Metastable Supersymmetry Breaking

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Intriligator, NS and Shih, hep-th/0602239, hep-th/0703281

Intriligator and NS, hep-ph/0702069

Dine and NS, unpublished

What will the LHC find?

- We do not know.
- Perhaps nothing. Is the standard model wrong?
- Only the Higgs particle. Most boring. Unnatural. Is the Universe Anthropic?
- More particles associated with an unnatural Universe
  - Split supersymmetry
  - …
- Natural Universe
  - Supersymmetry (SUSY)
  - Extra dimensions
  - …
- Something we have not yet thought of

In my view supersymmetry is the most conservative and most conventional possibility.

It predicts many new particles: superpartners of the particles of the standard model.

Supersymmetry must be broken

- These superpartners are heavier than their counterparts. (Hopefully they'll be found at the LHC.)

- Therefore supersymmetry must be broken.

- The details of how supersymmetry is broken and how SUSY breaking is fed (mediated) to the light particles determines their spectrum. This will be studied at the LHC.

- Today, we'll focus on supersymmetry breaking.
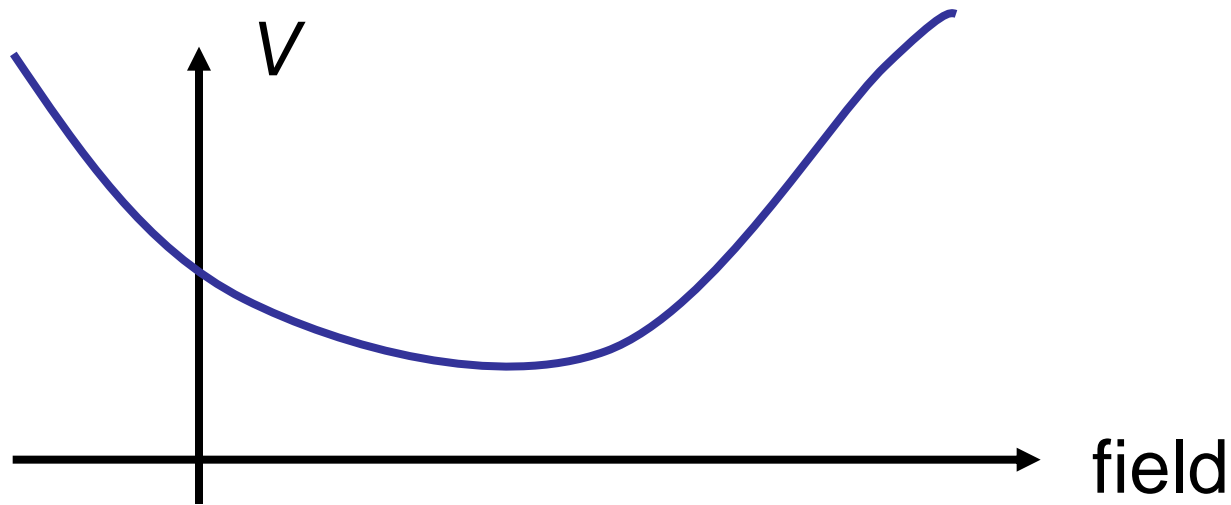
Spontaneous supersymmetry breaking

$$\mathcal{L} = \mathcal{L}_{SUSY}$$

$$Q|0\rangle \neq 0 \iff E \neq 0$$
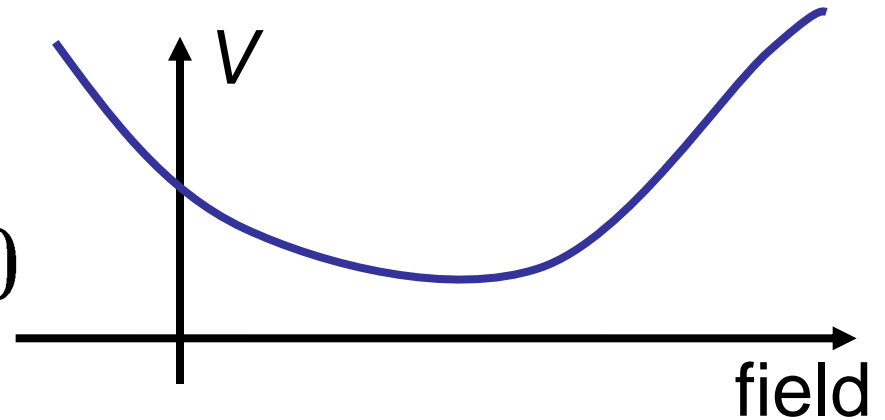
The theory is supersymmetric but its ground state is not.

(This nonzero vacuum energy should not be confused with the cosmological constant. The latter can be adjusted to its desired value.)

More specifically, if there are no gauge fields, the theory is characterized by a holomorphic function – superpotential *W.*
Supersymmetry is broken if and only if *W* does not have stationary points – no solution of

$$\partial W = 0.$$

Supersymmetry breaking should be small

- We want the Universe to be approximately supersymmetric.

- Hope that supersymmetry is dynamically broken [Witten]:

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

This will naturally explain why it is small.

- For that we need a tiny nonperturbative effect in a gauge theory.

Role of R-symmetry (Nelson and NS)

If there are *n* fields ϕ_i ,

$$\partial_i W = 0$$

are *n* equations with *n* unknowns, and hence generically there is a solution (possibly more), and supersymmetry is unbroken.

Adding symmetries does not help – they reduce the number of unknowns but also the number of equations.

With an R-symmetry, the superpotential should have R-charge 2.

Let the field ϕ_i have R-charge r_i. Then,

$$W = \phi_1^{2/r_1} F(\phi_i / \phi_1^{r_i/r_1})$$

and

$$\partial_i W = 0$$

are *n equations with n-1 unknowns. So generically, there is no solution!*

- Assuming that *W* is generic (and a few other minor assumptions), supersymmetry is spontaneously broken, iff the theory has a global R-symmetry.

- This result applies also when supersymmetry is dynamically broken – the theory has a strongly coupled gauge theory – because the low energy theory can be described by an effective Lagrangian with chiral superfields.
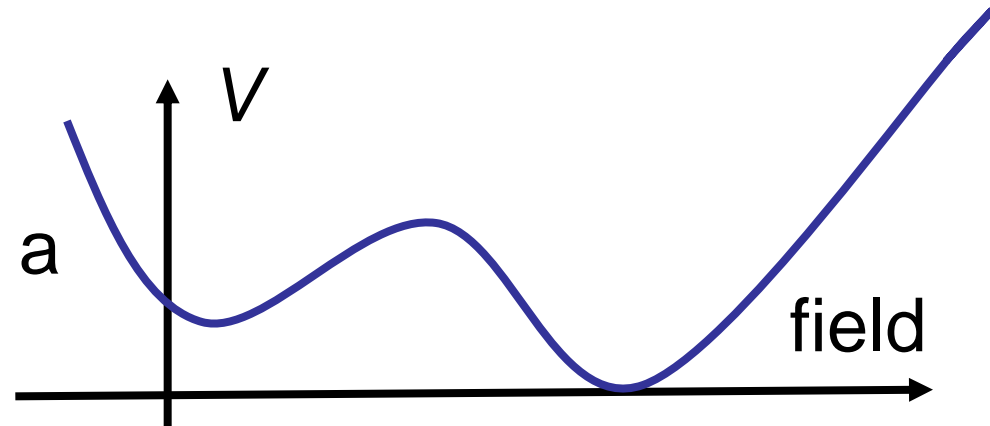
The role of an approximate R-symmetry

Consider a theory with an exact R-symmetry when a small parameter ϵ is set to zero.

For $\epsilon = 0$
SUSY is broken.
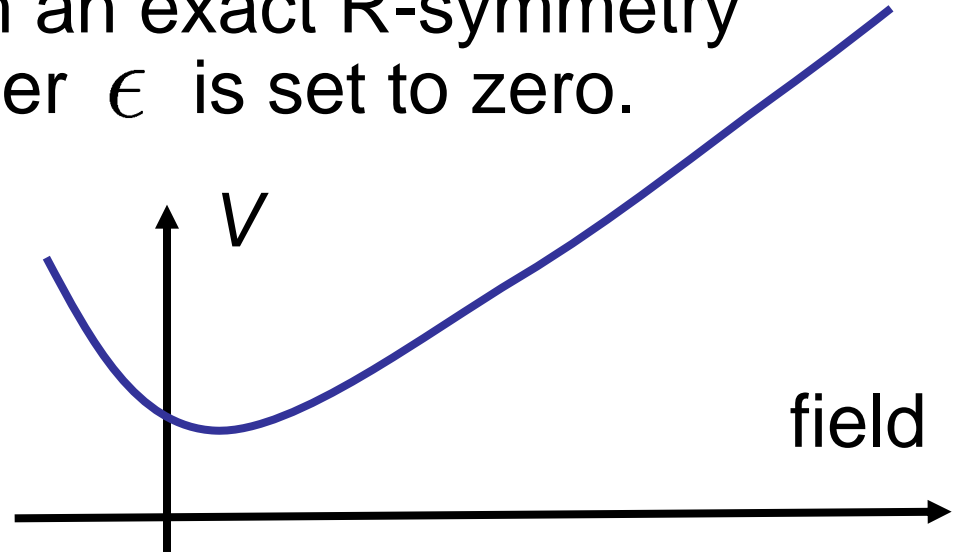
For $\epsilon \neq 0$
SUSY is unbroken,
but SUSY is broken in a
metastable state.

Looking for dynamical supersymmetry breaking (DSB)

- Many constraints on dynamical supersymmetry breaking:
  - The Witten index (and hence the theory should be chiral)
  - $U(1)_R$

- Supersymmetry breaking is not generic – most supersymmetric field theories do not break supersymmetry.

- But some theories do.

Metastable supersymmetry breaking

- Easy to find examples with classical metastable supersymmetry breaking [e.g. Ellis, Llewellyn Smith, Ross (82)…]

- All known examples of gauge mediation supersymmetry breaking models restore supersymmetry somewhere in field space [Dine, Nelson…(94…)].

- Some early examples of metastable DSB (MDSB) [Dimopoulos, Dvali, Rattazzi, Giudice…(97…)]

Metastable SUSY breaking is inevitable

- For breaking SUSY we need an R-symmetry.
- Nonzero gaugino masses mean that this R-symmetry should be broken.

- If the R-symmetry is spontaneously broken, there is a massless Goldstone boson.
- So the R-symmetry should be explicitly broken.
- Gravity effects explicitly break the R-symmetry (no continuous global symmetries in a theory with gravity, the added terms needed to adjust the c.c. break the R-symmetry), thus giving mass to the Goldstone boson [Bagger, Poppitz, Randall]. This mass might not be large enough.

- We see that the R-symmetry must be explicitly broken.
- Therefore, in the absence of gravity we must have metastable SUSY breaking.

  We conclude that (with mild assumptions) we live in a metastable state!

- This is in accord with the fact that in all known realistic models of DSB the SUSY breaking vacuum is metastable.
- There are independent gravitational reasons for metastability: nonzero cosmological constant (hard to make sense of de-Sitter space), string landscape of vacua.

Examples with MDSB

- It turns out that metastable dynamical supersymmetry breaking is generic.

- Many simple supersymmetric theories have long lived metastable nonsupersymmetric vacua.

- The simplest example: SQCD with N_c colors and N_f flavors with $N_c < N_f < 3N_c/2.$

Review of *N=1* SQCD

[Veneziano, Yanielowicz,…]

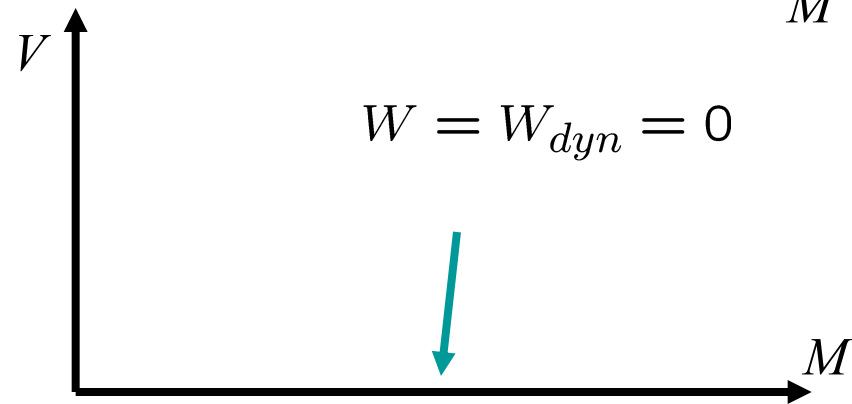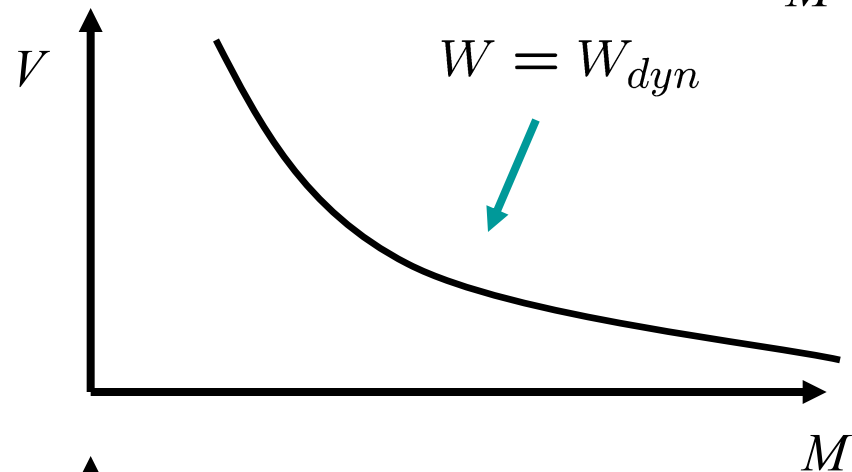With N_f massive flavors:

$$Tr(-1)^F = N_c \quad \text{SUSY vacua}$$

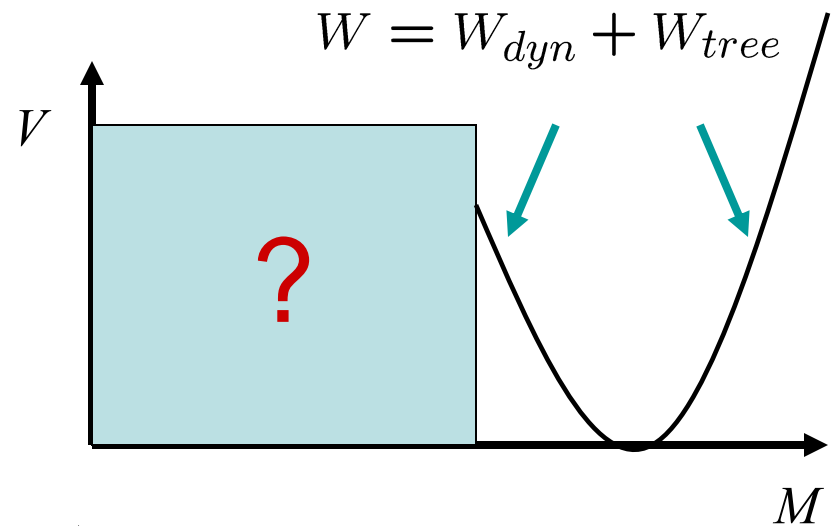
With $N_f < N_c$ massless flavors
[Affleck, Dine and NS]:

$$W_{dyn} \sim \left(\frac{\Lambda^{3N_c - N_f}}{\det M} \right)^{\frac{1}{N_c - N_f}}$$

No static vacuum. Runaway.

With $N_f \geq N_c$ massless flavors

A continuous space of quantum vacua – moduli space.

$W = W_{dyn} + W_{tree}$

V

?

M

V

$W = W_{dyn}$

M

V

$W = W_{dyn} = 0$

M

For massive electric flavors: N_c SUSY vacua

$$W_{tree} = \mathrm{Tr}\, mQ\widetilde{Q} = \mathrm{Tr}\, mM$$

Gaugino condensation in the low-energy $SU(N_c)$ SYM:

$$\langle M \rangle = \frac{\partial}{\partial m} W_{eff}(m) = \frac{\partial}{\partial m} N_c (\det m \Lambda^{3N_c - N_f})^{1/N_c}$$

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

For $N_f > N_c$ the vacua are near the origin
(for $m_0 \to 0,\ M \to 0$), where the electric theory is
strongly coupled.

Review of Duality in $N = 1$ SQCD [NS]

Electric Theory: $SU(N_c) \times [SU(N_f) \times SU(N_f)]$ $W_{tree} = 0$

$$Q \in \quad N_c \quad N_f \quad 1$$
$$\tilde{Q} \in \quad \overline{N_c} \quad 1 \quad \overline{N}_f$$

Asymptotically free if $N_f < 3N_c$ (IR free if not)

Magnetic Theory: $SU(N_f - N_c) \times [SU(N_f) \times SU(N_f)]$ $W_{dual} = \tilde{q}\Phi q$

$$q \in \quad N_f - N_c \quad \overline{N}_f \quad 1$$
$$\tilde{q} \in \quad \overline{N_f - N_c} \quad 1 \quad N_f$$
$$\Phi \in \quad 1 \quad N_f \quad \overline{N}_f$$

Asymptotically free if $N_f > 3N_c/2$ (IR free if not)

Classically different. Quantum theories are related.

Review Duality in *N =1* SQCD, cont.

$$\frac{3}{2}N_c < N_f < 3N_c$$

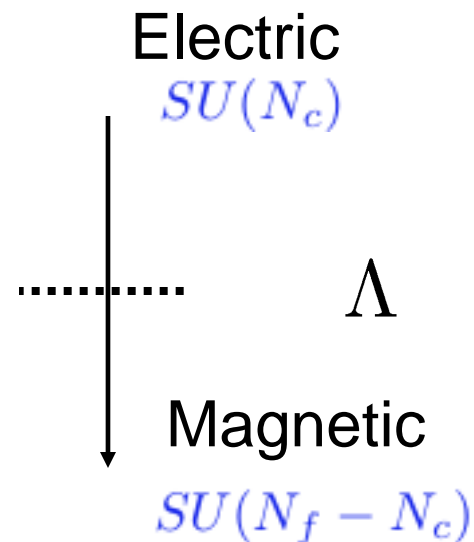Interacting superconformal field theory.

Electric $SU(N_c)$

Magnetic $SU(N_f - N_c)$

Λ

Same IR SCFT
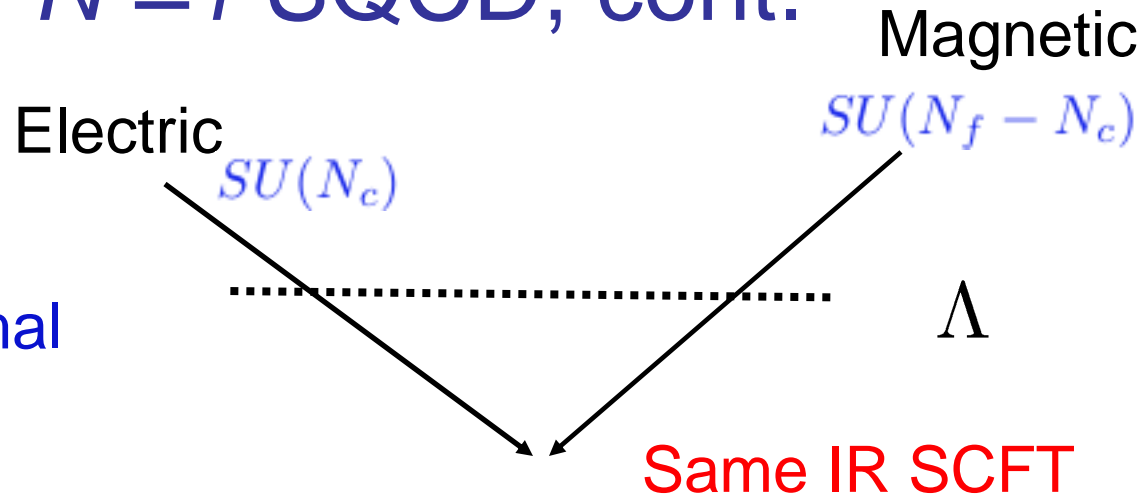
$$N_c \leq N_f \leq \frac{3}{2}N_c$$

"Free Magnetic phase"

Magnetic theory is IR free ...

Electric $SU(N_c)$

Λ

Magnetic $SU(N_f - N_c)$

20

The magnetic theory is IR free for $N_c + 2 \leq N_f \leq \frac{3}{2} N_c$.

It gives an effective description at low energies. UV cutoff Λ .

$$W_{IR} = \tilde{q} \Phi q \qquad \text{where} \qquad \Lambda \Phi = M = \tilde{Q} Q$$

The Kahler potential of the IR free fields is smooth near the origin and can be approximated as

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

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

(We can rescale the fields such that $\alpha = \beta = 1$, but then there is a parameter in the superpotential and in $\Lambda \Phi = M$.)

The SUSY vacua, now in the magnetic dual:

For generic $\langle M \rangle \neq 0$ the dual quarks q get a mass $\Phi = M/\Lambda$ from $W_{dual} = \tilde{q}\Phi q$ and can be integrated out.

Gaugino condensation in the magnetic theory then yields an additional term:

$$W_{dual} = (N_c - N_f)\left(\frac{\det M}{\Lambda^{3N_c - N_f}}\right)^{1/(N_f - N_c)} + \mathrm{Tr}\, mM$$

Gives the same N_c SUSY vacua and $\langle M \rangle$ as found in electric theory.

Rank condition SUSY breaking

Give the electric flavors small masses: $\quad m = m_0 \mathbb{I}_{N_f}$

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

In the magnetic dual this yields: $\qquad W_{tree} = \operatorname{Tr} q\Phi\tilde{q} - \mu^2 \operatorname{Tr}\Phi$

SUSY broken at tree level!

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

$$\frac{\partial W_{tree}}{\partial \Phi_f^g} = \tilde{q}_g^c q_c^f - \mu^2 \delta_g^f \neq 0$$

(rank N_f -N_c)   (rank N_f)

using the classical rank of $(q\tilde{q})_g^f$ (appropriate if free-magnetic). This SUSY breaking is a check of the duality. Otherwise, would have had unexpected, extra SUSY vacua.

The low energy theory has SUSY breaking vacua

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

Actually a compact space of non-SUSY vacua

$$\mathcal{M} = \frac{U(N_f)}{S\left(U(N_f - N_c) \times U(N_c)\right)}$$

Exactly massless Goldstone bosons.
An exactly massless, Goldstone fermion, from DSB.
Extra massless fermions, from pseudo-moduli.

This pattern of symmetry breaking is very mysterious in the microscopic/fundamental electric description (broken vector-like symmetries…).

Dynamical SUSY restoration

$\text{Tr}(-1)^F = N_c$ SUSY vacua, in magnetic theory via:
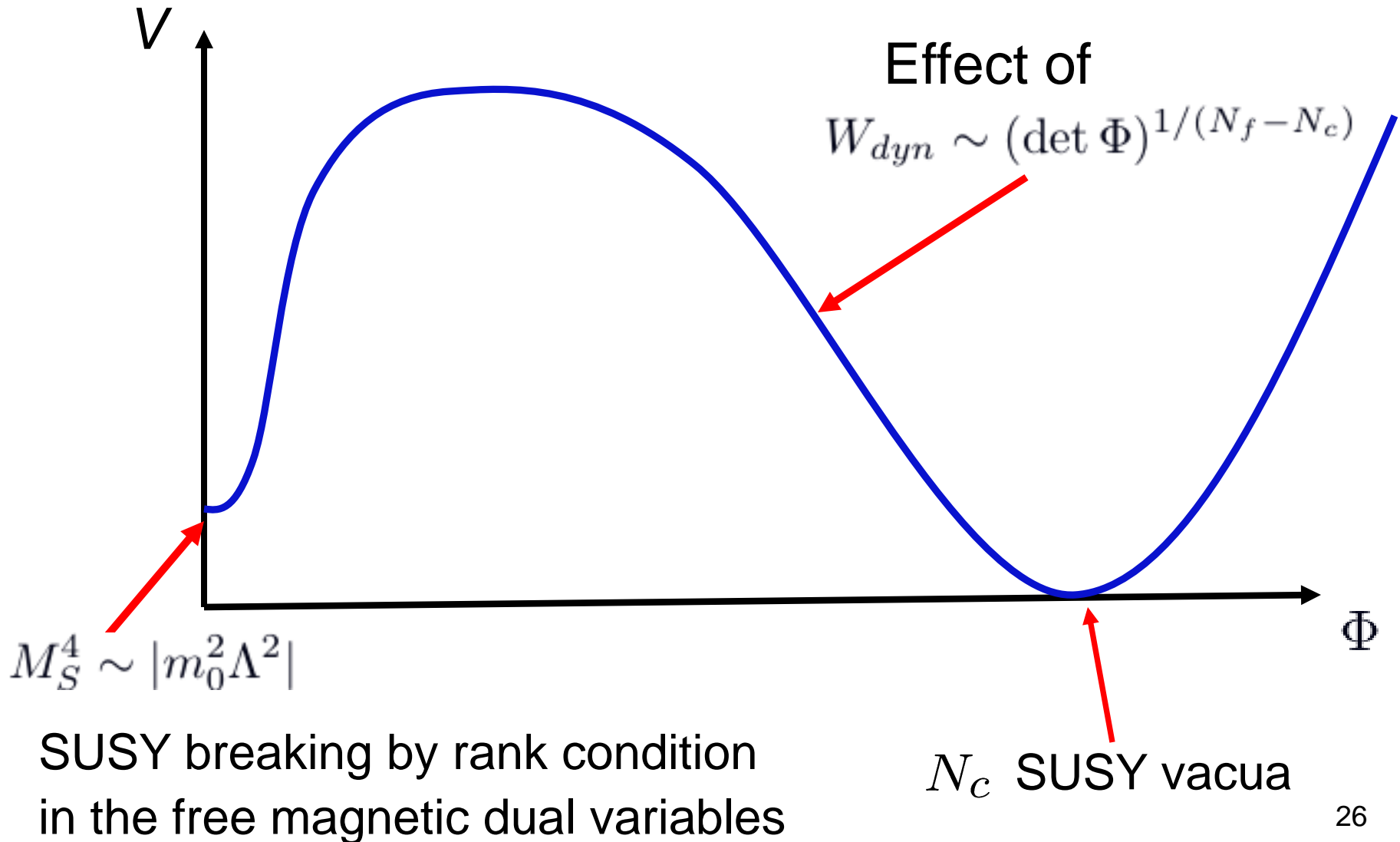
$$W_{dyn} \sim (\det \Phi)^{1/(N_f - N_c)}$$

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: $\bar{\Phi} \ll \Lambda$.

Sketch of the full potential

V

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

Φ

$M_S^4 \sim |m_0^2 \Lambda^2|$

SUSY breaking by rank condition
in the free magnetic dual variables

N_c SUSY vacua

General lessons for QFT

Independent of the applications to supersymmetry breaking, this is a surprising result in QFT.

- A complicated feature is generated in the effective potential.

- It involves directions in field space, which do not have a semi-classical meaning.

- The pattern of global symmetry breaking and spectrum at the metastable vacuum violate general arguments about quantum field theory.

Lifetime of metastable DSB vacua

Estimate height and width of potential:

$V_{peak} \sim |\mu^4|$

$V_{DSB} \sim |\mu^4|$

Φ
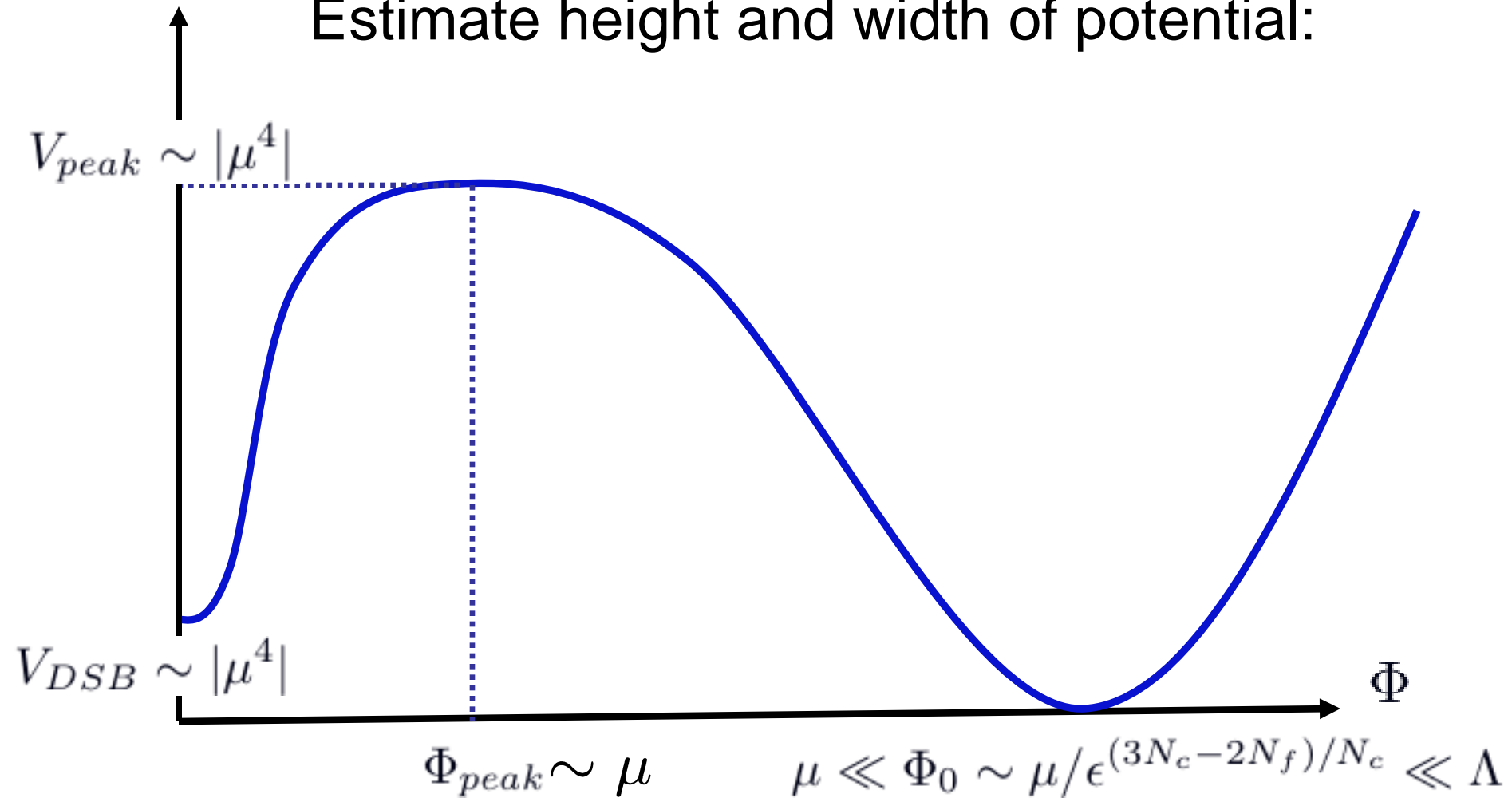
$\Phi_{peak} \sim \mu$

$\mu \ll \Phi_0 \sim \mu/\epsilon^{(3N_c - 2N_f)/N_c} \ll \Lambda$

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

Lifetime of DSB vacua, cont.

Decay probability $\quad \sim \exp(-S_{bounce})$ $\qquad$ [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 metastable DSB vacuum is parametrically long-lived
for $\epsilon = \sqrt{|m_0/\Lambda|} = |\mu/\Lambda| \ll 1$.

This is essential; metastable states make sense only
when they are parametrically long-lived.

Particle physics application

- Use this kind of a model as a module which breaks supersymmetry using some of the known mediation mechanisms: gravity mediation, gauge mediation,…
- Some of the known obstacles/difficulties are viewed in a new light
  - R-symmetry and its breaking
  - Naturalness, μ problem
  - Landau poles

R-symmetry as the organizing principle

- Exact R-symmetry which is spontaneously broken
  - Massless "R-axion" (R-breaking gravitational effects can help [Bagger, Poppitz, Randall])
- Add small field theoretic explicit breaking
  - Metastable vacuum
- Large explicit R-breaking in the MSSM but the susy breaking sector has an approximate R-symmetry […Murayama, Nomura; Aharony, NS…]
  - Metastable vacuum
  - SUSY broken at high energies

- Can also use that to organize the soft breaking terms

Cosmology

This mechanism for SUSY breaking leads to many new cosmological questions.

- At high temperatures the lowest free energy state is at the origin.
- As the Universe cools down, there is a second order transition to nonzero q (broken SUSY vacuum) [Abel, Chu, Jaeckel, Khoze; Craig, Fox, Wacker; Fischler, Kaplunovsky, Krishnan, Mannelli, Torres].
- At lower temperatures the SUSY vacuum with nonzero Φ becomes the lowest free energy state. There is a first order transition to that state, but it takes a long time.
- The cosmological evolution leads to the metastable SUSY breaking vacuum.

- Combine this story with inflation.
- Can our almost flat potential be used for the inflaton?

Conclusions and Outlook

- Supersymmetry is a likely possibility for LHC/TeV physics.

- Accepting metastability leads to surprisingly simple models of DSB.

- In fact, metastable SUSY breaking appears to be inevitable.

- Suggests MDSB is generic in $N=1$ SUSY field theory and in the landscape of string vacua.

- The cosmology of this setup is interesting and it poses new questions.

- Find a successful model of SUSY breaking and mediation to the observed world.

- Hopefully, there are distinct experimental signals, e.g. patterns of superpartner masses which will be seen at the LHC.