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SUSY breaking in a meta-stable vacuum: applications to model building

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- Introduction (MSB versus DSB)

- The ISS model of MSB

Intriligator, Seiberg, Shih hep-th/0602239

- Model Building with MSB:

- Naturalised Susy GUT

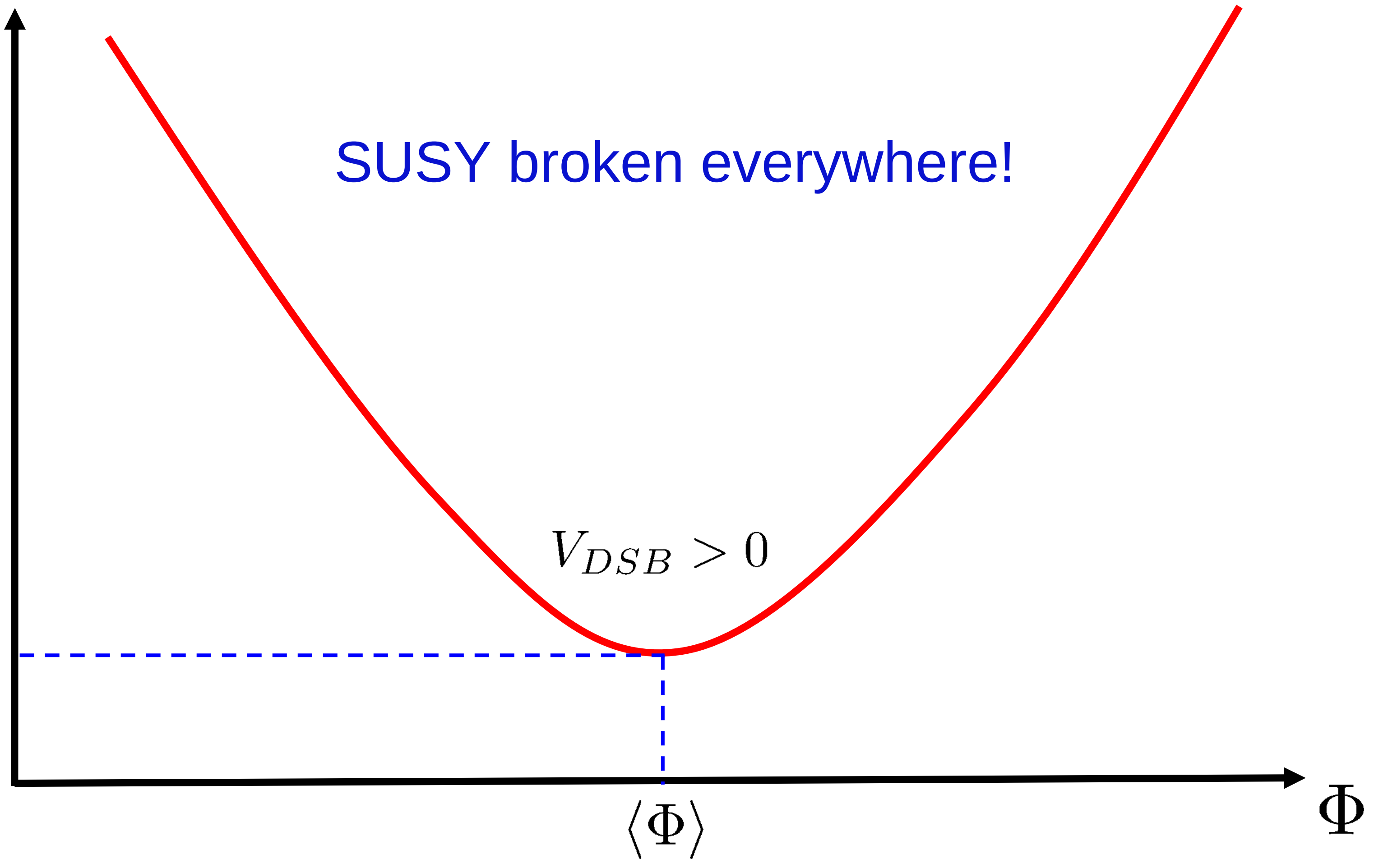
S Abel, J Jaeckel, VVK hep-th/0703086

- Meta-stable susy breaking within the Standard Model

S Abel, VVK hep-ph/0701069

Introduction

Conventional picture of DSB:



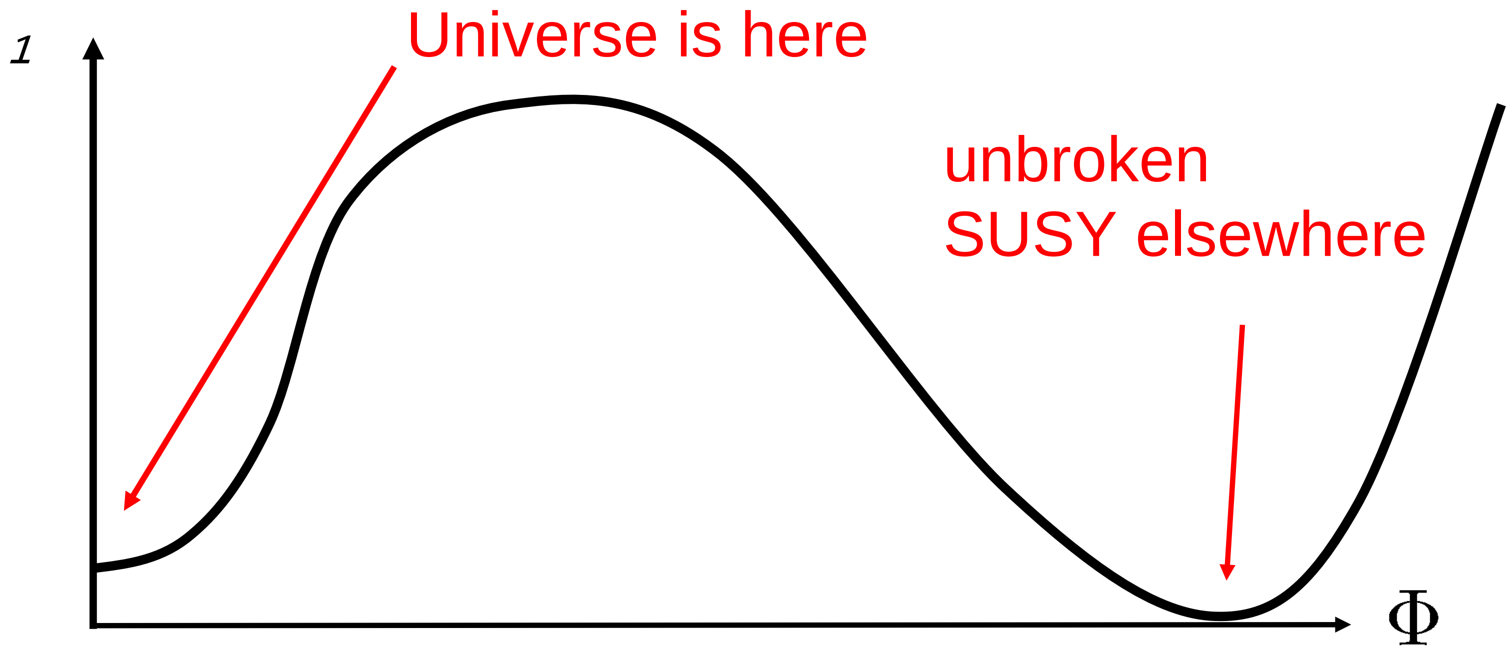
Problems with the DSB scenarios

- DSB is non-generic: many constraints on theories with DSB. Such as the Witten index constraint and the R-symmetry constraint.

- DSB is hard to analyze: in particular, one needs to know the Kahler potential, which is not protected by holomorphicity.

ISS picture of meta-stable SUSY breaking

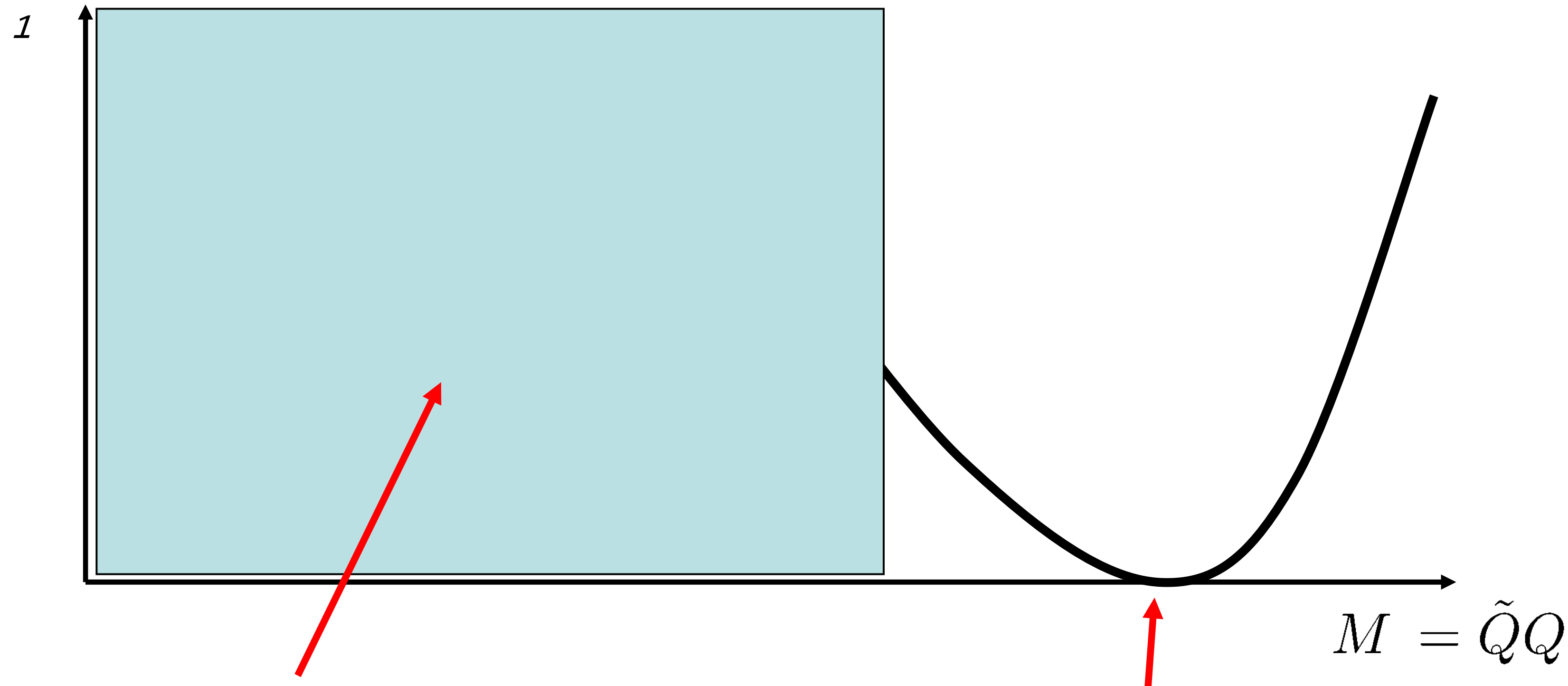
Intriligator, Seiberg, Shih hep-th/0602239



see also an early idea of

J Ellis, C Llewellyn Smith, G Ross PLB 114 (1982) 227

Effective potential of N=1 SQCD with massive quarks



Potential near the origin can be uncovered using Seiberg duality

N_c SUSY vacua

$$\langle M \rangle \sim \left(\Lambda^{3N_c - N_f} m^{N_f - N_c}\right)^{1/N_c}$$

Seiberg Duality

Microscopic:
(electric)

$$W_{\rm cl} = m \mathrm{Tr}\, Q\tilde{Q}$$

	$SU(N_c)_{\rm gauge}$	$SU(N_f)$	$SU(N_f)$
Q	N_c	N_f	1
$\tilde{Q}$	$\overline{N}_c$	1	$\overline{N}_f$

Macroscopic:
(magnetic)

$SU(N)$ gauge theory with $N := N_c - N_f$

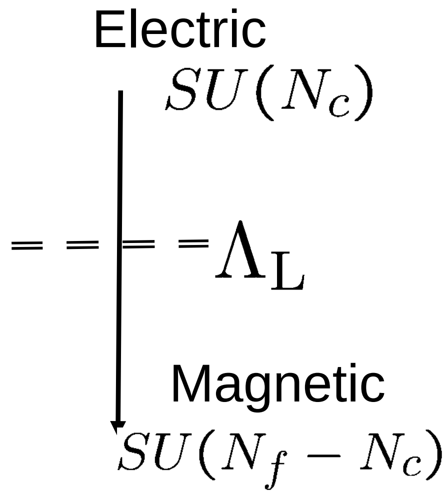
$$W_{\rm cl} = h \mathrm{Tr}\, \varphi \Phi \tilde{\varphi} + h\mu^2 \mathrm{Tr}\, \Phi$$

magnetic quarks φ and $\tilde{\varphi}$ originate from barions
singlet field Φ originates from mesons

$$\Phi = \frac{Q\tilde{Q}}{\Lambda_L} \qquad \mu^2 := \Lambda_L m$$

Consider the macroscopic theory

We take $N_c + 1 < N_f \leq \frac{3}{2} N_c$ where the magnetic theory is IR free



	$SU(N)_{\rm gauge}$	$SU(N_f)$	$SU(N_f)$
φ	N	N_f	1
$\tilde{\varphi}$	$\overline{N}$	1	$\overline{N}_f$
Φ	1	$\overline{N}_f$	N_f

$N := N_f - N_c$ $\qquad$ $N_f > 3N$

$$b_0 = 3N - N_f < 0$$

$$e^{-8\pi^2/g^2(E)} = \left(\frac{E}{\Lambda_L}\right)^{-b_0}$$

- β-function is positive,
- the theory is free in the IR and
- strongly coupled in the UV
- where it develops a Landau pole at scale Λ_L

$N_c + 1 \le N_f < \frac{3}{2} N_c$ For example, $N_c = 5$, $N_f = 7$.

Since weakly coupled in the IR:
take the canonical Kahler potential $K = \varphi\bar{\varphi} + \tilde{\varphi}\bar{\tilde{\varphi}} + \Phi\bar{\Phi}$

The tree level superpotential of the theory
is an O'Raifeartaigh model and breaks SUSY!

$$W_{cl} = h \, \mathrm{Tr}_{N_f}(\varphi^a \Phi \tilde{\varphi}_a) - h\mu^2 \mathrm{Tr}_{N_f} \Phi$$

The rank condition gives SUSY-breaking $|\mathrm{vac}\rangle_+$:

$$F_{\Phi^i_j} = h\,(\varphi^a_i \tilde{\varphi}^j_a - \mu^2 \delta^j_i) \neq 0$$

cannot be satisfied since $\varphi^a_i \tilde{\varphi}^j_a$ has rank $N = N_f - N_c < N_f$

Metastable vacuum $|\text{vac}\rangle_+$:

$$\langle\varphi\rangle = \langle\tilde{\varphi}^T\rangle = \mu \begin{pmatrix} \mathbb{1}_N \\ 0_{N_f-N} \end{pmatrix}, \quad \langle\Phi\rangle = 0\,, \qquad V_+ = (N_f - N)|h^2\mu^4|$$

- Supersymmetry is broken since $V_+ > 0$. It originates from the rank condition.
- $SU(N)$ gauge group is completely Higgsed near the origin by the vevs of φ and $\tilde{\varphi}$ and $m_{\text{gauge}} = g\mu$.
- ISS showed that $|\text{vac}\rangle_+$ has no tachyonic directions at one loop. It is classically stable, and quantum-mechanically is long-lived.

And the SUSY preserving minima $|\mathrm{vac}\rangle_0$?

Consider giving a VEV to Φ

- Then $m_\varphi, m_{\tilde{\varphi}} = h\Phi_0$ and we can integrate out $\varphi, \tilde{\varphi}$.
- The β-function reverses sign since now, $N_f = 0$, and the theory confines with $W_{\mathrm{dyn}} = N\Lambda^3_{\mathrm{eff\,SYM}}$
- The non-perturbative contribution to superpotential is determined by *integrating out heavy* φ *and* $\tilde{\varphi}$ *modes;*

$$W = W_{\mathrm{cl}} + W_{\mathrm{dyn}}$$

$$W_{\mathrm{dyn}} = N \left(\frac{h^{N_f} \det_{N_f} \Phi}{\Lambda_L^{N_f - 3N}} \right)^{\frac{1}{N}}$$

SUSY preserving minima $|\text{vac}\rangle_0$ at

$$\begin{aligned} \langle\varphi\rangle &= \langle\tilde{\varphi}\rangle = 0 \quad ; \quad \langle\Phi\rangle = \Phi_0 = \mu\gamma_0 \mathbf{1}_{N_f} \\ \gamma_0 &= \left(h\epsilon^{\frac{N_f-3N}{N_f-N}}\right)^{-1} \gg 1 \quad ; \quad \epsilon := \mu/\Lambda_L \ll 1 \end{aligned}$$

It follows that

$$\mu \ll \Phi_0 \ll \Lambda_L$$

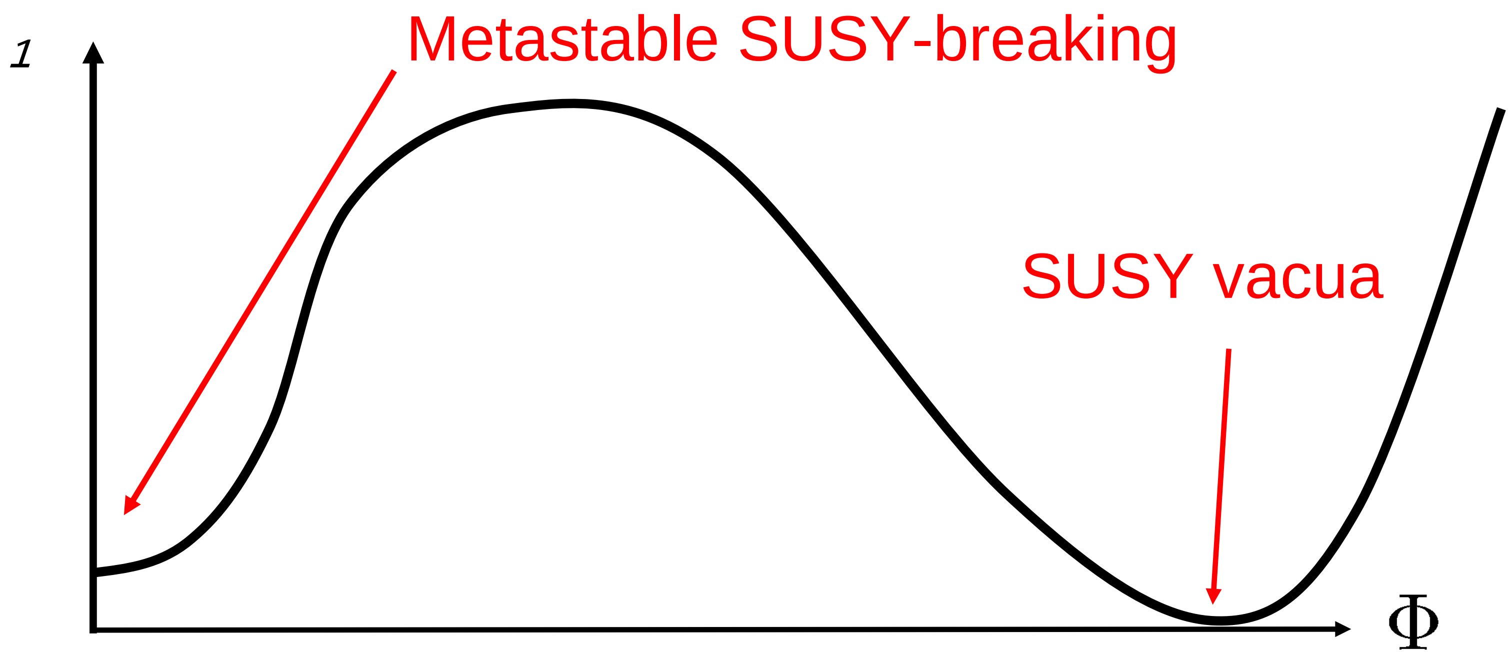
SUSY vacua are far away from the origin in Φ direction, but below Λ_L. The potential is very wide.

- There are actually N_c SUSY preserving vacua differing by phase $e^{2\pi i/N_c}$ as required by Witten index of the microscopic theory!
- It is always possible by choosing $\epsilon \ll 1$ to ensure that the decay of $|\text{vac}\rangle_+$ is longer than the age of the Universe.

The key features of this effective potential are

(1) the large distance between the two vacua, $\gamma_0 \gg 1$, and

(2) the slow rise of the potential to the left of the SUSY preserving vacuum.



A natural question:

Why did the Universe start from the non-supersymmetric vacuum in the first place ?

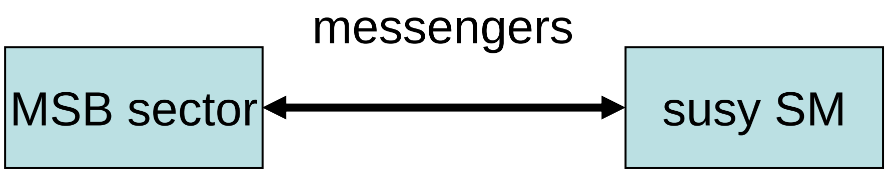
Our answer: in the ISS model thermal effects drive the Universe to the susy-breaking vacuum even if it starts after inflation in the susy-preserving one.

See: Joerg Jaeckel's talk tomorrow:

`Lving on the edge: why our universe preferred a meta-stable state'

S Abel, C-S Chu, J Jaeckel, VVK	hep-th/0610334
S Abel, J Jaeckel, VVK	hep-th/0611130
N Craig, P Fox, J Wacker	hep-th/0611006
W Fischler *et al*	hep-th/0611018
L Anguelova, R Ricci, S Thomas	hep-th/0702168

Model Building with MSB



Gauge Mediation simplified:

- M Dine, J Mason hep-ph/0611312
- R Kitano, H Ooguri, Y Ookouchi hep-ph/0612139
- H Murayama, Y Nomura hep-ph/0612186
- C Csaki, Y Shirman, J Terning hep-ph/0612241
- O Aharony, N Seiberg hep-ph/0612308

One can think of

Two orthogonal approaches to use MSB for model building:

Naturalised Supersymmetric Grand Unification

Use Hidden sectors to break susy and to generate and explain all mass scales in the theory.

-including the GUT-scale and the mu-parameter (but proton decay…)

Abel-Jaeckel-VVK hep-ph/0703086

Visible sector susy-breaking in the Standard Model

No hidden sectors, no GUTs, direct link between susy-breaking and electroweak breaking (but price to pay…)

Abel-VVK hep-ph/0701069

Naturalised Supersymmetric Grand Unification

- *MSB-sector* is responsible for metastable supersymmetry breaking.
- *R-sector* dynamically generates all mass-parameters in the full model by retrofitting.
- The visible sector is the $SU(5)$ susy *GUT-sector*.

GUT $SU(5)$ is the gauged $SU(N_f = 5)$ flavour symmetry of the R-sector, and the adjoint Higgs Φ_{GUT} is the traceless part of the R-sector mesons $\tilde{Q}_R Q_R$.

GUT-sector is coupled to the MSB-sector via messenger fields f and $\tilde{f}$.

Interactions between the sectors

Superpotential $\mathcal{W}_1$ is responsible for the retrofitting.

$$\mathcal{W}_1 = tr(W_R^2)[\frac{1}{g_R^2} + \frac{a_1}{16\pi^2 M_p^2} tr(\tilde{Q}_{MSB} Q_{MSB})$$

$$+ \frac{a_2}{16\pi^2 M_p^2} tr(\tilde{f} f) + \frac{a_3}{16\pi^2 M_p^2} tr(\tilde{H} H)]$$

The SYM develops a gaugino condensate $\langle W_R^2 \rangle = \langle \lambda_R^2 \rangle = \Lambda_R^3$.
This generates masses $m_{Q_{MSB}}, m_H$ of the order $\sim \Lambda_R^3 / M_p^2$.

$$\boxed{\mu_{MSSM} = \frac{a_3}{16\pi^2} \frac{\Lambda_R^3}{M_p^2} \gtrsim 10^2 \div 10^3 \text{ GeV}} \text{ for } \Lambda_R \gtrsim 10^{14} \text{ GeV}$$

$$\mu_{MSB}^2 \equiv \Lambda_{MSB} m_{Q_{MSB}} = \frac{a_1}{16\pi^2} \frac{\Lambda_{MSB} \Lambda_R^3}{M_p^2}$$

Interactions between the sectors

Superpotential $\mathcal{W}_2$ couple the messenger fields of the GUT sector and the quark bilinears from the hidden sectors

$$\mathcal{W}_2 = \frac{b_1}{M_p} tr(\tilde{f} f) \, tr(\tilde{Q}_{MSB} Q_{MSB}) + \frac{b_2}{M_p} (\tilde{f} f) \, (\tilde{Q}_R Q_R)$$

$\langle \tilde{Q}^i_R Q^j_R \rangle$ will be generated dynamically in the R-sector:

$$\langle \tilde{Q}^i_R Q^j_R \rangle = M^2_{GUT} \, \mathrm{diag}(+1, +1, +1, -1, -1)$$

The mass term for the messengers is then

$$m_f = b_2 \frac{M^2_{GUT}}{M_p}$$

Interactions between the sectors

Superpotential $\mathcal{W}_3$ couples the Higgs (anti)-fundamental fields of the GUT sector to the Higgs which arises from mesons of the R-sector

$$\mathcal{W}_3 = \frac{\kappa}{M_p} H \cdot \left(tr(\tilde{Q}_R Q_R) + \tilde{Q}_R Q_R \right) \cdot \tilde{H}$$

These two terms are included to raise the mass of the Higgs triplet fields and do not give any additional mass to the doublets since

$$\langle tr(\tilde{Q}^i_R Q^j_R) \rangle + \langle \tilde{Q}^i_R Q^j_R \rangle = 2 M^2_{GUT} \, \mathrm{diag}(+1, +1, +1, 0, 0)$$

$$m_{H_3, \bar{H}_3} \approx 2 \kappa M^2_{GUT} / M_p$$

R-sector-generation of the GUT scale

$N_f = 5 < N_c - 1$

There is an Affleck-Dine-Seiberg superpotential in the R-sector which leads to run-away vacua and renders the theory inconsistent. We stabilise it again with a retrofitting

$$\mathcal{W}_R = \left(\frac{\Lambda_{SQCD}^{3N_c - N_f}}{\det_{N_f}(\tilde{Q}_R Q_R)} \right)^{\frac{1}{N_c - N_f}} + \frac{d}{2M_p} tr(\tilde{Q}_R Q_R)^2$$

The F-flatness solution gives for the meson $M_{ij} = \tilde{Q}^i_R Q^j_R$

$$\langle M_{ii} \rangle^2 = \frac{M_p}{d} \left(\frac{\Lambda_{SQCD}^{3N_c - N_f}}{\det_{N_f} \; M} \right)^{\frac{1}{N_c - N_f}}$$

in the diagonal basis

R-sector-generation of the GUT scale

For $N_f = 5$ there are three inequivalent discrete solutions

$$\langle M_{ij} \rangle = \langle M \rangle \, \mathrm{diag}(1,1,1,1,1) \quad => \quad SU(5)$$

$$\langle M_{ij} \rangle = \langle M \rangle \, \mathrm{diag}(1,-1,-1,-1,-1) \quad => \quad SU(4)$$

$$\boxed{\langle M_{ij} \rangle = \langle M \rangle \, \mathrm{diag}(1,1,1,-1,-1) \quad => \quad SU(3)\times SU(2)\times U(1)}$$

The VEV of the meson field should be expressed in terms of the dynamical scale Λ_R of the effective pure SYM $SU(N_c - N_f)$ theory in the R-sector

$$\boxed{\langle M \rangle \equiv M_{GUT}^2 = \frac{1}{\sqrt{d}} \sqrt{\Lambda_R^3 M_p}}$$

R-sector-generation of the GUT scale

Eliminating Λ_R we get at a relation between μ_{MSSM} and M_{GUT}

$$M_{GUT}^2 = \frac{4\pi}{\sqrt{a_3\, d}} \left(\mu_{MSSM} M_p^3\right)^{1/2}$$

With $M_p \sim 10^{19}\,\mathrm{GeV}$ and $\mu_{MSSM} \sim 10^2 \div 10^3\,\mathrm{GeV}$ we find

$$M_{GUT} \sim 10^{15} \div 10^{17}\,\mathrm{GeV}$$

if we choose the constants $a_3,\ d$ in the range $10^{-3} \div 10^1$.

Metastable supersymmetry breaking

Use canonically normalised $\Phi_{MSB} = \frac{Q_{MSB}\tilde{Q}_{MSB}}{\Lambda_{MSB}}$.

Near $\Phi_{MSB} = 0$ supersymmetry is broken by the rank condition at the scale μ_{MSB} and

$$\langle tr(F_{\Phi^{ij}_{MSB}}) \rangle \sim \mu^2_{MSB}$$

This supersymmetry breaking is gauge mediated to the GUT sector by the messengers $\tilde{f}$, f and generates Majorana mass terms for the gauginos

$$\boxed{m_\lambda \sim b_1 \frac{g^2}{16\pi^2} \frac{\Lambda_{MSB}}{M_p} \frac{tr(F_{\Phi_{MSB}})}{m_f} \sim 1\,\mathrm{TeV}}$$

by choosing Λ_{MSB} which is a free parameter.

Naturalised GUT Summary

A simple model of an $SU(5)$ GUT with gauge mediated susy-breaking from a metastable vacuum of a hidden sector.

All mass parameters and hierarchies of the model are generated dynamically

$$\mu_{MSSM} = \frac{a_3}{16\pi^2}\frac{\Lambda_R^3}{M_p^2} \sim 10^2 \div 10^3\,\mathrm{GeV}$$

$$M_{GUT}^2 = \frac{4\pi}{\sqrt{a_3\, d}}\left(\mu_{MSSM} M_p^3\right)^{1/2}\ ,\ M_{GUT} \sim 10^{15} \div 10^{17}\,\mathrm{GeV}$$

However, as typical for simple $SU(5)$ GUT models, proton longevity remains a problem because the Higgs triplet is not sufficiently heavy $m_{H_3,\bar{H}_3} \approx 2\kappa M_{GUT}^2/M_p$

A natural avenue to explore in this class of models is embedding the $SU(5)$ structure within $SO(10)$.

S. A. Abel, S. Förste, J. Jaeckel and V. V. Khoze, *in preparation*

Alternative: Metastability within the SM

$$SU(N)_{\mathrm{ISS\,magnetic}} \equiv SU(2)_L$$

In this approach ISS model is not a Hidden sector. It is embedded into the electroweak sector of the Standard Model. Total gauge group of the theory is $SU(3)_c \times SU(2)_L \times U(1)_Y$.

Electroweak Higgses will be identified with φ fields of the ISS.

The $SU(2)_L$ gauge factor is strongly coupled in the UV at $\Lambda_L > M_{\mathrm{Pl}}$. Perfectly OK to work with the 'magnetic' version ('electric' version is unknown and not needed).

A “no-go” theorem

$STr(M^2) = 0$ at tree-level; can be applied to differently charged fields independently, so that for example it predicts

$$m_{\tilde{d}}^2 + m_{\tilde{s}}^2 + m_{\tilde{b}}^2 \sim (5\text{GeV})^2$$

To avoid this, we require that the SUSY breaking mass splittings are induced at 1-loop. $M_W \approx g\mu$ and expect e.g.

$$M_{gluino} \sim \frac{1}{16\pi^2}\frac{F_\Phi}{m_R} \sim \frac{h\mu^2}{16\pi^2 m_R} \sim \frac{h}{16\pi^2} M_W .$$

Need $h \gg 1$; strong coupling in the Higgs sector to overcome the loop suppresson.

Superpotential

Identify ISS Higgses φ_1 and φ_2 with electroweak Higgses.

Metastable vacuum follows from the rank condition: $N_f \geq 3$.

Take $N_f = 3$ and $|\mu_1| > |\mu_2| > |\mu_3| > 0$

to avoid massless Goldstones.

$$W_{Higgs} = h\, Tr_{N_f}[\varphi \Phi \tilde{\varphi} - \mu^2 \Phi]$$

$$W_{Yuk} = \lambda_U Q \varphi_2 U + \lambda_D Q \varphi_1 D + \lambda_E L \varphi_1 E$$

$$W_R = \frac{g^2}{16\pi^2} \frac{1}{m_R} Tr(\Phi)\, W_A^{\alpha} W_{\alpha}^{A}$$

	$SU(2)_L$	$U(1)_Y$	$U(1)_3$	$U(1)_R$	PQ	L	B
Φ_i^j	1	$\frac{1}{2}(\delta_{i1}-\delta_{i2}+\delta_{j2}-\delta_{j1})$	$\frac{1}{2}(\delta_{j3}-\delta_{i3})$	2	0	0	0
φ	$\square$	$-\frac{1}{2}$,$+\frac{1}{2}$,0	0,0,1	0	1	0	0
$\tilde{\varphi}$	$\bar{\square}$	$+\frac{1}{2}$,$-\frac{1}{2}$,0	0,0,-1	0	-1	0	0
L	$\bar{\square}$	$-\frac{1}{2}$	0	1	$-\frac{1}{2}$	1	0
E	1	1	0	1	$-\frac{1}{2}$	-1	0
Q	$\bar{\square}$	$\frac{1}{6}$	0	1	$-\frac{1}{2}$	0	$+\frac{1}{3}$
D	1	$\frac{1}{3}$	0	1	$-\frac{1}{2}$	0	$-\frac{1}{3}$
U	1	$-\frac{2}{3}$	0	1	$-\frac{1}{2}$	0	$-\frac{1}{3}$

$$W_{Yuk} = \lambda_U Q\varphi_2 U + \lambda_D Q\varphi_1 D + \lambda_E L\varphi_1 E$$

$$W_{Higgs} = h\, Tr_{N_f}[\varphi\Phi\tilde{\varphi} - \mu^2\Phi]$$

$$W_R = \frac{g^2}{16\pi^2}\frac{1}{m_R} Tr(\Phi)\, W_A^{\alpha} W_{\alpha}^{A}$$

SU(2) and SUSY breaking

There is a metastable vacuum follows from the rank condition. It breaks SUSY and the gauge symmetry

$$SU(2)_L \times U(1)_Y \quad \rightarrow \quad U(1)_{QED}$$

$$\begin{aligned} F_{\Phi_{33}} &= h\mu_3^2 \\ \varphi_{i=1,2} = \tilde{\varphi}_{1,2} &= \mu_i \\ M_W &= g_2\sqrt{\mu_1^2 + \mu_2^2} \end{aligned}$$

Effect of the R-breaking term

One-loop gluino masses

$$
\begin{aligned}
W_\lambda &= \frac{\alpha_s Tr(\Phi)}{4\pi\, m_R}\mathcal{W}^\alpha \mathcal{W}_\alpha \\
M_\lambda &= \frac{\alpha_s h \mu^2}{4\pi\, m_R}
\end{aligned}
$$

$h \gg 1$ for $M_\lambda \gtrsim 100$GeV; Higgs sector is strongly coupled. (But decouples as $h \longrightarrow \infty$.) Very heavy Higgsses.

Masses of squarks and sleptons are generated from gaugino masses as a 1-loop effect. Precisely like in gauge mediation.

Summary

MSSM: M is for Metastable

S Abel, VVK hep-ph/0701069

- No need for a hidden susy-breaking sector
- MSB occurs in the SU(2) x U(1) of the SM
- Direct link between the susy-breaking and electro-weak symmetry breaking
- Extremely compact low-energy SM-like theory
- But have to pay a price for breaking susy and electroweak symmetry in the same visible sector

=> strongly coupled Higgs sector

Final Summary:

- The ISS model of MSB.

- Why the early Universe preferred the non-supersymmetric vacuum

Model Building with MSB:

- Naturalised Susy Grand Unification

- Meta-stable susy breaking within the Standard Model