String Theory and Cosmology

Marco Zagermann

Max-Planck-Institute for Physics, Munich

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft
DFG

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Outline

1. **String theory**

2. **String theory at the MPP**

3. **String theory and Cosmology**

4. **Inflation and de Sitter vacua in IIA string theory**

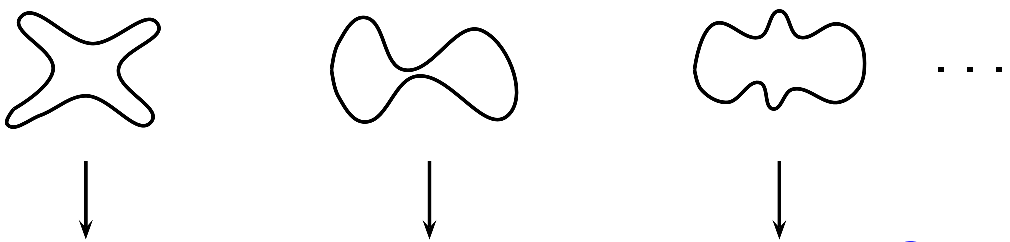
1. String Theory

Idea:

Point particle → closed or open

"String"

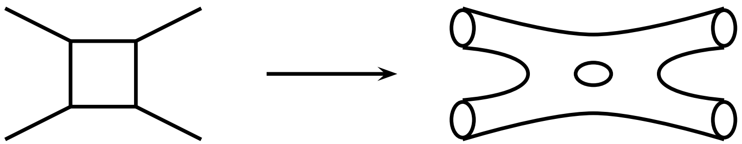
⇒ **One string – many oscillation modes:**



Particle A Particle B Particle C ⋯

⇒ **"Unified" theory of all particles and interactions**

Finite extension smoothes out quantum divergencies:



= finite

⇒ **Perturbative theory of quantum gravity !**

Many more curious properties:

- **Quasi-uniqueness**

  $\Rightarrow$ **I, IIA, IIB, HetE, HetO** $\longrightarrow$ **“M-theory”**

- **Supersymmetry**

- **10D spacetimes**

  $\Rightarrow$ **Compactification:** $\mathcal{M}^{(10)} = \mathcal{M}^{(4)} \times \mathcal{M}^{(6)}$

  $\Rightarrow$ $\mathcal{M}^{(6)}$ **is not unique** $\Rightarrow$ **Many effective 4D theories**

  $\Rightarrow$ **Many light scalar fields (“moduli”)**

  (E.g., from internal metric components, etc.)

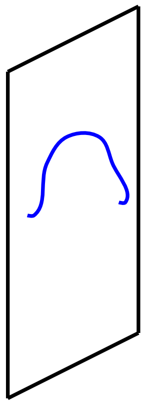
  $\Rightarrow$ **Have to be made sufficiently massive**

  (“Moduli stabilization”)

  $\Rightarrow$ **Flux compactifications + quantum corrections**

  $\Rightarrow$ **“Landscape” of string theory vacua**

- **Solitonic extended objects**



D-branes

- **Duality symmetries**
  - **Between different string compactifications**
    $\Rightarrow$ **T-duality/mirror symmetry, S-duality, ...**
  - **Between string theory/gravity and gauge theories**
    $\Rightarrow$ **"AdS/CFT correspondence"**

2. String Theory at the MPP

I. Scattering amplitudes, low mass strings, topological strings

Lüst, Stieberger, Knapp, Härtl, Schlotterer,. . .

- String Hunter's Companion for the LHC

  Lüst, Nawata, **Schlotterer, Stieberger,** Taylor

- Multiparton amplitudes, higher point spin field correlators

  Haertl, Schlotterer, Stieberger

- Disk scattering of open and closed string moduli

  Knapp, Stieberger

- D-branes in topological string theory, mirror symmetry

  Knapp

II. Particle Phenomenoloy from string theory, vacuum structure

Lüst, Blumenhagen, Jurke, Moster, Plauschinn, Schmidt-Sommerfeld,...

- General string landscape constraints

  Dvali, **Lüst**

- Orientifolds without vector structure

  Bachas, Bianchi, **Blumenhagen, Lüst,** Weigand

- D-brane instantons

  Blumenhagen, Schmidt-Sommerfeld

- Moduli stabilization with instantons

  Blumenhagen, Moster, Plauschinn

- GUT models from F-theory/type IIB orientifolds

  Blumenhagen, Braun, T. Grimm, Weigand; **Jurke**

III. AdS/CFT and strongly coupled systems

Lüst, Erdmenger, O'Bannon, Ammon, Meyer, Ngo, Rust, Greubel, Kerner . . .

- Heavy meson diffusion and phase diagrams of AdS/CFT plasmas
  Erdmenger, Kaminski, Kerner, Rust, Teaney
- Transport coefficients for hydrodynamics
  Erdmenger, Haack, **Kaminski,** Yarom
- Flavor superconductivity
  Ammon, Erdmenger, Kaminski, Kerner
- Superconducting fermions
  O'Bannon
- AdS/CFT dual of Fayet-Iliopoulos terms
  Ammon, Erdmenger, Hoehne, Lüst, Meyer

IV. Supergravity, moduli stabilization and cosmology

Lüst, Zagermann, Koerber, Wrase, Caviezel, S. Körs, T. Schmidt, ...

- IIA flux compactifications on manifolds with G-structure
  Caviezel, Koerber, Körs, Lüst, Tsimpis, **M.Z.**
- Mathematical aspects of flux compactifications
  Koerber, Lüst, Martucci, Tsimpis
- Supersymmetric anomalous $U(1)'$ models
  De Rydt, **T. Schmidt,** Trigiante, Van Proeyen, **M.Z.**,
  cf. also **Plauschinn**
- AdS/CFT applications
  Koerber, Wrase,...
- Various aspects of string cosmology
  Caviezel, Haack, Kallosh, **Koerber, S. Körs,** Krause, Linde,
  Lüst, Wrase, M.Z.

3. String Theory and Cosmology

If string theory aspires to be truely fundamental, it also has to be consistent with cosmological constraints

These constraints have by now become precise enough to allow for a serious discussion of the cosmological implications of string theory

$\Rightarrow$ **"String cosmology"**

Many interesting questions concerning e.g.

- **Dark matter and astroparticle physics**
- **Dark energy/cosmological constant problem**
- **Inflation**
- **Cosmic strings and other defects**
- **Time-dependent solutions in string theory**
- **Big Bang singularity?**

$\Rightarrow$ **This talk: Inflation (and de Sitter vacua)**

Inflation = **Period of accelerated cosmic expansion in the very early Universe**

$\Rightarrow$ **Elegant solution to various cosmological "problems":**

- **Homogeneity problem**
- **Flatness problem**
- **Origin of primordial density perturbations**

(• Monopole problem)

etc. . . .

Simplest implementation:

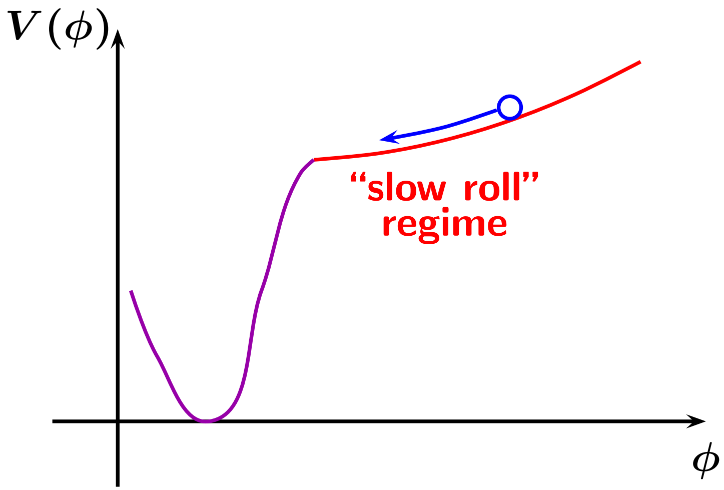
Single-field slow-roll inflation:

- **Scalar field ϕ (“inflaton”)**
- **Scalar potential $V(\phi)$**

$$V(\phi) > 0$$

$$\epsilon \equiv \frac{1}{2}\left(\frac{M_P V'}{V}\right)^2 \ll 1$$

$$\eta \equiv \left|\frac{M_P^2 V''}{V}\right| \ll 1$$



Interesting for string theory, because:

- ϵ, η can be very sensitive even to Planck-suppressed corrections to V
- $\rho_{\text{inf}} \equiv V^{1/4}$ can be as high as $M_{\text{GUT}} \approx 10^{16}\text{GeV}$

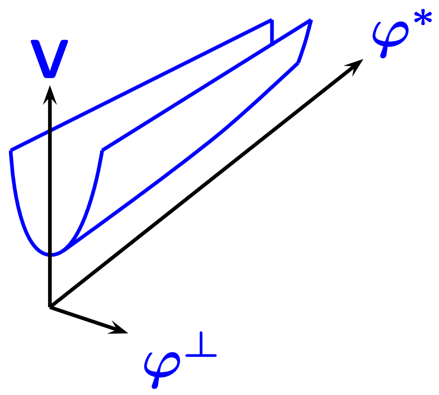
$\Rightarrow$ Possibly unique window to very high energy physics in the earliest moments of the Universe

$\Rightarrow$ Derive realistic and consistent inflationary models from string theory!

What could be the inflaton?

A popular approach:

Inflaton $\phi \equiv$ a particular modulus, φ^*



Generic problem:

Stabilize the orthogonal moduli, $\varphi^\perp$, without spoiling the flatness of V along φ^*

$\Rightarrow$ $\boxed{V_{tot} = V_{inf} + V_{stab}}$ $\Leftarrow$ Hope for little interference

Two typical problems one may encounter:

Problem 1: **Generically, moduli stabilization and slow-roll inflation do interfere!**

Reason: $\mathbf{V}_{\mathbf{stab}} = \mathbf{V}_{\mathbf{stab}}(\varphi^{\perp}, \varphi^{*})$

A model where interference can be well-controlled:

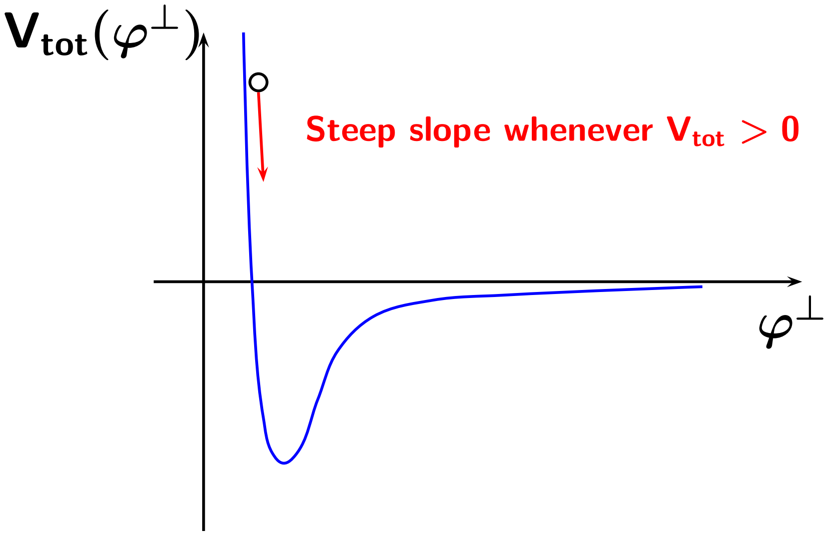
D3/D7-brane inflation on $\mathbf{K3} \times \mathbf{T}^2/\mathbb{Z}_2$

Haack, Kallosh, Krause, Linde, Lüst, M.Z. (2008)

$\Rightarrow$ **CMB fits with subdominant cosmic string contribution**

Battye, Garbrecht, Moss (2006); Bevis, Hindmarsh, Kunz, Urrestilla (2007)

Problem 2: Some moduli may get destabilized whenever $V_{tot} > 0$



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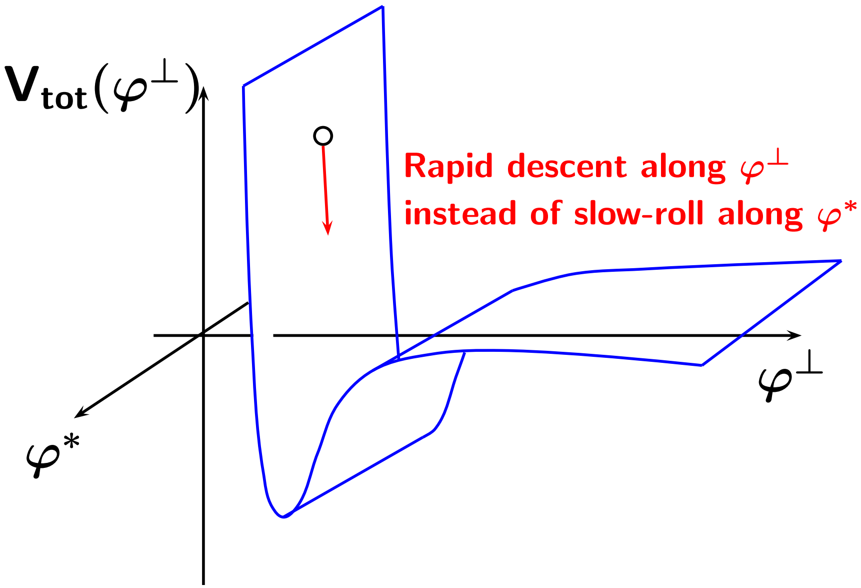

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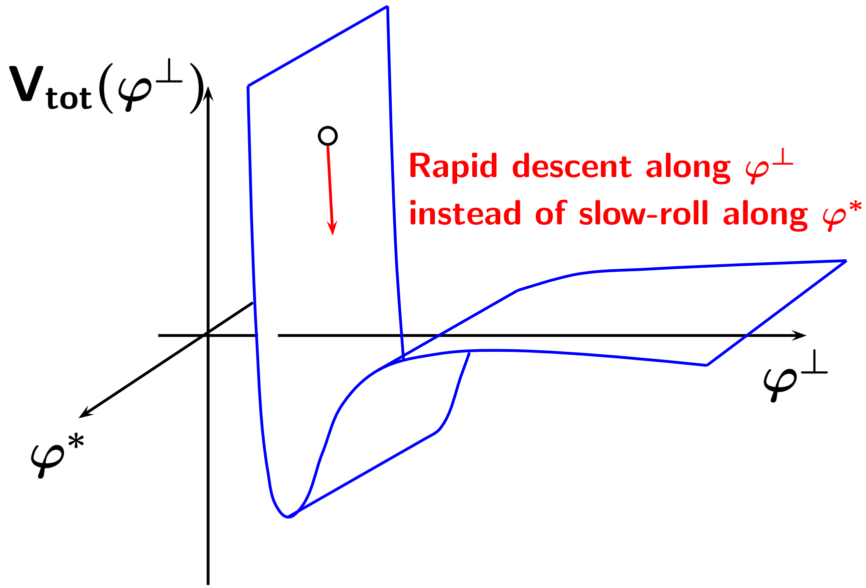


This actually occurs in classical type IIA compactifications on Ricci-flat manifolds (with fluxes and O6/D6 sources)

4. Inflation in type IIA string theory

Classical potential for type IIA compactifications:

$$\mathbf{V}_{\text{tot}}(\rho, \tau, \ldots) = \mathbf{V}_{\text{flux}}(\rho, \tau, \ldots) + \mathbf{V}_{\text{O6/D6}}(\tau, \ldots) + \mathbf{V}_{\text{curv.}}(\rho, \tau, \ldots)$$

ρ = **volume modulus**

τ = **4D dilaton**

$\mathbf{V}_{\text{curv}} \propto (-\mathbf{R})$ **(R = 6D scalar curvature)**

4. Inflation in type IIA string theory

Classical potential for type IIA compactifications:

$$V_{tot}(\rho,\tau,\ldots) = V_{flux}(\rho,\tau,\ldots) + V_{O6/D6}(\tau,\ldots) + V_{curv.}(\rho,\tau,\ldots)$$

ρ = volume modulus

τ = 4D dilaton

$V_{curv} \propto (-R)$ (R =6D scalar curvature)

For $R \geq 0$ (e.g. Ricci-flat manifolds), the particular (ρ,τ)-dependence of V_{tot} implies

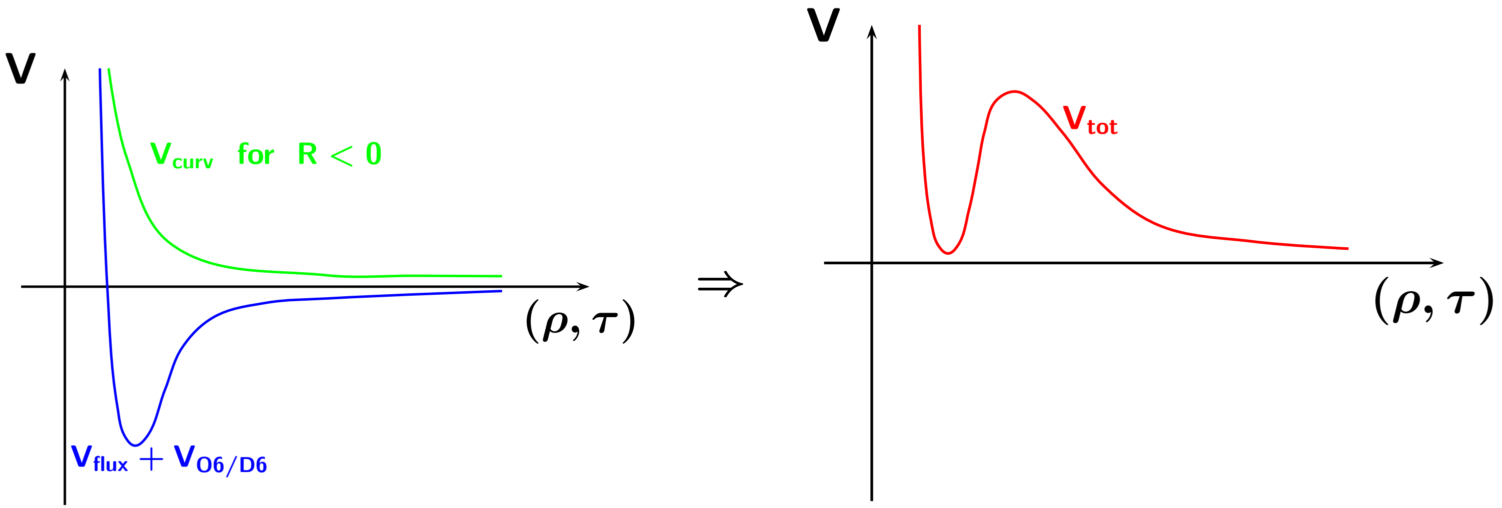
$$\epsilon \equiv \frac{G^{AB}\partial_A V_{tot}\partial_B V_{tot}}{V_{tot}^2} \geq \frac{27}{13} \quad \text{whenever} \quad V_{tot} > 0$$

Hertzberg, Kachru, Taylor, Tegmark (2007)

⇒ Potential is **too steep** along (ρ,τ) for inflation **if $R \geq 0$!**

⇒ This also **rules out de Sitter vacua** (cf. today's acceleration)

$\Rightarrow$ **Try negative internal curvature: $R < 0$**



Cf. Silverstein (2007), Haque,Shiu,Underwood,Van Riet (2008)

Problem: What about field directions other than ρ, τ ?

$\Rightarrow$ **Need model, where V_{tot} is known w.r.t. all moduli!**

A well-understood class with $R \neq 0$, where V_{tot} is known explicitly:

Manifolds with SU(3)-structure based on coset spaces:

$$\frac{G_2}{SU(3)}, \quad \frac{Sp(2)}{S(U(2)\times U(1))}, \quad \frac{SU(3)}{U(1)\times U(1)}, \quad \frac{SU(3)\times U(1)}{SU(2)}, \quad SU(2)\times SU(2)$$

$$\frac{SU(2)^2\times U(1)}{U(1)}, \quad SU(2)\times U(1)^3$$

Koerber, Lüst, Tsimpis; Caviezel, Koerber, S. Körs, Lüst, Tsimpis, M.Z. (2008)

Another no-go theorem along a different direction in field space except for $SU(2)\times SU(2)$
$\Rightarrow$ $\boxed{\epsilon \geq 2}$

Caviezel, Koerber, S. Körs, Lüst, Wrase, M.Z. (to appear)

Related Work: Flauger, Ihl, Paban, Robbins, Wrase (to appear)

Only case not covered by no-go theorem: $\mathbf{SU(2) \times SU(2)}$

$\Rightarrow$ $\epsilon = \mathbf{0}$ **indeed possible, but** $\eta < -\mathbf{2.4}$ **(large tachyonic mass)**

$\Rightarrow$ **Are there better extrema?**

Conclusion:

- **Inflation and de Sitter vacua in type IIA more difficult than expected**
- **It is important to check minimization w.r.t. all moduli**
- **Maybe additional ingredients and/or quantum corrections are helpful**
- **Better understanding of cosmology in IIA theory would be nice, b/c particle physics model building is very far developped in IIA (e.g., by the Munich group...)**
- **To be continued**

Suggested further reading...

- **J. Erdmenger (Ed.):**

  String Cosmology

  With contributions from

  M. Ammon, R. Brandenberger, C. Burgess, S. Das,
  J. Erdmenger, A. Krause, R. Myers, G. Shiu, M. Wyman, **M.Z.**

  Wiley-VCH (2009)

- **R. Blumenhagen, D. Lüst, S. Theisen:**

  Basic Concepts of String Theory

  Textbook, Springer (2009), (Sec. Ed. of Lüst/Theisen)

- **R. Blumenhagen, E. Plauschinn:**

  Introduction to Conformal Field Theory

  Lecture Notes in Physics, Springer (2009)