A Pedestrian Excursion to the Swampland

Karim Benakli

(LPTHE, Paris)

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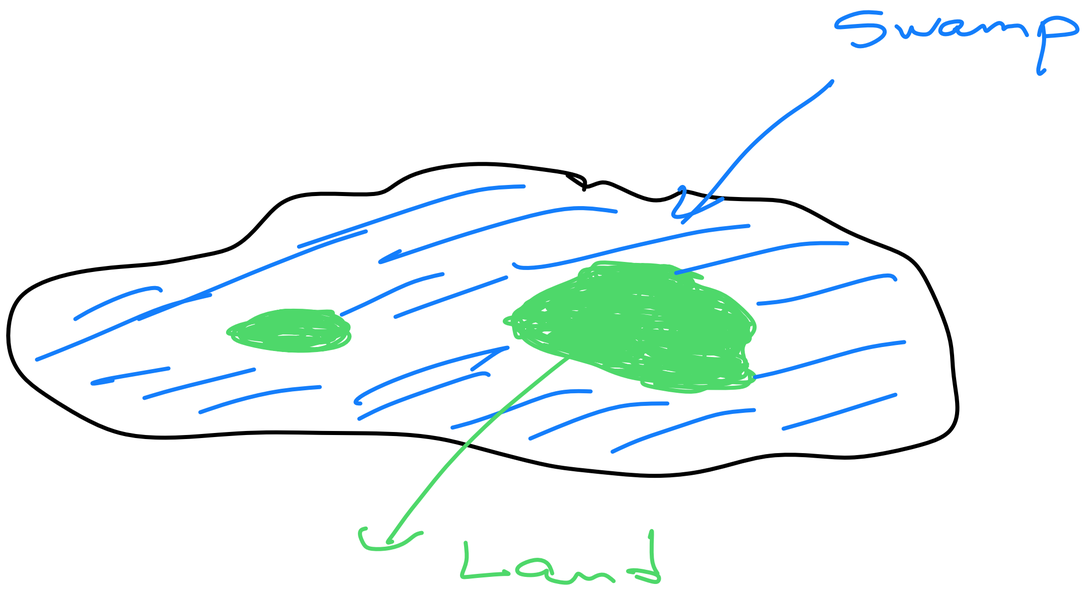
THE SWAMPLAND PROGRAM

Among the set of a priori consistent QFT which ones can arise as the LOW ENERGY EFFECTIVE FIELD THEORIES of QUANTUM THEORY OF GRAVITY

EFT have a cut-off

$$\Lambda_{UV} \lesssim M_{Pl}$$



CONJECTURE Some kind of symmetries are NOT ALLOWED in a Quantum Theory of Gravity

Wheeler - Polchinski - Banks Seiberg

* No global symmetries

* Completness Hypothesis : All irreducible representations of any gauge group should be present

(Ex: Smallest U(1) charge should be present)

* The internal gauge group should be compact

Global symmetry in Lorentz invariant QFT

Harlow - Ooguri '18

Definition

G symmetry group, $g \in G$, $U(g)$ unitary operator

* $U(g)\,U(g') = U(gg') \qquad g, g' \in G$

* $\exists\, O(x)$ such that $U^\dagger(g)\, O(x)\, U(g) \neq O(x)$

  $O(x)$ local gauge invariant state

* $U^\dagger(g)\, T_{\mu\nu}(x)\, U(g) = T_{\mu\nu}(x)$

Heuristic arguments

Black hole evaporation

Global charge conservation

→ Infinite number of stable remnants

→ Entropy diverges

Empirical evidence

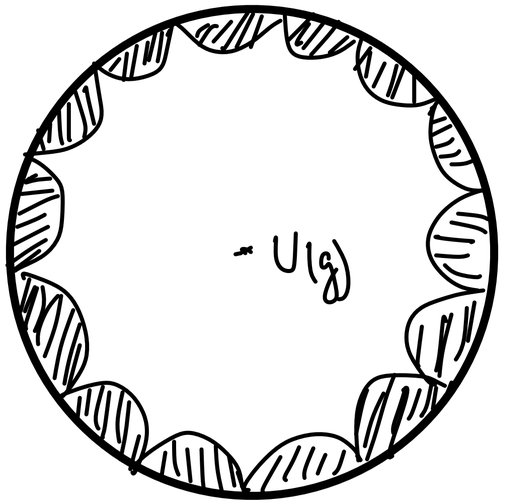
World sheet CFT

→ Global continuous symmetries are gauged

→ All known discrete symmetries are gauged

Holography arguments

Harlow Dogwi 1/18



→ Symmetry splittable on the boundary

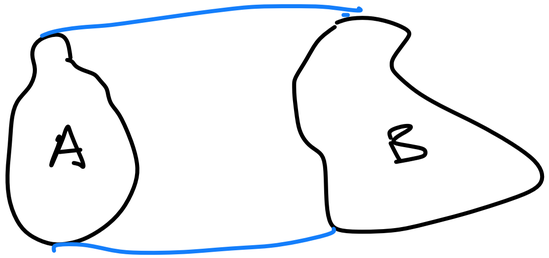
→ Sensitive to small regions

→ Do not see the operator in the bulk.

Cobordism

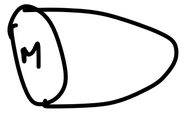
Mcnamara – Vafa

A ∪ B is the boundary of a manifold



A and B two compact manifolds

Def: 2 k-dimensional backgrounds M, N of QG theory are "cobordant" if they are related by a sequence of allowed topology changes.

A boundary is cobordant to empty space 

$\rightarrow \Omega_M = 0$

$\Omega_D^{QG} \equiv$ Equivalent classes of QG theories with D macroscopic dimensions

In a QG theory, all cobordism classes are trivial $\Omega_D^{QG} = 0$ $\left(\Omega^*_{D-d} = 0\right)$

Mcnamara–Vafa

No Global symmetry

+

Completness Hypothesis

$\Big\} \Rightarrow$

Cobordism Conjecture

$\Downarrow$

trivialisation needed

in some string theory

Compactification

$\Rightarrow$ New non-SUSY defects

Weak Gravity Conjecture (WGC)

In a flat space-time, for a single U(1) gauge theory with gauge coupling g, the WGC requires

$\exists$ massive charged state satisfying

$$|gq| \geq \sqrt{\frac{D-3}{D-2}}\,\frac{m}{M_{Pl}}$$

Arkani-Hamed Motl - Nicolis Vafa '06

* Decay of extremal BHs $\Rightarrow$ super-extremal states
* Overall long range repulsive force (BPS bound violated)
* Gravity «weaker» than gauge force
* No gravitational bound states

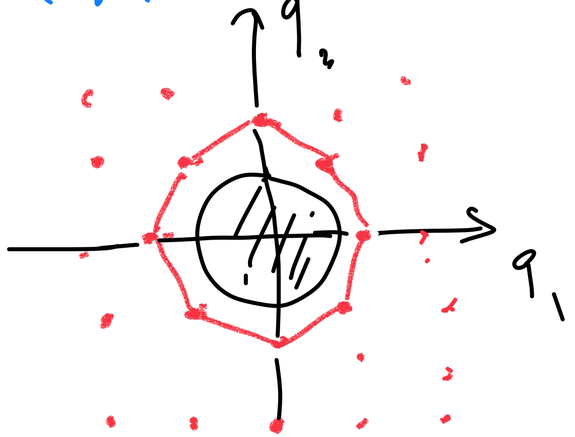
Extension to multiple U(1)s:

Cheung-Remmen

Decays of extremal BH requires

$\exists$ state of mass m such that

$$\sum_i \left(\frac{g_i q_i}{m}\right)^2 \geq 1$$



Convex Hull

Dimensional reduction

$$U(1) + U(1)_{KK} \longrightarrow 2\ U(1)s$$

$U(1)_{KK}$ ← graviphoton

WGC violated unless infinte number of charges

BPS completness Kim, Shiu, Vafa '19

If a charge can be carried by a BPS state, then a BPS state with this charge should be part of the physical spectrum

→ This rules out $E_8 \times U(1)^{248}$, $U(1)^{496}$, rank $> 26-d$ $(d<10)$ for 16 supercharges

Sharpend WGC Ooguri, Vafa '17

The WGC can only be saturated by BPS states in a SUSY theory.

Magnetic WGC:

$$\frac{m_{mag}}{M_{Pl}} \simeq \frac{\Lambda_{UV}}{g^2 M_{Pl}} \leqslant \frac{1}{g} \quad \Rightarrow \quad \Lambda_{UV} \lesssim g M_{Pl}$$

For many $U(1)$s: $\Lambda_{UV} \lesssim \min(g_i) M_{Pl}$

Application: (D = 4)

E.M. $\rightarrow$ $m_e = 511$ keV $\quad g_{em} \sim 0.3 \longrightarrow 0.3 \gtrsim 10^{-21}$

$m \sim$ TeV $\quad q = 1 \longrightarrow g \gtrsim 10^{-15}$

Magnetic

$g \sim 10^{-14}$ for fitting XENON 1T anomaly

K.B-Branchina-Laforgue-Vermet

$\Rightarrow \Lambda_{UV} \sim 10 - 100$ TeV

$\rightarrow$ Low string scale scenario

One way to get the WGC was: Decay of BH.

Non SUSY theory: higher order corrections to the extremal BH

$$\frac{M}{\varphi} = 1 \longrightarrow \frac{M}{\varphi} \leq 1$$

Kats - Petrov '07

$$\left[\text{BH} \Rightarrow \frac{M}{\varphi} > 1 - \frac{1}{\varphi^2}(2c_1 + 8c_2 + \cdots) \right]$$

"Black Hole Weak Gravity Conjecture"

AdS WGC:

Massive particles emitted in BH decay will fall back

$\Rightarrow$ Different decay channels

* scalar ϕ condensate $(m_\phi \ell)^2 \leq \frac{1}{2}(q_\phi g M_{Pl})^2 - \frac{3}{2}$ Gubser '08, Harthdl-Herzog Horowitz '08
* AdS/CFT $\Delta^2 \leq \frac{9 c_T}{40 c_V} q^2$ Nakayama-Nomura '15
* scalar hair $\{(\Delta-2)^2, 4(\Delta-2)^2, 3(\Delta-1)(\Delta-3)\} \leq \frac{9 c_T}{40 c_V} q^2$
* Super-extremality $\Delta^2 \leq 32\pi^2 \ell^2 \frac{\left(-1+\sqrt{1+12 q^2/\ell^2}\right)\left(2+\sqrt{1+12 q^2/\ell^2}\right)}{27}$
* Cosmic censorship $\Delta \leq q\mu$, $\Delta = \frac{3}{\ell} + \sqrt{\frac{9}{4\ell^2} + m^2}$, $\mu = \frac{Q}{r_+}$ Cristofaro, Horowitz, Santos '18

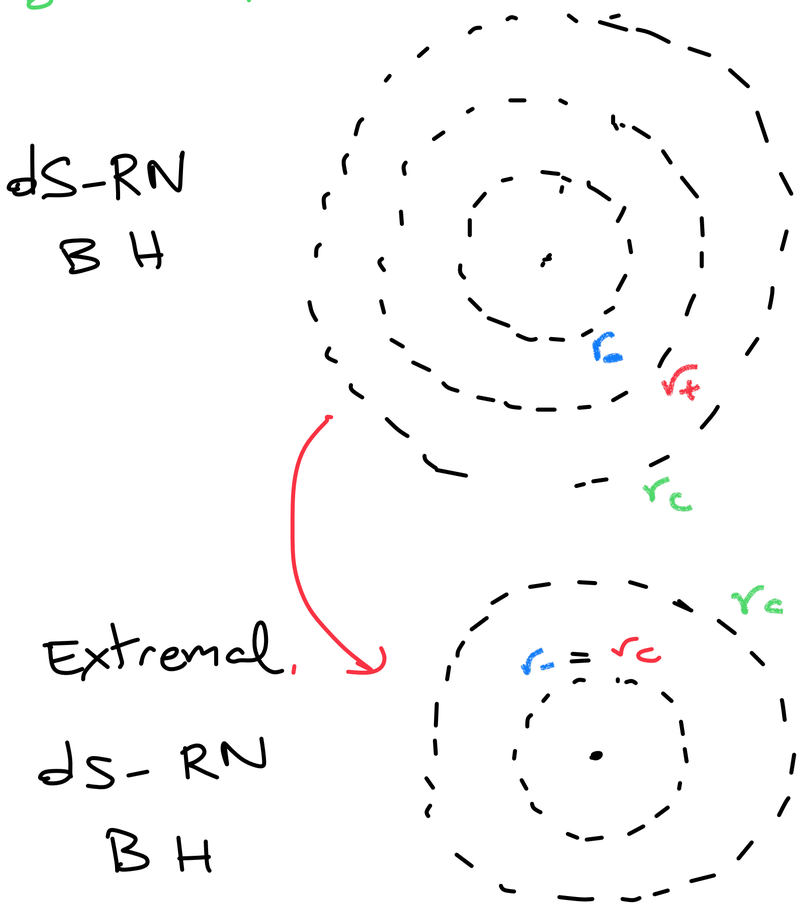
de Sitter case:

K.B. - Antoniadis '20

In the weak curvature limit

$$\frac{m^2}{M_{Pl}^2} \leq g^2 q^2 - \frac{(g^2 q^2)^2 \Lambda}{48\pi^2 M_{Pl}^2} + \cdots \qquad \Lambda \to 0$$

from superextremality requirement



Other proposal from BH decay:

$$\frac{m^2}{M_{Pl}^2} \leq g q \frac{M_P}{\sqrt{\Lambda}}$$

Montero - Van Riet - Venken '19

Scalars:

$$S = \int d^4x \left[R - \frac{(\partial\phi)^2}{2} - \frac{1}{4} e^{-2\alpha\phi} F^2 \right]$$

Heidenreich-Reece Rudelius '15

$\Rightarrow$ Dilatonic WGC:

$$\boxed{g^2 q^2 \geq \frac{1+\alpha^2}{2} \frac{m^2}{M_{Pl}^2}}$$

$$S = \int d^4x \left[R - \frac{k_{ij}}{2} \partial_\mu \phi^i \partial^\mu \phi^j - \frac{1}{4g^2} F^2 \right]$$

RFC $\boxed{g^2 q^2 \geq \frac{1}{2} \frac{m^2}{M_{Pl}^2} + k_{ij} \frac{\partial_i m \partial_j m}{4 m^2}}$

Palti '17

Heidenreich-Reece Rudelius '19

$\Rightarrow$ Repulsive force Conjecture

What if we consider scalars only without gauge forces?

- $2\left(V'''(\phi)\right)^2 - V''(\phi)\,V''''(\phi) \geq \dfrac{\left(V''(\phi)\right)^2}{M_{Pl}^2}$ Gonzalo-Ibanez '19

- For any scalar ϕ, there should exist at least one state X such that the interaction between X and ϕ is at least as strong than the gravitational one. K.B - Branchina Lafforgue-Marmet '20

- In pair productions, gravitational process are subdominant Gonzalo-Ibanez '20

Example 1:

$$V(\phi) = \frac{1}{2} m_0^2 \phi^2 + \frac{\mu}{3!} \phi^3 + \frac{\lambda}{4!} \phi^4$$

$$\rightarrow \quad \left| \lambda - \frac{5}{3} \frac{\mu^2}{m_0^2} \right| \geq \frac{m_0^2}{M_{Pl}^2}$$

Example 2: For $V(\phi, X) = m_0^2(\phi) X^2 + \sum_n \lambda_n(\phi) X^n$

$$\left| \frac{\partial_\phi V}{V} \right|_{X=0} \geq \frac{a}{M_{Pl}} \qquad \phi \in \mathbb{R}$$

$$\left| \frac{\partial_\phi \partial_\phi V}{V} \right|_{X=0} \geq \frac{b}{M_{Pl}^2} \qquad \phi \in \mathbb{C}$$

AdS & dS Dilatonic WGC

K.B - Branchina - Lafforgue-Marnet

$$\int d^4x \left\{ R - 2(\partial\phi)^2 - e^{-2\alpha\phi} F^2 - V(\phi) \right\}$$

$$V(\phi) = \frac{2}{3} \frac{\Lambda}{1+\alpha^2} \left(\alpha^2(3\alpha^2-1)\, e^{-2\frac{\phi-\phi_0}{\alpha}} + (3-\alpha^2)\, e^{2\alpha(\phi-\phi_0)} + 8\alpha^2 e^{\alpha(\phi-\phi_0) - \frac{\phi-\phi_0}{\alpha}} \right)$$

Dilatonic BH solution

- Gao-Zhang
- Elvang - Freedman - Liu
- Mignemi

Behaviour depends on $\alpha > \frac{1}{\sqrt{3}}$ or $\alpha = \frac{1}{\sqrt{3}}$ or $\frac{1}{\sqrt{3}} > \alpha > 0$

$\alpha > \frac{1}{\sqrt{3}} \Rightarrow \varphi^2 \geq (1+\alpha^2) M^2$

$\alpha = \frac{1}{\sqrt{3}} \Rightarrow \varphi^2 \geq \frac{4}{3} M^2 + \frac{4^3}{3^3} \frac{M^4 \Lambda}{3} + \cdots$

$\alpha < \frac{1}{\sqrt{3}} \Rightarrow$ dS extremality is not reached $\varphi^2 \geq \frac{M^2}{1-\alpha^2}$

Swampland Distance Conjecture — Ooguri – Vafa

String theory → no parameters → vev of scalar fields

An infinite tower of states becomes light at infinite field distance limit

$$m(\mathcal{B}) \simeq m(\mathcal{A})\, e^{-\lambda \Delta\phi} \quad \text{when} \quad \Delta\phi \to \infty$$

with $\Delta\phi \equiv$ distance(P, Q)

$$\Rightarrow \Delta\phi \leq \frac{1}{\lambda} \log \frac{M_P}{\Lambda_{UV}}$$

Examples: * K.K. $m_{KK} = \frac{n}{R} = \frac{n}{L} e^{-\sqrt{\frac{D-1}{D-2}}\, \kappa \phi}$

* $g_s \to \infty \Rightarrow$ D-branes become light
* $g_s \to 0 \Rightarrow$ string oscillators become light

other proposals:

* AdS conjecture: $m \sim |\Lambda|^{\alpha}$ for $\Lambda \to 0$ $(\alpha > 0)$ — Lust-Palti-Vafa

* AdS instability: Non-SUSY AdS are unstable (decays in a Hubble time) — Ooguri-Vafa

  ↕ Sharpened WGC

* de Sitter conjecture: $\frac{|\nabla V|}{V} \geq \frac{c}{M_{Pl}}$ $c > 0$ $c \sim \mathcal{O}(1)$ — Obied-Ooguri-Spodyneiko-Vafa

  $\min(\nabla_i \nabla_j V) \leq -\frac{c' V}{M_{Pl}^2}$ $c' > 0$; $c' \sim \mathcal{O}(1)$

* Transplanckian Censorship Conjecture: $\frac{|\nabla V|}{V} \geqslant \frac{2}{\sqrt{(d-1)(d-2)}}$ — Bedroya-Vafa

  ds minimum short-lived $\tau \leq \frac{1}{H} \log \frac{M_P}{H}$

* Gravitino distance conjecture (see Alvaro Herraez talk)

CONCLUSIONS

* What is the principle that leads to the WGC?
* What are the WGC states?
* What role does supersymmetry plays in the Swampland conjectures (SDC, ...)?
* How much are the String Theory evidence generic for Quantum Gravity?
* Any application to phenomenology?