Workshop SM & Beyond CORFU 10 September 2019

String loop corrections and de Sitter vacua

George K. Leontaris

University of Ioannina

Ιωαννινα

GREECE

based on work with Ignatios Antoniadis and Yifan Chen

arXiv: 1803.08941 ; 1809.05060 & to appear

A few facts about Cosmology and de Sitter Vacua

▲ *Major Observational Discovery* ~ 20 *years ago:*

Accelarating Expansion of the Universe

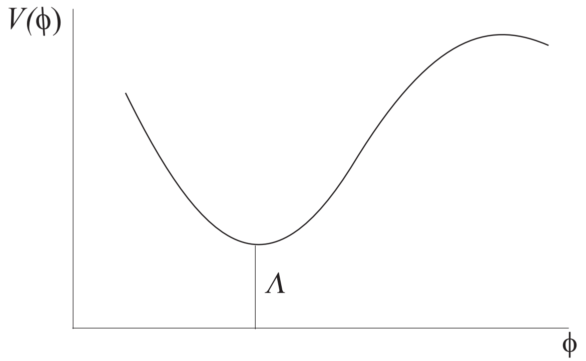
▲ *explained with* **Dark Energy** *permeating all of space*

$\Lambda \approx 10^{-120}$ (*in 4-d Planck units*)

equivalently, positive vacuum energy

▲ *Simple Effective Field Theory description:*

Potential Energy $V(\phi)$ of a scalar field, ϕ



▲ de Sitter vacua ▲

Zeitgeist *(String Theory)*

▲ String Landscape: Ongoing debate on the existence of dS vacua

Some discouraging no-go theorems and conjectures

▲ *Maldacena-Nunez no-go theorem (hep-th/0007018)*:

There are no stable dS compactifications of 10-d SUGRA

Assumption: compactification manifold $\rightarrow$ *non-singular*, but:

▲ Singular manifolds are acceptable and useful in string theory

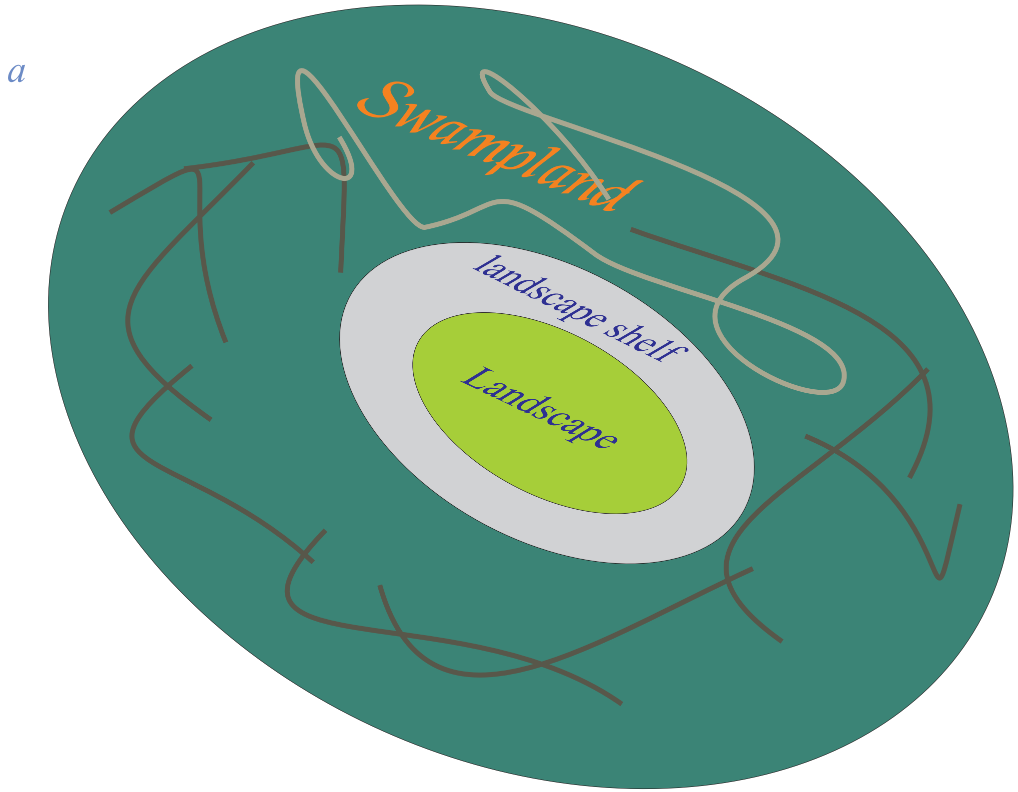
▲ *Vafa et al conjecture (hep-th/1806.08362)*:

The scalar field potential $V(\phi)$ *of a consistent field theory (in the sense that* $\exists$ *UV completion) satisfies constraints such as:*

$$\frac{|\nabla V|}{V} \geq \frac{c}{M_{Pl.}} \quad \frac{\min(\nabla_i V \nabla_j V)}{V} \leq -\frac{c'}{M_{Pl.}^2}$$

i.e., according to the spirit of time ... all dS vacua fall into the:

SWAMPLAND!



String landscape is surrounded by a vast swampland of inconsistent field theories of dS vacua... (according to recent conjectures...)

Grayzone populated by 'stringy' dS vacua not unanimously adopted

$\mathcal{A}$im of our $\mathcal{W}$ork

- Propose a solution to the Moduli Stabilisation problem
- Examine whether a dS vacuum exists in String Theory

(⋯ based on **perturbative** quantum corrections only!)

- If yes,

examine if slow roll inflation can be accommodated.

Outline of the present Talk

- *Effective Supergravity from type II-B*
- R^4-terms and localised gravity
- D7 branes and logarithmic corrections
- F-term and D-term potential
- on de Sitter vacua
- Concluding Remarks

★ Type II-B/F-theory

★ **Moduli** Space (*notation*)

▲ Graviton, dilaton and Kalb-Ramond (KR)-field

$$g_{\mu\nu},\ \phi,\ B_{\mu\nu} \to B_2$$

▲ Scalar, 2- and 4-index fields (*p-form potentials*)

$$\mathbf{C_0}, C_{\mu\nu}, C_{\kappa\lambda\mu\nu} \to C_p,\ p = 0, 2, 4$$

1. ▲ $C_0,\ \phi$ $\to$ *combined to* **axion-dilaton** *modulus:*

$$S = C_0 + i\, e^{-\phi} \to C_0 + \frac{i}{g_s}$$

2. z_a : *Complex Structure (CS)* moduli (*shape*)

3. T_i : Kähler (*size*) 4-cycle moduli

▲ Fact ▲

▲ ∃ **plethora** *of* **moduli fields** *in CY compactifications*→
... if massless → problems with fifth forces and other cosmological issues...

▲ Task ▲

▲ Generate a potential and assure positive mass-squared for all moduli fields ⇒

⇒ *Moduli Stabilisation* ⇐

Type II-B effective Supergravity

Basic 'ingredients':

Superpotential $\mathcal{W}$ *and Kähler potential* $\mathcal{K}$

▲ The Superpotential $\mathcal{W}$ ▲

▲ *Field strengths:*

$$F_p := d\,C_{p-1},\ \ H_3 := d\,B_2,\ \ \Rightarrow \mathbf{G_3} := F_3 - S H_3$$

▲ *Holomorphic* $(3,0)$*-form :* $\Omega(z_a)$

Flux-induced superpotential (*G. V. W. hep-th/9906070*):

$$\mathcal{W}_0 = \int \mathbf{G_3} \wedge \Omega(z_a)$$

▲ Supersymmetric conditions:

$$\mathcal{D}_{z_a}\mathcal{W} = 0, \quad \mathcal{D}_S\mathcal{W} = 0\ :$$

$\Rightarrow$ z_a *and* S **stabilised** $\Leftarrow$

but!

▲ Kähler moduli $\notin \mathcal{W}_0$ $\Rightarrow$ remain unfixed! ▲

▲ The Kähler potential ▲

$$\mathcal{K}_0 = -\sum_{i=1}^{3} \ln(-i(T_i - \bar{T}_i)) - \ln(-i(S - \bar{S})) - \ln(i \int \Omega \wedge \bar{\Omega}) \cdot$$

▲ The scalar potential ▲

$$\begin{aligned} V &= e^{\mathcal{K}} (\sum_{I,J} \mathcal{D}_I \mathcal{W}_0 \mathcal{K}^{I\bar{J}} \mathcal{D}_{\bar{J}} \mathcal{W}_0 - 3|\mathcal{W}_0|^2) \\ &= e^{\mathcal{K}} \sum_{I,J=z_a,\neq T_i} D_I \mathcal{W}_0 \mathcal{K}^{-1}_{I\bar{J}} D_{\bar{J}} \mathcal{W}_0 \;\; (D_I \mathcal{W}_0 = 0, \text{ flatness}) \\ &\quad + e^{\mathcal{K}} \left(\sum_{I,J=T_i} \mathcal{K}_0^{I\overline{J}} D_I \mathcal{W}_0 D_{\overline{J}} \mathcal{W}_0 - 3|\mathcal{W}_0|^2 \right) \;\; (= 0, \text{ no scale}) \end{aligned}$$

Kähler moduli completely **undetermined**!

A bottom-up approach

$\Downarrow$ ...need to include **Quantum corrections ...** $f(\tau)$ ...

"breaking" no-scale structure:

$$\mathcal{K} = -2\log\left(\tau^{\frac{3}{2}} + \gamma f(\tau)\right), \quad \mathcal{V} = \tau^{\frac{3}{2}}, \quad |\gamma| < 1$$

Resulting F-term potential (γ-expansion):

$$V_F \propto \gamma\tau^{-\frac{9}{2}}\left(3f(\tau) - 4\tau f'(\tau) + 4\tau^2 f''(\tau)\right)$$

Some possible $f(\tau)$ functions:

▲▲α) power-law corrections (V_F: *homogeneous*) $f(\lambda\tau) = \lambda^n f(\tau)$)

$$f(\tau) \propto \tau^n \;\Rightarrow\; \boxed{V_F \propto \tau^{n-\frac{9}{2}}} \Rightarrow \nexists \;\; (V_F)_{min}$$

▲▲β) **logarithmic** $f(\tau) \propto \log\tau$: [a]

$$\boxed{V_F \propto \gamma\tau^{-\frac{9}{2}}\left(\log(\tau) - \frac{8}{3}\right) + \cdots} \Rightarrow \ \exists \ (V_F)_{min} \ \forall\ \gamma < 0$$

▲ Moreover, adding a constant $\xi = \gamma\log(\mu)$:

$$\begin{aligned}\mathcal{K} &= -2\log\left(\mathcal{V} + \gamma\log(\mathcal{V}) + \xi + \mathcal{O}(\frac{1}{\mathcal{V}})\right)\\ &= -2\log\left(\mathcal{V} + \gamma\log(\mu\mathcal{V}) + \mathcal{O}(\frac{1}{\mathcal{V}})\right)\end{aligned}$$

At $(V_F)_{min}$ volume size controlled by parameter μ:

$$\mathcal{V}_{min} = \frac{1}{\mu}e^{\frac{13}{3}}$$

$\Rightarrow$ large volume expansion for $\mu = e^{-\frac{\xi}{|\gamma|}} \ll 1$ (... $\xi \gg |\gamma|$)

[a] motivated by log-corrections in Antoniadis-Bachas, PLB450(99)83.

Origin of ξ and $f(\tau)$

from

$\mathcal{PERTURBATIVE}$

String Loop Corrections

▲ α'^3 **Corrections** ▲

Imply redefinition of 4-d dilaton (*Becker et al, hep-th:0204254*)

$$
\begin{aligned}
e^{-2\phi_4} &= e^{-2\phi_{10}}(\mathcal{V} + \xi) \\
&= e^{-\frac{1}{2}\phi_{10}}\,(\hat{\mathcal{V}} + \hat{\xi}) \quad \text{(Einstein frame)}
\end{aligned}
$$

with $\mathcal{V} \to$ *6d-volume*, $t^k \to$ Kähler class deformations

$$
\begin{aligned}
\mathcal{V} &= \frac{1}{3!}\kappa_{ijk} v^i v^j v^k \\
v^k &= -\mathrm{Im}(t^k) = \hat{v}^k\, e^{\frac{1}{2}\phi_{10}} \\
\xi &= -\frac{\zeta(3)}{4(2\pi)^3}\chi
\end{aligned}
$$

Introducing the definitions:

$$
\begin{aligned}
T^k &= b + i\,\hat{\mathcal{V}}^k \\
\hat{\mathcal{V}}_k &= \frac{1}{3!}\kappa_{ijk}\hat{v}^i\hat{v}^j \\
S &= C_0 + i\,e^{-\phi_{10}} \qquad (1)
\end{aligned}
$$

Kähler potential written as: $(\hat{v}_k = \hat{v}_k(T^j))$

$$
\begin{aligned}
\mathcal{K} &= -\ln(\{-i(S-\bar{S})\}) \\
&\quad -2\ln\left\{-i(T^k-\bar{T}^k)\hat{v}_k + \frac{\xi}{\sqrt{2}}(-i(S-\bar{S}))^{\frac{3}{2}}\right\} \qquad (2) \\
&\quad +\mathcal{C}.\mathcal{S}. \qquad (3)
\end{aligned}
$$

... involved dependence on T^k and S.

▲▲ String Coupling Loop Corrections ▲▲

important in the presence of D-branes

(*Antoniadis, Chen, G.K.L.: hep-th/1803.08941* & *to appear*)

In String Theory:

multigraviton scattering generates higher derivative couplings in curvature *(see Green, Vanhove, hep-th/9704145; Antoniadis, Ferrara, Minasian, Narain, hep-th/9707013, Kiritsis, Pioline hep-th/9707018)*

Type II 10-d effective action with $\mathcal{EH}$ & R^4 terms:

$$\mathcal{S} \quad \supset \quad \frac{c}{l_s^8}\int_{M_{10}} e^{-2\phi}\mathcal{R}_{(10)} + \frac{d}{l_s^2}\int_{M_{10}} (-2\zeta(3)e^{-2\phi} + 4\zeta(2))R^4 \wedge e^2$$

Leading correction term in type II-B action:

$$\propto R^4$$

Reduction on $\mathcal{M}_4 \times \mathcal{X}_6$, (with $\mathcal{M}_4$ 4-d Minkowski) induces:

$$\Rightarrow \quad \frac{c}{l_s^8} \int_{M_4 \times \mathcal{X}_6} e^{-2\phi} \mathcal{R}_{(10)} + \underbrace{2d \frac{\chi}{l_s^2} \int_{M_4} (\zeta(2) - \zeta(3) e^{-2\phi}) \mathcal{R}_{(4)}}_{\textit{induced } \mathcal{EH} \textit{ term}},$$

localised Einstein Hilbert ($\mathcal{EH}$) term $\propto$ Euler characteristic

$$\frac{1}{3!(2\pi)^3} \chi = \int R \wedge R \wedge R$$

▲▲ *this $\mathcal{EH}$ term possible in 4-dimensions only*!

$$\Downarrow$$

$\chi \neq 0 \Rightarrow$ localised graviton kinetic terms: $\cdots (\mathcal{V} + \beta \chi) \mathcal{R} \cdots \Rightarrow$

Localisation "Width"

• Origin → 1-loop amplitude: two massless gravitons and one KK-excitation.

• Computations will be done in the orbifol limit: $CY \to T^6/Z_N$.

• Tree-level contribution $\propto \zeta(3)$ to $\mathcal{EH}$-term vanishes in orbifold background $CY \to T^6/Z_N$.

• 1-loop contribution only from SUSY preserving $\mathcal{N} = (1,1)$ odd-odd spin structure of partition function (Antoniadis et al hep-th/0209030)

$$Z_{odd}^{(1,1)} \to \sum_{f=0,\ldots,n_f} \chi_f \equiv \chi$$

$(0,\ldots,n_f$ =fixed points)

Localisation width of w/f of $R_{(4)}$. Amplitude: (*in odd-odd spin structure, one graviton vertex in* $(-1,-1)$*-ghost picture*)

$$\langle V^2_{(0,0)} V_{(-1,-1)} \rangle = -\mathcal{C}_{\mathcal{R}} \frac{1}{N^2} \sum_{\substack{f=0,\ldots,n_f \\ k=0,\ldots,N-1}} e^{i\gamma^k q\cdot x_f} \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^2} \int \prod_{i=1,2,3} \frac{d^2 z_i}{\tau_2} {\sum_{(h,g)}}' e^{\alpha' q^2 F_{(h,g)}(\tau, z_i)}$$

• $\mathcal{C}_{\mathcal{R}}$ tensor structure, $F_{(h,g)}$: twisted sectors $(f,g) = (l,m)\frac{v}{N}$

Localisation "seen" in Gaussian profile of Fourier transform : ($\rightarrow R_{(4)}$ coef. in 6d-space):

$$\rightarrow \frac{N}{w^6} e^{-\frac{y^2}{2w^2}}, \quad w^2 \sim \alpha' F_{(f,g)} \sim \frac{\ell_s^2}{N} \rightarrow \text{eff.width}$$

▲▲ Introducing 7-branes ▲▲

Localised vertices can emit gravitons and KK-excitations in 6d

⇒ KK-exchange between graviton vertices and $D7$-branes

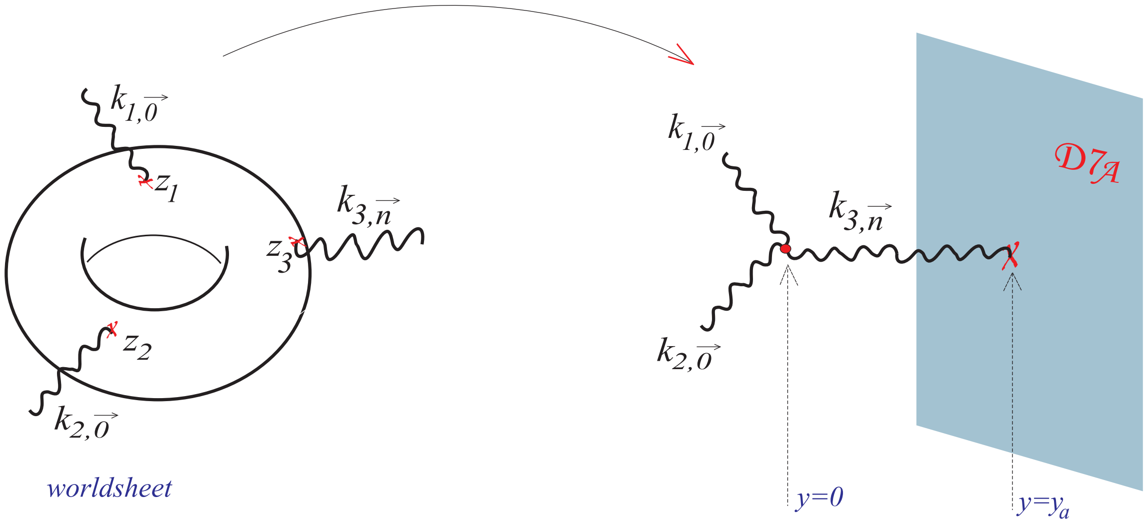


Figure: non-zero contribution from 1-loop; 3-graviton scattering amplitude 2 massless 1 KK Graviton scattering $\langle V^2_{(0,0)} V_{(-1,-1)}\rangle$ & KK-propagating in 2-d towards $D7$

Amplitude is a product of:

- vertex $\langle V^2_{(0,0)} V_{(-1,-1)} \rangle \;\to\; \mathcal{C}_{\mathcal{R}} N e^{-w^2 q_\perp^2/2}$
- the two-dimensional propagator, $\propto \frac{1}{q_\perp^2}$
- contribution from a $D7$-brane/$O7$-plane.

$$\begin{aligned} A_S &= -\mathcal{C}_{\mathcal{R}} \sum_{q_\perp \neq 0} g_s^2 T N e^{-w^2 q_\perp^2/2} \frac{1}{q_\perp^2 R_\perp^2} \;, \\ &\to -\mathcal{C}_{\mathcal{R}} g_s^2 T \frac{2\pi}{\sin\frac{2\pi}{N}} \left\{ -\frac{\gamma}{2} + \log\left(\frac{R_\perp}{w}\right) + \ldots \right\} \end{aligned} \qquad (4)$$

Including both Corrections:

$$\frac{1}{(2\pi)^3} \int_{M_4 \times \mathcal{X}_6} e^{-2\phi} \mathcal{R}_{(10)} + \frac{4\zeta(2)\chi}{(2\pi)^3} \int_{M_4} (1 + \sum_{i=1,2,3} e^{2\phi} T_i \log(R^i_\perp) \mathcal{R}_{(4)} \;,$$

Kähler moduli

STABILISATION

Recall that $\mathcal{V} = \frac{1}{6}\,\kappa_{ijk}\,v^i v^j v^k$. ($\kappa_{ijk}$ intersection numbers)

Assuming a particular case...

$$\kappa_{123} = \kappa_{132} = \kappa_{231} = \kappa_{213} = \kappa_{312} = \kappa_{321} = 1$$

$$\tau_1 = v_2 v_3,\ \tau_2 = v_1 v_3,\ \tau_3 = v_1 v_2,$$

$$\mathcal{V} \to \sqrt{\tau_1 \tau_2 \tau_3}$$

Kähler part becomes

$$\mathcal{K} \quad = \quad -\ln(-i(T^k - \bar{T}^k)v_k) = \ln(\sqrt{\tau_1 \tau_2 \tau_3}) \equiv \ln(\mathcal{V}) \tag{5}$$

▲▲ Loop corrections to the Kähler potential involving the Kähler moduli are written in the form:

$$\delta = \sum_k \gamma_k \log(\tau_k)$$

... inclusion in the tree-level Kähler...

$$\begin{aligned} \mathcal{K} &= -2\ln\left[e^{-2\phi}(\mathcal{V}+\xi)+\delta\right] \\ &= -\ln[-i(S-\bar{S})] - 2\ln\left(\hat{\mathcal{V}}+\hat{\xi}+\hat{\delta}\right) \end{aligned}$$

with $S = b + ie^{-\phi}$, $\hat{\delta} = \delta g_s^{1/2}$

▲▼ ξ and δ break **no-scale** structure of Kähler potential →

$$\mathbf{V}_{\text{eff}} \neq \mathbf{0}$$

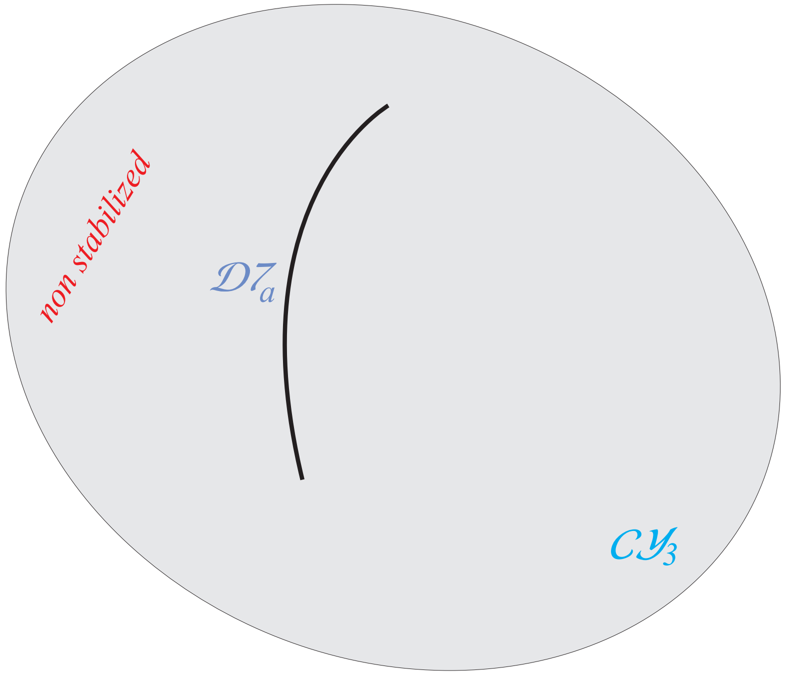
Stabilisation and $D7$ Branes

Looking for the minimum number of $D7$ branes required to stabilise the T_i-fields and lead to a dS minimum.

Quantum corrections from a single $D7$ Brane

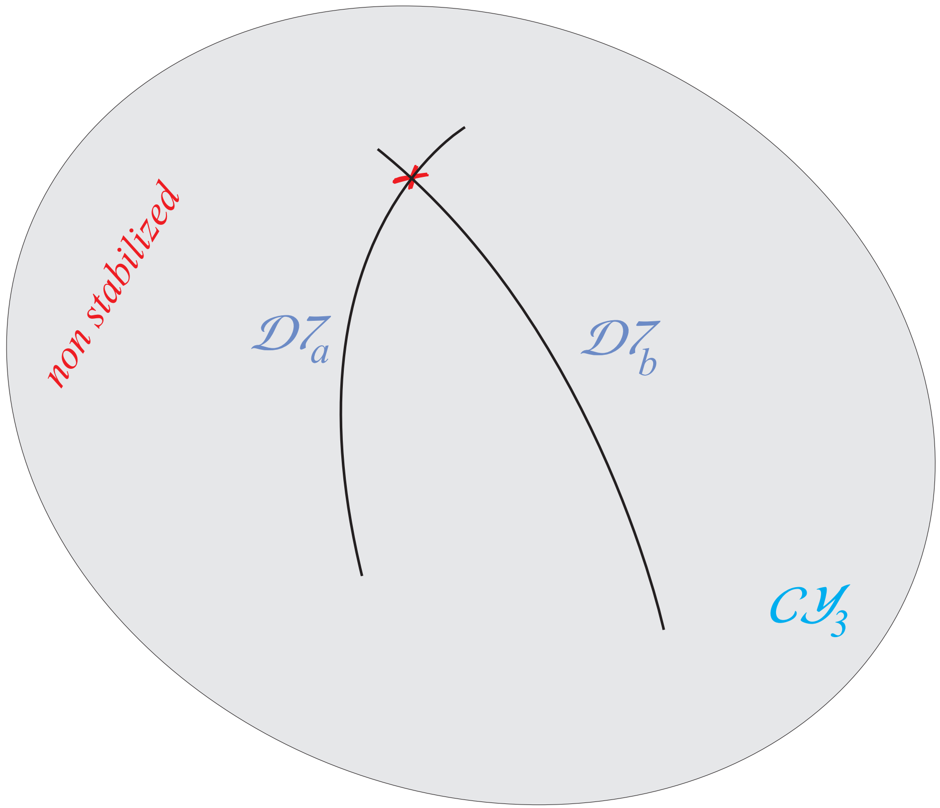
- *volume parametrised in terms of τ, u 4-cycle moduli:* $\mathcal{V} = \tau\sqrt{u}$

$$\mathcal{K} = -2\ln\left(\tau\sqrt{u} + \xi + \eta\ln u\right)$$



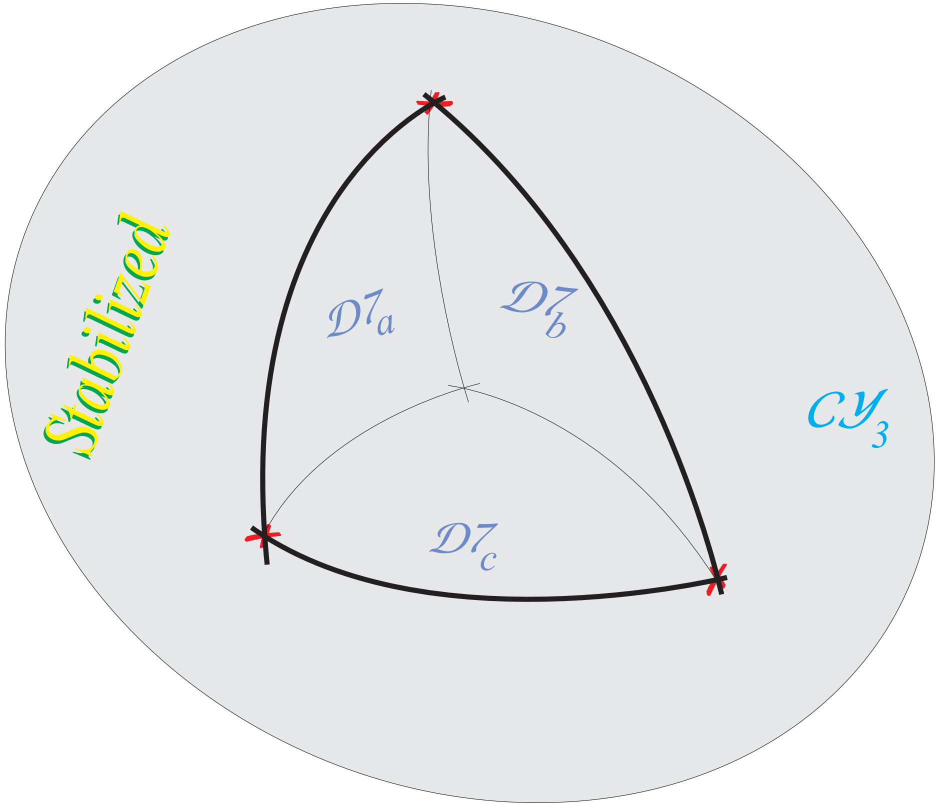
- $\exists$ minimum for u-direction iff $\eta < 0$, however ...
- stabilisation of τ-direction not possible with only one $D7$!

$$\mathcal{K} = -2\ln\left(\mathcal{V} + \xi + \gamma_1 \ln u_1 + \gamma_2 \ln u_2\right)$$



▲ ... *not even for two intersecting D7s!*

Stabilisation requires three intersecting $D7$s! (at least)



▲ Kähler potential including loop corrections: from $3 \times D7$:

$$\mathcal{K} = -2\ln\{\mathcal{V} + \sum_{k=1}^{3}\gamma_k \ln(\mu\mathcal{V}/\tau_k)\}$$

F-term potential (*assuming* $\gamma_k \to \gamma$):

$$V_F \;\approx\; 3\gamma\frac{\ln\mu\mathcal{V} - 4}{\mathcal{V}^3} + \mathcal{O}(\gamma^3)$$

▲ **Inclusion of $\mathcal{D}$-terms**:

$$V_{\mathcal{D}} \;=\; \sum_a \frac{d_a}{\tau_a}\left(\frac{\partial\mathcal{K}}{\partial\tau_a}\right)^2 \;\approx\; \sum_a \frac{d_a}{\tau_a^3} + \cdots$$

Minimisation of $V_{\rm eff} = V_F + V_{\mathcal{D}}$ w.r.t.:

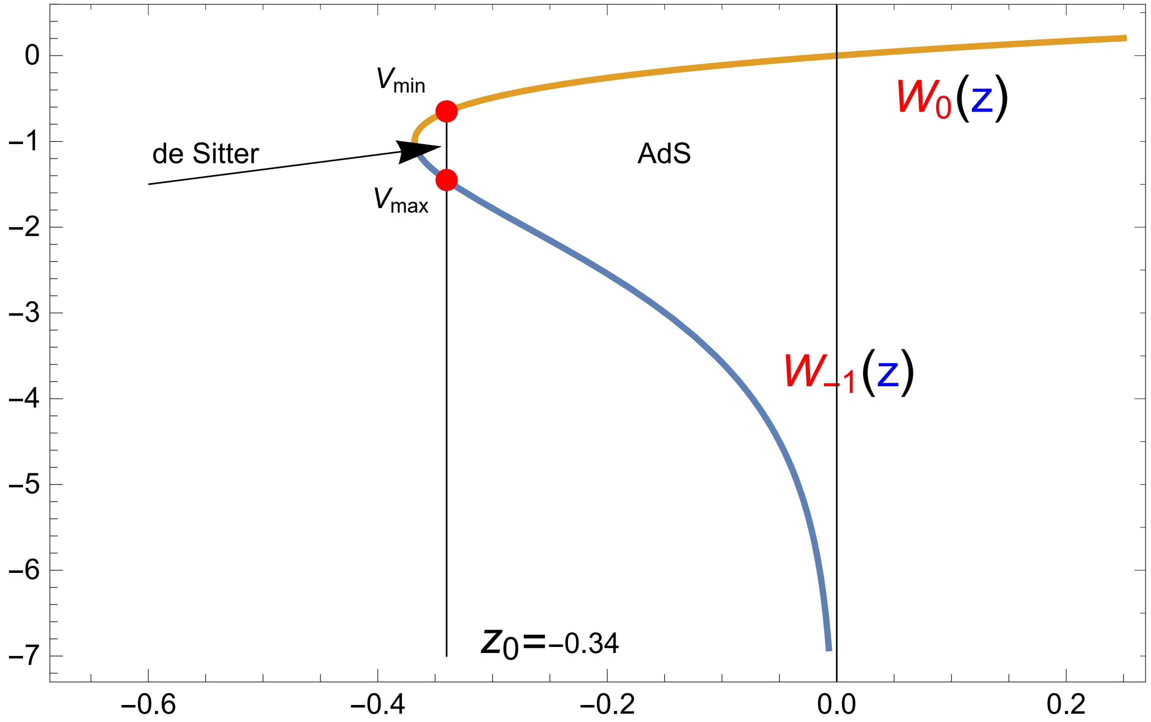
$$\tau_1, \tau_2 \; and \; \mathcal{V} = \sqrt{\tau_1\tau_2\tau_3} \;\Rightarrow$$

$$V_{\rm eff} \propto \gamma\frac{\ln\mu\mathcal{V} - 4}{\mathcal{V}^3} + \frac{d}{\mathcal{V}^2}$$

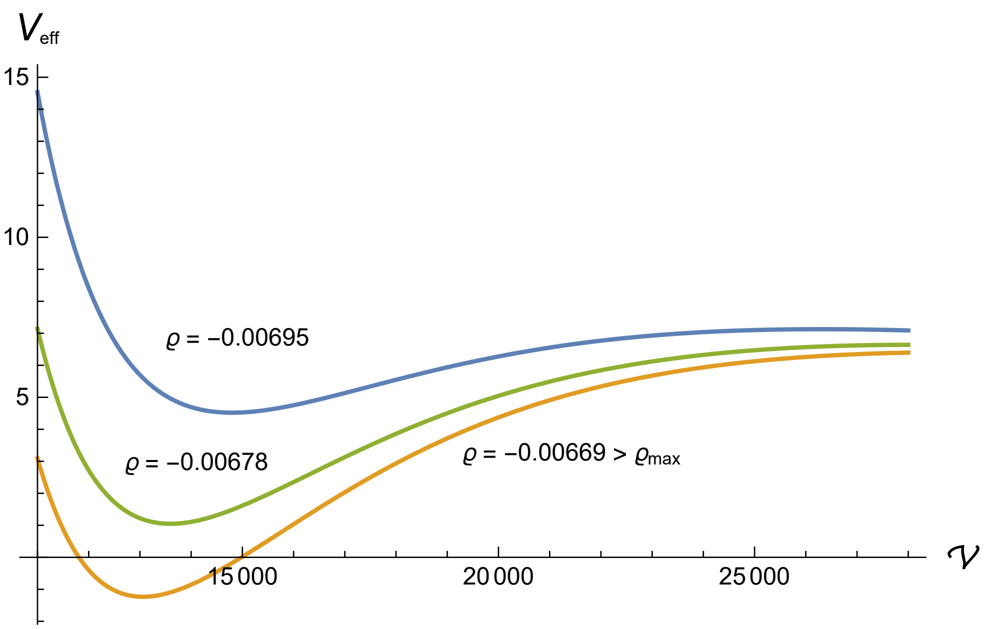
▲ de Sitter vacua ▲

minimum $V_{\text{eff}} = V_F + V_{\mathcal{D}}$ *at* $\mathcal{V}_0$ *must be positive:* $\left(W = \frac{13}{3} - \ln \mu\mathcal{V}\right)$

$$V_{\text{eff}}^{min} = \frac{\gamma}{\mathcal{V}_0^3} + \frac{d}{\mathcal{V}_0^2} > 0 \;\rightarrow\; -7.24 < 10^3\varrho < -6.74,\;\; \varrho = \frac{d}{\mu\gamma}$$



Plot of V_{eff} vs $\mathcal{V}$ for fixed $\varrho = \frac{d}{\gamma\mu\mathcal{W}_0^2}$.
The lower curve corresponds to AdS vacuum.
At large volume, the potential vanishes asymptotically after passing from a maximum.



★ Conclusions ★

★ *IIB/F-theory:*

- Stabilisation of Kähler MF possible with

Perturbative Corrections:

$$\mathcal{K} = -2\ln\left(\mathcal{V} + \xi + \gamma_i \ln \tau_i\right)$$

Origin of log-corrections:

Induced Einstein-Hilbert terms from R^4-couplings in 10-d theory.

This $\mathcal{EH}$-term $\exists$ in $4d$ only!

$$\Downarrow$$

In the present context, *induced* EH-term ... indispensable element for a $4d$ de Sitter Universe

★ Thank you for your attention ★

University of Ioannina

$\mathcal{SUSY}$ 2021 Conference

21-25 June 2021 (pre-SUSY school 18-20 June)