"Toward a Construction of Non-classical String Solutions"

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Outline:

I No-go results

II Status of the IIB landscape

III Toward a construction of non-classical string solns.

$\mathbb{R}^4 \times$  F-theory

CY_4

AdS ? dS ? Swampland vs landscape

$\mathbb{R}^4 \times$ (small theory) classical string solns.

CFT

- Not supersymmetric
- $V_{1\text{-loop}} \sim \int_F Z_{1\text{-loop}}$
- $\Lambda \rightarrow \Lambda + \delta\Lambda$

- Scale separated AdS ?
- de Sitter ?

- Including string loops but not string non-perturbative.

I No-go results

- Dark energy $M_{obs} \sim 10^{-30} M_{pl}$

70% of the obs critical energy.

landscape

or

time-dependent dark energy

Refined de Sitter conjecture

$$M_p \frac{|V'|}{V} \equiv \lambda \gtrsim O(1)$$

or

$$-M_p^2 \frac{V''}{V} \equiv c^2 \geq O(1)$$

(i) $V(\phi) = A e^{-\lambda\phi}$

(ii) $V(\phi) = B \cos(c\phi)$

$c \sim 0.16$ at 68% CL. Numbers

Data set	c 68% (95%) C.L.	$\lambda_{\rm eff}$ 68% (95%) C.L.	$\lvert\Delta\phi\rvert$ $[M_P]$ 68% (95%) C.L.
CMB	$c < 2.3\,(3.1)$	$\lambda_{\rm eff} < 1.4\,(2.2)$	$\lvert\Delta\phi\rvert < 0.51\,(0.66)$
CMB + SN	$c < 0.25\,(1.4)$	$\lambda_{\rm eff} < 0.40\,(0.71)$	$\lvert\Delta\phi\rvert < 0.11\,(0.19)$
CMB + H_0	$c < 0.17\,(0.84)$	$\lambda_{\rm eff} < 0.31\,(0.58)$	$\lvert\Delta\phi\rvert < 0.09\,(0.16)$
ALL	$c < 0.16\,(0.73)$	$\lambda_{\rm eff} < 0.29\,(0.53)$	$\lvert\Delta\phi\rvert < 0.08\,(0.15)$

to explain.

No-go results

Approach 1 — Spacetime

Classic no-go (Gibbons)

SUGRA $D = 10, 11$

$$S = \frac{1}{2\kappa^2} \int \sqrt{g}\, R + \dots$$

$$R_{\mu\nu} \sim \left(T_{\mu\nu} - \frac{1}{D-2} T g_{\mu\nu} \right)$$

T obeys SEC (strong energy condition)

$$R_{00} \geq 0 \qquad \Big(R_{\mu\nu} u^\mu u^\nu \geq 0$$

$\uparrow$ time-like $\Big)$

SEC violation

Het SUGRA $(g_{\mu\nu}, \phi, H, F)$

$$S = \frac{1}{2\kappa^2} \int d^{10}x \sqrt{-g}\, e^{-2\phi} \Big[R + 4(\partial\phi)^2 - \frac{1}{2}|H|^2 - \frac{\alpha'}{4}\left(\mathrm{tr}|F|^2\right) + O(\alpha') \Big]$$

$$R_{MN} = \frac{1}{2} \nabla_M \phi \nabla_N \phi + \cdots$$

$$R_{00} = \frac{1}{2}(\dot{\phi})^2 + \cdots \geq 0.$$

$$ds^2 = w^2(y)\left(g_{\mu\nu} dx^\mu dx^\nu + g_{ij}(y)\, dy^i dy^j \right)$$

$$R_{00}^{(D=10)} = R_{00}^{(d)} + \frac{1}{8w^8} \nabla^2 w^2 \geq 0$$

$$\Rightarrow R_{00}^{(d)} \geq 0.$$

Same argument rules out

$\mathbb{R}^4 \times CY_3$ w/ flux.

Branes / anti-branes — conventional stress-energy $\therefore$ don't work.

<u>Orientifolds</u>:

localized objects w/ negative tension

Violate NEC. Need higher derivative interactions (4 derivatives)

Heterotic:

(a) Leading higher deriv are known

(b) Understand the w.s. description

$O(\alpha')$

$$\longrightarrow \; -\frac{\alpha'}{4}\left(\mathrm{tr}|F|^2 - \mathrm{tr}|R_+|^2\right) + O(\alpha'^2)$$

$$H = \ell B + \frac{\alpha'}{4}\left(\cos\left(\Omega_+ - \cos(A) \right) \right)$$

(Bergshoeff, de Roo)

- Einstein eom
- Dilaton eom

R_{00} is not positive.

$\Longrightarrow$ $d = 4$; $d = 4$ Planck mass is finite.

$R_{\mu\nu} = \Lambda g_{\mu\nu}$ (could do FLRW)

$$\Lambda = -\frac{\alpha'}{2V'} \int \Sigma \,|\ |^2 + o(\alpha'^2)$$

$\Rightarrow$ $\Lambda \leq 0$. Perfect square.

No uplifting, no acceleration.

Approach 2 — worldsheet physics

Tree-level

$$S_{het} = \frac{1}{2\kappa^2}\int d^{10}x \sqrt{-g}\, e^{-2\phi}\Big[R + \frac{\alpha'}{4}\,\mathrm{tr}\,|R_+|^2 + (\alpha')^3 R^4 + \dots\Big]$$

Mink / AdS Type. Also solutions w flux (non-Kähler torsional backgrounds)

(Maxfield, Melnikov, Kutasov, v.S.)

$dS_4 \longmapsto$ isometry $so(4,1)$

Realized w symmetries $(J^a, \bar{J}^a)$

$\Rightarrow \bar{\partial} J^a + \partial \bar{J}^a = 0.$

Wick rotate $X^0 \to iX^0$. Typically can't do this because of flux.

Only flux is H_3 so dS_3 is "problematic".

$\Rightarrow \bar{\partial} J^a = 0 = \partial \bar{J}^a$ KM symmetry

$\langle JJ \rangle \sim \frac{k}{z^2}$ $\quad \langle \bar{J}\bar{J} \rangle \sim \frac{\bar{k}}{\bar{z}^2}$

by conf inv.

[Not what happens in $\mathbb{R}^{2,1}$ where rot. gen. are not promoted to KM]

Gravity $k > 0$, $\bar{k} > 0$

Left should be super KM.

$\Rightarrow k \geq 4$.

dS length scale $L^2 \sim k\,l_s^2$

Critical string theory

$$(c, \bar{c}) = (15, 26)$$

The SKM already uses up

$$c_{SKM} = \left(\frac{k-4}{k} + \frac{1}{2}\right) 10 \quad (dS_4)$$

Leaves $c_{SKM} + c_{other} = 15$

$c_{other} > 0.$

Once $k > 21$, $c_{other} < 3/2$

$\Rightarrow$ must be an $N=1$ minimal model

w/ $c_{other} = \frac{30}{k-1} = \frac{3}{2}\left(1 - \frac{8}{p(p+2)}\right)$

Discrete solutions:

$(k-4, p) \in \{(18,12), (21,6), (29,4)\}$

No macroscopic de Sitter.

- dilaton doesn't have to be stabilized
- can have tachyons
- no stable or unstable vacua.

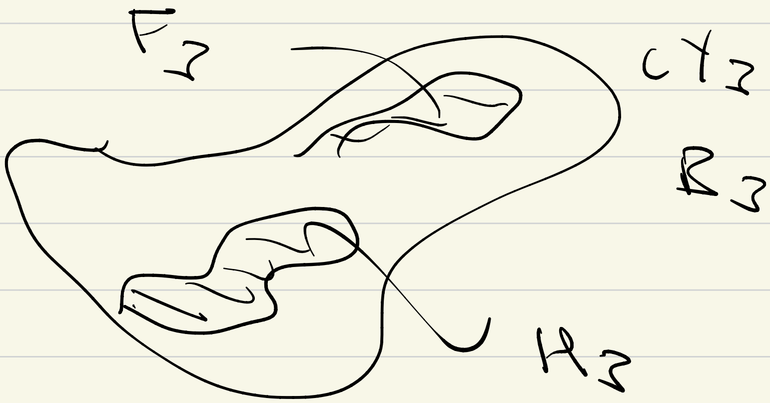
Missing:

- string loops
- string non-pert.

II. Status of Minh IIB Landscape

In IIB or M-theory

F-theory



$\times \mathbb{R}^4$

$F_5 \neq 0$

flux background. No SUGRA soln. (period).

$N=1$ effective theory $D=4$

- characterized by K, W

w/ potential $V = e^K \left(K^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - 3|W|^2 \right)$

(*) $K = -3 \log(\rho + \bar{\rho})$

no scale

$$W = W_0 = \int G_3 \wedge \Omega_3$$

"Add" instantons $W = W_0 + A e^{-\rho}$

+ uplift.

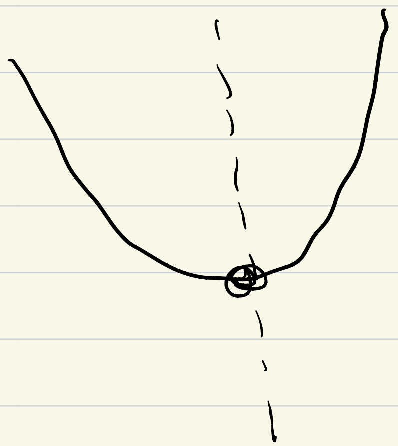
If $W_0 \neq 0 \Rightarrow$ susy broken classically

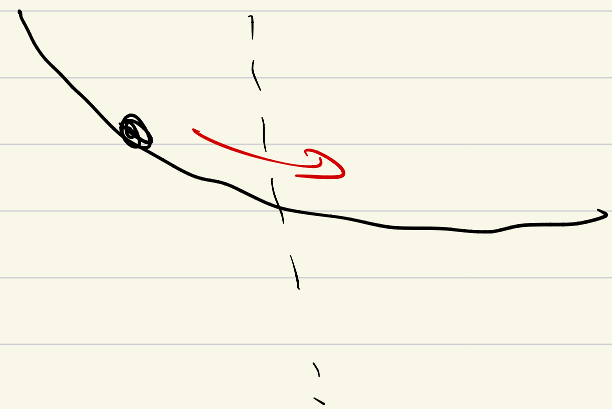
and these backgrounds are not solns of the quantum effective action in any approx.

off-shell configuration

W_0 is an obstruction to solving

The spacetime com.





Landscape $O(10^{2000})$ CY_4

(geometric)

CY_4

$W_0 = 0$

$O(1)$ or no solutions

per CY

$h^{3,1} \longrightarrow D_i W = 0$.

$+1$ $\qquad W = 0$.

Instantons $\longrightarrow$ Euclidean space

but this is cplx.

More like a theory than YM.

Effective field theory?

M-theory : $\mathbb{R}^3 \times$ 

$$S_2 = \int \sqrt{-g}R - \int C \wedge G \wedge G$$

no soln.

$$S_8 = \int R^4 + \dots \int C \wedge X_8 + \dots$$

cancels flux stress-energy $\sim \frac{\chi}{24}$

tadpole (allow flux)

R^4 $\quad K \to K_{\text{no-scale}} + \delta K$

Cannot ignore.

No solution if $W_0 \neq 0$.

III Non-classical string solutions

- de Sitter
- scale-separated AdS
- Non-susy AdS / CFT ? (Ooguri-Vafa, Freivogel-Kleban)

Idea: $V_{1\text{-loop}} \sim \int Z_{1\text{-loop}}$

balanced against a shift

in Λ and/or fluxes.

$D=10$ tachyon free non-susy

strings ; 3 examples

$V_{1\text{-loop}} > 0$.

"String island" (Dabholkar & Harvey)

SUSY asymmetric orbifolds w/

only the dilaton left.

T^4 $\quad$ $\mathcal{N}^{4,4}(A_4)$ asymmetric

orbifold by $\mathbb{Z}_5$ left & shift right

16 susies.

Type II on T^4/G

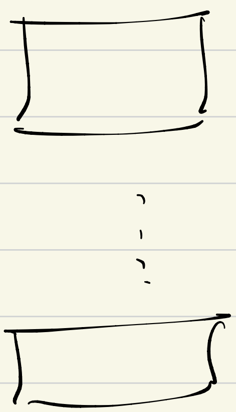
- no tachyons
- no moduli

w/ Zihni Baykara, Daniel Robbins

All attempts in Type have led to tachyons.

Heterotic $T^4/(\mathbb{Z}_5$ & shift$)$.

Wilson line moduli $E_8 \times E_8$.



T^3

$E_8 \times E_8$

	Λ	$\Lambda^\perp$	Δr	E_t
$\mathbb{Z}_1$	$\Gamma_{3,3} \oplus E_8 \oplus E_8$	$\emptyset$	0	-1
$\mathbb{Z}_2$	$\Gamma_{3,3} \oplus D_4 \oplus D_4$	$D_4 \oplus D_4$	8	$-1/2$
$\mathbb{Z}_3$	$\Gamma_{3,3} \oplus A_2 \oplus A_2$	$E_6 \oplus E_6$	12	$-1/3$
$\mathbb{Z}_4$	$\Gamma_{3,3} \oplus A_1 \oplus A_1$	$E_7 \oplus E_7$	14	$-1/4$
$\mathbb{Z}_5$	$\Gamma_{3,3}$	$E_8 \oplus E_8$	16	$-1/5$
$\mathbb{Z}_6$	$\Gamma_{3,3}$	$E_8 \oplus E_8$	16	$-1/6$

Table 5: Lattices Λ, complements $\Lambda^\perp$, rank reduction Δr and zero-point energies in the twisted sector E_t for the Z_m asymmetric orbifolds corresponding to triples.

T^3

"triple" flat connection

$$\int_{T^3} CS = \frac{1}{5}, \ 2/5, \ 3/5, \ 4/5$$

asymmetric orbifolds $\left\{ \begin{array}{l} \mathbb{Z}_5 \\ \mathbb{Z}_6 \end{array} \right.$

$$\int_{T^3} CS = 1/6, \ 5/6$$

$(\frac{1}{5}, 4/5)$: complete rank reduction

$$\Gamma^{4,20} \longrightarrow \Gamma^{4,4}$$

In progress.

$\mathbb{R}^6 \times T^4/G$

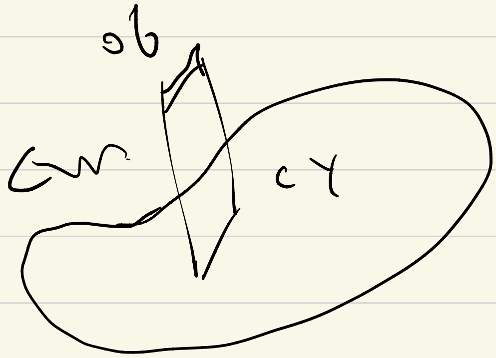
$$\downarrow$$

$$\underbrace{AdS_3 \times S^3}_{\text{NS-flux}} \times T^4/G$$

$e^{\phi} \sim \sqrt{a_5/a}$

$L^2 \sim l_s^2 a_5.$

Massive IIA



$\times \mathbb{R}^4$

dilaton Tadpole

$SU(3) \times SU(3)$