The supersymmetric anti-D3-brane action in KKLT

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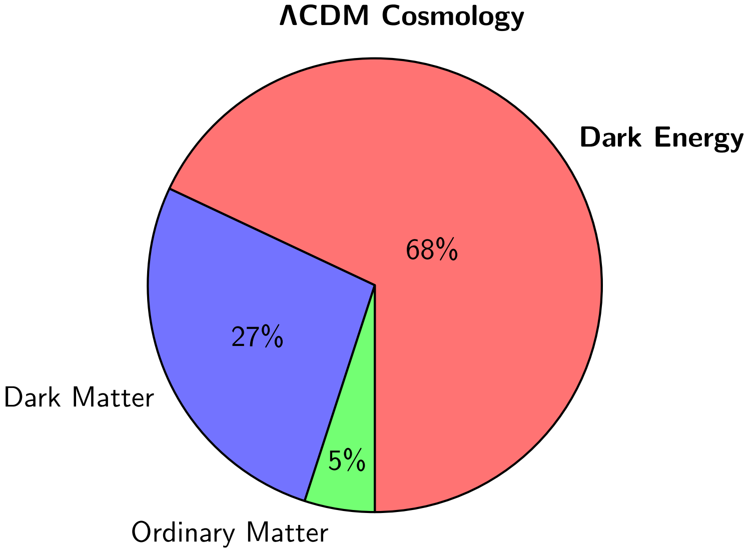
Based on 1906.07727, with C. Roupec, T. Wrase and Y. Yamada

Introduction

Our observed Universe

[Planck '18]



What do we know about Dark Energy?

- 68% of the total energy of observable universe

- Measured energy density $\mathcal{V} \sim 10^{-122} M_P^4 > 0$ [Planck '18]

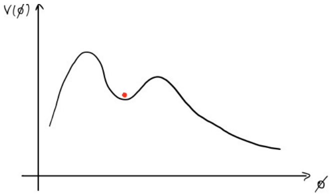
- Assuming FRW universe and equation of state $P = w\rho$, **accelerated expansion** occurs for

$$\frac{\ddot{a}}{a} = -\frac{1}{6}(\rho + 3P) = -\frac{1}{6}\rho(1 + 3w) > 0 \quad \Longleftrightarrow \quad w < -\frac{1}{3}$$

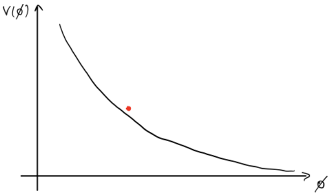
  Measured value $w = -1.03 \pm 0.03$ [Planck '18]

How to explain Dark Energy?

Accelerated expansion: possible explanations



constant vacuum energy
de Sitter vacuum
$w = -1$



slowly changing in time
quintessence
$w > -1$

At present they are both compatible with experiments

$w = -1.03 \pm 0.03$ [Planck '18]

de Sitter vacuum

- Dark energy = positive cosmological constant

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu}(R + 2\Lambda) = 0$$

- Understand it microscopically $\quad \rightarrow \quad$ string theory

$$\Lambda \quad \sim \quad \langle \mathcal{V}(\phi) \rangle$$

- Problems: moduli stabilization, corrections, ...

Moreover

- de Sitter breaks supersymmetry
  [Pilch, van Nieuwenhuizen, Sohnius '85]

$$\mathcal{V}_{\mathsf{SUGRA}} = (\delta(\text{spin-}1/2))^2 - (\delta(\text{spin-}3/2))^2 > 0$$

De Sitter and string theory

Some bad news

- It is not straightforward to obtain dS from string theory.
- Is the difficulty accidental or is manifestation of some principle yet to be understood?
- It has been even conjectured that there is no dS!
  [Danielsson, Van Riet '18; Obied, Ooguri, Spodyneiko, Vafa '18; Ooguri, Palti, Shiu, Vafa '18]
- No-go theorems
  [Maldacena, Núñez '00; Hertzberg, Kachru, Taylor, Tegmark '07; Flauger, Paban, Robbins, Wrase '08; Wrase, Zagermann '10; Junghans, Zagermann '16,...]

Some good news

- **Moduli stabilization**: compactifications with fluxes. Usually 10d SUGRA is trustable at large volume $L/l_s \gg 1$ and weak coupling $e^{\phi} \ll 1$

- **Supersymmetry breaking**: extendend objects (D-branes)

  $$\text{Brane susy-breaking} \qquad \mathcal{V} \sim e^{\gamma\phi}$$

  [Sugimoto '99; Antoniadis, Dudas, Sagnotti '99; Aldazabal, Uranga '99; Angelantonj, Antoniadis, D'Appollonio, Dudas, Sagnotti '00]

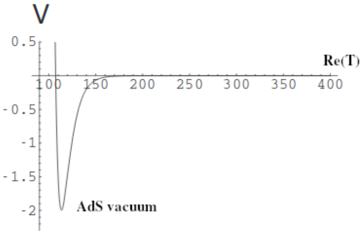
- The first proposal for a dS construction in string theory with massless fields and tunable $\Lambda = \mathcal{V}_{min}$ has been given by [Kachru, Kallosh, Linde, Trivedi '03]

KKLT - moduli stabilization

[Kachru, Kallosh, Linde, Trivedi '03;
Kachru, Kallosh, Linde, Maldacena, McAllister, Trivedi '03]

Setup: IIB compactified on CY with orientifold

1. Stabilize CS moduli and axio-dilaton using fluxes
   [Giddings, Kachru, Polchinski '01]
2. Stabilize Kähler moduli using non-perturbative effects



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

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

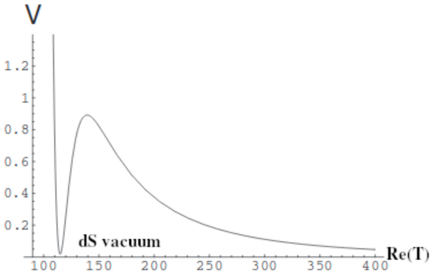
Stable and supersymmetric AdS vacuum

KKLT - supersymmetry breaking and uplift

[Kachru, Kallosh, Linde, Trivedi '03;
Kachru, Kallosh, Linde, Maldacena, McAllister, Trivedi '03]

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

$$\mathcal{V} = \mathcal{V}_{KKLT} + \frac{\mu^4}{(T+\bar{T})^2}$$ **metastable dS**



Anti-D3-brane in KKLT

- Most delicate step in the procedure.
- It breaks supersymmetry **spontaneously** $\rightarrow$ **goldstino**
- On the world volume fields susy is non-linear
  [Kallosh, Wrase '14; Bergshoeff, Dasgupta, Kallosh, Van Proeyen, Wrase '15; Kallosh, Quevedo, Uranga '15; Bandos, Heller, Kuzenko, Martucci, Sorokin '15; García-Etxebarria, Quevedo, Valandro '15; Vercnocke, Wrase '16; Kallosh, Vercnocke, Wrase '16]
- Can we still use the standard SUSY language?
- It would help in understanding better (this step of) KKLT.

The low energy description

What is the effective description?

Setup: 4d $\mathcal{N} = 1$ supergravity + **goldstino**

First step: scalar potential [Ferrara, Kallosh, Linde '14]

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

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

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

However

- Full action? [Garcia del Moral, Parameswaran, Quiroz, Zavala '17]

Supersymmetry on the brane

- **D3-brane: linear SUSY**

  3 scalars $H^a \longleftrightarrow$ 3 fermions χ^a chiral multiplet $\{H^a, \chi^a\}$

  1 fermion $\lambda \longleftrightarrow$ 1 vector v_μ vector multiplet $\{\lambda, v_\mu\}$

- **anti-D3-brane: non-linear SUSY** $\lambda \sim$ **goldstino**

  $H^a \longleftrightarrow \partial H^a \lambda + \ldots$ $\chi^a \longleftrightarrow \chi^a \lambda + \lambda^2 + \ldots$

  $\lambda \longleftrightarrow \lambda^2 + \ldots$ $v_\mu \longleftrightarrow \lambda \not{F} + \ldots$

  - More complicated transformations than linear SUSY
  - All of them involve the goldstino
  - How to deal with this?

Non-linear supersymmetry

[Volkov, Akulov '73;
Rocek '78; Lindstrom, Rocek '79; Casalbuoni, De Curtis, Dominici, Feruglio, Gatto '89]

- Recent progress in non-linear supersymmetry.
  [Antoniadis, Bergshoeff, Dall'Agata, Derendinger, Dudas, Farakos, Ferrara, Freedman, Kallosh, Kehagias, Komargodski, Kuzenko, Markou, Porrati, Sagnotti, Seiberg, Sorokin, Tartaglino-Mazzucchelli, Tournoy, Van Proeyen, Wrase, Yamada, Zwirner,...]

- General recipe to describe ANY low energy spectrum.
  [Dall'Agata, Dudas, Farakos '16; NC, Dall'Agata, Farakos '17]

- Apply it to de Sitter and KKLT

The strategy

[NC, Roupec, Wrase, Yamada '19]

- Embed all worldvolume fields in constrained superfields

worldvolume field	linear SUSY	non-linear SUSY
1 goldstino	X	$X^2 = 0$
3 massive fermions	Y^i	$XY^i = 0$
3 complex scalars	H^a	$X\bar{H}^a = \text{chiral}$
1 vector	W_α	$XW_\alpha = 0$

- Couple them to closed string fields in 4d $\mathcal{N} = 1$ supergravity

1. Kähler potential K 2. superpotential W 3. gauge kin. function $f(\tau)$

- Match with anti-D3-brane action
[Martucci, Rosseel, Van den Bleeken, Van Proeyen '05; Bergshoeff, Kallosh, Kashani-Poor, Sorokin, Tomasiello '05]
- Non-trivial restriction: modular invariance

A particular problem

[NC, Roupec, Wrase, Yamada '19]

$$\text{D3 action} \quad \xleftrightarrow{\text{RR sign flip}} \quad \overline{D3}\ \text{action}$$

- Therefore $f(\tau) \quad \xleftrightarrow{\text{RR sign flip}} \quad f(\bar{\tau})$ **antiholom.**

  NOT compatible with susy

- Solution: non-linear supersymmetry

$$f_{\overline{D3}} = \bar{D}^2 \left(\frac{\bar{X} f(\bar{\tau})}{\bar{D}^2 \bar{X}} \right) = f(\bar{\tau}) + \text{goldstino} \qquad \textbf{chiral!}$$

- Inspired by new D-term in supergravity

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

- A similar problem happens for the fermionic mass

The supersymmetric anti-D3-brane action in KKLT

[NC, Roupec, Wrase, Yamada '19]

$$K = -\log(-i(\tau - \bar\tau)) - 3\log\left[(T+\bar T)\left(-i\int \Omega\wedge\bar\Omega\right)^{\frac{1}{3}} + k(H^a,\bar H^a)\right]$$

$$\quad - 3\log\left(1 - C_1 X\bar X - C_2\delta_{i\bar\jmath}Y^i\bar Y^{\bar\jmath}\right)$$

$$W = \int G_3\wedge\Omega + Ae^{-aT} + \mu^2 X + \frac{1}{2}M_{ij}Y^iY^j$$

$$f_{\overline{D3}} = \bar D^2\left(\frac{\bar X f(\bar\tau)}{\bar D^2\bar X}\right), \quad M_{ij} = \bar D^2\left(\frac{\bar X\, e^{-4\mathcal{A}-2u}\, m_{ij}}{\bar D^2\bar X\,(-i(\tau-\bar\tau))^{\frac{1}{2}}\,(-i\int\Omega\wedge\bar\Omega)^{-\frac{1}{6}}}\right)$$

$$\mathcal{V}_{\overline{D3}} = 2\,e^{4\mathcal{A}(H^a,\bar H^a)-8u},$$

where

$$e^{4u} = (T+\bar T) + k(H^a,\bar H^a)\left(-i\int\Omega\wedge\bar\Omega\right)^{-\frac{1}{3}} = (V_6)^{\frac{2}{3}}$$

$$C_1 = \frac{e^{-4\mathcal{A}(H^a,\bar H^a)}}{3(-i(\tau-\bar\tau))(T+\bar T+k(H^a,\bar H^a)\,(-i\int\Omega\wedge\bar\Omega)^{-\frac{1}{3}})\,(-i\int\Omega\wedge\bar\Omega)}$$

$$C_2 = \frac{e^{-4\mathcal{A}(H^a,\bar H^a)}}{3(-i(\tau-\bar\tau))(T+\bar T+k(H^a,\bar H^a)\,(-i\int\Omega\wedge\bar\Omega)^{-\frac{1}{3}})^2\,(-i\int\Omega\wedge\bar\Omega)^{\frac{1}{3}}}$$

Conclusion

- A possible explanation for Dark Energy is de Sitter vacuum
- Microscopic origin: string theory and brane susy breaking
- Particular setup: $\overline{D3}$ brane used in KKLT
- We derived the complete low-energy effective theory for the $\overline{D3}$ brane, using 4d $\mathcal{N} = 1$ language

Thank you!