Moduli stabilization with Matter uplifting in Heterotic string theory

SUSY 08

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based on the work in progress with S. Shin

Low energy effective theory from string compactifications

Couplings $= f(\langle S\rangle, \langle T\rangle)$, S (Dilaton) : string coupling strength

T (Volume modulus) : size of the compactified space

$\Rightarrow$ Moduli F-terms (F^S, F^T) : source of soft SUSY breaking terms

Moduli stabilization : NP effects and fluxes are natural sources of moduli fixing.

Nearly flat dS vacuum

Supersymmetric field configuration always extremizes scalar potential V.

$F^S = F^T = 0 \Rightarrow \langle V\rangle < 0$,

Kachru, Kallosh, Linde, Trivedi

Uplifting effects - KKLT (type IIB) : anti-branes (non-linearly realized SUSY)

- Matter uplifting : hidden sector F-term SUSY breaking

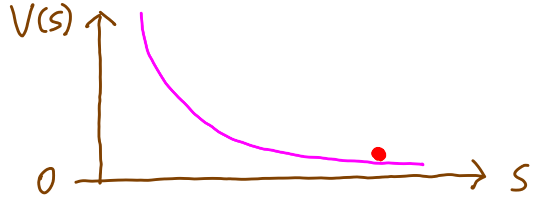
Dilaton stabilization in heterotic string

Gauge Kinetic function : $f_a = S$ ($\mathrm{Re}\, S_0 \approx 2$ for gauge coupling unification)

$\Rightarrow$ Gaugino condensation would generate NP superpotential $W_{NP} \sim e^{-aS}$.

Tree-level Kähler potential + NP superpotential with single gaugino condensate

$\Rightarrow$ Run-away potential

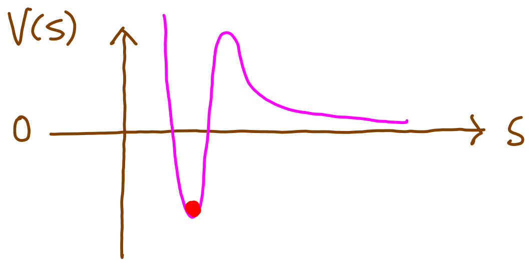


(I) Racetrack mechanism

Krasnikov, Casas

(Controllable) NP superpotential with multi gaugino condensates

$W_{NP} = A_1 e^{-a_1 S} - A_2 e^{-a_2 S}$, $(A_1, A_2 = \mathcal{O}(1),\ a_1, a_2 = \mathcal{O}(4\pi^2))$



$\Rightarrow$ little fine tuning : $(a_1 - a_2)/(a_1 + a_2) \sim \frac{1}{4\pi^2}$,

Typically $F^S \sim 0$, $F^T \sim m_{3/2}$

AdS vacuum : $\langle V \rangle \sim - m_{3/2}^2 M_{Pl}^2$, Casas, Binetruy et al, Barreiro et al,

(2) Large (uncontrollable) NP corrections to Kähler potential

W_{NP} : single gaugino condensate

$\Rightarrow F^S \sim m_{3/2}$, $F^T = 0$ (T-duality)

dS vacuum : $\langle V \rangle \sim m_{3/2}^2 M_{Pl}^2$.

* For both (1), (2), it is difficult to tune the vacuum energy to be small enough.

Löwen, Nilles

Matter uplifting in heterotic

Löwen, Nilles : Polony type uplifting sector (Z).

Tree-level Kähler potential + W_{np} with single gaugino condensate

$\Rightarrow$ S is stabilized at a dS vacuum with $\langle V \rangle \approx 0$.

Little hierarchy structure : $F^Z \sim m_{3/2}$.

$$F^S \sim m_{3/2} / \ln(M_{Pl}/m_{3/2}).$$

$f_a = S$: Dilaton mediation gives comparable contribution to gaugino masses as anomaly mediation ($\sim m_{3/2}/8\pi^2$, always present).

$\Rightarrow$ Mirage pattern of gaugino masses

Stabilization of volume modulus T

$\rightarrow$ T is assumed to be fixed at a self dual point (T-duality) with $F^T = 0$.

* Generically uplifting matter Z has non-trivial $SL(2,Z)$ modular transformation.

→ SUSY breaking by Z might shift T from the self dual point, if then $F^T \sim m_{3/2}$.

* In the absence of uplifting sector, the self dual points typically correspond to local maxima or saddle points.

→ Uplifting potential might give an important contribution to m_T.

In this work,

1. We examine moduli stabilization and SUSY breaking in the Löwen-Nilles scheme while explicitly including T.

2. Generalizing the scheme to the situation with an anomalous $U(1)$ gauge symmetry, we also examine the effects of anomalous $U(1)$ sector.

(effective theories from string theory often contain anomalous $U(1)$ gauge symmetries.)

1. Moduli stabilization with matter uplifting

Modular invariant action (tree-level Kähler potential)

$$K = -\ln(S+\bar{S}) - 3\ln(T+\bar{T}) + (T+\bar{T})^n Z\bar{Z}, \quad n: \text{modular weight of } Z$$

$$W = \eta(T)^{-6}\Omega(S,T,Z), \quad \eta(T): \text{Dedekind eta function of modular weight } \tfrac{1}{2}$$

$\Rightarrow$ $G = K + \ln|W|^2$ and Ω are modular invariant.

Perturbative shift symmetry ($\mathrm{Im}S \to \mathrm{Im}S + \text{constant}$) $\Rightarrow$ $\Omega \sim e^{-aS}$ (gaugino condensation)

Scalar potential

$$V_F = e^G\left(G^{-1}_{I\bar{J}} G_I G_{\bar{J}} - 3\right), \quad G_I \equiv \partial_I G.$$

F-term : $F^I = -e^{G/2} G^{-1}_{I\bar{J}} G_{\bar{J}}$, (SUSY breaking)

Modular invariance : properties at self dual points ($T=1,\ e^{i\pi/6}$)

(1) $F^T \propto G_{Z\bar{Z}} G_{\bar{T}} - G_{\bar{T}Z} G_{\bar{Z}} = 0$ for $\forall Z$.

$\Rightarrow$ Fixed at a self dual point, T does not break SUSY.

(2) For Z satisfying $nZ\partial_Z V_F = 0$, the modular invariance leads to $\partial_T V_F = 0$.

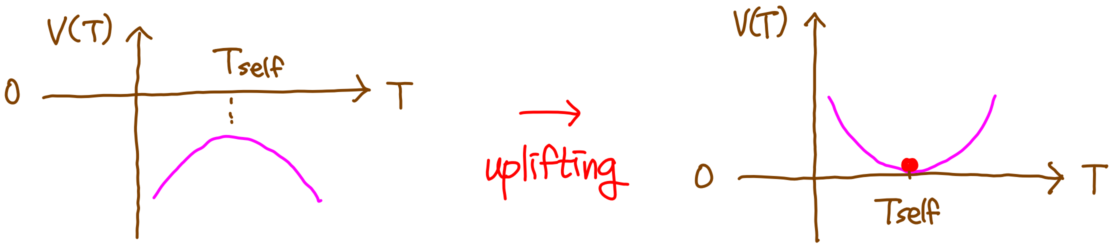
$\Rightarrow$ Self dual points are stationary points of potential ($\partial_Z V_F = 0 \Rightarrow \partial_T V_F = 0$).

Stabilization of volume modulus T

(Z' : modular weight $=0$)

In the field basis $(S,\ T,\ Z' = \eta(T)^{-2n} Z)$, there are no mass mixings between T and $(S,\ Z')$, where n (matter modular weight) is a non-positive rational number of $\mathcal{O}(1)$.

$\Rightarrow$ For $\langle V_F \rangle \simeq 0$ with reasonable values of n and Z_0, it turns out that self dual points correspond to local minima ($m_T \sim m_{3/2}$).



(Saddle or maximum)

$\Rightarrow$ T can be stabilized at a self dual point without breaking SUSY.

SUSY breaking pattern

From $\partial_Z V_F = 0$, ① T can be stabilized at a self dual point with $F^T = 0$,

② for $V_F = 0$, $G_{SZ} F^S + G_{ZZ} F^Z + G_{Z\bar{Z}} F^{Z*} = 0$.

NP origin of dilaton superpotential : it is natural possibility to have $|G_{SZ}| \gg |G_{ZZ}|, |G_{Z\bar{Z}}|$, $(S = \mathcal{O}(1))$

→ F^S is then suppressed compared to F^Z,

→ F^Z is the main source of SUSY breaking ($V_F = 0$).

Löwen, Nilles : $W = Ae^{-aS} + \omega + \mu^2 Z$ (Polony-type superpotential for Z)

⇒ S and Z are well stabilized at a dS vacuum with $\langle V_F \rangle \approx 0$,

$F^S \sim F^Z / \ln(M_{Pl}/m_{3/2})$, $m_S \sim \ln(M_{Pl}/m_{3/2})\, m_{3/2}$, $m_Z \sim m_{3/2}$.

The uplifting sector plays a crucial role both in stabilizing S and in adjusting the vacuum energy.

2. Moduli stabilization in the presence of anomalous U(1)

String compactification often involves an anomalous $U(1)_A$ gauge symmetry with anomalies cancelled by Green-Schwarz mechanism:

$f_a = S$,

$U(1)_A$ transformation : $S \to S - i\alpha_A(x)\cdot\delta_{GS}$, $\delta_{GS} = \mathcal{O}(1/8\pi^2)$

$\Rightarrow$ Field-dependent FI term : $\xi_{FI} = \delta_{GS}\,\partial_S K = \mathcal{O}(M_{Pl}^2/8\pi^2)$ for $S = \mathcal{O}(1)$.

$U(1)_A$ charged field X to avoid a large FI D-term

$D_A \sim \xi_{FI} + q_X|X|^2 \approx 0 \Rightarrow \langle X\rangle \sim \sqrt{\xi_{FI}}$: spontaneous breaking of $U(1)_A$

- Massive vector superfield $\sim V_A + q_X \ln|X|$ (Goldstone : composed mostly of X)
- Flat direction of D-term potential $\sim S$ (need to stabilize S)
- Gauge boson mass : $M_A^2 = \mathcal{O}(\delta_{GS} M_{Pl}^2)$

Effects of $U(1)_A$

Gauge invariance + stationary conditions

→ relation between VEVs of $U(1)_A$ charged F-terms and D-term

For $V_{tot} = V_F + V_D \simeq 0$ with $m_{3/2} \ll M_{pl}$, and $S = \mathcal{O}(1)$

$$F^S \sim g_X \frac{F^X}{X_0}, \quad D_A \sim g_X \left| \frac{F^X}{X_0} \right|^2$$

⇒ (1) D-term contribution to vacuum energy

$V_{tot} = |D_A|^2 + |F|^2 - 3 m_{3/2}^2 M_{pl}^2$: negligible compared to F-term contributions

(2) D-term contribution to sfermion masses

$m_i^2 = -g_i D_A$: comparable to the dilaton mediation

(D-term SUSY breaking induces only soft scalar masses)

Soft SUSY breaking terms

$(F^T = 0)$

Source of soft terms : Dilaton mediation $F^S \sim m_{3/2} / \ln(M_{Pl}/m_{3/2})$

Uplifting sector mediation $F^Z \sim m_{3/2}$

$U(1)_A$ sector mediation $\frac{F^X}{X_0} \sim F^S$, $D_A \sim |F^S|^2$

Anomaly mediation $\sim m_{3/2}/8\pi^2$

Pattern of soft terms : dependence of effective couplings on S, Z, X, V_A

$$\mathcal{L} = \int d^4\theta \, Y_i \bar{Q}^i e^{2 g_i V_A} Q^i + \left\{ \int d^2\theta \left(\frac{1}{4} f_a W^a W^a + \lambda_{ijk} Q^i Q^j Q^k \right) + \text{h.c.} \right\},$$

$f_a = S$ (tree-level)

(perturbative shift symmetry, Im S)

$$Y_i = (S+\bar{S})^{\frac{1}{3}} \cdot \left(1 + \xi_i \left| \frac{Z}{M_{Pl}} \right|^2 + \eta_i \left| \frac{X}{M_{Pl}} \right|^2 \right), \qquad \lambda_{ijk} \propto \left(\frac{X}{M_{Pl}} \right)^{-(g_i + g_j + g_k)/g_X},$$

Effective cross-couplings with visible matter fields (source of flavor violations)

Sequestering $\Rightarrow$ strong suppression of cross-couplings

(1) Gaugino masses at M_{GUT}

$M_a(M_{GUT})$ * Dilaton mediation $= \frac{F^S}{S+S^*} \sim \frac{m_{3/2}}{\ln(M_{Pl}/m_{3/2})}$: universal

* Anomaly mediation (super-conformal anomaly)

$= \frac{b_a}{16\pi^2} m_{3/2}$: proportional to β-function

* Uplifting sector mediation (due to the Konishi anomaly)

$= C_a^i \xi_i \frac{Z_0}{M_{Pl}} \cdot \frac{1}{8\pi^2} m_{3/2}$: non-universal (C_a^i : quadratic Casimir of Q^i)

$\Rightarrow$ negligible if $|Z_0| \ll M_{Pl}$ or $|\xi_i| \ll 1$ (sequestering).

(Contribution from F^X : negligible because $|X_0| \ll M_{Pl}$)

Dilaton mediation gives a comparable contribution to M_a as anomaly mediation.

$\Rightarrow$ Mirage mediation pattern (for $|Z_0| \ll M_{Pl}$ or $|\xi_i| \ll 1$)

(2) Sfermion soft terms : $m_i^2|\tilde{Q}^i|^2 + A_{ijk}\, y_{ijk}\, \tilde{Q}^i \tilde{Q}^j \tilde{Q}^k$

$$A_{ijk}(M_{GUT}) = \left[\left(\frac{1}{3} - \frac{g_i}{g_x} \right) \frac{m_{3/2}}{\ln(M_{Pl}/m_{3/2})} - \gamma_i \frac{m_{3/2}}{16\pi^2} - \xi_i \frac{z_0}{M_{Pl}} \cdot m_{3/2} \right] + [i \leftrightarrow j] + [i \leftrightarrow k] ,$$

$$m_i^2(M_{GUT}) = \left(\frac{1}{3} - \frac{g_i}{g_x} \right) \left| \frac{m_{3/2}}{\ln(M_{Pl}/m_{3/2})} \right|^2 - \frac{d\gamma_i}{d\ln\mu} \frac{|m_{3/2}|^2}{32\pi^2} - \xi_i |m_{3/2}|^2 + (\text{mixed contributions}).$$

- Dilaton mediation : flavor-independent
- $U(1)_A$ sector mediation : A-couplings from F^X, sfermion masses from D_A
- Anomaly mediation : determined by the anomalous dimension of matter fields

⇒ those mediations give comparable contributions to sfermion soft terms

- Uplifting sector mediation : $\xi_i = \mathcal{O}(1)$ leads to heavy sfermion mass of $\mathcal{O}(m_{3/2})$.

(general feature of matter uplifting scenarios)

* It is plausible to assume that $g_i + g_j + g_k = 0$ for a large Yukawa coupling $y_{ijk} = \mathcal{O}(1)$.

⇒ For $|\xi_i| \ll 1$ (sequestering), sfermion soft-terms take the mirage mediation pattern.

Summary

In heterotic string theory, by introducing the uplifting sector, dilaton can be stabilized at a dS vacuum with nearly vanishing vacuum energy in a controllable approximation.

* Volume modulus can be stabilized at a self dual point without breaking SUSY.

* The uplifting sector plays a crucial role in stabilizing both dilaton and volume modulus.

Within the Löwen-Nilles scheme, gaugino masses take the mirage pattern.

* In the presence of anomalous $U(1)$ gauge symmetry, $U(1)_A$ sector mediation gives a comparable contribution to sfermion soft terms as dilaton mediation.

* If visible matter fields are sequestered from the uplifting sector, sfermion soft terms also take the mirage pattern.

END

Note)

$SL(2,\mathbb{Z})$: $T \to \dfrac{aT - ib}{icT + d}$ where $ad - bc = 1$ $(a, b, c, d \in \mathbb{Z})$

$$\eta(T) \to e^{i\theta}(icT + d)^{\frac{1}{2}}\eta(T), \quad \eta(T) = e^{-\frac{\pi}{12}T}\prod_{n=1}^{\infty}(1 - e^{-2n\pi T}).$$

$\eta(\frac{1}{T}) = \sqrt{T}\,\eta(T)$ and $\eta(T - i) = e^{i\pi/12}\eta(T)$.

self dual : $T = 1$ for $T \to \frac{1}{T}$, $(Z \to \frac{Z}{T^n})$

$T = e^{i\pi/6}$ for $T \to \dfrac{1}{T - i}$.

(fundamental domain : $\mathrm{Re}\,T > 0$, $-\frac{1}{2} < \mathrm{Im}\,T < \frac{1}{2}$, $1 \leq |T|$).

* T-duality, discrete shift symmetry ($T \to T + in$, $n \in \mathbb{Z}$).

$$|D_A| \lesssim \frac{m_{3/2}^2 M_{pl}^2}{m_A^2}$$