Evading the Weak Gravity Conjecture
with New Models of Winding Inflation?

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Outline

- Introduction

- Recent developments:

  Progress in F-term axion monodromy (Tuning, its implementation in F-theory, backreaction...)

- **Very** recent developments:

  A new model ("F-term winding inflation") and its standing in view of the weak gravity conjecture

'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

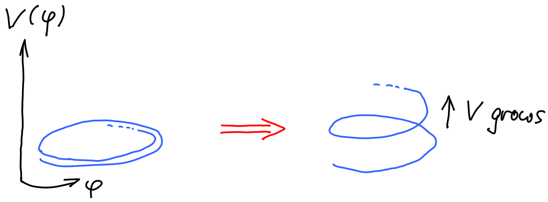
- Do they exist in the type IIB / F-theory landscape as we understand it at present?

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

One possible solution: Monodromy inflation

Silverstein/Westphal/McAllister '08
Kaloper, Lawrence, Sorbo '08...'11

The periodicity of an axion is weakly broken by the scalar potential....



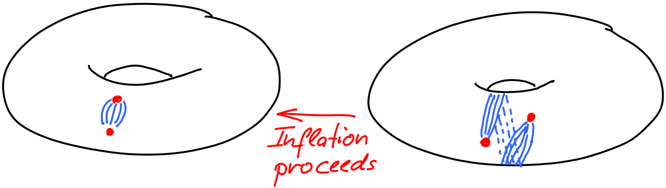
F-term axion monodromy

- Recently, the first suggestions have emerged for realizing this in 4d supergravity, with stabilized moduli

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

- In particular, in our suggestion inflation can be viewed as 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:

$$W = w(z) + a\, u$$

- For parametric control and stability, we want $a \ll 1$; This requires $a = a(z)$

for an alternative approach see
Blumenhagen, Herrschmann, Plauschinn '14
Blumenhagen, Font, Fuchs, Herschmann, Plauschinn, Wolf '15

for recent related work see e.g.
Bielleman, Ibanez, Marchesano, Pedro, Valenzuela '14...'15
Escobar, Landete, Marchesano, Regalado '15

Tuning in F-term axion monodromy

- Thus, we must consider the structure

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

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

- Since $V \supset |DW|^2 \supset |(\partial_z a)u|^2$,

we need to also tune $\partial_{z^i} a$ for all relevant i

cf. critical discussion with Quevedo/Cicoli at String Pheno '14

- To realize this, the functional form of complex-structure periods must have a certain minimal amount of complexity
- This is not available in 3-folds at large complex structure, but is available in 4-folds

At the technical level....

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

$$\Pi_\alpha = \begin{pmatrix} 1 \\ z^I \\ \frac{1}{2}\kappa_{IJK} z^J z^K + \mathcal{O}\left(e^{2\pi i\, n_J z^J}\right) \\ -\frac{1}{3!}\kappa_{IJK} z^I z^J z^K + \mathcal{O}\left(e^{2\pi i\, n_J z^J}\right) \end{pmatrix} ,$$

as well as for Kahler and superpotential

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

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

- Analogously for 4-folds....

Tuning and **backreaction** in F-term axion monodromy

- An analysis a la Denef/Douglas reveals that,
  given geometries with appropriate period structure,
  the tuning can be realized

cf. parallel talk by Patrick Mangat

- Properly understanding of backreaction of $\{z^i\}$
  under large displacement of u is essential;

  This analysis is interesting in itself and may be more generally useful.....

cf. parallel talk by Fabrizio Rompineve

While much remains to be done,

it is also interesting to ask whether the methods above

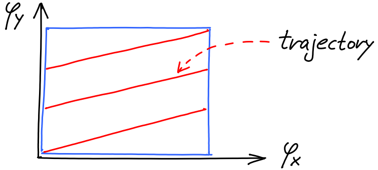
(related to periods at large complex structure and flux-effects)

can also be useful on the 'KNP side' of large-field inflation....

KNP / Winding inflation revisited

Kim/Nilles/Peloso '04
Berg/Pajer/Sjors '09
Ben-Dayan/Pedro/Westphal '14

- Getting the required winding trajectory is not straightforward (even before WGC-based no-go arguments)

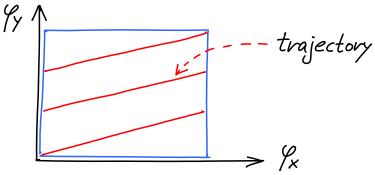


- Indeed, periodicities are in general defined by the instantons (or vice versa):

$$V \supset e^{-m_x}\cos(\varphi_x/f_x) + e^{-m_y}\cos(\varphi_y/f_y) + \cdots$$

$$\cdots + e^{-(Mm_x+Nm_y)}\cos(M\varphi_x/f_x + N\varphi_y/f_y)$$

KNP / Winding inflation (continued)



- Thus, some ingenuity is needed to ensure that one of the higher instantons (i.e. $M, N \gg 1$) dominates the potential
- Wouldn't it be much nicer to use a totally different (non-instantonic) tool to enforce the winding trajectory?
- Indeed, one could try 'gauging away' part of the axion-field-space, making sure that the remaining field-direction is 'winding'

Shiu/Staessens/Ye '15

F-term winding inflation

- Since gauging corresponds to D-terms, one might call the above idea 'D-term winding inflation'
- By contrast, in 'our' context of complex-structure moduli, it appears more natural to realize winding using a 'flux-induced' F-term constraint Abe, Kobayashi, Otsuka '14
- This is indeed possible. Hence we call our suggestion 'F-term winding inflation'
- The basic idea rests on two complex structure moduli u, v:

$$\{\varphi_x, \varphi_y\} \quad \longrightarrow \quad \{\mathrm{Re}(u), \mathrm{Re}(v)\}$$

- In addition, we just need $W_{Flux} \supset f(z)(Mu - Nv)$

F-term winding inflation (continued)

- To appreciate the details, recall again the basic formulae for periods

$$\Pi_\alpha = \begin{pmatrix} 1 \\ z^I \\ \frac{1}{2}\kappa_{IJK} z^J z^K + \mathcal{O}\left(e^{2\pi i\, n_J z^J}\right) \\ -\frac{1}{3!}\kappa_{IJK} z^I z^J z^K + \mathcal{O}\left(e^{2\pi i\, n_J z^J}\right) \end{pmatrix},$$

as well as for Kahler and superpotential

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

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

F-term winding inflation (continued)

- Now, rename $\quad S \to z^0 \quad$ and $\quad \{z^J\} \to \{z^j, u, v\}$

- First, ensure (by flux tuning) that, in the SUSY vacuum,

$$e^{-2\pi\,\mathrm{Im}u} \ll e^{-2\pi\,\mathrm{Im}v} \ll 1$$

- Focus (for now) on non-exponential u, v-terms only:

  We choose flux numbers such that u and v appear in W only linearly and with proportional prefactors:

$$W \quad \supset f(z)(Mu - Nv)$$

  (For concreteness, let $M = 1$ and $N \gg 1$)

F-term winding inflation (continued)

- This gives the desired structure

$$K = -\log\left(\mathcal{A}(z,\bar{z},u-\bar{u},v-\bar{v}) + \mathcal{B}(z,\bar{z},v-\bar{v})e^{2\pi i v} + \mathrm{c.c.}\right)$$

$$W = w(z) + f(z)(u - Nv) + g(z)e^{2\pi i v}$$

- Without exponential terms, it is clear that W leaves one of the originally shift-symmetric directions $\mathrm{Re}(u)$ and $\mathrm{Re}(v)$ flat
- If $N \gg 1$, this direction is closely aligned with $\mathrm{Re}(u)$
- The exponential terms induce a long-range cosine potential for this light field φ:

$$e^{2\pi i v} \quad \rightarrow \quad \cos(2\pi\varphi/N)$$

F-term winding inflation (continued)

- We have derived the scalar potential from K and W above, finding natural inflation (at leading order)

- Backreaction of the z-moduli is important (affecting the prefactors at the $\mathcal{O}(1)$ level, but not the qualitative result)

- Reason: No tuning except $e^{-2\pi\,\mathrm{Im}u} \ll e^{-2\pi\,\mathrm{Im}v} \ll 1$

  cf. parallel talk by Lukas Witkowski

- Finally, our model is consistent with LVS Kahler moduli stabilization (though pheno-details are missing and important corrections and 'flattening' are expected, as in F-term axion monodromy)

  Dong, Horn, Silverstein, Westphal '10
  AH, Mangat, Rompineve, Witkowski '14
  Buchmüller, Dudas, Heurtier, Westphal, Wieck, Winkler '15

F-term winding inflation and the Weak Gravity Conjecture

- Do we clash with no-go arguments against natural inflation based on the WGC?

  Arkani-Hamed, Motl, Nicolis, Vafa '06
  .....Rudelius '14
  de la Fuente, Saraswat, Sundrum '14
  Montero, Uranga, Valenzuela '15
  Brwon, Cottrell, Shiu, Soler '15
  Bachlechner, Long, McAllister '15.....

- Indeed, the usual statement $q/m > 1$ translates to $f\,m < 1$ for instantons

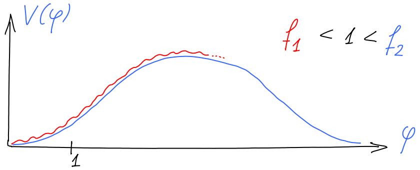
- This clashes with our single-field 'instanton'-potential:

$$V \sim e^{-2\pi \mathrm{Im} v} \cos(4\pi\varphi/N)$$

- How can this be, given that our original multi-axion model was of a generic 'stringy' type (and certainly consistent with the WGC) ?

F-term winding inflation and the Weak Gravity Conjecture

- It is crucial to recall that both 'basis instantons' are relevant for our effective axion:
$$e^{2\pi i u} \quad \text{and} \quad e^{2\pi i v}$$
- By a mild tuning of $\mathrm{Im}(u)$, we can make the first 'instanton's' effects exponentially suppressed



- Thus, the 'heavier' instanton satisfies the WGC, while the 'lighter' instanton realizes natural inflation
- This naturally fits a known loophole for the mild WGC

Rudelius '14
Brown, Cottrell, Shiu, Soler '15

Summary/Conclusions

- Large-field inflation is a challenge and an opportunity
- This remains true even if the tensor modes (or field-range) are way below last year's BICEP claim
- In LCS/LVS 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)

- In F-term winding inflation, a flux constraint forces the axion(s) on a winding trajectory
- Given our present understanding, this looks much less tuned
- It is consistent with the mild WGC, but clashes with the strong form