Multifield D5 brane inflation in the throat

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27th International conference on Supersymmetry and Unification of Fundamental Interactions SUSY2019

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Outline

Cosmological inflation

Background
  Warped Resolved Conifold (WRC)
  Moving D-branes in the warped throat

4D effective Scalar field potential

Cosmological evolution
  Multifield behaviour

Summary

Background
Inflation

- The period of accelerated expansion (Exponential) of early Universe.

\[ ds^2 = -dt^2 + a^2(t) dx^2 \quad \text{with} \quad \ddot{a} > 0 \]

- The horizon problem, flatness problem and magnetic monopoles are taken care of.
Inflation

- **Toy Model:** Canonical scalar field slowly rolling down a potential

\[ S = \int d^4x \sqrt{-g} \left[ \frac{M^2_{pl}}{2} R - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) \right] \]
Key ingredients:

▶ String flux compactification of type IIB string theory on CY3
▶ Probe D5-brane moving in Warped Resolved Conifold throat approximation
▶ We study the multifield cosmological evolution of a probe brane moving near the tip region of WRC.
Key ingredients:

- String flux compactification of type IIB string theory on CY3
- Probe D5-brane moving in Warped Resolved Conifold throat approximation
- We study the multifield cosmological evolution of a probe brane moving near the tip region of WRC.

Figure: The Bulk
The metric on a Resolved Conifold (RC) looks like,

\[
\begin{align*}
    ds^2_{RC} &= \tilde{g}_{mn}dy^m dy^n = \\
    &\left(\frac{r^2 + 6u^2}{r^2 + 9u^2}\right) dr^2 + \frac{1}{9} \left(\frac{r^2 + 9u^2}{r^2 + 6u^2}\right) r^2 (d\psi + \cos \theta_1 d\phi_1 + \cos \theta_2 d\phi_2)^2 + \frac{1}{6} (d\theta_1^2 + \sin^2 \theta_1 d\phi_1^2) + \frac{1}{6} (r^2 + 6u^2) \times \\
    &\left(d\theta_2^2 + \sin^2 \theta_2 d\phi_2^2\right)
\end{align*}
\]

Warped Resolved Conifold (WRC)

The warped 10D spacetime is obtained by placing \( N \) D3-branes at the tip (localised at the north pole of \( S^2 \)) or placing \( M \) D5-brane in the throat.
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The resulting geometry is the **Warped Resolved Conifold** with 10D metric

$$ds^2 = \mathcal{H}^{-1/2}(\rho, \theta_2) ds^2_{FRW} + \mathcal{H}^{1/2}(\rho, \theta_2) ds^2_{RC}$$

*L.A. Zayas, A.A. Tseytlin JHEP 0011:028,2000*
Warped Resolved Conifold (WRC)

The warped 10D spacetime is obtained by placing $N$ D3-branes at the tip (localised at the north pole of $S^2$) or placing $M$ D5-brane in the throat or both.

Expression for the WRC warp factor is given by

$$\mathcal{H}(\rho, \theta) = \left(\frac{L_{T_{1,1}}}{3u}\right)^4 \sum_{l=0}^{\infty} (2l + 1) H_l^A(\rho) P_l[\cos \theta]$$

The D5 brane embedding

We take the simple embedding of the D5-brane in the 10D spacetime as in \[1,2\]

$$\xi^a = (x^\mu, \theta_1, \phi_1) \text{ where } \mu = 0, 1, 2, 3$$

We turn on a non-zero worldvolume electric flux $F_2$ of strength $q$, along $\Sigma_2$.

The D5-brane dynamics

We consider a warped metric ansatz for a flux compactification given by,

\[ ds^2 = e^{2A(y)} g_{\mu\nu} dx^\mu dx^\nu + e^{-2A(y)} \tilde{g}_{mn} dy^m dy^n \]


The D5-brane dynamics is given by the DBI and CS term,

\[ S_{D5} = S_{D5}^{DBI} + S_{D5}^{CS} \]

we can write down the 4D effective action,

\[ = \int d^4x \sqrt{g_{FRW}} \left[ \frac{M_p}{2} \mathcal{R}_4 + \frac{1}{2} G_{ab} \partial_\mu \phi^a \partial^\mu \phi^b - V(r, \theta_2) \right] \]
The potential $V(r, \theta)$

Where $G_{ab}$ is,

$$ G_{ab} = \begin{pmatrix} 4\pi p T_5 F^{1/2} \frac{r^2 + 6u^2}{r^2 + 9u^2} & 0 \\ 0 & 4\pi p T_5 F^{1/2} \frac{r^2 + 6u^2}{6} \end{pmatrix} $$

We consider brane potential of the general form,

$$ V(r, \theta) = V_0 + \varphi(r) + \lambda(\Phi_- + \Phi_h), \quad \lambda = 4\pi^2 l_s^2 p q T_5 g_s, \quad \rho = \frac{r}{3u} $$

$$ \varphi(r) = 4\pi p T_5 H^{-1}[F^{1/2} - l_s^2 \pi q g_s], \quad \text{where,} \quad F \equiv \frac{H}{9} (r^2 + 3u^2)^2 + (\pi l_s^2 q)^2 $$

$$ \Phi_- = \frac{5}{72} [81(9\rho^2 - 2)\rho^2 + 162 \log(9(\rho^2 + 1)) - 9 - 160 \log(10)] $$

$$ \Phi_h = a_0 \left[ \frac{2}{\rho^2} - 2 \log \left( \frac{1}{\rho^2} \right) \right] + 2a_1 \left[ 6 + \frac{1}{\rho^2} - 2(2 + \rho^2) \log \left( 1 + \frac{1}{\rho^2} \right) \right] \cos \theta $$

$$ + \frac{b_1}{2} (2 + 3\rho^2) \cos \theta $$

$$ H = \left( \frac{L^{T_{1,1}}}{3u} \right)^4 \left( \frac{2}{\rho^2} - 2 \ln \left( \frac{1}{\rho} + 1 \right) \right), \quad L^{4}_{T_{1,1}} = \frac{27\pi}{4} Ng_s l_s^4 $$

The potential $V(r, \theta)$

The hierarchies of scales:

\[ M_{pl} > M_s > M_C > H \]
D5-brane multifield inflationary evolution

The background EOM can be written as,

\[
(\phi^a)'' + 3 \left( 1 - \frac{\varphi'^2}{6M_p^2} \right) (\phi^a)' + \Gamma^a_{bc} (\phi^b)' (\phi^c)' + \frac{1}{H^2} G^{ab} \partial_b V = 0
\]

\[
H^2 = \frac{V}{3M_p^2} (1 - \frac{\varphi'^2}{6M_p^2}) \quad \text{where} \quad \varphi'^2 = G_{ab} v^a v^b
\]

The decay constant is given by, \( f = \sqrt{G_{\theta \theta}} \)
Choices of IC

Decay constants for different values of the wrapping number $p$ for the case study with $r_{min} = 456.797$ and $\theta_{min} = 33\pi$, using values of the parameters in previous table.

<table>
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<th>$p$</th>
<th>$f/M_p$</th>
<th>$r_{initial}$</th>
<th>$\theta_{initial}$</th>
<th>$N_{tot}$</th>
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<td>37</td>
<td>4.53</td>
<td>410</td>
<td>106.473</td>
<td>75.64</td>
</tr>
</tbody>
</table>

Field behavior

Figure: For $f = 7.07M_{Pl}$
Cosmological prediction

A Maharana, I Zavala PhysRevD 2018
Cosmological prediction

Planck 2018 results. X. Constraints on inflation 2018
Local Non-gaussianianity $f_{NL}^{local}$

Covariant formalism

$$f_{NL} = -\frac{5}{6} \frac{N^{,A}N^{,B}D_AD_BN}{(N,N^,I)^2}$$

$$N_{,r} = \frac{N(r + \Delta r, \theta) - N(r - \Delta r, \theta)}{2\Delta r}$$

Outside throat Double D-brane inflation
Turn rate

This multifield behaviour can be characterised using the following unit vectors, along and orthogonal, to the inflationary trajectory,

\[ T^a \equiv \frac{\phi'^a}{|\phi'|}, \quad N^a \equiv -\frac{T'^a}{|T'|} \]

together with the turning rate \( \eta_\perp \), defined by

\[ \eta_\perp = |T'^a| \]

A Achucarro, V Atal, M Kawasaki, F Takahashi 2015,
A AChucarro, G Palma 2019

Figure: For \( f = 7.07M_{Pl} \)
Effective mass-squared of the isocurvature perturbation is given by,

\[ m_{\text{eff}}^2 = N^a N^b \nabla_a \nabla_b V - 3 \Omega^2 + \epsilon H^2 \mathcal{R} \]

For \( R < 0 \) may give rise to geometrical destabilisation during inflation if \( m_{\text{eff}}^2 < 0 \)
R of the field manifold

**Figure:** For $f = 7.07 M_{Pl}$

- Effective mass-squared of the isocurvature perturbation is given by,

\[ m_{eff}^2 = N^a N^b \nabla_a \nabla_b V - 3\Omega^2 + \epsilon H^2 R \]

- For $R < 0$ may give rise to geometrical destabilisation during inflation if $m_{eff}^2 < 0$, but we don’t have that!

Conclusion:

- **Inflation type:** Monomial like, Natural inflation, Double D-brane

- **Warping,** brane flux $q$ as well as **wrapping** helps to obtain **super-Planckian** decay constant $f$ where having control over backreaction.

- We confirm that multifield behaviour is certain in our model contrary to KT
Thank you
Appendix 1: Moduli stabilisation

- This is an open string inflation, so we are assuming that all closed string moduli have been stabilised at their minima, decoupled from the WRC. They are not affecting the brane dynamics.
- RC has $h^{2,1} = 0$ and $h^{1,1} = 1$. The axio-dilaton can be stabilised by turning on $(3,0)$-form fluxes which breaks $\mathcal{N} = 1$ SUSY.
- When the compact case is considered in RC, the bulk Calabi-Yau may have a different topology, allowing for $h^{2,1} > 0$, and so SUSY preserving primitive $(2,1)$-form fluxes may be turned on, stabilizing the additional complex-structure moduli and the axiodilaton.
Appendix 2: Backreaction of branes

- Ways to constrain the wrapping parameter $p$ and brane flux $q$.
  D5-brane can be used as a probe iff its contribution to the Einstein equation is much smaller than that of the stack of $N$ D3-brane.

The traced Einstein equation is given by,

$$(T^m_m - T^\mu_\mu)^{loc} = (7 - p) T_p \Delta^{(9-p)}(\Sigma_{p-3})$$

The condition of controlled backreaction using WRC metric is,

$$\frac{p}{2N} \frac{T_5}{T_3} \frac{\Delta^{(4)}(\Sigma_2)}{\Delta^{(6)}(\Sigma_0)} \ll 1 \quad \Rightarrow \quad p \ll \frac{12N(2\pi)^2 \mathcal{H}^{-1/2} l_s^2}{\sin \theta_1 r^2}$$


- Backreaction due to D5 is smaller near the tip!

The constrain on $q$ is,

$$\frac{T_5 \rho_3^{pq} D^5}{T_3 \rho_3^N D^3} \ll 1 \quad \Rightarrow \quad pq \ll \frac{T_3}{T_5} \frac{N}{\pi l_s^2 \sin \theta_1} = \frac{4\pi N}{\sin \theta_1}$$

- Large parameter space where these conditions can be satisfied, giving rise to a successful period of inflation.

S. Thomas, Z Kenton JHEP 2015
Appendix 3: Conifold

It is a cone over the base $T^{1,1} \sim S^2 \times S^3$, with singularity at the tip.

The resolved conifold is one of the two smooth versions of the non-compact Calabi-Yau three fold,