Large-Field Inflation in String Theory

(axion monodromy in a controlled 4d-SUGRA regime)

in collab. with **S.C. Kraus and L. Witkowski**

(Heidelberg)

Outline

- Role of String Theory in Inflationary Model Building
- Relevance of Large Field Inflation
- Axion Monodromy
- New 'F-term' or 4d-SUGRA models of Axion Monodromy
- Summary/Conclusions

Inflation in field theory is 'easy' . . .

- We just need $V(\varphi)$ with

$$\frac{1}{2}\left(\frac{V'}{V}\right)^2 \ll 1 \qquad \text{and} \qquad \left|\frac{V''}{V}\right| \ll 1$$

Large-field method:

- If $\varphi \gg 1$ (in Planck units), simple (e.g. power-law) potentials will do the job

- Suppressing (all!) higher-dim. operators can presumably be realized with a shift symmetry

Linde '83; Freese/Frieman/Olinto '90

Small-field method:

- Motivation: Quantum-gravity-based ‘unease’ about $\varphi \gg 1$
- Advantage: Need only to worry about leading operators (high powers of φ are tiny)
- Disadvantage: The coefficients of the first few operators (1, φ^2, φ^4) need to be engineered/tuned to ensure flatness

cf. e.g. ‘hybrid infl.’, Linde ’91, . . . , talks by Buchmüller, Domcke, Dudas, . . .

Personal conclusion:

- In QEFT, things are as good as it gets w/o Quant.Grav.
- It is in the UV completion (i.e. mostly string theory) where things become difficult and hence interesting

  (cf. assumptions about higher-dim. operators)

...thus, from now on, focus on

Inflation in String Theory:

- Small-field models can presumably be realized through
  - tuning (KKLMMT)
  - model building (stringy 'hybrid' or 'Kähler modulus' inflation)

Dvali/Tye '98, Garcia-Bellido/Rabadan/Zamora '01,
Dasgupta/$\cdots$/Kallosh '02
Conlon/Quevedo '05, Cicoli/Burgess/Quevedo '09

- Large-field models have remained 'more of a challenge'

...thus, from now on, focus on

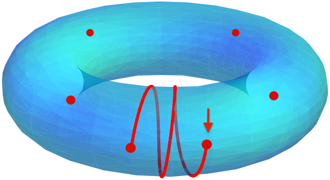
Large-Field Inflation in String Theory:

More serious motivation:

- Large-field models are 'robust'
  (in the sense of not requiring very special potentials)
- If sizeable tensor modes are found (e.g. by BICEP2),
  $\Delta\varphi \gtrsim 1$ is more or less enforced
- If, furthermore, string-theoretic problems with large-field inflation persist, this may rule out string theory

Origin of problems:

- The moduli space of string compactifications is (mostly) compact and, in fact, small
- All fields of string compactifications can, in some way, be derived from those (compact) moduli
- The known non-compact directions (such as decompactification) quickly lead to $V = 0$.



Main Approaches to Large-Field Inflation in String Theory:

- Our main ingredient are always axions
  `Four our purposes:` periodic real scalars with (approximate) shift symmetry

- Simplest example: $\varphi = \int_{S^1} A_5 dx^5$
  (Wilson line, with an S^1-field space)

(1) Extend axion range by (judiciously) combining several axions

Kim/Nilles/Peloso '04, Dimopoulos/Kachru/McGreevy/Wacker '05

(2) Break periodicity by introducing a monodromy in axion field space

Silverstein/Westphal, McAllister/Silverstein/Westphal '08

Our focus here: Axion Monodromy

'Old' Axion Monodromy Models:

Silverstein/Westphal, McAllister/Silverstein/Westphal '08

- Want to build on recent progress in moduli stabilization ('flux landscape')
- This is understood best in type IIB
- (One) natural idea: Use $\varphi = \int_{S^2} B_2$,

  with monodromy introduced by pullback to D7-brane:

$$S_{\rm DBI} \sim \int \sqrt{-\det(g_{\mu\nu} + F_{\mu\nu} + B_{\mu\nu})}$$

- Unfortunately, this has a supergravity η-problem since,

  symbolically, $K \supset |G - \overline{G}|^2 \, ; \qquad G \sim C_2 + iB_2$

- By contrast, the crucial shift symmetry can be maintained if

$$\varphi = \int_{S^2} C_2 \ ,$$

But this requires D7 $\rightarrow$ NS5,
which in turn requires an anti-NS5 (for tadpole cancellation).

- As a result, SUSY is broken explicitly and the desired 4d effective supergravity description of moduli stabilization is lost.

(See, however, recent progress in the F-theory context:
Palti/Weigand, 1403.7507)

- The 'canonical' way out is to appeal to special types of warped throats (the existence of which is difficult to establish) to control the anti-NS5 backreaction

A New Class Axion Monodromy Models

- This situation may have fundamentally improved with a recent series of papers:

  Marchesano/Shiu/Uranga, 1404.3040
  Blumenhagen/Plauschinn 1404.3542
  AH/Kraus/Witkowski 1404.3711

  as well as:

  Ibanez/Valenzueala
  Arends,AH,. . . , Lüst, Mayrhofer, Weigand
  McAllister/Silverstein/Westphal/Wrase
  Franco/Galloni/Retolaza/Uranga

  Executive Summary:

- Let the Kähler potential be shift-symmetric, $K \supset |G - \overline{G}|^2$, with $\mathrm{Re}(G)$ an axionic (periodic) direction

- Let $W = W(G)$ introduce a monodromy

- Crucial: This arises frequently in string compactifications !

Marchesano/Shiu/Uranga:

- One crucial aspect: 'Massive Wilson Lines'
- Idea: Let the D-brane geometry be an S^1 fibration
- 'Twist' this fibration such that the S^1-cycle becomes globally trivial (as in twisted tori)

Blumenhagen/Plauschinn:

- Use C_0 of $S = 1/g_s + iC_0$.
- Since $K = -\ln(S + \overline{S})$ and $W = A(z) + SB(z)$, tuning for a small mass of S is easy
- Stabilizing $\mathrm{Re}(S)$ remains a challenge

Finally (and for the rest of the talk):

'Our' Chaotic-D7-brane scenario

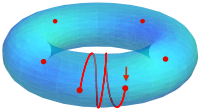
(with Kraus/Witkowski)

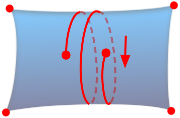
- Start with older 'D7-brane' proposal ('fluxbrane inflation')

AH, Kraus, Lüst, Steinfurt, Weigand '11
... + Küntzler '12

- Central point: In type IIB at at 'large complex structure', certain D7-brane position moduli have shift symmetry

- In addition: They are part of the flux superpotential, which may induce a (small!) monodromy





Origin of Shift symmetry

(A) Via D6 branes in type IIA mirror dual

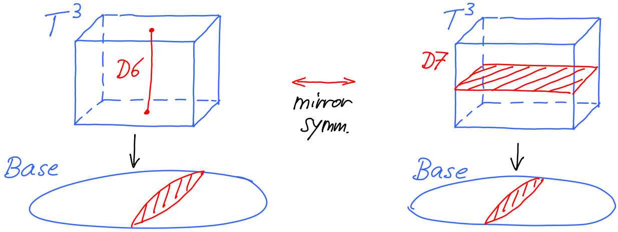
- complex D6-brane moduli combine a (real) position modulus with a (real) Wilson line
- By mirror symmetry, both become D7-brane position moduli
- The (shift-symmetric) Kähler potential ‘remembers’ which direction of D7-brane motion comes from a Wilson line:

$$K \supset f(c - \overline{c})$$

Origin of Shift symmetry

(A) Via D6 branes in type IIA mirror dual

- The ‘Wilson-line-type’ modulus corresponds to moving the D7-brane in the fibre-T^3 of the SYZ picture of the type IIB Calabi-Yau



- This ‘Wilson-line-type’ modulus is our axion/inflaton

Origin of Shift symmetry

(B) Via F-theory / Mirror symmetry of 4-folds

- D7 brane moduli and complex structure moduli are part of the complex structure of the F-theory 4-fold: $\{c, u\} \equiv \{z\} \equiv \{t\}$.

- For the mirror dual 4-fold, these are all (shift-symmetric) Kähler moduli:

$$K \supset -\ln[\kappa_{ijkl}(t-\overline{t})^i(t-\overline{t})^j(t-\overline{t})^k(t-\overline{t})^l]$$

- Hence (symbollically):

$$K \supset -\ln[(u-\overline{u})^4 + (u-\overline{u})^2(c-\overline{c})^2]$$

Superpotential and flux-tuning

- The F-theory superpotential takes the general form

$$W = N^A \, \Pi_A(u^i, c^i)$$

- By flux tuning, we assume

$$W = W_0 + \alpha c + \frac{\beta}{2} c^2$$

with

$$\alpha = \alpha(u^i, c^i) \ll 1$$
$$\beta = \beta(u^i, c^i) \ll 1$$

Complete Model and Inflationary Potential

- Our 4d-supergravity analysis is based on

$$K = -2\ln\tilde{\mathcal{V}} - \ln\left(A + iB(c-\overline{c}) - \frac{D}{2}(c-\overline{c})^2\right)$$

and

$$W = W_0 + \alpha c + \frac{\beta}{2}c^2 + e^{-2\pi T_s}$$

- Here T_s is the 'blowup-cycle' of the Large-Volume moduli stabilization proposal (which, together with T_b and the α'-correction, also appears in $\tilde{\mathcal{V}}$)

- The full scalar potential follows from the standard supergravity formula and lead to a 'chaotic' potential for $\varphi \sim \mathrm{Re}(c)$

In some more detail:

$$V = e^K \left(K^{T_i T_j} D_{T_i} W \overline{D_{T_j} W} - 3|W|^2 + K^{c\bar{c}} |D_c W|^2 \right)$$

- The first two terms stabilize T_b and T_s as in the standard LVS (at any given value of c)

- The last term provides the chaotic inflaton potential for $\mathrm{Re}(c)$ (which is small, but large enough to justify treating c as constant in the LVS terms)

  This appears to be consistent with the 'non-SUSY way out' mentioned in the talk of E. Dudas

Phenomenology

- The leading-order scalar potential (for canonically normalized inflaton $\varphi \sim \mathrm{Re}(c)$) thus reads

$$V = \frac{1}{2} m_\varphi^2 \varphi^2 \qquad \text{with} \qquad m_\varphi^2 = \frac{|\beta|^2}{\mathcal{V}^2}$$

- To get a 'maximal' tensor/scalar ratio $r \simeq 0.16$, we need $m_\varphi \simeq 0.5 \cdot 10^{-5}$

- The inflaton field excursion is $\varphi_{60} \simeq 14$

- To ensure stability of Kähler moduli, the inflaton potential needs to stay below the LVS stabilization scale:

$$m_\varphi^2 \varphi_{60}^2 \simeq 0.5 \cdot 10^{-8} \ll \frac{|W_0|^2}{\mathcal{V}^3}$$

- This works e.g. for $\mathcal{V} \simeq 10^3$, $|W_0| \simeq 10$, and $\beta \simeq 0.5 \cdot 10^{-2}$

Phenomenology (continued)

- Next, we need to worry about stability of $\mathrm{Im}(c)$, which becomes light in the large complex structure limit $\mathrm{Im}(z) \gg 1$
- A sufficient condition is

$$\frac{\varphi_{60}\,|\beta|\,\mathrm{Im}(z)^2}{|W_0|} < 1$$

- The resulting limit $\mathrm{Im}(z) < 12$ is fortunately consistent with keeping corrections $\sim \exp(2\pi i z)$ tiny
- Finally, we have both loop corrections (suppressed by volume and π-factors) and 'instanton' corrections ($\sim \exp(2\pi i z)$)
- They induce oscillations on top of the φ^2 potential. While small, they could be a 'smoking gun' for such models

Summary/Conclusions

- Inflation (and especially large-field inflation) is a challenge and an opportunity for string theory
- Considerable progress towards moduli stabilization in monodromy models has recently been made
- In particular, the dynamics of D7-branes in flux compactifications provides a ground where explicit exampes appear within reach ('Chaotic D7-brane inflation')

Challenges:

- Explicitly realize the required large complex structure limit
- Is tuning a necessity or just a drawback of large-field models?