilde{a}} < 0.05$ GeV in the regions of high T_R.

To push the value of T_R higher, we would need to diminish even further the value of $m_{\tilde{a}}$ (as suggested by Fig. 2*b*).) which also diminishes the amount of NTP axino dark matter. In Fig. 6, we again plot the m_0 *vs.* $m_{1/2}$ plane for the same parameters as in Fig. 4 so that we saturate the CDM abundance with axions. However, in this case we adopt $\Omega_{\tilde{a}}^{TP}h^2 = 0.006$ (saturating the WMAP $\Omega_{CDM}h^2$ error bar), and take $\Omega_{\tilde{a}}^{NTP}h^2 = 6 \times 10^{-6}$. The much smaller value of $\Omega_{\tilde{a}}^{NTP}h^2$ (than that used in Fig. 4) means the value of $m_{\tilde{a}}$ will be much smaller all over the plane than in the Fig. 4 case. To balance the lower value of $m_{\tilde{a}}$ in the fixed value of $\Omega_{\tilde{a}}^{TP}h^2$, a much higher value of T_R will be needed. We now see that the contours of T_R plotted in Fig. 6 move well into the 10^7 GeV regime: enough to sustain the non-thermal leptogenesis mechanism. In fact, the preferred regions of high T_R are precisely those regions of mSUGRA parameter space that are *most disfavored* by neutralino CDM! In this case, the stau and HB/FP regions, preferred in mSUGRA, can only sustain T_R values in the 10^3 GeV range. The regions with $m_0 \sim 1$ TeV and $m_{1/2} \sim 200 - 400$ GeV allow for T_R values well in excess of 10^7 GeV. This region of parameter space is usually neglected in simulation studies for the LHC, since it severely disagrees with the conjecture of thermally produced neutralino CDM. For this reason, we list a benchmark point A in Table 1 with

precision in $\Omega_{\tilde{a}}^{TP}h^2$ is not needed, so long as we know that T_R is much below $\sim 10^6$ GeV.

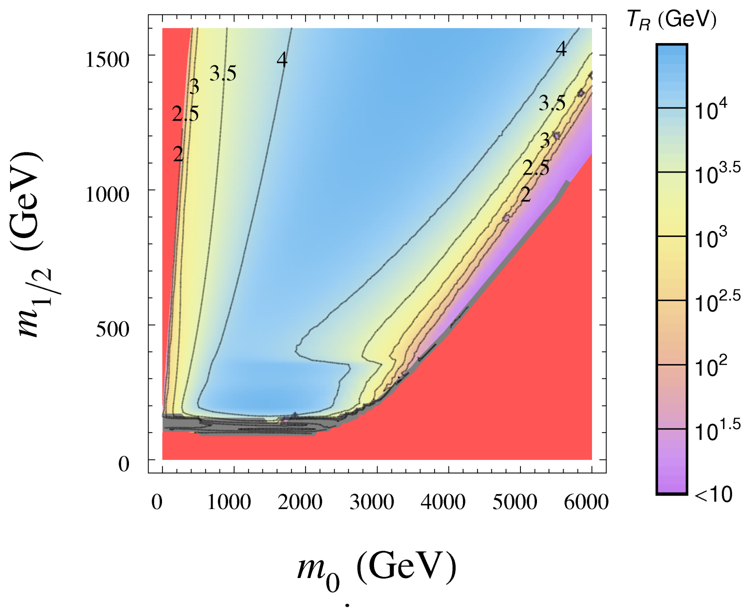

Figure 4: Contours of constant T_R in the m_0 *vs.* $m_{1/2}$ plane for $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$. We assume $\Omega_a h^2 = 0.11$, and $\Omega_{\tilde{a}}^{TP} h^2 = \Omega_{\tilde{a}}^{NTP} = 0.003$. The lower right red region is excluded due to lack of appropriate EWSB, while the left-side red region yields a stau NLSP. The gray region is excluded by LEP2 limits on the chargino mass.

$m_0 = 1500$ GeV, $m_{1/2} = 200$ GeV, $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$. In this region, squarks and sleptons have mass in the TeV range, while $m_{\tilde{g}} \sim 500$ GeV. LHC collider events should thus be dominated by gluino pair production, followed by gluino three-body decays into $q\bar{q}\tilde{\chi}_i^0$ and $q\bar{q}'\tilde{\chi}_i^\pm$ final states. The $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ will decay into $f\bar{f}'\tilde{\chi}_1^0$ and $f\bar{f}\tilde{\chi}_1^0$ respectively, where f denotes any SM fermion states whose decay modes are kinematically allowed. In particular, the decays $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 e^+e^-$ and $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \mu^+\mu^-$ each occur at $\sim 3\%$, since the decay is dominated by Z^* exchange.

Fig. 7 shows contours of $m_{\tilde{a}}$ for the case as shown in Fig. 6. Here, we see much smaller $m_{\tilde{a}}$ values below 100 keV are generated. These low values of $m_{\tilde{a}}$ would yield warm thermally produced axinos. However, since the bulk of DM is constituted by axions, the temperature of the small fraction of axinos is not relevant.

In Fig. 8, we again plot contours of constant T_R in the m_0 *vs.* $m_{1/2}$ plane for $A_0 = 0$ and $\mu > 0$, but this time for $\tan\beta = 30$. The larger value of $\tan\beta$ leads to larger values of b and τ Yukawa couplings, and a lower value of m_A[35]. This in turn leads to larger rates for neutralino annihilation via s-channel A^* exchange diagrams, and somewhat lower neutralino relic density values. We again asume $\Omega_a h^2 = 0.11$, $\Omega_{\tilde{a}}^{TP} h^2 = 0.006$ and $\Omega_{\tilde{a}}^{NTP} = 6 \times 10^{-6}$ and calculate the requisite value of T_R. From the figure, it is seen that the stau and HB/FP regions lead to lower values of $T_R \sim 10^3 - 10^5$ GeV, while regions with $m_0 \sim 800 - 2000$ GeV can still lead to T_R in excess of 10^7 GeV, enough to sustain non-thermal leptogenesis.

The corresponding contours of $m_{\tilde{a}}$ for the $\tan\beta = 30$ case are shown in Fig. 9. They

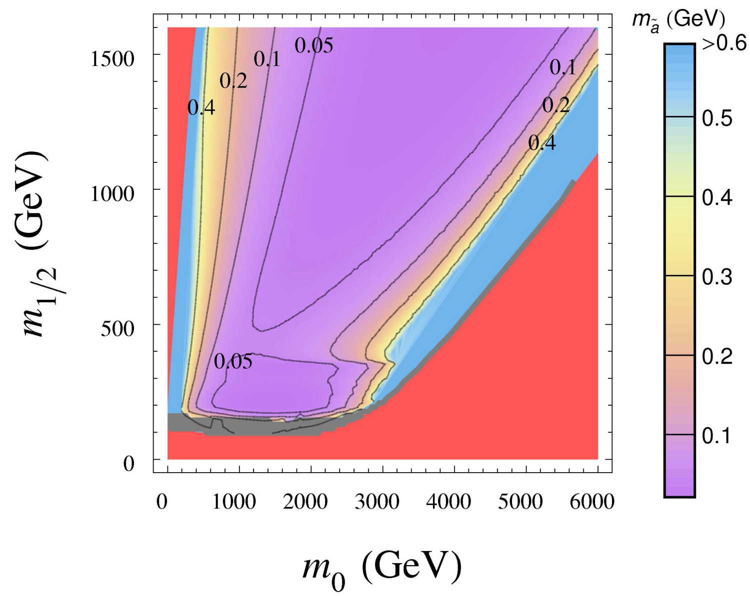

Figure 5: Contours of constant $m_{\tilde{a}}$ in the m_0 *vs.* $m_{1/2}$ plane for $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$. We assume $\Omega_a h^2 = 0.11$, and $\Omega_{\tilde{a}}^{TP} h^2 = \Omega_{\tilde{a}}^{NTP} = 0.003$.

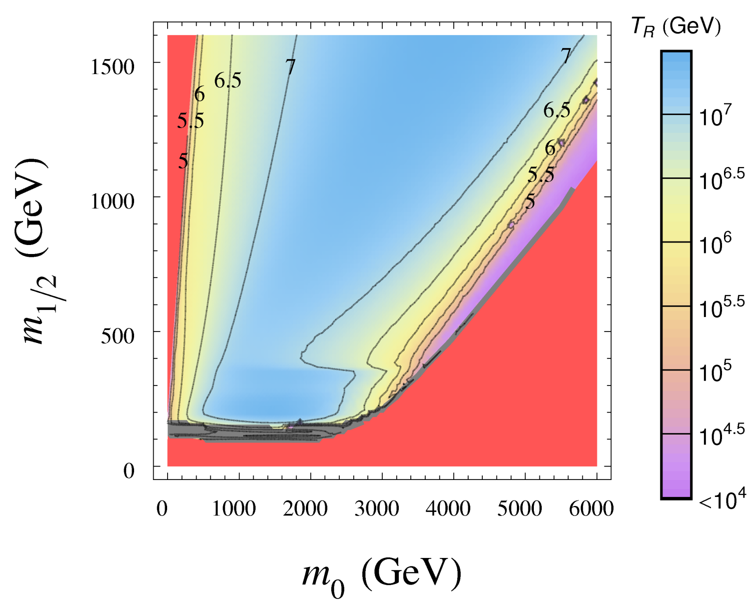

Figure 6: Contours of constant T_R in the m_0 *vs.* $m_{1/2}$ plane for $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$. We assume $\Omega_a h^2 = 0.11$, and $\Omega_{\tilde{a}}^{TP} h^2 = 0.006$ and $\Omega_{\tilde{a}}^{NTP} = 6 \times 10^{-6}$.

range from above 1 GeV in the stau co-annihilation and HB/FP region, to below 100 keV in the regions of $T_R > 10^7$ GeV. We list in Table 1 an mSUGRA benchmark point B with $\tan\beta = 30$ and mainly axion CDM. In this case, as in the case of benchmark point A, gluino pair production occurs at a large rate. However, in this case, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z$ at $\sim 100\%$,

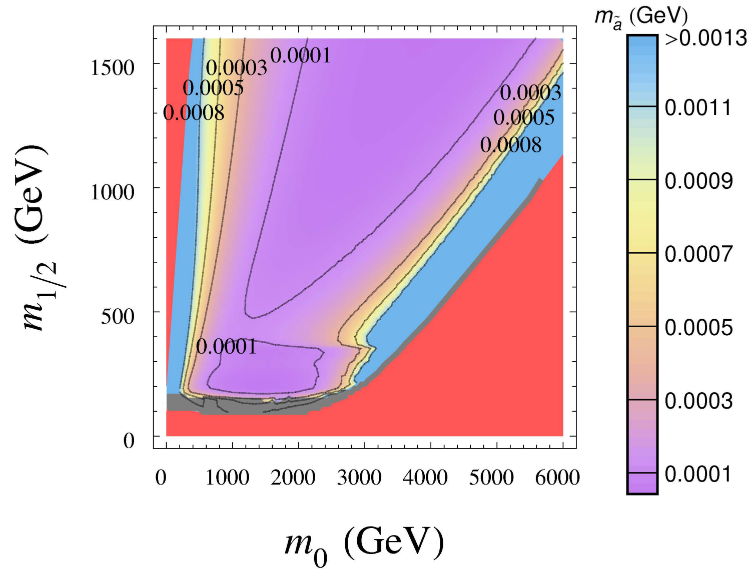

Figure 7: Contours of constant $m_{\tilde{a}}$ in the m_0 *vs.* $m_{1/2}$ plane for $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$. We assume $\Omega_a h^2 = 0.11$, and $\Omega_{\tilde{a}}^{TP} h^2 = 0.006$ and $\Omega_{\tilde{a}}^{NTP} = 6 \times 10^{-6}$.

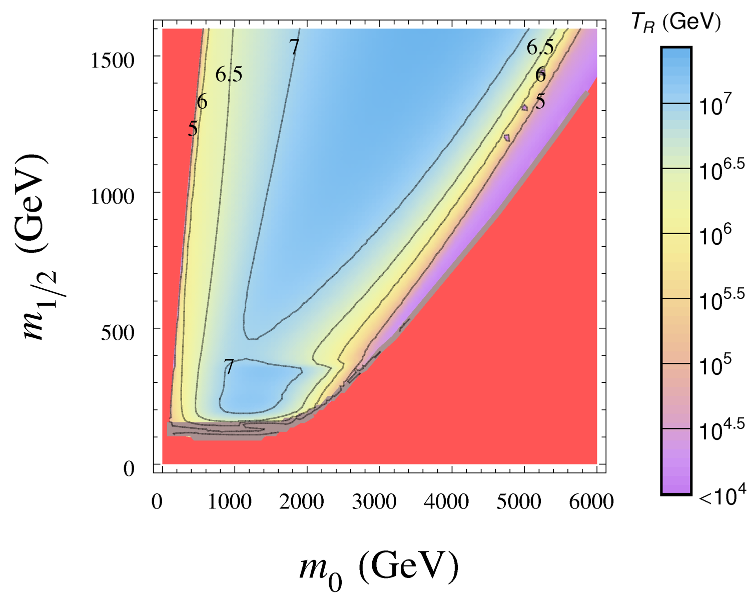

Figure 8: Contours of constant T_R in the m_0 *vs.* $m_{1/2}$ plane for $A_0 = 0$, $\tan\beta = 30$ and $\mu > 0$. We assume $\Omega_a h^2 = 0.11$, and $\Omega_{\tilde{a}}^{TP} h^2 = 0.006$ and $\Omega_{\tilde{a}}^{NTP} = 6 \times 10^{-6}$.

so LHC events will be rich in multi-jet plus Z plus $E_T^{\rm miss}$ signatures[36].

It should now be apparent that by conjecturing a large value of the PQ scale f_a/N such that axion CDM saturates the relic density, then by taking decreasingly low values of axino mass, large values of T_R may be generated. To illustrate this graphically, we plot

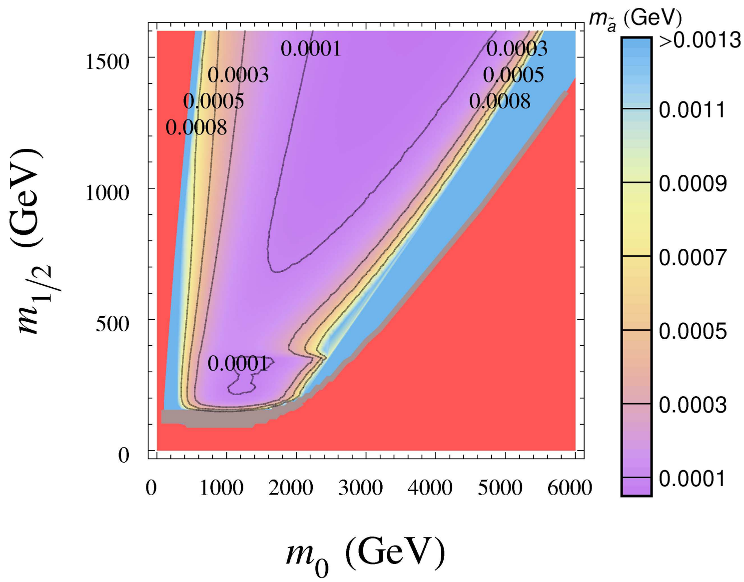

Figure 9: Contours of constant $m_{\tilde{a}}$ in the m_0 *vs.* $m_{1/2}$ plane for $A_0 = 0$, $\tan\beta = 30$ and $\mu > 0$. We assume $\Omega_a h^2 = 0.11$, and $\Omega_{\tilde{a}}^{TP} h^2 = 0.006$ and $\Omega_{\tilde{a}}^{NTP} = 6 \times 10^{-6}$.

in Fig. 10 the value of T_R required versus $m_{\tilde{a}}$ for the mSUGRA point $m_0 = 1000$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$. We assume $\Omega_a h^2 = 0.11$, and that $\Omega_{\tilde{a}}^{TP} h^2 + \Omega_{\tilde{a}}^{NTP} = 0.006$. For $m_{\tilde{a}} = 0.08$ GeV, the axino portion of the relic density is comprised almost entirely of non-thermally produced axino DM from neutralino decay. As we decrease $m_{\tilde{a}}$ from this value, the portion of NTP axino DM decreases, and since the sum is constant, the TP portion increases. Since the value of $\Omega_{\tilde{a}}^{TP} h^2$ is proportional to $m_{\tilde{a}}$, a large increase in T_R is needed to keep pace. We see in the extreme limit, values of T_R as high as 10^{10} GeV can be generated (putting us in conflict with the gravitino problem) for values of $m_{\tilde{a}}$ as low as 10^{-8} GeV (far below the usual theory expectations for $m_{\tilde{a}}$[29]).

4. Summary and conclusions

In this paper, we have examined the consequences for the mSUGRA model if dark matter is composed of an axion/axino admixture, rather than neutralinos. We have considered this scenario along with cosmological consequences of the gravitino problem (which restricts $m_{3/2} > 5$ TeV and re-heat temperatures $T_R \lesssim 10^9$ GeV) and leptogenesis. While thermal leptogenesis requires $T_R \gtrsim 10^9$ GeV (in conflict with the gravitino problem), non-thermal leptogenesis– wherein heavy right-hand neutrino states are produced additionally via inflaton decay– can allow for successful baryogenesis with $T_R \gtrsim 10^6$ GeV. (In addition, Affleck-Dine leptogenesis may occur at these values of T_R, although it may also occur at even lower T_R values.)

We explored mSUGRA parameter space for regions of high T_R with three components of dark matter: dominant axion CDM, along with small portions of thermally and non-

parameter	Pt. A	Pt. B
m_0	1500	1000
$m_{1/2}$	200	300
A_0	0	0
$\tan\beta$	10	30
μ	304.5	368.4
$m_{\tilde{g}}$	568.2	773.3
$m_{\tilde{u}_L}$	1541.1	1178.4
$m_{\tilde{t}_1}$	912.3	774.2
$m_{\tilde{b}_1}$	1264.5	965.7
$m_{\tilde{e}_R}$	1500.6	1005.8
$m_{\tilde{\chi}_1^\pm}$	148.7	227.8
$m_{\tilde{\chi}_2^0}$	148.0	227.0
$m_{\tilde{\chi}_1^0}$	80.0	122.4
m_A	1510.6	912.2
m_h	112.4	112.8
$\Omega_{\tilde{\chi}_1^0}h^2$	9.2	6.5
$BF(b\to s\gamma)$	3.1×10^{-4}	2.5×10^{-4}
Δa_μ^{SUSY}	1.5×10^{-10}	9.7×10^{-10}

Table 1: Masses in GeV units and parameters for two mSUGRA model benchmark points with mainly axion CDM: $\Omega_a h^2 = 0.11$. We take $f_a/N = 5\times 10^{11}$ GeV, along with $\Omega_{\tilde{a}}^{TP} = 0.006$ and $\Omega_{\tilde{a}}^{NTP} = 6\times 10^{-6}$. We also take $m_t = 172.6$ GeV.

thermally produced axino DM (which may be either warm or cold). We find the highest values of T_R occur in the regions of mSUGRA space which are typically most *disfavored* by neutralino CDM. Likewise, the regions of mSUGRA parameter space most favored by neutralino CDM are actually most disfavored by mixed axion/axino DM. By combining high T_R values with fine-tuning considerations (which prefer lower values of m_0 and especially $m_{1/2}$), we find mSUGRA with mainly axion CDM prefers $m_0 \sim 800 - 2000$ GeV, with $m_{1/2} \sim 150 - 400$ GeV. There are several consequences of this scenario:

- LHC SUSY events will be dominated by gluino pair production, followed by gluino three body decays to charginos and neutralinos.
- Current and future WIMP direct and indirect dark matter detection experiments will likely find null results.
- The ADMX[37], or other direct axion detection experiments, stand a good chance of finding an axion signal. The ultimate axion rate predictions are of course model dependent.

A related scenario for sparticle spectra with mainly axion CDM has been put forward in Refs. [38] in the context of $t-b-\tau$ Yukawa-unified SUSY models. These models– expected from simple $SO(10)$ SUSY GUT theories– predict a spectrum of scalars in the

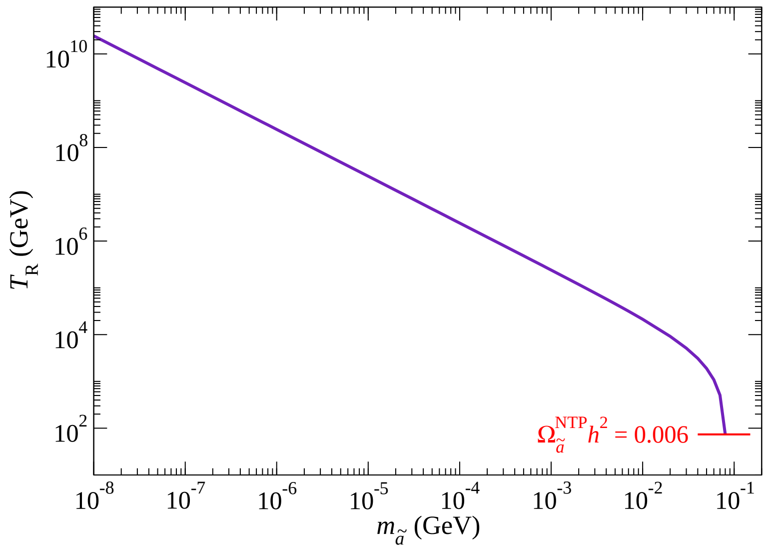

Figure 10: Plot of the value of T_R needed versus $m_{\tilde{a}}$ for the mSUGRA point with $m_0 = 1000$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$. We assume $\Omega_a h^2 = 0.11$, and that $\Omega_{\tilde{a}}^{TP} h^2 + \Omega_{\tilde{a}}^{NTP} = 0.006$.

range of $5 - 15$ TeV: much higher than allowed in mSUGRA. Additionally, Yukawa unified models require $\tan\beta \sim 50$. Thus, the mSUGRA model– in contrast to Yukawa-unified models[39]– allows for the possibility of first and second generation squark masses which are accessible to LHC, and which would augment the gluino production rate, since $\tilde{q} \to q\tilde{g}$ decay is expected. In addition, mSUGRA models with mainly axion CDM allow for lower values of $\tan\beta$ and hence smaller values of b and τ Yukawa couplings. In this case, a lower multiplicity of b-quark jets is expected in LHC SUSY events.

References

[1] J. Dunkley *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **180** (2009) 306

[2] For a recent review, see P. Sikivie, `hep-ph/0509198`; M. Turner, *Phys. Rept.* **197** (1990) 67; J. E. Kim and G. Carosi, arXiv:0807.3125 (2008);

[3] R. Peccei and H. Quinn, *Phys. Rev. Lett.* **38** (1977) 1440 and *Phys. Rev.* **D 16** (1977) 1791.

[4] S. Weinberg, *Phys. Rev. Lett.* **40** (1978) 223; F. Wilczek, *Phys. Rev. Lett.* **40** (1978) 279.

[5] L. F. Abbott and P. Sikivie, *Phys. Lett.* **B 120** (1983) 133; J. Preskill, M. Wise and F. Wilczek, *Phys. Lett.* **B 120** (1983) 127; M. Dine and W. Fischler, *Phys. Lett.* **B 120** (1983) 137; M. Turner, *Phys. Rev.* **D 33** (1986) 889.

[6] H. Pagels and J. Primack, *Phys. Rev. Lett.* **48** (1982) 223. J. Feng, A. Rajaraman and F. Takayama, *Phys. Rev. Lett.* **91** (2003) 011302 and *Phys. Rev.* **D 68** (2003) 085018

[7] H. P. Nilles and S. Raby, *Nucl. Phys.* **B 198** (1982) 102.

[8] For recent reviews of axion/axino dark matter, see F. Steffen, arXiv:0811.3347 (2008); L. Covi and J. E. Kim, arXiv:0902.0769 (2009).

[9] E. J. Chun, J. E. Kim and H. P. Nilles, *Phys. Lett.* **B 287** (1992) 123.

[10] K. Rajagopal, M. Turner and F. Wilczek, *Nucl. Phys.* **B 358** (1991) 447.

[11] A. Chamseddine, R. Arnowitt and P. Nath, *Phys. Rev. Lett.* **49** (1982) 970; R. Barbieri, S. Ferrara and C. Savoy, *Phys. Lett.* **B 119** (1982) 343; N. Ohta, Prog. Theor. Phys. **70** (1983) 542; L. Hall, J. Lykken and S. Weinberg, *Phys. Rev.* **D 27** (1983) 2359.

[12] A. Freitas, F. Steffen, N. Tajuddin and D. Wyler, arXiv:0904.3218 (2009).

[13] G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, *Comput. Phys. Commun.* **177** (2007) 894.

[14] L. Covi, L. Roszkowski, R. Ruiz de Austri and M. Small, *J. High Energy Phys.* **0406** (2004) 003; A. Brandenburg, L. Covi, K. Hamaguchi, L. Roszkowski and F. Steffen, *Phys. Lett.* **B 617** (2005) 99; K. Y. Choi, L. Roszkowski and R. Ruiz de Austri, *J. High Energy Phys.* **0804** (2008) 016.

[15] P. Sikivie and Q. Yang, arXiv:0901.1106 (2009).

[16] F. Paige, S. Protopopescu, H. Baer and X. Tata, `hep-ph/0312045`; http://www.nhn.ou.edu/∼isajet/

[17] J. E. Kim and H. P. Nilles, *Phys. Lett.* **B 138** (1984) 150.

[18] K. Kohri, T. Moroi and A. Yotsuyanagi, *Phys. Rev.* **D 73** (2006) 123511; for an update, see M. Kawasaki, K. Kohri, T. Moroi and A. Yotsuyanagi, *Phys. Rev.* **D 78** (2008) 065011.

[19] S. Soni and H. A. Weldon, *Phys. Lett.* **B 126** (1983) 215; V.Kaplunovsky and J. Louis, *Phys. Lett.* **B 306** (1993) 269; A. Brignole, L. Ibanez and C. Munoz, *Nucl. Phys.* **B 422** (1994) 125.

[20] For a recent analysis, see M. Carena, G. Nardini, M. Quiros and C. Wagner, *Nucl. Phys.* **B 812** (2009) 243.

[21] A. A. Affolder *et al.* [CDF Collaboration], Phys. Rev. Lett. **84** (2000) 5273;

[22] A. A. Affolder *et al.* [CDF Collaboration], Phys. Rev. Lett. **84** (2000) 5704; V. M. Abazov *et al.* [D0 Collaboration], arXiv:0811.0459 [hep-ex]; V. M. Abazov *et al.* [D0 Collaboration], Phys. Lett. B **665** (2008) 1 .

[23] M. Fukugita and T. Yanagida, *Phys. Lett.* **B 174** (1986) 45; M. Luty, *Phys. Rev.* **D 45** (1992) 455; M. Luty, *Phys. Rev.* **D 45** (1992) 455; W. Buchmüller and M. Plumacher, *Phys. Lett.* **B 389** (1996) 73 and *Int. J. Mod. Phys.* **A 15** (2000) 5047; R. Barbieri, P. Creminelli, A. Strumia and N. Tetradis, *Nucl. Phys.* **B 575** (2000) 61; G. F. Giudice, A. Notari, M. Raidal, A. Riotto and A. Strumia, *Nucl. Phys.* **B 685** (2004) 89; for a recent review, see W. Buchmüller, R. Peccei and T. Yanagida, *Ann. Rev. Nucl. Part. Sci.* **55** (2005) 311.

[24] W. Buchmuller, P. Di Bari and M. Plumacher, Annal. Phys. **315** (2005) 305.

[25] G. Lazarides and Q. Shafi, *Phys. Lett.* **B 258** (1991) 305; K. Kumekawa, T. Moroi and T. Yanagida, *Prog. Theor. Phys.* **92** (1994) 437; T. Asaka, K. Hamaguchi, M. Kawasaki and T. Yanagida, *Phys. Lett.* **B 464** (1999) 12.

[26] M. Ibe, T. Moroi and T. Yanagida, *Phys. Lett.* **B 620** (2005) 9.

[27] I. Affleck and M. Dine, Nucl. Phys. B **249** (1985) 361.

[28] H. Murayama and T. Yanagida, *Phys. Lett.* **B 322** (1994) 349; M. Dine, L. Randall and S. Thomas, *Nucl. Phys.* **B 458** (1996) 291.

[29] L. Covi, J. E. Kim and L. Roszkowski, *Phys. Rev. Lett.* **82** (1999) 4180; L. Covi, H. B. Kim, J. E. Kim and L. Roszkowski, *J. High Energy Phys.* **0105** (2001) 033. L. Covi, L. Roszkowski and Small, *J. High Energy Phys.* **0207** (2002) 023.

[30] K. Jedamzik, M. LeMoine and G. Moultaka, JCAP**0607** (2006) 010.

[31] A. Brandenburg and F. Steffen, JCAP**0408** (2004) 008.

[32] H. E. Haber, R. Hempfling and A. Hoang, *Z. Physik* **C 75** (1996) 539.

[33] D.Pierce, J. Bagger, K. Matchev and R. Zhang, *Nucl. Phys.* **B 491** (1997) 3.

[34] H. Baer, C. Balazs, A. Belyaev, *J. High Energy Phys.* **0203** (2002) 042.

[35] H. Baer, C. H. Chen, M. Drees, F. Paige and X. Tata, *Phys. Rev. Lett.* **79** (1997) 986.

[36] H. Baer, X. Tata and J. Woodside, *Phys. Rev.* **D 42** (1990) 1450.

[37] L. Duffy *et al.*, *Phys. Rev. Lett.* **95** (2005) 091304 and *Phys. Rev.* **D 74** (2006) 012006; for a review, see S. Asztalos, L. Rosenberg, K. van Bibber, P. Sikivie and K. Zioutas, *Ann. Rev. Nucl. Part. Sci.* **56** (2006) 293.

[38] H. Baer, S. Kraml, S. Sekmen and H. Summy, *J. High Energy Phys.* **0803** (2008) 056; H. Baer and H. Summy, *Phys. Lett.* **B 666** (2008) 5; H. Baer, M. Haider, S. Kraml, S. Sekmen and H. Summy, JCAP**0902** (2009) 002.

[39] H. Baer, S. Kraml, S. Sekmen and H. Summy, *J. High Energy Phys.* **0810** (2008) 079.