de Sitter vacua from non-perturbative flux compactifications

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OUTLINE

- Introductory words
- Flux compactifications and de Sitter vacua: KKLT and beyond
- A single step F-term dS stabilisation: the model, tools, solutions, constraints
- Summary and outlook
Cosmic acceleration came to stay:

Early Universe: **Inflation**

Late Universe: **Dark Energy**

(~68% energy density content made of Dark Energy)

Cosmological Constant, $\Lambda > 0$, consistent with data
• Crucial to make further progress in understanding the origin of de Sitter (dS) vacua in string theory.

• If amount of dS vacua is huge, string theory landscape may explain the tiny value of the CC today $\Lambda \sim 10^{-120}$ (if responsible for present day acceleration!)

• In any case important to understand dS vacua in ST/SUGRA. Find systematic ways to generate stable dS vacua.
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2. Add (mod. independent) non-perturbative terms to stabilise Kähler moduli: only adS can be obtained

3. Uplift the minimum to a dS, positive vacuum energy by adding an anti-D-brane

$$V_{tot} = V_{AdS} + V_{uplift}$$
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In 4D N=1, via duality, non-geometric fluxes were found and stable dS vacua have been found in STU models with isotropic and non-isotropic fluxes.

[Shelton-Taylor-Wecht, '05]
[de Carlos-Guarino-Moreno, '09]
[Damian-Diaz-Loaiza-Sabido, '13]
[Blåbäck-Danielsson-Dibitetto, '13]
WIDENING THE DS LANDSCAPE

Consider IIB $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$ orbifold compactification with (isotropic) fluxes $H_3, F_3$ ($S, T_i = T, U_i = U$)

In this case, the Kähler potential is

$$K = -\log[-i(S + \bar{S})] - 3\log[-i(T + \bar{T})] - 3\log[-i(U + \bar{U})]$$

*[Simultaneously with Danielsson-Dibitetto, '13 in IIA]*
We consider the tree-level flux superpotential plus a moduli dependent non-perturbative term

\[ W = P(a_i, U) - SP(b_i, U) \]

\[ P(f_i, U) = f_0 - 3f_1 U + 3f_2 U^2 - f_3 U^3 \]

\[ a_i = \text{RR flux} , \ b_i = \text{NSNS flux} \]

\[ \tilde{a}_i, \tilde{b}_i = \text{“non - perturbative flux”} \]

\[ x = 2\pi/K , \text{ for gaugino condensation} \]
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- **duality covariance in non-geometric fluxes and heterotic orbifolds**
Heterotic $T^6/Z_N$ orbifolds fertile arena for (semi-)realistic particle physics model building. Free CFT, can compute LEEFT, N=1 sugra.

LEEFT inherits modular symmetry: $W, K$ are modular covariant. In particular (STU) moduli dependent non-perturbative terms can be computed:

$$W_{NP} = A_3 e^{-aS} \eta^\alpha(T_i, U_j) + A_4 e^{-bS} \eta^\beta(T_i, U_j)$$

[Parameswaran-Ramos-Sanchez-IZ, '11]
HETEROTIC ORBIFOLDS

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We found dS vacua with tachyons. Can we use Johan’s et al. approach to include moduli dependent NP terms?

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Form of WNP motivated by

- duality covariance in non-geometric fluxes and heterotic orbifolds*
- fluxed instanton effects  \[ \text{[Uranga, '09]} \]
- expansion in small U
We consider the tree-level flux superpotential plus a moduli dependent non-perturbative term

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We look for dS vacua in a single step stabilisation of all moduli, avoiding SUSY adS stage, direct dS stable vacua: all moduli contribute to SUSY breaking, lifting the potential

\[ V = e^K \left( |DW|^2 - 3|W|^2 \right) \]

\[ D_i W = \partial_i W + \partial_i K W \]
We want to find stable dS solutions in an effective way

\[ D_I V = 0 \]

\[ V_0 > 0 \]

\[ (m^2)^I_J = \frac{K^{IJ} D_K D_J V}{V} > 0 \]

to solve (numerically) this system we use various techniques
Any solution to the equations of motion can be represented by a solution in the origin of moduli space:

\[ S = T = U = i \]

The solution can be moved to any point using symmetries of the potential, preserving the solution.

The equations reduce to quadratic equations in the fluxes!

\[ D_I V = \sum (\text{fluxes})^2 (\text{scalars})^{(\text{mixed powers})} \]

For the non-perturbative term, \( f(U, S)e^{-ixT} \) at the origin we also take

\[ x = 1 \]
Equations of motion are implied by SUSY

\[ D_I W \equiv A_I + iB_I = 0 \quad \Rightarrow \quad D_I V = 0 \]

these SUSY parameters \( A_I, B_I \) are linear combinations of fluxes. Split these into SUSY and SUSY combinations.

When written in terms of the SUSY parameters, the eom`s take schematic form:

\[ D_I V = \sum (\text{SUSY})^2 + \sum (\text{SUSY})(\text{SUSY}) \]

In other words, they become linear in the fluxes (SUSY combi)
For this to work, one needs at least as many SUSY & SUSY parameters (2N) as real fields (N=real fields):

- Specify the SUSY parameters
- Solve the N linear SUSY equations for N of the fluxes
- Solve the N linear eom wrt the other N fluxes
- Look for stable dS

With this approach, all fields take part in SUSY
We have 6 real fields STU: need 12 fluxes.
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We add 4 more non-perturbative fluxes $\tilde{a}_i$

$$W = P(a_i, U) - S P(b_i, U) + P(\tilde{a}_i, U) e^{ixT}$$
1. Select a population at random (vectors of SUSY)
2. Calculate all desired quantities ($V, m^I_J, ...$)
3. Mutate (perturb some parts of SUSY vectors)
4. Calculate properties for children
5. Select best solutions using fitness function
6. Repeat 3-6 until termination
Solutions: abundant!

\[ \tilde{\gamma} = \frac{|DW|^2}{3|W|^2} \]

Stability/dS overlap very large (c.t. non-geo solutions)
Constraints

Can get a reliable N=1 sugra solution

- Large Volume \( V \sim r^6 \gg 1 \)
- Small string coupling \( g_s^{-1} \gg 1 \)
- Flux quantisation

by rescaling of the fluxes and \( x = 2\pi/K \)

\[ \text{Im} T = V^{2/3} \]
\[ (\text{Im} S)^{-1} = g_s \]
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Rescaled Solution 5

\[ \{a_0, a_1, a_2, a_3, b_0, b_1, b_2, b_3, K\} = \{-1, 4, 1, -12, 4, 0, -1, 0, 67\} \]

\[ \{\tilde{a}_0, \tilde{a}_1, \tilde{a}_2, \tilde{a}_3\} \approx \{0.180917, -0.0186322, 0.0494774, 0.0191168\} \]

\[ V_0 \sim 1.3 \times 10^{-7} \]

\[ m_i \sim \{70027.5, 29274.4, 6043.98, 338.867, 16.0712, 7.88339\} \]

\[ V \sim 50, \quad g_s \sim 0.2 \]
SUMMARY/OUTLOOK

• Extended the dS landscape in type IIB flux compactifications

• One step (F-term) dS moduli stabilisation using moduli dependence of non-perturbative terms.

• Our work has motivated recent work on analytic method to construct abundant of dS vacua!

[Kallosh-Linde-Vernocke-Wrasse, ’14]

• Of course need to extend to more realistic ST_iUi case, compute NP term, relax of susy Ansatz, etc
Grazie