Metastable supersymmetry breaking vacua from conformal dynamics

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Abstract. We study the scenario that conformal dynamics leads to metastable supersymmetry breaking vacua. At a high energy scale, the superpotential is not R-symmetric, and has a supersymmetric minimum. However, conformal dynamics suppresses several operators along renormalization group flow toward the infrared fixed point. Then we can find an approximately R-symmetric superpotential, which has a metastable supersymmetry breaking vacuum, and the supersymmetric vacuum moves far away from the metastable supersymmetry breaking vacuum. We show a 4D simple model. Furthermore, we can construct 5D models with the same behavior, because of the AdS/CFT dual.

Keywords: supersymmetry, conformal dynamics, metastable supersymmetry breaking vacua

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INTRODUCTION

Conformal dynamics provides several interesting aspects in supersymmetric models as well as non-supersymmetric models, because conformal dynamics exponentially suppresses or enhances certain operators. One interesting aspect is that conformal dynamics can suppress flavor-dependent contributions to soft SUSY breaking terms which lead to flavor changing neutral current processes constrained strongly by current experiments. Then, flavor-blind contributions such as anomaly mediation [2] would become dominant [3, 4, 5, 6, 7, 8]. Another interesting aspect is that conformal dynamics can generate hierarchical structure of Yukawa couplings for quarks and leptons [9, 10].

Here we study a new application of conformal dynamics for supersymmetric models, that is, realization of metastable SUSY breaking vacua by conformal dynamics. Its idea is as follows. The Nelson-Seiberg argument [11] implies that generic superpotential has a SUSY minimum, but R-symmetric superpotential has no SUSY minimum, that is, SUSY is broken in such a model. Thus, if we add explicit R-symmetry breaking terms in R-symmetric superpotential, a SUSY minimum would appear. However, when such R-symmetry breaking terms are tiny, the previous SUSY breaking minimum would survive and a newly appeared SUSY preserving minimum would be far away from the SUSY breaking point in the field space. That is the metastable SUSY breaking vacuum [12, 13, 14]. We try to realize such a metastable SUSY breaking vacuum by conformal dynamics. We start with a superpotential without R-symmetry. However, we assume the conformal dynamics. Because of that, certain couplings are exponentially suppressed. Then, we could realize an R-symmetric superpotential or an approximately R-symmetric superpotential with tiny R-symmetry breaking terms. It would lead to a stable or metastable SUSY breaking vacuum. We study this scenario by using a simple model. Also, we study 5D models, which have the same behavior.

4D CONFORMAL MODEL

Our model is the $SU(N)$ gauge theory with $N_f$ flavors of chiral matter fields $\phi_i$ and $\tilde{\phi}_i$, which are fundamental and anti-fundamental representations of $SU(N)$. The flavor number satisfies $N_f \geq \frac{2}{3}N$, and that corresponds to the conformal window [15, 16], that is, this theory has an IR fixed point [17]. The NSVZ beta-function of physical gauge coupling $\alpha = g^2/8\pi^2$ is

$$\beta_{\alpha}^{\text{NSVZ}} = -\frac{\alpha^2}{1-N\alpha}(3N-N_f+N_f/\gamma_f), \quad (1)$$

where $\gamma_f$ is the anomalous dimension of $\phi_i$ and $\tilde{\phi}_i$ [18, 19]. Since the IR fixed point corresponds to $\beta_{\alpha}^{\text{NSVZ}} = 0$, around that point the matter fields $\phi_i$ and $\tilde{\phi}_i$ have anomalous dimensions $\gamma_f = -(3N-N_f)/N_f$, which are negative.

In addition to the fields $\phi_i$ and $\tilde{\phi}_i$, we introduce singlet fields $\Phi_{ij}$ for $i, j = 1, \cdots, N_f$. The gauge invariance allows the following superpotential at the renormalizable
level,

\[ W = h \phi_i \Phi_j \tilde{\phi}_j + f Tr_{i j} \Phi_{i j} + \frac{m}{2} Tr_{i k} \Phi_{i j} \Phi_{j k} + \frac{\lambda}{3} Tr_{i j} \Phi_{i j} \Phi_{j k} \Phi_{k l}. \]  

(2)

Here we have preserved the SU(N_f) flavor symmetry. Even if the SU(N_f) flavor symmetry is broken, e.g. by replacing \( f Tr_{i j} \Phi_{i j} \) by \( f_i j \Phi_{i j} \), the following discussions would be valid. For simplicity, we assume that all of couplings, \( h, f, m, \lambda \), are real, although the following discussions are available for the model with complex parameters, \( h, f, m \) and \( \lambda \). We assume that the mass terms of \( \phi_i \) and \( \tilde{\phi}_j \) vanish.

If \( m = \lambda = 0 \), the above superpotential corresponds to the superpotential of the Intriligator-Seiberg-Shih (ISS) model [20]. We consider that our theory is an effective theory with the cutoff \( \Lambda \). We assume that dimensionless parameters \( h \) and \( \lambda \) are of \( O(1) \) and dimensionful parameters \( f \) and \( m \) satisfy \( f \approx m^2 \) and \( m \ll \Lambda \). We denote physical couplings as \( \hat{h} = (Z_0 Z^T Z_0) \sim h \), \( f_i j = (Z_0 Z^T Z_0)^{-1/2} f_{i j} \), \( \tilde{m} = (Z_0 Z^T Z_0)^{-1} m \) and \( \hat{\lambda} = (Z_0 Z^T Z_0)^{-3/2} \lambda \), where \( Z_0, Z_*, Z_0 \) are wavefunction renormalization constants for \( \phi_i, \tilde{\phi}_j, \Phi \), respectively.

First, we study the behavior of this model around the energy scale \( \Lambda \). The F-flat conditions are obtained as

\[ \partial \Phi_i W = h \phi_i \tilde{\phi}_j + f \delta_{i j} + m \Phi_{i j} + \lambda \Phi_{j k} \Phi_{k l} = 0, \]

\[ \partial \phi_i W = h \phi_i \tilde{\phi}_j = 0, \]

\[ \partial \tilde{\phi}_i W = h \phi_i \Phi_i = 0. \]

These equations have a supersymmetric solution for generic values of parameters, \( h, m, \lambda \). We decompose \( \phi, \tilde{\phi} \) and \( \Phi \) as

\[ \Phi = \begin{pmatrix} Y & Z^T & X \end{pmatrix}, \quad \phi = \begin{pmatrix} \chi \\ \rho \end{pmatrix}, \quad \tilde{\phi}^T = \begin{pmatrix} \tilde{\chi} \\ \tilde{\rho} \end{pmatrix}, \]

where \( Y, \chi, \tilde{\chi} \) are \( N \times N \) matrices, \( X \) is an \( (N_f - N) \times (N_f - N) \) matrix, \( Z, \tilde{\rho} \) and \( \tilde{\rho} \) are \( (N_f - N) \times N \) matrices. Let us consider the slice with \( Z = \tilde{Z} = \rho = 0 \), and we find a supersymmetric solution,

\[ x_s = -m \pm \sqrt{m^2 - 4 f \lambda} \frac{1}{2 \lambda}, \]

(7)

and

\[ f \delta_{i j} + h \chi_i \tilde{\chi}_j = 0, \quad Y_{i j} = 0, \]

(8)

where \( x_s \) is defined as \( X_{i j} = x_s \delta_{i j} \). In addition, the D-flat conditions correspond to \( |\chi_i| = |\tilde{\chi}_j| \).

Now let us study the behavior around the IR region. We assume that the gauge coupling is around the IR fixed point, i.e., \( \beta_{\alpha} \approx 0 \), and that \( \phi_i \) and \( \tilde{\phi}_j \) have negative anomalous dimensions \( \gamma_0 \). In addition, we assume that the physical Yukawa coupling \( \hat{h} \) is driven toward IR fixed points. The beta-function of \( \hat{h} \) is obtained as

\[ \beta_{\hat{h}} = \hat{h}(\gamma_0 + \gamma_0 + \gamma_0). \]

(9)

The condition of the fixed point leads to \( 2 \gamma_0 + \gamma_0 = 0 \). Since \( \gamma_0 < 0 \), we obtain a positive anomalous dimension for \( \Phi_{i j} \). Then, physical couplings, \( f, \tilde{m} \) and \( \hat{\lambda} \), are suppressed exponentially toward the IR direction as

\[ \hat{f}(\mu) = (\frac{\mu}{\Lambda})^{2 \gamma_0} \hat{f}(\Lambda), \quad \tilde{m}(\mu) = (\frac{\mu}{\Lambda})^{3 \gamma_0} \tilde{m}(\Lambda), \]

\[ \hat{\lambda}(\mu) = (\frac{\mu}{\Lambda})^{3 \gamma_0} \hat{\lambda}(\Lambda). \]

(10)

Thus, the mass parameter \( \tilde{m} \) and 3-point coupling \( \hat{\lambda} \) are suppressed faster than \( \hat{f} \). If we neglect \( \tilde{m} \) and \( \hat{\lambda} \) but not \( \hat{f} \), the above superpotential becomes the superpotential of the ISS model, and there is a SUSY breaking minimum around \( \Phi_{i j} = 0 \) because of the rank condition. We consider the overall direction, \( x_i = x_i \delta_{i j} \), and we use the canonically normalized basis, \( \hat{x} \). We add the mass term \( m^2 |\hat{\chi}|^2 \) in the one-loop effective potential and analyze the potential, \( V = V_{\text{SUSY}} + m^2 |\hat{\chi}|^2 \) around \( \hat{x} \).

Eventually, at a high energy scale corresponding to \( \tilde{z}_0 = O(1) \), we have \( |\hat{f}|, |\hat{m}|^2 \gg m^2 \), because \( m^2 \) is smaller than \( \hat{f} \) by a loop factor. The potential and the stationary condition are controlled by \( |\hat{f}|, |\hat{m}|^2, \hat{\lambda} \), but not \( m_\chi \). Thus, there is no (SUSY breaking) minimum around \( \hat{x} = 0 \), but we have a supersymmetric minimum (7). However, toward the IR direction, \( \tilde{m}^2 \) becomes suppressed faster than \( m^2 \). Then, the couplings \( \hat{f} \) and \( m^2 \) are important in the potential so that we find a metastable SUSY breaking vacuum around \( \hat{x} \),

\[ \hat{x}_0 = \frac{\hat{f} \hat{m}^2}{m^2}. \]

(11)

Both breaking scales of the SU(N) gauge symmetry and supersymmetry at the metastable SUSY breaking point \( \hat{x}_0 = 0 \) are determined by \( O(\hat{f}(\mu)) \). Thus, such an energy scale is estimated as \( \mu_{IR} \sim \hat{f}(\mu_{IR}) \), i.e.

\[ \mu_{IR} \sim \left( \frac{\hat{f}(\Lambda)}{\Lambda^{2 \gamma_0}} \right)^{1/(2-\gamma_0)}, \]

(12)

and at this energy scale conformal renormalization group flow is terminated.

So far, we have assumed that the mass term of \( \phi_i \) and \( \tilde{\phi}_j \), \( m_\phi \phi_i \phi_j \), vanishes. Here, we comment on the case with such terms. The physical mass \( \tilde{m}_\phi \) becomes enhanced as

\[ \tilde{m}_\phi(\mu) = \left( \frac{\mu}{\Lambda} \right)^{2 \gamma_0} \tilde{m}_\phi(\Lambda), \]

(13)

because of the negative anomalous dimension \( \gamma_0 \). At \( \mu \sim \tilde{m}_\phi(\mu) \), the matter fields \( \phi_i, \tilde{\phi}_j \) decouple and this
theory removes away from the conformal window. Thus, if $\hat{m}_\phi(\mu) > \mu R$, the conformal renormalization group flow is terminated at $\mu_D \approx \hat{m}_\phi(\mu_D) = (\mu_D/\Lambda)^{2\hat{c}_m}(\Lambda)\hat{c}_m(\Lambda)\hat{c}_m(\Lambda)$.

We have studied the scenario that conformal dynamics leads to metastable SUSY breaking vacua. As an illustrating example of our idea, we have used the simple model. Our scenario could be realized by other models.

5D MODEL

There would be an AdS dual to our conformal scenario. Indeed, we can construct simply various models within the framework of 5D orbifold theory. Renormalization group flows in the 4D theory correspond to exponential profiles of zero modes like $e^{-c_i R y}$, where $R$ is the radius of the fifth dimension, $y$ is the coordinate for the extra dimension, i.e. $y = [0, \pi]$ and $c_i$ is a constant. The parameter $c_i$ corresponds to anomalous dimension in the 4D theory, and each field would have a different constant $c_i$. In 4D theory, values of anomalous dimensions are constrained by concrete 4D dynamics. However, constants $c_i$ do not have such strong constraints, although they would correspond to some charges. Hence, 5D models would have a rich structure and one could make model building rather simply. In Ref. [1], we show a simple 5D model compactified on $S^1/Z_2$.

CONCLUSION AND DISCUSSION

We have studied the scenario that conformal dynamics leads to approximately R-symmetric superpotential with a metastable SUSY breaking vacuum. We have shown a simple model to realize our scenario. At a high energy scale, there would be only SUSY minimum and at low energy metastable SUSY breaking vacuum would appear.

We can make 5D models with the same behavior. Since in our 4D scenario, metastable SUSY breaking vacua are realized by conformal dynamics, such a SUSY breaking source would be sequestered from the visible sector by conformal dynamics.

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3 We assume that the radion is stabilized.