Fluxes, Gaugino Condensates and Moduli Stabilization in Heterotic Vacua

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WORK IN PROGRESS…

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Plan of the Talk:

- Introduction
- The DKP model…Why THIS model?

  $M_{3/2}$ SMALL → HOW? → Many directions:

  1. Large volume compactification
  2. Gaugino condensate
  3. A new possibility…
- Moduli stabilization in a Minkowski vacuum with broken susy
- (Tree-level) soft terms
- A toy-model
- Conclusions

Introduction: moduli stabilization

- Moduli: neutral scalar fields with perturbatively flat potential (typically due to susy).
- All the coupling constants of the effective theories describing the low energy dynamics of string vacua depend on the moduli vev.

- Let's consider a model in the framework of heterotic orbifold compactifications…

Moduli Identification:

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- Let's consider N=1 compactifications of the heterotic theory on $T^6/(Z2xZ2)$
- If we neglect the E_8xE_8 or SO(32) gauge bosons, the bosonic fields of the D=10 heterotic theory are:

Metric-g_{MN} Dilaton-Φ 2-form-B_{MN}

- Moduli identification: $M = [\mu = 0, 1, 2, 3; \; i = 5, 6, 7, 8, 9, 10]$

$$e^{-2\Phi} = s\,(t_1\,t_2\,t_3)^{-1}\,, \qquad g_{\mu\nu} = s^{-1}\,\tilde{g}_{\mu\nu}\,,$$

$$g_{i_A j_A} = \frac{t_A}{u_A}\begin{pmatrix} u_A^2 + \nu_A^2 & \nu_A \\ \nu_A & 1 \end{pmatrix}\,, \qquad (A = 1, 2, 3)\,,$$

$$B_{\mu\nu} \leftrightarrow \sigma\,, \quad B_{56} = \tau_1\,, \quad B_{78} = \tau_2\,, \quad B_{910} = \tau_3\,,$$

$$S = s + i\,\sigma\,, \quad T_A = t_A + i\,\tau_A\,, \quad U_A = u_A + i\,\nu_A\,, \quad (A = 1, 2, 3)$$

$$K = -\ln(S + \overline{S}) - \sum_{A=1}^{3}\ln(T_A + \overline{T}_A) - \sum_{A=1}^{3}\ln(U_A + \overline{U}_A)$$

(COMBINED) Heterotic Fluxes:

- Possible fluxes are:

	x^5	x^6	x^7	x^8	x^9	x^{10}
Z_2 :	$-$	$-$	$-$	$-$	$+$	$+$
Z_2' :	$+$	$+$	$-$	$-$	$-$	$-$

1) 8 3-form fluxes [Derendinger, Ibanez, Nilles '85]

$$\widetilde{H}_{579} \equiv \Lambda_{111} \quad \leftrightarrow \quad 1\,,$$

$$\widetilde{H}_{679} = \widetilde{H}_{589} = \widetilde{H}_{5710} \equiv \Lambda_{114} \quad \leftrightarrow \quad i\,(U_1 + U_2 + U_3)\,,$$

$$\widetilde{H}_{689} = \widetilde{H}_{5810} = \widetilde{H}_{6710} \equiv \Lambda_{144} \quad \leftrightarrow \quad -(U_1\,U_2 + U_2\,U_3 + U_1\,U_3)$$

$$\widetilde{H}_{6810} \equiv \Lambda_{444} \quad \leftrightarrow \quad -i\,U_1 U_2 U_3\,.$$

2) 24 geometrical fluxes [Scherk, Schwarz '79]

$$\omega^{i_A}{}_{i_B i_C} \quad [(ABC) = (123), (231), (312)]$$

$$\omega^{i_A}{}_{i_B i_C} \quad \longrightarrow \quad W \sim i\,T_A\,,\; T_A U_B\,,\; i\,T_A U_B U_C\,,\; T_A U_1 U_2 U_3$$

- In the heterotic theory, H-fluxes and geometrical fluxes can never generate N=1 superpotentials with both constant and linear terms in S. We can't reach the stabilization of all the 7 moduli including dilaton…NON-PERTURBATIVE EFFECTS!

Gaugino Condensation:

- Does gaugino condensation break susy?

To see whether susy is broken or not we have to look for susy transformation of fermionic states. This will give us the auxiliary fields, a VEV of which will break susy.

In the LOCAL case: $F_i = exp(-G/2)(G^{-1})_i^j G_j + \frac{1}{4} f_k (G^{-1})_i^k \lambda\lambda$

[Ferrara, Girardello, Nilles; Dine et al.]

- The two terms cancel → SUSY is RESTORED by gaugino condensation (KKLT)

- When the first term is vanishing → $M_S^2 \simeq \frac{\mu^3}{M_p} = \frac{<\lambda\lambda>}{M_p}$ $m_{3/2} = \frac{\mu^3}{M_p^2}$

- How can we keep low the gravitino mass?
  - $m_{3/2} = c/\sqrt{V},$
  - $m_{3/2} = c\,w(S)/\sqrt{V},$
  - DKP-model

The DKP model:
[Derendinger, Kounnas, Petropoulos '06]

- Heterotic theory on $T^6/(Z2xZ2)$

$$K = -\log\left(S+\overline{S}\right) - \sum_{A=1}^{3}\log\left(T_A+\overline{T}_A\right)\left(U_A+\overline{U}_A\right)$$

$$W = 3\hat{A}U + \hat{D}U_4 \qquad U_4 = U^3 \qquad \xi = T_1 - T_2 \qquad w(S) = \Lambda^3 e^{-S}$$

$$\begin{aligned}\hat{A} &= \left[\alpha + \alpha' w(S)\right]\xi + A w(S),\\ \hat{D} &= \left[\delta + \delta' w(S)\right]\xi + D w(S),\end{aligned}$$

$$\mathrm{e}^{-K}V = \sum_i \left|W - W_i(Z_i+\overline{Z}_i)\right|^2 - 3|W|^2$$

- AIM: let's find stationary points where susy breaks in Minkowski space $\langle V\rangle = 0\,, \qquad \langle W\rangle \neq 0$
- Suppose that $\langle W_J\rangle=0$ for a modulus…
- Let's consider then the case where moduli splits into:

1) $\langle W_j\rangle = 0 \quad \langle F_j\rangle = \langle W\rangle \neq 0,$ for precisely 3 fields/NO-SCALE

2) $\langle F_J\rangle=0$ for the moduli U and S

$$\partial_j V = 0,\ \forall j, \Rightarrow \mathrm{Re}\,\xi = 0, \quad S = s - i\pi/2 \text{ and } U_i = u_i \text{ real}$$

The Double Suppression:

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$$\langle W_{T_1} \rangle = \langle W_{T_2} \rangle = 0$$

$$< F_S > = < F_U > = 0$$

ξ=ξ(s)

u=u(s)

Equation for s

- Large-s expansion with ratios between fluxes coefficient of order one:

$$\xi \approx -\frac{D}{\delta}\, w \qquad u \approx \sqrt{\frac{-3\alpha}{\delta}}. \qquad s \approx \log\left(\frac{4\Lambda^3 D\alpha}{D\alpha - A\delta}\right) - \frac{1}{4\log\left(\frac{4\Lambda^3 D\alpha}{D\alpha - A\delta}\right)}$$

- Double suppression:

$$e^{-K/2} m_{3/2} = \frac{A\delta' - D\alpha' + \frac{A\delta - D\alpha}{w}}{\alpha + \alpha' w}\left(-3\frac{\alpha + \alpha' w}{\delta + \delta' w}\right)^{3/2} w^2$$

1) $E_{vac}=0$, 2) $m_{3/2}$

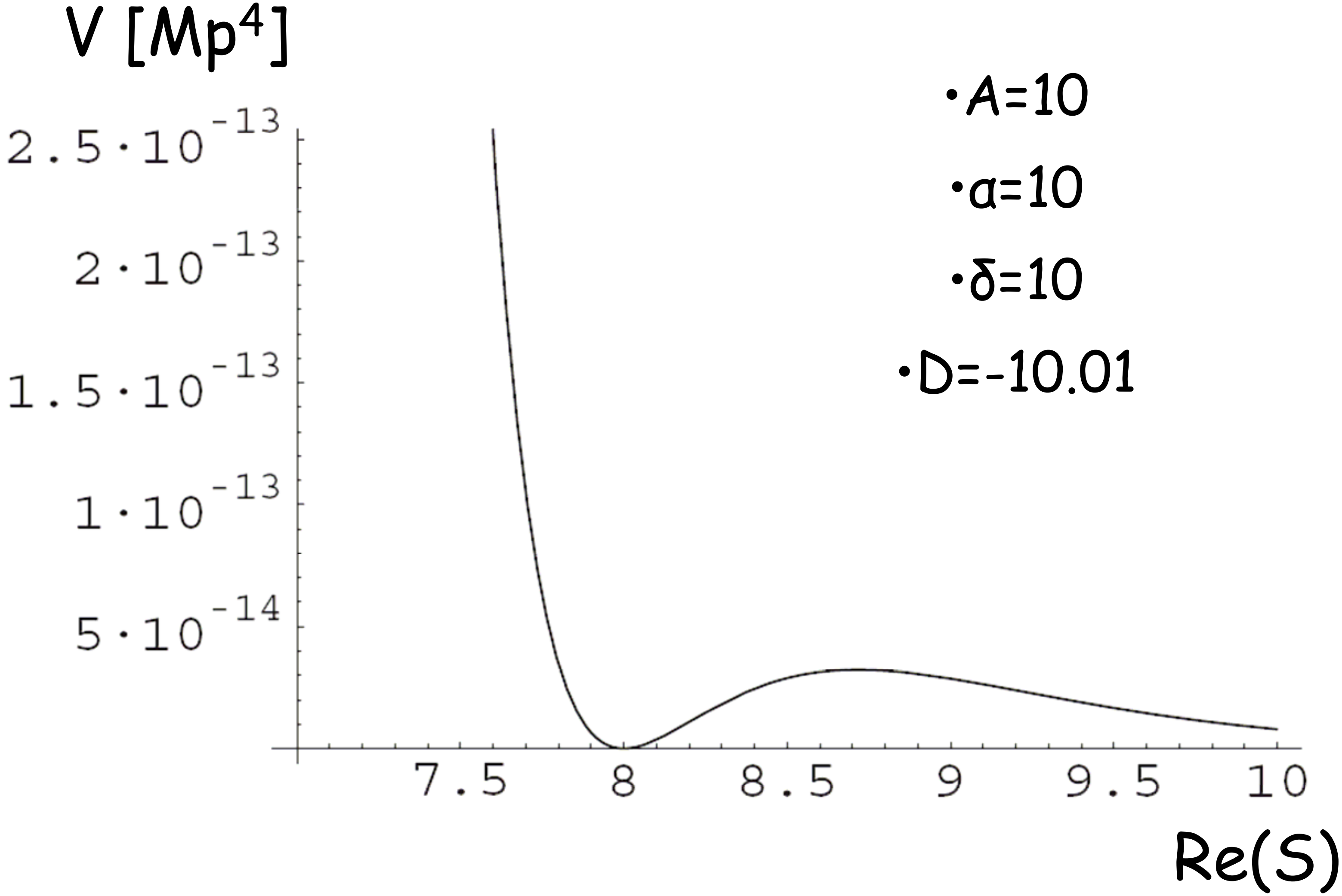
SUSY is BROKEN

- Aδ/Da of order one, w<<1 → Double suppression ?FINE-TUNING?

- We choose the parameters to obtain a large value of s:

$$\Lambda \simeq M_p \qquad s \simeq 10 \quad \rightarrow \quad \left(\frac{g^2}{4\pi}\right)_{FT-GUT} \simeq \frac{1}{24} \qquad w << 1$$

Dilaton Stabilization:



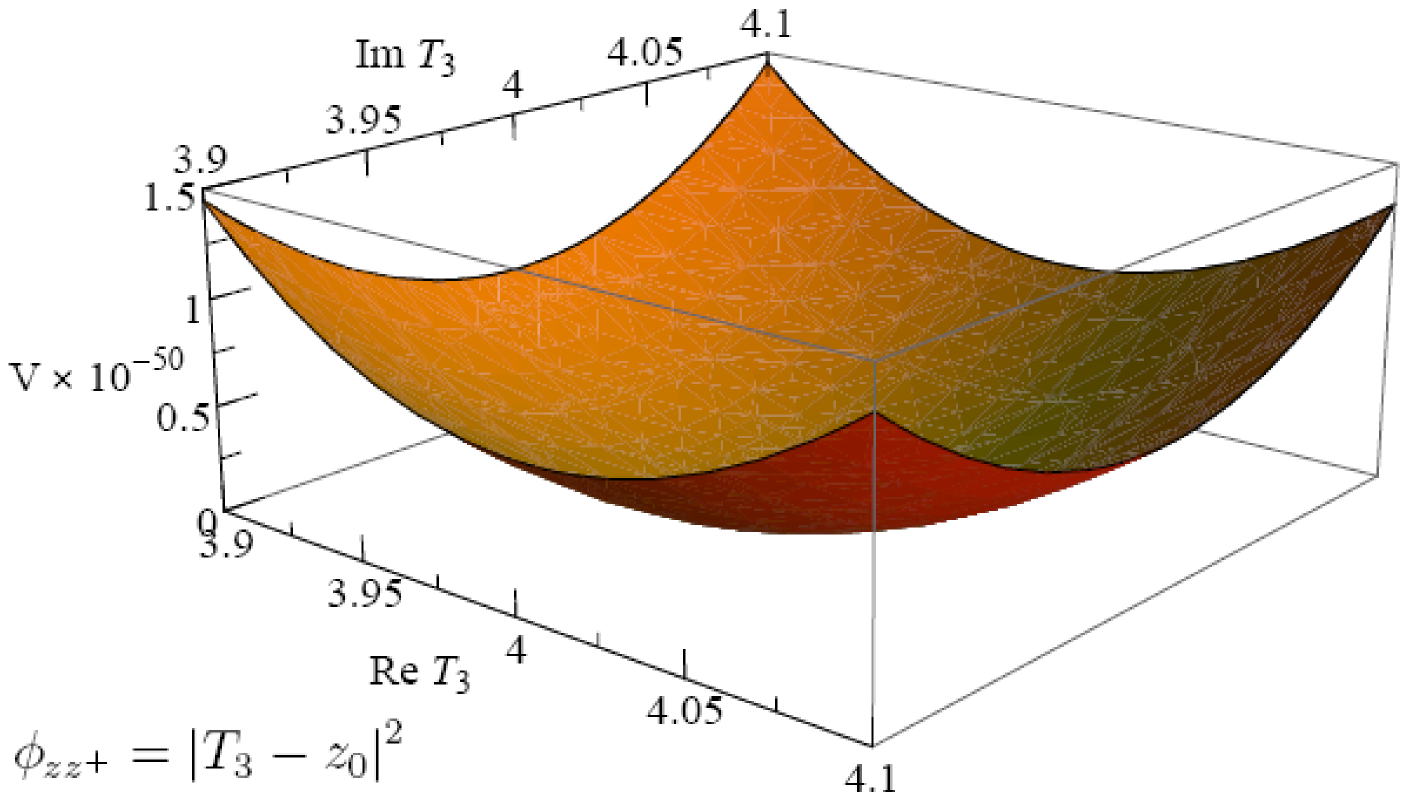
- A=10
- α=10
- δ=10
- D=-10.01

T3-stabilization: local no-scale

[Cremmer, Ferrara, Kounnas, Nanopoulos]

$$G = K + log\,|W|^2$$

$$G = -\frac{3}{2}log[f(z) + f^+(z^+)]^2. \quad \rightarrow \quad G = -\frac{3}{2}log(f + f^+ + \phi)^2$$



$$\phi_{zz^+} = |T_3 - z_0|^2$$

•We can stabilize T3 in a MINKOWSKI vacuum because the stabilizing function has been chosen very carefully… Is this vanishing vacuum energy generic and robust?

Tree-level soft terms:

$$\alpha = 100, A = 10, D = -10.00001, \delta = -100$$

$$S_{min} = 15 - i\pi/2$$

- F-terms:

$$F_S = 0$$ $$F_U = 0, F_{T_1} = F_{T_2} = F_{T_3} = -8m_{3/2}$$

$$K = -\sum_{A=1}^{3} log(T_A + T_A^*) + \sum_{\alpha} \Phi_\alpha \Phi_\alpha^* (T_1 + T_1^*)^{-n_\alpha^1} (T_2 + T_2^*)^{-n_\alpha^2} (T_3 + T_3^*)^{-n_\alpha^3}$$

$$\mathcal{K}_\alpha = \frac{\partial^2 K}{\partial \Phi_\alpha \partial \Phi_\alpha^*}$$

$$m_\alpha^2 = m_{3/2}^2 - F^{*m} F^n \partial_m \partial_n log \mathcal{K}_\alpha$$

$$A_{\alpha\beta\gamma} = F^m [\widehat{K_m} + \partial_m log Y_{\alpha\beta\gamma} - \partial_m log(\mathcal{K}_\alpha \mathcal{K}_\beta \mathcal{K}_\gamma)]$$

$$M_a = \frac{1}{2} (Re f_a)^{-1} F^m \partial_m f_a,$$

} Vanishing soft terms

A toy-model:

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•The only S-dependence of the superpotential in the DKP model is encoded in the gaugino condensate

$$W_{toy-model} = -A(Te^{-aS} + T^2) \rightarrow W \simeq e^{-2S}$$

$$K = -log(S+S^*) - 3log(T+T^*).$$

The double suppression is recovered with a "run-away" dilaton

• THE GENERAL CASE: moduli stabilization can be achieved but the vacuum energy is tipically non-vanishing (e.g. KKLT)… up/down-lifting sector is necessary.

•Dilaton stabilization in heterotic: the down-lifting [V. Loewen, H.P. Nilles 2008]

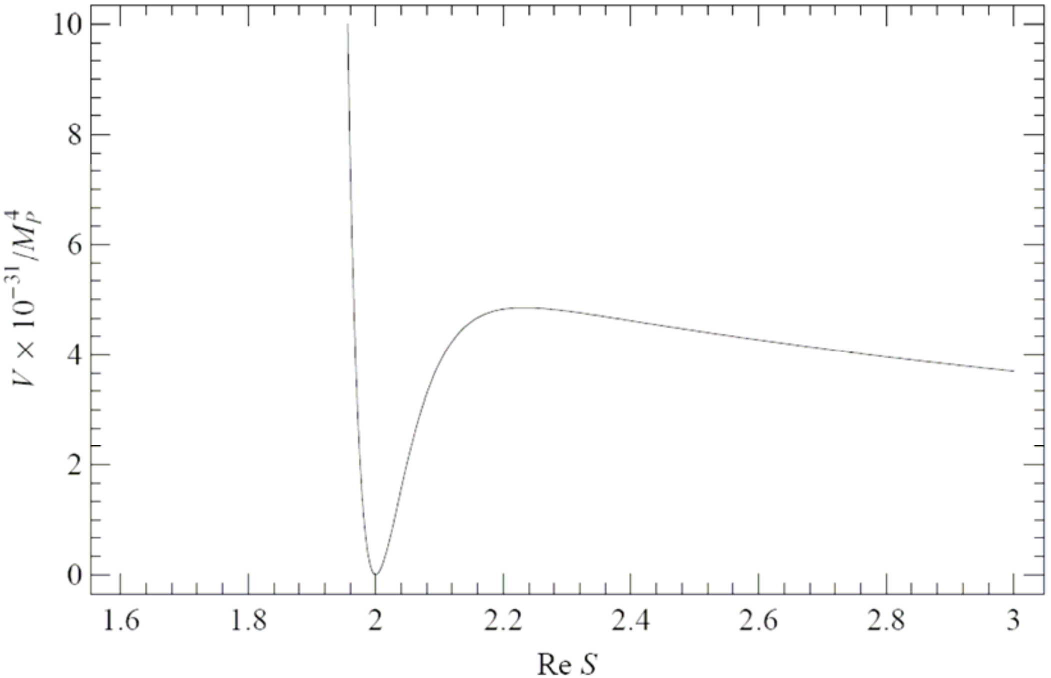
$$K = -log(S+S^*) + CC^*$$

$$W = \omega + \mu^2 C - 2Ae^{-2S}$$

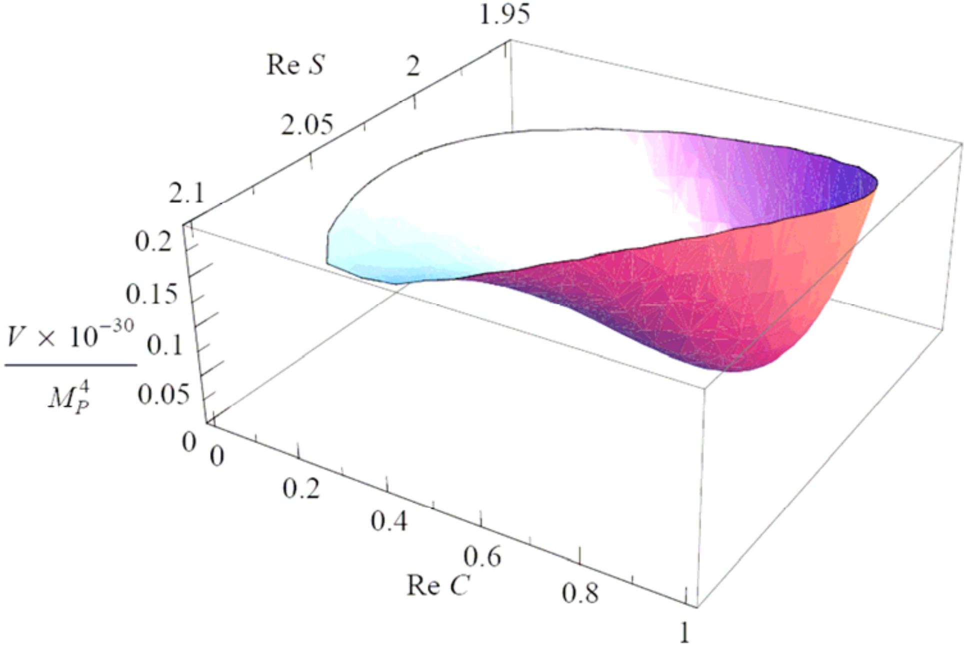
$$m_{3/2} = e^{G/2} = e^{K/2}|W| \simeq \mu^2$$

ω	μ^2	C_0	F^S	F^C	$m_{3/2}$	m_S	m_C
3×10^{-16}	1×10^{-15}	0.73	7×10^{-17}	1×10^{-15}	2 TeV	141 TeV	3 TeV

Toy model: the scalar potential



- $A=1$
- gauge group SU(8)



- Is this vanishing vacuum energy generic and robust?

Conclusions:

- A model in the framework of orbifold compactifications of heterotic theory has been presented.
- The moduli stabilization problem has been addressed exploiting the fluxes, condensates and corrections to the Kaehler potential.
- A Minkowski vacuum with broken SUSY has been found.
- Tree-level soft terms are vanishing.
- A toy-model encompassing the main features of the DKP set-up has been discussed.

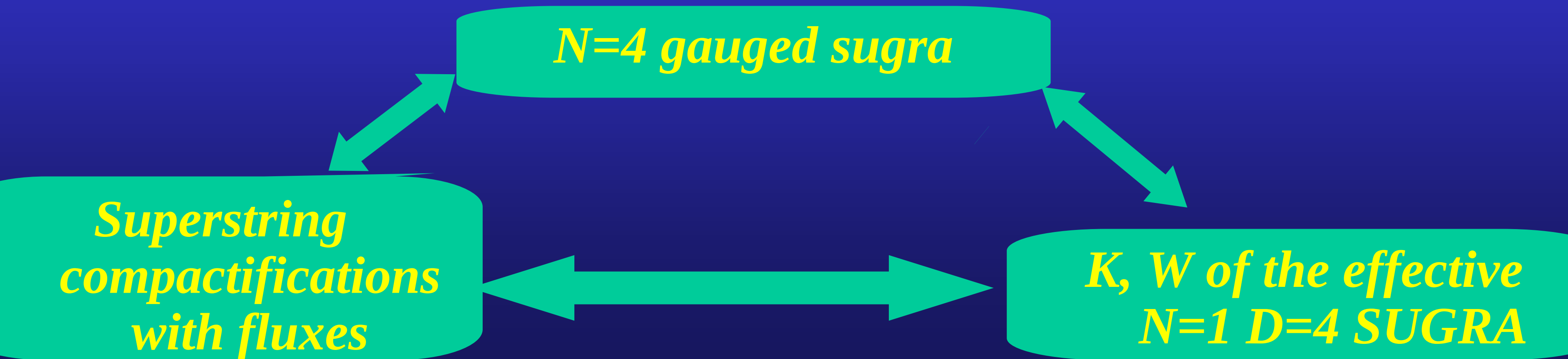
WORK IN PROGRESS…

Towards the construction of the superpotential:

- Heterotic theory on a T^6 $\rightarrow$ D=4 N=4 SUGRA
- (Extended) SUGRA has many vector fields
- The ungauged version can be deformed by imposing a non-abelian gauge algebra: "gauged supergravity"
- Consequences: covariantization of derivatives, gravitino mass terms…

$$\mathcal{M}_{3/2}{}^{ij} = -\frac{4}{3}\varphi^*_{(R)}\, f_{RST}\, \phi^{ikR}\phi^{S}_{kl}\phi^{ljT}$$

- Irrelevant in the visible sector (MSSM): extended susy does not apply (chirality) … We must reduce the amount of susy.



N=1 superpotentials from N=4 gaugings: 1° step

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[Derendinger, Kounnas, Petropoulos, Zwirner]

- Supergravity multiplet: 6 vector fields
- n vector multiplets, each with 6 real scalars

$$\phi^R_{ij} = -\phi^R_{ji} \qquad (i, j, \ldots = 1, \ldots, 4, \quad R = 1, \ldots, 6+n)$$

With constraints and symmetry: 6n physical scalars

•Parameters are some structure constants $f^R{}_{ST}$ of the algebra gauged by the (6+n) vector fields: (6+n)-dimensional group

•Formally we can write a gravitino mass:

$$-(1/2)\,\mathcal{M}_{3/2}{}^{ij}\,\overline{\psi}_{\mu i}\sigma^{\mu\nu}\psi_{\nu j} + \mathrm{h.c.} \qquad \mathcal{M}_{3/2}{}^{ij} = -\frac{4}{3}\varphi^*_{(R)}\,f_{RST}\,\phi^{ikR}\phi^S_{kl}\phi^{ljT}$$

- Z2xZ2 truncation leads to N=1 susy and to 7 moduli in D=4. The constraint equations allow to rewrite the gravitino mass as function of N=1 scalars and structure constants. K and W are obtained by separating the holomorphic part in N=1 gravitino mass using $m_{3/2} = e^{K/2}W$ → $W=W(f^R{}_{ST})$

Fluxes and gaugings: 2° step

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- Consider a real scalar field coupled to gravity in 5D:

$$S_\lambda = \int \left(-\hat{R} * \mathbf{1} - \frac{1}{2}\hat{\mathrm{d}}\hat{\lambda} \wedge *\hat{\mathrm{d}}\hat{\lambda} \right)$$

$$\lambda \longrightarrow \lambda + a$$

- Let us compactify the action on a circle with coordinate y
- Ansatz:

$$\lambda(x,y) = \lambda(x) + my$$

$$(\hat{\mathrm{d}}\hat{\lambda})_4 = \mathrm{d}\lambda \ , \qquad (\hat{\mathrm{d}}\hat{\lambda})_y = m\,\mathrm{d}y$$

- The "field strength" is independent of y. If we integrate it over the circle we obtain a non-trivial flux through this circle which is proportional to m
- Parameters of the effective sugra are the "gauging structure constants" and these are also the flux parameters
- After the truncation to N=1

we can write:

$$f_{Aa_1\,Bb_2\,Cc_3} = \Lambda_{a_1b_2c_3}\,\epsilon_{ABC} \qquad (a_1, b_2, c_3 = 1, \ldots, 4)$$

CONSTANT FIELD STRENGTH

Gaugino Condensation:

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• Consider a pure SYM SU(N) with a vector superfield in the adjoint representation

$$V_{WZ}(x,\theta,\bar{\theta}) = -\theta\sigma_\mu\bar{\theta}A^\mu + i\theta\theta\bar{\theta}\bar{\lambda} - i\bar{\theta}\bar{\theta}\theta\lambda + \frac{1}{2}\theta\theta\bar{\theta}\bar{\theta}D$$

• 1 loop β function running $\mu^3 = \Lambda^3 e^{\frac{8\pi^2}{Ng^2(\Lambda)}}$

• We assume confinement in the IR and a low energy spectrum consisting of singlet boundstates

• Question: Does gaugino condensation occur? (i.e. does ΛΛ receive a non-vanishing VEV?) [Veneziano, Yankielowicz '82]

• Assume that the superfield $S=W^\alpha W_\alpha$ (the only gauge invariant superfield that contains ΛΛ we can construct)is the only relevant degree of freedom at low energy.

• At the classical level the theory is scale and chiral invariant (spoiled by anomalies). Writing the most general globally supersymmetric effective lagrangian consistent with these symmetries they arrive at:

$$L_{eff} = \int d^4\theta\,(SS^*)^{1/3} + \int d^2\theta\left[S\log\frac{S}{\mu^3} - S\right] + h.c.$$

→ $< \lambda\lambda > = \mu^3 \neq 0$

The Racetrack mechanism:

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[Krasnikov]

- Pure N=1 SYM:

$$< \lambda\lambda > = \mu^3 \neq 0 \qquad \mu^3 = \Lambda^3 e^{\frac{8\pi^2}{N g^2(\Lambda)}}$$

- We can summarize the fact that gauginos condense with a low energy superpotential

$$W = N\mu^3$$

$$\frac{1}{g^2} \rightarrow S$$

$$W(S) = A e^{-\frac{24\pi^2 S}{b}}$$

$$\beta(g) = -b\, g^3/16\pi^2$$

Dilaton rescaling

- **RACETRACK**: A mechanism to stabilize the chiral fields governing the holomorphic gauge kinetic terms of a supersymmetric theory with two or more non-abelian gauge groups

$$W(S) = \sum_i A_i e^{-\frac{24\pi^2 S}{b_i}}$$

- Threshold effects to holomorphic gauge kinetic function

[Dixon, Kaplunovsky, Louis]

$$f = S + \epsilon T$$

Removing the flat directions:

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- T1+T2 and T3 are flat-directions

<V>=exp(<K>) {ZERO}

- To remove the flat-directions we will modify the Kaehler potential demanding the flatness condition only locally [Cremmer, Ferrara, Kounnas, Nanopoulos]

$$V = 9e^{4G/3} G^{-1}_{zz^+} \partial_z \partial_{z^+} e^{-G/3},$$

$$G = K + log\,|W|^2$$

z=T3

Global No-Scale

$$G = -\frac{3}{2} log[f(z) + f^+(z^+)]^2.$$

Local No-Scale

$$\partial_z \partial_{z^+} e^{-G/3} = \phi_{zz^+}(z, z^+)$$

$$\phi_{zz^+}(z_0, z_0^+) = 0.$$

$$\phi_{zz^+} \geq 0, \forall z \in \mathcal{D}$$

$$G = -\frac{3}{2} log(f + f^+ + \phi)^2$$

$$G_{zz^+} = 3\frac{|f_z + \phi_z|^2 - \phi_{zz^+}(f + f^+ + \phi)}{(f + f^+ + \phi)^2} > 0.$$

- We choose the stabilizing function:

$$\phi_{zz^+} = |T_3 - z_0|^2$$

$$V_0 = 3\frac{\phi_{zz^+}(f + f^+ + \phi)}{|f + f^+ + \phi|^3 \left[|f_z + \phi_z|^2 - \phi_{zz^+}(f + f^+ + \phi)\right]}.$$

Quantum corrections:

- To discuss the pattern of soft terms the stabilization of moduli is a crucial step.

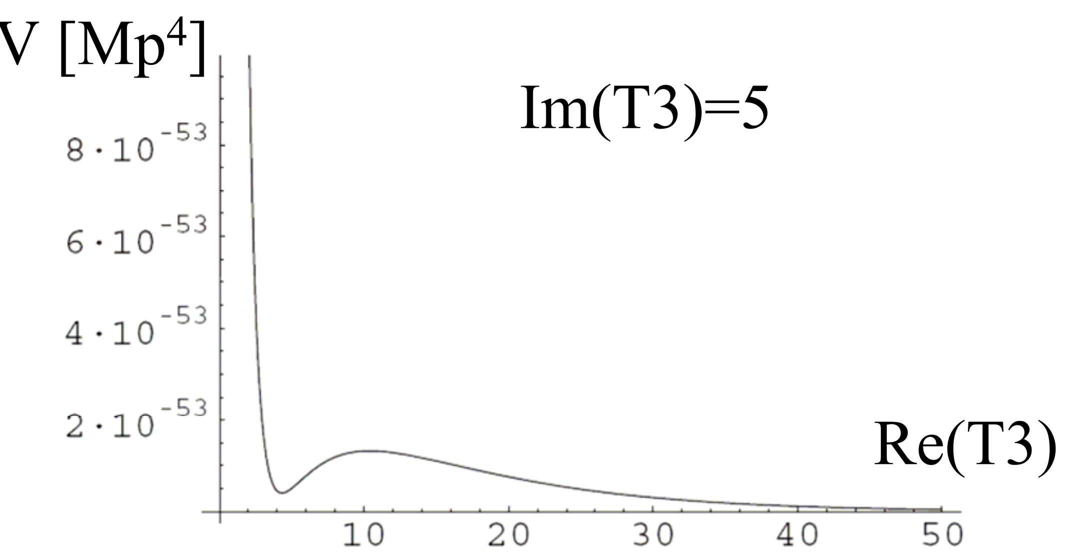
Gaugino masses: $$\frac{1}{2}(Ref_a)^{-1}F^m\partial_m f_a$$

- However $<F_S>$=0 and gaugino mass is vanishing at TREE-LEVEL
- Quantum corrections are necessary!

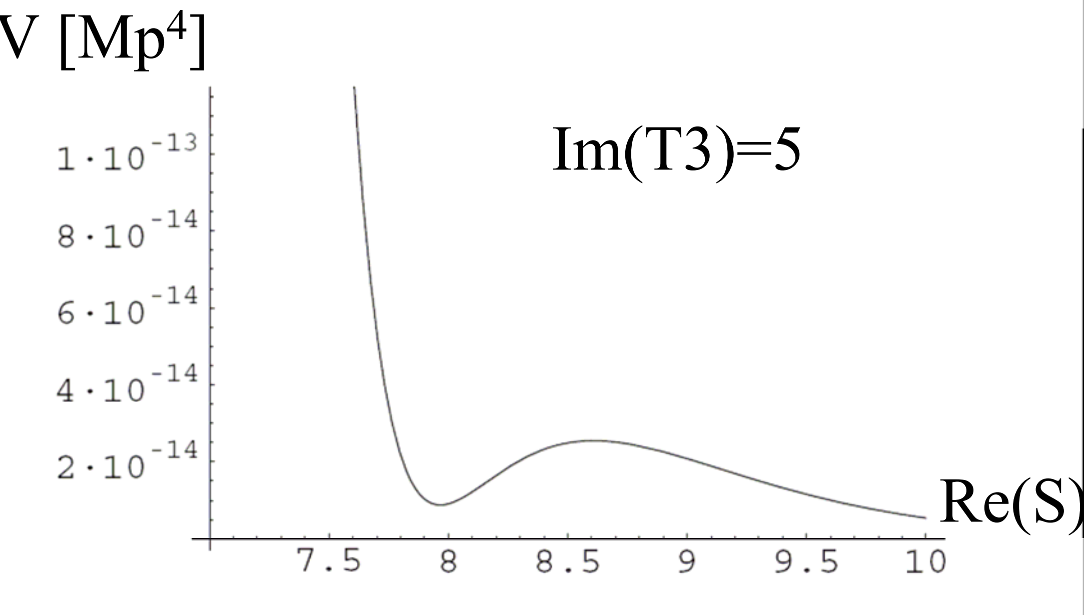
[Dixon, Kaplunovsky, Louis]

- The gauge kinetic function: $f = S + \epsilon T,$
- In the superpotential: $w = \Lambda^3 e^{-(S+\epsilon T)}$
- The Kaehler potential: no correction in this model [De Carlos, Casas, Munoz]
- F-terms=? V=?

Moduli Stabilization with S+ET correction:



- Im(T3)=4……Minkowski
- Im(T3)=5……dS



- Im(T3)=4……dS!!!
- Im(T3)=5……dS