

R symmetries in the landscape

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ABSTRACT: In the landscape, states with R symmetries at the classical level form a distinct branch, with a potentially interesting phenomenology. Some preliminary analyses suggested that the population of these states would be significantly suppressed. We survey orientifolds of IIB theories compactified on Calabi-Yau spaces based on vanishing polynomials in weighted projective spaces, and find that the suppression is quite substantial. On the other hand, we find that a Z_2 R -parity is a common feature in the landscape. We discuss whether the cosmological constant and proton decay or cosmology might select the low energy branch. We include also some remarks on split supersymmetry.

KEYWORDS: Superstring Vacua, Flux compactifications, dS vacua in string theory.

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1. Introduction

Recent studies of string configurations with fluxes have provided support for the idea that string theory possesses a vast landscape of string [1–5]. In the landscape, three distinct branches of states have been identified [6]. One branch has broken supersymmetry already in the leading approximation. Another has unbroken supersymmetry at tree level, with negative cosmological constant. A third has unbroken supersymmetry and vanishing cosmological constant at tree level. Non-perturbatively, we might expect that supersymmetry breaking occurs generically in the latter two cases, so the distinctions between these states, individually, are not sharp. However, the statistics of these three branches are quite distinct. The first, “non-supersymmetric branch” has a distribution of states which strongly peaks at the highest energy scale; states with a low scale of supersymmetry breaking, $m_{3/2}$, are suppressed by $m_{3/2}^{12}$ [7, 8]. The second, “intermediate scale branch”, has a distribution of scales roughly logarithmic in $m_{3/2}$, $\int \frac{dm_{3/2}^2}{m_{3/2}^2 \ln(m_{3/2})}$. The third, “low scale” branch will be the focus of this paper. Here the distribution behaves as

$$\int \frac{dm_{3/2}^2}{m_{3/2}^4}. \tag{1.1}$$

For unbroken supersymmetry, vanishing of the cosmological constant implies the vanishing of W . Vanishing of W is often connected with R symmetries. R symmetries are symmetries which transform the supercharges non-trivially. Among these, we can consider two broad classes, those which transform the superpotential by a non-trivial phase, and Z_2 symmetries under which the superpotential is invariant. Conventional R -parity is an example of the latter, and we will refer to such Z_2 symmetries more generally as R -parities. These are not, in any general way, connected with vanishing W . We will reserve the term R symmetry for those symmetries which transform W . In [6] it was argued that states on the low scale branch were likely to arise as a result of discrete R symmetries. In [8], some aspects of these states were considered and some counting performed. In typical constructions of flux vacua, an R symmetry can arise if the underlying theory, in the absence of fluxes, possesses such a symmetry, and if the non-vanishing fluxes are themselves neutral under the symmetry. As explained in [8], for a reasonably generic superpotential consistent with the symmetries, the potential has stationary points preserving both supersymmetry and R symmetry¹. This can be illustrated by compactification of the IIB theory on an orientifold of the familiar quintic in CP^4 . On a subspace of the moduli space, prior to performing the orientifold projection, the quintic is known to possess a large discrete symmetry, $Z_5^4 \times S_5$ [12, 13]. The projection can preserve a subgroup of this group. It is not difficult to classify the fluxes according to their transformation properties under these symmetries². If one tries to turn on fluxes in such a way as to preserve a single Z_5 , one finds that it is necessary to set more than 2/3 of the fluxes to zero. In landscape terms, this means that the dimensionality of the flux lattice is reduced by 2/3, and correspondingly there is a drastic reduction in the number of states. One of the principle goals of the present paper is to assess whether this sort of reduction is typical.

One of the observations of [8] is that in the bulk of R -symmetric states, supersymmetry and R symmetry are likely to be unbroken. We will explain this observation further, and discuss the assumptions on which it relies.

Discrete symmetries are of interest for other reasons. One of the most important is to suppress proton decay. Usually one considers R parity, but more general R symmetries can suppress not only dimension four but also dimension five operators. R parity is distinctive in that it does not rotate the superpotential. As a result, it need not be spontaneously broken (it does not forbid a mass for gauginos). It also does not lead to a non-vanishing $\langle W \rangle$. So states on the intermediate branch can be R -parity-symmetric. We will discuss the distinctions between R parity and R symmetries further in this paper.

R symmetries have received attention recently for another reason: they are part of the rationale for the “split supersymmetry” scenario [14]. We will discuss a number of issues related to this proposal here as well.

This paper is organized as follows. In the next section we will describe a counting exercise based on Calabi-Yau models constructed as complete intersections in weighted

¹In [9] and [10], explicit features of the superpotential [11] are employed to actually find and count solutions with these properties

²We will correct an error in the identification of symmetries in [8], but this will not qualitatively alter the earlier conclusions

projective spaces. We will see that the results for the quintic are rather general: we find no examples where more than 1/3 of the possible fluxes preserve an R symmetry. In section 3, we verify our identification of discrete symmetries of these models by studying Gepner models [15]. In sections 4 and 5, we explain why supersymmetry and R symmetry are typically unbroken in these states at the classical level, and consider non-perturbative effects which can break these symmetries. In the final sections, we discuss split supersymmetry and R parity. We explain why split supersymmetry seems an unlikely outcome of the landscape and contrast R -parity and more general R symmetries. We conclude with a discussion of selection effects which might favor one or another branch of the landscape.

2. R symmetries in weighted projective spaces

Already in [12, 13], the existence of discrete symmetries in Calabi-Yau spaces has been noted. It is instructive to enumerate these symmetries before implementing the orientifold projection. These symmetries can be thought of as discrete subgroups of the original Lorentz invariance of the higher dimensional space. The quintic in CP^4 provides a familiar example. The construction of the Calabi-Yau space begins with a choice of a vanishing quintic polynomial. The polynomial

$$P = \sum_{i=1}^5 z_i^5 = 0 \tag{2.1}$$

exhibits a large discrete symmetry. Each of the z_i 's can be multiplied by $\alpha = e^{\frac{2\pi i}{5}}$. In addition, there is a permutation symmetry which exchanges the z_i 's. To see that these are R symmetries, one can proceed in various ways. One can, first, construct the holomorphic three form. Defining variables $x_i = z_i/z_5$, this can be taken to be [13]:

$$\Omega = dx_1 dx_2 dx_3 \left(\frac{\partial P}{\partial x_4} \right)^{-1}. \tag{2.2}$$

It is easy to check that as long as $\frac{dP}{dz_i} \neq 0, i = 1, \dots, 5$ (the transversality condition) this formula is “democratic”; the singling out of z_4 and z_5 is not important. Ω transforms under any symmetry like the superpotential. This follows from the fact that $\Omega_{IJK} = \eta^T \Gamma_{IJK} \eta$, where η is the covariantly constant spinor. So we can read off immediately that under, say, $z_1 \rightarrow \alpha z_1$, the superpotential transforms as $W \rightarrow \alpha W$. Similarly, under an odd permutation, the superpotential is odd.

The complex structure moduli are in one to one correspondence with deformations of the polynomial P , so it is easy to determine their transformation properties under the discrete symmetry. Overall, there are 101 independent polynomials. So, for example, the polynomial $z_1^3 z_2^2$ transforms as α^3 under the symmetry above. $z_1^4 z_5$, on the other hand, is not an independent deformation, since it can be absorbed in a holomorphic redefinition of the z_i 's. For the landscape, it is also important to understand how the possible fluxes transform: fluxes are paired with complex structure moduli. Because they correspond to RR states, they transform differently than the scalar components of the moduli. As we explain

below, the criterion that a flux not break and R symmetry is that *the corresponding modulus transform under the symmetry like the holomorphic 3 form*. The effective lagrangian for the light fields will exhibit a symmetry if all fluxes which transform non-trivially vanish.

To see how the transformation properties of the fluxes relate to those of the moduli, we can proceed by using equation 2.2 to construct the holomorphic three form. If we deform the polynomial by $P \rightarrow P + \psi h(z_i)$, then:

$$\delta\Omega = dx^1 \wedge dx^2 \wedge dx^3 \psi \frac{\partial h}{\partial x^4} \left(\frac{\partial P}{\partial x^4} \right)^{-2}. \tag{2.3}$$

If this is to be invariant, the transformation of h must compensate that of $dx_1 \dots dx_4$. Since h transforms like ψ , we see that ψ must transform like Ω .

So in the case of the quintic, consider the transformation $z_1 \rightarrow \alpha z_1$, where $\alpha = e^{\frac{2\pi i}{5}}$. Under this transformation, Ω transforms like α . So the invariant fluxes correspond to polynomials with a single z_1 factor. Examples include $z_1 z_2^2 z_3$, $z_1 z_2^2 z_3^2$ and $z_1 z_2 z_3 z_4 z_5$. Altogether, of the 101 independent polynomial deformations, 31 transform properly.

However, we need to consider the orientifold projection. In the IIB theory, this projection takes the form [16]:

$$\mathcal{O} = (-1)^{F_L} \Omega_p \sigma^* \quad \sigma^* \Omega = -\Omega. \tag{2.4}$$

Here Ω_p is orientation reversal on the world sheet; σ is a space-time symmetry transformation. In the case of the quintic, a suitable Z_2 transformation can be found among the various permutations. An example is the cyclic transformation:

$$z_2 \rightarrow z_3 \quad z_3 \rightarrow z_4 \quad z_4 \rightarrow z_5 \quad z_5 \rightarrow z_2. \tag{2.5}$$

There are 27 polynomials invariant under this symmetry, so $h_{2,1}$ is reduced from 101 to 27. The number of fluxes which are invariant under the symmetry is reduced to 9. This is only 1/3 of the total.

In the flux landscape, it is the fact that there are a large number of possible fluxes which accounts for the vast number of states. If one thinks of the fluxes as forming a spherical lattice, it is the large radius of the sphere and the large dimension of the space which account for the huge number of states. Reducing the dimensionality significantly drastically reduces the number of states; e.g. if 2/3 of the fluxes must be set to zero, 10^{300} states becomes 10^{100} . In the case of the quintic, we we have just seen that requiring, for example, the $z_1 \rightarrow \alpha z_1$ symmetry requires that more than 1/3 of the fluxes vanish. In the end, though, the dimension of the flux lattice was not so large in this case. A natural question is whether such a large fractional reduction in the dimensionality of the lattice is typical.

A large class of Calabi-Yau spaces have been constructed as hypersurfaces in weighted projective spaces [17]. The corresponding polynomials can exhibit complicated sets of discrete symmetries. Here we will consider some examples chosen from the list.

A case in which there is a large number of fluxes even after the orientifold projection is provided by $WCP_{1,1,1,6,9}^4$ [18]. This model is, for a particular radius and choice of polynomial, one of the Gepner models [15] and so we have more than one check on our analysis.

Take the polynomial to be:

$$P = z_1^{18} + z_2^{18} + z_3^{18} + z_4^3 + z_5^2 = 0. \tag{2.6}$$

Then there are $h_{2,1} = 272$ independent deformations of the polynomial. There is also a rich set of discrete symmetries:

$$Z_{18}^3 \times Z_3 \times Z_2 \times S_3. \tag{2.7}$$

One can construct Ω as in eq. 2.2; one finds that under $z_1 \rightarrow e^{\frac{2\pi i}{18}} z_1$, Ω transforms as:

$$\Omega \rightarrow e^{\frac{2\pi i}{18}} \Omega, \tag{2.8}$$

and similarly for the other coordinates. In particular, $\Omega \rightarrow -\Omega$ under the transformation $z_5 \rightarrow -z_5$. Now all of the polynomials are invariant under the Z_5 . Any polynomial linear in z_5 can be absorbed into a redefinition of z_5 (just as the $z_i^4 z_j$ type polynomials do not correspond to physical deformations in the case of the quintic). So all of the fluxes are odd under the symmetry. So if we take this to be the σ of the orientifold projection, then all of the complex structure moduli and the fluxes survive.

Now we want to ask: what fraction of the fluxes preserve a discrete symmetry of the orientifold theory. Consider, for example, $z_4 \rightarrow e^{\frac{2\pi i}{3}} z_4$. Invariant fluxes are paired with polynomial deformations linear in z_4 . There are 55 such polynomials. So, as in the case of the quintic, approximately 1/3 of the fluxes are invariant under the symmetry. Indeed, surveying numerous models and many symmetries, we have found no examples in which 1/2 or more of the fluxes are invariant. The model $WCP_{1,1,1,6,9}^4$ [18] is particularly interesting, since it has the largest $h_{2,1}$ in this class.

In the next section, to confirm our identification of these symmetries, we discuss R symmetries in the Gepner models.

3. Identifying R symmetries in the Gepner models

A number of the models in weighted projective spaces have realizations as Gepner models [15]. These provide a useful laboratory to check our identification of symmetries and field transformation properties. We adopt the notation of [18]. States of the full theory are products of states of $N = 2$ minimal models with level P . These are labelled:

$$\begin{pmatrix} \ell & q & s \\ \bar{\ell} & \bar{q} & \bar{s} \end{pmatrix} \tag{3.1}$$

Here $\ell = 0, \dots, P$, and $\ell + q + s = 0 \pmod{2}$. The right-moving conformal weight and U(1) charge are:

$$h = \frac{\frac{1}{4}\ell(\ell+2) - q^2/4}{(P+2)} + \frac{1}{8}s^2; \quad Q = \frac{-q}{P+2} + \frac{1}{2}s. \tag{3.2}$$

and similarly for the left movers. Each of the minimal models has a Z_{P+2} symmetry; states transform with a phase:

$$e^{-\frac{i\pi(q+\bar{q})}{P+2}} \tag{3.3}$$

The right-moving supersymmetry operator is a product of operators in each of the minimal models of the form:

$$S = \begin{pmatrix} 0 & 1 & 1 \\ 0 & \bar{0} & \bar{0} \end{pmatrix}. \tag{3.4}$$

From this we can immediately read off the transformation properties of S under the discrete symmetries, and determine whether or not the symmetries are R symmetries.

The quintic in CP^4 is described by a product of 5 models with $P = 3$. Following Gepner, we can identify the complex structure moduli associated with various deformations of the symmetric polynomial by considering their transformation properties under the discrete symmetries. So, for example, the polynomial $z_1^3 z_2$ is identified with the state:

$$\begin{pmatrix} 3 & 3 & 0 \\ 3 & 3 & 0 \end{pmatrix} \begin{pmatrix} 2 & 2 & 0 \\ 2 & 2 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}^3. \tag{3.5}$$

One can enumerate all of the states in this way, and repeat the counting we did before.

Now consider the model $WCP_{1,1,1,6,9}^4$ [18], with the polynomial of equation 2.6. For a particular choice of radius, this is described by the Gepner model which is the product $(16, 16, 16, 1)$. We see that the symmetry is $Z_{18} \times Z_{18} \times Z_{18} \times Z_3$. The Z_2 which takes the coordinate Z_5 of the weighted projective space into minus itself, $z_5 \rightarrow -z_5$, is equivalent, because of the identifications of the weighted projective space, to the transformation:

$$z_{1,2,3} \rightarrow e^{\frac{2\pi i}{18}} z_{1,2,3} \quad z_4 \rightarrow e^{\frac{2\pi i}{3}} z_4. \tag{3.6}$$

This is an R symmetry; it multiplies S_α^2 , and hence the superpotential, by -1 . Again we can enumerate the states. For example, the polynomial $z_1^{16} z_2^2$ is identified with the operator:

$$\begin{pmatrix} 16 & 16 & 0 \\ 16 & 16 & 0 \end{pmatrix} \begin{pmatrix} 2 & 2 & 0 \\ 2 & 2 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}^3. \tag{3.7}$$

This is clearly invariant under the symmetry above. It is a simple matter to enumerate all of the possible states and check that they are invariant.

So, as we stated earlier, all of the fluxes are invariant under the Z_2 , since the scalar moduli are odd. It is a simple matter to check that the supercharges transform by -1 under the R parity symmetry we identified earlier, and to reproduce our counting for the Z_{18} symmetry as well.

It is particularly easy to survey models which have realizations as Gepner models. We have found no examples where more than $1/3$ of the fluxes are invariant under an R symmetry.

4. Supersymmetry and R-symmetry breaking at tree level

One can ask whether in a theory with R symmetries, supersymmetry and R symmetry are spontaneously broken. We have seen that invariant fluxes are paired with moduli which transform like the superpotential. We have also seen that typically less than $1/2$ of the moduli transform in these way.

Call X_i , $i = 1, \dots, N$, those moduli which transform like the superpotential under R symmetries. Denoting the other fields by Y_a , These break into two groups: those invariant under the R symmetry, ϕ_α , $\alpha = 1, \dots, P$, and those which transform in some way, χ_r . Including terms at most linear in fields which transform under the R symmetry, the superpotential has the form:

$$W = \sum_{i=1}^N X_i f_i(\phi_\alpha) \tag{4.1}$$

If $N \leq P$, then provided that the f_i 's are reasonably generic functions, the equations $f_i = 0$ have solutions, so there are vacua with $X_i = f_i = 0$, and supersymmetry and the R symmetry are unbroken. Consider our example based on $WCP_{1,1,1,6,9}^4$ [18]. We studied there the Z_3 symmetry, $z_4 \rightarrow e^{\frac{2\pi i}{3}} z_4$, and saw that there are 55 X_i fields, i.e. $N=55$. There are many more ϕ fields (corresponding to polynomials with no z_4); $P = 217$. So among the fluxes which are invariant under the symmetry, generically one expects to find supersymmetric, R symmetric stationary points of the action. Another symmetry one can study is the symmetry $z_1 \rightarrow e^{\frac{2\pi i}{18}} z_1$. There are 28 fluxes invariant under the symmetry, and correspondingly $N = 28$ (these are all of the polynomials linear in z_1). It turns out that there are 28 polynomials invariant under the symmetry. So in this case, $N = P$, and again one expects R -symmetric, supersymmetric solutions. What is striking is that if one does find vacua with N close to $h_{2,1}$, so that there might not be a huge suppression, *supersymmetry and/or R symmetry typically will be broken*. This situation, if it occurs, might be relevant to the ideas of split supersymmetry, which we discuss further below.

5. Non-perturbative mechanisms for supersymmetry and R -symmetry breaking

We have seen that discrete R symmetries tend to give solutions of the classical equations with unbroken supersymmetry and vanishing W (and hence vanishing cosmological constant) with very mild assumptions about the form of the superpotential. Even if supersymmetry and R symmetry are unbroken at the level of the classical analysis, one expects that generically they will be broken by quantum effects. We can speculate on a number of breaking mechanisms. First, discrete symmetries may suffer from non-perturbative anomalies [19]. As a result, non-perturbative effects can generate an explicit violation of the symmetry. In generic states in the landscape, the couplings are presumably strong, so there is no real sense in which the theory possesses such a symmetry at all. But in a significant subset, these effects may be small (e.g. exponential in small couplings). Such effects could, in addition to breaking the R symmetry, break supersymmetry and generate positive and negative contributions to the cosmological constant.

Another possibility is that the R symmetry might be broken spontaneously by low energy dynamics.³ Gaugino condensation is an obvious example, which spontaneously

³Because the discrete symmetries are gauge symmetries, the distinction between explicit and spontaneous breaking has limited meaning, but the terminology is useful here nevertheless.

breaks any R symmetry. Models of dynamical supersymmetry breaking generically break R symmetries as well.

All of these effects are typically exponentially small as some coupling goes to zero. As a result, the scales of supersymmetry and R symmetry breaking tend to be distributed roughly uniformly on a log scale. This was the basis of the argument of [6] for the distribution of states on this branch.

6. Observations on split supersymmetry

The authors of [14] made the interesting observation that if one simply removes the squarks and sleptons from the MSSM, coupling unification works as well or better than if these fields are at the TeV scale. They suggested that such a splitting of the spectrum might be typical of the landscape. For example, we are used to the idea that fermion masses are often protected by chiral symmetries, while something like supersymmetry is required to protect scalar masses.

Upon further thought, however, there is a problem with this idea. The fermions whose masses one wants to protect are the gauginos. In $N = 1$ theories, the only symmetries which can protect gaugino masses are R symmetries. But in the context of supergravity, if supersymmetry breaking is large and the cosmological constant is small, the R symmetry is necessarily badly broken by the non-vanishing expectation value of the superpotential. At best, one expects that gaugino masses will be suppressed relative to squark masses by a loop factor. Ref. [14] constructed field theory models with larger suppression, but it is not clear that the features of these models are typical of regions of the landscape. One could speculate that there might be some anthropic selection for a dark matter particle, but this would at best explain why one gaugino was tuned to be light, not the three required for successful unification.

We have seen, in addition, that the studies of IIB vacua suggest that in the bulk of R -symmetric states, supersymmetry and R symmetry are likely to be unbroken at tree level, and the statistics of these states suggests that the vast majority of states with small cosmological constant will have small supersymmetry and R symmetry breaking. One can legitimately object that the IIB states might not be suitably representative. In particular, this argument relies crucially on a pairing of moduli and fluxes, which might not hold in all regions of the landscape.

Suppose we do find R symmetric flux configurations for which the superpotential does not have R -symmetric, supersymmetric stationary points (i.e. configurations for which there are more X -type than ϕ -type moduli). Let's ask how natural it might be to preserve the R symmetry if supersymmetry is broken. Usually, preservation of a symmetry is technically natural, since it is simply a question of a sign of a particular term in an effective action. In the case of the landscape, however, where there are many fields, preserving a symmetry requires that *many terms* in the action have the same sign. The authors of [14] discuss this issue in some toy models, where perturbative corrections all have the same sign. In the framework of supergravity models, already at the classical (tree) level, potentials for the moduli appear, and one can ask what happens. We have not performed

a general analysis, but as a toy model, have considered the T_6/Z_2 orientifold, where the Kahler potential can be written explicitly. With various assumptions about supersymmetry breaking, one typically finds that at stationary points of the potential with unbroken R symmetry, some moduli transforming under the symmetry have negative masses, some positive masses.

In any case, in order to understand the smallness of the cosmological constant, at least within any semiclassical analysis, it is necessary that the R symmetry be very badly broken so that $\langle W \rangle$ is large.

7. R parity

We have seen that R symmetries are quite costly in the landscape. Only a tiny fraction of states in the flux vacua respect any R symmetry. R parity is different, however. In many cases, there is an R parity which is respected by all of the fluxes. Consider, again, $WCP_{1,1,1,6,9}^4$ [18]. We study the Z_2 symmetry:

$$z_i \rightarrow e^{\frac{4\pi i}{9}} z_i, \quad i = 1 \dots 3; \quad z_4 \rightarrow e^{\frac{2\pi i}{3}} z_4. \quad (7.1)$$

Under this symmetry, Ω is invariant, but the supercharges transform with a -1 (this is clear from our formulas for the Gepner version of the model). Because Ω is invariant, fluxes are invariant if the corresponding polynomial is invariant. It is easy to check that every polynomial is invariant under the Z_2 . (These symmetry properties are readily checked in the Gepner construction as well). This sort of symmetry appears in many of the models.

Such Z_2 R parity does not lead to $W = 0$ vacua. The typical state in this case lies on the intermediate scale or high scale branch of the landscape ($W \neq 0$, supersymmetry broken or unbroken). So R parity is a common feature of the intermediate scale branch of the landscape.

8. Conclusions: phenomenology on the low energy branch of the landscape

It would be exciting if one could argue that the low energy branch of the landscape were favored. This branch is likely to have a phenomenology similar to that of gauge-mediated models. However, we have seen that R symmetry is rather rare in the landscape, even as R parity is common. We can ask whether there are effects which might select for the low energy branch. Possibilities include:

1. The cosmological constant: on the low energy branch, very low scales for supersymmetry breaking are favored. So many fewer states are required than on the other branches to obtain a suitably small cosmological constant. If one supposes that the supersymmetry breaking scale is, say, 10 TeV, while that on the intermediate scale branch is 10^{11} GeV, one needs 10^{28} fewer states. But our analysis here suggests that the suppression of states on the low energy branch is far larger.
2. Proton decay: R symmetries can account for the absence of proton decay. But we have seen R parity is much more common than R symmetry, so the latter would seem a more plausible resolution to the problem of proton decay.

3. Cosmology: The low energy branch has a severe cosmological moduli problem. If SUSY is broken at, say, 100 TeV, the moduli are extremely light and dominate the energy density of the universe at very early times. This leads to too much dark matter, and it is likely that this is selected against.

All of these considerations strongly suggest that the low energy branch of the landscape is disfavored. We have given elsewhere arguments which might favor the intermediate scale branch, and explored its phenomenology [20]. The recognition that R parity is common provides further support for this branch.

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