Fluxbrane Inflation

(with S. Kraus, D. Lüst, S. Steinfurt, T. Weigand)

Outline

- The famous no-go-theorem for brane-antibrane inflation
- How it is avoided by fluxbrane inflation
- The fluxed D7-D7 potential
  - 10d-sugra perspective
  - string-loop perspective
- 4d-sugra formulation on generic CY (D-term inflation)
- Phenomenology (avoidance of cosmic string constraints)
- Summary & Outlook

Introduction

- in 4d eff. FT : We will always set $M_p = 1$.
- (slow-roll) inflation:

$$\mathcal{L} = \frac{1}{2}(\partial\varphi)^2 - V(\varphi) + \cdots$$

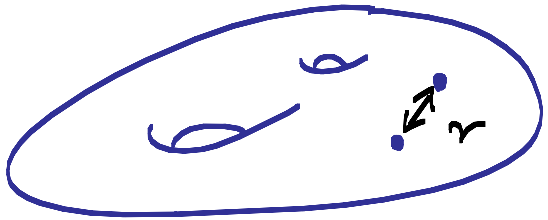
$$\epsilon \sim (V'/V)^2 \quad \& \quad \eta \sim V''/V \quad \ll 1$$

- actually, we need slightly more: $\int d\varphi \, \frac{V}{V'} \gtrsim 60$
- flat potentials can arise
  - from (axionic) shift symmetries (→ Westphal et al.)
  - in the Kähler moduli space (→ Cicoli et al.)
  - can be analysed generically in 4d sugra (→ Louis et al.)

- <u>Our focus</u>: brane inflation (φ is the position of a brane in the compactification space)

A no-go theorem

(Burgess et al. , '01)



} volume $\mathcal{V}$

$\boxed{l_s = 1}$

$$\mathcal{L} \sim g_s^{-2}\, \mathcal{V}\, \mathcal{R} + g_s^{-1}\, \mathcal{V}_{\parallel} \left[(\partial r)^2 - \left(A - B \frac{g_s}{r^{d_\perp - 2}} \right) \right]$$

- go to Einstein frame
- normalise r canonically ($r \to \varphi$)
- calculate $\eta = V''/V$

$$\boxed{-\eta \sim \frac{B}{A} \cdot \left(\frac{L_\perp}{r} \right)^{d_\perp}}$$

$$\mathcal{V} = \mathcal{V}_{\parallel} \cdot L_\perp^{d_\perp}$$

Known ways around the no-go-theorem:

- Warping

– D3 - $\overline{D3}$ in strongly warped region (KS throat) (→ KKLMMT)

– nevertheless: Kähler stabilization induces large corrections,
which fundamentally change the inflation model
(→ inflection-point inflation)

- D3/D7 (→ Dasgupta/Herdeiro/Hirano/Kallosh '02
...

– fluxed D7 & D3 Haack/Kallosh/Krause/Linde/Lüst/Zagermann '08)

– need very large stack of D3's to get D7 moving

– alternatively: work near tachyon-condensation point (fine-tuned)
or use very anisotropic space

Our main idea:

Brane - antibrane pair

$\Downarrow$

Brane - brane pair with gauge-flux $\mathcal{F}$ & $-\mathcal{F}$

- attractive force is due to flux $B \sim |\mathcal{F}|^4$ (not $|\mathcal{F}|^2$!)
- when branes collide, only the flux is annihilated $A \sim |\mathcal{F}|^2$

$$-\eta \sim \frac{B}{A}\left(\frac{L_\perp}{r}\right)^{d_\perp} \sim |\mathcal{F}|^2 \left(\frac{L_\perp}{r}\right)^{d_\perp}$$

$$\Rightarrow \quad \underline{\underline{-\eta \ll 1}}$$

(since, if $V_{\parallel} \sim R^{d_{\parallel}} \gg 1$, $|\mathcal{F}|^2 \sim p^2/R^4 \ll 1$)

More motivation:

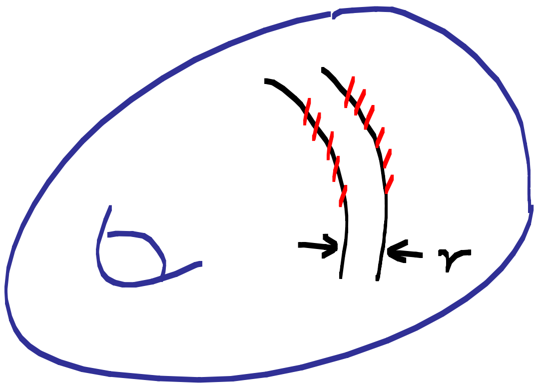
- We want to work in type IIB / F-theory flux landscape

  (moduli stabilization & SUSY-breaking relatively well understood, tuning of cosmol. constant doable, attractive particle phenom.)

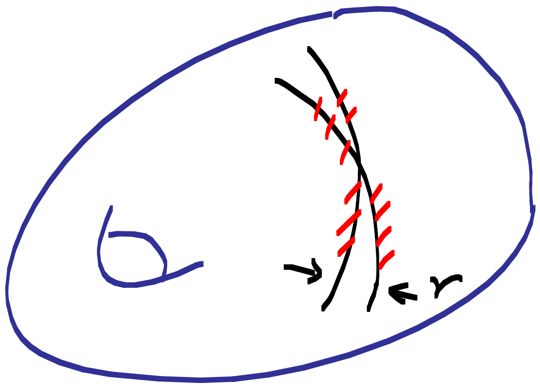
- Hence: fluxed D7-branes ; $d_\perp = 2$

  $$L_\perp \sim R \gg 1 \quad \Rightarrow \quad -\eta \sim \frac{1}{R^2 r^2} \ll 1 \text{ easy to realize}$$

- Geometric setting:



vs.



10d sugra perspective

(focussing on parallel D7 branes)

- geometry near "background" brane (without flux):

$$ds^2 = Z_7^{-1/2}\, ds^2(\mathbb{R}^{1,7}) + Z_7^{1/2}\, ds^2(\mathbb{R}^2)$$

$$Z_7 = 1 - \frac{g_s}{2\pi} \ln(r/R)$$

$$e^{\phi} = g_s\, Z_7^{-1}$$

- action of parallel "probe" brane in this background (with flux $\mathcal{F}$):

$$S_{DBI} = -2\pi \int d^8x\, e^{-\phi} \sqrt{-\det(g+\mathcal{F})}$$

$$\supset \frac{\pi}{2} \int d^8x\, e^{-\phi} \sqrt{-\det g_{1,7}}\; g_{1,7}^{\mu\nu} g_{1,7}^{\rho\sigma} \mathcal{F}_{\mu\rho} \mathcal{F}_{\nu\sigma}$$

$$e^{-\phi}\sqrt{g_{1,7}^{8}}\, g_{1,7}^{-2} \sim z_7 \left(z_7^{-1/2}\right)^4 \left(z_7^{-1/2}\right)^{-2} \sim 1$$

$\Rightarrow$ The F^2 term carries no z_7 and hence no r-dependence

A more intuitive explanation:

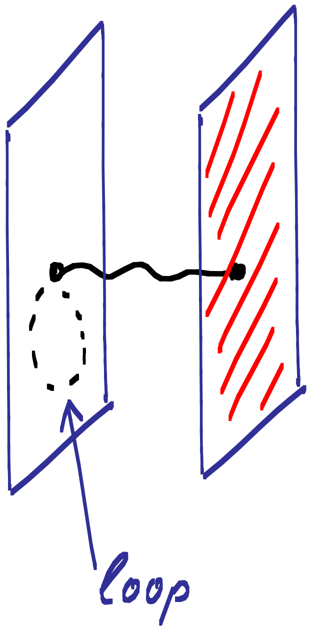
- Consider a fluxed D3-brane in the background of a fluxless stack of N D3-branes
- This is the standard AdS/CFT setting: $e^{\phi} = \text{const}$
  $g_{\mu\nu} = g_{\mu\nu}(r)$
- The flux at order F^2 does not "see" the variation of $g_{\mu\nu}$ since $\sqrt{-g}\, F^2$ is scale invariant
- This generalizes to Dp-branes ($\to$ Jevicki/Kazama/Yoneya '98)

- At order F^4 this cancellation does not persist giving

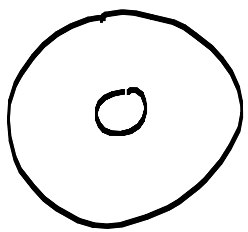
$$\boxed{V \sim V_{\parallel} \left(F_{45}^{\,2} - F_{67}^{\,2} \right)^2 \ln (r/R)}$$

- Next, we repeat this analysis from the

string 1-loop perspective



$\Rightarrow$



annulus
(with flux-modified boundary conditions)

$\Rightarrow$ This precisely reproduces the 10d-sugra result above

$\boxed{\text{But now we know it holds also for } r \ll 1 \text{ !}}$

Comments:

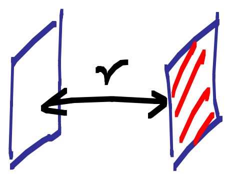
- The analysis of the open string spectrum also tells us when tachyons occur (reheating):

$$r_{\text{crit.}} \sim \mathcal{F}$$

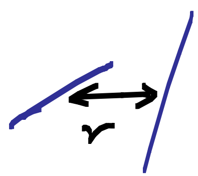
(this is an extremely sub-stringy distance at large volumes)

- We need also to be sure that inflation does not end prematurely because of brane recombination (we give a topological condition ensuring the absence of massless vector like states at the intersection locus)

- Finally, we note that our setting is T-dual to "angled brane inflation":



vs.



(→ Garcia-Bellido / Rabadan / Zamora '01)

We are now ready to move on to

Generic CY's

$$S_{DBI} \sim \int d^4x\, e^{-\phi} \sqrt{-g_{1,3}} \cdot \Gamma \quad ; \quad \Gamma = \int_\Sigma \sqrt{\det(g+\mathcal{F})}$$

To evaluate Γ, we use the crucial relation

$$\frac{1}{2}(J+i\mathcal{F})\wedge(J+i\mathcal{F}) = e^{i\theta}\sqrt{\frac{\det(g+\mathcal{F})}{\det g}}\; \mathrm{Vol}_\Sigma$$

(→ Marino, Minasian, Moore, Strominger '99)

This gives

$$\Gamma = \sqrt{\left[\mathrm{Re}\int \frac{1}{2}(J+i\mathcal{F})^2\right]^2 + \left[\mathrm{Im}\int \frac{1}{2}(J+i\mathcal{F})^2\right]^2}\,,$$

to be Taylor-expanded in $\mathcal{F}$... (→ Haack, Kreft, Lüst, Van Proeyen, Zagermann)

- The leading, F-independent term is cancelled because our brane is supersymmetric

- The F^2-term gives

$$V = \frac{1}{2} g_{YM}^2 \xi^2 \quad \text{with} \quad \frac{1}{g_{YM}^2} \sim \frac{1}{2g_s} \int J \wedge J$$

$$\xi \sim \frac{1}{\mathcal{V}} \int J \wedge F$$

(D-term inflation)

- Including the crucial F^4-term, we find

$$\boxed{V = \frac{1}{2} g_{YM}^2 \xi^2 \left[1 + \frac{1}{4} \left\{ \frac{\left(\int J \wedge F\right)^2}{\left(\frac{1}{2}\int J \wedge J\right)^2} - 4 \frac{\left(\frac{1}{2}\int F \wedge F\right)^2}{\frac{1}{2}\int J \wedge J} \right\} \frac{g_s}{2\pi} \ln(r/R) \right]}$$

This can be written as

$$V = \frac{1}{2} g_{YM}^2 \xi^2 \left[1 + \frac{g_{YM}^2}{16\pi^2} \cdot c \cdot \ln(\varphi/\varphi_0) \right]$$

$$c = -2\int F^2 + \left(\int J \wedge F\right)^2 \Big/ \left(\frac{1}{2}\int J^2\right)$$

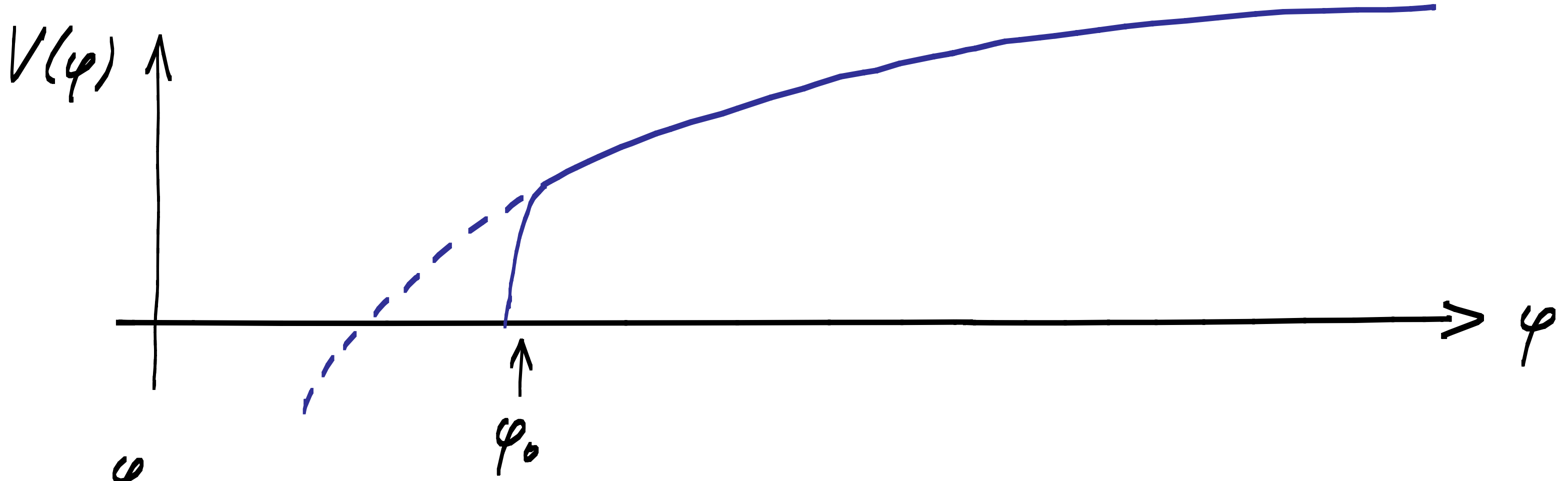
For $c \sim 1$, this is just the generic potential of D-term inflation.

Crucial: If Kähler moduli are appropriately stabilized and $\int F^2 = 0$, we can have $c \ll 1$.

This will allow us to evade the cosmic string bound.

Phenomenology

$$V = V_0 \left(1 + \alpha \ln(\varphi/\varphi_0)\right)$$



$$N = \int_{\varphi_0}^{\varphi_N} d\varphi \, \frac{V}{V'} \approx \frac{1}{2\alpha}\left(\varphi_N^2 - \varphi_0^2\right) \approx \frac{\varphi_N^2}{2\alpha} \overset{!}{\approx} 60$$

$$\epsilon = \frac{\alpha}{4N} \quad ; \quad \eta = -\frac{1}{2N} \qquad \Longrightarrow \qquad \epsilon \ll -\eta$$

$$n_s = 1 - 6\epsilon + 2\eta \simeq 1 + 2\eta \simeq 1 - \frac{1}{N} \approx 0.983$$

$$\left(\text{WMAP7}: \; n_s = 0.968 \pm 0.012 \right)$$

Furthermore:

$$\tilde{\xi} \equiv \left. \frac{V^{3/2}}{V'} \right|_{\varphi = \varphi_N} = 5.4 \cdot 10^{-4}$$

$$\Rightarrow \quad \frac{\alpha}{V_0} = \frac{1}{(2\pi)^2 \tilde{\xi}^2} \left(\int -\mathcal{F}^2 \right) + 2 \frac{\hat{\mathcal{V}}(x_3)^2}{\hat{\mathcal{V}}(\Sigma_1)} \overset{!}{=} 4.2 \cdot 10^8$$

Hence, if $-\int \mathcal{F}^2 = 1$, we find $\tilde{\xi}_{min} \approx 4 \cdot 10^{-6}$

The cosmic string bound is $\tilde{\xi}_{max} \simeq 2.5 \cdot 10^{-6}$ $\Rightarrow$ $\boxed{\text{chose } \int \mathcal{F}^2 = 0}$

For a roughly isotropic CY, $\hat{\mathcal{V}}(X_3) \sim \hat{R}^6$ & $\hat{\mathcal{V}}(\Sigma) \sim \hat{R}^4$, we obtain:

$$2 \cdot \hat{R}^8 = 4.2 \cdot 10^8$$

$$\boxed{\hat{R} = 11}$$

Finally, with $\hat{\mathcal{V}}(X_3)^2 / \hat{\mathcal{V}}(\Sigma)$ fixed in this way, we re-evaluate the cosmic string bound on ξ, finding the requirement

$$\boxed{\frac{\left(\int \hat{J} \wedge F\right)^2}{\frac{1}{2}\int \hat{J} \wedge \hat{J}} \lesssim 0.4}$$

$\Rightarrow$ a very moderate tuning of Kähler moduli is sufficient.

Just for the record: $\boxed{r_N \approx 0.1 \cdot g_s^{-1/4}}$

Moduli stabilization & further issues

- $\xi \sim \frac{1}{\mathcal{V}} \int J \wedge F$ depends on Kähler moduli, the stabilization of which is hence crucial

(work in progress with M. Küntzler + ...)

One possibility:

- Work in context of LARGE volume compactifications (Balasubramanian et al, '05), where the possibility of a "D-term uplift" has been demonstrated (Cremades et al, '07)

A crucial (& partially open) issue

- with the D-terms, we unavoidably get F-terms
- they are accompanied by e^K, with

$$K = -\ln\left(-i(S-\bar{S}) + i\mathcal{L}_{A\bar{B}}\,\zeta^A\bar{\zeta}^B\right)$$

D7-moduli (→ Jockers/Louis)

- this spoils the flatness in $\varphi = |\zeta^1|$
- however, with this type of ζ-dependence of K, we necessarily get a ζ-dependence of W.

(see also "open string landscape" & recent work on D7-superpotentials)

- this is an $O(g_s)$, i.e. truly F-theoretic effect

- all we will need is an extremum in the (bulk-flux- or superpotential-induced) "ξ-landscape", with an m^2 at the %-level of the generic expectation.

- This should be doable at the expense of a mild flux-tuning.

Summary & Outlook

- Fluxbrane inflation evades the familiar no-go-theorems for bran-antibrane inflation in a novel way
- It offers a very natural way to satisfy the cosmic string constraint (which is otherwise a serious problem in many models of D-term inflation)

- Kähler moduli stabilization is known to work in principle (cf. LARGE volume models)
- $O(g_s)$-flux effects (probably) reintroduce (small?) tuning