



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

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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

⇒ **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:

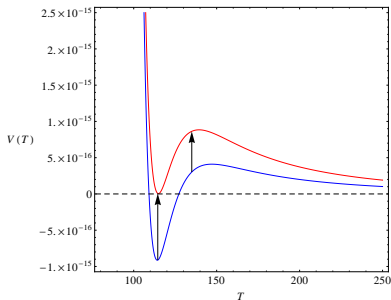
$$\mathcal{L} = K_{a\bar{b}} D_\mu \phi^a D^\mu \phi^{\bar{b}} - V + \dots, \quad \boxed{V = e^K \left(K^{a\bar{b}} D_a W \overline{D_b W} - 3|W|^2 \right)}$$

$$\begin{aligned} \text{▶ } W &= W_0(S, U_i) + W_{n.p.}(T_i) \\ &= \int F_3 \wedge \Omega(U_i) - iS \int H_3 \wedge \Omega(U_i) + \sum_i A_i e^{-a_i T_i} \end{aligned}$$

$$\text{▶ } K = -2 \ln \hat{\mathcal{V}}(T_i) - \ln(S + \bar{S}) - \ln \left(-i \int \bar{\Omega}(U_i) \wedge \Omega(U_i) \right)$$

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]



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

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

$$= 2(h^{1,1} - h^{2,1})$$

A sufficient condition for dS for the Kähler moduli T_i

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

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

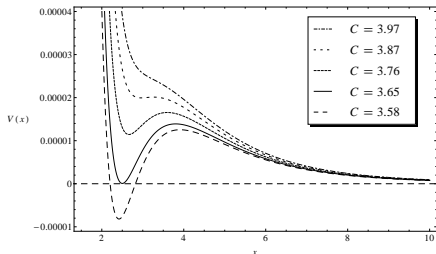
$$V \simeq 4AW_0 \frac{at e^{-at}}{\hat{V}^2} \cos(a\tau) + \frac{3\hat{\xi}W_0^2}{4\hat{V}^3} \sim \frac{2C}{9x^{9/2}} - \frac{e^{-x}}{x^2}, \quad C = \frac{-27W_0\hat{\xi}a^{3/2}}{64\sqrt{2}A}$$

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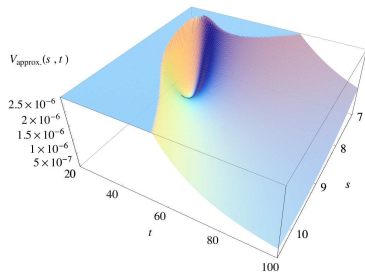


- ▶ Breaks SUSY spontaneously
- ▶ $t \gg 1$ can be achieved for $a = 2\pi/N \ll 1$
- ▶ Need large gauge group $SU(N)$, typically $N \sim 30 - 100$
- ▶ Can be extended to arbitrary $h^{1,1}$ of 'swiss cheese' type

Sufficient for dS: $3.65 < C < 3.89$

Including all moduli S and U_i : General Analysis

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



- ▶ $V(S) + V(U)$ 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: $\delta S/S_0 \sim \hat{\xi}/\hat{V}$, $\delta U_i/U_{i0} \sim \hat{\xi}/\hat{V}$
- ▶ SUSY breaking hierarchy: $F_{S,U_i} \sim \hat{\xi}/\hat{V} F_T$
- ▶ Mass hierarchy: $m_T \sim \hat{\xi}/\hat{V} m_{S,U_i}$, $m_{3/2} < m_i$ and $m_{3/2} \ll m_{KK}$

Result: If $V_{ij}^{(U)} > 0$ 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

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

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 $m_{T_i}^2$ for large $h^{2,1}$?

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Concrete toy example based on T^6 :

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

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

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

\Rightarrow 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..)