F-term Uplifting in Metastable Vacua at Finite Temperature

Chloé Papineau

DESY

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Outline

1. Motivations
2. The Intriligator-Seiberg-Shih model
3. Combining both setups
4. The model at finite temperature
5. Conclusions

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1. **Motivations**
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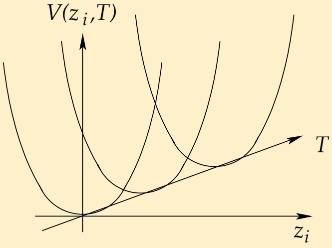
General framework

Supersymmetry breaking

- Spontaneous SUSY breaking ⇒ massless Goldstino.
  ↪ Break SUSY in a SUGRA context . At low energy, the soft breaking terms are parametrised by the gravitino mass (gravity mediation).
- SUGRA is non-renormalisable ⇒ String framework → Moduli stabilisation ?

Moduli

- Flat directions of the potential arising whenever one considers extra dimensions. Need to be stabilised.
- In string theory : make use of non-zero background fluxes + non-perturbative effects.



General framework

Dynamical SUSY breaking

- Consists of a spontaneous symmetry breaking.
- Relies on non-perturbative phenomena, typically a strong coupling regime.
- Allows to explain the generation of an intermediate scale (dimensional transmutation) particularly interesting for SUSY breaking :

$$\textit{Ex. :} \qquad M_{SUSY} \simeq M_P \exp\left(-\frac{8\pi^2}{b_0 g^2(M_P)}\right) \quad .$$

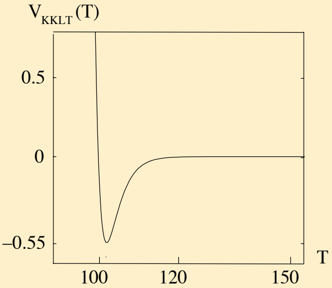
- Mechanisms naturally present in QCD $\hookrightarrow \Lambda_{QCD}$.
- For some moduli : only way to stabilise them.

The KKLT model : before uplift

hep-th/0301240

- Most of the moduli are stabilised by fluxes.
- The volume modulus T is partly stabilised by NP effects.
- The resulting potential is

$$K_1 = -3\ln\left(T+\overline{T}\right) \quad ,$$
$$W_1 = W_0 + ae^{-bT} \quad .$$



The minimum is supersymmetric and lies at $D_T W_1 = 0$.

Correspondingly,

$$V_{\rm min} = -\frac{a^2b^2e^{-2bT_0}}{6T_0} \sim -m_{3/2}^2 M_{\rm Pl}^2 < 0 \quad .$$

The modulus T has been stabilized but the resulting vacuum energy is negative → AdS vacuum.

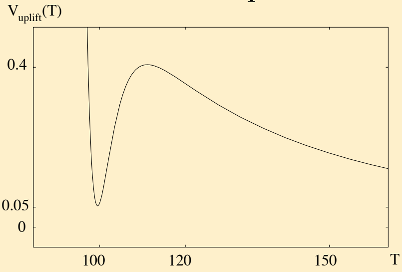
Uplifting the potential

The minimum needs to be uplifted to $V_{\min} \geqslant 0$. Adding an anti $D3$-brane far from where the SM fields stand produces a potential

$$V_{\text{lift}} = \frac{D}{\left(T + \overline{T}\right)^2}$$

where D can easily be fine-tuned in order to get a small positive cosmological constant because the x-dims are warped.

SUSY is explicitly broken
$\Rightarrow$ the effective theory cannot be put in a standard 4D supergravity form
$\hookrightarrow$ bad control on the theory.



Uplifting with F-terms

Dudas, CP, Pokorski ; Abe, Higaki, Kobayashi, Omura ; Lebedev, Lowen, Mambrini, Nilles, Ratz ; Postma *et al.*

We consider now a setup

$$\begin{aligned} K &= K_1(T) + K_2(\phi) \\ W &= W_1(T) + W_2(\phi) \end{aligned}$$

with $F^\phi = e^{K_2/2} K_2^{\phi\bar\phi} D_{\bar\phi}\overline{W}_2 \neq 0$. The scalar potential is

$$V = e^K \left[K^{T\overline{T}} D_T W D_{\overline{T}}\overline{W} + K^{\phi\bar\phi} D_\phi W D_{\bar\phi}\overline{W} - 3|W|^2 \right] \quad .$$

The two sectors are sufficiently decoupled to assume $D_T W_1 \simeq 0$ and $T \simeq T_0$. Therefore a zero cosmological constant is achieved if

$$\langle V \rangle \simeq 0 \quad \Rightarrow \quad e^{K_1} K^{\phi\bar\phi} F_\phi \overline{F}_{\bar\phi} \simeq 3 m_{3/2}^2 M_P^2 \quad .$$

$m_{3/2}$ is related to the ϕ-subsector parameters and can therefore be suppressed compared to the Planck mass : a small $m_{3/2}$ can be obtained.

Uplifting with F-terms

However, the point $T = T_0$ is slightly displaced, and one can show that the SUSY breaking is communicated to the modulus sector

$$F_T \simeq \frac{3}{2b\mathrm{Re}\,T} F_\phi \ll F_\phi$$

since, for a gravitino mass around the TeV, we find $bT_0 \simeq 30$.

Soft terms

Coupling to the MSSM in gravity mediation, one finds

- the soft scalar masses to be $m_0 \simeq m_{3/2} \sim$ TeV.
- the gaugino masses depend on the gauge kinetic function

$$M^a_{1/2} \propto \alpha_a F^T + \beta_a F^\phi \quad .$$

For generic α_a and β_a, again one has $M^a_{1/2} \simeq m_{3/2}$. If for some reason, $\beta_a \ll 1$, then F^T is dominant and the gaugino masses are suppressed.

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1 Motivations

2 **The Intriligator-Seiberg-Shih model**

3 Combining both setups

4 The model at finite temperature

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The ISS Model

hep-th/0602239

It is the magnetic dual of a SUSY-QCD theory and has N_f flavors and a gauge group $SU(N = N_f - N_c)$. It is perturbative at low energy if $N_f \geqslant 3N$.
The model is described by :

$$\begin{aligned} K_2 &= \operatorname{Tr}|\varphi|^2 + \operatorname{Tr}|\widetilde{\varphi}|^2 + \operatorname{Tr}|\Phi|^2 \quad , \\ W_2 &= h\operatorname{Tr}(\widetilde{\varphi}\Phi\varphi) - h\mu^2 \operatorname{Tr}\Phi \quad . \end{aligned}$$

The case $SU(N)$ ungauged

$N_f > N$ (i.e $N_c > 0$) $\Rightarrow$ the F-terms cannot all vanish : SUSY is broken and the vacuum energy is $|h^2\mu^4|(N_f - N)$.
The vev's of the fields are

$$\Phi_0 = 0 \quad , \quad \varphi_0 = \widetilde{\varphi}_0^T = \begin{pmatrix} \mu \mathbb{1}_N \\ 0 \end{pmatrix} \quad .$$

Tree-level masses and 1L masses are $\sim |h\mu|$ and $|h^2\mu|$.

The case $SU(N)$ gauged

The SUSY breaking vacuum is not modified since the gauge sector is not affected by the vev's.
If searching for $\langle\Phi\rangle \neq 0$, the quark flavours become massive and can be integrated out $\Rightarrow$ the low energy theory becomes UV free and after gaugino condensation :

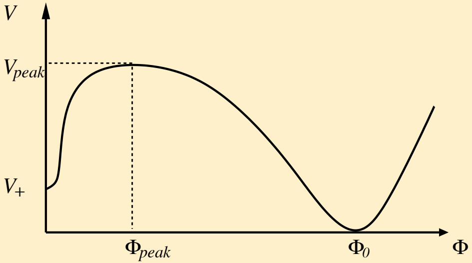
$$W_{low} \;=\; N\left(h^{N_f}\,\Lambda_m^{-\left(N_f-3N\right)}\;\det\Phi\right)^{1/N} \;-\; h\mu^2 \mathrm{Tr}\,\Phi \quad .$$

which leads to N supersymmetric vacua. The vev of Φ is

$$\langle h\Phi\rangle \;=\; \mu\,\epsilon^{-\left(N_f-3N\right)/\left(N_f-N\right)}\,\mathbb{1}_{N_f} \quad \text{where} \quad \epsilon = \frac{\mu}{\Lambda_m} \quad .$$

These vacua correspond to the vacua found in the UV description. The metastable vacuum, however, cannot be seen in the electric theory.

Low energy potential for SUSY-QCD with N_f flavors



The tunneling probability can be determined as

$$\Gamma \sim e^{-S_{\rm bounce}} \quad , \quad S_{\rm bounce} \sim \epsilon^{-4(N_f-3N)/(N_f-N)} \gg 1 \quad .$$

So taking $\epsilon \to 0$, i.e taking $\Lambda_m \to \infty$, the dynamical metastable vacuum can be made arbitrarily large.

Remark : $\mu \ll \Lambda_m \Longleftrightarrow m \ll \Lambda$

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ISS-KKLT : the potential

Dudas, CP, Pokorski

The model is simply

$$K = K_1 + K_2 = -3\ln(T+\bar{T}) + \mathrm{Tr}\,|\varphi|^2 + \mathrm{Tr}\,|\widetilde{\varphi}|^2 + \mathrm{Tr}\,|\Phi|^2 \,,$$
$$W = W_1 + W_2 = W_0 + ae^{-bT} + h\mathrm{Tr}\,(\widetilde{\varphi}\Phi\varphi) - h\mu^2\mathrm{Tr}\,\Phi \,,$$

We are considering a supergravity theory, thus the scalar potential is :

$$V = e^K \left[K^{T\overline{T}} D_T W D_{\overline{T}} \overline{W} + K^{i\bar{j}} D_i W D_{\bar{j}} \overline{W} \; - \; 3|W|^2 \right]$$

Since ISS and KKLT sectors are coupled only through gravitational effects, there should be a minimum close to the metastable vacuum χ_0^i and close to the KKLT vacuum. We expand V in powers of $\bar{\chi}_{\bar{i}}\chi^i / M_{\mathrm{Pl}}^2$ and get

$$V \simeq \frac{1}{(T+\bar{T})^3} V_{\mathrm{ISS}}(\chi^i, \bar{\chi}_{\bar{i}}) \; + \; V_{\mathrm{KKLT}}(T, \bar{T}) \; + \; \ldots$$

and, as usual $m_{3/2}^2 = |W|^2 \exp(K)$.

Improvements

Look for the vacuum inserting $\chi^i = \chi^i_0$ directly into V and asking for zero cosmological constant :

$$W_0 \ + \ \frac{ab(T_0 + \bar{T}_0)}{3} \, e^{-bT_0} \ = \ 0 \, ,$$

which gives T_0. Actually, T contributes to SUSY breaking :

$$F^T \ \simeq \ \frac{a}{(T_0 + \bar{T}_0)^{1/2}} \, e^{-bT_0} \, ,$$

but **this contribution is suppressed compared to F^Φ**.

Recall $\langle V_{ISS} \rangle = (N_f - N)|h^2 \mu^4|$. At zeroth order, the cosmological constant is

$$\Lambda \ = \ V_{KKLT}(T_0, \bar{T}_0) \ + \ \frac{(N_f - N) h^2 \mu^4}{(T_0 + \bar{T}_0)^3} \, .$$

Improvements - suite

Therefore the uplift is ensured by the ISS sector. Asking for $\Lambda = 0$ implies

$$3\,|W_0|^2 \;\sim\; h^2\,(N_f - N)\,\mu^4\,.$$

The gravitino mass is given by $m_{3/2} \sim W_0/(T_0 + \bar{T}_0)^{3/2}$, so in order to have it in the TeV range, we need a small μ, which is ensured from its dynamical origin (related to the dilaton S). And recall the lifetime of the metastable vacuum is longer as μ is smaller. Therefore, so far, for ungauged $SU(N)$, we have :

- uplifted the KKLT potential using the metastable vacuum of ISS ,
- obtained a small or zero cosmological constant ,
- broken SUSY ,
- obtained a TeV scale gravitino mass .

The supersymmetric vacua

We look for $\langle\Phi\rangle \neq 0$, which imply that the quarks become massive and can be integrated out. The vev $\langle\Phi\rangle$ is the same, but the minimum of the potential is now

$$V_0 \simeq -\frac{3}{(T_s+\bar{T}_s)^3}\left|W_0 - \frac{(N_f-N)\mu^3}{\epsilon^{(N_f-3N)/(N_f-N)}}\right|^2,$$

for the corresponding minimum for T_s.
The SUSY preserving vacua have turned into AdS. The bounce action is modified into :

$$S_{\text{bounce}} \sim \frac{(T_s+\bar{T}_s)^3}{\epsilon^{4(N_f-3N)/(N_f-N)}} \gg 1\,,$$

which increases the lifetime of the metastable vacuum compared to the ISS setup.

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Reminder

- The model is

$$
\begin{aligned}
K &= K_1 + K_2 = -3\ln(T+\bar{T}) + \mathrm{Tr}\left|\chi^i\right|^2 \,, \\
W &= W_1 + W_2 = W_0 + ae^{-bT} + h\mathrm{Tr}\left(\widetilde{\varphi}\Phi\varphi\right) - h\mu^2\mathrm{Tr}\,\Phi \,, \\
V &\simeq \frac{1}{(T+\bar{T})^3}\, V_{\mathrm{ISS}}(\chi^i, \bar{\chi}_{\bar{i}}) \;+\; V_{\mathrm{KKLT}}(T,\bar{T}) \,.
\end{aligned}
$$

- At zero temperature, the cosmological constant is zero when the ISS fields are in the metastable vacua.
- Far away in the ISS field space there are supersymmetric vacua. These are separated from the metastable vacua by a barrier.
- The origin of the ISS field space is a saddle point : it is a minimum in the mesons direction, and a maximum in the squarks direction.

Plan of the computation

We treat both sectors separately : we compute the relevant temperatures in the ISS field space by imposing $T = T_0$ stabilised. When we will turn to the modulus sector, we will consider that the ISS fields lie in the interesting minimum.

The relevant temperatures in the ISS sector

Fischler, Kaplunovsky, Krishnan, Mannelli, Torres

- The critical temperature of phase transition towards the metastable vacua (2^{nd} order)
- The temperature at which the supersymmetric vacua form
- The temperature of energy degeneracy between the origin and the SUSY vacua (1^{st} order)
- The temperature of energy degeneracy between the metastable and the SUSY vacua

Phase transition in the squarks direction

• At zero temperature, the origin is unstable in the squarks direction.
• At very high temperature, the origin is the only vacuum.

• When temperature lowers down, a tachyonic direction appears in the squarks direction.

We compute the masses in terms of the shifted fields, and compare the thermal masses and the tree-level masses

$$\mathcal{M}_1^{\Theta\,2} = \left(\partial V_1^{\Theta} / \partial\left(\varphi^2, \widetilde{\varphi}^2\right)\,\right)_{\varphi\,,\,\widetilde{\varphi}=0} \longleftrightarrow \pm h^2\mu^2 / \,\left(T_0 + \overline{T}_0\right)^3 \,.$$

Asking for the determinant of the total one-loop mass matrix to be zero, $\det \mathcal{M}^{\Theta} = 0$, one finds the critical temperature to be

$$\Theta_c^2 \;=\; \mathcal{O}\left(\left|\mu^2\right|\right) \;\sim\; \left(4 \cdot 10^{-7} M_P\right)^2 \quad .$$

The formation of the SUSY vacua

SUSY vacua $\hookrightarrow$ take into account the NP term

$$W_{\rm dyn} = N \left(h^{N_f} \, \Lambda_m^{-\left(N_f - 3N\right)} \, \det \Phi \right)^{1/N} .$$

<u>But</u> valid at low energy $\ll m_{\varphi,\tilde{\varphi}} \sim \langle h\Phi / T^{3/2} \rangle \Rightarrow$ for temperatures $\Theta \ll m_{\varphi,\tilde{\varphi}}$.

Expanding $W_{\rm dyn}$ around a diagonal vev $\Phi = \Phi_0 \mathbb{1}_{N_f} + \phi$ alows to compute exactly the temperature of formation $\Theta_{\rm susy}$.

However, $\Theta_{\rm susy}$ depends on the Landau scale Λ_m of the theory. Numerical results show that

$$10^4 \leqslant \Lambda_m \leqslant 10^{15} \quad \Longrightarrow \quad 1.5 \cdot 10^{-8} \leqslant m_{\varphi,\tilde{\varphi}} \leqslant 7.4 \cdot 10^{-6} \quad .$$

These masses for the squarks are already smaller than the critical temperature $\Theta_c \sim 10^{-7}$. The SUSY vacua form after the metastable ones.

Degeneracy temperatures

They are found from comparing the vacuum energies between the different local minima :

• the fields can go from the origin to the SUSY vacua for temperatures lower than

$$\Theta^2_{\text{origin}-\text{SUSY}} \simeq \mathcal{O}\left(\frac{h\mu^2}{(T_0+\overline{T}_0)^{3/2}}\right) \quad ,$$

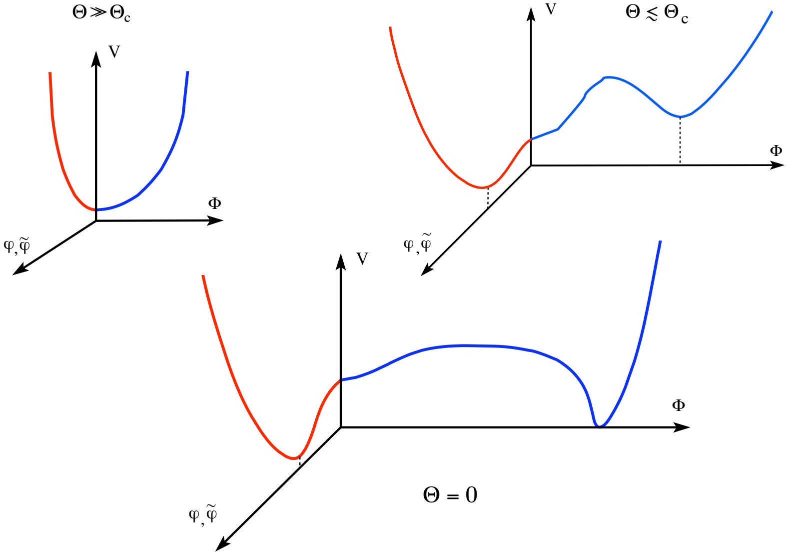
• the fields can go from the metastable to the SUSY vacua for temperatures lower than

$$\Theta^2_{\text{metastable}-\text{SUSY}} \simeq \mathcal{O}\left(\frac{h\mu^2}{(T_0+\overline{T}_0)^{3/2}}\right) \sim \left(7 \cdot 10^{-9} M_P\right)^2 \quad .$$

Both temperatures are $\ll \Theta_c^2$ due to their dependence in T_0.

The whole picture in the ISS sector

Fischler, Kaplunovsky, Krishnan, Mannelli, Torres

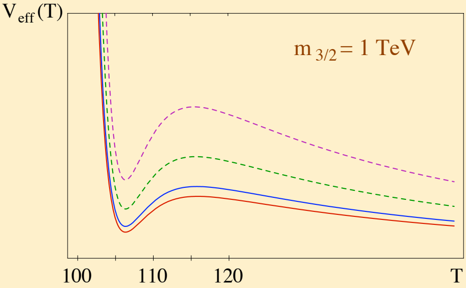


Modulus destabilisation

Buchmüller, Hamaguchi, Lebedev, Ratz

The modulus does not thermalise because it interacts very weakly with the thermal bath (ISS, MSSM).
However, its potential receives FT corrections through the term $\sim V_{\text{ISS}} / (T + \overline{T})^3$ at lowest order in supergravity.

In order for the model to be valid, the destabilisation temperature has to satisfy $\Theta_{\text{destab.}} \gg \Theta_c$. In this case, the fields ISS sit at the origin.



Our analysis $\Rightarrow$ there is no destabilisation at all !!

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Conclusions

At zero temperature

We have combined the KKLT and the ISS models and got

- the stabilisation of all moduli ,
- a dynamical SUSY breaking in a long-lived vacuum of tuned zero energy ,
- a low gravitino mass.

Temperature evolution

- the modulus is not destabilised by FT corrections,
- the ISS fields do end up in the metastable vacua,
- the tunnelling becomes possible at a very low temperature, which ensures the long lifetime.

Challenges

- Problem of overshooting, dynamics,
- Inflation.