String Theory and Cosmic Inflation

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What is String Phenomenology?

String Theory:

- fundamental objects: strings instead of particles
- there are 5 superstring theories in 10d
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String Phenomenology:

String Theory in 10d \[\rightarrow\] Compactification \[\rightarrow\] Standard Model in 4d
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- fundamental objects: strings instead of particles
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String Phenomenology:

String Theory in 10d \[\rightarrow\] Compactification \[\rightarrow\] Standard Model in 4d

*Here:* type IIB string theory with orientifold projection
What is Inflation?

**Inflation** ≡

very early time period of accelerated expansion of the universe [Guth, Linde, Starobinsky, Steinhardt, Mukhanov, ... ’80s]
What is Inflation?

Inflation \equiv very early time period of accelerated expansion of the universe [Guth, Linde, Starobinsky, Steinhardt, Mukhanov, ... '80s]

Described by scalar inflaton field $\phi$ with certain potential $V(\phi)$. 
Motivation from Inflation

Initially [BICEP2 '14] observed a large tensor-to-scalar ratio: \( r = 0.2 \).

Lyth bound: \( \frac{\Delta \phi}{M_{Pl}} = O(1) \sqrt{\frac{r}{0.01}} \)

- study large-field inflation \((\Delta \phi > M_{Pl})\)
- recent data from [Planck '15]: \( r < 0.11 \)
  \( \rightarrow \) large-field inflation not yet ruled out!
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- higher-order corrections to inflaton potential:
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- higher-order corrections to inflaton potential:
  \( \Rightarrow \) axions with shift symmetry

- consider interplay with moduli stabilization in string theory
Large-Field Inflation with Axions

- **Natural Inflation** with one axion $\phi$

  axion potential: \[ V(\phi) = V_0 \left( 1 - \cos \frac{\phi}{f} \right) + \ldots \]

  $\rightarrow$ inflation only for $f > M_{\text{Pl}}$

  $\rightarrow$ **Problem:** $f < M_{\text{Pl}}$ for controlled string compactification

- **Aligned Inflation** with two axions and $f_{\text{eff}} > M_{\text{Pl}}$

- **N-flation** with many axions and $f_{\text{eff}} > M_{\text{Pl}}
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Our approach:

F-term axion monodromy inflation [Hebecker, Kraus, Witkowski ’14; Blumenhagen, Plauschinn ’14; Marchesano, Shiu, Uranga ’14;]

$\rightarrow$ controlled breaking of the axion shift symmetry

$\rightarrow$ generate polynomial inflaton potential

*Need:* axion that is parametrically lighter than all other moduli
Motivation from String Phenomenology

Important task:

| Massless 'moduli' fields from 10d | Moduli Stabilization | Very heavy fields in 4d |

’Fluxes’ generate scalar potential stabilizing moduli at the minima.
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Idea:

1. generate scalar potential stabilizing all moduli except one axionic moduli
2. add new fluxes to stabilize the unfixed axion, such that it is parametrically lighter than all other moduli
3. realize axion monodromy inflation

No-Go Theorem:
There is no supersymmetric vacuum with stabilized non-tachyonic moduli and unfixed axions!

[Conlon '07]
Motivation from String Phenomenology

Important task:

\[
\begin{array}{ccc}
\text{Massless} & \text{Moduli} & \text{Very} \\
\text{’moduli’} & \text{Stabilization} & \text{heavy} \\
\text{fields from 10d} & \text{fields in 4d}
\end{array}
\]

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\[\text{No-Go Theorem:} \quad \text{There is no supersymmetric vacuum with stabilized non-tachyonic moduli and unfixed axions!} \quad \text{[Conlon ’07]}\]
Objective

Requirements for realizing single-field F-term axion monodromy inflation in the context of moduli stabilization:

- vacua: non-supersymmetric + tachyon-free
- all saxionic moduli stabilized with one axion $\Theta$ enabling inflation
- controllable mass hierarchies

$$M_{Pl} > M_s > M_{KK} > M_{mod} > H_{inf} > M_\Theta$$
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Moduli Space

\textbf{Moduli} $\equiv$ metric deformations of compactified space (CY) preserving CY properties

$\rightarrow$ Correspond to massless fields in 4d
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Moduli of type IIB orientifold compactifications [Grimm '04]:

<table>
<thead>
<tr>
<th>modulus</th>
<th>name</th>
<th>$\rightarrow$ shape deformations</th>
<th>$\rightarrow$ size deformations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S = s + ic$</td>
<td>axio-dilaton</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$U^i = v^i + i u^i$</td>
<td>complex structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_\alpha = \tau_\alpha + i \rho_\alpha + \ldots$</td>
<td>Kähler</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$G^a = S b^a + i c^a$</td>
<td>axionic odd</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Moduli space described by Kähler manifold together with a Kähler potential.
Fluxes and Moduli Stabilization

Type IIB superstring theory in 10d contains the 2-forms $B_2$ and $C_2$.

**Flux** $\equiv$ field strength with non-trivial vacuum expectation value

- combine the 3-form fluxes $H = \langle dB_2 \rangle$ and $\mathcal{F} = \langle dC_2 \rangle$:
  
  $$G_3 = \mathcal{F} - iSH$$

- fluxes are quantized and can be expanded in $\tilde{f}^\Lambda, f_\Lambda, \tilde{h}^\Lambda, h_\Lambda \in \mathbb{Z}$
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- fluxes are quantized and can be expanded in $\tilde{f}^\Lambda, f_\Lambda, \tilde{h}^\Lambda, h_\Lambda \in \mathbb{Z}$

Fluxes generate (F-term) scalar potential fixing the moduli vevs and thereby giving a large mass to the moduli:

$$V_F = \frac{M_{Pl}^4}{4\pi} e^K \left( K^{IJ} D_I W D_J \overline{W} - 3|W|^2 \right)$$

with Kähler potential $K$ and Gukov-Vafa-Witten superpotential $W$.

$\rightarrow$ Moduli Stabilization
New fluxes from string dualities:

**T-duality:**

Compactification on T-dual circles yields the same physics!
Geometric and Non-Geometric Fluxes

New fluxes from string dualities:

**T-duality:**

Compactification on T-dual circles yields the same physics!

\[
\begin{align*}
H_{abc} &\quad \leftrightarrow \quad T_c \\
\downarrow &\quad \leftrightarrow \quad \downarrow \\
\text{NS-NS flux} &\quad \text{geometric} \\
\end{align*}
\]

\[
\begin{align*}
f^{c}_{ab} &\quad \leftrightarrow \quad T_b \\
\downarrow &\quad \downarrow \\
\text{geometric} &\quad \text{non-geom.} \\
\end{align*}
\]

\[
\begin{align*}
Q^{bc}_{a} &\quad \leftrightarrow \quad T_a \\
\downarrow &\quad \downarrow \\
\text{non-geom.} &\quad \text{non-geom.}
\end{align*}
\]

Apply to flux compactification

[Grana, Louis, Waldram ’06; Benmachiche, Grimm ’06; Wecht ’07; Shelton, Taylor, Wecht ’07]:

\[
\frac{1}{R}
\]
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Flux-Scaling Scenario

See [Blumenhagen, Font, Fuchs, Herschmann, Plauschinn, Sekiguchi, Wolf ’15]

A simple example ($q \in \mathbb{Z}$ denotes non-geometric flux):

**Superpotential** with 3 fluxes turned on:

$$W = i\tilde{f} + i hS + iqT$$

**Kähler potential** of an isotropic torus $T^6$ with frozen complex structure moduli:

$$K = -3 \log(T + \overline{T}) - \log(S + \overline{S})$$
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**Kähler potential** of an isotropic torus $T^6$ with frozen complex structure moduli:

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**Scalar potential** generated by fluxes:

$$V = \frac{M_{Pl}^4}{4\pi \cdot 2^4} \left[ \frac{(hs - \tilde{f})^2}{s\tau^3} - \frac{6hq s + 2q\tilde{f}}{s\tau^2} - \frac{5q^2}{3s\tau} + \frac{1}{s\tau^3} (hc + q\rho)^2 \right]$$

$\implies$ orthogonal combination of $\theta = hc + q\rho$ is not stabilized!
Extrema of the scalar potential:

<table>
<thead>
<tr>
<th>solution</th>
<th>$(s, \tau, \theta)$</th>
<th>non-susy</th>
<th>tachyon-free</th>
<th>$\Lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$(-\frac{\tilde{f}}{2h}, -\frac{3\tilde{f}}{2q}, 0)$</td>
<td>no</td>
<td>no</td>
<td>AdS</td>
</tr>
<tr>
<td>2</td>
<td>$(\frac{\tilde{f}}{8h}, \frac{3\tilde{f}}{8q}, 0)$</td>
<td>✓</td>
<td>no</td>
<td>AdS</td>
</tr>
<tr>
<td>3</td>
<td>$(-\frac{\tilde{f}}{h}, -\frac{6\tilde{f}}{5q}, 0)$</td>
<td>✓</td>
<td>✓</td>
<td>AdS</td>
</tr>
</tbody>
</table>

Note: uplift to dS space needed!
Flux-Scaling Scenario

- mass eigenvalues of moduli:

\[ M_{\text{mod},i}^2 = \mu_i \frac{hq^3}{\tilde{f}^2} \frac{M_{\text{Pl}}^2}{4\pi \cdot 2^4} \quad \text{with} \quad \mu_i \approx (6.2, 1.7; 3.4, 0) \]

\[ \rightarrow \] the massless state is the axionic combination \( qc - h\rho \)

\[ \rightarrow \] massive states are parametrically of the same mass
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- gravitino mass like moduli masses with \( \mu_{\frac{3}{2}} \approx 0.833 \)
\[ \rightarrow \text{high-scale susy breaking} \]
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- gravitino mass like moduli masses with \( \mu_\frac{3}{2} \approx 0.833 \)

\[ \rightarrow \text{high-scale susy breaking} \]

- Kähler moduli are stabilized by non-geometric \( Q \)-flux

- scaling with fluxes allows to control many properties of the vacua (\( s, \tau \) in perturbative regime)

\[ \rightarrow \text{neglect string loop- and } \alpha'\text{-corrections} \]
Axion Monodromy Inflation

- stabilize massless axion via $W_{ax} = \lambda W + f_{ax} \Delta W$
- realizes F-term axion monodromy inflation
Axion Monodromy Inflation

- stabilize massless axion via $W_{\text{ax}} = \lambda W + f_{\text{ax}} \Delta W$
- realizes F-term axion monodromy inflation
- tensor-to-scalar ratio $r$ (for fixed fluxes):

![Graph showing the relationship between $r$ and $\lambda$.]
Axion Monodromy Inflation

- stabilize massless axion via $W_{ax} = \lambda W + f_{ax} \Delta W$
- realizes F-term axion monodromy inflation
- tensor-to-scalar ratio $r$ (for fixed fluxes):

![Graph showing the relationship between $\lambda$ and $r$]

- **Problem:** large $\lambda \Rightarrow M_{KK} \simeq M_{\text{mod}}$
  small $\lambda \Rightarrow H_{\text{inf}} > M_{\text{mod}}$
Axion Monodromy Inflation

Backreacted uplifted inflaton potential $V_{\text{back}}(\phi)$ of our simple model for a specific choice of $\lambda$ and the fluxes:

[Blumenhagen, Font, Fuchs, Herschmann, Plauschinn ’15]
Axion Monodromy Inflation

Backreacted uplifted inflaton potential $V_{\text{back}}(\phi)$ of our simple model for a specific choice of $\lambda$ and the fluxes:

[Blumenhagen, Font, Fuchs, Herschmann, Plauschin n ’15]

\[ \lambda = 60 \]
\[ r \sim 0.133 \]
**Quadratic Inflation**

\[ \lambda = 10 \]
\[ r \sim 0.08 \]
**Linear Inflation**

\[ \lambda = 1 \]
\[ r \sim 0.0015 \]
**Starobinsky Inflation**

- interpolation between polynomial and Starobinsky-like inflation
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Conclusion:

- systematic analysis of non-susy, stable minima of the scalar potential generated by type IIB orientifolds on CY including non-geometric fluxes
- all moduli stabilized at tree-level
- F-term axion monodromy inflation in principle possible, but control of mass hierarchies is difficult

Open question:

- multi-field inflation: trajectory and non-Gaussianity?
- dS vacua or dS uplift?
- uplift to full string theory?
- include some Kaluza-Klein and string states?
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Thank you!
Generalizations

There exist various other scaling scenarios including

- complex structure moduli $U$
- axionic-odd moduli $G$
- more Kähler moduli
- geometric- and so-called $P$-fluxes

Interesting features:

- all moduli stabilized (except some axions)
- in most cases non-supersymmetric, tachyon-free minima
- in some cases new tachyons
  $\rightarrow$ uplift tachyonic Kähler moduli via D-term