Low Energy Supergravity Revisited

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Global Supersymmetry: Natural extension of the Standard Model

- Each SM state has a superpartner and the Higgs $\rightarrow$ 2 Higgses
- Supersymmetry breaking
  - (i) Spontaneously $\rightarrow$ phenomenologically problematic
  - (ii) Explicitly $\rightarrow$ phenomenologically acceptable

Soft-terms

Girardello and Grisaru - Nucl.Phys.B149 (1982) 65

- Renormalisability $\rightarrow$ soft divergences
- Used to phenomenological studies on Supersymmetry
  $\hookrightarrow$ Linear, bilinear (masses) and trilinear terms
- Two approaches
  - (i) Bottom-up
    - $\hookrightarrow$ put by hand
    - $\hookrightarrow$ weakly constrained phenomenology
  - (ii) Top-down
    - $\hookrightarrow$ generated dynamically
    - $\hookrightarrow$ strongly constrained phenomenology

Local Supersymmetry: Supergravity

- Gravity is naturally embedded
- Three fundamental functions
  - (i) Kähler potential K → characterises the kinetic terms of the scalar fields (among other things)
  - (ii) Superpotential W → characterises Yukawa-interactions between particles (among other things)
  - (iii) Kinetic gauge function f → characterises the kinetic terms for the gauge fields
- New sector added Z (hidden)
  - → neutral under SM gauge group
  - → used to break the supersymmetry

Three usual mechanisms in Supergravity breaking

Supersymmetry breaking (spontaneously) occurs in the hidden sector
and
communicated to the observable sector via soft-terms

- Gauge mediated
- Anomaly mediated
- Gravity mediated

Gravity mediation scenario

(i) Both sectors are coupled via Kähler Potential at Planck scale (m_p)

(ii) Supergravity is spontaneously broken in the hidden sector
- $\hookrightarrow$ Gravitino becomes massive: $m_{3/2}$ (Super-Higgs mechanism)
- $\hookrightarrow$ Generate soft terms for the observable sector

(iii) Low energy model by taking the limit $m_p \to \infty$
- $\hookrightarrow$ Interactions between hidden and observable sector are Planck suppressed
- $\hookrightarrow$ Gravitino mass becomes finite
- $\hookrightarrow$ Soft terms are scaled by gravitino mass

Soni & Weldon's approach

Phys.Lett. B126 (1983) 215

- Scalar Potential (F-terms)

$$V(Z,\Phi) = \exp\left(K/m_p^2\right)\left(\mathcal{D}_I W (K^{-1})^I{}_{J^*}\mathcal{D}^{J^*}\bar{W} - 3\left|\frac{W}{m_p}\right|^2\right) \quad \text{with} \quad \mathcal{D}_I W = \partial_I W + \frac{1}{m_p^2} W \partial_I K$$

- Constraint
  - $\to$ obtain a low energy model in the limit $m_p \to \infty$
  - $\to$ the observable sector Φ can never be multiplied by positive powers of m_p
- Assumptions ($Z = m_p z \to z$ is dimensionless)

$$K(z,z^\dagger,\Phi,\Phi^\dagger) = \sum_{n=0}^{N} m_p^n k_n(z,z^\dagger,\Phi,\Phi^\dagger) \qquad W(z,\Phi)) = \sum_{n=0}^{M} m_p^n W_n(z,\Phi)$$

Gravity mediation scenario

(i) Both sectors are coupled via Kähler Potential at Planck scale (m_p)

(ii) Supergravity is spontaneously broken in the hidden sector
 ↪ Gravitino becomes massive: $m_{3/2}$ (Super-Higgs mechanism)
 ↪ Generate soft terms for the observable sector

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- Constraint
 → obtain a low energy model in the limit $m_p \to \infty$
 → the observable sector Φ can never be multiplied by positive powers of m_p

- Solution

$$\begin{aligned} K(z,z^\dagger,\Phi,\Phi^\dagger) &= m_p^2 k_2(z,z^\dagger) + m_p k_1(z,z^\dagger) + k_0(z,z^\dagger,\Phi,\Phi^\dagger) \\ W(z,\Phi) &= m_p^2 W_2(z) + m_p W_1(z) + W_0(z,\Phi) \end{aligned}$$

Soni & Weldon's approach

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- Canonical Kähler potential

$$\begin{aligned} K(z, z^\dagger, \Phi, \Phi^\dagger) &= m_p^2 z^i z_i^\dagger + \Phi^a \Phi_a^\dagger \\ W(z, \Phi) &= m_p^2 W_2(z) + m_p W_1(z) + W_0(z, \Phi) \end{aligned}$$

- Non-canonical Kähler potential

$$\begin{aligned} K(z, z^\dagger, \Phi, \Phi^\dagger) &= m_p^2 k_2(z, z^\dagger) + m_p k_1(z, z^\dagger) + k_0(z, z^\dagger, \Phi, \Phi^\dagger) \\ W(z, \Phi) &= m_p^2 W_2(z) + m_p W_1(z) + W_0(z, \Phi) \end{aligned}$$

Since 1983

Soni & Weldon's solution

↓

Analytic expression of soft-terms

↓

Phenomenological studies at low energy

Scalar Potential - Canonical Kähler Potential

$$V(Z,\Phi) = \exp\left(K/m_p^2\right)\left(\mathcal{D}_I W (K^{-1})^I{}_{J^*}\mathcal{D}^{J^*}\bar{W} - 3\left|\frac{W}{m_p}\right|^2\right) \quad \text{with} \quad \mathcal{D}_I W = \partial_I W + \frac{1}{m_p^2} W \partial_I K$$

→ tower of differential equations where all positive powers of m_p should be $\Phi, \Phi^\dagger$ independent.

$$\begin{aligned} V \quad = \quad & \exp\left(K/m_p^2\right) \sum_{c\geq 0} m_p^c \Bigg\{ \sum_{0\leq m\leq c} \frac{\partial W_m}{\partial \Phi^a}\frac{\partial \bar{W}_{c-m}}{\partial \Phi_a^\dagger} + \sum_{0\leq m\leq c+4} W_m \bar{W}_{c-m+4}\Phi_a^\dagger \Phi^a \\ + \quad & \sum_{0\leq m\leq c+2}\Bigg(\left(\frac{\partial W_m}{\partial z^i} + z_i^\dagger W_m\right)\left(\frac{\partial \bar{W}_{c-m+2}}{\partial z_i^\dagger} + z^i \bar{W}_{c-m+2}\right) \\ & + \Phi^a \frac{\partial W_m}{\partial \Phi^a}\bar{W}_{c-m+2} + \Phi_a^\dagger \frac{\partial \bar{W}_m}{\partial \Phi_a^\dagger} W_{c-m+2} - 3 W_m \bar{W}_{c-m+2}\Bigg)\Bigg\} \end{aligned}$$

Scalar Potential - Canonical Kähler Potential

$$V(Z,\Phi) = \exp\left(K/m_p^2\right)\left(\mathcal{D}_I W (K^{-1})^I{}_{J^*}\mathcal{D}^{J^*}\bar{W} - 3\left|\frac{W}{m_p}\right|^2\right) \text{ with } \mathcal{D}_I W = \partial_I W + \frac{1}{m_p^2} W \partial_I K$$

→ tower of differential equations where all positive powers of m_p should be Φ,$\Phi^\dagger$ independent.

Proposition

Let $P(z)$, $Q(z)$ and $R(z)$ be three holomorphic functions such that $P \neq 0$, then if we have the following identity

$$\left(\frac{dQ}{dz^i} + z_i^\dagger Q\right)\left(\frac{d\bar{P}}{dz_i^\dagger} + z^i \bar{P}\right) - 2Q\bar{P} + R\bar{Q} = 0$$

then

$$Q = 0$$

Resolution of the tower of differential equations

Two solutions possible:

(i) Soni & Weldon's solution

(ii) A new solution

Soni & Weldon's solution

- Kähler potential

$$\begin{aligned} K(z, z^\dagger, \Phi, \Phi^\dagger) &= m_p^2 z^i z_i^\dagger + \Phi^a \Phi_a^\dagger \\ W(z, \Phi) &= m_p^2 W_2(z) + m_p W_1(z) + W_0(z, \Phi) \end{aligned}$$

- Non-canonical Kähler potential → Superpotential unchanged

New solution

- Canonical Kähler potential (S-fields are supposed to be observable)

$$\begin{aligned} K(z, z^\dagger, S, S^\dagger, \Phi, \Phi^\dagger) &= m_p^2 z^i z_i^\dagger + S^p S_p^\dagger + \Phi^a \Phi_a^\dagger \\ W(z, \Phi) &= m_p \left[W_1(z) + S^p W_{1,p}(z)\right] + S^p W_{0,p}(z) + W_0(z, \Phi) \end{aligned}$$

- Non-canonical Kähler potential → 4 new solutions listed

(i) Inspired by No-Scale model

$$\begin{aligned} K(z, z^\dagger, \Phi, \Phi^\dagger) &= m_p^2 k_2(z, z^\dagger, \Phi, \Phi^\dagger) + k_0(z, z^\dagger, \Phi, \Phi^\dagger) \\ W(z, \Phi) &= m_p^2 W_2(z, \Phi) + W_0(z, \Phi) \end{aligned}$$

$$G_2 = k_2 + \ln \left| \frac{W_2}{m_p} \right|^2 \rightarrow \partial_I G_2 (G_2^{-1})^I{}_{J*} \partial^{J*} G_2 = 3$$

New solution

$$
\begin{aligned}
K(z, z^\dagger, S, S^\dagger, \Phi, \Phi^\dagger) &= m_p^2 z^i z_i^\dagger + S^p S_p^\dagger + \Phi^a \Phi_a^\dagger \\
W(z, \Phi) &= m_p \left[W_1(z) + S^p W_{1,p}(z)\right] + S^p W_{0,p}(z) + W_0(z, \Phi)
\end{aligned}
$$

Main features

- Introduction of a new field $\rightarrow$ S-fields (can take a vev)
- S-fields share properties of two other sectors
  - (i) Observable
    $\rightarrow$ Planck suppressed when $m_p \rightarrow \infty$
  - (ii) Hidden
    $\rightarrow$ neutral under SM gauge group
    $\rightarrow$ directly coupled with m_p (in W definition)

SW solution New solution

$$
m_{3/2} = \frac{1}{m_p^2} \langle W \exp\left(K/2m_p^2\right) \rangle
$$

New solution

$$K(z,z^\dagger,S,S^\dagger,\Phi,\Phi^\dagger) = m_p^2 z^i z_i^\dagger + S^p S_p^\dagger + \Phi^a \Phi_a^\dagger$$
$$W(z,\Phi) = m_p\left[W_1(z) + S^p W_{1,p}(z)\right] + S^p W_{0,p}(z) + W_0(z,\Phi)$$

Main features

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SW solution

$$m_{3/2}^{SW} \sim \left\langle W_2 \exp\left(z^i z_i^\dagger/2\right) \right\rangle \sim M$$

New solution

$$m_{3/2}^{MRT} \sim \frac{1}{m_p}\left\langle \left(W_1 + S^p W_{1,p}\right) \exp\left(z^i z_i^\dagger/2\right) \right\rangle \sim M^2/m_p$$

New solution

$$
\begin{aligned}
K(z,z^\dagger,S,S^\dagger,\Phi,\Phi^\dagger) &= m_p^2 z^i z_i^\dagger + S^p S_p^\dagger + \Phi^a \Phi_a^\dagger \\
W(z,\Phi) &= m_p\left[W_1(z) + S^p W_{1,p}(z)\right] + S^p W_{0,p}(z) + W_0(z,\Phi)
\end{aligned}
$$

Main features

- Introduction of a new field $\rightarrow$ S-fields (can take a vev)
- S-fields share properties of two other sectors
  - (i) Observable
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    - $\rightarrow$ neutral under SM gauge group
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SW solution

- $m_{3/2}^{SW} \sim M$
- soft-terms $\rightarrow$ scaled by $m_{3/2}$

New solution

- $m_{3/2}^{MRT} \sim M^2/m_p$
- soft-terms $\rightarrow$ scaled by $m_{3/2}$

Work in progress - Model-building

$$W(z,\Phi) = m_p\,[W_1(z) + S^p\,W_{1,p}(z)] + S^p\,W_{0,p}(z) + W_0(z,\Phi)$$

- Mass scale: $[W] = M^3$
  - $\rightarrow [W_1] = M_1^2$, $[W_{1,p}] = M_2$, $[W_{0,p}] = M_3^2$ and $[W_0] = M_4^3$
    - $\hookrightarrow$ Some fundamental scales: M_{SUSY}, M_{GUT} ?
- Vacuum energy constraint
  - $\rightarrow$ Cosmological constant value: $V\Big|_{z^i=\langle z^i\rangle, S^p=\langle S^p\rangle} = 0$
  - $\rightarrow$ Minimisation: $\frac{\partial V}{\partial S^p}\Big|_{z^i=\langle z^i\rangle, S^p=\langle S^p\rangle} = 0$ and $\frac{\partial V}{\partial z^i}\Big|_{z^i=\langle z^i\rangle, S^p=\langle S^p\rangle} = 0$
- First approximation: $M_1 = M_2 = M_3 = M_4 = M$
  - $\rightarrow$ Consistency of the $\langle S\rangle$-scale (by assumptions, suppressed by Planck scale m_p)
    - $\hookrightarrow W_{1,p}(\langle z^i\rangle) = \left(\partial W_{1,p}/\partial z^i\right)\Big|_{z^i=\langle z^i\rangle} = 0$
- $\langle S\rangle \sim M$
  - $\rightarrow m_S = 0$ at leading order in powers of M/mp and $m_S \neq 0$ at NLO
  - $\rightarrow$ Planck suppressed coupling with the observable sector Φ

Conclusion - Gravity-mediated supersymmetry breaking

- Canonical Kähler potential K
  - $\rightarrow$ 1 new solution
  - $\rightarrow$ Some phenomenological consequences (gravitino mass, S-fields, etc)
  - $\rightarrow$ Model-building based on the new S-fields
- Non-canonical Kähler potential K
  - $\rightarrow$ 4 new solutions with one inspired by No-scale model
  - $\rightarrow$ μ-problem: the solution à la Giudice-Masiero remains valid (among other things)

Perspectives

- Finish the Model-building based on the S-fields
- Phenomenological study of the new solution inspired by No-scale model

$$V(z,\Phi) = \exp\left(K/m_p^2\right)\left(\mathcal{D}_I W (K^{-1})^I{}_{J^*}\mathcal{D}^{J^*}\bar{W} - 3\left|\frac{W}{m_p}\right|^2\right)$$

$$\begin{aligned} V \quad = \quad & \exp\left(K/m_p^2\right)\sum_{c\geq 0} m_p^c \Bigg\{ \sum_{0\leq m\leq c}\frac{\partial W_m}{\partial\Phi^a}\frac{\partial \bar{W}_{c-m}}{\partial\Phi_a^\dagger} + \sum_{0\leq m\leq c+4} W_m \bar{W}_{c-m+4}\Phi_a^\dagger\Phi^a \\ + \quad & \sum_{0\leq m\leq c+2}\Bigg(\left(\frac{\partial W_m}{\partial z^i} + z_i^\dagger W_m\right)\left(\frac{\partial \bar{W}_{c-m+2}}{\partial z_i^\dagger} + z^i \bar{W}_{c-m+2}\right) \\ & + \ \Phi^a\frac{\partial W_m}{\partial\Phi^a}\bar{W}_{c-m+2} + \Phi_a^\dagger\frac{\partial \bar{W}_m}{\partial\Phi_a^\dagger}W_{c-m+2} - 3W_m\bar{W}_{c-m+2}\Bigg)\Bigg\} \end{aligned}$$

For $M > 0$:

$\rightarrow c = 2M$

$$\frac{\partial W_M}{\partial\Phi^a}\frac{\partial \bar{W}_M}{\partial\Phi_a^\dagger} \sim_\Phi 0$$

$$\hookrightarrow W_M(z,\Phi) = W_{M,0}(z) + \Phi^a W_{M,a}(z)$$

$\rightarrow c = 2M-1$

$$\frac{\partial W_M}{\partial\Phi^a}\frac{\partial \bar{W}_{M-1}}{\partial\Phi_a^\dagger} + \frac{\partial W_{M-1}}{\partial\Phi^a}\frac{\partial \bar{W}_M}{\partial\Phi_a^\dagger} \sim_\Phi 0$$

$$\hookrightarrow W_{M-1}(z,\Phi) = W_{M-1,0}(z) + \Phi^a W_{M-1,a}(z)$$

$$V(z,\Phi) = \exp\left(K/m_p^2\right)\left(\mathcal{D}_I W (K^{-1})^I{}_{J^*}\mathcal{D}^{J^*}\bar{W} - 3\left|\frac{W}{m_p}\right|^2\right)$$

$$\begin{aligned} V \;=\; & \exp\left(K/m_p^2\right)\sum_{c\geq 0} m_p^c \Bigg\{ \sum_{0\leq m\leq c} \frac{\partial W_m}{\partial \Phi^a}\frac{\partial \bar{W}_{c-m}}{\partial \Phi_a^\dagger} + \sum_{0\leq m\leq c+4} W_m \bar{W}_{c-m+4}\Phi_a^\dagger \Phi^a \\ + & \sum_{0\leq m\leq c+2}\Bigg(\left(\frac{\partial W_m}{\partial z^i} + z_i^\dagger W_m\right)\left(\frac{\partial \bar{W}_{c-m+2}}{\partial z_i^\dagger} + z^i \bar{W}_{c-m+2}\right) \\ & + \Phi^a \frac{\partial W_m}{\partial \Phi^a}\bar{W}_{c-m+2} + \Phi_a^\dagger \frac{\partial \bar{W}_m}{\partial \Phi_a^\dagger} W_{c-m+2} - 3 W_m \bar{W}_{c-m+2}\Bigg)\Bigg\} \end{aligned}$$

Case: $M = 1$

We obtain the new solution: $W(z,\Phi) = m_p\left[W_1(z) + \Phi^a W_{1a}(z)\right] + W_0(z) + \Phi^a W_{0a}(z)$

$\rightarrow c = 2M - 2$, we split the differential equation using holomorphic properties

$$\left(\frac{\partial W_{M,a}}{\partial z^i} + z_i^\dagger W_{M,a}\right)\left(\frac{\partial \bar{W}_M{}^a}{\partial z_i^\dagger} + z^i \bar{W}_M{}^a\right) = W_{M,a}\bar{W}_M{}^a$$

$$\hookrightarrow W_{M,a}(z) = 0 \Rightarrow W_M(z,\Phi) = W_{M,0}(z)$$

$\rightarrow c = 2M - 3$

$$W_{M-2,ab}\bar{W}_{M-1}{}^b + \left(\frac{\partial W_{M-1,a}}{\partial z^i} + z_i^\dagger W_{M-1,a}\right)\left(\frac{\partial \bar{W}_{M,0}}{\partial z_i^\dagger} + z^i \bar{W}_{M,0}\right) - 2W_{M-1,a}\bar{W}_{M,0} = 0$$

$$\hookrightarrow \text{as } W_{M,0} \neq 0 \Rightarrow W_{M-1,a}(z) = 0 \Rightarrow W_{M-1}(z,\Phi) = W_{M-1,0}(z)$$

For $M = 2$:

$\rightarrow c = 4 : W_M(z,\Phi) = W_{M,0}(z) + \Phi^a W_{M,a}(z)$

$\rightarrow c = 3 : W_{M-1}(z,\Phi) = W_{M-1,0}(z) + \Phi^a W_{M-1,a}(z)$

$\rightarrow c = 2 : W_{M,a}(z) = 0 \Rightarrow W_M(z,\Phi) = W_{M,0}(z)$

$\rightarrow c = 1 : W_{M,0} \neq 0 \Rightarrow W_{M-1,a}(z) = 0 \Rightarrow W_{M-1}(z,\Phi) = W_{M-1,0}(z)$

Case: $M = 2$

We obtain the solution found by Soni & Weldon: $W(z,\Phi) = m_p^2 W_2(z) + m_p W_1(z) + W_0(z,\Phi)$

For $M > 2$:

$\rightarrow c = 2M : W_M(z,\Phi) = W_{M,0}(z) + \Phi^a W_{M,a}(z)$
$\rightarrow c = 2M-1 : W_{M-1}(z,\Phi) = W_{M-1,0}(z) + \Phi^a W_{M-1,a}(z)$
$\rightarrow c = 2M-2 : W_{M,a}(z) = 0 \Rightarrow W_M(z,\Phi) = W_{M,0}(z)$
$\rightarrow c = 2M-3 : W_{M,0} \neq 0 \Rightarrow W_{M-1,a}(z) = 0 \Rightarrow W_{M-1}(z,\Phi) = W_{M-1,0}(z)$
$\rightarrow c = 2M-4 :$

$$\frac{\partial W_{M-2}}{\partial \Phi^a}\frac{\partial \bar{W}_{M-2}}{\partial \Phi_a^\dagger} + \left(\frac{\partial W_{M,0}}{\partial z^i} + z_i^\dagger W_{M,0}\right)\left(\frac{\partial \bar{W}_{M-2}}{\partial z_i^\dagger} + z^i \bar{W}_{M-2}\right) - 3W_{M,0}\bar{W}_{M-2}$$
$$+\left(\frac{\partial W_{M-1,0}}{\partial z^i} + z_i^\dagger W_{M-1,0}\right)\left(\frac{\partial \bar{W}_{M-1,0}}{\partial z_i^\dagger} + z^i \bar{W}_{M-1,0}\right) - 3W_{M-1,0}\bar{W}_{M-1,0}$$
$$+\left(\frac{\partial W_{M-2}}{\partial z^i} + z_i^\dagger W_{M-2}\right)\left(\frac{\partial \bar{W}_{M,0}}{\partial z_i^\dagger} + z^i \bar{W}_{M,0}\right) + \left(\Phi^a\frac{\partial W_{M-2}}{\partial \Phi^a} + \text{h.c.}\right) - 3W_{M-2}\bar{W}_{M,0}$$
$$+\Phi^a\Phi_a^\dagger W_{M,0}\bar{W}_{M,0} \sim_\Phi = 0\ .$$

$$W_{M-2}(z,\Phi) = \frac{1}{2}\Phi^a\Phi^b W_{M-2,ab}(z) + \Phi^a W_{M-2,a}(z) + W_{M-2,0}(z)$$

$$\left|W_{M,0}\right|^2 + \sum_b \left|W_{M-2,ab}\right|^2 = 0$$

$$\Rightarrow W_{M,0}(z) = W_{M-2,ab}(z) = 0 \Rightarrow \text{contradiction}$$

Soni & Weldon solution

$$K(z,z^\dagger,\Phi,\Phi^\dagger) = m_p^2 K_2(z,z^\dagger) + m_p K_1(z,z^\dagger) + K_0(z,z^\dagger,\Phi,\Phi^\dagger)$$
$$W(z,\Phi) = m_p^2 W_2(z) + m_p W_1(z) + W_0(z,\Phi)$$

New solutions

$$(i) \quad \begin{cases} K(z,z^\dagger,\Phi,\Phi^\dagger) = m_p^2 K_2(z,z^\dagger) + m_p K_1(z,z^\dagger) + K_0(z,z^\dagger,\Phi,\Phi^\dagger) \\ W(z,\Phi) = m_p\left[W_1(z) + \Phi^a W_{1a}(z)\right] + \Phi^a W_{0a}(z) + W_0(z) \end{cases}$$

$$(ii) \quad \begin{cases} K(z,z^\dagger,\Phi,\Phi^\dagger) = m_p^2 K_2(z,z^\dagger) + m_p K_1(z,z^\dagger,\Phi,\Phi^\dagger) + K_0(z,z^\dagger,\Phi,\Phi^\dagger) \\ W(z,\Phi) = m_p\left[W_1(z) + \Phi^a W_{1a}(z)\right] + W_0(z,\Phi) \end{cases}$$

$$(iii) \quad \begin{cases} K(z,z^\dagger,\Phi,\Phi^\dagger) = m_p^2 K_2(z,z^\dagger,\Phi,\Phi^\dagger) + m_p K_1(z,z^\dagger,\Phi,\Phi^\dagger) + K_0(z,z^\dagger,\Phi,\Phi^\dagger) \\ W(z,\Phi) = m_p W_1(z,\Phi) + W_0(z,\Phi) \end{cases}$$

$$(iv) \quad \begin{cases} K(z,z^\dagger,\Phi,\Phi^\dagger) = m_p^2 K_2(z,z^\dagger,\Phi,\Phi^\dagger) + K_0(z,z^\dagger,\Phi,\Phi^\dagger) \\ W(z,\Phi) = m_p^2 W_2(z,\Phi) + W_0(z,\Phi) \end{cases}$$

Inspired by
No-scale model

No-Scale Model

$$V(z,\Phi) = \exp\left(K/m_p^2\right)\left(\mathcal{D}_I W (K^{-1})^I{}_{J^*}\mathcal{D}^{J^*}\bar{W} - 3\left|\frac{W}{m_p}\right|^2\right)$$

$$K(z,z^\dagger,\Phi,\Phi^\dagger) \qquad \text{and} \qquad W(z,\Phi)$$

$$\mathcal{G} = K + m_p^2 \ln\left|\frac{W}{m_p}\right|^2$$

$$V = m_p^2 e^{\frac{\mathcal{G}}{m_p^2}}\left(\mathcal{G}_I(\mathcal{G}^{-1})^I{}_{J*}\mathcal{G}^{J*} - 3m_p^2\right)$$

$$\mathcal{G}_I(\mathcal{G}^{-1})^I{}_{J*}\mathcal{G}^{J*} = 3m_p^2 \Rightarrow V = 0$$

$\rightarrow$ cosmological constant is equal to zero at tree-level of geometrical way.