MSSM Dark Matter Constraints and Decaying B-balls.

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Abstract

In the MSSM, LSP dark matter could arise from the decay of B-balls rather than from thermal relics, with a quite different dependence on the MSSM parameters and a natural correlation with the baryon asymmetry. We discuss the constraints imposed on the properties of B-balls and the MSSM spectrum by experimental constraints and show that B-balls cannot form from an Affleck-Dine condensate with 100\% efficiency in the absence of LSP annihilations after they decay. For likely formation efficiencies the LSP and slepton masses are typically constrained to be light. The effects of LSP annihilations after the B-balls decay are discussed; for sufficiently small decay temperatures annihilations will play no role, opening up the possibility of experimentally testing the scenario.

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The conventional view of the cosmology of the Minimal Supersymmetric Standard Model (MSSM) \cite{1} at temperatures less than that of the electroweak phase transition, \(T_{ew}\), is of a radiation dominated Universe in which the baryon number is generated at temperatures greater than or equal to \(T_{ew}\) and the dark matter is composed of thermal relic neutralino LSPs \cite{2, 3}. Recently it has been shown that the MSSM can sustain a very different post-inflation cosmology \cite{5, 6}. In this scenario the baryon asymmetry comes from a variant of the Affleck-Dine (AD) mechanism \cite{7}, B-ball Baryogenesis (BBB) \cite{5, 6}, in which the baryon number originates from the collapse of a \(d \geq 6\) AD condensate to a mixture of free squarks and non-topological solitons, B-balls. The reheating temperature must be less than \(10^{3-5}\) GeV in order that the B-balls do not thermalize \cite{6}. For the particular case of a \(d=6\) AD condensate, which we will focus on in the following, the Universe is dominated by the energy density of an inflaton down to temperatures typically of the order of 1 GeV, which is fixed by the observed baryon asymmetry when the CP violating phase responsible for the asymmetry is of the order of 1 \cite{6}. In particular, this is expected to be true for D-term inflation models \cite{8, 9}. The resulting B-balls have large charges and typically decay at temperatures between 1 MeV and 1 GeV \cite{6, 9}. Being made of squarks, they initially decay to LSPs and baryons with a similar number density. If the B-ball decay temperature is below the freeze-out temperature of the LSPs and there are no subsequent annihilations of the LSPs, the similarity of the number densities will be preserved. In general, the resulting dark matter density will differ from that expected purely from thermal relics and will be determined by the MSSM parameters together with the B-ball parameters. Given the B-ball parameters, the MSSM parameters can be constrained by the resulting density of dark matter. Conversely, the B-ball parameters can be constrained by the dark matter density for a given set of MSSM parameters. Such constraints will serve as an important test of the scenario once the B-ball parameters, which are calculable (although non-trivial), are better known.

Under the assumption that \(\Omega = 1\) as a result of a period of inflation, primordial nucleosynthesis bounds on the density of baryons in the Universe \cite{10} suggest that 90% of the mass in the Universe must be in the form of non-baryonic dark matter,
a conclusion supported by structure formation models and by direct observations of galactic rotation curves [2]. (One should, however, note that recent supernova surveys [11] indicate that there might exist a non-zero cosmological constant $\Lambda$. If so, the matter density could be much less than the critical density). Recent observations of deuterium features in the spectra of quasars [12], as well as determinations of the metallicity of extragalactic HII regions on which extrapolations of the primordial $^4\text{He}$ abundance are based, have led to a somewhat conflicting picture of the baryon asymmetry [13]. The baryon asymmetry appears to be either relatively high, as favoured by deuterium observations, in which case there might be a problem with the $^4\text{He}$ abundance, or relatively low, in which case there might be a problem understanding the stellar evolution of the high D/$^3\text{H}$ abundance required. Because of this unclear situation, which is likely to be due to hidden systematic errors, for the purposes of the present paper we will adopt a conservative nucleosynthesis bound [10] on the baryon density, $0.0048 < \Omega_B h^2 < 0.013$, where the age of the Universe requires that $h$ satisfies $0.4 \lesssim h \lesssim 0.65$ for an $\Omega = 1$ Universe. The ratio of the number density of baryons to dark matter particles, $\sigma_B$, is then constrained to satisfy

$$\sigma_B = (0.48 - 1.3) \times 10^{-2} h^{-2} \frac{m_{DM}}{m_N},$$

where $m_{DM}$ is the mass of the dark matter particle and $m_N$ is the nucleon mass. For example, for the case of dark matter particles with weak scale masses, with $h \approx 0.5$ and $m_{DM} \approx m_W$ we obtain $\sigma_B \approx 1.5 - 4$; a highly suggestive result. Most baryogenesis mechanisms give no explicit connection between the densities of baryons and dark matter; it is implicitly assumed that their similarity is a result either of coincidence or of some hidden anthropic selection effect [14], neither of which is particularly satisfying as an explanation. The similarity of the dark matter and baryon densities (in particular their number densities) can best be explained if they are produced by the same mechanism.

\footnote{For an alternative connection between B-balls and the baryon to dark matter ratio, in the context of gauge-mediated SUSY breaking models with stable B-balls [15], see reference [16].}
If the reheating temperature is much less than $T_f$, there will be essentially no thermal relic background of LSPs, since the additional entropy released during the inflaton matter domination period will strongly suppress the thermal relic density by a factor $(T_R/T_f)^5$. (The LSPs have a freeze-out temperature of $T_f \approx m_{\text{LSP}}/20$ \cite{4}, where $m_{\text{LSP}}$ is the LSP neutralino mass. The present direct experimental bound on the LSP mass, valid for any $\tan \beta$ (but assuming $m_{\tilde{\nu}} \geq 200$ GeV), is $m_{\text{LSP}} \geq 25$ GeV \cite{17}.

If one assumes the MSSM with universal soft SUSY breaking masses and unification \cite{6}, LEP results can be combined to yield an excluded region in the $(m_{\text{LSP}}, m_{\tilde{\nu}_R})$-plane \cite{18}. In the case of $\tilde{e}_R$, which provides the most stringent bound, the excluded region is roughly parametrized by $m_{\text{LSP}} \lesssim 0.95 m_{\tilde{\nu}_R}$ for $45$ GeV $\lesssim m_{\tilde{\nu}_R} \lesssim 78$ GeV (this result holds for $\tan \beta = 2$ and $\mu = -200$ GeV) \cite{18}. Therefore the LSP freeze-out temperature is expected to be greater than about 1-2 GeV). Thus there are two possibilities, depending on $T_R$ and $T_f$: either the LSP cold dark matter density, $\Omega_{\text{LSP}}$, will be given solely by the LSP density which originated from the B-ball decay, which we denote by $\Omega_{\text{BB}}$, or there will also be a relic density so that $\Omega_{\text{LSP}} = \Omega_{\text{BB}} + \Omega_{\text{relic}}$. We will consider both possibilities in the following.

Let us first discuss some general aspects of the production of neutralino dark matter via B-ball decays. Once the d=6 AD condensate collapses, a fraction $f_B$ of the total B asymmetry ends up in the form of B-balls. The B-balls have charges $B \approx 10^{23} f_B (1 \text{ GeV}/T_R)$ \cite{1} and subsequently decay at a temperature

$$T_d \approx 0.01 \left( \frac{f_s}{f_B} \right)^{1/2} \left( \frac{0.01}{|K|} \right)^{3/4} \left( \frac{m}{100 \text{ GeV}} \right) \left( \frac{T_R}{1 \text{ GeV}} \right)^{1/2} \text{ GeV} , \quad (2)$$

where $m$ is the B-ball squark mass and $f_s$ is the possible enhancement factor if the squarks can decay to a pair of scalars rather than to final states with two fermions; we have estimated $f_s \approx 10^3$ \cite{3}. ($f_B$ and $T_d$ are the only B-ball parameters which enter into the determination of the LSP density from B-ball decay). For example, with $T_R \approx 1$ GeV, as suggested by the d=6 AD mechanism, and with $f_B$ in the range 0.1 to 1 (in accordance with our previous argument \cite{8} that B-ball formation from an AD condensate is likely to be very efficient, although the numerical value of $f_B$ is not yet known), $T_d$ will generally be in the range 1 MeV to 1 GeV. In this case the B-balls will
decay below the LSP freeze-out temperature. The neutralino density will then consist of a possible thermal relic component, \( n_{\text{relic}}(T) \), and a component from B-ball decays, \( n_{\text{BB}}(T) \). The value of \( n_{\text{BB}}(T) \) will depend upon whether or not the LSPs from B-ball decay can subsequently annihilate. The upper limit on \( n_{\text{LSP}}(T) \) from annihilations is given by

\[
\frac{H}{<\sigma v>_{\text{ann}}} < n_{\text{limit}}(T) \equiv \frac{H}{<\sigma v>_{\text{ann}}} T, \tag{3}
\]

where \(<\sigma v>_{\text{ann}}\) is the thermal average of the annihilation cross-section times the relative velocity of the LSPs, which can be generally written in the form \(<\sigma v>_{\text{ann}} = a + bT/m_{\text{LSP}} \). If \( n_{\text{LSP}}(T) < n_{\text{limit}}(T) \), and if \( f_B \) is not too small compared with 1, there will be a natural similarity between the number density of LSPs and that of the baryons. Otherwise the annihilation of neutralinos will suppress the number density of LSPs relative to that of the baryons, although we will still have an interesting non-thermal neutralino relic density.

Assuming that \( n_{\text{LSP}}(T_d) < n_{\text{limit}}(T_d) \), the LSP density from B-ball decays will be given by

\[
n_{\text{BB}} = 3f_B n_B, \tag{4}
\]

where three LSPs are produced per unit baryon number from the decay of the B-ball squarks. Thus the B-ball produced LSP and baryonic densities will be related by

\[
\frac{\Omega_B}{\Omega_{\text{BB}}} = \frac{m_N}{3f_B m_{\text{LSP}}}. \tag{5}
\]

B generation via the AD mechanism requires inflation [7, 8], and although varieties of inflationary models exist with \( \Omega_{\text{tot}} < 1 \), we will nevertheless adopt the point of view that inflation implies \( \Omega_{\text{tot}} = 1 \) to a high precision. We may then write

\[
\Omega_{\text{tot}} = \Omega_0 + \Omega_{\text{LSP}} + \Omega_B = \Omega_0 + \Omega_{\text{relic}} + \left( \frac{3f_B m_{\text{LSP}}}{m_N} + 1 \right) \Omega_B = 1, \tag{6}
\]

where \( \Omega_0 \) includes the hot dark matter (HDM) component and/or a possible cosmological constant. Therefore \( \Omega_B \) is fixed by \( \Omega_0, f_B \) and \( m_{\text{LSP}} \) together with the MSSM parameters entering into the annihilation rate. Applying nucleosynthesis bounds on
\( \Omega_B \) then gives constraints on these parameters. Note that, so long as LSP annihilations after B-ball decay can be neglected, the resulting LSP density is independent of \( T_d \).

Let us first consider the case where the thermal relic density \( \Omega_{\text{relic}} \) is negligible. This would be true if \( T_R \) was sufficiently small compared with the freeze-out temperature \( T_f \). We then obtain the limit

\[
76.9(1 - \Omega_0)h^2 - 1 \lesssim \frac{3m_{\text{LSP}}f_B}{m_N} \lesssim 208.3(1 - \Omega_0)h^2 - 1 .
\] (7)

With \( \Omega_0 = 0 \) this would result in a bound on the LSP mass given by

\[
3.8f_B^{-1} \text{GeV} \lesssim m_{\text{LSP}} \lesssim 29f_B^{-1} \text{GeV} ,
\] (8)

where we have used \( 0.4 \lesssim h \lesssim 0.65 \). If \( f_B = 1 \) this would be only marginally compatible with present experimental constraints and then only if we do not consider universal soft SUSY breaking masses. Larger values of \( \Omega_0 \) impose even tighter bounds on \( m_{\text{LSP}} \), requiring \( f_B < 1 \). Therefore, in the absence of annihilations after B-ball decays, LSP dark matter from B-balls is likely to be compatible with nucleosynthesis bounds only if a significant fraction of the baryon asymmetry exists outside the B-balls. Reasonable values of \( f_B \) can, however, accommodate an interesting range of LSP masses; for example, values in the range 0.1 to 1 (which we consider to be reasonable) allow LSP masses as large as 290 GeV. \( f_B \) can be calculated theoretically, but this requires an analysis of the non-linear evolution of the unstable AD condensate [19]. The comparison of the theoretical value with the dark matter constraints will be an important test of this scenario.

We next consider the case with \( T_R > T_f \). In this case there will be a significant thermal relic density and we can use nucleosynthesis bounds on \( \Omega_B \) to constrain the masses of the particles responsible for the LSP annihilation cross-section. The constraints will depend on the identity of the LSP and the masses of the particles entering the LSP annihilation cross-section. In general, this would require a numerical analysis of the renormalization group equations for the SUSY particle spectrum. However, for the case of universal scalar and gaugino masses at a large scale, the LSP is likely to be mostly bino and the lightest scalars are likely to be the right-handed sleptons [20].
This is consistent with the requirement that the LSP does not have a large coupling to the Z boson, which would otherwise efficiently annihilate away the thermal relics. However, there will be a small, model-dependent Higgsino component which will be important for LSP masses close to the Z pole. For LSP masses away from this pole, it will be a reasonable approximation to treat the LSP as a pure bino. In this preliminary study we will consider the pure bino approximation, although the possible suppression of the thermal relic density around the Z pole due to a Higgsino component and the subsequent weakening of MSSM constraints should be kept in mind.

For the case of a pure bino, the largest contribution to the annihilation cross-section comes from $t$-channel $\tilde{l}_R$ exchange in $\chi\chi \rightarrow l^+l^-$ [21]. In that case one finds [20]

$$\Omega_{\text{relic}} h^2 = \frac{\Sigma^2}{M^2 m_{\text{LSP}}^2} \left[ \left( 1 - \frac{m_{\text{LSP}}^2}{\Sigma} \right)^2 + \frac{m_{\text{LSP}}^4}{\Sigma^2} \right]^{-1} ,$$  \hspace{1cm} (9)

where $M \approx 1$ TeV and $\Sigma = m_{\text{LSP}}^2 + m_{\tilde{l}_R}^2$. Plugging this into Eq. (8) and using the range of $\Omega_B$ allowed by nucleosynthesis, one may obtain allowed ranges in the $(m_{\text{LSP}}, m_{\tilde{l}_R})$-
Figure 2: The allowed region in the \((f_B, m_{\text{LSP}})\)-plane for fixed \(m_{\tilde{l}_R}\), assuming that the total CDM density \(\Omega = 0.9\) and the Hubble parameter \(h = 0.65\).

plane. These are demonstrated in Fig. 1 for different values of \(\Omega_0\) and \(h\).

In the conventional MSSM case Eq. (9) would imply that both \(m_{\text{LSP}}\) and \(m_{\tilde{l}_R}\) should be less than about 200 GeV. Because of the added B-ball contribution a more stringent constraint follows in the present case. If the reheating temperature is larger than the LSP freeze-out temperature, and if we consider the range \(0.1 \lesssim f_B \lesssim 1\) to be the most likely, we may conclude that only a very light sparticle spectrum is consistent with \(\Omega = 1\); this is so in particular if there is a cosmological constant with \(\Omega_0 \approx 0.7\), as suggested by recent supernova studies \cite{11}. In any case, it is evident that in the case \(T_R > T_f\) we obtain significant constraints on the B-ball formation efficiency from MSSM constraints. This is demonstrated in Fig. 2 for the case of \(\Omega_0 = 0.1\), where we plot the allowed regions in the \((f_B, m_{\text{LSP}})\)-plane for fixed values of \(m_{\tilde{l}_R}\). As can be seen, in the case of \(T_R > T_f\) dark matter constrains \(f_B\) to be less than about 0.6. If the SUGRA-based LEP limit \(m_{\text{LSP}} \lesssim 0.95m_{\tilde{e}_R}\ (45\ \text{GeV} \lesssim m_{\tilde{e}_R} \lesssim 78\ \text{GeV})\) is implemented \cite{18}, the limit on \(f_B\) would be even lower. This serves to emphasize the need for an accurate theoretical determination of \(f_B\).

So far we have considered B-ball decay in the absence of LSP annihilations. How-
ever, depending on $T_d$, annihilations after the B-balls decay may significantly reduce the final LSP density. For the case where $T_R > T_d$, the limiting density for pure binos may be expressed in terms of the thermal relic density at present as

$$n_{\text{limit}}(T_d) \approx \frac{g(T_f)}{g(T_\gamma)} \frac{T_f^2 T_d^2 \rho_o}{T_b^3 m_{LSP}} \Omega_{\text{relic}},$$  

where $T_b$ is the temperature above which the $b$ term in the thermally averaged annihilation cross-section comes to dominate, $T_\gamma \approx 2.4 \times 10^{13}$ GeV is the present photon temperature and $\rho_o = 7.5 \times 10^{-47} h^2$ GeV$^4$ is the present energy density of the Universe. Assuming that $T_d$ is sufficiently small compared with $T_f$, in order that the thermal relic density can be neglected compared with the limiting density, the condition for the annihilations to be negligible becomes

$$f_B \leq f_{Bc} \approx 0.1 \left( \frac{5 \times 10^{-11}}{\eta_B} \right) \left( \frac{100 \, \text{GeV}}{m_{LSP}} \right) \left( \frac{1 \, \text{GeV}}{T_d} \right)^2 \left( \frac{T_d}{T_b} \right)$$

$$\times \left( \frac{\Sigma^{1/2}}{100 \, \text{GeV}} \right)^4 \left[ \left( 1 - \frac{m_{lSP}^2}{\Sigma} \right)^2 + \frac{m_{lSP}^2}{\Sigma^2} \right]^{-1},$$

where the baryon asymmetry is constrained by nucleosynthesis to be in the range $\eta_B = (3 - 8) \times 10^{-11}$. In this we have used $T_f \approx m_{LSP}/20$. If annihilations are significant, the LSP density is given by that expected from B-ball decays without annihilations but with $f_B$ replaced by $f_{Bc}$. Therefore, so long as $f_{Bc}$ is not very much smaller than 1, there will still be a similar number density of baryons and dark matter in this case. If $T_d > T_R$, the B-balls will decay during the inflaton matter dominated era and the baryon number and limiting density will differ from the case where B-balls decay during radiation domination. This results in a stronger bound on $f_B$,

$$f_B \leq \frac{2}{5} \left( \frac{T_R}{T_d} \right)^3 f_{Bc}, \quad T_d > T_R.$$

Thus values of $T_R$ less than $T_d$ are strongly disfavoured.

For the case of a pure bino, the $a$ and $b$ entering the annihilation cross-section are given by

$$a = \frac{1}{2\pi} \frac{p}{m_{LSP}} \left( \frac{g_1^2}{2m_{lR}^2} \right)^2 m_{lR}^2; \quad b = \frac{6}{\pi} \frac{p}{m_{LSP}} \left( \frac{g_1^2}{2m_{lR}^2} \right)^2 m_{LSP}^2,$$  

$$\Omega_{\text{relic}},$$  

(10)
where $p$ is the final state momentum and we have assumed the $\tilde{t}_R$ are degenerate and that the $a$ term is dominated by the $\tau$ lepton contribution. Thus $T_b$ is given by

$$T_b = \frac{1}{12} \left( \frac{m_\tau}{m_{LSP}} \right)^2 m_{LSP} \approx 0.005 \left( \frac{50 \text{ GeV}}{m_{LSP}} \right) \text{ GeV}.$$  \hspace{1cm} (14)

Therefore, for the case of pure binos, $T_b$ will typically be less than about 5 MeV. We can therefore consider $T_b < T_d$ in the following. For example, for the case with $m_{LSP} \approx m_{\tilde{t}_R}$, which will give the tightest bound on $f_B$ for a given $T_d$ and $m_{LSP}$, we obtain, for $T_R > T_d$,

$$f_B \leq f_{Bc} \approx 0.8 \left( \frac{5 \times 10^{-11}}{\eta_B} \right) \left( \frac{1 \text{ GeV}}{T_d} \right)^2 \left( \frac{m_{\tilde{t}_R}}{100 \text{ GeV}} \right)^3.$$ \hspace{1cm} (15)

Thus, with $m_{LSP} \approx m_{\tilde{t}_R} \approx 50 \text{ GeV}$, we find that $f_{Bc} \approx 0.1 T_d^{-2} \text{ GeV}^2$. Therefore $T_d \lesssim 0.3 \text{ GeV}$ will allow all values of $f_B$ to evade annihilations after B-ball decay. If $T_d \approx 1 \text{ GeV}$, the final LSP density will correspond to the case where $f_B = f_{Bc} \approx 0.1$. This shows that annihilations after B-ball decays can result in an LSP density compatible with MSSM dark matter constraints even if $f_B \approx 1$, whilst still having a similar number density of baryons and dark matter particles; for $f_{Bc} \approx 0.1$, we would obtain $\sigma_B \approx 3$.

It is possible to reach only very broad conclusions at present, as the B-ball decay parameters $f_B$ and $T_d$ are unknown and, in addition, the results depend on the reheating temperature after inflation. However, both $f_B$ and $T_d$ are, in principle, calculable in a given model: $f_B$ by solving the non-linear scalar field equations governing the formation of B-balls from the original Affleck-Dine condensate and $T_d$ by calculating the charge and decay rate of the B-balls accurately. $T_d$, which will depend explicitly on the reheating temperature after inflation, is the more model-dependent of the two. The reheating temperature can be estimated under the assumption that the baryon asymmetry originates from an Affleck-Dine condensate with CP violating phase of the order of 1, and, indeed, can be calculated given all the details of an inflation model, but $T_R$ is likely remain an important source of theoretical uncertainty in the B-ball decay scenario. However, it is quite possible that $T_d$ and $T_R$, by being sufficiently small and large relative to $T_f$ respectively, play no direct role in determining the final LSP density.
The B-ball decay scenario for MSSM dark matter is a natural alternative to the thermal relic LSP scenario, and has the considerable advantage of being able to explain the similarity of the baryon and dark matter densities. Should future experimental constraints on the parameters of the MSSM prove to be incompatible with thermal relic dark matter but consistent with B-ball decay dark matter for some set of B-ball parameters, it would strongly support the B-ball decay scenario. In particular, should the LSP mass be determined experimentally, the ratio of the number density baryons to dark matter would then be constrained by nucleosynthesis bounds on the baryon asymmetry. This would impose significant constraints on the reheating temperature and B-ball parameters, which, by comparing with the theoretical value of $f_B$, could even provide a “smoking gun” for the validity of the B-ball decay scenario, should annihilations happen to play no role in determining the present LSP density.

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