Anomaly Mediated Supersymmetry Breaking Demystified

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Spontaneous Supersymmetry Breaking

- Hamiltonian

$$H = P^0 = \frac{1}{4}\left(Q_1 Q_1^\dagger + Q_1^\dagger Q_1 + Q_2 Q_2^\dagger + Q_2^\dagger Q_2\right).$$

- SUSY breaking means that vacuum $|0\rangle$ is not invaraint under SUSY transformations,

$$Q_\alpha|0\rangle \neq 0 \quad \text{and} \quad Q^\dagger_{\dot{\alpha}}|0\rangle \neq 0.$$

- So the vacuum energy is **positive** in the case of Spontaneous SUSY breaking.

$$\langle 0|H|0\rangle > 0.$$

Hidden Sector SUSY breaking

- Visible sector SUSY breaking is not viable. For instance,

$$m_{\tilde{e}_1}^2 + m_{\tilde{e}_2}^2 = 2m_e^2,$$

  is not acceptable.

- SUSY is broken in the hidden sector, and its effect is mediated to the visible sector.

  $\longrightarrow$ Mediation mechanism is required.

Hidden Sector SUSY breaking

- Planck-scale-mediated SUSY breaking (PMSB).

$$m_{soft} \sim \frac{\langle F \rangle}{M_P}, \quad \sqrt{\langle F \rangle} \sim 10^{10} - 10^{11}\ \mathrm{GeV}.$$

$\longrightarrow m_{soft} \sim \frac{\Lambda^3}{M_P^2}$, for gaugino condensation. $\Lambda \sim 10^{13}$ GeV.

Hidden Sector SUSY breaking

- Gauge-mediated SUSY breaking (GMSB).

$\longrightarrow$ Messengers : New chiral supermultiplets those couple to SUSY breaking VEV $\langle F \rangle$ and also have gauge interaction.

$\longrightarrow$ Soft SUSY breaking terms are derived from the loop diagrams involving some messenger particle.

$$m_{soft} \sim \frac{\alpha_a}{4\pi} \frac{\langle F \rangle}{M_{mess}}$$

$\longrightarrow$ Flavor blind (No FCNC) and $\sqrt{\langle F \rangle} \sim 10^4$ GeV.

Anomaly Mediated Supersymmetry Breaking (AMSB)

- SUSY breaking source is only non-zero $\langle F \rangle$ (Superconformal compensator).
- Assume that no dimensionful parameters in the action.
  $\rightarrow$ SUSY breaking is not tranmitted to the visible sector.
- But in the anomaly loop, SUSY breaking is manifest.

Conformal Anomaly - Massless QCD

- For scale transformations $x \longrightarrow e^{\varrho} x$,

$$
\begin{aligned}
q_j(x) &\longrightarrow e^{3\varrho/2} q_j(e^{\varrho} x), \\
A^a_m(x) &\longrightarrow e^{\varrho} A^a_m(e^{\varrho} x).
\end{aligned}
$$

- The current is J^m_{scale},

$$
J^m_{\mathrm{scale}} = x_n T^{mn}, \quad \partial_m J^m_{\mathrm{scale}} = T^n_n = 0,
$$

- By quantum effect, non-zero trace is generated,

$$
\check{S}_{\mathrm{eff}} = \int d^4 x \varrho \, T^m_m, \quad T^m_m = \frac{\beta_{\mathrm{QCD}}(g)}{2g} F^a_{nl} F^{anl},
$$

Chiral Anomaly Supermultiplet and Chiral compensator

- In conformal supergravity, the gravitational superfield is

$$\mathcal{H}^m(x,\theta,\bar\theta) = \theta\sigma^a\bar\theta e_a^m(x) + \frac{i}{2}\bar\theta\bar\theta\theta\psi^m(x) - \frac{i}{2}\theta\theta\bar\theta\bar\psi^m(x) + \frac{1}{4}\theta\theta\bar\theta\bar\theta\hat\nu^m(x).$$

  Here $\hat\nu^m(x)$, $e_a^m(x)$ and $\psi_\alpha^m(x)$ are a $U(1)_R$ gauge transformations, vierbein and gravitino, respectively, with DOF 3,5, and 8.

- This multiplet couples to supercurrents, - energy momentum tensor T_{mn}, supersymmetry current S_α^m (along with its conjugate, $\bar S_{\dot\alpha}^m$) and R-current j_m^R.

Chiral Anomaly Supermultiplet and Chiral compensator

- Suppose that they are anomalous,

$$\xi_\alpha \equiv \gamma_m S^m_\alpha \neq 0, \quad \mathring{t} \equiv T^m_m \neq 0, \quad \mathring{r} \equiv \partial^m j^R_m \neq 0.$$

- They form chiral anomlay supermultiplet with auxiliary fields a and b,

$$\mathcal{X}(x,\theta) \equiv \mathcal{A}(x) + \sqrt{2}\theta\xi(x) + \theta\theta\mathcal{F}(x), \quad \bar{D}\mathcal{X} = 0,$$

where $\mathcal{A} = a + ib$ and $\mathcal{F} = \mathring{t} + i\mathring{r}$

Chiral Anomaly Supermultiplet and Chiral compensator

- Superfield which couples to CASM?

  $\longrightarrow$ the trace anomaly $\mathring{t}$ - dilaton, $\varrho(x) = 1/2 \ln \det[e_a^m]$.
  $\longrightarrow$ the $U(1)_R$ anomaly $\mathring{r}$ - the local R-symmetry, $\delta(x)$ (NGB of $U(1)_R$).
  $\longrightarrow$ the supersymmetry anomaly ξ_α - the dilatino ($\sim \bar{\Psi}_\alpha(x) = \sigma_m^{\alpha\dot{\alpha}} \bar{\psi}_{\dot{\alpha}}^m(x)$).

- So, the chiral compensator,

$$\chi^3(x,\theta) \equiv e^{2\varrho(x)+2i\delta(x)}[1+\sqrt{2}\theta\bar{\Psi}(x)+\theta\theta M^*(x)],$$

Chiral Anomaly Supermultiplet and Chiral compensator

- Chiral compensator is invrinat measure,

$$d^4x' d^2\theta' \chi'^3(x',\theta') = d^4x d^2\theta \chi^3(x,\theta).$$

- We can comprehend this property by decomposing the chiral compensator as

$$d^4x d^2\theta \chi^3(x,\theta) = \left\{ d^4x\, e^{2\varrho(x)} \right\} \left\{ d^2\theta\, e^{2i\delta(x)} [1+\sqrt{2}\theta^\alpha \bar{\Psi}_\alpha(x) + \theta\theta M^*(x)] \right\}.$$

- Invarinat measure+trace anomaly $\rightarrow$ Action,

$$S_{\mathcal{X}} = \int d^4x\, d^2\theta\, \chi^3(x,\theta) \mathcal{X}(x,\theta) + c.c.$$

Chiral Anomaly Supermultiplet and Chiral compensator

- Effective theory viewpoints,

$$\varphi(x,\theta) = M_{\rm pl}\,\chi^3(x,\theta) = M_{\rm pl} e^{2\varrho+2i\delta}[1+\sqrt{2}\theta^\alpha\bar{\Psi}_\alpha + \theta\theta M^*].$$

$$S_{\mathcal{X}} = \int d^4x\, d^2\theta \frac{1}{M_{\rm pl}}\varphi(x,\theta)\mathcal{X}(x,\theta) + c.c.$$

- Non-vanishing VEV $\langle\varphi\rangle/M_{\rm pl} = 1+\theta\theta\langle M\rangle$ (with $\langle\varrho\rangle = \langle\delta\rangle = 0$) leads to soft terms in the visible sector.
- Component fields,

$$S_{\mathcal{X}} = \int d^4x\,[e^{2\varrho+2i\delta}(M^*\mathcal{A} + \bar{\Psi}\xi + \mathcal{F}) + c.c.].$$

$\rightarrow$ First term with nonzero vev M leads soft term.
$\rightarrow$ $\langle\delta\rangle - F\widetilde{F} \sim$ axion

Linear Anomaly Supermultiplet and Vector Superfield

- Assume that

$$\partial^m j_m^R = 0,$$
$$\xi_\alpha = \gamma_m S_\alpha^m \neq 0, \quad \mathring{t} = T_m^m \neq 0.$$

- j_m^R, ξ_α, and $\mathring{t}$ form Linear Anomaly supermultiplet(LASM).

- Most generally, LASM is written

$$\begin{aligned} L(x,\theta,\bar\theta) \quad = \quad & C(x) + i\theta\Xi - i\bar\theta\bar\Xi + \theta\sigma^m\bar\theta j_m^R(x) \\ & -\frac{1}{2}\theta\theta\bar\theta\bar\sigma^m\partial_m\Xi(x) - \frac{1}{2}\bar\theta\bar\theta\theta\sigma^m\partial_m\bar\Xi(x) - \frac{1}{4}\theta\theta\bar\theta\bar\theta\,\Box C(x). \end{aligned}$$

- $\mathring{t} \sim \Box C, \quad \xi_\alpha \sim \sigma^m_{\alpha\dot\alpha}\partial_m\bar\Xi^{\dot\alpha}.$

Linear Anomaly Supermultiplet and Vector Superfield

- Couples what? - Using the following supersymmetric generalization of $U(1)_R$ gauge transformations:

$$\mathcal{V} \to \mathcal{V} + \Lambda + \Lambda^+,$$

with Λ being a chiral field ($\bar{D}\Lambda = 0$).

- The most generally,

$$\begin{aligned}
\mathcal{V}(x,\theta,\bar{\theta}) &= s(x) + i\theta\omega(x) - i\bar{\theta}\bar{\omega}(x) \\
&+\frac{i}{2}\theta\theta[p(x)+iq(x)] - \frac{i}{2}\bar{\theta}\bar{\theta}[p(x)-iq(x)] \\
&-\theta\sigma^m\bar{\theta}\nu_m(x) + i\theta\theta\bar{\theta}[\bar{\tau}(x) + \frac{i}{2}\bar{\sigma}^m\partial_m\omega(x)] \\
&-i\bar{\theta}\bar{\theta}\theta[\tau(x) + \frac{i}{2}\sigma^m\partial_m\bar{\omega}(x)] + \frac{1}{2}\theta\theta\bar{\theta}\bar{\theta}[\mathbf{d}(x) + \frac{1}{2}\Box s(x)].
\end{aligned}$$

Linear Anomaly Supermultiplet and Vector Superfield

- In the Wess-Zumino gauge where $s = \omega = p = q = 0$,and we identify ν_m, τ_α and $\mathbf{d}$ are the gauge field, gaugino, and D-term, respectively, for $U(1)_R$.

- $U(1)_R$ gauge transformations

$$\nu_m \to \nu_m - i\partial_m(\Lambda| - \Lambda^+|).$$

Note that $\mathbf{d}$ and τ_α are gauge invariant component fields in $\mathcal{V}$. $\sim$ dilaton and dilatino?

Linear Anomaly Supermultiplet and Vector Superfield

- Roughly, we can identify

$$\begin{aligned} \nu_{\alpha\dot{\alpha}} &= \Psi_\alpha \bar{\Psi}_{\dot{\alpha}}, \\ \tau_\alpha &= \bar{\Psi}_\alpha M, \\ \mathbf{d} &= M^* M, \end{aligned}$$

where $\nu_{\alpha\dot{\alpha}} = \nu_m \sigma^m_{\alpha\dot{\alpha}}$.

- The action is

$$S_L = \int d^4x d^2\theta d^2\bar{\theta}\, \mathcal{V} L.$$

Remind that $[\mathcal{V}] = 0$ and $[L] = 2$.

Linear Anomaly Supermultiplet and Vector Superfield

- This transforms as

$$\int d^4x d^4\theta\, \mathcal{V} L \to \int d^4x d^4\theta\, (\mathcal{V} + \Lambda + \Lambda^+) L,$$
$$= \int d^4x d^4\theta\, \mathcal{V} L + \int d^4x d^2\theta \Lambda(\bar{D}^2 L) + \int d^4x d^2\bar{\theta} \Lambda^+ (D^2 L).$$

- The condition should be satified

$$D^2 L = \bar{D}^2 L = 0,$$

L is anything but *the R-current superfield*.

Linear Anomaly Supermultiplet and Vector Superfield

- Component fields,

$$S_L = \int d^4x \, (\nu^m j_m^R + \frac{1}{2} \mathbf{d} \, C + \tau \, \Xi + \bar{\tau} \, \bar{\Xi}).$$

$\rightarrow$ The second term is only relavant for the soft sfermion masses. (footprints of conformal anomaly)

The MSSM

- Set $\langle M^* \rangle = m_{3/2}$ and $\mathbf{d} = m_{3/2}^2$.
- The action,

$$S = \int d^4x\, d^2\theta d^2\bar{\theta}\, \phi_i^{+} e^{2gV} \phi_i + \left[\int d^4x\, d^2\theta \left(\frac{1}{4} W^{a\alpha} W^a_\alpha + \frac{1}{3!} y^{ijk} \phi_i\phi_j\phi_k \right) + h.c. \right].$$

The MSSM

- CASM from the gauge kinetic term, with the supersymmetrization of massless QCD,

$$\mathcal{X} = \frac{\beta(g)}{2g} W^{a\alpha} W^a_\alpha,$$

$$\beta(g) = -\frac{g^3}{16\pi^2}[3C_2(G) - FC_2(\mathcal{R})],$$

where $C_2(G) = N$ and $C_2(\mathcal{R}) = 1/2$ for $SU(N)$. Then

$$M_\lambda = \frac{\beta(g)}{g} m_{3/2}.$$

The MSSM

- CASM form Yukawa interaction.

$$S_{\rm eff} = \int d^4x\, d^2\theta\, \frac{1}{3!}\, y^{ijk}\left\{\frac{1}{32\pi^2}[y^{*irs}y^{i'rs} - 4g^2 C_2(\mathcal{R})\delta_{ii'}]\frac{\mu^{-2\varepsilon}}{2\varepsilon}\phi_{i'}\phi_j\phi_k + (cyclic)\right\}.$$

- Replacing μ by $e^{-\varrho}\mu$ and then picking up the linear term in ϱ,

$$\begin{aligned}\check{S}_{\rm eff} &= -\int d^4x\, d^2\theta\, \varrho\, \frac{1}{3!}\, y^{ijk}\left\{\frac{1}{32\pi^2}[y^{*irs}y^{i'rs} - 4g^2 C_2(\mathcal{R})\delta_{ii'}]\,\phi_{i'}\phi_j\phi_k + (cy\right. \\ &= \int d^4x\, d^2\theta\, \varrho\, \frac{1}{3!}(\gamma_i + \gamma_j + \gamma_k) y^{ijk}\phi_i\phi_j\phi_k.\end{aligned}$$

- The CASM reads

$$\mathcal{X} = \frac{1}{3!}(\gamma_i + \gamma_j + \gamma_k) y^{ijk}\phi_i\phi_j\phi_k.$$

The MSSM

- A term is given by

$$A_{ijk} = -(\gamma_i + \gamma_j + \gamma_k) y^{ijk} m_{3/2}.$$

- We supersymmetrize the dilaton. That is, the dilaton is transformed into the the chiral compensator:

$$e^{2\varrho} \to \chi^3 = e^{2\varrho + 2i\delta}[1 + \sqrt{2}\theta\bar{\Psi} + \theta\theta M^*]).$$

Under this transformation,

$$\begin{aligned} \ln \mu^2 &\to \ln \mu^2 + \ln \chi^{-3} \\ &= \ln \mu^2 - 2\varrho - 2i\delta - \sqrt{2}\theta\bar{\Psi} - \theta\theta M^*. \end{aligned}$$

- We can derive the interaction dilaton(ino)(axion) and CASM like this.

The MSSM

- LASM, evaluated at two loop,

$$
\begin{aligned}
L &= -\frac{1}{4}\dot{\gamma}_i \, \phi_i^{+} \phi_i, \\
\dot{\gamma}_i &= \frac{\partial \gamma_i^j}{\partial \ln \mu}.
\end{aligned}
$$

Then,

$$m_i^2 = \frac{1}{4}\dot{\gamma}_i^i m_{3/2}^2.$$

Summary and Outlook

- We present the novel field-theorectical understanding of the Anomaly Mediated Supersymmetry breakikng.
- It is more understandable compared with the conventional spurion method.
- We can reproduce the results with the anomaly superfields interactions.
- In addition to that, we can write down the dilaton-interaction action, which can be used for study of hidden sector.
- More study on the hidden sector and Einstein supergravity will be pursued.