Challenges of an accelerating Universe in supersymmetric theories

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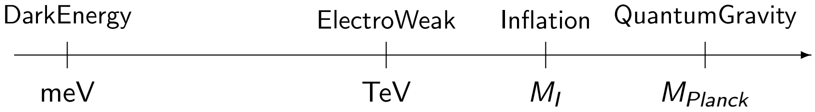
Universe evolution: based on positive cosmological constant

- Dark Energy

  simplest case: infinitesimal (tuneable) +ve cosmological constant

- Inflation (approximate de Sitter)

  describe possible accelerated expanding phase of our universe [8]



Relativistic dark energy   70-75% of the observable universe

negative pressure: $p = -\rho \;\; \Rightarrow$ cosmological constant

$$R_{ab} - \frac{1}{2} R g_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4} T_{ab} \;\; \Rightarrow \;\; \rho_\Lambda = \frac{c^4 \Lambda}{8\pi G} = -p_\Lambda$$

Two length scales:

- $[\Lambda] = L^{-2} \leftarrow$ size of the observable Universe

  $\Lambda_{obs} \simeq 0.74 \times 3H_0^2/c^2 \simeq 1.4 \times (10^{26}\,\mathrm{m})^{-2}$

  Hubble parameter $\simeq 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

- $[\frac{\Lambda}{G} \times \frac{c^3}{\hbar}] = L^{-4} \leftarrow$ dark energy length $\simeq 85\mu\mathrm{m}$

de Sitter spacetime

vacuum solution of Einstein equations with +ve cosmological constant

and maximal symmetry: 10 isometries like flat space

$SO(4,1)$ vs Poincaré E_4

hyperboloid from 5 dimensions: $-y_0^2 + \vec{y}^2 = \frac{1}{H^2}$

$$R_{\mu\nu\lambda\rho} = H^2(g_{\mu\lambda}g_{\nu\rho} - g_{\mu\rho}g_{\nu\lambda}) \qquad R = 12H^2 = 4\Lambda$$

Flat slicing: $ds^2 = -dt^2 + e^{2Ht}d\vec{x}^2$ exponential expansion

FRW with flat 3-space and scale factor $a(t) = e^{Ht}$

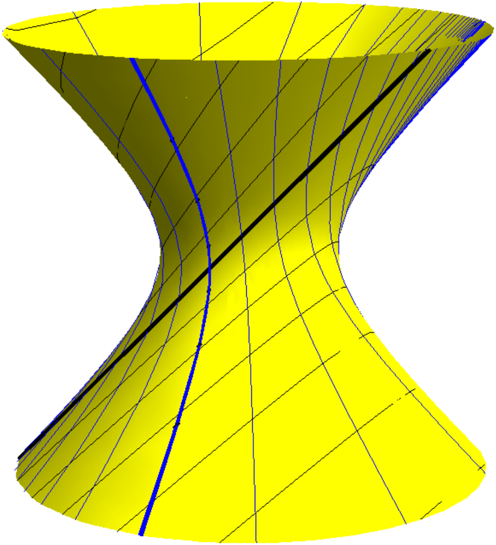
isometries: 3 space translations, 3 rotations, 1 scale, 3 special conformal

e.g. scale: $\vec{x} \to \omega^2\vec{x}$ and $t \to t - \omega/H$

Closed slicing: $ds^2 = -dt^2 + \frac{1}{H^2}ch^2 Ht\, d\Omega_3^2 \leftarrow$ unit sphere S^3

Open slicing: $ds^2 = -dt^2 + \frac{1}{H^2}sh^2 Ht\, dH_3^2 \leftarrow$ unit hyperbolic H^3

de Sitter spacetime



de Sitter spacetime: static coordinates

$$ds^2 = -(1 - H^2 r^2) dt^2 + \frac{dr^2}{1 - H^2 r^2} + r^2 d\Omega_2^2 \quad \leftarrow \ \text{unit sphere } S^2$$

describes $1/4$ of the spacetime

similarity with a black hole metric:

no singularity but cosmological horizon at $r = H^{-1} \equiv r_C$ [11] [13]

Observed Universe: homogeneous, isotropic and (spacially) flat

$\Rightarrow$ all regions causally connected in the past

But in contradiction with Einstein's equations

observed universe has a huge number of causally disconnected regions

Inflation proposal:

postulates an exponentially expanding period in early times

a small region becomes fast exponentially large

$\Rightarrow$ explains homogeneity, isotropy and flatness problems

it needs 50-60 e-foldings of expansion at least

It predicts also small anisotropies from slight deviation from de Sitter space

temperature/density perturbations from quantum fluctuations

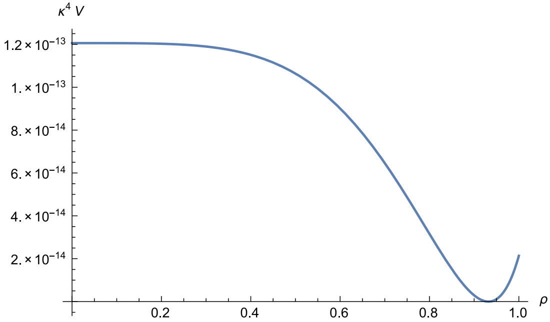
Inflation:

Theoretical paradigm consistent with cosmological observations

But phenomelogical models with not real underlying theory [2]

introduce a new scalar field that drives Universe expansion at early times

Inflaton potential



slow-roll region with V', V'' small compared to the de Sitter curvature

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

$\longrightarrow$ ongoing debate... [25] [30]

Swampland Program

Vafa '05, Ooguri-Vafa '06

Not all effective field theories can consistently coupled to gravity

-anomaly cancellation is not sufficient

- consistent ultraviolet completion can bring non-trivial constraints

those which do not, form the 'swampland'

criteria $\Rrightarrow$ conjectures

supported by arguments based on string theory and black-hole physics

The first and most established example is the Weak Gravity Conjecture:

gravity is the weakest force implying a minimal non-trivial charge

$$q \geq m/\sqrt{2} \quad \text{in Planck units } 8\pi G = \kappa^2 = 1$$

Arkani-Hamed, Motl, Nicolis, Vafa '06

Reissner-Nordstøm black hole

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$f(r) = 1 - \frac{2M}{r} + \frac{Q^2}{r^2} \qquad M = \frac{m}{8\pi},\ Q = \frac{q^2}{32\pi^2}$$

Q^2: repulsive electric energy, while $-2M$: attractive gravity force [6]

Two horizons at $r = r_\pm$ satisfying $f(r) = 0$: $r_\pm = M\left(1 \pm \sqrt{1 - \frac{Q^2}{M^2}}\right)$

- $Q^2 < M^2$: two real roots with $0 < r_-$ (inner) $< r_+$ (outer horizon)

  r_- hides the singularity at $r = 0$, while between horizons t is space like

- $Q^2 = M^2$: $r_- = r_+ \Rightarrow$ extremal BH

  electric and gravity forces are balanced

- $Q^2 > M^2$: complex roots, no horizon $\Rightarrow$ naked singularity at $r = 0$

  the repulsive force is stronger than gravity and forbids BH horizons

Weak Gravity conjecture

Existence of states with $Q^2 > M^2$ minimal non-trivial charge

$\Rightarrow$ Charged black holes can decay

no BH remnants

since naked singularities are forbidden by the Weak Cosmic Censorship

Next: generalisation to de Sitter space using similar arguments

I.A.-Benakli '20

Reissner-Nordstøm black hole in de Sitter space [6]

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$f(r) = 1 - \frac{2M}{r} + \frac{Q^2}{r^2} - \frac{\Lambda}{3}r^2 \qquad M = \frac{m}{8\pi},\ Q = \frac{q^2}{32\pi^2},\ \Lambda = \frac{3}{l^2} = 3H^2$$

$f(r) = 0 \Rightarrow$ 4 roots: one -ve (unphysical), one +ve, two +ve or complex

Define $P(r) \equiv -r^2 f(r) = l^{-2}r^4 - r^2 + 2Mr - Q^2$

$\Rightarrow$ its discriminant $\Delta \propto -\frac{27}{l^2}(Ml)^4 + (l^2 + 36Q^2)(Ml)^2 - Q^2(l^2 + 4Q^2)^2$

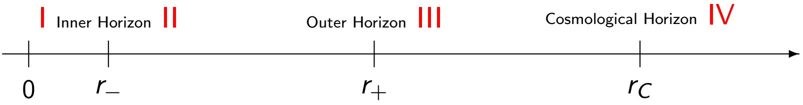
- $\Delta > 0 \Rightarrow$ 3 positive roots: $0 < r_- < r_+ < r_C$

  r_C: cosmological horizon ($\to \infty$ when $\Lambda \to 0$)

- $\Delta = 0 \Rightarrow r_- = r_+ < r_C$, or $r_- < r_+ = r_C$
- $\Delta < 0 \Rightarrow r_\pm$ complex and $r_C > 0$, or $r_- > 0$ and r_+, r_C complex

Reissner-Nordstøm black hole in de Sitter space

$\Delta > 0 \Rrightarrow 3$ Horizons 4 Regions [16]



Δ is quadratic polynomial of $M^2 l^2$ with roots

$$M_{\pm}^2(l, Q^2) = \frac{1}{54l}\left[l(l^2 + 36Q^2) \pm \left(l^2 - 12Q^2\right)^{3/2}\right]$$

$\Delta < 0$ outside the roots (for $l^2 \geq 12Q^2$), or for $l^2 \leq 12Q^2$

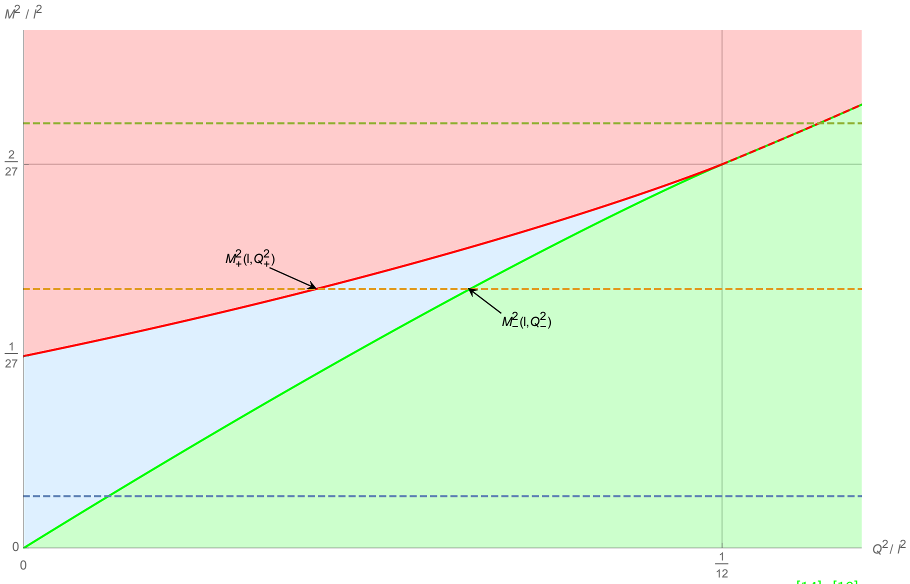
For $\Delta > 0 \Rightarrow$ four regions: $0 < r_- < r_+ < r_C$

- **Region IV:** $r > r_C$

  t space-like, the cosmological constant dominant over all forces
- **Region III:** $r_+ \leq r \leq r_C$ $\quad f(r) \sim 1$ constant
- **Region II:** $r_- \leq r \leq r_+$ BH interior

  t space-like, dominance of gravitational attraction
- **Region I:** $0 < r \leq r_-$ $\quad$ dominance of electromagnetic repulsion

Define $Q_\pm$: $M_\pm^2(l, Q_\pm^2) = M^2$ $\quad Q_+ \leq Q_-$



[14] [19]

Comparison of forces

1. $M^2 < \frac{l^2}{27}$: Q_+ does not exist

   As $Q \nearrow$, $Q < Q_-$ and $M > M_-(l, Q^2) \Rightarrow r_- \nearrow$, $r_+ \searrow$, $r_C \nearrow$

   Region II shrinks with $r_+ \to r_-$

   As $Q > Q_-$ and $M^2 < M_-^2(l, Q^2) \Rightarrow \Delta < 0$ and Region II disappears

   The repulsive electric force is stronger and forbids BH horizons

2. $\frac{l^2}{27} \leq M^2 \leq \frac{2l^2}{27}$: 3 horizons $\Rightarrow Q \in [Q_+, Q-], M \in [M_-, M_+]$

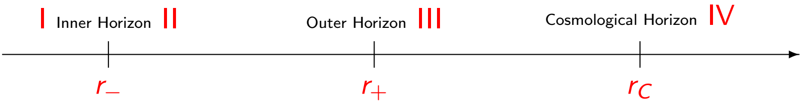
   As $Q \searrow$ towards $Q_+ \Rightarrow r_- \searrow$, $r_+ \nearrow$ and $r_C \searrow$ Region III shrinks

   For $Q < Q_+$ Region III disappears and dS space is 'eaten' by the BH

   As $Q \nearrow$ towards $Q_- \Rightarrow r_- \nearrow$, $r_+ \searrow$ and $r_C \nearrow$ Region II disappears

   For $Q > Q_-$ the electric force is strong and forbids again BH horizons

Comparison of forces



3. $M^2 = \frac{2l^2}{27} \Rightarrow Q_+ = Q_- = l/\sqrt{12}$

   at $Q = Q_\pm$ the 3 horizons coincide $r_- \to r_+ \to r_C \to l/\sqrt{6}$

4. $M^2 > \frac{2l^2}{27}$: there is only one horizon defined at $\delta M = \delta Q^2/l$

   in the parametrization $M = \sqrt{\frac{2}{27}}\, l + \delta M,\ Q^2 = \frac{l^2}{12} + \sqrt{\frac{2}{3}} \delta Q^2$

   $\delta M > \delta Q^2/l$: dS 'eaten' by the BH

   $\delta M < \delta Q^2/l$: electric repulsion forbids BH horizons

Weak Gravity conjecture in dS space: minimal non-trivial charge $q_{\min}(m, l)$

defined in the green region of the figure [16] I.A.-Benakli '20

Weak gravity conjecture in dS space [16]

- **Small charge:** $Q^2 \leq \frac{l^2}{12} \left(q^2 \leq \frac{\pi}{\Lambda G}\right)$:

  $M^2 < M_-^2(l, Q^2) = \frac{1}{54l}\left[l(l^2 + 36Q^2) - \left(l^2 - 12Q^2\right)^{3/2}\right]$

  $\Rightarrow$ flat space limit: $Q^2 > M^2 + \frac{M^4}{l^2} + \mathcal{O}(1/l^4)$

- **Large charge:** $Q^2 \geq \frac{l^2}{12} \left(q^2 \geq \frac{\pi l^2}{3G}\right)$: $M^2 < \frac{3}{2}\frac{1}{l^2}\left(Q^2 + \frac{5}{36}l^2\right)^2$

  $\Rightarrow$ strong curvature limit ($l \to 0$): $Q^2 > \sqrt{\frac{2}{3}}lM - \frac{5}{36}l^2$

  independent of the Newton constant: $q > \left(\frac{32\pi^2}{3}\right)^{1/4}\sqrt{lm}$

Conclusions on WGC on dS space

Weak gravity conjecture in an accelerating Universe:

- existence of a state with charge larger than a minimal value

  generalising the flat space result $Q^2 > M^2$ in Planck units

  minimal charge depends on the mass and the Hubble constant

- small cosmological constant $H < M$ (also $H < \frac{M_P}{\sqrt{12}Q}$) $\Rightarrow$

  power corrections to the flat result $Q^2 > M^2 + M^4 H^2$

- large cosmological constant $\Rightarrow$

  minimal charge^2 linear in mass $Q^2_{\min} \sim M/H$

  constraints for particle physics models of inflation

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 $\Rightarrow$ $W_0 = 0 \rightarrow$ dS vacuum   Friedman '77

• exception: non-linear supersymmetry

Non-linear SUSY in supergravity

I.A.-Dudas-Ferrara-Sagnotti '14

$$K = X\bar{X} \quad ; \quad W = f\,X + W_0$$

$X \equiv X_{NL}$ nilpotent goldstino superfield [24]

$$X_{NL}^2 = 0 \Rightarrow X_{NL}(y) = \frac{\chi^2}{2F} + \sqrt{2}\theta\chi + \theta^2 F$$

$$\Rightarrow \quad V = |f|^2 - 3|W_0|^2 \quad ; \quad m_{3/2}^2 = |W_0|^2$$

- V can have any sign   contrary to global NL SUSY
- NL SUSY in flat space $\Rightarrow f = \sqrt{3}\, m_{3/2} M_p$
- R-symmetry is broken by W_0

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

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

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

Supergravity generalisation: straightforward

unitary 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 introduces a cosmological constant in the absence of matter

Presence of matter $\Rightarrow$ non trivial scalar potential   net result: $\xi_1 \to \xi_1\, e^{K/3}$

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 $m_{3/2}$

In general $\xi_1 \to \xi_1\, f(m_{3/2}[\phi, \bar{\phi}])$ I.A.-Rondeau '99

It can also be written in $N = 2$ supergravity [9]

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

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 RR companions of geometric moduli are projected away $\Rightarrow$

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

complex structure and dilaton $\rightarrow$ 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:

localised couplings + closed string propagation in $d \leq 2$

Effective propagation of massless bulk states in $d \leq 2 \Rightarrow$ IR divergences [30]

$d = 1$: 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

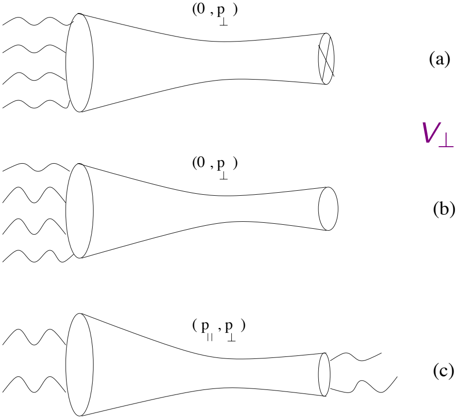
Type II strings: correction to the Kähler potential $\leftrightarrow$ Planck mass

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 [??]

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

χ: Euler number $= 4(n_H - n_V)$ 4-loop σ-model $\nearrow$ vanishes for orbifolds decompactification limit in the presence of branes



$$\mathcal{A} \sim \frac{1}{V_\perp} \sum_{|p_\perp|<M_s} \frac{1}{p_\perp^2} F(\vec{p}_\perp)$$

$$V_\perp = \prod_i R_i \quad \vec{p}_\perp = (n_1/R_1, \cdots, n_d/R_d)$$

$$R_i \sim R >> l_s \Rightarrow$$

$$\mathcal{A} \sim \begin{cases} \mathcal{O}(R) & \textit{for } d{=}1 \\ \mathcal{O}(\log R) & \textit{for } d{=}2 \\ \text{finite} & \textit{for } \text{d} > 2 \end{cases}$$

local tadpoles: $F(\vec{p}_\perp) \sim \left(2^{5-d} \prod_{i=1}^d (1 + (-)^{n_i}) - 2 \sum_{a=1}^{16} \cos(\vec{p}_\perp \vec{y}_a)\right)$

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

Kähler potential:

$$\mathcal{K} = -2\ln\left(\mathcal{V} + \xi + \eta\ln\frac{\mathcal{V}_\perp}{w^2} + \mathcal{O}(\frac{1}{\mathcal{V}})\right) = -2\ln\left(\mathcal{V} + \eta\ln\mu^2\mathcal{V}_\perp\right) \quad w^2 \simeq |\chi|$$

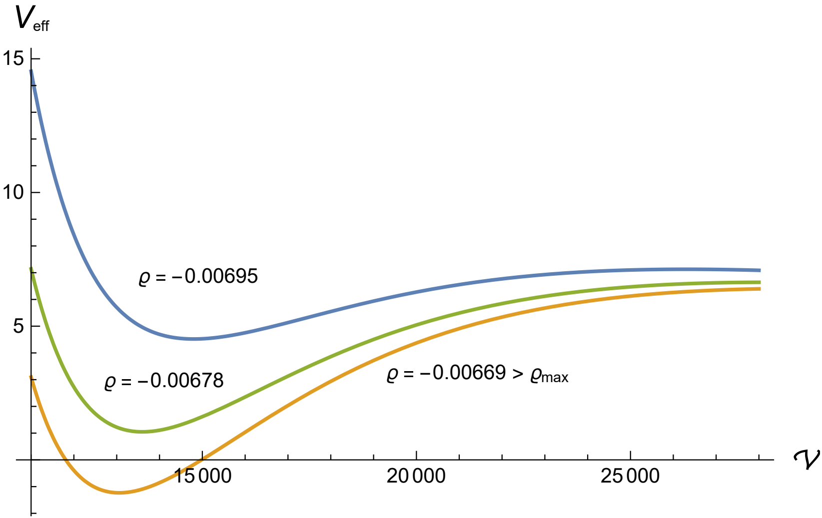
$$\xi = -\tfrac{1}{4}\chi f(g_s)\,; \quad f(g_s) = \begin{cases} \zeta(3) \simeq 1.2 & \text{smooth CY} \\ \frac{\pi^2}{3}g_s^2 & \text{orbifolds} \end{cases} \qquad \eta = -\tfrac{1}{2}g_s T_0 \xi$$ [28]

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

and minimising with respect to transverse volume ratios

$$\Rightarrow\ V \simeq \frac{3\eta\mathcal{W}_0^2}{\mathcal{V}^3}\left(\ln\mu^6\mathcal{V} - 4\right) + 3\frac{d}{\mathcal{V}^2}$$ $\mathcal{W}_0$: constant superpotential, d: D-term

dS minimum: $-0.007242 < \dfrac{d}{\eta\mathcal{W}_0^2\mu^6} \equiv \rho < -0.006738$ with $\mathcal{V} \simeq e^5/\mu^6$



2 extrema min+max $\rightarrow -0.007242 < \rho < -0.006738 \leftarrow$ +ve energy of min

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

dS minimum: $-0.007242 < \dfrac{d}{\eta \mathcal{W}_0^2 \mu^6} \equiv \rho < -0.006738$ with $\mathcal{V} \simeq e^5/\mu^6$

exponentially large volume:

$$\mu = \frac{e^{\xi/6\eta}}{w} = \sqrt{|\chi|}\, e^{-\frac{1}{3 g_s T_0}} \to 0 \quad \Rightarrow$$

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 $(T_0 > 0)$

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

I.A.-Lacombe-Leontaris '20