Brane Inflation and Moduli Stabilization

Guy Gur-Ari

Weizmann Institute

In collaboration with Ofer Aharony

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Inflation

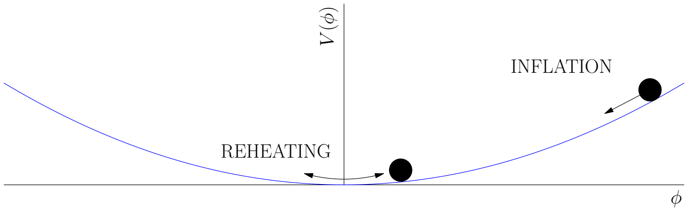
- Motivation: Solve fine-tuning problems in cosmology:
  Flatness, Isotropy, Baryogenesis, ...
- Assume early period of exponential expansion $a(t) = e^{Ht}$
- To avoid fine-tuning, need $a(t_\mathrm{f})/a(t_\mathrm{i}) \gtrsim e^{60}$

The basic setup:

- Scalar field with a shallow potential

$$V(\phi) = \lambda\,\phi^{\alpha}\,, \qquad \alpha \lesssim 1$$

- Starts at a large value, rolls down slowly



Large-Field Inflation

To get $a_f/a_i = e^{60}$, need initial field value $\phi_0 > M_{\text{planck}}$

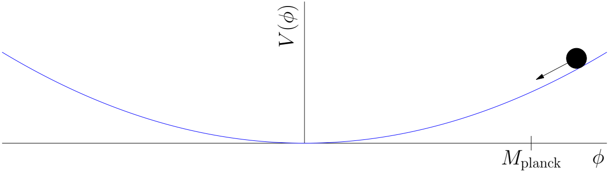
- Gravitational waves imprinted in CMB spectrum
- Measurable in next few years

Fine-tuning problems:

- Planck-suppressed operators become important, ruin shallow potential:

$$\mathcal{L}_{\text{eff}} \supset \frac{\mathcal{O}_4}{M_{\text{pl}}^2}\phi^2 + \cdots$$

- Large field inflation not natural in effective field theory
  - Turn to UV complete theory



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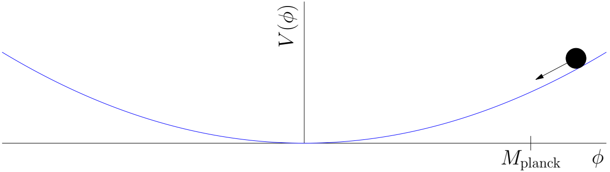
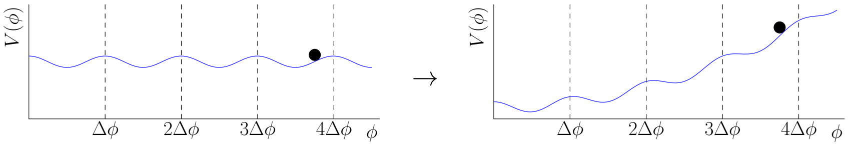


Large-Field Inflation using Monodromy

Still need control over corrections.

Basic idea:

- Take a periodic field, $V(\phi) = V(\phi + \Delta\phi)$
- Same quantum corrections in each period, even for large ϕ
- Break the periodicity ("monodromy")
- Original symmetry helps control corrections



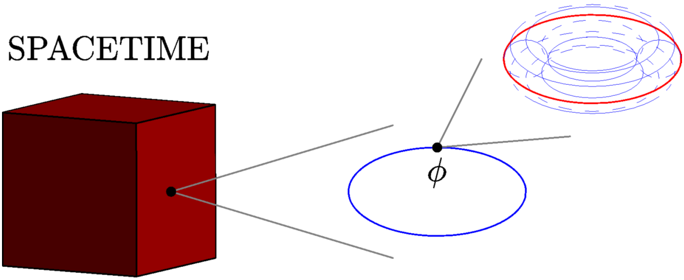
Brane Monodromy [Silverstein and Westphal, 2008]

Use natural string theory objects:

- Internal manifold: Start with $T^2 \times S^1 \times X_3$
- Add a D4-brane:
  - Fills spacetime
  - Wraps a 1-cycle on T^2, localized on base S^1

At low energy,

- Position of brane on base cycle $\rightarrow$ periodic scalar field $\phi(x, t)$
- If brane stretches $\rightarrow$ potential $V(\phi)$



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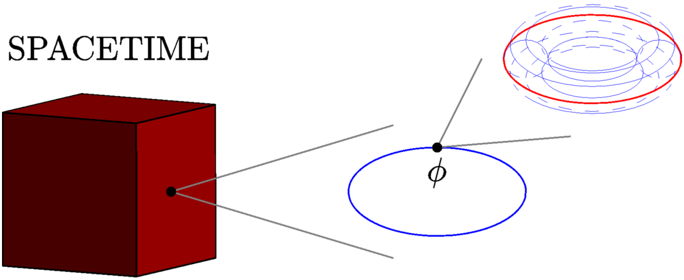

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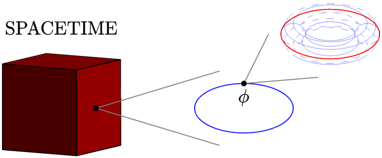
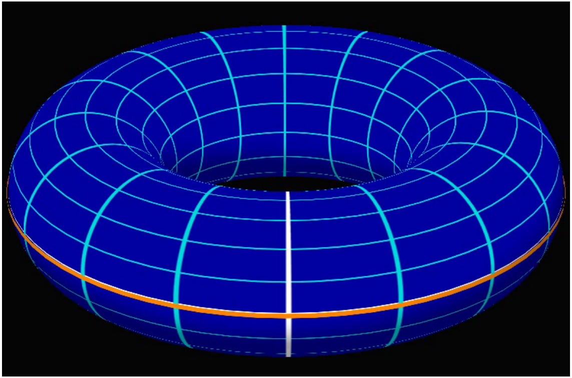
Introduce monodromy:

- Twist the $T^2 \times S^1$: $\tau \to \tau + 1$ when going around the base circle
- Brane stretches as it moves in ϕ,

$$V(\phi) \propto \phi^{2/3}$$





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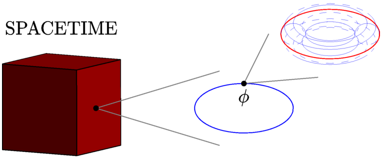

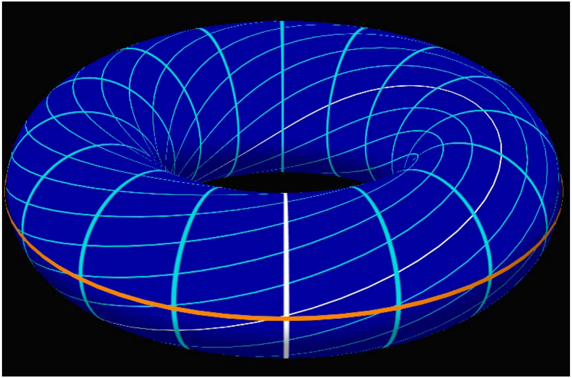

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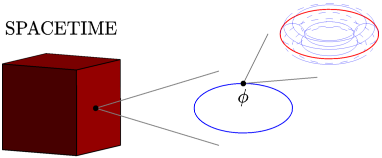
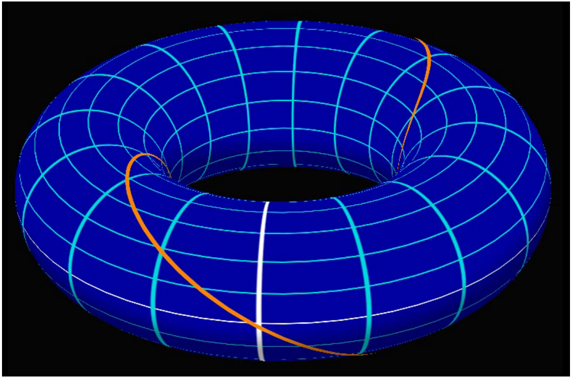


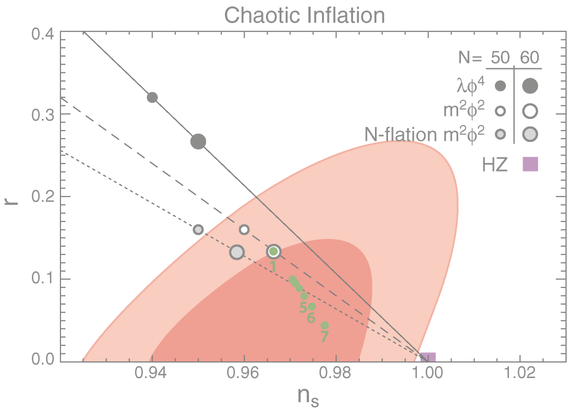


Generalization to Twisted 6-Torus

- We generalized from $T^2 \times S^1 \rightarrow T^5 \times S^1$, found more potentials:

$$V(\phi) \propto \phi^{2/3} \quad \longrightarrow \quad \phi^{2/3},\ \phi^1,\ \phi^{6/5},\ \phi^{4/3},\ \phi^{10/7},\ \phi^{3/2},\ \phi^2$$

- Exponent is related to cosmological observables n_s, r



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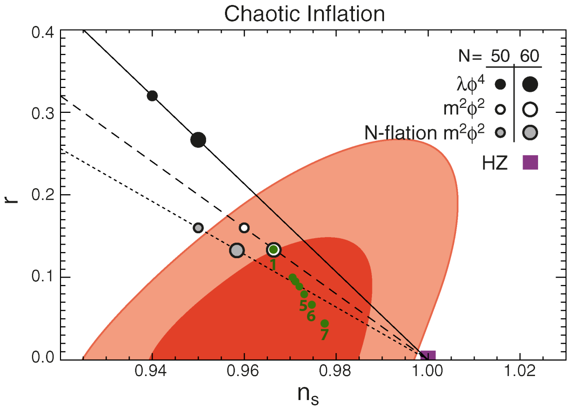

Realistic Construction [Silverstein, 2008]

Strategy for $\mathcal{M}_3 = T^2 \times S^1$:

- Manifold: Two copies of twisted torus, $\mathcal{M}_3 \times \tilde{\mathcal{M}}_3$
- Assume SUGRA limit and smearing approximation
- Arrange de Sitter vacuum with small cosmological constant
- Add D4 brane as probe $\rightarrow$ inflation

Requirements:

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Moduli Stabilization

The moduli:

- Dilaton $g \sim e^{\phi}$
- Metric G_{ij} (21 modes)
- Axions $B_{ij},\ C_i,\ \ldots$

Stabilization mechanisms:

- Negative curvature $\rightarrow$ need negative energy source
- Add O6 plane, $\mathcal{M}_3 \leftrightarrow \tilde{\mathcal{M}}_3$
  - Orientifold removes 9 metric moduli
- Twist reduces isometry: $U(1)^3 \rightarrow U(1)$
  - KK gauge bosons eat 2 metric moduli

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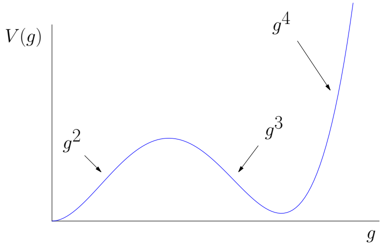

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Moduli Stabilization

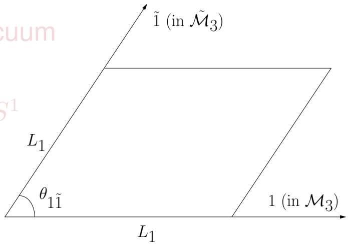
Remaining moduli:

$$g, \quad L_1, L_2, L_3, \quad \theta_{1\tilde{1}}, \theta_{2\tilde{2}}, \theta_{3\tilde{3}}, \quad G_{12}, G_{1\tilde{2}}, G_{1\tilde{3}}, G_{2\tilde{3}}$$

- Add ingredients that stabilize diagonal modes L_i
  - Fluxes, KK monopoles, discrete Wilson lines
- Tune parameters to form local minimum for dilaton

What about the angular modes?

- We found that $\theta_{1\tilde{1}}, \theta_{2\tilde{2}}$ destabilize the vacuum
- No obvious way to stabilize
- Analogous problems in all twisted $T^5 \times S^1$



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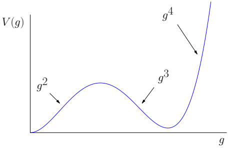

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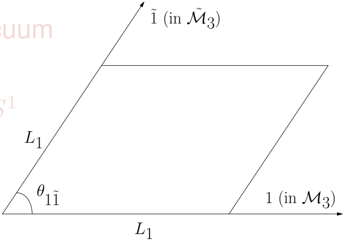

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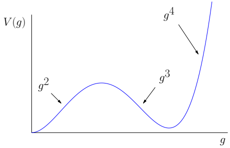

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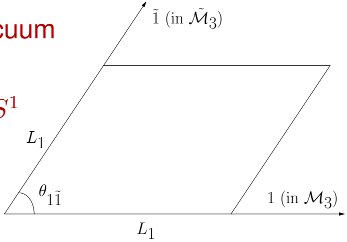

Summary

- Large-field inflation is not natural in effective field theory
- Monodromy helps control corrections
- First string theory implementation uses branes on twisted tori
- ... but is unstable due to angular metric modes
- We found no stable examples, cannot rule out existence
- Conclusion: Moduli stabilization is complicated!

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