# Workshop seminar: The swampland program I

## 1. Introduction / motivation: "A ridiculous number"

- Reasonable question for string phenomenologists:
  "What is the number of distinct <u>semi-realistic</u> 4d vacua of string theory?"

<u>a subclass</u>: type IIB on ~~CY~~ Calabi-Yau threefold ($\mathcal{N}=2$ in 4d)

$$\xrightarrow[\text{projection}]{\text{O3/O7 orientifold}} \boxed{\text{4d } \mathcal{N}=1 \text{ SUGRA}}$$

- A typical CY has $\mathcal{O}(100)$ distinct <u>three-cycles</u>
- These can be threaded with quantized units of three-form "fluxes"

$$\boxed{\text{i.e. } \underbrace{F_3}_{\text{RR - three-form}} \sim {\sum_{\Sigma}}' \underbrace{M_\Sigma}_{\text{integer}} \cdot \underbrace{\omega_\Sigma}_{\sim \text{ volume form of 3-cycle } \Sigma}}$$

(and similarly for $H_3$)

- The flux-quanta seem to be constrained only by a certain charge-cancellation condition

$$\# \geq \int F_3 \wedge H_3$$

<u>one</u> example: $\boxed{\#\text{ of flux choices } \simeq 10^{230}}$

[hep-th/0312104]

- Recently, this <u>lower bound</u> has been significantly updated:

in non-perturbative generalization of IIB string theory ($\equiv$ F-theory)

$\exists$ a <u>single</u> geometry that gives rise to $\mathcal{O}(10^{272,000})$ flux-vacua!

[1511.03209]

- Let's highlight this #:

$$\boxed{N_{vac} > 10^{272,000} \sim 10^{10^5}}$$

- <u>Let's compare:</u>

Avogadro's constant $\boxed{N_A \sim 10^{23}}$.

= # of carbon atoms in 12g of $^{12}C$

# of particles in the observable universe

$\mathrel{\hat{=}} \boxed{10^{80}}$

- Such large #'s usually contain a lot of Physics!

$N_A \gg 1 \longrightarrow$ atoms are small!

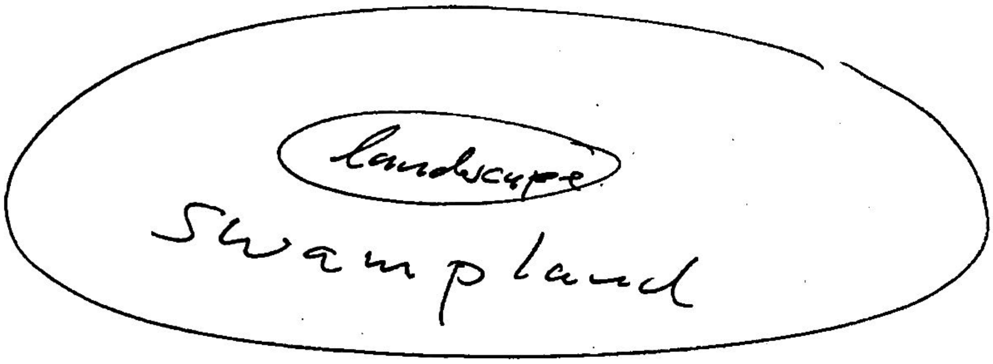
$\longrightarrow$ $\boxed{\text{statistical mechanics}}$

$\hbar \sim 10^{-34} \ll 1 \longrightarrow$ $\boxed{\text{Quantum mechanics}}$

$c \sim 10^{8} \gg 1 \longrightarrow$ $\boxed{\text{special relativity}}$

$N_{vac} \sim 10^{10^5} \ggg 1 \longrightarrow$ $\boxed{\text{swampland program}}$

- <u>The swampland program:</u>
  - What are completely universal features shared by all string compactifications? (top-down point of view)
  - What is the subset of (seemingly) consistent effective field theories that descend from a fully consistent theory of Quantum Gravity ("the landscape"), and what is its complement ("the swampland") (bottom-up p.o.v.)




- <u>Cautionary remarks:</u>
  - Some "swampland criteria" are found by investigating "large" classes of string solutions
    ↳ in view of the # $10^{10^5}$ this should be viewed with a healthy skepticism...

- some arguments are "bottom-up" but based on subjective notions of what is / is not acceptable in a healthy theory...

<u>But:</u> Some arguments are very intriguing and/or convincing; some can actually be proven (say in AdS/CFT) and though some will turn out to be wrong, we learn a lot by considering them!

— end of introduction —

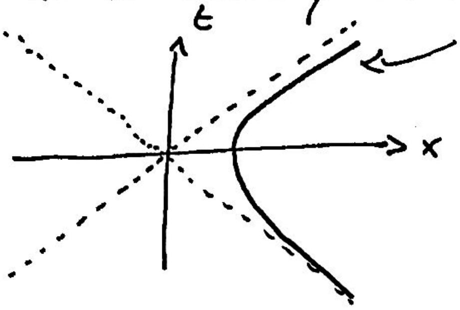
## 2. No global symmetries:

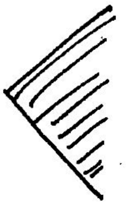
- One of the oldest statements is this:
  "All global symmetries of an EFT should eventually be gauged or turn out to be approximate notions"
- The classical argument involves an evaporating black hole...

**Hawking radiation:**

Hawking '74: "Black holes evaporate via emitting thermal radiation"

This is closely related to the "Unruh effect":



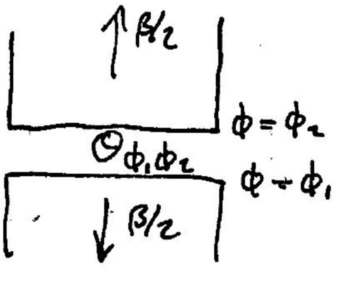

accelerating observer only has access to the "Rindler wedge" $\simeq$ 

What does she see?

at rest, $\langle 0|\mathcal{O}|0\rangle = \mathrm{tr}(\rho_{|0\rangle}\mathcal{O})$

with $\rho_{|0\rangle} = |0\rangle\langle 0| = \lim_{\beta\to\infty} \frac{e^{-\beta H}}{Z}$

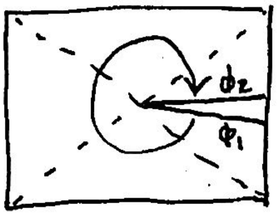
$$= \lim_{\beta\to\infty} \mathrm{tr}\left(\frac{e^{-\frac{1}{2}\beta H}}{\sqrt{Z}}|\phi_1\rangle\langle\phi_1|\mathcal{O}|\phi_2\rangle\langle\phi_2|\frac{e^{-\frac{1}{2}\beta H}}{\sqrt{Z}}\right)$$

$= \lim_{\beta\to\infty}$ $\frac{1}{\sqrt{Z}}$ $\frac{1}{\sqrt{Z}}$ 

$=$ euclidean path integral

but an accelerating observer only has access to right Rindler wedge, so should trace over "what happens on the left"

$$\leadsto \langle \mathcal{O} \rangle_R \simeq$$




so should choose angular coord.

$$ds^2 = dr^2 + r^2 d\theta^2$$

$$\leadsto \rho_R = \frac{e^{-2\pi K}}{Z} \quad , \quad K = \frac{\partial}{\partial \theta}.$$

analytic continuation: $\theta = i\chi$

$$\leadsto ds^2 = -r^2 d\chi^2 + dr^2$$

$$\frac{\partial}{\partial \chi} = \text{boost generator}$$

$$\equiv (\text{Hamiltonian of accel. observer at } r = \text{const.}) \times r = r \cdot H$$

$$\Rightarrow \rho_R = \frac{e^{-2\pi r H}}{Z} \quad , \quad r = \frac{1}{a}$$

with $a$ = proper accel.

$$\Rightarrow \boxed{T_{\text{Unruh}} = \frac{a}{2\pi}}$$

<u>Schwarzschild:</u> $ds^2 = -\left(1 - \frac{2MG}{r}\right) dt^2 + \left(1 - \frac{2MG}{r}\right)^{-1} dr^2 + \ldots$

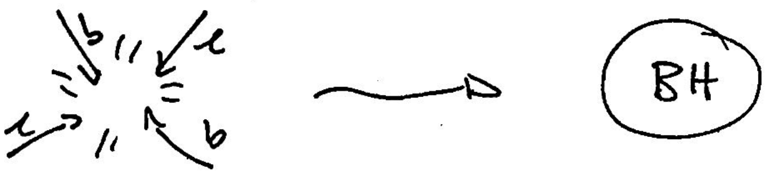
$$\xrightarrow{r \simeq 2MG} \underbrace{-\frac{\tilde{r}^2}{16 M^2 G^2} dt^2 + d\tilde{r}^2}_{= \text{Rindler wedge!}} + \ldots$$

$$\Rightarrow \boxed{T_{\text{Hawking}} = \frac{1}{2\pi} \cdot \frac{1}{(4MG)} = \frac{\hbar c^3}{8\pi M G k_B}}$$

So: BH's evaporate thermally.

Back to global symmetries:

- Consider e.g. $U(1)_{B-L}$ of the SM.
- It seems to be a perfectly healthy global symmetry (i.e. it holds at the level of the renormalizable SM Lagrangian & is anomaly-free)
- Now we form a BH out of baryons & leptons of total B-L ~~each~~ charge $q$



- As things stand, we can no longer detect its charge due to the "no-hair theorem"
- The BH evaporates via Hawking radiation which does not return to us our baryons & leptons:

$$|q\rangle \xrightarrow[\text{formation}]{\text{BH}} |q\rangle_{BH} \xrightarrow[\text{evaporation}]{\text{BH}} |q' \approx 0\rangle$$

$$\underbrace{\text{"}\Rightarrow\text{"}} \; U(1)_{B-L} \text{ is broken!}$$

assume * Einstein gravity is valid near the horizon (after all, $G_N R_{Ricci}\big|_{horizon} \ll 1$ )

** Nothing remarkable happens at the end stage of evaporation when $M_{BH} \sim M_{pl}$.

- assumption ** is hard to doop: (Susskind '95)
  - If the charge is released in final stages where $M_{BH} \sim M_{pl}$
    $\exists$ a huge $= \infty$ # of Planck-scale BH-species characterized by all possible (global) $U(1)$-charges. ($\equiv$ BH-remnants)

$\Rightarrow$ in thermal Rindler atmosphere at acceleration $\ll M_p$ one observes a number density

$$N_i \sim \exp\left(-\frac{2\pi}{a} M_p\right)$$

of each remnant species.

But an arbitrarily large number of remnant species would overcome the exponential suppression factor

~~$\Rightarrow$ at modest accelerations~~

$\Rightarrow$ even at negligible accelerations we would be flooded by remnants!

- Note that this doesn't work for local symmetries: The charge of gauged $U(1)$ is measured by a flux integral at $\infty$:

$$q_{gauged} \sim \int_{\substack{\text{sphere}\\ \text{at } \infty}} *F_2$$

- Note that the requirement "no global symmetries" is automatic in perturbative String theory:

  An exact global symmetry at world-sheet level comes with a conserved current $j(z)$ s.t. $q = \frac{1}{2\pi i} \oint dz\, j(z) - d\bar{z}\, \bar{j}(\bar{z})$

  $j(z)$ & $\bar{j}(\bar{z})$ have conformal weights $(1,0)$ respectively $(0,1)$

  ↳ Can construct vertex operators

  $$j(z)\, \bar{\partial} X^\mu e^{ik\cdot X} \quad \& \quad \bar{j}(\bar{z})\, \partial X^\mu e^{ikX}$$

  with conformal weights $(1,1)$

  $\longleftrightarrow$ space time gauge bosons!

- Also in AdS / CFT:
  Every global symmetry of the CFT is a gauge symmetry from the bulk perspective.
  [1810.05338] : Non-perturbative proof by Harlow & Ooguri

- <u>This raises a puzzle:</u>
  Given a gauged symmetry, let's send the gauge coupling to zero: $g \longrightarrow 0$

  $\Rightarrow$ <u>global symmetry</u> which should be forbidden!

<u>So:</u> How small can we make the gauge coupling?

# 3. The weak gravity conjecture

— or "how small can $g$ be?" —

- Consider a ~~charged~~ BH with extremal charge $Q \cong M \cdot M_{pl}$ w.r.t. a gauged $U(1)$.

- If there exists a particle of charge $q$ and mass $m$ s.t.

$$\boxed{q \gtrsim m/M_{pl}}$$

the BH may lower its charge by emitting this particle.

Reason: Electrical repulsion $\sim q \cdot Q$ is stronger than gravitational attraction $\sim \frac{mM}{(M_{pl})^2}$

Weak gravity conjecture: [hep-th/0601001] $\boxed{\text{Such a particle must always exist.}}$

This should also hold for magnetic charges:

$$\boxed{\begin{array}{c}\exists! \text{ a magnetic monopole with} \\ m_{\text{monopole}} \lesssim M_{pl} \cdot g_{mag} \sim \frac{M_{pl.}}{g_{el.}}\end{array}}$$ "magnetic version"

Crucial point: This constrains the EFT cutoff!

A monopole is a field theory soliton with $F \sim \frac{1}{g_{el.}} \sin\theta \, d\theta \wedge d\varphi$

$$\Rightarrow m_{\text{monopole}} \gtrsim \int_{1/\Lambda}^{\infty} |F|^2 \sim \frac{1}{(g_{el.})^2} \int_{1/\Lambda}^{\infty} \frac{dr}{r^2}$$

$$\sim \frac{\Lambda}{(g_{el.})^2}$$

where $\Lambda =$ EFT cutoff

Plugging this into "mWGC" we obtain

$$\frac{\Lambda}{(g_{el})^2} \lesssim m_{\text{monopole}} \lesssim \frac{M_{pl.}}{g_{el.}} \Rightarrow \boxed{\Lambda \lesssim g_{el.} M_{pl.}}$$

$\rightsquigarrow$ The EFT breaks down prematurely i.e. $\Lambda \ll M_{pl.}$

## Why should such a bound hold?

- A remnant problem?

If $g \ll 1$, can construct $\mathcal{O}(1/g)$ Planckian BH's with charges ~~$1/g$~~

$$0, g, 2g, \ldots, \frac{g-1}{g}, 1$$

Of course in the limit $g \to 0$ we recover the remnant problem

$$N_{\text{remnants}} \sim \frac{1}{g} \exp\left(-2\pi \frac{M_{pl}}{a}\right) \longrightarrow \infty$$

But this does not justify the requirement

$$\frac{1}{g} \ll \frac{M_{pl}}{\Lambda} \quad \ldots$$

- A violation of Bekenstein-Hawking?

$$S_{\text{Black Hole}} \overset{?}{=} \frac{A_{\text{horizon}}}{4G} \cancel{+ \log(1/g)}$$

$$- \log(g)$$

$$= S_{\text{Bekenstein-Hawking}} - \log(g)$$

$\leadsto$ not appealing but far from an obvious inconsistency...

- Another handwavy argument:

There should not exist a large # of absolutely stable states not protected by any symmetry...

- Main "piece" of evidence:

All known string compactifications satisfie some form of the conjecture

e.g. [1606.08437]

But also: For an AdS/CFT argument, see [1510.07911].

- Apparantly, an analogue of the conjecture holds for every p-form symmetry.

Here is an interesting special case:

$p=0$: The zero-form is an axion, $A_0 \equiv \phi$

The electrically charged object is an instanton

$$- \int \frac{1}{g^2} |F_2|^2 \quad + q \int_{\text{w.-l.}} A_1 \quad \cancel{+} \; m \int d\tau$$

$\Big\downarrow$ analogy (& sometimes T-duality [1503.04783])

$$- \int \frac{f^2}{2} |F_1|^2 \quad + \quad q \cdot A_0 \Big|_{\substack{\text{position} \\ \text{of instanton}}} \quad - \underbrace{S_E}_{\text{euclidean action}}$$

$$\hookrightarrow \qquad q \cdot g \geq m/M_{pl}$$

$\Big\downarrow$ analogy

$$\boxed{q/f \gtrsim S_E}$$

Generically (= in absence of two many unbroken supersymmetries)

such an instanton generates an effective potential

$$V(\phi) \sim e^{-S_E}\left(1 - \cos\left(q\frac{\phi_c}{f}\right)\right)$$

$\phi_c \equiv$ canonically normalized axion.

Control over this expression requires $S_E > 1$ so that higher order terms $\mathcal{O}(e^{-2S_E})$ are suppressed ("dilute instanton gas")

$\overset{\text{WGC}}{\Longrightarrow}$ "wiggles" in potential over distances in field space $< M_p$!

$\Downarrow$

problem for axion large field inflation...

A <u>related conjecture:</u>

"Swampland Distance Conjecture" [hep-th/0605264] by Ooguri/Vafa

... stay tuned!