Susy and its breaking, Lecture 1

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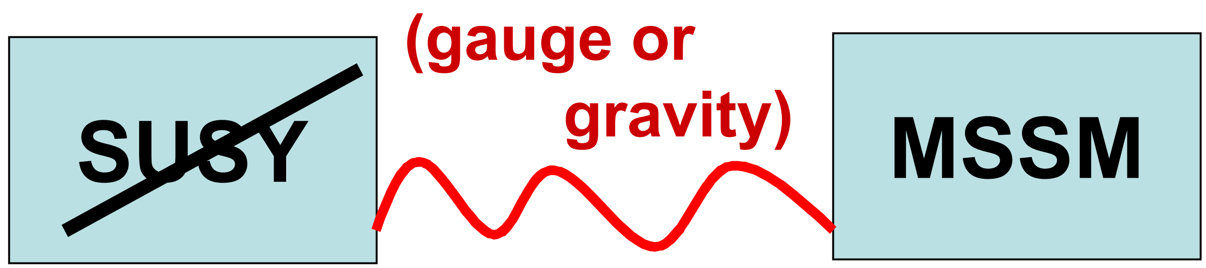
Susy breaking, and mediation



We'll first discuss the susy breaking sector.

Later lectures will discuss aspects of mediation.

Dynamical Supersymmetry Breaking:

- No explicit breaking: $\mathcal{L} = \mathcal{L}_{SUSY}$
- Vacuum spontaneously breaks SUSY.
- SUSY breaking related to some dynamical scale (non-perturbative in coupling)

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

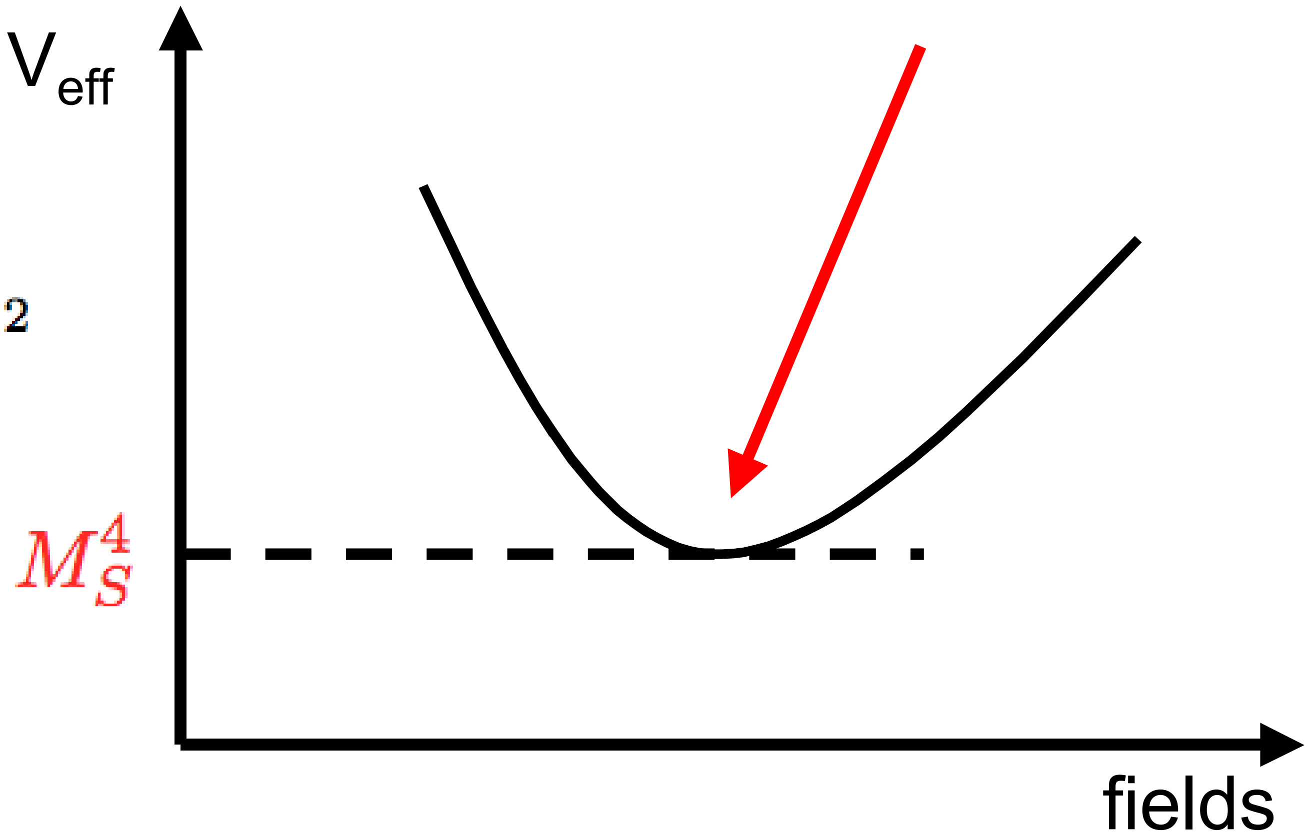
Can naturally get hierarchies (Witten).

Dynamical Supersymmetry Breaking

$H = Q^2$

$\langle H \rangle = \left| Q|0\rangle \right|^2$

~~susy~~ order parameter



Aside: with gravity, can add an extra negative contribution, so $\Lambda_{C.C.} \leq M_S^4$. Will ignore gravity.

Low energy effective field theory

E

$\mathcal{L}_{micro}$ "UV completion"

Λ

$\mathcal{L}_{eff}$ "Low energy theory =LET"

Susy breaking is an IR effect, see in LET.

Top down: find "nice" UV theory, need LET under control. Bottom up: pick nice LET, and later justify that it has a UV completion.

Low energy effective field theory

$$\mathcal{L}_{eff} = \int d^4\theta K_{eff}(\Phi_i, \bar{\Phi}_i) + \int d^2\theta W_{eff}(\Phi_i) + h.c.$$

Holomorphy, constraints, "Known".

Generally unknown, but **if** LET is an IR free theory, then K_{eff} = canonical, up to LET calculable loop corr's + cutoff-suppressed higher dim operators,

E.g. $$K_{eff}(X, \bar{X}) = X\bar{X} + \frac{c}{|\Lambda|^2}(X\bar{X})^2 + \ldots$$

c = gen'ly unknown. Can neglect for $X \ll \Lambda$

SUSY breaking and R-symmetry

Nelson, Seiberg

Unbroken susy iff $\partial_a W(\Phi^a) = 0 \qquad \forall a = 1 \ldots k$

k conditions on k fields, generically have solution(s).
Susy breaking is non-generic, requires a tuned W...

…Unless there is an R-symmetry. Then

$$W = \Phi_1^{2/r_1} W(\Phi^a \Phi_1^{-r_a/r_1}) \quad a = 1 \ldots k-1$$

Now unbroken susy = k conditions on k-1 variables.
Generically no solution. Susy is generically broken.

Simplest example of susy breaking

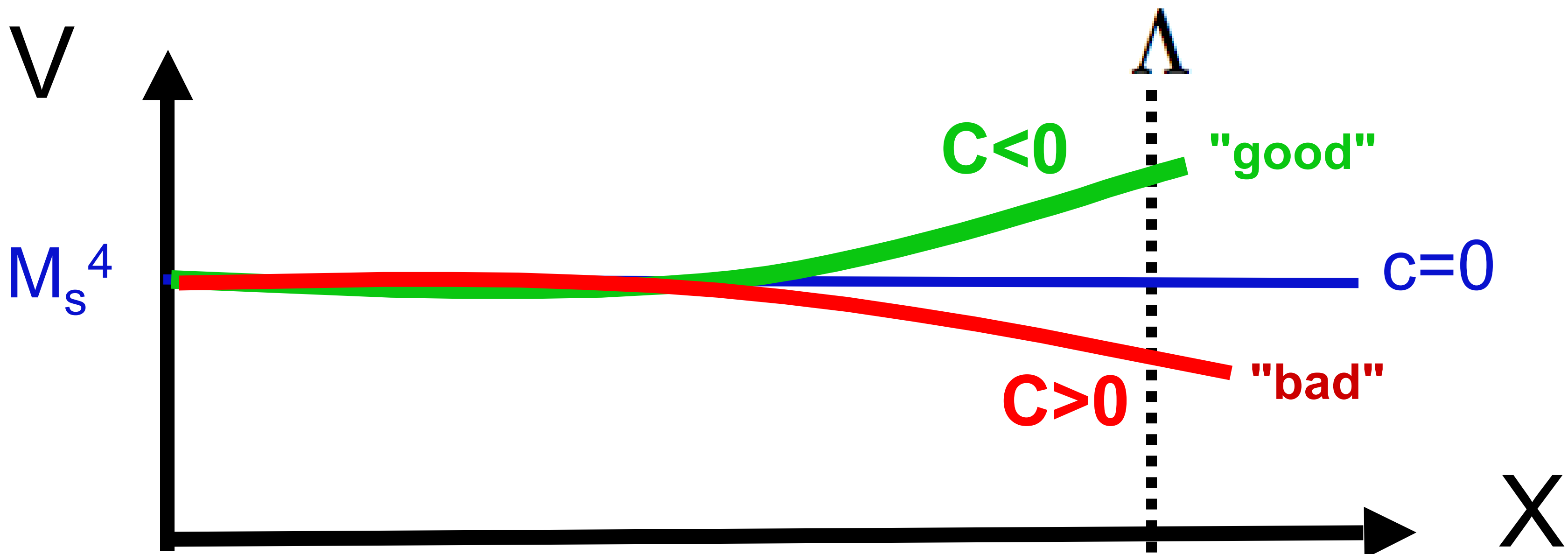
LET: $W_{eff} = M_s^2 X \qquad R(X) = 2$

$$K_{eff}(X, \bar{X}) = X\bar{X} + \frac{c}{|\Lambda|^2}(X\bar{X})^2 + \ldots$$

Susy is broken: $\dfrac{dW}{dX} = M_s^2 \neq 0$

Not yet **DSB**, M_s looks by hand. Can naturalize by finding UV completion where M_s is dynamically generated, $M_s \sim \Lambda^{\#}$

Simplest example, continued

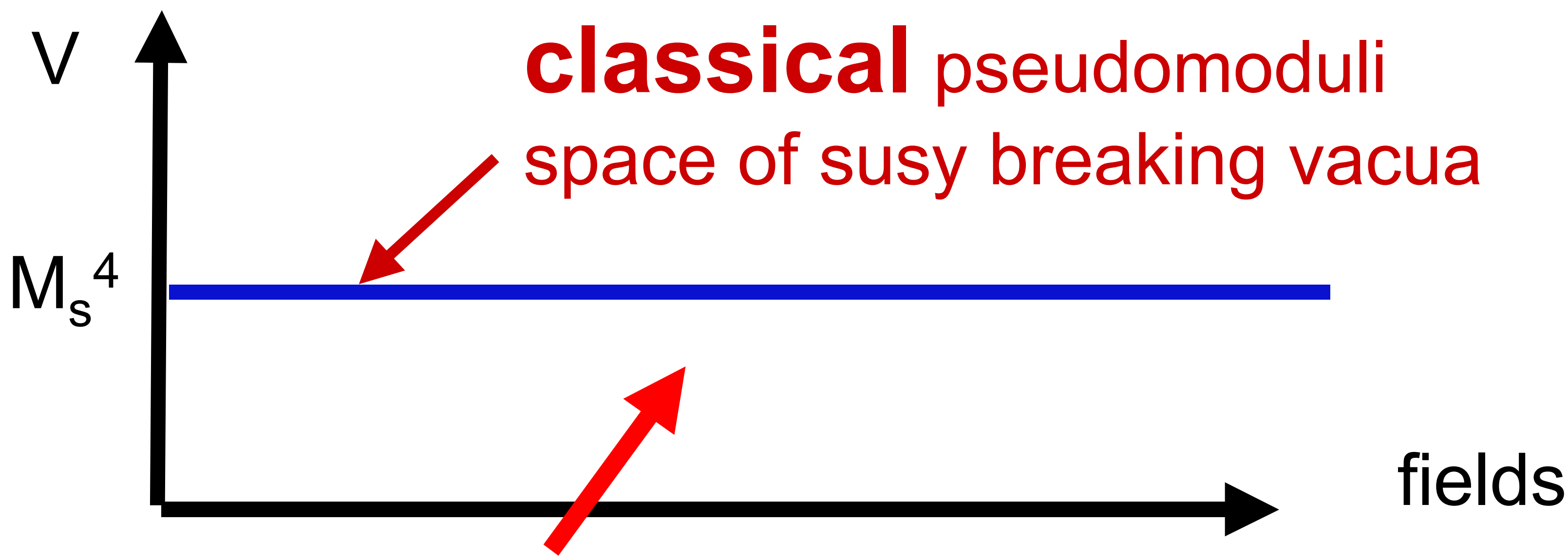


$$V = K^{-1}_{X\bar{X}}|W'|^2 = |M_s|^4(1 + \frac{4c|X|^2}{|\Lambda|^2} + \ldots)^{-1}$$

Pseudomoduli: tree-level F-term breaking with (approx.) K=K_{can} always have (approx.) flat dirs. One is goldstino's superpartner. Good? Bad?

Classical pseudomoduli

Tree-level F-term susy breaking & $K=K_{can}$ implies pseudomoduli. One is Goldstino's partner.



Physically inequivalent, non-susy vacua.
Degeneracy gen'ly lifted by K corrs & loops in LET

O'R models of tree-level susy

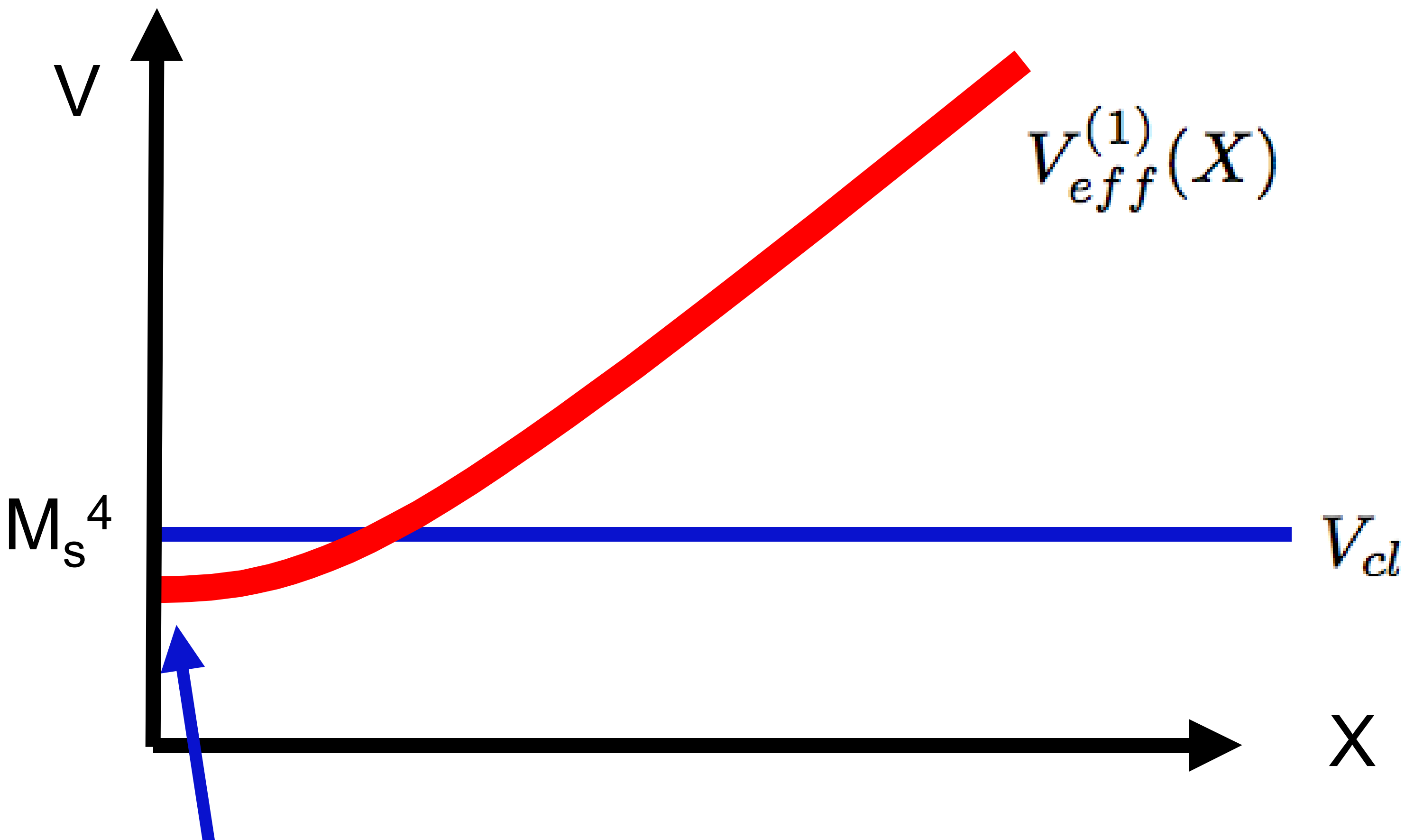
E.g. $$W = \frac{1}{2} h X \phi_1^2 + m\phi_1\phi_2 + fX$$

$$V_{cl} = |\frac{1}{2} h\phi_1^2 + f|^2 + |hX\phi_1 + m\phi_2|^2 + |m\phi_1|^2$$

generalize: $$W = \sum_{i=1}^{r} X_i g_i(\varphi_{j=1\ldots s<r})$$

Can also generalize by taking fields ϕ in reps of some gauge group G.

Pseudomodulus lifting in O'R.



Quantum vacuum at origin, X=0.
This is where $U(1)_R$ is unbroken.

Pseudomoduli lifted by QM

$$V_{eff}^{(1)} = \frac{1}{64\pi^2} Str\left(\mathcal{M}^4 \log\left(\frac{\mathcal{M}^2}{\Lambda^2}\right)\right)$$

← Coleman-Weinberg potential.

$$= \frac{1}{64\pi^2}\left[Tr\left({m_B}^4 \log\left(\frac{{m_B}^2}{\Lambda^2}\right)\right) - Tr\left({m_F}^4 \log\left(\frac{{m_F}^2}{\Lambda^2}\right)\right)\right]$$

Comments: pseudomoduli often stabilized at origin, where the R-symmetry is not spontaneously broken. Can (somewhat) avoid this in models with gauge Interactions, or complicated W. Some models have many pseudomoduli, with some only stabilized by multi-loop effective potential.

Pseudomodulus lifting in O'R.

$$W = h(\frac{1}{2}X\phi_1^2 + m\phi_1\phi_2 - \mu^2 X)$$

Compute $V_{eff}^{(1)} = \frac{1}{64\pi^2} Str\left(\mathcal{M}^4 \log\left(\frac{\mathcal{M}^2}{\Lambda^2}\right)\right)$ via

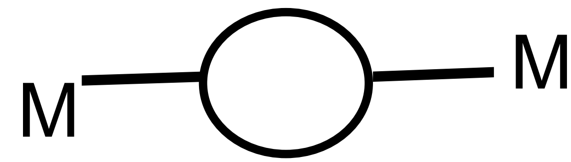
$$m_0^2 = |h|^2\left(|m|^2 + \frac{1}{2}\eta|\mu^2| + \frac{1}{2}|X|^2 \pm \frac{1}{2}\sqrt{|\mu^4| + 2\eta|\mu^2||X|^2 + 4|m|^2|X|^2 + |X|^4}\right)$$

$$m_{1/2}^2 = \frac{1}{4}|h|^2(|X| \pm \sqrt{|X|^2 + 4|m|^2})^2$$

Just plug in these classical eigenvalues, to get full potential $V_{eff}^{(1)}(X)$. It lifts the X degeneracy,

CW potential vs susy effective V

If susy splittings are small, can also compute V_{eff} in susy effective field theory. E.g. Integrate out massive fields, with $W = \frac{1}{2} M_{ij}\phi^i\phi^j$



$$K_{eff} = -\frac{1}{32\pi^2} Tr[MM^\dagger \log(MM^\dagger/\Lambda^2)]$$

E.g. O'R: $M = h\begin{pmatrix} X & m \\ m & 0 \end{pmatrix}$ $\rightarrow$ $K_{eff}(X, \bar{X})$

$W_{low} = -h\mu^2 X$ Nice, often easier way to get V, correct to leading order in small F.

E.g. large pseudomodulus vev

$$K_{eff} \approx Z_X X^\dagger X \ , \qquad V = Z_X^{-1}|f|^2 + \text{finite}$$

$$V \approx \text{const} + 2V_0 \Delta\gamma_X \log \frac{hX}{\Lambda}$$

$$Z \approx 1 + \frac{|h|^2}{32\pi^2} \log |\frac{\Lambda}{hX}|^2$$

In this limit, get pseudomodulus potential from 1-loop running. Generalization for any large pseudo-modulus vev; get multi-loop V from 1-loop running.

R-symmetry problem

- Generic W, w/o $U(1)_R$: susy unbroken.
- Generic W, with $U(1)_R$: susy broken.

Nelson & Seiberg

Problem: R-symmetry is **bad**: forbids gaugino masses. If breaking is only spontaneous, also bad: get massless R-axion. Need explicit breaking.

Approximate U(1)$_R$ and metastable susy breaking

Suppose a small R-symmetry breaking parameter ϵ

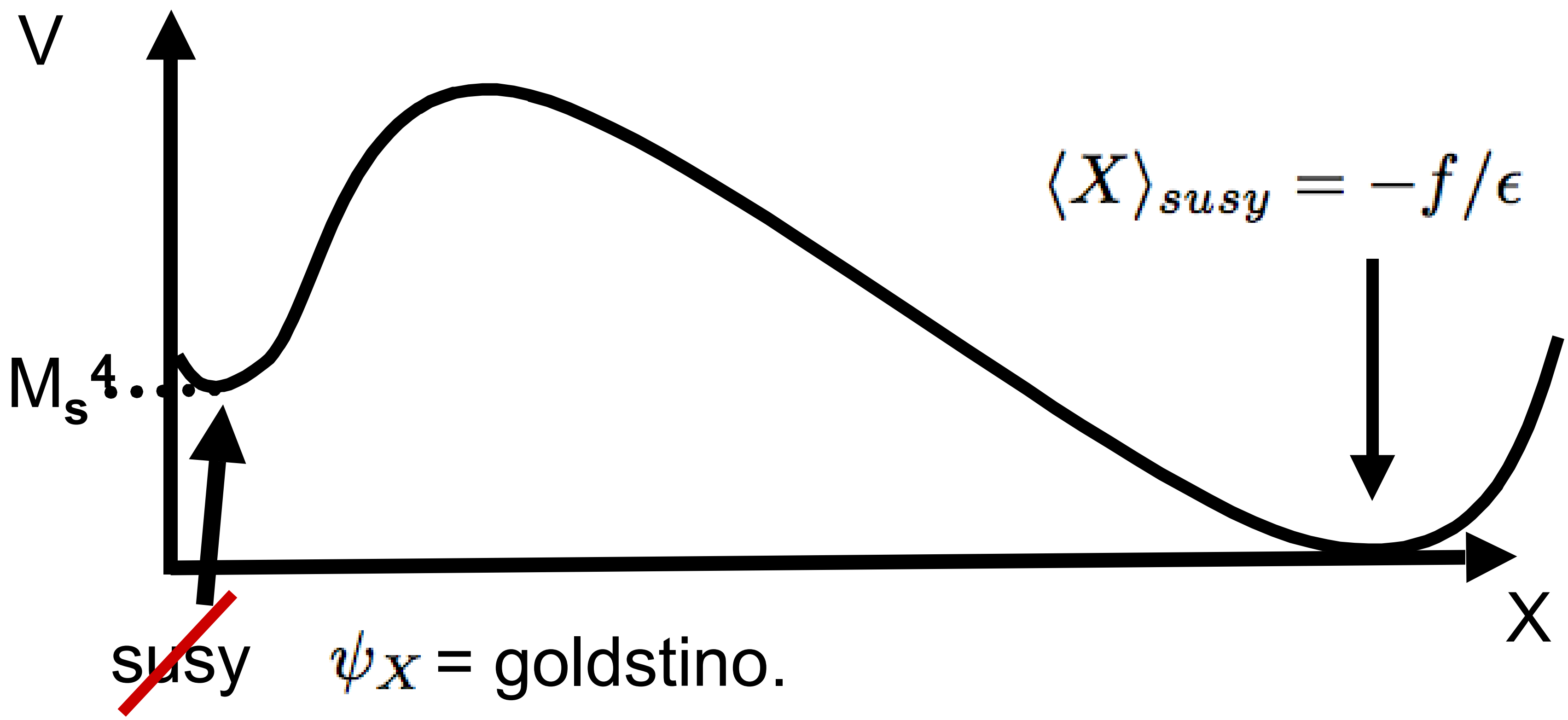
$\epsilon = 0$: R-symmetry, and broken susy.
(Assume a compact space of vacua.)

$\epsilon \neq 0$: Susy vacua, at $\Delta\Phi \sim \epsilon^{-\#}$
Susy breaking vacua only slightly perturbed; now they're metastable. Long lived for $\epsilon \ll 1$ since $\Delta\Phi \sim \epsilon^{-\#}$ is large.

Conclude: metastability is required for realistic, generic models of susy breaking!

Simple Example

$$W = fX + \frac{1}{2}\epsilon X^2 \quad \Bigg| \quad K = X\bar{X} - \frac{c}{|\Lambda^2|}(X\bar{X})^2 + \ldots$$



Meta-stable susy breaking in similarly modified O'R model

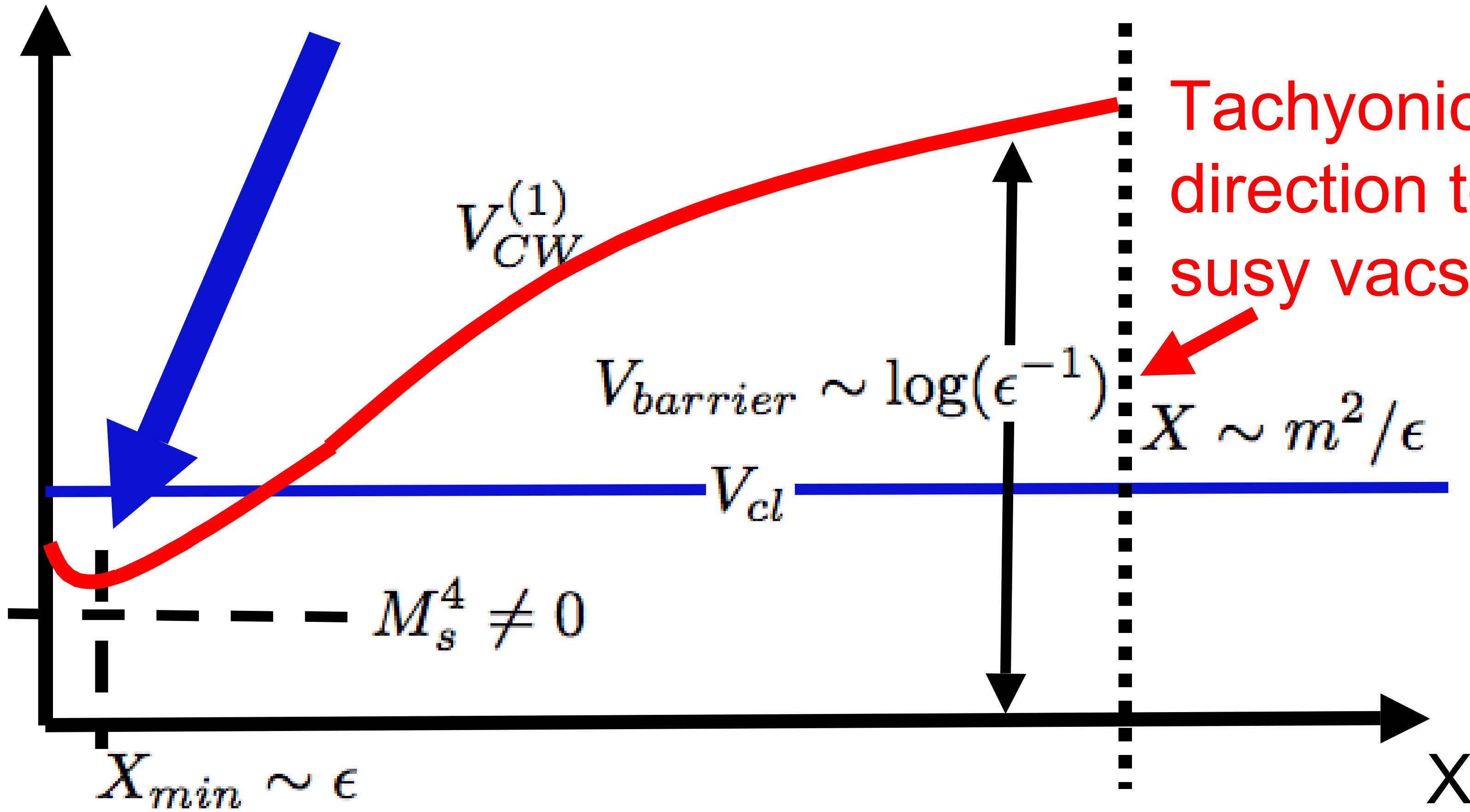
$$W = \frac{1}{2} h X \phi_1^2 + m \phi_1 \phi_2 + f X + \frac{1}{2} \epsilon m \phi_2^2$$

Deformation adds a susy vacuum, comes in from infinity:

$$\langle X \rangle_{susy} = \frac{m}{h\epsilon}$$

Also the susy breaking vacuum that we've seen before, with X near origin:

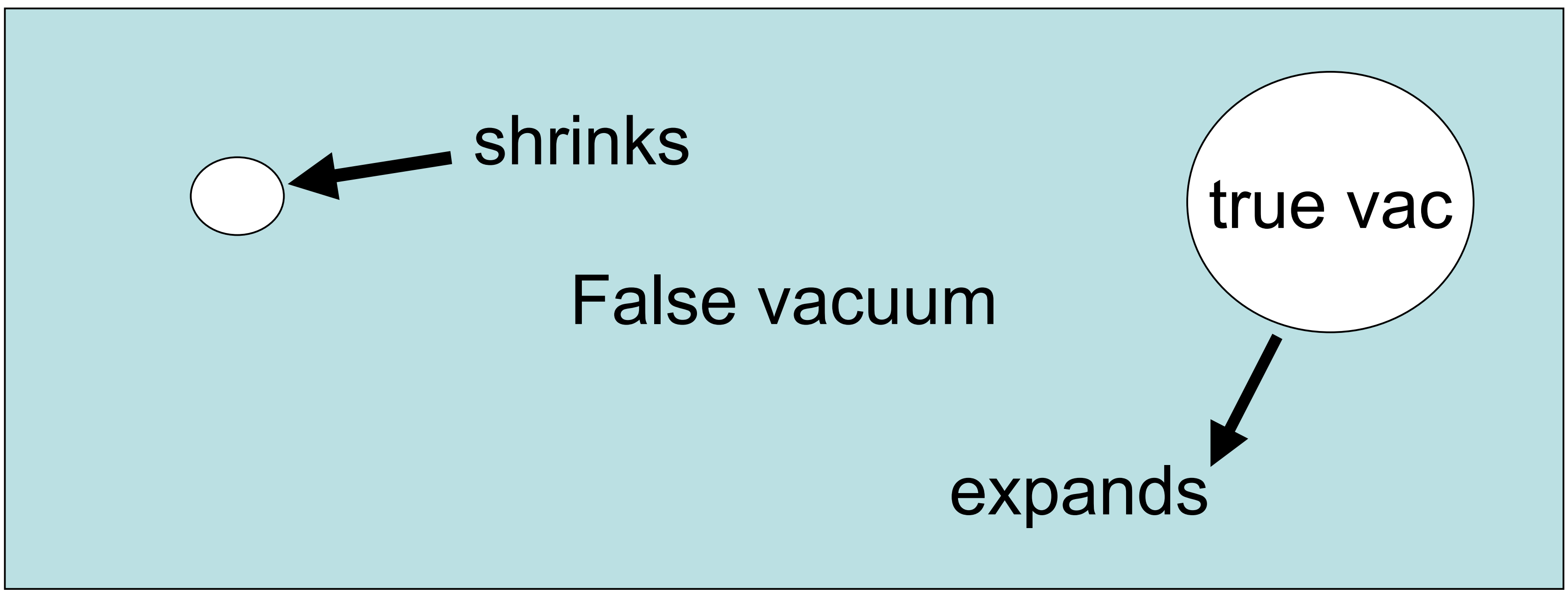
Meta-stable susy breaking in modified O'R model



Meta-stable state long lived for $\epsilon \ll 1$

Recall how false vacua decay

By tunnelling, can nucleate a bubble of true vacuum. Like boiling. Bubble expands only if it is big enough (energetically favorable volume effect vs unfavorable surface effect).



False vacua decay, cont.

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

The "bounce action" is the Euclidean action of the tunneling trajectory. Turn potential upside down, and compute the classical action of the field config. with b.c.'s of tunneling trajectory. Large action, so long-lived metastable vac, if the barrier is high and/or wide relative to difference in vacuum energy in false vs true vacua. E.g. if barrier is low, then

$$S_{bounce} \sim \Delta\Phi^4/V_0$$

Our example: $V_0 \sim \epsilon^0$, $V_{barrier} \sim \log \epsilon^{-1}$. $\Delta\Phi \sim \epsilon^{-1}$

Dynamical(!) Supersymmetry Breaking

Witten index shows that susy gauge theories with Vector-like (non-chiral) matter have susy vacua.

Many other DSB constraints: massless goldstino, R-symmetry, avoid runaways, etc..

DSB seems non-generic in field and string theory.

Metasable DSB relaxes some of these conditions.
Next time: SQCD, and metastable DSB there.
Suggests metastable DSB is generic.