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

→ "topological" properties of the 4d model;

II - Metric properties (Size & Shape)

→ "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?

A minimal option: the KKLT proposal:

I - Introduce fluxes for the closed string p-forms

→ Stabilization of shape (complex structure) moduli.

Giddings, Kachru, Polchinski '01

II - Introduce non-perturbative corrections (gaug. cond.)

→ Stabilization of the volume (Kaehler) moduli;

Kachru, Kallosh, Linde, Trivedi '03

"minimal" option: there is a single Kaehler modulus.

The minimal option is very specific:

extend to more Kaehler's, introduce new effects

Include the effect of

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

Task & Outline

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

I - Brief review of the KKLT proposal:

II - 6d SUGRA as a playground to “test” extensions of KKLT (two Kaehler moduli)

- 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;
- Discussion (the 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)

$$W = W_0 + e^{-S}, \quad K = -\log(S + \bar{S})$$

  → 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.

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

$$SO(1,9) \rightarrow SO(1,6) \times \mathbf{SO(4)}_R.$$

- 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 $SU(2)_{R1}$ $\rightarrow$ $SU(2)_{R1}$ 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

$\rightarrow$ 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

→ 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 ...)

Model independent features

I - The outcome

existence of 2 moduli, one governing the gaugino condensation, the other governing the D-term potential (S: coupling, T: volume)

is generic in KKLT model building (D7-branes)

Haack et al '06

II - The need for extra stabilization mechanisms (other than gaugino condensation) is generic:

Given T the volume of a cycle wrapped by a D7-brane where the SM is located, generically

$$W_{non\ pert.} \sim \prod_i \Phi^i_{SM}\, e^{-T}$$

➞ T cannot be stabilized by perturbative effects

Blumenhagen, Moster, Plauschinn '07

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

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

Loop corrections as Kaehler corrections

- The effect of the loop corrections can be rephrased in SUGRA language → Kaehler corrections

$$\Delta K \sim \frac{1}{S + \bar{S}} \, log(T + \bar{T})$$

- These corrections are generically present in string compactifications

Hebecker, von Gersdorff '05;
Berg, Haack, Koers '05.

and may have a role in moduli stabilization (not really in the present situation).

The complete potential: stabilization

Potential: function of s=Re[S], t=Re[T], c=Im[S], τ.

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

$$\rightarrow V_{gaugino} = \frac{1}{st}\left((s^2 + 2s)e^{-s} - 2|W_0|se^{-s/2}\right) = \frac{V_{KKLT}}{t}$$

II - D-term potential

$$\rightarrow V_D = \frac{f^2}{2st^2}$$

III - Loop corrections

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

Parametric study of the stabilization:

I - V_{KKLT} stabilizes s (W_0 vs gaugino cond.),

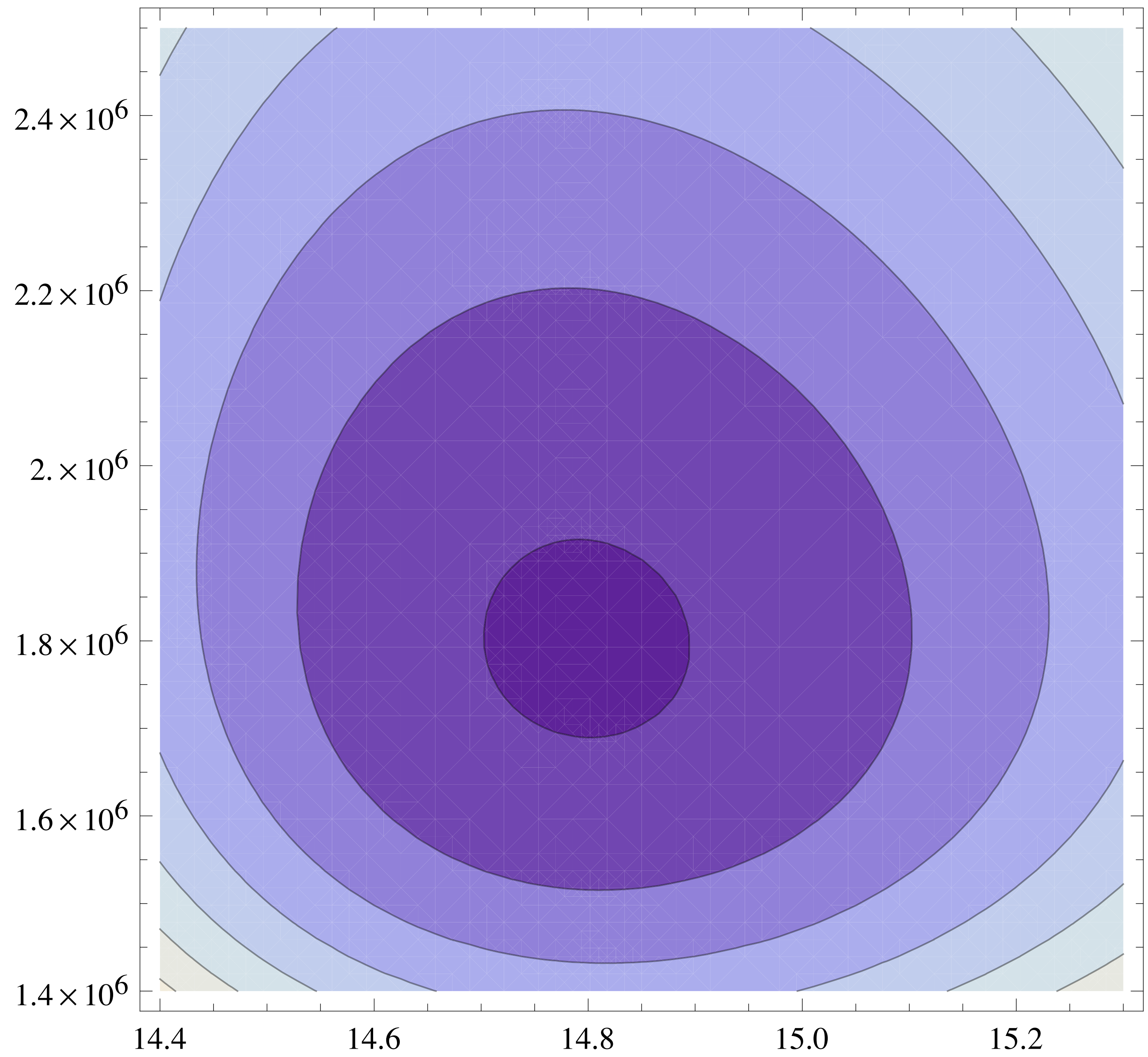
$s_m \sim O(2\log[1/W_0]) \rightarrow s_m \sim O(10)$ for $W_0 \sim 10^{-2}$

II - $V(s_m,t) = -\,O(W_0^2/s_m)\, t^{-1} + O(10^2/s_m)\, t^{-2} + O(1/s_m^2)\, t^{-2}$

- Stabilization of t via the D-term potential,

  $t_m \sim 100\, W_0^{-2} \rightarrow t_m \sim O(10^6)$ for $W_0 \sim 10^{-2}$
- Perturbative corrections irrelevant (s-suppressed)

The minimum: $W_0 \sim 10^{-2}$



$t \sim 10^6$

$s \sim 15$

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.

Outlook

- Pure 6d perspective: stabilization of the complex structure modulus;

- Stabilization in the presence of partial D-term cancellation:
    - the role of "matter moduli";
    - the role of more general Kaehler corrections (no S-suppression);

- A complete realistic model!