

Moduli stabilization in string theory

①

Compactifications 10.1

5D spacetime $\mathbb{R}^{3,1} \times S^1$

coordinates $\{x^\mu, y\}$, $y = y + 2\pi n R$, $n \in \mathbb{Z}$

real scalar $\phi(x^\mu, y) = \sum_{k \in \mathbb{Z}} \phi_k(x^\mu) e^{iky/R}$

$$\bar{\phi}(x^\mu, y) = \phi(x^\mu, y) \Rightarrow \phi_k^*(x^\mu) = \phi_{-k}(x^\mu)$$

$$S = -\int d^4x dy \partial_\mu \phi \partial^\mu \phi = -\int d^4x dy (\partial_\mu \phi \partial^\mu \phi + \partial_y \phi \partial^y \phi)$$

$$= -\int d^4x dy \sum_{k, \ell} (\partial_\mu \phi_k \partial^\mu \phi_\ell - k \ell \phi_k \phi_\ell) e^{i\gamma(k+\ell)/R}$$

$$= -\int d^4x (2\pi R) \sum_k (\partial_\mu \phi_k \partial^\mu \phi_{-k} + \frac{k^2}{R^2} \phi_k(x^\mu) \phi_{-k}(x^\mu))$$

$k=0$ massless scalar in 4D

$k \neq 0$ KK-tower of massive scalar fields

In string compactifications we usually neglect the KK-tower, i.e. we restrict to energies below

the KK-scale $E \ll M_{\text{KK}} \sim \frac{1}{R}$

Fields with spacetime index

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5D vector field $A_\mu(x^\mu, y) = \begin{pmatrix} \sum_k A_{\mu k}(x^\mu) e^{iky/R} \\ \sum_k A_{\gamma k}(x^\mu) e^{iky/R} \end{pmatrix}, A_{\mu, k} = A_{\mu, -k}^*$

$$S = -\int d^4x dy (F^{\mu\nu} F_{\mu\nu}) = -\int d^4x dy (F_{\mu\nu} F^{\mu\nu} + F_{\gamma\mu} F^{\gamma\mu} + F_{\mu\gamma} F^{\mu\gamma})$$

$$F_{\gamma\mu} = \partial_\gamma A_\mu - \partial_\mu A_\gamma = \sum_k \frac{ik}{R} A_{\mu k} e^{iky/R} - \sum_k \partial_\mu A_{\gamma k} e^{iky/R}$$

$$F_{\gamma\mu} F^{\gamma\mu} = F_{\mu\gamma} F^{\mu\gamma} = \sum_{k,l} \left(-\frac{k l}{R^2} A_{\mu k} A_l^\mu + \partial_\mu A_{\gamma k} \partial^\mu A_{\gamma l} - \frac{ik}{R} A_{\mu k} \partial^\mu A_{\gamma l} - \frac{i l}{R} A_{\mu k} \partial^\mu A_{\gamma l} \right) e^{i(k+l)y/R}$$

$$S = -\int d^4x (2\pi R) \sum_k \left(F_{\mu\nu k} F_{-k}^{\mu\nu} + \frac{k^2}{R^2} A_{\mu k} A_{-k}^\mu + \partial_\mu A_{\gamma k} \partial^\mu A_{\gamma, -k} - \frac{ik}{R} A_{\mu k} \partial^\mu A_{\gamma, -k} + \frac{ik}{R} A_{\mu, -k} \partial^\mu A_{\gamma, k} \right)$$

$$= -\int d^4x (2\pi R) \sum_k \left(F_{\mu\nu k} F_{-k}^{\mu\nu} + \left(\partial_\mu A_{\gamma k} - \frac{ik}{R} A_{\mu k} \right) \left(\partial^\mu A_{\gamma, -k} + \frac{ik}{R} A_{\gamma, -k}^\mu \right) \right)$$

$$= -\int d^4x (2\pi R) \left[F_{\mu\nu 0} F_0^{\mu\nu} + \underbrace{\partial_\mu A_{\gamma 0} \partial^\mu A_{\gamma 0}}_{\text{massless scalar}} + \text{massive KK vectors} \right]$$

$A_{y,0}$ is a real scalar that arises since the vector A_m wraps a 1-cycle, i.e. the S^1 (3)

A higher dimensional analogue:

fields arising in type IIB string theory

B_{2MN} can wrap 2-cycles
 C_{2MN} can wrap 2-cycles
 C_{4MNPQ} can wrap 4-cycles

} gives scalars in 4D

Additional scalar can come from the metric,

for $\mathbb{R}^{3,1} \times S^1$

$$g_{MN} = \begin{pmatrix} g_{\mu\nu} & g_{\mu y} \\ g_{y\mu} & g_{yy} \end{pmatrix}$$

\uparrow \uparrow
4D vector 4D scalar

String (flux) Compactifications

Graña hep-th/0509003 (4)

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String theory is very difficult and we cannot usually solve it in non-trivial backgrounds.

The low energy limits of the super string theories are 10D supergravities (strings \rightarrow point particles)

$$E \ll M_{\text{string}} = (\alpha')^{-1/2}$$

We will restrict here to type IIB string theory/supergravity which is the most studied in the context of flux compactifications and string cosmology.

The 10D supergravity preserves 32 supercharges in flat space and the spectrum is

$$\left. \begin{array}{l} g_{MN} \\ B_{MN} \\ \phi \end{array} \right\} \text{NSNS sector}$$

$$\left. \begin{array}{l} C_0 \\ C_{2MN} \\ C_{4MNP} \end{array} \right\} \text{RR sector}$$

There are also fermions coming from the NSR sector. ⁽⁵⁾

Since we have supersymmetry we do not need to keep track of the fermions. Their action is fixed by the bosonic action combined with the SUSY transformations.

We want to compactify from 10D to 4D and preserve at most $\mathcal{N}=1$ SUSY, i.e. 4 supercharges in 4D. The reason for this is that for 4D $\mathcal{N} \geq 2$ the left- and right-handed fermions are related via supersymmetry and therefore have the same quantum numbers.

In the standard model of particle physics the left-handed electron and the neutrino sit in an $SU(2)$ doublet $\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$ the right-handed electron is an $SU(2)$ singlet $e_R \Rightarrow \mathcal{N} \leq 1$

$\mathcal{N}=0$ would mean that all SUSY is broken at the compactification scale $M_{KK} \sim \frac{1}{R} \sim \frac{1}{(\text{vol}_6)^{1/6}}$. This is possible but technically harder.

We therefore restrict to 4D $\mathcal{N}=1$ models for which we have the best mathematical tools and that are the best studied models. ⑥

In 10D the 32 supersymmetry transformations parameters are two 10D Majorana-Weyl spinors ϵ^i , $i=1,2$

The 10D SUSY transformation for the gravitino ψ_M (the spin $\frac{3}{2}$ superpartner of the graviton) is

$$\delta \psi_M = \nabla_M \epsilon^i = \left(\partial_M - \frac{i}{4} \omega_M^{AB} \Gamma_{AB} \right) \epsilon^i = 0$$

10D gamma matrices

In flat space the two 16 component spinors ϵ^i satisfy this equation and we preserve 32 supercharges

For a CY_3 manifold, the non-trivial spin connection ω_M^{AB} , allows only for 4 non-zero components in each ϵ^i . Hence a CY_3 manifold preserves 8 supercharges which is $\mathcal{N}=2$ in 4D.

A compactification cannot lead directly to $\mathcal{N}=1$ in 4D since for each ϵ^i we can either get one or zero 4D spinor with 4 components. ϵ^1 and ϵ^2 have the same chirality and therefore we can only get $\mathcal{N}=2$ (or $\mathcal{N}=0$) or $\mathcal{N}=4$

To get $\mathcal{N}=1$ in 4D we need to do an additional $\textcircled{7}$ orientifold projection:

We mod out by $\Omega_p (-1)^{F_L} I$ string
↓
length

Ω_p string world sheet parity $\Omega_p: \sigma \rightarrow l - \sigma$

F_L left-moving worldsheet fermion number

I spacetime involution, e.g. $I: x^\mu \rightarrow x^\mu$
 $y^i \rightarrow -y^i \quad i=1,2,\dots,6$
 gives O3-plane extending
 along x^μ , sitting at $y^i=0$

An orientifold projection break $\frac{1}{2}$ of the supersymmetry

flat space example $\epsilon^1 = \prod_{\substack{0123 \\ x^\mu}} \epsilon^2 = - \prod_{\substack{456789 \\ y^i}} \epsilon^2$

$\Rightarrow \mathcal{N}=1$ for CY_3 compactifications with orientifold projection

The involution I can have fixed points of codim 6 and codim 2, i.e. give rise to O3- and O7-planes (O5/O9 also possible)

The orientifold projection also truncates the spectrum. ⁽⁸⁾

Since $(\Omega_p (-1)^{F_L} I)^2 = 1$ all fields are either mapped to plus themselves or minus themselves (in the latter case they are projected out)

Example: B_{MN} and C_{2MN} are mapped to minus themselves by $\Omega_p (-1)^{F_L}$. So they only give rise to 4D fields, if their "legs" extend along 2-cycles that are odd under I .

flat space: $I: x^m \rightarrow x^m$
 $y^i \rightarrow -y^i$

$B_{ur} \rightarrow B_{ur}$
 $B_{ij} \rightarrow B_{ij}$ } projected out

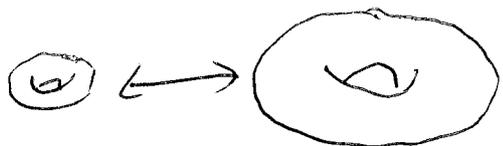
$B_{\mu i} \rightarrow -B_{\mu i}$ survives
(but no 1-cycles in CY_3)

ϕ, C_0 are invariant under $\Omega_p (-1)^{F_L} I$. They give rise to a 4D complex scalar $\tau = C_0 + i e^{-\phi}$.

τ is called the axio-dilaton

The internal part of the metric gives also rise to scalars that for a CY_3 can be conveniently packaged into a 2-form $J_{a\bar{b}}$ $a, \bar{b} = 1, 2, 3$ called the "Kähler form" and a 3-form Ω_{abc} (not to be confused with the world-sheet parity operator Ω_P). Ω_{abc} is called the holomorphic 3-form since it has 3 holomorphic indices.

The real scalar fields in $J_{a\bar{b}}$ control the size of 2-cycles inside the CY_3 :



The complex scalar fields inside Ω_{abc} determine the shape of the CY_3 manifold

[2D analogue  same volume but thinner]

From 10D to 4D SUGRA

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We can now reduce the 10D IIB SUGRA action

$$S_{\text{IIB}}^{\text{bosonic}} = \frac{1}{2\kappa_{10}^2} \int d^4x d^6y \sqrt{g} \left\{ R - \frac{\partial_M \tau \partial^M \tau}{\text{Im}(\tau)} - \frac{G_3 \cdot \bar{G}_3}{12 \text{Im}(\tau)} - \frac{\tilde{F}_5^2}{4 \cdot 5!} \right\} + \frac{1}{8_i \kappa_{10}^2} \int \frac{C_4 \wedge G_3 \wedge \bar{G}_3}{\text{Im}(\tau)} + S_{\text{loc}}$$

$$g_{MN} = \begin{pmatrix} e^{2A(y_i)} g_{\mu\nu} & 0 \\ 0 & e^{-2A(y_i)} g_{ij} \end{pmatrix}$$

$g_{\mu\nu}$ maximally symmetric:
Minkowski, dS or AdS

g_{ij} CY_3 metric
 $e^{A(y_i)}$ warp factor

$$F_{p+1} = dC_p \quad H_3 = dB_2$$

$$\tau = G_0 + i e^{-\phi}$$

$$G_3 = F_3 - \tau H_3$$

$$\tilde{F}_5 = F_5 - \frac{1}{2} C_2 \wedge H_3 + \frac{1}{2} B_2 \wedge F_3$$

S_{loc} contribution from O-planes and/or D-branes

$G_3 \cdot \bar{G}_3$ and \tilde{F}_5^2 denote contractions with the metric

Now we can reduce this to 4D \rightarrow takes some time (11)
 \rightarrow skip details

Simplifying assumptions:

- 1) Neglect KK-modes: $E \ll M_{KK}$
- 2) Neglect vectors (don't arise unless we have $H_+^3(CY_3) \neq 0$ ~~no~~ no even 3-cycles)
- 3) Assume B_{MN} & C_{2MN} don't contribute
 $\Leftrightarrow H_-^2(CY_3) = 0$ no odd 2-cycles

The resulting 4D theory is constrained by $\mathcal{N}=1$ supersymmetry.

4D $\mathcal{N}=1$ SUGRA

In 4D $\mathcal{N}=1$ SUGRA we have only complex scalars

$\tau = C_0 + i e^{-\phi}$ axio-dilaton scalar

$$\pi^A = \int \Omega_{abc} \sum_3^A$$

complex structure "moduli"
 $A=1,2,\dots,h^3$ (projective coordinates, only h^3-1 independent scalars)

$$T^B = \int C_4 + i \int J \sum_4^B$$

Kähler moduli
 $B=1,2,\dots,h_+^4 = h_+^{2,2} = h_+^4$

\uparrow
number of even 4-cycles

The 4D $\mathcal{N}=1$ SUGRA is described in terms (12)

of 2 functions (since we don't have vectors):

the holomorphic superpotential $W(\phi^I) \in \mathbb{C}$ all scalar fields
 $\phi^I = \{\tau, \theta^A, T^B\}$

the real Kähler potential $K(\phi^I, \bar{\phi}^{\bar{I}}) \in \mathbb{R}$

The bosonic action for $M_{Pl} = 1$ is

$$I^{\text{bosonic}} = - \int d^4x \sqrt{-g} \left[-\frac{1}{2} R + K_{I\bar{J}} \partial_\mu \phi^I \partial^\mu \bar{\phi}^{\bar{J}} + V(\phi^I, \bar{\phi}^{\bar{I}}) \right]$$

$$V(\phi^I, \bar{\phi}^{\bar{I}}) = e^K (K^{I\bar{J}} D_I W \overline{D_{\bar{J}} W} - 3|W|^2) \in \mathbb{R}$$

$$K_{I\bar{J}} = \partial_{\phi^I} \partial_{\bar{\phi}^{\bar{J}}} K(\phi^I, \bar{\phi}^{\bar{I}}), \quad K^{I\bar{J}} \text{ inverse matrix}$$

$$K^{I\bar{J}} K_{\bar{J}L} = \delta^I_L$$

$$D_I W = \partial_{\phi^I} W + W \partial_{\phi^I} K$$

In the (fluxless) case we have

$$K = -2 \ln(\text{vol}_6) - \ln(-i(\tau - \bar{\tau})) - \ln(-i \int_{CY_3} \Omega \wedge \bar{\Omega})$$

$$W=0 \Rightarrow V=0$$

$$\text{vol}_6 = K_{B_1 B_2 B_3} t^{B_1} t^{B_2} t^{B_3}$$

$$t^B = \int \gamma_{ab}^B$$

$$\sum_2^B$$

$$\text{Im}(T^B) = \frac{\partial(\text{vol}_6)}{\partial t^B}$$

The moduli problem

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We do not see any massless scalars. If there were massless scalars then corrections might lead to minima outside the regime of validity of our theory:

small volume $\text{Re}(T^B) \lesssim 1 \Rightarrow \alpha'$ corrections

large coupling $\text{Im}(\tau) = e^{-\phi} \lesssim 1 \Rightarrow$ string loop corrections

infinity $\text{vol}_6 \rightarrow 10D$ theory (decompactification limit)

very light scalars can also lead to 5th forces and problems in the early universe cosmology.

How do we ~~do~~ make the scalars heavy?

(see Giddings, Kachru, Polchinski
hep-th/005097)

3-form fluxes \bar{F}_3, H_3 through 3-cycles can stabilize the axio-dilaton at small coupling and all complex structure moduli:

$$W = \int_{C^3} G_3(\tau) \wedge \Omega_3(\Pi^A)$$

Gukov, Vafa, Witten
hep-th/9906070

Note: 1) CY_3 manifolds have no 1- and 5-cycles
 So we cannot turn on topologically
 non-trivial F_1 or F_5 .

2) The volume moduli are associated with even
 $0, 2, 4, 6$ -cycles but we have no fluxes with
 an even number of legs

3) Tad pole: The orientifold $O3$ -planes (as well as $D3$ -branes)
 and the $F_3 + H_3$ flux

$$d\tilde{F}_5 = ddC_4 + H_3 \wedge F_3 + S_{D3/O3}^{loc}$$

$$\int_{CY_3} d\tilde{F}_5 = 0 = \int_{CY_3} H_3 \wedge F_3 + Q_{D3/O3}^{loc}$$

There is an upper limit on the number of
 fluxes we can turn on

Let us restrict to the case of a single

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Kähler modulus T

$$\Rightarrow \text{vol}_6 = -i (T - \bar{T})^{\frac{3}{2}}$$

$$K = -3 \ln(-i(T - \bar{T})) - \ln(-i(\tau - \bar{\tau})) - \ln(-i \int_{CY_3} \Omega \wedge \bar{\Omega})$$

$$W = \int_{CY_3} G_3(\tau) \wedge \Omega(\pi^* A)$$

The Kähler sector enjoys a no-scale property:

$$D_T W = \partial_T W + W \partial_T K = -\frac{3W}{T - \bar{T}}$$

$$K_{T\bar{T}} = \partial_T \partial_{\bar{T}} K = -\frac{3}{(T - \bar{T})^2} = \frac{3}{4 \text{Im}(T)^2} > 0$$

$$K^{T\bar{T}} D_T W \overline{D_T W} = -\frac{(T - \bar{T})^2}{3} \left(-\frac{3W}{T - \bar{T}}\right) \left(+\frac{3\bar{W}}{T - \bar{T}}\right) = 3|W|^2$$

$$\Rightarrow V = e^K \left(K^{T\bar{T}} D_T W \overline{D_T W} + K^{\tau\bar{\tau}} D_\tau W \overline{D_\tau W} + K^{A_1 \bar{A}_2} D_{A_1} W \overline{D_{A_2} W} - 3|W|^2 \right)$$

$$= e^K \left(\underbrace{K^{\tau\bar{\tau}} D_\tau W \overline{D_\tau W}}_{\geq 0} + \underbrace{K^{A_1 \bar{A}_2} D_{A_1} W \overline{D_{A_2} W}}_{\geq 0} \right) \geq 0$$

T-independent

$$e^K \propto \frac{1}{i(T - \bar{T})^3} \Rightarrow D_\tau W = D_{A_1} W = 0 \quad \text{otherwise}$$

$\text{Im}(T)$ will run to infinity, i.e. to 10D flat space

We can find Minkowski solution ($V_{\min} = 0$)
 by solving $D_{\bar{T}} W = D_A W = 0$ but T remains a
 flat direction

SUSY is generically broken since

$$F_T = D_T W = -\frac{3W_{\min}}{T-\bar{T}} \text{ is generically not zero}$$

i.e. if $W_{\min} = \int G_3(\tau_{\min}) \wedge \Omega_3(\pi_{\min}^A) \neq 0$ then
 SUSY is broken

The first dS vacua (i.e. $V_{\min} > 0$) in string theory

Kachru, Kallosh, Linde, Trivedi hep-th/0301240

String theory does not allow for exact directions
 like a continuous shift symmetry
 $\Rightarrow \text{Re}(T)$ is lifted by corrections

1) Euclidean instantons can wrap 4 internal directions
 in the CY_3 (these branes are instantons = localized in time)

$$\Rightarrow W \rightarrow W + A e^{2\pi i T} \text{ breaks to a discrete shift symmetry}$$

"A" is a function of the complex structure moduli
 $A = A(\pi^A)$

2) A stack of D7-branes can extend along the 4 non-compact directions and wrap an internal 4-cycle. The D7-branes give rise to a non-abelian gauge theory with gauge group $SU(N)$.

If there is no "matter" (i.e. if $h^{1,1}(\Sigma^4) = 0$), then the theory undergoes gluino condensation $\langle \lambda\lambda \rangle \neq 0$. This also leads to a superpotential contribution

$$W \rightarrow W + A e^{2\pi i T/N}$$

3) The Kähler potential $K = -3 \ln(i(T - \bar{T}))$ receives α' corrections (see below)

The superpotential corrections of the form ~~ΔW~~ $\Delta W = A e^{i\alpha T}$ with $\alpha = \begin{cases} 2\pi & \text{ED3's} \\ 2\pi/N & \text{D7's} \end{cases}$ are exponentially

small for large volume (which we need to suppress corrections)

$$\Delta W = A e^{-a \text{Im}(T) + i\alpha \text{Re}(T)}$$

So ΔW is smaller than the flux contributions:

First stabilize all complex structure moduli and the axio-dilaton

$$\Rightarrow W = \int_{C^4_3} G_3(\tau_{\min}) \wedge \Omega_{\min} = W_0 = \text{const.}$$

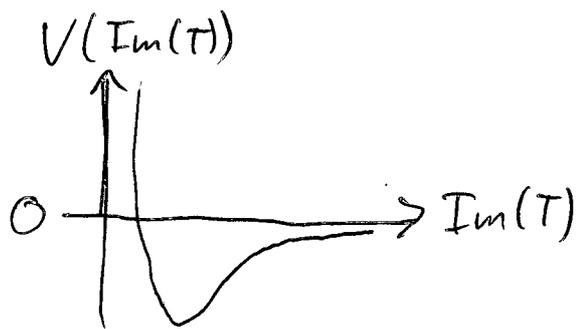
$$A(\tau_{\min}) = \text{const.}$$

Now we can study the Kähler modulus stabilization (18)

$$K = -3 \ln(-i(T - \bar{T}))$$

$$W = W_0 + A e^{2aT}$$

There exist a supersymmetric minimum that satisfies $D_T W = 0$. We find $\text{Re}(T) = 0$ and the following potential



- Problems:
- 1) Supersymmetry is not broken
 - 2) The value of the potential at the minimum $V_{\min} < 0$. Observation require $V_{\min} > 0$

Solution: Add an "uplifting term": an anti-D3-brane

This breaks supersymmetry spontaneously and adds a positive term to the potential

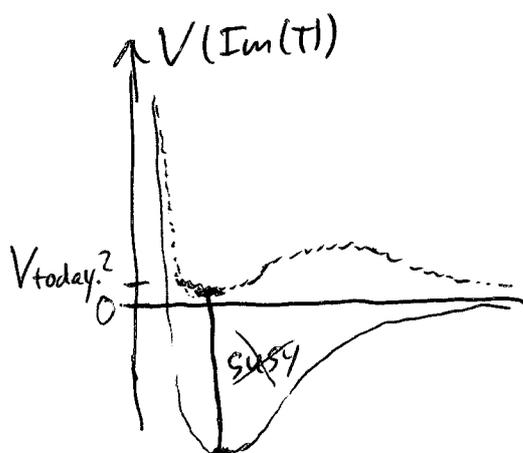
$$V \rightarrow V + \frac{D}{\text{Im}(T)^3} \quad (\text{or } V + \frac{D}{\text{Im}(T)^2} \text{ with warping})$$

For example for

$$W_0 = 10^{-4}, A = 1$$

$$a = 1, D = 3 \times 10^{-9}$$

one gets



Comments:

- The SUSY breaking scale ~~SUSY~~ is independent of $V_{min} = V_{today} > 0$
- W_0 is usually order 1 but cancellations can lead to $|W_0| \ll 1$
- $A=1$ is reasonable but hard to calculate in practice
- $\alpha = .1$ a stack of $N \approx 10 \cdot 2\pi$ D7-branes
- $D = 3 \times 10^{-9}$ is related to the tension of the anti-D3-brane
If the anti-D3-brane is in a region of strong warping $e^{-A} \gg 1$, then D is naturally exponentially small

The Large Volume Scenario (LVS)

Balasubramanian, Berglund, Conlon, Quevedo hep-th/0502058

- A different way of stabilizing the Kähler moduli sector
- Leads to exponentially large volume
- Uses α' corrections from string theory
- Requires at least two Kähler moduli and a CY_3 manifold of "swiss cheese type" with ~~positive~~ Euler number $\chi(CY_3) < 0 \Leftrightarrow h^{2,1} > h^{1,1}$
negative

$$K_{\text{Kähler}} = -2 \log(\text{vol}_6) \rightarrow -2 \log \left[\text{vol}_6 + \frac{\xi}{2} \left(\frac{-i(\tau - \bar{\tau})}{2} \right)^{3/2} \right] \quad (20)$$

$$\xi = - \frac{\zeta(3) \chi(CY_3)}{2(2\pi)^3}$$

α' -correction
see Becker, Becker, Haack,
Louis hep-th/0204254

need $\xi > 0$

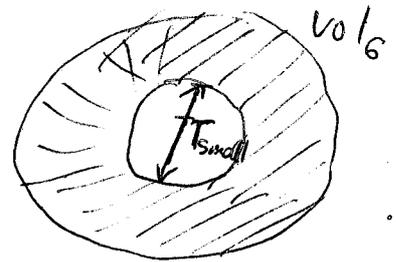
The superpotential is not renormalized in perturbation theory but will again receive the same non-perturbative corrections.

"Swiss cheese volume"

Restrict to two moduli $T_{\text{large}}, T_{\text{small}}$

$$\text{vol}_6 = \text{Im}(T_{\text{large}})^{3/2} - \text{Im}(T_{\text{small}})^{3/2}$$

$$\text{vol}_6 > 0 \Rightarrow \text{Im}(T_{\text{large}}) > \text{Im}(T_{\text{small}})$$



$$W = W_0 + A e^{i\alpha T_{\text{small}}} + \tilde{A} e^{i\tilde{\alpha} T_{\text{large}}}$$

subleading \Rightarrow neglect

Upon minimizing the scalar potential one

finds $\text{vol}_6 \propto e^{i\alpha \text{Im}(T_{\text{small}})} |W_0| \gg 1$

$$\text{Im}(T_{\text{small}}) \propto \xi \gg 1$$

$|W_0|$ does not need to be particularly small

(21)
The scalar potential has a non-supersymmetric
AdS minimum, i.e. $V_{\min} < 0$.

One can again obtain $V_{\min} > 0$ by adding
an anti-D3-brane as uplift.

The scales in string compactifications

string scale $M_s = \frac{1}{\sqrt{\alpha'}}$

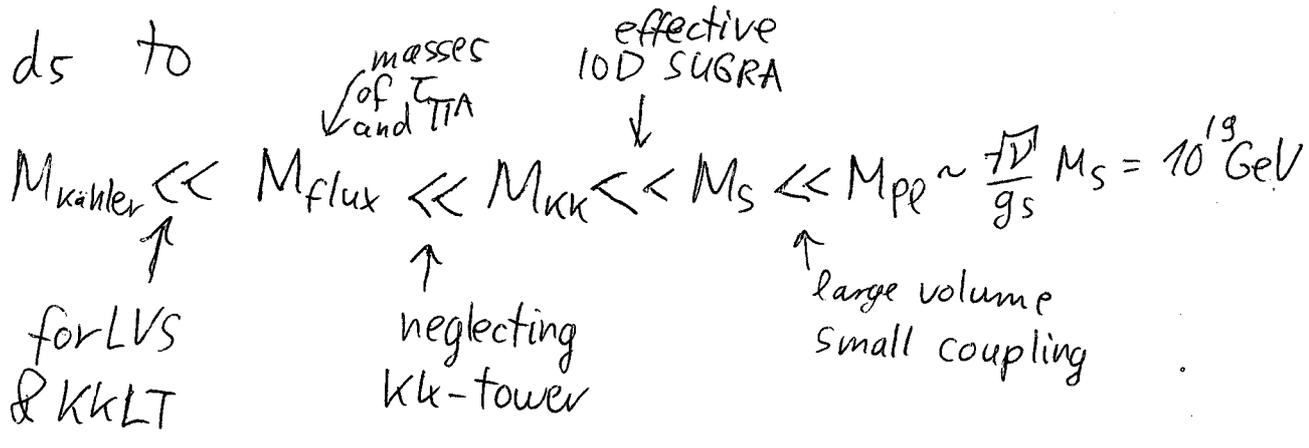
The internal volume $vol_6 = V (\alpha')^3 \Rightarrow M_{KK} \sim M_s V^{-1/6}$

4D Planck scale $M_{Pl} \sim \frac{1}{g_s} \left(\frac{M_s}{M_{KK}}\right)^3 M_s \sim \frac{\sqrt{V}}{g_s} M_s, g_s = e^\phi$

We want to neglect string loops $\Leftrightarrow e^\phi \ll 1$

(extra) α' corrections $\Leftrightarrow V \gg 1$

This leads to



For large field inflation with $V_{\text{inf}}^{1/4} \sim 10^{16} \text{ GeV}$ we can neglect only fields with masses above the Hubble

scale $H \sim \sqrt{V_{\text{inf}}^{1/4} M_{\text{Pl}}} \sim 10^{14} \text{ GeV}$

So ideally we want $M_{\text{Kähler}} \gg H \sim 10^{14} \text{ GeV}$

This is technically challenging but not impossible.