Moduli stabilization in (string) model building: gauge fluxes and loops

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Introduction: the string-pheno paradigma

- Low energy string theory: d=10, $\mathcal{N}$=I/II SUGRA.
- Necessary a compatification on a 6d space K, such that SUSY is reduced to $\mathcal{N}$=1 in 4d.

The choice of K:

I - Topological properties
$\rightarrow$ "topological" properties of the 4d model;

II - Metric properties (Size & Shape)
$\rightarrow$ "parameters" of the 4d model.

Point: I - Size & Shape are vev's of dynamical fields;
II - Flat potential at tree-level.

Which control on the phenomenology of the model?

- More in general we have to choose a *background* for all the 4d scalars (internal components of metric, p-forms ...)

Non-trivial background for the closed string p-forms wrapped in the internal space (IIB Strings)

→ Stabilization of shape (complex structure) moduli.

Giddings, Kachru, Polchinski '01

→ In case there is a *single* size (Kähler) modulus extra effects (gaugino condensation) can fix it.

Kachru, Kallosh, Linde, Trivedi '03

The minimal option is very specific:

an extension is necessary.

Include the effect of

- gauge (open string) fluxes → D-term stabilization;
- loop corrections;
- α' corrections.

Task & Outline

Study of the effects due to
gauge fluxes and loop corrections
in a 6d toy model

I - Review of the KKLT proposal:
- basic ingredients (fluxes & gaugino condensation)
- the sequestered "uplifting" sector.

II - Realization and extension (two Khäler moduli) from 6d perspective.
- 6d SUGRA + SYM compactified on T^2/Z_2 ;
- Scherk-Schwarz mechanism as a source of W_0 ;
- The presence of gauge fluxes: D-term potential;
- Loop corrections;
- The complete potential: complete stabilization.

The KKLT proposal: basic issues

Kachru, Kallosh, Linde, Trivedi '03

- Take a compactification of Type IIB string on a CY with a single Kähler modulus S.

- Include closed string fluxes

  ➞ stabilization of complex structure moduli, that can be integrated out. A constant superpotential term W_0.

- Include non-perturbative effects (gaugino condensation)

$$W = W_0 + e^{-S}$$

  ➞ stabilization of S at a SUSY AdS minimum, with

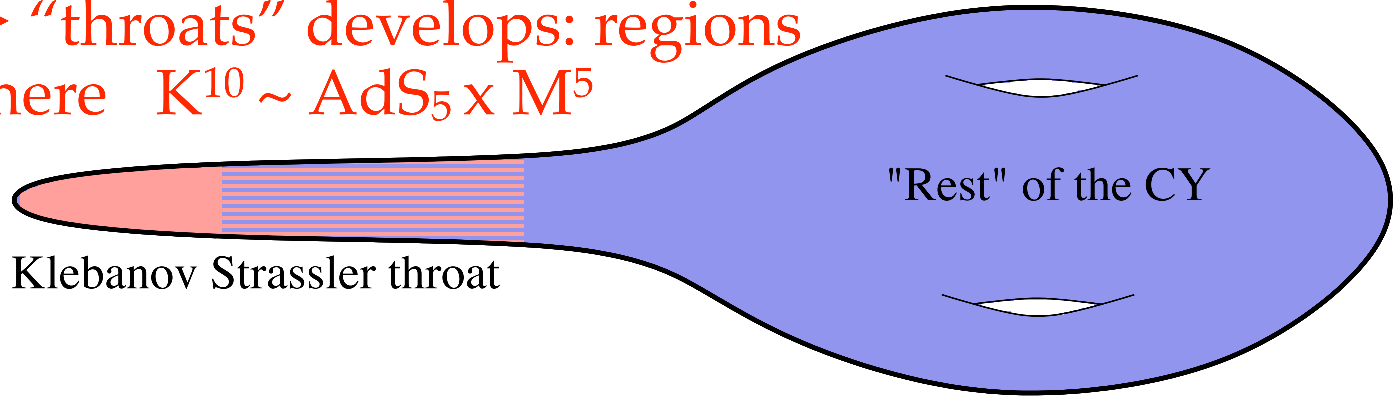
$$S > 1, \qquad V_{Min} \sim -|W_0|^2.$$

- Include a SUSY breaking mechanism

  ➞ SUSY breaking and "uplifting" of the minimum.

The uplifting sector: sequestering in the throat

- The flux modifies the geometric background:
  → "throats" develops: regions
  where $K^{10} \sim AdS_5 \times M^5$



- The AdS_5 can be seen as a realization of the Randall-Sundrum model: use the same language.
- The bottom of the throat (IR brane) is sequestered from the rest of the space, the top of the throat or UV brane, that is the visible brane.
- The details of the SUSY breaking sector are invisible in the visible sector: the SUSY breaking sector can be modelled in *any* way, the visible effects are just the same.

Choi, Falkowski, Nilles, Olechowski; Lebedev, Nilles, Ratz; Brümmer, Hebecker, MT., ...

6d SUGRA

- The bosonic 6d action is Nishino, Sezgin ‘86

$$(-g_6)^{-\frac{1}{2}}\mathcal{L} = -\frac{1}{2}\mathcal{R} - \frac{1}{2}\partial_M\phi\partial^M\phi - \frac{1}{24}e^{2\phi}H_{MNP}H^{MNP} - \frac{1}{4}e^{\phi}F_{MN}F^{MN}$$

with

$$H_{MNP} = \partial_M B_{NP} + F_{MN}A_P + \text{cyclic perm.} = (dB + F\wedge A)_{MNP}$$

and is invariant under the gauge transformations

$$\delta A = d\Lambda, \qquad \delta B = -\Lambda F + dC$$

where Λ is a scalar and parametrizes the "F" gauge symmetry and C is a 1-form and parametrizes the "B" gauge symmetry.

This action can be seen as the outcome of a K3 compactification of string theory, in case the internal moduli fields are neglected.

Compactification to 4d: effective SUGRA

- We can consider a compactification on an internal T^2/Z_2.

$$(g_6)_{MN} = \begin{pmatrix} r^{-2}(g_4)_{\mu\nu} & 0 \\ 0 & r^2(g_2)_{mn} \end{pmatrix}, \quad (g_2)_{mn} = \frac{1}{\tau_2}\begin{pmatrix} 1 & \tau_1 \\ \tau_1 & |\tau|^2 \end{pmatrix}$$

the dimensional reduction produces the following fields
- 4d metric g_4 + internal metric components r, τ_1, τ_2;
- 4d B field, i.e. one scalar c + internal $B_{56} = b$;
- 4d gauge field F;
- dilaton.

- g_4 and F fill the standard 4d SUGRA/SYM action;
- the scalars are organised in 3 chiral multiplets, S, T, τ, with Kähler potential

$$K = -\log(S+\bar{S}) - \log(T+\bar{T}) - \log(\tau+\bar{\tau})$$

- the gauge kinetic function is $2S$.

Scherk-Schwarz mechanism: a source for W_0

- R-Symmetry in 6d SUGRA

Let 6d SUGRA be defined as a compactification of 10d SUGRA

- T^4 compactification: the 10d Lorentz group is broken as

$$SO(1,9) \longrightarrow SO(1,6) \times \boldsymbol{SO(4)}_R.$$

- K3 compactification:
  - consider K3 ~ T^4/Z_n for simplicity
  - let $SO(4)_R = SU(2)_{R1} \times SU(2)_{R2}$
  - take Z_n in $SU(2)_{R1}$ $\longrightarrow$ $SU(2)_{R1}$ is broken but $SU(2)_{R2}$ remains as an active R-symmetry!

- SS compactification of 6d SUGRA

Consider a generic bulk field Φ and define

$$\Phi(x^5+2\pi, x^6) = T_5\Phi(x^5, x^6),\ \ \Phi(x^5, x^6+2\pi) = T_6\Phi(x^5, x^6)$$

with T_5 and T_6 being $SU(2)_R$ operators.

In case one of the matrices is non-trivial

$\longrightarrow$ SS compactification

Dudas, Grojean '97;
Barbieri, Hall, Nomura ...;

- Consistency conditions: T^2 compactification

T_i is the embedding in $SU(2)_R$ of the translation t_i along x^i.
Since $t_5\, t_6 = t_6\, t_5$ we need $T_5\, T_6 = T_6\, T_5$.

- Consistency conditions: T^2/Z_N compactification

In case of an orbifold, also the orbifold rotation r is embedded into the R-symmetry group, via a matrix R. Such a matrix is *fixed* (up to discrete choice) by the requirement of having SUSY in the 4d model, and is *non-trivial*.

Again, the commutation relations of t_5, t_6, and r define commutation relations for T_5, T_6, and R. These are non-trivial, since R is non-trivial.

In case a solution exists with T_5 and/or T_6 non-trivial

$\longrightarrow$ SS compactification

If then the non-trivial T's can be chosen in a "continuos" way, linked to the identity, then the breaking is described by a constant superpotential term W_0.

Such is the case in T^2/Z_2 compactifications ... Lee '05

... and only in this case in the 2d case.

Gauge background: D-term potential

- We can consider a constant background $F_{56} = f$.
- The fields A^5, A^6 are not globally defined:

$$A(z+\pi) = A(z) + d\Lambda_0$$

- Thus also B_{56} is not globally defined: since $H = dB + F \wedge A$ and H is gauge invariant, it follows $B(z+\pi) = B(z) - \Lambda_0 F$, thus both A and B have a non-trivial profile in the internal space.
- In order to single out the zero modes of A and B we
  - a) define $A = \langle A \rangle + \mathcal{A}$, splitting the background field, not globally defined, from the "quantum fluctuations", globally defined and with standard constant zero-mode (standard KK massless state);
  - b) redefine the field B as $B = \mathcal{B} + \langle A \rangle \wedge \mathcal{A}$ so that the new field $\mathcal{B}$ is also globally defined with ....

Kaloper, Myers '99; Villadoro PhD Thesis '06

- Given the redefinition:

$$\delta\mathcal{B}_{56} = -2\Lambda f$$

→ $\mathcal{B}$ transforms (as expected)

→ the gauge transformation is the double of what one would naively expect from $H = dB + F \wedge A$

- The "new" SUGRA is exactly the old one, provided that one redefines the field $b = B_{56}$ as $b = \mathcal{B}_{56}$. In this way the field T, whose imaginary part is b, transforms under the gauge transformation.

- Given such a transformation we can infer the D-term potential $D = i\, K_I\, X^I$, where X^I is the Killing vector, in the present case being $X^T = -i\, f$.

- Thus we have $D = f\,/\,t$, and $V_D = \dfrac{f^2}{2st^2}$.

- We can compute the potential also directly from the F^2 term in the lagrangian, the two results coincide.

D-term + W_0 + gaugino condensation : a clash?

- Take the KKLT model
  - single modulus S
  - superpotential $W = W_0 + e^{-S}$

- Can we use a D-term potential to break SUSY and uplift the AdS minimum? No, for two reasons:

I - The D-term is associated with a gauge transformation involving one modulus. If there is only S then it must transform, but this is incompatible with $W = W_0 + e^{-S}$.

Choi et al.; Dudas, Vempati; Villadoro, Zwirner

- Present case: no clash! The field transforming is T, and the field entering the gaugino condensation term is S.

see also Haack et al. '06 for a realization with D7-branes

(other way out: $A(M)\, e^{-S}$ Achucarro et al; Dudas et al; Haack et al....)

II - D-terms and F-terms are related, and it is impossible to uplift a SUSY minimum (F = 0) via a D-term.

- Present case: no clash! The minimum with non-zero D-term is non-SUSY: F_T is not zero! (but no uplift ...)

Loop corrections

- We can introduce in the system bulk fields (hypers) charged under the U(1) gauge group.
- These fields have a standard KK reduction in absence of a gauge background.
- In the presence of a gauge background the KK reduction is deeply modified:

Bachas '95

$$m_n^2 = \frac{2|f|}{r^4}\left(n + \frac{1}{2}\right) \quad \text{for bosons,}$$

$$m_n^2 = \frac{2|f|}{r^4}\left(n + \frac{1}{2} \pm \frac{1}{2}\right) \quad \text{for fermions,}$$

and the degeneracy can be deduced via the Dirac index:

$$d_n = f\,/\,(2\pi) = N$$

- From the 4d spectrum the 1-loop potential follows

$$V_{loop} = \frac{\alpha |f|^3}{(2\pi)^3 (st)^2}$$

The complete potential: stabilization

Ingredients:

I - $W = W_0 + e^{-S}$ (from SS twist and gaugino condensation)

II - D-term potential $V_D = \dfrac{f^2}{2st^2}$

III - Loop corrections $V_{loop} = \dfrac{\alpha|f|^3}{(2\pi)^3(st)^2}$

Step 1:

Neglect t and include only I: $\rightarrow$ KKLT potential in $S, \tilde{V}(s)$

s fixed in a SUSY AdS minimum

Step 2:

Include t $\rightarrow$ $V = \tilde{V}(s)/t$ runaway behaviour in t

Step 3:

Include the D-term (II) $\rightarrow$ stabilization of t in a non-SUSY AdS minimum

Step 4:

Include the loop effect (III) $\rightarrow$ no destabilization (but also no uplift)

Conclusions

- We have shown the role of gauge fluxes/D-terms in the stabilization of a 6d SUGRA model, that can be seen as a non-trivial extension of the KKLT model.
  - No clash D-term vs $W = W_0 + e^{-S}$: extra modulus!
  - D-term crucial in the stabilization the extra modulus.
  - No uplifting via the D-term.

- Computed the 1-loop corrections to the potential, and re-cast them as corrections to the Khäler potential.
  - No de-stabilization of the minimum.
  - No uplifting.

- "By-product": we considered SS compactification in 2d as a source for W_0
  - Possible for T^2 or T^2/Z_2 compactifications;
  - Not possible for T^2/Z_N compactifications.