question: which scalars remain as good inflaton candidates?

$\sim$ i) positions of D3-branes on the compact 6D CY_3

$\sim$ ii) scalars related to the gauge symmetries of the C_p p-form gauge fields:

$\rightarrow$ axions

let's see ...

i): - D3-brane fills 3+1, is a point in the CY_3. Its 6 coord. x^i on the CY_3 are scalar fields ϕ^i in 4D.

- D3-branes try to respect SUSY if there $\rightarrow$ they are BPS-states of the extended SUSY

$\Rightarrow$ positions ϕ^i have no potential for SUSY D3-branes

- D3-branes are charged under C_4 4-form gauge field of IIB...

analogy

EM charge q - coupling:

$\sim q\int A_\mu dx^\mu = q\int A,$

D3-brane charged under C_4 - coupling:

$\sim \int C_4$

- there are D3-branes & $\overline{D3}$-antibranes, with opposite charge under C_4:
  - $\rightarrow$ if D3's are SUSY on a given CY_3
  - $\Rightarrow$ a $\overline{D3}$ breaks SUSY
- a pair D3, $\overline{D3}$ separated by distance r in the CY_3:
  - $\overline{D3}$ breaks SUSY, feels force from C_4 towards the D3 ...

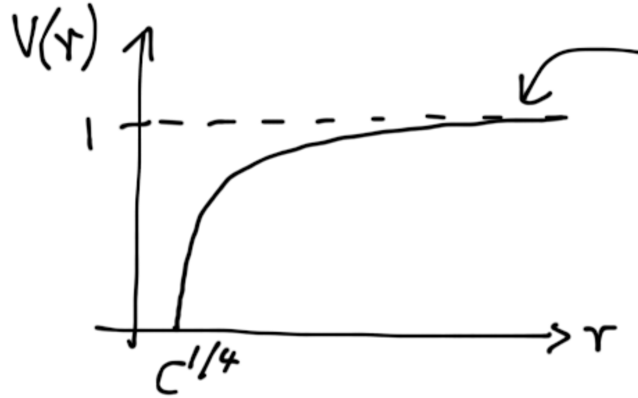
$\Rightarrow$ potential: $V(r) \sim -\dfrac{c}{r^4}$

$\longleftrightarrow$ <u>Gauss' law in 6D</u>

and $V(r)$ will be:

- constant > 0 for $r \to \infty$
- vanish for $r \to 0$, as then D3 & $\overline{D3}$ annihilate and SUSY restores ...

$$\Rightarrow V(r) \sim 1 - \frac{c}{r^4}$$



flat: $D3-\overline{D3}$ brane inflation

2 important points:

- D3-brane inflation is small-field

$\rightsquigarrow$ why?

a) $r < R_{CY}$: D3-brane moves inside CY_3 ...

b) relation between M_p^{10D} and M_p in 4D:

$$M_p^2 \sim \left(M_p^{10D}\right)^8 \cdot \text{volume}_{CY}$$

$$\Leftrightarrow \quad \frac{1}{\alpha'^2} \sim \frac{M_p^4}{\text{volume}_{CY}^2} \sim \frac{M_p^4}{R_{CY}^{12}}$$

implies, that all energy forms scale $\sim \frac{1}{R_{CY}^{12}}$ in 4D if Einstein-Hilbert term is $\sim M_p^2 R$

$\Rightarrow$ kinetic term for r:

$$\frac{1}{\alpha'^2}(\partial r)^2 \sim \frac{(\partial r)^2}{R_{CY}^{12}}$$

$\Rightarrow$ canonically normalized scalar ϕ_r:

$$\phi_r \sim \frac{r}{R_{CY}^6} < \frac{1}{R_{CY}^5} << 1$$

if $R_{CY} >> 1$ in string units.

- the same rescaling introduces a dangerous dim-6 operator into $V(r)$:

$$V_{10D}(r) \sim \left(1 - \frac{c}{r^4}\right)$$

$$\rightarrow V_{4D}(r) \sim \frac{V_{10D}(r)}{R_{CY}^{12}}$$

in general, due to backreaction of energy density of ~~SUSY~~ $\overline{D3}$:

$$R_{CY}^{12} = R_{CY}^{12}(r) \sim \left(R_{CY}^{(0)}\right)^{12} - r^2$$

$$\Rightarrow V_{4D}(r) \sim \frac{V_{10D}(r)}{\left(R_{CY}^{(0)}\right)^{12}}\left(1 + \frac{r^2}{\left(R_{CY}^{(0)}\right)^{12}} + \dots\right)$$

$$\sim V_{4D}^{(0)}(\phi_r)\cdot\left(1 + \phi_r^2 + \dots\right)$$

the quadratic correction term in the bracket implies, however:

$$\eta = \frac{V''}{V} = \underbrace{\frac{V_{4D}^{(0)\,''}}{V_{4D}^{(0)}}}_{=\eta^{(0)} \ll 1} + 1$$

<u>'eta problem'</u>

too large for inflation!

Note that moduli stabilization fixes $R_{CY}^{(0)}$, not the full $R_{CY}(r)$...

how to fix this?

→ accounted for just one dim-6 term!

→ search for all - and fine-tune them away...

to do this, note:

IIB on a CY_3 with fluxes G_3 gives 4D $\mathcal{N}=1$ supergravity:

→ scalar potential

$$V(R_{S_i^2}, R_{S_a^3}) = e^K \left(K^{I\bar{J}} D_I W \overline{D_J W} - 3|W|^2\right)$$

sizes of the S_i^2 & S_a^3 of the CY_3

↳ $I, J = R_{*(S_i^2)}, R_{S_a^3}$

K : Kahler potential → kinetic terms

& superpotential W:

$$W = \int_{CY_3} G_3 \wedge \Omega_3(R_{S_a^3}) + \sum_i A_i \, e^{-\frac{1}{g^2_{YM,i}}\left(R_{*(S_i^2)}\right)}$$

internal 6D Poincaré dual

fixes the S_a^3

fixes the $R_{*(S_i^2)}$

→ imagine, some of the A_i are $A_i(r)$ ⇒ further dim-6 contributions to $V_{4D}(r)$, and we can tune...

Can determine complete catalog of relevant higher-dim. contributions to $V_{4D}(r)$ from string theory $\rightarrow$ showcase for necessity & sufficiency of string theory as a UV completion of small-field inflation!

A fundamental property of stringy inflaton candidates:

field range $\Delta\phi < M_P$

$\rightsquigarrow$ have seen this for brane position

$\rightsquigarrow$ also true for case ii) candidates:

$\rightarrow$ gauge symmetries of p-form gauge fields C_p correspond to scalars with shift symmetries & periodicity:

$\rightarrow$ p-form axions: $c_p = \int_{\Sigma^p} C_p$

- they enjoy shift symmetries from the C_p - gauge symmetries...

  $\Rightarrow$ no potential in perturbation theory

- string theory is invariant under:

$$c_p \to c_p + 2\pi \quad \text{'periodicity'}$$

and again: $\mathcal{L}^{4D}_{kin.} \sim \dfrac{(\partial c_p)^2}{R_{CY}^{12}}$

$$\Rightarrow \phi_{c_p} \sim \frac{c_p}{R_{CY}^6} < M_p$$

- one exception:

$\rightarrow$ Dp-branes couple to C_p!

action of a Dp-brane:

$$S_{D_p} \sim \frac{1}{\alpha'^{\frac{p+1}{2}}} \int d^{p+1}\xi \sqrt{-\det(g_{\mu\nu}+B_{\mu\nu})}$$

'DBI-action'

simple example:

put B_2 on a S^2 in CY_3

$\Rightarrow$ axion $b = \int_{S^2} B_2$

there are D5-branes, which see B_2 as above:

$$\Rightarrow S_{D5} \sim \frac{1}{\alpha'^3} \int_{M^4 \times S^2} d^6x \sqrt{-g_{4D}\left(g_{S^2} + B_2\right)}$$

$$\sim \frac{1}{\alpha'^2}\int d^4x\sqrt{-g_{4D}}\,\sqrt{\mathrm{vol}_{S^2}^2+b^2}$$

$\Rightarrow$ scalar potential

$$V(b) \sim \sqrt{\mathrm{vol}_{S^2}^2+b^2} \sim b$$

at large b !

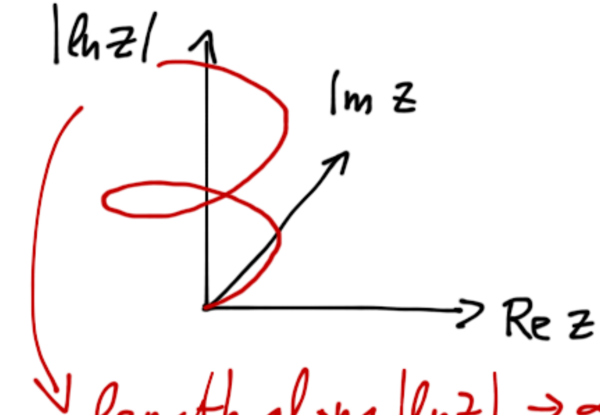
$\rightarrow$ potential is not periodic in b, although everything else is:

<u>"$V(b)$ has monodromy in b."</u>

$\Rightarrow$ gives parametrically <u>unbounded</u> field range:

- no periodicity
- no relation to limiting size of the CY_3

$\rightsquigarrow$ analogy: $|\ln z|$, $z \in \mathbb{C}$, $|z| = 1$



length along $|\ln z| \to \infty$, z periodic

$\Rightarrow$ axion monodromy inflation with 5-branes gives large-field inflation in string theory with:

$$\boxed{V(\phi) \sim \phi \quad \text{at } \phi \gg M_P}$$

$$\Rightarrow \boxed{\phi_{60} \simeq 11\, M_P\,,\; n_s \simeq 0.975,\; r \simeq 0.08}$$

(controlled setups by: McAllister, Silverstein & AW in 2008)

crucial: string theory generated the shift symmetry from SUSY & stringy gauge symmetry $\longrightarrow$

concrete UV completion of large-field model class!