Metastability

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In particle physics, we have often considered the possibility that the universe might be metastable. Bounds on top and Higgs masses; crutch in model building.

Recently, a convergence of ideas which strongly suggest that we are necessarily in a metastable state. These come from:

- Considerations of dynamical supersymmetry breaking in field theory.
- Possible existence of a string *landscape*.

Dynamical Supersymmetry Breaking

Models with Dynamical Supersymmetry Breaking (DSB) known for some time. But until recently, dynamical supersymmetry breaking seemed an exceptional phenomenon.

1. Chiral

2. Non-vanishing Witten index

3. No flat directions.

4. R symmetries (Nelson-Seiberg)

The resulting particle physics models suffered from various deficiencies:

- If DSB in a hidden sector in supergravity, gauginos light, and no amelioration of the flavor problems of ordinary supergravity theories.

- If DSB at lower scale, gauge mediation. But resulting models quite complicated. Most models have DSB scale at least 10^4 times the scale of weak interactions.

The ISS Model

Intriligator, Shih and Seiberg discovered susy breaking in a surprising context: a vectorlike theory, in which the Witten index was known to be non-zero, and without an exact R symmetry. Their model is just SUSY QCD, with $N_f > N + 1$, and *massive* quarks. Such theories were thought not to break supersymmetry because:

1. The Witten index, $\Delta = N$.

2. In the limit of large mass, this theory reduces to a pure, SUSY gauge theory, which is known not to break susy. For many questions, holomorphy of quantities such as the superpotential is enough to insure that there are supersymmetric minima.

Ironically, such gauge theories were originally proposed (with vanishing quark masses) as models of dynamical supersymmetry breaking; Witten's computation of the index was viewed as clinching the case that such theories did not break supersymmetry.

In the electric phase, the theory has an $SU(N_f) \times SU(N_f)$ flavor symmetry, as well as a $U(1)_R$ symmetry under which Q and $\bar{Q}$ have charge $\frac{N_f - N}{N_f}$.

The breaking of supersymmetry is readily understood by considering the theory in its magnetic phase. In the infrared, the massless theory is described by an $SU(N_f - N)$ gauge theory with N_f q and $\bar{q}$ fields in the fundamental, and a set of "mesons", $\Phi_{f\bar{f}}$. The theory has superpotential:

$$W = \bar{q}\Phi q. \tag{1}$$

$\bar{q}$, q transform as $(\bar{N}_f, 1)$, $(1, \bar{N}_f)$ under the $SU(N_f) \times SU(N_f)$ flavor symmetry of the theory in the electric phase, without the mass term. Φ transforms as an $(\bar{N}_f, N_f)$. Under the $U(1)_R$, $\bar{q}, q$ carry charge N/N_f; Φ carries charge $2(1 - N/N_f)$.

Including the Mass Term

For small m, treat mass term as a perturbation. Transforms as $(\bar{N}_f, N_f)_{2(1-N/N_f)}$

So in the magnetic theory,

$$\delta W = h \mathrm{Tr}\ m\Lambda\Phi \tag{2}$$

has the same transformation numbers under the flavor symmetries as the underlying quark mass term.

SUSY Breaking in the Magnetic Theory

An important feature of the magnetic theory is that the kinetic terms for the dual quarks and the mesons are non-singular, and near the origin they can be taken to be canonical. It is a simple matter to check that the potential has a stable local minimum near the origin. There is a supersymmetric minimum away from the origin, which moves farther away as $m \to 0$.

The equation

$$\frac{\partial W}{\partial \Phi} = 0 \tag{3}$$

requires that $\bar{q}_f q'_f$ be proportional to the unit matrix. But q_f is an $N \times N_f$ matrix. By a symmetry transformation and the use of the D term equations (and field redefinitions), this may be brought to the form:

$$\bar{q}_f q'_f = \begin{pmatrix} v^2 \; I_{N\times N} & 0 & 0 & \dots \\ 0 & 0 & 0 & \dots \end{pmatrix}. \tag{4}$$

So one cannot satisfy the condition, and supersymmetry is broken.

What about the Witten Index?

Turn off m. Under the continuous R symmetry:

$$\Phi \to e^{2i\alpha(N_f-N)/N_f}\Phi \tag{5}$$

so expect non-perturbative superpotential:

$$W = \Lambda^{(-3N+N_f)/(N_f-N)} \mathrm{det}\Phi^{1/(N_f-N)}. \tag{6}$$

With small mass term, N roots of $\frac{\partial W}{\partial \Phi} = 0$.

ISS As Basis of a Phenomenology

One loop computation: Potential for Φ has minimum at origin.

For a range of parameters, the vacuum with broken susy is highly metastable.

In the presence of the mass term, the original theory has a discrete, Z_N R symmetry ($\alpha = 2\pi/N$). q, $\bar{q}$ are neutral under this symmetry. Φ transforms. The symmetry is unbroken in the magnetic phase.

This R symmetry forbids a mass for gauginos.

Recent models: Murayama and Nomura; Csaki, Shirman and Terning;Aharony and Seiberg; Abel and Khoze; Amarati, Girardello and Mariotti. All focus on breaking R symmetries of ISS; some on generating the scale m dynamically. Some of these strategies require breaking SUSY at high scales.

More on some of these models later

Here focus on Mason, M.D. (following on Feng, Silverstein, M.D.) – simple model building strategy which allows susy breaking at low scales.

Retrofitting O'Raifeartaigh Models

Metastability opens new vistas on the problem of dynamical supersymmetry breaking.

Any O'Raifeartaigh Model can be converted into a dynamical model (Silverstein: "dynamicized"). Model building with DSB transformed from something difficult and highly constrained, to something almost too easy.

Chiral fields, A, Y and Z

$$W = \lambda Z(A^2 - \mu^2) + MYA. \tag{7}$$

Generate μ dynamically. SU(N) pure gauge theory:

$$\int d^2\theta \frac{Z}{4M} W_\alpha^2. \tag{8}$$

Since

$$\langle W_\alpha^2 \rangle = \langle \lambda\lambda \rangle = \exp(-\frac{8\pi^2}{Ng^2(M)}) = \Lambda^3 e^{-8\pi Z/N} \tag{9}$$

integrating out the gauge fields, leaves a superpotential:

$$W = \lambda Z A^2 + \frac{\Lambda^3 e^{-8\pi Z/b_0}}{M} + MYA \tag{10}$$

(M can be dynamical as well.)

Structure is *natural*: Discrete Symmetries

This structure is natural, in the sense that one can account for it with discrete symmetries. The gauge theory has a Z_N discrete symmetry, so if Z and Y are neutral, and A transforms like λ (with phase $e^{2\pi i/N}$), the only couplings of dimension three or less which are invariant are those above.

The original O'Raifeartaigh theory had a flat direction classically:

$$V = |F_Z|^2 \tag{11}$$

independent of Z. At one loop, Coleman-Weinberg calculation gives a minimum at $Z = 0$ with curvature of order μ^2.

The corrections to the superpotential in powers of Z have little effect near the origin,

$$W = \lambda Z A^2 + \frac{\Lambda^3 e^{-8\pi Z/b_0}}{M} + \lambda' Y A^2 \tag{12}$$

but the system has a (supersymmetric) minimum at $Z \to \infty$ (runaway). Combined with the CW calculation, local minimum at origin, susy minimum at ∞.

Gravity Mediation

Already as models of gravity mediation, these theories are interesting.

Couple to (super) gravity, along with fields of MSSM. Introduce constant in superpotential to tune cosmological constant. Then squarks and sleptons gain mass at tree level. No symmetry prevents coupling of Z to W_α^2 (unlike simplest conventional models of DSB). So gaugino masses also at tree level.

These models, while providing a dynamical explanation of the hierarchy, still have the standard difficulty of gravity mediation: They offer no insight into flavor problems.

Gauge Mediation

What about as models of gauge mediation?

In the simple model we have described, the dynamical scale, μ, is a parameter, and so is the scale of susy breaking. But the low energy theory possesses an unbroken R symmetry. This is a feature of all models with only chiral fields, an R symmetry, and fields with R charges 0 and 2 (Shih). So we need to enlarge the class of models.

First, more scales.

O'Raifeartaigh Models with More Scales

The scale μ arose as $\mu^2 = \Lambda^3/M_p$. By coupling fields to higher dimension operators, we can generate other combinations.

In standard O'Raifeartaigh model:

$$W = Z(A^2 - \mu^2) + M\ AB \qquad (13)$$

Replace scales by:

$$Z(A^2 - \frac{W_\alpha^4}{M_p^4}) + AB\frac{W_\alpha^2}{M_p^2}. \qquad (14)$$

Note $M \sim \mu \sim \Lambda^3/M_p^2$.

Approaches to Breaking R Symmetry

1. Consider more exotic O'Raifeartaigh Models (Shih, to appear). In these, can couple fields directly to messengers.

2. Include operators which explicitly break the accidental R symmetry (Murayama and Nomura, Aharony and Seiberg,...)

3. Include gauge interactions which induce spontaneous breaking of the R symmetry (Dine, Mason; Intriligator, Shih and Seiberg (to appear).

Explicit Breaking of the R Symmetry

This can be done in many ways. Include messengers (two sets) transforming as 5 and $\bar{5}$. First write an O'Raifeartaigh model:

$$W = \lambda Z(5\bar{5} - \mu^2) + mQ\bar{5} + m'5\bar{Q} + \epsilon\bar{Q}Q. \qquad (15)$$

For small ϵ, supersymmetry is restored for large Q. A structure of this type can be enforced by discrete symmetries, with all of the dimensional parameters of the same order of magnitude, and arising dynamically.

It is not hard to check that there is a one loop tadpole for Z. So (since the Z mass is also generated at one loop) there is a Z vev of order ϵ, and we have the standard gauge-mediated structure. But we also have mass terms (those for Q and $\bar{Q}$, which are independent of the vev of Z. So the standard gauge-mediated formula for the scalar masses need not hold.

Gauge Mediation

If couple messengers, a striking difference between spontaneous, explicit breaking of R symmetry.

- Spontaneously break R Symmetry: Usual gauge-mediated formula for squark, slepton, and gaugino masses.

$$\widetilde{m}^2 = 2\Lambda^2 \left[C_3 \left(\frac{\alpha_3}{4\pi}\right)^2 + C_2 \left(\frac{\alpha_2}{4\pi}\right)^2 + \frac{5}{3}\left(\frac{Y}{2}\right)^2 \left(\frac{\alpha_1}{4\pi}\right)^2 \right], \quad (16)$$

  where $\Lambda = F_S/S$, and $C_3 = 4/3$ for color triplets and zero for singlets, $C_2 = 3/4$

$$m_{\lambda_i} = c_i \, \frac{\alpha_i}{4\pi} \, \Lambda \, . \quad (17)$$

- Explicit breaking: These formulas no longer hold; the constants C_3, C_2, and c_i are replaced by unknown constants.

Approaches to Generating μ, B_μ terms

1. Dynamically generate μ; B_μ (Murayama, Aharony and Seiberg, M.D., Arkani-Hamed, Seiberg, Thomas (in progress)).

$$\int d^4\theta Z^\dagger Z H_U H_d = B_\mu H_U H_D + \text{c.c.} \tag{18}$$

$$\int d^2\theta \frac{1}{M^3} Z H_U H_D W_\alpha^2 = \int d^2\theta \mu H_U H_D \ldots . \tag{19}$$

2. NMSSM-like structure with additional singlet(s) (Dine, Mason).

Models with Gauge Interactions

It is well known that gauge interactions in supersymmetric theories tend to give negative contributions to potentials (inverted hierarchy).

A simple model with a $U(1)$ gauge interaction:

$$W = M(Z^+\phi^- + Z^-\phi^+) + \lambda Z^0(\phi^+\phi^- - \mu^2). \qquad (20)$$

Breaks SUSY:

$$\phi^+ = \phi^- = v \qquad v^2 = \frac{\lambda^2\mu^2 - M^2}{\lambda^2} \qquad (21)$$

(up to phases) while

$$F_{Z^+} = F_{Z^-} = Mv; \quad F_{Z^0} = \frac{M^2}{\lambda}. \qquad (22)$$

There is a flat direction with

$$Z^\pm = -\frac{\lambda Z^0 \phi^\pm}{M}. \qquad (23)$$

Again, need to do Coleman-Weinberg calculation. For large Z, one can do the calculation easily using supergraphs. Work to second order in $F_{Z^\pm}$, F_{Z^0}. Study diagrams with two external Z fields. Result is:

$$V = \frac{1}{16\pi^2}\int d^4\theta(\lambda^2 Z^{0\dagger}Z^0 - 4g^2(Z^{+\dagger}Z^+ + Z^{-\dagger}Z^-))\ln(|Z|^2) \tag{24}$$

Need that the coefficient of the log be positive. Question is then behavior near the origin.

Full Calculation of the Potential

Near origin, need to diagonalize mass matrix exactly, use Coleman-Weinberg formula:

$$V = \frac{1}{64\pi^2}\sum(-1)^F m^4 \ln(m^2). \tag{25}$$

Result:

So for a range of parameters, there is a metastable minimum.

Intriligator, Shih, Seiberg (to appear): For some choices of μ and Λ, narrow range of g, but this turns out not to be general (Mason).

So we can now build models. Fields Z have non-zero scalar and auxiliary components. Can couple to 5 and $\bar{5}$ of messengers.

$$\lambda' Z^0 \bar{M} M. \tag{26}$$

Squarks, sleptons: usual gauge-mediated spectrum. Similarly gauginos.

Scale is a parameter we are free to choose. Can be anything from 10 TeV to somewhat below intermediate scale.

μ term, $SU(2) \times U(1)$ breaking.

Usual problems if couple Z directly to $H_U H_D$ ($B_\mu \gg \mu^2$).

Add Singlet(s)

To obtain comparable couplings, couple singlets to Higgs and messengers and generate negative mass-squared for singlet in perturbation theory. We'll also double the messenger sector (for reasons to be explained)

$$Z^0(y_1 M_1 \bar{M}_1 + y_2 M_2 \bar{M}_2) + \tag{27}$$

$$S(h_1 M_1 \bar{M}_2 + h_2 M_2 \bar{M}_1) + S H_U H_D + S^3. \tag{28}$$

The computation of the S potential near the origin is straightforward. Suppose $y_1 \approx y_2$, $h_1 \approx h_2$. In this case, the masses of the messenger fields are approximately equal, and the calculation of the S mass is simple. The one loop terms in the S potential proportional to $|S|^2$ vanish, left with

$$\mathcal{L}_S = \frac{y_1^2|F|^2(S^2 + S^{*2})}{|Z^0|^2 16\pi^2}. \tag{29}$$

So the real part of S acquires an expectation value,

$$\text{Re } S^2 = \frac{y_1^2|F|^2}{|Z^0|^2\lambda^2 16\pi^2} \tag{30}$$

and $F_S = \lambda S^2$. For λ is of order one, B_μ and μ^2 are of the same order.

It is hard, however, to obtain a superpotential of this form as a consequence of symmetries. E.g. Z_2 R-symmetry:

$$Z^0 \to Z^0 \quad S \to -S \quad M_1 \to -M_1 \tag{31}$$

$$\bar{M}_2 \to -\bar{M}_2 \quad \bar{M}_1, M_2 \to \bar{M}_1, M_2. \tag{32}$$

This symmetry allows all of the required couplings, but it also permits $Z^0 S$, $(Z^0)2S$, which are problematic. More general symmetries have similar problems. But perhaps just not clever enough.

It is not hard to write down a working model with two singlets which achieves a suitable μ term with the desired properties.

Alternative Strategies

Many proposals implementing ideas of metastable DSB have appeared recently. Most involve high scale breaking.

- Amarati, Girardello and Mariotti: analyze a version of ISS with adjoint fields. R symmetry broken, but gaugino masses are still suppressed, highly constraining the scales.

- Murayama and Nomura: break R symmetry of ISS through non-renormalizable couplings to messengers and explicit supersymmetric mass term. Breaking at relatively high scales. Additional mass term perhaps unappealing.

- Aharony and Seiberg: Generate mass parameters of ISS, as well as supersymmetric mass for messengers, from coupling to a high scale gauge theory, as in Feng et al. R symmetry broken in the construction. Scales constrained; high scale of susy breaking. GUT along these lines of Abel, Jackel, Khoze

$$\int d^2\theta \left[\frac{1}{M_p} Q_i \bar{Q}^i f \bar{f} + \mathrm{Tr}(W_\alpha^2)\left(\frac{1}{g^2} + \frac{1}{M_p^2}(Q_i\bar{Q}^i + f\bar{f})\right)\right] \tag{33}$$

Scales still constrained due to $1/M_p$.

- Csaki, Shirman and Terning: more elaborate. Also generalize ISS, break R symmetry through superpotential couplings. Scale of susy breaking can be low, $10-100$, TeV, but only if there is an ultraviolet scale $\Lambda_{UV} < 10^{11}$ GeV.

- Abel and Khoze: Particularly ambitious. Identify some of the quarks of the magnetic phase with Higgs fields. Masses still from loops, so very large Yukawa required in the magnetic phase (order 100's). Not clear if this can emerge from a consistent analysis.

Within the models of Mason and M.D., instead of breaking R symmetry spontaneously, add further couplings to break explicitly – essentially Murayama et al, Aharony and Seiberg. (Seiberg: with retrofitting, one can do anything one wants). Also generate μ term, etc.

Once one has adopted this point of view, can also rethink messenger couplings.

Challenges for a Phenomenology

We have seen various phenomenological possibilities. Personally, I advocate narrowing by thinking about fine tuning.

- Gravity mediation has nice features in this framework, but still badly tuned (flavor, electroweak scale)

- Gauge mediation: nice models with high scales (Murayama et al, Aharony and Seiberg, Abel and Khoze) but weak scale badly tuned (1%).

- Very low energy gauge mediation (10's of Tev). Little fine tuning, provided don't have usual gauge-mediated formula, new dynamics at few TeV (scalars or gauge interactions) (in progress with Seiberg, Thomas).

Metastability and the String Theory Landscape

If landscape ideas correct, our universe is certainly a metastable state. What might select states like ours?

Much discussion of measures for eternal inflation, etc. An easier and more primitive question: what classes of states *are* metastable. Most local minima of effective potential decay rapidly (tunneling rates of order one). Classes of states which might be highly metastable (study in IIB landscape; stars indicate my confidence level):

1. Weak coupling – no (*)
2. Light particles – no (*)
3. Low energy supersymmetry – yes (***)
4. Large volume – yes (*)
5. Warping (without susy) – no (*)

Conclusions

Metastability seems part of our future.

- Dynamical Susy breaking: requires approximate R symmetry. Approximate to be consistent with phenomenology $\Rightarrow$ instability of our universe.

- Landscape ideas: inherent.

Previously, because DSB an exceptional phenomenon, could imagine that we would simply guess the correct microscopic theory. This now looks unlikely: we have seen that we can produce DSB models to order, with almost any desired features Instead we should explore phenomenology of supersymmetry with various scales of breaking more generally. Fine tuning a guide.

String theory might provide another guide. If landscape ideas correct, try to argue what classes of theories are generic, and perhaps understand some of their features. Metastability might provide a guiding principle.