D-Term Triggered Dynamical Supersymmetry Breaking

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Introduction

SUSY is one of the leading candidates beyond the SM, but has to be broken at low energy

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

F or D??

F-term DSB has been well studied so far and is induced by nonperturbative effects such as instantons due to the nonrenormalization theorem

D-term breaking is NOT affected by the nonren. theorem

D-term DSB is possible in principle, but NO explicit model has been known

➡ **D-term DSB (DDSB) in a self-consistent Hartree-Fock approximation**

Action: N=1 U(N) gauge theory w/ an adjoint chiral multiplet

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

Assumptions

- General N=1 U(N) action of an adj. Φ & V w/ 3 input fcts
- Vacuum in the unbroken phase of U(N)
- ∂W=0@tree level
- VEV of the third derivative of $\mathcal{F}$ nonvanishing

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

Dim 5 operator ⇒ Dirac gaugino mass

Source of Supersymmetry Breaking

Fermion masses

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

$\langle D\rangle \neq 0$ & $\langle \partial_a\partial_a W\rangle \neq 0$ ➡

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

Gaugino(m₋) becomes massive by nonzero <D>

⇒ SUSY is broken

D-term EOM

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

Dirac bilinears condensation ⟶ Gap eq.

$\left\langle D^0\right\rangle \neq 0$ ➡ $\left\langle F^0\right\rangle \neq 0$ Fermion masses are modified

$$\mathcal{M}_a = \begin{pmatrix} -\frac{i}{2}g^{aa}\mathcal{F}_{0aa}F^0 & -\frac{\sqrt{2}}{4}\sqrt{g^{aa}\left(\mathrm{Im}\,\mathcal{F}\right)^{aa}}\mathcal{F}_{0aa}D^0 \\ -\frac{\sqrt{2}}{4}\sqrt{g^{aa}\left(\mathrm{Im}\,\mathcal{F}\right)^{aa}}\mathcal{F}_{0aa}D^0 & g^{aa}\partial_a\partial_a W + g^{aa}g_{0a,a}\bar{F}^0\end{pmatrix} = \begin{pmatrix} m^a_{\lambda\lambda} & m^a_{\lambda\psi} \\ m^a_{\psi\lambda} & m^a_{\psi\psi}\end{pmatrix}$$

$$m_\pm = \left(tr\mathcal{M}\right)\lambda^{(\pm)} = \frac{tr\mathcal{M}}{2}\left[1 \pm \sqrt{\left(1+if\right)^2 + \left(1 + \frac{i}{2}f\right)^2\Delta^2}\right], \Delta \equiv -\frac{2m_{\lambda\psi}}{m_{\psi\psi}}, f \equiv \frac{2im_{\lambda\lambda}}{tr\mathcal{M}}$$

NG Fermion

Supercurrent

$$\eta_1\mathcal{S}^{(1)\mu} = \sqrt{2}g_{ab}\eta_1\sigma^\nu\bar{\sigma}^\mu\psi^a\mathcal{D}_\nu\bar{\phi}^b + \sqrt{2}ig_{ab}\eta_1\sigma^\mu\bar{\psi}^a F^b - i\mathcal{F}_{ab}\eta_1\sigma_\nu\bar{\lambda}^a F^{\mu\nu b} + \frac{1}{2}\mathcal{F}_{ab}\varepsilon^{\mu\nu\rho\delta}\eta_1\sigma_\nu\bar{\lambda}^a F^{\rho\delta b} - \frac{i}{2}\bar{\mathcal{F}}_{ab}\eta_1\sigma^\mu\bar{\lambda}^a D^b + \frac{\sqrt{2}}{4}\left(\mathcal{F}_{abc}\psi^c\sigma^\nu\bar{\sigma}^\mu\lambda^b - \bar{\mathcal{F}}_{abc}\bar{\lambda}^c\bar{\sigma}^\mu\sigma^\nu\bar{\psi}^b\right)\eta_1\sigma_\nu\bar{\lambda}^a$$

➡ NGF is a linear combination of λ^0 & ψ^0

Coupling to SUGRA, the gravitino becomes massive by super-Higgs mechanism

$$m_{3/2} \underset{\langle V\rangle=0}{\cong} e^{\langle K\rangle/2M_P^2}\frac{\sqrt{\left|\left\langle D_a W\right\rangle\right|^2 + g^2\left\langle D^a\right\rangle^2/2}}{\sqrt{3}M_P}$$

Effective potential in the HF approximation

↓

tree ~ 1-loop in the $\hbar$ expansion

3 constant Bkg fields

$\varphi \equiv \varphi^0$ (complex), U(N) invariant scalar

$D \equiv D^0$ (real), $F \equiv F^0$ (complex)

Potential consists of 3 parts

$$V = V_{tree} + V_{1-loop} + V_{c.t.}$$

Potential@tree level

$$V_{tree}\left(D, F, \bar{F}, \varphi, \bar{\varphi}\right) = -gF\bar{F} - \frac{1}{2}\left(\mathrm{Im}\,\mathcal{F}''\right)D^2 - FW' - \bar{F}\bar{W}'$$

EOM ⟶

$$V^{tree}_{scalar}\left(\varphi, \bar{\varphi}\right) = g^{-1}\left|W'(\varphi)\right|^2$$

1-loop effective potential

$$V_{1-loop}=\frac{N^2|tr\mathcal{M}|^4}{32\pi^2}\left[A(\gamma)\left(\left|\lambda^{(+)}\right|^4+\left|\lambda^{(-)}\right|^4-\left|\frac{m_s}{tr\mathcal{M}}\right|^4\right)\right.$$
$$\left.-\left|\lambda^{(+)}\right|^4\log\left|\lambda^{(+)}\right|^2-\left|\lambda^{(-)}\right|^4\log\left|\lambda^{(-)}\right|^2+\left|\frac{m_s}{tr\mathcal{M}}\right|^4\log\left|\frac{m_s}{tr\mathcal{M}}\right|^4\right]$$

$$\lambda^{(\pm)}=\frac{1}{2}\left(1\pm\sqrt{(1+if)^2+\left(1+\frac{i}{2}f\right)^2\Delta^2}\right),A(\gamma)=\frac{1}{2}-\gamma+\frac{1}{2-d/2}$$

$m_s(\varphi,\bar{\varphi})\equiv g^{-1}(\varphi,\bar{\varphi})W''(\varphi)$ (scalar gluon mass)

Divergences are subtracted by a SUSY counter term

$$V_{c.t.}=-\frac{1}{2}\mathrm{Im}\int d^2\theta\Lambda\mathcal{W}^{0\alpha}\mathcal{W}^0_\alpha\Rightarrow-\frac{1}{2}(\mathrm{Im}\,\Lambda)D^2$$

and a renormalization condition $\left.\frac{1}{N^2}\frac{\partial^2V}{(\partial D)^2}\right|_{D=0,\varphi=\varphi_*,\bar{\varphi}=\bar{\varphi}_*}=2c$

Potential analysis

F-term is treated to be perturbative in our analysis

$$\frac{\partial V(D,\varphi,\bar{\varphi},F=\bar{F}=0)}{\partial D}=0\quad\Rightarrow\text{ gap equation}$$

$$\frac{\partial V(D,\varphi,\bar{\varphi},F=\bar{F}=0)}{\partial\varphi}=\frac{\partial V(D,\varphi,\bar{\varphi},F=\bar{F}=0)}{\partial\bar{\varphi}}=0$$

Stationary values ➡ $(D_*,\varphi_*,\bar{\varphi}_*)$

$$\left.\frac{\partial V(D=D_*(F,\bar{F}),\varphi=\varphi(F,\bar{F}),\bar{\varphi}=\bar{\varphi}_*(F,\bar{F}),F,\bar{F})}{\partial F}\right|_{D,\varphi,\bar{\varphi},\bar{F}\text{ fixed}}=0\quad ➡\quad(F_*,\bar{F}_*)$$

& its conjugate

Gap equation

$$0=\left.\frac{\partial V_0}{\partial D}\right|_{\varphi,\bar{\varphi}}$$

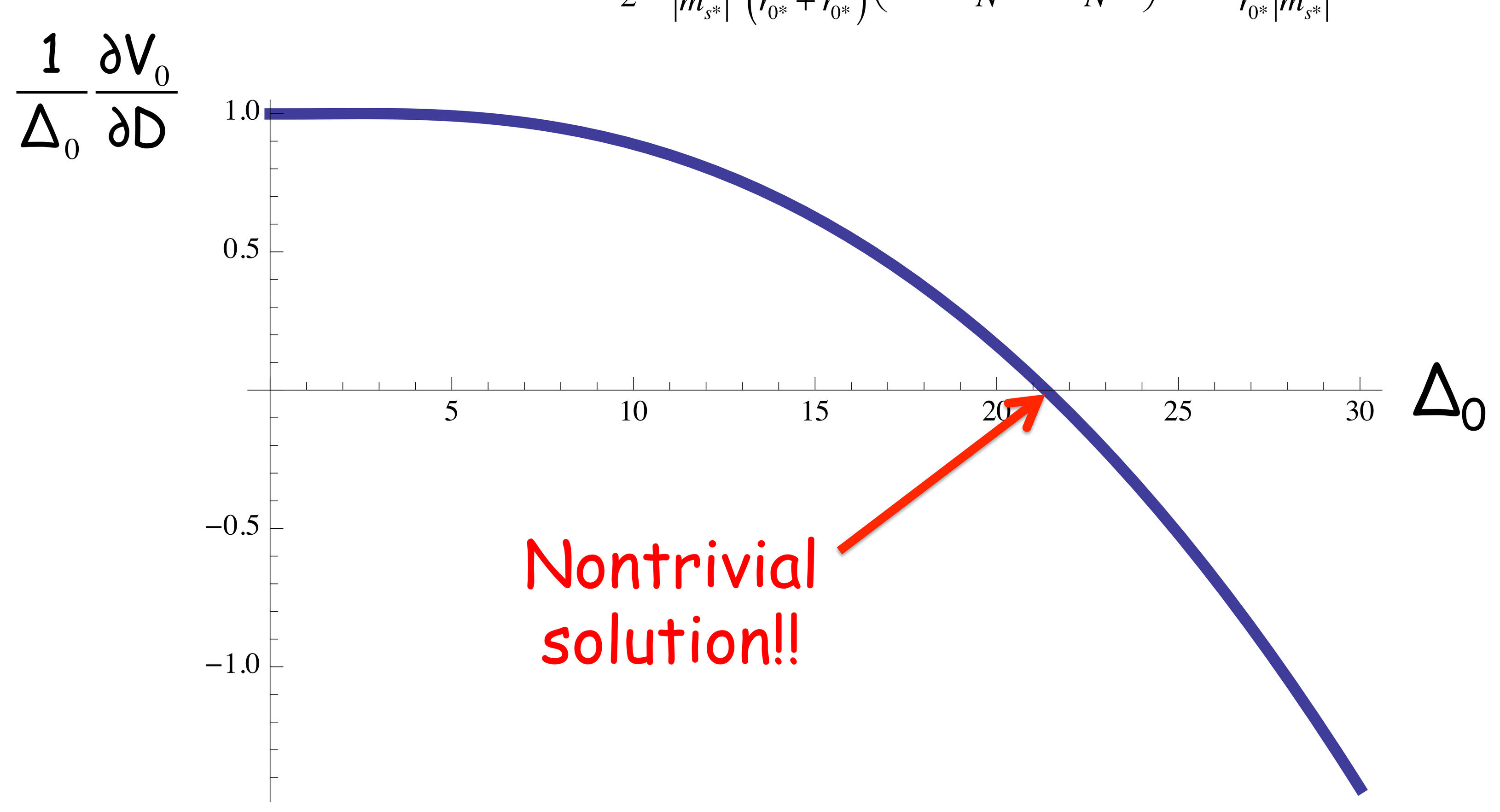
Trivial solution $\Delta_0=0$ is NOT lifted

$$=\Delta_0\left[c'+\frac{1}{64\pi^2}-\delta(\varphi,\bar{\varphi})+\frac{1}{32\pi^2}\frac{\tilde{A}}{4}\Delta_0^2\right.$$
$$\left.-\frac{1}{64\pi^2\sqrt{1+\Delta_0^2}}\left\{\lambda_0^{(+)3}\left(2\log\lambda_0^{(+)2}+1\right)-\lambda_0^{(-)3}\left(2\log\lambda_0^{(-)2}+1\right)\right\}\right]$$

$$\lambda_0^{(\pm)}=\frac{1}{2}\left(1\pm\sqrt{1+\Delta_0^2}\right)$$

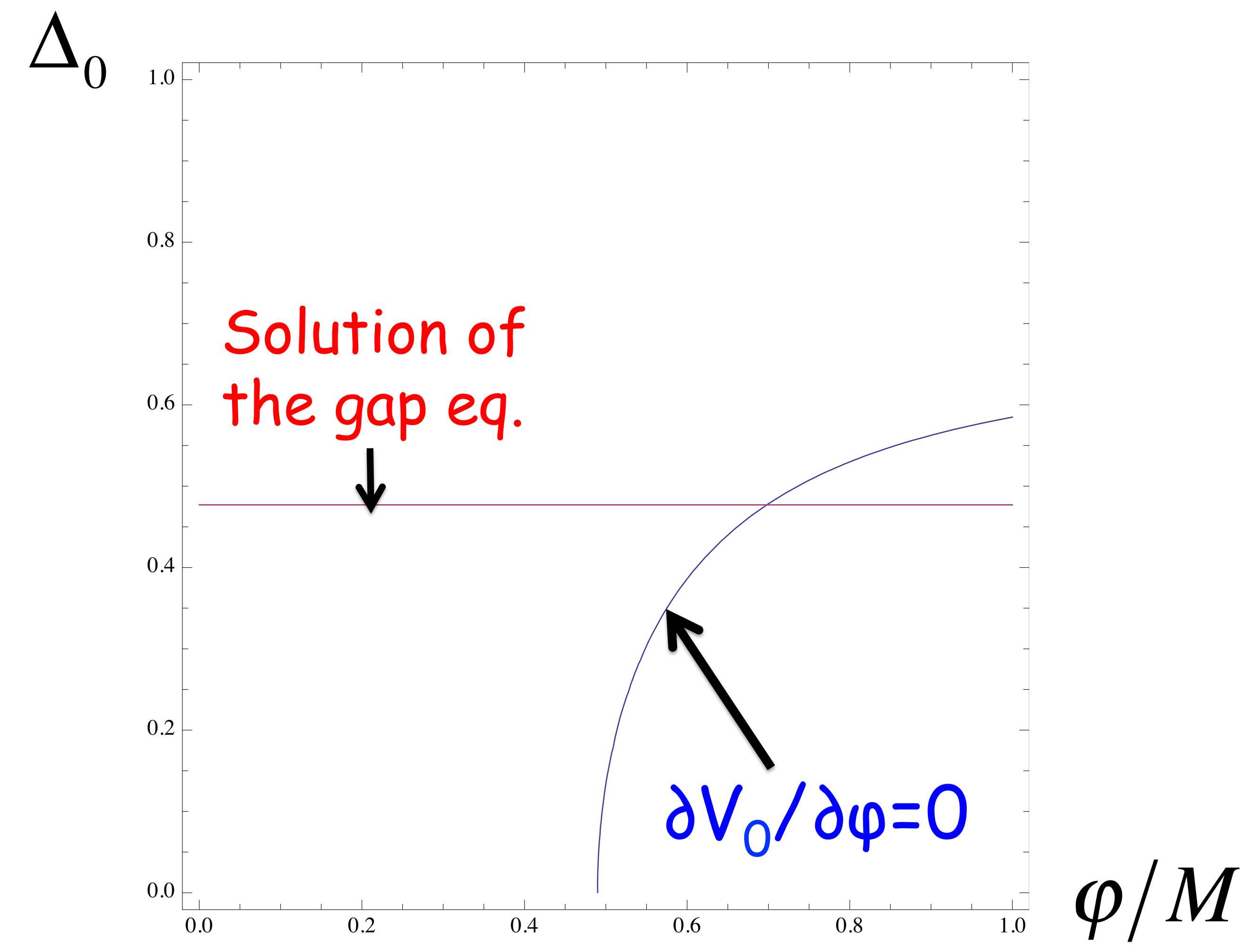
$$\delta(\varphi,\bar{\varphi})\equiv\frac{1}{2}\left(\frac{\mathrm{Im}\,\mathcal{F}''_*/N^2+\mathrm{Im}\,\Lambda/N^2}{r_{0*}^2|m_{s*}|^4}\right)\left[\frac{\dfrac{\mathrm{Im}\,\mathcal{F}''/N^2+\mathrm{Im}\,\Lambda/N^2}{\mathrm{Im}\,\mathcal{F}''_*/N^2+\mathrm{Im}\,\Lambda/N^2}}{r_0^2|m_s|^4/r_{0*}^2|m_{s*}|^4}-1\right],\ r_0\equiv\frac{\sqrt{2g^{-1}(\mathrm{Im}\,\mathcal{F}'')^{-1}}\mathcal{F}'''}{2g^{-1}W''}$$

$$\tilde{A}(c,\Lambda,\varphi_*,\bar{\varphi}_*)\equiv\frac{1}{2}+\frac{32\pi^2}{|m_{s*}|^4\left(r_{0*}^2+\bar{r}_{0*}^2\right)}\left(2c+\frac{\mathrm{Im}\,\mathcal{F}''_*}{N^2}+\frac{\mathrm{Im}\,\Lambda}{N^2}\right),\ c'\equiv\frac{c}{r_{0*}^2|m_{s*}|^4}$$



SUSY is dynamically broken

$(\Delta_{0*},\varphi_*=\bar{\varphi}_*)$ determined as the intersection point of two real curves in the $(\Delta_{0*},\varphi=\bar{\varphi})$ plane



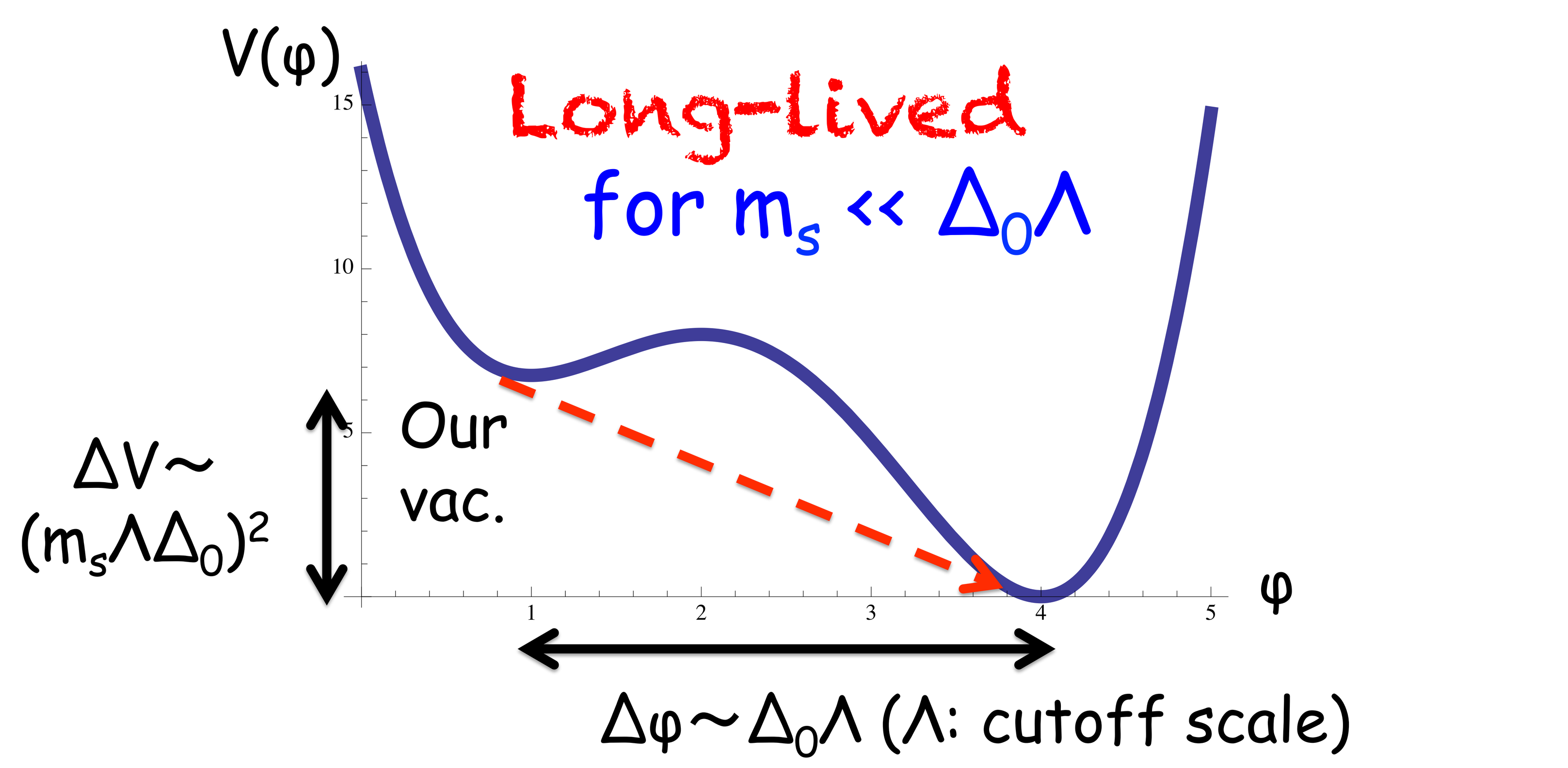
Determination of F

$$\frac{\partial V}{\partial F}=0\Rightarrow F_*\approx\frac{1}{g(\varphi_*,\bar{\varphi}_*)}\left[-\bar{W}(\varphi_*,\bar{\varphi}_*)+\left.\frac{\partial}{\partial F}V_{1-loop}(D_*,\varphi_*,\bar{\varphi}_*,F,\bar{F})\right|_{F=\bar{F}=0}\right]$$

Numerical Samples

$c'+\frac{1}{64\pi^2}$	$\tilde{A}/(4\cdot 32\pi^2)$	Δ_{0*}	φ_*/M $\left(-\frac{N^2}{\mathrm{Im}(i+\Lambda)}\right)$	$\lvert F_*/D_*\rvert$	$\lvert f_{3*}\rvert$
0.002	0.0001	0.477	0.707 (10000)	2.621 $(m=M)$	1.77
0.002	0.0001	0.477	0.707 (10000)	0.524 $(m\ll M)$	0.35
0.002	0.0001	0.477	0.707 (10000)	0.860 $(m=0.4M)$	0.58
0.003	0.001	1.3623	0.8639 (2000)	0.825 $(m=M)$	>1
0.003	0.001	1.3623	0.8639 (2000)	0.224 $(m\ll M)$	0.43
0.003	0.001	1.3623	0.5464 (5000)	1.092 $(m=M)$	>1
0.003	0.001	1.3623	0.5464 (5000)	0.142 $(m\ll M)$	0.27
0.003	0.001	1.3623	0.5464 (5000)	0.911 $(m=0.9M)$	1.76
0.003	0.001	1.3623	0.3863 (10000)	1.444 $(m=M)$	>1
0.003	0.001	1.3623	0.3863 (10000)	0.100 $(m\ll M)$	0.19
0.003	0.001	1.3623	0.3863 (10000)	0.960 $(m=0.8M)$	1.85

Metastability of our false vacuum



Decay rate of our vacuum $\propto\exp\left[-\frac{\langle\Delta\phi\rangle^4}{\langle\Delta V\rangle}\right]\approx\exp\left[-\frac{(\Delta_0\Lambda)^2}{m_s^2}\right]\ll 1$

Stability of our vacuum

$c'+\frac{1}{64\pi^2}$	$\tilde{A}/(4\cdot 32\pi^2)$	Δ_{0*}	φ_*/M $\left(-\frac{N^2}{\mathrm{Im}(i+\Lambda)}\right)$	scalar gluon mass (m_s^2/M^2)
0.002	0.0001	0.477	0.707 (10000)	$0.4998+0.0056\,N^2+8.607\times10^{-7}N^4$
0.003	0.001	1.3623	0.8639 (2000)	$0.7463+0.0106\,N^2+2.653\times10^{-4}N^4$
0.003	0.001	1.3623	0.5464 (5000)	$0.2986+0.0008\,N^2+4.694\times10^{-5}N^4$
0.003	0.001	1.3623	0.3863 (10000)	$0.1492-0.0024\,N^2+7.235\times10^{-5}N^4$

Confirmed the existence of the local minimum