Axion Monodromy Inflation

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Based on: Liam McAllister, Eva Silverstein, Alexander Westphal, TW 1405.3652
Outline

• Why string cosmology

• Axion monodromy inflation:
  – BICEP2 as motivation
  – New constructions in string theory

• Conclusion
Why string cosmology?

There are (at least) three reasons:

1. Extrapolating backwards in time using GR we hit a singularity

2. The cosmological constant in the current universe seems to be very small and non-zero

3. Inflation is UV sensitive
Why string cosmology?

1. Extrapolating backwards in time using GR we hit a singularity
   - String theory is a UV complete theory of quantum gravity
   - We know how string theory can resolve time-like singularities
   - The cosmic singularity is much more complicated

   see for example H. Liu, G. Moore and N. Seiberg  arxiv:gr-qc/0301001

= long term goal
Why string cosmology?

2. The cosmological constant in the current universe seems to be very small and non-zero

- Compactifications of string theory give rise to dS vacua
  
- There seem to be so many string vacua ($10^{500}$) that a very small cosmological constant (as observed in our universe) can plausible arise $\implies$ landscape
  
- Our understanding of dS vacua is still very basic

$\equiv$ work in progress
Why string cosmology?

3. Inflation is UV sensitive

• The energy scale of inflation is below the Planck scale, so that we can use GR + QFT (bottom-up)

• However, higher dimensional operators lead to the eta-problem

\[
V(\phi_0) = V_0 \left( 1 + \sum_{n=1}^{\infty} c_n \left( \frac{\phi - \phi_0}{M_{pl}} \right)^n \right) \Rightarrow \eta = M_{pl}^2 \frac{V''}{V} = \sum_{n=2}^{\infty} n(n-1) c_n \left( \frac{\phi - \phi_0}{M_{pl}} \right)^{n-2}
\]

• If \( \phi - \phi_0 \ll M_{pl} \) then we need to control \( c_2 \)
Why string cosmology?

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\]

- If \( \phi - \phi_0 \geq M_{pl} \) then we need to control all \( c_n \)
Why string cosmology?

- The size of these higher dimensional operators can often be checked in string theory models of inflation.
- String theory might tell us what is (and is not) possible in a theory of quantum gravity.
- String theory compactifications can lead to new ideas for inflationary models.
Why string cosmology?

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• String theory might tell us what is (and is not) possible in a theory of quantum gravity

• String theory compactifications can lead to new ideas for inflationary models

Bottom-up (QFT+GR) and top-down (string theory) approaches complement each other
Goals of string cosmology

Description of the early universe cosmology in a UV complete theory of quantum gravity
Goals of string cosmology

Description of the early universe cosmology in a UV complete theory of quantum gravity

Not a simple task:

• String theory has several extra dimensions that we need to compactify

• The simplest compactifications give rise to 4D theories with many massless scalar fields $\phi^I$

$\Rightarrow$ Moduli Problem
Goals of string cosmology

Description of the early universe cosmology in a UV complete theory of quantum gravity

Not a simple task:

• We can generate a potential for these scalar fields
• However, to describe our universe we need:

\[ V(\phi^I)|_{\text{min}} \approx 10^{-120} M_{Pl}^4 \] but \( m_{\phi^I} \) much larger, a period of inflation ending in this dS vacuum, a reheating mechanism, a standard model sector, dark matter ....
Goals of string cosmology

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Currently too complicated!
Goals of string cosmology

Description of the early universe cosmology in a UV complete theory of quantum gravity

Break the problem down into pieces:

• Try to generate a potential that allows for a period of inflation that ends in a dS vacuum

• In explicit models it is often possible to do more (like discussing a reheating mechanism or adding an SM sector)
Outline

• Why string cosmology

• Axion monodromy inflation:
  – BICEP2 as motivation
  – New constructions in string theory

• Conclusion
BICEP2 result

A small telescope at the south pole with the primary goal of measuring the very faint polarization of the cosmic microwave background (CMB).
BICEP2 result

Only gravitational waves can generate B-modes in the CMB

Seljak & Zaldarriaga '97
Kamionkowski, Kosowsky, Stebbins '97

curl-free

div-free
BICEP2 result

March 2014 data release after *three long nights*: 2010-2012

**BICEP2 I: Detection Of B-mode Polarization at Degree Angular Scales**

Abstract:

• We find an *excess of B-mode power* over the base lensed-LCDM expectation in the range 30<l<150, inconsistent with the null hypothesis at a significance of >5σ.

• The observed B-mode power spectrum is well-fit by a lensed-LCDM + tensor theoretical model with tensor/scalar ratio \( r=0.20\pm0.07-0.05 \), with \( r=0 \) disfavored at 7.0σ.
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Primordial B-modes can tell us the energy scale of inflation:

$$\Delta^2_t \approx \frac{2}{3\pi^2} \frac{V}{M_{Pl}^4}$$
BICEP2 result

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\[
r = \frac{\Delta_t^2}{\Delta_s^2} = .2 \quad \Rightarrow \quad (V_{\inf})^{1/4} \approx 2 \times 10^{16} \text{GeV} \left(\frac{r}{0.1}\right)^{1/4} \approx 2 \times 10^{16} \text{GeV}
\]
“Can you say it again?”
In the analysis of BICEP2 data, the lensed-beam temperature tensors have been utilized to constrain the parameters of the cosmological models. The additional systematics, including those from the operations and estimation excess contamination, have been accounted for in the analysis.

The approach taken involves the use of multi-maps, such as PLANCK for the CMB data, and the BICEP2 data for the B-modes. The interferometric maps are crucial in this analysis, as they provide evidence for the existence of primordial gravitational waves.

The detection of B-modes by BICEP2 is significant, as it provides direct evidence for inflationary cosmology. The results obtained from BICEP2 are compared with other experiments, such as PLANCK and WMAP, and are found to be consistent within the errors.

The significance of the BICEP2 results is highlighted by the red triangle symbols in the plot, which represent the detection of B-modes with a confidence level of 95%. The comparison with theoretical predictions, such as the spectral index and the tensor-to-scalar ratio, further strengthens the evidence for inflation.

The equation $(V_{\text{inf}})^{1/4} \approx 2 \times 10^{16} \text{GeV}$ indicates the scale at which inflation occurred, which is much larger than the energy scale probed by the Large Hadron Collider (LHC). This is a remarkable result, showcasing the potential of ground-based experiments in probing fundamental physics.
BICEP2 result

Alan Guth and Andrei Linde are very happy!!!
BICEP2 result

A word of caution:

Flauger, Hill, Spergel  1405.7351
BICEP2 result

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We have to wait for Planck
(and probably many more experiments)
BICEP2 result

Simple potentials favored: \( V(\phi) = \phi^p, \ p \leq 4 \)
Lyth bound

David Lyth  hep-ph/9606387:

A large value of the scalar to tensor ratio leads to large field range, so called large-field inflation:

\[ \frac{\Delta \phi}{M_{Pl}} \geq 2 \sqrt{r_{.01}} \approx 10 \]
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How can we trust a low energy expansion?

\[ V(\phi) = V(\phi_0) \left( 1 + \sum_{n \geq 1} c_n \left( \frac{\phi - \phi_0}{M_{Pl}} \right)^n \right) \]
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\[\implies \text{String theory very useful}\]
Axion monodromy inflation

Having a UV complete theory of quantum gravity seems very useful, but this is not enough: Usually we expect to have new features in the potential whenever we move by one Planck distance.
Axion monodromy inflation

Having a UV complete theory of quantum gravity seems very useful, **but this is not enough:** Usually we expect to have new features in the potential whenever we move by one Planck distance.

For inflation we need

\[ V(\phi) \]

\[ M_P \]
Axion monodromy inflation

- String compactification usually have 100-1000 scalar fields
- We want to move one field over 10 Planck distances without disturbing the other fields (too much)
- The best approach seems to use a field with a (broken) shift symmetry as inflaton
Axion monodromy inflation

• In string compactification we find many axion fields

• These axion fields have only derivative couplings in the 4D effective theory

\[ S = \int d^4 x \, \partial_\mu a \cdot (...)^{\mu} \]

• This leads to a shift symmetry for these axion fields

\[ a \rightarrow a + c, \quad c \in \mathbb{R} \]
Axion monodromy inflation

*Side note:*

Usual lore:

There are no continuous global symmetries in a theory of quantum gravity
Axion monodromy inflation

*Side note:*
Usual lore:

There are no continuous global symmetries in a theory of quantum gravity

• This seems to be true in string theory
• The continuous shift symmetry of axions is broken by non-perturbative effects to a discrete symmetry

\[ a \rightarrow a + f_a n, \quad n \in \mathbb{Z} \]

The discrete shift symmetry still forbids many corrections!
Axion monodromy inflation

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Usual lore:

There are no continuous global symmetries in a theory of quantum gravity

A continuous shift symmetry:
Axion monodromy inflation

*Side note:*  
Usual lore:  
There are no continuous global symmetries in a theory of quantum gravity

A discrete shift symmetry:

![Graph showing a function V(a) with oscillating feature at a certain point](image-url)
Axion monodromy inflation

*Side note:*
Usual lore:

There are no continuous global symmetries in a theory of quantum gravity

The axion potential after breaking the symmetry:
Axion monodromy inflation

Liam McAllister, Eva Silverstein, Alexander Westphal, TW 1405.3652

• String theory has higher dimensional generalizations of gauge fields: $B_2$ and $C_p$
Axion monodromy inflation

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• String theory has higher dimensional generalizations of gauge fields: $B_2$ and $C_\rho$

• Their gauge invariance gives rise to the shift symmetry of the 4D axions after compactification

E&M: $A_M(X^M)dX^M = A_\mu(x^\mu)dx^\mu + a(x^\mu)dy + ..., \quad a(x^\mu) = A_y(x^\mu)$
Axion monodromy inflation

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$A(X^M) \to A(X^M) + d(c \cdot y) = A(X^M) + c dy$

$\Rightarrow \quad a(x^\mu) = a(x^\mu) + c, \quad c \in \mathbb{R}$
Axion monodromy inflation

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• String theory has higher dimensional generalizations of gauge fields: $B_2$ and $C_p$

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• In compactifications of critical string theory half of the light fields are axions
Axion monodromy inflation

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• String theory has higher dimensional generalizations of gauge fields: $B_2$ and $C_p$

• Their gauge invariance gives rise to the shift symmetry of the 4D axions after compactification

• In compactifications of critical string theory half of the light fields are axions

• Turning on background fluxes in the internal dimension breaks this shift symmetry and generates a polynomial potential for the axions
Axion monodromy inflation

- We focus on compactification of the 10D type IIA/B string theory and axions arising from $B_2$
- The 10D low energy action contains terms of the form

$$S = -\frac{1}{\alpha'^4} \int_M d^{10}x \sqrt{-G} \left\{ \frac{1}{g_s^2} |dB_2|^2 + \sum_p |\tilde{F}_p|^2 \right\}$$
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• For type IIA with $F_0=Q_0$ or type IIB with $F_1=Q_0$ we find

$$S = -\frac{1}{\alpha'4} \int_M d^{10}x \sqrt{-G} \left\{ \frac{1}{g_s^2} |dB_2|^2 + |Q_0B_2|^2 + |Q_0B_2B_2|^2 + ... \right\}$$

$$\tilde{F}_3 = dC_2 + F_1B_2 \quad \tilde{F}_5 = dC_4 + F_1B_2 + \frac{1}{2} F_1B_2B_2$$
Axion monodromy inflation

• Upon reduction to 4D, B will give rise to an axion

Potential: \( V(b) = c_0 + c_2 b^2 + c_4 b^4 \)

\[
S = -\frac{1}{\alpha'{}^4} \int_M d^{10}x \sqrt{-G} \left\{ \frac{1}{g_s^2} |dB_2|^2 + |Q_0B_2|^2 + |Q_0B_2B_2|^2 + \ldots \right\}
\]

Kinetic term
for axion \( b \)
Axion monodromy inflation

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\]

• What about Planck suppressed operators?
• We turn on \( \left| \tilde{F} \right|^2 \supset \left| Q_0 B_2 B_2 \right|^2 \). What about \( \left| \tilde{F} \right|^4 \supset \left| Q_0 B_2 B_2 \right|^4 \) ?
• Can we break the shift symmetry by only turning on the operator \( \left| \tilde{F} \right|^2 \supset \left| Q_0 B_2 B_2 \right|^2 \)?
Axion monodromy inflation

• Upon reduction to 4D, B will give rise to an axion

\[ V(b) = c_0 + c_2 b^2 + c_4 b^4 \]

\[ S = -\frac{1}{\alpha'4} \int d^{10}x \sqrt{-G} \left\{ \frac{1}{2} g_s^2 |dB_2|^2 + |Q_0 B_2|^2 + |Q_0 B_2 B_2|^2 + \ldots \right\} \]

• What about Planck suppressed operators?

• We turn on \( |\tilde{F}|^2 \Rightarrow |Q_0 B_2 B_2|^2 \). What about \( |\tilde{F}|^4 \Rightarrow |Q_0 B_2 B_2|^4 \) ?

• Can we break the shift symmetry by only turning on the operator \( |\tilde{F}|^2 \Rightarrow |Q_0 B_2 B_2|^2 \) ? **NO!**
Axion monodromy inflation

- Upon reduction to 4D, B will give rise to an axion

Potential: \( V(b) = c_0 + c_2 b^2 + c_4 b^4 \)

\[
S = -\frac{1}{\alpha'^4} \int_M d^{10} x \sqrt{-G} \left\{ \frac{1}{g_s^2} |dB_2|^2 + |Q_0 B_2|^2 + |Q_0 B_2 B_2|^2 + \ldots \right\}
\]

- What about Planck suppressed operators?

- In this setup all the operators \( |\tilde{F}|^{2n} \supset |Q_0 B_2 B_2|^{2n} \) appear, but they are all suppressed by the string coupling:

\[
\ldots \supset g_s^{2(n-1)} |\tilde{F}|^{2n} \supset g_s^{2(n-1)} |Q_0 B_2 B_2|^{2n} \ll |Q_0 B_2 B_2|^2 \quad \text{for} \quad g_s \ll 1
\]
Axion monodromy inflation

• We see that in string compactifications axions arise naturally with a variety of exponents
• We can suppress the infinite number of dangerous irrelevant operators
• Can we build explicit models in which these axions serve as inflaton?
Axion monodromy inflation

• We see that in string compactifications axions arise naturally with a variety of exponents
• We can suppress the infinite number of dangerous irrelevant operators
• Can we build explicit models in which these axions serve as inflaton?

1. This requires us to stabilize all moduli in a dS vacuum
2. Then we have to ensure that moving the B-axion a lot does not destabilize our construction
Axion monodromy inflation

Stabilizing all fields in a dS vacuum:
- A variety of constructions exist like KKLT, LVS etc.
- Most of these use perturbative and non-perturbative ingredients

Generically small barriers towards a runaway direction
Axion monodromy inflation

Stabilizing all fields in a dS vacuum:

• A variety of constructions exist like KKLT, LVS etc.
• Most of these use perturbative and non-perturbative ingredients
  ➔ Generically small barriers towards a runaway direction
• String theory has 10D flat Minkowski space as its solution so all dS vacua are metastable but barriers can be high
Axion monodromy inflation

Stabilizing all fields in a dS vacuum:

• A variety of constructions exist like KKLT, LVS etc.
• Most of these use perturbative and non-perturbative ingredients

== Generically small barriers towards a runaway direction

• We use the dS vacua construction of Saltman and Silverstein hep-th/0411271 that breaks supersymmetry at the compactification scale and has high barriers
Axion monodromy inflation

We compactify type IIB string theory on the product of three Riemann surfaces $\Sigma_1 \times \Sigma_2 \times \Sigma_3$ and add 7-branes and fluxes.
Axion monodromy inflation

- In four dimensions this leads to a slightly complicated potential $V(\phi')$

- We can usually not keep all other fields fixed at their minimum value while the axion moves over many Planck distance

$\implies$ Flattening of the potential
Axion monodromy inflation

Example:

\[ V \sim M_{pl}^4 \frac{g_s^4}{L^{12}} \left( \frac{Q_1^2}{u^3} + \frac{Q_2^2}{L^4} u b^4 + Q_3^2 u^3 \right) \]

- flux quanta (can be chosen)
- one extra scalar field
- axion = inflaton
Axion monodromy inflation

Example:

\[ V \sim M_{pl}^4 \frac{g_s^4}{L^{12}} \left( \frac{Q_1^2}{u^3} + \frac{Q_2^2}{L^4} u b^4 + \phi_3^0 u^3 \right) \]
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\[ \implies u = \frac{3^{1/4} L}{b} \sqrt{\frac{Q_1}{Q_2}} \approx \frac{1}{b} \]
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\[ \implies u = \frac{3^{1/4} L}{b} \sqrt{\frac{Q_1}{Q_2}} \propto \frac{1}{b} \]

Flattening: \( V \propto b^4 \) \( \rightarrow \) \( V \propto b^3 \)
Axion monodromy inflation

Generic feature in our models:

- One or more fields adjust their value during inflation and thereby flatten the scalar potential

\[
V(b, \phi^I) = \sum_{n=0}^{p_0} c_n(\phi^I) b^n \xrightarrow{\phi^I = \phi_{\text{min}}, b \gg 1} \tilde{c}(\phi_{\text{min}}^I) b^p, \quad p \leq p_0
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• Other nice ideas with fractional power:

  – F. Takahashi 1006.2801
  – K. Harigaya, M. Ibe, K. Schmitz, T. T. Yanagida 1211.6241, 1403.4536, 1407.3084
Axion monodromy inflation

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• There is some freedom in choosing fluxes to control the flattening

• We find \( p = 3, 2, 4/3, 2/3 \) (previously only \( p \leq 2 \))
Axion monodromy inflation

We find

\[ V(\phi) = \phi^p, \quad p \approx 3, 2, \frac{4}{3}, \frac{2}{3} \]
Axion monodromy inflation

- Our models are just a proof of principle
- Axions arise very generically in string theory
Axion monodromy inflation

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- Axion monodromy inflation leads to a variety of different predictions
- For $r \approx .1$ future experiments will be able to measure it to the percent level
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• Axions arise very generically in string theory
• Axion monodromy inflation leads to a variety of different predictions
• For $r \approx .1$ future experiments will be able to measure it to the percent level

We will be able to distinguish between these different models!
Conclusion

• String theory very useful for understanding inflation
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• If BICEP2 results are confirmed
  • they have detected the imprint of quantum fluctuations of the gravitational field, stretched to superhorizon scales.
  • inflation took place at the GUT scale and we can observe its imprints!
  • we have an unprecedented window on quantum gravity!
Conclusion

• String theory very useful for understanding inflation

• If BICEP2 results are confirmed
  • they have detected the imprint of quantum fluctuations of the gravitational field, stretched to superhorizon scales.
  • inflation took place at the GUT scale and we can observe its imprints!
  • we have an unprecedented window on quantum gravity!

• We are in the golden era of (string) cosmology, in which our models are confronted with ever improving data

THANK YOU!