Supersymmetry breaking through radiative corrections

Stéphane Lavignac (IPhT Saclay)

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in collaboration with B. Bajc and T. Mede [arXiv:1202.2845]

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Introduction

Supersymmetric unification is appealing, but its predictions (e.g. proton decay) depend on many unknowns, including ~~SUSY~~

$$A\left(p \to K^+ \bar{\nu}\right) \propto \frac{1}{m_T \; m_{\rm susy}}$$

Two ways to introduce ~~SUSY~~ in SGUTs:

- separate sector/dynamics
- unify supersymmetry and gauge symmetry breaking sectors: an old idea

Witten 81 - Dine, Fischler 82 - Dimopoulos, Raby 83 - Banks, Kaplunovsky 83 - Derendinger, Savoy 82 - Kaplunovsky 84 ...

And more recently: Murayama 97 - Dimopoulos, Dvali, Rattazzi, Giudice 98 - Luty 97 - Agashe 98, 00 - Bajc, Melfo 08

so far all approaches used several fields and/or dynamical ~~SUSY~~

→ is it possible to break (in a perturbative way) supersymmetry and the gauge symmetry with the same field?

Motivations for breaking supersymmetry and the gauge symmetry with the same field:

(i) economy

(ii) ~~SUSY~~ transmitted to the observable sector via gauge interactions, with the heavy gauge fields acting as messenger fields

$$M_\lambda \;=\; C_\lambda\, \frac{\alpha_{GUT}}{4\pi}\, \frac{F}{v} \qquad\qquad m_\Phi^2 \;=\; C_\Phi \left(\frac{\alpha_{GUT}}{4\pi}\right)^2 \left|\frac{F}{v}\right|^2$$

$\langle\sigma\rangle = v + F\theta^2$ ~~GUT~~ and ~~SUSY~~ field ($v \sim M_{\rm GUT}$ messenger scale)

Crucial to have a single field: if several fields involved, negative scalar masses arise at the 1-loop level [Intriligator, Sudano]
$\Rightarrow$ cannot be cured by the renormalization group running

[there are ways to suppress these 1-loop contributions, e.g. $v_1 \ll v_2$, but difficult to build a consistent model]

(iii) the gaugino mass problem of direct gauge mediation with chiral messenger fields is absent [Komargodski, Shih]

Basic principle

Remember Witten's inverted hierarchy mechanism:

Tree-level SUSY (à la O'Raifeartaigh) $V_0(\sigma) = |F|^2$ σ = flat direction

1-loop effective potential: $$V_{\text{eff}}(\sigma) = \frac{|F|^2}{1 + (c_g - c_\lambda)\log\left(|\sigma|^2/\mu^2\right)}$$

competition between gauge (c_g) and Yukawa (c_λ) contributions

$$c_g > c_\lambda \qquad |\sigma| \text{ tends to increase}$$

$$c_g < c_\lambda \qquad |\sigma| \text{ tends to decrease}$$

Assuming asymptotic freedom, σ stabilized at v such that $c_g(v) = c_\lambda(v)$

[original motivation: generate the hierarchy $M_W \,/\, M_{\text{GUT}} \sim \langle\sigma\rangle$]

Several fields needed to realize this mechanism [Witten's original proposal has 3 fields: σ = singlet + 2 adjoints of SU(5)]

Consider instead a single (charged) field:

$$V_0(\sigma) = |F(\sigma)|^2 \qquad F(\sigma) \neq \text{const.} \qquad \text{SUSY unbroken at tree level}$$

Seek a (metastable) ~~SUSY~~ minimum in the 1-loop effective potential:

$$V_{\text{eff}}(\sigma) \;=\; \frac{|F(\sigma)|^2}{1 + c\log\left(|\sigma|^2/\mu^2\right)}$$

Anticipating $m_{\text{soft}} \sim (\alpha/4\pi)(F/v) \sim 1\,\text{TeV}$ with $v \sim M_{\text{GUT}}$, we require $F(v) \ll v^2$, hence Yukawa couplings must be suppressed and $c \simeq c_g > 0$

Conditions for the appearance of a ~~SUSY~~ minimum:

$$(i) \quad F'(v) = cF(v)/v \qquad\qquad (ii) \quad \left|\frac{c^2}{v^2}F(v)\right| \;\geq\; \left|F'' + \frac{c}{v^2}F(v)\right|$$

where the general solution of (ii) can be parametrized as

$$F''(v) = (ac^2 - c)F(v)/v^2\,, \qquad |a| \leq 1$$

Since c is a 1-loop coefficient, this implies some tuning between superpotential parameters

An explicit SU(5) example

The field σ is identified with the SM singlet component of an adjoint Σ :

$$\Sigma = \frac{\sigma}{\sqrt{30}}\ \mathrm{Diag}(2,2,2,-3,-3) + \cdots$$

with $W = \frac{\mu}{2}\,\mathrm{Tr}\,\Sigma^2 + \sqrt{30}\,\frac{\lambda}{3}\,\mathrm{Tr}\,\Sigma^3 + \frac{\kappa_1}{4M}\,\mathrm{Tr}\,\Sigma^4 + \frac{\kappa_2}{4M}\left(\mathrm{Tr}\,\Sigma^2\right)^2$

$\Rightarrow\ V_0(\sigma) = |F(\sigma)|^2 \qquad F(\sigma) = \mu\sigma - \lambda\sigma^2 + \frac{\kappa}{M}\sigma^3 \qquad \kappa = 7\kappa_1/30 + \kappa_2$

Using the explicit expression for F(σ), the minimum conditions (i) and (ii) can be rewritten as conditions on μ, λ and κ/M (with |a| ≤ 1):

$$\mu = \frac{F(v)}{2v}\left(6 - 5c + ac^2\right)$$

$$\lambda = \frac{F(v)}{v^2}\left(3 - 4c + ac^2\right)$$

$$\frac{\kappa}{M} = \frac{F(v)}{2v^3}\left(2 - 3c + ac^2\right)$$

since $\frac{F(v)}{v^2} \sim (\alpha/4\pi)^{-1}\,\frac{m_{\rm soft}}{M_{\rm GUT}} \ll 1$

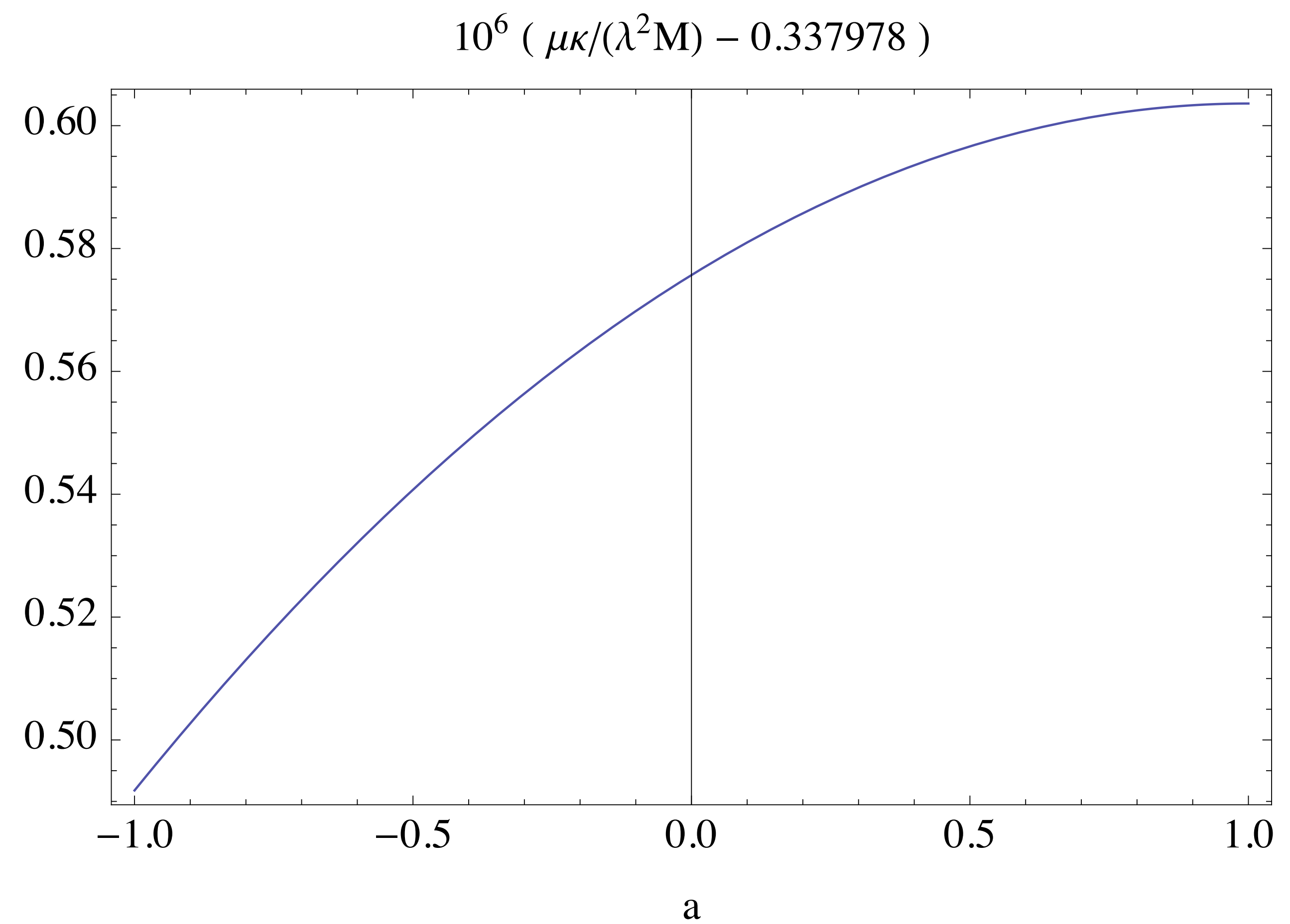
all superpotential parameters must be small $\Rightarrow\ c \simeq c_g > 0$

We can therefore compute the 1-loop effective potential neglecting all superpotential parameters, in which case only the heavy X and Y vector multiplet contribute, with masses $m_X = m_Y = 5\, g^2_{\rm GUT}\, |\sigma|^2/6$

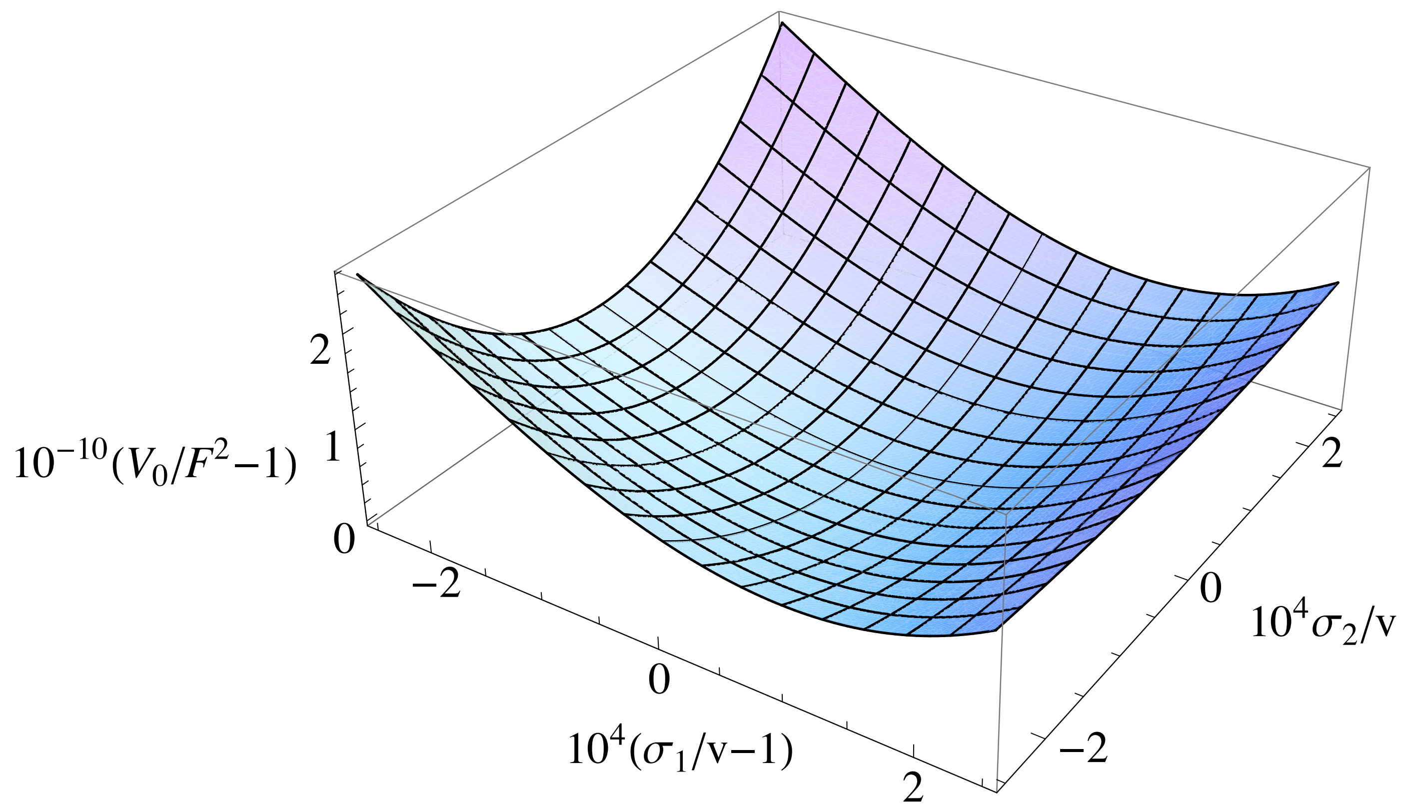
This gives: $$c = \frac{1}{16\pi^2} \times 12 \times \frac{5}{6}\, g^2_{\rm GUT} = 10\, \frac{\alpha_{GUT}}{4\pi} \approx 0.04$$

Since c is small, the minimum conditions amount to a fine-tuned relation between superpotential parameters:

the combination $\mu\, \kappa/(\lambda^2 M)$ is fixed with a precision of 10^{-6}



Once this is satisfied, a local ~~SUSY~~ minimum appears in $V_{\rm eff}(\sigma)$



Lifetime given by the inverse transition rate to the SUSY vacuum at $\sigma = 0$:

$$e^S \quad \text{with} \quad S \sim \frac{(\Delta\sigma)^4}{\Delta V} = \frac{v^4}{|F(v)|^2} \sim \left(\frac{\alpha_{\rm GUT}}{4\pi}\right)^2 \frac{M_{\rm GUT}^2}{m_{\rm soft}^2} \sim 10^{21}$$

Gauge coupling unification and proton decay

An extra constraint from gauge coupling unification: the colour octet and weak triplet components of the adjoint Σ get their masses from $W(\Sigma)$

$\Rightarrow$ if no tuning in $\kappa = 7\kappa_1/30 + \kappa_2$, one ends up with $m_3, m_8 \lll M_{\rm GUT}$

due to $\mu,\ \lambda v,\ \kappa v^2/M \sim F(v)/v \sim (\alpha/4\pi)^{-1} m_{\rm soft}$

$\Rightarrow$ gauge couplings unify above the Planck mass M

To avoid this, must tune $\kappa \ll \kappa_1, \kappa_2 \Rightarrow$ fixed ratio $m_3 \simeq 4 m_8 \simeq \dfrac{2}{3}\kappa_1 \dfrac{v^2}{M}$

$$M_{GUT} = M^0_{GUT}\left(\frac{M^0_{GUT}}{\sqrt{m_3 m_8}}\right)^{1/2} \qquad m_T = m^0_T\left(\frac{m_3}{m_8}\right)^{5/2} = 32 m^0_T$$

[Bachas, Fabre, Yanagida]

with $3.5\times 10^{14}\,{\rm GeV} \leq m^0_T \leq 3.6\times 10^{15}\,{\rm GeV}$

$M^0_{\rm GUT} \simeq 2\times 10^{16}\,{\rm GeV}$

[Murayama, Pierce]

$\Rightarrow$ can achieve $m_T \approx M_{\rm GUT} \approx 10^{17}\,{\rm GeV}$, thus delaying proton decay

Price to pay: tuning of the order of 10^{-10} between κ_1 and κ_2

Model-building aspects

The wrong SU(5) mass relations can be corrected by higher-dimensional operators involving Σ :

$$W_{Y_e,Y_d} = (Y_3)_{ij}\, 10^i_F \bar{5}^j_F \bar{5}_H + (Y_4)_{ij}\, 10^i_F \left(\frac{\Sigma}{M_P}\, \bar{5}^j_F\right) \bar{5}_H + \cdots$$

Since Σ has a non-vanishing F-term, these also generate large A-terms for down quarks and charged leptons – however still consistent with CCB constraints if only metastability is required

[the absence of CCB minima can be ensured if n>5 operators are present]

The doublet-triplet splitting can be achieved by tuning the couplings of Σ to the $5_H, \bar{5}_H$ Higgs multiplets (two fine-tunings needed for μ and Bμ)

Also possible to avoid any fine-tuning by using the missing partner mechanism, at the price of replacing the adjoint Σ by a 75

[the discussion of GUT and SUSY breaking proceeds as before with a different value of c; also the spectrum of intermediate states and the gauge coupling running is modified]

Superpartner spectrum

The MSSM soft terms receive several contributions:

$$m_\Phi^2 = \Delta_{Sugra} m_\Phi^2 + \Delta_{GM} m_\Phi^2 + \Delta_{(\Sigma_3,\Sigma_8)} m_\Phi^2 + \Delta_{(T,\bar{T})} m_\Phi^2$$

$$M_a = \Delta_{Sugra} M_a + \Delta_{GM} M_a + \Delta_{(\Sigma_3,\Sigma_8)} M_a + \Delta_{(T,\bar{T})} M_a$$

Supergravity contributions will generally dominate due to

$$m_{GM} \equiv \frac{\alpha_{\rm GUT}}{4\pi} \frac{F}{M_{\rm GUT}} \lesssim m_{3/2} = \frac{F}{\sqrt{3} M} \quad \text{for} \quad M_{\rm GUT} \gtrsim 10^{16}\,\text{GeV}$$

unless they are suppressed by some mechanism (e.g. sequestering)

Gauge-mediated contributions can be computed using the wave-function renormalization technique. Assuming the minimal field content and doublet-triplet splitting by fine-tuning, one obtains, in units of m_{GM}:

m_Φ^2/m_{GM}^2	Q	U^c	E^c	L	D^c	H_u, H_d
Δ_{GM}	-11	-4	6	-3	-6	-3
$\Delta_{(\Sigma_3,\Sigma_8)}$	44	32	0	12	32	12
$\Delta_{(T,\bar{T})}$	$\frac{804}{75}$	$\frac{864}{75}$	$\frac{48}{25}$	$\frac{12}{25}$	$\frac{816}{75}$	$\frac{12}{25}$
total	$\frac{1093}{25}$	$\frac{988}{25}$	$\frac{198}{25}$	$\frac{237}{25}$	$\frac{922}{25}$	$\frac{237}{25}$

M_a/m_{GM}	M_3	M_2	M_1
Δ_{GM}	-4	-6	-10
$\Delta_{(\Sigma_3,\Sigma_8)}$	6	4	0
$\Delta_{(T,\bar{T})}$	2	0	$\frac{4}{5}$
total	4	-2	$-\frac{46}{5}$

A-terms only receive contributions from gauge messengers (leaving aside supergravity contributions):

$$A_u = 10\, m_{GM}\ ,\ \ A_d = 8\, m_{GM}\ ,\ \ A_e = 12\, m_{GM}$$

The gauge-mediated contributions are rather large in units of m_{GM}
$\Rightarrow$ may dominate even if moderate suppression of gravity contributions

Large stop A-term but same sign as the gluino mass: goes in the wrong direction for the Higgs mass since M_3 contributes with a minus sign to the RGE of A_t $\Rightarrow$ in the absence of other contributions (e.g. from supergravity) must rely on multi-TeV stop masses to reach 125 GeV

$\Rightarrow$ whole spectrum heavy in this simple SU(5) example (unobservable at LHC)

Conclusions

Supersymmetry and the gauge symmetry can be broken by the same field in spite of the absence of a tree-level flat direction. The local ~~gauge~~ and ~~SUSY~~ minimum is induced radiatively in the effective potential, far away from the gauge-invariant SUSY vacuum

For this mechanism to work, a fine-tuned correlation between superpotential parameters is needed

This mechanism can be implemented in Grand Unified Theories. The simplest SU(5) realization shows interesting features, such as an increase of the colour triplet mass, which delays proton decay

However, gauge-mediated contributions to the MSSM soft terms alone do not allow for an Higgs mass as high as 125 GeV unless the whole spectrum is heavier than 2-3 TeV. Supergravity contributions may however dominate, but then predictivity is lost.

More complicated unified models may evade this conclusion.