dS vacua and inflation

Timm Wrase

TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

INSTITUTE FOR THEORETICAL PHYSICS

Lecture 4

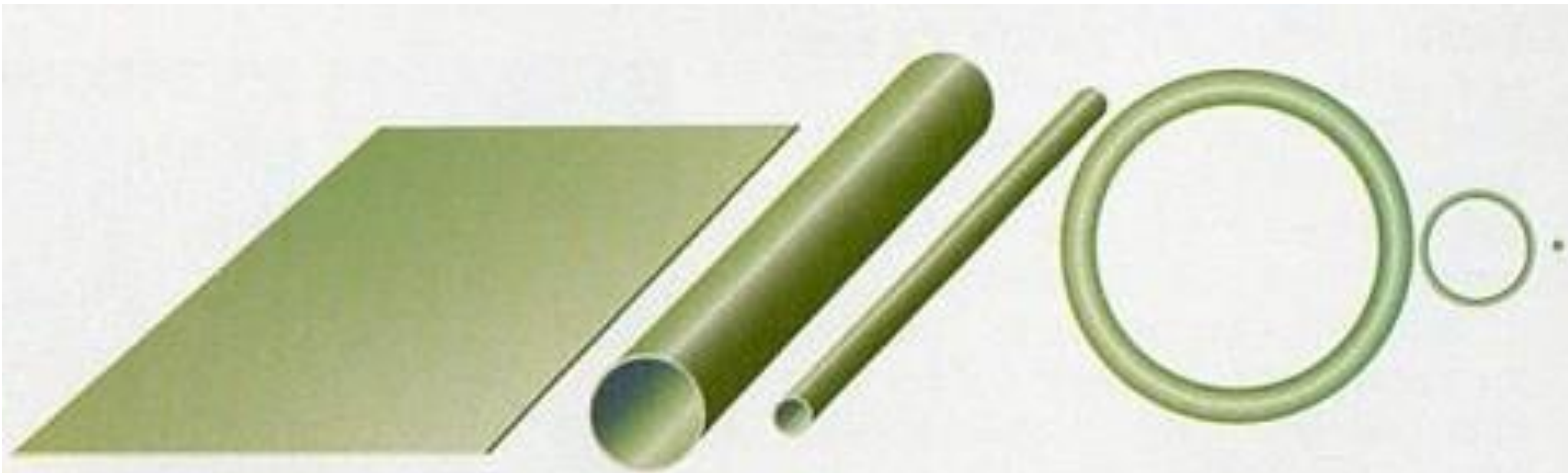
Recap lecture 3

- To study a full fledged string theory in a non-trivial background is very complicated
- The low energy limits of various string theories are 10 (9+1) dimensional theories of point particles

Recap lecture 3

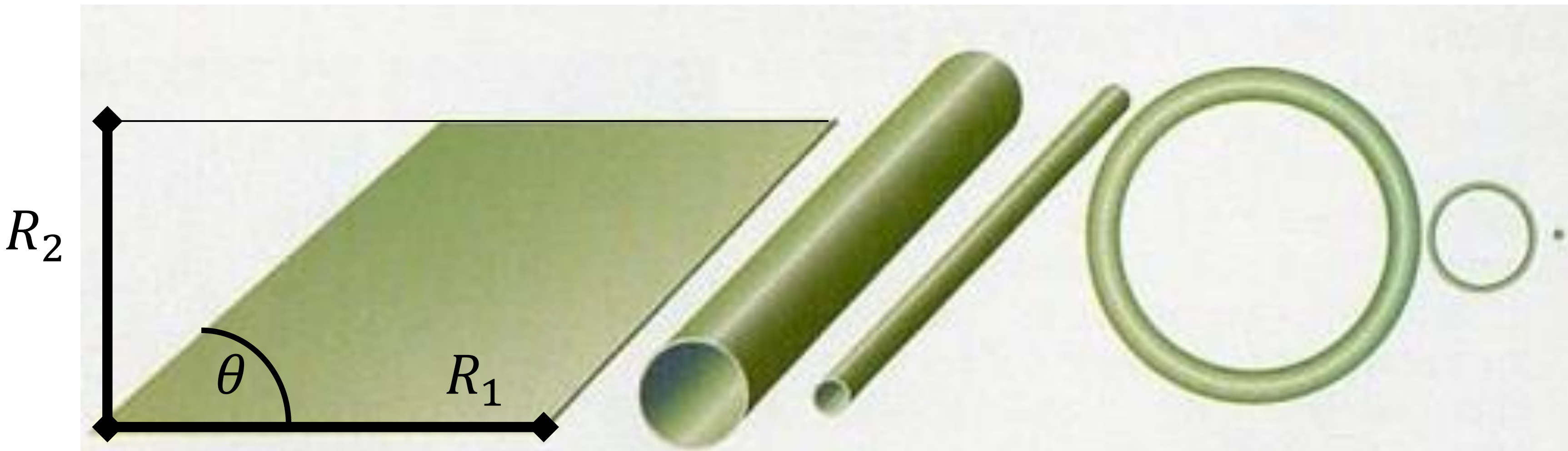
- To study a full fledged string theory in a non-trivial background is very complicated
- The low energy limits of various string theories are 10 (9+1) dimensional theories of point particles
- We can “compactify” 6 dimensions on the product of six circles (or more complicated spaces)
- This gives rise to a 4 (3+1) dimensional theory with many massless scalar fields plus many massive scalar fields (the so called KK-tower) with $M_{KK} \sim \frac{1}{R}$

Recap lecture 3



- Precision measurements of gravity require for a single extra dimension $R \leq 10^{-4}$ meters
- The Planck length is $l_p \approx 10^{-35}$ meters
- Plenty of room for extra dimensions of space

Recap lecture 3



- The simplest string compactification involves the product of three identical $T^2 = S^1 \times S^1$
- There are three real parameters

$R_1 R_2$ controls the size

$\frac{R_1}{R_2}$ and θ control the shape

Recap lecture 3

- These parameters appear in the metric

$$g_{MN}(x^\mu, y^I)$$

and are therefore spacetime dependent, i.e. they are dynamical fields

Recap lecture 3

- These parameters appear in the metric

$$g_{MN}(x^\mu, y^I)$$

  and are therefore spacetime dependent, i.e. they are dynamical fields

- Reducing our 10d theory to 4d via

$$S = \int d^4x d^6y \sqrt{-g_{10}}(\ldots) = \int d^4x \sqrt{-g_4}[\ldots]$$

  they will give rise to three real 4d scalar fields

Recap lecture 3

- The 10d theory contains other fields
- Two scalars ϕ and C_0 that can be combined into one complex scalar $S = C_0 + i\ e^{-\phi}$

Recap lecture 3

- The 10d theory contains other fields

- Two scalars ϕ and C_0 that can be combined into one complex scalar $S = C_0 + i\, e^{-\phi}$

- The string coupling (interaction strength) is given by

$$g_s = e^{\phi}$$

- One field with four indices that can extend along the internal directions C_{MNOP} to give a 4d scalar c_4

Recap lecture 3

- Upon reducing these to four dimensions we get:

- One complex 4d scalar $S(\mathrm{x}^{\mu}) = C_0 + i\, e^{-\phi}$
- One complex 4d scalar $T(x^{\mu}) = c_4 + (R_1 R_2)^2$
- One complex 4d sclar $U(x^{\mu}) \sim \frac{R_1}{R_2}\, e^{i\,\theta}$
- This is the so called STU model

Recap lecture 2

- Supergravity (SUGRA) is a theory that is invariant under local supersymmetry transformations
- This requires the theory to be invariant under local Lorentz transformations i.e. we need general relativity (GR)

Recap lecture 2

- Supergravity (SUGRA) is a theory that is invariant under local supersymmetry transformations
- This requires the theory to be invariant under local Lorentz transformations i.e. we need general relativity (GR)
- The invariance under this additional supersymmetry constrains the resulting theory
- The bosonic part of the action together with supersymmetry determines the fermionic action

Recap lecture 2

- In a 4d $N = 1$ theory without vectors the bosonic action is given by (we now set $M_P = 1$)

$$S = \int d^4x \sqrt{-g} \left(\frac{1}{2} R - K_{I\bar{J}} \partial_\mu \phi^I \partial^\mu \bar{\phi}^{\bar{J}} - V_F \right)$$

Recap lecture 2

- In a 4d $N = 1$ theory without vectors the bosonic action is given by (we now set $M_P = 1$)

$$S = \int d^4x \sqrt{-g} \left(\frac{1}{2} R - K_{I\bar{J}} \partial_\mu \phi^I \partial^\mu \bar{\phi}^{\bar{J}} - V_F \right)$$

$$V_F = e^K (K^{I\bar{J}} D_I W \overline{D_J W} - 3|W|^2)$$

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

$$K = K(\phi^I, \bar{\phi}^{\bar{J}}), \qquad W = W(\phi)$$

The STU model

- The string compactification from above for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

$$K = -\log\big(-i(S-\bar{S})\big) - 3\log\big(-i(T-\bar{T})\big) - 3\log\big(-i(U-\bar{U})\big)$$

$$W = 0$$

The STU model

- The string compactification from above for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

$$K = -\log\big(-i(S-\bar{S})\big) - 3\log\big(-i(T-\bar{T})\big) - 3\log\big(-i(U-\bar{U})\big)$$

$$W = 0$$

$$\Rightarrow \quad D_I W = \partial_{\phi^I} W - W\,\partial_\phi K = 0$$

The STU model

- The string compactification from above for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

$$K = -\log\left(-i(S - \bar{S})\right) - 3\log\left(-i(T - \bar{T})\right) - 3\log\left(-i(U - \bar{U})\right)$$

$$W = 0$$

$$\Rightarrow \quad D_I W = \partial_{\phi^I} W - W\,\partial_\phi K = 0$$

$$\Rightarrow \qquad V_F = e^K\left(K^{I\bar{J}} D_I W \overline{D_J W} - 3|W|^2\right) = 0$$

How do we generate a potential?

- We can threat the internal space with fluxes
- For example, we can have $F_{y^1 y^2} \neq 0$ so that

$$\int_{T^2} d^2y \sqrt{g_{T^2}} F_{y^1 y^2} F^{y^1 y^2} = V(\phi^I) \neq 0$$

How do we generate a potential?

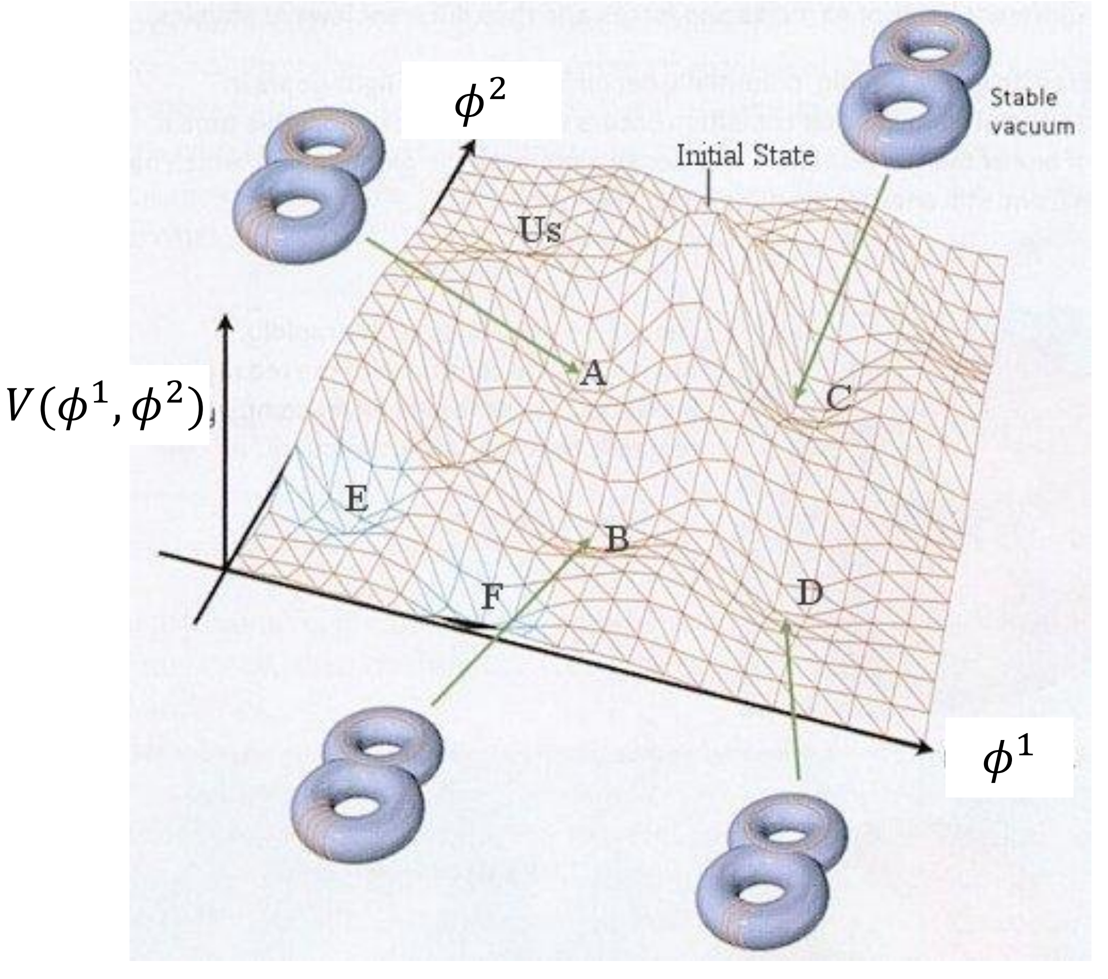
- We can threat the internal space with fluxes
- For example, we can have $F_{y^1 y^2} \neq 0$ so that

$$\int_{T^2} d^2y \sqrt{g_{T^2}} F_{y^1 y^2} F^{y^1 y^2} = V(\phi^I) \neq 0$$

- The particular type IIB string theory only has fluxes with 3-indices that we can turn on F_{MNO} and H_{MNO}

How do we generate a potential?

- We can threat the internal space with fluxes



The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

$$K = -\log\left(-i(S-\bar{S})\right) - 3\log\left(-i(T-\bar{T})\right) - 3\log\left(-i(U-\bar{U})\right)$$

$$W = W_{GVW}(S, U)$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

$$K = -\log\big(-i(S-\bar{S})\big) - 3\log\big(-i(T-\bar{T})\big) - 3\log\big(-i(U-\bar{U})\big)$$

$$W = W_{GVW}(S, U)$$

$$\begin{aligned} D_T W &= \partial_T W + W \partial_T K = 0 - \frac{3W}{T-\bar{T}}\,, \\ K_{T\bar{T}} &= \partial_T \partial_{\bar{T}} K = -\frac{3}{(T-\bar{T})^2}\,. \end{aligned}$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

$$K = -\log\bigl(-i(S-\bar{S})\bigr) - 3\log\bigl(-i(T-\bar{T})\bigr) - 3\log\bigl(-i(U-\bar{U})\bigr)$$

$$W = W_{GVW}(S, U)$$

$$\begin{aligned} D_T W &= \partial_T W + W\partial_T K = 0 - \frac{3W}{T-\bar{T}}\,, \\ K_{T\bar{T}} &= \partial_T \partial_{\bar{T}} K = -\frac{3}{(T-\bar{T})^2}\,. \end{aligned}$$

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

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

$$K = -\log\big(-i(S-\bar{S})\big) - 3\log\big(-i(T-\bar{T})\big) - 3\log\big(-i(U-\bar{U})\big)$$

$$W = W_{GVW}(S,U)$$

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

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

$$K = -\log\left(-i(S-\bar{S})\right) - 3\log\left(-i(T-\bar{T})\right) - 3\log\left(-i(U-\bar{U})\right)$$

$$W = W_{GVW}(S, U)$$

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

$$V = e^K \left(K^{T\bar{T}} D_T W \overline{D_T W} + K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{j}}} D_{U^i} W \overline{D_{U^j} W} - 3|W|^2\right)$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

$$K = -\log\big(-i(S-\bar{S})\big) - 3\log\big(-i(T-\bar{T})\big) - 3\log\big(-i(U-\bar{U})\big)$$

$$W = W_{GVW}(S, U)$$

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

$$\begin{aligned} V &= e^K \left(K^{T\bar{T}} D_T W \overline{D_T W} + K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i\bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^j} W} - 3|W|^2\right) \\ &= e^K \left(K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i\bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^j} W}\right) . \end{aligned}$$

The STU model

$$\begin{aligned} V &= e^K \left(K^{T\bar{T}} D_T W \overline{D_T W} + K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^j} W} - 3|W|^2 \right) \\ &= e^K \left(K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^j} W} \right) . \end{aligned}$$

The STU model

$$
\begin{aligned}
V &= e^K \left(K^{T\bar{T}} D_T W \overline{D_T W} + K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^{\jmath}} W} - 3|W|^2 \right) \\
&= e^K \left(K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^{\jmath}} W} \right) .
\end{aligned}
$$

- The modulus T satisfies the so called *no-scale property* since its contribution inside the parenthesis cancels the $-3|W|^2$ term.

The STU model

$$
\begin{aligned}
V &= e^K \left(K^{T\bar{T}} D_T W \overline{D_T W} + K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{j}}} D_{U^i} W \overline{D_{U^j} W} - 3|W|^2 \right) \\
&= e^K \left(K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{j}}} D_{U^i} W \overline{D_{U^j} W} \right) .
\end{aligned}
$$

- The modulus T satisfies the so called *no-scale property* since its contribution inside the parenthesis cancels the $-3|W|^2$ term.

- The Kähler metric controls the kinetic terms and therefore has to be positive definite. This means that the above scalar potential is the sum of two positive definite terms.

The STU model

$$
\begin{aligned}
V &= e^K \left(K^{T\bar{T}} D_T W \overline{D_T W} + K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^j} W} - 3|W|^2 \right) \\
&= e^K \left(K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^j} W} \right) .
\end{aligned}
$$

- The modulus T satisfies the so called *no-scale property* since its contribution inside the parenthesis cancels the $-3|W|^2$ term.
- The Kähler metric controls the kinetic terms and therefore has to be positive definite. This means that the above scalar potential is the sum of two positive definite terms.

$$
e^K \propto e^{-3\log\left(-i\,(T-\bar{T})\right)} = \frac{1}{8\,Im(T)^3} \quad \Rightarrow \quad V = \frac{1}{8\,Im(T)^3} F(S, U, \bar{S}, \bar{U})
$$

The STU model

$$
\begin{aligned}
V &= e^K \left(K^{T\bar{T}} D_T W \overline{D_T W} + K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^j} W} - 3|W|^2 \right) \\
&= e^K \left(K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^j} W} \right) .
\end{aligned}
$$

- The modulus T satisfies the so called *no-scale property* since its contribution inside the parenthesis cancels the $-3|W|^2$ term.

- The Kähler metric controls the kinetic terms and therefore has to be positive definite. This means that the above scalar potential is the sum of two positive definite terms.

$$
e^K \propto e^{-3\log(-i\,(T-\bar{T}))} = \frac{1}{8\,Im(T)^3} \quad \Rightarrow \quad V = \frac{1}{8\,Im(T)^3} F(S, U, \bar{S}, \bar{U})
$$

$$
\partial_{Im(T)} V = -\frac{3}{8\,Im(T)^3} F(S, U, \bar{S}, \bar{U}) \quad \Rightarrow \quad Im(T) = \infty \quad \text{or} \quad F = 0
$$

The STU model

$$
\begin{aligned}
V &= e^K \left(K^{T\bar{T}} D_T W \overline{D_T W} + K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^{\jmath}} W} - 3|W|^2 \right) \\
&= e^K \left(K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^{\jmath}} W} \right) .
\end{aligned}
$$

- The modulus T satisfies the so called *no-scale property* since its contribution inside the parenthesis cancels the $-3|W|^2$ term.

- The Kähler metric controls the kinetic terms and therefore has to be positive definite. This means that the above scalar potential is the sum of two positive definite terms.

$$
e^K \propto e^{-3\log(-i\,(T-\bar{T}))} = \frac{1}{8\,Im(T)^3} \quad \Rightarrow \quad V = \frac{1}{8\,Im(T)^3} F(S, U, \bar{S}, \bar{U})
$$

$$
\partial_{Im(T)} V = -\frac{3}{8\,Im(T)^3} F(S, U, \bar{S}, \bar{U}) \quad \Rightarrow \quad Im(T) = \infty \quad \text{or} \quad F = 0
$$

Size of the internal space is infinite! Not 4d!

The STU model

$$\begin{aligned} V &= e^K \left(K^{T\bar{T}} D_T W \overline{D_T W} + K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^{\jmath}} W} - 3|W|^2 \right) \\ &= e^K \left(K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^{\jmath}} W} \right) . \end{aligned}$$

- The modulus T satisfies the so called *no-scale property* since its contribution inside the parenthesis cancels the $-3|W|^2$ term.
- The Kähler metric controls the kinetic terms and therefore has to be positive definite. This means that the above scalar potential is the sum of two positive definite terms.

$$e^K \propto e^{-3\log(-i\,(T-\bar{T}))} = \frac{1}{8\,Im(T)^3} \quad \Rightarrow \quad V = \frac{1}{8\,Im(T)^3} F(S,U,\bar{S},\bar{U})$$

$$\partial_{Im(T)} V = -\frac{3}{8\,Im(T)^3} F(S,U,\bar{S},\bar{U}) \quad \Rightarrow \quad Im(T) = \infty \quad \text{or} \quad F = 0$$

Need $D_U W = D_S W = 0$

The STU model

$$
\begin{aligned}
V &= e^K \left(K^{T\bar{T}} D_T W \overline{D_T W} + K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^{\jmath}} W} - 3|W|^2 \right) \\
&= e^K \left(K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^{\jmath}} W} \right) .
\end{aligned}
$$

Need $D_U W = D_S W = 0$

- We have to solve two complex equations for two complex variables S and U

The STU model

$$\begin{aligned} V &= e^K \left(K^{T\bar{T}} D_T W \overline{D_T W} + K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^{\jmath}} W} - 3|W|^2 \right) \\ &= e^K \left(K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^{\jmath}} W} \right) . \end{aligned}$$

Need $D_U W = D_S W = 0$

- We have to solve two complex equations for two complex variables S and U
- Generic solutions are isolated points (no massless directions)

The STU model

$$
\begin{aligned}
V &= e^K \left(K^{T\bar{T}} D_T W \overline{D_T W} + K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^j} W} - 3|W|^2 \right) \\
&= e^K \left(K^{S\bar{S}} D_S W \overline{D_S W} + K^{U^i \bar{U}^{\bar{\jmath}}} D_{U^i} W \overline{D_{U^j} W} \right) .
\end{aligned}
$$

Need $D_U W = D_S W = 0$

- We have to solve two complex equations for two complex variables S and U
- Generic solutions are isolated points (no massless directions)
- The masses have to positive since $V \geq 0$ so that $V(S_{min}, U_{min}) = 0$ is a global minimum

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

$$K = -\log\big(-i(S-\bar{S})\big) - 3\log\big(-i(T-\bar{T})\big) - 3\log\big(-i(U-\bar{U})\big)$$

$$W = W_{GVW}(S, U)$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

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

$$W = W_{GVW}(S, U) \to W_{GVW}(S_{min}, U_{min}) = W_0 = const.$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

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

$$W = W_0$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

$$K = -3\log\left(-i(T - \bar{T})\right)$$

$$W = W_0$$

- $Re(T) \rightarrow Re(T) + c$, is a continuous shift symmetry which is forbidden in string theory (potentially in any theory of quantum gravity)

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

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

$$W = W_0$$

- $Re(T) \to Re(T) + c$, is a continuous shift symmetry which is forbidden in string theory (potentially in any theory of quantum gravity)
- There are non-perturbative corrections that lift it

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

$$K = -3\log\left(-i(T - \bar{T})\right)$$

$$W = W_0 + \mathrm{A}e^{\mathrm{iaT}} + \mathrm{c}\left(\mathrm{A}\,\mathrm{e}^{\mathrm{iaT}}\right)^2 + \cdots \qquad\qquad \mathrm{A, a, c} \sim \mathrm{O}(1)$$

- $Re(T) \to Re(T) + x$, is a continuous shift symmetry which is forbidden in string theory (potentially in any theory of quantum gravity)
- There are non-perturbative corrections that lift it

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

$$K = -3\log\left(-i(T - \bar{T})\right)$$

$$W = W_0 + \mathrm{Ae}^{\mathrm{iaT}} + \mathrm{c}\left(\mathrm{A\ e}^{\mathrm{iaT}}\right)^2 + \cdots$$

- To keep only the leading term we need

$$\left|\mathrm{Ae}^{\mathrm{iaT}}\right| \gg \left|\mathrm{Ae}^{\mathrm{iaT}}\right|^2$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

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

$$W = W_0 + \mathrm{A}\mathrm{e}^{\mathrm{iaT}} + \mathrm{c}\left(\mathrm{A}\ \mathrm{e}^{\mathrm{iaT}}\right)^2 + \cdots$$

- To keep only the leading term we need

$$\left|\mathrm{A}\mathrm{e}^{\mathrm{iaT}}\right| \gg \left|\mathrm{A}\mathrm{e}^{\mathrm{iaT}}\right|^2$$

$$1 \gg \left|\mathrm{A}\mathrm{e}^{\mathrm{iaT}}\right| = |Ae^{-a\,Im(T)}|$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

$$K = -3\log\left(-i(T - \bar{T})\right)$$

$$W = W_0 + \mathrm{Ae^{iaT}} + \mathrm{c}\left(\mathrm{A\ e^{iaT}}\right)^2 + \cdots$$

- To keep only the leading term we need

$$\left|\mathrm{Ae^{iaT}}\right| \gg \left|\mathrm{Ae^{iaT}}\right|^2$$

$$1 \gg \left|\mathrm{Ae^{iaT}}\right| = |Ae^{-a\,Im(T)}|$$

$$a\,Im(T) > 1$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

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

$$W = W_0 + \mathrm{Ae}^{\mathrm{iaT}}$$

$$D_T W = \partial_T W + W \partial_T K = \mathrm{i}aAe^{\mathrm{i}aT} - 3\frac{W_0 + Ae^{\mathrm{i}aT}}{T - \bar{T}}$$

$$T = b + \mathrm{i}\rho$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

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

$$W = W_0 + \mathrm{Ae^{iaT}}$$

$$D_T W = \partial_T W + W \partial_T K = \mathrm{i}aAe^{\mathrm{i}aT} - 3\frac{W_0 + Ae^{\mathrm{i}aT}}{T - \bar{T}} \qquad T = b + \mathrm{i}\rho$$

$$0 = \mathrm{Re}(D_T W) = -aAe^{-a\rho}\mathrm{Im}(e^{\mathrm{i}ab}) - 3\frac{Ae^{-a\rho}\mathrm{Im}(e^{\mathrm{i}ab})}{2\rho}$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

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

$$W = W_0 + \mathrm{Ae}^{\mathrm{iaT}}$$

$$D_T W = \partial_T W + W \partial_T K = \mathrm{i}aAe^{\mathrm{i}aT} - 3\frac{W_0 + Ae^{\mathrm{i}aT}}{T - \bar{T}} \qquad T = b + \mathrm{i}\rho$$

$$0 = \mathrm{Re}(D_T W) = -aAe^{-a\rho}\mathrm{Im}(e^{\mathrm{i}ab}) - 3\frac{Ae^{-a\rho}\mathrm{Im}(e^{\mathrm{i}ab})}{2\rho} \qquad \mathrm{Re}(T) = b = 0$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

$$K = -3\log\left(-i(T - \bar{T})\right)$$

$$W = W_0 + \mathrm{Ae^{iaT}}$$

$$D_T W = \partial_T W + W \partial_T K = \mathrm{i}aAe^{\mathrm{i}aT} - 3\frac{W_0 + Ae^{\mathrm{i}aT}}{T - \bar{T}} \qquad T = b + \mathrm{i}\rho$$

$$0 = \mathrm{Re}(D_T W) = -aAe^{-a\rho}\mathrm{Im}(e^{\mathrm{i}ab}) - 3\frac{Ae^{-a\rho}\mathrm{Im}(e^{\mathrm{i}ab})}{2\rho} \qquad \mathrm{Re}(T) = b = 0$$

$$0 = \mathrm{Im}(D_T W) = aAe^{-a\rho} + 3\frac{W_0 + Ae^{-a\rho}}{2\rho}$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

$$K = -3\log\left(-i(T - \bar{T})\right)$$

$$W = W_0 + \mathrm{Ae}^{\mathrm{iaT}}$$

$$D_T W = \partial_T W + W \partial_T K = \mathrm{i}aAe^{\mathrm{i}aT} - 3\frac{W_0 + Ae^{\mathrm{i}aT}}{T - \bar{T}}$$

$$T = b + \mathrm{i}\rho$$

$$0 = \mathrm{Re}(D_T W) = -aAe^{-a\rho}\mathrm{Im}(e^{\mathrm{i}ab}) - 3\frac{Ae^{-a\rho}\mathrm{Im}(e^{\mathrm{i}ab})}{2\rho}$$

$$\mathrm{Re}(T) = b = 0$$

$$0 = \mathrm{Im}(D_T W) = aAe^{-a\rho} + 3\frac{W_0 + Ae^{-a\rho}}{2\rho}$$

$$W_0 = -Ae^{-a\rho_{min}}\left(1 + \frac{2}{3}a\rho_{min}\right) \neq 0$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

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

$$W = W_0 + \mathrm{A}\mathrm{e}^{\mathrm{iaT}}$$

$$T = b + \mathrm{i}\rho \qquad \mathrm{Re}(T) = b = 0 \qquad W_0 = -Ae^{-a\rho_{min}}\left(1 + \frac{2}{3}a\rho_{min}\right) \neq 0$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U\}$ gives after compactification

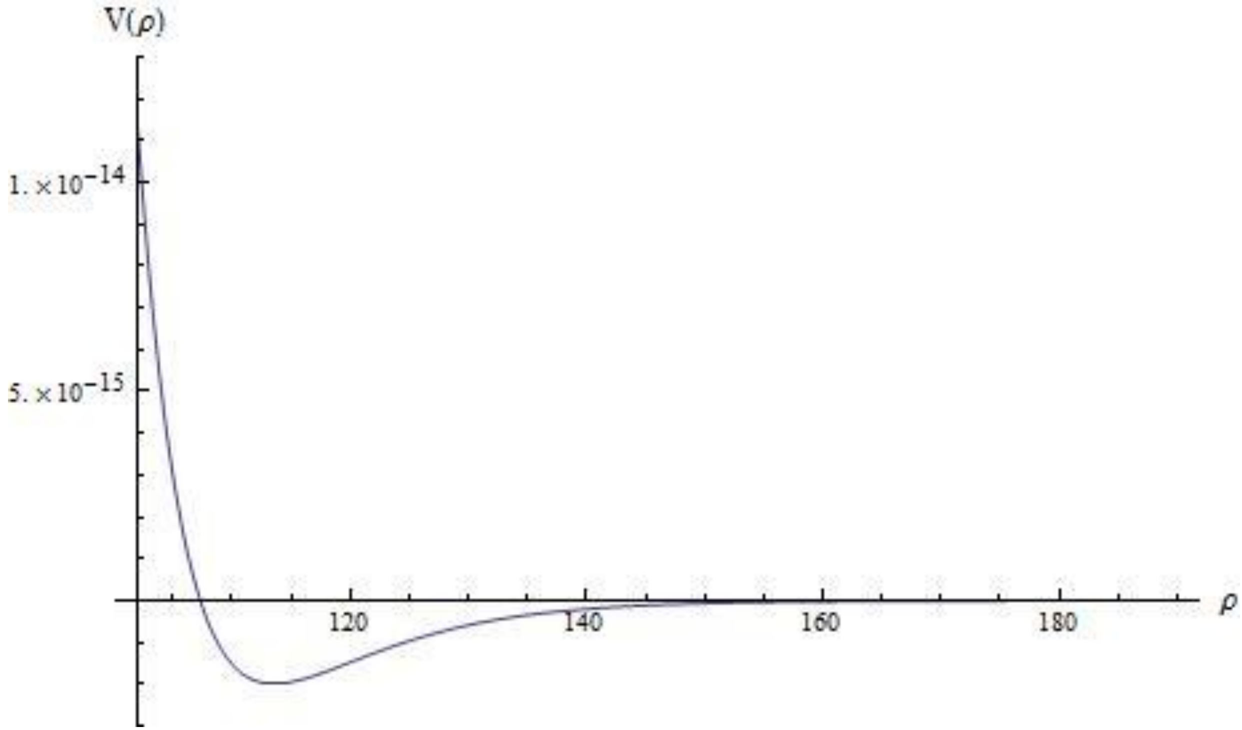
$$K = -3\log\left(-i(T - \bar{T})\right)$$

$$W = W_0 + \mathrm{Ae}^{\mathrm{iaT}}$$

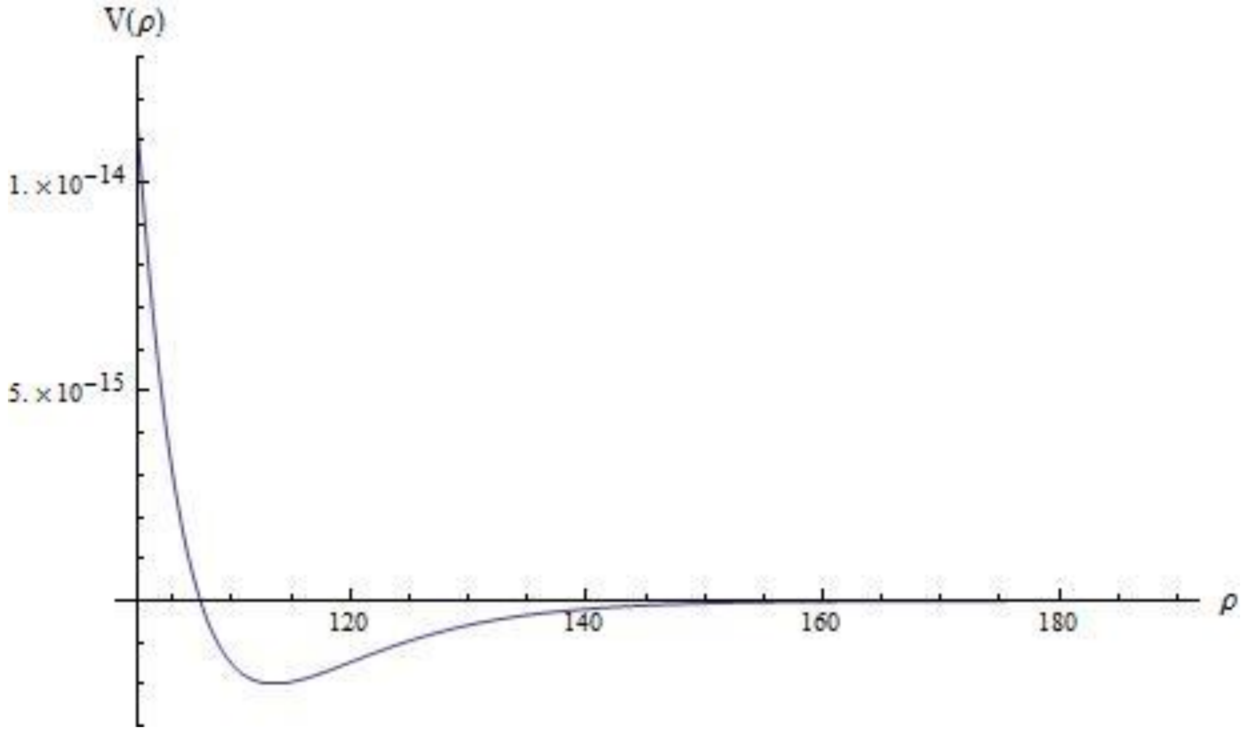
$$T = b + \mathrm{i}\rho \qquad \mathrm{Re}(T) = b = 0 \qquad W_0 = -Ae^{-a\rho_{min}}\left(1 + \frac{2}{3}a\rho_{min}\right) \neq 0$$

$$V_F = e^K\left(K^{T\bar{T}} D_T W \overline{D_T W} - 3|W|^2\right) \xrightarrow{D_T W = 0} V_F = -3e^K|W|^2 < 0$$

The STU model



The STU model



- We need a new ingredient that takes us to $V_{min} > 0$
- Can add a higher dimensional stringy object $\overline{D3}$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U, N\}$ gives after compactification

$$K = -3\log\left(-i(T - \bar{T})\right) + N\bar{N}$$

$$W = W_0 + \mathrm{Ae}^{\mathrm{iaT}} + \mu\, N \equiv W_{KKLT} + \mu\, N$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U, N\}$ gives after compactification

$$K = -3\log\big(-i(T-\bar{T})\big) + N\bar{N}$$

$$W = W_0 + \mathrm{Ae}^{\mathrm{iaT}} + \mu\, N \equiv W_{KKLT} + \mu\, N$$

- N is very special it does not correspond to a usual supersymmetry multiplet with scalar and fermion. It contains only one single fermion χ. χ is the goldstino

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U, N\}$ gives after compactification

$$K = -3\log\big(-i(T-\bar{T})\big) + N\bar{N}$$

$$W = W_0 + \mathrm{Ae}^{\mathrm{iaT}} + \mu\, N \equiv W_{KKLT} + \mu\, N$$

- N is very special it does not correspond to a usual supersymmetry multiplet with scalar and fermion. It contains only one single fermion χ. χ is the goldstino
- Supersymmetry is now broken and non-linearly realized
- The would be scalar in N is a fermion bilinear $\chi\chi$!

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U, N\}$ gives after compactification

$$K = -3\log\big(-i(T - \bar{T})\big) + N\bar{N}$$

$$W = W_0 + \mathrm{A}\mathrm{e}^{\mathrm{iaT}} + \mu\, N \equiv W_{KKLT} + \mu\, N$$

- Use the usual formula but set $N = 0$ in the end since it is a fermion bilinear and we only care about the scalars

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U, N\}$ gives after compactification

$$K = -3\log\big(-i(T-\bar{T})\big) + N\bar{N}$$

$$W = W_0 + \mathrm{Ae}^{\mathrm{iaT}} + \mu\, N \equiv W_{KKLT} + \mu\, N$$

- Use the usual formula but set $N = 0$ in the end since it is a fermion bilinear and we only care about the scalars

$$D_N W \;=\; \partial_N W + W\partial_N K = \mu + W\bar{N} = \mu\,,$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U, N\}$ gives after compactification

$$K = -3\log\big(-i(T-\bar{T})\big) + N\bar{N}$$

$$W = W_0 + \mathrm{Ae}^{\mathrm{iaT}} + \mu\, N \equiv W_{KKLT} + \mu\, N$$

- Use the usual formula but set $N = 0$ in the end since it is a fermion bilinear and we only care about the scalars

$$\begin{aligned} D_N W &= \partial_N W + W\partial_N K = \mu + W\bar{N} = \mu\,, \\ D_T W &= \partial_T W + W\partial_T K = \partial_T W_{KKLT} - \frac{3}{T-\bar{T}} W_{KKLT} \equiv D_T W_{KKLT} \end{aligned}$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U, N\}$ gives after compactification

$$K = -3\log\big(-i(T - \bar{T})\big) + N\bar{N}$$

$$W = W_0 + \mathrm{Ae}^{\mathrm{iaT}} + \mu\, N \equiv W_{KKLT} + \mu\, N$$

$$\begin{aligned} D_N W &= \partial_N W + W\partial_N K = \mu + W\bar{N} = \mu\,, \\ D_T W &= \partial_T W + W\partial_T K = \partial_T W_{KKLT} - \frac{3}{T - \bar{T}} W_{KKLT} \equiv D_T W_{KKLT} \end{aligned}$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U, N\}$ gives after compactification

$$K = -3\log\big(-i(T-\bar{T})\big) + N\bar{N}$$

$$W = W_0 + \mathrm{Ae}^{\mathrm{iaT}} + \mu\, N \equiv W_{KKLT} + \mu\, N$$

$$\begin{aligned} D_N W &= \partial_N W + W \partial_N K = \mu + W\bar{N} = \mu\,, \\ D_T W &= \partial_T W + W \partial_T K = \partial_T W_{KKLT} - \frac{3}{T-\bar{T}} W_{KKLT} \equiv D_T W_{KKLT} \end{aligned}$$

We see that supersymmetry is now broken since $D_N W = \mu \neq 0$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U, N\}$ gives after compactification

$$K = -3\log\big(-i(T-\bar{T})\big) + N\bar{N}$$

$$W = W_0 + \mathrm{Ae}^{\mathrm{iaT}} + \mu\, N \equiv W_{KKLT} + \mu\, N$$

$$\begin{aligned} D_N W &= \partial_N W + W\partial_N K = \mu + W\bar{N} = \mu\,, \\ D_T W &= \partial_T W + W\partial_T K = \partial_T W_{KKLT} - \frac{3}{T-\bar{T}} W_{KKLT} \equiv D_T W_{KKLT} \\ V &= e^K (K^{T\bar{T}} D_T W \overline{D_T W} + K^{N\bar{N}} D_N W \overline{D_N W} - 3|W|^2) \end{aligned}$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U, N\}$ gives after compactification

$$K = -3\log\big(-i(T-\bar{T})\big) + N\bar{N}$$

$$W = W_0 + \mathrm{Ae}^{\mathrm{iaT}} + \mu\, N \equiv W_{KKLT} + \mu\, N$$

$$\begin{aligned} D_N W &= \partial_N W + W\partial_N K = \mu + W\bar{N} = \mu\,, \\ D_T W &= \partial_T W + W\partial_T K = \partial_T W_{KKLT} - \frac{3}{T-\bar{T}} W_{KKLT} \equiv D_T W_{KKLT} \end{aligned}$$

$$\begin{aligned} V &= e^K (K^{T\bar{T}} D_T W \overline{D_T W} + K^{N\bar{N}} D_N W \overline{D_N W} - 3|W|^2) \\ &= \frac{1}{8\rho^3} (K^{T\bar{T}} D_T W_{KKLT} \overline{D_T W_{KKLT}} + |\mu|^2 - 3|W_{KKLT}|^2) \end{aligned}$$

The STU model

- The string compactification from above with fluxes for $\{\phi^I\} = \{S, T, U, N\}$ gives after compactification

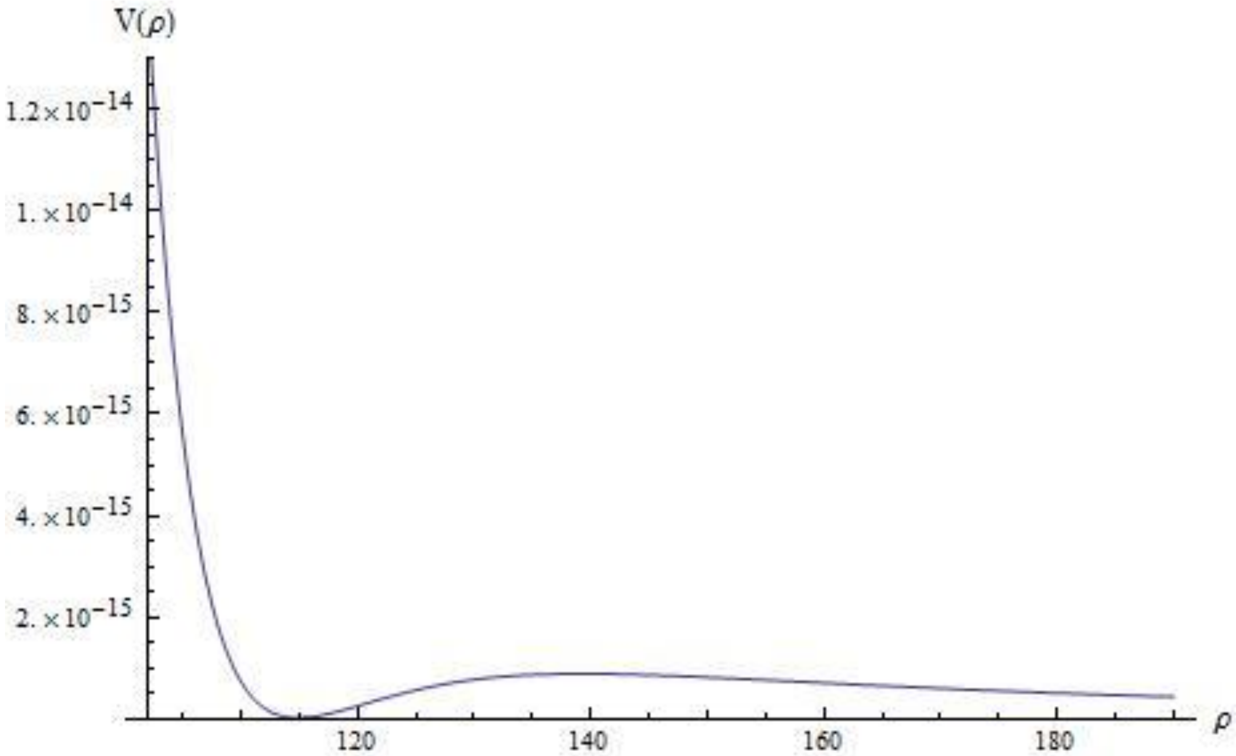
$$K = -3\log\big(-i(T-\bar{T})\big) + N\bar{N}$$

$$W = W_0 + \mathrm{Ae}^{\mathrm{iaT}} + \mu\, N \equiv W_{KKLT} + \mu\, N$$

$$\begin{aligned} D_N W &= \partial_N W + W \partial_N K = \mu + W\bar{N} = \mu\,, \\ D_T W &= \partial_T W + W \partial_T K = \partial_T W_{KKLT} - \frac{3}{T-\bar{T}} W_{KKLT} \equiv D_T W_{KKLT} \end{aligned}$$

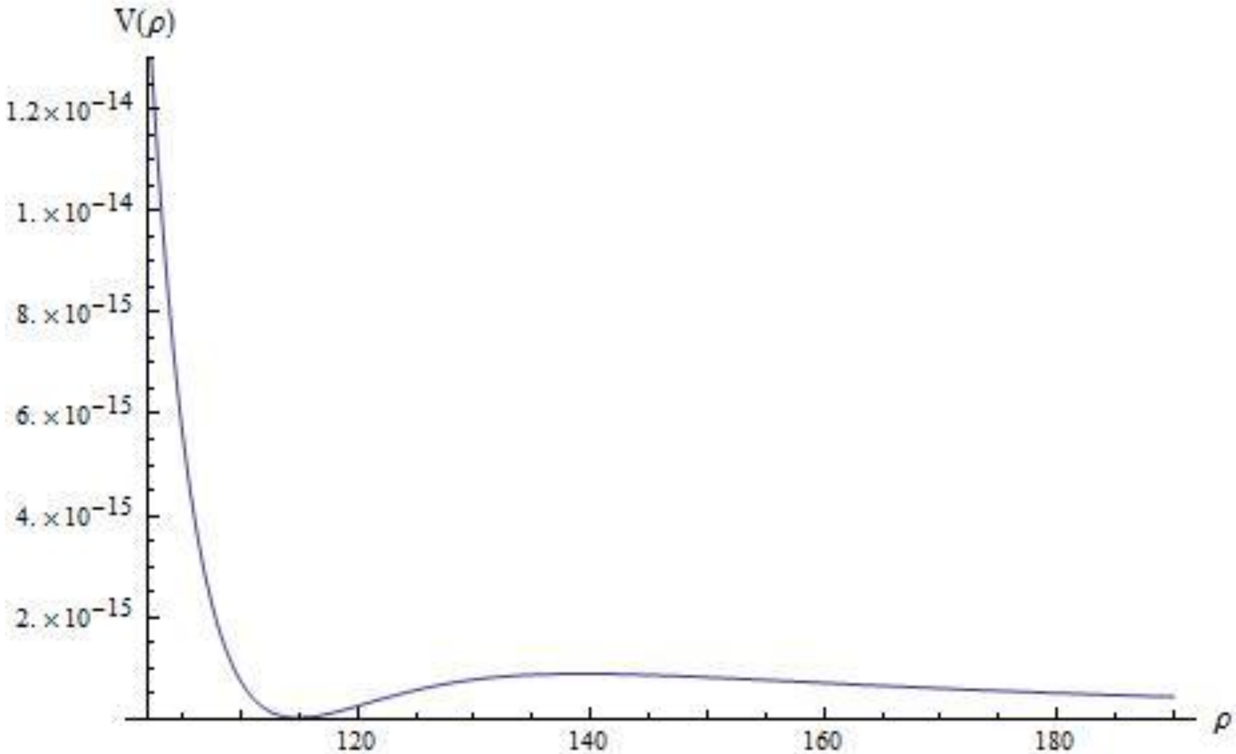
$$\begin{aligned} V &= e^K (K^{T\bar{T}} D_T W \overline{D_T W} + K^{N\bar{N}} D_N W \overline{D_N W} - 3|W|^2) \\ &= \frac{1}{8\rho^3}(K^{T\bar{T}} D_T W_{KKLT} \overline{D_T W_{KKLT}} + |\mu|^2 - 3|W_{KKLT}|^2) \\ &= V_{KKLT} + \frac{|\mu|^2}{8\rho^3}\,. \end{aligned}$$

The STU model



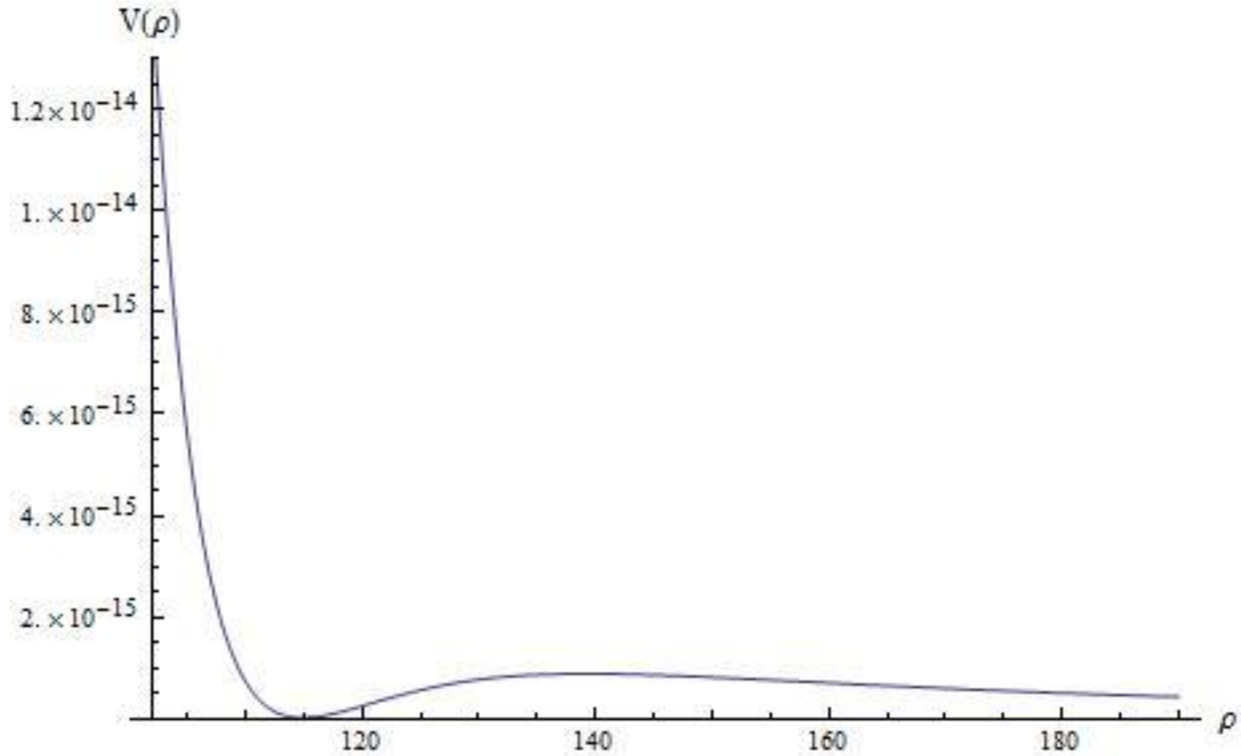
- For an appropriate choice of μ we find $V_{min} > 0$

The STU model



- For an appropriate choice of μ we find $V_{min} > 0$
- One can in principle fine-tune $V_{min} \approx 10^{-120}$

The STU model



- For an appropriate choice of μ we find $V_{min} > 0$
- One can in principle fine-tune $V_{min} \approx 10^{-120}$
- SUSY breaking scale $D_N W = \mu$ independent of V_{min}