Sparticle spectrum and Electroweak Symmetry Breaking of Mixed Modulus-Anomaly Mediation in Fluxed String Compactification Models

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Based on Kiwoon Choi, Kwang-Sik Jeong and K.O., hep-ph/0504037.

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I. Introduction

- Recently KKLT has proposed an interesting set-up in which all the moduli are stabilized by flux and non-perturbative dynamics on branes. SUSY AdS vacuum is up-lifted to dS vacuum by additional SUSY breaking potential. S. Kachru, R. Kallosh, A. Linde and S.P. Trivedi, 2003

- In this class of models, SUSY breaking mediated by F-term of modulus fields are suppressed and comparable to the anomaly mediated contribution. $\longrightarrow$ open up various new phenomenological possibilities.

  K. Choi, A. Falkowski, H.P. Nilles, M. Olechowski and S. Pokorski, 2004

  K. Choi, A. Falkowski, H.P. Nilles, M. Olechowski, 2005.

- In this talk we address new phenomenological features of this mixed modulus-anomaly mediation, focusing on sparticle mass spectrum and electroweak symmetry breaking.

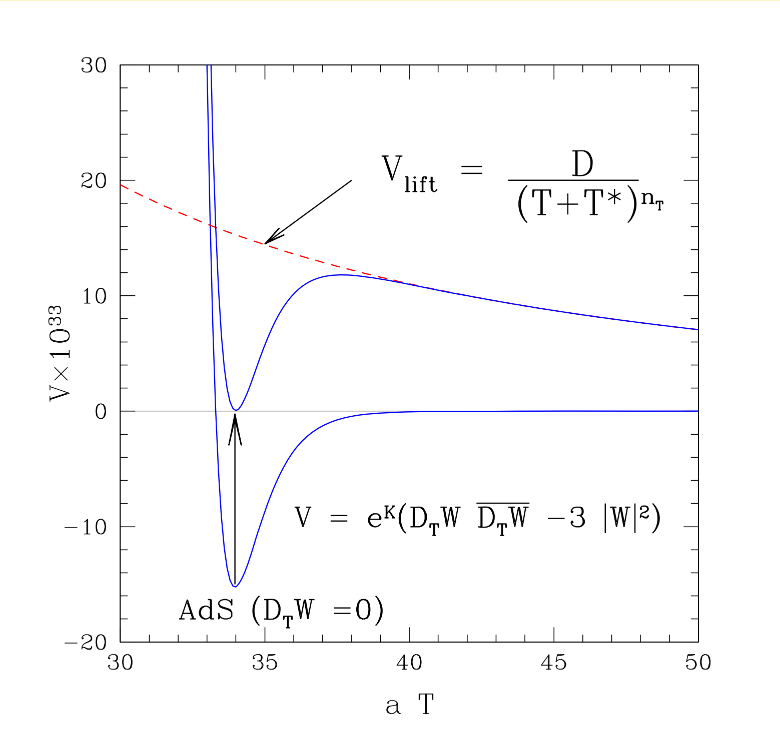
II. KKLT Set-Up

Let us consider Type II B string theory compactified on Calabi-Yau orientifold. KKLT set-up is defined by the following 3 steps.

- Stabilize dilaton S and complex structure moduli Z_i by introducing flux. Kähler moduli are not fixed. $\mathcal{K} = -3\ln(T+T^*)$, $\mathcal{W} = w_0$:no scale

- Stabilize Kähler moduli by nonperturbative dynamics *e.g.* gaugino condensation on $D7$ brane. $\mathcal{W} = w_0 - Ae^{-aT}$

- Uplift AdS vacuum to dS vacuum with additional SUSY breaking potential *e.g.* introducing $\overline{D3}$ brane.



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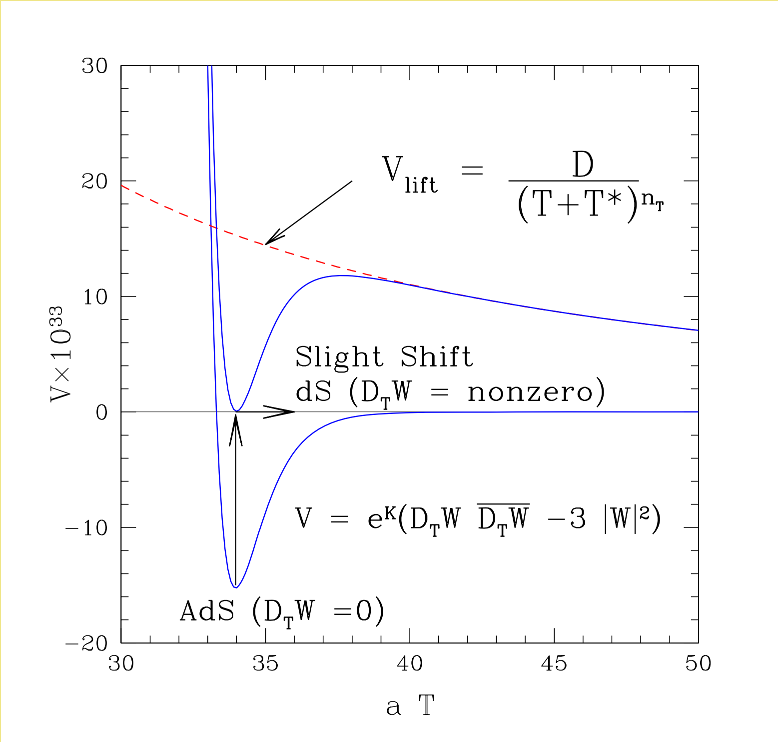


Shift of Kähler modulus T at the minimum of the potential is small
$\rightarrow$ Modulus F-term $(-e^{K/2}K^{TT^*}D_T\mathcal{W}^*\ ) << $ the gravitino mass $(e^{K/2}\mathcal{W})$.

$$M_0 \equiv \frac{F^T}{T+T^*} \approx \frac{n_T}{2aRe(T)} m_{3/2}, \quad \langle aT \rangle \approx \ln\left(\frac{M_{\rm Pl}}{m_{3/2}}\right) \approx 4\pi^2$$

Modulus mediation $\approx$ Anomaly mediation

We parameterize their ratio as,

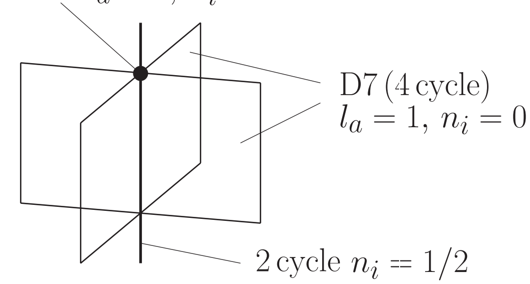
$$\alpha \quad = \quad \frac{m_{3/2}}{\ln\left(M_{\rm Pl}/m_{3/2}\right)} \frac{1}{M_0} \approx \frac{2}{n_T}, \qquad \left(V_{lift} = \frac{D}{(T+T^*)^{n_T}}\right).$$

Original KKLT predicts $\alpha_{KKLT} \approx 1$ (Up-lifting by $\overline{D3}$, $n_T = 2$).
However, in the following, we do not specify the up-lifting mechanism and leave α (or n_T) as a free parameter.

III. Soft Terms in Mixed Modulus-Anomaly Mediation

Gauge k-fn. & Kähler on D3/D7:

$$
\begin{aligned}
f_a &= T^{l_a}, \\
\mathcal{K}_{\rm eff} &= K_0 + \frac{Q_i^* Q_i}{(T+T^*)^{n_i}}
\end{aligned}
$$



L.E. Ibanez, C. Munoz and R. Rigolin Nucl. Phys. **B553**, 43 (1999)

L.E. Ibanez, hep-ph/0408064; B.C. Allanach, A. Brignole and L.E. Ibanez, hep-ph/0502151

$$
\begin{aligned}
M_a &= \overbrace{l_a M_0}^{\text{Modulus Mediation}} + \overbrace{\frac{b_a}{4\pi^2 (T+T^*)} \frac{F^C}{C_0}}^{\text{Anomaly Mediation}}, \qquad \left(\frac{F^C}{C_0} \approx m_{3/2} \right) \\
A_{ijk} &= (3 - n_i - n_j - n_k) M_0 - \frac{1}{16\pi^2} (\gamma_i + \gamma_j + \gamma_k) \frac{F^C}{C_0},
\end{aligned}
$$

$$m_i^2 = \overbrace{(1-n_i)\left|M_0\right|^2}^{\text{Modulus Mediation}} \quad \overbrace{-\frac{1}{32\pi^2}\frac{d\gamma_i}{d\ln\mu}\left|\frac{F^C}{C_0}\right|^2}^{\text{Anomaly Mediation}}$$
$$\underbrace{+\frac{1}{8\pi^2}\left\{T\left(\frac{\partial\gamma_i}{\partial T}\right)M_0\left(\frac{F^C}{C_0}\right)^* + \text{h.c.}\right\}}_{\text{Interference Term}},$$

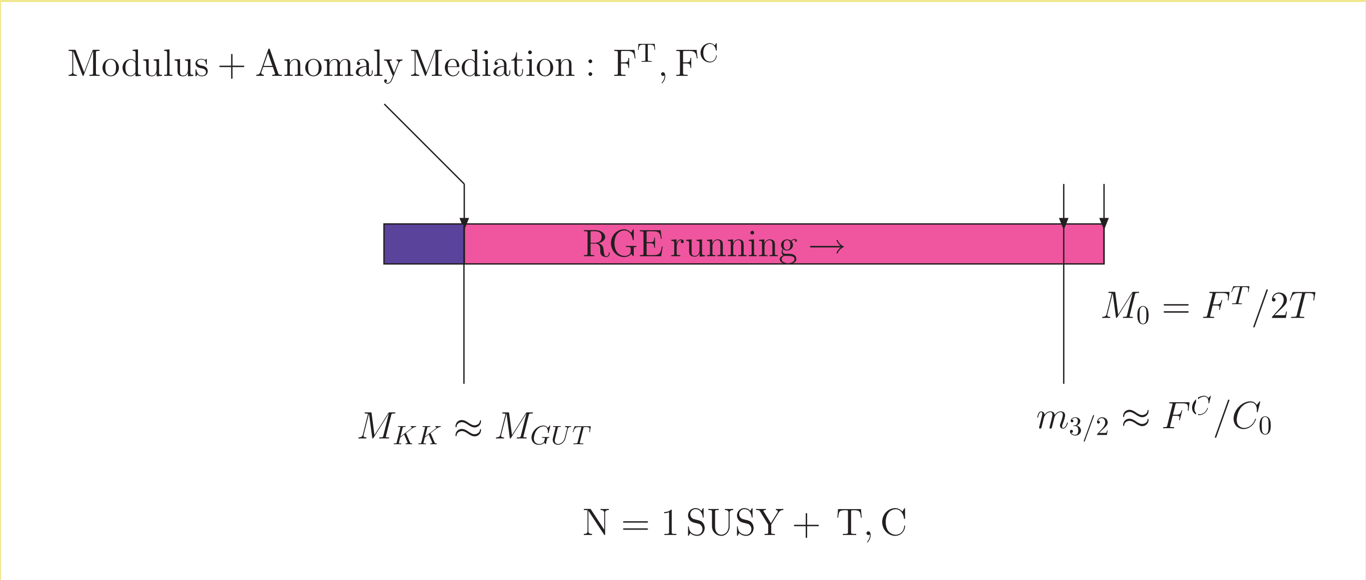
where,

$$T\left(\frac{\partial\gamma_i}{\partial T}\right) = \sum_{jk}(3-n_i-n_j-n_k)\left|\frac{y_{ijk}}{2}\right|^2 - \sum_a l_a T_a(Q_i) g_a^2$$

Interference term arises via modulus dependence of anomalous dim.

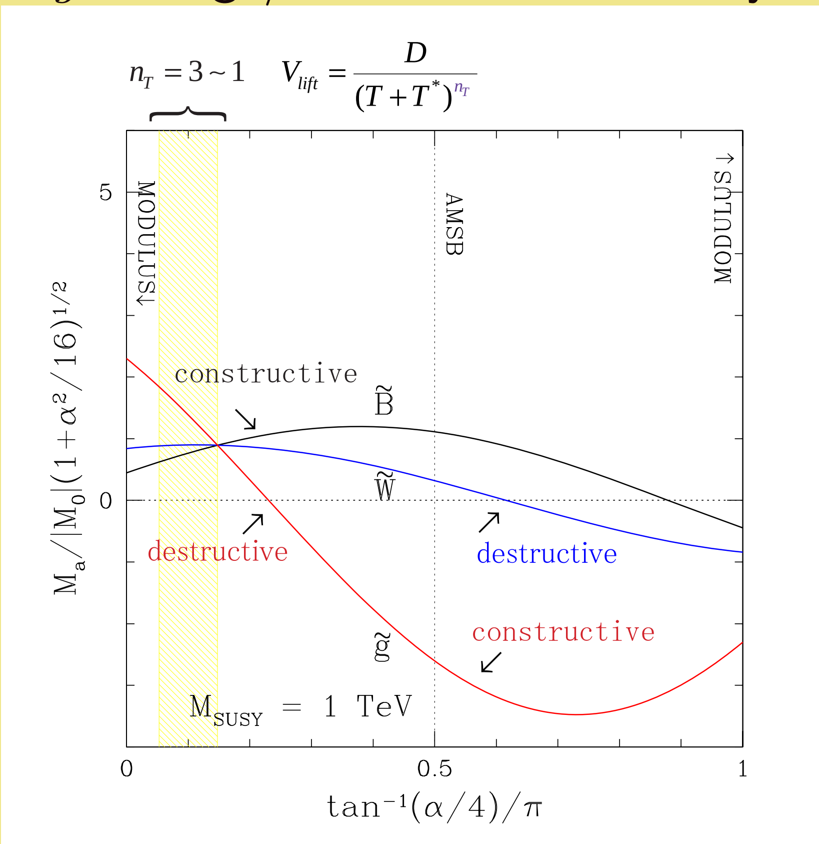
K. Choi, A. Falkowski, H.P. Nilles, M. Olechowski and S. Pokorski JHEP **0411**, 076 (2004)

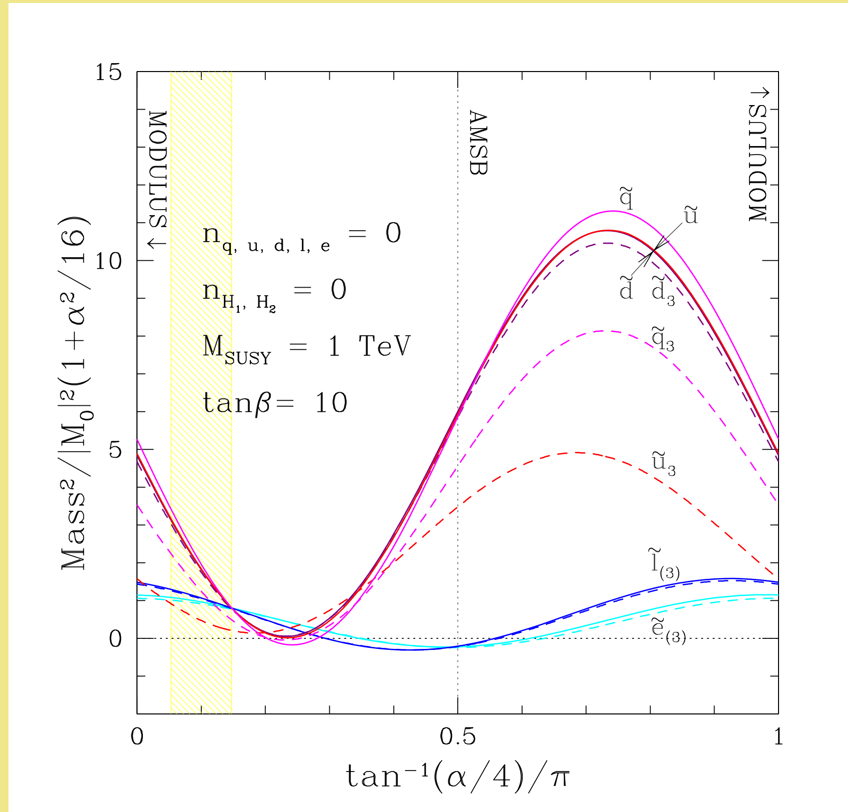
Low energy mass spectrum is calculated by renormalization group equation.



Because the D3 SM gauge fields case ($l_a = 0$) ≈ Anomaly mediation has been examined by literature, Here we concentrate on D7 ($l_a = 1$) case.

$e.g.$ Gauge/Matter fields on 4-cycle of D7 (See relative size for fixed α).





Constructive/destructive interference between modulus and anomaly med. provide distinctive pattern of soft breaking terms ($\tilde{g}/\tilde{W}$, $\tilde{B}/\tilde{W}$, $\tilde{q}/\tilde{\ell}$ ...).

IV. "Mirage" Messenger Scale

$$
\begin{aligned}
M_a\left(\mu/M_{GUT}\right) &= \frac{g_a^2}{g_{GUT}^2}\left[M_0 + \frac{b_a}{4\pi^2(T+T^*)}\frac{F^C}{C_0}\right], \\
&= M_0\left[1 - \frac{b_a g_a^2}{8\pi^2}\left\{\ln\left(\frac{M_{GUT}}{\mu}\right)^2 - \alpha\ln\left(\frac{M_{GUT}}{m_{3/2}}\right)\right\}\right], \\
&= M_a\left(\mu/m_{3/2}^{\alpha/2}M_{GUT}^{1-\alpha/2}\right)\Big|_{\text{w/o Anomaly Mediation}}
\end{aligned}
$$

$$
\frac{1}{g_a^2} = \frac{1}{g_{GUT}^2} + \frac{b_a}{8\pi^2}\ln\left(\frac{M_{GUT}}{\mu}\right)^2 \quad \to \quad \frac{g_a^2}{g_{GUT}^2} = 1 - \frac{b_a g_a^2}{8\pi^2}\ln\left(\frac{M_{GUT}}{\mu}\right)^2
$$

Anomaly mediation effectively *shifts* the modulus mediation scale

$$
M_{\text{GUT}} \longrightarrow M_{\text{Mirage}} = m_{3/2}^{\alpha/2} \times M_{GUT}^{1-\alpha/2}
$$

If $y_{ijk} \neq 0$ only for $n_i + n_j + n_k = 2$, similar relations hold for trilinear scalar couplings and soft masses (Anomaly Med. $\leftrightarrow$ RG running).

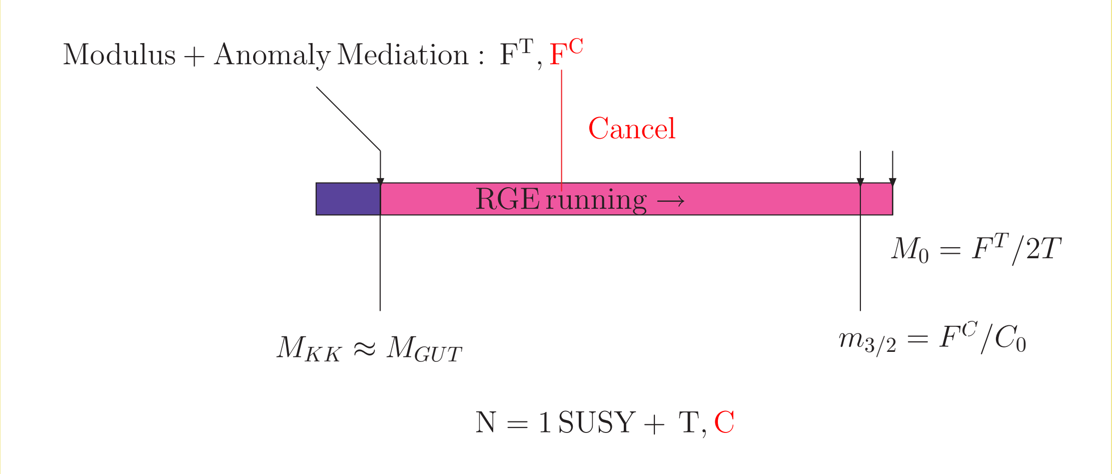
$$
\begin{aligned}
A_{ijk}(\mu) &= M_0 \Bigg[(3 - n_i - n_j - n_k) \\
&\quad + \frac{1}{8\pi^2} (\gamma_i(\mu) + \gamma_j(\mu) + \gamma_k(\mu)) \ln \left(\frac{m_{3/2}^{\alpha/2} M_{GUT}^{1-\alpha/2}}{\mu} \right) \Bigg], \\
m_i^2(\mu) &= |M_0|^2 \Bigg[(1 - n_i) \\
&\quad + \frac{1}{4\pi^2} \left\{ \gamma_i(\mu) - \frac{1}{2} \frac{d\gamma_i(\mu)}{d \ln \mu} \ln \left(\frac{m_{3/2}^{\alpha/2} M_{GUT}^{1-\alpha/2}}{\mu} \right) \right\} \ln \left(\frac{m_{3/2}^{\alpha/2} M_{GUT}^{1-\alpha/2}}{\mu} \right) \Bigg]
\end{aligned}
$$

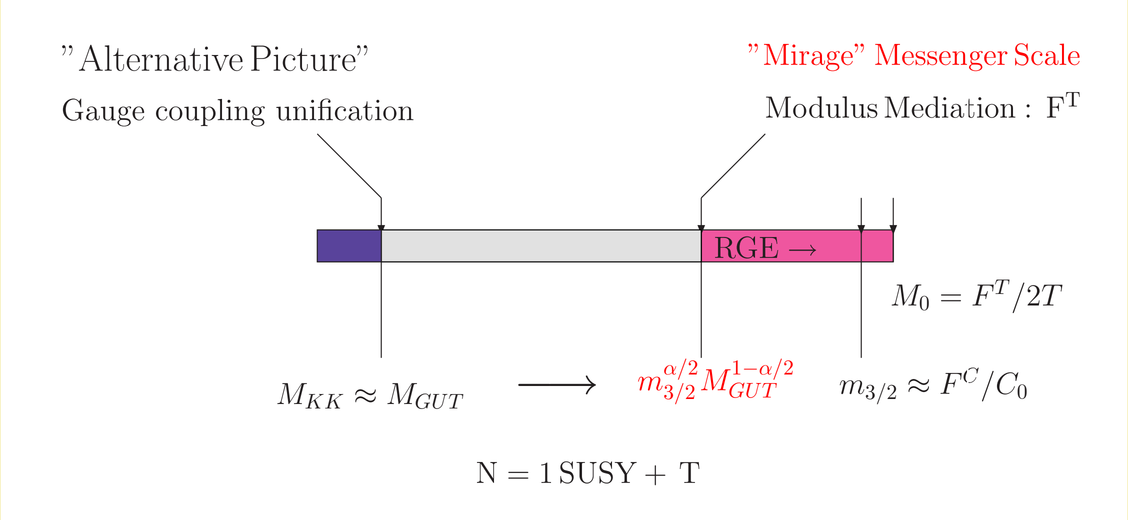
Summarizing,

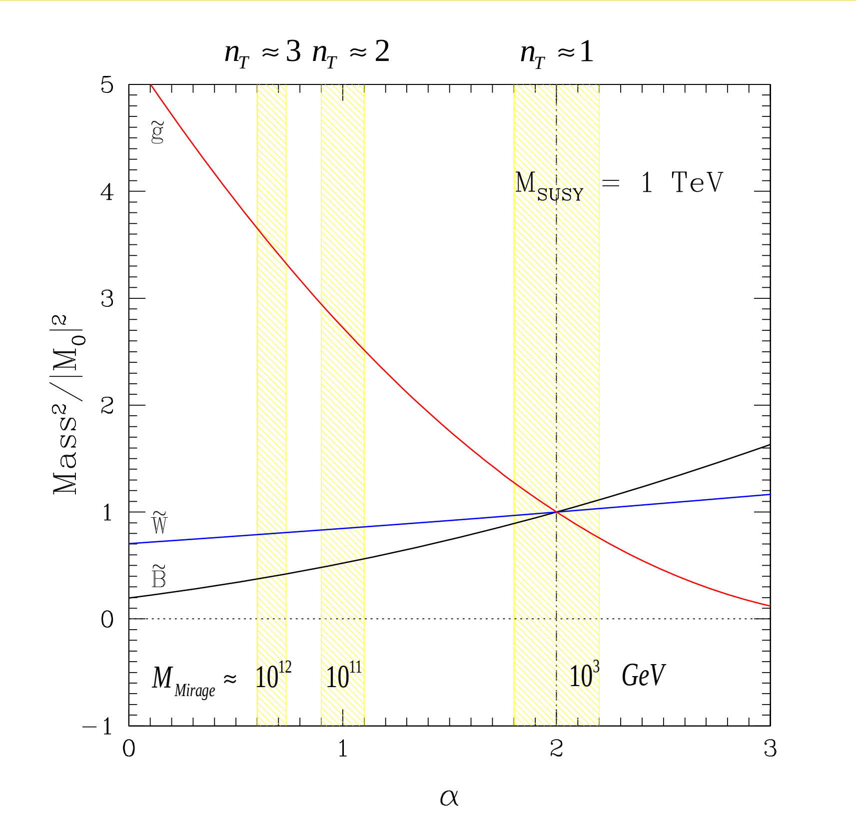
Correspondence between anomaly mediation and RGE effect due to gauge (and selected Yukawa) interaction.

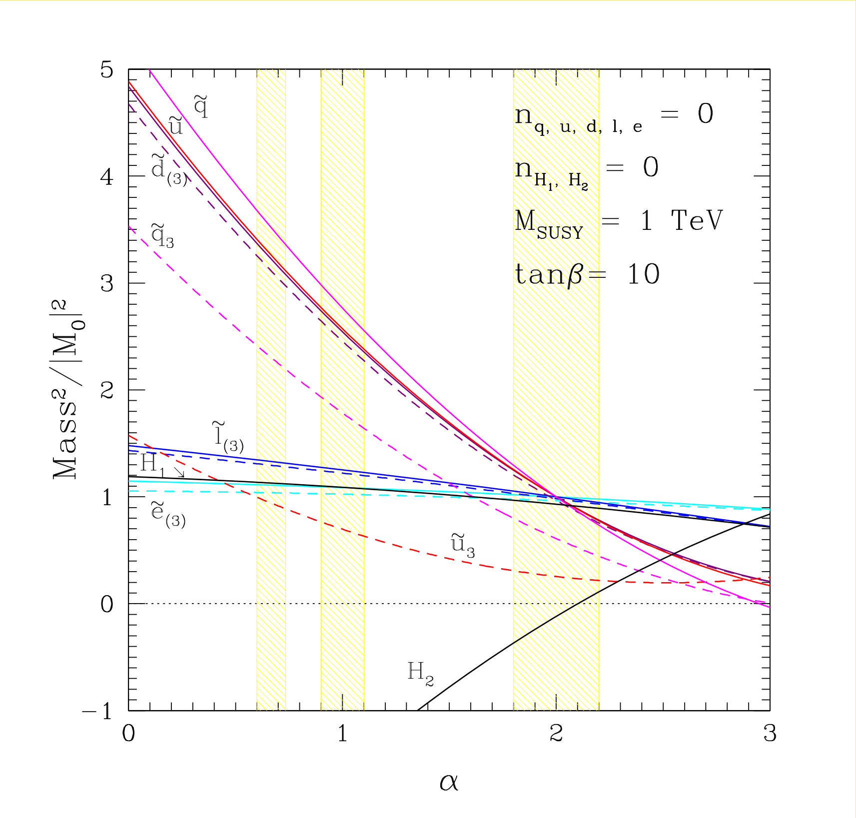
Anomaly med. effectively shifts Modulus med. scale: Mirage Messenger Scale. (Up to correction from Yukawa interaction)

Note that this is a model independent feature of anomaly mediation.



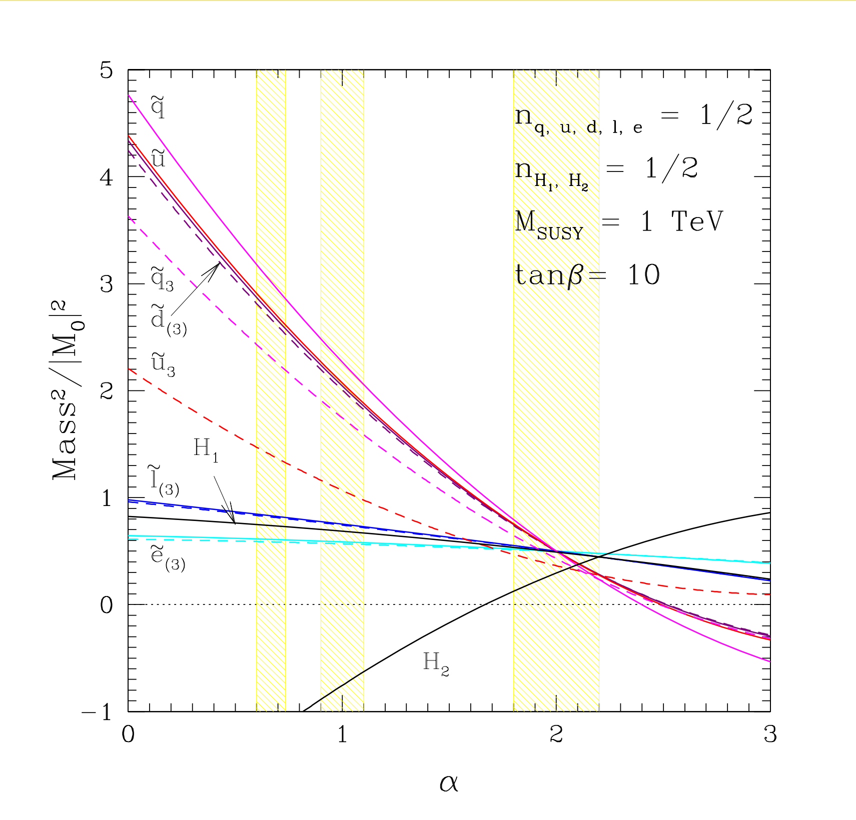


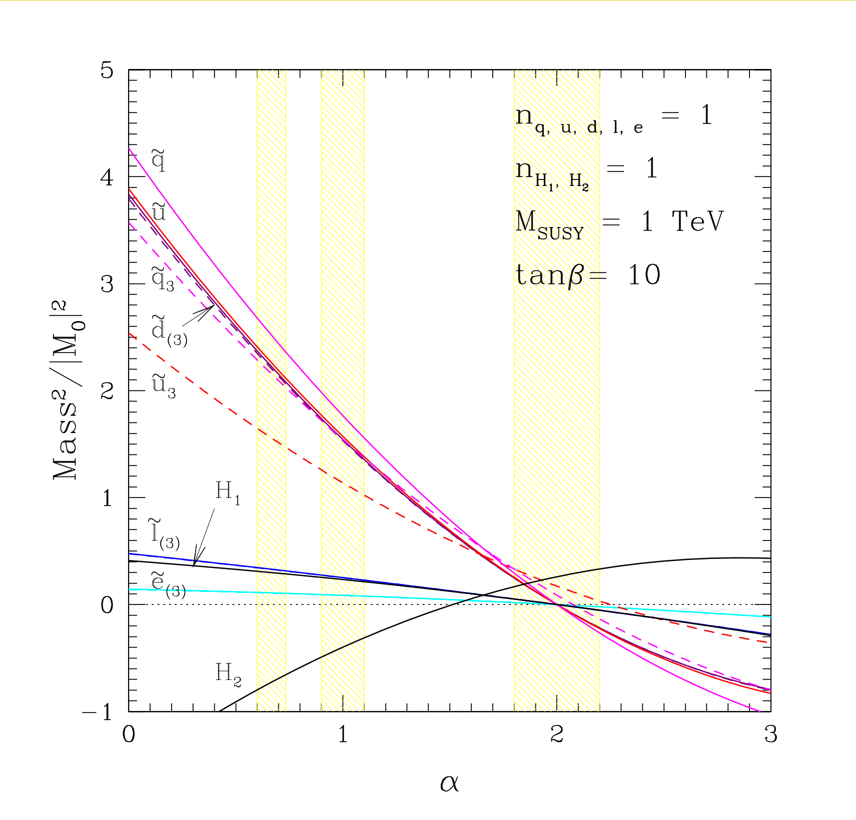




* Dashed curves denote the 3rd generation.

Lowered messenger scale leads to squeezed gauginos or squarks/sleptons spectrum (the 1st and 2nd gen.) relative to pure modulus med (mSUGRA).





Similar for matters on the intersection (2-cycle) or D3. Distinctive pattern of mass spectrum can be tested by future collider experiments (LHC/ILC).

V. Electroweak Symmetry Breaking

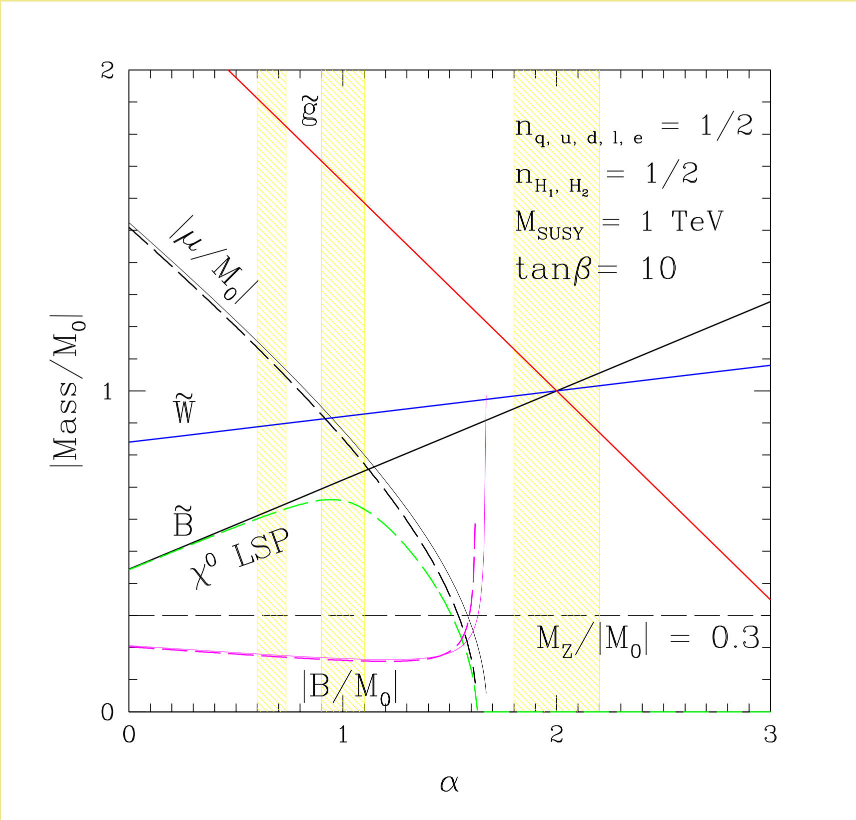
Electroweak symmetry breaking depends on the model of Higgs sector.
Here we simply assume the MSSM ($\mathcal{W} = \mu H_1 H_2, \ \mathcal{L}_{Soft} = -B\mu H_1 H_2$).

$$V = (m_{H_1}^2 + |\mu|^2)|H_1^0|^2 + (m_{H_2}^2 + |\mu|^2)|H_2^0|^2 - \left(B\mu H_1^0 H_2^0 + \text{c.c.}\right) + \frac{1}{8}(g_1^2 + g_2^2)\left(|H_1^0|^2 - |H_2^0|^2\right)^2$$

Minimizing V, we can solve μ and B for fixed $\tan\beta = \langle H_2^0 \rangle / \langle H_1^0 \rangle$

$$\mu^2 = -\frac{M_Z^2}{2} + \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1}, \quad |B\mu| = \frac{\tan\beta}{1 + \tan^2\beta}(m_{H_1}^2 + m_{H_2}^2 + 2\mu^2).$$

e.g. Matter/Higgs on the intersection.



- Radiative symmetry breaking is weaken (small μ) and $M_{\tilde{B}}$ is lifted due to lowered messenger scale.

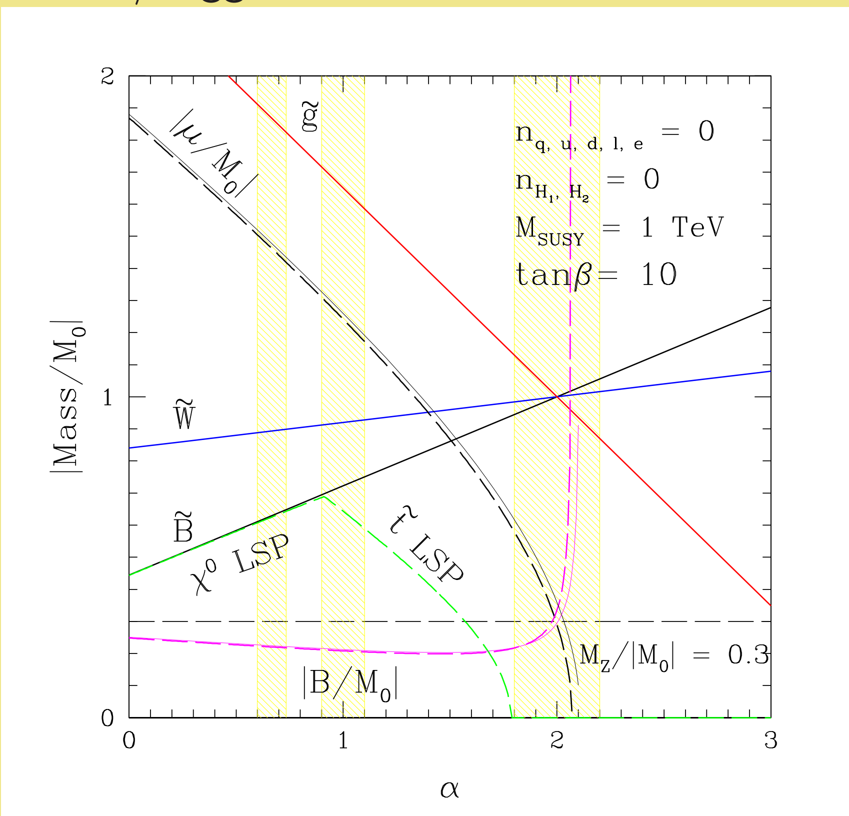
- The lightest neutralino has considerable wino and higgsino components and can be pure higgsino. Impact on nature of cold dark matter (Thermal relic abundance/ detection).

C.f.

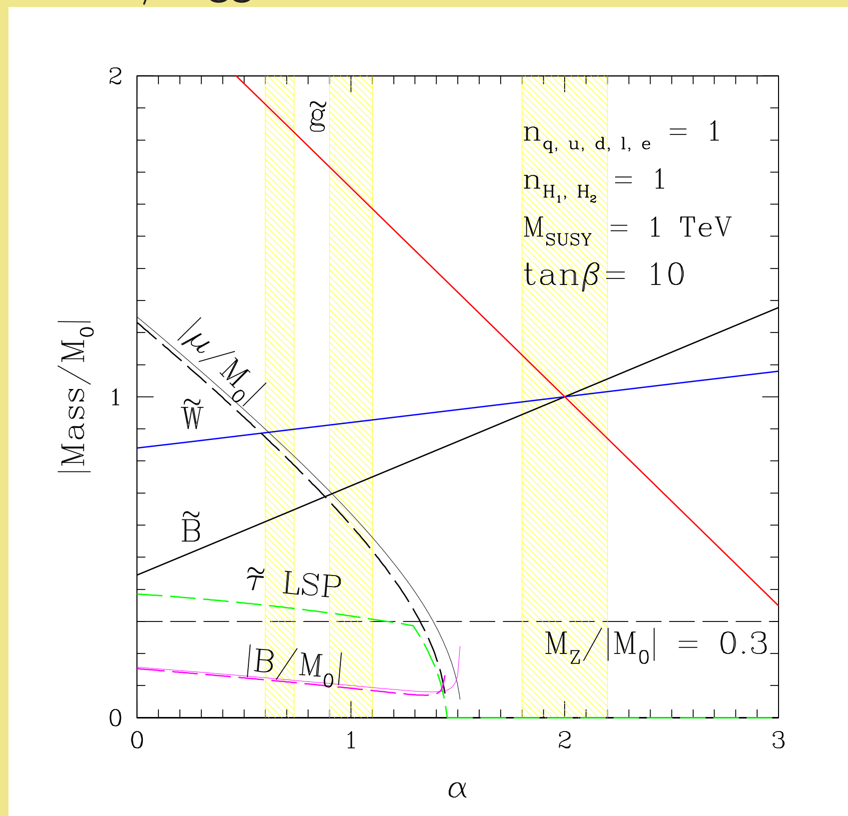
M. Endo, M. Yamaguchi, K. Yoshioka hep-ph/0504036

A. Falkowski, O. Lebedev, Y. Mambrini

Matter/Higgs on D7

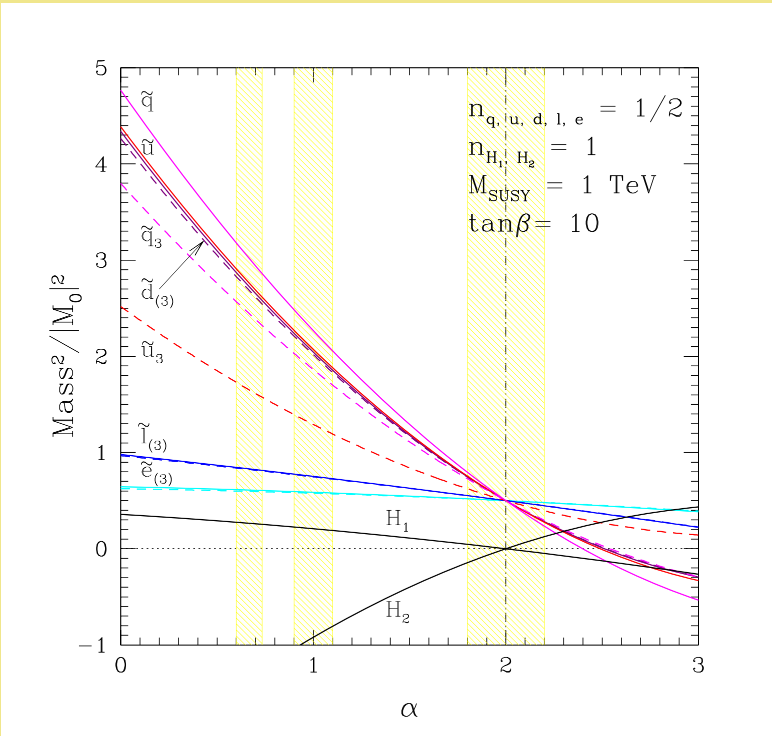


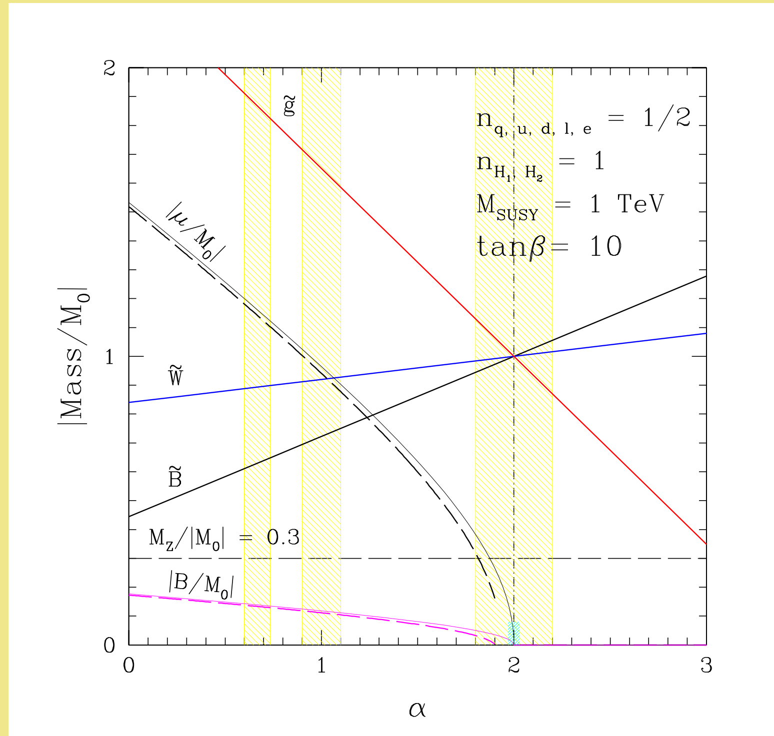
Matter/Higgs on D3



Exact position of mixed region and nature of LSP is model dependent.

Special choice: Matters on intersection/Higgs on D3 → Exact cancellation.





Little Hierarchy (Sparticles/Higgs) is "prediction" at $\alpha \approx 2$ ($V_{\rm lift} = \frac{D}{(T+T^*)}$).

VI. Summary

1. Flux compactification and brane models provide the first viable string model for soft SUSY breaking with stabilized moduli and $\Lambda \approx 0$.

2. Weak scale hierarchy: $m_{3/2} >> M_0 = F^T/2T \approx m_{3/2}/4\pi^2$
   $\rightarrow$ Both moduli and anomaly mediations play important role.

3. We identified that the role of anomaly mediation is effectively lowering (or raising) the modulus messenger scale (Mirage Messenger Scale).

4. Compressed weak scale spectrum compared with known mechanisms in the market while gauge coupling unification is intact $\rightarrow$ LHC/ILC.

5. Weakened radiative electroweak symmetry breaking $\longrightarrow$
   the lightest neutralino : mixed (bino/wino/higgsino) or pure higgsino.

   Considerable impact on dark matter physics and cosmology as well as with hierarchically heavier gravitino.