# String Cosmology

Marco Zagermann
(MPI for Physics, Munich)

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft
DFG

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

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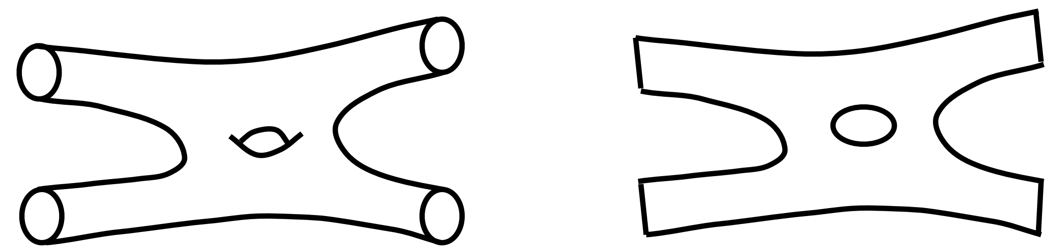
# String Theory

- "Unified" theory of all particles and interactions
  - Particles:


  - Interactions:



etc.

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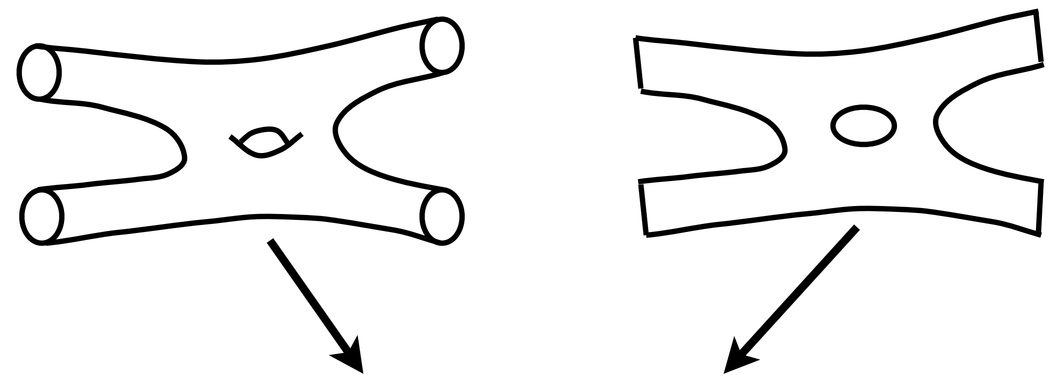

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- UV-Completeness:

Finite

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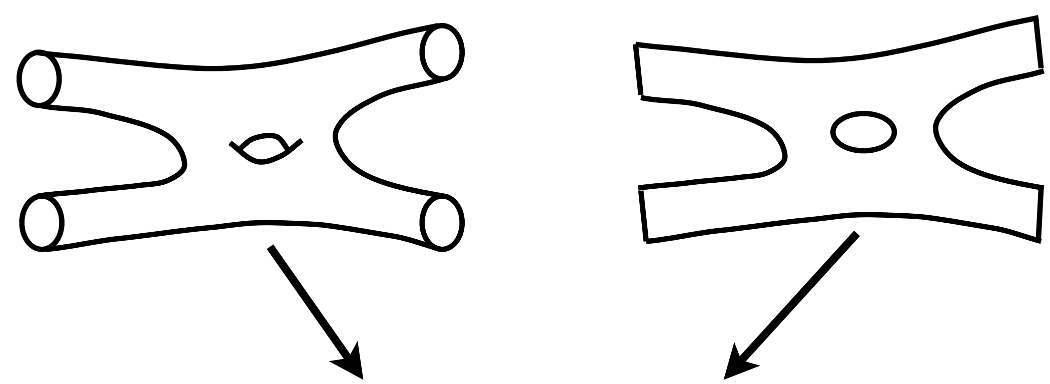

etc.

- UV-Completeness: Finite

⇒ Perturbatively consistent theory of quantum gravity

(+ Gauge interactions + Supersymmetry)

Cf. talks by Conlon, Gray, Camara, Uranga

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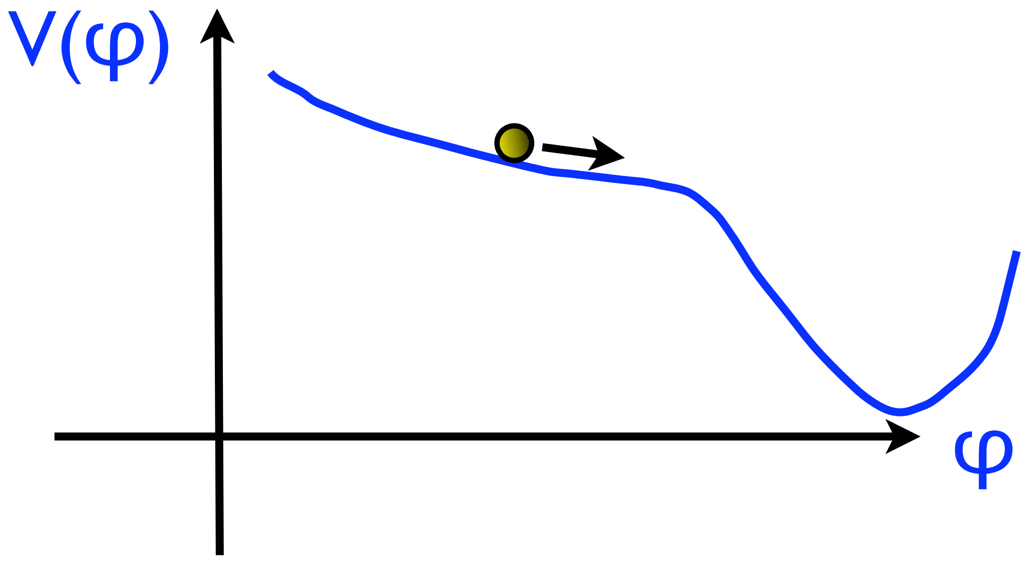
- Cosmology may probe very high energy scales
  $\Rightarrow$ Detailed dynamics may be highly UV-sensitive.

  Prime example: The UV-sensitivity of inflation

# Slow-roll inflation:




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

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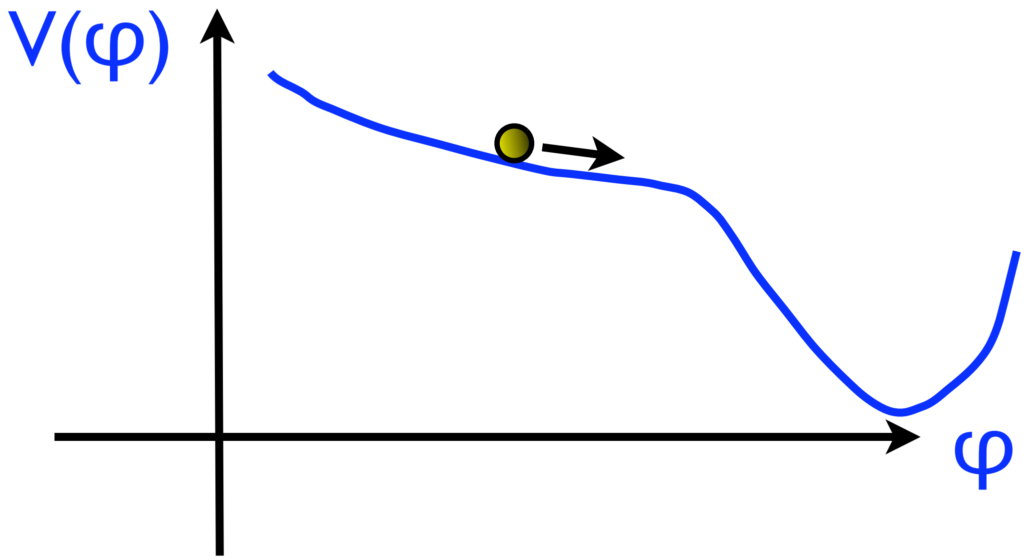


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- UV-sensitivity of inflation:
  - $\eta$ is sensitive to Planck suppressed operators:

$$\Delta V \sim \frac{\langle V\rangle \varphi^2}{M_P^2} \Longrightarrow \Delta\eta = \mathcal{O}(1)$$

  - Possibly very high energy scales

$$V_{inf}^{1/4} \sim M_{GUT}\ \epsilon^{1/4}$$

  - Detectable tensor modes require large field excursions: $\Delta\varphi \sim M_P$

- Certain "stringy" features may be relevant for cosmology
  - Extra dimensions: $\mathcal{M}^{(10)} = \mathcal{M}^{(6)} \times \mathcal{M}^{(4)}$

Small & compact

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  - Moduli:

    4D scalars describing deformations of compactification data

    Cf. Joe Conlon's talk

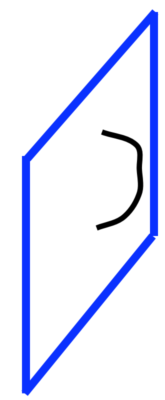
    ⇒ May cause phenomenological problems

    (E.g. 5th force, overclosure, BBN, ...)

    ⇒ Possibly good inflaton candidates

– Extended objects:

Fundamental string



Dp-brane

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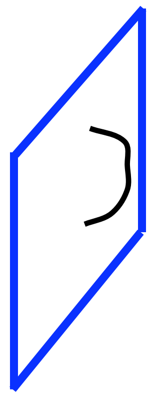

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– Quantum gravity → Big Bang singularity?

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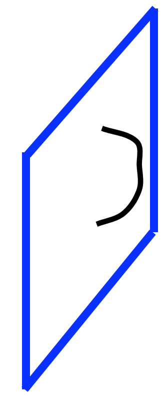

Dp-brane

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<u>In any case:</u> Contraints on string theory from cosmology are quite complementary to constraints from particle physics → Test string theory?

# Rest of the talk:

1. Moduli stabilization
2. de Sitter vacua
3. Inflation
4. Cosmic (super)strings?
5. Tensor modes?
6. de Sitter and Inflation beyond IIB?
7. Conclusions

# 1. Moduli stabilization

10D → 4D $\Rightarrow$ Moduli fields in $\mathcal{L}_{\mathrm{eff}}^{\mathrm{4D}}$

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From 6D components of 10D fields

$$(\mathbf{g_{mn}}, \phi, \mathbf{B_{mn}}, \mathbf{C_{m \ldots p}})$$

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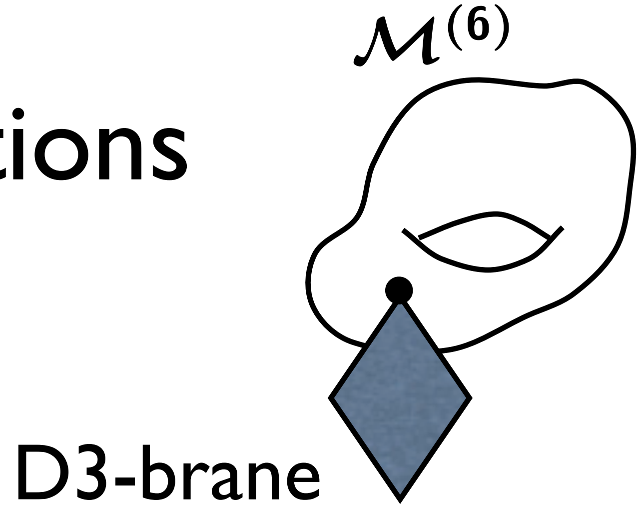
(ii) Open string moduli:

E.g. D-brane positions/orientations



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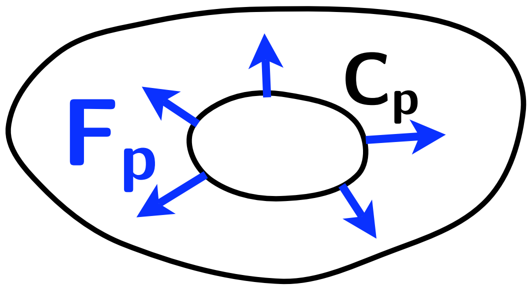
Two important mechanisms:

(i) Fluxes of p-form field strengths $F_p$




$\Rightarrow$ Potential for $C_p$-deformation modulus

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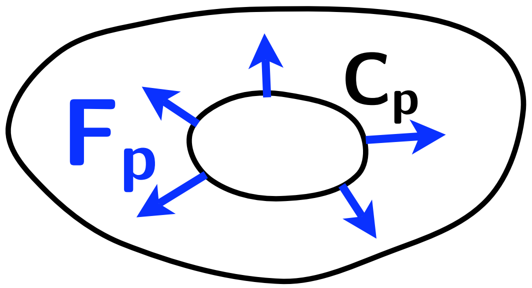



⇒ Potential for $C_p$-deformation modulus

(ii) Quantum corrections

⇒ Most relevant for moduli not stabilized by fluxes

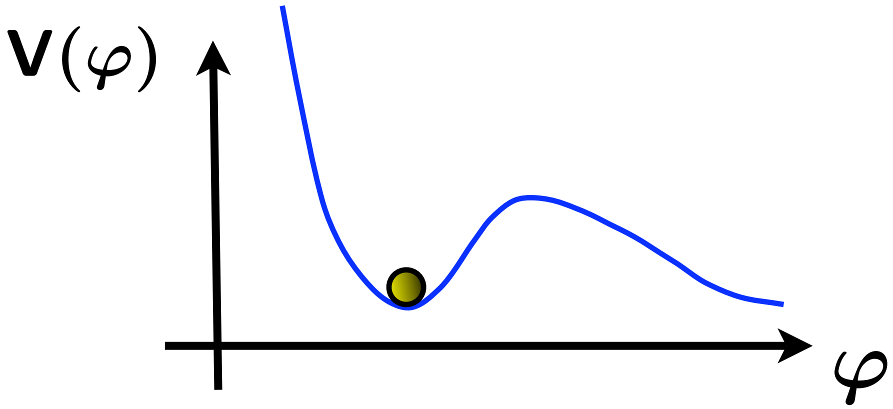
⇒ Popular inflaton candidates

The interplay of fluxes and quantum corrections is presently best understood in type IIB string theory

$\Rightarrow$ So far, most work on string cosmology in type IIB

# 2. de Sitter vacua

<u>Idea:</u>




( $\Lambda_{\text{eff}} > 0$ $\Rightarrow$ Today's accelerated expansion)

## A popular scenario:

Giddings, Kachru, Polchinski (2001)
Kachru, Kallosh, Linde, Trivedi (2003)

IIB string theory on Calabi-Yau orientifolds
with 3-form fluxes & quantum corrections

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IIB string theory on Calabi-Yau orientifolds
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- Stabilized by fluxes:
  – Complex structure moduli (“shape moduli”)
  – Dilaton ($\rightarrow$ string coupling)

- Stabilized by subleading quantum effects:
  – Kähler moduli (“size moduli” $\ni$ volume modulus)
  (– D3-brane positions)

# Volume stabilizaton:

$$W = W_{flux} + Ae^{-a\rho}$$

Gaugino cond. on D7-branes
or D3-brane instantons

$$K = -3 \ln[(\rho + \bar{\rho})]$$

$$\Rightarrow \boxed{V_F^{stab} = e^K \left[\mathcal{D}_i W \overline{\mathcal{D}^i W} - 3|W|^2\right]} \Rightarrow \boxed{\text{AdS}}$$

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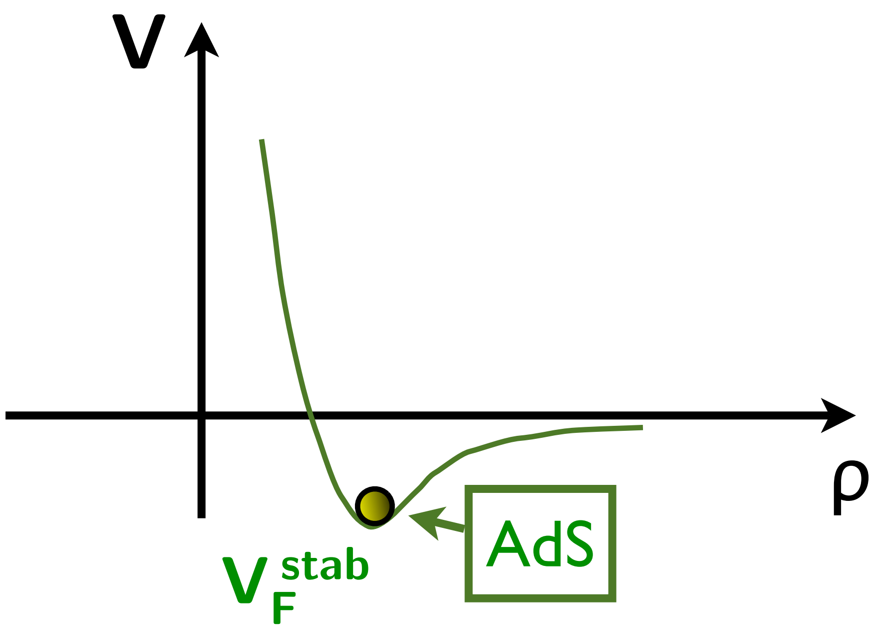

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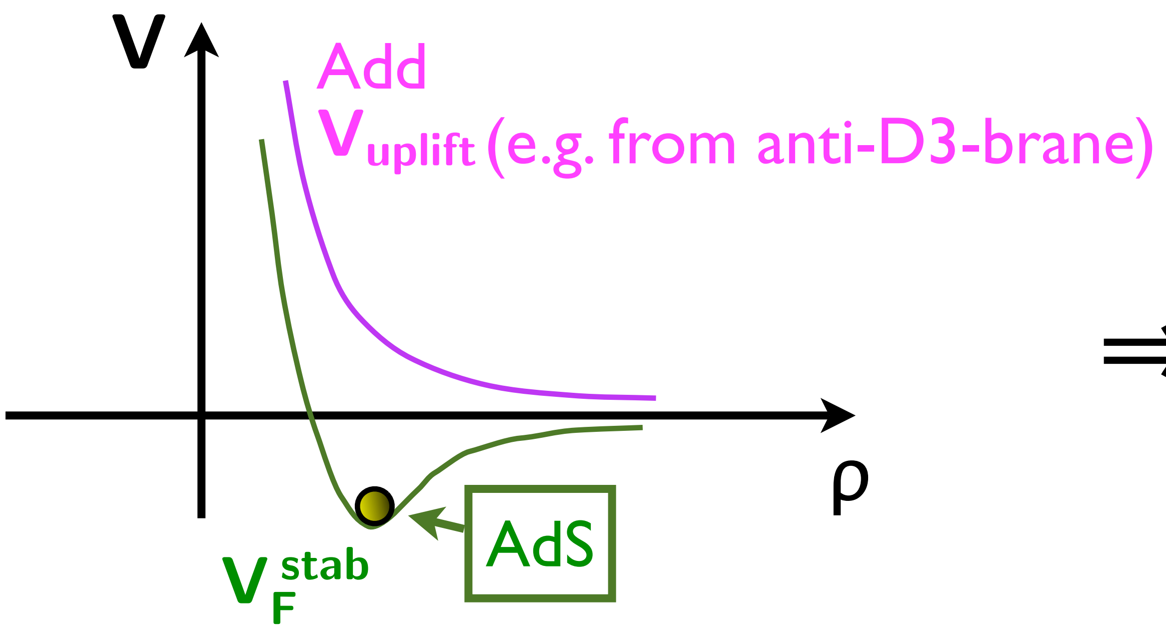
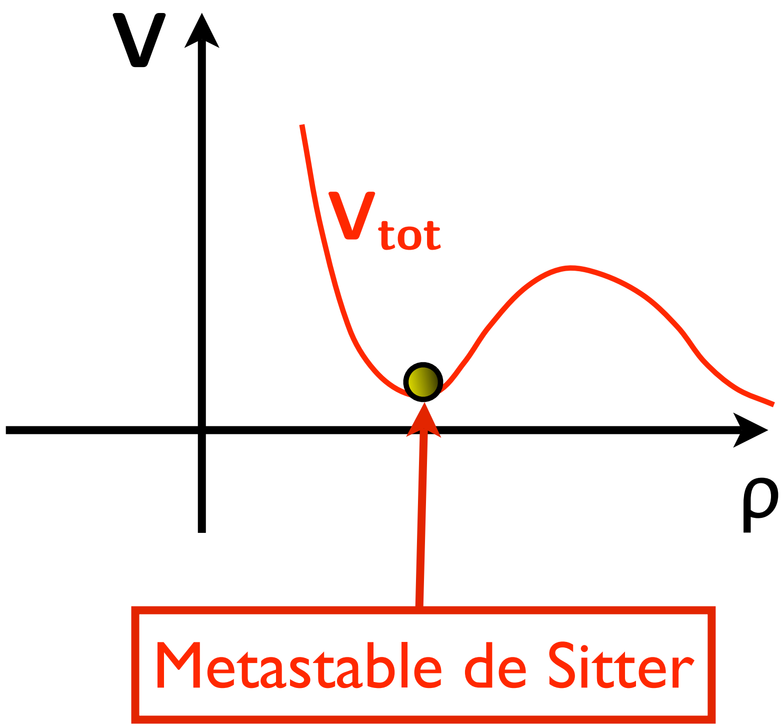



$\Rightarrow$



A related interesting setup: Large volume scenario

Balasubramanian, Berglund (2004)

Balasubramanian, Berglund, Conlon, Quevedo (2005)

$$\mathsf{K} = \textsf{tree level} + \alpha'$$

Becker, Becker, Haack, Louis (2002)

$$\mathsf{W} = \mathsf{W}_{\mathsf{flux}} + \sum_i \mathsf{A}_i e^{-a_i T_i}$$

Cf. Joe Conlon's talk

# 3. Inflation

Most scenarios:

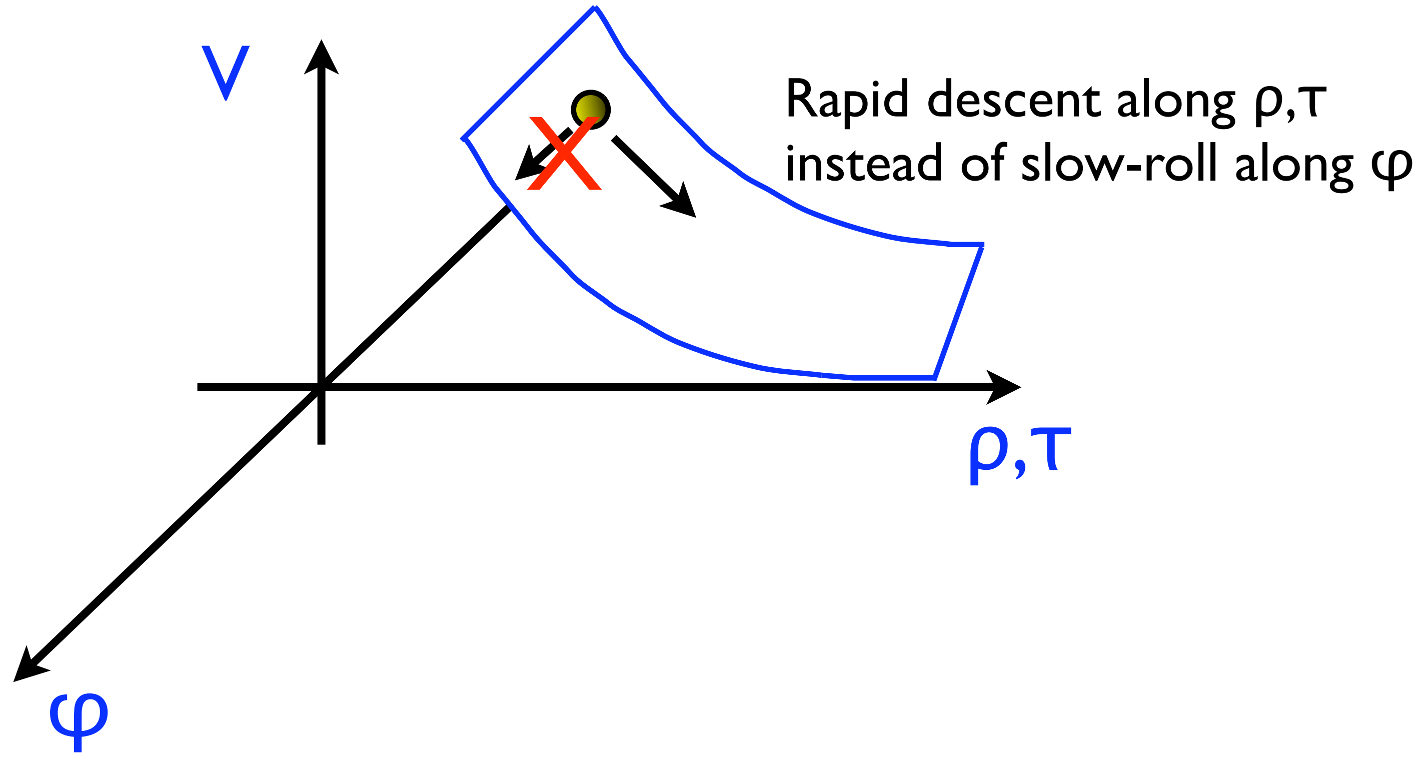
Inflaton = a modulus that receives a potential only at subleading order (quantum corrections)

Problem:

Some moduli tend to interfere severely with inflation

E.g. - Volume modulus ρ
- Dilaton τ

⇒ Tend to be steep runaway directions of simplest potentials:



$\Rightarrow$ **Inflation and moduli stabilization can not be discussed separately**

## Most popular framework:

Type IIB string theory on CY-orientifolds with fluxes

(because moduli stabilization is so well understood)

## Fixed by fluxes at tree-level:

- Complex structure moduli
- Axion-dilaton

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Remaining light moduli:

- D3-brane moduli (e.g. D3-positions on CY)
- Kähler moduli (e.g. volume modulus)

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Good inflaton candidates!

- Brane inflation models:

Inflaton = D3-brane position on CY

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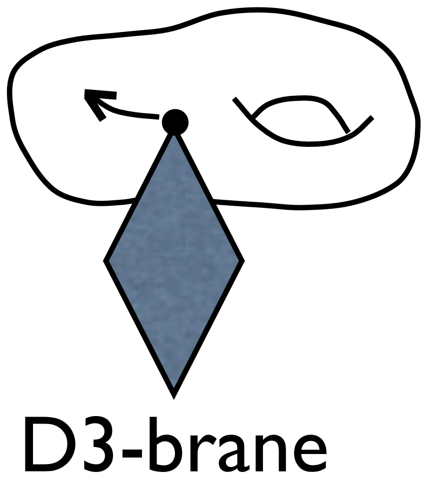

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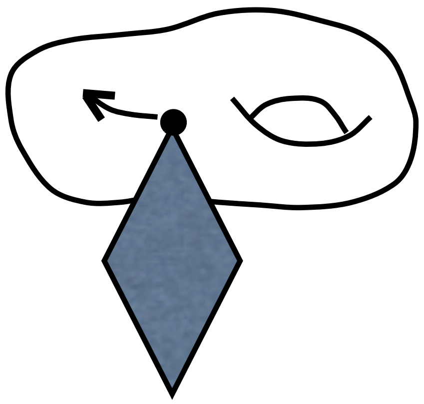


D3-brane

(i) Warped D3/$\overline{\text{D3}}$-inflation

(ii) D3/D7-inflation

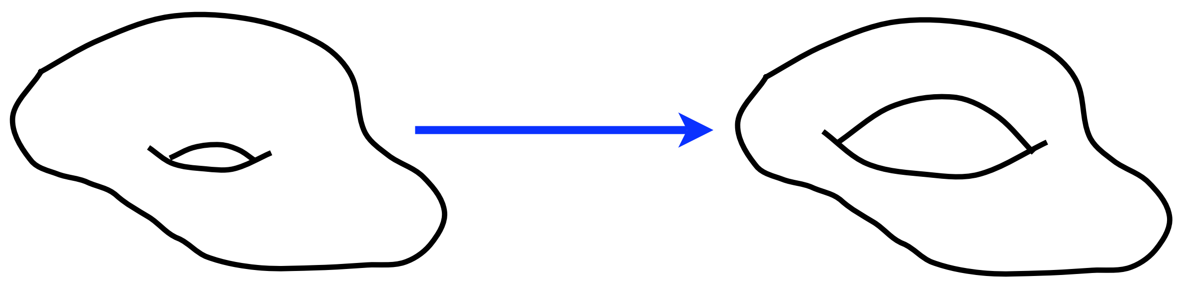
(iii) DBI-inflation

⋮

- Kähler moduli inflation models

Inflaton = a Kähler modulus
(or its axionic partner)

(= Closed string modulus)



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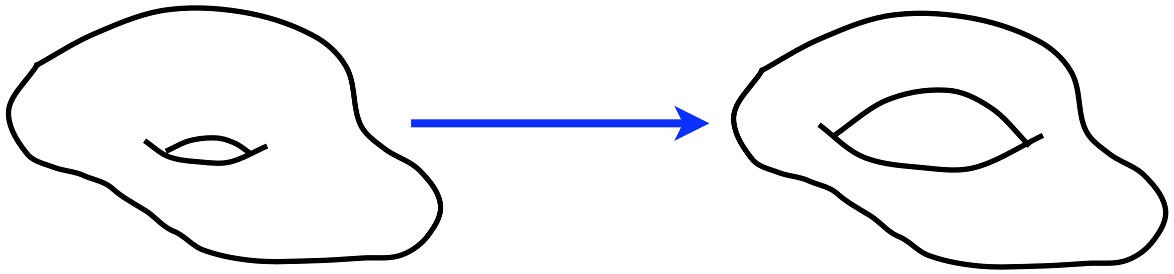


(i) Racetrack inflation

(ii) Blow-up modulus inflation

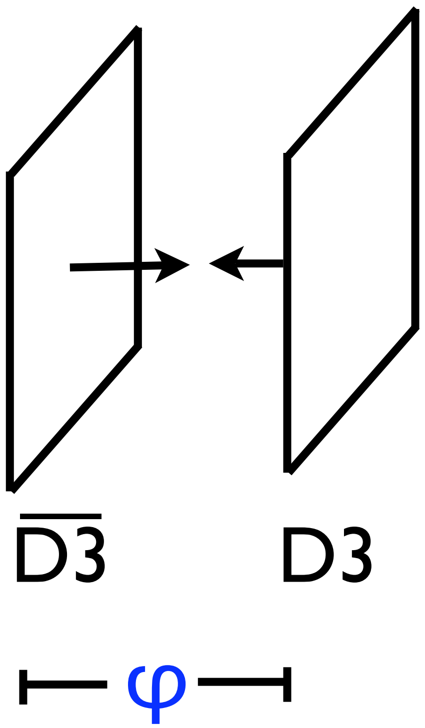
(iii) Fiber inflation

Also: Volume modulus inflation, axion inflation,...

# Warped D3/$\overline{\text{D3}}$-brane inflation

Original idea:

Dvali, Tye (1999),...



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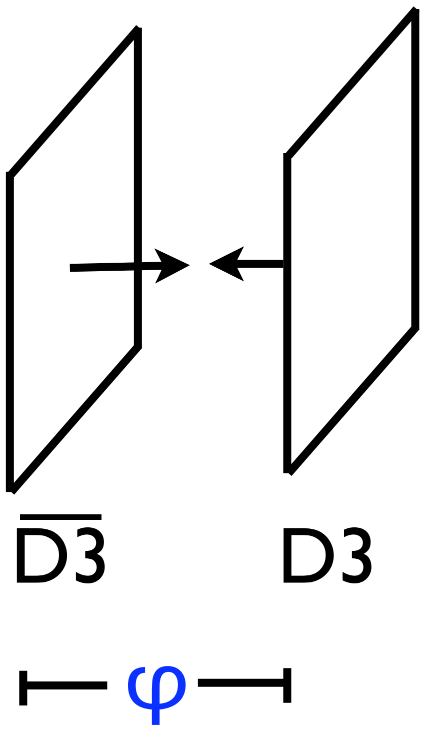


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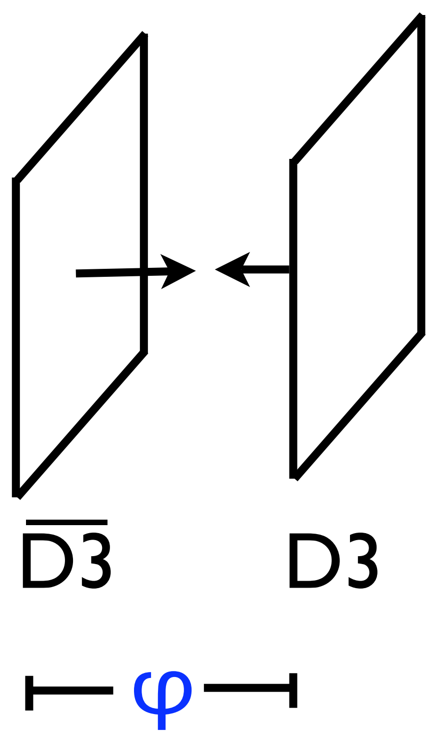


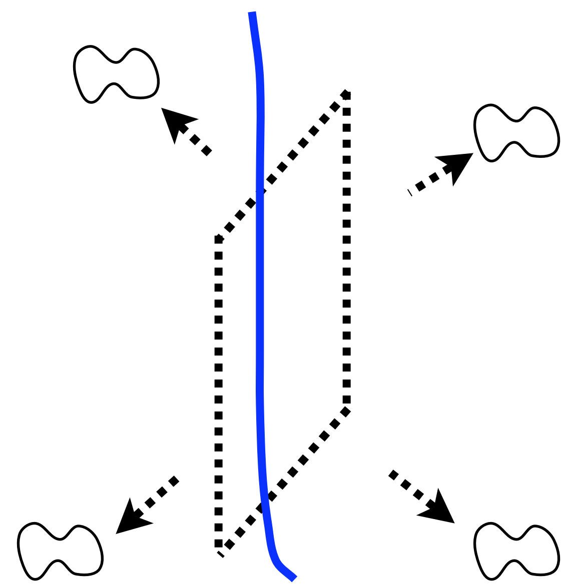

Annihilation into
closed string radiation
+ cosmic strings
(D1-branes)

Sen (1999)
Jones, Stoica, Tye (2002)
Sarangi, Tye (2002)
Dvali, Vilenkin (2002)

$$V_{\text{Coulomb}} \propto \left(1 - \frac{c}{\varphi^4}\right)$$

Problem: Finite separation $\varphi$ in compact space

$\Rightarrow$ $$\boxed{\eta = \mathcal{O}(1)}$$

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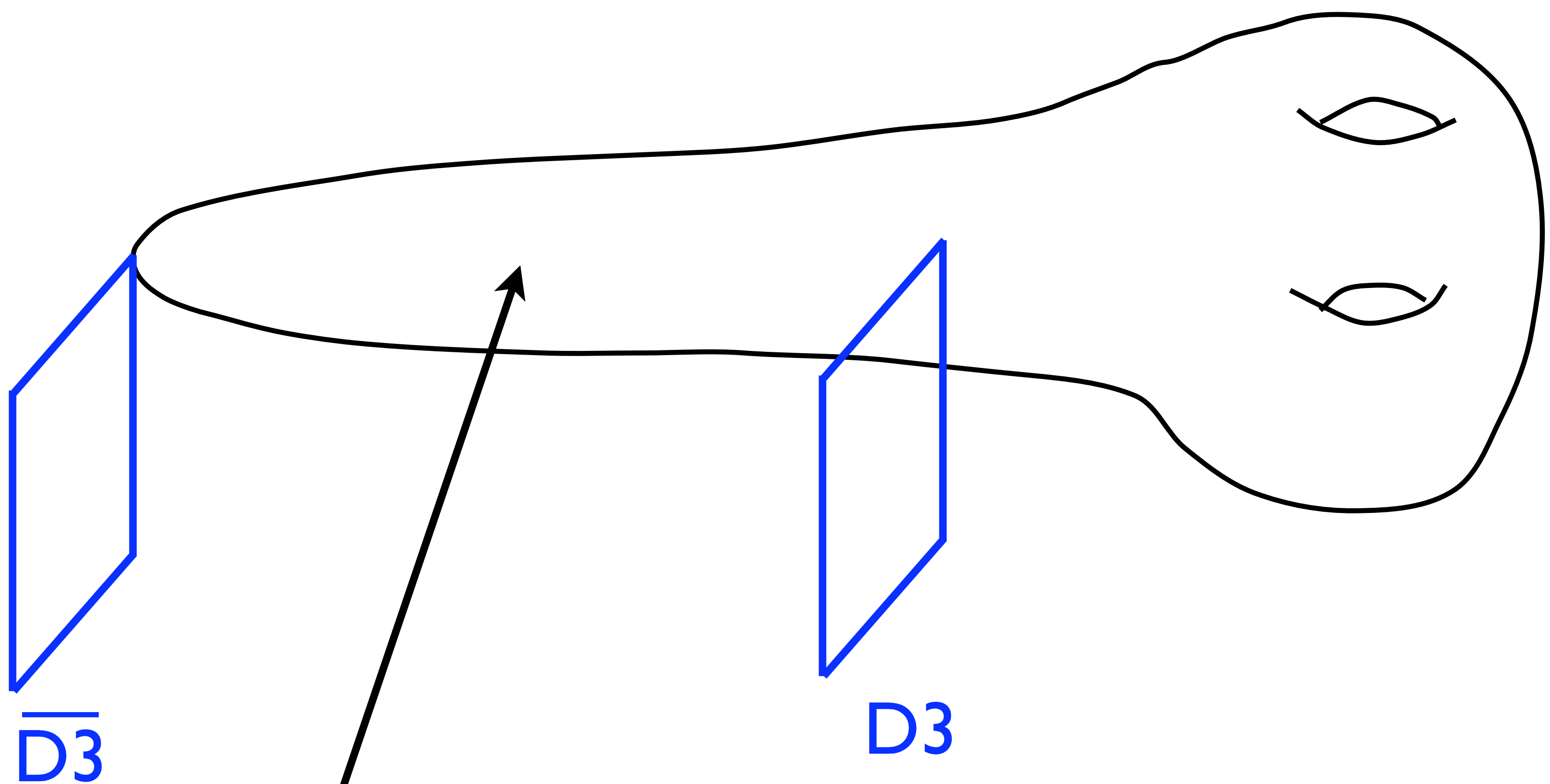
$\Rightarrow$ **Warped D3/D3-brane inflation**

KKLMMT (2003)




Warped Throat:

$$\mathbf{ds^2_{(6)} = h^{1/2}(\varphi)\left[d\varphi^2 + \varphi^2 ds^2_{(5)}\right]}$$

$\varphi_0 \longmapsto \varphi$

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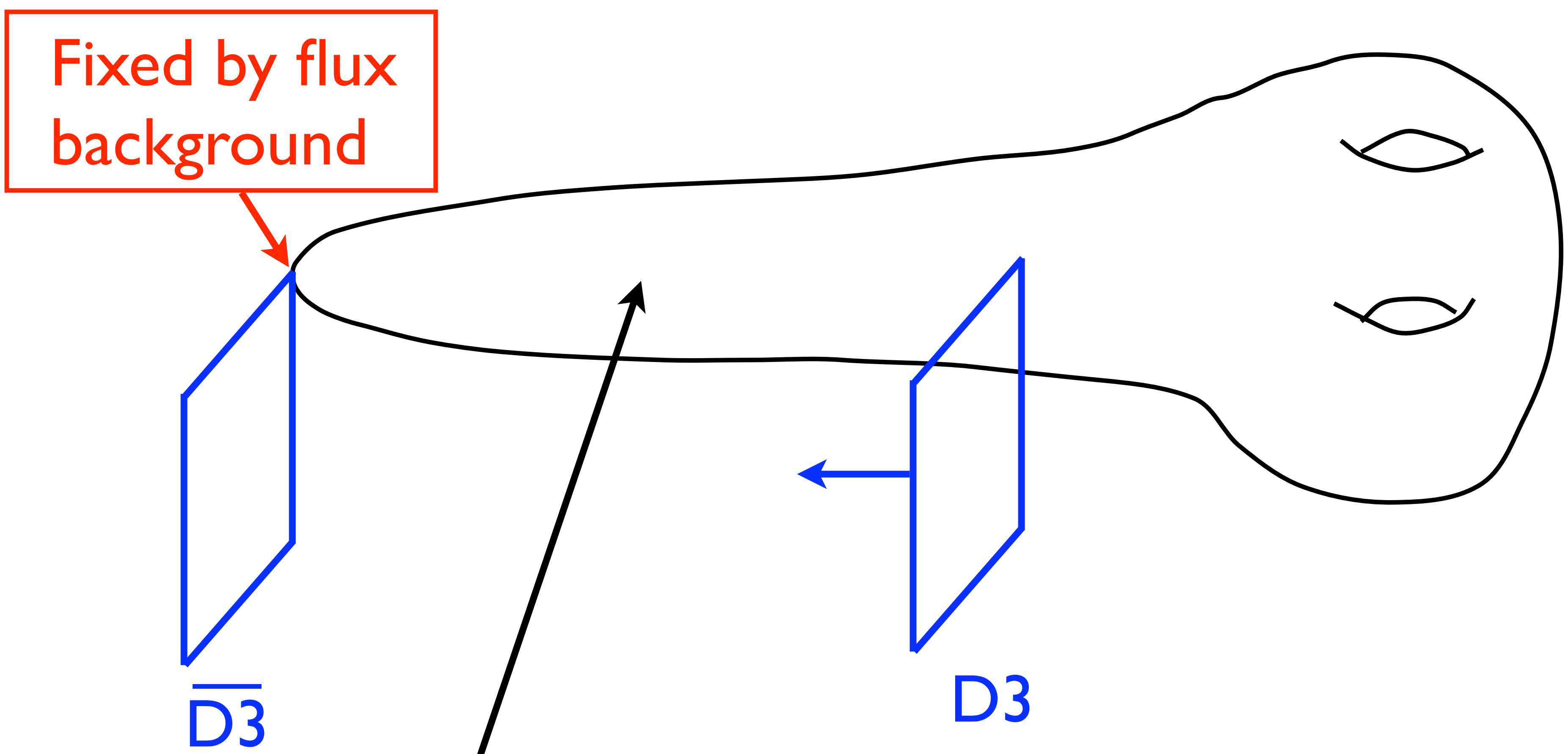


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Additional benefit:

KKLMMT (2003)

Strong warping also redshifts the cosmic string tension

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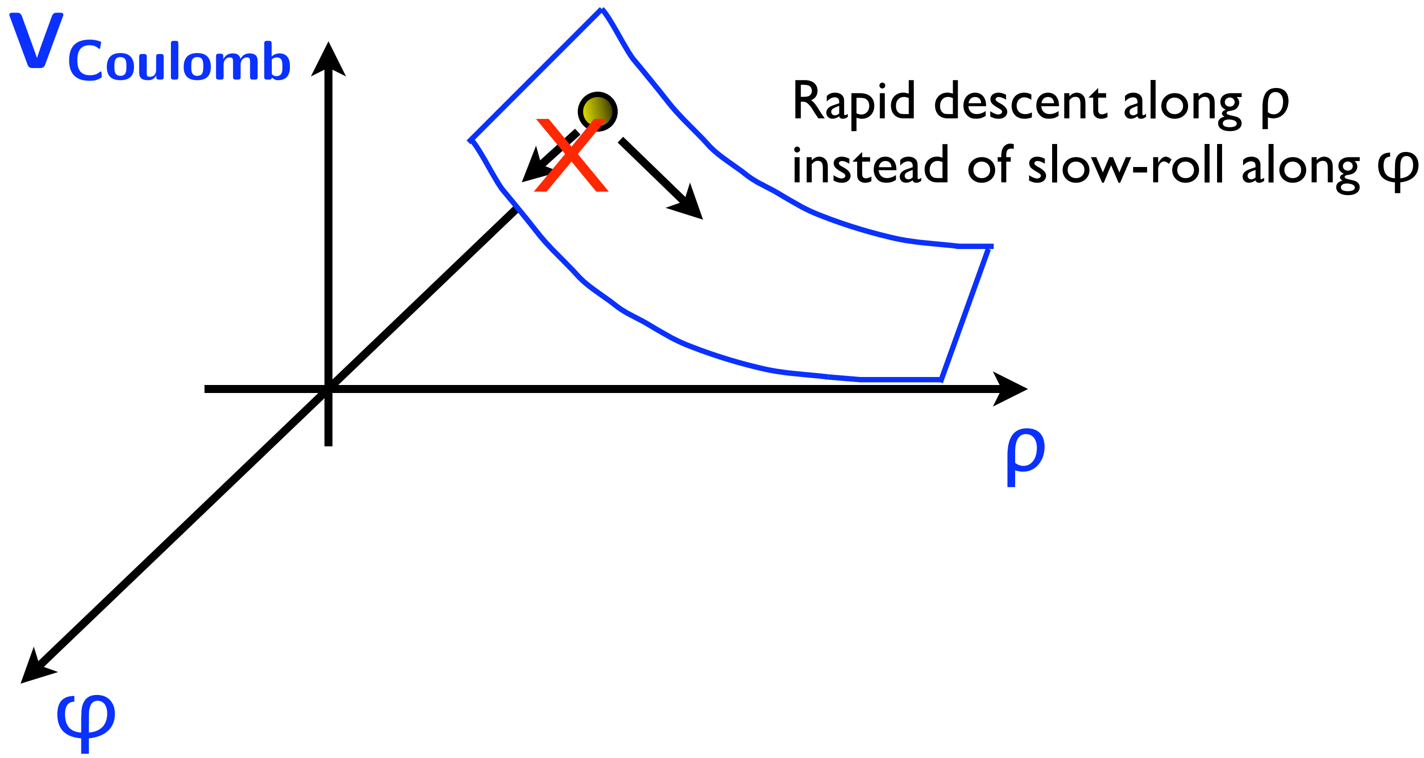
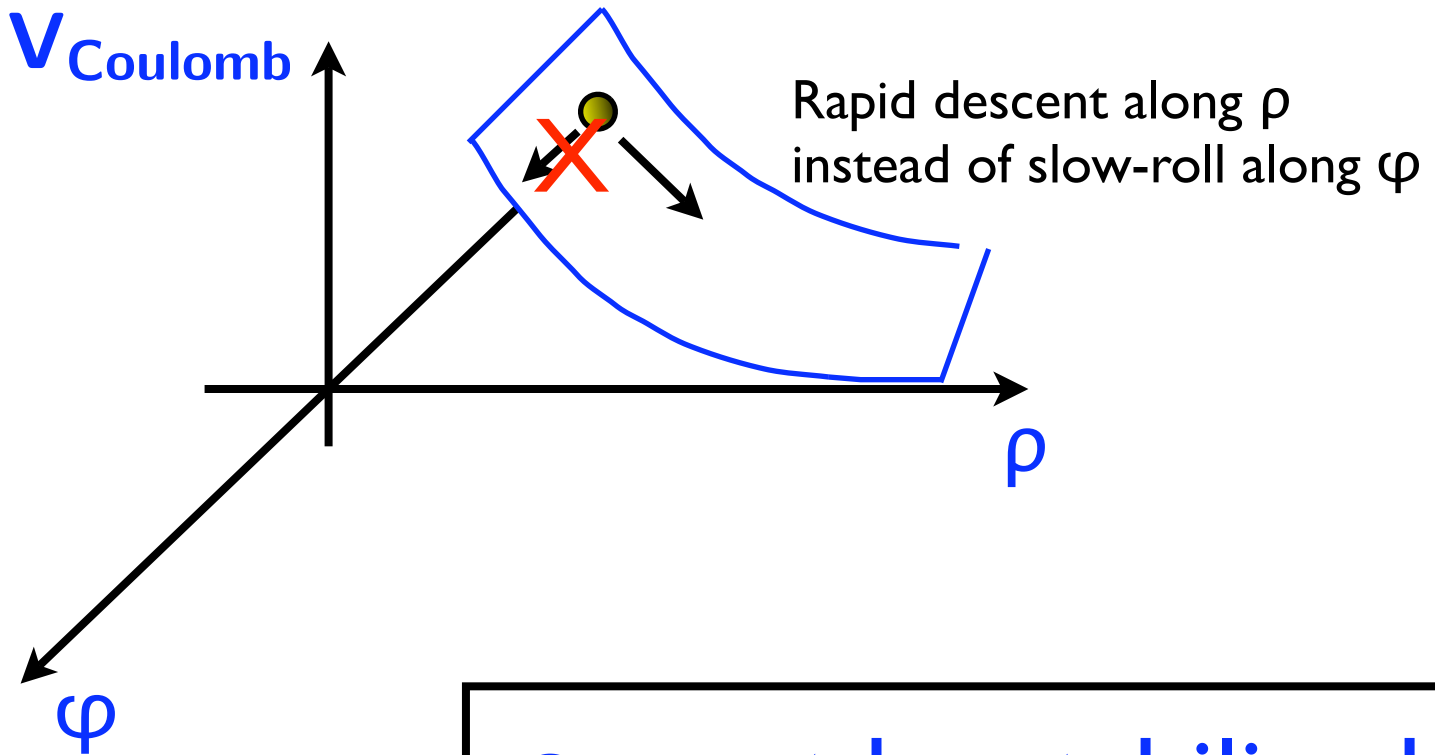
A remaining problem:

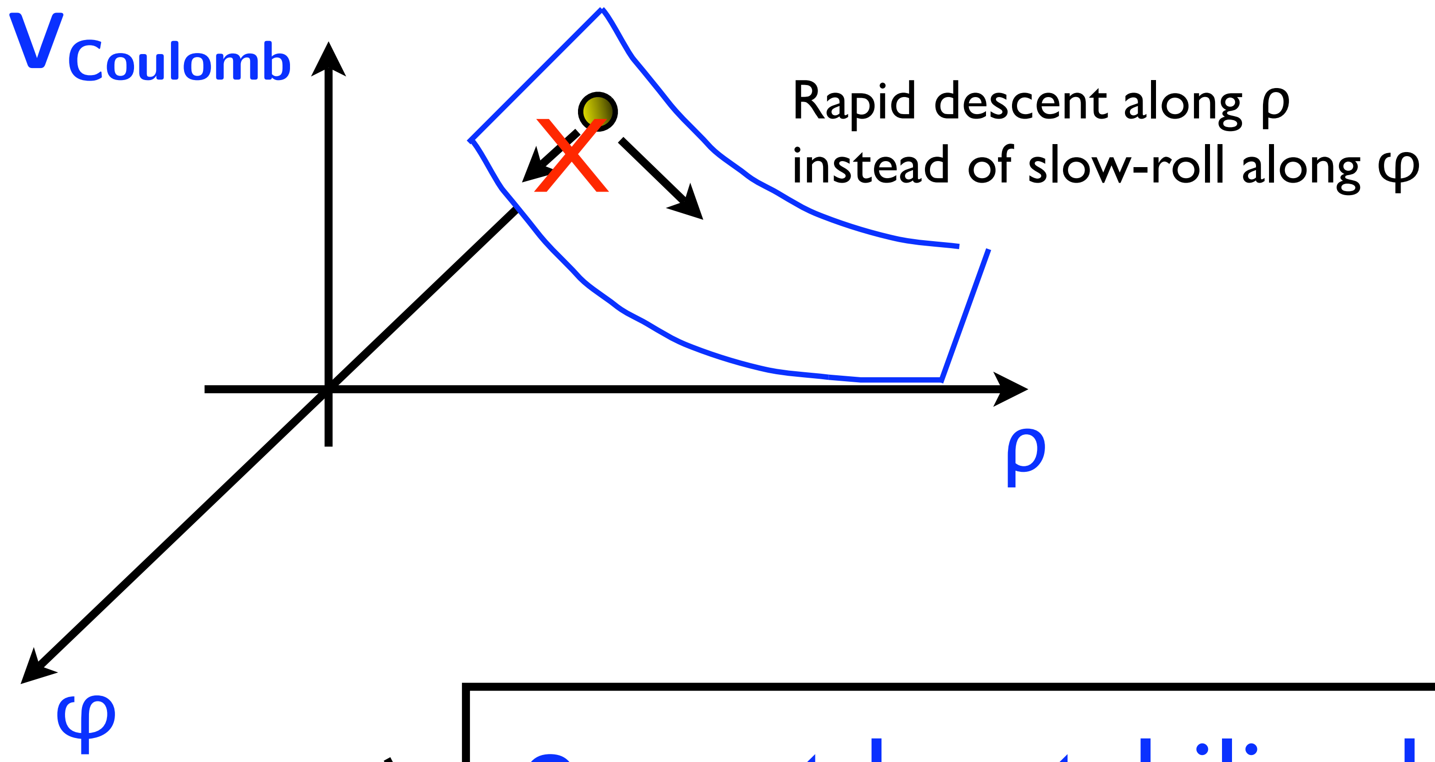
$\mathbf{V}_{\text{Coulomb}}$ is rapidly decreasing function of volume modulus ρ



$V_{Coulomb}$
Rapid descent along ρ
instead of slow-roll along φ
ρ
φ




⇒ **ρ must be stabilized !**

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E.g. via nonperturbative superpotential: KKLT (2003)

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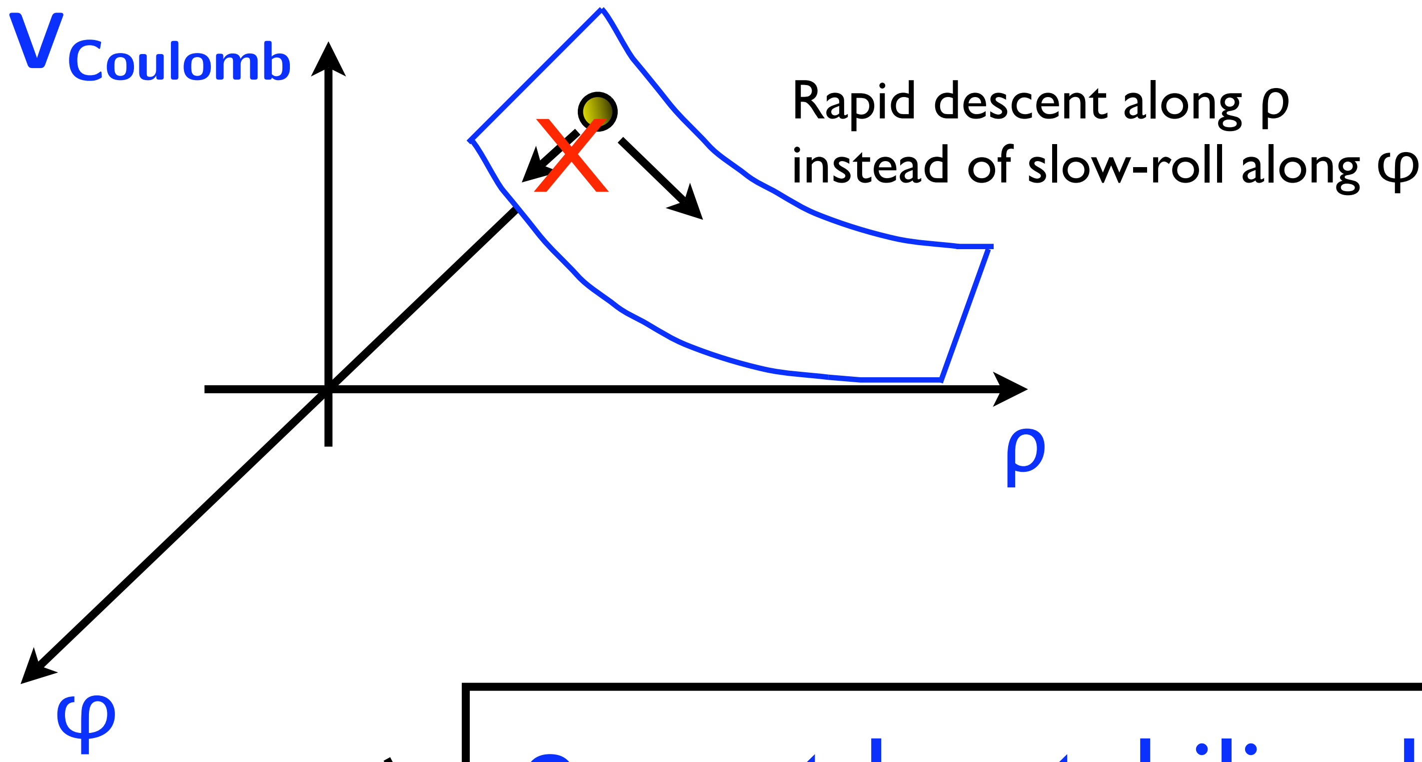


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In the presence of D3-branes:

$$\mathbf{W} = \mathbf{W_{flux}} + \mathbf{A}(\varphi, \ldots)\mathbf{e}^{-\mathbf{a}\rho}$$

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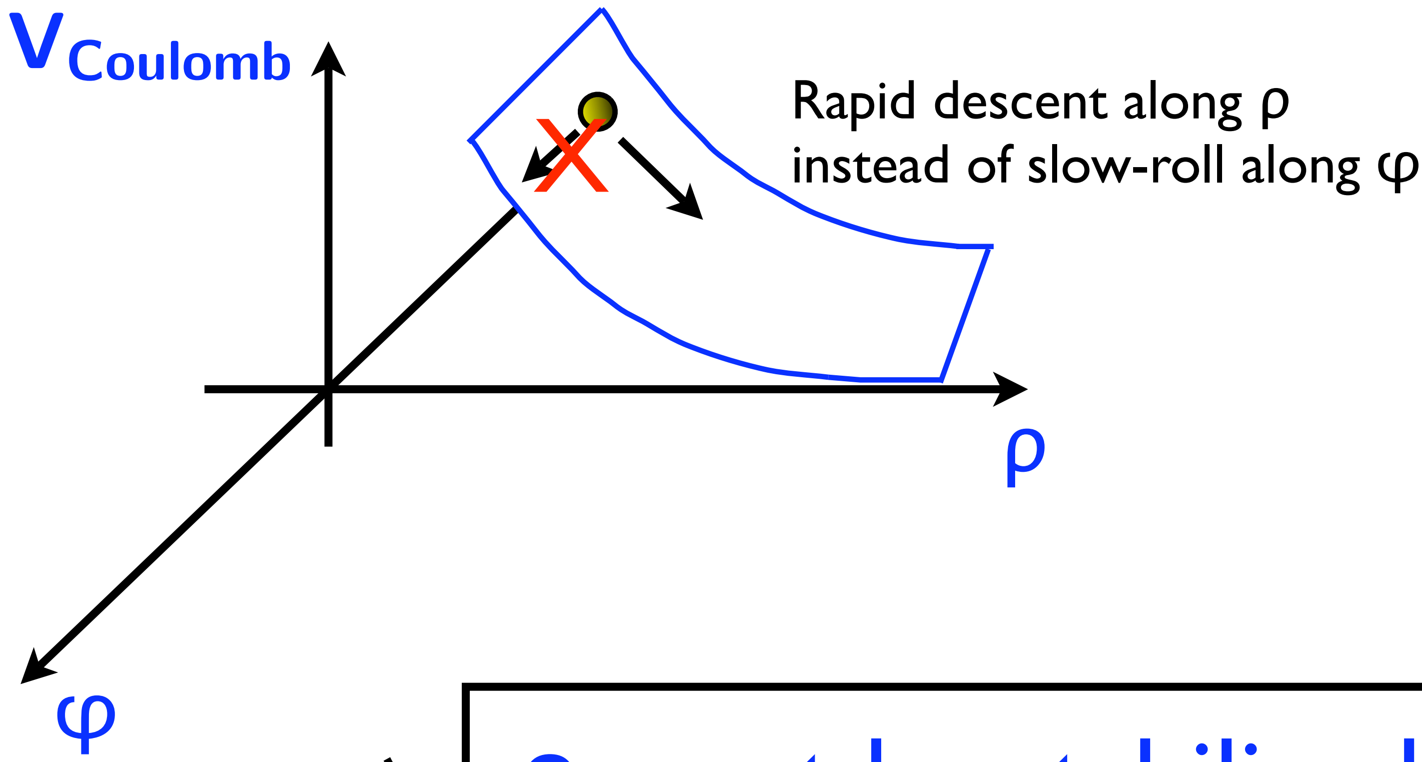
De Wolfe, Giddings (2002)

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$$\mathbf{K} = -\mathbf{3}\ \mathbf{ln}[(\rho + \bar{\rho} + |\varphi|^2)]$$

$\Rightarrow$ New inflaton dependences ! KKLMMT (2003)

## ⇒ Compute A(φ):

Backreaction of D3 on warp factor
(Tree-level supergravity calculation)

Giddings, Maharana (2005)
Baumann, Dymarsky, Klebanov, Maldacena, McAllister,Murugan (2006)
Baumann, Dymarsky, Klebanov, McAllister (+ Steinhardt) (2007)
Krause, Pajer (2007)
Baumann, Dymarsky, Kachru, Klebanov, McAllister (2008)

One finds:

Generically $\varphi^{3/2}$-terms

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One lesson:

Detailed computational control is important

# 4. Cosmic (super)strings

Brane inflation models → Typically cosmic strings at the end of inflation

Closed string inflation models → Typically no cosmic strings

- D1-branes
- Fundamental strings
- (p,q)-strings
- wrapped Dp-branes (p>1)

May have different properties than ordinary gauge theory solitons

E.g. Copeland, Myers, Polchinski (2003)

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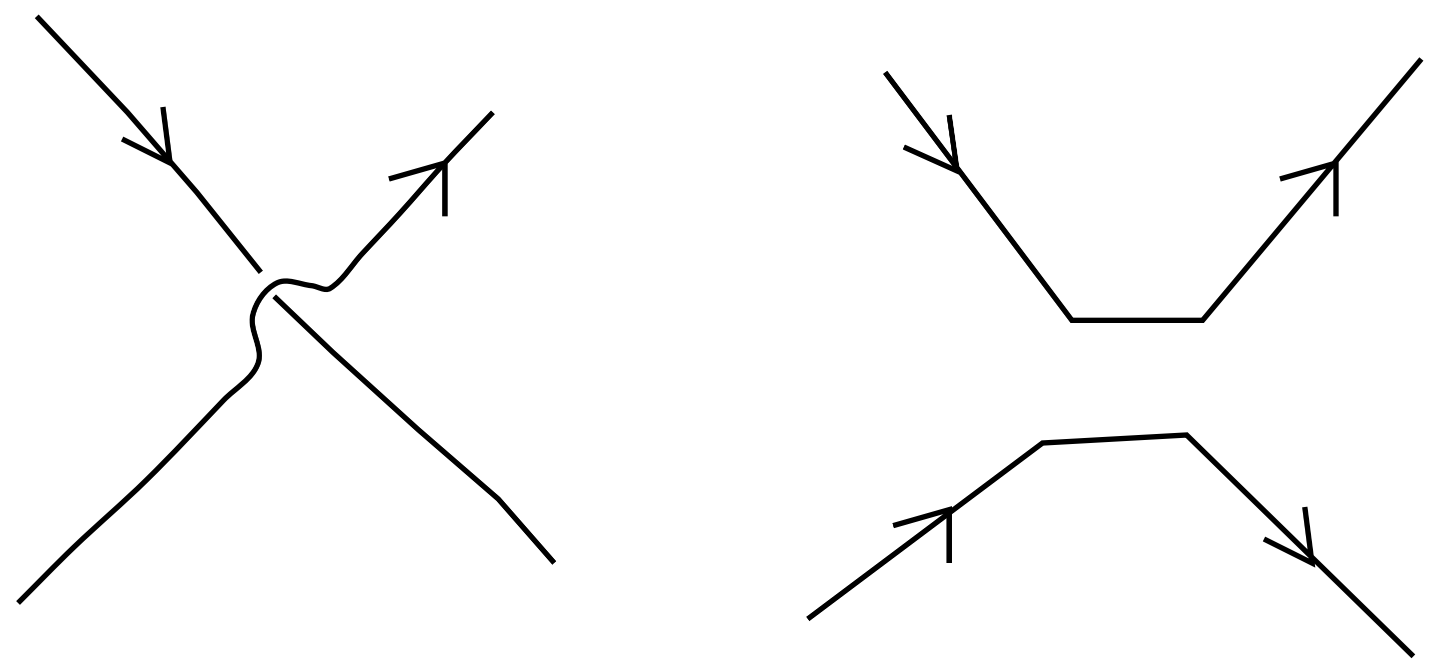

Reconnection probability:

P=1 for standard gauge theory vortices

P<<1 possible for cosmic superstrings

$\Rightarrow$ Cosmic strings could be very interesting window into string theory if realized in nature

# 5. Observable tensor modes?

$$\boxed{\left(\frac{\Delta\varphi}{M_P}\right) \sim \left(\frac{r}{0.01}\right)^{\frac{1}{2}}}$$

Lyth bound

Lyth (1996)

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Lyth (1996)

Strong geometrical constraints for D3-inflation models:

- D3 on symmetric torus
- D3 in warped throat

E.g. Baumann, McAllister (2006)

$\Rightarrow$ r unobservably small

# Some recent suggestions:

- Wrapped Dp-branes

Kobayashi, Mukohyama, Kinoshita (2007)
Becker, Leblond, Shandera (2007)

- Large complex structure

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

- Monodromy inflation

Silverstein, Westphal (2008)
McAllister, Silverstein, Westphal (2008)

- Fiber inflation

Cf. Cicoli's talk

- Wilson line DBI inflation

Cf. Zavala's talk

- Multi axion inflation models

Dimopoulos, Kachru, McGrevy, Wacker (2005)
Easther, McAllister (2005)
Kallosh, Sivanandam, Soroush (2007)
Grimm (2007)
Tye, Xu, Zhang (2008)

- Multibrane models

E.g. Becker, Becker, Krause (2005)
Krause (2007)

# 6. Inflation beyond type IIB?

Not much explored

E.g. Becker, Becker, Krause (2005)

Moduli stabilization best understood in IIB

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Moduli stabilization best understood in IIB

But:

In a sense, moduli stabilization is even simpler in IIA

Grimm, Louis (2004)

Kachru, Kashani-Poor (2004)

Derendinger, Kounnas, Petropoulos, Zwirner (2004, 2005)

Villadoro, Zwirner (2005)

de Wolfe, Giryavets, Kachru, Taylor (2005)

## Type IIA on Calabi-Yau spaces with

- p-form fluxes
- D6-branes/O6-planes

All geometric moduli may be stabilized
in parameterically controlled classical regime
$\Rightarrow$ Quantum corrections negligible

## Type IIA on Calabi-Yau spaces with

- p-form fluxes
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All geometric moduli may be stabilized
in parameterically controlled classical regime
⇒ Quantum corrections negligible

⇒ Very controlled inflation models?

Unfortunately:

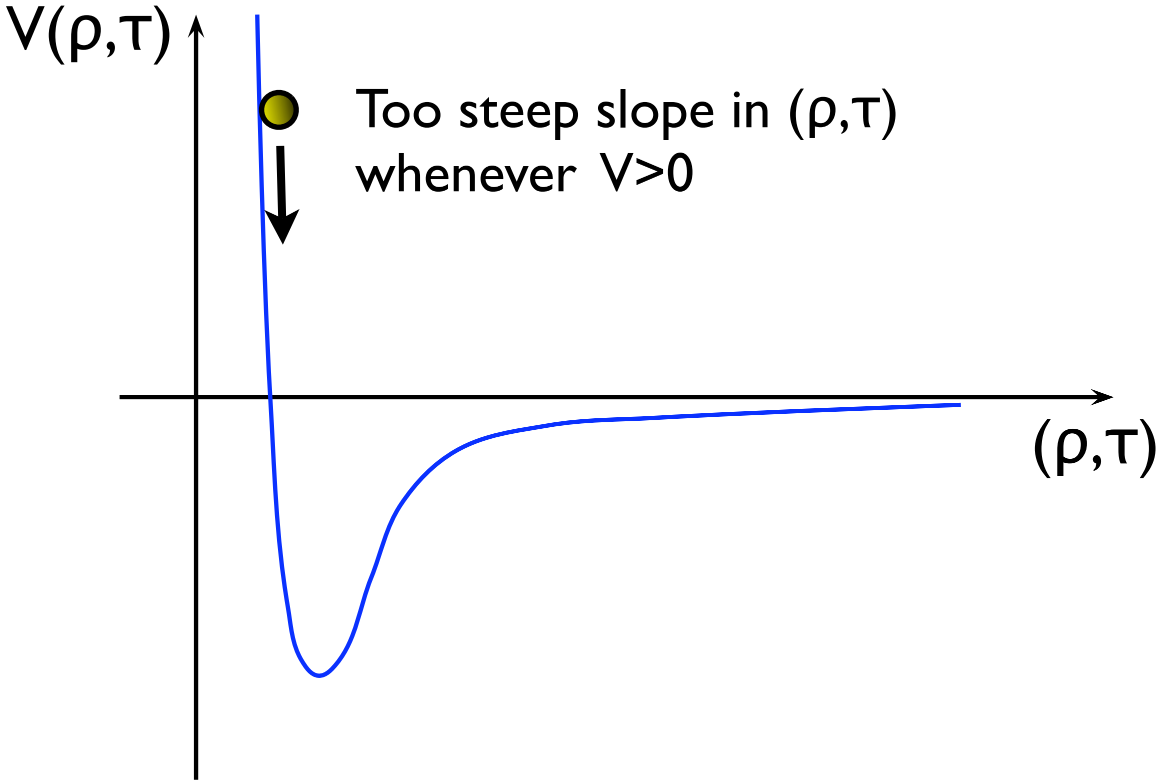
No-go theorem:

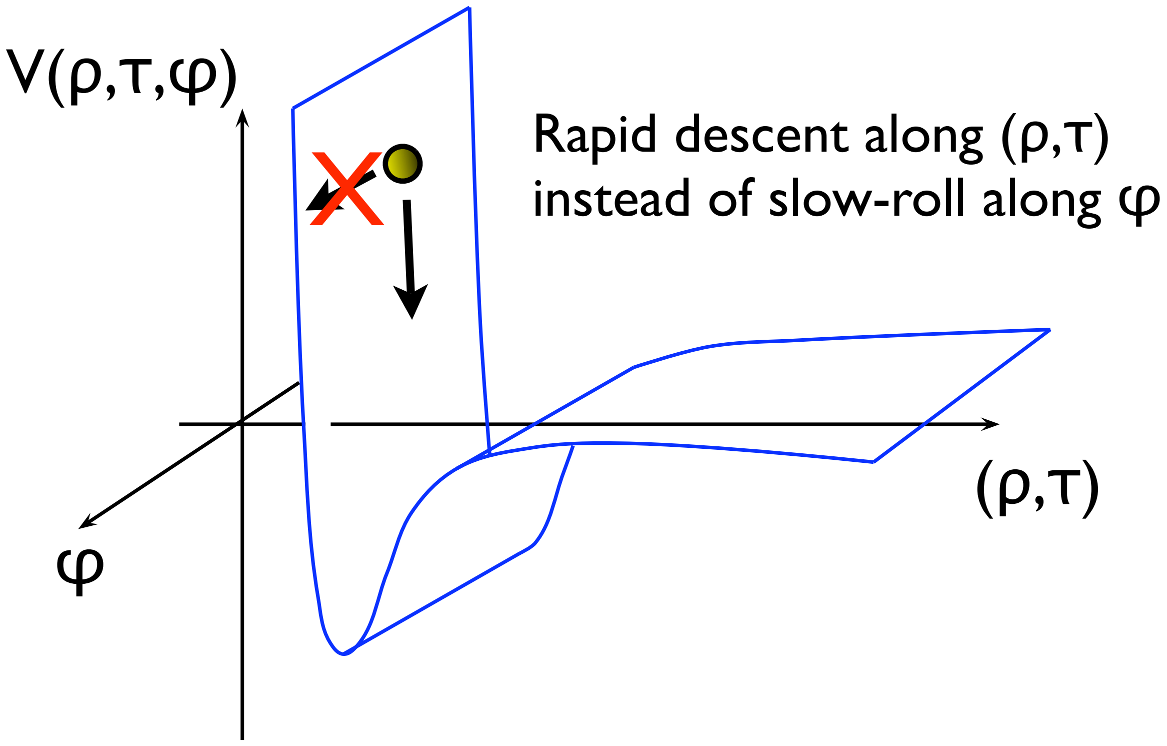
Classical IIA compactifications with

- $\mathcal{M}^{(6)} =$ Calabi-Yau ($\rightarrow$Ricci-flatness)
- O6/D6 sources
- p-form fluxes (incl. Romans' mass)

$\Rightarrow$No de Sitter vacua and no slow-roll inflation !

Hertzberg, Kachru, Taylor, Tegmark (2007)




$$\varepsilon \geq 27/13$$

A simple way to circumvent the no-go:

**Abandon Ricci-flatness of compact space**

## Several recent attempts:

(i) $\mathcal{M}^{(6)} = (\mathrm{Nil}_3 \times \mathrm{Nil}_3')/\mathcal{O}$

Haque, Shiu, Underwood, Van Riet (2008)

(ii) $\mathcal{M}^{(6)}$ = Cosets with SU(3)-structure

Caviezel, Koerber, Körs, Lüst, Wrase, M.Z. (2008)

(iii) $\mathcal{M}^{(6)}$ = More general twisted tori

Flauger, Paban, Robbins, Wrase (2008)

But:

New No-go theorems along different moduli directions or tachyons

# 7. Conclusions

- Early Universe cosmology is UV-sensitive (E.g. inflation) $\Rightarrow$ String theory
- Moduli stabilization cannot be ignored
- Best studied models in IIB (de Sitter vacua & inflation)
- Cosmic superstrings?
- Detectable tensor modes? Many recent suggestions
- Inflation elsewhere in the landscape? So far unsuccessful in IIA