D-term Dynamical SUSY Breaking

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Introduction

SUPERSYMMETRY

is one of the attractive scenarios solving the hierarchy problem, but it must be broken at low energy

Dynamical SUSY breaking(DSB)
is most desirable to solve
the hierarchy problem

F-term DSB is induced by non-perturbative effects
due to nonrenormalization theorem
and well studied so far

D-term SUSY breaking @tree level is well known,

but no known explicit model of D-term DSB
as far as we know

In this talk, we will accomplish

D-term DSB (DDSB) in a self-consistent Hartree-Fock approx.

Tree ~ 1-loop

Plan

- Introduction
- Basic Idea
- V_{eff} @1-loop
- Gap equation &
  nontrivial solution
- $\langle F^0 \rangle \neq 0$ induced by $\langle D^0 \rangle \neq 0$
- Comments on model building
- Summary

Basic Idea

N=1 SUSY U(N) gauge theory with an adjoint chiral multiplet

$$\mathcal{L} = \int d^4\theta K\left(\Phi^a, \bar{\Phi}^a, V\right) + \int d^2\theta \,\mathrm{Im}\frac{1}{2}\tau_{ab}\left(\Phi^a\right)\mathcal{W}^{a\alpha}\mathcal{W}^b_\alpha + \left[\int d^2\theta W\left(\Phi^a\right) + h.c.\right]$$

$$\mathcal{W}^a_\alpha = -i\lambda^a_\alpha(y) + \left[\delta^\beta_\alpha D^a(y) - \frac{i}{2}\left(\sigma^\mu\bar{\sigma}^\nu\right)^\beta_\alpha F^a_{\mu\nu}(y)\right]\theta_\beta$$

$$\Phi^a = \phi^a(y) + \sqrt{2}\theta\psi^a(y) + \theta\theta F^a(y) \quad y^\mu = x^\mu + i\theta\sigma^\mu\bar{\theta}$$

N=2→N=1 partial breaking models naturally applicable

Antoniadis, Partrouche & Taylor (1996)
Fujiwara, Itoyama & Sakaguchi (2005)

$$\mathcal{L}_{U(N)} = \mathrm{Im}\left[\int d^4\theta Tr\bar{\Phi}e^V\frac{\partial\mathcal{F}(\Phi)}{\partial\Phi} + \int d^2\theta\frac{1}{2}\frac{\partial^2\mathcal{F}(\Phi)}{\partial\Phi^a\partial\Phi^b}\mathcal{W}^{a\alpha}\mathcal{W}^b_\alpha\right] + \left(\int d^2\theta W(\Phi) + h.c.\right)$$

$$W(\Phi) = Tr\left[2e\Phi + m\frac{\partial\mathcal{F}(\Phi)}{\partial\Phi}\right]$$

Electric & Magnetic FI terms

N=1 SUSY U(N) gauge theory with an adjoint chiral multiplet

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$$\Phi^a = \phi^a(y) + \sqrt{2}\theta\psi^a(y) + \theta\theta F^a(y) \quad y^\mu = x^\mu + i\theta\sigma^\mu\bar{\theta}$$

Fermion masses

Important D=5 operator

$$\int d^2\theta \tau_{ab}(\Phi)\mathcal{W}^{a\alpha}\mathcal{W}^b_\alpha \supset \tau_{abc}(\Phi)\psi^c\lambda^a D^b + \tau_{abc}(\Phi)F^c\lambda^a\lambda^b$$

Dirac mass term

$$\int d^2\theta W(\Phi) \supset -\frac{1}{2}\partial_a\partial_b W(\Phi)\psi^a\psi^b$$

$$\tau_{abc} \equiv \partial\tau_{ab}(\Phi)/\partial\phi^c$$

Fermion mass terms

Mixed Majorana-Dirac type masses ($\langle F\rangle=0$ assumed)

$$-\frac{1}{2}\begin{pmatrix}\lambda^a & \psi^a\end{pmatrix}\begin{pmatrix}0 & -\frac{\sqrt{2}}{4}\tau_{abc}D^b \\ -\frac{\sqrt{2}}{4}\tau_{abc}D^b & \partial_a\partial_c W\end{pmatrix}\begin{pmatrix}\lambda^c \\ \psi^c\end{pmatrix}+h.c.$$

Mass matrix

$$M_F \equiv \begin{pmatrix}0 & -\frac{\sqrt{2}}{4}\langle\tau_{0aa}D^0\rangle \\ -\frac{\sqrt{2}}{4}\langle\tau_{0aa}D^0\rangle & \langle\partial_a\partial_a W\rangle\end{pmatrix}$$

$\langle D^0\rangle$: U(1) part of D-term if $\langle D \rangle \neq 0 \ \& \ \langle \partial_a \partial_a W \rangle \neq 0$

$$m_{\pm} = \frac{1}{2} \langle \partial_a \partial_a W \rangle \left[1 \pm \sqrt{1 + \left(\frac{2 \langle D \rangle}{\langle \partial_a \partial_a W \rangle} \right)^2} \right]$$

$$D \equiv -\frac{\sqrt{2}}{4} \tau_{0aa} D^0$$

Gaugino becomes massive
by nonzero <D>

⇒ SUSY is broken

D-term equation of motion:

$$\left\langle D^0 \right\rangle = -\frac{1}{2\sqrt{2}} \left\langle g^{00} \left(\tau_{0cd} \psi^d \lambda^c + \bar{\tau}_{0cd} \bar{\psi}^d \bar{\lambda}^c \right) \right\rangle$$

Dirac bilinears condensation

The value of <D> will be determined by the gap equation

V_{eff}@1-loop

1-loop effective potential for D-term

$$V_{1-loop} = \sum_a \int \frac{d^4k}{(2\pi)^4} \ln\left[\frac{\left(m_a^2\lambda^{(+)2} - k^2 - i\varepsilon\right)\left(m_a^2\lambda^{(-)2} - k^2 - i\varepsilon\right)}{\left(m_a^2 - k^2 - i\varepsilon\right)\left(-k^2 - i\varepsilon\right)}\right]$$

$$= \frac{1}{32\pi^2}\sum_a |m_a|^4 \left[A(d)\left(\Delta^2 + \frac{1}{8}\Delta^4\right) - \lambda^{(+)4}\log\lambda^{(+)2} - \lambda^{(-)4}\log\lambda^{(-)2}\right]$$

$$A(d) = \frac{3}{4} - \gamma + \frac{1}{2 - d/2} \xrightarrow{d=4} \infty$$

$$m_a \equiv \left\langle g^{aa}\partial_a\partial_a W\right\rangle, \lambda^{(\pm)} \equiv \frac{1}{2}\left[1 \pm \sqrt{1+\Delta^2}\right], \Delta \equiv \frac{\langle \tau_{0aa} D\rangle}{\sqrt{2}m_a}$$

SUSY counterterm added

$$V_{c.t.} = -\mathrm{Im}\frac{\Lambda}{2}\int d^2\theta \mathcal{W}^{\alpha 0}\mathcal{W}^0_\alpha = -\mathrm{Im}\frac{\Lambda}{2}\left(D^0\right)^2$$

1-loop effective potential for D-term

Tree level D-term pot. + 1-loop CW pot.

+ counter term

$$V^{(D)}_{1-loop} = \sum_a |m_a|^4 \left\{ \left(c + \frac{1}{64\pi^2} \right) \Delta^2 + \Lambda'_{res} \frac{\Delta^4}{8} - \frac{1}{32\pi^2} \left[\lambda^{(+)4} \log \lambda^{(+)2} + \lambda^{(-)4} \log \lambda^{(-)2} \right] \right\}$$

$$\frac{1}{\sum_a |m_a|^4} \frac{\partial^2 V^{(D)}_{1-loop}}{(\partial\Delta)^2}\bigg|_{\Delta=0} = 2c$$

$$\Lambda'_{res} \equiv c + \beta + \Lambda_{res} + \frac{1}{64\pi^2} = \frac{1}{32\pi^2} A(d),$$

$$\beta \equiv \frac{\langle g_{00} \rangle |\langle \partial_a \partial_a W \rangle|^2}{\sum_a |m_a|^4 |\langle \tau_{0aa} \rangle|^2}, \quad \Lambda_{res} \equiv \frac{(\mathrm{Im}\,\Lambda) |\langle \partial_a \partial_a W \rangle|^2}{\sum_a |m_a|^4 |\langle \tau_{0aa} \rangle|^2}$$

Gap equation
&
Nontrivial solution

Gap equation

$$0=\frac{\partial V^{(D)}_{1-loop}}{\partial\Delta}$$

Trivial solution Δ=0 is NOT lifted unlike NJL

$$=\Delta\left[c+\frac{1}{64\pi^2}+\frac{\Lambda'_{res}}{4}\Delta^2\right.$$

$$\lambda^{(\pm)}\equiv\frac{1}{2}\left(1\pm\sqrt{1+\Delta^2}\right)$$

$$\left.-\frac{1}{64\pi^2\sqrt{1+\Delta^2}}\left\{\lambda^{(+)3}\left(2\log\lambda^{(+)2}+1\right)-\lambda^{(-)3}\left(2\log\lambda^{(-)2}+1\right)\right\}\right]$$

Approximate form

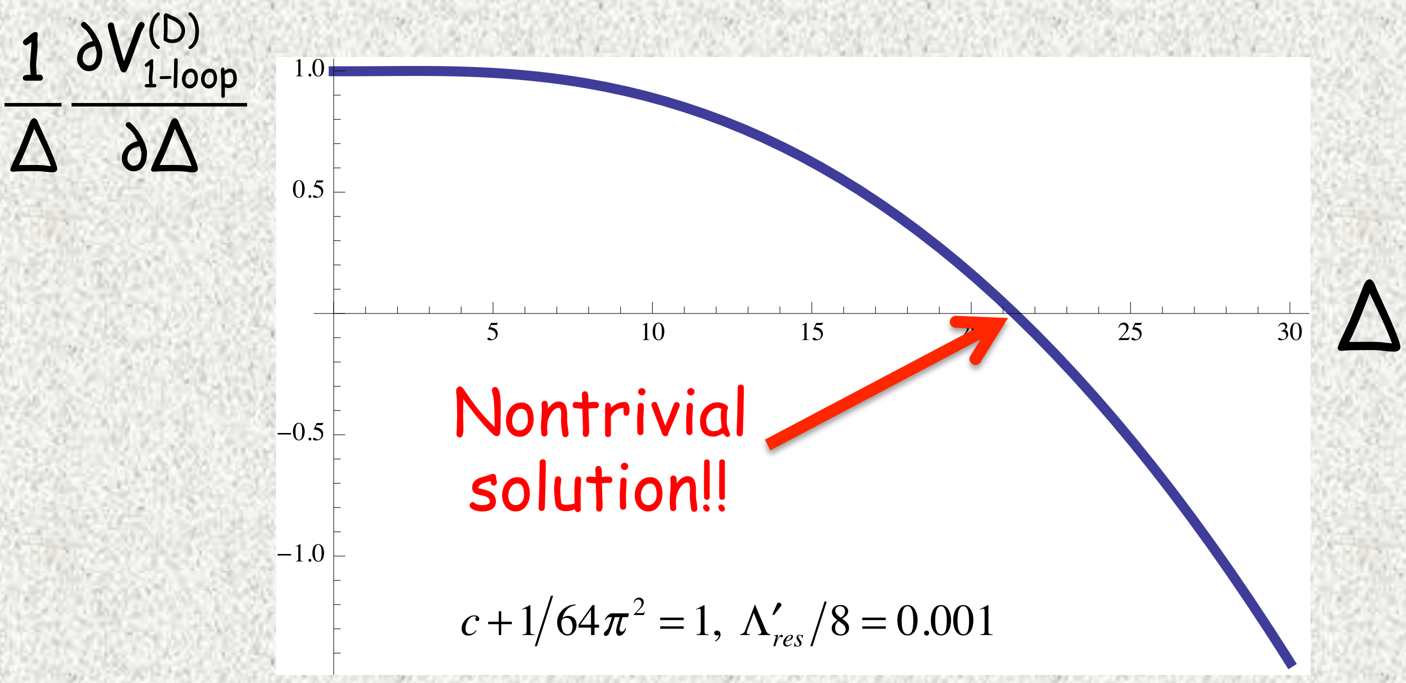
$$\Delta^2\ll 1:\Delta^2\simeq-\frac{4c}{\Lambda'_{res}-5/\left(64\pi^2\right)}\quad(c<0)$$

$$\Delta^2\gg 1:c+\frac{1}{64\pi^2}+\Lambda'_{res}\left(\frac{\Delta}{2}\right)^2\simeq\frac{1}{32\pi^2}\left(\frac{\Delta}{2}\right)^2\log\left(\frac{\Delta}{2}\right)^2\quad\left(\Lambda'_{res}>0\right)$$

Gap equation

$$0 = \frac{\partial V^{(D)}_{1-loop}}{\partial \Delta} = \Delta \Bigg[c + \frac{1}{64\pi^2} + \frac{\Lambda'_{res}}{4}\Delta^2$$

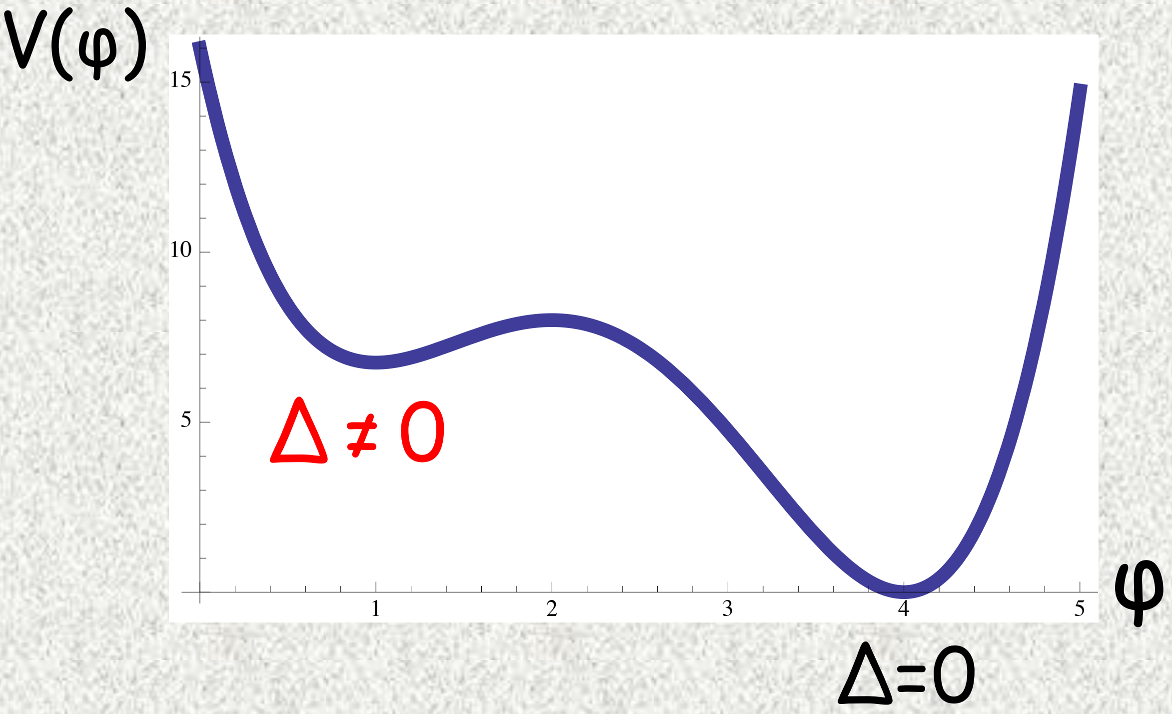
$$- \frac{1}{64\pi^2\sqrt{1+\Delta^2}} \left\{ \lambda^{(+)3}\left(2\log\lambda^{(+)2}+1\right) - \lambda^{(-)3}\left(2\log\lambda^{(-)2}+1\right) \right\} \Bigg]$$



$E \geqq 0$ in SUSY

⇒ Trivial solution $\Delta=0$ is NOT lifted

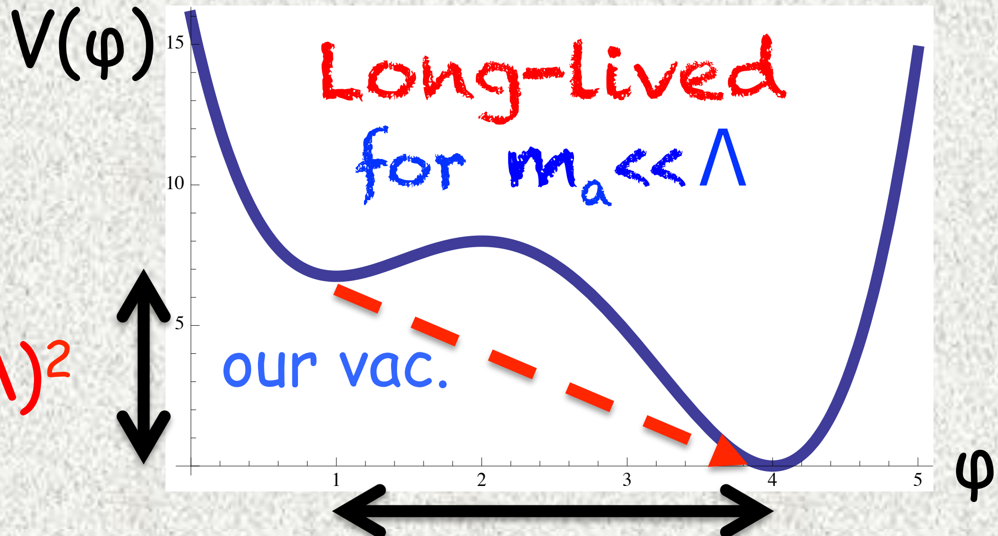
⇒ Our SUSY breaking vac. is a local min.



Metastability of our false vacuum

<D> = 0 tree vacuum is not lifted

⇒ check if our vacuum <D> ≠ 0 is sufficiently long-lived



$\Delta V \sim (m_a \Lambda)^2$

$\Delta\varphi \sim \Lambda$

Coleman & De Luccia(1980)

Decay rate of the false vacuum

$$\propto \exp\left[-\frac{\langle \Delta\phi \rangle^4}{\langle \Delta V \rangle}\right] \approx \exp\left[-\frac{\Lambda^2}{m_a^2}\right] \ll 1$$

m: mass of Φ, Λ: cutoff scale

$\left\langle F^{0} \right\rangle \neq 0$ induced by $\left\langle D^{0} \right\rangle \neq 0$

$ Fermion mass

$\langle D^0 \rangle \neq 0$ induces nonvanishing $\langle F^0 \rangle$

Effective potenital up to 1-loop

$$V = g^{ab}\,\partial_a W\,\overline{\partial_b W} - \frac{1}{2} g_{ab} D^a D^b + V_{1-loop} + V_{c.t.}$$

Stationary condition

$$\langle \delta V \rangle = 0 \Rightarrow \left| \langle F^0 \rangle \right|^2 + \frac{m_0}{\langle g^{00}\,\partial_0 g_{00} \rangle} \langle F^0 \rangle + \frac{1}{2} \langle D^0 \rangle^2 + 2 \langle g^{00} \rangle \langle V_{1-loop} \rangle = 0$$

with $\langle \bar{\delta} V \rangle = 0$

we further obtain

$$\frac{m_0}{\langle g^{00}\,\partial_0 g_{00} \rangle} \langle F^0 \rangle = \frac{m_0^*}{\langle \overline{g^{00}\,\partial_0 g_{00}} \rangle} \langle \bar{F}^0 \rangle$$

These determine the value of nonvanishing F-term

Fermion masses

SU(N) part:

$$\mathcal{L}_{mass}^{(holo)} = -\frac{1}{2}\left\langle g_{0a,a}\right\rangle\left\langle \bar{F}^{0}\right\rangle \psi^{a}\psi^{a} + \frac{i}{4}\left\langle \mathcal{F}_{0aa}\right\rangle\left\langle F^{0}\right\rangle \lambda^{a}\lambda^{a}$$
$$-\frac{1}{2}\left\langle \partial_{a}\partial_{a}W\right\rangle \psi^{a}\psi^{a} + \frac{\sqrt{2}}{4}\left\langle \mathcal{F}_{0aa}\right\rangle\left\langle D^{0}\right\rangle \psi^{a}\lambda^{a}$$

U(1) part:

NG fermion: admixture of λ^{0} and ψ^{0}

Comments on Model Building

Following the model of Fox, Nelson & Weiner (2002),

consider a N=2 gauge sector & N=1 matter sector in MSSM

↑ Chirality, Asymptotic freedom

Take the gauge group $G' \times G_{SM}$ (G'=U(1):hidden sector)

D=5 gauge kinetic term

provides Dirac gaugino mass term

$$\int d^2\theta \tau_{abc}(\Phi)\Phi^c_{SM}\mathcal{W}'^{\alpha a}\mathcal{W}^b_{\alpha SM} \Rightarrow \tau_{abc}(\langle\Phi\rangle)\langle D'^a\rangle\psi^c_{SM}\lambda^b_{SM}$$

↑ Scalar gluon: distinct from the other proposals

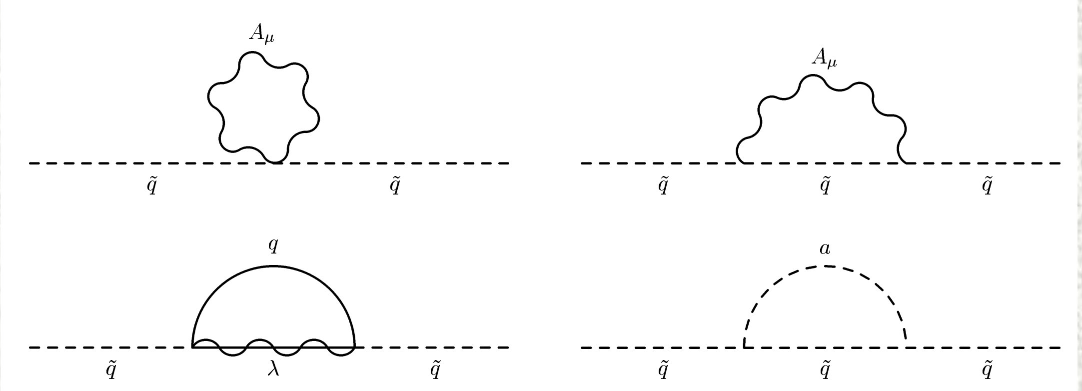
Gaugino masses are generated at tree level

Once gaugino masses are generated at tree level, sfermion masses are generated by RGE effects

Sfermion masses @1-loop

$$M_{sf}^2 \approx \frac{C_i(R)\alpha_i}{\pi} M_{\lambda_i}^2 \log\left[\frac{m_a^2}{M_{\lambda_i}^2}\right]$$

(i = SU(3)$_C$, SU(2)$_L$, U(1)$_Y$)



Fox, Nelson & Weiner, JHEP08 (2002) 035

Flavor blind ⇒ No SUSY flavor & CP problems

Summary

- New mechanism of DDSB proposed
- Shown a nontrivial solution of the gap eq. with nonzero <D> in a self-consistent H-F approx.
- Our vacuum is metastable & can be made long-lived
- Phenomenological Application briefly discussed