SFB-lectures

Phenomenological Aspects of String Theory

Jan Louis

Universität Hamburg

Outline of the lectures:

1. Overview (January 19)
2. Compactifications (January 26)
3. Supersymmetry Breaking (February 2, today)

Hamburg, February 2007

Recall: $D = 4, N = 1$ effective Lagrangian

➪ spectrum:

multiplet	B	F
gravity multiplet	$g_{\mu\nu}$	Ψ_μ
vector multiplets	V_μ	χ
chiral multiplets	M	λ

➪ effective Lagrangian

$$\begin{aligned} L &= -\left(\tfrac{1}{2}R + G_{I\bar{J}} D_\mu M^I D^\mu \bar{M}^{\bar{J}} + \tfrac{1}{4}\mathrm{Re} f_{\kappa\lambda}\ F^\kappa_{\mu\nu} F^{\lambda\mu\nu} + \tfrac{1}{4}\mathrm{Im} f_{\kappa\lambda}\ F^\kappa \tilde{F}^\lambda + V\right) , \\ &\quad + \text{fermions} \\ V &= e^K \left(G^{I\bar{J}} D_I W D_{\bar{J}} \bar{W} - 3|W|^2\right) + \frac{1}{2}\left(\mathrm{Re}\ f\right)^{-1\ \kappa\lambda} D_\kappa D_\lambda \ . \end{aligned}$$

L is completely determined in terms of K, W, f:

- Kähler metric: $G_{I\bar{J}} = \partial_I \bar{\partial}_J K(M, \bar{M})$
- holomorphic superpotential: $W(M), \quad D_I W = \partial_I W + (\partial_I K) W$
- holomorphic gauge kinetic function: $f(M) = g^{-2} + i\,\frac{\Theta}{8\pi^2}$

Properties of K, W, f

- Kähler potential K receives quantum corrections at all orders
- Superpotential W has no perturbative quantum corrections

$$W = W^{(0)} + W^{(\mathrm{np})}$$

- gauge kinetic function f has only 1-loop quantum corrections

$$f = f^{(0)} + f^{(1)} + f^{(\mathrm{np})}$$

two different kinds of chiral multiplets:

- matter fields Q^I: quarks and leptons
- moduli fields T^i: flat directions of V

Supersymmetry breaking

- order parameters: $\langle \delta \text{fermions} \rangle$

  equivalently:

$$\langle D_\kappa \rangle = 0 \ , \qquad \langle F_I \rangle = 0 \ , \qquad F_I \equiv D_I W = \partial_I W + (\partial_I K) W = 0$$

  cosmological constant in supersymmetric vacua:

$$\langle V \rangle = -3 \langle e^K |W|^2 \rangle \leq 0$$

  $\Rightarrow$ supersymmetric vacua: anti-de-Sitter or Minkowski

  $\Rightarrow$ de-Sitter vacua require broken supersymmetry (via F or D-terms)

- particle physics requirement:

  scale of supersymmetry breaking (in the SM sector) $= \mathcal{O}(M_{EW})$??

  $\Rightarrow$ in string theory we need to generate the hierarchy $\frac{M_{EW}}{M_{Pl}} \approx 10^{-17}$

generic scenario: supersymmetry broken in hidden sector

communicated to observable (SM) sector by messenger sector:

1. gravitational/moduli mediation
2. gauge mediation
3. anomaly mediation

Hidden Sector $\Rightarrow$ Messenger Sector $\Rightarrow$ Observable Sector

dominant terms in limit $M_{Pl} \to \infty, M_{\rm Susy}{\rm fixed}$:

soft supersymmetry breaking terms (measured by LHC):

- scalar masses $m^2_{IJ} Q^I \bar{Q}^J$
- gaugino masses $m_\kappa \chi^\kappa \chi^\kappa$
- holomorphic quadratic and trilinear scalar terms (B- and A-terms)

$$B_{IJ} Q^I Q^J + A_{IJK} Q^I Q^J Q^K$$

Example: gaugino condensation

gaugino condensation is non-perturbative effect of supersymmetric field theories

hidden sector: asymptotically free gauge theory becomes strong at

$$\Lambda = M_{\rm Pl}\, e^{-\frac{8\pi^2}{bg^2}}$$

such effects generate

1. a hierarchy $\frac{\Lambda}{M_{\rm Pl}} \ll 1$ if g and/or b are small

$$M_{\rm Susy} \approx \frac{\Lambda^3}{M_{\rm Pl}^2} \quad \Rightarrow \quad \Lambda \sim 10^{13} - 10^{14} GeV \rightarrow M_{\rm Susy} \sim 10^1 - 10^3 GeV$$

2. a potential for the moduli

$$V \cong \frac{|\Lambda\,(g(T))|^6}{M_{\rm Pl}^2}$$

$\Rightarrow$ possibility of

- hierarchically breaking of supersymmetry
- stabilization of moduli

Apply to (perturbative) heterotic string

gauge kinetic function for gauge group $G = \Pi_a G_a$

$$f_a = S + f_a^{(1)}(T) \ , \qquad S = e^{-2\phi} + i\, a$$

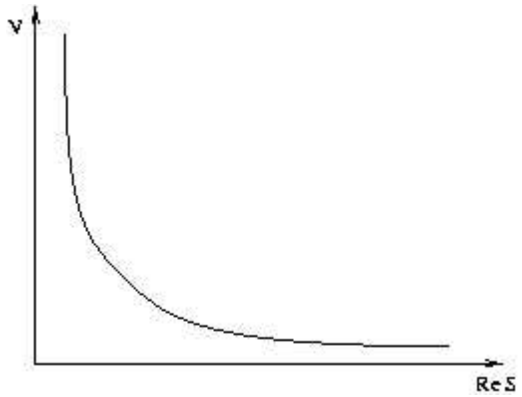
this implies:

1. gauge coupling unification at $M_{\rm GUT} \approx 5 \cdot 10^{17} GeV$

   $\Rightarrow$ mismatch with data: factor 20

2. potential for dilaton S and other moduli T is generated

   dilaton problem: runaway potential, non-perturbatively unstable vacuum



Modification: racetrack potential

considers two (or more) confining gauge groups each with different $f^{(1)}$

(this situation easily exists in string theory).

condensation scale for each group factor

$$\Lambda_a = M_{\rm Pl}\, e^{-\frac{8\pi^2}{b_a}(S+f_a^{(1)})}\,, \quad \Rightarrow \quad V \approx \frac{1}{M_{\rm Pl}^2}\left|\Lambda_1^3 + \Lambda_2^3\right|^2$$

minimum at $|\Lambda_1| = |\Lambda_2|$

$$\Rightarrow \langle S\rangle \approx \frac{b_1 b_2}{b_2 - b_1}\left(\frac{f_1^{(1)}}{b_1} - \frac{f_2^{(1)}}{b_2}\right), \quad \text{but} \quad \langle F_S\rangle = 0$$

tension between weak coupling (large S) and large hierarchy & fine-tuning

generalizations:

- $f_a^{(1)} = f_a^{(1)}(T) \Rightarrow \langle F_T\rangle \neq 0$
  but generically large FCNC and large cosmological constant
- add hidden matter $\Rightarrow$ additional hidden matter condensates
  $\Rightarrow$ less fine-tuning possible

Recently: study of meta-stable non-susy vacua [Intriligator, Seiberg, Shih]

motivation: dynamical supersymmetry breaking ($F_{\text{hidden matter}} \neq 0$) difficult

reason: supersymmetry minima generically exist

ISS: consider meta-stable non-supersymmetric vacua

- no tachyonic direction but not lowest ground state
- tunneling rate arranged to be low
- such vacua generically appear in supersymmetric gauge theories
  example: $SU(N)$ gauge theory with $N_f > 3N$ vector-like flavors

$\Rightarrow$ 'easily' embedded in string theory

$\Rightarrow$ gauge mediation possible:

* hidden sector couples via gauge interaction to observable sector
* no FCNC
* gravitino is LSP (dark matter candidate)

Supersymmetry breaking in type II string theory

Recall: type II vacua need space-time filling D-branes (and orientifold-planes)
non-Abelian gauge theory arises from excitations of Branes

$\Rightarrow$ gauge coupling $g^{-2} \sim$ Vol(wrapped cycle)

$\Rightarrow$ no longer automatically universal and more 'flexibility'

basic idea for supersymmetry breaking:

use

- background fluxes (recall: $\int_{\gamma_p^I \in Y} F_p = e_I \neq 0$)
- generalized compactifications (recall: $SU(3)$-structure manifolds
  globally defined spinor η exists but not covariantly constant $\nabla\eta \neq 0$)
- possibly non-perturbative effects (gaugino condensation, etc.)

hard facts:

- potential for moduli is generated
- stable supersymmetric ground states with all moduli fixed have been constructed

a little less clear: (and currently investigated)

- precise mechanism for supersymmetry breaking
- generation of hierarchy
- pattern of soft masses in realistic models
- cosmological constant

Prototype: **GKP – KKLT** [Giddings,Kachru,Polchinski; Kachru,Kallosh,Linde,Trivedi]

setup:

- type IIB string theory compactified on conifold (singular C-Y manifold) with background fluxes H_3, F_3

$$\Rightarrow \qquad \text{superpotential:} \quad W_0 = \int_{Y_6} (F_3 + \tau H_3) \wedge \Omega(z)$$

  $\tau = l + ie^{\phi}$ (complex type IIB dilaton), $\Omega =$ Calabi-Yau three-form

  $z = h^{(1,2)}$ complex structure moduli

  $\Rightarrow$ stabilization of $h^{(1,2)}$ complex structure moduli

- non-perturbative effects to stabilize $h^{(1,1)}$ Kähler moduli T

$$W = W_0 + ce^{-aT}$$

  W has supersymmetric AdS-vacuum

- add anti-D3 branes at 'tip' of conifold throat to explicitly break supersymmetry and 'arrange' the cosmological constant

last step is unsatisfactory and improvement is attempted –

– without complete success so far

Possibilties for 'uplift'

➪ D-term uplift [Burgess,Kallosh,Quevedo,...]

- $\langle D \rangle \neq 0$ is difficult to arrange in brane-models (delicate geometrical condition)
- generically also requires non-zero F-term

➪ F-term uplift [Lebedev,Nilles,Ratz,...]

add extra sector as before

- gauge theory with metastable non-supersymmetric vacuum
- gauge theory with stable non-supersymmetric vacuum (dynamical supersymmetry breaking)

advantage compared to heterotic scenario discussed above:

all moduli can be explicitly stabelized!

Generating the hierarchy

three basic options:

1. D-branes and fluxes 'warp' the space-time

$$ds^2 = e^{2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu + e^{-2A(y)}g_{mn}dy^m dy^n$$

$e^{A(y)}$ = warp factor, determined in terms of fluxes, can be exponentially small

$\Rightarrow$ masses exponentially suppressed in strongly warped regions (=throats)

two possibilities:

- SM on Branes at tip of throat $\Rightarrow$ suppression of $m_{\rm Higgs}$
- supersymmetry breaking hidden sector at tip of throat
  $\Rightarrow$ suppression of $m_{\rm Susy}$

2. non-perturbative effects $\sim e^{-\frac{8\pi^2}{bg^2}}$ as before

Discussion/Summary

- potential for moduli is generated by
  background fluxes, torsion and non-perturbative effects
- supersymmetric vacua with all moduli stabilized have been constructed
- precise mechanism for hierarchical supersymmetry breaking not yet identified

  generation of hierarchy:
  - non-perturbative effects
  - warping

  mechanism for supersymmetry breaking
  - dynamical supersymmetry breaking
  - racetrack models
  - metastable non-supersymmetric vacua

mechanism for supersymmetry breaking is the bottleneck

for further phenomenological studies