New D-term and de Sitter vacua in supergravity

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with F. Farakos, M. Tournoy and A. van Proeyen

Motivations for de Sitter

- **de Sitter vacuum**: solution of Einstein equations with positive cosmological constant.

  - Today the cosmological constant is small but positive [Planck Coll., '15]

$$\Lambda \simeq +3 \cdot 10^{-122}$$

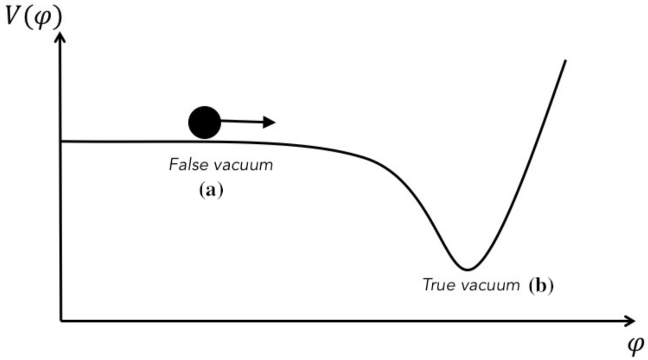
  - Inflation occurred in a de Sitter phase

$$a \sim e^{Ht} \sim e^{\sqrt{\Lambda} t} \qquad \rightarrow \qquad \ddot{a} > 0$$

A successful microscopic theory should describe de Sitter.

Stable and unstable de Sitter

- **Unstable**: inflation **(a)**.
- **Stable**: current epoch **(b)**.



de Sitter and supersymmetry breaking

A positive cosmological constant breaks supersymmetry.

$$V = e^K(|\nabla W|^2 - 3|W|^2) + \frac{1}{2}D^2 > 0$$

if

- $\langle \nabla W \rangle \neq 0$ $\rightarrow$ F-term breaking
- $\langle D \rangle \neq 0$ $\rightarrow$ D-term breaking

[Fayet, Iliopoulos '74; Freedman '77]

Difficulties in obtaining de Sitter

- Moduli stabilization [Kallosh, Linde, Vercnocke, Wrase '14; Antoniadis, Chen, Leontaris '18].
- Break supersymmetry. [Farakos, Kehagias '13; Dudas, Ferrara, Kehagias, Sagnotti '15; Berghsoeff, Freedman, Kallosh, Van Proeyen '15; Hasegawa, Yamada '15; Ferrara, Porrati, Sagnotti '15; NC, Dall'Agata, Farakos, Porrati '16]
- Flat potential (for inflation). [Antoniadis, Bergshoeff, Dall'Agata, Dudas, Ferrara, Freedman, Kallosh, Kehagias, Linde, Sagnotti, Van Proeyen, Wrase, Zwirner]

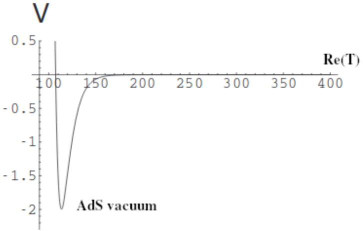
Anti de Sitter vacua from string theory

[Kachru, Kallosh, Linde, Trivedi '03]

Setup: IIB string theory compactified on CY in GKP background.

Moduli stabilization

1. Stabilize complex-structure moduli and axion-dilaton using fluxes.
2. Stabilize Kähler moduli using non-perturbative effects.



1. $K = -3log(T + \bar{T})$
2. $W = W_0 + Ae^{-aT}$

$$V_{KKLT} = e^K(|\nabla_T W|^2 - 3|W|^2)$$

Stable and supersymmetric AdS vacuum.

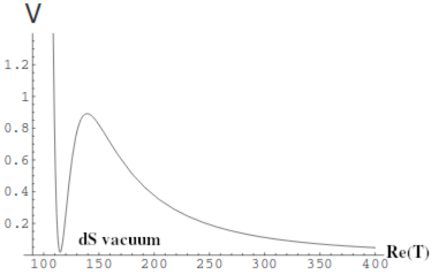
de Sitter vacua from string theory

[Kachru, Kallosh, Linde, Trivedi '03]

Break supersymmetry and uplift

- Add $\overline{D3}$ branes to break supersymmetry and to uplift the vacuum energy

$$V = V_{KKLT} + \frac{\mu^4}{(T + \bar{T})^2}$$



What is the effective description?

Ingredients

- 4d $\mathcal{N} = 1$ supergravity
- Spontaneously broken SUSY in dS $\rightarrow$ goldstino

Open question until [Ferrara, Kallosh, Linde '14]

- Add a goldstino chiral multiplet S, such that $S^2 = 0$

$$K = -3 log(T + \bar{T} - S\bar{S}) \qquad W = W_0 + Ae^{-aT} - \mu^2 S$$

- Uplift of the scalar potential $V = V_{KKLT} + \frac{\mu^4}{(T+\bar{T})^2}$.

but

- F-term breaking.
- Supersymmetry non-linearly realized.

Our proposal

[NC, Farakos, Tournoy, van Proeyen '17]

- Spontaneous SUSY breaking with D-term.
- New embedding of Fayet–Iliopoulos D-term into supergravity.
- Linear supersymmetry off-shell.
- No-gauged R-symmetry $\rightarrow$ no restrictions [Barbieri, Ferrara, Nanopoulos, Stelle '82; Villadoro, Zwirner '05; Komargodski, Seiberg '09]

A new D-term

[NC, Farakos, Tournoy, van Proeyen '17]

Standard FI D-term

$$\mathcal{L} = -3 \int d^4\theta E \, e^{-\frac{1}{3}(K + \Gamma(\xi, V))} + \frac{1}{4}\left(\int d^2\Theta (2\mathcal{E}) \mathcal{W}^2 + cc \right)$$

- Gauged $\mathrm{U(1)_R}$.
- Smoot $\xi \to 0$ limit.

$$V = V_{SUGRA} + \frac{\xi^2}{2}$$

New D-term

$$\mathcal{L} = -3 \int d^4\theta E \, e^{-\frac{K}{3}} + 8\,\xi \int d^4\theta E \, \frac{\mathcal{W}^2 \bar{\mathcal{W}}^2}{\mathcal{D}^2 \mathcal{W}^2 \bar{\mathcal{D}}^2 \bar{\mathcal{W}}^2} \mathcal{D}^\alpha \mathcal{W}_\alpha + \frac{1}{4}\left(\int d^2\Theta (2\mathcal{E}) \mathcal{W}^2 + cc \right)$$

- No gauged $\mathrm{U(1)_R}$ $\to$ W_0 **allowed!**
- Limit $\xi \to 0$ ill-defined.

$$V = V_{SUGRA} + \frac{\xi^2}{2} e^{2K/3}$$

Recovering KKLT

Consider one chiral superfield T

$$K(T,\bar{T}) = -3\log(T+\bar{T}) \qquad W = W_0 + Ae^{-aT}$$

Coupling it to the new D-term

$$V = V_{SUGRA} + \frac{\xi^2}{2}e^{2K/3} \quad \to \quad V = V_{KKLT} + \frac{\xi^2}{2(T+\bar{T})^2}$$

- **Same scalar potential of KKLT uplift!**
- No need for constrained superfields and non-linear SUSY.

The new D-term gives a low energy effective description of the KKLT setup.

Conclusions

- A microscopic theory should describe de Sitter.
- KKLT obtained de Sitter vacua from string theory.
- Despite criticisms, look for effective descriptions.
- New D-term captures the low energy physics of KKLT.

Future directions

- Inflation and cosmology. [Aldabergenov, Ketov '17; Addazi, Marciano, Ketov, Khlopov '18; Antoniadis, Chatrabhuti, Isono, Knoops '18]
- Uplift with only chiral multiplets. [Farakos, Kehagias, Riotto '18]
- Extended SUSY.

Thank you for your attention!

Extra

F-term vs D-term breaking

F-term

- Break SUSY with a chiral multiplet

$$\Phi = \{\phi, \chi, F\}, \qquad \langle F \rangle \sim \langle \nabla W \rangle \neq 0$$

- χ is the goldstino.
- Scalars to be stabilized in the vacuum.

D-term

- Break SUSY with a vector multiplet

$$V = \{v_\mu, \lambda, D\}, \qquad \langle D \rangle \neq 0$$

- λ is the goldstino.
- No scalars.

Fayet–Iliopoulos D-term

- Vector multiplet

$$V_{\mathrm{WZ}} = -\theta\sigma^m\bar{\theta}A_m - i\bar{\theta}^2\theta^\alpha\lambda_\alpha + i\theta^2\bar{\theta}_{\dot{\alpha}}\bar{\lambda}^{\dot{\alpha}} + \frac{1}{2}\theta^2\bar{\theta}^2 D\,.$$

- Fayet–Iliopoulos model

$$\mathcal{L} = \frac{1}{4}\left(\int d^2\theta\mathcal{W}^2(V) + c.c.\right) + 2\xi\int d^4\theta V$$

$$= -\frac{1}{4}F^{mn}F_{mn} - i\lambda\sigma^m\partial_m\bar{\lambda} + \frac{1}{2}D^2 + \xi\,\mathrm{D}\,.$$

Freedman model

- Superspace Lagrangian

$$\mathcal{L} = -3 \int d^4\theta \, E \, e^{\frac{2}{3}\xi V} + \frac{1}{4} \left(\int d^2\Theta \, 2\mathcal{E} \, \mathcal{W}^2(V) + c.c. \right) .$$

- Component Lagrangian

$$e^{-1}\mathcal{L}\Big|_{\lambda=0} = -\frac{1}{2} R + \frac{1}{2} \epsilon^{klmn} \left(\overline{\psi}_k \overline{\sigma}_l \mathcal{D}_m \psi_n - \psi_k \sigma_l \mathcal{D}_m \overline{\psi}_n \right) - \frac{1}{4} F_{mn} F^{mn} + \frac{i}{2} \xi \epsilon^{klmn} \overline{\psi}_k \overline{\sigma}_l \psi_n A_m - \frac{1}{2} \xi^2 .$$

New FI D-term

- Superspace Lagrangian

$$\mathcal{L}_{NEW} = \frac{1}{4}\left(\int d^2\Theta\, 2\mathcal{E}\, \mathcal{W}^2(V) + c.c.\right) + 8\,\xi \int d^4\theta\, E\, \frac{W^2\overline{\mathcal{W}}^2}{\mathcal{D}^2\mathcal{W}^2\overline{\mathcal{D}}^2\overline{\mathcal{W}}^2}\, \mathcal{D}^\alpha \mathcal{W}_\alpha \,.$$

- Component Lagrangian

$$e^{-1}\mathcal{L}_{NEW} = -\frac{1}{4}F_{mn}F^{mn} - i\overline{\lambda}\overline{\sigma}^m\mathcal{D}_m\lambda + \frac{1}{2}\mathrm{D}^2 - \xi\mathrm{D} + \xi\,\mathcal{O}\left(\lambda,\overline{\lambda}\right) \,.$$

- The gravitino is not charged under the U(1).

New D-term in supergravity

- Superspace Lagrangian

$$\mathcal{L} = -3\left(\int d^2\Theta\, 2\mathcal{E}\,\mathcal{R} + c.c.\right) + \left(\int d^2\Theta\, 2\mathcal{E}\, W_0 + c.c.\right) + \mathcal{L}_{NEW}\,.$$

- Component Lagrangian

$$e^{-1}\mathcal{L}\Big|_{\lambda=0} = -\frac{1}{2}R + \frac{1}{2}\epsilon^{klmn}\left(\overline{\psi}_k\overline{\sigma}_l\mathcal{D}_m\psi_n - \psi_k\sigma_l\mathcal{D}_m\overline{\psi}_n\right) - \frac{1}{4}F_{mn}F^{mn} - \left(\frac{1}{2}\xi^2 - 3|W_0|^2\right) - \overline{W}_0\psi_a\sigma^{ab}\psi_b - W_0\overline{\psi}_a\overline{\sigma}^{ab}\overline{\psi}_b\,.$$

New D-term coupled to matter

- Chiral superfields

$$\Phi^i = A^i + \sqrt{2}\Theta\chi^i + \Theta^2 F^i \,.$$

- Superspace Lagrangian for matter

$$\mathcal{L}_{K,W} = \int d^2\Theta\, 2\mathcal{E} \left[\frac{3}{8}(\overline{\mathcal{D}}^2 - 8\mathcal{R})e^{-\frac{1}{3}K(\Phi^i,\overline{\Phi}^i)} + W(\Phi^i)\right] + c.c.$$

- Component Lagrangian for matter (bosonic sector)

$$\begin{aligned} e^{-1}\mathcal{L}_{K,W} =& -\frac{1}{2}R - K_{i\bar{j}}\partial A^i \partial \overline{A}^{\bar{j}} \\ & - e^K\left[(K^{-1})^{i\bar{j}}(W_i + K_i W)(\overline{W}_{\bar{j}} + K_{\bar{j}}\overline{W}) - 3W\overline{W}\right]. \end{aligned}$$

- Total Lagrangian

$$\mathcal{L} = \mathcal{L}_{K,W} + \mathcal{L}_{NEW}$$

Some properties

- Uplift of the scalar potential

$$V = V_{SUGRA} + \frac{\xi^2}{2} e^{2K/3}$$

- Supersymmetry always broken, $\langle D \rangle \sim \xi \neq 0$, but linearly-realized off-shell.
- No higher derivatives in the bosonic sector.
- **No gauged** $\mathrm{U}(1)_\mathrm{R} \quad \rightarrow \quad W_0$ **allowed!**

Moreover

- It can coexist with the standard D term. [Antoniadis, Chatrabhuti, Isono, Knoops '18]
- Restore Kähler invariance. [Antoniadis, Chatrabhuti, Isono, Knoops '18]