Dynamical SUSY Breaking in Meta-Stable Vacua

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Dynamical Supersymmetry Breaking:

- No explicit breaking**:** $\mathcal{L} = \mathcal{L}_{SUSY}$
- Vacuum spontaneously breaks SUSY.
- SUSY breaking related to some dynamical scale

$$\Lambda = M_{cutoff} e^{-\frac{c}{g(M_{cutoff})^2}} \ll M_{cutoff}$$

Can naturally get hierarchies (Witten).

Dynamical SUSY breaking is hard

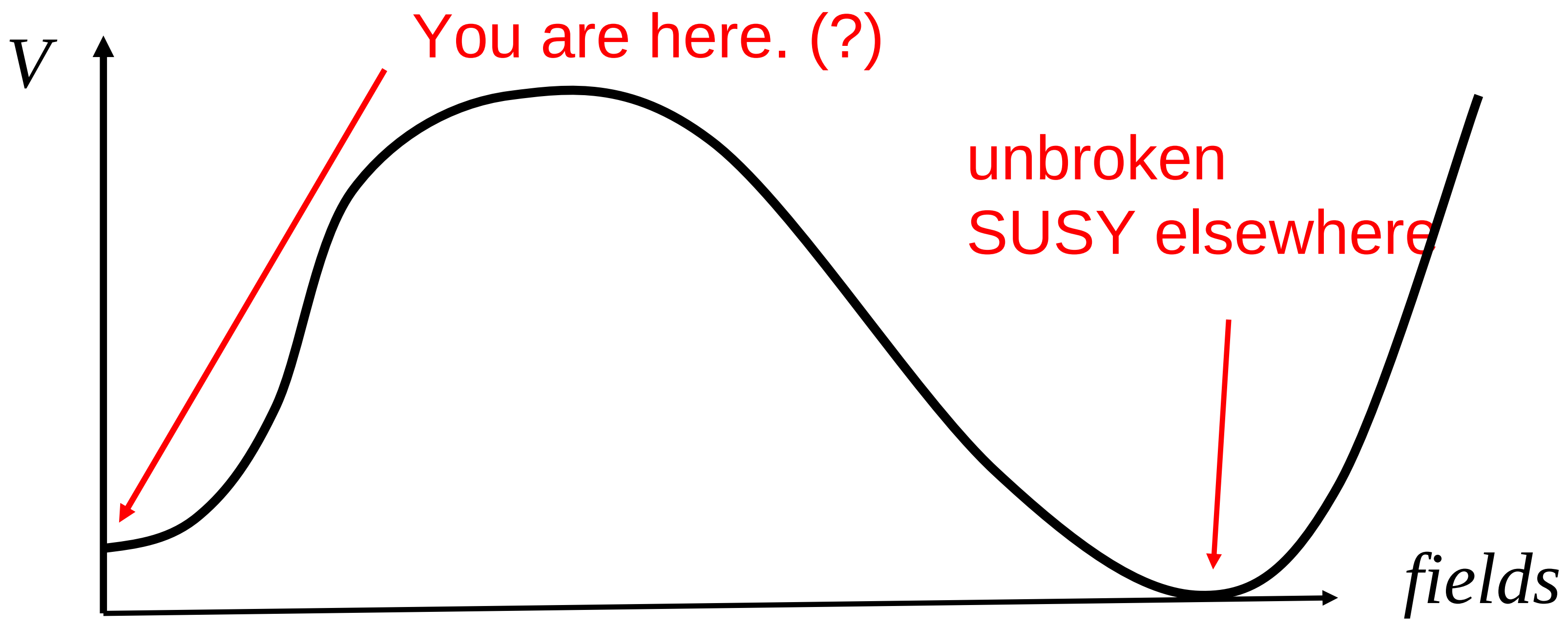
- Witten index: All SUSY gauge theories with massive, vector-like matter have $Tr(-1)^F \neq 0$ SUSY vacua.

  So for broken SUSY, seem to need a chiral gauge theory. **DSB looks non-generic.**
- Most of our techniques to analyze SUSY theories are based on holomorphy/chirality/BPS.

  SUSY breaking depends on the Kahler potential which is hard to control.

Perhaps we should try a new approach...

Perhaps we live in a long-lived false vacuum



An old idea. Here, also in the SUSY breaking sector. Find simpler models of DSB. **Suggests meta-stable DSB is generic.**

$\mathcal{N}$=1 SU(N_c) SQCD with N_f flavors

We will focus on the range of the number of colors and flavors $N_c \le N_f \le \frac{3}{2} N_c$ Infra-red free magnetic (Seiberg).

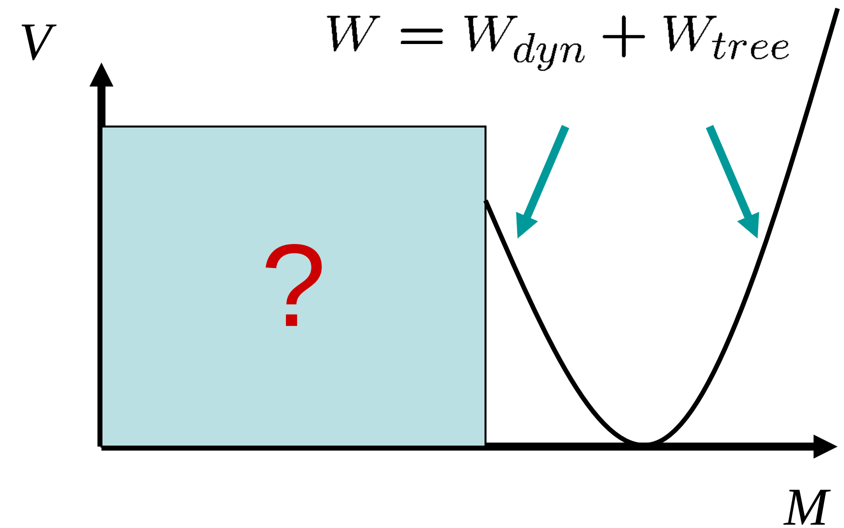
When all the quarks are massive, $W_{tree} = \mathrm{Tr}\, mQ\widetilde{Q} = \mathrm{Tr}\, mM$

there are $Tr(-1)^F = N_c$ SUSY vacua.

For $m = m_0 \mathbb{1}_{N_f}$

$$\langle M \rangle = (m_0^{N_f - N_c} \Lambda^{3N_c - N_f})^{1/N_c} \mathbb{1}_{N_f}$$

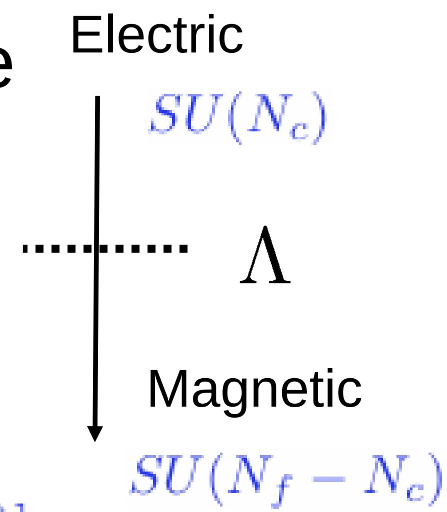
Study the limit $m_0 \ll \Lambda$
in the region near the origin.



There, we should use magnetic dual variables…

The magnetic theory (Seiberg)

We will focus on $N_c + 2 \leq N_f \leq \frac{3}{2} N_c$ where the theory is in a free magnetic phase; i.e. the magnetic theory is IR free.



The magnetic theory is

$$SU(N_f - N_c) \times [SU(N_f) \times SU(N_f)]$$

$$\begin{array}{ccccc} q & \in & N_f - N_c & \overline{N}_f & 1 \\ \tilde{q} & \in & \overline{N_f - N_c} & 1 & N_f \\ \Phi & \in & 1 & N_f & \overline{N}_f \end{array}$$

with $$W_{dual} = \tilde{q} \Phi q$$

The magnetic theory, cont.

$W_{dual} = \tilde{q}\Phi q$ where $\Lambda\Phi = M = \tilde{Q}Q$

UV cutoff of this IR free theory is Λ .

The Kahler potential for the IR free fields is smooth near the origin and can be taken to be canonical:

$$K_{IR} = \frac{1}{\alpha}\mathrm{Tr}\,\Phi^\dagger\Phi + \frac{1}{\beta}\mathrm{Tr}\,(q^\dagger q + \widetilde{q}^\dagger\widetilde{q}) + O(\frac{1}{\Lambda^2})$$

Key point: The leading Kahler potential is known, up to two dimensionless normalization constant factors.

Rank condition SUSY breaking

Quark masses are described in the magnetic dual by

$$W_{tree} = \mathrm{Tr}\, q\Phi\widetilde{q} - \mu^2 \mathrm{Tr}\, \Phi$$

SUSY broken at tree level!

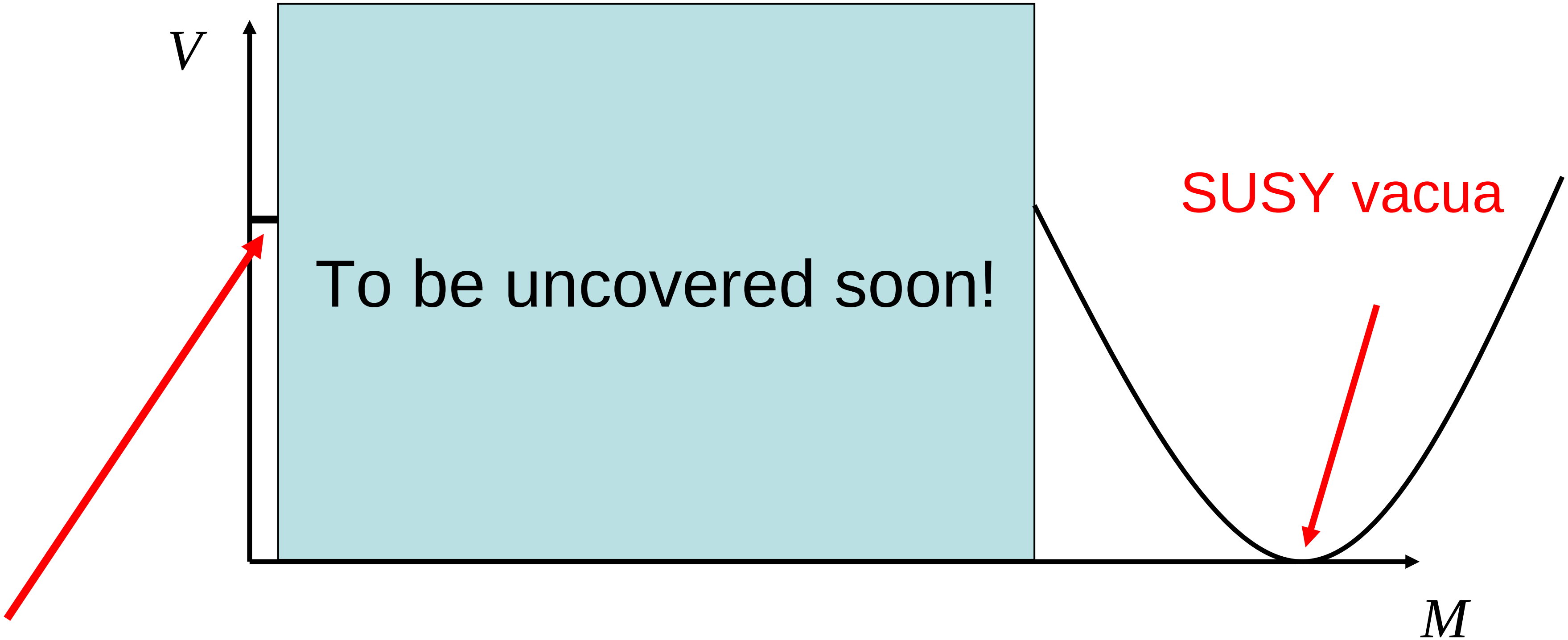
$$\mu^2 = -m_0 \Lambda$$

$$F^{\dagger}_{\Phi^g_f} \sim \frac{\partial W_{tree}}{\partial \Phi^g_f} = \tilde{q}^c_g q^f_c - \mu^2 \delta^f_g \neq 0$$

(rank N_f - N_c) (rank N_f)

(using the classical rank of $(q\widetilde{q})^f_g$.)
This SUSY breaking is a check of the duality. Otherwise, would have had unexpected, extra SUSY vacua.

Summary: the potential with massive flavors



For *M* at the origin SUSY broken by rank condition in the magnetic description. Reliable in free magnetic range: $N_f < \frac{3}{2} N_c$

This ends our review of things understood more than a decade ago.

DSB vacua near the origin, via F.M. dual

$$W_{tree} = \mathrm{Tr}\, q\Phi\widetilde{q} - \mu^2 \mathrm{Tr}\,\Phi \qquad \mu^2 = -m_0\Lambda$$

Classical vacua (up to global symmetries) with broken SUSY:

$$\Phi = \begin{pmatrix} 0 & 0 \\ 0 & \Phi_0 \end{pmatrix} \qquad q = \begin{pmatrix} q_0 \\ 0 \end{pmatrix} \qquad \widetilde{q}^T = \begin{pmatrix} \widetilde{q}_0 \\ 0 \end{pmatrix} \qquad \widetilde{q}_0 q_0 = \mu^2 \mathbb{I}_{N_f - N_c}$$

Pseudo-moduli:

Arbitrary $N_c \times N_c$ and $(N_f - N_c) \times (N_f - N_c)$ matrices

DSB: $V_{min} = N_c \alpha |\mu^4| \neq 0$

Pseudo-flat directions are lifted in the quantum theory (typical of tree-level breaking).

Pseudo-moduli get a potential at 1-loop in the magnetic theory

Use $$W_{tree} = \mathrm{Tr}\, q\Phi\tilde{q} - \mu^2 \mathrm{Tr}\,\Phi$$

$$K_{IR} = \frac{1}{\alpha}\mathrm{Tr}\,\Phi^\dagger\Phi + \frac{1}{\beta}\mathrm{Tr}\,(q^\dagger q + \tilde{q}^\dagger\tilde{q}) + O(\frac{1}{\Lambda^2})$$

1-loop effective potential for pseudo-moduli:

$$V_{eff}^{(1)} = \frac{1}{64\pi^2}\mathrm{Tr}(-1)^F \mathcal{M}^4 \log\frac{\mathcal{M}^2}{\Lambda^2}$$

mass matrices are functions of the pseudo-moduli

1-loop vacuum energy

Higher loops (higher powers of small α, β) are smaller, because the magnetic theory is IR free.

Effect of the one-loop potential for the pseudo-moduli

The effective potential is minimized (up to symmetries):

$$\Phi = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}, \qquad q = \tilde{q}^T = \begin{pmatrix} \mu \mathbb{I}_{N_f - N_c} \\ 0 \end{pmatrix}$$

All pseudo-moduli get non-tachyonic masses at one-loop.

SUSY broken: $V_{min} \approx N_c \alpha |\mu^4| = N_c \alpha |m_0^2 \Lambda^2| > 0$

Vacua (meta) stable (we'll discuss tunneling soon).

Vacua mysterious in electric description. $\langle M \rangle = 0, \ \langle B \rangle \neq 0$

Not semi-classical, very quantum mechanical.

Effects from the microscopic theory

There are (uncalculable) contributions to V_{eff} from high energy modes ($\sim \Lambda$), e.g. loops of SUSY split massive particles. Is this a problem? No.

All such effects can be summarized by corrections to the Kahler potential and lead to effects which are real analytic in $\mu^2 = -m_0 \Lambda$. Our calculated V_{eff}^{1-loop} is not real analytic in $\mu^2 = -m_0 \Lambda$, because it arises from integrating out modes which are massless as $m_0 \to 0$.

Corrections from UV modes are thus negligible for

$$\epsilon^2 = |m_0/\Lambda| = |\mu^2/\Lambda^2| \ll 1$$

Dynamical SUSY restoration

$\mathrm{Tr}(-1)^F = N_c$ SUSY vacua, in magnetic theory via:

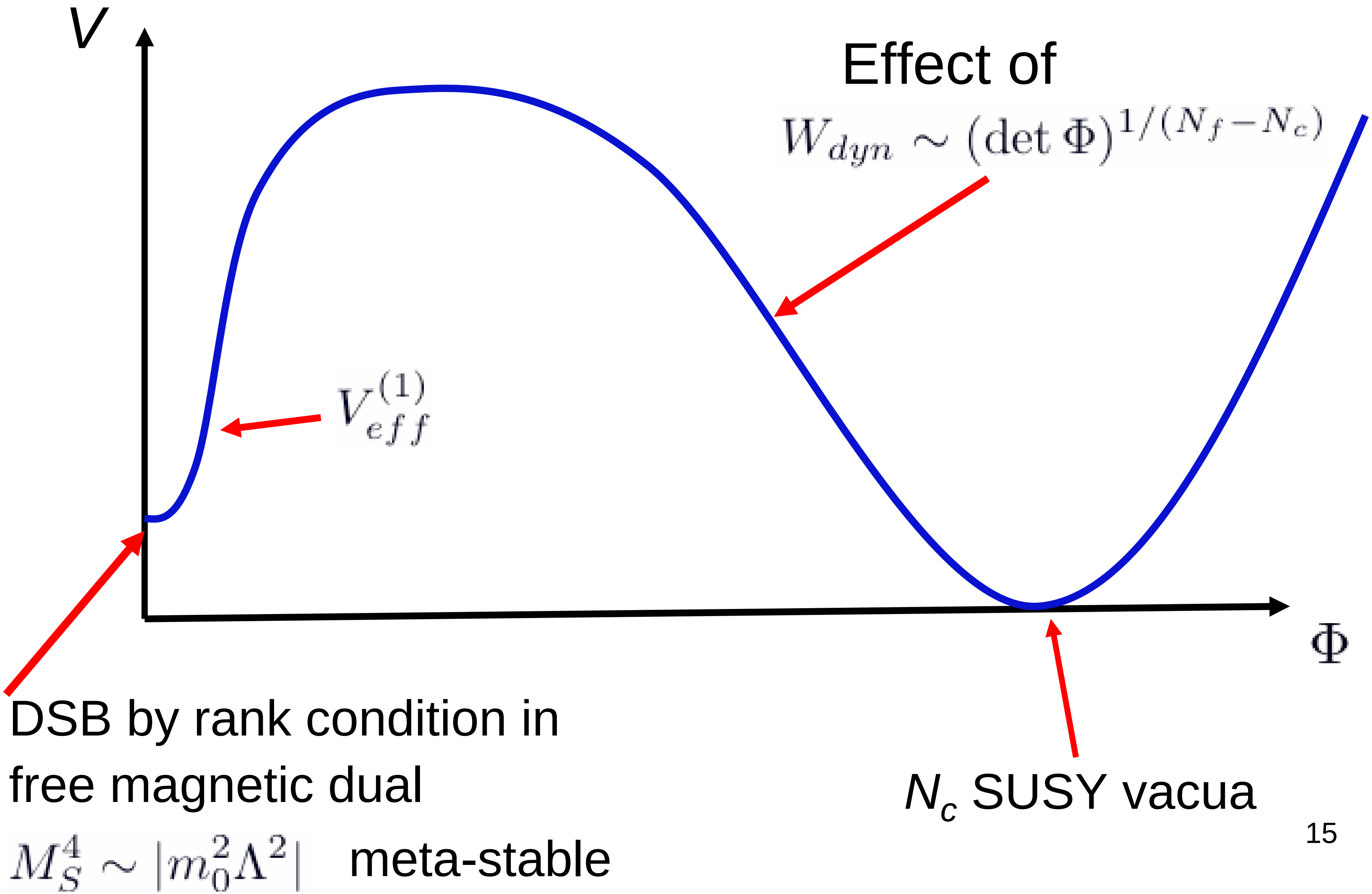
$$W_{dyn} \sim (\det \Phi)^{1/(N_f - N_c)}$$

Non-perturbatively restores SUSY in the magnetic theory.

In free magnetic range, $N_f < 3N_c/2$, this term is $\sim \Phi^{\# > 3}$, so insignificant for the DSB vacua near the origin.

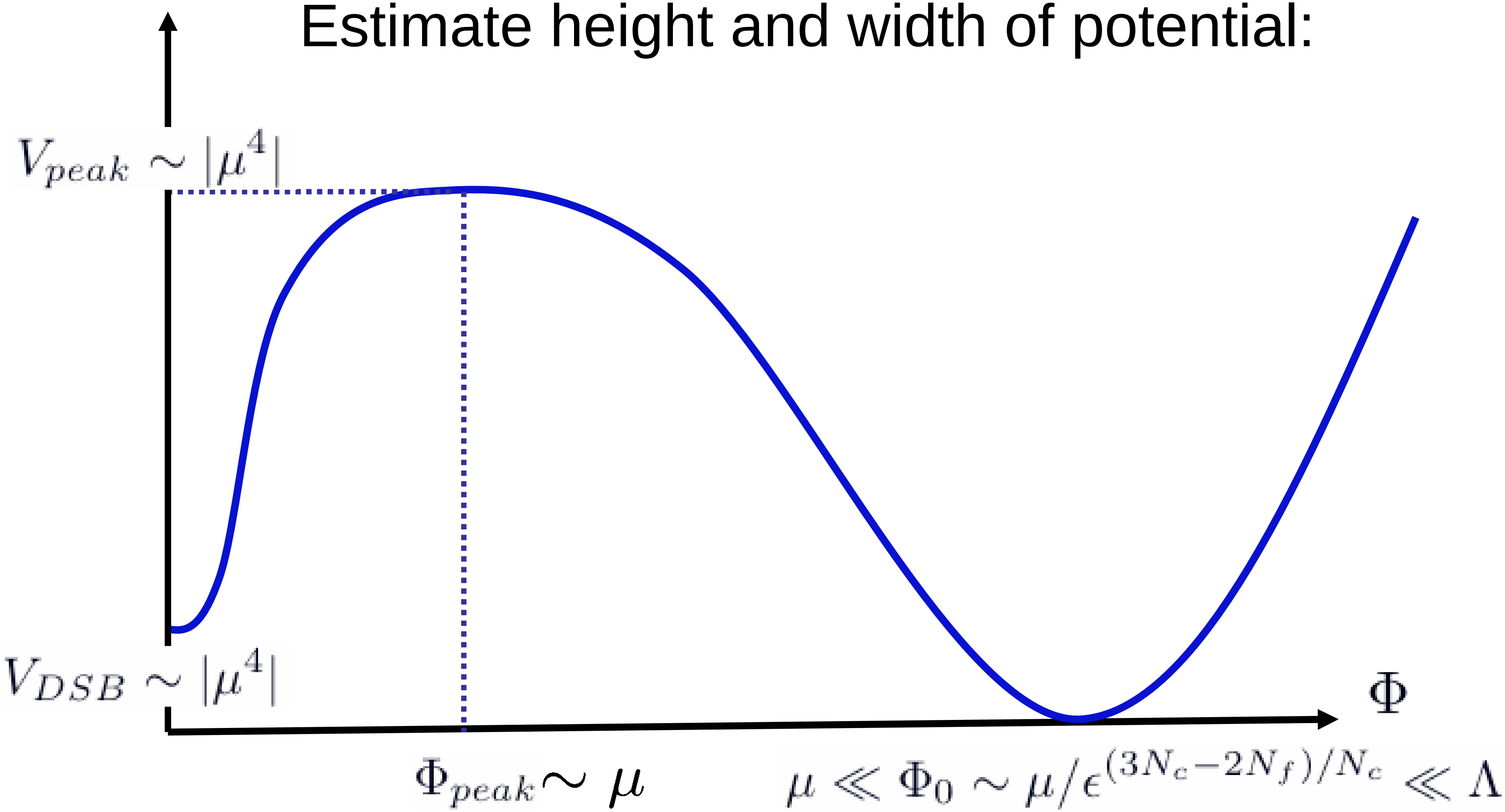
For $\epsilon^2 = |\mu^2/\Lambda^2| = |m_0/\Lambda| \ll 1$, can reliably analyze effect of this term elsewhere, and find the SUSY vacua in the magnetic theory, staying below its cutoff: $\Phi \ll \Lambda.$

Sketch of the full potential



Lifetime of meta-stable DSB vacua

Estimate height and width of potential:



(Recall $\mu^2 = -m_0\Lambda$, $\epsilon = \sqrt{|m_0/\Lambda|} = |\mu/\Lambda| \ll 1$.)

Lifetime of DSB vacua, cont.

Decay probability $\sim \exp(-S_{bounce})$ (e.g. Langer,Coleman)

Use the classical, Euclidean action of the bounce. Since $V_{DSB} \sim V_{peak}$, the thin-wall approximation not valid. Can nevertheless estimate:

$$S_{bounce} \sim \frac{|\Delta\Phi|^4}{V_{DSB}} \sim \epsilon^{-4(3N_c-2N_f)/N_c} \gg 1$$

Our meta-stable DSB vacuum is parametrically long-lived for $\epsilon = \sqrt{|m_0/\Lambda|} = |\mu/\Lambda| \ll 1$.

Actually a moduli space of DSB vacua

DSB vacua: $$\mathcal{M} = \frac{U(N_f)}{S\left(U(N_f - N_c) \times U(N_c)\right)}$$ **(SSB)**

Large configuration space of vacua. Non-trivial topology. Solitonic strings.

The massless spectrum of the DSB vacua are:

Exactly massless Goldstone bosons, and a Goldstino.
Some extra massless fermions (from pseudo-moduli).

Electric description: naively no massless fields, since quarks have masses and SYM has a mass gap. (True in susy vacua.)

Prospects for Model Building

Longstanding model building challenges:

- Naturalness.
- Direct gauge mediation leads to Landau poles.
- R-symmetry problem.

They can be revisited.

The new DSB mechanisms offer new perspectives on these issues and provide new avenues for model building.

R-symmetry problem

DSB without susy vacua requires a $U(1)_R$ symmetry (or a non-generic superpotential). (Affleck, Dine, Seiberg; Nelson, Seiberg). But for nonzero Majorana gluino masses, $U(1)_R$ should be broken. To avoid unwanted Goldstone boson, $U(1)_R$ should be explicitly broken, which might restore SUSY. (Gravity may help.)

Our examples: no exact $U(1)_R$. (Indeed, SUSY vacua.) Meta-stable DSB vacua have accidental approximate $U(1)_R$. Perhaps it is better if that symmetry is also spontaneously broken. (Our model also has an exact discrete R-symmetry, again bad for gaugino masses; it can be explicitly broken by added interactions.)

Outlook

- Accepting meta-stability leads to surprisingly simple models of DSB.
- Can find similar other models (e.g. with *m* replaced with a dimensionless or irrelevant coupling). E.g. Ooguri & Ookouchi* (*talk).
- Suggests meta-stable DSB is generic in $\mathcal{N} = 1$ SUSY field theory, and in the landscape of string vacua.
- Extend to the landscape of string vacua. Relate to anti-D-branes in KS geometry? (note: baryonic). Counting vacua.
- Cosmology.