Tuning and Backreaction in F-term Axion Monodromy Inflation

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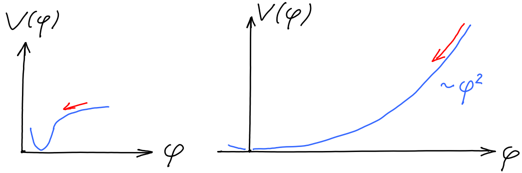
Outline

- Why look for large-field inflation models?
- Proposals: KNP vs. axion-monodromy models
- Recent progress: F-term axion monodromy
- Tuning requirements and their implementation in F-theory
- Backreaction; Kahler moduli stabilization; landscape restrictions

Preliminaries

- Slow-roll inflation comes in two variants:
  small- and large-field models

  (Always in units where $\overline{M}_P = 1$)



- Small-field models require a (tuned) very flat potential

- Large-field models work with generic potentials
  (e.g. $V(\varphi) \sim \varphi^2$), but the field-range $\Delta\varphi \gg 1$ is a challenge

'Why look for large-field models in string theory?'

1) Observations

- The amount of primordial gravity waves is measured by the tensor-to-scalar ratio:

$$r = \frac{\Delta_T^2}{\Delta_R^2} \simeq 8 \left| \frac{d\varphi}{dN} \right|^2 \quad \Rightarrow \quad \Delta\varphi \simeq 20\sqrt{r}$$

- Thus, even though the BICEP 'discovery' went away, the need to consider large-field models may return

- Note: The new Planck/BICEP analysis still sees a ($\sim 1.8\sigma$) hint for $r \simeq 0.05$

- Much better values/bounds are expected soon

'Why look for large-field models in string theory?'

2) Fundamental

- Do (parametrically) large-field models exist in consistent quantum gravity theories?

  see e.g. Arkani-Hamed/Motl/Nicolis/Vafa '06 .... Conlon '12

- Do they exist in the type IIB / F-theory landscape as we understand it at present?

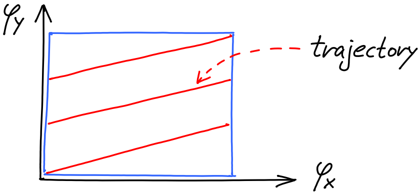
- Basic obstacle: Moduli spaces of string compactifications are 'essentially' compact

  (Note: Of course, specific non-compact directions exist, e.g. large-volume or large-complex-structure. However, in these directions the potential decays way too quickly.)

Kim-Nilles-Peloso mechanism

Kim, Nilles, Peloso '04

- One such idea is to realize a 'winding' trajectory on a 2d periodic field space:

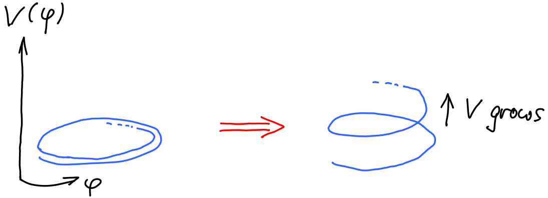


- Clearly, such a trajectory can be much longer than the (naive) field range
- The technical challenge is the realization of the required potential in concrete string models

Our focus here: Monodromy inflation

Silverstein/Westphal/McAllister '08

- We start with a single, periodic inflaton φ
- The periodicity is then weakly broken by the scalar potential



- Various concrete stringy realizations have been discussed; for an F-theoretic suggestion see

Palti/Weigand '14

F-term axion monodromy

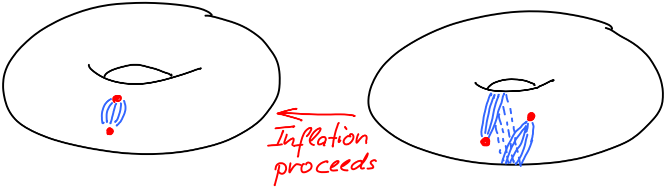
- Very recently, the first suggestions have emerged how this could be realized in a quantitatively controlled way

  (i.e. in a 4d supergravity description, stabilized moduli)

  Marchesano/Shiu/Uranga '14
  Blumenhagen/Plauschinn '14
  AH/Kraus/Witkowski '14

- In particular, in our suggestion inflation corresponds to D7-brane-motion

- The monodromy arises from a flux sourced by the brane



F-term axion monodromy (continued)

- One starts with shift-symmetric Kahler potential

$$K = K(u - \overline{u})$$

- Concretely, this can be realized in the large-complex structure limit of a 3-fold or 4-fold (where u could be a brane position)

Arends, AH, Heimpel, Kraus, Lüst, Mayrhofer, Schick, Weigand
McAllister, Silverstein, Westphal, Wrase
Blumenhagen, Herrschmann, Plauschinn
Hayashi, Matsuda, Watari '14

see Garca-Etxebarria, Grimm, Valenzuela for possible alternatives

- The shift symmetry is broken (and a monodromy introduced) by e.g. a flux choice

$$W = w + au\,,$$

- To keep this effect small, one needs small a

F-term axion monodromy (continued)

- Complex structure moduli $\{z^i\}$ other than u need to be included:
$$W = w(z) + au$$
- They can be much heavier than $\text{Re}(u)$, if $a \sim 1$ and $w \gg 1$

Blumenhagen, Herrschmann, Plauschinn '14

- However, the inflationary energy is then still high and Kahler moduli stabilization is problematic
- Thus, we want $a \ll 1$, which requires $a = a(z)$

AH, Mangat, Rompineve, Witkowski '14

Tuning in F-term axion monodromy

- Thus, we must consider the structure

$$K = K(z, \overline{z}, u - \overline{u}) \quad , \qquad W = w(z) + a(z)u \ ,$$

  with $a(z) \ll 1$ at the starting point $DW = 0$

- We appeal to the standard no-scale cancellation in the Kahler moduli sector

- The scalar potential is then determined by the (two) F-terms

$$\begin{aligned} D_u W &= D_u w + a + K_u a u \\ D_z W &= D_z w + (\partial_z a + K_z a) u \end{aligned}$$

- With $y \equiv \mathrm{Re}(u)$, we find

$$V \sim |K_u a|^2 y^2 + |\partial_z a + K_z a| y^2 + \cdots$$

Tuning in F-term axion monodromy (continued)

- To keep the potential

$$V \sim |K_u a|^2 y^2 + |\partial_z a + K_z a| y^2 + \cdots$$

  flat, we need to tune both $a \ll 1$ and $a_z \ll 1$

- Depending on how many of the z^i actually enter $a(z)$, the tuning price can be very high

- We believe that this is a generic feature of F-term axion monodromy models (although our explicit analysis is limited to complex-structure and F-theory/D7-brane models)

Towards concrete realizations

- Let us write $\{z^i, u\} \equiv \{z^I\}$ and consider the 3-fold period vector

$$\Pi_\alpha = \begin{pmatrix} 1 \\ z^I \\ \frac{1}{2}\kappa_{IJK} z^J z^K + \sum_p A_{Ip} e^{-\sum_J a_{pJ} z^J} \\ -\frac{1}{3!}\kappa_{IJK} z^I z^J z^K + \sum_p B_p e^{-\sum_J b_{pJ} z^J} \end{pmatrix}$$

as well as Kahler and superpotential

$$K = -\ln(S - \overline{S}) - \ln\left[\Pi_\alpha(z,u)\overline{\Pi}^\alpha(\overline{z},\overline{u})\right]$$

$$W = (N_F - S N_H)^\alpha \Pi_\alpha(z,u)$$

Towards concrete realizations (continued)

- Assuming that (at least) u is in the large-complex-structure limit, W takes the form

$$W = w(S,z) + a(S,z)u + \frac{1}{2}b(S,z)u^2 + \frac{1}{3!}c(S)u^3$$

- Moreover,

$$c(S) \sim (m + nS)\,,$$

  with $m, n \in \mathbb{Z}$ and $S = \frac{i}{g_s} + C_0$.
  Thus, a tuning $c \ll 1$ is impossible and c must be set to zero.

- $b(S,z)$ has a piece linear in z, with an S-dependent prefactor. A similar argument can again be made.

- This goes on and the whole structure collapses to $a = b = c = 0$.

Towards concrete realizations (continued)

- The above was oversimplified. The actual no-go theorem for tuning the coefficients of u^n in W relies on

  a) The maximally cubic field dependence (at LCS)

  b) The linear additional S-dependence

- These conditions are violated in F-theory fourfold at LCS

- The period vector is structurally as above, just with 4-th order polynomials

- As a result, for fourfolds it is in principle possible to realize

$$K = K(z, \bar{z}, u - \bar{u}) \quad , \qquad W = w(z) + a(z)u \ ,$$

with $a(z) \ll 1$ and $a_z(z) \ll 1$ in a SUSY vacuum

Backreaction

- The scalar potential

$$V = e^K \left(K^{I,J} D_I W \overline{D_J W} \right)$$

can be worked out and, with $u = ix + y$, takes the schematic form

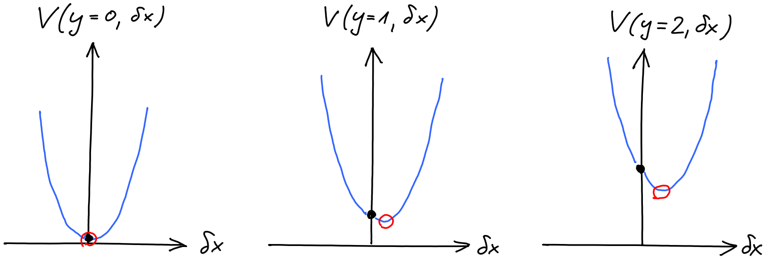
$$V = A(z, \bar{z}, x) + B(z, \bar{z}, x)\, y + C(z, \bar{z}, x)\, y^2$$

(in the SUSY vacuum $\{z_0, \bar{z}_0, x_0, y_0 = 0\}$ we have $A = B = 0$)

- At large y, certain field displacements $\delta z \equiv z - z_0$ etc. arise
- Since the 'naive' potential is very flat ($C(z_0, \bar{z}_0, x_*) \ll 1$ by tuning), even small δz induce $\mathcal{O}(1)$ corrections.

Backreaction (continued)

- The backreacted potential arises by minimizing $V(z, \overline{z}, x, y)$ with respect to $\{z, \overline{z}, x\}$ at each y:



- Thus, while the 'naive' potential is by definition quadratic, the backreacted potential is flatter and could potentially even become non-monotonic

cf. related considerations by Dong, Horn, Silverstein, Westphal, '10

Backreaction (continued)

- Specifically, we tune $a \sim \epsilon$ and $(a_z + K_z a) \sim \epsilon^2$ (with $\epsilon \ll 1$)
- Working up to quadratic order in δz^i (and writing $z^i = v^i + iw^i$) we find

$$V = \frac{1}{2}\Delta^T \mathcal{D}(y)\Delta + b^T(y)\Delta + \mu^2 y^2 \ ,$$

where

$$\Delta = \{\delta x, \delta v^i, \delta w^i\}$$

and $\mathcal{D}$, b are complicated (but in principle explicit) matrix and vector-valued expressions

Backreaction (continued)

- Minimization in $\{z, \bar{z}, x\}$ gives the fully backreacted potential $V_{eff}(y)$ – a very complicated function
- However, at $1 \ll y \ll 1/\epsilon$, things simplify and we find

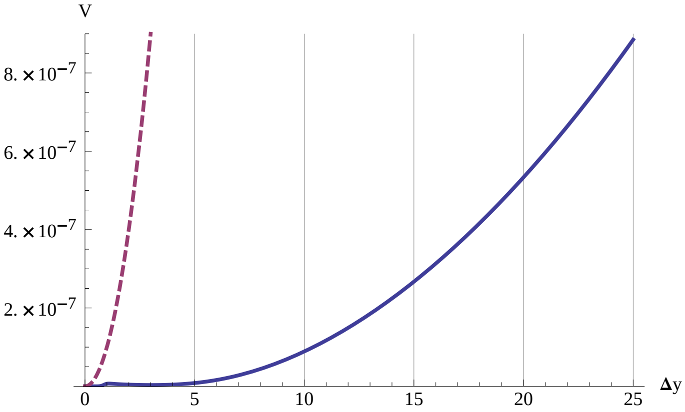
$$V_{eff}(y) \sim \left(-\mathcal{O}(1)\epsilon^4 + \mu^2\right) y^2$$

  where also $\mu^2 \sim \epsilon^4$

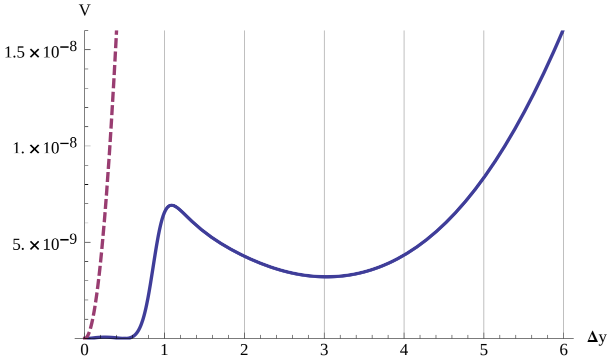
- In this regime, large-field quadratic inflation can proceed
- Kahler moduli stabilization à la LVS is not disrupted thanks to $\epsilon \ll 1$

Illustration of naive and fully backreacted potentials

in a (supergravity level) numerical example



Blowup of non-monotonic region at (relatively) small y



- Note that this might, independently of inflation, be of interest as an *F*-term uplifting proposal

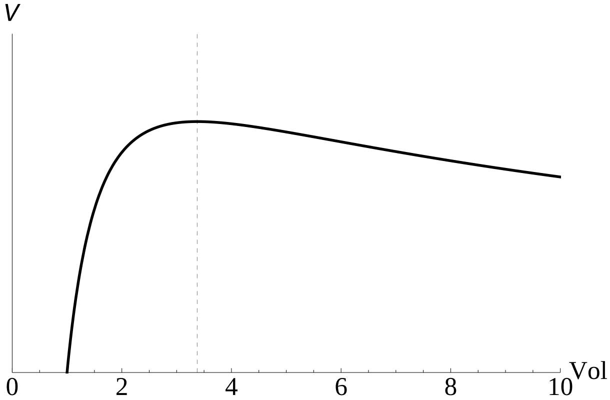
cf. e.g. Kallosh, Linde, Vercnocke, Wrase '14

An alternative, less severe tuning option (very briefly...)

- Replace $a \sim \epsilon\,,\ (a_z + K_z a) \sim \epsilon^2$ by $a \sim a_z \sim \epsilon$
- As before: Include backreaction order by order in ϵ by determining the shifts $\{\delta z, \delta\overline{z}, \delta x\}$ at each y
- However, now we find a simple (quadratic) y-dependence only at $y \gg 1/\epsilon$
- Hence $W \sim w + ay$ changes significantly during inflation
- Since, in the LVS, the volume is 'fixed' at $\mathcal{V} \sim W$, the universal Kahler modulus now also backreacts
- Nevertheless, large-field inflation remains possible (but no pheno yet...)

An alternative, less severe tuning option – illustration

- Scalar potential with complex-structure and Kahler modulus backreaction (plotted as a function of the volume)



Can the tuning be realized?

- Is the underlying flux landscape large enough?
- We follow the classical analysis of Denef/Douglas '04
- For a fourfold with a D3-tadpole bound $L_* = \chi/24$, they find

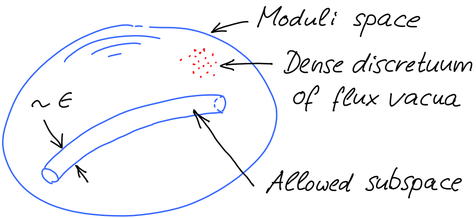
$$\mathcal{N} \sim \frac{(2\pi L_*)^{2m}}{(2m)!} \int_{\mathcal{M}} d^{2m}z \det g \;\rho(z)$$

SUSY flux vacua

- Here the second factor is an appropriately weighted integral over moduli space (expected to give an $\mathcal{O}(1)$ number)

Can the tuning be realized? – Illustration

We need to be inside a tubular region (of size ϵ) around the submanifold defined by $a = a_{z^i} = 0$



Can the tuning be realized? (continued)

- In our application, $\mathcal{N}$ is replaced by

$$\mathcal{N}(|a_I| < \epsilon) \sim \frac{(2\pi L_*)^{(b_4 - J_f - J_t)/2}}{(b_4 - J_f - J_t)/2)!} \cdot (\pi\epsilon^2)^{J_t} \times \mathcal{O}(1)$$

  where b_4 defines the dimension of the (4-form) flux space,

  J_f subtracts the number of fluxes forbidden by the F-theory limit and the assumed linearity of W as a function of u

  J_t counts the tuning conditions (i.e. how many of the moduli appear in $a(z)$)

- For e.g. $\varphi_{max} \sim 15$, $L_* \sim 900$, $b_4 \sim 23000$, and assuming that 300 of the 3800 moduli appear in a, we find that 10^{300} of the 10^{1700} flux vacua survive

see Denef '08 for this exmample

Summary/Conclusions

- Large-field inflation is a challenge and an opportunity for string theory
- This remains true even if the tensor modes (or field-range) are way below last year's BICEP claim
- In 'our' variant of F-term axion monodromy, a high tuning price has to be paid (and we don't know of an equally 'complete' and less tuned version)
- We need the κ_{IJKL}'s of a proper F-theory 4-fold (and, ideally, also the subleading (non-instantonic) terms in the periods)
- Need a better 10d/stringy understanding

  developing e.g. recent work of Ibanez, Marchesano, Valenzuela