Cosmological Aspects of Type II Flux Compactifications

Timm Wrase

R. Flauger, D. Robbins, S. Paban, TW 0812.3886 [hep-th]
C. Caviezel, P. Koerber, S. Körs, D. Lüst, TW, M. Zagermann 0812.3551 [hep-th]
D. Robbins, TW 0709.2186 [hep-th]
D. Robbins, M. Ihl, TW 0705.3410 [hep-th]
M. Ihl, TW hep-th/0604087

Outline

- Motivation
- Type IIA flux compactifications
- Slow-roll inflation and dS vacua in type IIA
- “T-dual” type IIB compactifications
- Conclusion and Outlook

Motivation

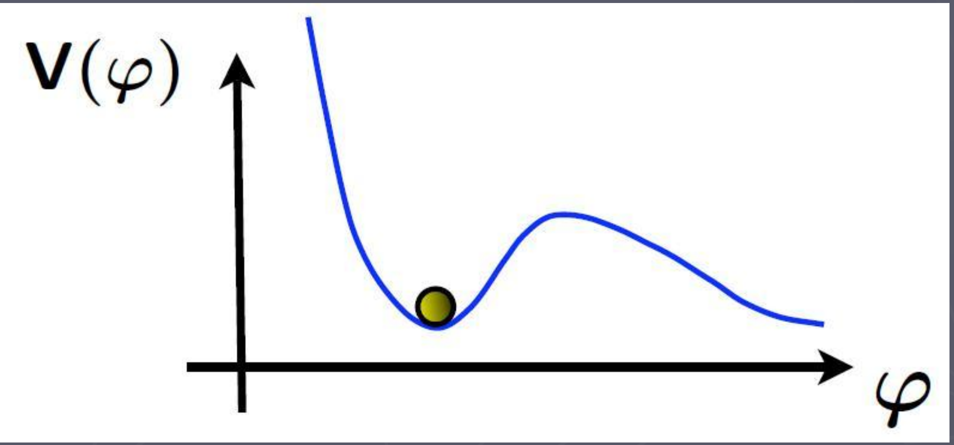
- Flux compactifications lead to a scalar potential $V(\varphi)$
- Stabilizes closed string moduli
- Interesting for cosmology: dS vacua and inflation

Motivation

dS vacuum requires

$$\varepsilon \sim (V'/V)^2 = 0$$

$$\eta \sim V''/V > 0$$

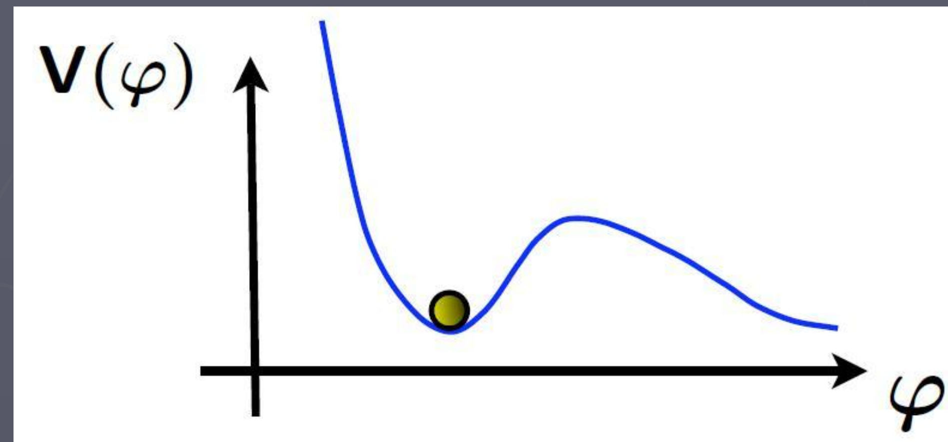


Motivation

dS vacuum requires

$$\varepsilon \sim (V'/V)^2 = 0$$

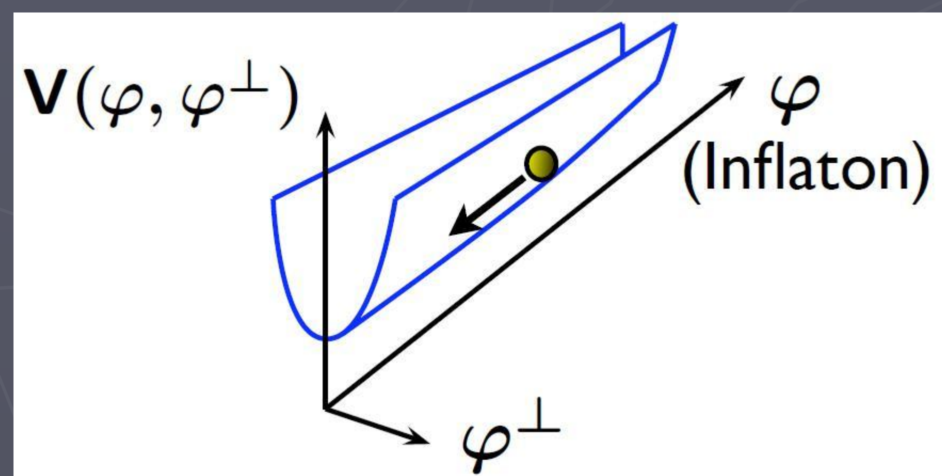
$$\eta \sim V''/V > 0$$



Inflation requires

$$\varepsilon \sim (V'/V)^2 << 1$$

$$|\eta| \sim |V''/V| << 1$$



Type II Flux Compactifications

Type II on a CY_3-manifold with orientifold projection

Type IIB intensively studied:

$$V(\varphi) = V_{classical} + V_{quantum}$$

- Can stabilize all moduli in certain cases
- Quantum corrections hard to compute precisely
- Interesting for cosmology

Kachru, Kallosh, Linde, Maldacena, McAllister, Trivedi
Burgess, Kallosh, Conlon, Quevedo
many, many others

Type II Flux Compactifications

Type II on a CY_3-manifold with orientifold projection

Type IIB intensively studied:

$$V(\varphi) = V_{classical} \boxed{+V_{quantum}}$$

- Can stabilize all moduli in certain cases
- Quantum corrections hard to compute precisely
- Interesting for cosmology

Kachru, Kallosh, Linde, Maldacena, McAllister, Trivedi
Burgess, Kallosh, Conlon, Quevedo
many, many others

Type IIA:

$$V(\varphi) = V_{classical}$$

- Can stabilize all moduli in certain cases
- Classical contributions sufficient
- Controlled regime in which corrections can be neglected
- No-go theorems against dS and inflation under mild assumptions

Type IIA flux compactifications

Compactify type IIA supergravity on a CY_3-manifold and do an orientifold projection. Turn on background fluxes:

RR fluxes: F_0, F_2, F_4, F_6 in CY_3 (only F_3 for IIB)

NSNS flux: H in CY_3

Type IIA flux compactifications

$$V_{\mathrm{F}} = e^{K}\left(K^{I\bar{J}} D_I W \overline{D_J W} - 3|W|^2\right)$$

$$K = 4D - \log\left(\tfrac{4}{3}\int J \wedge J \wedge J\right)$$

$$W = \int \Omega_c \wedge H + \int e^{J_c} \wedge F_{RR}$$

$$\Omega_c = C_3 + 2ie^{-D}\,\mathrm{Re}(\Omega)$$

$$J_c = B + iJ$$

$$F_{RR} = F_0 + F_2 + F_4 + F_6$$

$$e^{-D} = e^{-\phi}\sqrt{vol_6}$$

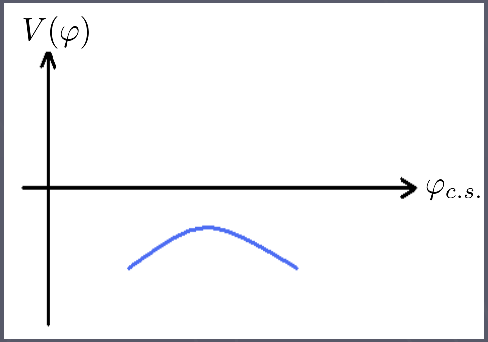
Grimm, Louis hep-th/0412277

DeWolfe, Giryavets, Kachru, Taylor hep-th/0505160

Solution to the F-term equations

J Kähler moduli	all stabilized	$\sim \sqrt{\frac{F_4}{F_0}}$
B_2 axion	all stabilized	$\sim \frac{F_2}{F_0}$
complex structure	all stabilized	by H
e^{ϕ}	stabilized	$\sim \frac{H}{(F_0 F_4^3)^{1/4}}$
C_3 axions	one linear combination	$\sim F_{RR}$
	(axions in $d + H \wedge$ cohomology unstabilized)	
Tadpole	$F_0 H = N_{O6}$ fixes $F_0 H$	

Summary of Results



- Can cancel the tadpole with fluxes
- All moduli are stabilized on a rigid CY_3
- Complex structure moduli have negative mass squared

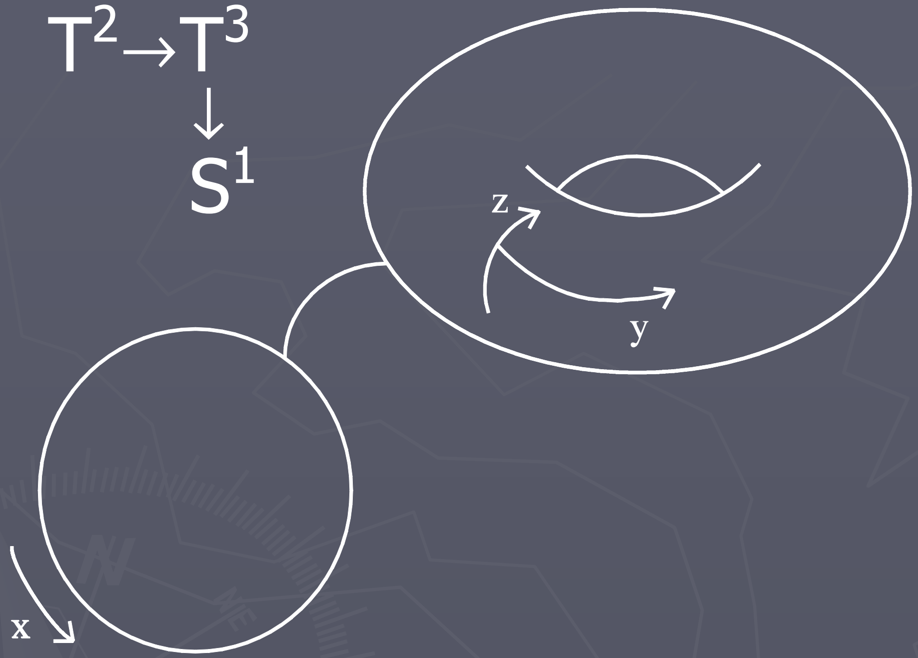
Conlon hep-th/0602233

- Large F_4 limit has large volume and small string coupling $\Rightarrow$ infinite number of trustworthy vacua
- 4-dimensional solutions lift to 10-dimensions

Acharya, Benini, Valandro hep-th/0607223

Generalized NSNS-fluxes: H-flux

$$T^2 \to T^3$$
$$\downarrow$$
$$S^1$$



$$ds^2 = dx^2 + dy^2 + dz^2$$

$$x, y, z \sim x, y, z + 1$$

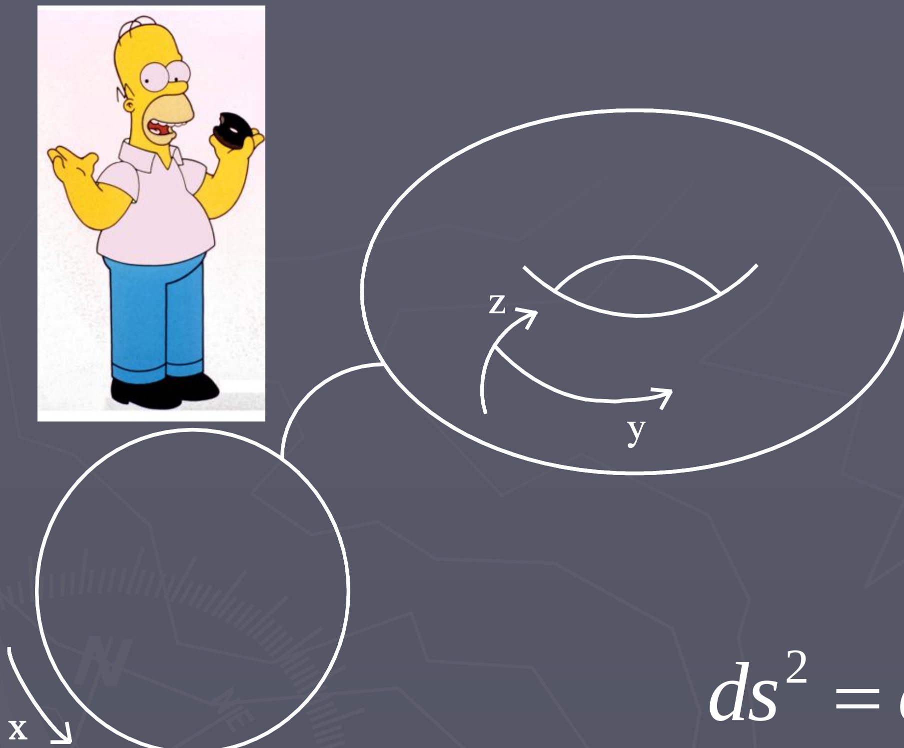
$$H = N dx \wedge dy \wedge dz$$

$$\int_{T^3} H = N$$

$$B = N x dy \wedge dz$$

If we go around the base $x \to x+1$, the B-field on the fiber gets shifted $B_{yz} \to B_{yz} + N$.

Generalized NSNS-fluxes: (geo) metric flux



T-duality along z:

$$B = 0 \;\Rightarrow\; H = 0$$

$$ds^2 = dx^2 + dy^2 + (dz + Nx\,dy)^2$$

If we go around the base $x \to x+1$, the fiber gets twisted $y \to y, z \to z - Ny$.

Generalized NSNS-fluxes: (geo) metric flux

The new space is not a torus anymore. It is often called twisted torus.

It has the global 1-forms

$$\eta^x = dx,\ \ \eta^y = dy,\ \ \eta^z = dz + Nxdy$$

The H_{ijk}-flux got turned into "metric flux" ω^i_{jk} defined by

$$d\eta^i = -\tfrac{1}{2}\omega^i_{jk}\eta^j \wedge \eta^k \qquad (\omega^z_{xy} = -N)$$

Expand fields and fluxes in η^i basis. They are generically not closed anymore:

$\Rightarrow$ compact space is SU(3)-structure manifold with curvature

SU(3)-structure manifolds

- Examples of SU(3)-structure manifolds include twisted tori and coset spaces G/H

Dabholkar, Hull hep-th/0210209
Dall'Agata, Ferrara hep-th/0502066
Hull, Reid-Edwards hep-th/0503114
D. Robbins, M. Ihl, TW 0705.3410 [hep-th]
Koerber, Lust, Tsimpis 0804.0614 [hep-th]
Caviezel, Koerber, Körs, Lüst, Zagermann 0806.3458 [hep-th]

- Natural expansion basis exists: G invariant forms

- Models expected to be consistent truncations

Cassani, Kashani-Poor 0901.4251 [hep-th]

Generalized flux compactifications

The superpotential changes to

$$W = \int \Omega_c \wedge \left(H - dJ_c \right) + \int e^{J_c} \wedge F_{RR}$$

Derendinger, Kounnas, Petropoulos, Zwirner hep-th/0411276
Villadoro, Zwirner hep-th/0503169
House, Palti hep-th/0505177
Cámara, Font, Ibáñez hep-th/0506066

It contains new terms mixing Ω_c and J_c.

F-terms from metric fluxes in IIA

The metric fluxes lead to different F-terms that depend generically on up to $\tilde{h}^{1,1}$ RR axions.

For $\tilde{h}^{1,1} \geq \tilde{h}^{2,1}$ scalar potential depends on ALL moduli.

Robbins, Ihl, TW 0705.3410 [hep-th]

Again C_3 axions in $d + H \wedge$ cohomology are unstabilized.

Generalized flux compactifications

Results:

- In many models all moduli can in principle be stabilized using metric fluxes and RR-fluxes only
- H- and metric fluxes are not sufficient to give fully stabilized Minkowski vacua

Micu, Palti, Tasinato hep-th/0701173

- Generalized fluxes give a charge to C_3 axions and lead to D-terms

D-terms from generalized fluxes

From C_3 we get U(1) gauge fields

$$C_3 = A^\alpha \wedge \mu_\alpha^{(2)} + c^I a_I^{(3)}$$

$$C_3 \to C_3 + d(\lambda^\alpha(x)\mu_\alpha^{(2)}) \;\Rightarrow\; A^\alpha \to A^\alpha + d\lambda^\alpha$$

D-terms from generalized fluxes

From C_3 we get U(1) gauge fields

$$C_3 = A^\alpha \wedge \mu_\alpha^{(2)} + c^I a_I^{(3)}$$

$$C_3 \to C_3 + d(\lambda^\alpha(x)\mu_\alpha^{(2)}) \;\Rightarrow\; A^\alpha \to A^\alpha + d\lambda^\alpha$$

with metric fluxes this becomes

$$\begin{aligned} C_3 &\to C_3 + d(\lambda^\alpha(x)\mu_\alpha^{(2)}) \\ &= A^\alpha \wedge \mu_\alpha^{(2)} + c^I a_I^{(3)} + d\lambda^\alpha \wedge \mu_\alpha^{(2)} \boxed{+\lambda^\alpha d\mu_\alpha^{(2)}} \\ &= \left(A^\alpha + d\lambda^\alpha\right)\wedge \mu_\alpha^{(2)} \boxed{+\left(c^I + \lambda^\alpha \hat{r}_\alpha^I\right)a_I^{(3)}} \end{aligned}$$

where $d\mu_\alpha^{(2)} = \hat{r}_\alpha^I a_I^{(3)}$. ("Q-fluxes" induce magnetic charges)

D-terms from generalized fluxes

The moduli potential gets the additional term

$$V_D = \tfrac{1}{2}(\mathrm{Re}\ f)^{-1\,\alpha\beta} D_\alpha D_\beta$$

$$D_\alpha = i\delta_\alpha \phi^I \partial_I K + \xi_\alpha$$

The Fayet-Iliopoulos term ξ_α vanishes. The holomorphic gauge kinetic couplings are

$$f_{\alpha\beta}^{electric} = i\int J_c \wedge \mu_\alpha^{(2)} \wedge \mu_\beta^{(2)}, \qquad f_{\alpha\beta}^{magnetic} = (f^{electric})^{-1}{}_{\alpha\beta}$$

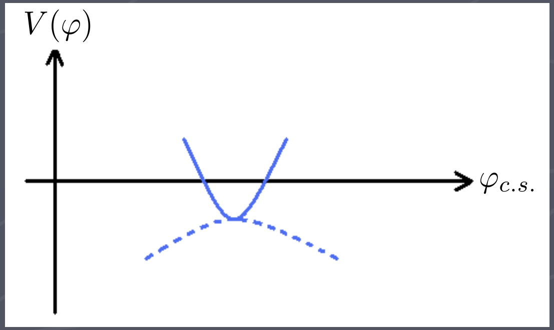
D-terms from generalized fluxes

$\partial_I K$ depends on the complex structure moduli so that the D-terms lift their masses:

$$V_D = \tfrac{1}{2} (\mathrm{Re}\, f)^{-1\,\alpha\beta} D_\alpha D_\beta = \tfrac{1}{2} (\mathrm{Re}\, f)^{-1\,\alpha\beta} (i\hat{r}_\alpha^I \partial_I K)(i\hat{r}_\beta^J \partial_J K)$$

where $d\mu_\alpha^{(2)} = \hat{r}_\alpha^I a_I^{(3)}$.

So the masses for the complex structure moduli can in principle be made positive



$$m_{\mathrm{c.s.}}^2 = -\tfrac{8}{9} |m_{BF}|^2 + |const.| \hat{r}^2$$

D-terms from generalized fluxes

Note however, that the D-terms cannot be used to "up-lift" a supersymmetric AdS vacuum. In N=1 supergravity we have

$$D_\alpha = i\delta_\alpha \phi^I \partial_I K + \xi_\alpha = i\delta_\alpha \phi^I \partial_I K + i\frac{\delta_\alpha W}{W}$$

$$= \frac{i\delta_\alpha \phi^I}{W}(W\partial_I K + \partial_I W) = i\frac{\delta_\alpha \phi^I D_I W}{W}$$

F-flatness $\Rightarrow$ D-flatness

Type IIA Flux Compactifications

IIA on CY_3 with fluxes:

- Can stabilize all moduli (except some RR axions) in an AdS vacuum
- Controlled regime
- No quantum corrections needed

Grimm, Louis hep-th/0412277
DeWolfe, Giryavets, Kachru, Taylor hep-th/0505160

Type IIA Flux Compactifications

IIA on CY_3 with fluxes:

- Can stabilize all moduli (except some RR axions) in an AdS vacuum
- Controlled regime
- No quantum corrections needed

Grimm, Louis hep-th/0412277
DeWolfe, Giryavets, Kachru, Taylor hep-th/0505160

IIA on (non Ricci flat) SU(3)-structure with fluxes:

- Can stabilize all moduli (except some RR axions) in an AdS vacuum
- Curvature leads to new F-term and D-term contributions
- No quantum corrections needed

Derendinger, Kounnas, Petropoulos, Zwirner hep-th/0411276
Villadoro, Zwirner hep-th/0503169
House, Palti hep-th/0505177
Cámara, Font, Ibáñez hep-th/0506066
D. Robbins, M. Ihl, TW 0705.3410 [hep-th]

Cosmological aspects in type IIA

CY$_3$ with fluxes: only AdS vacua, no slow-roll inflation:

Identify scaling with respect to

$$\rho = (vol_6)^{1/3}, \quad \tau = e^{-\phi}\sqrt{vol_6}$$

$$V_H \propto \rho^{-3}\tau^{-2}, \; V_{F_p} \propto \rho^{3-p}\tau^{-4}, \; V_{O6} \propto \tau^{-3}$$

$$-\rho\partial_\rho V - 3\tau\partial_\tau V = 9V + \sum_p p \underbrace{V_{F_p}}_{\sim |F_p|^2 \geq 0} \geq 9V \;\Rightarrow\; \varepsilon \sim \left(\frac{V'}{V}\right)^2 \geq \frac{27}{13}$$

DeWolfe, Giryavets, Kachru, Taylor hep-th/0505160

Hertzberg, Kachru, Taylor, Tegmark 0711.2512 [hep-th]

$\Rightarrow$ Need more ingredients to get a richer potential!

Cosmological aspects in type IIA

SU(3)-structure manifolds: lead to new terms in the scalar potential that evades the no-go theorem

$$\rho = (vol_6)^{1/3}, \quad \tau = e^{-\phi}\sqrt{vol_6}$$

$$V_H \propto \rho^{-3}\tau^{-2},\ V_{F_p} \propto \rho^{3-p}\tau^{-4},\ V_{O6} \propto \tau^{-3},\ \boxed{V_R \propto \rho^{-1}\tau^{-2}}$$

$$-\rho\,\partial_\rho V - 3\tau\,\partial_\tau V = 9V + \sum_p p\,V_{F_p} - 2V_R \quad \Rightarrow \quad \varepsilon \geq ?$$

$V_R \propto -R_6$ Need manifolds with negative curvature.

Silverstein 0712.1196 [hep-th]
Caviezel, Koerber, Körs, Lüst, Tsimpis, Zagermann 0806.3458 [hep-th]
Haque, Shiu, Underwood, Van Riet 0810.5328 [hep-th]
Danielsson, Haque, Shiu, Van Riet 0907.2041 [hep-th]

Cosmological aspects in type IIA

New no-go theorems using other directions in moduli space:

Applicable to models with:

Factorization of Kähler sector

$$vol_6 = \kappa_{abc} k^a k^b k^c = k^0 \tilde{\kappa}_{de} k^d k^e, \quad d,e \neq 0$$

and/or factorization of complex structure sector $Z^I = \int_{\Gamma^I} \Omega, \; I = 1,\ldots,\tilde{h}^{2,1}+1$

$$1 = p(Z) = p_1(Z_{(1)}) \cdot p_2(Z_{(2)}), \quad \{Z_{(1)}\} \cap \{Z_{(2)}\} = 0$$

and restrictions on curvature (“metric fluxes”).

Flauger, Robbins, Paban, TW 0812.3886 [hep-th]
Caviezel, Koerber, Körs, Lüst, TW, Zagermann 0812.3551 [hep-th]

Cosmological aspects in type IIA

New no-go theorems using other directions in moduli space:

Applicable to models with:

Factorization of Kähler sector

$$vol_6 = \kappa_{abc} k^a k^b k^c = k^0 \tilde{\kappa}_{de} k^d k^e, \quad d, e \neq 0$$

and restrictions on curvature ("metric fluxes"), e.g.

$$J = k^0 w_0 + k^a w_a$$

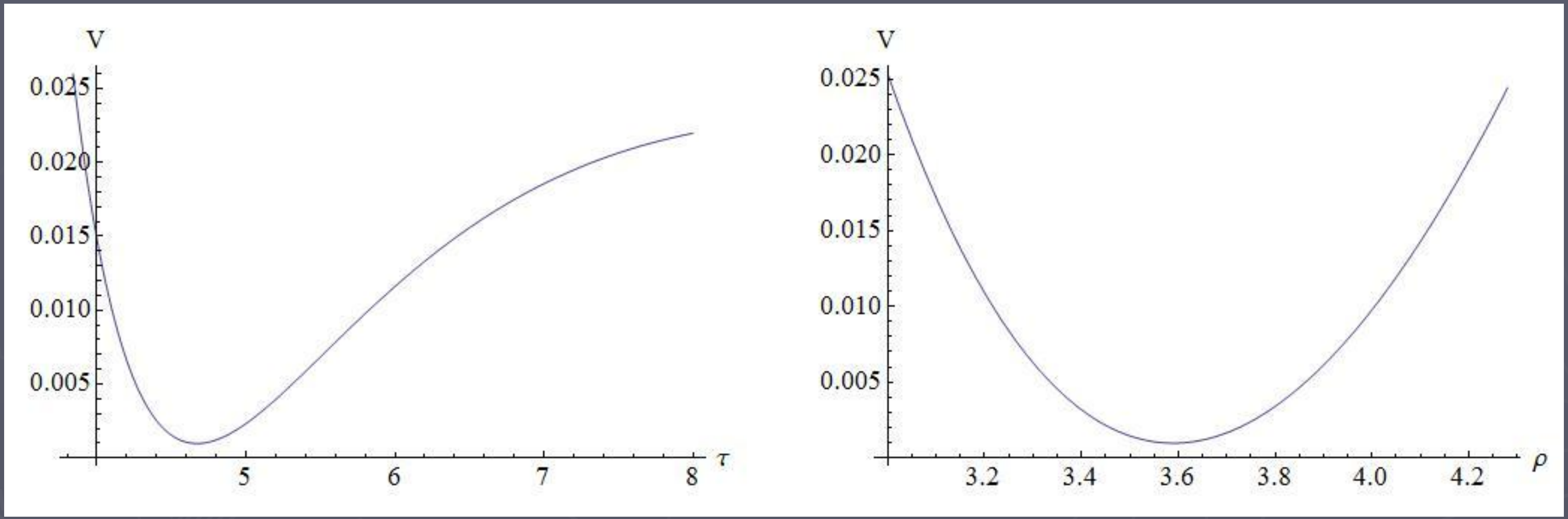
$$\left.\begin{aligned} dw_0 &= 0 \\ dw_a &\neq 0 \end{aligned}\right\} \Rightarrow \varepsilon \geq \frac{9}{5}, \qquad \left.\begin{aligned} dw_0 &\neq 0 \\ dw_a &= 0 \end{aligned}\right\} \Rightarrow \varepsilon \geq 2.$$

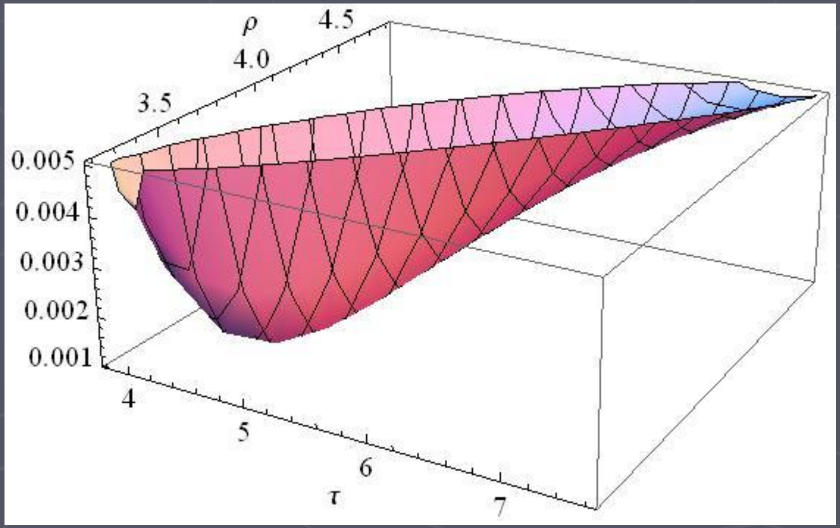
Cosmological aspects in type IIA

New no-go theorems using other directions in moduli space:

- Exclude almost all models (cosets, twisted tori) that were studied
- $\check{T}^6/Z_2 x Z_2$ and SU(2)xSU(2) evade all known no-go theorems. Numerically we indeed find $\varepsilon \approx 0$!

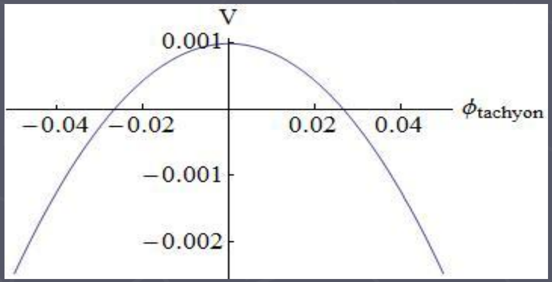
Type IIA on SU(2)xSU(2)





Cosmological aspects in type IIA

- $\check{T}^6/Z_2 x Z_2$ and SU(2)xSU(2) evade all known no-go theorems. Numerically we indeed find $\varepsilon \approx 0$!
- But one tachyonic direction: $\eta \leq -1.5$



Flauger, Robbins, Paban, TW 0812.3886 [hep-th]
Caviezel, Koerber, Körs, Lüst, TW, Zagermann 0812.3551 [hep-th]

- Out of 14 directions, along one we have a maximum
- No-go theorems for η parameter don't apply

Covi, Gomez-Reino, Gross, Louis, Palma, Scrucca 0804.1073 [hep-th]
Covi, Gomez-Reino, Gross, Louis, Palma, Scrucca 0805.3290 [hep-th]

Cosmological aspects in type IIA/IIB

- Type IIB O3/O7 or O5/O9 on SU(3)-structure, without corrections insufficient moduli stabilization?

Graña hep-th/0509003
Benmachiche, Grimm hep-th/0602241
Robbins, TW 0709.2186 [hep-th]

- SU(2)-structure compactifications with two orientifold projections $\Rightarrow N = 1$ in 4d
- SU(2)-structure manifolds have 1- and 5-forms

$\Rightarrow$ RR fluxes F_1, F_3, F_5 for IIB

Caviezel, TW, Zagermann to appear

Cosmological aspects in type IIA/IIB

Type IIA on $T^6/Z_2 x Z_2$ with

O6-planes

SU(3)-structure

O-plane	1	2	3	4	5	6
O6	X		X	X		
O6	X				X	X
O6		X	X		X	
O6		X		X		X

Type IIB on $T^2 x T^4/Z_2$ with

O5-planes and O7-planes

SU(2)-structure

O-plane	1	2	3	4	5	6
O5			X	X		
O5					X	X
O7	X	X	X		X	
O7	X	X		X		X

Cosmological aspects in type IIA/IIB

T-dual to SU(3)-structure but might lead to new examples:

- SU(3)- and SU(2)-structure spaces have metric-flux
- T-duality might lead to non-geometric spaces

  $\Rightarrow$ supergravity applicable in T-dual description?

Wecht 0708.3984 [hep-th]

- SU(2)-structure compactifications not T-dual to geometric SU(3)-spaces are new

Cosmological aspects in type IIA/IIB

- Can in principle stabilize (almost) all moduli in type IIA and type IIB
- Only very few cosets and twisted $T^2 x T^4 / Z_2$
- Concrete examples only interesting in type IIB
- Can derive new no-go theorems to exclude dS vacua and slow-roll in several concrete examples
- Again no general no-go theorem exists

Conclusion – type IIA on SU(3)

- Type IIA flux compactifications give scalar potentials that depend on (almost) all moduli
- No-go theorem against slow-roll inflation and dS vacua exist for CY_3 with fluxes
- Can evade previous no-go theorem in compactifications on SU(3)-structure manifolds
- Many new no-go theorems exclude most examples
- Few numerical extrema but only with η-problem

Conclusion – type IIB on SU(2)

- Type IIB flux compactifications give scalar potentials that depend on (almost) all moduli
- Only very few concrete examples
- Can derive new no-go theorems against slow-roll inflation and dS vacua for specific cases

Outlook / Future research

- Try to study more models and understand whether the η-problem is specific to our model or generic
- Include more ingredients like:
  (non-) susy D6-branes, α' and string loop corrections

  Villadoro, Zwirner hep-th/0602120
  Palti, Tasinato, Ward 0804.1248 [hep-th]

  co-isotropic D8-branes — Font, Ibáñez, Marchesano hep-th/0602089

  NSNS source — Villadoro, Zwirner 0706.3049, 0710.2551 [hep-th]
  Silverstein 0712.1196 [hep-th]
- Study non-geometric compactifications spaces

  Aldazabal, Cámara, Font, Ibáñez hep-th/0602089
  de Carlos, Guarino, Moreno 0907.5580 [hep-th]
- Study models that preserve more SUSY

  Cassani, Kashani-Poor 0901.4251 [hep-th]
  Diederik Roest 0902.0479 [hep-th]
  Dall'Agata, Villadoro, Zwirner 0906.0370 [hep-th]

Outlook / Future research

- Try to study more models and understand whether the η-problem is specific to our model or generic
- Include more ingredients like:
  (non-) susy D6-branes, α' and string loop corrections

  Villadoro, Zwirner hep-th/0602120
  Palti, Tasinato, Ward 0804.1248 [hep-th]

  co-isotropic D8-branes — Font, Ibáñez, Marchesano hep-th/0602089

  NSNS source — Villadoro, Zwirner 0706.3049, 0710.2551 [hep-th]
  Silverstein 0712.1196 [hep-th]
- Study non-geometric compactifications spaces

  Aldazabal, Cámara, Font, Ibáñez hep-th/0602089
  de Carlos, Guarino, Moreno 0907.5580 [hep-th]
- Study models that preserve more SUSY

  Cassani, Kashani-Poor 0901.4251 [hep-th]
  Diederik Roest 0902.0479 [hep-th]
  Dall'Agata, Villadoro, Zwirner 0906.0370 [hep-th]

THANK YOU!