SUSY Breaking at the Tip of Throat and Mirage Mediation

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We discuss some features of supersymmetry breaking induced by a brane-localized source which is stabilized at the IR end of warped throat, and also the resulting mirage mediation pattern of soft terms of the visible fields which are localized in the bulk space corresponding to the UV end of throat. Such supersymmetry breaking scheme can be naturally realized in KKLT-type string compactification, and predicts highly distinctive pattern of low energy superparticle masses which might be tested at the LHC.

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1. Introduction

Low energy supersymmetry (SUSY) [1] is one of the prime candidates for physics beyond the standard model at the TeV scale which will be probed soon at the LHC. One key question on low energy SUSY is the origin of soft SUSY breaking terms of the visible gauge/matter superfields in low energy effective lagrangian. Most phenomenological aspects of low energy SUSY are determined by those soft terms which would be induced by the auxiliary components of some messenger superfields [2]. To identify the dominant source of soft terms and determine low energy superparticle masses, one needs to compute the relative ratios between the auxiliary components of different messenger fields. This requires an understanding of how the messenger fields are stabilized at a phenomenologically viable vacuum.

In string theory, moduli fields (including the string dilaton) are plausible candidates for the messenger of SUSY breaking [3]. In addition to moduli fields, the 4-dimensional supergravity (SUGRA) multiplet provides a model-independent source of SUSY breaking called anomaly mediation [4], which is most conveniently described by the 4D SUGRA compensator. Recent KKLT construction [5] of de Sitter (dS) vacuum possibly stabilizing all moduli in Type IIB string theory has led to a new pattern of soft terms named "*mirage mediation*" [6, 7]. In KKLT compactification, 4D $N = 1$ SUSY is broken by anti-brane (or any kind of brane providing SUSY-breaking dynamics) stabilized at the IR end of warped throat. On the other hand, the visible sector is favored to be localized around the UV end of throat in order to realize the high scale gauge coupling unification at $M_{GUT} \sim 2 \times 10^{16}$ GeV. It turns out that in such setup the visible sector soft terms are determined dominantly by two comparable contributions [6]: the Kähler moduli mediation and the anomaly mediation. The resulting soft parameters are unified at a mirage messenger scale hierarchically lower than M_{GUT}, leading to *significantly compressed low energy superparticle masses* [7, 8] compared to other mediation schemes such as mSUGRA, gauge mediation and anomaly mediation. Furthermore, under a plausible assumption, mirage mediation provides more concrete predictions on the superparticle masses, which have a good chance to be tested at the LHC if the gluino or squarks are light enough to be copiously produced. In fact, the two key ingredients of mirage mediation, i.e. (i) brane-localized SUSY breaking at the IR end of warped geometry and (ii) non-perturbative stabilization of the gauge coupling modulus, might be realized in more generic class of string theories or brane models [7]. In this talk, I discuss some features of SUSY breakdown that occurs at the tip of throat as in KKLT-type compactification, and also the low energy superparticle spectrum in the resulting mirage mediation scheme.

2. 4D effective action of KKLT-type compactification

One important feature of KKLT-type compactification [5] is the presence of warped throat which is produced by 3-form fluxes [9]. The compactified internal space consists of a bulk space which might be approximately a Calabi-Yau (CY) manifold, and a highly warped throat attached at CY with SUSY-breaking brane stabilized at its IR end. In such geometry, the bulk CY can be identified as the UV end of throat. To realize the high scale gauge coupling unification, the visible gauge and matter fields are assumed to live on D branes stabilized within the bulk CY.

The 4D effective theory of the KKLT-type compactification of Type IIB string theory includes the UV superfields $\Phi_{UV} = \{T, U, X\}$ and V^a, Q^i, where T and U are the Kähler and complex structure moduli of the bulk CY, V^a and Q^i are the gauge and matter superfields confined on the visible sector D branes, and X denotes the open string moduli on those D branes at the UV side. There are also 4D fields localized at the IR end of throat, $\Phi_{IR} = \{Z, \Lambda^\alpha\}$, where Z is the throat (complex structure) modulus superfield parameterizing the size of 3-cycle at the IR end, and Λ^α is the Goldstino superfield confined on SUSY-breaking brane[1] which might be an anti-brane as in the original KKLT proposal or any kind of brane providing SUSY-breaking dynamics. In the rigid superspace limit, the Goldstino superfield is given by [10]

$$\Lambda^\alpha = \frac{1}{M_{\mathrm{SUSY}}^2}\xi^\alpha + \theta^\alpha + ..., \tag{2.1}$$

where ξ^α is the Goldstino fermion, and the ellipses stand for the Goldstino-dependent higher order terms in the θ-expansion. In addition to the above UV and IR fields, there is of course the 4D SUGRA multiplet which is quasi-localized in the bulk CY, and also the string dilaton superfield S whose wavefunction is approximately a constant over the whole internal space.

The 4D effective action of KKLT-type compactification takes the form:

$$\int d^4x \sqrt{g}\left[\int d^4\theta\, CC^* \left\{-3\exp\left(-\frac{K}{3}\right)\right\}\right.$$
$$\left.+ \left\{\int d^2\theta \left(\frac{1}{4}f_a W^{a\alpha}W_\alpha^a + C^3 W\right) + \mathrm{h.c}\right\}\right] \tag{2.2}$$

where $g_{\mu\nu}$ is the 4D metric in the superconformal frame, $C = C_0 + F^C\theta^2$ is the 4D SUGRA compensator, K is the Kähler potential, and $f_a = T + lS$ ($l =$ rational number) are holomorphic gauge kinetic functions which are assumed to be universal to accommodate the high scale gauge coupling unification[2]. The UV and IR fields are geometrically separated by warped throat, thus are *sequestered* from each other in $e^{-K/3}$:

$$-3\exp\left(-\frac{K}{3}\right) = \Gamma_{UV} + \Gamma_{IR}, \tag{2.3}$$

where

$$\Gamma_{UV} = \Gamma_{UV}^{(0)}(S+S^*, \Phi_{UV}, \Phi_{UV}^*) + \mathscr{Y}_i(S+S^*, \Phi_{UV}, \Phi_{UV}^*)Q^{i*}Q^i,$$
$$\Gamma_{IR} = \Gamma_{IR}^{(0)}(S+S^*, Z, Z^*) + \left(\frac{C^{*2}}{C}\Lambda^2\Gamma_{IR}^{(1)}(S+S^*, Z, Z^*) + \mathrm{h.c}\right)$$
$$+ CC^*\Lambda^2\Lambda^{*2}\Gamma_{IR}^{(2)}(S, S^*, Z, Z^*) + ..., \tag{2.4}$$

where $\Phi_{UV} = \{T, U, X\}$, and Γ_{IR} is expanded in powers of the Goldstino superfield Λ^α and the superspace derivatives $D_A = \{\partial_\mu, D_\alpha, \bar{D}_{\dot\alpha}\}$. The above effective action is written on flat superspace background and the SUSY-breaking auxiliary component of the 4D SUGRA multiplet is encoded

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[1]There can be other IR fields, e.g. the position moduli and gauge fields confined on SUSY-breaking brane. Those IR fields are not considered here as they do not play an important role for the transmission of SUSY breakdown.

[2]Here $\partial f_a/\partial T = 1$ can be considered as our normalization convention of T.

in the F-component of the compensator C. In the superconformal gauge in which $C = C_0 + F^C \theta^2$, the 4D action is invariant under the rigid Weyl transformation under which

$$C \to e^{-2\sigma}C, \quad g_{\mu\nu}^C \to e^{2(\sigma+\sigma^*)}g_{\mu\nu}^C, \quad \theta^\alpha \to e^{-\sigma+2\sigma^*}\theta^\alpha, \quad \Lambda^\alpha \to e^{-\sigma+2\sigma^*}\Lambda^\alpha, \qquad (2.5)$$

where σ is a complex constant, and this determines for instance the C-dependence of Γ_{IR}.

The effective superpotential of KKLT compactification contains three pieces:

$$W = W_{\text{flux}} + W_{\text{np}} + W_{\text{Yukawa}}, \qquad (2.6)$$

where the flux-induced W_{flux} stabilizing S, U, Z, X includes the Gukov-Vafa-Witten superpotential $W_{GVW} = \int (F_3 - 4\pi i S H_3) \wedge \Omega$, where Ω is the holomorphic $(3,0)$ form of the underlying CY space, W_{np} is a non-perturbative superpotential stabilizing T, and finally W_{Yukawa} denotes the Yukawa couplings of the visible matter fields. Generically, each piece takes the form:

$$\begin{aligned}
W_{\text{flux}} &= \left(\mathscr{F}(U,X) + \frac{N_{RR}}{2\pi i} Z \ln Z + \mathscr{O}(Z^2) \right) \\
&\quad - 4\pi i S \left(\mathscr{H}(U,X) + N_{NS} Z + \mathscr{O}(Z^2) \right), \\
W_{\text{np}} &= \mathscr{A}(U,X) e^{-8\pi^2(k_1 T + l_1 S)}, \\
W_{\text{Yukawa}} &= \frac{1}{6} \lambda_{ijk}(U,X) Q^i Q^j Q^k,
\end{aligned} \qquad (2.7)$$

where k_1, l_1 are rational numbers, N_{RR}, N_{NS} are integers defined as $N_{RR} = \int_\Sigma F_3, N_{NS} = -\int_{\tilde{\Sigma}} H_3$, where Σ is the 3-cycle collapsing along the throat, $\tilde{\Sigma}$ is its dual 3-cycle, and F_3 and H_3 are the RR and NS-NS 3-forms, respectively. Here Z is defined as $\int_\Sigma \Omega = Z$, and then $\int_{\tilde{\Sigma}} \Omega = \frac{1}{2\pi i} Z \ln Z +$ holomorphic [9]. In the above, we assumed that the axionic shift symmetry of T, i.e. $T \to T +$ imaginary constant, is preserved by W_{flux} and W_{Yukawa}, while it is broken by W_{np}. To achieve an exponentially small vacuum value of Z, which corresponds to producing a highly warped throat, one needs N_{RR}/N_{NS} to be positive. The exponential suppression of W_{np} in the large volume limit $\text{Re}(T) \gg 1$ implies that k_1 is positive also.

The above 4D effective action of KKLT-type compactification involves many model-dependent functions of moduli, which are difficult to be computed for realistic compactification. Fortunately, the visible sector soft terms can be determined by only a few information on the compactification, e.g. the rational parameters l, k_1, l_1 in f_a and W_{np} and the modular weights which would determine the T-dependence of $\mathscr{Y}_i$, which can be easily computed or parameterized in a simple manner. In particular, soft terms are *practically independent* of the detailed forms of $\Gamma_{UV}^{(0)}, \Gamma_{IR}, \mathscr{F}, \mathscr{H}, \mathscr{A}$ and λ_{ijk}. This is mainly because (i) the heavy moduli $\Phi = \{S, U, X\}$ stabilized by flux have negligible F-components, $F^\Phi/\Phi \sim m_{3/2}^2/m_\Phi \ll m_{3/2}/8\pi^2$, thus do not participate in SUSY-breaking, and (ii) the SUSY-breaking IR fields Z and Λ^α are sequestered from the observable sector.

The vacuum value of Z is determined by W_{flux}, and related to the metric warp factor e^{2A} at the tip of throat as

$$Z \sim \exp\left(-8\pi^2 N_{RR} S_0 / N_{NS} \right) \sim e^{3A}, \qquad (2.8)$$

where S_0 is the vacuum value of S determined by $D_S W = 0$. Since the scalar component of CC^* corresponds to the conformal factor of $g^{\mu\nu}$, which can be read off from the Weyl transformation

(2.5), C in Γ_{IR} should appear in the combination $Ce^A \sim CZ^{1/3}$. Then the C-dependence determined by the Weyl invariance (2.5) suggests [11] that

$$
\begin{aligned}
\Gamma_{IR}^{(0)} &\sim (ZZ^*)^{1/3} \sim e^{2A}, \\
\Gamma_{IR}^{(1)} &\sim Z \sim e^{3A}, \\
\Gamma_{IR}^{(2)} &\sim (ZZ^*)^{2/3} \sim e^{4A}
\end{aligned}
\tag{2.9}
$$

for which

$$
m_Z \sim \frac{F^Z}{Z} \sim e^A
\tag{2.10}
$$

as anticipated. Here and in the following, unless specified, we use the unit with the 4D Planck scale $M_{Pl} = 1/\sqrt{8\pi G_N} = 1$.

The SUSY breaking at the tip of throat provides a positive vacuum energy density of the order of $M_{\text{SUSY}}^4 \sim e^{4A}$. This positive vacuum energy density should be cancelled by the negative SUGRA contribution of the order of $m_{3/2}^2$, which requires

$$
m_{3/2} \sim e^{2A}.
\tag{2.11}
$$

One then finds the following pattern of mass scales [6]:

$$
\begin{aligned}
m_{S,U,X} &\sim \frac{1}{M_{st}^2 R^3} \sim 10^{16}\,\text{GeV}, \\
m_Z &\sim e^A M_{st} \sim 10^{10}\,\text{GeV}, \\
m_{\text{soft}} &\sim \frac{m_{3/2}}{\ln(M_{Pl}/m_{3/2})} \sim \frac{m_T}{[\ln(M_{Pl}/m_{3/2})]^2} \sim 10^3\,\text{GeV},
\end{aligned}
\tag{2.12}
$$

where m_{soft} denotes the soft masses of the visible fields, e.g. the gaugino masses, and the string scale M_{st} and the CY radius R are given by $M_{st} \sim \frac{1}{R} \sim 10^{17}$ GeV.

The heavy moduli S, U, X and the throat modulus Z couple to the light visible fields and T only through the Planck scale suppressed interactions. Those hidden sector fields can be integrated out to derive an effective action of V^a, Q^i, T and the Goldstino superfield Λ^α renormalized at a high scale near M_{GUT}. After this procedure, the effective action can be written as [6, 7]

$$
\int d^4x \sqrt{g} \left[\int d^4\theta\, CC^* \Omega_{\text{eff}} + \left\{ \int d^2\theta \left(\frac{1}{4} f_a^{\text{eff}} W^{a\alpha} W_\alpha^a + C^3 W_{\text{eff}} \right) + \text{h.c} \right\} \right],
\tag{2.13}
$$

where

$$
\begin{aligned}
f_a^{\text{eff}} &= T + l S_0, \\
\Omega_{\text{eff}} &= -3e^{-K_0/3} + \mathscr{Y}_i Q^{i*} Q^i - e^{4A} CC^* \Lambda^2 \bar{\Lambda}^2 \mathscr{P}_{\text{lift}} \\
&\quad - \left(\frac{e^{3A} C^{*2}}{C} \Lambda^2 \Gamma_0 + \text{h.c} \right), \\
W_{\text{eff}} &= w_0 + \mathscr{A} e^{-8\pi^2(k_1 T + l_1 S_0)} + \frac{1}{6} \lambda_{ijk} Q^i Q^j Q^k,
\end{aligned}
\tag{2.14}
$$

where $S_0 = \langle S \rangle$, $K_0 = K_0(T + T^*)$ is the Kähler potential of T, $e^{K_0/3} \mathscr{Y}_i$ is the Kähler metric of Q^i, $\mathscr{P}_{\text{lift}}$ and Γ_0 are constants of order unity, and finally w_0 is the vacuum value of W_{flux}. Note that

at this stage, all of $e^{2A}, \mathscr{P}_{\text{lift}}, \Gamma_0, S_0, w_0$, and $\mathscr{A}$ correspond to field-independent constants obtained after S, U, X and Z are integrated out. As we have noticed, the condition for vanishing cosmological constant requires

$$w_0 \sim e^{2A} \sim e^{-8\pi^2 l_0 S_0} \qquad \left(l_0 = \frac{2N_{RR}}{3N_{NS}} > 0\right), \tag{2.15}$$

and the weak scale SUSY can be obtained for the warp factor value $e^{2A} \sim 10^{-14}$. For such a small value of warp factor, one finds that the vacuum values of $\text{Re}(T)$ and the SUSY-breaking auxiliary components are determined as follows *independently of* the moduli Kähler potential K_0 [6, 7]:

$$
\begin{aligned}
k_1 \text{Re}(T) &= (l_0 - l_1)\text{Re}(S_0) + \mathscr{O}\left(\frac{1}{4\pi^2}\right) \\
\frac{F^C}{C} &= m_{3/2}\left(1 + \mathscr{O}\left(\frac{1}{4\pi^2}\right)\right), \\
\frac{F^T}{T + T^*} &= \frac{l_0}{l_0 - l_1} \frac{m_{3/2}}{\ln(M_{Pl}/m_{3/2})}\left(1 + \mathscr{O}\left(\frac{1}{4\pi^2}\right)\right), \\
F^{S,U,X} &\sim \frac{m_{3/2}^2}{m_{S,U,X}} \ll \frac{m_{3/2}}{8\pi^2}.
\end{aligned}
\tag{2.16}
$$

Note that $\text{Re}(S_0)$, $\text{Re}(T)$ and $\frac{1}{g_{GUT}^2} = \text{Re}(T) + l\text{Re}(S_0)$ are all required to be positive for $k_1 > 0$ and $l_0 > 0$, implying

$$l_0 - l_1 > 0, \quad l_0 - l_1 + k_1 l > 0. \tag{2.17}$$

One of the interesting features of SUSY breaking at the IR end of throat is the *sequestering* property, i.e. there is no sizable Goldstino-matter contact term:

$$\Delta m_i^2 CC^* \Lambda^2 \bar{\Lambda}^2 Q^{i*} Q^i \tag{2.18}$$

in Ω_{eff} of (2.13), which would give an additional contribution Δm_i^2 to the soft scalar mass-squares. This amounts to that there is no operator of the form $(ZZ^*)^{1/3} Q^{i*} Q^i$ or $(ZZ^*)^{2/3} \Lambda^2 \bar{\Lambda}^2 Q^{i*} Q^i$ in $e^{-K/3}$ of (2.2). Since Q^i and Λ^α are geometrically separated by warped throat, such contact term can be generated only by the exchange of bulk field propagating through the throat. Simple operator analysis assures that the exchange of chiral multiplet can induce only a higher order operator in the superspace derivative expansion, while the exchange of light vector multiplet $\tilde{V}$ can generate the Goldstino-matter contact term with $\Delta m_i^2 \sim \langle D_{\tilde{V}} \rangle$, where $D_{\tilde{V}}$ is the D-component of $\tilde{V}$ [12, 13]. Quite often, throat has an isometry symmetry providing light vector field which might generate the Goldtino-matter contact term. However, in many cases, the isometry vector multiplet does not develop a nonzero D-component, and thereby not generate the contact term [12, 14]. As an example, let us consider the SUSY breaking by anti-$D3$ brane stabilized at the tip of Klebanov-Strassler (KS) throat which has an $SO(4)$ isometry [15]. Adding anti-$D3$ at the tip breaks SUSY and also $SO(4)$ down to $SO(3)$. However the unbroken $SO(3)$ assures that the $SO(4)$ vector multiplets have vanishing D-components, thus do not induce the Goldstino-matter contact term. In fact, this is correct only up to ignoring the isometry-breaking deformation of KS throat, which is caused by

attaching the throat to compact CY. Recently, the effect of such deformation has been estimated [14], which found

$$\Delta m_i^2 \lesssim \mathcal{O}(e^{\sqrt{28}A}) \sim 10^{-8} m_{3/2}^2. \tag{2.19}$$

This is small enough to be ignored compared to the effects of F^C and F^T obtained in (2.16).

3. Mirage mediation pattern of soft terms

The result (2.16) on SUSY-breaking F-components indicates that $F^T/T \sim m_{3/2}/4\pi^2 \gg |F^\Phi|$ ($\Phi = S, U, X$), and thus soft terms are determined dominantly by the Kähler moduli-mediated contribution and the one-loop anomaly mediated contribution which are comparable to each other. For the canonically normalized soft terms:

$$\mathcal{L}_{\text{soft}} = -\frac{1}{2} M_a \lambda^a \lambda^a - \frac{1}{2} m_i^2 |\phi^i|^2 - \frac{1}{6} A_{ijk} y_{ijk} \phi^i \phi^j \phi^k + \text{h.c.}, \tag{3.1}$$

where λ^a are gauginos, ϕ^i are sfermions, y_{ijk} are the canonically normalized Yukawa couplings, the soft parameters at energy scale just below M_{GUT} are given by

$$
\begin{aligned}
M_a &= M_0 + \frac{b_a}{16\pi^2} g_{GUT}^2 m_{3/2}, \\
A_{ijk} &= \tilde{A}_{ijk} - \frac{1}{16\pi^2} (\gamma_i + \gamma_j + \gamma_k) m_{3/2}, \\
m_i^2 &= \tilde{m}_i^2 - \frac{1}{32\pi^2} \frac{d\gamma_i}{d\ln\mu} m_{3/2}^2 \\
&\quad + \frac{1}{4\pi^2} \left[\sum_{jk} \frac{1}{4} |y_{ijk}|^2 \tilde{A}_{ijk} - \sum_a g_a^2 C_2^a(\phi^i) M_0 \right] m_{3/2},
\end{aligned}
\tag{3.2}
$$

where the moduli-mediated soft masses M_0, $\tilde{A}_{ijk}$ and $\tilde{m}_i^2$ are given by

$$
\begin{aligned}
M_0 &= F^T \partial_T \ln(\text{Re}(f_a)) \\
&= \frac{F^T}{T + T^*} \frac{\text{Re}(T)}{\text{Re}(T) + l\text{Re}(S_0)} \simeq \frac{F^T}{T + T^*} \left(\frac{l_0 - l_1}{l_0 - l_1 + k_1 l} \right), \\
\tilde{A}_{ijk} &= F^T \partial_T \ln(\mathscr{Y}_i \mathscr{Y}_j \mathscr{Y}_k), \\
\tilde{m}_i^2 &= -|F^T|^2 \partial_T \partial_{\bar{T}} \ln(\mathscr{Y}_i),
\end{aligned}
\tag{3.3}
$$

and $b_a = -3\text{tr}\left(T_a^2(\text{Adj})\right) + \sum_i \text{tr}\left(T_a^2(\phi^i)\right)$, $\gamma_i = 2\sum_a g_a^2 C_2^a(\phi^i) - \frac{1}{2}\sum_{jk} |y_{ijk}|^2$, where $C_2^a(\phi^i) = (N^2 - 1)/2N$ for a fundamental representation ϕ^i of the gauge group $SU(N)$, $C_2^a(\phi^i) = q_i^2$ for the $U(1)$ charge q_i of ϕ^i, and $\omega_{ij} = \sum_{kl} y_{ikl} y_{jkl}^*$ is assumed to be diagonal.

Taking into account the 1-loop RG evolution, the above soft masses at M_{GUT} lead to the following low energy gaugino masses

$$M_a(\mu) = M_0 \left[1 - \frac{1}{8\pi^2} b_a g_a^2(\mu) \ln\left(\frac{M_{\text{mir}}}{\mu}\right) \right], \tag{3.4}$$

showing that the gaugino masses are unified at the *mirage messsenger scale* [7]:

$$M_{\text{mir}} = \frac{M_{GUT}}{(M_{Pl}/m_{3/2})^{\alpha/2}},$$ (3.5)

where

$$\alpha \equiv \frac{m_{3/2}}{M_0 \ln(M_{Pl}/m_{3/2})} = \frac{l_0 - l_1 + k_1 l}{l_0} \left(1 + \mathcal{O}\left(\frac{1}{4\pi^2}\right)\right),$$ (3.6)

while the gauge couplings are still unified at $M_{GUT} = 2 \times 10^{16}$ GeV. The low energy values of A_{ijk} and m_i^2 generically depend on the associated Yukawa couplings y_{ijk}. However if y_{ijk} are negligible or if $\tilde{A}_{ijk}/M_0 = (\tilde{m}_i^2 + \tilde{m}_j^2 + \tilde{m}_k^2)/M_0^2 = 1$, their low energy values also show the mirage unification feature [7]:

$$A_{ijk}(\mu) = \tilde{A}_{ijk} + \frac{M_0}{8\pi^2}(\gamma_i(\mu) + \gamma_j(\mu) + \gamma_k(\mu)) \ln\left(\frac{M_{\text{mir}}}{\mu}\right),$$

$$m_i^2(\mu) = \tilde{m}_i^2 - \frac{M_0^2}{8\pi^2} Y_i \left(\sum_j c_j Y_j\right) g_Y^2(\mu) \ln\left(\frac{M_{GUT}}{\mu}\right)$$

$$+ \frac{M_0^2}{4\pi^2} \left\{\gamma_i(\mu) - \frac{1}{2}\frac{d\gamma_i(\mu)}{d\ln\mu} \ln\left(\frac{M_{\text{mir}}}{\mu}\right)\right\} \ln\left(\frac{M_{\text{mir}}}{\mu}\right),$$ (3.7)

where Y_i is the $U(1)_Y$ charge of ϕ^i. Quite often, the moduli-mediated squark and slepton masses have a common value, i.e. $\tilde{m}_{\tilde{Q}}^2 = \tilde{m}_{\tilde{L}}^2$, and then the squark and slepton masses of the 1st and 2nd generation are unified again at M_{mir}.

In regard to phenomenology, the most interesting feature of mirage mediation is that it gives rise to *significantly compressed low energy SUSY spectrum* compared to other popular schemes such as mSUGRA, gauge mediation and anomaly mediation. This feature can be easily understood by noting that soft parameters are unified at $M_{\text{mir}} = M_{GUT}(m_{3/2}/M_{Pl})^{\alpha/2}$ which is hierarchically lower than M_{GUT} if α has a positive value of order unity. Indeed, the result (3.6) shows that α is (approximately) a positive rational number for the rational numbers k_1, l, l_0, l_1 obeying the constraints (2.17). Another, but related, interesting feature of mirage mediation is that the little SUSY fine tuning problem of the MSSM can be significantly ameliorated in TeV scale mirage mediation scenario with $M_{\text{mir}} \sim 1$ TeV, i.e. $\alpha \simeq 2$ [7, 16].

In fact, mirage mediation provides more concrete prediction under a rather plausible assumption. Assuming that f_a are (approximately) universal, which might be required to realize the gauge coupling unification at M_{GUT}, the low scale gaugino masses at the RG point $\mu \sim 500$ GeV are given by

$$M_1 \simeq M_0(0.42 + 0.28\alpha),$$
$$M_2 \simeq M_0(0.83 + 0.085\alpha),$$
$$M_3 \simeq M_0(2.5 - 0.76\alpha),$$ (3.8)

leading to [17]

$$M_1 : M_2 : M_3 \simeq (1 + 0.66\alpha) : (2 + 0.2\alpha) : (6 - 1.8\alpha).$$ (3.9)

The low scale masses of the 1st and 2nd generations of squarks and sleptons are also easily obtained to be

$$
\begin{aligned}
m_{\tilde{Q}}^2 &\simeq \tilde{m}_{\tilde{Q}}^2 + M_0^2(5.0 - 3.6\alpha + 0.51\alpha^2), \\
m_{\tilde{D}}^2 &\simeq \tilde{m}_{\tilde{D}}^2 + M_0^2(4.5 - 3.3\alpha + 0.52\alpha^2), \\
m_{\tilde{L}}^2 &\simeq \tilde{m}_{\tilde{L}}^2 + M_0^2(0.49 - 0.23\alpha - 0.015\alpha^2), \\
m_{\tilde{E}}^2 &\simeq \tilde{m}_{\tilde{E}}^2 + M_0^2(0.15 - 0.046\alpha - 0.016\alpha^2),
\end{aligned}
\tag{3.10}
$$

where $\tilde{Q}, \tilde{D}, \tilde{L}$ and $\tilde{E}$ denote the $SU(2)_L$ doublet squark, singlet up-squark, singlet down-squark, doublet lepton, and singlet lepton, respectively. Assuming that the matter Kähler metrics obey simple unification (or universality) relations such as $\mathscr{Y}_Q = \mathscr{Y}_E$ and $\mathscr{Y}_D = \mathscr{Y}_L$ which would yield $\tilde{m}_{\tilde{Q}}^2 = \tilde{m}_{\tilde{E}}^2$ and $\tilde{m}_{\tilde{D}}^2 = \tilde{m}_{\tilde{L}}^2$, we find

$$
\begin{aligned}
& M_1^2 : (m_{\tilde{Q}}^2 - m_{\tilde{E}}^2) : (m_{\tilde{D}}^2 - m_{\tilde{L}}^2) \\
& \simeq (0.18 + 0.24\alpha + 0.09\alpha^2) : (4.9 - 3.5\alpha + 0.53\alpha^2) : (4.0 - 3.1\alpha + 0.54\alpha^2).
\end{aligned}
\tag{3.11}
$$

Note that these ratios are independent of the presence of extra matter fields at scales above TeV.

If the idea of low energy SUSY is correct and the gluino or squark masses are lighter than 2 TeV, some superparticle masses, e.g. the gluino mass and the first two neutralino masses as well as some of the squark and slepton masses, might be determined at the LHC by analyzing various kinematic invariants of the cascade decays of gluinos and squarks. It is then quite probable that the LHC measurements of those superparticle masses are good enough to test the above predictions of mirage mediation [18].

4. Conclusion

Warped throat appears often in fluxed compactification of string theory. If SUSY-breaking brane carrying a positive energy density is introduced into the compactification geometry containing warped throat, it is naturally stabilized at the tip of throat. On the other hand, the high scale gauge coupling unification at $M_{GUT} \sim 2 \times 10^{16}$ GeV suggests that the visible gauge and matter fields are localized in the bulk space corresponding to the UV end of throat. If (some of) the moduli which determine the 4D gauge couplings were stabilized (before introducing SUSY-breaking brane) by non-perturbative dynamics at a SUSY-preserving configuration as in the KKLT compactification, the SUSY-breaking brane at the tip of throat leads to a highly distinctive pattern of soft terms of the visible fields localized at the UV end of throat. The resulting soft parameters are unified at a mirage messenger scale hierarchically lower than M_{GUT}, while the gauge couplings are unified still at M_{GUT}, leading to the term "mirage mediation". The low energy superparticle masses in mirage mediation are significantly compressed compared to those in mSUGRA, gauge mediation and anomaly mediation. Furthermore, under a plausible assumption, the scheme provides more concrete predictions on the superparticle masses, which might be tested at the LHC.

Acknowledgments

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