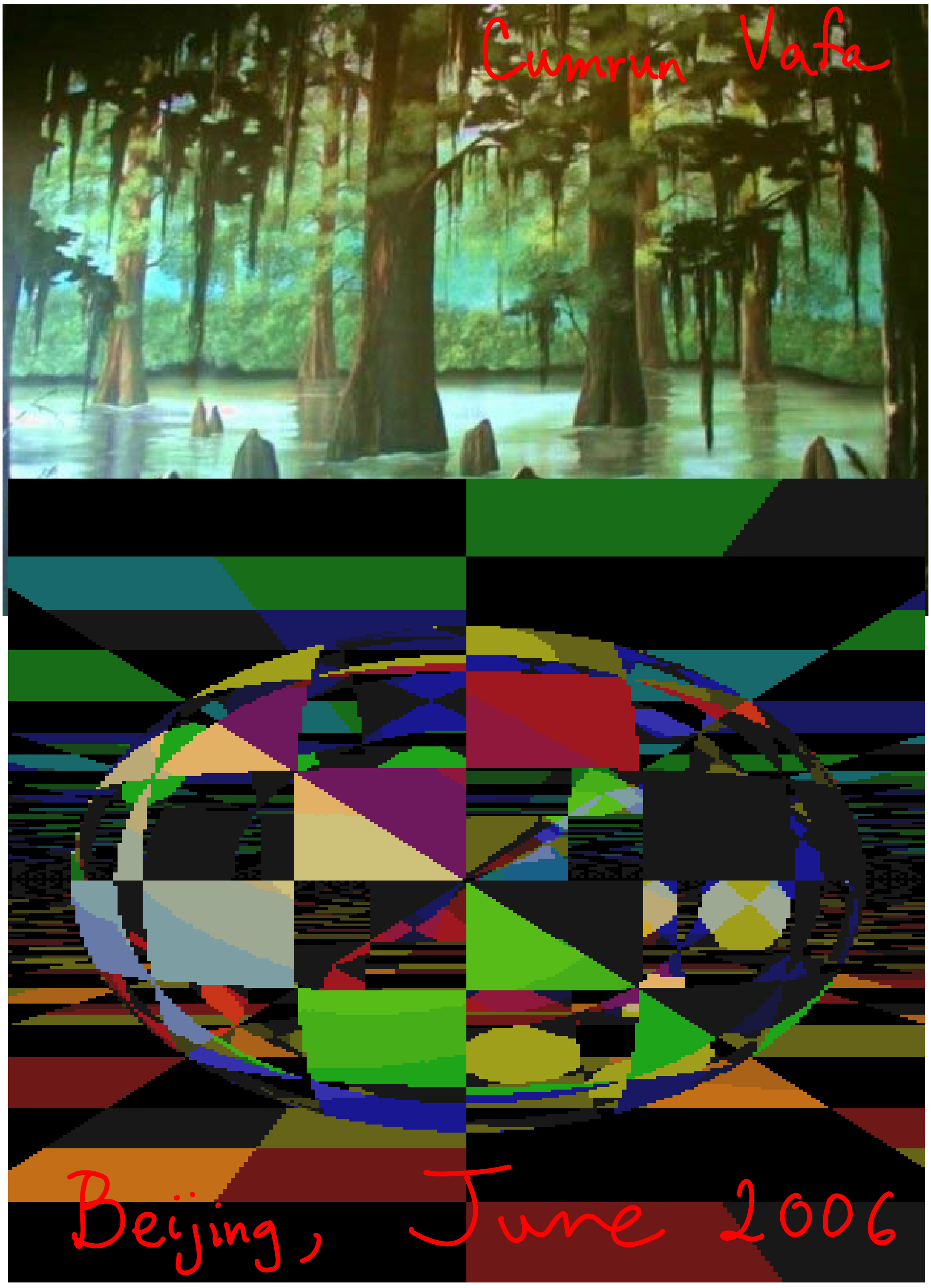
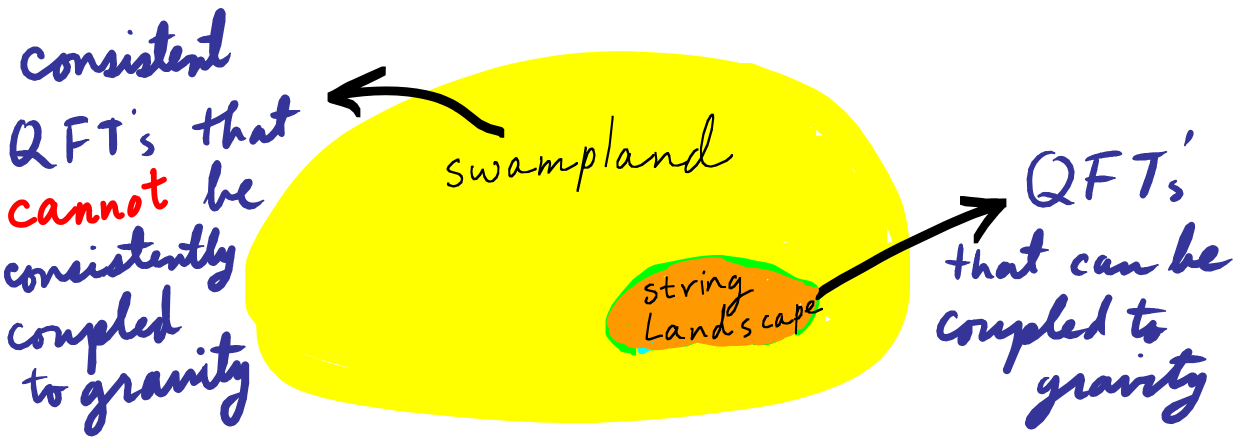
String Landscape + the Swampland



Suppose $\mathcal{L}_{QFT}$ is a consistent QFT.

Since string theory is the only consistent quantum theory of gravity known to date we will interpret this question as follows:



We conjecture a few criteria which distinguish the String Landscape from the Swampland. We will not be able to prove these conjectures; we will find many non-trivial examples supporting these conjectures. These conjectures are about the space of flat directions $\mathcal{M}_X$ for compactification X, as well as the nature of gauge groups + gauge coupling constants + # of light fields:

The Conjectures

0 – $\mathcal{M}_X \longleftrightarrow \langle \phi \rangle$

"No adjustable parameters"

1 – $\phi \in \mathcal{M}_X \longleftarrow$ "string landscape"

$\mathcal{L} = \int \ldots + |\nabla \phi|^2$

$\mathrm{Vol}(\mathcal{M}_X) =$ finite

(more precisely $\mathcal{M}_X^\Lambda : (m \gg \Lambda)$)

– $=$

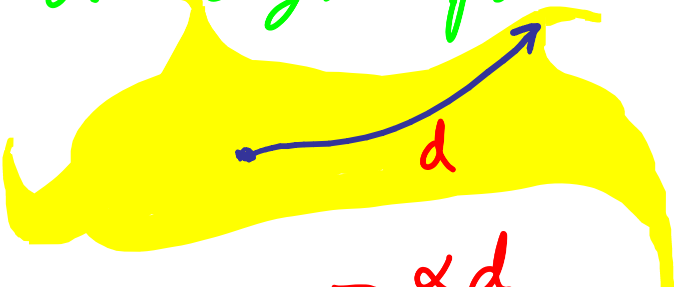
uniform bound

(depending only on d)

– Choices for gauge groups

- Gauge coupling constants cannot be too weak $\approx$ gravity is the weakest force

- Diameter of $\mathrm{diam}(\mathcal{M}_X) = \infty$ and pts at ∞ correspond to appearance of a tower of light particles with m :



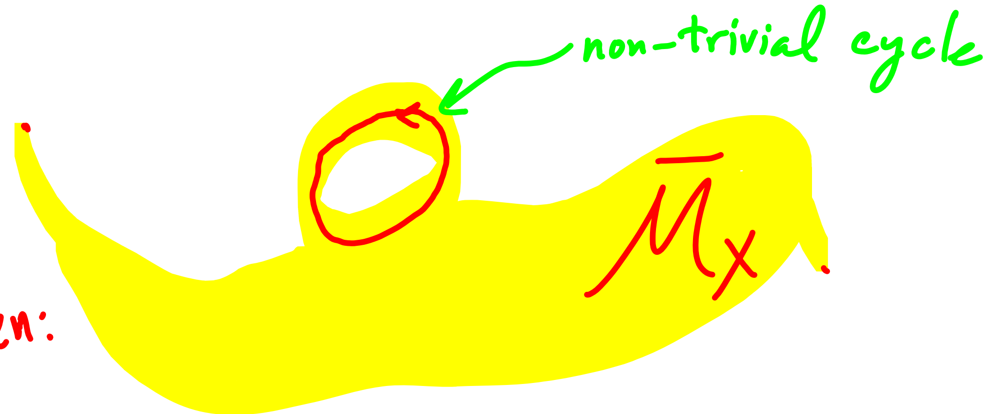
$$m(d) \sim e^{-\alpha d}$$

6 – $R(d \to \infty) < 0$

(scalar curvature)

7 – $\pi_1(\bar{M}_x) = \emptyset$

Can't happen:



We provide evidence for these conjectures + show they can all be violated if we decouple gravity, (for example by taking

$$\rightarrow \int \cdot R \rightarrow \text{gravity decoupled}$$

lower dim.

$= M_{Pl}^{d-2} \rightarrow \infty$

Based on

Conjectures

hep-th/0509212

Title: **The String Landscape and the Swampland**
Authors: **Cumrun Vafa </find/hep-th/1/au:+Vafa_C**

+

hep-th/0601001

Title: **The String Landscape, Black Holes and Gravity as the Weakest Force**
Authors: **Nima Arkani-Hamed </find/hep-th/1/au:**

+

hep-th/0605264

Title: **On the Geometry of the String Landscape and the Swampland**
Authors: **Hirosi Ooguri </find/hep-th/1/au:+Ooguri_H/0/1/0/all/0/1>**,

(related work : Douglas et. al.
Kachru et. al.
Li et. al.
Motl et. al.)

— $\mathcal{M} \longleftrightarrow \langle \phi \rangle$

is an obvious fact in string theory, but it did not have to be the case. Note that QFT's without gravity do have adjustable parameters.

I — Finiteness of Vol.

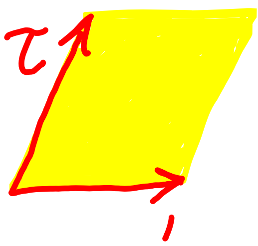
Examples of finiteness:

Let $X = T^2 \times \cdots$

Then $\phi \in \mathcal{M}^{cplx}_{T^2} \times \cdots$

$$Vol(\phi) = \int \frac{d^2\tau}{\tau_2^2} < \infty$$

fundamental domain



Other examples

$$X = CY \text{ 3-fold}$$

$$\phi \in \mathcal{M}_{CY}^{cplx}$$

There are arguments (Todorov) (Douglas et.al.)

$$\mathrm{Vol}\left(\mathcal{M}_{CY}^{cplx}\right) < \infty$$

More subtle applications:

Kähler moduli

Dualities $\begin{cases} \text{T-duality} \\ \text{(mirror sym.)} \\ \text{S-duality} \end{cases} \longleftrightarrow \mathrm{Vol}(\mathcal{M}_X)$ finite

e.g. τ (coupling const) in Type IIB

$(SL(2,\mathbb{Z}) \longrightarrow \mathrm{Vol}(\tau) =$ finite

This is a "gravity" effect.

If we decoupled "gravity" by taking X = non-compact

then the volume is not finite,

(e.g. $\mathrm{Vol}(\phi \in \mathrm{QFT}) = \infty$)

$\phi \in \mathbb{R}^n$

2 − $\boxed{(\dim \mathcal{M}_X) = \text{bounded}}$

This is meant as a uniform bound. (fixed, for $\dim X$ = fixed)

Example: X : CY^3

$$(\dim_{\mathbb{C}} \mathcal{M}_X) = h^{1,1} + h^{1,2}$$

The conjecture in this case suggests $h^{1,1}$, $h^{2,1}$ bounded.

(This has been conjectured by Douglas)

It is not known whether this mathematical conjecture is true or false. Currently there is no counterexample (i.e., no ∞ sequence of CY with increasing hodge #'s).

Again this conjecture is if we decouple gravity

The decoupling of gravity can be done by taking

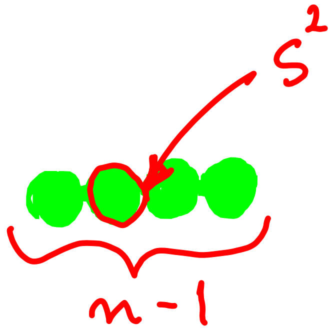
X : Non-compact

In this case $\exists$ counter-examples:

$$X = \mathbb{C}^2/\mathbb{Z}_n \qquad \mathbb{Z}_n : (z_1, z_2) \to (\omega z_1, \omega^{-1} z_2)$$

$$\omega^n = 1$$

This gives rise to A_{n-1} singularity which can be resolved:



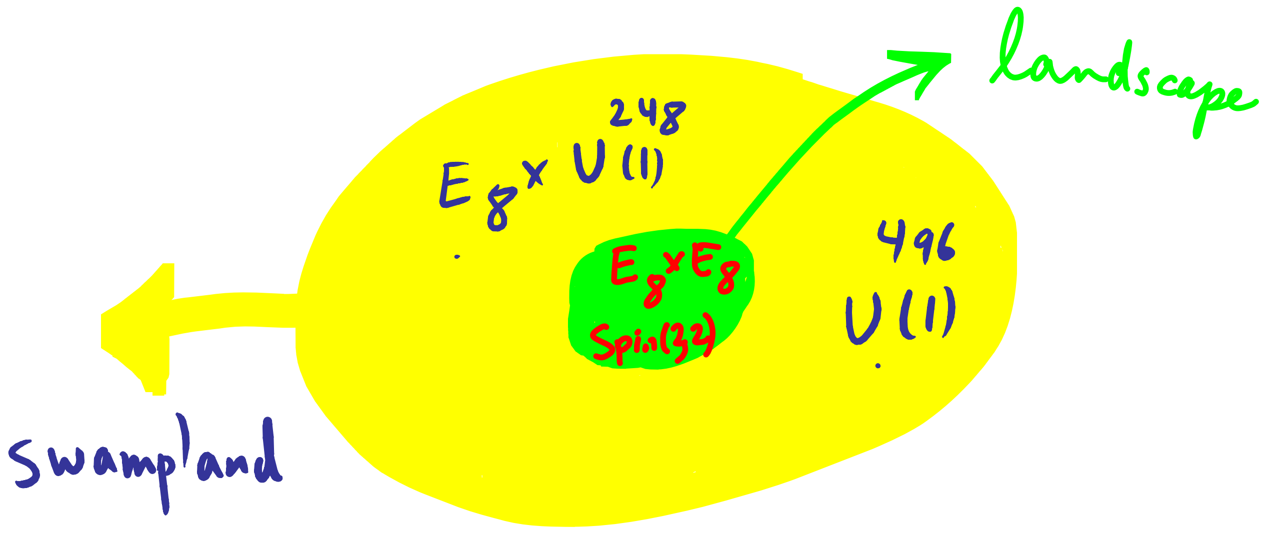
This finiteness of $\dim(\mathcal{M}_X)$ has a counterpart conjecture involving a on the $\dim(\mathcal{M}_X)$ at least in certain cases. For example if we consider $\mathcal{N}=2$ supersymmetric compactifications to $d=4$, we always seem to end up with scalar field. (CY case: $h_2 \geq 1$).

Conjecture 2 $\Rightarrow$ $\dim G < \infty$

But it seems there are more restrictions on G.

Examples:

$d=10$, $\mathcal{N}=1$ susy $\Longrightarrow$ $G = E_8 \times E_8$ or $G = Spin(32)/\mathbb{Z}_2$



In other words, even though $E_8 \times U(1)^{248}$ and $U(1)^{496}$ are semiclassically consistent choices for gauge group G, but they are not realized in string theory (nor in its non-perturbative completions, M- or F- theories)

We conjecture that these choices are actually inconsistent as a full quantum theory.

There are similar restrictions in other dimensions. For example

$d=4$ locally $\mathbb{C}^2/\mathbb{Z}_n \Rightarrow G = U(n)$

but in the context of a compact

theory $\mathbb{C}^2/\mathbb{Z}_n \subset K3$

$\Rightarrow$ rank$(G) = 20$

In addition

not all rank $= 20$ gauge groups are realized.

(G realized $\Longleftrightarrow$ $\subset$)

root lattice

self-dual even integral lattice

Again these restrictions on G seem correlated with having a dynamical gravity, in particular for X: non-compact no restrictions known.

(Example: $\mathbb{C}^2/\mathbb{Z}_n \to U(n)$ $\forall n$)

– Strength of gauge coupling const.

Consider a $U(1)$ gauge theory with coupling constant g

<u>Claim</u>: $\exists$ light charged particle

$$m \lesssim g \, M_{Planck}$$

$g \gtrsim \frac{m}{M_{pl}}$

+

Checks

1) Heterotic strings:

$$M_s \sim g\, M_{Planck}$$

$\exists$ light states, strings,

and $\Lambda > M_s$ effective

gauge theory breaks down

2) KK reductions

$$g\, M_{Pl} \sim \frac{1}{R} \, ;$$

$\Lambda > \frac{1}{R}$ effective gauge theory breaks down

Clearly the condition is vacuous when $M_{Pl} \to \infty$

$\left(g \gtrsim \frac{m}{M_{Pl}} \sim 0 \right)$

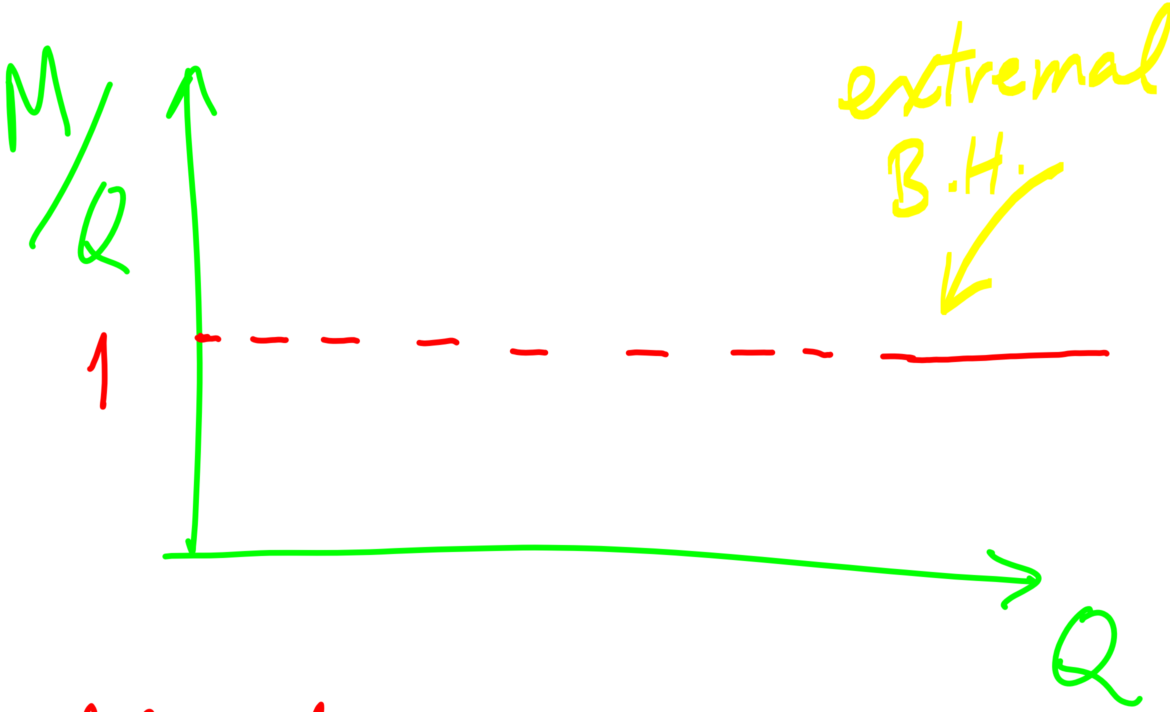
One way to motivate this conjecture:

(Unless protected by some charge):

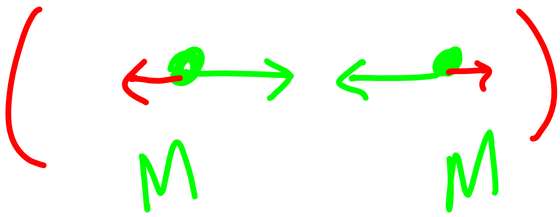
$\not\exists$ Stable particles $< \infty$

$$\left(\frac{M}{Q}\right)_{min} < 1$$

Extremal Black holes



If $\frac{M}{Q} > 1 \Rightarrow M > Q$

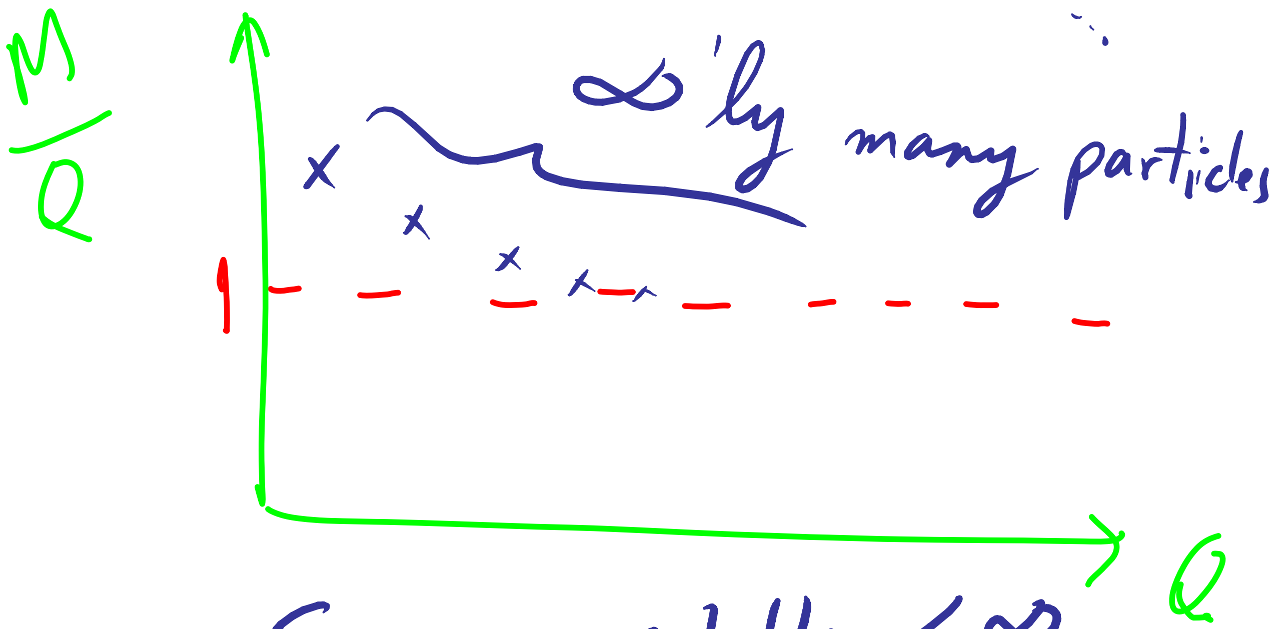


= attractive force

$\Rightarrow$ bound state

$M' < 2M \qquad Q' = 2Q$

If $\frac{M'}{Q'} > 1 \rightarrow$ continue M'', Q'' ...



So # stable $< \infty$

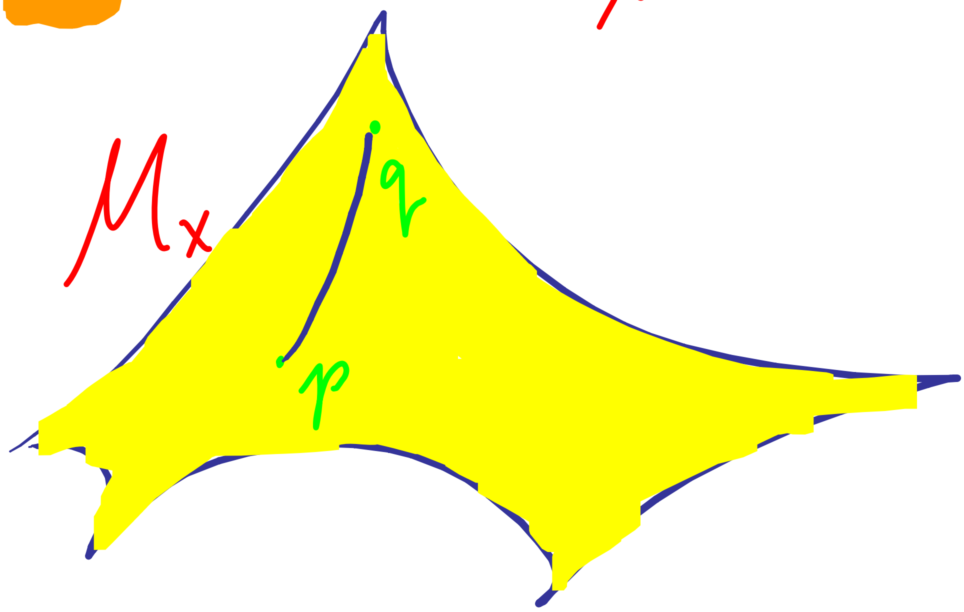
$$\Downarrow$$

$$\exists \left(\frac{M}{Q} < 1\right) \rightarrow \left(M/Q\right)_{min} < 1$$

Non-trivial example:

Non-susy BH in heterotic string compactifications.

— Diam. $(\mathcal{M}_x) = \infty$



$$\text{Diam} \equiv \max_{p,q \in \mathcal{M}_x} \left[d(p,q) \right]$$

Diam $= \infty$;

fix p; look at all q

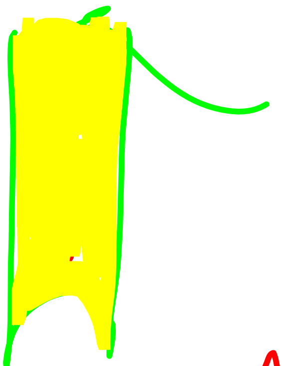
there are points at ∞ ;

Moreover pts. at ∞ correspond to the regions with an ∞ tower of light particles:

as $d_{(p,q)} \to \infty$, for some α.

Examples: T^2 compactification

τ:

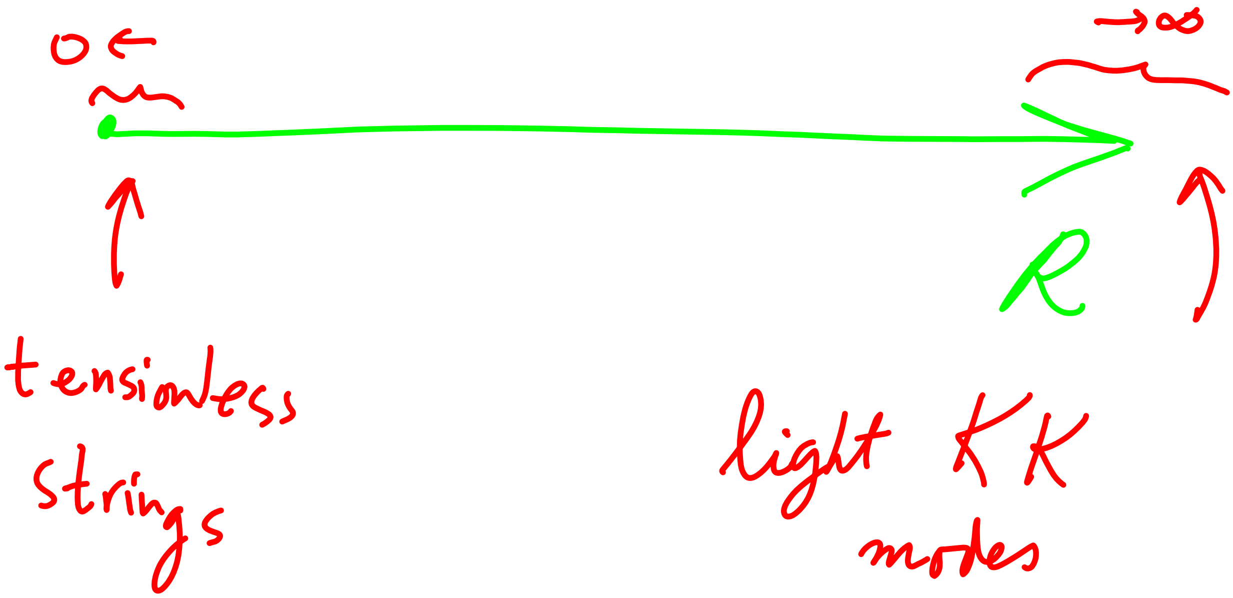


$$d = \int^{1/\Lambda} \frac{d\tau_2}{\tau_2} \sim \ln \frac{1}{\Lambda}$$

$$\Lambda \sim e^{-d}$$

Another example :

M-theory on S^1_R :



Counter examples if we decouple gravity :

$$\mathrm{diam}(M_X) \neq \infty$$

$$M_X = G/H$$

e.g. $G = SU(2)$; $H = U(1)$

Also in field theory

even if $\mathrm{diam}(\mathcal{M}_X) = \infty$

$\not\Rightarrow$ extra light modes:

e.g. $\mathcal{N}=4$ YM

$G = SU(2)$

$$\mathcal{M}_X = \mathbb{R}^6/\mathbb{Z}_2 \ni \phi^i$$

$p \in \mathcal{M}_X$ at ∞ correspond

to $W^\pm$ infinitely <u>massive</u>;

no extra light particles appear.

6 - $R(d=\infty) < 0.$

Note : $\left.\begin{array}{l} d = \infty \\ \text{vol} = \text{finite} \end{array}\right\}$ clash

$\longrightarrow$ $R\big|_{\infty} < 0$ is almost a requirement.

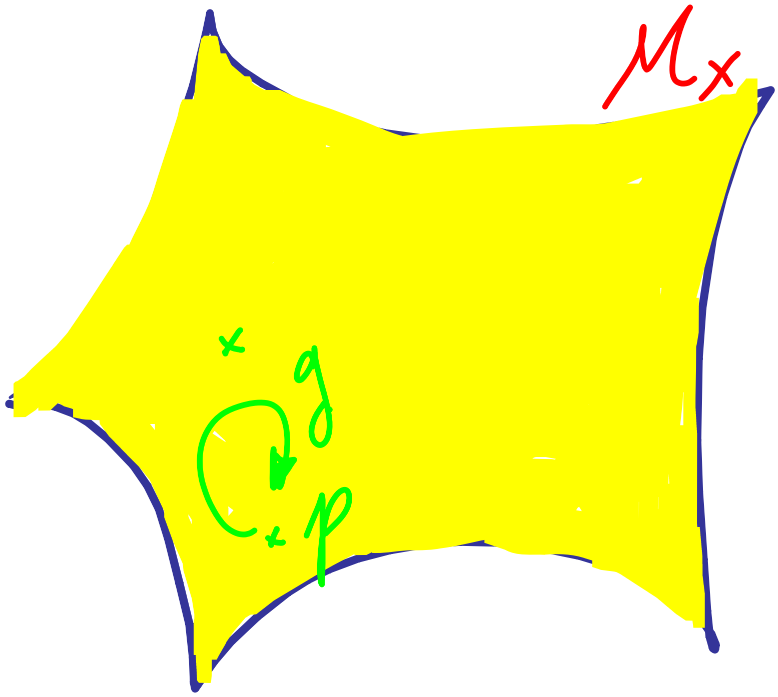
Example : $G(\mathbb{Z}) \backslash G / H$

that appear in string theory have $R<0$.

Condition violated for field theory w/o gravity: for $\mathcal{N}=2$ gauge theories $R>0$

– $\pi_1(M_x) = \phi$

Intuition: Duality group is generated by gauge symmetry.



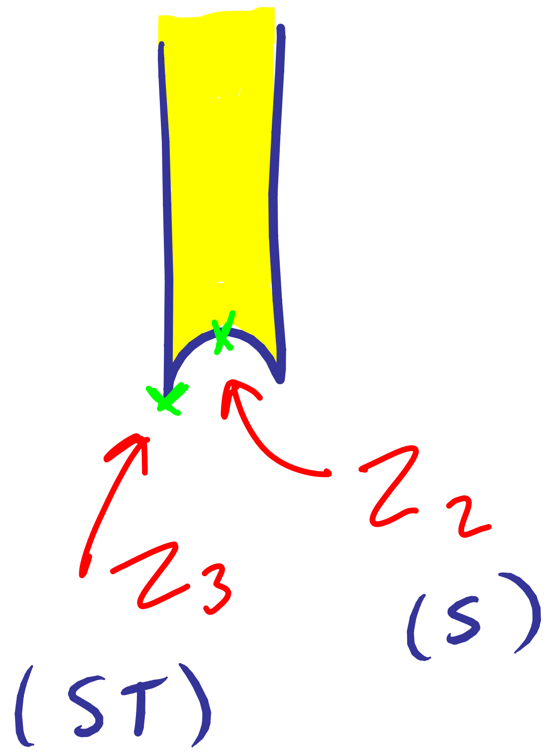
$$M_x = T_x / \Gamma$$

Γ ← duality group

$p \in T_x$ fixed by $g \in \Gamma$

$\Rightarrow$ $g \in$ gauge group at p.

Example:



$SL(2,\mathbb{Z})$ generated by S, ST

If Γ generated by elements with fixed pts $\Rightarrow \pi_1(\mathcal{M}_X) = \phi$

(Another intuition: compactification to 1+1 $\Rightarrow$ global charge $\Rightarrow$ not allowed in a quantum gravity)

Again, counterexample can be constructed if gravity is decoupled:

e.g. Axion $\quad \pi_1(\text{Axion}) = \mathbb{Z}$

(Suggests axion is always accompanied by an extra field when coupled to gravity)

Conclusion

Dynamical gravity puts restrictions on allowed theories

Mathematically

$\underbrace{X \text{ compact}}$ vs. $\underbrace{\text{non-compact}}$

$\Downarrow$

more restrictive

In particular:

$\mathrm{Vol}(X) < \infty \Rightarrow \mathrm{Vol}(\mathcal{M}_X) < \infty$

Also: $\dim(\mathcal{M}_X) < \infty$
(uniform)

$X = \text{singular} \Rightarrow G:$ restrictive

We have also seen finiteness have other consequences:

$$\left(M/Q\right)_{\min} < 1$$

(gravity is the weakest force)

$$\Rightarrow \exists \text{ scale}$$

$$\Lambda \sim g\, M_{Pl}$$

$$E > \Lambda$$

effective field theory breaks down

– $\operatorname{diam}(\mathcal{M}_X) = \infty$

(points at ∞) $\Rightarrow$ ($m \xrightarrow{\text{Tower of}} 0$)

– $R\big|_{d \to \infty} < 0$

– $\pi_1(\mathcal{M}_X) = \emptyset$

It would be important to:

– Try to find counterexamples

or – Try to understand why they are true.

– Broaden the list of conjectures.