KING'S College LONDON

Theoretical constraints on brane inflation and cosmic superstring radiation

arXiv:1105.1784 [hep-th]

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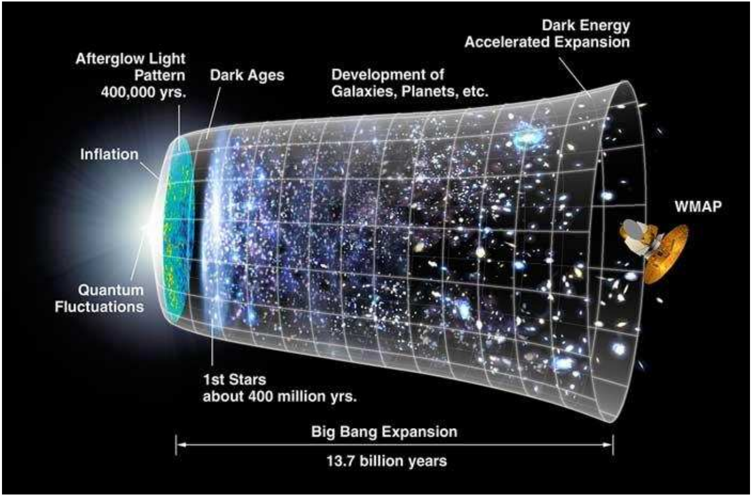
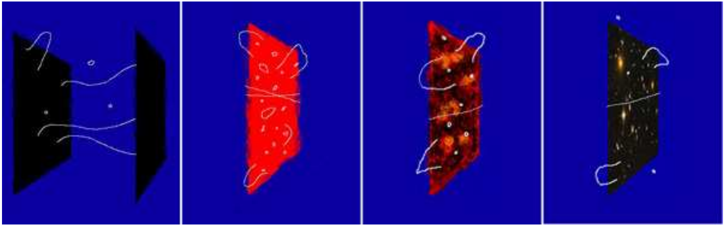
Motivation


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Motivation

Cosmic strings vs cosmic superstrings



- Cosmic superstrings are produced at the end of brane inflation.
- They can have richer networks and radiation modes than cosmic strings, BUT...
- they are subject to consistency conditions on the underlying string theory and brane inflation models

Outline

1. PART I: CONSTRAINTS ON BRANE INFLATION MODELS
    - Supergravity constraints
    - D3/D7 inflation
    - Brane-antibrane inflation
2. PART II: CONSTRAINTS ON CSS RADIATION
    - Cosmic superstrings
    - CSS radiation
    - Allowed radiation
    - The axionic wavefunction
3. CONCLUSIONS

The FI term

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$$\xi D \in \xi \int d^2\theta d^2\bar{\theta} V \, ,$$

  where V is a real vector superfield, provides one of 2 ways to induce spontaneous supersymmetry breaking.
- However, it is **very** difficult to couple it to supergravity:

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  where V is a real vector superfield, provides one of 2 ways to induce spontaneous supersymmetry breaking.
- However, it is **very** difficult to couple it to supergravity:
- FI term ⇒ FZ supermultiplet no longer gauge invariant
- R-symmetry ⇒ gauge-invariant R-current, BUT
- Both methods result in an identical sugra theory with a continuous global symmetry *Komargodski & Seiberg, 0904.1159; Dienes & Thomas, 0911.0677*
- Forbidden (covariant entropy bound) *[See e.g. Banks & Seiberg, 1011.5120]*

Supergravity constraints

So, in consistent supergravity theories:

1. Field-independent FI terms are not allowed
2. The moduli space cannot be compact *Komargodski & Seiberg, 1002.2228*:
   - well-defined FZ multiplet $\iff$ exact Kähler form J
   - Then, $\int_\gamma J \wedge J \wedge J \ldots = 0$ for γ compact.
   - i.e. exact Kähler form $\iff$ noncompact moduli space

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Note that

1. the moduli space can be a discrete set of points
2. making the FI term field-dependent will render the moduli space noncompact
3. these conditions are equivalent to the conditions for unbroken $\mathcal{N} = 1$ supersymmetry in an AdS_4 background. *Adams et al, 1104.3155*:

Implications for brane inflation

- D3/D7 is a string embedding of **D-term inflation**, which uses the FI term ξ to break SUSY and start inflation.
- In D3/D7 and D3/$\overline{\mathrm{D3}}$, need to stabilize the volume, while allowing the branes to move.
- **Such moduli stabilization cannot be done in a supersymmetric way**: the closed string modulus cannot be larger than the open string one or the SUSY breaking scale

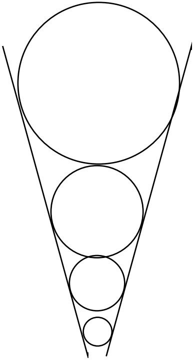


Figure: A compact space fibered by an unfixed modulus

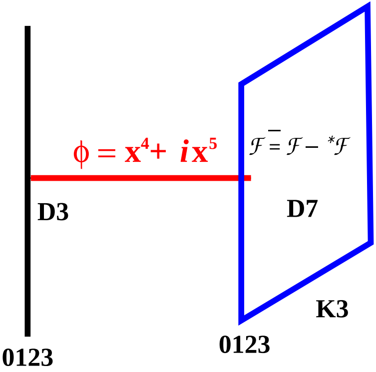
Constraint on D3/D7

The NSD flux on the D7 gives a field-dependent FI term via GS mechanism:

$$\xi = \frac{\delta_{GS}}{\mathrm{vol(K3)}}$$

where $s = vol(K3) + \imath C_{(4)}$, s the Kahler modulus.

[Binetruy, Dvali, Kallosh, Van Proeyen, 0402046; Burgess, Kallosh, Quevedo, 0309187, RG, Sakellariadou and Sypsas, 1008.0087]



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- ✓ ξ is field dependent!
- X But Vol(K3) must be stabilised above the SUSY scale
- ? Is ξ constant?
- ✓ No – it depends on r :

$$\xi^2 \sim \frac{1}{g^2}\int_{\mathrm{K3}} \mathcal{F}^- \wedge \star\mathcal{F}^-$$

$$\xi^2 = \xi^2(r)$$

[Haack et al, 0804.3961]; Dasgupta et al, 0405247; RG, Sakellariadou and Sypsas, 1105.1784]

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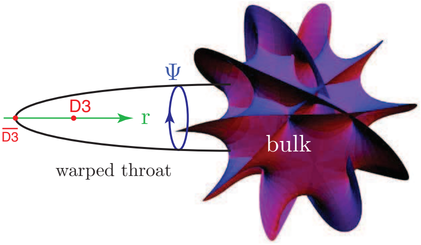
Then bifurcation point and Hubble constant depend on $r \Rightarrow$ still D-term inflation?

Constraint on D3/$\overline{\mathrm{D3}}$



[stolen from Baumann and McAllister, 0901.0265]

- No FI term, but the moduli space must be noncompact
- But we want to stabilize the volume!

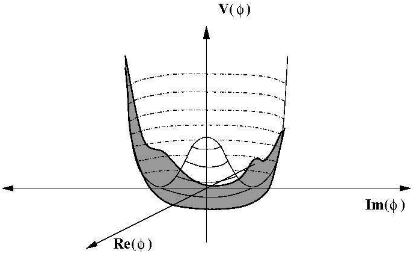
- Moduli space will be a discrete set of points [Adams et al 1104.3155]
- In this case, there is no flat direction for the inflaton...
- Have to **break** SUSY, then can stabilize volume below this scale [KKLT, KKLMMT]
- **Crucial point: volume is not tied to the SUSY scale (Unlike D3/D7)**

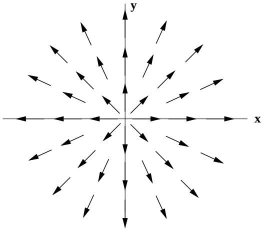
Cosmic strings

- Topological defects are expected to have formed during phase transitions in the early universe:

$$G \rightarrow H \rightarrow \ldots \rightarrow SU(3)\times SU(2)\times U(1) \rightarrow SU(3)\times U(1)_{\mathrm{em}}.$$

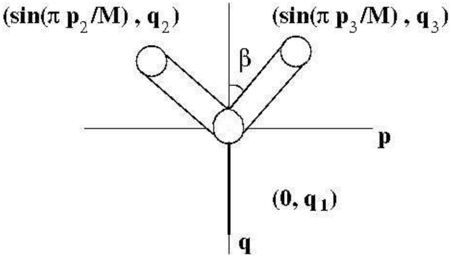
- **Cosmic strings** will form when the vacuum manifold $\mathcal{M} = G/H$ is not simply connected.





Cosmic superstrings

- CSS are produced at the end of brane inflation
- These can be
    - F strings (fundamental strings)
    - D strings (D1 branes)
    - (p,q) strings (bound states)
    - wrapped Dp-branes
    - wrapped M branes ....
- Can form junctions
- Richer spectrum than cosmic strings



CSS in brane inflation

- A network of (p,q) strings is produced
- Tension is too large in D3/D7 (can make semilocal)
- In D3/$\overline{\mathrm{D3}}$, warping lowers the tension:

$$T_{(p,q)} = \frac{h_l^2}{2\pi\alpha'}\sqrt{\frac{q^2}{g_s^2}+\left(\frac{bM}{\pi}\right)^2\sin^2\left(\frac{\pi(p-qC_0)}{M}\right)},$$

where $h_l \ll 1$ is the warp factor at the bottom of the throat:

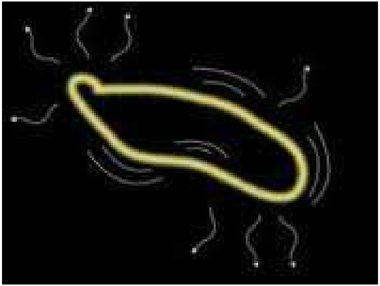
$$ds^2 = h^2(y)\eta_{\mu\nu}dx^\mu dx^\nu + g_{mn}dy^m dy^n$$

[Firouzjahi, Leblond and Tye, hep-th/0603161; also Herzog and Klebanov, hep-th/0111078, Hartnoll and Portugues, hep-th/0405214, Gubser et al, 0405282]

CSS radiation

- (p, q) strings are charged under B_2^{NS} and C_2^{RR}
- They can lose energy via emission of massless RR or NSNS particles
- C_2 is Hodge dual to an axion ϕ in 4D, so the RR particle is called an axion:

$$\star dC_2 = d\phi$$



Warped background - radiation

- In flat space, power radiation from RR emission $\sim$ radiation from gravitational wave emission.
- In a warped background ($h \ll 1$), RR/NSNS radiation can be enhanced for D-strings: [Firouzjahi, 0710.4609]

$$
\begin{aligned}
S_{\mathrm{D,4dim}} &= \frac{M_{\mathrm{P}}^2}{2}\int d^4x\sqrt{-g}\left(R - \frac{\beta g_s}{12}F_3^2\right) \\
&\quad -\mu_{eff}\int dtdx\sqrt{-\gamma} + \mu_1\int dtdxC_2\,, \\
\frac{P_{\mathrm{RR}}}{P_{\mathrm{g}}} &= \left(\frac{8\Gamma_{\mathrm{RR}}}{\pi\Gamma_{\mathrm{g}}}\right)\frac{g_{\mathrm{s}}}{\beta h^4}\,, \qquad \mu_{eff} = h^2\mu_1 g_s^{-1} \\
\beta &= \frac{\int d^6y\sqrt{g_6}h^{-2}(y)}{\int d^6y\sqrt{g_6}h^2(y)}\,.
\end{aligned}
$$

What about (p,q) strings??

Flux compactification

- The only known consistent compactification of the KS throat is the GKP flux compactification [Giddings, Kachru, Polchinski, hep-th/0105097]
- GKP involves an orientifold projection

$$\mathcal{O} \;=\; (-1)^{F_{\rm L}}\Omega_p\sigma^\star \;,$$

- This acts on the NSNS and RR two-forms as

$$\mathcal{O}B_2 \;=\; -\sigma^\star B_2 \qquad \text{and} \qquad \mathcal{O}C_2 \;=\; -\sigma^\star C_2 \;,$$

- $\sigma^\star$ acts on the internal manifold, so $B_{\mu\nu}$ and $C_{\mu\nu}$ are projected out
- ⇒ Their zero modes do not appear in the spectrum [Copeland, Myers, Polchinski, hep-th/0312067]

Allowed radiation

For a (p,q) string which is actually a *wrapped D3 brane* , RR radiation is possible if there exists a two-cycle $\Omega_2 \in H^2_-$:

$$D_2(x^M) \quad = \quad d_2(x^\mu) + d(x)\Omega_2 + V_1(x) \wedge \alpha_1 \ ,$$

- d_2 is projected out
- $d(x)$ (model-dependent axion) is allowed if $\Omega_2 \in H^2_-$ exists
- This does not help the case of an F-string (B_{01}).

Similarly, the decomposition

$$C_4(x^M) = c_4(x^\mu) + c_2(x^\mu) \wedge \Omega_2 + c_1(x^\mu) \wedge \Omega_3 + c(x^\mu) \wedge \Omega_4$$

with $\mathcal{O}C_4 = \sigma^\star C_4$ can give rise to RR radiation via $c_2(x^\mu) \wedge \Omega_2$ as long as Ω_2 is odd under the involution.

Enhancement?

We have seen that

- D-strings and F-strings in warped throat have no NSNS or RR axions
- Two types of model-dep RR axion are possible for (p,q) strings which are wrapped D3 branes

Q: *But what about the proposed enhancement of axionic radiation in the throat?*

Axionic wavefunction I

- dimensional reduction in a warped geometry is nontrivial
- EOM, including warping and compensating terms, given for the universal Kähler volume modulus and the universal axion a

$$C_4 = aJ \wedge J,$$

where J is the Kähler form ($\sigma^\star J = J$)
[Frey, Torroba, Underwood and Douglas, 0810.5768]

- $\mathcal{O}C_4 = \sigma^\star C_4$ and $\sigma^\star J = J$ so the universal axion is allowed in a compactified throat geometry.
- However, there is no way to couple it to a string.
- $\Rightarrow$ only nonuniversal axions can couple to the (p, q) string constructed from a wrapped D3(say)-brane

Axionic wavefunction II

Nonuniversal axions pose a problem:[Frey, Torroba, Underwood and Douglas, 0810.5768]

- It is not known how to solve the EOM (only formal expressions can be given)
- compensators are required which result in mixing between C_2 and C_4.
- The resulting wavefunction is needed to calculate the magnitude of the radiation,
- Thus the amplitude of such radiation is an open question.

Conclusions

1. Brane inflation models subject to sugra consistency constraints
2. FI term in D-inflation must depend on an unfixed modulus
3. D3/D7: $\xi = \xi(r)$, but will this affect inflation?
4. D3/$\overline{\mathrm{D3}}$: moduli space cannot be compact;
   - it can be a discrete set of points
   - one can play with the SUSY breaking scale
5. Enhancement of axionic radiation does not translate to (p,q) strings:
   - axionic radiation ruled out for F,D strings in a throat
   - RR radiation possible for wrapped D3 branes, but hard to quantify

Warped Compactification

- Dimensional reduction of light fields is non-trivial in flux compactifications [Frey, Torroba, Underwood and Douglas, 0810.5768]
- Consider the universal volume or Kähler modulus. In the unwarped case this corresponds to a rescaling

$$g_{mn} \rightarrow e^{2u} g_{mn} \ , \tag{1}$$

and fluctuation

$$ds^2 = e^{-6u(x)} g_{\mu\nu} dx^\mu dx^\nu \ , \tag{2}$$

- It pairs with the universal axion given by

$$C_4 = \frac{1}{2} a(x) J \wedge J \ , \tag{3}$$

where J is the Kähler form of the CY, into the complex field $\rho = a + \imath e^{4u}$.

Warped Compactification

- In a warped background it is not immediately clear how to define the fluctuations u or a.
- Naively writing

$$\begin{aligned} ds^2 &= e^{2A(y)}e^{-6u(x)}\eta_{\mu\nu}dx^\mu dx^\nu \\ &\quad + e^{-2A(y)}e^{2u(x)}g_{mn}(y)dy^m dy^n \ , \end{aligned}$$

  do not solve the ten-dimensional Einstein equations.
- It turns out that additional components (called compensators) in the metric will be required, complicating the dimensional reduction.
- 2 compensators are required for definition of the universal axion, and these enter in the EOM
- Compensators for nonuniversal axion result in mixing between C_2 and C_4.