Towards brane-antibrane inflation in type IIA string theory: the holographic MQCD model

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Summary:

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- 3. KKLT/KKLMMT scenario
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- 6. The potential and consequences for cosmology
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1. Introduction

•Inflation $\rightarrow$ need a scalar field with a flat potential $\rightarrow$ slow roll ($\epsilon = M_P^2(V'/V)^2 \ll 1$ and $\eta = M_P^2 V''/V \ll 1$)

•But quantum corrections can spoil it. Also, need a fundamental theory near M_{Pl} to **derive** $V(\phi)$.

•Natural to look for string theory potentials. But, $\nexists$ fully consistent embedding of inflation in string theory yet.

•String theory has *many* light scalars (moduli) $\rightarrow$ need to stabilize most. Stabilization and/or quantum corrections generically spoil slow roll.

•One standard model $\rightarrow$ KKLT/KKLMMT in IIB string theory.

•But it has same problems generically.

•Also, IIB easier to build model. How about the T-dual type IIA? No good model yet.

•Here: model based on a T-dual analog of KKLMMT $\rightarrow$ a first step towards IIA inflation.

•Based on a holographic MQCD gauge theory.

•We find the shape of the scalar potential and argue that it can fit experimental constraints.

2. Problems of embedding inflation in string theory

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•String theory: quantum theory of gravity, living in 10d (IIB) or 11d (IIA $\rightarrow$ M theory at strong coupling)

•Need to do something with extra dimensions $\rightarrow$ Kaluza-Klein reduction: small compact space, or or transverse $\rightarrow$ a brane (matter restricted to a 4d model)

•$\exists$ many moduli (light scalars) $\rightarrow$ parametrize the "size" of the space (including the overall volume) $\rightarrow$ Kähler structure moduli and the "shape" of the space (like the ratio of radii of a torus) $\rightarrow$ complex structure moduli.

•As well: related fields (e.g. B_{ij} components)

•In brane scenario, brane positions in transverse space are also light scalars.

•Need to stabilize (most of) the moduli, at least now $\rightarrow$ we don't see light scalars. But also, for simplest inflation $\rightarrow$ we want just one scalar to roll $\rightarrow$ inflaton.

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•Stabilization mechanisms $\rightarrow$ quantum (often nonperturbative) potentials $\rightarrow$ hard to calculate.

•Easiest: fluxes of antisymmetric tensor fields in extra dimensions give stabilizing superpotentials.

•Example of flux: 11d supergravity "spontaneous compactification" to 4d on $AdS_4 \times S^7$ (Freund-Rubin): $F_{\mu\nu\rho\sigma} \propto \epsilon_{\mu\nu\rho\sigma}$ ($\mu, \nu, \rho, \sigma = 1, ..., 4$ and F_{MNPQ}=4-form fields strength in 11d)

•GVW superpotential for G-flux: $G = F^{RR} - \tau H^{NS}$

$$W = \int_{K_6} \Omega \wedge G$$

where Ω=holomorphic 3-form on G.

•Generic potential in string theory has $V''/V \sim 1/M_{Pl}^2 \Rightarrow \eta \sim 1 \rightarrow$ "the eta problem in string theory" $\rightarrow$ naturally, quantum corrections for scalar mass $\Rightarrow$ run to cut-off scale (M_P): $\Delta\eta \sim \Delta m^2/3H^2 \geq 1$

•One can choose non-generic points in moduli space $\rightarrow$ but then how to justify initial conditions.

•We still need *full quantum potential* to be sure.

•Stabilizing potentials by flux $\rightarrow$ generically the last field to be stabilized: volume $\rightarrow$ introduce steep regions in potential $\Rightarrow$ spoils slow-roll.

•Recent progress $\rightarrow$ towards computing the full quantum potential.

•Popular example: brane, or brane-antibrane potential $\rightarrow$ brane motion in extra dimensions $\rightarrow$ motion in 4d scalar field space $\rightarrow$ inflation.

•Another big problem: de Sitter (dS) background is very difficult in string theory $\rightarrow$ susy requires AdS $\Rightarrow$ need some susy breaking, but still to have stability.

3. KKLT/KKLMMT scenario

•$\rightarrow$ based on brane-antibrane inflation.

•In flat space $D - \bar{D}$ potential is

$$V(y) = A - \frac{B}{y^{d_\perp - 2}}$$

where $A = 2T_p V_\parallel \rightarrow$ free branes, and interaction potential $\rightarrow$ attractive.

•Canonically normalize $\Rightarrow$

$$\eta \sim -\beta(d_\perp - 1)(d_\perp - 2)\left(\frac{r_\perp}{V}\right)^{d_\perp}$$

•On a torus however, $\exists$ images of branes $\Rightarrow \exists$ metastable positions $(D - \bar{D} - D - \bar{D} - ...) \Rightarrow$

$$V(z) = A - Cz^4$$

where z=displacement from metastable positions $\Rightarrow$ inflation only if we start near $z = 0$.

•KKLT: mechanism for de Sitter vacua in strng theory.

•Warped throat geometry of Klebanov-Strassler (KS) type $\to$ cigar type

$$\begin{aligned} ds^2 &= e^{2A} g_{\mu\nu} dx^\mu dx^\nu + e^{-2A(y)} g_{mn} dy^m dy^n \\ g_{mn} dy^m dy^n &= dr^2 + r^2 ds^2_{X_5} \end{aligned}$$

($X_5 = T^{1,1}$) glued to a CY_3 to cap off the throat $\to$ compactification.

•$\exists$ G-gflux $\Rightarrow$ tree level superpotential $W = W_0$, and nonperturbative superpotential $W = Ae^{ia\rho}$, ρ=volume modulus (Euclidean D3-brane instanton or gluino condensation on D7-branes).

•Tree-level Kähler potential

$$K = -3 \ln[-i(\rho - \bar{\rho})]$$

$\Rightarrow$ supersymmetric potential $\Rightarrow$ AdS vacuum.

•But we can introduce an anti-D3-brane at tip of cigar ($\exists$ exponentially small warping there) $\Rightarrow \delta V = D/(\mathrm{Im}\rho)^3$ nonsusy potential $\Rightarrow$ dS vacuum.

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•KKLMMT: proposal for brane-antibrane inflation, where $\bar{D}3$ is the above in KKLT (fixed) and $\exists$ moving D3 on warped throat geometry.

•KS $\sim$ log-corrected AdS. For AdS: consider D3-brane as another D3-source, modifying the harmonic function $h(r) = e^{-4A}$:

$$\frac{R^4}{r^4} \to \frac{R^4}{r^4} + \frac{R^4/N}{(r-r_1)^4} \simeq R^4\left(\frac{1}{r^4} + \frac{1}{N}\frac{1}{r_1^4}\right)$$

•Calculate DBI action of $\bar{D}3$-brane in this background $\Rightarrow$ potential

$$V(\phi) = \frac{4\pi^2\phi_0^4}{N}\left(1 - \frac{1}{N}\frac{\phi_0^4}{\phi^4}\right)$$

•flat potential $\to$ though volume stabilization generically spoils it. And could be quantum corrected.

4. Holographic MQCD

•MQCD $\rightarrow$ generalization of 4d $\mathcal{N}=1$ SYM theory in M theory with one extra parameter (g_s, or radius of 11th dimension)

•Constructed by Witten (1997) as: 2 NS5-branes, $\|$ in 3+1 dimensions ($x^0,...,x^3$) and extended in 2 new different directions: x^4, x^5 with $v = x^4 + ix^5$, vs. x^7, x^8, with $w = x^7 + ix^8$, and separated in x^6 by a length L.

•Linked by p D4-branes of length L.

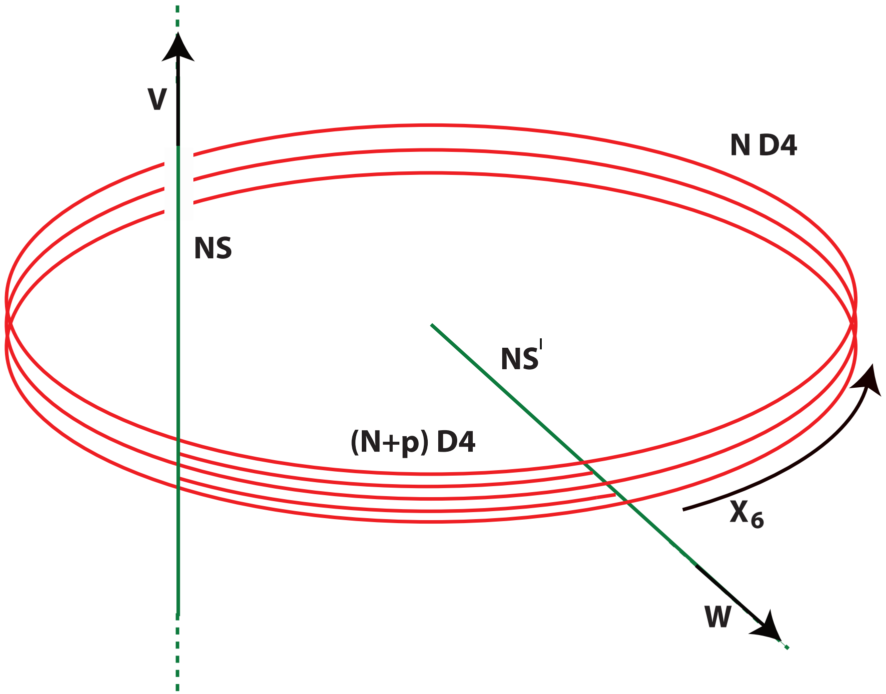
•Has a solution in M theory: $\exists$ single M5-brane $\mathbb{R}^4 \times \Sigma$, with $w = \zeta v^{-1}$, $v^n = t$, $w^n = \zeta n t^{-1}$. ($t = e^{-z}$, $z = R^{-1}x^6 + ix^{10}$)

•Holographic MQCD $\to$ gravitational description of MQCD, where we add N D4-branes $\|$ the p D4-brane plane, with $N \geq p$- probe approximation $\to$ replace the N D4-branes by their gravity background

$$ds^2 = H^{-1/3}(dx_\mu^2 + dx_6^2 + dx_{11}^2) + H^{2/3}(|dv|^2 + |dw|^2 + dx_7^2)$$
$$C_6 = H^{-1} d^4x \wedge dx_6 \wedge dx_{11}, \quad H = 1 + \frac{\pi \lambda_N l_s^2}{|\vec{r} - \vec{r}_0|^3}$$

•NS5-branes and p D4-branes form a single curved M5-brane in the background.

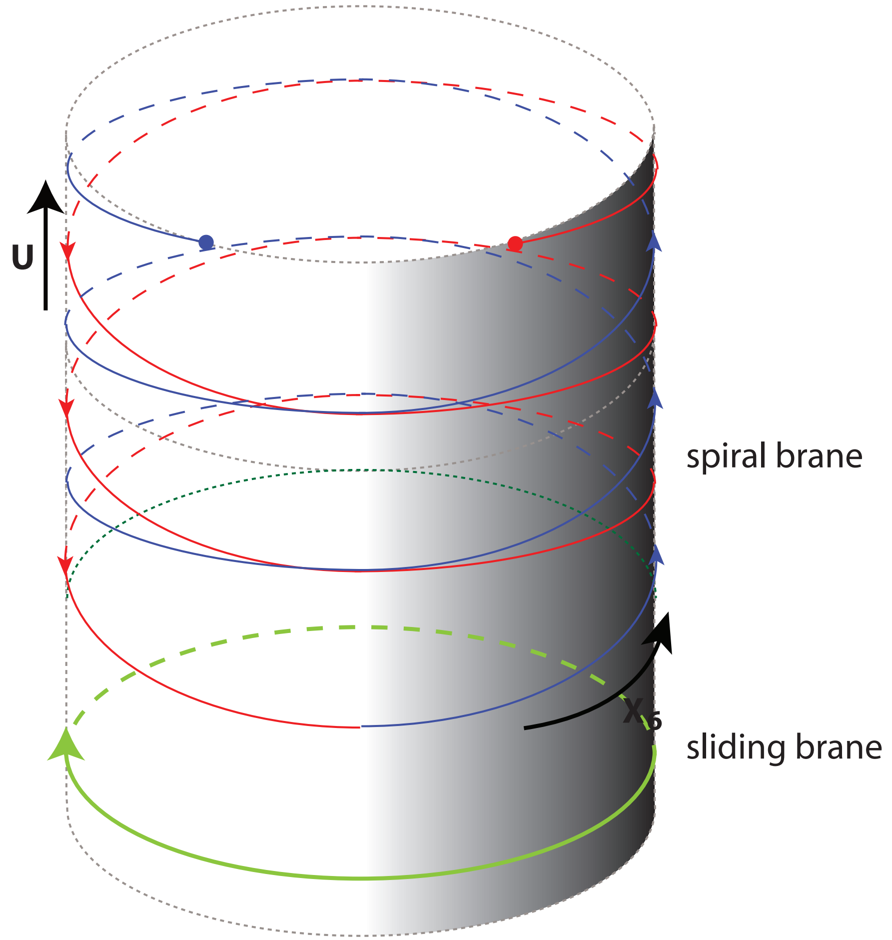
•Compact $x_6 \Rightarrow$ M5-brane on cylinder (x_6, u) spirals down from $u = \infty$ to u_0 and then back up $\to$ carries p units of D4-brane charge.

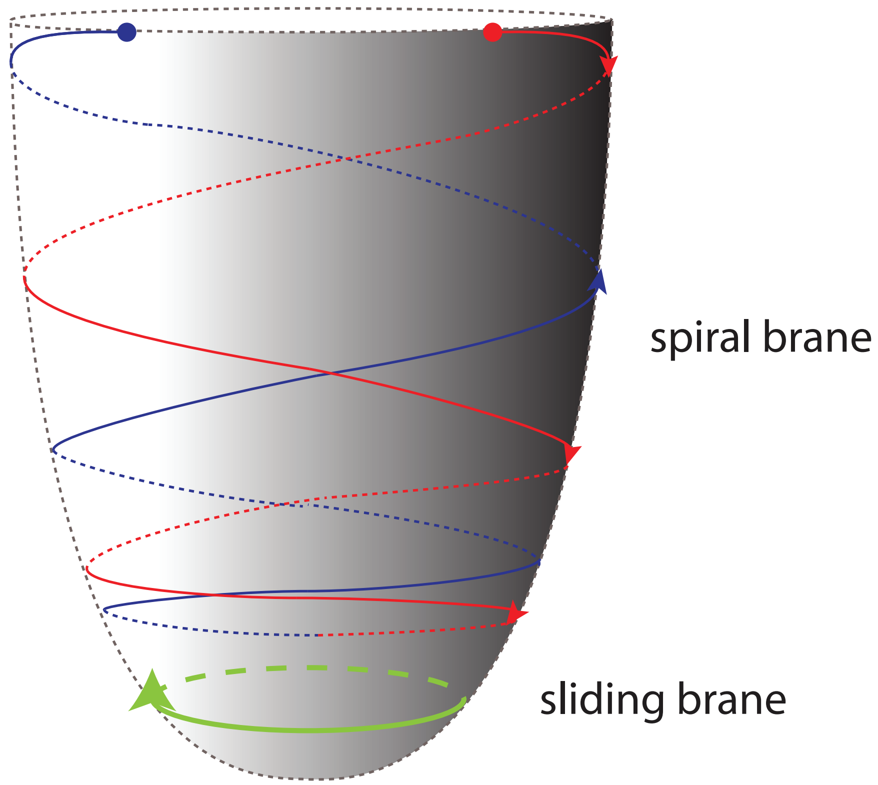


•Is T-dual to KKLT susy set-up.

•Cigar topology: non-supersymmetric model $\rightarrow$ double Wick rotated near-extremal D4-brane $\Rightarrow$ cigar instead of cylinder

$ds^2 = H^{-1/3}[-dt^2+dx_i^2+f(r)dx_6^2+dx_{11}^2]+H^{2/3}[(f^{-1}(r)-1)dr^2+|dv|^2+|dw|^2+dx_7^2]$


U
X_5
spiral brane
sliding brane


spiral brane
sliding brane

5. Two set-ups for holographic MQCD

Model 1

•Consider the nonsusy deformation of holo MQCD set-up: in T-dual KKLT, $\exists$ anti-D3 at tip of KS $\rightarrow$ take Wick-rotated near-extremal D4-brane $\rightarrow$ make $\bar{D}3$ perturbation of background.

•Then: semi-infinite cigar in r over S^4, for $r_{min} = r_H$, and cigar in r over x_6. Cut-off cigar at r_{max}, gluing another space $\rightarrow$ compactify.

•(x_6, r) is T-dual to $(r, T^{1,1})$ in KKLT, glued onto $CY_3 \Rightarrow (x_6, r, S^4)$ glued onto CY_3 space W, T-dual to M. (susy breaking $\Rightarrow \exists$ small additional energy at gluing region)

•Add also sliding D4-brane on cigar $\rightarrow$ like KKLMMT.

•Action for D4-brane in double-Wick rotated near-extremal D4-brane $\Rightarrow$

$$S = -\frac{T_p}{g_s}\int H_p^{-1}(r)\left[\sqrt{f_p + \frac{H_p(r)}{f_p} g^{\mu\nu} \mathrm{d}_\mu r \mathrm{d}_\nu r} - 1\right]$$

•Then, the potential is

$$V_4(r) = +\frac{T_4 R}{g_s} H^{-1}(r)[\sqrt{f(r)} - 1] = +\frac{T_4 R}{g_s} \frac{1}{1+\alpha_4(\frac{r_4}{r})^3}\left[\sqrt{1-\frac{r_H^3}{r^3}} - 1\right] < 0$$

•Going from $V(\infty) = 0$ to $V(r_H) \simeq -T_4 R (r_H/r_4)^3/g_s$.

•$\exists$ a plateau for $r_H \ll r \ll r_4$,

$$V(r) \simeq -\frac{T_4 R}{2 g_s \alpha_4}\left(\frac{r_H}{r_4}\right)^3\left[1 + \frac{1}{4}\frac{r_H^3}{r^3} - \frac{r^3}{\alpha_4 r_4^3}\right]$$

•The spiralling brane has a negligible effect on the potential (calculated)

Model 2

•consider a sliding anti-brane in a susy (cylinder) background $\Rightarrow$ cylinder in (x_6, r) and semi-infinite in (r, S^4).

•Space terminates at $r = 0$ however $\Rightarrow$ by adding a CY_3, the space is again truly compactified.

•Calculation of potential is similar: consider the action of an anti-brane in a susy background.

•Find

$$V_4(r) = \frac{2T_4R}{g_s}\frac{1}{1+\frac{r_4^3}{r^3}}$$

•Potential now varies between $V(0) = 0$ and

$$V(\infty) = \frac{2\pi R}{g_s}$$

with an infinite derivative at 0:

$$V_4'(r) = \frac{6T_4 R}{g_s r} \frac{r_4^3/r^3}{1 + r_4^3/r^3} \to \infty (r \to 0)$$

•Neglect again contribution of spiral, though now form of correction is less rigorous $\to$ again only interaction between brane and antibrane via modified background, and no backreaction.

6. The potential and consequences for cosmology

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•**Model 1**: The potential on the plateau is

$$V(\phi) \simeq \frac{T_4 R}{g_s}\left(\frac{\phi_H}{\phi_4}\right)^3 \left[N - \frac{1}{2\alpha_4}\left(1 + \frac{\phi_H^3}{4\phi^3} - \frac{\phi^3}{\alpha_4 \phi_4^3}\right)\right]$$

and gives for the slow-roll parameters and the number of e-folds

$$\epsilon \equiv \frac{1}{2}\left(M_P \frac{V'}{V}\right)^2 \simeq \frac{1}{2}\left[\frac{3M_P}{2N\phi}\left(\frac{1}{4}\frac{\phi_H^3}{\phi^3} + \frac{\phi^3}{\phi_4^3}\right)\right]^2$$

$$\eta \equiv M_P^2 \frac{V''}{V} = \frac{3M_P^2}{2N\phi^2}\left(-\frac{\phi_H^3}{\phi^3} + 2\frac{\phi^3}{\phi_4^3}\right)$$

$$\mathcal{N} = \frac{8N}{15}\frac{\phi_{in}^5 - \phi_{end}^5}{M_P^2 \phi_H^3}$$

•Note that ϕ_4/M_P is generically large, so we are generically on the plateau $\phi_H \ll \phi \ll \phi_4$ (for generic ϕ, of order M_P), for a red spectrum we need $\eta < 0$, or $\phi < \sqrt{2^{-1/3}\phi_H\phi_4}$ (since $\epsilon \ll |\eta|$), and we can easily get 60 e-folds.

•Also, COBE normalization puts a constraint on V at horizon exit, which gives

$$V_p = N\left(\frac{T_4 R}{g_s}\right)\left(\frac{\phi_H}{\phi_4}\right)^3 \sim 12\pi\epsilon \times 10^{-10} M_P^4$$

•Reheating: $V'(\phi)$ seems finite at $\phi = 0$, but divergent kinetic term $\sim \sqrt{(\mathrm{d}\phi)^2/(r - r_H)}$, so effective description breaks down $\Rightarrow$ usual brane-antibran reheating mechanism.

•**Model 2**: the potential on the plateau is

$$V_4(\phi) = \frac{2T_4 R}{g_s} \frac{1}{1 + \frac{\phi_4^3}{\phi^3}}$$

. leading to

$$\begin{aligned} \epsilon &= \frac{1}{2}\left[\frac{3M_P}{\phi}\frac{\phi_4^3/\phi^3}{1+\phi_4^3/\phi^3}\right]^2 \\ \eta &= -\frac{M_P^2}{\phi^2}\frac{\phi_4^3/\phi^3(32+30\phi_4^3/\phi^3)}{(1+\phi_4^3/\phi^3)^2} \\ \mathcal{N} &\simeq \frac{\phi_{in}^5 - \phi_{end}^5}{3M_P^2\phi_4^3} \end{aligned}$$

so we always have a red spectrum ($\epsilon > 0$ and $\eta < 0$, and $n_s - 1 = -6\epsilon + 2\eta$), but we can have slow-roll for non-generic $\phi \gg M_P$, or if $\phi \sim M_P$, we need $\phi_4 \ll M_P$, needing the non-generic $V_5 m^4/(\sqrt{\alpha'}N^{2/3}) \gg 1$. However, reheating is simpler since now $V'(\phi) = \infty$ at $\phi = 0$.

•COBE normalization gives

$$V_f \sim \frac{2T_4 R}{g_s} \sim 12\pi\epsilon \times 10^{-10} M_P^4$$

7. Conclusions

•Inflation is difficult to obtain in string theory. A standard model (try) is KKLT/KKLMMT in IIB string theory.

•It is based on the KS throat geometry, compactified by gluing a CY_3.

•We can write a gravity dual to MQCD, T-dual to the KKLT construction.

•Based on it, we presented two models in IIA string theory, one with a compactified non-susy cigar geometry, and one with a compactified cylinder geometry, but with a sliding antibrane.

•The cosmology coming from it is consistent with current experiments, but it has the usual problems of KKLMMT.