$T^a = t^a + i b^a$ Kähler moduli

$z^\alpha = u^\alpha + i \cdot v^\alpha$ c.s. moduli

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

kinetic terms from Kähler potential K:

$$K = -\ln\left(i(\tau - \bar\tau)\right) - 2\ln \mathcal{V}_{CY_3}(T^a, \bar T^{\bar a}) \Big|\ \text{quantum corrections}$$

$$- \ln\left(-i \int \Omega_3(z^\alpha) \wedge \bar\Omega(\bar z^{\bar\alpha})\right) + \underbrace{\Delta K_{\alpha', g_s}}$$

$$G_{a\bar b} = \frac{\partial^2 K}{\partial T^a \partial \bar T^{\bar b}}, \quad G_{\alpha\bar\beta} = \partial_\alpha \partial_{\bar\beta} K, \quad G_{\tau\bar\tau} = \partial_\tau \partial_{\bar\tau} K$$

scalar potential V:

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

from K and holomorphic superpotential:

$$W = W(\tau, T^a, z^\alpha)$$

on a CY_3 classical result:

$\Delta K_{\alpha', g_s}, W = 0 \Rightarrow V = 0 \to$ 'moduli'

$\Rightarrow$ cosmological & 5^{th}-force disaster!

solution: p-form fluxes $\int_{\Sigma_p} F_p$

+ perturb. string corrections
+ instanton effects $\sim$ moduli scalar potential

$\longrightarrow$ can fix all the moduli

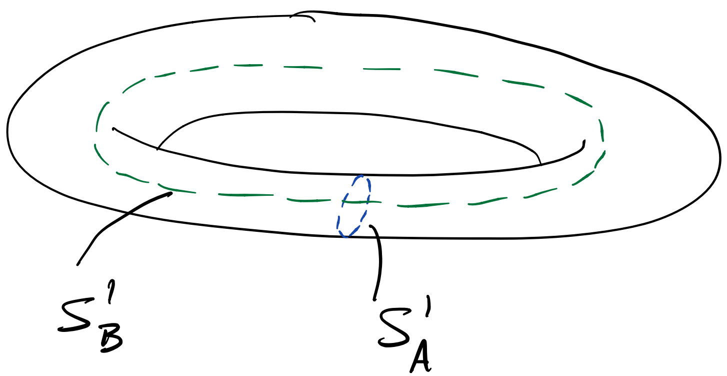
$\sim$ MANY vacua! | string landscape

simple example:

KKLT vacua (Kachru, Kallosh, Linde, Trivedi 2003)

based on CY_3 compactification with fluxes in GKP (Giddings, Kachru, Polchinski 2001)

T^2 - toy example of GKP:

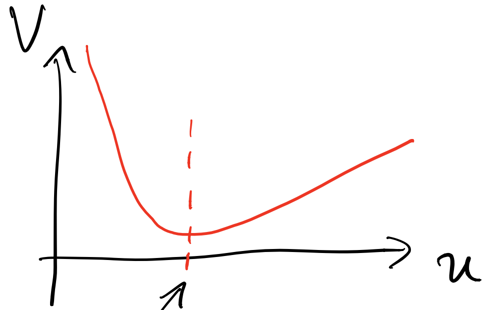


$$\mathcal{V} = L_A L_B \,, \qquad u = \frac{L_A}{L_B}$$

$$\int_{S^1_A} F_1 = M \,, \qquad \int_{S^1_B} F_1 = -K$$

$$V = \frac{M^2}{L_A^2} + \frac{K^2}{L_B^2} = \frac{1}{\mathcal{V}} \cdot \left(\frac{M^2}{u} + K^2 \cdot u \right)$$

assume $\langle \mathcal{V} \rangle$ given:



$$\langle u \rangle = \frac{M}{K}$$

'flux discretuum of vacua'

fixes $u = \frac{L_A}{L_B}$, leaves

$\mathcal{V}$ unfixed.

• turn on quantized field strengths 'fluxes':

$$M^\alpha = \int_{\Sigma_\alpha} F_3 \,, \quad K^\alpha = \int_{\Sigma_\alpha} H_3$$

$\downarrow$

$$W = W_0(z^\alpha, T) \equiv \int \left(F_3 - iT\cdot H_3\right)\wedge \Omega_3$$

$\Rightarrow$ produces V_F stabilizing all z^α and T at SUSY points $D_\alpha W = D_T W = 0$

$\Rightarrow$ $D_{T_a} W \neq 0$, but $K^{a\bar b} D_{T_a} W \overline{D_{T_b} W} = 3$

$\sim$ $V = 0$ still: 'no-scale'

• example: $h^{1,1} = 1$, one T

$\Rightarrow$ $K = -3\ln(T+\bar T) + K(\mathcal{T}, c.s.)$

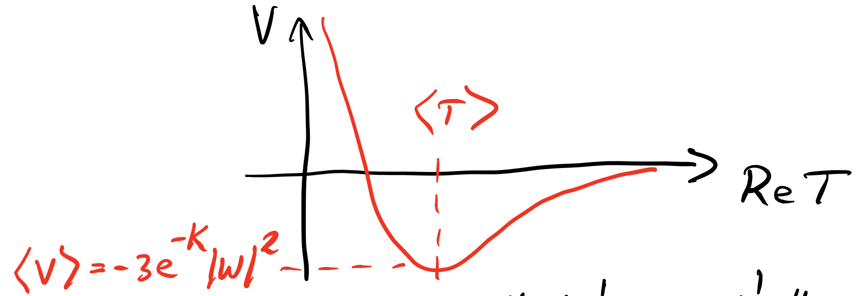
$\sim$ put N D7-branes (8-dim. branes) on 4-cycle dual to 2-cycle of T

$\rightarrow$ $SU(N)$ SYM theory, produces instanton in W:

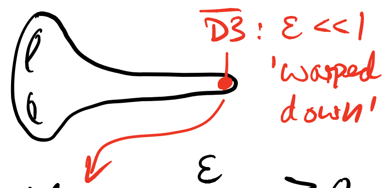
$$W_{np} = A\cdot e^{-\frac{1}{g^2_{YM}}} = A\cdot e^{-\frac{2\pi}{N}T}$$

$$\Rightarrow \quad W = W_0 + A\cdot e^{-\frac{2\pi}{N}\cdot T}$$

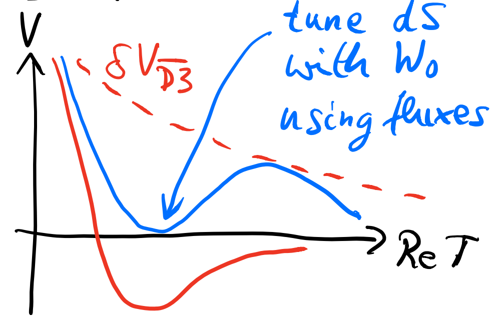
$\sim$ stabilizes T at $D_T W = 0$, $W \neq 0$ SUSY AdS vacuum



• fluxes generate red-shifted, 'warped' throat like RS1 in CY_3; place SUSY-breaking $\overline{D3}$-brane there:



$$\delta V_{\overline{D3}} = \frac{\varepsilon}{(T+\bar T)^2} > 0$$



CS couplings in generalized field strengths $\tilde{F}_p$ due to B_2

gauge invariance:

$$\left.\begin{aligned} B_2 &\to B_2 + d\Lambda_1 \\ C_{p-1} &\to C_{p-1} - \Lambda_1 \wedge F_{p-2} \end{aligned}\right\} (*)$$

$\Rightarrow$ gauge invariance of H_3, $\tilde{F}_p$ under $(*)$

$\Leftrightarrow$ shift symmetry of axions:

$$b_i = \int_{\Sigma_2^i} B_2$$

2-cycles

non-perturbative effects:

$\to$ e.g. Euclidean strings $\sim$ worldsheet instantons:

$$\Delta S_{4D} \sim e^{-i\int B_2}$$

$\Rightarrow$ discrete shift symmetry as left-over: $b_i \to b_i + 2\pi$

kinetic terms:

$$\frac{1}{\alpha'^4}\int d^{10}x\sqrt{-g}\,|dB_2|^2 \sim \int d^4x\sqrt{-g}\,\underbrace{\frac{L^6}{\alpha'}}_{M_P^2}\frac{(\partial_\mu b_i)^2}{L^4}$$

$$\sim \int d^4x\sqrt{-g}\, f_b^2(\partial_\mu b_i)^2$$

$$\boxed{f_b^2 = \frac{M_P^2}{L^4}}$$

axion decay constant

$\Rightarrow$ canonical axion field:

$$\phi_b = f_b\, b$$

has periodicity range:

$$\phi_b \to \phi_b + \frac{2\pi M_P}{L^2} \ll \phi_b + M_P$$

at large volume $L \gg 1$

$\rightsquigarrow$ generic problem $\overset{!}{\triangledown}$

solution: spontaneous breaking of B_2-gauge invariance

$\Rightarrow$ B_2-axion becomes massive

$\Rightarrow$ non-periodic potential for B_2 "axion monodromy"

$\rightsquigarrow$ analogue of superconductivity:

$$\mathcal{L} = \left|\partial_\mu\phi + i q A_\mu \phi\right|^2 - \underbrace{\lambda\left(\phi\bar{\phi} - \rho^2\right)^2}_{V(\phi)}$$

VEV: $\langle\phi\rangle = \rho \cdot e^{iC_0}$

C_0 is flat direction in $V(\phi)$ at $\phi = \langle\phi\rangle$

$$= \left|i\rho e^{iC_0}\partial_\mu C_0 + i\rho e^{iC_0}\cdot q A_\mu\right|^2$$

$$= \rho^2\left(dC_0 + q A_1\right)^2$$

$\boxed{1311.2312}$

$\rightsquigarrow$ combined gauge invariance:

$$\begin{cases} C_0 \to C_0 - q\,\Lambda_0 \\ A_1 \to A_1 + d\Lambda_0 \end{cases}$$

VEV ρ & ϕ-charge q breaks "by itself" gauge invariance of A_1; in unitary gauge C_0 eaten by A_1 $\Rightarrow$ A_1 becomes massive

$\Rightarrow$ non-periodic, quadratic potential for $a(x) = \int_{\Sigma_1} A_1$

string theory analogue for B_2:

$$|\tilde{F}_p|^2 = |dC_{p-1} + B_2 \wedge F_{p-2}|^2$$

put flux: $\int_{\Sigma_{p-2}} F_{p-2} = N$

on $(p-2)$-cycle Σ_{p-2}

$\rightsquigarrow$ charges C_{p-1} under B_2-gauge invariance

& spontaneously breaks B_2-invariance

$\Rightarrow$ quadratic potential:

$$V \sim N^2 \cdot b^2, \quad b = \int_{\Sigma_2} B_2$$

in addition: also flux

$$M = \int_{\Sigma_p} F_p$$