The Phenomenology of Cosmological Supersymmetry Breaking

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Abstract

We point out phenomenological consequences of the assumption that Supersymmetry breaking is of cosmological origin.
1 Introduction

The suggestion[1] that Supersymmetry (SUSY) breaking is entirely of cosmological origin has met with considerable skepticism. To a large extent, this is due to my own failings. I have been unable to present either a conclusive calculation of the large SUSY breaking effects on local physics that I claim to follow from the existence of a cosmological horizon, nor a definitive demonstration of the inconsistency of the old paradigm of SUSY breaking in a Lorentz invariant vacuum state of M-theory.

The purpose of the present paper is not to engage in further polemics on these issues, but rather to emphasize the phenomenological consequences that follow from the assumption of Cosmological SUSY Breaking (CSB). I begin with a brief recapitulation of the arguments for CSB, and then demonstrate that they lead to dramatic conclusions. In CSB, the cosmological constant (in Planck units) is a (perhaps the only) tunable parameter of the theory. It takes on discrete values, with an accumulation point at zero. The basic hypothesis of the theory is that the limiting system is a Super Poincare Invariant vacuum state of M-theory. I will argue that this state cannot belong to a continuous moduli space of vacua with a boundary where the semiclassical approximation is valid. It must be an isolated point. Furthermore it must be a point of enhanced (discrete) R-symmetry. These considerations imply that the limiting theory has four Poincare invariant dimensions with only minimal SUSY. There are a number of other consequences as well, but the low energy arguments presently available do not allow one to uniquely predict the low energy theory.

In this paper I have adopted the following strategy. I present the general phenomenological implications of Cosmological SUSY Breaking and then combine them with known facts about the low energy theory to find constraints on the low energy description of SUSY breaking. One is led to a system with one or more $U(1)$ gauge groups beyond the standard model and a collection of nonchiral standard model fields that transform under these new gauge symmetries. There are Fayet-Iliopoulos (FI) terms for the new $U(1)$ fields, that are crucial to low energy SUSY breaking. It is tempting to view these new $U(1)$ fields as the origin of a Froggat-Nielsen [6] model of flavor physics, but I will mostly leave this aspect of the problem to future work. In the bulk of the paper, I freely mix up constraints from Cosmological SUSY Breaking with strictly phenomenological constraints, but make a careful separation between them in the Conclusions.

The point of view on SUSY breaking that I have elaborated is part of a rather different vision of the structure of the quantum theory of gravity than is currently held by the majority
of the community. I have tried to avoid contaminating the present paper with long diatribes about background independence etc., but in case I accidentally refer to the general framework I am writing a companion paper, which outlines my general viewpoint.

Finally, a note about scales. The models that I will present in this paper look like models of low energy SUSY breaking. Most previous attempts to make low energy models insisted on explaining the TeV scale in terms of low energy gauge dynamics. It is the essence of the idea of CSB that the origin of the low scale of SUSY breaking cannot be understood at low energies. Rather, the $\Lambda \rightarrow 0$ limit is viewed as a critical phenomenon, and $m_{3/2} \sim (\Lambda/M_P^4)^{\alpha} M_P$. where $\alpha$ is a critical exponent determined by dynamics near the horizon of de Sitter space. In [1] I conjectured that $\alpha = \frac{1}{4}$ in order to reproduce an old guess about the relation between SUSY breaking and the TeV scale. In fact, given the current stage of knowledge $\alpha$ could be anything. Thus I cannot argue that CSB rules out Hidden Sector SUSY breaking models. Nor can I rule out the possibility that different terms in the low energy effective Lagrangian might be controlled by different critical exponents. One might for example imagine that some of the quark mass hierarchies could be explained by a variety of critical exponents, and would thus depend on very high energy dynamics.

Since there are so many possibilities, I have decided to concentrate on the simplest one, presented in [1]. That is, the low energy effective Lagrangian is a supersymmetric, R symmetric system, with no relevant operators, and all irrelevant operators scaled by the unification or Planck scales. This is modified by dimensionful terms which break both SUSY and R symmetries (the SUSY breaking must be spontaneous, for reasons explained below), and which are assumed to be characterized by a single scale, near a TeV.

2 Basic framework

The basic tenets of the CSB conjecture are simple

- There are no Poincare invariant, SUSY violating theories of quantum gravity.

- A positive cosmological constant measures the number of physical states in the Hilbert space of quantum gravity on asymptotically deSitter (AsdS) space. As such it is a fundamental and freely tunable parameter in the theory, rather than the result of a calculation which gives the low energy effective Lagrangian.
Supersymmetry is of course broken in dS space. In the limit of vanishing cosmological constant the theory approaches a supersymmetric theory in asymptotically flat space. The rate at which the gravitino mass approaches zero is (in Planck units) $\Lambda^\alpha$, where the critical exponent $\alpha$ is not calculable in low energy effective field theory. It reflects the dynamics of the huge degenerate spectrum of near horizon states\footnote{In previous work, I have characterized the high energy states as huge black holes. In fact, most of the states in dS space are near horizon states.} that appear in the asymptotically flat limit.

I will not pause here to justify these statements. The reader can consult \cite{1} and the companion to this paper, for such justification as exists. My goal here is to explain how this framework puts strong constraints on low energy phenomenology. Let me present these constraints as an itemized list:

- The limit of a dS theory with vanishing cosmological constant is an $\mathcal{N} = 1$, $d = 4$ Super Poincare invariant and $R$ symmetric vacuum state of M-theory. SUSY follows from conjecture 1 above, and $R$ symmetry is necessary as well, to enforce Poincare invariance. However, the limiting theory must have a small deformation which allows us to discuss the low energy physics of a space with small cosmological constant. Extended supergravities in four dimensions, and higher dimensional supergravities, do not have such a small deformation. Ten dimensional IIA SUGRA has a cosmological constant but it is quantized. Furthermore, the spacetime it describes is the region between BPS eight branes, and is not dS space. Only minimal four dimensional SUGRA (with appropriate superpotential for chiral superfields) has dS solutions. $R$ symmetry (a discrete $R$ symmetry bigger than the $\mathbb{Z}_2$ of $(-1)^F$ is sufficient) is necessary to explain the vanishing of the superpotential at the supersymmetric minimum.

- The limiting theory has no moduli. Here we must be a bit careful. By moduli I mean (assuming point 1) chiral superfields with no potential, which live in a noncompact space and obey a certain condition at the boundaries. To see this, consider the putative, slightly deformed theory with small cosmological constant. This theory has a potential for the moduli. If the potential goes to zero at the boundaries of moduli space then there is a solution of the low energy equations of motion, which describes a spacetime that is asymptotically expanding in a subluminal manner, and obviously has an infinite number of states. Furthermore, even if the potential has a local dS minimum, there is likely to be Coleman-DeLucia instanton that describes the decay of this dS space into the
asymptotically expanding one. Thus the quantum mechanics behind such a low energy effective theory must have an infinite number of states and cannot be the finite model of dS space we are studying. Note that these conditions do not rule out compact moduli spaces or moduli spaces that are effectively compactified by SUSY violating potentials (for small but nonzero $\Lambda$). We know of no SUSic examples of such compactified moduli spaces in string theory.

- In the low energy effective theory, SUSY is violated spontaneously. This sounds like a vacuous statement. SUSY is a local symmetry in the field theoretic approximation, and any explicit violation can be made to look spontaneous by introducing a compensating goldstino field. The nontrivial content of the statement again comes from studying the limit of vanishing $\Lambda$. In this limit, SUSY is restored and the goldstino must lie in a linear supermultiplet. Thus, the limiting theory must have a massless matter supermultiplet.

- The simplest possible low energy effective theory would have only massless chiral multiplets, $Z_i$. The absence of mass terms is explained by the discrete $R$ symmetry, for appropriate choices of quantum numbers\footnote{To all orders in perturbative string theory, masses can vanish due to a combination of stringy world sheet symmetries, and spacetime SUSY. In exceptional cases one can also argue that instanton corrections are absent, and use holomorphy to prove that certain superpotential terms vanish exactly. However, if our chiral fields are not moduli (as implied by the above), no such argument applies. We will assume that in this case all terms in the superpotential allowed by symmetries, are present.}. If $Z_i = 0$ is the point in field space corresponding to the Super Poincare Invariant vacuum in question then the superpotential has the form:

$$W = A^{ijk}Z_iZ_jZ_k + o(Z^4/M), \quad (1)$$

while the Kahler potential is

$$K = M^2\left(\sum |Z/M|^2 + o(Z^3/M^3)\right). \quad (2)$$

The mass scale $M$ might be the four dimensional Planck mass. Alternatively, we might imagine that our SUSY vacuum incorporates Witten’s mechanism\footnote{To all orders in perturbative string theory, masses can vanish due to a combination of stringy world sheet symmetries, and spacetime SUSY. In exceptional cases one can also argue that instanton corrections are absent, and use holomorphy to prove that certain superpotential terms vanish exactly. However, if our chiral fields are not moduli (as implied by the above), no such argument applies. We will assume that in this case all terms in the superpotential allowed by symmetries, are present.} for producing a hierarchy between the fundamental scale $M \ll M_P$ and the Planck mass. In this case some of the fields may be scaled by $M_P$ instead of $M$. The constant, linear, and quadratic terms in $W$ are not allowed by the $R$ symmetry.

In order to fine tune a large hierarchy between the gravitino mass and the cosmological constant (something that is guaranteed at a fundamental level by our assumption that the critical exponent $\alpha$ is much smaller than its classical value.) we must assume that CSB also
breaks the $R$ symmetry, allowing a constant term in $W$. Since the $R$ symmetry is discrete, this will appear as explicit, rather than spontaneous breaking. The superpotential will have corrections:

$$\delta W = W_0 + F^i Z_i + \mu^{ij} Z_i Z_j.$$  \hspace{1cm} (3)

Fine tuning of the cosmological constant requires $F^i \sim W_0/M_P$. There is no obvious a priori argument for the size of the mass matrix $\mu$. Obvious choices are $|\mu| \sim (W_0/M_P)^{1/2}$ and $|\mu| \sim W_0^{1/3}$. I have not been able to imagine an argument which makes $\mu$ much smaller than this. For either choice (and a wide range of other less plausible ones), the superpotential has a SUSY minimum at a value of $Z_i$ where the low energy effective theory is valid. Since the superpotential is generically nonvanishing, this is a SUSic, AdS vacuum. Thus, the purely chiral scenario is not consistent with CSB. The hypothetical SUSY low energy theory does not admit a small perturbation which is a dS space. The hypothesis of CSB thus requires that the low energy theory contain gauge fields.

- Many gauge models are ruled out as well. For example, pure nonabelian SUSY gauge theories always spontaneously break $R$ symmetry. They cannot appear in the low energy effective action of a theory with CSB. This is also true of a large class of models with chiral fields transforming under a non abelian gauge group (e.g. $SU(N_C)$ with $N_F \leq N_C$). I have not attempted to make a systematic delineation of the boundaries of this class. It is notable however that the Supersymmetric Standard Model with two or more generations does not suffer from this problem. In the absence of SUSY breaking, the low energy theory of the $N_g \geq 2$ SSM is infrared free or superconformally invariant. It is consistent with the preservation of a variety of discrete $R$ symmetries.

- From now on I will concentrate on hypothetical vacua whose low energy theory includes the SSM. This restriction is not derived from any low energy consistency condition. The explanation of why the particular groups and representations of the SSM arise can only come from a complete understanding of M-theory. According to our principles, it is not permissible to simply add soft SUSY breaking terms to the SSM Lagrangian. The cosmological constant can be tuned to zero, bringing the dynamics that breaks SUSY into the low energy regime (how low depends on the value of $\alpha$). There are no SUSY terms that can be added to the SSM Lagrangian to spontaneously break SUSY\footnote{I will assume that the scale of all CSB effects is much smaller than the fundamental scale $M$. This amounts to assuming that $\alpha$ is not terribly small.}. Thus,  

\footnote{Except a Fayet-Iliopoulos (FI) term for hypercharge, which has well known phenomenological problems. It is also inconsistent with the idea of grand unification, since the origin of the hypothetical FI term comes from CSB dynamics well above the Planck scale.}
the hypothesis of CSB requires us to introduce further low energy fields to explain SUSY breaking. We will call this the SUSY breaking sector (SSS). There are several possible scenarios for the dynamics of the SSS.

- There may be an interesting class of models where the SSS is a nontrivial superconformal fixed point theory. CSB would add relevant perturbations to these models that spontaneously break SUSY. For example, consider the famous \((3,2)\) model of dynamical SUSY breaking. If we add chiral fields in \((3 + \bar{3}, 2)\), \((1, 2)\) and \((3 + \bar{3}, 1)\) to this model we can find a nontrivial superconformal window. Mass terms for these vectorlike fields would be forbidden by the discrete \(R\) symmetry, and induced by CSB. For a range of values of the \(SU(3)\) and \(SU(2)\) couplings, the low energy dynamics will look like a superconformal theory which crosses over to a massive theory with dynamical SUSY breaking. Such theories might be coupled to the SSM by marginal (i.e. realizing the standard model gauge group as a flavor group of the superconformal theory) or irrelevant couplings. I know too little of the taxonomy of superconformal theories to make a survey of this class of models in this paper.

- Restricting our attention to theories in the vicinity of Gaussian fixed points, there seems to be only one mechanism for generating SUSY breaking consistent with our rules. We must introduce a new \(U(1)\) gauge theory and assume that CSB produces an FI term for it, as well as mass terms for chiral fields charged under the \(U(1)\). This spontaneously breaks SUSY because of the competition between \(F\) and \(D\) term constraints. One possibility of coupling this SSS to the SSM is through irrelevant terms. If these terms were scaled by the fundamental scale \(M\), this would generate squark masses of order \(F/M\), where \(m_{3/2} \sim F/M_P = 10^{-120\alpha} M_P\). The experimental bounds would be satisfied if \(\alpha < 1/6\). However, to get comparable gaugino masses we would have to introduce singlet fields as well. Moreover, there is a serious problem with the \(\mu\) term of the SSM. In the SUSY limit it can be taken to vanish because of \(R\) symmetry. However, as noted above, the smallest reasonable value for the induced \(\mu\) term from CSB is of order \(\sqrt{F}\) which is much larger than any SUSY breaking mass scale. \(SU(2) \times U(1)\) will remain unbroken and the model is incompatible with phenomenology. The simplest model which might avoid this disaster introduces vectorlike standard model multiplets (to preserve coupling unification we probably want complete \(SU(5)\) multiplets) with vectorlike coupling to the new \(U(1)\). All conventional standard model fields are taken \(U(1)\) neutral. For a range of values of the CSB induced FI term, and mass terms for these multiplets the tree level vacuum breaks SUSY and preserves the entire standard model group. One may hope that the radiative
corrections due to the top quark coupling will break $SU(2) \times U(1)$ in the standard fashion. SUSY breaking in the standard model will occur more or less as in gauge mediation, and there will be no problems with flavor changing processes. Note however that there are important differences. First of all, the $\mu$ term is induced at tree level in the effective theory. Secondly, SUSY breaking is not as soft as in gauge mediation with dynamical SUSY breaking. The SUSY breaking terms are in the effective Lagrangian all the way up to the GUT scale. We will discuss this model in more detail in the next section, and argue that one cannot in fact achieve $SU(2) \times U(1)$ breaking by radiative corrections. This indicates the need for more ambitious models, in which conventional fields carry charge under the new $U(1)$. These models are highly constrained. We will discuss them in the next section as well.

3 Models

The simplest model, allowed by the considerations of the previous section, which breaks SUSY without breaking charge and color, contains a number $N_5$ of 5 and $\bar{5}$ representations of $SU(5)$. We denote these fields by $F^a$ and $\bar{F}_a$. We must insist that $N_5 < 4$ to preserve perturbative coupling unification. These multiplets carry a vectorlike representation of $U_F(1)$. There is also an anomaly free collection of $SU(5)$ singlet fields charged under $U_F(1)$.

When the cosmological constant vanishes, the arguments of the previous section tell us that we must have an R symmetric SUSic vacuum state. We also assume that the Fayet-Iliopoulos term for $U_F(1)$ vanishes in this limit. If it did not, it would have to be at least of order $M_{GUT}$, and $U_F(1)$ would not appear in the low energy theory. We assume that mass terms $m^a_5 F^a \bar{F}_a$ as well as any $U_F(1)$ invariant mass terms for the singlets are forbidden by the R-symmetry. The $\mu$ term for the standard model Higgs fields is also forbidden by this R-symmetry.

When the cosmological constant is turned on, R violating mass terms, a constant $W_0$ in the superpotential, and an FI term are generated. In principle the critical exponents for all of these terms could be different and this could generate a hierarchy of scales. I have explained in the introduction why I choose to restrict attention to the simplest possibility. That is, all of these dimensionful parameters except $W_0$ are determined in terms of a single mass scale $M_P \left( \frac{\Lambda}{M_P} \right)^\alpha M_P$ with $\alpha \sim 1/8$ and dimensionless numbers of order 1.

We presume $SU(5)$ is broken to the standard model by a higher dimensional mechanism and that the conventional Higgs bosons are the only incomplete four dimensional $SU(5)$ multiplet in the low energy spectrum.
For a range of these dimensionless coefficients, the resulting effective potential has an absolute minimum at which $U_F(1)$ and SUSY are broken, and the standard model gauge group is preserved. The fields $F^a$ and $\bar{F}^b$ obtain SUSY violating masses at tree level from the expectation value of the $U_F(1)$ D term.

It appears however that this model will not spontaneously break $SU(2) \times U(1)$. The $\mu$ term induced by CSB gives a positive mass squared to both Higgs doublets. Radiative corrections will give these fields SUSY violating mass terms as well, and these can be negative. However, they are suppressed relative to the $\mu$ term, by a two loop factor. Indeed, at one loop, only standard model gauginos will get SUSY violating masses, since the tree level SUSY breaking affects only the new vectorlike multiplets and the singlets. Note that $SU(3) \times SU(2) \times U(1) \times U_F(1)$ gauge symmetry does not allow renormalizable couplings between the chiral multiplets in the standard model and the new fields. Nonrenormalizable couplings are scaled by the GUT scale and give only tiny corrections. Even after renormalization group running, it seems unlikely that the two loop terms can compete with the positive mass squared from the $\mu$ term.

Thus, we are forced to give $U_F(1)$ quantum numbers to standard model fields. This is of course very interesting. The simplest possibility is to give equal and opposite $U(1)_F$ charges to the up and down Higgs. The $\mu$ term is still allowed but now we can break $SU(2) \times U(1)$ at tree level by appropriate adjustment of parameters. This kind of model has two problems. There are no Yukawa couplings between the Higgs and quarks and leptons, and the electroweak breaking scale is the same as the mass scale of a host of new particles, with standard model couplings. It is hard to see how one could get the top quark mass right, or avoid problems with precision electroweak data.\footnote{I would like to thank D.E. Kaplan for a discussion of this point.}

The latter problem seems to be shared by any model in which the tree level $\mu$ term appears. Since we are only allowed to invoke local gauge symmetries, the $U(1)_F$ must forbid the $\mu$ term. This generates an $SU(2)^2 \times U(1)_F$ anomaly, unless we give appropriate $U(1)_F$ quantum numbers to quarks and leptons.

We are thus driven to a class of models in which $U(1)_F$ acts as a family symmetry.\footnote{These models are strongly constrained. Since I have not yet found any satisfactory models, let me simply list the constraints.}

- The model consists of the standard model, plus vectorlike standard model fields (including singlets) and one or more new $U(1)$ gauge symmetries. Call the group of these symmetries...
$U(1)_F$ even if it is a product of several $U(1)$ groups.

- All gauge symmetries are anomaly free.

- All relevant couplings are of the same order of magnitude. Irrelevant operators are scaled by either the GUT or Planck scales.

- The $\mu$ term is forbidden by $U(1)_F$ and is replaced by a trilinear coupling $SH_uH_d$. $S$ gets a small VEV from loop corrections to generate a $\mu$ term smaller than the scale of masses of all the new vectorlike standard model matter. The $\mu$ scale will also be the scale of electroweak symmetry breaking.

- $U(1)_F$ must commute with $SU(5)$ or a larger GUT group. Otherwise it would have to be part of a nonabelian group and could not get an FI D term.

- All fields charged under the standard model, except for the standard Higgs bosons, must come in complete GUT multiplets.

- The vectorlike standard model matter should not lead to Landau poles that conflict with perturbative unification. This is a very strong constraint.

- $U(1)_F$ must explain the quark and lepton mass and mixing hierarchies, and provide adequate suppression of baryon and lepton number violating operators.

It seems quite plausible that these constraints are so strong that they have no solution at all. I have not yet been able to prove that.

4 Conclusions

The reader should be convinced by now that CSB has profound phenomenological implications. It implies that the world is four dimensional and is described at low energies by a small perturbation of a model which is supersymmetric and either infrared free or superconformally invariant in the infrared. Within the class of Lagrangian models this restricts us to either purely abelian models or nonabelian models with appropriate matter content. For example, the standard model gauge group requires at least two generations of quarks and leptons.

When perturbed by the most general set of relevant supersymmetric perturbations, the superconformal model must spontaneously break SUSY. Within the class of Lagrangian models,
we saw that the only such models were those with FI D terms for some set of $U(1)$ gauge fields. General considerations show that these $U(1)$’s must be external to the standard model, and in fact commute with a GUT group. We then showed that phenomenological considerations (primarily a viable mechanism for electroweak breaking) led us to a highly constrained set of models in which the new $U(1)$’s act as family (Froggatt-Nielsen) symmetries. The constraints on these models are very strong and there may be no models that satisfy them.

If that is the case, there are two avenues of retreat for the true believer in CSB. One can consider, instead of models with a Lagrangian description, nontrivial fixed point theories. Spontaneous SUSY breaking by relevant perturbations of superconformal fixed point theories has been studied [4], but not extensively.

Alternatively one could introduce the hypothesis that different terms in the low energy effective Lagrangian had different scaling behavior as the cosmological constant is taken to zero. This could change some of our ground rules at crucial points. It might also link some of the observed hierarchies in low energy particle physics directly to physics at the very highest energies. There are both pleasant and unpleasant aspects to such a linkage. On the one hand, it would prevent us from making predictions about the parameters that describe experiment until we understand the full theory of quantum gravity. On the other hand, the full theory of quantum gravity would be directly linked to measurable experimental quantities. This would perhaps provide a final answer to the hard core phenomenologist’s question of why he needs string theory.

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