A sufficient Condition for de Sitter Vacua in type IIB String Theory

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arXiv:1107.2115 [hep-th] with Alexander Westphal

CP3-Origins/DESY/Göttingen Autumn School on Particle Physics and Cosmology, 12.10.2011

Outline:

1. Introduction: de Sitter vacua in Type IIB

2. A sufficient condition for de Sitter vacua for the Kähler moduli T_i

3. Including all moduli S and U_i

4. Conclusions & Outlook

Introduction: de Sitter vacua in String Theory

Cosmology:

- Acceleration of the universe on large scales is observed
- Simplest explanation: Small cosmological constant

String Theory:

- Consistent quantum gravity and unification candidate
- Can contain constructions leading to the MSSM

$\Rightarrow$ **Can one construct (metastable) de Sitter vacua with small cosmological constant?**

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Framework: Compactify Type IIB (10 D) on orientifolded Calabi-Yau (6 D) to $\mathcal{N} = 1$ Supergravity (4 D)

To obtain metastable de Sitter use

- Background fluxes [Giddings, Kachru, Polchinski '01]
- Non-perturbative effects [Kachru, Kallosh, Linde, Trivedi '03]

Introduction: IIB Compactifications

Spectrum:

- $D = 10$: 3-form field strength F_3, H_3, Spinors, ...
- $D = 4$: $h^{1,1}$ Kähler moduli T_i, $h^{2,1}$ complex structure moduli U_i and dilaton S (#moduli is determined by Calabi-Yau manifold)

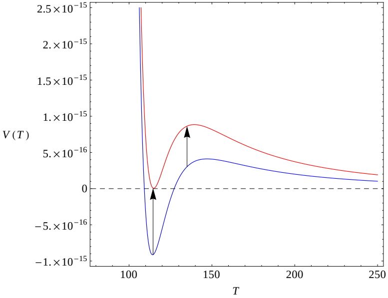
$D = 4$, $\mathcal{N} = 1$ effective supergravity Lagrangian:

$$\mathcal{L} = K_{a\bar{b}} D_\mu \phi^a D^\mu \phi^{\bar{b}} - V + \ldots, \qquad \boxed{V = e^K \left(K^{a\bar{b}} D_a W \overline{D_b W} - 3|W|^2 \right)}$$

- $W = W_0(S, U_i) + W_{n.p.}(T_i)$
$$= \int F_3 \wedge \Omega(U_i) - i\, S \int H_3 \wedge \Omega(U_i) + \sum_i A_i\, e^{-a_i T_i}$$
- $K = -2 \ln \hat{\mathcal{V}}(T_i) - \ln(S + \bar{S}) - \ln \left(-i \int \bar{\Omega}(U_i) \wedge \Omega(U_i) \right)$

Introduction: Uplifting to de Sitter

- KKLT Scenarios with $\overline{D3}$-Brane uplifting $\rightarrow$ Explicit SUSY breaking
  [Kachru, Kallosh, Linde, Trivedi '03]
- LARGE Volume Scenarios with D-Term uplifting $\rightarrow$ de Sitter strongly model-dependent
  [Balasubramanian, Berglund, Conlon, Quevedo'05],[Cicoli, Conlon, Quevedo'08]
- **Large Volume Scenarios with F-Term uplifting by α' corrections**
  [Balasubramanian, Berglund '05], [Becker, Becker, Haack, Louis '02], [Westphal '07]



$$K = -2\ln\left(\hat{\mathcal{V}}(T_i) + \alpha'^3\hat{\xi}(S)\right),$$

$$\hat{\xi}(S) \propto \underbrace{(-\chi)}_{\substack{\text{Euler Number}\\ =2(h^{1,1}-h^{2,1})}} \cdot (S+\bar{S})^{3/2}$$

A sufficient condition for dS for the Kähler moduli T_i

Expand potential for one Kähler modulus $T = t + i\tau$

- $\hat{\mathcal{V}} \gg \hat{\xi}$ $\Rightarrow$ Large Volume $\hat{\mathcal{V}} \simeq \gamma t^{3/2} \sim \mathcal{O}(100 \ldots 1000)$
- $|W_0| \gg Ae^{-at}$ $\Rightarrow$ Non-perturbative effects are small

$$V \simeq 4AW_0 \frac{at\, e^{-at}}{\hat{\mathcal{V}}^2} \cos(a\tau) + \frac{3\hat{\xi} W_0^2}{4\hat{\mathcal{V}}^3} \sim \frac{2C}{9x^{9/2}} - \frac{e^{-x}}{x^2}, \quad C = \frac{-27 W_0 \hat{\xi} a^{3/2}}{64\sqrt{2}A}$$

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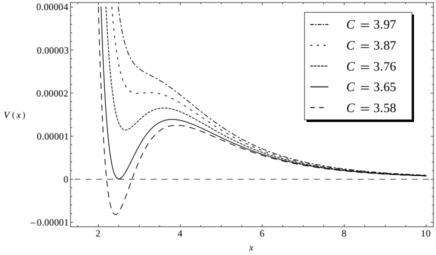
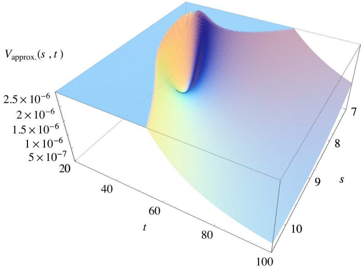


Sufficient for dS: $3.65 < C < 3.89$

- Breaks SUSY spontaneously
- $t \gg 1$ can be achieved for $a = 2\pi/N \ll 1$
- Need large gauge group $SU(N)$, typically $N \sim 30 - 100$
- Can be extended to arbitrary $h^{1,1}$ of 'swiss cheese' type

Including all moduli S and U_i: General Analysis

$$V = \underbrace{V^{(T)} + V^{(T,S)}}_{\text{1st order in } \hat{\xi}/\hat{\mathcal{V}}} + \underbrace{V^{(S)} + V^{(U)}}_{\text{0th order in } \hat{\xi}/\hat{\mathcal{V}}}$$



- $V^{(S)} + V^{(U)}$ stabilize the S and U_i supersymmetrically by fluxes at $D_i W(S_0, U_{i0}) = 0$ [GKP '01]
- $V^{(T)} + V^{(T,S)}$ induce small shifts from the SUSY minimum: $\delta S/S_0 \sim \hat{\xi}/\hat{\mathcal{V}}$, $\delta U_i/U_{i0} \sim \hat{\xi}/\hat{\mathcal{V}}$
- SUSY breaking hierarchy: $F_{S,U_i} \sim \hat{\xi}/\hat{\mathcal{V}} F_T$
- Mass hierarchy: $m_T \sim \hat{\xi}/\hat{\mathcal{V}} m_{S,U_i}$, $m_{3/2} < m_i$ and $m_{3/2} \ll m_{KK}$

Result: If $\mathbf{V_{ij}^{(U)}} > 0$ to 0-th order $\Rightarrow$ metastable dS vacuum

Including all moduli S and U_i: $h^{2,1}$ dependence

We want enough fluxes available to tune cosmological constant small

$$\Rightarrow h^{2,1} \sim \mathcal{O}(100)$$ [Bousso, Polchinski '00]

2 potential caveats:

- $\delta S/S_0$ and $\delta U_i/U_{i0}$ dependence on $h^{2,1}$? $\Rightarrow \sim (h^{2,1})^n, \;\; n \in [-1, 0]$
- 2nd order in $\hat{\xi}/\hat{\mathcal{V}}$ backreaction on $\langle T_i \rangle$ and $m^2_{T_i}$ for large $h^{2,1}$?

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Concrete toy example based on T^6:

$$K_{c.s.} = -\sum_{i=1}^{h^{2,1}} \ln\left(U_i + \bar{U}_i\right) \ ,$$

$$W_0 = c_1 + \sum_{i=1}^{h^{2,1}} d_{1i} U_i - (c_2 + \sum_{i=1}^{h^{2,1}} d_{2i} U_i) S$$

$\Rightarrow$ Can be solved analytically to 0th order for arbitrary $h^{2,1}$

$\Rightarrow$ No dangerous backreaction for this example

Conclusions & Outlook

Conclusions:

- Sufficient condition for de Sitter with all moduli stabilized for all Calabi-Yau threefolds of 'swiss cheese' type
- Systematical understanding of de Sitter condition based on properties of the Calabi-Yau $\hat{\xi}$ and fluxes W_0 (F-Theory data)
- Well controlled SUSY breaking by F-Terms only, don't need extra sector
- Small cosmological constant by tuning background fluxes [Bousso, Polchinski '00]

Outlook:

- Verify sufficient de Sitter condition for concrete F-Theory fourfold $\mathbb{P}^4_{[1,1,1,6,9]}$ (work in progress..)