

Singlet-Stabilized Minimal Gauge Mediation

David Curtin

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In Collaboration with Yuhsin Tsai



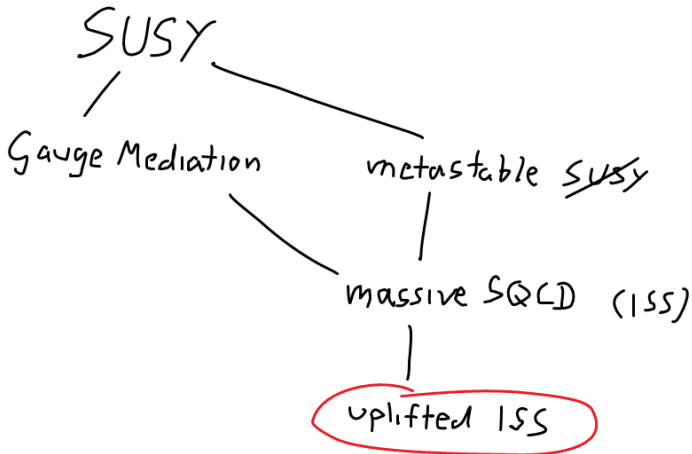
Cornell Institute for High Energy Phenomenology

Friday Theory Seminar

October 22, 2010

1. Review & Motivation
2. Singlet-Stabilized Gauge Mediation
3. Stabilizing the Uplifted Vacuum

Review & Motivation



SUSY solves the Hierarchy Problem

- 1 How is SUSY-breaking transmitted to SSM?
- 2 How is SUSY broken?

How is SUSY-breaking transmitted to SSM?

Gravity Mediation: always there

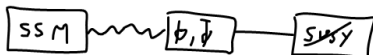
- $m_{soft} \sim \frac{F}{M_{pl}^*}$
- Problems:
 - Flavor
 - calculability

Gauge Mediation

- flavor universal soft masses
- requires lower SUSY-breaking scale
- often calculable

Gauge Mediation

- Minimal Gauge Mediation



$$W_{\text{eff}} = X \bar{\phi} \phi \quad \text{where} \quad \langle X \rangle = X + \theta^2 F \quad \Rightarrow \quad m_{\text{soft}} \sim \frac{\alpha}{4\pi} \frac{F}{X}$$



- Direct Gauge Mediation



- G_{SM} embedded in flavor group of SUSY-breaking sector
- Very compatible with 'dynamical SUSY-breaking' ideal!

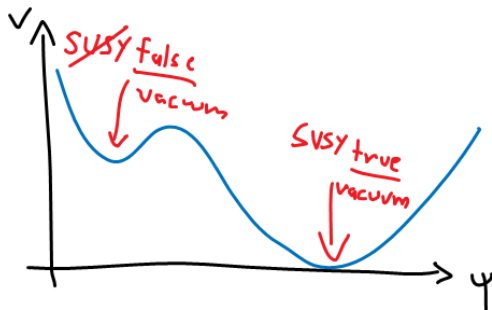
How is SUSY broken?

- Want a model where $m_{SUSY} \ll M_{pl}$ is dynamically generated:
Dynamical SUSY Breaking (DSB).
- Known example of small dynamical mass scale in nature: Λ_{QCD}
(due to logarithmic running of gauge coupling).
⇒ Will probably need nonperturbative physics!
- True SUSY very difficult! (Witten Index Argument).
 - No SUSY-vacua → either chiral or contain massless matter
 - 3-2, 4-1, ITIY, ...
 - Difficult to make into realistic DGM model

How about metastable SUSY?

Allowing the existence of SUSY-vacua removes many restrictions.

⇒ now just need to make sure that there is an uplifted local minimum of the potential.

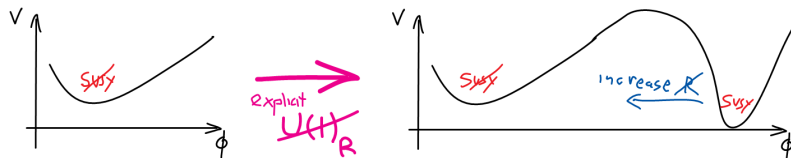


Of course the false vacuum should have a lifetime longer than the age of the universe!

Two good reasons for believing in metastable SUSY

1. Avoiding massless R -axions

- Can show that SUSY requires R -symmetry (phase invariance of SUSY-generators)
- R -symmetry forbids gaugino masses
→ must be spontaneously broken
→ massless R -axion
BAD cosmologically & phenomenologically [SUGRA effects?]
- R -symmetry must be explicitly broken
⇒ **metastable SUSY!**



2. Avoiding split-SUSY spectrum

- Problem: in Direct Gauge Mediation often get $m_\lambda \ll m_{\tilde{f}}$
- **Little Hierarchy Problem!**
- Can show that this is due to global vacuum structure of the theory.
- m_λ vanishes to LO in SUSY if we live in lowest-lying vacuum of the renormalizable theory (Komargodski, Shih 2009).
(Making SUSY maximal does not help.)
- \Rightarrow **metastable SUSY!**

Remark

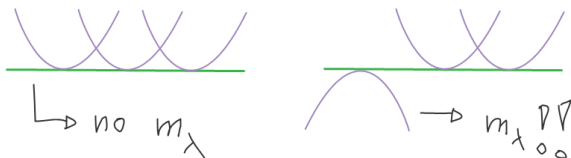
It is useful to elaborate slightly on this.

Many models of dynamical SUSY breaking can be described by a generalized O’Raifeartaigh model at low energies.

Such a model always has a field that is undetermined at tree-level but gets a potential at 1-loop: **Pseudomodulus (PM)**.

If this model implements Direct Gauge Mediation, then **messengers** which are

- **tachyonic** for some values of the PM **contribute to m_λ**
- **stable** everywhere **do not contribute** to m_λ



In fact, constructing such models is **easy!**

Simplest example:
SUSY-QCD with small quark mass

(Intriligator, Seiberg, Shih 2006).

SUSY-QCD & Seiberg Duality

Start with $SU(N_c)$ SUSY-QCD with N_f vector-like quarks:

	$SU(N_c)$	$SU(N_f)$	$SU(N_f)$	$U(1)_B$	$U(1)_R$
Q	\square	\square	1	1	$\frac{N_f - N_c}{N_c}$
\bar{Q}	$\bar{\square}$	1	$\bar{\square}$	-1	$\frac{N_f - N_c}{N_c}$

$N_f < 3N_c \rightarrow$ asymptotically free \rightarrow strongly coupled for $E < \Lambda$

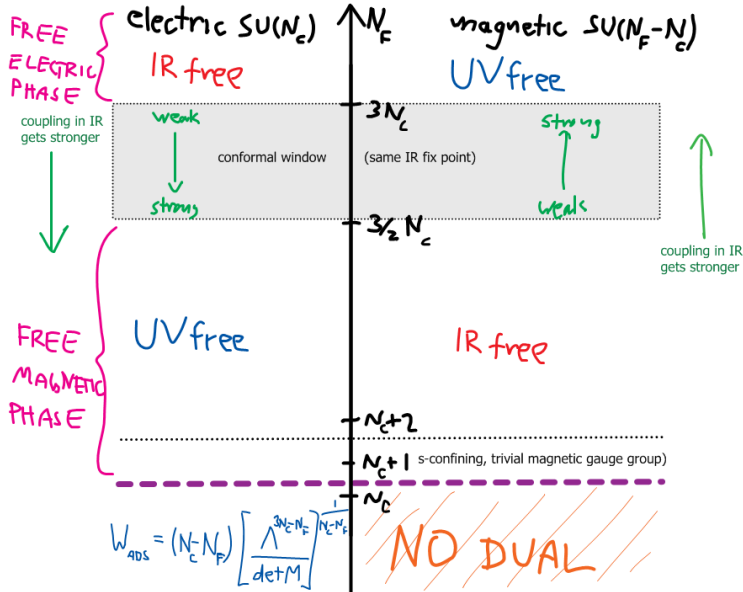
For $N_c < N_f < 3/2N_c$ the strongly coupled IR-physics is described by another SUSY-QCD which is IR-free

	$SU(N_f - N_c)$	$SU(N_f)$	$SU(N_f)$	$U(1)_B$	$U(1)_R$
q	\square	$\bar{\square}$	1	$\frac{N_c}{N_f - N_c}$	$\frac{N_c}{N_f}$
\bar{q}	$\bar{\square}$	1	\square	$-\frac{N_c}{N_f - N_c}$	$\frac{N_c}{N_f}$
M	1	\square	$\bar{\square}$	0	$2\frac{N_f - N_c}{N_f}$

$$W = \text{Tr} q M \bar{q}$$

This is an approximate duality valid in the IR only!

SUSY-QCD & Seiberg Duality



The ISS Model

- Consider SQCD in free magnetic phase with small quark mass:

$$SU(N_c) \text{ with } W = mQ\bar{Q} \Rightarrow \cancel{SU(N_f)^2} \rightarrow SU(N_f)$$

where $m \ll \Lambda$ (does not affect duality).

- magnetic theory: $SU(N)$ with $W = h\text{Tr}qM\bar{q} - \underbrace{h\mu^2 \text{Tr}M}_{\sim \Lambda m}$

(Define $N = N_f - N_c$)

- Notice apparent R -symmetry $R(q, \bar{q}, M) = 0, 0, 2$

- SUSY-breaking** by rank condition: $F_{M^i} = \underbrace{hq^i\bar{q}_j}_{\text{rank } N} - \underbrace{h\mu^2\delta_j^i}_{\text{rank } N_f > N}$

Where is the SUSY-vacuum?

- We know this theory has a SUSY-minimum. Where is it in the magnetic description?
- Consider large meson VEVs: $W = h\text{Tr}qM\bar{q} - h\mu^2\text{Tr}M$
- squarks get large mass \rightarrow integrate out
 - \rightarrow pure SYM
 - \rightarrow gaugino condensation
 - \rightarrow SUSY minimum (nonperturbative SUSY-restoration!)

$$q = \bar{q} = 0, \quad M = \Lambda_m \left(\frac{\mu}{\Lambda_m} \right)^{2N/(N_f - N)}$$

- R -symmetry was accidental! It is weakly but explicitly broken by gauge anomaly \Rightarrow meta-stable SUSY-breaking!

“Semi-Dynamical” Meta-Stable SUSY-Breaking

ISS is not true dynamical meta-stable SUSY-breaking due to the **small quark mass put in by hand**.

However, its simplicity & non-perturbative mechanism make it an instructive model-building sand box!

Use it to build a model of Direct Gauge Mediation.

ISS and Direct Gauge Mediation

- $$\langle q\bar{q} \rangle = \begin{pmatrix} N & N_F - N \\ \mu^2 & 0 \end{pmatrix} \begin{matrix} N \\ N_F - N \end{matrix} \Rightarrow \begin{matrix} \cancel{SU(N)} \times \cancel{SU(N_f)} \\ \downarrow \\ SU(N)_D \times SU(N_f - N) \end{matrix}$$

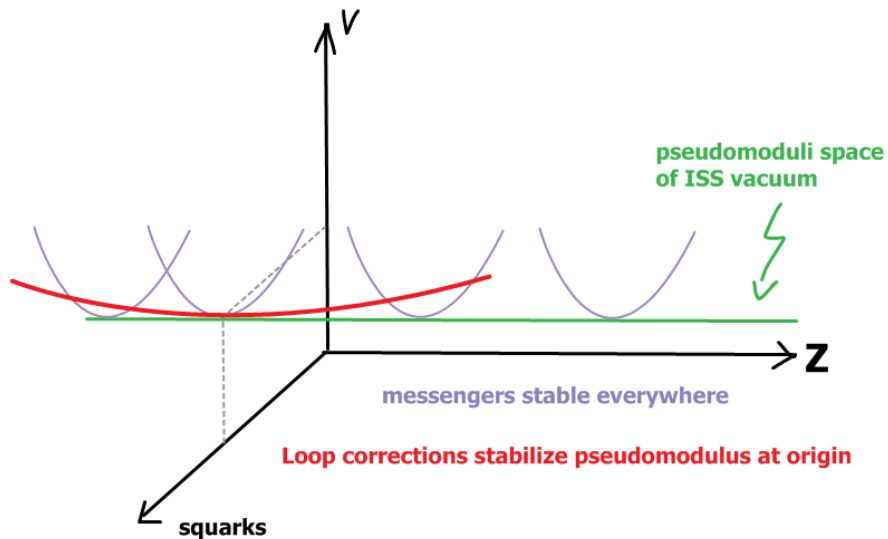
- Decompose fields into representations of unbroken symmetries:

$$M = \begin{pmatrix} N & N_F - N \\ V & Y \\ \bar{Y} & Z \end{pmatrix} \begin{matrix} N \\ N_F - N \end{matrix}, \quad q = \begin{pmatrix} \mu + \chi_1 & \rho_1 \end{pmatrix}, \quad \bar{q} = \begin{pmatrix} \mu + \bar{\chi}_1 \\ \bar{\rho}_1 \end{pmatrix}$$

Pseudomodulus: no potential at tree-level. Loop effects stabilize it at the origin $\Rightarrow U(1)_R$ is unbroken!

Embed G_{SM} in $SU(N_f - N)$: vectors could be messengers of DGM!

ISS Vacuum



- Unbroken R -symmetry forbids gaugino masses (violations from NP effects too small) → **must give the pseudomodulus Z a VEV!**

$$M = \begin{pmatrix} N & N_F - N \\ V & Y \\ \bar{Y} & Z \end{pmatrix} \begin{matrix} N \\ N_F - N \end{matrix}$$

- Even if we break R -symmetry spontaneously the ISS vacuum is still the lowest-lying vacuum in the renormalizable theory → suppressed gaugino mass!

⇒ Need to break R -symmetry explicitly!

Deforming the ISS Model

There are many ways to break the magnetic R -symmetry *spontaneously*, but to break it *explicitly* we must add terms of the form

$$\delta W_{el} \sim \frac{1}{\Lambda_{UV}} Q\bar{Q}Q\bar{Q} \longrightarrow \delta W_{mag} \sim \epsilon \mu M^2 \quad \text{where} \quad \epsilon \sim \frac{\Lambda^2}{\mu \Lambda_{UV}} \ll 1$$

This introduces new SUSY-vacua at $M \sim \mu/\epsilon!$

Good:

- Get gaugino mass at LO in SUSY

Bad:

- strong tension between reasonable m_λ and lifetime of false vacuum
- deformation can be non-generic or contrived

New Idea: Uplift the ISS Model

- In the ISS vacuum, $\langle q\bar{q} \rangle$ has maximum rank N .
- Let's expand around a configuration with fewer squark VEVs instead:

$$\text{rank}\langle q\bar{q} \rangle = k < N$$

At tree-level there will be tachyonic stuff but just run with it for now!

- Different symmetry breaking pattern:

$$\cancel{SU(N) \times SU(N_f) \times U(1)_R \times U(1)_B} \rightarrow SU(N-k) \times SU(k)_D \times SU(N_f-k) \times U(1)_{B'} \times U(1)_{B''}$$

New Idea: Uplift the ISS Model

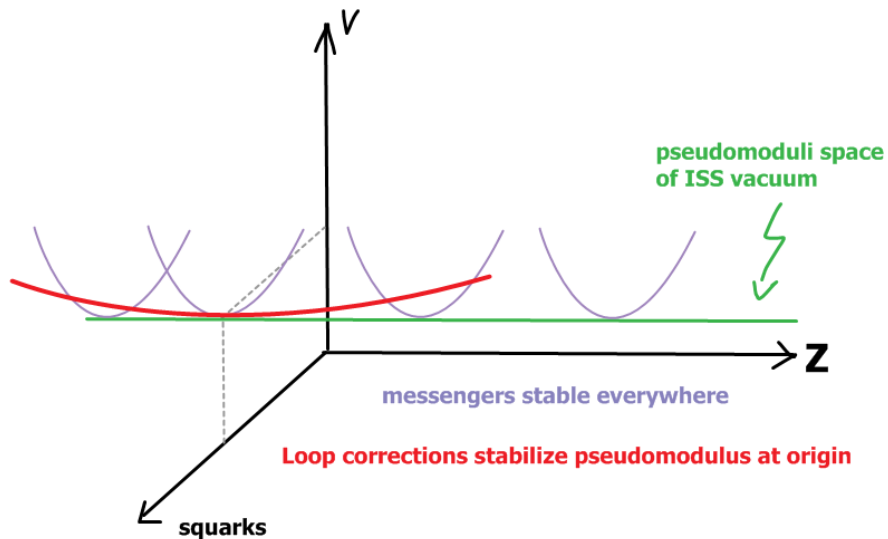
$$M = \begin{pmatrix} k & N_F - k \\ V & Y \\ \bar{Y} & Z \end{pmatrix} \begin{matrix} k \\ N_F - k \end{matrix}$$

$$q = \begin{pmatrix} k & N_F - k \\ \mu + \chi_1 & \rho_1 \\ \chi_2 & \rho_2 \end{pmatrix} \begin{matrix} k \\ N - k \end{matrix} \quad \bar{q} = \begin{pmatrix} k & N - k \\ \mu + \bar{\chi}_1 & \bar{\chi}_2 \\ \bar{\rho}_1 & \bar{\rho}_2 \end{pmatrix} \begin{matrix} k \\ N_F - k \end{matrix}$$

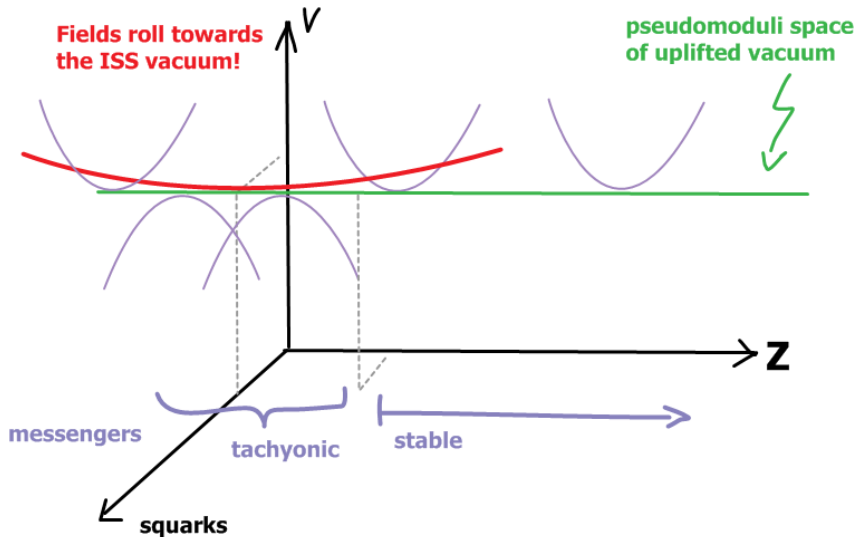
Direct Gauge Mediation: Embed G_{SM} in $SU(N_f - k)$

- flat at tree-level: pseudomodulus
- messengers stable everywhere: do not help with m_λ
- these messengers are tachyonic for $|Z| < \mu \Rightarrow$ generate gaugino mass at LO!

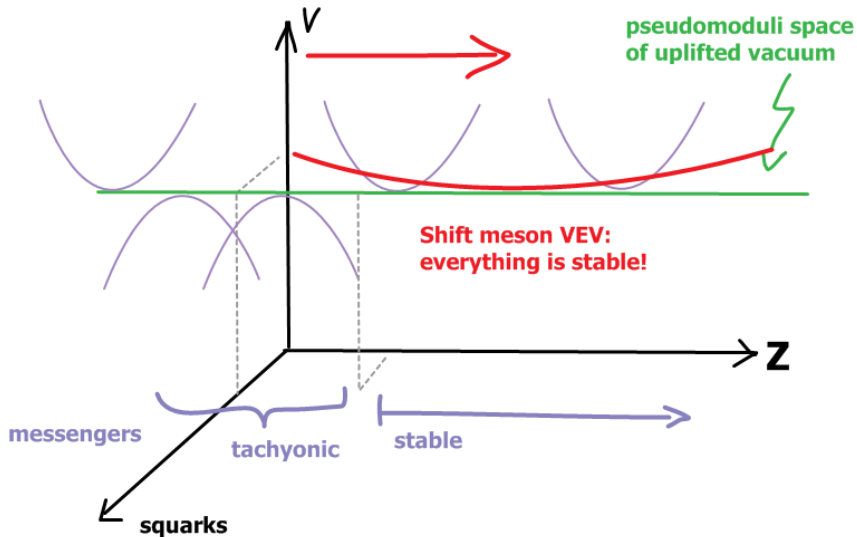
ISS Vacuum



Uplifted Vacuum



Model Building Quest



- magnetic theory: $W = h\text{Tr}qM\bar{q} - h\mu^2\text{Tr}M$
- Need to give meson a VEV $\langle Z \rangle > \mu$
- Problem: in a renormalizable WZ model can't have SUSY vacuum if one of the VEVs \gg mass scales in Lagrangian.
- Possible Solution: Split quark masses:

$$\mu^2 \times \mathbf{1} \longrightarrow \begin{pmatrix} k & N_F - k \\ \mu_1 & \\ & \mu_2 \end{pmatrix} \begin{matrix} k \\ N_F - k \end{matrix} \quad \text{where } \mu_1 \gg \mu_2$$

- $\rho_2, \bar{\rho}_2$ messengers tachyonic for $|Z| < \mu_2$

Leaves possible window for SUSY minimum: $\mu_2 \ll |Z| \ll \mu_1$

To shift Z -VEV, again break R -symmetry explicitly by adding **extremely finely tuned** meson deformations

$$\delta W_{mag} = \epsilon_1 \mu_2 \text{Tr}(Z^2) + \epsilon_2 \mu_2 (\text{Tr}Z)^2$$

Good:

- It works! Get reasonable gaugino masses.
- **Very important proof-of-principle!**

Bad:

- Extremely contrived form of deformations
- Non-generic couplings
- Imposed mass hierarchies
- Requires enormous flavor symmetries, at least $SU(24)$
⇒ **Landau Pole of SM gauge couplings below M_{GUT}**

We want to build new & improved ISS model!

- Needs to be uplifted to solve gaugino mass problem
- Want hidden sector to be minimal, i.e. $SU(5)$ flavor symmetry. This will avoid the Landau Pole.

Also would like minimal clutter (contrived deformations, nongeneric couplings).

Singlet-Stabilized Minimal Gauge Mediation

Start Building Our Model

Choose Magnetic Gauge Group $SU(N)$

Possible number of squark VEVs: $\text{rank}\langle q\bar{q}\rangle = k = 0, 1, \dots, N$

\Rightarrow make minimal choice $N = 1$

\Rightarrow trivial magnetic gauge group

Only two pseudomoduli spaces: ISS ($k = 1$) and **uplifted** ($k = 0$)

Choose Flavor Group $SU(N_f)$

Want minimal hidden flavor group to avoid Landau Pole.

Uplifted ISS has unbroken flavor group $SU(N_f - k)$, with $k = 0$ here.

\Rightarrow Choose $N_f = 5$.

Start Building Our Model

Ansatz for magnetic theory: “ $SU(1)_c$ ” \times $SU(5)_f$

$$W = h\bar{\phi}_i M_j^i \phi^j - hf^2 M_j^i.$$

	$SU(5)$	$U(1)$	$U(1)_R$
ϕ^i	\square	1	0
$\bar{\phi}_j$	$\bar{\square}$	-1	0
M	Adj + 1	0	2

Identify $SU(5)$ flavor group with G_{SM}

Both these fundamentals will be tachyonic for small $|M|$ in the uplifted pseudomoduli space

\Rightarrow **A Single Pair Of Minimal Gauge Mediation Messengers!**

Need to stabilize the meson at nonzero VEV.

Need to generate Meson VEV

Deform the model to generate an effective potential (tree + loop) which pushes the meson away from the origin.

- **Meson Deformations:** $\delta W_{mag} \sim \epsilon f M^2?$

From GKK we know this can't work for our small flavor group.

- **Baryon Deformations:** $\delta W_{el} \sim \frac{1}{\Lambda_{UV}^2} Q^5 \rightarrow \delta W_{mag} \sim m\phi\phi?$

Only works for $SU(7) \rightarrow SU(2) \times SU(5)$. Very non-renormalizable in electric theory.

- **Add A Singlet Sector Coupled To The Meson!**

(Witten 1981; Dine & Mason 2006; Csaki, Shirman & Terning 2006)

Inverted Hierarchy Mechanism (Witten 1981)

- Take an O’Raifeartaigh Model that ~~SUSY~~. It will have a pseudomodulus X .
- If there are no gauge interactions, the effective potential at 1-loop will look like

$$V_{tree} = M^4 \lambda^2 \quad \longrightarrow \quad V_{eff} = M^4 \lambda^2 \left[1 + b \frac{\lambda^2}{8\pi^2} \log \frac{|X|^2}{\Lambda^2} \right]$$

SUSY-breaking scale, tree contribution, 1-loop contribution

- This can be written as

$$V_{eff} = M^4 \lambda(X)^2 \quad \text{where} \quad \lambda(X)^2 = \lambda^2 \left[1 + b \frac{\lambda^2}{8\pi^2} \log \frac{|X|^2}{\Lambda^2} \right]$$

- Effective coupling λ increases with X : consequence of RGE
 $\Rightarrow X$ is stabilized at the origin.
- Gauge Interactions try to decrease λ for larger X
 \Rightarrow can drive X away from the origin!

Add Singlet Sector To Our Model

$$W = h\bar{\phi}M\phi + (-hf^2 + dS\bar{S})\text{Tr}M + m'(S\bar{Z} + Z\bar{S})$$

	Z	\bar{Z}	S	\bar{S}
$U(1)_S$	1	-1	1	-1
$U(1)_R$	2	2	0	0

For m' not too large, singlets get VEV

→ ~~$U(1)_S$~~ and ~~$U(1)_R$~~

→ negative log contribution in 1-loop potential V_{CW}

⇒ $\langle M \rangle \neq 0$ possible

Not quite done!

- Split up the meson M into singlet and adjoint components

$$M = M_{adj} + M_{sing}$$

- M_{sing} is stabilized by the singlet sector

$$V_{CW}(M_{sing}) = V_{CW}^{mess} + V_{CW}^{sing}$$

drives towards region where messengers are tachyonic

drives away from region where messengers are tachyonic

- What about the **adjoint meson**?

$$V_{CW}(M_{adj}) = V_{CW}^{mess}$$

TACHYONIC!

Fix the Adjoint Instability

How to stabilize the Adjoint Meson?

- 1 **Add Flavor Adjoint:** $\Delta W_{mag} = m_{adj}MK$
→ **Landau Pole**
- 2 **Couple to field with $R = -2$ that gets a VEV**
 $\Delta W_{mag} = MMA$
→ complicated & highly non-renormalizable in electric theory
- 3 **Meson Deformation:** $\Delta W_{mag} = m_{adj}\text{Tr}(M_{adj})^2$ (~~R~~)

Some simple Meson Deformations are very hard to avoid in uplifted ISS models!

Complete Model for SUSY Sector in SSMGM

Magnetic Theory below scale Λ :

Trivial Gauge Group, $SU(5)$ flavor symmetry:

$$W = h\bar{\phi}_i M_j^i \phi^j + (-hf^2 + dS\bar{S})\text{Tr}M + m'(Z\bar{S} + S\bar{Z}) + m_{adj}\text{Tr}(M'^2) + a\frac{\det M}{\Lambda_m^2}$$

(Instanton Term restores SUSY for $M \sim \sqrt{f\Lambda}$)

Electric Theory above scale Λ :

augmented massive $SU(4)_c \times SU(5)_f$

$$W = \left(\tilde{f} + \frac{\tilde{d}}{\Lambda_{UV}} S\bar{S} \right) Q\bar{Q} + m'(Z\bar{S} + S\bar{Z}) + \frac{\tilde{c}}{\Lambda_{UV}} \text{Tr}(Q\bar{Q})'^2$$

Scales of Parameters

$$W = \left(\tilde{f} + \frac{\tilde{d}}{\Lambda_{UV}} S \bar{S} \right) Q \bar{Q} + m' (Z \bar{S} + S \bar{Z}) + \frac{\tilde{c}}{\Lambda_{UV}} \text{Tr}(Q \bar{Q})'^2$$

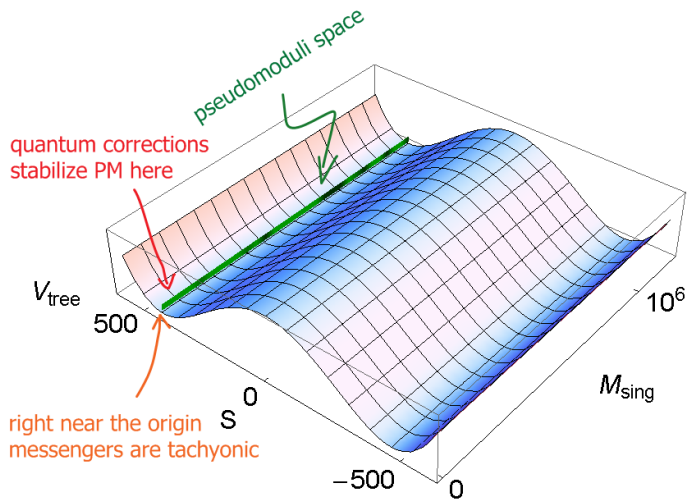
- $m', f \ll \Lambda$ free parameters. Generally $f \lesssim 10m'$.
- $\Lambda \lesssim \Lambda_{UV}/100$ for calculability. But no minima for $\Lambda \ll \Lambda_{UV}/100$.

	Λ	Λ_{UV}	
Scenario 1	10^{16}	10^{18}	(GeV)
Scenario 2	10^{14}	10^{16}	

- $h \sim 1$ unknown.
- typical size of $d \sim \frac{\Lambda}{\Lambda_{UV}} \sim 0.01$, $m_{adj} \sim d\Lambda$.

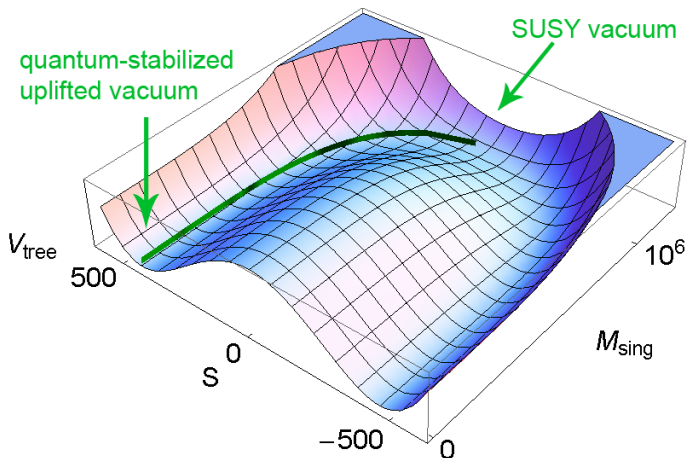
Is tiny $d \ll h \sim 1$ problematic for analysis at 1-loop? **NO!**

Vacuum Structure without Instanton Term

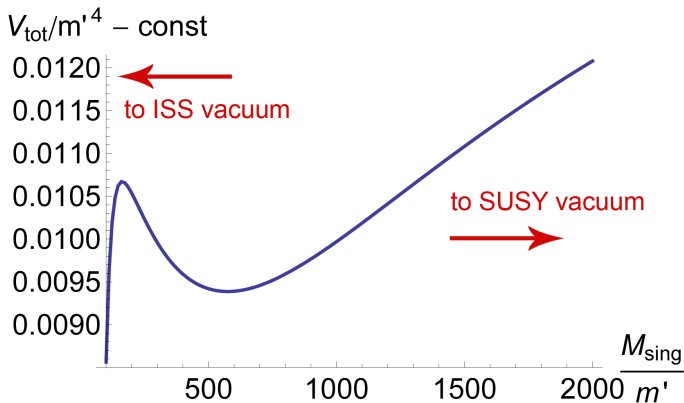


Effect of Instanton Term

Creates SUSY-minimum at $M_{sing} \sim \sqrt{\Lambda f}$



Effective Potential Along Pseudomoduli Space



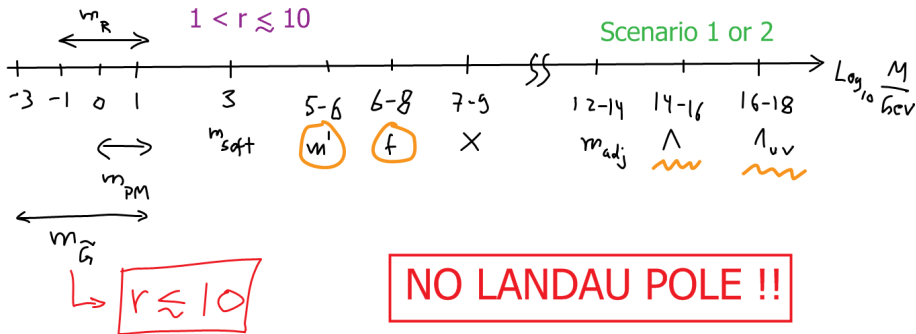
Meson stabilized at $\langle M_{\text{sing}} \rangle = O(1) \times \sqrt{\frac{h}{d}} f$

Direct Gauge Mediation

Gauge $SU(5)$ flavor symmetry and identify with G_{SM} .

$$W_{\text{eff}} = X \bar{\phi} \phi \quad \text{where} \quad X = \frac{h}{\sqrt{N_f}} M_{\text{sing}} \Rightarrow m_{\text{soft}} \sim \frac{\alpha}{4\pi} \frac{F}{X}$$

Important parameter for scales is $r = \sqrt{N_f h d} \frac{f}{m'} > 1$.



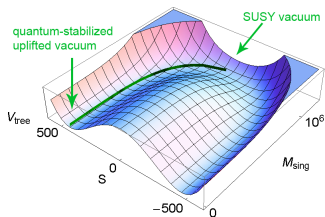
Stabilizing the Uplifted Vacuum

We need to understand the stabilization in detail

Why bother? We know that it's possible to get minima in the effective potential along the pseudomoduli space.

- Need to understand whether existence of minima is **generic** or **tuned**
→ If tuned, what conditions must be satisfied by the UV completion to make it generic?
- We have $d \ll h$, so how do we know we can **trust our 1-loop calculation**?

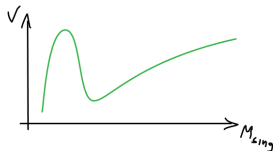
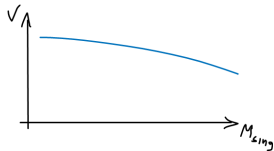
Effective Potential Along Uplifted Pseudomoduli Space



$$V_{eff} = V_{tree} + V_{CW}$$

$$V_{tree} = \text{const} - c \frac{m'^2}{\Lambda} M_{sing}^4$$

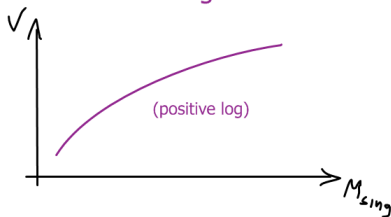
$$V_{CW} = \frac{1}{64\pi^2} \text{STr} m^4 \log \frac{m^2}{\Lambda^2}$$



(masses depend on $M_{sing} \leftrightarrow$ pseudomodulus)

1-Loop Contribution

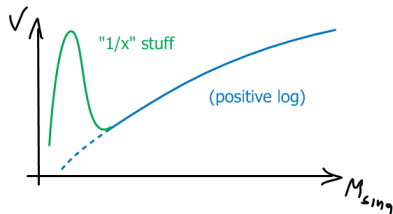
Messengers



Singlet masses depending on g



Singlet masses NOT depending on g



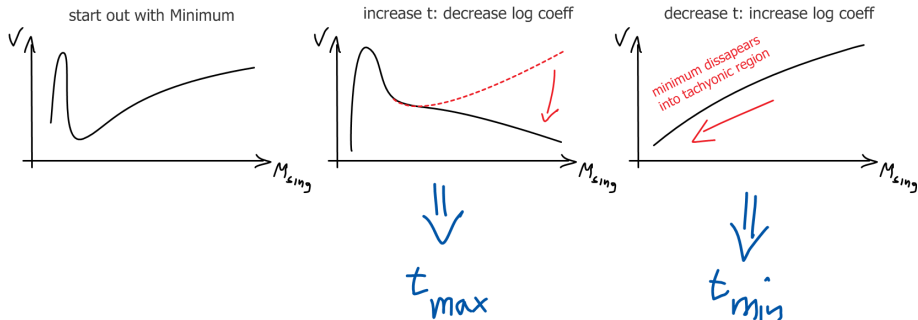
$$V_{CW} = \text{const}$$

$$+ \frac{1}{8\pi} (1-t) \log M_{sing}$$

$$+ \frac{1}{x} \text{ stuff}$$

Nature of Tuning

$$V_{CW} = \frac{1}{8\pi}(1 - t) \log M_{sing} + \text{"}\frac{1}{X}\text{ stuff"} + \text{const}$$



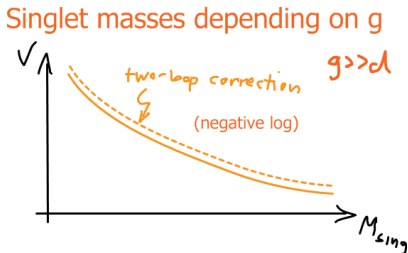
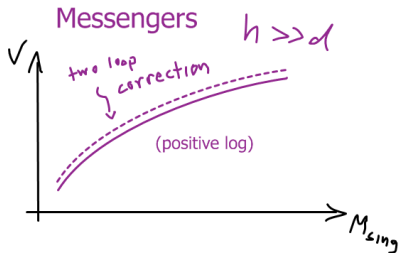
We find that $\frac{1}{2} \lesssim t \lesssim 1$ is required for minimum:

$$\frac{m'}{f} = 2g\sqrt{N_f \frac{d}{h}} \left(1 - \frac{d^2}{h^2} \frac{N_f}{2} t \right)$$

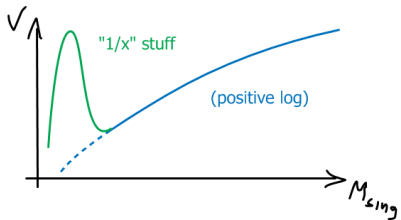
$\Rightarrow 10^{-4}$ tuning!

- Typical for such models.
- Ideally explain with UV completion.

Can We Trust 1-Loop calculation?



Singlet masses NOT depending on g



"Large" 2-loop corrections do NOT affect part of V_{CW} that generates local minimum

Conclusions

Conclusions

- ISS models are an extremely simple example of non-perturbative meta-stable SUSY-breaking.
- Problems:
 - Many Direct Gauge Mediation Models have **Landau Poles**.
 - Uplifted ISS models avoid **tiny gaugino masses** but are difficult to stabilize.
- We proposed **Singlet-Stabilized Minimal Gauge Mediation**: a 'minimal' uplifted ISS model with $SU(5)$ flavor symmetry.
⇒ **No Landau Pole, No Gaugino Mass Problem.**
- Lots of work to be done to address the origin of smaller mass scales (ISS) and problems with tuning & UV completion (SSMGM).