String Theory and Cosmic Inflation

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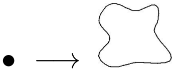
Contents

Contents

What is String Phenomenology?

String Theory:



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- there are 5 superstring theories in 10d

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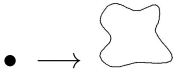

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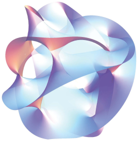
String Phenomenology:

String Theory in 10d $\xrightarrow{\text{Compactification}}$ Standard Model in 4d



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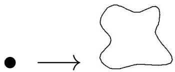

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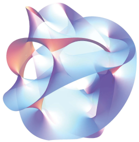
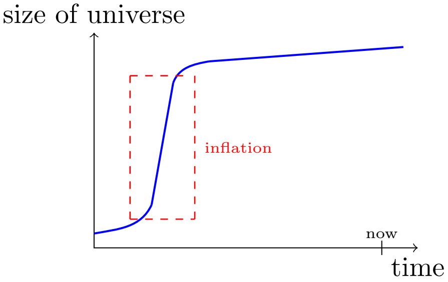


Here: type IIB string theory with orientifold projection

What is Inflation?

Inflation $\equiv$

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



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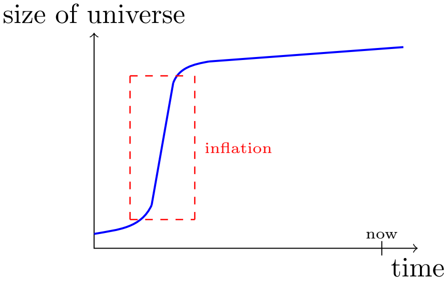

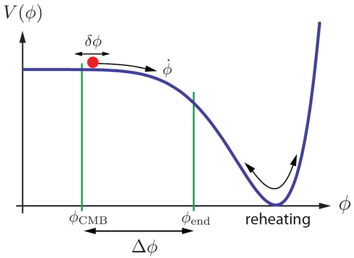

Described by scalar inflaton field ϕ with certain potential $V(\phi)$.

Motivation from Inflation

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

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

- study large-field inflation ($\Delta\phi > M_{\mathrm{Pl}}$)
- recent data from [Planck '15]: $r < 0.11$
  $\longrightarrow$ *large-field inflation not yet ruled out!*

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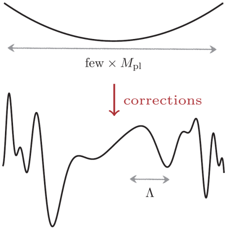
- higher-order corrections to inflaton potential:

  $\Longrightarrow$ axions with shift symmetry



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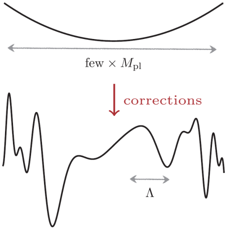

- higher-order corrections to inflaton potential:

  $\Longrightarrow$ axions with shift symmetry

- consider interplay with moduli stabilization in string theory

Large-Field Inflation with Axions

- Natural Inflation with one axion ϕ

$$\text{axion potential:} \qquad V(\phi) = V_0\left(1 - \cos\frac{\phi}{f}\right) + \dots$$

$\longrightarrow$ inflation only for $f > M_{\mathrm{Pl}}$
$\longrightarrow$ *Problem:* $f < M_{\mathrm{Pl}}$ for controlled string compactification

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

- N-flation with many axions and $f_{\mathrm{eff}} > M_{\mathrm{Pl}}$

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Our approach:

F-term axion monodromy inflation [Hebecker, Kraus, Witkowski '14; Blumenhagen, Plauschinn '14; Marchesano, Shiu, Uranga '14;]
$\longrightarrow$ controlled breaking of the axion shift symmetry
$\longrightarrow$ 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	$\xrightarrow[\text{Stabilization}]{\text{Moduli}}$	Very heavy fields in 4d

'Fluxes' generate scalar potential stabilizing moduli at the minima.

Motivation from String Phenomenology

Important task:

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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
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↯ *No-Go Theorem:* There is no supersymmetric vacuum with stabilized non-tachyonic moduli and unfixed axions! [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 Θ enabling inflation
- controllable mass hierarchies

$$M_{\rm Pl} > M_{\rm s} > M_{\rm KK} > M_{\rm mod} > H_{\rm inf} > M_{\Theta}$$

Contents

Moduli Space

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

$\longrightarrow$ Correspond to massless fields in 4d

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Moduli of type IIB orientifold compactifications [Grimm '04]:

modulus	name	
$S \;= s + i\,c$	axio-dilaton	
$U^i = v^i + i\,u^i$	complex structure	$\rightarrow$ shape deformations
$T_\alpha = \tau_\alpha + i\,\rho_\alpha + \ldots$	Kähler	$\rightarrow$ size deformations
$G^a = S\,b^a + i\,c^a$	axionic odd	

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 $\mathfrak{F} = \langle dC_2 \rangle$:
$$G_3 \;=\; \mathfrak{F} - iSH$$
- fluxes are quantized and can be expanded in $\tilde{\mathfrak{f}}^\Lambda$, $\mathfrak{f}_\Lambda$, $\tilde{h}^\Lambda$, $h_\Lambda \in \mathbb{Z}$

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

$$V_F \;=\; \frac{M_{\mathrm{Pl}}^4}{4\pi}\, e^K \Big(K^{I\bar{J}} D_I W D_{\bar{J}} \overline{W} - 3\big|W\big|^2 \Big)$$

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

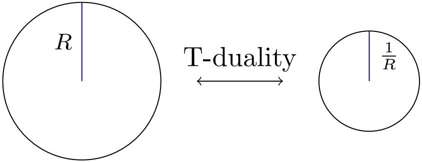
$\longrightarrow$ Moduli Stabilization

Geometric and Non-Geometric Fluxes

New fluxes from string dualities:

T-duality:

Compactification on T-dual circles yields the same physics!



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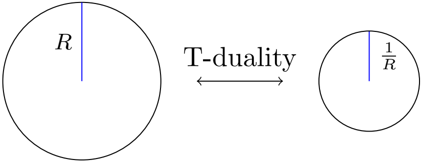

Apply to flux compactification
[Grana, Louis, Waldram '06; Benmachiche, Grimm '06; Wecht '07; Shelton, Taylor, Wecht '07]:

$$\begin{array}{ccccccc} H_{abc} & \overset{T_c}{\longleftrightarrow} & f_{ab}^{c} & \overset{T_b}{\longleftrightarrow} & Q_a^{bc} & \overset{T_a}{\longleftrightarrow} & R^{abc} \\ \downarrow & & \downarrow & & \downarrow & & \downarrow \\ \text{NS-NS flux} & & \text{geometric} & & \text{non-geom.} & & \text{non-geom.} \end{array}$$

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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:

$$W = i\tilde{\mathfrak{f}} + ihS + iqT$$

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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Scalar potential generated by fluxes:

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

$\Longrightarrow$ orthogonal combination of $\theta = hc + q\rho$ is not stabilized!

Flux-Scaling Scenario

Extrema of the scalar potential:

solution	(s, τ, θ)	non-susy	tachyon-free	Λ
1	$(-\frac{\tilde{\mathfrak{f}}}{2h}, -\frac{3\tilde{\mathfrak{f}}}{2q}, 0)$	no	no	AdS
2	$(\frac{\tilde{\mathfrak{f}}}{8h}, \frac{3\tilde{\mathfrak{f}}}{8q}, 0)$	✓	no	AdS
3	$(-\frac{\tilde{\mathfrak{f}}}{h}, -\frac{6\tilde{\mathfrak{f}}}{5q}, 0)$	✓	✓	AdS

Note: uplift to dS space needed!

Flux-Scaling Scenario

- mass eigenvalues of moduli:

$$M^2_{\mathrm{mod},i} = \mu_i \, \frac{hq^3}{\tilde{\mathfrak{f}}^2} \, \frac{M^2_{\mathrm{Pl}}}{4\pi \cdot 2^4} \qquad \text{with} \qquad \mu_i \approx \, (6.2, 1.7\,;\, 3.4, 0)$$

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- gravitino mass like moduli masses with $\mu_{\frac{3}{2}} \approx 0.833$

$\longrightarrow$ high-scale susy breaking

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- gravitino mass like moduli masses with $\mu_{\frac{3}{2}} \approx 0.833$
$\longrightarrow$ 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,τ in perturbative regime)
$\longrightarrow$ neglect string loop- and α'-corrections

Axion Monodromy Inflation

- stabilize massless axion via $W_{\text{ax}} = \lambda W + f_{\text{ax}}\, \Delta W$
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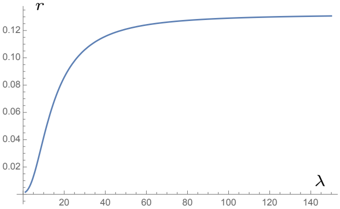

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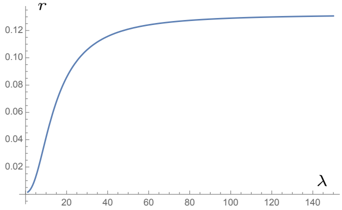

- *Problem*: large $\lambda \;\Rightarrow\; M_{\mathrm{KK}} \simeq M_{\mathrm{mod}}$
  small $\lambda \;\Rightarrow\; H_{\mathrm{inf}} > M_{\mathrm{mod}}$

Axion Monodromy Inflation

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

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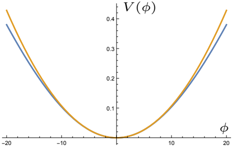
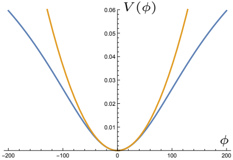
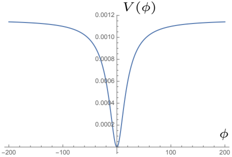


$\lambda = 60$
$r \sim 0.133$
Quadratic Inflation



$\lambda = 10$
$r \sim 0.08$
Linear Inflation



$\lambda = 1$
$r \sim 0.0015$
Starobinsky Inflation

- interpolation between polynomial and Starobinsky-like inflation

Contents

Conclusion and Outlook

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

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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?

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
  $\longrightarrow$ uplift tachyonic Kähler moduli via D-term