

# Discrete R Symmetries and Low Energy Supersymmetry

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## Plan for Today: “New, Improved” Models of Dynamical Supersymmetry Breaking

It is often said that SUSY breaking is a poorly understood problem. But much has been known for many years; problem is that models were complicated. Stable, dynamical SUSY breaking requires chiral representations of gauge groups, other special features which are not particularly generic. Model building is hard.

All of this changed with work of Intriligator, Shih and Seiberg (ISS): Focus on *metastable* susy breaking.

## Metastable Supersymmetry Breaking

Quite generic. First, non-dynamical.

O’Raifeartaigh Model:

$$W = X(\lambda A^2 - f) + mAY \quad (1)$$

SUSY broken, can’t simultaneously satisfy

$$\frac{\partial W}{\partial X} = \frac{\partial W}{\partial Y} = 0. \quad (2)$$

E.g.  $m^2 > f$  gives  $\langle A \rangle = \langle Y \rangle = 0$ ,  $\langle X \rangle$  undetermined by the classical equations.  $f$  is order parameter of susy breaking.

This model has a continuous "R Symmetry". In accord with a theorem of Nelson and Seiberg, which asserts that such a symmetry is required, generically, for supersymmetry breaking.. In components, using the same labels for the scalar component of a chiral field and the field itself:

$$X \rightarrow e^{2i\alpha} X \quad Y \rightarrow e^{2i\alpha} Y \quad A \rightarrow A \quad (3)$$

while the fermions in the multiplet have  $R$  charge smaller by one unit, e.g.

$$\psi_X \rightarrow e^{i\alpha} \psi_X \quad \psi_Y \rightarrow e^{i\alpha} \psi_Y \quad \psi_A \rightarrow e^{-i\alpha} \psi_A. \quad (4)$$

(For those familiar with superspace, this corresponds to  $\theta \rightarrow e^{i\alpha\theta} \quad d\theta \rightarrow e^{-i\alpha} d\theta$ .)

Under an  $R$  symmetry, the supercharges and the superpotential transform:

$$Q_\alpha \rightarrow e^{i\alpha} Q_\alpha \quad \bar{Q}_{\dot{\alpha}} \rightarrow e^{-i\alpha} \bar{Q}_{\dot{\alpha}} \quad W \rightarrow e^{2i\alpha} W. \quad (5)$$

One loop effects generate a potential for  $X$   
(Coleman-Weinberg) with minimum at  $\langle X \rangle = 0$ .

We don't expect (exact) continuous global symmetries in nature, but discrete symmetries are more plausible. Take a discrete subgroup of the  $R$  symmetry, e.g.  $\alpha = 2\pi/N$ ; a *discrete R* symmetry ( $Z_N$ ) Allows

$$W = X(\lambda A^2 - f) + mAY + \frac{X^{N+1}}{M^{N-2}} + \dots \quad (6)$$

$$W \rightarrow \alpha^2 W \quad (7)$$

(We will assume  $M \sim M_p$ ).

At low energies the last term is irrelevant, so in this model, there is a continuous  $R$  symmetry as an accidental consequence of the discrete symmetries (the model can be the most general consistent with symmetries).

One expects that the model has supersymmetric vacua, and it does:

$$X = (fM^{N-2})^{1/N+1}. \quad (8)$$

But the minimum near the origin persists, with positive energy ( $\approx f^2$ ), so the susy-breaking vacuum is *metastable*.

## Retrofitting: Supersymmetry Breaking Made (too?) Easy

ISS: A beautiful dynamical example. But for a number of reasons (to which we will return) I will focus on models which are, at first sight, somewhat more ad hoc, but also simpler.

"Retrofitting".

Would like to generate the scale,  $f$ , dynamically.

**Basic ingredient: dynamical generation of a scale, without susy breaking.**

**Candidate mechanism: gaugino condensation.**



## Gaugino Condensation

Pure susy gauge theory: One set of adjoint fermions,  $\lambda$ .  
Quantum mechanically:  $Z_N$  symmetry.

$$\langle \lambda\lambda \rangle = N\Lambda^3 e^{\frac{2\pi ik}{N}} \quad (9)$$

breaks discrete symmetry, but not susy.

# Retrofitting the O'Raifeartaigh Model

Feng, Silverstein, M.D. Take our earlier model, and replace  $f \rightarrow \frac{\Lambda^3}{M}$ :

$$W = -\frac{1}{4} \left( 1 + \frac{cX}{8\pi^2} \right) \frac{W_\alpha^2}{M_p} + XA^2 + mYA + \frac{X^{N+1}}{M_p^{N-2}}. \quad (10)$$

At low energies, we can replace the gaugino bilinear by its expectation value as a function of  $X$  (i.e. integrate out the massive degrees of freedom):

$$\langle \lambda\lambda \rangle = N\Lambda^3 e^{-\frac{cX}{NM_p}} \equiv W_0 - fX \quad (11)$$

$$W_0 = N\Lambda^3; \quad f = \frac{c\Lambda^3}{M_p}, \quad (12)$$

the low energy effective superpotential is (for  $X \ll M_p$ ):

$$W = W_0 + X(A^2 - f) + XA^2 + mYA, \quad (13)$$

## A skeptic can argue that this is all a bit silly:

- 1 We have introduced a new gauge interaction *solely* to generate an additional mass scale.
- 2 We still have a mass parameter  $M$ , put into the model by hand.
- 3 Anything else you might wish to complain about.

The rest of this talk will be devoted to confronting these questions.

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- 1 The first failing is actually a major success. We have generated a constant in  $W$  of the correct order of magnitude to cancel the c.c. Retrofitting almost inevitable(?).
- 2 Richer dynamics – a simple generalization of gaugino condensation – can account for both scales dynamically.
- 3 The  $\mu$  problem of gauge mediation is readily solved in this framework.

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# Other Consequences of Discrete R Symmetries

- 1 In “gauge mediation” (lower scale breaking),  $R$  symmetries can play a role in suppressing proton decay and other rare processes.
- 2 We will argue that in “gravity mediation”,  $R$  symmetries (discrete) are inevitably broken by Planck scale amounts and are not interesting. We will be lead to a general theorem about supersymmetry and R symmetry breaking (Festuccia, Komargodski, and M.D.).

# Why Retrofitting is (Almost) Inevitable

## Supergravity and the Cosmological Constant

In supergravity theories, the low energy theory is specified by three functions, the superpotential, Kahler potential, and gauge coupling function(s). The potential takes the form

$$V = e^{K(\phi, \phi^*)} \left[ F_i g^{\bar{i}i} F_{\bar{i}}^* - 3|W|^2 \right] \quad (14)$$

where

$$F_i = \frac{\partial W}{\partial \phi_i} + \frac{\partial K}{\partial \phi_i} W. \quad (15)$$

and  $g_{\bar{i}i}$  is the Kahler metric.

- 1 The generalization of the susy order parameter,  $\frac{\partial W}{\partial \phi_i}$ , of globally susy theories, is

$$F_i = \frac{\partial W}{\partial \phi_i} + \frac{\partial K}{\partial \phi_i} W.$$

- 2 If the cosmological constant is to be extremely small,

$$|\langle W \rangle| \approx \sqrt{3} |F| M_p \quad (16)$$

- 3 The gravitino mass is

$$m_{3/2} = e^{K/2} \langle W \rangle.$$

# "Supergravity" Models

There is a sense in supergravity theories that a superpotential,  $W \sim FM_p$  is "natural". Suppose  $\phi$  a pseudomodulus, with superpotential

$$W = f M_p g(\phi/M_p). \quad (17)$$

Polonyi model an example:

$$W = f(Z + \alpha M_p). \quad (18)$$

One finds  $Z \sim M_p$ , so  $W \sim FM_p$ .

What might account for the small value of the constant in the superpotential?  $\rightarrow$  R symmetry (presumably discrete). Might lead to an approximate continuous symmetry at small  $\phi$ , accounting for susy breaking in sense of Nelson-Seiberg; interesting from other points of view (proton decay, etc.). But in fact, in order to cancel c.c.,  $\phi$  vev always large, if the superpotential scales as above.

## Aside: A Theorem About the Superpotential

In a theory with an approximate, continuous  $R$  symmetry one can make this statement rigorous:

$$|\langle W \rangle| < \frac{1}{2} f_a F \quad (19)$$

(Festucia, Komogordski, M.D.).

This is the subject of a separate seminar. For our problem, it makes rigorous the intuition from the simple model that canceling the *c.c.* requires Planckian breaking of the  $R$  symmetry (and then why was susy dynamically broken?) Alternatively, additional dynamical scales, as in the retrofitted models.



# The Cosmological Constant in Gauge Mediation

To obtain small cosmological constant, we need  $\langle W \rangle \sim FM_p$ . A traditional critique of gauge mediation (Banks): if breaking of SUSY,  $R$  dynamical,  $W \sim \Lambda^3$ ;  $F \sim \Lambda^2 \leftrightarrow$  Need more interactions and another scale [think retrofitting!] or a big constant in  $W$ , unrelated to anything else.

# R symmetries and the Cosmological Constant

In the case of an unbroken  $R$  symmetry,  $\langle W \rangle = 0$ . So the breaking of any  $R$  symmetry is a requirement for obtaining small cosmological constant.

In retrofitted models, if the scale  $M \sim M_p$ , then

$$W \sim FM_p \sim \Lambda^3. \quad (20)$$

In other words, the scale of gaugino condensation is just what is required to obtain a small c.c.

From this point of view, retrofitting seems inevitable. From now on, focus on low energy breaking (gauge mediation).

[Could do the same in gravity mediation; somewhat different in spirit than the discussion above, but interesting models.]

## Problems with our earlier model

- 1 Model has two scales. One attempt to avoid (related to ideas of Green, Wiegand.), is not compatible with the requirement of small c.c. (we would have to add still *other* interactions to cancel the c.c.
- 2 The model does not spontaneously break the R symmetry (once one performs the Coleman-Weinberg analysis; this is in accord with a theorem of D. Shih). Can be modified following constructions of Shih.
- 3 When developed into a model of gauge mediation, the model has other difficulties, such as the  $\mu$  problem.

Many of these difficulties might be avoided if we had order parameters for the breaking of the  $R$  symmetry of lower dimension (e.g. gauge singlet chiral superfields).

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# The Essence of Gaugino Condensation

Gaugino condensation is considered in many contexts, but its principal distinguishing feature is that it breaks a discrete  $R$  symmetry without breaking supersymmetry. Many other models, such as supersymmetric QCD with massive quarks, dynamically break such symmetries, but it would be helpful to have models like pure susy gauge theory, with scales generated by dimensional transmutation.

# Models with Singlets

$SU(N)$  gauge theory with  $N_f < N$  massless flavors,  $N_f^2$  singlets,  $S_{f,f'}$

$$W = y S_{f,f'} \bar{Q}_{f'} Q_f - \frac{1}{3} \gamma \text{Tr} S^3 \quad (21)$$

For convenience, we have taken the superpotential to respect an  $SU(N_f)$  symmetry;  $\gamma$  and  $y$  can be taken real, by field redefinitions. Anomaly free discrete symmetry  $Z_{2(3N-N_f)}$   $R$ -symmetry,

$$\alpha = e^{\frac{2\pi i}{6N-2N_f}} \quad (22)$$

$$\lambda \rightarrow \alpha^{3/2} \lambda \quad S_{f,f'} \rightarrow \alpha S_{f,f'} \quad (Q, \bar{Q}) \rightarrow \alpha(Q, \bar{Q}). \quad (23)$$



# Understanding the Symmetry

Instanton generates:

$$\langle \lambda \lambda \dots \lambda \lambda \psi_Q \dots \psi_{\bar{Q}} \rangle \quad (24)$$

which transforms with phase

$$\alpha^{2N\frac{3}{2}} \alpha^{N_f(1-3/2)} = \alpha^{3N-N_f}. \quad (25)$$

(Special cases considered in the past by Yanagida)

The system is readily analyzed in various limits. For  $\gamma \ll y$ , ignore the  $S^3$  coupling.  $\langle S \rangle$  generates a mass for  $M$ . For  $N_f < N$ , non-perturbative dynamics generate the familiar

$$W_{dyn} = (N - N_f) \Lambda^{\frac{3N - N_f}{N - N_f}} \det(\bar{Q}Q)^{-\frac{1}{N - N_f}}. \quad (26)$$

In the  $SU(N_f)$  symmetric limit, the  $\frac{\partial W}{\partial \phi} = 0$  equations admit solutions of the form

$$S_{f,f'} = s \delta_{f,f'} \quad Q_f \bar{Q}_{f'} = v^2 \delta_{f,f'}. \quad (27)$$

with

$$v = \left( \frac{\gamma}{y^3} \right)^{\frac{N - N_f}{6N - 2N_f}} \alpha^k \Lambda; \quad s = \left( \frac{y^{N_f}}{\gamma^N} \right)^{\frac{1}{3N - N_f}} \alpha^k \Lambda. \quad (28)$$

Perturbing away from the symmetric limit, one can then check that there is no qualitative change in the solutions (e.g. the number is unchanged). For  $N_f \geq N$ , the theory has baryonic flat directions, and does not have a discrete set of supersymmetric ground states. Adding additional singlets and suitable (non-renormalizable) couplings, one can again spontaneously break the discrete symmetries. One can also consider generalizations to other gauge groups and to different matter content. (Kehayias).

# New, Improved Models of Metastable DSB

In gauge mediated models, there are wide range of possible scales.

$$10^5 \text{ GeV} \leq M \leq 10^{14} \text{ GeV} \quad 10^5 \text{ GeV} \leq \sqrt{F} \leq 10^{8.5} \text{ GeV} \quad (29)$$

We revisit gauge-mediated model building using retrofitting and the enlargement of gaugino condensation.

There is now remarkable freedom to build models (perhaps disappointing to have so much freedom). There are, for example, many possible choices of scale. In terms of the effective O’Raifeartaigh model, one can have mass scales much larger than, or comparable to, the supersymmetry breaking scale. Similarly, messengers can exhibit supersymmetry breaking masses comparable to the average masses, or much smaller. The underlying dynamics associated with supersymmetry breaking can be at scales as low as  $10^5$  GeV, or far higher.

# Models with a Hierarchy of Scales

We will retrofit a model which spontaneously breaks a continuous  $R$  symmetry. Perhaps the simplest example [Shih] is provided by a theory with fields  $\phi_{\pm 1}, \phi_3, X_2$ , where the subscripts denote the  $R$  charge, and with superpotential:

$$W = X_2(\phi_1\phi_{-1} - f) + m_1\phi_1\phi_1 + m_2\phi_{-1}\phi_3. \quad (30)$$

Motivated by this model, consider a theory with fields  $X_0, S_{2/3}, \phi_0, \phi_{2/3}, \phi_{4/3}$ , where the subscript denotes the discrete  $R$  charge ( $\phi_q \rightarrow \alpha^q \phi_q$ , where  $\alpha$  is a root of unity).  $S_{2/3}$  is a field with a large mass and an  $R$  symmetry breaking vev,

$$W = \frac{1}{M_p} X_0 S_{2/3}^3 + y X_0 \phi_{2/3} \phi_{4/3} + \lambda_1 S_{2/3} \phi_{2/3} \phi_{2/3} + \lambda_2 S_{2/3} \phi_{4/3} \phi_0 \quad (31)$$

(up to terms involving higher dimension operators). The resulting low energy effective theory is that of eqn. 30, with

$$m_1 = \lambda_1 S_{2/3} \quad m_2 = \lambda_2 S_{2/3} \quad f = -\frac{S_{2/3}^3}{M_p}. \quad (32)$$

Below the scale  $S_{2/3}$ , the theory possesses an accidental, (approximate) continuous  $R$  symmetry which is spontaneously broken.

$m_i^2 \gg f$ . If  $X$  couples to some messenger fields, the scale for gauge mediated masses is set by  $\Lambda_m$ :

$$W_{mess} = X\bar{M}M \quad \Lambda_m = \frac{F_X}{X} \approx \frac{S^2}{M_p}. \quad (33)$$

If  $\Lambda_m \sim 10^5$  GeV, for example, then we have  $S \sim 10^{11.5}$  GeV.



It is also not difficult to write down models with a lower scale of supersymmetry breaking with many similar features (i.e. where  $\langle X \rangle^2 \sim F_X \sim 10^5 \text{ GeV}$ ).

# The $\mu$ Problem

Generating a  $\mu$  term in gauge mediation has long been viewed as a challenging problem.

Retrofitting has been discussed as a solution to the  $\mu$  problem (Yanagida, Thomas, Dine and Mason, Green and Wiegand, others). If the source of the  $\mu$  term is a coupling of the gaugino condensate responsible for the hidden sector  $F$  term,

$$W_\mu = \frac{W_\alpha^2}{M_p^2} H_U H_D \quad (34)$$

the resulting  $\mu$  term is very small; it would seem necessary to introduce still *another* interaction, with a higher scale. Not only does this seem implausibly complicated, but it is once more problematic from the perspective of the c.c.

Models with singlets, on the other hand, allow lower dimension couplings and larger  $\mu$  terms. In the hierarchical model, for example, if the product  $H_U H_D$  has  $R$  charge  $4/3$ , it can couple to  $S^2/M_p$  with coupling  $\lambda$ .

$$W_\mu = \lambda \frac{S_{2/3}^2}{M_p} H_U H_D. \quad (35)$$

Then

$$\mu = \Lambda_m \quad (36)$$

The  $F$  component of  $S$  is naturally of order  $m_{3/2}^2$ , so this does not generate an appreciable  $B_\mu$  term; the  $B_\mu$  term must be generated at one loop. A rough calculation yields  $\tan \beta \sim 30$ . Alternative structures lead to different scaling relations (more detailed analysis in progress with John Mason).

We can similarly solve the  $\mu$  problem in the single-scale models. Again,  $W_{\mu}$ , for a range of  $F$ 's and  $\lambda$ 's, yields a  $\mu$  term of a suitable size.

# Roles for Discrete $R$ Symmetries

- 1 Account for structure of susy breaking sector
- 2 Account for structure of messenger sector (segregation from visible sector; stability (or not) of messengers.
- 3 Suppression of B,L Violating Dimension Four and Five Operators

For the third point, don't have time for details here, but we see that cosmological constraint provides a (lower) bound on the extent of  $R$  symmetry breaking.

One arguably should impose a variety of constraints, esp. anomaly constraints (e.g. Yanagida et al). Imposing anomaly constraints requires making plausible – but not strictly necessary – assumptions on the form of the microscopic theory. E.g. messengers, other fields, can mass at the (large) scale of  $R$  symmetry breaking. Fields in the same  $SU(5)$  multiplet need not transform in the same way. In any case, such symmetries, we have seen, are necessarily broken by significant amounts. If order parameters include gauge singlet chiral fields, suppressing dangerous dimension four operators is challenging and constrains the symmetries. Other interesting issues include domain walls and inflation.

# Conclusions

If I were giving this talk 15 years ago, I would be very optimistic about the imminent discovery of susy, given the ease with which one can construct relatively simple models of dynamical supersymmetry breaking and gauge mediation. [ If I am at all hesitant, this is because of the "little hierarchy", but this is for another talk.]



- 1 Retrofitting allows construction of broad classes of viable models.
- 2 The scales required for retrofitting are precisely those required to account for a small cosmological constant.
- 3 "Gaugino Condensation" is one realization of a broad phenomenon, which permits models with a range of possible scales (and accounts for dimensional transmutation).
- 4 Within these frameworks, the  $\mu$  problem is not a problem, and one anticipates a large  $\tan \beta$ .
- 5 Discrete  $R$  symmetries seem likely to play a role in accounting for many of the features of low energy susy; in gauge mediation (but not in gravity mediation) they might account for the proton lifetime and suppression of other rare processes.

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**THE END**

**On the Other Hand, In Case you Want More:**



# Discrete R Symmetries and Proton Decay

Most supersymmetric model building seeks to suppress dangerous dimension four lepton and baryon number violating operators by imposing  $R$  parity.  $R$  parity is not really an  $R$  symmetry at all (it is an ordinary symmetry times a  $360^\circ$  rotation). Unlike the  $R$  symmetries we are focussing on in this paper, there is no requirement that it be broken; this leads, most strikingly, to stable dark matter.

Discrete  $R$  symmetries might forbid dangerous dimension four *and* dimension five operators. Must be broken; the size of this breaking, and the transformation properties of the fields, will control the size of  $B$  and  $L$  violating effects (e.g. Yanagida et al, Banks).

In model building with discrete symmetries, one would seem to have a great deal of freedom in both the choice of symmetry group and in the transformation properties of the fields. One, arguably (Yanagida) should, impose a variety of constraints. E.g.

- 1 Absence of anomalies.
- 2  $\mu$  term forbidden in the superpotential
- 3 Kahler potential terms permitted which give rise to a  $\mu$  term of order the supersymmetry breaking scale.

Very restrictive (Yanagida, Private Communication)

Imposing anomaly constraints requires making plausible – but not strictly necessary – assumptions on the form of the microscopic theory. E.g. messengers, other fields, can mass at the (large) scale of  $R$  symmetry breaking. Fields in the same  $SU(5)$  multiplet need not transform in the same way. But the limited solutions subject to these restrictions are interesting and give pause. [Thanks to Professor Yanagida for his comments on these issues]. Other interesting issues [again raised by Professor Yanagida] include domain walls and inflation.

Most discussions of the use of  $R$  symmetries to suppress proton decay are framed in the context of gravity mediation, and we have seen that once one requires a small cosmological constant, this is problematic.

# R Symmetries in Gauge Mediation

Symmetry which forbids dimension four and five operators (for purposes of illustration): *Conventional R parity*, and an  $R$  symmetry, under which all quark and lepton superfields are neutral, while the Higgs transform like the superpotential. This forbids all dangerous dimension four and dimension five operators. Once  $R$  symmetry breaking is accounted for, dimension five operators may be generated, but they will be highly suppressed.

We can contemplate more interesting symmetries, which do not include  $R$  parity, and for which the Higgs, quarks and leptons have more intricate assignments under the  $R$  symmetry. Given that the  $R$  symmetry is necessarily broken, dangerous dimension four operators will be generated.

Consider, first, the case where the R symmetry is broken by a gaugino condensate in a pure gauge theory. Suppose that  $B$  and  $L$ -violating operators of the form

$$\delta W_{b,l} \sim \frac{W_\alpha^2}{M_p^3} \Phi \Phi \Phi \quad (37)$$

are permitted by the symmetries. Even if  $\sqrt{F}$  is as large as  $10^9$  GeV,  $W/M_p^3 \approx 10^{-18}$ , more than adequately suppressing proton decay.

In the presence of a singlet field such as  $S$ , the constraints are more severe. Even in the low gravitino mass case, the small parameter,  $S/M_p$ , is of order  $10^{-9}$ . So suppression of dangerous operators by a single factor of  $S$  is not adequate. One requires that many operators be suppressed by two powers of  $S$ .