SUSY breaking and soft terms in models with anomalous U(1) and NP Polonyi term

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❖ Anomalous $U(1)_A$

$U(1)_A$ often appears in string compactification to four dimensions.

Green-Schwarz mechanism of anomaly cancellation

$$L = \tfrac{1}{4}\left(k_a S + \Delta_a\right) W^a W^a \Big|_{\theta^2}$$: S transforms non-linearly under $U(1)_A$.

Kaehler potential in SUGRA : $K_0 = K_0(S + S^* - \delta_{GS} V_A)$

- S-dependent FI term : $\xi_{FI} = \dfrac{\delta_{GS}}{2} K_0'$,
- Massive $U(1)_A$ gauge boson : $M_A^2 = 2 g_A^2 M_{GS}^2 + \cdots$, where $M_{GS}^2 = \dfrac{\delta_{GS}^2}{4} K_0''$

In the basis with $k_a = O(1)$: $\delta_{GS} = O(1/8\pi^2)$

$K_0'' > 0$: FI term is a monotonic function of $t=S+S^*$, and $M_{GS} \neq 0$.

❖ Anomalous $U(1)_A$

SUSY breaking with $m_{3/2} \ll M_{Pl}$: SM singlet fields to compensate the FI term

$$\to M_A^2 = 2g_A^2 M_{GS}^2 + O(\xi_{FI})$$

Massive $U(1)_A$ vector field : $V_H = V_A - \frac{1}{2}(\phi_A + \phi_A^*)$

$$R = \frac{-\xi_{FI}}{M_{GS}^2}$$

$$\begin{cases} \text{Large } R : \phi_A \sim \text{SM singlet} \\ \text{Small } R : \phi_A \sim S \end{cases}$$

V_H is decoupled at low energy scales $\ll M_A$.

→ SUSY breaking in $U(1)_A$ would rely on the size of R.

Examine how SUSY is broken and transmitted to SUSY SM, depending on R!

❖ Minimal model

One SM singlet X to maintain the $U(1)_A$ D-flatness

$$K = K_0(S + S^* - \delta_{GS}V_A) + Z_X(S + S^* - \delta_{GS}V_A)\,|X|^2\, \underline{e^{-2V_A}}$$

$U(1)_A$ charge of $X : q_X = -1 \;\rightarrow\; R > 0$

Transmission of SUSY breaking to the supersymmetric SM

- Modulus mediation : $M_a\big|_{MM} = \frac{k_a g_a^2}{2} F^S, \qquad m_i^2 = O(M_a^2)$
- Anomaly mediation : $M_a\big|_{AM} = \frac{b_a g_a^2}{8\pi^2} m_{3/2}, \qquad m_i^2 = O(M_a^2)$
- Gauge mediation with messenger fields : $M_a\big|_{GM} = \frac{N_\Phi g_a^2}{8\pi^2}\frac{F^X}{X}, \qquad m_i^2 = O\left(\frac{M_a^2}{N_\Phi}\right)$

  e.g. N_Φ messengers in $5+\overline{5}$ of $SU(5)$

- Anomalous $U(1)_A$ mediation : $m_i^2\big|_{aM} = -q_i g_A^2 D_A$
- Uncontrollable gravity mediation via M_{Pl}-suppressed operators : $m_i^2 \sim |F^X|^2$

❖ SUSY breaking in $U(1)_A$ sector

Relations between F and D terms

- Gauge invariance $\Rightarrow m_{3/2}D_A = K_{I\bar{J}}\eta^I F^{J*}, \ (\eta^S = -\delta_{GS}/2, \eta^X = -X)$
- Gauge invariance + Minimum condition

$$\Rightarrow D_A \simeq \frac{-2F^I F^{J*}\partial_I \partial_{\bar{J}}\left(\eta^L \partial_L K\right)}{M_A^2} \quad \text{for } m_{3/2} \ll M_A \text{ and } |F|,|D_A| \leq O(m_{3/2}M_{Pl})$$

Relative importance of mediation mechanisms

- S-independent Z_X : $F^S \simeq -\frac{\delta_{GS}}{2}R\frac{F^X}{X}, \quad g_A^2 D_A \simeq \frac{R}{1+R}\left(1+\frac{\delta_{GS}}{2}R\frac{K_0'''}{K_0''}\right)\left|\frac{F^X}{X}\right|^2$

$$\Rightarrow M_a\big|_{MM} \sim RM_a\big|_{GM}.$$

$U(1)_A$-mediation is non-negligible for $O(10^{-6}) \leq R \leq O(10^3)$.

- Suppression of $U(1)_A$-mediation for large R if $K_0'/Z_X = \text{(constant)}$.
- Relative size of AM depends on the mechanism to adjust C.C.

2. $U(1)_A$: Stabilization of GS modulus

❖ Stabilization of S

Non-perturbative Polonyi term (e.g. from string instanton effects) :

$$W = \omega_0 + Ae^{-aS}X, \quad \text{where } a = 2/\delta_{GS} = O(8\pi^2), \; \omega_0 = O(m_{3/2})$$

In the basis of S such that $\delta_{GS} = O(1/8\pi^2)$ and $A = O(1)$: $a(S+S^*) \sim \ln\left|\xi_{FI}/m_{3/2}^2\right|$

by shifting and rescaling

❖ Vacuum structure for $Z_X=1$

V_F :

$$\arg(e^{-aS}X) = \begin{cases} \arg(\omega_0/A) + \pi, & R > 2 \\ \arg(\omega_0/A), & R < 2 \end{cases}, \quad \text{for } |X|^2 \ll 1.$$

After fixing $\arg(e^{-aS}X)$ at the minimum, two stationary conditions :

$$\text{1. (approximate) D-flatness : } g_A^2 D_A = -\frac{a}{K_0''}\left(V_F' + (\partial_t \ln g_A^2)V_D\right),$$

$$\text{2. Lifting of D-flat direction : } \partial_{|X|}V_F = \frac{2a|X|}{K_0''}\left(V_F' + (\partial_t \ln g_A^2)V_D\right).$$

2. $U(1)_A$: Stabilization of GS modulus

❖ Stabilization of S

SUSY minimum

- Present in the region with R>2 : $|X|^2 = -\xi_{FI}$ and $\left|\frac{A}{\omega_0}\right| \frac{e^{-at/2}}{\sqrt{-\xi_{FI}}} = \frac{1}{1-\xi_{FI}}$.
- At most one because FI term is a monotonically increasing function of $t=S+S^*$.

SUSY breaking minimum

- Assume $\left|\left(\frac{\delta_{GS}}{2}\right)^{n-2} \frac{\partial_t^n K_0}{K_0''}\right| \le O\left(\frac{1}{(at)^{n-2}}\right) \ll 1 \ \ (n \ge 3)$ at the minimum

  → Plausible as V_F is induced by NP Polonyi term

- Present in the region with R<2 : $|X|^2 \simeq -\xi_{FI}$ and $\left|\frac{A}{\omega_0}\right| \frac{e^{-at/2}}{\sqrt{-\xi_{FI}}} \simeq \frac{1}{R}$.
- C.C. can be cancelled by F^X for small R : $R \simeq \frac{1}{3}\left(M_{GS}/M_{Pl}\right)^2$
- SUSY breaking minimum with R>2 only for non-trivial K_0

3. ET : Low energy description

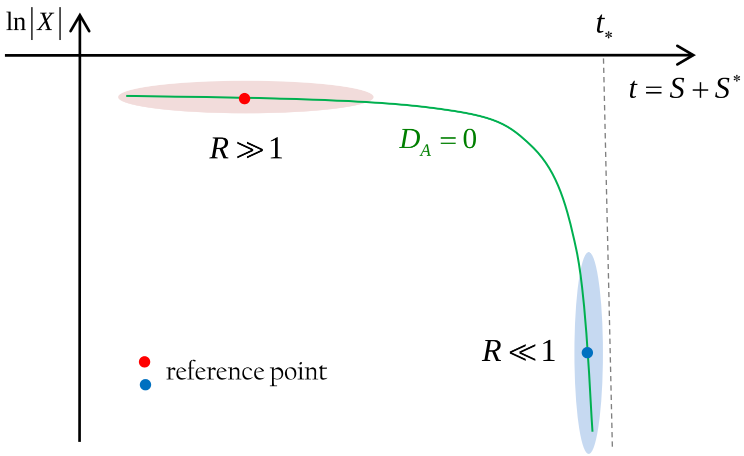
❖ Low energy effective theory

Integrating out heavy $U(1)_A$ vector superfield V_H : $M_A \geq M_{GS} \gg m_{3/2}$

SUSY theory of $\phi = aS - \ln X + (\text{constant})$ representing the D-flat direction

- Effects of V_H are to generate corrections to K.
- Useful to examine the vacuum and soft terms!

Careful! : ϕ_A depends on the expectation values of S and X.



e.o.m $\frac{\partial K}{\partial V_H} = 0$ in would-be unitary gauge

→ ET is valid in a limited region of ϕ, but still useful for examining large/small R.

$$\begin{cases} \phi_A \sim \ln X, & \text{for } R \gg 1 \\ \phi_A \sim aS, & \text{for } R \ll 1 \end{cases}$$

❖ Region with large R

Model of one string modulus $\tilde{S} = S - \frac{1}{a}\ln(X / X_{\bar{0}})$

$$K_{eff} \simeq K_0(\tilde{S} + \tilde{S}^*) - \tfrac{1}{a} K_0'(\tilde{S} + \tilde{S}^*), \quad W_{eff} = \omega_0 + A_{\bar{0}} e^{-a\tilde{S}}$$

with $A_{\bar{0}} = AX_{\bar{0}}$ (X ~ D-flat direction)

→ NP superpotential stabilizes $\tilde{S}$ at a SUSY minimum.

Sequestered uplifting to get a de-Sitter vacuum, as in KKLT

- e.o.m for V_H is not affected.
- Uplifting induces small vacuum shift, and consequently F^S :

$$\frac{F^{\tilde{S}}}{\tilde{S} + \tilde{S}^*} \simeq \frac{2m_{3/2}}{a\tilde{t}} = O\left(\frac{m_{3/2}}{\ln|A/\omega_0|}\right)$$ independently of the detailed form of K_0

→ Mirage mediation

F-term uplifting in extended model → Mixed gravity-gauge mediation

- $W = mX\chi \rightarrow W_{eff} = mX_{\bar{0}}\tilde{\chi}$: $\tilde{\chi}$ plays a role of the Polonyi field.

Dudas et al. JHEP0804,015 and 0903,011

❖ Region with small R

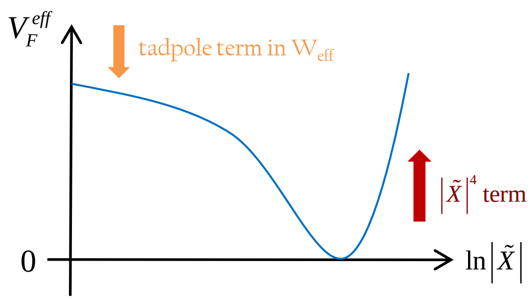
Polonyi Model $\tilde{X} = X e^{-a(S-S_{\bar{0}})}$

$$K_{eff} \simeq Z_X |\tilde{X}|^2 - \frac{1}{2}\frac{Z_X^2}{M_{GS}^2}|\tilde{X}|^4, \; W_{eff} = \omega_0 + m_{\bar{0}}^2 \tilde{X}$$

S ~ D-flat direction

$$\text{with } M_{GS}^2 = \frac{\delta_{GS}^2}{4} K_0''(S_{\bar{0}} + S_{\bar{0}}^*), \; m_{\bar{0}}^2 = A e^{-aS_{\bar{0}}}$$

- $|\tilde{X}|^4$ term in K_{eff} with negative coefficient lifts the potential. (sign : independent of q_X)



→ SUSY breaking minimum with C.C=0 at

$$|\tilde{X}| \simeq \frac{M_{GS}^2}{\sqrt{3}M_{Pl}} \quad \text{with} \quad \frac{F^{\tilde{X}}}{\tilde{X}} \simeq 3\left(\frac{M_{Pl}}{M_{GS}}\right)^2 m_{3/2}$$

Polonyi scalar mass : $O(m_{3/2} M_{Pl} / M_{GS})$

Gauge mediation with messengers : $\Phi + \Phi^c$ having $W = y_\Phi X \Phi \Phi^c$

Kitano, PLB641,203

- One loop potential by messenger Yukawa interactions can destabilize the vacuum.

$$\rightarrow \sum_\Phi y_\Phi^2 < 8\pi^2 \frac{M_{GS}}{M_{Pl}} \text{ needed to avoid it.}$$

❖ Soft terms in large R

Mirage mediation : MM~AM

- Mirage unification of gaugino masses at M_{mir}.

Choi et al. JHEP0509,039

- $M_{mir} \ll M_{GUT}$ in KKLT : Compressed low energy sparticle spectrum

Effects of integrating out V_H

$$\begin{cases} K_Q = Z_i \left|Q^i\right|^2 e^{2q_i V_A}, \\ W_Q = \frac{1}{6}\lambda_{ijk} X^{q_i+q_j+q_k} Q^i Q^j Q^k, \end{cases} \rightarrow \begin{cases} K_Q^{eff} \simeq Z_i \left(\frac{Z_X(\tilde{t})}{Z_X(t_0)} \frac{K_0'(t_0)}{K_0'(\tilde{t})} \right)^{q_i} \left|Q^i\right|^2, \\ W_Q^{eff} = \frac{1}{6}\lambda_{ijk} X_0^{q_i+q_j+q_k} Q^i Q^j Q^k. \end{cases} \quad (\tilde{t} = \tilde{S} + \tilde{S}^*)$$

Kaehler modulus : $K_0 = -n_0 \ln(S + S^* - \delta_{GS} V_A),\ \ Z_I = (S + S^* - \delta_{GS} V_A)^{-n_I},\ \ f_a = kS$

$$\Rightarrow \begin{cases} R = O(8\pi^2) \\ X_0 \sim M_{Pl}/\sqrt{8\pi^2} \end{cases}$$

- Sfermion soft terms are determined by effective modular weight : $n_i \rightarrow n_i^{eff} = n_i + q_i(1 - n_X)$
- Suppression of D-term contribution for $\frac{K_0'(\tilde{t})}{Z_X(\tilde{t})} = (\text{constant}) \Rightarrow n_X = 1$:

  → $U(1)_A$ as flavor symmetry accounting for hierarchical Yukawa couplings.

❖ Soft terms in small R

Polonyi Model : Gauge mediation + D-term contribution

$$\begin{cases} K_Q = Z_i \left|Q^i\right|^2 e^{2q_i V_A}, \\ W_Q = \tfrac{1}{6}\lambda_{ijk} X^{q_i+q_j+q_k} Q^i Q^j Q^k, \end{cases} \rightarrow K_Q^{eff} \simeq Z_i \left(1 + q_i \frac{\left|\tilde{X}\right|^2}{M_{GS}^2}\right)\left|Q^i\right|^2, \quad W_Q^{eff} = \tfrac{1}{6}\lambda_{ijk}\tilde{X}^{q_i+q_j+q_k} Q^i Q^j Q^k.$$

- Soft terms : $M_a\big|_{GM} = N_\Phi g_a^2 M_0, \quad \Delta m_i^2 = -q_i \frac{4}{3}\left(\frac{8\pi^2 M_{GS}}{M_{Pl}}\right)^2 M_0^2$ where $M_0 = -\frac{3}{2}\left(\frac{M_{Pl}}{8\pi^2 M_{GS}}\right)^2 8\pi^2 m_{3/2}$

e.g. a blowing up mode of orbifold fixed points

S describing singular limit of some cycle at which FI=0 : $K_0 \simeq \frac{1}{2}k_0^2\left(S + S^* - t_* - \delta_{GS}V_A\right)^2$

- For k_0=O(1), $M_{GS} \sim M_{GUT}$ and $R \sim (8\pi^2)^{-2}$.
- D-term contribution~ GM : Sparticles with TeV masses for $m_{3/2}$ in GeV range
- Small Higgs mu-term : $W = A_H e^{-aS} H_u H_d \rightarrow W_{eff} = \mu H_u H_d$

Sweet spot SUSY

Ibe and Kitano, JHEP0708,016

- Gauge mediation + Higgs sector having direct interactions with Polonyi field suppressed by Λ_s
- Global $U(1)_{PQ}$ broken only by Polonyi term : small mu and suppression of dangerous operators
- For $\Lambda_s \sim M_{GUT}$ (i.e. $m_{3/2}$~GeV), consistent quite well with various phenomenological and cosmological requirements

- Polonyi sector: same as ET from $U(1)_A$. Sfermion spectrum and the origin of mu: different.

4. Summary

❖ Summary

- In models with $U(1)_A$, SUSY breaking and its transmission crucially depend on the ratio R between the two mass scales generated by the GS mechanism ξ_{FI} and M_{GS}^2 .

- For the GS modulus stabilized by NP Polonyi term, one is led to mirage mediation for large R, while to sweet-spot SUSY for small R.

  In both cases, anomalous D-term gives a comparable contribution to soft scalar masses.

- The analysis of the vacuum and SUSY breaking becomes more clear and intuitive within the effective theory constructed by integrating out the $U(1)_A$ vector superfield.