Surveying Pseudomoduli: The Good, The Bad, and The Incalculable

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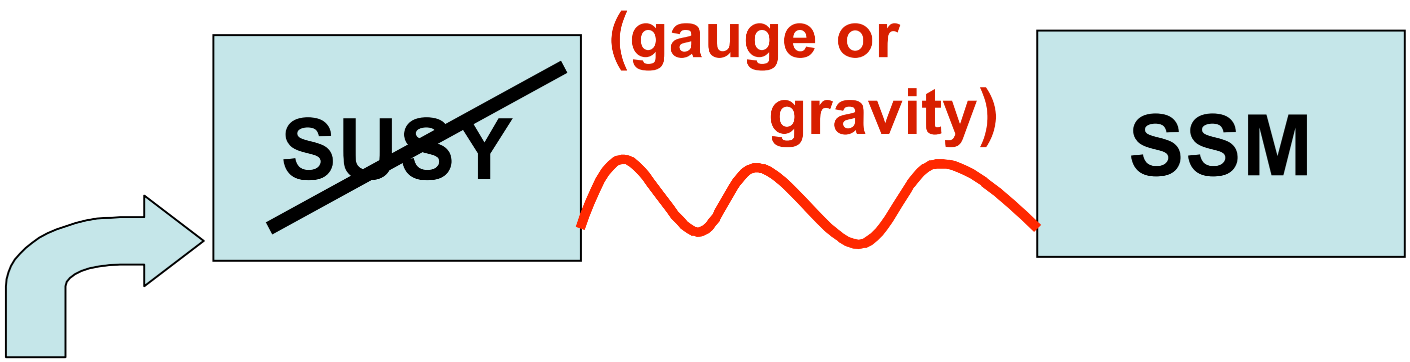
Clay Institute, October 15, 2008

Based on work with David Shih and Matt Sudano **arXiv:0809.3981**

Dynamical Supersymmetry Breaking and Mediation



DSB: susy broken only spontaneously, and via

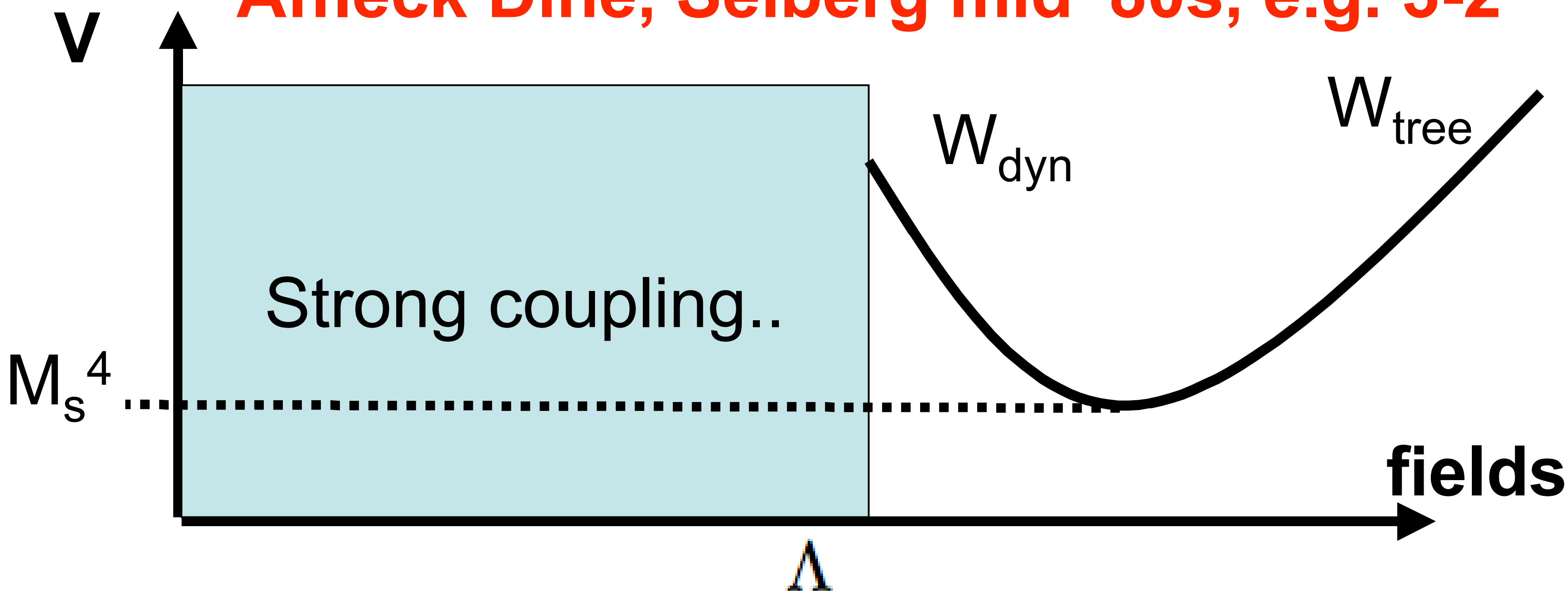
$$\Lambda = M_{cutoff} e^{-c/g(M_{cutoff})^2} \ll M_{cutoff}$$

naturalizing hierarchies. Messengers, with susy-split masses. Direct gauge mediation: flavor symm, to couple to SM or BSM gauge fields.

Challenges: R symm, Landau poles, $\mu/B\mu$ …

Original Models of DSB

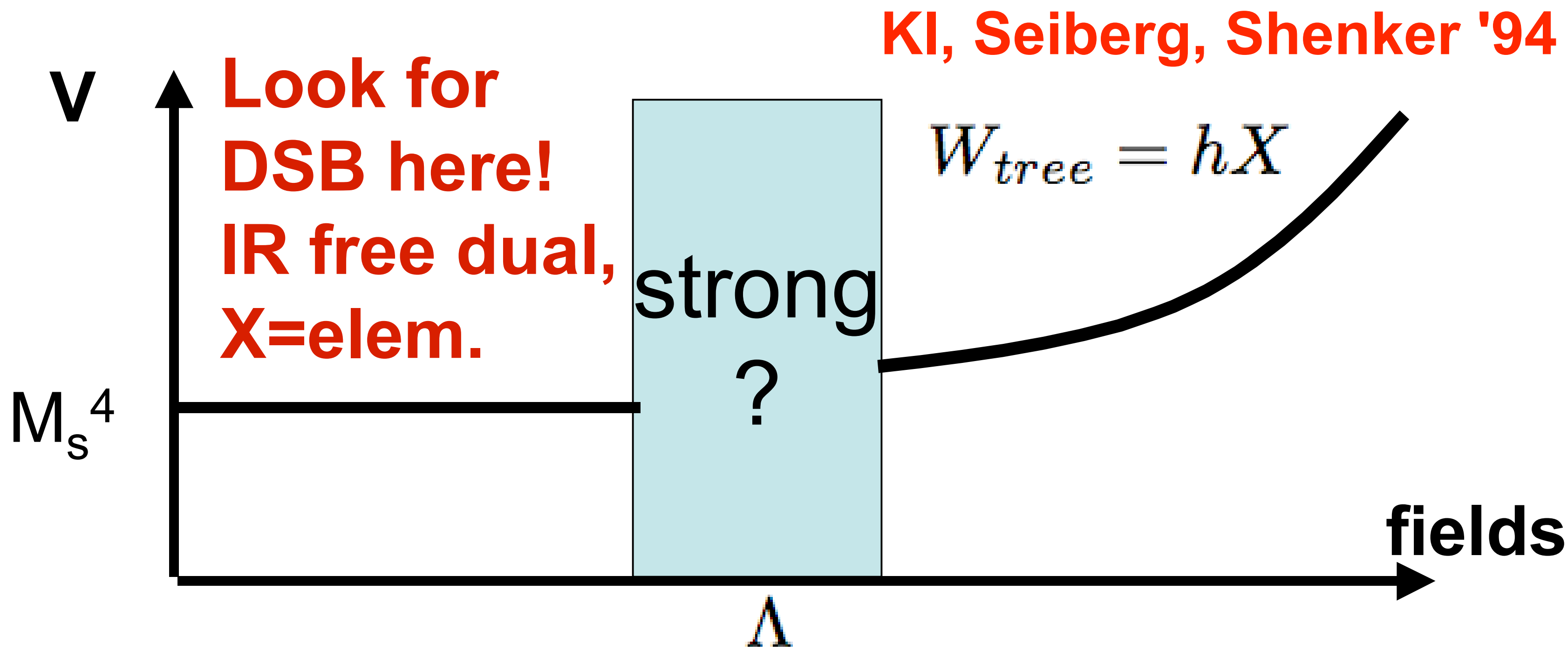
Affleck Dine, Seiberg mid '80s, e.g. 3-2



Very few examples where this actually happens. Generically, unbroken susy vacua. DSB looks nongeneric. + Challenges for direct gauge mediation. Led to intricate models of mediation.

Dine, Nelson, Nir, Shirman '90s

DSB via IR free duals



Original model inconclusive for two reasons: (i) IR free or CFT? (ii) even if IR free, where is the minimum? **Pseudomodulus**. Other examples conclusive (e.g. ITIY) some model building +'s.

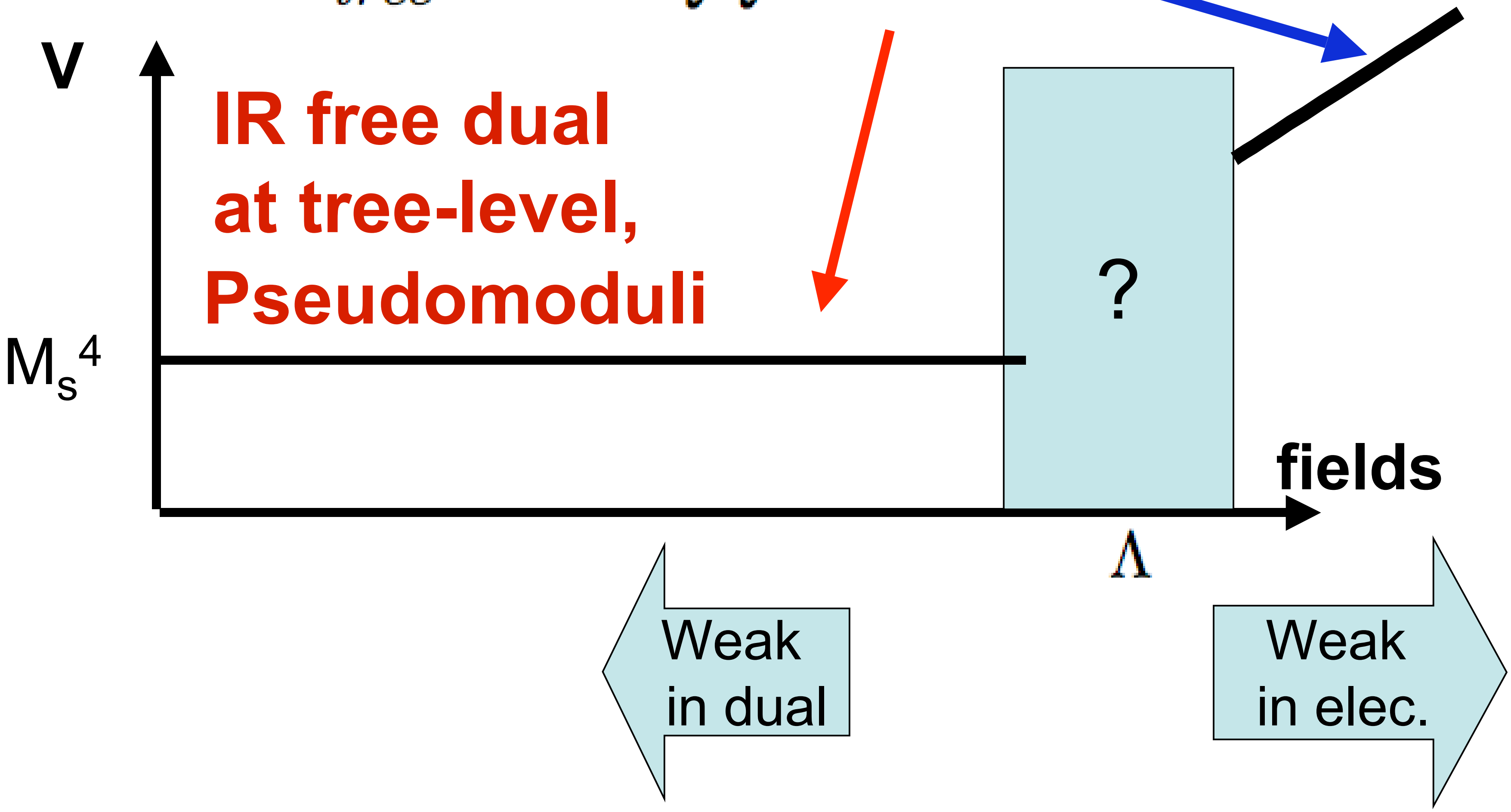
$U(1)_R$ and metastability

- Need $U(1)_R$ for SSB generically. Nelson, Seiberg.
- Need broken $U(1)_R$ for gaugino masses.
- Spontaneous breaking only gives unacceptable R-axion.
- Need explicit breaking. Approximate $U(1)_R$ for SSB, leads to metastable susy breaking. Metastability is generic. (ISS2)

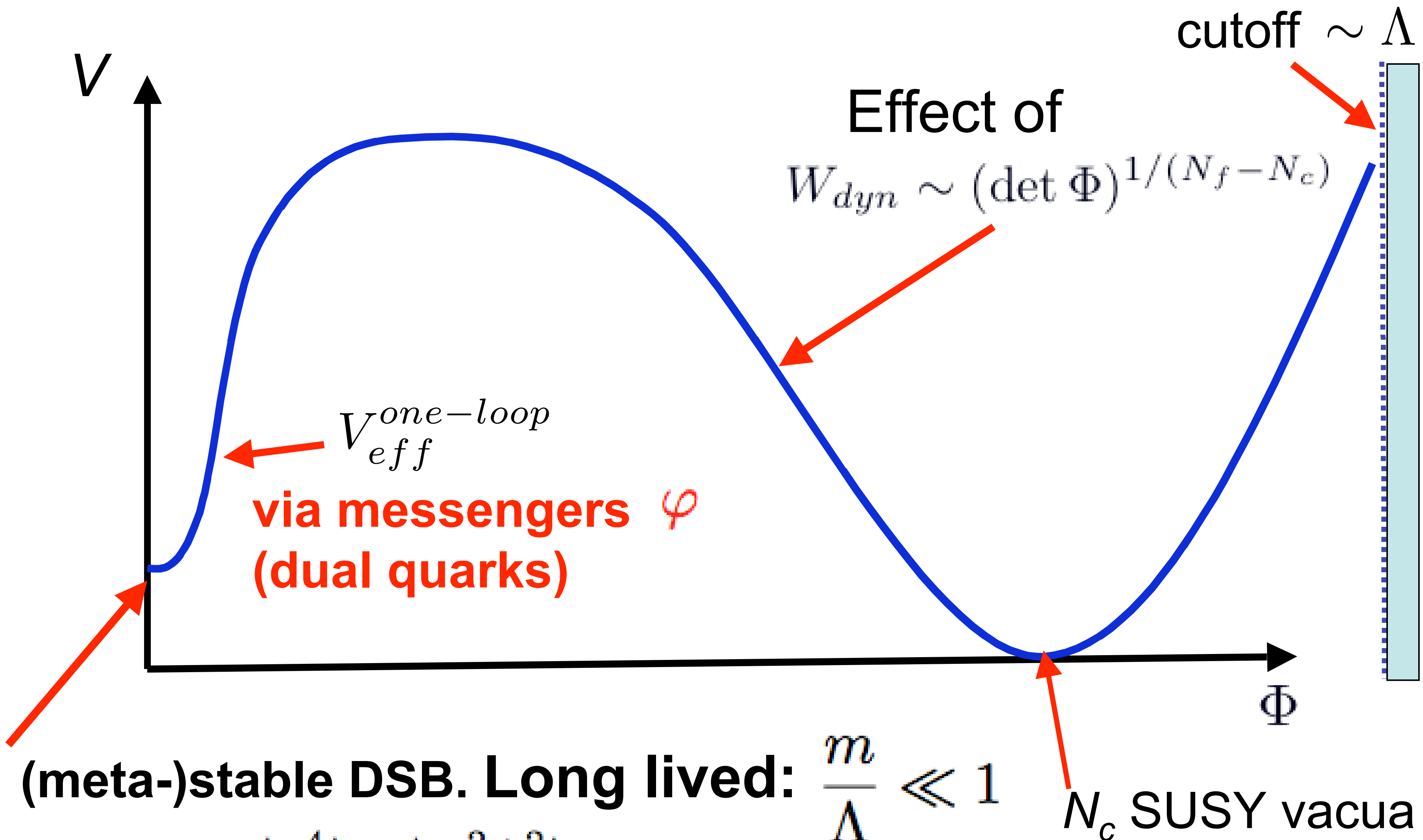
Meta-stable DSB in SQCD

KI, Seiberg, Shih '06

$$W_{tree} = \mathrm{Tr}\, m Q\tilde{Q} = \mathrm{Tr}\, m M$$



DSB in SQCD's IR free dual



$$V_{DSB} \sim |\mu^4| \sim |m^2 \Lambda^2|$$

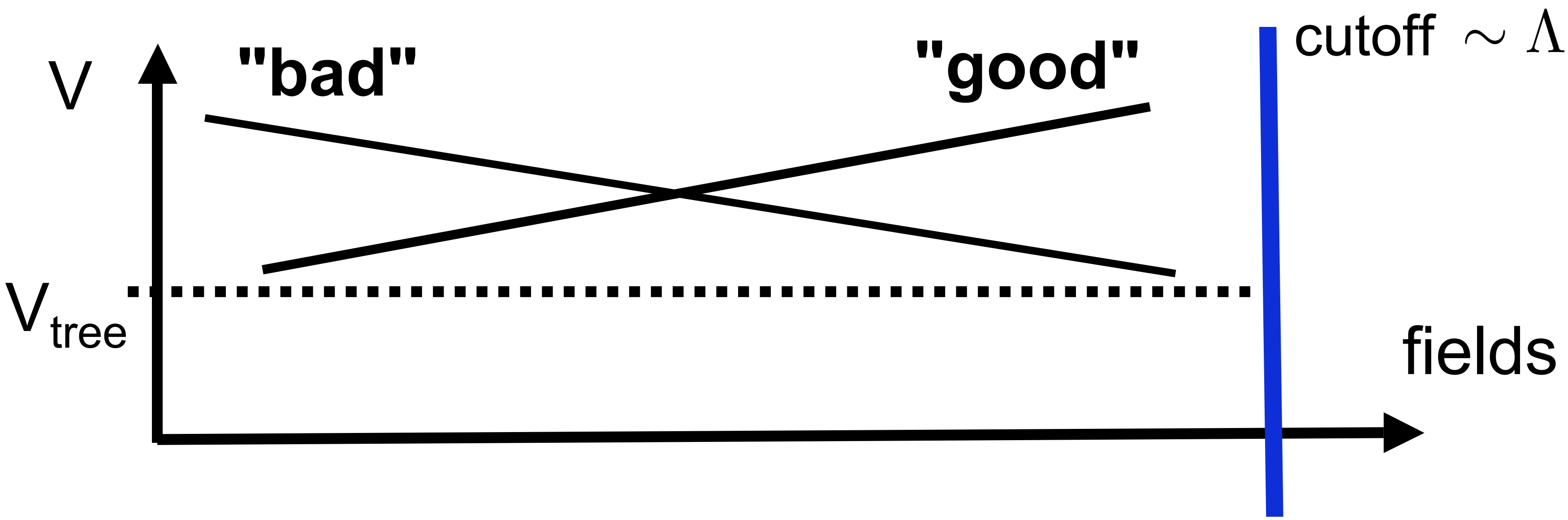
Explore for other models of meta-stable DSB

- Look for models where (accidental) $U(1)_R$ is spontaneously broken, $\langle \Phi \rangle \neq 0$.
- Models where m is replaced with a Yukawa or irrelevant coupling, more naturally small.
- How generic is meta-stable DSB? How generic is calculability?
- Survey the classes of theories with known IR free duals.
- General issue: pseudomoduli. Problematic? Can their gentle slopes be useful for model building?

Surveying Pseudomoduli: the good, bad, and incalculable

K.I. David Shih, Matt Sudano

DSB in IR free duals always have **pseudomoduli**. Often only lifted at 2 or more loops. **Crucial** to determine their behavior. It takes just one bad pseudomodulus to spoil any model of DSB.



(Can fix "bad" pseudomoduli "by hand". Even do some good)

Can add to electric UV theory a new interaction.
Higher dim ops in UV. Mass terms in IR free dual.

Add: $W_{tree} \supset \frac{c}{M_*^{2d_X-3}} X_{bad}^2$

Can introduce new susy vacuum.

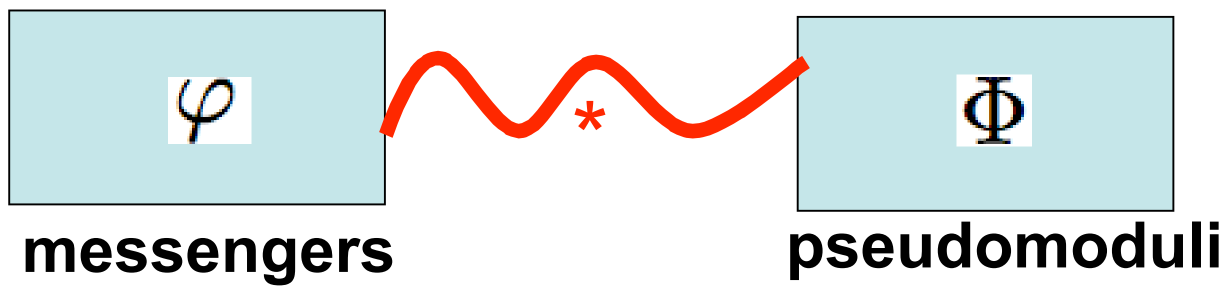
or $W_{tree} \supset \frac{c}{M_*^{d_X-2}} X_{bad} \Sigma$

Can introduce new pseudomodulus.

Stabilizes bad pseudomodulus. **E.g. Franco, Uranga; etc..**
Can also lead to spont. $U(1)_R$ breaking. **Giveon, Katz, Komargodski, Shih**
We'll only discuss **dyn.** lifting here.

Pseudomoduli dynamically lifted via variants of gauge mediation

In **calculable** cases, IR free dual has susy-split messengers e.g., for SQCD case, dual quarks φ.
Also find examples with gauge messengers.

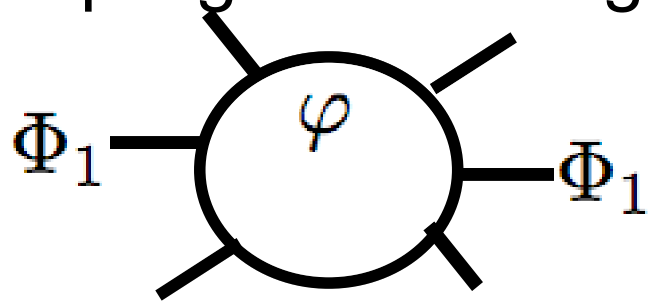


* IR free interactions. Gauge, or Yukawa, or power-law irrelevant W interaction terms.
Pseudomodulus lifted at loop # needed to couple to virtual messengers.

Classify pseudomoduli types

- Gauge singlets with direct coupling to messengers

$$W_{low} \supset \Phi_1 \varphi^2 + \widetilde{\Phi}_1 \varphi \chi$$



$$\Longrightarrow V_{CW}^{(1)}(\Phi_1)$$

These are lifted at 1-loop, and "good". E.g. SQCD example.

- Gauge singlets with indirect coupling to messengers

$$W_{low} \supset \Phi_2 \chi^2$$

$$\Phi_2 \leftrightarrow \chi \leftrightarrow \varphi$$

These are lifted at 1-loops, and "bad". E.g. SQCD with massive & massless flavors.

Pseudomoduli types cont.

- Higgsing pseudomod, gauge coupled to messengers

Charged matter q, with D- and F- flat pseudomod.

$\Phi_q \leftrightarrow \text{gauge} \leftrightarrow \varphi$ Lifted at 2 loops, "good."

matter messengers. Also consider case of gauge messengers, when $F_{X_{charged}} \neq 0$:

$\Phi_q \leftrightarrow \text{gauge}$ Lifted at 1 loop, "bad."

With gauge messengers, 1 fewer loop, opposite slope.

Pseudomoduli types cont.

- Saxion-type pseudomoduli $W_{low} \supset \Phi_3 p^2$

$$\Phi_3 \leftrightarrow p \leftrightarrow \text{gauge} \leftrightarrow \varphi$$

Lifted at 3-loops if charged matter messengers.
"Bad" slope, runaway to cutoff.

Or if there are gauge messengers, $F_{X_{charged}} \neq 0$:

$$\Phi_3 \leftrightarrow p \leftrightarrow \text{gauge}$$

Lifted at 2-loops, and "good" slope.

Pseudomoduli types cont.

- Power-law irrelevantly coupled pseudomodulu, e.g.

$$W_{low} \supset \frac{1}{\Lambda^{n+m-2}} \Phi_4 \varphi^n p^m \qquad n + m \geq 3$$

(Some can become relevant, if m<3 and $\langle \varphi \rangle \neq 0.$)

All such pseudomoduli have **incalculable** effective potentials. Their perturbative lifting is **not** robust, not parameterically larger than incalc. effects of unknown irrelevant terms K_{eff}.

Recall it's a low-energy theory

$$K_{eff} = \bar{X}X + \bar{\Phi}\Phi + \frac{\boxed{c}^{*}}{|\Lambda|^2}\bar{X}X\bar{\Phi}\Phi + \ldots$$

$$W_{low} \supset fX \qquad \epsilon \equiv \frac{|f|}{|\Lambda|^2} \ll 1$$

Need a small parameter.

*Unknown coefficients in higher-dim op terms,

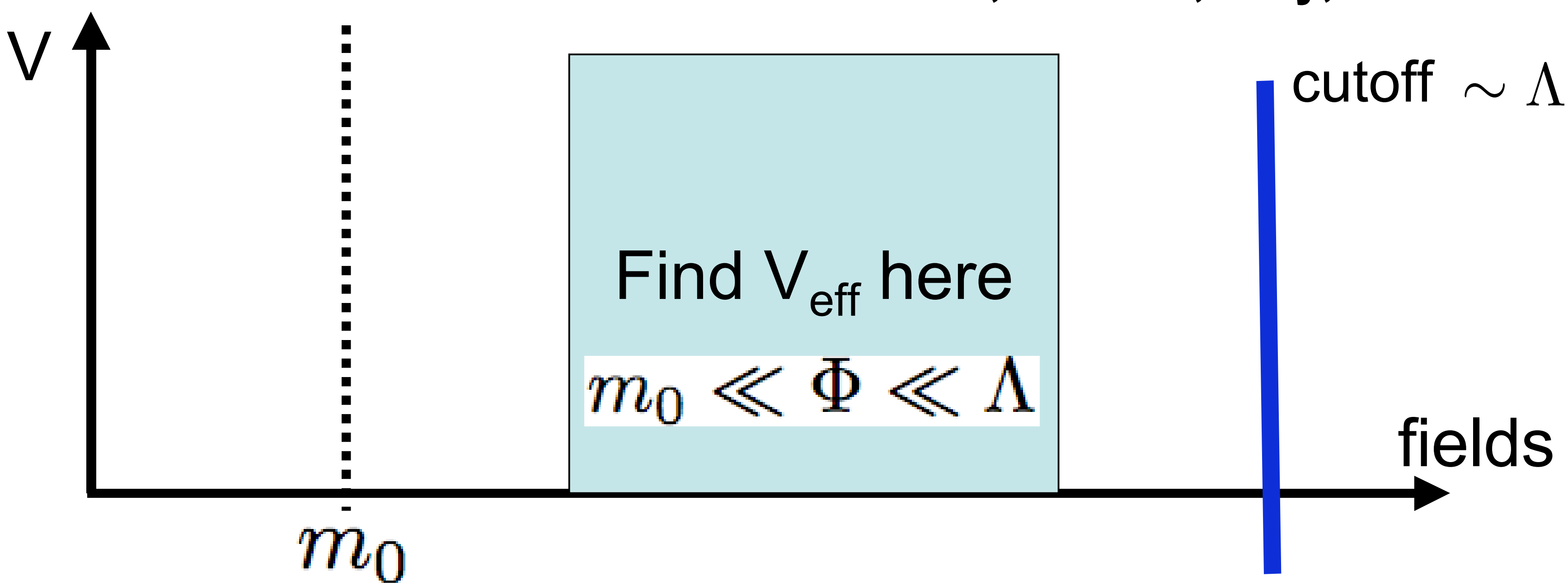
$$V_{eff,unknown} \sim |\epsilon|^2$$

Calculable effective V's must be param. larger.
Gauge and Yukawa coupled pseudomoduli have **calculable** effective potentials. Power-law irrelevantly coupled pseudomoduli do not.

Can compute $V_{eff}^{L>1}$ in an easy regime

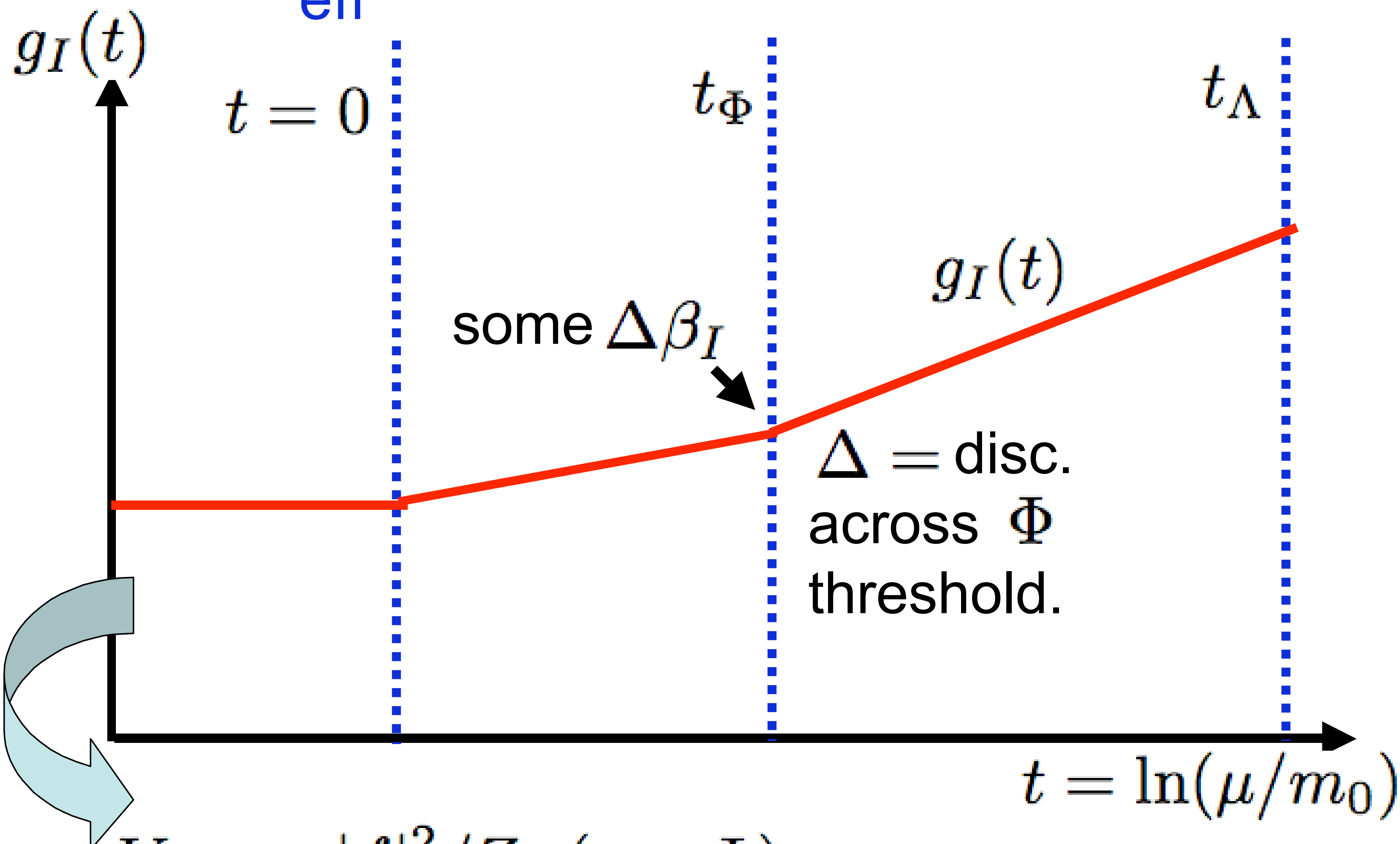
Regime where V_{eff} is determined simply by leading-log RG running of V_0, with just 1-loop data:

~ a'la Arkani-Hamed, Giudice, Luty, Rattazzi



$m_0 \sim \sqrt{f}$ = scale of tree-level masses of low-energy thy.

V_{eff} from RG thresholds



$V_{eff} \approx |f|^2/Z_X(m_0;\Phi)$ Renormalization of V_o

Result for V_{eff} in this regime

$$V_{eff}(\Phi) \approx const. - \frac{2}{n!} V_0 \Delta\Omega_X^{(n)} \left(-\log \frac{|\Phi|}{m_0} \right)^n$$

$$\Delta\Omega_X^{(n)} = \Delta\left(\frac{d^{n-1}\gamma_X}{dt^{n-1}}\right)$$

Use lowest non-zero loop order n of disc. across Φ threshold.

E.g.

$$\Delta\Omega_X^{(3)} = \sum_{IJ} \frac{\partial\gamma_X^{(1)}}{\partial g_I} \frac{\partial\beta_I^{(1)}}{\partial g_J} \Delta\beta_J^{(1)}$$

Leading-log running: Multi-loop effect via **just 1-loop data.**

"bad" if $(-1)^{n+1}\Delta\Omega_X^{(n)} < 0$ "good" if pos.

Simplest example

Pseudomoduli with direct coupling to messengers in this regime have

$$V_{eff}^{(1)}(\Phi) \approx 2V_0 \Delta\gamma_X^{(1)} \log \frac{|\Phi|}{m_0}$$

E.g. $W \supset h_X X \varphi^2 + h \Phi \varphi^2$ leads to $|\Phi|$

$$\Delta\gamma_X^{(1)} = \frac{h_X^2}{16\pi^2} \Delta n_\varphi$$

number of messengers which get mass at threshold.

Higgsing pseudomoduli

$$V_{eff}(\Phi_q) \approx -V_0 \Delta\Omega_X^{(2)} \left(\log \frac{|\Phi|}{m_0} \right)^2$$

$$W_{low} \supset h_X X \varphi \widetilde{\varphi} \qquad F_X = f \neq 0$$

$$\Delta\Omega_X^{(2)} = \Delta\left(\frac{d\gamma_X}{dt}\right) = \frac{\partial \gamma_X}{\partial h_X} \Delta\beta_{h_X} = 2h_X \frac{\partial \gamma_X}{\partial h_X} \Delta\gamma_\varphi$$

$$= -8 \frac{h_X^2}{16\pi^2} \frac{g^2}{16\pi^2} T(r_\varphi)(|G| - |G'|) < 0$$

Therefore, increasing potential; "good".

E.g. saxion-type pseudomoduli

$$W_{low} \supset \Phi p^2$$

Saxion. Neutral

Charged under gauge group

Lifted at 3-loops.

$$\Phi \leftrightarrow p \leftrightarrow \text{gauge} \leftrightarrow \varphi$$

messengers,

$$V_{eff}(\Phi) \approx \frac{2}{3!} V_0 \Delta\Omega_X^{(3)} \left(\log \frac{|\Phi|}{m_0}\right)^3$$

$$\Delta\Omega_X^{(3)} = \frac{\partial \gamma_X^{(1)}}{\partial h_X} \frac{\partial \beta_{h_X}^{(1)}}{\partial g} \Delta\beta_g^{(1)} < 0$$

"Bad"

+   -   +

Gauge messengers cases

$$F_{X_{charged}} \neq 0$$

Higgsing pseudomoduli now lifted at 1-loop:

$$\Delta\Omega^{(1)}_{X_i} = \Delta\gamma_{X_i} = -2\frac{g^2}{16\pi^2}\Delta c(r_{X_i}) < 0$$ "Bad"

Saxion pseudomoduli now lifted at 2-loops:

$$\Delta\Omega^{(2)}_{X_i} = \frac{\partial\gamma^{(1)}_{X_i}}{\partial g}\Delta\beta^{(1)}_g < 0$$ "Good"

In general,

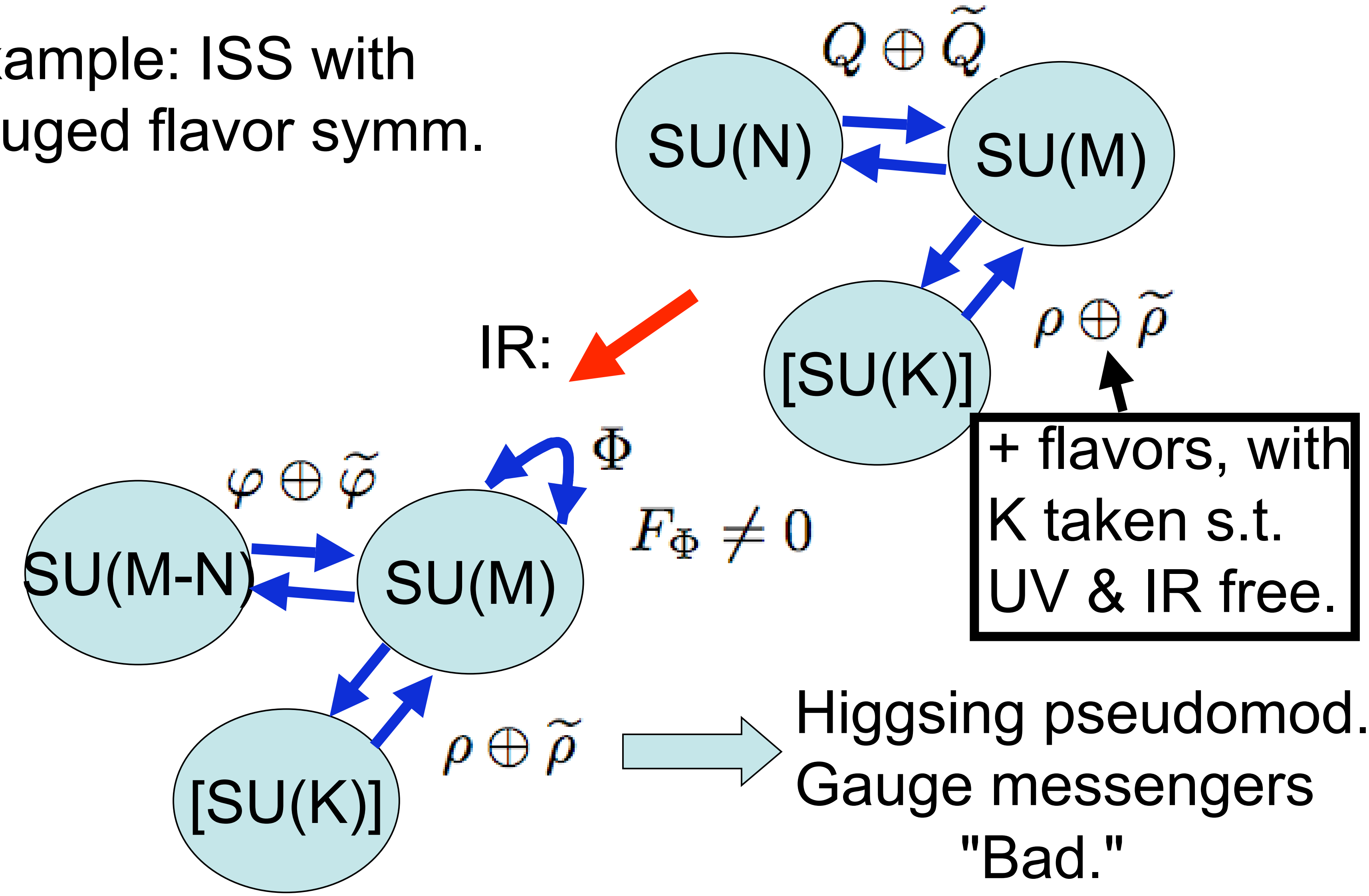
$$V \sim (-1)^{n+1} V_0 \Delta\Omega^{(n)}_X \log^n \Phi$$

$$n \rightarrow n-1$$

"Good" $\leftrightarrow$ "Bad"

Survey many classes of models

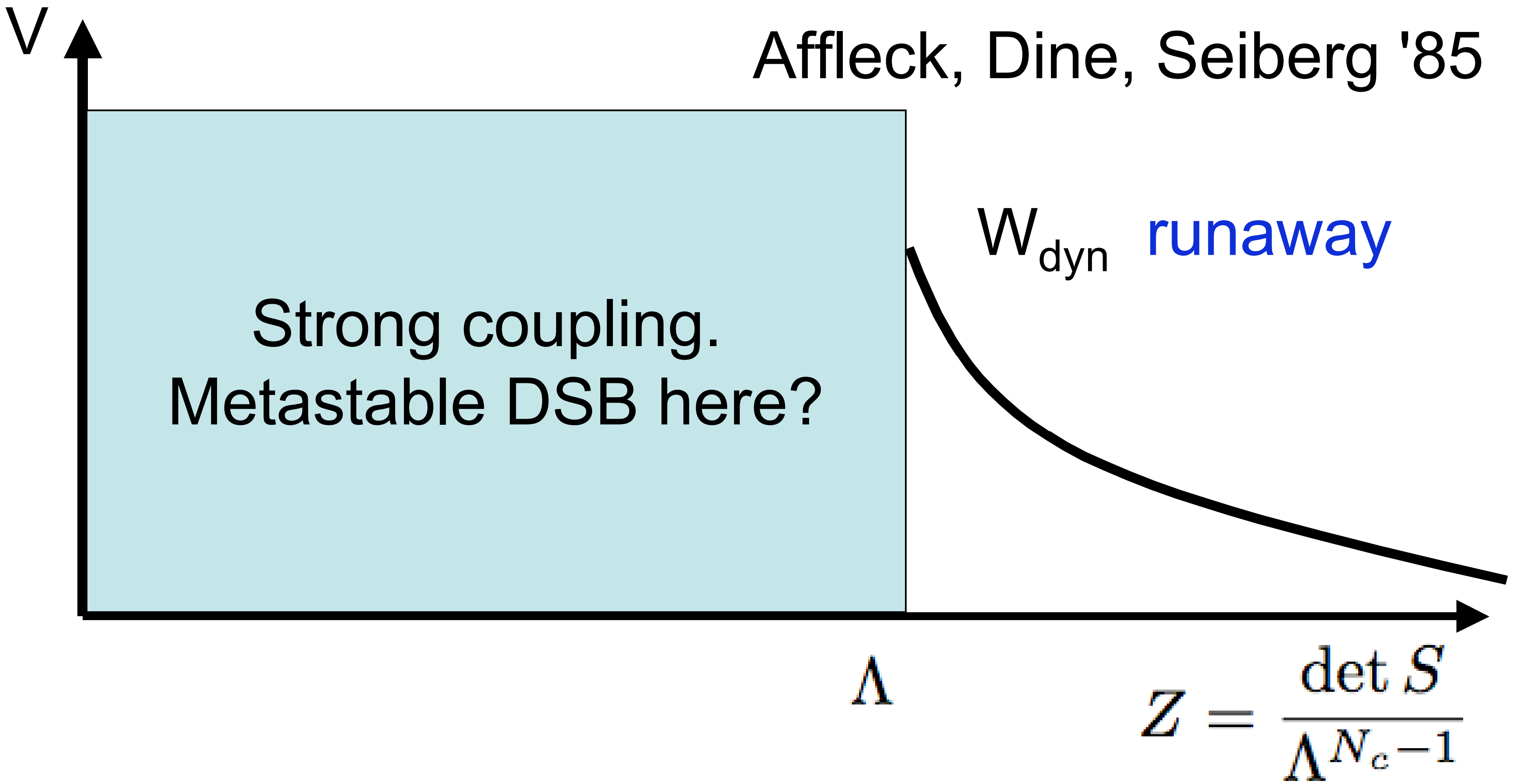
Example: ISS with gauged flavor symm.



More examples

E.g. SU(N) with symmetric tensor S & N_f= N+4 anti-fundamentals, $W_{tree} = \lambda \mathrm{Tr} S\widetilde{Q}\widetilde{Q} \equiv \lambda\Lambda^2 \mathrm{Tr}\Phi.$

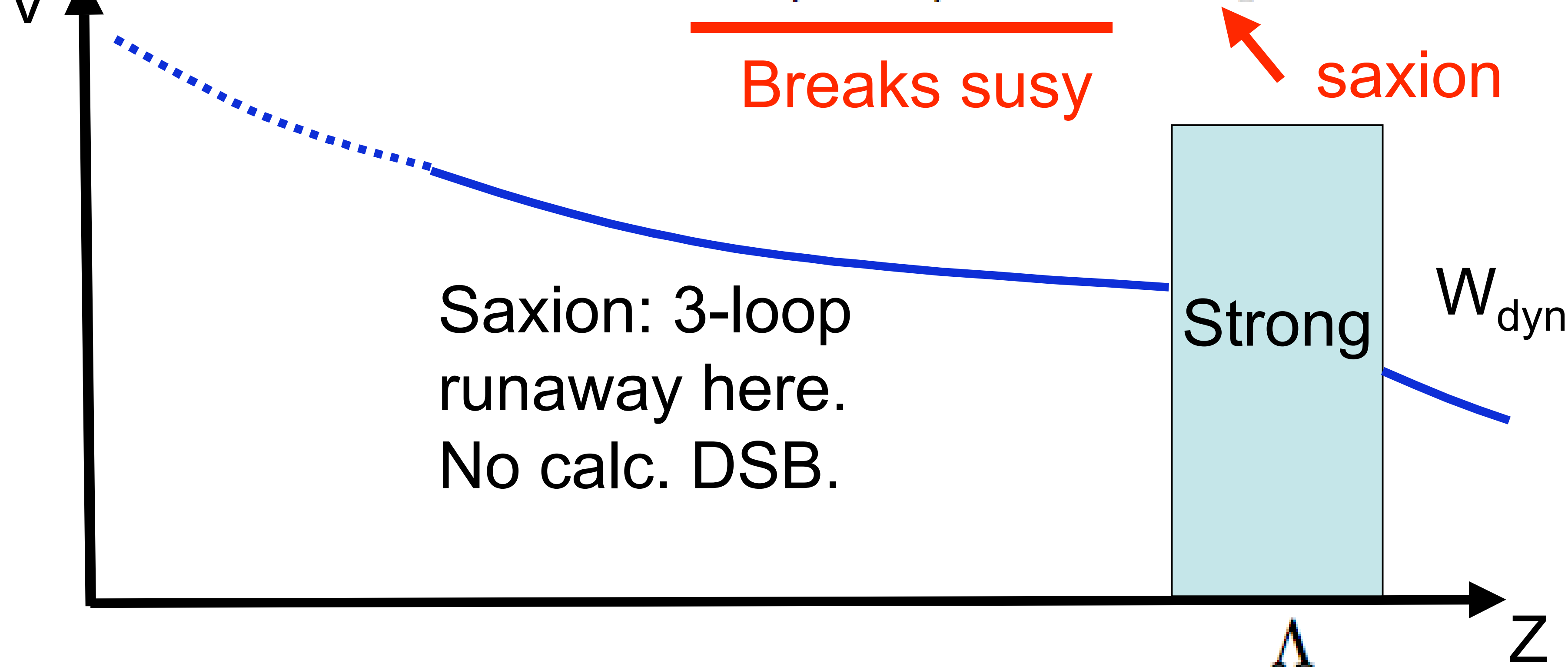
Affleck, Dine, Seiberg '85



IR free dual: "bad", no DSB

Pouliot Strassler: SO(8) with spinor p, N_f vectors φ, and singlets Φ, Z. Get

$$W_{dual} = \mathrm{Tr}\Phi\varphi^2 - \mu^2\mathrm{Tr}\Phi + Zp^2$$



Variants with DSB

- Gauge the flavor symmetry. Saxion lifted at 2-loops, with "good" potential for DSB in IR free dual.

- Add $$\Delta W_{tree,UV} = \frac{c}{M_p^{N_c-2}} \Sigma \det S$$

$$\rightarrow \Delta W_{tree,IR} = m_Z \Sigma Z$$

Eliminate bad pseudomod. by hand.

Introduces Higgsing pseudomodulus p^2, dynamically lifted at 2-loops, good.

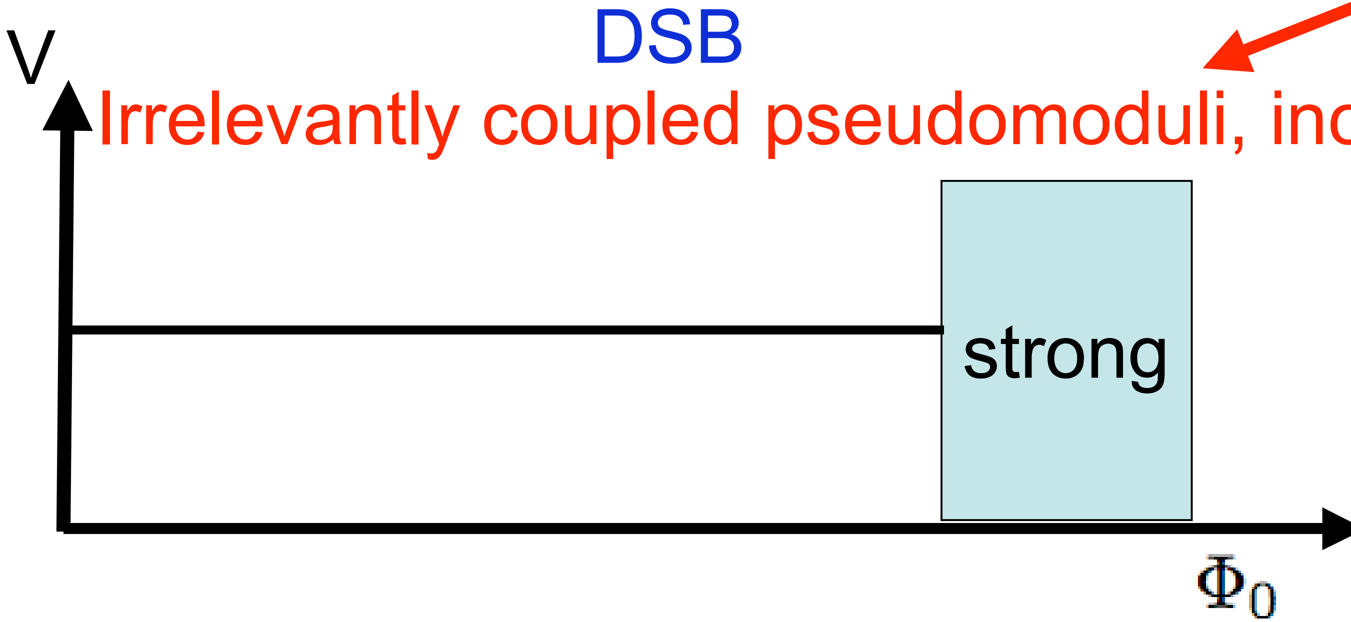
Incalculable pseudomoduli

Many examples! Occurs in many known duals.

E.g. Kutasov duality $W_{elec} = \mathrm{Tr}X^3 + \lambda \mathrm{Tr}XQ\widetilde{Q}$

$$W_{dual} = \underbrace{\mathrm{Tr}\Phi_1\varphi\widetilde{\varphi} - \mu^2\mathrm{Tr}\Phi_1}_{\text{DSB}} + \mathrm{Tr}Y^3 + \frac{a}{\Lambda}\mathrm{Tr}\Phi_0\varphi Y\widetilde{\varphi},$$

Irrelevantly coupled pseudomoduli, incalculable V.



(Can salvage by lifting by hand. **Ooguri, Ookouchi; Amariti, Girardello, Mariotti**)

A class of examples: IR free duals without gauge fields

SQCD with $N_f = N_c + 1$: Calculable, metastable DSB!

Sp analog: incalculable pseudomoduli. DSB?

Scan over many known other examples, (Csaki, Schmaltz, Skiba)

Most have fields entering in W_{dyn} via irrelevant terms, become incalculable pseudomoduli.
Suggests that calculability is perhaps not generic.

Conclude

- Fate of models with IR free DSB hinges on pseudomoduli potential. Can be good, bad or incalculable.
- Classify general pseudomoduli types, and determine behavior of V_{eff}. Variant of gauge mediation.
- Can apply to building new models of DSB. Survey large classes of models.
- Pseudomoduli's gentle slopes useful?