Accelerated Expansion and the dS conjecture

Max Brinkmann

Ringberg, 08.11.21

The dS conjecture

The (refined) dS conjecture

$$|\nabla V| \geq \frac{c}{M_p} \cdot V \qquad \text{or} \qquad \min(\nabla_i \nabla_j V) \leq -\frac{c'}{{M_p}^2} \cdot V$$

with $c, c' > 0$ and $\mathcal{O}(1)$.

Clearly, the dS conjecture forbids

- (meta-)stable dS vacua/extrema $\nabla V = 0,\ V > 0$
- slow-roll inflation/quintessence models $\epsilon_V \equiv \frac{1}{2}\left(\frac{\nabla V}{V}\right)^2 \ll 1$

Other matching indications against dS vacua (S-matrix...)

The dS conjecture

The (refined) dS conjecture

$$|\nabla V| \geq \frac{c}{M_p} \cdot V \qquad \text{or} \qquad \min(\nabla_i \nabla_j V) \leq -\frac{c'}{{M_p}^2} \cdot V$$

with $c, c' > 0$ and $\mathcal{O}(1)$.

Clearly, the dS conjecture forbids

- (meta-)stable dS vacua/extrema $\nabla V = 0,\ V > 0$
- slow-roll inflation/quintessence models $\epsilon_V \equiv \frac{1}{2}\left(\frac{\nabla V}{V}\right)^2 \ll 1$

Other matching indications against dS vacua (S-matrix...)

Should we expect no accelerated expansion from string theory?

Evidence

Most general and damning arguments for dS conjecture come from

- classical/treelevel
- parametric control
- asymptotic regimes

Evidence

Most general and damning arguments for dS conjecture come from

- classical/treelevel
- parametric control
- asymptotic regimes

These expressions are qualitatively clear: approximations are good.

But I have a hard time defining them precisely.

Tree-level

- Classical SUGRA
- Fluxes, D-branes, O-planes

- no string loops
- no non-perturbative effects

Tree-level

- Classical SUGRA
- Fluxes, D-branes, O-planes

- no string loops
- no non-perturbative effects (except D-branes)

Tree-level

- Classical SUGRA
- Fluxes, D-branes, O-planes

- no string loops
- no non-perturbative effects (except D-branes)

Non-perturbative effects often become important in the minimum:

- KKLT, LVS
- Racetrack in perturbatively flat directions

Parametric Control

Parametric (exponentially) good control

We like to have parametric control over the compactification:

- parametrically large volume
- parametrically small string coupling / dilaton

Parametric Control

Parametric (exponentially) good control

We like to have parametric control over the compactification:

- parametrically large volume
- parametrically small string coupling / dilaton

Parametric loss of control

param. large volume $\leftrightarrow$ param. small KK masses

Asymptotic regimes

Infinite control

Approximations should be *arbitrarily good*!

Asymptotic regimes

Infinite control

Approximations should be *arbitrarily good*!

Can we really have infinite control?

- Same Problem (for Kähler moduli)
- Emergent String Conjecture $\rightarrow$ KK/string states become light

Models we like to think about

- treelevel
- parametric control
- asymptotic regimes

We generally need things to be "parametrically large, but not too large"...

Models we like to think about

- treelevel
- parametric control
- asymptotic regimes

We generally need things to be “parametrically large, but not too large”...

String uncertainty principle?

This “arbitrarily well-controlled” regime is very special at best, measure zero at worst!

The bulk

So what to do?

- Include quantum effects
- unstable - but "stable enough" - configurations

The bulk

So what to do?

- Include quantum effects
- unstable - but "stable enough" - configurations

- TCC: asymptotical dS conjecture [Bedroya, Vafa '19]
- Quantum log-corrections to conjectures [Blumenhagen, MB, Makridou '19]
- Transients with accelerated expansion [Cicoli, Dibitetto, Pedro '20; wip]

Trans-Planckian censorship conjecture [Bedroya, Vafa '19]

Trans-Planckian censorship conjecture (TCC)

Sub-Planckian fluctuations should never cross the Hubble horizon.
For a monotonically decreasing positive potential,

$$M_{\mathrm{pl}} \left\langle \frac{-V'}{V} \right\rangle \Bigg|_{\phi_i}^{\phi_f} > \frac{1}{\Delta\phi} \log\left(\frac{V_i}{A}\right) + c\,.$$

This bounds the lifetime of a (quasi-)dS phase to

$$T \leq \frac{1}{H} \log\left(\frac{M_{\mathrm{pl}}}{H}\right)\,.$$

- Asymptotically $\Delta\phi \to \infty$ equivalent to dS conjecture.
- Lifetime bound is weaker: log-correction.

Quantum log-corrections [Blumenhagen, MB, Makridou '19]

AdS distance conjecture

The limit $\Lambda \to 0$ is at *infinite distance* in field space and there is a *tower of light states* with

$$m_{\text{tower}} = c_{\text{AdS}} \, |\Lambda|^{\alpha}$$

for $\alpha > 0$.

- Usually this tower is assumed to be the KK-tower.
- Satisfied by most treelevel vacua.

Quantum log-corrections [Blumenhagen, MB, Makridou '19]

AdS distance conjecture

The limit $\Lambda \to 0$ is at *infinite distance* in field space and there is a *tower of light states* with

$$m_{\text{tower}} = c_{\text{AdS}} \, |\Lambda|^{\alpha}$$

for $\alpha > 0$.

KKLT

$$m_{\text{KK}}^2 \sim \frac{1}{\log^2 |\Lambda|} |\Lambda|^{\frac{1}{3}} .$$

LVS

$$m_{\text{KK}}^2 \sim \frac{1}{\log^{\frac{2}{9}} |\Lambda|} |\Lambda|^{\frac{4}{9}} .$$

Quantum log-corrections [Blumenhagen, MB, Makridou '19]

AdS distance conjecture

The limit $\Lambda \to 0$ is at *infinite distance* in field space and there is a *tower of light states* with

$$m_{\text{tower}} = c_{\text{AdS}} \, |\Lambda|^{\alpha}$$

for $\alpha > 0$.

Quantum log corrections for non-perturbative vacua

$$m_{\text{tower}} = c_{\text{AdS}} \, |\Lambda|^{\alpha} \frac{1}{\log |\Lambda|^{\beta}}$$

for $\alpha, \beta > 0$.

Origin of log-corrections

Scalar potentials come in typical forms

- *Canonically normalized* potential for nonperturbative contributions:

$$V \sim A\, e^{-c\phi}\, e^{-(b e^{a\phi})} + V_{\text{others}}\,.$$

- Quantum vacuum balances "others" against this term.
- Mass scale is then also set by the double exponential.
- Inverting, we find $e^{a\phi} \sim -b_1 \log(|V|) + b_0$.

Mass scale

$$\begin{aligned} m^2 \sim \partial_\phi^2 V &\sim \left(c^2 + 2abc\, e^{a\phi} ba^2\, e^{a\phi} + (ab)^2 e^{2a\phi}\right) V \\ &\sim -\left(c_2^2 \log^2(|V|) + c_1 \log(|V|) + c_0\right) V\,. \end{aligned}$$

Back to the dS conjecture

Same logic for dS conjecture:

Comparing the dS conjecture to the double exponential form, the natural guess for a *quantum dS conjecture* would be

$$\frac{|\nabla V|}{V} \geq \left(c_1 \log |V| + c_2 \right) .$$

This is exactly the form of the TCC!

Back to the dS conjecture

Same logic for dS conjecture:

Comparing the dS conjecture to the double exponential form, the natural guess for a *quantum dS conjecture* would be

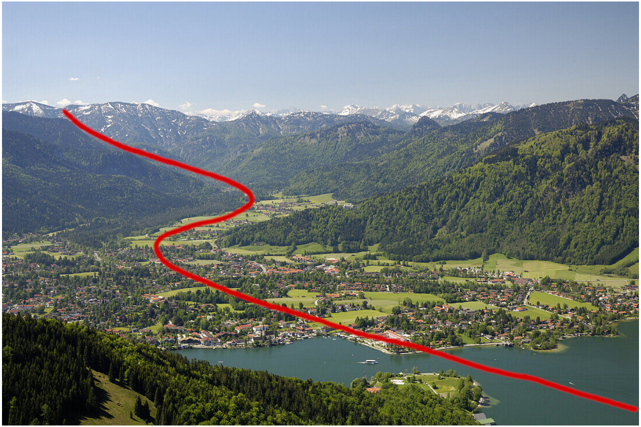
$$\frac{|\nabla V|}{V} \geq \left(c_1 \log|V| + c_2\right).$$

This is exactly the form of the TCC!

Quantum or local, these log corrections allow for short-lived dS vacua.

Quintessence

Simple single-field models of Quintessence are excluded by dS conjecture. But single field scenarios not natural in string theory anyways!



Multifield Quintessence

Accelerated Expansion

$$\text{Slow-roll:} \quad \epsilon_H = -\frac{\dot{H}}{H^2}\,, \quad 0 < \epsilon_H < 1$$

Single field case

$$\epsilon_V \equiv \frac{1}{2}\left(\frac{\nabla V}{V}\right)^2 = \epsilon_H\,, \quad \epsilon_V \gtrsim 1 \quad \text{(dS conj.)}$$

The dS conjecture forbids flat potentials needed for slow roll...

Multifield Quintessence

Accelerated Expansion

$$\text{Slow-roll:} \quad \epsilon_H = -\frac{\dot{H}}{H^2}\,, \quad 0 < \epsilon_H < 1$$

Single field case

$$\epsilon_V \equiv \frac{1}{2}\left(\frac{\nabla V}{V}\right)^2 = \epsilon_H\,, \quad \epsilon_V \gtrsim 1 \quad \text{(dS conj.)}$$

The dS conjecture forbids flat potentials needed for slow roll...

Multifield case

Non-canonical kinetic coupling:
"Rotation" energy contributes to expansion, $\epsilon_V \neq \epsilon_H$!
Allows for steeper potentials while accelerating.

The model

$$S = \int \mathrm{d}^4x \sqrt{-g} \left(\frac{{M_p}^2}{2} R - \frac{1}{2} (\partial \phi_1)^2 - \frac{1}{2} f(\phi_1)^2 (\partial \phi_2)^2 - V(\phi_1) \right)$$

Natural situation in String theory

e.g. Kähler moduli in IIB flux vacua: $T = \tau + i\vartheta, \; K = -p \log(T + \overline{T})$

$$\mathcal{L}_{\mathrm{kin}} \sim K_{T\overline{T}} \partial T \partial \overline{T} = \frac{p}{4\tau} \left((\partial \tau)^2 + (\partial \vartheta)^2 \right)$$

$\phi_1 = \sqrt{p/2} \log(\tau)$	$f(\phi_1) = \sqrt{p/2}\, e^{\sqrt{2/p}\, \phi_1}$
$\phi_2 = \vartheta$	$V(\phi_1) \sim \frac{1}{\tau} = e^{-\sqrt{2/p}\, \phi_1}$

The model

Friedmann equations

$$H^2 = \frac{1}{6{M_p}^2}\left({\dot{\phi}_1}^2 + f^2{\dot{\phi}_2}^2 + 2V + \rho_{\text{matter}}\right)$$

Defining new variables:

$$\begin{aligned} x_1 &= \dot{\phi}_1 \;\; (\sqrt{6}HM_p)^{-1} \\ x_2 &= f\dot{\phi}_2\,(\sqrt{6}HM_p)^{-1} \\ y_1 &= \sqrt{V}\,(\sqrt{3}HM_p)^{-1} \end{aligned}$$

In a flat Universe: $\Omega_{\text{matter}} = 1 - ({x_1}^2 + {x_2}^2 + {y_1}^2) > 0.$

The model

Friedmann equations

$$H^2 = \frac{1}{6{M_p}^2}\left(\dot{\phi_1}^2 + f^2\dot{\phi_2}^2 + 2V + \rho_{\text{matter}}\right)$$

Defining new variables:

$$\begin{aligned} x_1 &= \dot{\phi}_1 \ \ (\sqrt{6}HM_p)^{-1}, \quad x_1 \in [-1,1] \\ x_2 &= f\dot{\phi}_2\,(\sqrt{6}HM_p)^{-1}, \quad x_2 \in [-1,1] \\ y_1 &= \sqrt{V}\,(\sqrt{3}HM_p)^{-1}, \quad y_1 \in [0,1] \end{aligned}$$

In a flat Universe: $\quad \Omega_{\text{matter}} = 1 - ({x_1}^2 + {x_2}^2 + {y_1}^2) > 0.$

Physical parameter space is half a 3-ball.
Eom give autonomous system for evolution of these variables.

The model

Kinetic coupling

$$k_1 = -M_p \frac{f_1}{f}\,, \qquad k_2 = -M_p \frac{V_1}{V}$$

In general, $k_i = k_i(\phi_i)$. Let's assume $k_i = \text{const}$ for simplicity.

The model

Kinetic coupling

$$k_1 = -M_p \frac{f_1}{f}\,, \qquad k_2 = -M_p \frac{V_1}{V}$$

In general, $k_i = k_i(\phi_i)$. Let's assume $k_i = \text{const}$ for simplicity.

Observables

scalar equation of state $\quad \omega_\phi = \frac{{x_1}^2 + {x_2}^2 - {y_1}^2}{{x_1}^2 + {x_2}^2 + {y_1}^2} \sim -1$

scalar energy density $\quad \Omega_\phi = {x_1}^2 + {x_2}^2 + {y_1}^2 \sim 0.7$

Fixed Points

	x_1	x_2	y_1	Ω_ϕ	ω_ϕ	existence
$\mathcal{K}_+$	1	0	0	1	1	all k_1, k_2
$\mathcal{K}_-$	-1	0	0	1	1	all k_1, k_2
$\mathcal{F}$	0	0	0	0	undefined	all k_1, k_2
$\mathcal{S}$	$\frac{\sqrt{3/2}}{k_2}$	0	$\frac{\sqrt{3/2}}{k_2}$	$\frac{3}{k_2^2}$	0	$k_2^2 \geq 3$
$\mathcal{G}$	$\frac{k_2}{\sqrt{6}}$	0	$\sqrt{1-\frac{k_2^2}{6}}$	1	$-1+\frac{k_2^2}{3}$	$k_2 < \sqrt{6}$
$\mathcal{NG}$	$\frac{\sqrt{6}}{(2k_1+k_2)}$	$\frac{\pm\sqrt{k_2^2+2k_2k_1-6}}{2k_1+k_2}$	$\sqrt{\frac{2k_1}{2k_1+k_2}}$	1	$\frac{k_2-2k_1}{k_2+2k_1}$	$k_2 \geq \sqrt{6+k_1^2}-k_1$

Fixed Points

	x_1	x_2	y_1	Ω_ϕ	ω_ϕ	existence
$\mathcal{K}_+$	1	0	0	1	1	all k_1, k_2
$\mathcal{K}_-$	-1	0	0	1	1	all k_1, k_2
$\mathcal{F}$	0	0	0	0	undefined	all k_1, k_2
$\mathcal{S}$	$\frac{\sqrt{3/2}}{k_2}$	0	$\frac{\sqrt{3/2}}{k_2}$	$\frac{3}{k_2^2}$	0	$k_2^2 \geq 3$
$\mathcal{G}$	$\frac{k_2}{\sqrt{6}}$	0	$\sqrt{1-\frac{k_2^2}{6}}$	1	$-1+\frac{k_2^2}{3}$	$k_2 < \sqrt{6}$
$\mathcal{NG}$	$\frac{\sqrt{6}}{(2k_1+k_2)}$	$\frac{\pm\sqrt{k_2^2+2k_2k_1-6}}{2k_1+k_2}$	$\sqrt{\frac{2k_1}{2k_1+k_2}}$	1	$\frac{k_2-2k_1}{k_2+2k_1}$	$k_2 \geq \sqrt{6+k_1^2}-k_1$

- The $\mathcal{NG}$ fixed points with $x_2 \neq 0$ exist only for multifield models
- Non-geodesic field trajectories, ϕ_2 dragged along by $\dot{\phi}_1$

Fixed Points

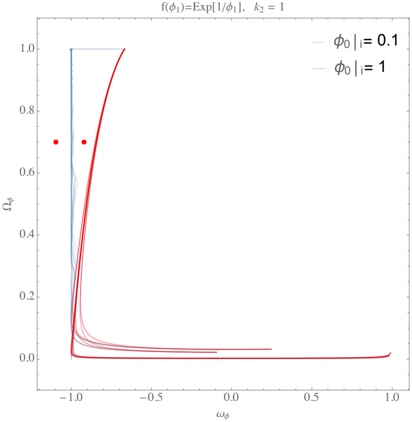
	x_1	x_2	y_1	Ω_ϕ	ω_ϕ	existence
$\mathcal{K}_+$	1	0	0	1	1	all k_1, k_2
$\mathcal{K}_-$	-1	0	0	1	1	all k_1, k_2
$\mathcal{F}$	0	0	0	0	undefined	all k_1, k_2
$\mathcal{S}$	$\frac{\sqrt{3/2}}{k_2}$	0	$\frac{\sqrt{3/2}}{k_2}$	$\frac{3}{k_2^2}$	0	$k_2^2 \geq 3$
$\mathcal{G}$	$\frac{k_2}{\sqrt{6}}$	0	$\sqrt{1-\frac{k_2^2}{6}}$	1	$-1+\frac{k_2^2}{3}$	$k_2 < \sqrt{6}$
$\mathcal{NG}$	$\frac{\sqrt{6}}{(2k_1+k_2)}$	$\frac{\pm\sqrt{k_2^2+2k_2k_1-6}}{2k_1+k_2}$	$\sqrt{\frac{2k_1}{2k_1+k_2}}$	1	$\frac{k_2-2k_1}{k_2+2k_1}$	$k_2 \geq \sqrt{6+k_1^2}-k_1$

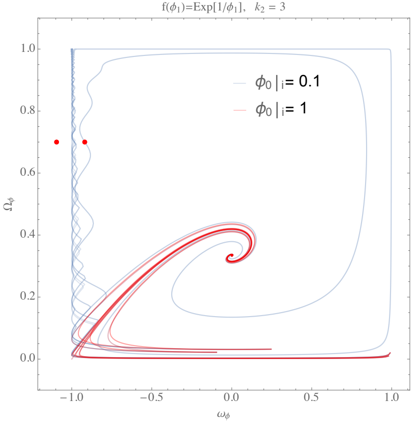
- The $\mathcal{NG}$ fixed points with $x_2 \neq 0$ exist only for multifield models
- Non-geodesic field trajectories, ϕ_2 dragged along by $\dot{\phi}_1$

- Only $\mathcal{G}$, $\mathcal{NG}$ can be accelerating $\omega_\phi < -1/3$
- But fixed points cannot fit $\Omega_\phi \sim 0.7$.

Transients

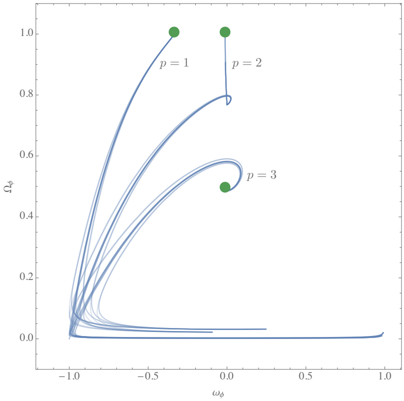
Many kinetic couplings allow for trajectories with viable transients.





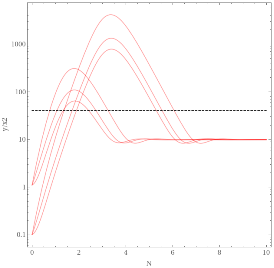
Transients

Unfortunately, the simple Kähler moduli case is not one of these cases. There is an accelerating phase, but the energy density does not fit.



Q-balls

- Non-perturbative instability related to the angular momentum charge.
- Screens the cosmological constant, prevents acceleration.
- Formation and stability of Q-balls has been studied (spintessence).
- Q-ball free wedge in parameter space.
- Trajectories can transition to this wedge before Q-balls can form.
- These can accelerate for $\mathcal{O}(1)$ e-folds.



Summary

- dS conjecture may hold for well controlled sectors.
- But string theory offers much more.
- Local or quantum effects give log contributions to dS conjecture.
- Even runaway Kähler modulus in IIB can have an accelerating phase.
- More involved potentials necessary for observations.

Summary

- dS conjecture may hold for well controlled sectors.
- But string theory offers much more.
- Local or quantum effects give log contributions to dS conjecture.
- Even runaway Kähler modulus in IIB can have an accelerating phase.
- More involved potentials necessary for observations.

Final remarks:

- Probably not good enough for inflation (rare & tachyonic) [Aragam et al '21].
- Also interesting: Radiative Generation of dS from AdS vacua [de Alwis '21].

Thank you for listening

Guten Appetit!