Title: Phenomenological aspects on N=1, four-dimensional Type IIB string theory compactifications with all moduli stabilised

Date: Mar 28, 2006 11:00 AM

URL: http://pirsa.org/06030023

Abstract: I will discuss phenomenological aspects on N=1, four-dimensional Type IIB string theory compactifications with all moduli stabilised. In particular, I will review a class of compactifications with exponentially large volumes of the Calabi-Yau manifold and derive explicit formulae for bulk and D3/D7 moduli masses. Then I will show what patterns of soft supersymmetry breaking terms can arise after renormalisation group running to the weak scale.

PHENOMENOLOGY OF TYPE IIB COMPACTIFICATIONS WITH ALL MODULI STABILISED

KERIM SURULIZ
UNIVERSITY OF CAMBRIDGE

BASED (MOSTLY) ON
hep-th/0512081
(w/ B. ALLANACH & F. QUEVEDO)
AND PREVIOUS WORK w/
J. CONLON, F. QUEVEDO

OUTLINE

- (soft) SUSY breaking, moduli fixing (KKLT)
- Large volume compactifications
- Moduli spectrum, soft terms
- List of possible scenarios
- RGE analysis, phenomenological constraints
- Conclusions.

Hierarchy problem $\rightarrow$ Low energy SUSY.

SUSY breaking. Parametrised by

$$\mathcal{L}_{soft} = -m^2_{ij}\phi_i\phi^*_j - \left(\frac{1}{3!}A^{ijk}\phi_i\phi_j\phi_k + \frac{1}{2}B^{ij}\phi_i\phi_j + \right.$$
$$\left. + \frac{1}{2}M^a\lambda_a\lambda_a + \text{h.c.}\right)$$

Soft terms $\rightarrow$ do not reintroduce quadratic divergences.

Fermion masses forbidden by gauge invariance.

Soft terms from string theory / SUGRA?

$N=1$ SUGRA

$$\begin{cases} \text{Bulk moduli} \\ \text{Matter living on branes} \end{cases}$$

SUSY broken in moduli sector

$\hookrightarrow$ mediated to visible sector.

Strategy until recently:

$\boxed{\text{Assume}}$ SUSY broken

moduli fixed

$\Lambda \approx 0$

Hard to find microscopic mechanisms for these.

Flux compactifications!

GKP/KKLT.

Fluxes freeze complex structure moduli + dilaton.

$$W = \int G_3 \wedge \Omega$$

Integrate these out, $W \to W_0$.

SUSY broken.

Include nonperturbative effects to fix remaining (Kähler) moduli.

$$W = W_0 + A e^{-aT}$$

$D_T W = 0 \to$ T fixed, SUSY restored!

SUSY broken in moduli sector
↳ mediated to visible sector.

Strategy until recently:

$\boxed{\text{Assume}}$ SUSY broken
moduli fixed
$\Lambda \approx 0$

Hard to find microscopic mechanisms for these.

Flux compactifications!

GKP / KKLT.

Fluxes freeze complex structure moduli + dilaton.

$$W = \int G_3 \wedge \Omega$$

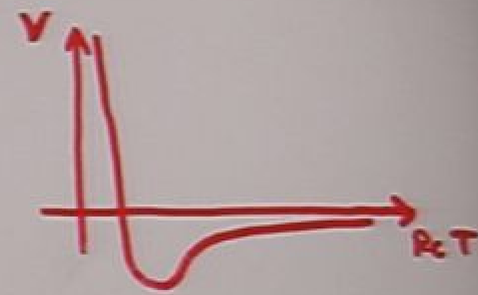
Integrate these out, $W \to W_0$.
SUSY broken.

Include nonperturbative effects to fix remaining (Kähler) moduli.

$$W = W_0 + A e^{-aT}$$

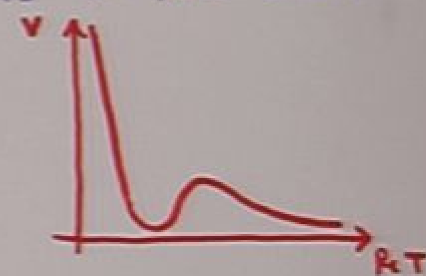
$D_T W = 0 \rightarrow T$ fixed, SUSY restored!

SUSY AdS minimum



Lift cosmological constant
using $\overline{D3}$s at bottom of warped throat.
(possibly also magnetized D7s or IASD fluxes)

D-term SUSY breaking
$\rightsquigarrow$ also F-term



Can we get the soft breaking terms?
Difficult, since

- stability must be checked explicitly
- all F-terms vanish before lifting
- Calabi-Yau volume $\mathcal{V} \sim |\ln W_0|$

$\Rightarrow W_0$ must be extremely small.

Lowest W_0 in explicit examples $\sim 10^{-4}$.

Alternative ?

Use perturbative α' as well as nonperturbative corrections. (Balasubramanian, Berglund, Conlon, Quevedo)

Find tachyon-free large volume minima.

No need to fine-tune W_0.

All moduli stabilised in a nonSUSY AdS minimum.

Finding spectrum, moduli + D3/D7 matter fields, should be possible.

Working example $\mathbb{P}^4_{1,1,1,6,9}$ $\left.\begin{matrix} h^{1,1}=2 \\ h^{2,1}=272 \end{matrix}\right\}$

$\mathcal{V}$ large parameter $\longrightarrow$ drop $O(1)$ contributions to masses etc.

Use standard $N=1$ SUGRA approach to find masses.

Kähler potential

$$K \sim -2\ln\Big(\underbrace{\mathcal{V} + \frac{\xi g_s^{3/2}}{2e^{3\phi/2}}}_{\alpha'\text{ correction}}\Big) - \ln(\overbrace{S+S^*}^{\text{dilaton}}) - \underbrace{\ln\Big(-i\int \Omega\wedge\bar{\Omega}\Big)}_{\text{complex structure}}$$

Superpotential

$$W \sim \int G_3 \wedge \Omega + A_4\, e^{-a_4 T_4} + A_5\, e^{-a_5 T_5}$$

T_4, T_5 Kähler moduli.

Can now find scalar potential

$$V = e^K \left(K^{i\bar{j}} D_i W\, \overline{D_j W} - 3|W|^2 \right)$$

+ kinetic terms

$\longrightarrow$ (bulk) moduli masses.

T_4 small, T_5 large.

Find

$$m_{\frac{3}{2}} \sim \frac{1}{\mathcal{V}} \quad , \quad m_S, m_{c.s.} \sim \frac{1}{\mathcal{V}}$$

$$m_{T_4} \sim \frac{1}{\mathcal{V}} \quad , \quad m_{T_5} \sim \frac{1}{\mathcal{V}^{3/2}}$$

Important to note $m_{KK} \gg m_{3/2}$

so effective SUGRA valid.

Also, string scale $\sim \frac{1}{\sqrt{\mathcal{V}}}$.

$\boxed{\text{Brane moduli}}$

D3 branes. Scalar fields corresponding to movement in transverse directions.

Massless in no-scale approximation!

No-scale broken by α' and np effects.

Need F-terms

Kähler potential

gauge kinetic function for gaugino masses

$$\boxed{F^{i} = e^{K/2} K^{i\bar{j}} D_{\bar{j}} W}$$

$$F^{4} \sim \frac{1}{\mathcal{V}} + \frac{1}{\mathcal{V}} \qquad F^{S} \sim \frac{1}{\mathcal{V}^2}$$

$$F^{5} \sim \frac{1}{\mathcal{V}^{4/3}} + \underbrace{\frac{1}{\mathcal{V}^{4/3}}}_{\text{nonperturbative contribution}} \qquad F^{z} = 0$$

Kähler potential $K = -2\ln\left(\mathcal{V} + (\alpha' \text{ corr})\right) + \cdots$

but with

$$T_\alpha = \underbrace{\tau_\alpha + i\rho_\alpha}_{\text{old } T_\alpha} + i\mu_3 \ell^2 (\omega_\alpha)_{i\bar{j}}\, \phi^i \left(\bar{\phi}^{\bar{j}} - \frac{i}{2}\bar{U}^{\hat{l}}(\hat{\lambda}_\alpha)^{\bar{j}}_{l}\, \phi^l\right)$$

Expand K in terms of the ϕ^i.

Calculate masses using

$$m_i^2 = m_{3/2}^2 + V_0 - F^m \bar{F}^{\bar{n}} \partial_m \partial_{\bar{n}} \log \tilde{K}_i$$

Similar formulae for A_{ijk}, $\hat{\mu}$, B_{ij}.

Gaugino masses:

$$f = \frac{S}{2\pi} \quad \text{for D3 branes}$$

$$\longrightarrow M = \frac{1}{2}(\mathrm{Re}\, f)^{-1} F^m \partial_m f \sim F^S \sim \frac{1}{\mathcal{V}^2}$$

(small!)

Also $m_i \sim \dfrac{1}{\mathcal{V}^{7/6}}$

Suppressed by $\mathcal{V}^{-1/6}$ wrt $m_{3/2}$.

D7 branes

Fixed already by fluxes — easily seen from F-theory perspective.

Expect D7 moduli masses $\sim m_{3/2}, m_{cs}$.

Confirmed by explicit calculation

$$K = -\log\left(S + S^* + \underbrace{2i\mu_7 f_{A\bar{B}}\zeta^A\bar{\zeta}^{\bar{B}}}_{\text{D7 part}}\right) - \dots$$

$$m_\zeta \approx m_{3/2}$$

Similarly gaugino masses $\sim m_{3/2}$

(for D7s $\quad f = \frac{1}{2\pi} T$)

Wilson line moduli $\quad m_w \sim \frac{1}{\mathcal{V}^{7/6}} \sim \mathcal{V}^{-1/6} m_{3/2}$

but generically not present.

NB have to wrap one of the small 4-cycles of standard model on D7s, otherwise $g_{YM}^{-2} = \mathrm{Re}\, f \approx 0$.

D3 – D7 strings.

Exact Kähler potential unknown, but can argue masses are $\sim \frac{1}{\mathcal{V}^{7/6}}$ by comparison with toroidal compactifications.

D – term contributions also present due to lifting term.

Effect of these small because

$$V_{AdS} \sim -\mathcal{O}\left(\frac{1}{\mathcal{V}^3}\right)$$

so that $D \sim \frac{\varepsilon}{\mathcal{V}^2}$ itself is small.

Anomaly mediated contributions

Always present, have to be taken into account for certain parameters + ranges of string scale.

scalar mass $m \sim b_0 \left(\frac{g^2}{16\pi^2}\right) m_{3/2}$

for D3s had $m \sim \mathcal{V}^{-1/6} m_{3/2}$.

Gauginos $m \sim \frac{1}{\mathcal{V}^2}$ before $\Rightarrow$ AMSB dominants, mainly.

The anomaly mediated contribution to gaugino masses on D3s actually subleading to $\frac{1}{\mathcal{V}^2}$,
due to mixing with moduli mediation
(super-Weyl, Kähler, σ-model anomalies) (Bagger / Poppitz)
Free parameters: W_0 and $\mathcal{V}$.
Three major scenarios

1) MSSM on D7s, various string scales.

2) MSSM on D3s with intermediate string scale

3) MSSM on D3s with GUT string scale

We analyse each of these in turn.

Scenario 1:

$$m_{3/2} \sim M, \quad A = -3M, \quad m_0 = |M|, \quad B = -2M$$

By tuning W_0 can vary M leaving the string scale fixed.

Perform a Renormalisation Group (**RG**) analysis:

predictions for the soft parameters hold at string scale, must evolve down to M_Z.

Used **SoftSUSY** (B. Allanach).

Which RGEs? If $M_{string} = M_{GUT}$, those of MSSM.

If M_{string} lower, might need extra matter at lower scale ($\sim 1\,\text{TeV}$) to achieve gauge unification.

However, can avoid this with

- branes at (certain) singularities
- magnetised branes
- stringy threshold corrections...

So try both.

For $M_{string} \sim 10^9\,\text{GeV}$ get stop LSP.

$\rightarrow$ no natural dark matter candidate (maybe moduli)

- must have R-parity violation, otherwise anomalously heavy isotopes.

EWSB. (μ, B) traded for $(\tan\beta, \tilde{m}, \mathrm{sgn}\,\mu)$

$$\left.\begin{aligned} \mu^2 &= \frac{-\tilde{m}^2_{H_1}\tan^2\beta + \tilde{m}^2_{H_2}}{\tan^2\beta - 1} - \frac{1}{2}M_Z^2 \\ \mu B &= \frac{1}{2}\sin 2\beta\left(\tilde{m}^2_{H_1} + \tilde{m}^2_{H_2} + 2\mu^2\right) \end{aligned}\right\} \text{at scale } \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

Scan over $\tan\beta$, evolve to M_{string}.

Cannot satisfy $B = -2M \longrightarrow$ leave μ, B free.

Impose constraints on the models:

- $b \to s\gamma$ branching ratio
- non-SM contribution to anomalous magnetic moment of the muon (prefers $\mu > 0$)
- Higgs mass (prefers bigger $\tan\beta$)
- WMAP constraint on relic density of dark matter Ωh^2 (if neutralino LSP)

This is done using **micrOmegas** interfaced with **SoftSUSY**. (highly constraining, but assumes a lot – cosmological model etc.)

Scan over M, $\tan\beta$, M_{string} (and sgn μ).

For larger string scales ($\gtrsim 10^{12}$ GeV)

possible to satisfy all the constraints.

Results do not alter significantly if assumption of gauge unification dropped.

Complete spectra can be produced.

---

2) D3 branes – $m_g \sim \frac{1}{\mathcal{V}^2}$

$$\tilde{m} \sim \frac{1}{\mathcal{V}^{7/6}}$$

large $\mathcal{V} \to$ split SUSY.

Need also large A-terms to be able to generate reasonable gaugino masses through RG flow. They enter at 2-loop level

$$\frac{d}{dt} M = \frac{2g^2}{16\pi^2} b M + \frac{2g_a^2}{(16\pi^2)^2}\left(\ldots + \sum \mathrm{tr}\,(Y^{+}h)\right)$$

Yukawa coupling

trilinear scalar (A-term)

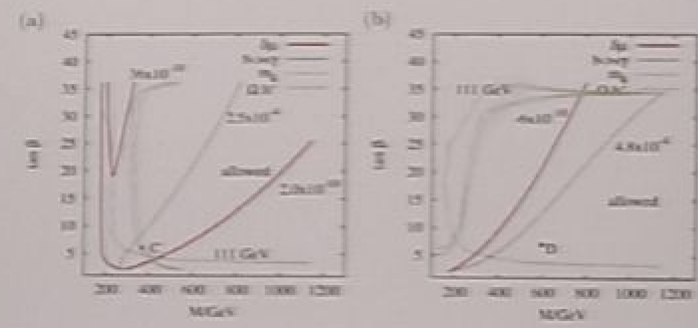


Figure 4: Contour plots of δa_μ, $BR(b \to s\gamma)$ and Ωh^2 on $\tan\beta$ and M for (a) $\mu > 0$ and (b) $\mu < 0$ and $m_\nu \sim 10^{12}$ GeV. 2σ bounds are used for $\mu > 0$ while 3σ ones are used for $\mu < 0$.

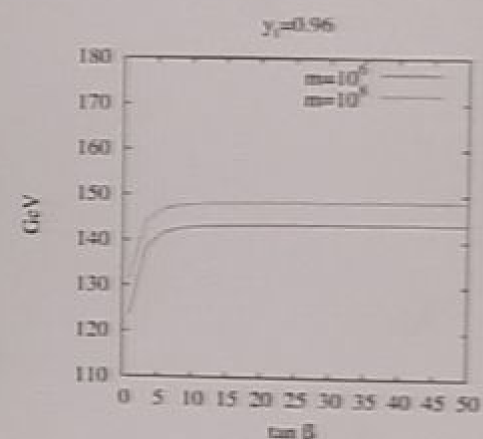


Figure 5: The value of the Higgs mass against $\tan\beta$ for $\tilde{m} = 10^{[illegible]}$GeV and $\tilde{m} = 10^{[illegible]}$GeV.

	A	B	C	D
m_s	10^9	10^9	10^{12}	10^{12}
$\tan\beta$	10	5	6	7
M	600	600	370	600
sgnμ	+	−	+	−
$\tilde{e}_L, \tilde{\mu}_L$	685	684	436	702
$\tilde{e}_R, \tilde{\mu}_R$	633	633	395	637
$\tilde{\tau}_L$	681	684	437	699
$\tilde{\tau}_R$	618	630	389	630
$\tilde{u}_1, \tilde{c}_1$	973	973	701	1099
$\tilde{u}_2, \tilde{c}_2$	1013	1013	728	1143
$\tilde{t}_1$	343	395	237	500
$\tilde{t}_2$	885	873	678	973
$\tilde{d}_1, \tilde{s}_1$	968	968	698	1093
$\tilde{d}_2, \tilde{s}_2$	1016	1016	732	1146
$\tilde{b}_1$	807	814	593	924
$\tilde{b}_2$	949	958	690	1078
χ_1^0	378	381	201	336
χ_2^0	543	556	321	544
χ_3^0	764	802	585	916
χ_4^0	782	807	601	919
$\chi_1^\pm$	543	556	321	544
$\chi_2^\pm$	781	808	600	921
A_0, H_0	1008	1065	732	1151
$H^\pm$	1012	1067	736	1153
$\tilde{g}$	1014	1014	736	1150
$\tilde{\nu}_{1,2}$	680	680	429	698
$\tilde{\nu}_3$	674	679	428	694
$B(b \to s\gamma)/10^{-4}$	2.8	4.4	2.9	4.3
$\delta a_\mu/10^{-10}$	3.0	−1.6	4.2	−2.0
Ωh^2	—	—	0.111	2.01

Table 4: Sparticle spectra for the intermediate scale models. All masses are in GeV.

Scan over M, $\tan\beta$, M_{string} (and sgn μ).

For larger string scales ($\gtrsim 10^{12}$ GeV)

possible to satisfy all the constraints.

Results do not alter significantly if assumption of gauge unification dropped.

Complete spectra can be produced.

---

2) D3 branes – $m_g \sim \frac{1}{\mathcal{V}^2}$

$$\tilde{m} \sim \frac{1}{\mathcal{V}^{7/6}}$$

large $\mathcal{V} \to$ split SUSY.

Need also large A-terms to be able to generate reasonable gaugino masses through RG flow. They enter at 2-loop level

$$\frac{d}{dt}M = \frac{2g^2}{16\pi^2}bM + \frac{2g_a^2}{(16\pi^2)^2}\left(\ldots + \sum \operatorname{tr}(Y^+ h)\right)$$

Yukawa coupling

trilinear scalar (A-term)

Scenario with $M_{string} \sim 10^{13}$ GeV, scalar masses $\tilde{m} \sim 10^7$ GeV, gauginos $m_g \sim 0$ GeV, A-terms $A \sim 10^4 - 10^7$ GeV.

RGE analysis: use RG equations of split SUSY above scale $\tilde{m}$ and the usual MSSM equations below $\tilde{m}$.

Salient feature – very heavy gluino.

Dark matter:

- $M_2 > M_1 \Rightarrow$ cannot be mostly Wino.
- can't be mostly Bino since not enough annihilation channels.

$\hookrightarrow$ mixed Bino – Higgsino, $(\mu \approx M_1)$

or mostly Higgsino $(\mu \ll M_1)$.

Both can be realised, depending on $\tan\beta$.

3) Can also find scenario on D3s with $\tilde{m} \simeq m_{gaugino}$. This requires $M_{string} \sim 10^{16}$ GeV and tuning W_0 to very small values.

One obtains generic, mSUGRA type scenarios (caveat: universality is not obvious here)

However precise relation between $\tilde{m}$ and m_g depend on unknown $\mathcal{O}(1)$ coefficients so this class cannot be analysed in detail.

Can also put D3s / D7s in a warped region of the CY.

This makes the string scale too low and lots of extra matter is needed for unification.

CONCLUSIONS

- Investigated a class of compactifications of Type IIB theory
- Can go quite far with the RGE analysis.
- Difficult to satisfy all constraints, even after relaxing certain predictions (e.g. $B = -2M$).
- Important to fix all moduli before computing soft terms! (e.g. volume $\longrightarrow$ string scale)
- Concrete embeddings of MSSM difficult to find and likely to be in nonperturbative regime (F - theory)
- Still, Type IIB most promising since moduli stabilisation story more subtle in Type IIA, Heterotic (although MSSM constructions with no exotics exist in the latter.)