A Hitchhiker's Guide to the Swampland

(A. Westphal, DESY)

literature:

- Arkani-Hamed, Motl, Nicolis & Vafa: hep-th/0601001 (WGC)
- Ooguri & Vafa: hep-th/0605264 (Swampland)

reviews:

- arXiv: 1711.00864 (Brennan, Carta, Vafa)
- arXiv: 0803.1194 (Denef)

text books:

- String Theory and Particle Physics
  - An Introduction to String Pheno
  (textbook by Ibanez & Uranga)

- Inflation and String Theory
  (textbook by Baumann & McAllister)
  also on arXiv: 1404.2601

What is the

Swampland?

Quick intro to string theory and its vacuum landscape – no swampland without landscape!

strings: 1-dim closed or open vibratory objects with length $\sqrt{\alpha'}$ & tension $\frac{1}{\alpha'}$

action: fluctuations of 2-dim worldvolume

$$S = \frac{1}{\alpha'} \int d^2\sigma \sqrt{-g}$$

space-time d.o.f.: always $g_{\mu\nu}$, $B_{\mu\nu}$, ϕ
⊕ SUSY ⇒ $D = 10$

dualities: e.g. T-duality

theory on S^1_R ≙ theory on $\tilde{S}^1_{\frac{1}{R}}$

⇒ Dp-branes from end-of-open strings
Dirichlet boundary conditions
⟷ fluctuating 'hyperplanes' with
$(p+1)$-dim. worldvolume

↓

10D effective spacetime action
dictated by 10D $\mathcal{N} = 1,2$ SUSY:

$$S = \frac{1}{2\kappa^{14}} \int d^{10}x \sqrt{-g}\, e^{-2\phi} \left(R + 4(\partial_M \phi)^2 + |H_3|^2 \right) + S_{\text{matter}}$$

$$S_{matter} = \frac{1}{\alpha'^{14}} \int d^{10}x \sqrt{-g} \cdot \left[\sum_p |\widetilde{F}_p|^2 + CS \right.$$

localized objects like: Dp-branes & Op-planes (orientifold planes)

$$\left. + \sum_p \left(T_p^B \frac{\delta^{9-p}(x_\perp)}{\sqrt{-g_\perp}} - T_p^O \frac{\delta^{9-p}(x_\perp)}{\sqrt{-g_\perp}} \right) + \text{higher-derivative} \right]$$

$$\widetilde{F}_p = F_p + B_2 \wedge F_{p-2}$$

CS couplings

$$F_p = dC_{p-1} \,, \quad H_3 = dB_2$$

10D → 4D: compactification

$$\mathcal{M}_{10} \to \mathcal{M}_4 \times X_6$$

$\text{vol}(X_6) \sim L^6$ small, but bigger than unity in units of $\sqrt{\alpha'}$ (string length) for control.

- many choices for X_6
- X_6 has deformation modes: massless 4D scalars - "moduli"
- correspond to volumes of p-dim. sub-manifolds of X_6: p-cycles Σ_p

$\Rightarrow$ <u>cosmological & 5th-force disaster !?</u>

<u>Solution:</u>

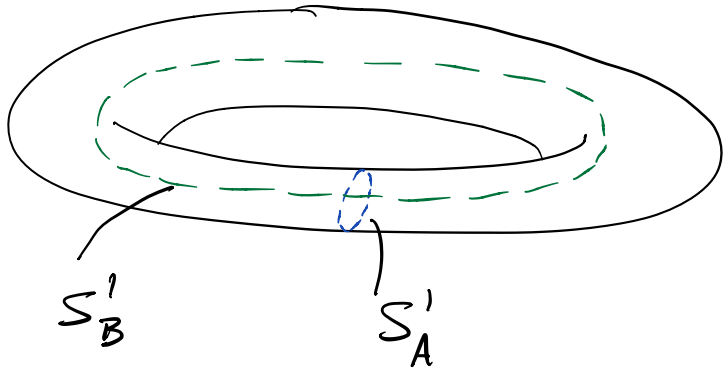
p-form fluxes $\int_{\Sigma_p} F_p$

+ pertarb. string corrections

+ instanton effects $\rightsquigarrow$ moduli scalar potential

$\longrightarrow$ can fix all the moduli

T^2 - by example of GKP:

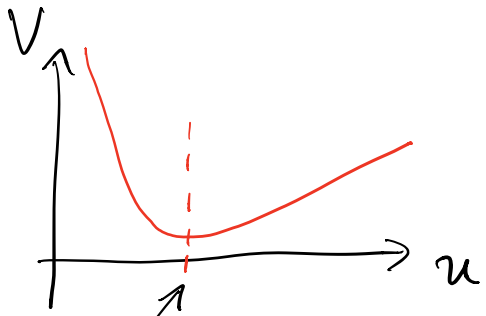


$$\mathcal{V} = L_A L_B \,, \quad u = \frac{L_A}{L_B}$$

$$\int_{S^1_A} F_1 = M \,, \quad \int_{S^1_B} F_1 = -K$$

$$V = \frac{M^2}{L_A^2} + \frac{K^2}{L_B^2} = \frac{1}{\mathcal{V}} \cdot \left(\frac{M^2}{u} + K^2 \cdot u \right)$$

assume $\langle V \rangle$ given:



$\langle u \rangle = \frac{M}{K}$ 'flux discretuum of vacua'

fixes $u = \frac{L_A}{L_B}$, leaves V unfixed.

$\rightsquigarrow$ <u>MANY</u> vacua ! | string landscape

$\#(\text{vac.}) \sim \#(\text{fluxes})^{\#(\text{cycles})} > 10^{100}$

⊕ in any of these can have gauge theories with fermions on brane stacks

↓

<u>Question</u>: Anything goes?

<u>More precisely</u>: Is there a UV completion, in string theory as quantum gravity, of any effective QFT which is consistent without coupling to gravity?

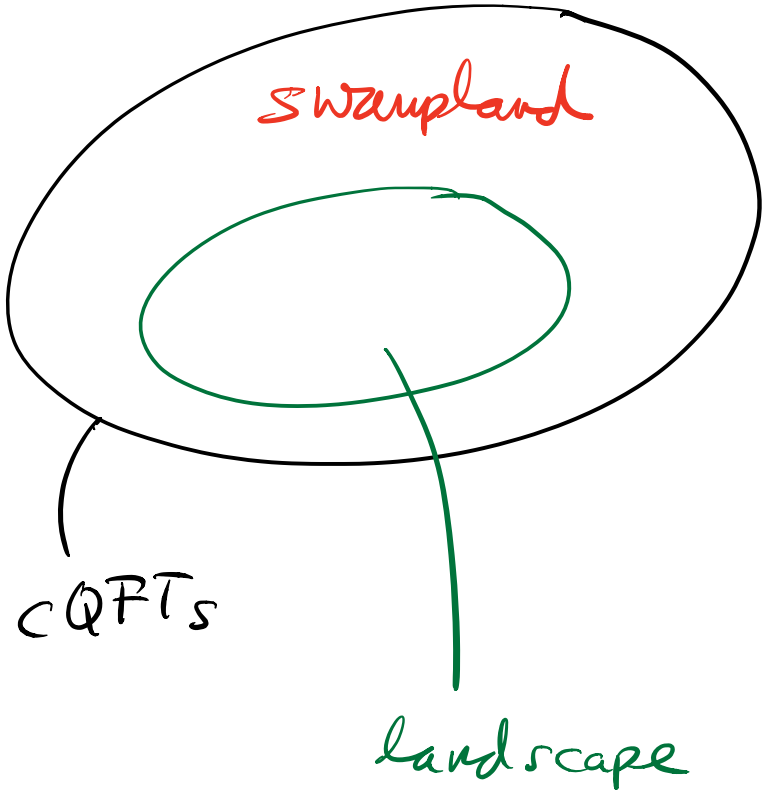
If answer is "No!"

⇒ Define the set of all effective QFTs consistent without gravity which do not UV complete in string theory

cQFTs

= Swampland

the complement is the string landscape



swampland = cQFTs / landscape

idea: use constraints from semi-classical gravity and/or example constructions in string theory to guess conjectures sketching the border between landscape & swampland.

→ Swampland Program

logic:

example sets & heuristic properties of semi-classical gravity + ST

↓ inductive reasoning

swampland conjectures

⇒ Checking a conjecture to further examples or linking it to another conjecture

does <u>not</u> prove it.

Conjecture must be proven using properties of explicit quantum gravity candidate like ST. Burden of proof on side of conjecture.

2005/2006 – now: beginning with Vafa/Ooguri-Vafa & then many others – a set of Swampland Conjectures

① No global symmetries:
EFTs with continuous or discrete global symm.s are in the Swampland, once consistently coupled to quantum gravity.

② All charges must appear:
EFT with U(1) gauge symm. must have states with charges in all $\mathbb{Z}$, if consistently coupled to QG.

(3) Finite number of massless fields.

(4) No ~~free~~ parameters.

(5) Moduli space $\mathcal{M}$ of landscape vacua is non-compact:

$$P_0 \in \mathcal{M} \overset{!}{\Rightarrow} \forall T > 0 \; \exists P : d(P_0, P) > T$$

(d: geodesic distance)

(6) If $T \to \infty$, infinite tower of states appears which:

$$m \sim e^{-\alpha \cdot T}$$

"Swampland Distance Conjecture" (SDC)

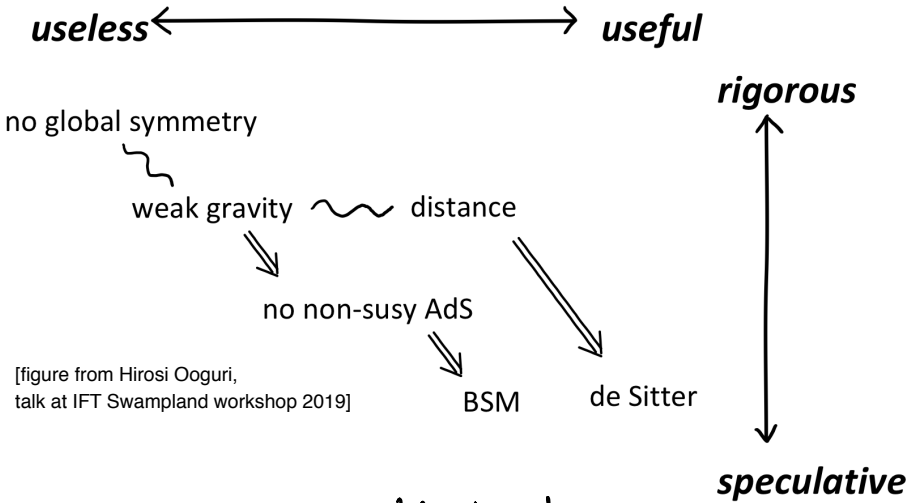
(7) $\pi_1(\bar{\mathcal{M}}) = 0$

(8) "Weak Gravity Conjecture" (WGC):
In any EFT consisting of GR + EM + finite # of states
$\Rightarrow \exists\, (m, Q) : \frac{m}{M_P} \leq Q$

(9) If "=" sign in WGC only for BPS states $\Rightarrow$
No stable non-SUSY AdS/CFT

(10) "Swampland de Sitter Conjecture"
(i) $|\vec{\nabla} V| \geq c \cdot |V|$, $c = O(1)$
(dSC)
(ii) $|\vec{\nabla} V| \geq c \cdot V$ or $\min \partial_i \partial_j V \leq -c' \cdot V$
$c, c' = O(1)$

Landscape of Swampland Conditions



current Hitchhiker's map: