de Sitter vs Quintessence in String Compactifications

Fernando Quevedo
ICTP + Cambridge
Vistas Swampland
Madrid, 2018

M. Cicoli, S. de Alwis, A. Maharana, F. Muia and FQ [arXiv:1808.08967]

Outline

- de Sitter
- Quintessence
- de Sitter vs Quintessence
- de Sitter and Quintessence ??
- No de Sitter and no Quintessence???

Moduli Stabilisation

Moduli Stabilisation in IIB

- Moduli S, T_i, U_a $\quad V_F = e^K \left(K^{-1}_{M\overline{N}} D_M W \overline{D}_{\overline{M}} \overline{W} - 3|W|^2 \right)$

$$W_{\rm tree} = W_{\rm flux}(U,S) \qquad K^{-1}_{i\bar{j}} K_i K_{\bar{j}} = 3$$ No-scale

$$V_F = e^K \left(K^{-1}_{a\bar{b}} D_a W D_{\bar{b}} W \right) \geq 0$$

Fix S,U but T arbitrary

- Quantum corrections $\quad \delta V \propto W_0^2 \delta K + W_0 \delta W$
- Three options: $W_0 \gg \delta W \qquad \delta K \gg \delta W$ Runaway: Dine-Seiberg problem

$$W_0 \sim \delta W = W_{\rm np}.$$
$$W_0 \ll 1$$

Fix T-modulus: KKLT

$$\delta K \sim W_0 \delta W$$
$$\delta K \sim 1/\mathcal{V} \text{ and } \delta W \sim e^{-a\tau}$$

Fix T-moduli: LVS

N=1, 4D Effective Field Theory

$$K = -2\log\left(\mathcal{V}_{\rm CY}\right) - \log\left(S+\bar{S}\right) - \log\left(\int \Omega\wedge\bar{\Omega}\right)$$

$$W = W_0 + Ae^{-aT_i} \qquad\qquad W_0 = \int G_3\wedge\Omega$$

e.g. KKLT

$$V/M_{\rm Pl}^4 = \frac{e^{K_{\rm cs}}}{6\tau^2}\left(aA^2(3+a\tau)e^{-2a\tau} - 3aAe^{-a\tau}W_0\right) \quad V_{\rm up} \simeq \left(\frac{T+\bar{T}}{2}\right)^{-2}$$

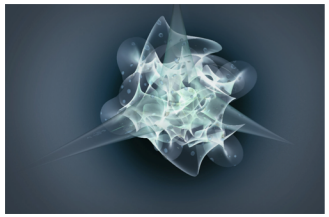
e.g. LVS

$$V_F \propto \left(\frac{K^{S\bar{S}}|D_S W|^2 + K^{a\bar{b}}D_a W \bar{D}_{\bar{b}}\bar{W}}{\mathcal{V}^2}\right) + \left(\frac{Ae^{-2a\tau}}{\mathcal{V}} - \frac{Be^{-a\tau}W_0}{\mathcal{V}^2} + \frac{C|W_0|^2}{\mathcal{V}^3}\right)$$

$$\mathcal{V} \sim e^{a_s\tau_s} \gg 1 \text{ with } \tau_s \sim \frac{\xi^{2/3}}{g_s}.$$

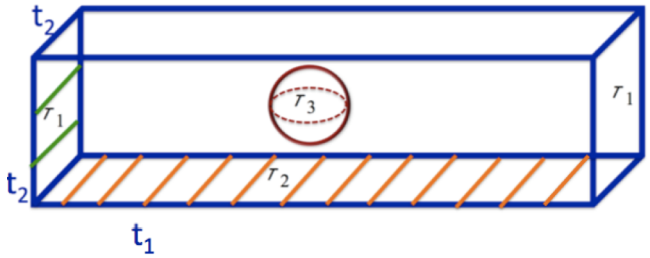
Kahler moduli

- Overall volume



- Blow-up

- Fibre moduli



- + their Axion partners

de Sitter

de Sitter

- Anti D3 brane
- D+F terms in EFT or T-branes
- Complex structure/Dilaton uplift ($D_U W \neq 0$, $D_S W \neq 0$)
- Non critical strings, negative curvature compactifications, Kahler uplift, nonperturbative effects on D3 branes, ...

e.g. T- Branes

4D EFT: F and D terms

$$V_{\rm tot} = V_D^{\rm bulk} + V_F = \frac{1}{\tau_b}\left(q_{D7}|\phi_{\rm dS}|^2 - \xi_{D7}\right)^2 + m_{3/2}^2|\phi_{\rm dS}|^2 + V_{\mathcal{O}(\mathcal{V}^{-3})}$$

$$V_{\rm tot} = V_{D,0}^{\rm bulk} + V_F = \frac{m_{3/2}^4\tau_b}{4q_{D7}^2} + \underbrace{m_{3/2}^2\frac{\xi_{D7}}{q_{D7}}}_{\mathcal{V}^{-8/3}} + V_{\mathcal{O}(\mathcal{V}^{-3})}$$

$$\langle V_{\rm tot}\rangle = \frac{3W_0^2}{4a_s^{3/2}\mathcal{V}^3}\left[\delta\mathcal{V}^{1/3} - \sqrt{\ln\left(\frac{\mathcal{V}}{W_0}\right)}\right] \quad \text{with} \quad \delta \simeq 0.01\left(\frac{a_s^{3/2}}{q_{D7}}\right)$$

10D: T-branes

$$J\wedge\mathcal{F}_{D7} + \left[\Phi,\bar{\Phi}\right]d\text{vol}_4 = 0, \qquad \langle\Phi\rangle = \begin{pmatrix} 0 & \phi_{\mathbf{6}_{+2}} \\ 0 & 0 \end{pmatrix}$$

IIB Advantages

- Fluxes imply (warped) Calabi-Yau
- No-scale structure
- Scales $m_{3/2} << M_s << M_p$
- Two sets of 3-fluxes F_3, H_3 (allows `tuning')
- GVW Superpotential W(S,U) not renormalised!
- Many loop (g_s) and α' corrections to K computed
- Kahler moduli gauge couplings $W_{np}(T)$

Achievements

- Remarkable: well defined prescription exists that includes all stringy ingredients: branes, orientifolds, warping, anti (T)-branes, perturbative, non-perturbative effects, etc.
- IIB with fluxes~ Calabi-Yau (moduli space understood).
- W_0<<1 is plausible (not achieved yet) due to the large number of fluxes.
- Perturbative effects in LVS in better control as the volume is exponentially large. All computed so far harmless.
- Antibrane: nonlinearly realised SUSY (see Wrase's talk)

$$X^2 = 0 \qquad \Delta W = c\,X, \qquad \Delta K = \beta\, X \bar{X}.$$

- Hierarchies:

$$E \ll M_{\rm KK} = \frac{M_s}{\mathcal{V}^{1/6}} \ll M_s \equiv \frac{1}{\ell_s} \equiv \frac{1}{2\pi\sqrt{\alpha'}} = g_s^{1/4}\frac{M_p}{\sqrt{4\pi\mathcal{V}}}\,.$$

$$m_{3/2} \simeq W_0 M_P/\mathcal{V} \qquad m_{3/2}/M_{KK} \ll 1$$

Potential Problems

- To EFT
- To fluxes
- To perturbative effects
- To nonperturbative effects
- To de Sitter

de Sitter Challenges

- Define S-matrix (resonance?)
- Classical no-go theorems
- No dS solution of string theory under full calculational control (KKLT, LVS,...?)

Challenges to KKLT, LVS,...

Danielson, Van Riet's talks

- Fluxes under control only in SUSY 10D Sethi
- All SUSY breaking part is 4D EFT (with string inputs).

  Trust EFT?
- Tuning $W_0 << 1$? in KKLT
- Higher correction in LVS?
- Antibranes (by hand, non susy, singularity?)
- T-branes in a controlled region? Bena et al.
- Antibranes and non-perturbative effects? Moritz et al.

e.g. Bounds on W_0

- Naively derivative expansion implies

$$\frac{|F|}{M_{KK}^2} \simeq W_0 \mathcal{V}^{1/3} \ll 1.$$

- But detailed calculations, expansion parameter is

$$\epsilon = \frac{\Delta M}{M} = \frac{m_{3/2}}{M_{KK}} = \frac{W_0}{\mathcal{V}^{1/3}} = \frac{gF}{M_{KK}^2},$$

Implying:

$$\frac{W_0}{\mathcal{V}^{1/3}} \ll 1\,,$$

Open Questions

- Full control of quantum corrections
- EFT of branes at singularities
- Realistic phenomenology (de Sitter but no SM?)
- F-theory moduli stabilisation
- Populating the landscape (large # of U moduli + vacuum transitions)
- ...

Partly full Partly empty

Quintessence

Swampland conjectures

- Swampland: Quantum gravity vs EFT ! Vafa et al.
- Weak gravity conjecture
- Distance conjecture Other talksl
- New ('anti' de Sitter?) conjecture: $M_p \frac{|\nabla V|}{V} \gtrsim c\,,$ Obied et al

(It would imply quintessence and no de Sitter and hard to have inflation!).

Challenges for the new conjecture

- Higgs potential with quintessence field? (at the <H>=0 point.

  Denef et al.
  Hebecker's talk?

- If V asymptotes to infinity from above even supersymmetric AdS forbidden.

  Conlon

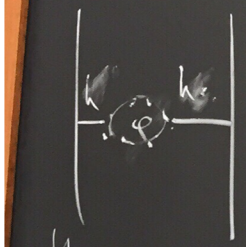
- Both addressed if modify conjecture (allow saddle points for V>0).

  see e.g. Andriot

$$A(\varphi)|H|^4 + C(\varphi)|H|^2 + B(\varphi)$$

$$V(H,\varphi) = A(\varphi)\left(|H|^2 - \alpha^2(\varphi)\right)^2 + B(\varphi)$$

$H = H_0 + h$.



$V_H = 0$; $H = 0$, $|H| = \alpha(\varphi)$

$$V_\varphi = A'\left(H^2 - \alpha^2\right)^2 + 2A(\quad)(-2\alpha\alpha') + B'$$

$H = 0$; $V_\varphi = A'\alpha^4 + 4A\alpha^3\alpha' + B' \geq c\,(A\alpha^4 + B)$

$H = \alpha$; $V_\varphi = B'$

$\geq c\,(B)$

Higgs and Quintessence

- Higgs as quintessence??

$$V = \Lambda^4 + C^4\, e^{-k\,h/M_{\rm p}} \qquad C \simeq 10^{-52} e^{2.5\cdot 10^{71}}\, M_{\rm p} \qquad k = 10^{88}$$

- Higgs-quintessence coupling?

$$V = f(\chi)\,\tilde{V}(h) + \hat{V}(\chi) \qquad \text{with} \qquad f(\chi) = e^{-\chi} \qquad \frac{f_\chi(\chi)\,\tilde{V}(h) + \hat{V}_\chi(\chi)}{f(\chi)\,\tilde{V}(h) + \hat{V}(\chi)} \simeq \frac{f_\chi(\chi)}{f(\chi)} \simeq 1$$

- Several fields?

$$V = f(\phi)\,\tilde{V}(h) + g(\phi) + \hat{V}(\chi)$$

Couplings to SM?, Supergravity?

See Hebecker's talk

de Sitter vs Quintessence

Quintessence from Strings?

- Need stabilise all moduli except for quintessence field: as difficult as getting de Sitter
- Or have many fields rolling but slower than quintessence. Difficult.
- Fifth force and varying couplings constraints (e.g. volume modulus or dilaton problematic)

e.g. Banks, Dine, Douglas '00

Yukawa's

$$\hat{Y}_{ijk} = e^{K/2} \frac{Y_{ijk}(U)}{\sqrt{\tilde{K}_i \tilde{K}_j \tilde{K}_k}},$$

Quintessence Candidates

- Modulus (fibre, blow-up) that does not couple directly to SM. It also would require a very small string scale (e.g. Ms~TeV)

Cicoli, et al '12

- Axions

$$\mathcal{L} = -\frac{1}{2}\partial^{\mu}\theta\partial_{\mu}\theta - \mu^{4}\left(1-\cos\left(\frac{\theta}{f}\right)\right),$$

K. Choi '99
Panda et al '11
Kaloper et al. '08
Kamionkowski et al '13

de Sitter and Quintessence

Axion Quintessence in LVS

$$m_a \simeq \sqrt{\frac{g_s}{8\pi}}\,\frac{M_p}{\mathcal{V}^{2/3}}\,e^{-\frac{\pi}{N}\mathcal{V}^{2/3}}M_p\,,$$

Naturally very small!

$$V = \Lambda^4 - \sum_{i=1}^{N_{\rm ULA}} \Lambda_i^4 \cos\left(\frac{a_i}{f_i}\right) + \cdots\,,$$

Minimum not necessarily at zero

$$\epsilon = \frac{1}{2}\left[\left(\frac{\Lambda_\ell}{\Lambda}\right)^4 \frac{M_p}{f_\ell}\right]^2 \frac{\sin^2\left(a_\ell/f_\ell\right)}{\left(1-\left(\Lambda_\ell/\Lambda\right)^4\cos\left(a_\ell/f_\ell\right)\right)^2} < 1\,.$$

Slow-roll

$$f_\ell \gtrsim M_p.$$

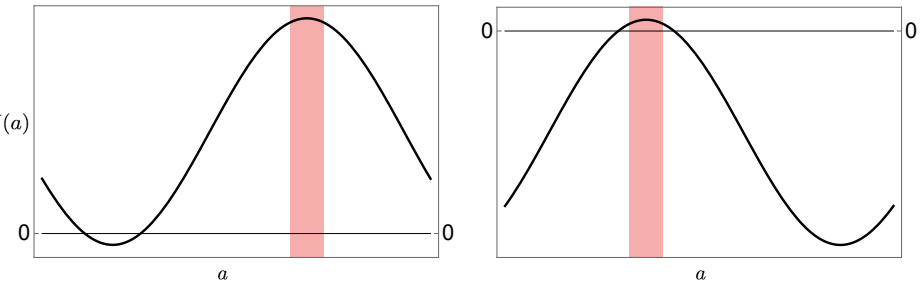
Not necessarily

ULA: (fuzzy) dark matter and dark radiation or dark energy and dark radiation?

(A)dS and Axion Quintessence

- Hilltop Quintessence

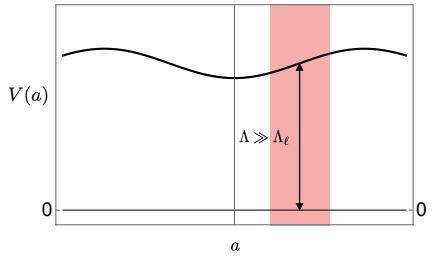
$\Lambda^4 + \Lambda_i^4 > 0$



- Quasi-natural quintessence

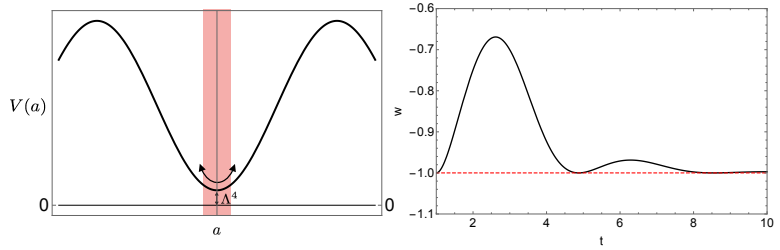
$$f_\ell \gtrsim \left(\frac{\Lambda_\ell}{\Lambda}\right)^4 M_p$$

$$f_\ell < M_p \qquad \Lambda \gg \Lambda_\ell .$$



$$w = \frac{p}{\rho} = \frac{\frac{\dot{a}^2}{2} - V}{\frac{\dot{a}^2}{2} + V} \sim -\frac{1 - \frac{1}{3}\epsilon}{1 + \frac{1}{3}\epsilon} \sim -1 + \frac{2}{3}\epsilon .$$

- Oscillating quintessence



Conclusions

- de Sitter and Quintessence: Many achievements, challenges, open questions

- Observational challenges for both! (w<-1 and varying??)

From: Joseph Polchinski <joep@kitp.ucsb.edu>
To: fq201@damtp.cam.ac.uk
Cc: Senarath de Alwis <dealwiss@gmail.com>
Date: Mon, 7 Aug 2017 17:01:48 -0700
Subject: Re: Question on: Hartle-Hawking

By the way, I have a new principle: if we have a seemingly powerful no-go theorem, then we will find a powerful exception just beyond the limit of validity of the theorem.

Example:

No stable atoms in classical electrodynamics.

No symmetries beyond Coleman-Mandula.

No composite graviton in field theory.

No de Sitter in classical GR (including branes).

(are there others?)

So [redacted] the no-go argument [redacted] is just a red flag that it is irrelevant.

Best,
Joe