de Sitter vacua, swampland and supergravity

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→ Aspects of non-linear SUSY

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Introduction

What if string theory has no de Sitter vacua?

See e.g. Dine, Seiberg '85, Danielsson, Van Riet '18

$\rightarrow$ We observe an expanding universe, and the simplest explanation is to have some dark energy dominating.

$\rightarrow$ On top of that, long-lived meta-stable de Sitter vacua would be the simplest (but maybe misleading?) solution.

$\rightarrow$ Extremely hard to find in controlled string theory setups - maybe impossible!

How can we uncover this difficulty in 4D supergravity?

$\rightarrow$ Scalar potentials of 4D supergravity typically arise from:

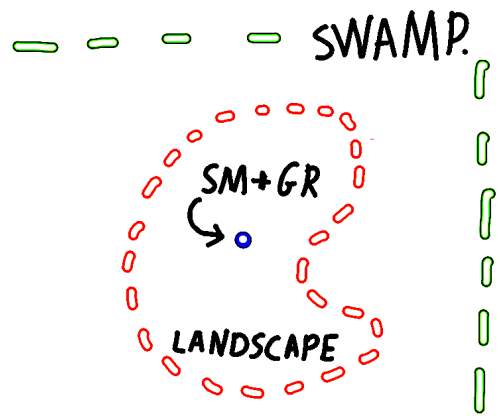
- Superpotentials.
- Gaugings.
- Non-linear supersymmetry.

The vast freedom in choosing the above ingredients makes it impossible to exclude de Sitter vacua in 4D supergravity.

$\rightarrow$ Can we find restrictions / implications from the swampland?

✗ Swampland: EFTs that do not arise from S.T.

✓ Landscape: EFTs that do arise from S.T.



We distinguish swamp from landscape with so-called conjectures: General properties that we guess and test on compactifications, black holes, quantum gravity, etc.

**We are talking about EFTs coupled to gravity.*

Which conjectures can restrict the ingredients of supergravity?

- Weak gravity conjecture (magnetic) gives UV cut-off

$$qg\, M_P > \Lambda_{UV}\,.$$

Arkani-Hamed, Motl, Nicolis, Vafa '06

- Non-supersymmetric (AdS) vacua (supported from flux) always decay.
Ooguri, Vafa '16

- Non-existence of stable de Sitter has been deemed as conjecture too; but we don't want to use it here.
Obied, Ooguri, Spodyneiko, Vafa '18, Andriot '18

Restrictions on de Sitter vacua from gaugings

Example: 4D N=1 Lagrangian of SG + FI term is

$$e^{-1}\mathcal{L} = -\frac{1}{2}M_P^2 R + \frac{1}{2}\epsilon^{\kappa\lambda\mu\nu}\left(\overline{\psi}_\kappa\overline{\sigma}_\lambda D_\mu\psi_\nu - \psi_\kappa\sigma_\lambda D_\mu\overline{\psi}_\nu\right)$$
$$-\frac{1}{4g^2}F_{\mu\nu}F^{\mu\nu} + i\xi\,\epsilon^{\kappa\lambda\mu\nu}\overline{\psi}_\kappa\overline{\sigma}_\lambda\psi_\mu A_\nu - 4g^2\xi^2 M_P^4\,.$$

- Since ξ is the gravitino charge, the WGC gives

$$\Lambda_{UV} \sim g\,\xi\,M_P\,.$$

- The vacuum energy is $4g^2\xi^2 M_P^2$ and so the Hubble is

$$H \sim g\xi M_P \sim \Lambda_{UV}\,,$$

therefore such simple de Sitter is not a good 4D EFT!

Example: FI-gauged 4D N=2 SG + N=2 vect.mult. has potential

$$V = \frac{1}{1-|z|^2}\left[\xi_0^2(|z|^2-3) - 2\xi_0\xi_1(z+\bar{z}) + \xi_1^2(1-3|z|^2)\right] ,$$

where $\xi_{0,1}$ are FI-gaugings and z a complex scalar.

- If we set $\xi_0 = 0$ and $\xi_1 = 2gq_{3/2}$ we find $H \sim \Lambda_{UV}$ since

$$\langle V \rangle = 4g^2 q_{3/2}^2 ,$$

  albeit tachyonic.

- Notably for $\xi_0 \neq 0$ and $\xi_1 = 0$ one can show that such SUSY AdS are not scale-separated. *Cribiori, Dall'Agata '22*

See e.g. Cribiori, FF '23

Further results:

- We have shown that all known stable de Sitter vacua of gauged N=2 suffer from the same issue. *Cribiori, Dall'Agata, FF '20, Dall'Agata, Emelin, FF, Morittu '21*

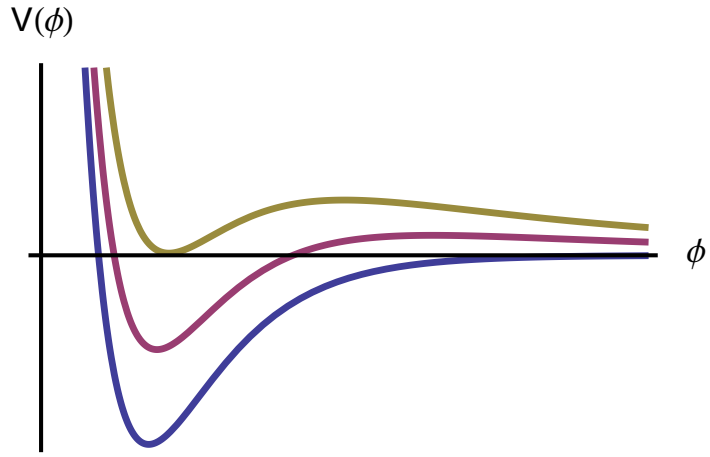
- All these examples have $m_{3/2} = 0$, $q_{3/2} \neq 0$, so also in tension with the "festina lente" bound. *Montero, Vafa, Van Riet, Venken '21*

- SG has a plethora of other couplings that could indirectly restrict de Sitter, even without gaugings (Yukawa couplings, magnetic moments, etc.).

Decay of vacua from non-linear realizations

KKLT adapted to supergravity with non-linear realizations:

1. No-scale Kähler with $W = W_0 + Ae^{-a\Phi}$.
2. + nilpotent chiral goldstino $K + X\overline{X}$ and $W + fX$.
3. Lift to metastable de Sitter.



Ferrara, Kallosh, Linde '14

We have broken supersymmetry, which according to the swampland, should always have a decay channel to SUSY.

- SUSY broken with a chiral superfield

$$X = A + \sqrt{2}\,\theta^\alpha G_\alpha + \theta^\alpha\theta_\alpha F\,,$$

that is constrained to satisfy

$$X^2 = 0\,.$$

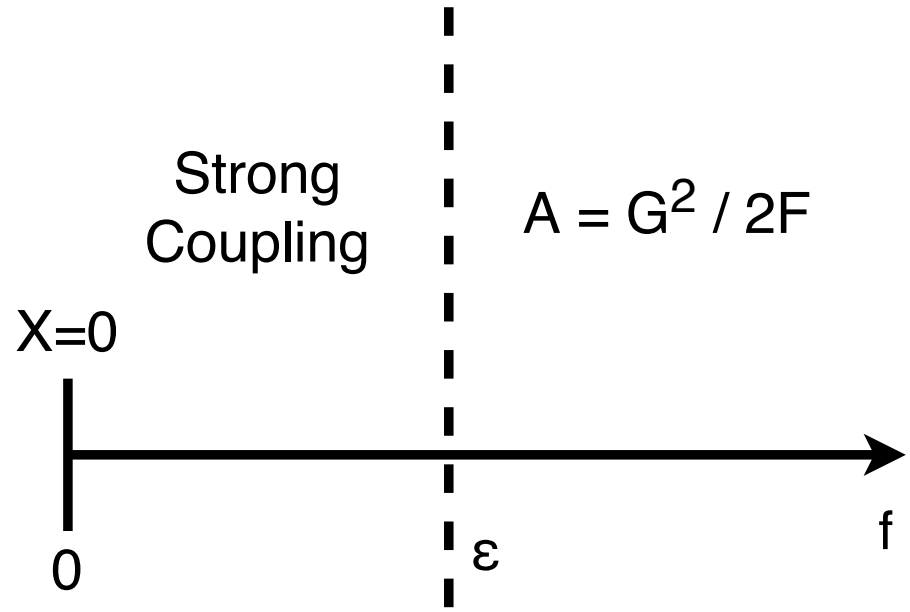
Rocek '78, Casalbuoni, De Curtis, Dominici, Feruglio, Gatto '89

- The equation $X^2 = 0$ is solved as

$$\text{I)}\;\; A \equiv \frac{G^2}{2F} \;\text{ assuming }\; \langle F\rangle \sim f \neq 0 \;\rightarrow\; \textit{Volkov} - \textit{Akulov}\,.$$

$$\text{II)}\;\; \text{If } \langle F\rangle = 0 \text{ then } X^2 = 0 \rightarrow X = 0\,.$$

- Solution II) neutralizes all fluctuations of X ('evaporates').



PUZZLE: To get SUSY the EFT passes from small *f*, but we cannot pass from there because the EFT breaks down.

Decay channel:

- Trade the auxiliary field of X with a 3-form:

$$F \sim \star dC_3$$

- Couple the 3-form to a super-membrane with charge Q, and assuming the decay to SUSY vacuum in one go

$$Q \sim f \,,$$

because $\Delta F \sim Q$.

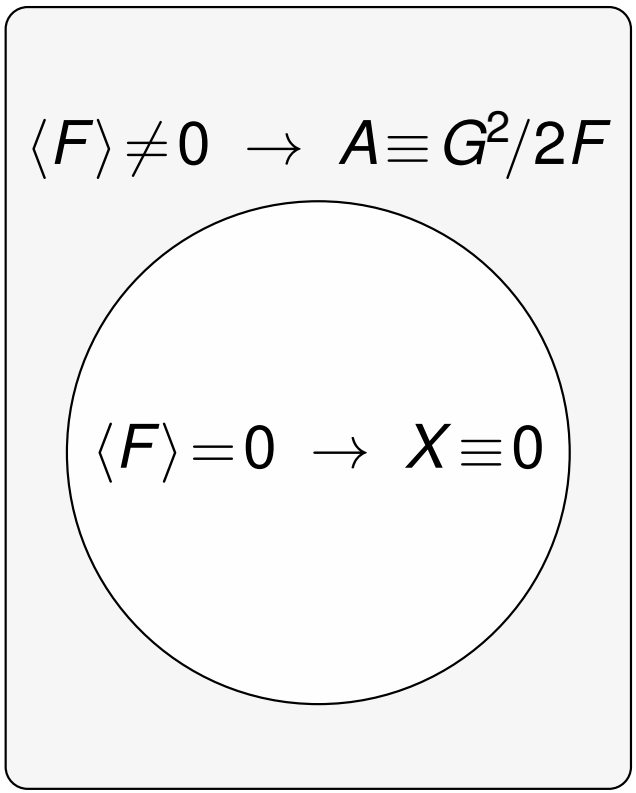
- The super-membrane tension T_3 also implies non-linear supersymmetry on its world-volume with

$$m \sim T_3^{1/3} \,.$$

We can solve $X^2 = 0$
depending on the background:

1. $\star dC_3 \neq 0 \quad \rightarrow \quad A = \frac{G^2}{2F}$.

2. $\star dC_3 = 0 \quad \rightarrow \quad X = 0$.



Decay time:

- Generically these can still be long-lived vacua depending on the properties of T_3 and Q.
- If we assume the two non-linear supersymmetries have the same strong coupling scale

$$f \sim m^2 \,,$$

then we get from BT very short life-time for dS because

$$P \sim e^{-B} \sim e^{-\frac{27\pi^2}{2}} \,.$$

- Incidentally this also realizes the WGC condition $T_3 < Q$.

Outlook

What if string theory has no de Sitter vacua?

Then we may be able to see this manifest in 4D supergravity equipped with established swampland conjectures:

- We can uplift SUSY AdS with pure NL SUSY $\rightarrow$ then it can decay via BT bubbles; constraints on the decay time?
- We can break SUSY and uplift with gaugings $\rightarrow$ then it can violate WGC or FL.
- We can break it with N=1 superpotentials $\rightarrow$ restrictions?

Thank you