De Sitter vacua in type IIB string theory/ F-theory by Kähler uplifting

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Motivation: Construct an explicit de Sitter vacuum in type IIB / F-theory

Cosmology:

- Acceleration of the universe on large scales is observed.
- Simplest explanation: dS space with small cosmological constant.

The setup we use:

- Non-perturbative effects $W = A_i\, e^{-a\, T_i}$, $a_i = 2\pi/N_i$
  [Kachru, Kallosh, Linde, Trivedi '03]
- Leading α'-corr. to the Kähler pot. $K = -2\ln(\hat{\mathcal{V}}(T_i) + \alpha'^3\hat{\xi}(S))$
  [Becker, Becker, Haack, Louis '02]
- Quantized RR and NS-NS fluxes $\int F_3, H_3 \in \mathbb{Z}$
  [Giddings, Kachru, Polchinski '01]

Uplifting to de Sitter

$W_0 \ll 1$, α'-correction negligible [KKLT '03]

$W_0 \neq 0$, α'-correction

[Balasubramanian,Berglund '05]

$\hat{\mathcal{V}} >>> \hat{\xi}$, W_0 arbitrary

$\hat{\mathcal{V}} >> \hat{\xi}$, $W_0 \sim \mathcal{O}(1-100)$

KKLT

LVS [Balasubramanian, Berglund,Conlon,Quevedo '05]

Kähler uplifting [Westphal '06]

- $\bar{D}3$ branes
- F-terms from matter fields [Lebedev,Nilles,Ratz'06]
- F-terms from metastable vacua in gauge theories [Intriligator,Seiberg,Shih'07]

- $\bar{D}3$ branes
- D-terms [Burgess,Kallosh,Quevedo'03, Haack,Krefl,Lüst,Van Proyen,Zagermann'06]
- F-terms from dilaton dep. non-pert. effects [Cicoli,Maharana,Quevedo,Burgess'12]

- F-terms from Kähler moduli + α'-correction sufficient for dS

Bottom up SUGRA analysis: Kähler uplifting

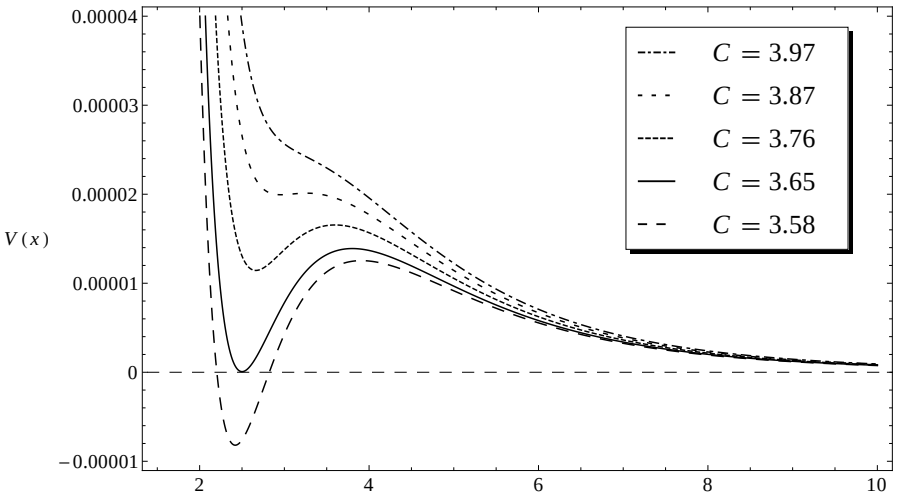
If a 3-fold is 'swiss-cheese', i.e. $\hat{\mathcal{V}}(T_i) = \gamma_1 \mathrm{Re}(T_1)^{3/2} - \sum_{i=2}^{h^{1,1}} \gamma_i \mathrm{Re}(T_i)^{3/2}$

one can perform a complete perturbative moduli stabilization in the limit

- $\hat{\mathcal{V}} \gg \hat{\xi}$ $\Rightarrow$ Large but not LARGE Volume $\hat{\mathcal{V}}$.
- $|W_0| \gg A e^{-at}$ $\Rightarrow$ Non-perturbative effects are small.
- $D_i W(S, U_j) \simeq 0$ $\Rightarrow$ Supersymmetric stabilization to 0-th order.

Sufficient for a de Sitter vacuum: [MR, Westphal '11]

- $3.65 < \dfrac{27|W_0|\hat{\xi} a^{3/2}}{64\sqrt{2}\gamma A} < 3.89.$
- $V^{(c.s.)}_{U_i U_j} > 0$ to 0-th order.
- $\hat{\mathcal{V}} \simeq \gamma N_1^{3/2} \Rightarrow$ Need $N_1 \gtrsim 30$.



Maximal gauge group rank in the landscape (I)

'Mini' landscape: 97,036 models of the F-theory type: [Kreuzer,Skarke '00]

- Ambient toric variety described by (resolution of) weight system

$$\mathbb{CP}_{n_1 n_2 n_3 n_4 n_\xi}: \quad 0 < n_1 \leq n_2 \leq n_3 \leq n_4 < n_\xi = \sum_i^4 n_i$$

- CY hypersurface $\xi^2 = P_{(2n_\xi,\dots)} = 0$.

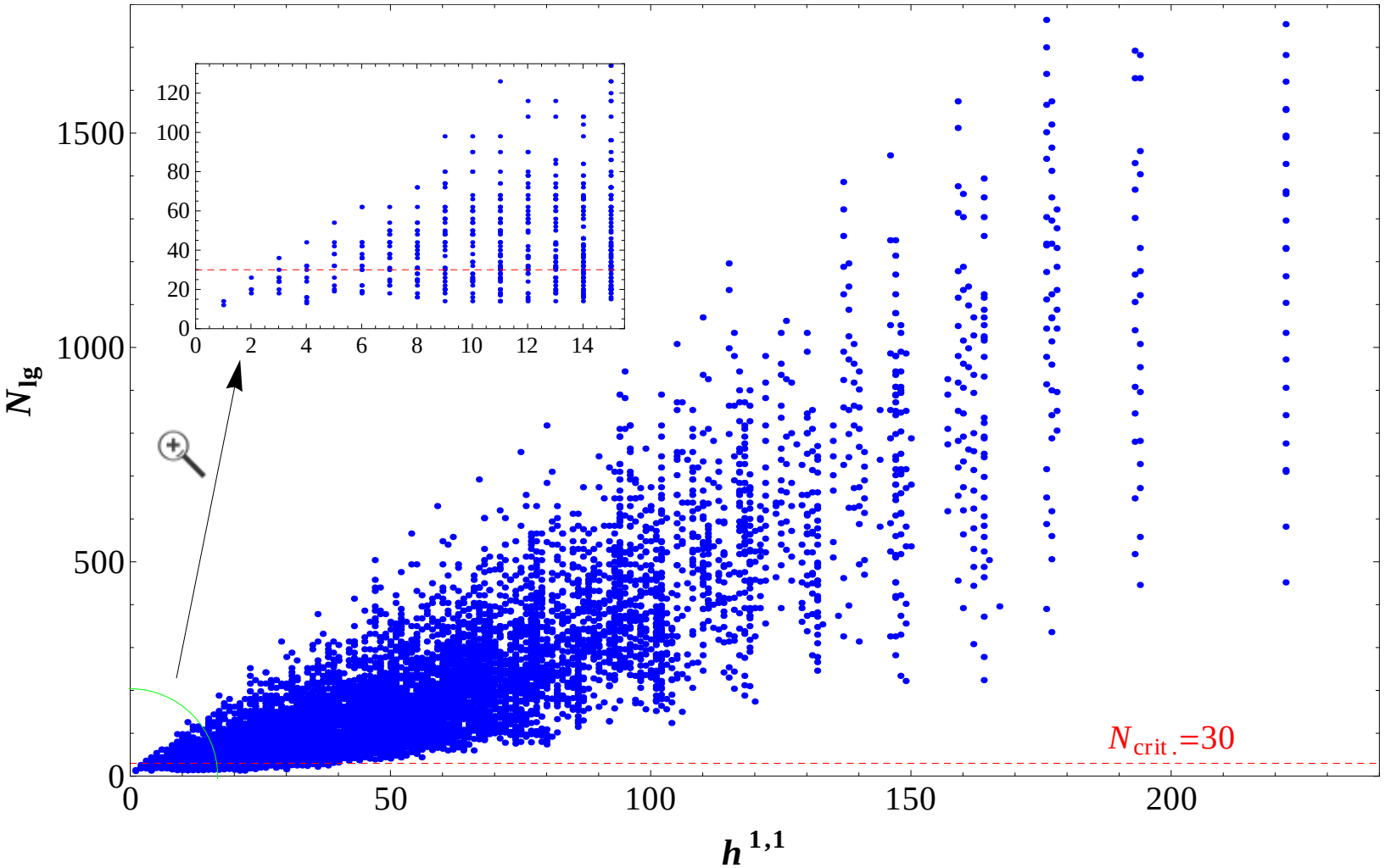
D7 branes:

- $[D7] = -8[O7] = -8(n_\xi, \dots)$
- More specifically for $\eta \in \bar{K}^4$, $\chi \in \bar{K}^6$: [Collinucci,Denef,Esole'09, Braun,Hebecker,Triendl'08, Sen'96]

$$[D7]: \quad 0 = \eta^2 - \xi^2\chi = u_1^{2N_1}\left(\tilde{\eta}^2_{(4n_\xi - n_1 N_1,\dots)} - \xi^2\tilde{\chi}_{(6n_\xi - 2n_1 N_1,\dots)}\right)$$

- $\Rightarrow$ Maximal gauge group $Sp(N_1)$ with rank $N_1 < N_{lg} \equiv 3\frac{n_\xi}{n_1}$.

Maximal gauge group rank in the landscape (II)



$\Rightarrow$ **$N_{lg} > 30$ quiet natural for larger $h^{1,1}$!**

Constraints on a consistent model

- Contribution of gaugino condensation to the superpotential, $A \neq 0$:
  - Rigid divisor? [Witten'96]
  - Can it be 'rigidified' by gauge flux $\mathcal{F}$? [Martucci'06, Bianchi,Collinucci,Martucci'11]
- Swiss-cheese?
- Flux: Freed-Witten anomalies?[Minasian,Moore'96, Freed,Witten'97]
- $N_1 \gg 1$ enforces factorization of D7 brane equation in coordinates $u_i \neq u_1$ [Cicoli,Mayrhofer,Valandro'11]?
- Stabilization inside the Kähler cone?
- Chiral matter at brane intersections that might destroy $A \neq 0$ [Blumenhagen,Moster,Plauschinn'08]?
- D3 tadpole: $Q^{D7-\text{stacks}} + Q^{O7} = Q^{\mathcal{F}} + Q^{RR,NS-NS} + Q^{D3-\text{branes}}$?
- Complex structure moduli stabilized such that sufficient condition for de Sitter is fulfilled: $W_0 \cdot \text{Re}(S)^{3/2}$ in right interval?

Explicit dS example: $\mathbb{CP}_{11169}$

Explicit AdS vacuum (KKLT) has been constructed [Denef,Douglas,Florea '04]

Some geometric properties:

- Calabi-Yau: $0 = \xi^2 = P_{18,4}(u_i)$ in

u_1	u_2	u_3	u_4	u_5	ξ
1	1	1	6	0	9
0	0	0	1	1	2

- $h^{1,1} = 2,\ h^{2,1} = 272$
- Divisors:

	$h^{0,0}$	$h^{1,0}$	$h^{2,0}$	$h^{1,1}$	χ_0
D_1	1	0	2	30	3
D_5	1	0	0	1	1

- $\hat{\mathcal{V}} = \sqrt{\frac{2}{3}}\left(\hat{\mathcal{V}}_1 + \frac{1}{3}\hat{\mathcal{V}}_5\right)^{3/2} - \frac{\sqrt{2}}{9}\hat{\mathcal{V}}_5^{3/2} \Rightarrow$ 'Approx. swiss-chesse'
- Complex structure moduli: $\mathbb{Z}_6 \times \mathbb{Z}_{18}$ modding: $h^{2,1}_{\text{inv.}} = 2$. with known prepotential. [Greene,Plesser'89], [Candelas,Font,Katz,Morrison'94]

A consistent dS model on $\mathbb{CP}_{11169}$: Kähler moduli

- Brane config. ($N_{lg} = 27$): $Sp(24)$ on D_1 forces $SO(24)$ on D_5.
- D_5 rigid, D_1 can be 'rigidified' by gauge flux $\Rightarrow Sp(24) \to SU(24)$.
- Brane intersections: Switch on gauge flux $F_{1/5} + c_1(D_{1/5})/2$ to cancel Freed-Witten anomalies and tune F_1, F_5 and B such that $\mathcal{F}_{1/5} = F_{1/5} - B$ is 'trivial' $\Rightarrow$ No chiral matter or D-terms.
- D3 tadpole: $Q^{RR,NS-NS} + Q^{D3-\text{branes}} = 114$.

$$\Rightarrow W = W_0 + A\, e^{-2\pi/24\, T_1} + B\, e^{-2\pi/22\, T_2},\ A, B \neq 0.$$

Kähler uplifting:

- If in the complex structure sector:
$$\langle W_0 \rangle = 0.812\,,\ \langle S \rangle = 6.99\,,\ \langle A \rangle = 1.11\,,\ \langle B \rangle = 1.00\,.$$
- **stable dS vacuum** with $\langle T_1 \rangle = 10.76$, $\langle T_2 \rangle = 12.15$ and $\hat{\mathcal{V}} = 52$.

A consistent dS model on $\mathbb{CP}_{11169}$: Complex structure

- Stabilizing the $h^{2,1}_{\text{inv.}} = 2$ moduli effectively fixes all other C.S. moduli at $D_i W = 0$ since V positive definite up to corrections $\mathcal{O}(\hat{\xi}/\hat{\mathcal{V}})$ [Giryavets,Kachru,Tripathy,Trivedi '03]

Strategy to find $\langle W_0 \rangle$, $\langle S \rangle$ suitable for Kähler uplifting: [DDF'04]

- Solve $(W_0, D_S W_0, D_{U_1} W_0, D_{U_2} W_0) = 0$, for the flux quanta $f_1, \ldots, f_6$, $h_1, \ldots, h_6$
- Include instanton corrections in the prepotential: shifts in $\langle W_0 \rangle$, $\langle S \rangle$, $\langle U_1 \rangle$ and $\langle U_2 \rangle$

A solution:

$$(f, h) = (-16, 0, 0, 0, -4, -2; 0, 0, 2, -8, -3, 0)\,, \quad Q^{RR,NS-NS} = 66\,,$$

$$\langle S \rangle = 6.99\,, \quad \langle U_1 \rangle = 1.01\,, \quad \langle U_2 \rangle = 0.967\,, \quad \langle W_0 \rangle = 0.812\,,$$

$$m^2_{U_1,U_2,S} \sim 10^{-5} - 10^{-1}\,, \qquad m^2_{T_1,T_2},\, m^2_{3/2} \sim 10^{-8} - 10^{-7}\,.$$

Conclusions & Outlook

Conclusions:

- Sufficient condition for de Sitter with all moduli stabilized.
- Well controlled spontaneous SUSY breaking by F-Terms only.
- Large gauge groups are quiet natural for many Kähler moduli.
- To meet all constraints of an explicit construction is challenging, toric geometry provides means for explicit calculations.
- Explicit consistent model has been constructed on $\mathbb{CP}_{11169}$. Only the dependence of the 1-loop determinant A remains implicit but negligible due to mass scale separation.

Outlook:

- Statistics of de Sitter vacua.