The cosmological constant in supergravity and string theory

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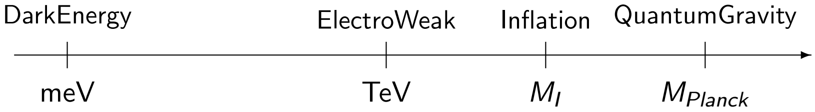
Universe evolution: based on positive cosmological constant

- Dark Energy

  simplest case: infinitesimal (tuneable) +ve cosmological constant

- Inflation (approximate de Sitter)

  describe possible accelerated expanding phase of our universe



The cosmological constant in Supergravity

Highly constrained: $\Lambda \geq -3m_{3/2}^2$

- equality $\Rightarrow$ AdS (Anti de Sitter) supergravity

  $m_{3/2} = W_0$: constant superpotential

- inequality: dynamically by minimising the scalar potential

  $\Rightarrow$ uplifting Λ and breaking supersymmetry

• Λ is not an independent parameter for arbitrary breaking scale $m_{3/2}$

What about breaking SUSY with a $<$D$>$ triggered by a constant FI-term?

standard supergravity: possible only for a gauged $U(1)_R$ symmetry:

absence of matter $\Rightarrow$ $W_0 = 0 \to$ dS vacuum   Friedman '77

• exception: non-linear supersymmetry

A new FI term Cribiori-Farakos-Tournoy-Van Proeyen '18

gauge invariant at the Lagrangian level but non-local

becomes local and very simple in the unitary gauge

Global supersymmetry: gauge field-srength superfield

$$\mathcal{L}_{\rm FI}^{new} = \xi_1 \int d^4\theta \frac{\mathcal{W}^2\overline{\mathcal{W}}^2}{\mathcal{D}^2\mathcal{W}^2\bar{\mathcal{D}}^2\overline{\mathcal{W}}^2}\mathcal{D}\mathcal{W} = -\xi_1 \mathrm{D} + \text{fermions}$$

It makes sense only when $<\mathrm{D}>\neq 0 \Rightarrow$ SUSY broken by a D-term

Supergravity generalisation: straightforward

unitarity gauge: goldstino $=$ $U(1)$ gaugino $= 0 \Rightarrow$ standard sugra $-\xi_1\mathrm{D}$

New FI term in supergravity

Pure sugra + one vector multiplet $\Rightarrow$

$$\mathcal{L} = R + \bar{\psi}_\mu \sigma^{\mu\nu\rho} D_\rho \psi_\nu + m_{3/2} \bar{\psi}_\mu \sigma^{\mu\nu} \psi_\nu - \frac{1}{4} F_{\mu\nu}^2 - \left(-3 m_{3/2}^2 + \frac{1}{2} \xi_1^2 \right)$$

- $\xi_1 = 0 \Rightarrow$ AdS supergravity
- $\xi_1 \neq 0$ uplifts the vacuum energy and breaks SUSY

  e.g. $\xi_1 = \sqrt{6} m_{3/2} \Rightarrow$ massive gravitino in flat space

The cosmological constant in Supergravity

I.A.-Chatrabhuti-Isono-Knoops '18

New FI-term evades this problem in the absence of matter

Presence of matter $\Rightarrow$ non trivial scalar potential

but breaks Kähler invariance

However new FI-term in the presence of matter is not unique

Question: can one modify it to respect Kähler invariance?

Answer: yes, constant FI-term + fermions as in the absence of matter

$\Rightarrow$ constant uplift of the potential, Λ free (+ve) parameter besides $m_{3/2}$

It can also be written in $N = 2$ supergravity

I.A.-Derendinger-Farakos-Tartaglino Mazzucchelli '19

Swampland de Sitter conjecture

String theory: vacuum energy and inflation models

related to the moduli stabilisation problem

Difficulties to find dS vacua led to a conjecture:

$$\frac{|\nabla V|}{V} \geq c \quad \text{or} \quad \min(\nabla_i \nabla_j V) \leq -c' \quad \text{in Planck units}$$

with c, c' positive order 1 constants Ooguri-Palti-Shiu-Vafa '18

Dark energy: forbid dS minima but allow maxima

Inflation: forbid standard slow-roll conditions

Assumptions: heuristic arguments, no quantum corrections

$\longrightarrow$ here: explicit counter example

Moduli stabilisation in type IIB

Compactification on a Calabi-Yau manifold $\Rightarrow$ $N = 2$ SUSY in 4 dims

Moduli: Complex structure in vector multiplets

Kähler class + dilaton in hypermultiplets

$\Rightarrow$ decoupled kinetic terms

turn on appropriate 3-form fluxes (primitive self-dual) $\Rightarrow$ $N = 1$ SUSY

+ orientifolds and D3/D7-branes

vectors and companions of geometric moduli are projected away $\Rightarrow$

all moduli in $N = 1$ chiral multiplets + superpotential for the

complex structure and dilaton $\to$ fixed in a SUSY way   Frey-Polchinski '02

Kähler moduli: no scale structure, vanishing potential (classical level)

Stabilisation of Kähler moduli

Non perturbative superpotential from gaugino condensation on D-branes

$\Rightarrow$ stabilisation in an AdS vacuum   Derendinger-Ibanez-Nilles '85

Uplifting using anti-D3 branes   Kachru-Kallosh-Linde-Trivedi '03

or D-terms and perturbative string corrections to the Kähler potential

Large Volume Scenario   Conlon-Quevedo et al '05

Ongoing debate on the validity of these ingredients in full string theory

While perturbative stabilisation has the old Dine-Seiberg problem

put together 2 orders of perturbation theory violating the expansion

possible exception known from filed theory:

logarithmic corrections $\rightarrow$ Coleman-Weinberg mechanism

Log corrections in string theory

Effective propagation of massless bulk states in $d \leq 2 \Rightarrow$ IR divergences

$d = 1$: linear, $d = 2$: logarithmic corrections for (brane) localised couplings

on the size of the bulk due to local closed string tadpoles I.A.-Bachas '98

e.g. gauge coupling corrections, linear dilaton dependence on the 11th dim

Type II strings: corrections to the Kähler potential $\leftrightarrow$ Planck mass

I.A.-Ferrara-Minasian-Narain '97

Large volume limit: it corresponds to a 4d localised Einstein-Hilbert term

in the 6d internal space I.A.-Minasian-Vanhove '02

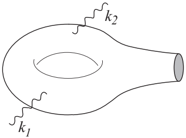
$$S_{\rm grav}^{IIB} = \frac{1}{(2\pi)^7 \alpha'^4} \int_{M_4 \times \mathcal{X}_6} e^{-2\phi} \mathcal{R}_{(10)} + \frac{\chi}{(2\pi)^4 \alpha'} \int_{M_4} \left(2\zeta(3) e^{-2\phi} + \frac{2\pi^2}{3} \right) \mathcal{R}_{(4)}$$

χ: Euler number $= 4(n_H - n_V)$ 4-loop σ-model $\nearrow$ vanishes for orbifolds

perturbative moduli stabilisation I.A.-Chen-Leontaris '18, '19

localised vertices from $\mathcal{R}_{(4)}$ can emit massless closed strings

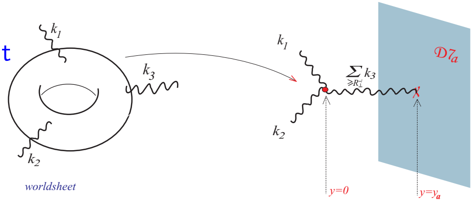
$\Rightarrow$ local tadpoles in the presence of distinct 7-brane sources



propagation in 2d transverse bulk $\rightarrow$ log $R_\perp$ corrections

computation in the degeneration limit

for Z_N orbifold



$$\sim - \sum_{q_\perp \neq 0} g_s^2 T N e^{w^2 q_\perp^2/2} \frac{1}{q_\perp^2 R_\perp^2} = -N g_s^2 T \log(R_\perp / w) + \cdots$$

$T = T_0/g_s$: brane tension ; $w \sim 1/\sqrt{N}$: localisation width

perturbative moduli stabilisation I.A.-Chen-Leontaris '18, '19

Kähler potential: $\mathcal{K} = -2\ln\left(\mathcal{V}+\xi+\eta\ln\mathcal{V}_\perp+\mathcal{O}(\frac{1}{\mathcal{V}})\right) = -2\ln\left(\mathcal{V}+\eta\ln\mu\mathcal{V}_\perp\right)$

$$\xi = -\tfrac{1}{4}\chi f(g_s)\,; \quad f(g_s) = \begin{cases} \zeta(3)\simeq 1.2 & \text{smooth CY} \\ \frac{\pi^2}{3}g_s^2 & \text{orbifolds} \end{cases} \qquad \eta = -\tfrac{1}{2}g_s T_0 \xi$$

Using 3 mutual orthogonal 7-brane stacks with D-terms (magnetic fluxes)

and minimising with respect to transverse volume ratios

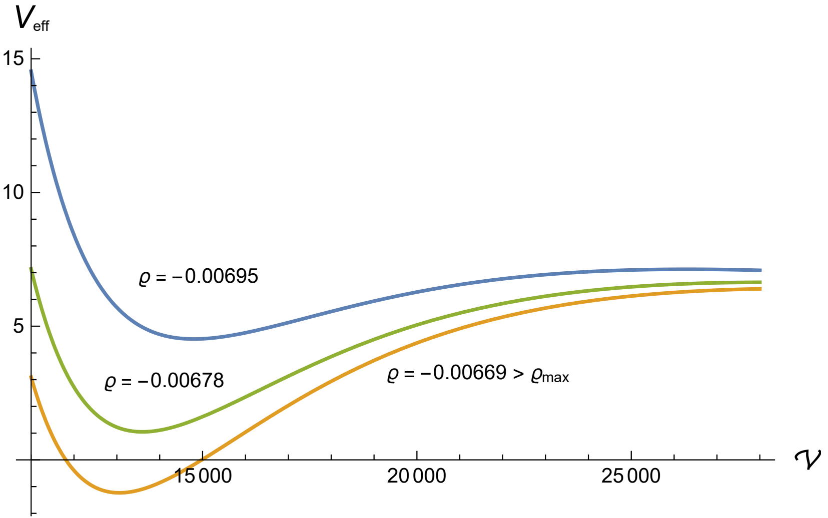
$\Rightarrow\ V \simeq \dfrac{3\eta\mathcal{W}_0^2}{\mathcal{V}^3}\left(\ln\mu\mathcal{V}-4\right)+3\dfrac{d}{\mathcal{V}^2}$ $\quad$ $\mathcal{W}_0$: constant superpotential, d: D-term

de Sitter minimum: $-0.007242 < \frac{d}{\eta\mathcal{W}_0^2\mu} \equiv \rho < -0.006738$ with $\mathcal{V}\simeq e^5/\mu$

exponentially large volume for $\mu = e^{\xi/\eta}/w = |\chi| e^{-\frac{2}{g_s T_0}} \to 0$

weak coupling and large χ or/and $\mathcal{W}_0$ from 3-form flux to keep ρ fixed

requirement: negative χ $(\eta < 0)$ and surplus of D7-branes $(T_0 > 0)$



2 extrema min+max → $-0.007242 < \rho < -0.006738$ ← +ve energy of min

Conclusions

Novel D-terms in supergravity that do not gauge the R-symmetry

allow to write a positive cosmological constant even without matter fields

their implementation in string theory: open problem

New mechanism of moduli stabilisation is string theory (type IIB)

- perturbative: weak coupling, large volume
- based on log corrections in the transverse volume of 7-branes

  due to local tadpoles induced by localised gravity kinetic terms

  arising only in 4 dimensions!
- can lead to de Sitter vacua in string theory

  explicit counter-example to dS swampland conjecture

Open question: realise slow-roll inflationary models in string theory