Title: A hike through the Swamp

Speakers: Miguel Montero

Collection: Puzzles in the Quantum Gravity Landscape: viewpoints from different approaches

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Abstract: At first sight, it seems that almost any QFT, seen as a low-energy effective field theory (EFT), can be coupled to gravity -- simply add an Einstein-Hilbert term, change all derivatives by covariant ones, and you're done. However, a growing body of evidence coming from String Theory compactifications, general properties of black hole evaporation, and rigorous results in holography, suggests that the opposite is true. We can work out the hidden constraints that quantum gravity consistency imposes in the matter sector systematically, an approach that receives the colourful name of "The Swampland Program". I will briefly review the program, its motivation, current results, and long-term goals.

A HIKE

THROUGH THE SWAMPLAND

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Puzzles in QG Landscape, Perimeter

Oct 23 2023

WARMING UP

This is a **quick hike** through the Swampland.

We'll briefly explain what the Swampland **is**,

then cover some of the more interesting
Swampland constraints

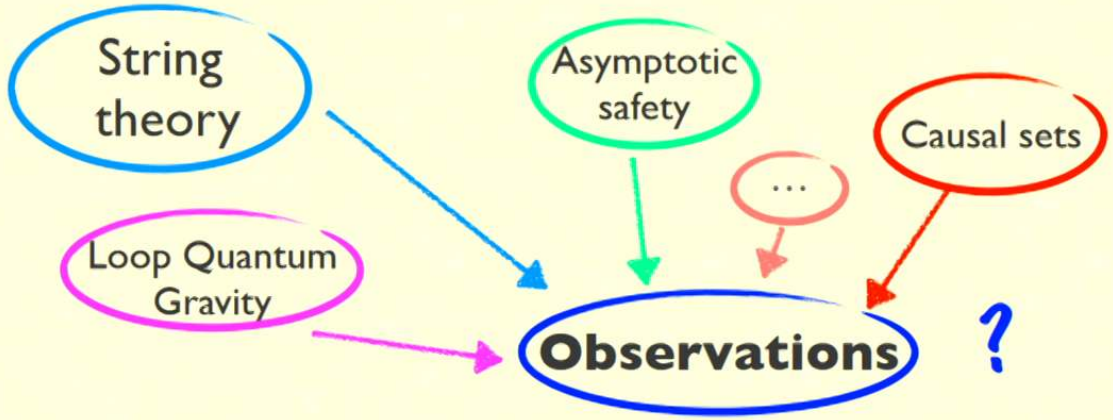
Just as in any nature hike, we will stop to observe the scenery

Quantum Gravity Research 101

$$M_P = 10^{19}\,\mathrm{GeV} \gg E_{\mathrm{Today}} \sim 10^3\,GeV$$

Direct experiment? No

QG research is eminently **theoretical**



Is it **even possible** to say anything interesting in the deep IR?

Classically, the answer is clearly **no**!

$$\frac{1}{8\pi M_P^2}\int d^4x\sqrt{-g}\,R+\int\sqrt{-g}\mathcal{L}_{\rm EFT}$$

QCD, SM, axions,
dark matter…

You can choose **any** QFT you like — the "EFT"

and couple it to gravity

In **quantum** gravity, however, this is not so clear…

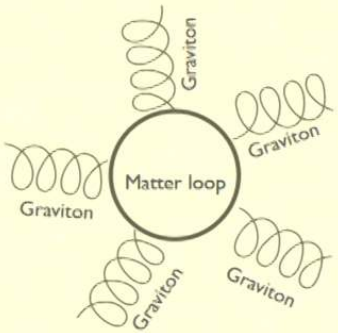
…because of the **lack of decoupling** in gravity!

(a.k.a. the Equivalence Principle)

Gravity couples to **everything**

so matter fields cannot be ignored when quantizing gravity

(they affect gravity via loop effects)

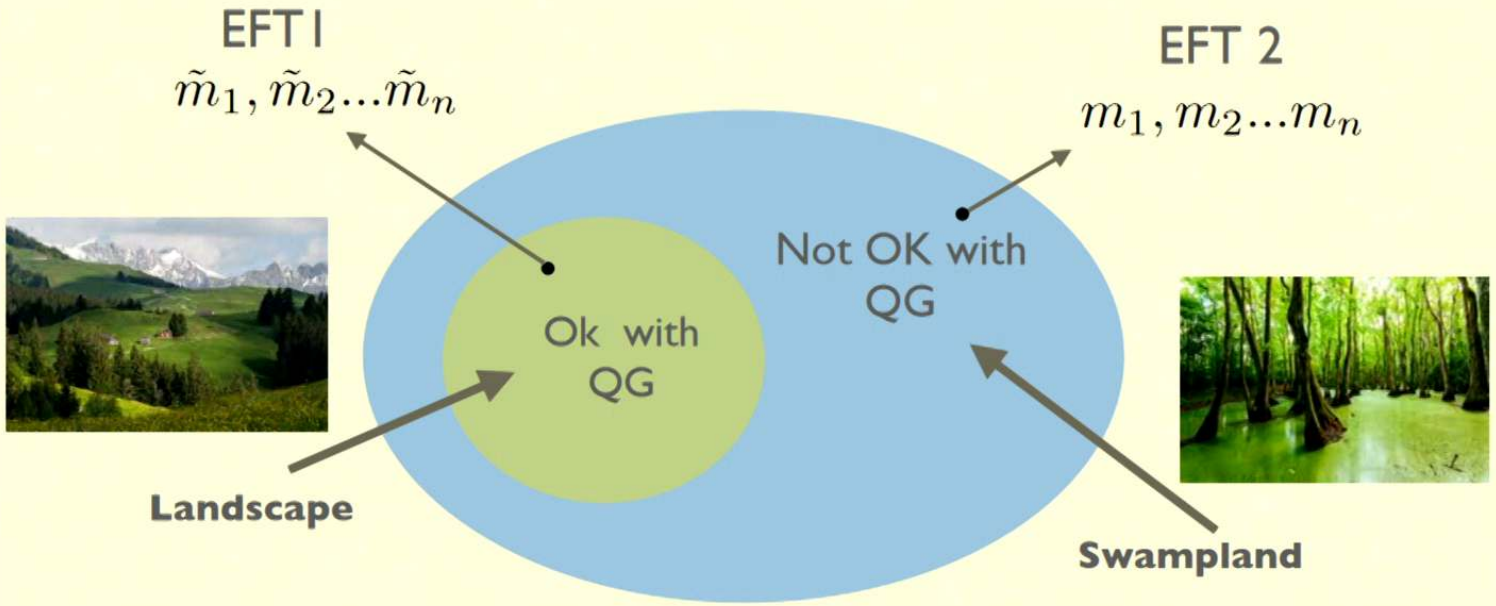


Since everything talks to everything else, there might be

$\mathcal{L}_{EFT}$ that can't be coupled to QG at the quantum level

(i.e. they do not arise as the deep IR description of any consistent QG)

Let us draw the abstract space of all EFT's



There is, in fact, a growing body of evidence that indeed, not any EFT can be coupled to gravity.

Swampland Program: Identify the **universal constraints** that a low-energy EFT must satisfy to be in the Landscape (i.e, so that it can be consistently coupled to QG)

General arguments (e.g. based on unitarity of BH evaporation) that do not depend on UV

Data obtained from the biggest theoretical lab there is in QG: **String Theory**

Why the **focus** on String Theory?

Only QG framework sufficiently developed to quantitatively check Swampland constraints

String theory

Asymptotic safety

…

Loop Quantum Gravity

Causal sets

To check Swampland constraints, I need detailed properties (how many fields & which kind, masses, couplings) of the EFT.

Furthermore, **huge** landscape of vacua! ($>10^{272000}$)

Q: Can we check Swampland in any other framework? How?

Q: Can you **prove** any of this?

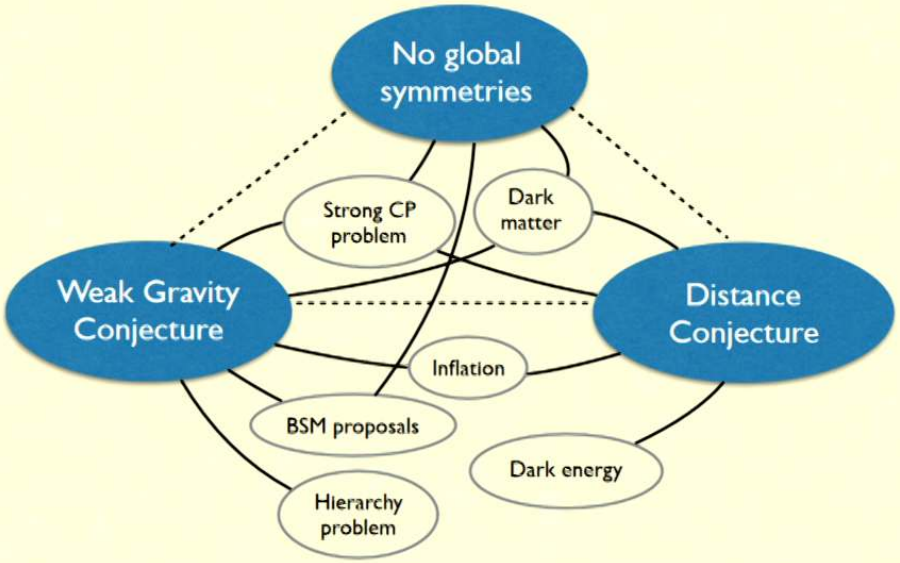
A: **Sometimes**, in restricted contexts that don't cover all the examples.

(e.g. with Lambda<0, we have AdS/CFT)

We don't have a framework to prove general things in quantum gravity

So we organize our knowledge in terms of **conjectures**

We will focus on these three in our hike.



No global symmetries

A symmetry/charge is a quantity conserved by **dynamical processes**

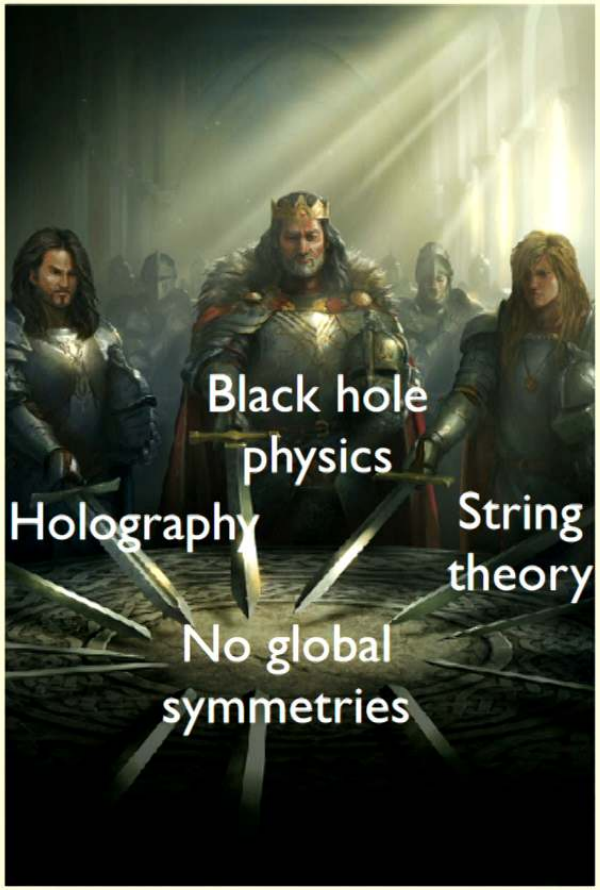
$$\begin{matrix} Q=0 \\ B-L=1 \end{matrix} \qquad n \to p^+ + e^- \bar{\nu}_e \qquad \begin{matrix} Q=0 \\ B-L=1 \end{matrix}$$

They are of **two kinds**:

(long range) **gauge symmetry** if the charge can be measured from far away (via electric field)

Global symmetry if the charge cannot be measured like this

Swampland



Lots of **evidence**:

Arguments about black hole decay/absence of remnants

Proof in perturbative ST

In AdS/CFT, for continuous global syms. equivalent to **Noether's theorem**

Recent proofs using entanglement entropy/islands in **flat space**

[Hsin, Iliesu, Yang '20, Chen, Lin '20, Bah, Chen, Maldacena '22]

Always true in every ST example

This has **real-world** consequences: B-L is a global sym. in the SM

So it is either coupled to a (yet unseen) **fifth force**

or

It is not a real symmetry, it is **broken**

Double beta decay, proton decay

This conjecture, by itself, does not lead to strong IR constraints… since it doesn't tell you at which energy scale is the symmetry broken.

But applied to generalized symmetries + supersymmetry, it becomes **very strong**

Example: Theories with minimal SUSY in d=7,8,9

Only two multiplets: Gravity multiplet + Vector multiplet

Lagrangian fully fixed by SUSY

So only question: **How many vector multiplets?**

	EFT	**Swampland prediction**	**ST constructions**
d=9	Any **odd** #of vectors	1 mod 8	1 mod 8
d=8	Any **even** # of vectors	2 mod 8	2 mod 8
d=7	Any # of vectors	Any odd # of vectors	1,3,5,9,11,13

Working on lower dim, less SUSY!

The Weak Gravity Conjecture

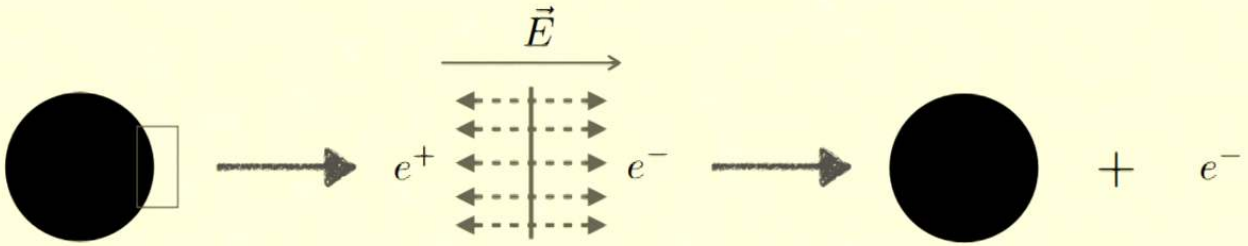
[Arkani-Hamed, Motl, Nicolis, Vafa '06]

There has to be a particle whose **electric charge** is bigger than its mass in Planck units:

$$m \leq gM_P$$

Gravity is the **weakest force**

Satisfied in real world by **electrons**, and related to kinematics of black hole evaporation



The Weak Gravity Conjecture

[Arkani-Hamed, Motl, Nicolis, Vafa '06]

Evidence comes from:

Statement true in every string compactification

Proof in perturbative string theory

[Arkani-Hamed, Motl, Nicolis, Vafa '06, Heidenreich-Reece-Rudelius '16, MM-Shiu-Soler '16]

Proof of some version of the statement in AdS/CFT

[MM '18]

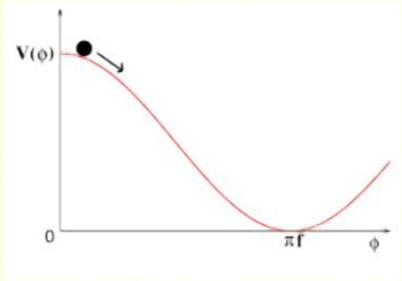
Proof attempts via unitarity/positivity bounds

(though some hurdles, see [Henriksson, McPeak, Russo, Vissi '22])

WGC does not constrain the SM very much…

…but puts constraints on models of **milli-charged dark matter**

and models of **natural inflation**



$$V(\phi) \sim e^{-\frac{M_P}{f}} \cos(\phi/f)$$

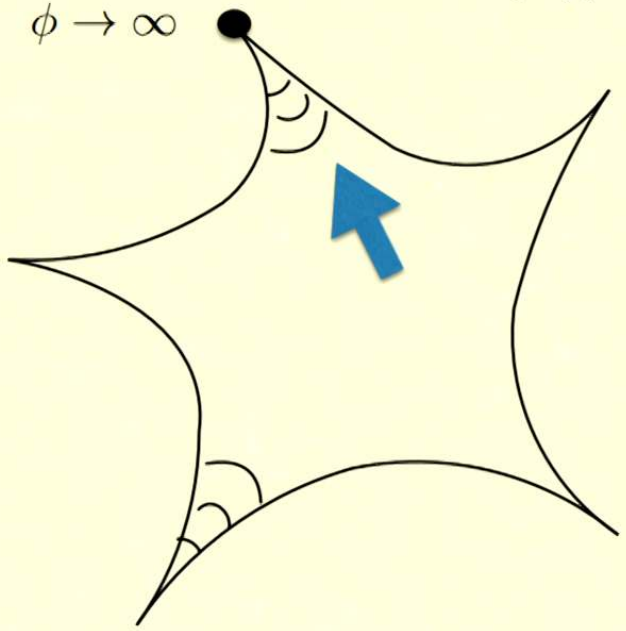
puts upper bound on
cosmological observables

The Distance Conjecture

In string theory, we often have **massles/light scalar fields,** called moduli.

$$m \sim m_0 \exp(-\alpha\phi) \to 0$$

$\phi \to \infty$



They control the couplings of the theory.

Empirical ST observation: As a scalar gets a very large vev, many states become light with respect to Planck mass and EFT breaks down

Distance Conjecture: These towers of states are **always** there at infinite distance limits

[Ooguri, Vafa '05]

Connection to no global symmetries and WGC:

In every infinite distance limit, some gauge coupling goes to zero.

[Gendler, Valenzuela '20]

In all examples, this tower is either a a **KK tower** or a **fundamental string**

(emergent string conjecture [Lee-Weigand-Lerche '19])

The Distance Conjecture is important for cosmology:

$$m(P) \sim m(Q) e^{-\alpha \Delta\phi} \longrightarrow \Delta\phi \lesssim \frac{1}{\alpha} \log\left(\frac{M_p}{\Lambda}\right)$$

$$\alpha \sim \mathcal{O}(1)$$

[Scalisi Valenzuela '19]

So we want to find out what's the **smallest possible** value of alpha

$$\alpha \geq \frac{1}{\sqrt{6}} \text{ for } \mathrm{CY}_3$$

[Grimm, Palti, Valenzuela'18]

[Bastian et al'20] [Gendler, Valenzuela'20]

And it may be relevant today; a KK tower of states with

$$m_{KK} \sim (5\,\mu m)^{-1}$$

is compatible with observations & suggested by Swampland

[MM, Vafa, Valenzuela '22]

$m^4 > 8\pi\alpha\, q^2 M_P \Lambda$ Dynamical cobordism

Gravitino mass conjecture

There is much more to the Swampland than the ideas sketched here.

Species bound

$\Omega^{\mathrm{QG}} = 0$ RFC

Nonsusy AdS is in the Swamp

Euclidean wormholes and WGC

Neutrino masses

$m^4 > 8\pi\alpha\, q^2 M_P \Lambda$

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Bubbles of nothing

Convexity of operator spectrum

Neutrino masses

Please, just **ask** about anything that caught your attention!

I love to chat & am around all week

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You can also join our biweekly online seminar series:

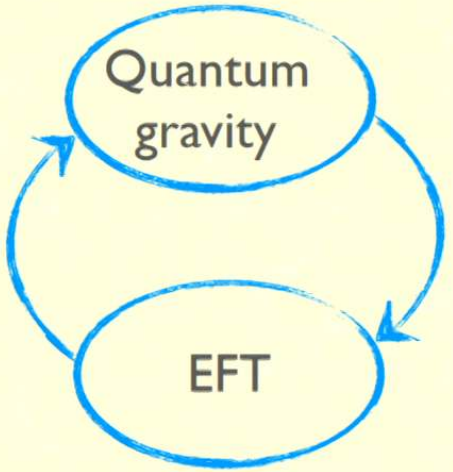
https://sites.google.com/view/swamplandseminars

The **take home** message is that quantum gravity imposes **nontrivial constraints** at low energies that we are just beginning to uncover

Research in Swampland is very **interdisciplinary**

Hardcore String Theory, Holography, Quantum information, algebraic geometry, algebraic topology, particle phenomenology…

… and that should be **extended** to include asymptotic safety, LQG, causal sets…

which is why I am excited to find out what we will **discover** together this week!

HOPE YOU ENJOYED THE HIKE!