The Swampland: a novel way to understand the implications UV completion?

Thomas Van Riet – KU Leuven

Cospa meeting, Brussels October 29, 2021

Based on:

1. 1903.06239 review E. Palti
2. 2107.00087 review Graña, Herráez
3. 2106.07650 M. Montero, C. Vafa, T. Van Riet and G. Venken

1. Motivation

2. Swampland bound examples

3. The Festina Lente bound.

4. Pheno applications

5. Conclusions.

1. Motivation

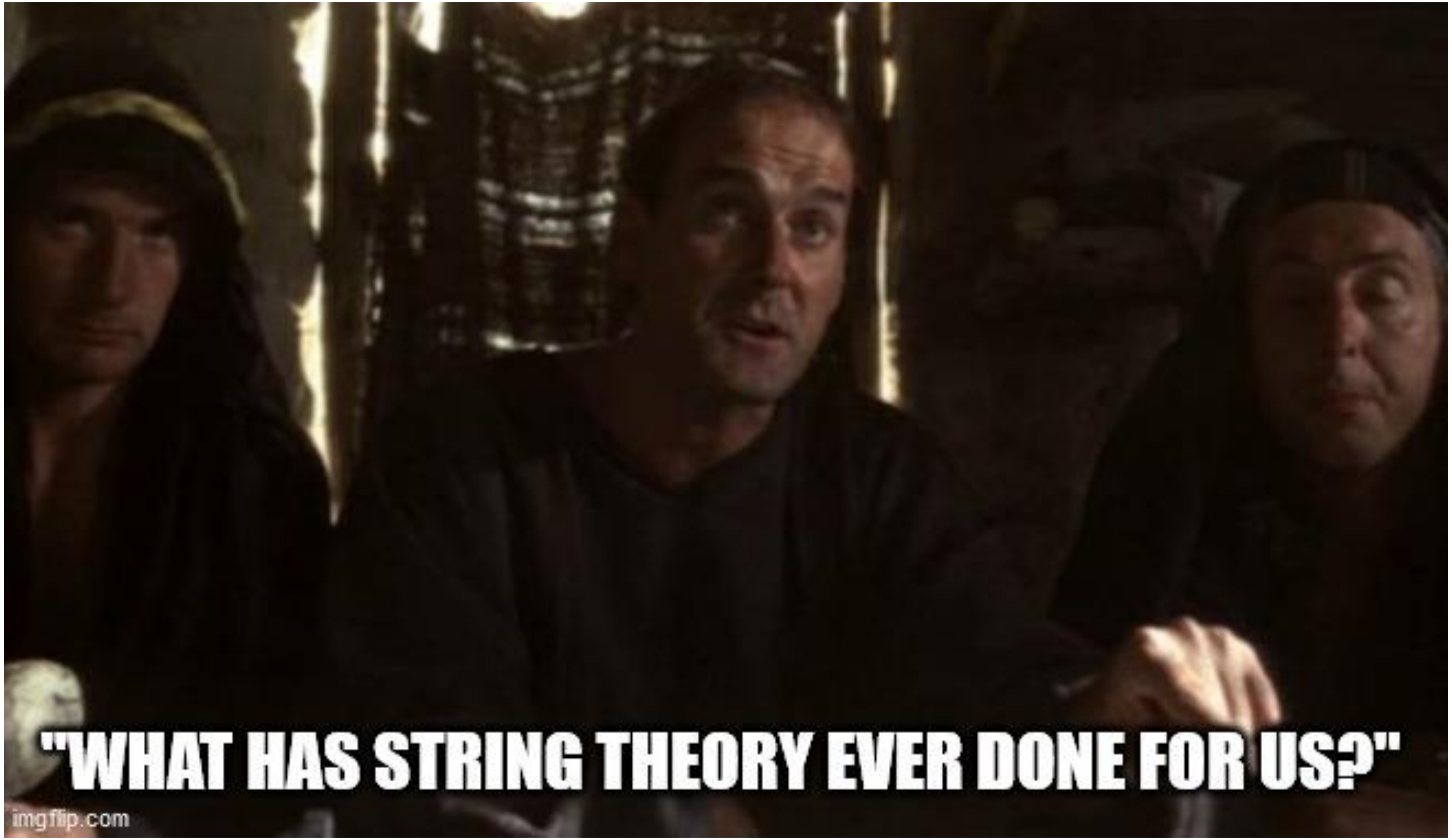
2. Swampland bound examples

3. The Festina Lente bound.

4. Pheno applications

5. Conclusions.

“Oh no, not another string theorist talking at an actual physics conference”



Where does this attitude come from?

- Go back 30 years in time:

→ Some string theorists: “We have found the theory of everything, now it is just a matter of identifying the correct Calabi Yau manifold on which we compactify heterotic string theory”

Where does this attitude come from?

- Go back 30 years in time:

→ Some string theorists: “We have found the theory of everything, now it is just a matter of identifying the correct Calabi Yau manifold on which we compactify heterotic string theory”

- 30 years later:

→ Some string theorists: “euh…$10^{\text{crazy number}}$ of vacua, multiverse, anthropics…”

Where does this attitude come from?

- Go back 30 years in time:

→ Some string theorists: "We have found the theory of everything, now it is just a matter of identifying the correct Calabi Yau manifold on which we compactify heterotic string theory"

- 30 years later:

→ Some string theorists: "euh…$10^{\text{crazy number}}$ of vacua, multiverse, anthropics…"

Now there is a paradigm shift, and it all started with the concept of "the Swampland" [Vafa, 2005]

Illustration in biology

The growth of leaves on a plant: helical structure upwards , average angle between leaves is golden angle. Distribution of seeds on a flower

Why?

(personal interpretation of chapter from *Mathematics of Life*, from Ian Stewart, 2011)

Illustration in biology

The growth of leaves on a plant: helical structure upwards , average angle between leaves is golden angle. Distribution of seeds on a flower

Why?

Answer 1: Leave distribution maximizes sunlight and rain absorption (Thompson, 1917)! Seed distribution maximizes amount of seeds on a given surface! Survival principle (Darwin).

(personal interpretation of chapter from *Mathematics of Life*, from Ian Stewart, 2011)

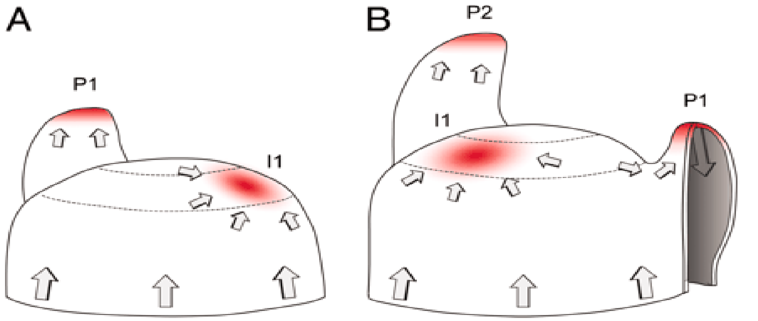
Illustration in biology

The growth of leaves on a plant: helical structure upwards , average angle between leaves is <u>golden angle</u>. Distribution of seeds on a flower

Why?

Answer 1: Leave distribution maximizes sunlight and rain absorption (Thompson, 1917)! Seed distribution maximizes amount of seeds on a given surface! Survival principle (Darwin).

Answer 2: It is the only option. Microscopic models for (Van der Waals) forces on lumps of cells during growth gives golden angle (Douady & Couder, 1992).



(personal interpretation of chapter from *Mathematics of Life*, from Ian Stewart, 2011)

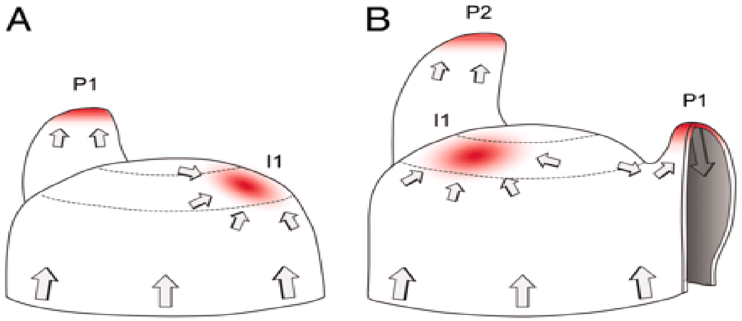
Illustration in biology

The growth of leaves on a plant: helical structure upwards , average angle between leaves is golden angle. Distribution of seeds on a flower

Why?

Answer 1: Leave distribution LANDSCAPE rain absorption (Thompson, 1917)! Seed distribution maximizes ar n surface! Survival principle (Darwin).

Answer 2: It is the only option. Microscopic models for (Van der Waals) forces on lumps of SWAMPLAND golden angle (Douady & Coud



(personal interpretation of chapter from *Mathematics of Life*, from Ian Stewart, 2011)

The Swampland: Set of effective field theories **coupled to gravity** that cannot be UV completed”.

The Swampland: Set of effective field theories **coupled to gravity** that cannot be UV completed”.

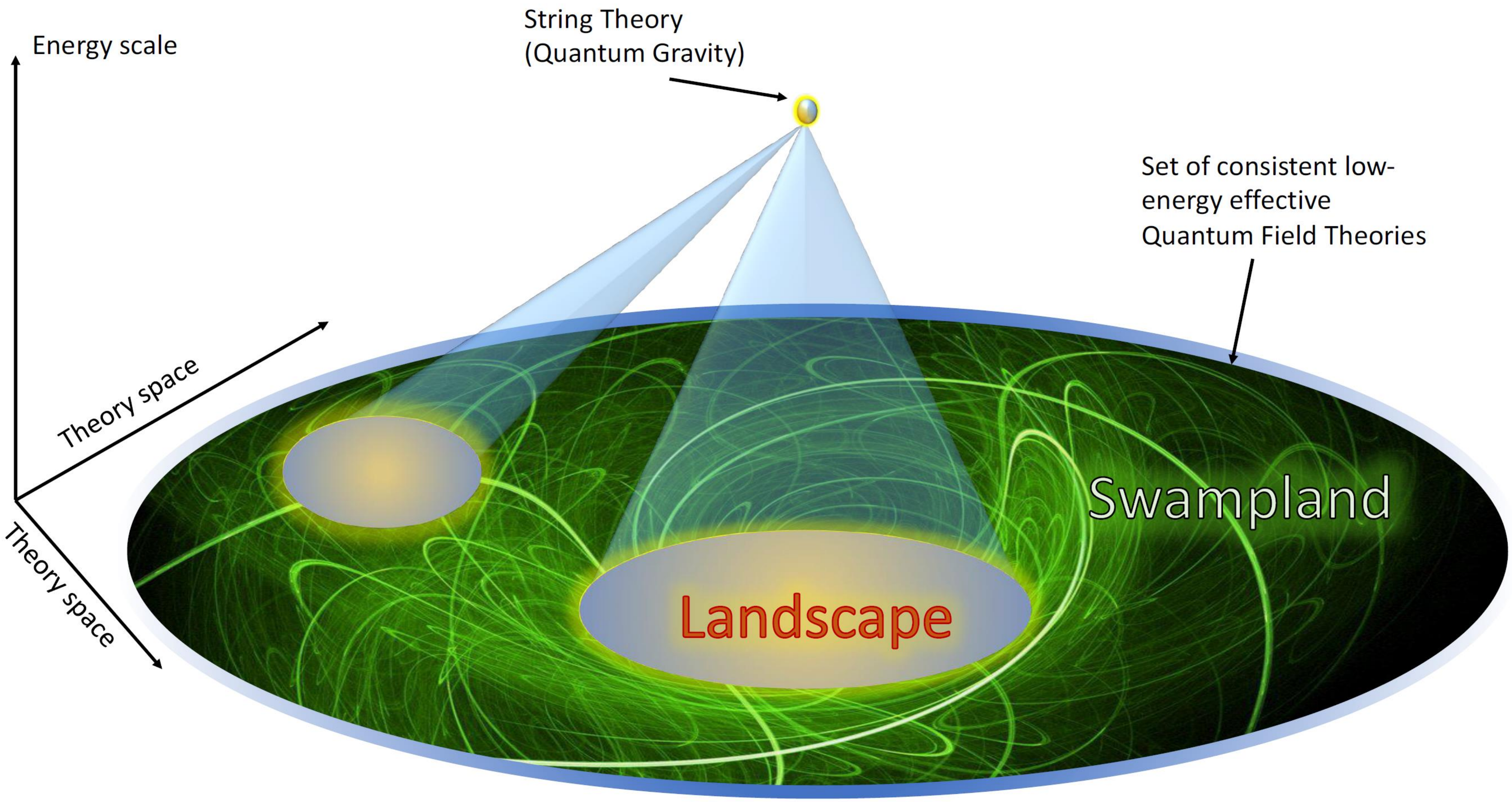
The landscape: the complementary set

The Swampland: Set of effective field theories **coupled to gravity** that cannot be UV completed".

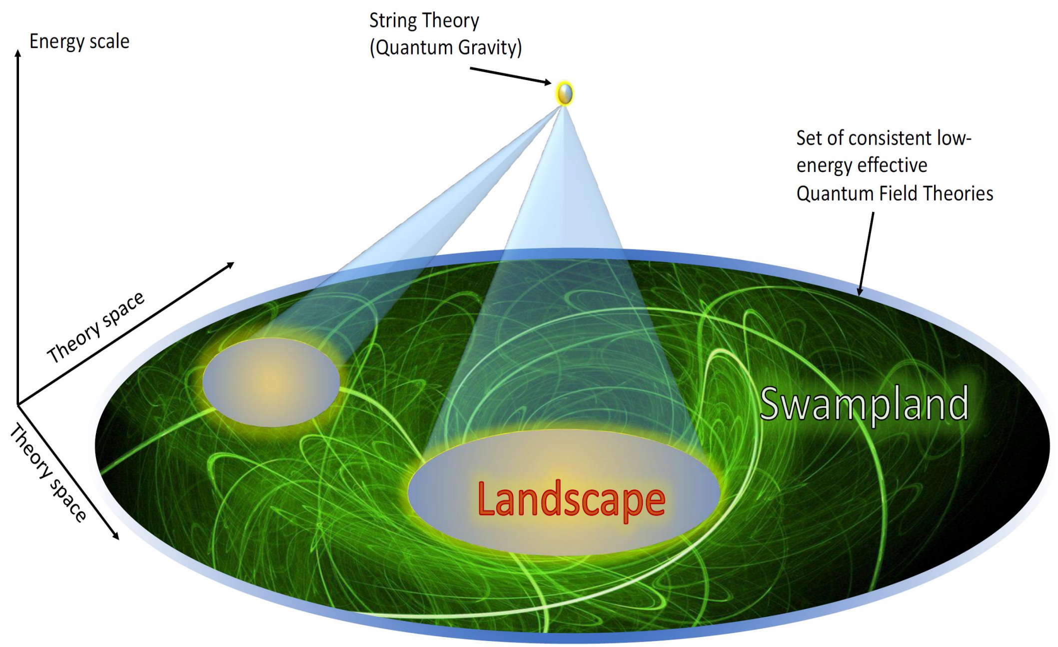
The landscape: the complementary set

Landscape: which effective field theories (EFTs) can we get from string theory (quantum gravity)?
Swampland: which EFTs can we **not** get?

Logically identical questions, "psychologically" different

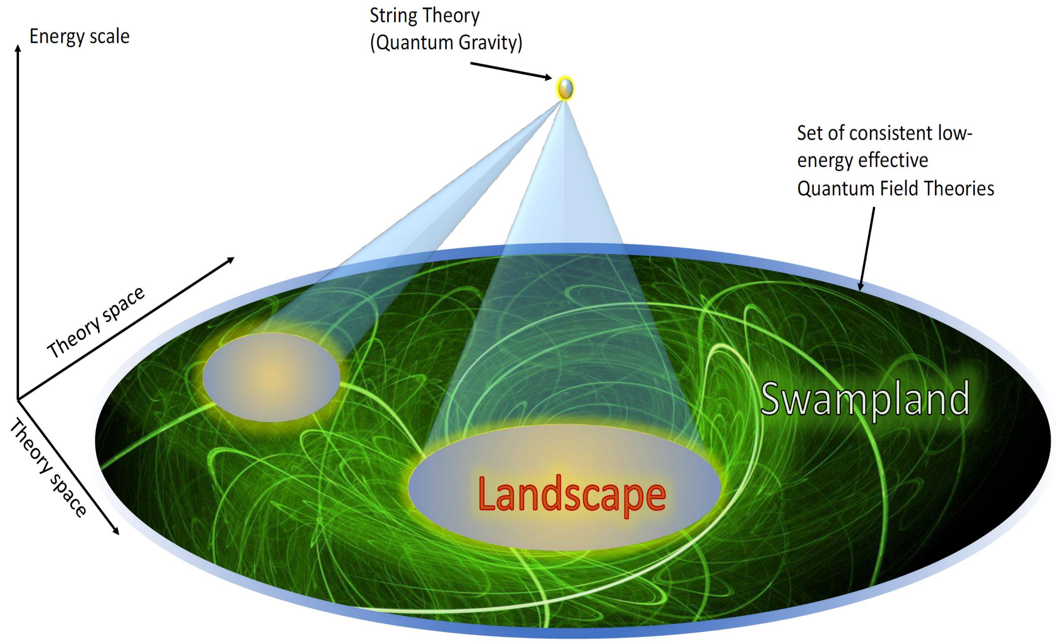


Taken from E. Palti 1903.06239



Instead of trying to "reverse engineer" effective field theories and arrive at an "almost anything goes" picture (landscape), we ask: 'what is not allowed?'.

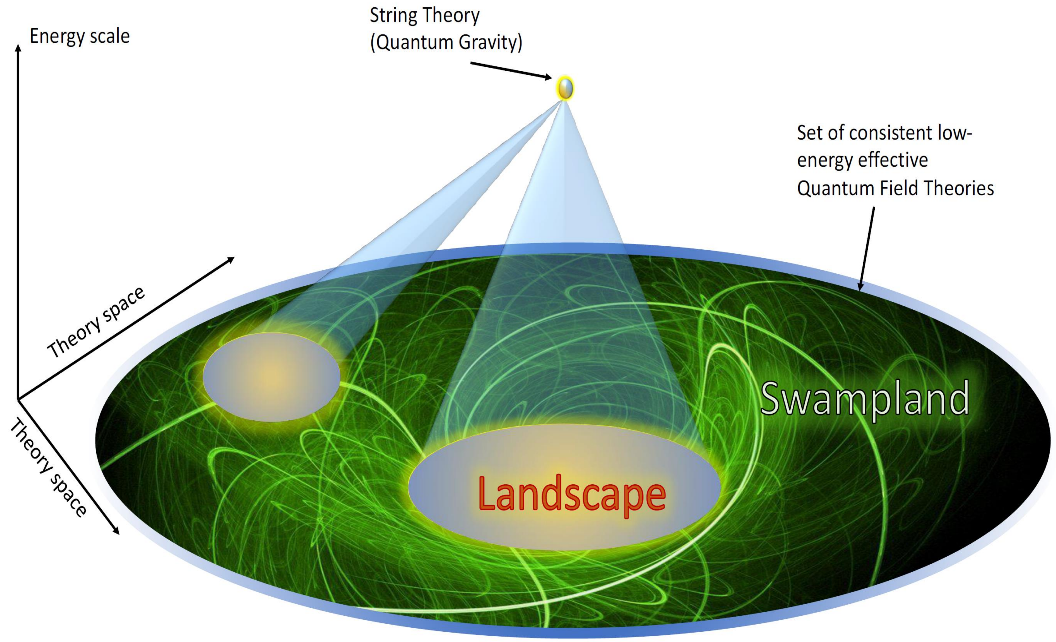
Approach entirely different: *inequalities instead of equalities.*



Instead of trying to "reverse engineer" effective field theories and arrive at an "almost anything goes" picture (landscape), we ask: 'what is not allowed?'.

Approach entirely different: *inequalities instead of equalities.*

- Keywords: **interdisciplinary** (pheno meets black hole physics, holography,…), **focusing on the 'why',** trying to find **patterns**.



Instead of trying to “reverse engineer” effective field theories and arrive at an “almost anything goes” picture (landscape), we ask: ‘what is not allowed?’.

Approach entirely different: *inequalities instead of equalities.*

- Keywords: **interdisciplinary** (pheno meets black hole physics, holography,…), **focusing on the ‘why’,** trying to find **patterns**.

- *Conjectures* instead of *statements*. Become theorems when proven. Usually conjectures come from 1) patterns in string compactifications + 2) heuristic reasoning with black holes.

1.Motivation

2. Swampland bound examples

3. The Festina Lente bound.

4. Pure Pheno applications

5. Conclusions.

No global symmetries conjecture

Consider a field theory with a global symmetry that is not a gauge symmetry. This global symmetry will be broken when coupled to gravity. [Banks-Dixon 1988] [Harlow-Ooguri 2018])

No global symmetries conjecture

Consider a field theory with a global symmetry that is not a gauge symmetry. This global symmetry will be broken when coupled to gravity. [Banks-Dixon 1988] [Harlow-Ooguri 2018])

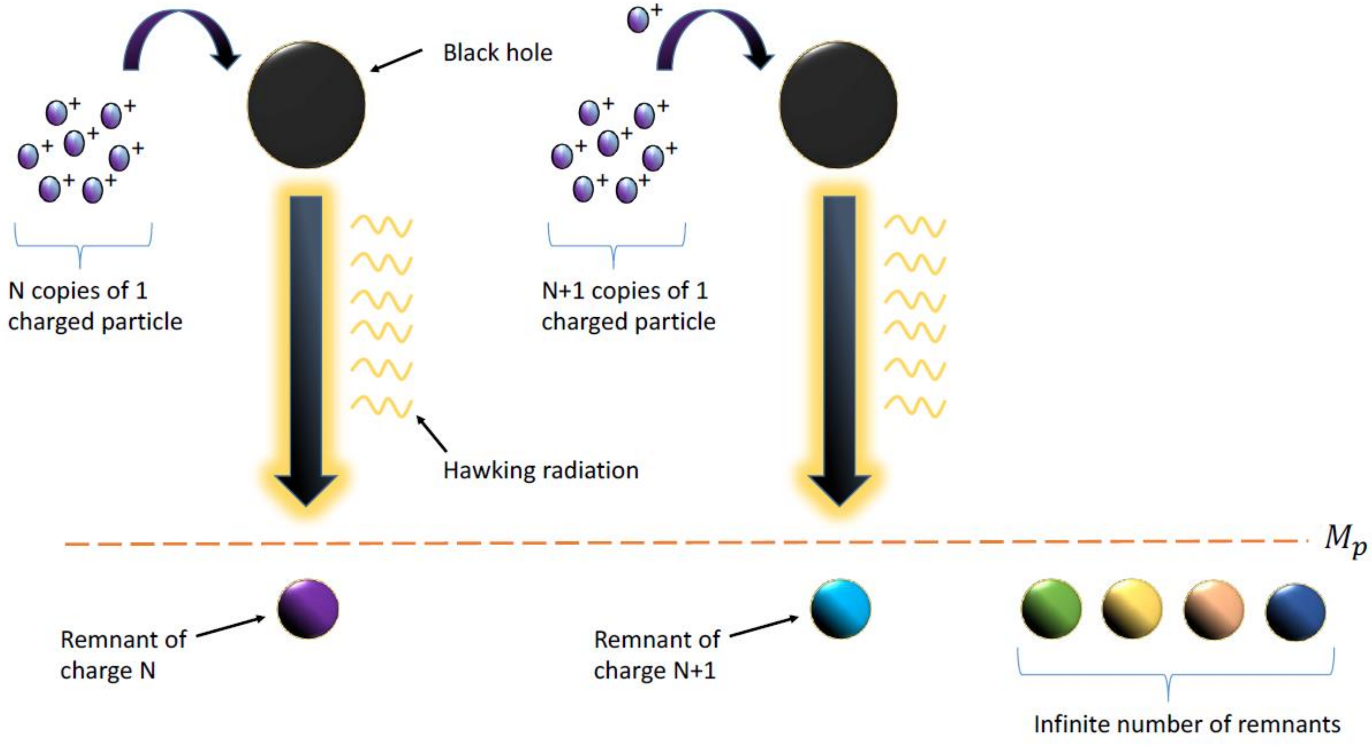
- Indeed, every consistent compactification of string theory has given field theories obeying this. Could have regarded this as circumstantial evidence.

No global symmetries conjecture

Consider a field theory with a global symmetry that is not a gauge symmetry. This global symmetry will be broken when coupled to gravity. [Banks-Dixon 1988] [Harlow-Ooguri 2018])

- Indeed, every consistent compactification of string theory has given field theories obeying this. Could have regarded this as circumstantial evidence.

- Before the proofs, there were already heuristic black hole arguments.

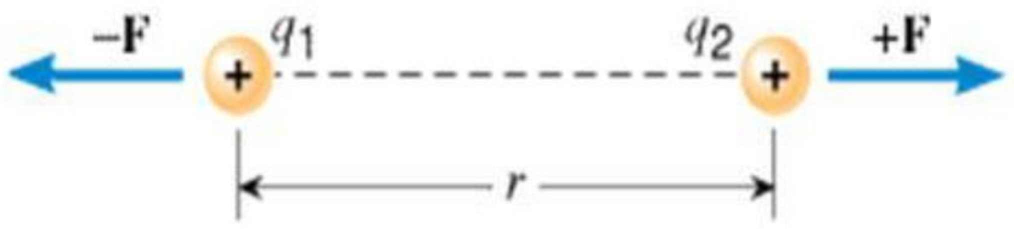



HOW INTERESTING
PLEASE, TELL ME MORE
memegenerator.net

OK, but it perhaps implies that gauge coupling constant cannot be arbitrary small? Gravity as weakest force?

Weak Gravity Conjecture [Arkani-Hamed, Motl, Nicolis, Vafa 2006]

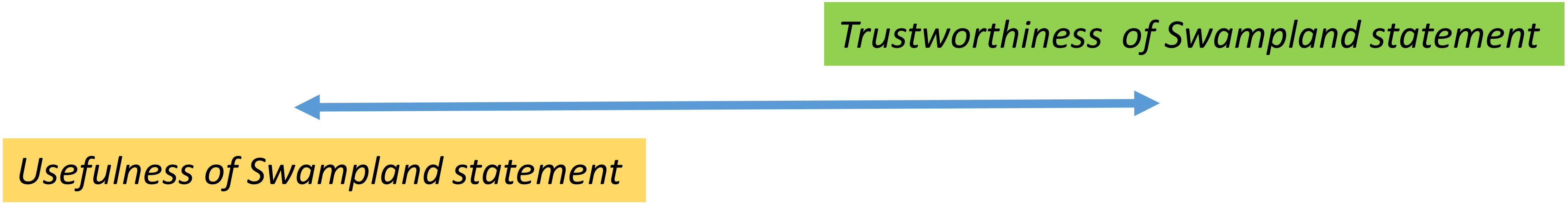
$$\frac{gq}{m} \geq \sqrt{\frac{d-3}{d-2}} M_p^{-\frac{(d-2)}{2}} \quad \text{for some charged state}$$



(b)

Constants in Nature not arbitrary, some parts of field theory space are empty when coupled to gravity, despite being "ok" (renormalisable, unitary…)

Current difficulty with Swampland program



1.Motivation

2. Swampland bound examples

3. The Festina Lente bound.

4. Pure Pheno applications

5. Conclusions.

Consider Einstein-Maxwell theory

$$S = \int d^d x \sqrt{-g} \left[\frac{1}{2} M_p^{d-2} \mathcal{R} - \frac{1}{4g^2} F_{\mu\nu} F^{\mu\nu} - V \right].$$

For constant V, the Hubble radius is then fixed by

$$\frac{(d-1)(d-2)}{2\ell_d^2} = M_p^{2-d} V.$$

- The Electric Weak Gravity bound is: $$\frac{gq}{m} \geq \sqrt{\frac{d-3}{d-2}} M_p^{-\frac{(d-2)}{2}} \quad \text{for some charged state}$$

- The Festina Lente bound is: $$m^4 \gtrsim (gq)^2 V \quad \text{for every charged state}$$

In 4D, in terms of fine structure constant, we have a window:

$$(8\pi\alpha V)^{1/4} < m < (8\pi\alpha)^{1/2} M_{\mathrm{P}}$$

$$\alpha = \frac{g^2}{4\pi}$$

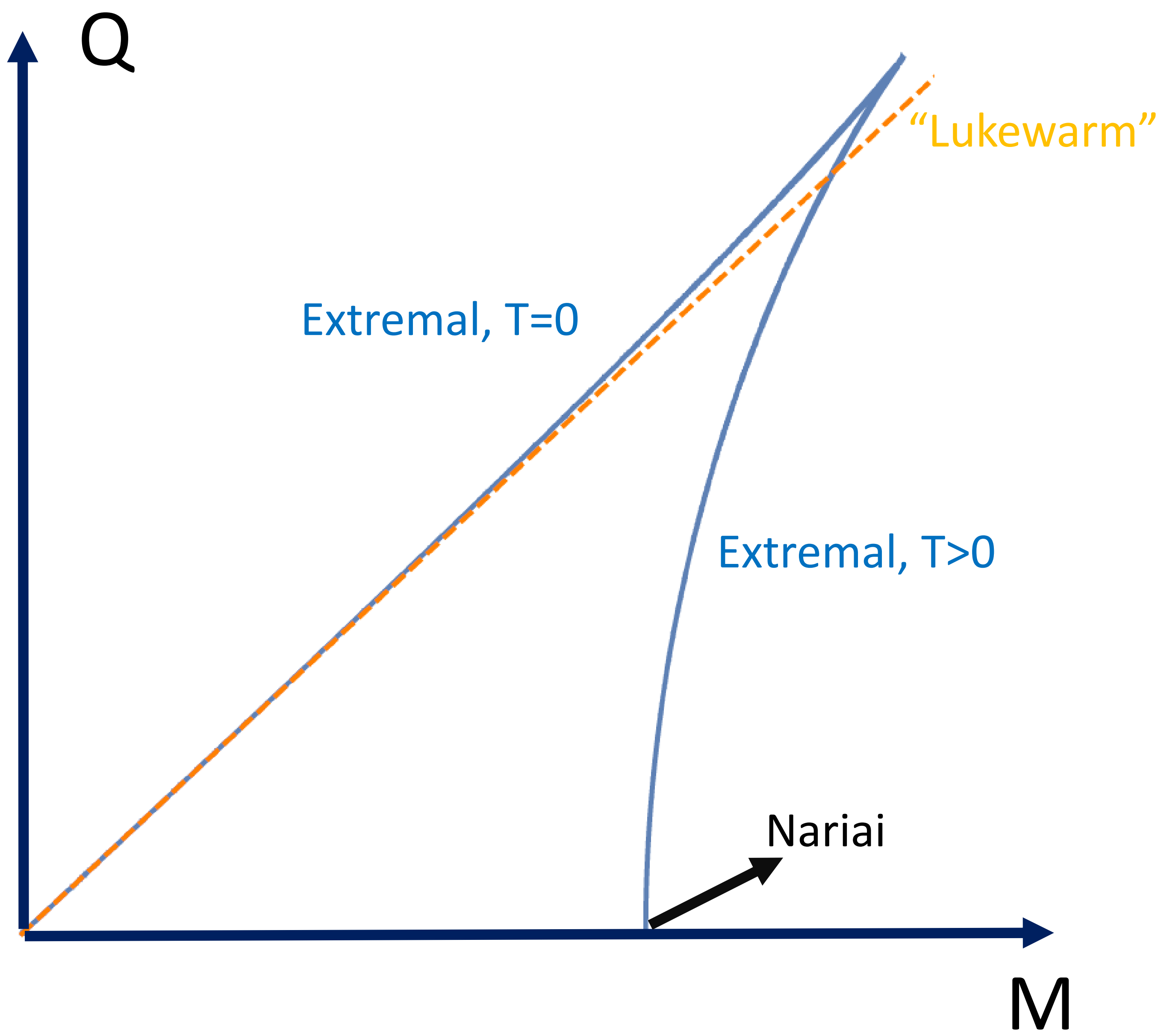
Quantum dynamics of charged black holes in de Sitter space

$$ds^2 = -U(r)dt^2 + \frac{dr^2}{U(r)} + r^2 d\Omega,$$

$$U(r) \equiv 1 - \frac{2M}{r} + \frac{Q^2}{r^2} - r^2$$

$$M \equiv \frac{GM}{\ell}, \qquad Q^2 \equiv \frac{Gg^2Q_r^2}{4\pi\ell^2}$$

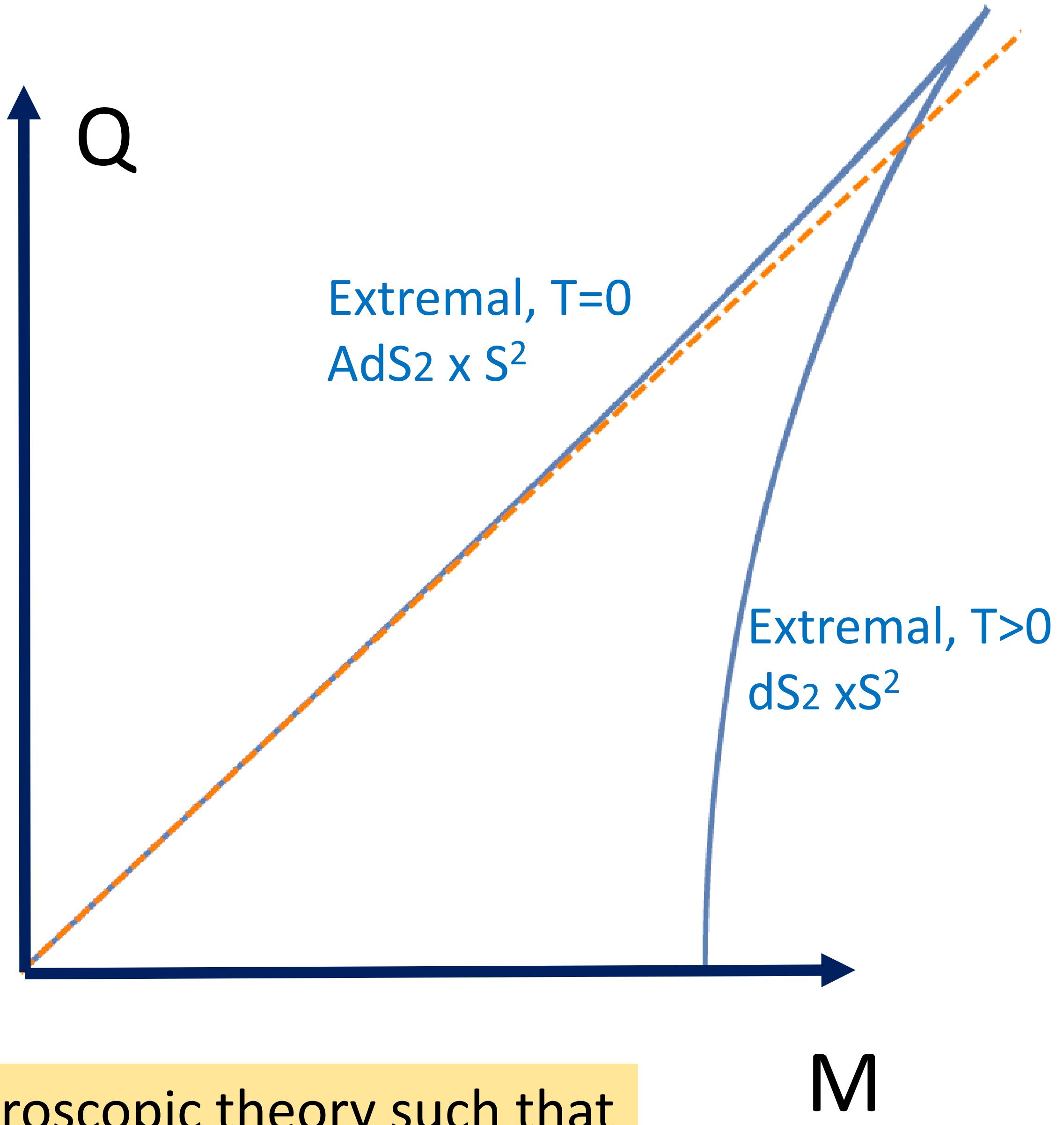
$$S = \frac{\pi}{4G}\left(r_{BH}^2 + r_{CH}^2\right)$$



Weak gravity principles for extremal black holes?

Left extremal branch. Almost like in flat space. But now black holes unstable without even requiring weak gravity conjecture.

Right extremal branch: Charged Nariai. Gigantic black holes probing cosmic horizon.

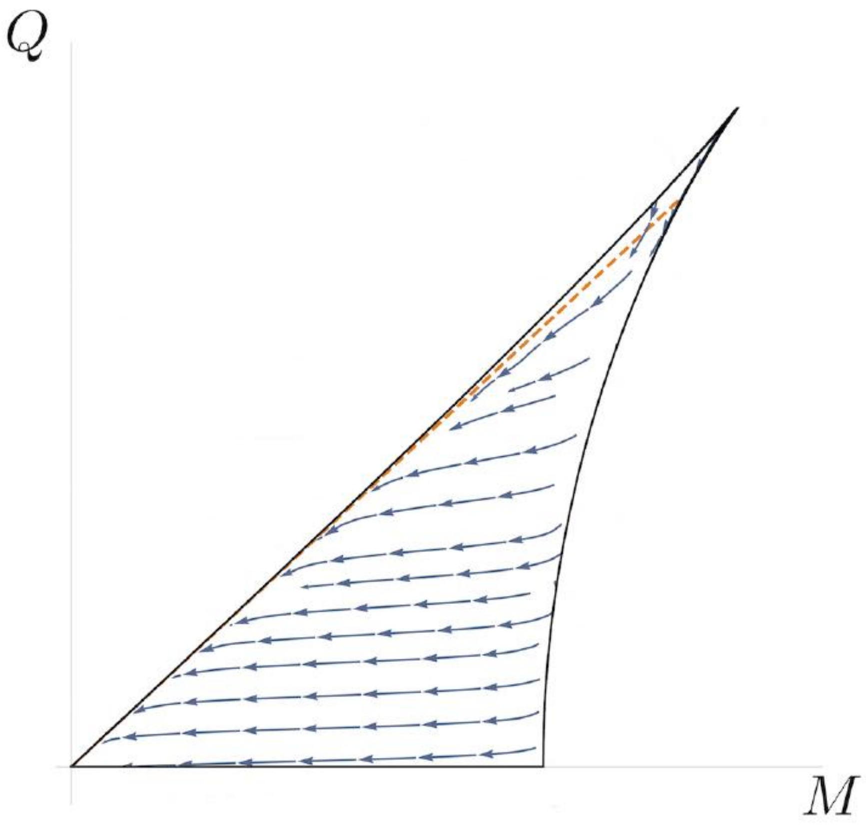


Guiding principle: constrain microscopic theory such that black holes *do not decay to region outside "shark fin"*.

Adiabatic motion in Q,M plane. Semi-classical analysis of Hawking&Schwinger radiation:

$$\dot{Q} = -4\pi\mathcal{J}, \qquad \frac{4r(r\dot{M} - Q\dot{Q})}{-2Mr + Q^2 - r^4 + r^2} = -16\pi r^4 G\mathcal{T}.$$

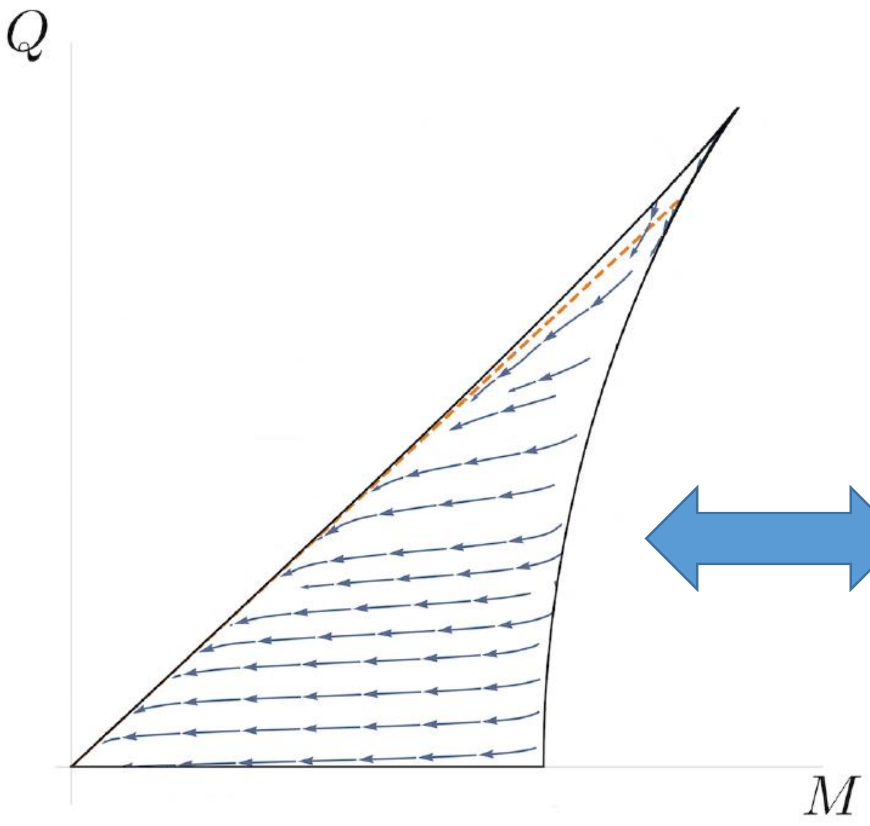
[Montero & Venken & VR 2019 , Lüben& Lüst & Ribes Metidieri 2020]

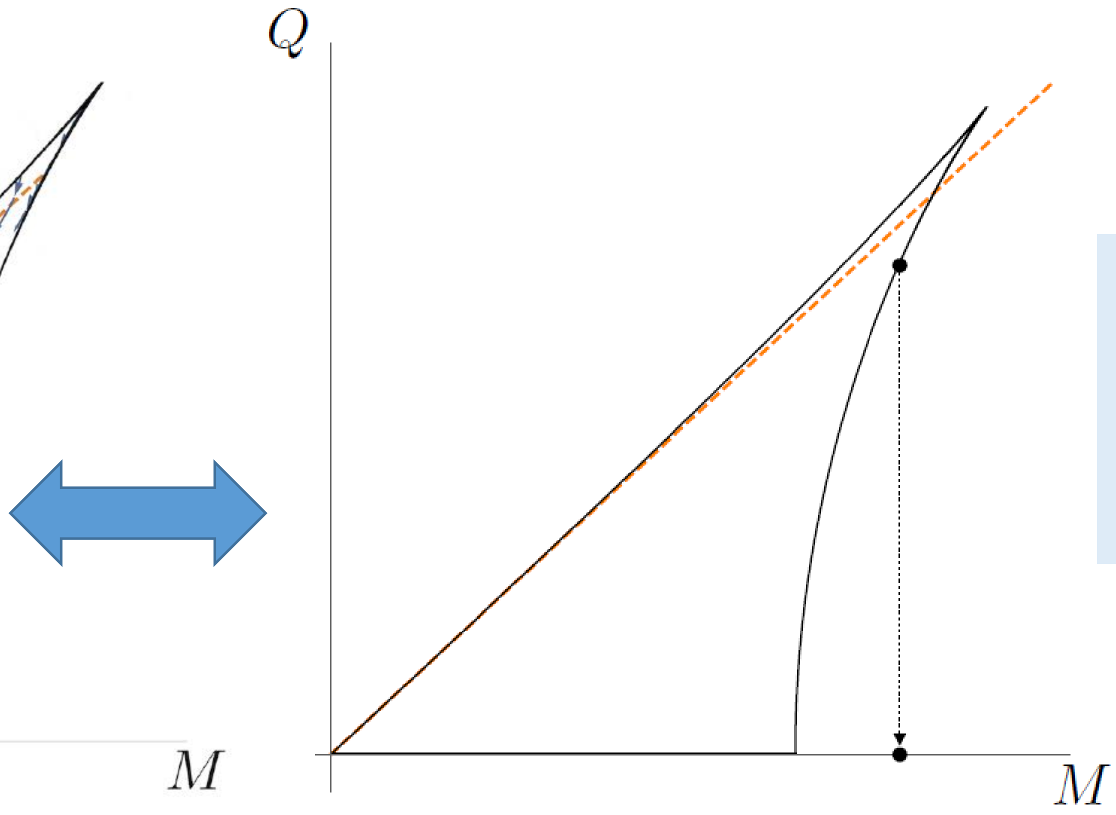


Adiabatic motion in Q,M plane. Semi-classical analysis of Hawking&Schwinger radiation:

$$\dot{Q} = -4\pi \mathcal{J}, \qquad \frac{4r(r\dot{M} - Q\dot{Q})}{-2Mr + Q^2 - r^4 + r^2} = -16\pi r^4 G\mathcal{T}.$$

[Montero & Venken & VR 2019 , Lüben& Lüst & Ribes Metidieri 2020]





Details J and T are such that evolution brings you to super-extremal branch unless you obey FL bound.

1. Motivation

2. Swampland bound examples

3. The Festina Lente bound.

4. Pheno applications

5. Conclusions.

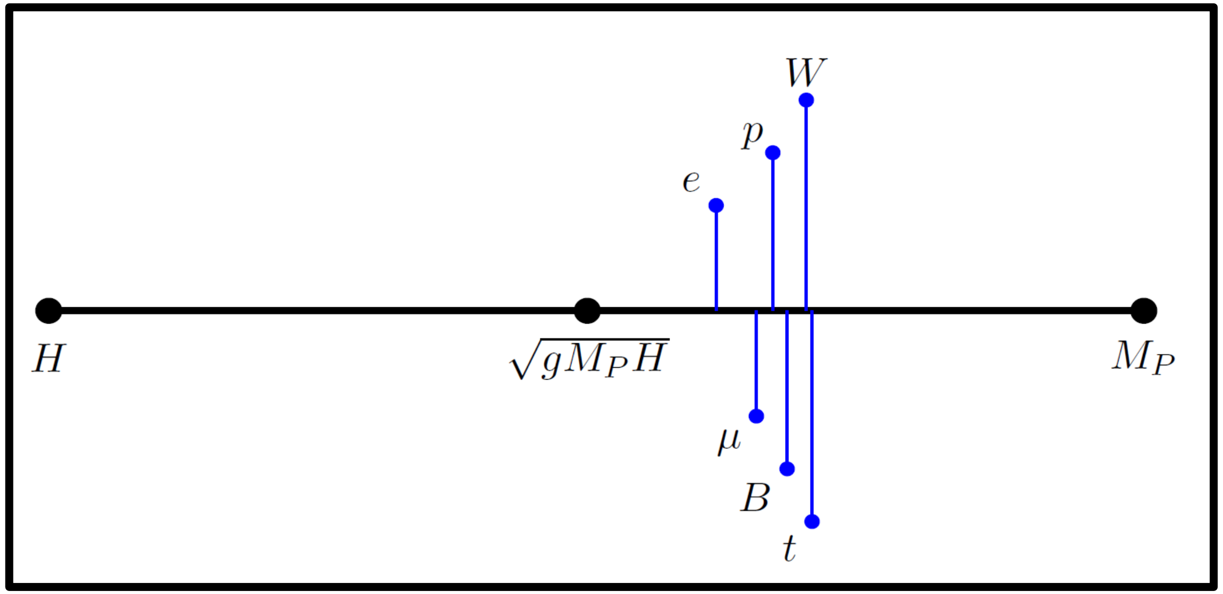
- All charged fields in the SM obey FL ☺

- All charged fields in the SM obey FL ☺

- Can FL help with explaining hierarchy problems?

→ CC hierarchy (Planck units): $$\Lambda \lesssim \frac{m^4}{4\pi\alpha}, \quad \xrightarrow{\text{Electron}} \quad \Lambda \lesssim 3 \cdot 10^{-89},$$

→ Electro weak hierarchy: $$v^2 \gtrsim \frac{1}{g} M_P H = \frac{V^{1/2}}{g}$$ (W-bosons, g=SU2 coupling)



Logarithmic scale

A non-abelian gauge theory automatically contains massless charged states: the gluons.
So massless non-abelian gauge fields are in contradiction with FL bound.

A non-abelian gauge theory automatically contains massless charged states: the gluons. So massless non-abelian gauge fields are in contradiction with FL bound.

→There cannot be a phase of the Standard Model where the weak interaction is long range: no local minimum at Phi = 0 for the Higgs potential.

A non-abelian gauge theory automatically contains massless charged states: the gluons. So massless non-abelian gauge fields are in contradiction with FL bound.

→There cannot be a phase of the Standard Model where the weak interaction is long range: no local minimum at Phi = 0 for the Higgs potential.

→The other possibility consistent with non-abelian gauge fields and FL, is confinement. Is realized by the gluons in the SM.

A non-abelian gauge theory automatically contains massless charged states: the gluons. So massless non-abelian gauge fields are in contradiction with FL bound.

→There cannot be a phase of the Standard Model where the weak interaction is long range: no local minimum at Phi = 0 for the Higgs potential.

→The other possibility consistent with non-abelian gauge fields and FL, is confinement. Is realized by the gluons in the SM.

FL predicts that in a de Sitter background non-abelian gauge fields must confine or be spontaneously broken, at a scale above H.

$$m_{\text{Gauge field}} \gtrsim H, \quad \text{or} \quad \Lambda_{\text{Confinement}} \gtrsim H$$

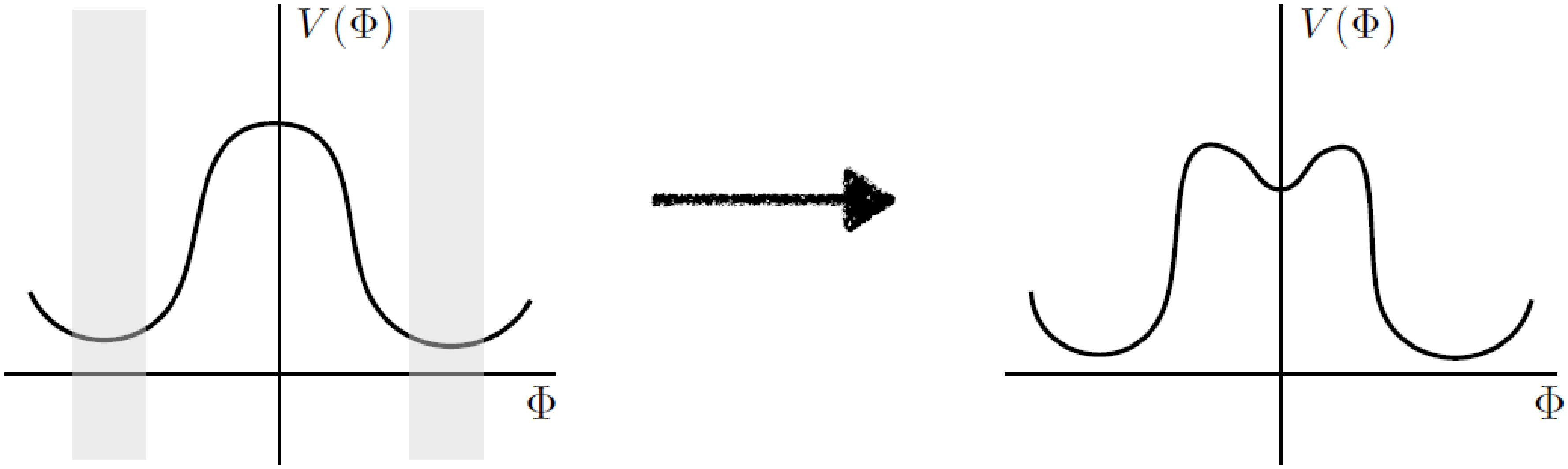


Figure 2. On the left, we show the usual shape of the "Mexican hat" Higgs potential, which arises from equation (4.5). However, only the region shaded in gray has been accessed experimentally. It is conceivable that the region near $\Phi \approx 0$ has a different shape, for instance, that of the "cowboy hat"

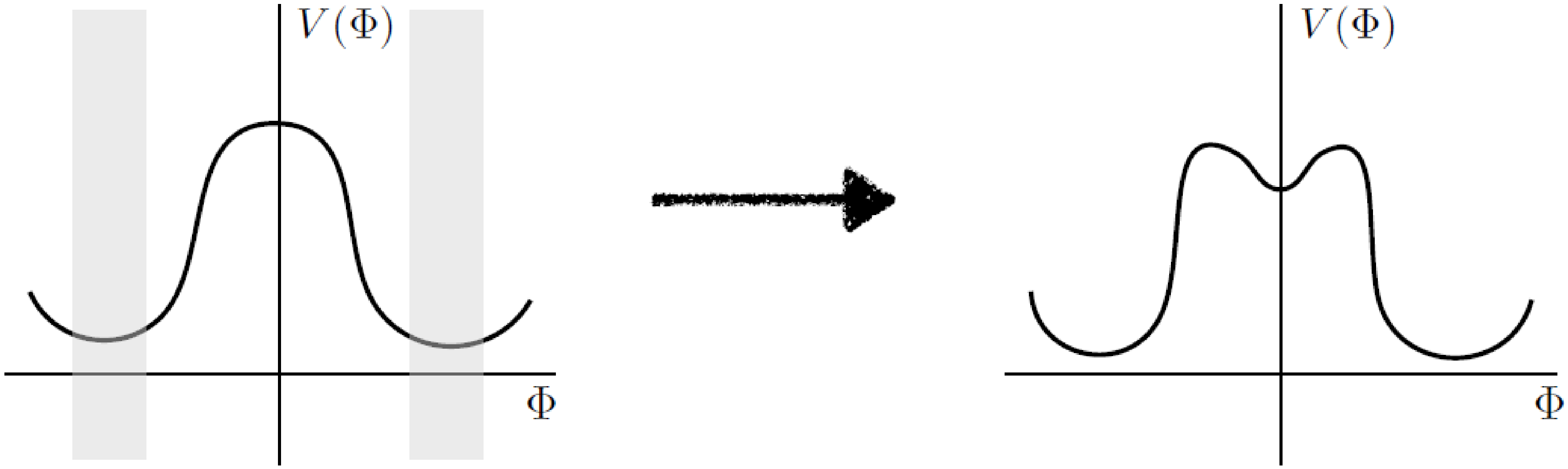


Figure 2. On the left, we show the usual shape of the "Mexican hat" Higgs potential, which arises from equation (4.5). However, only the region shaded in gray has been accessed experimentally. It is conceivable that the region near $\Phi \approx 0$ has a different shape, for instance, that of the "cowboy hat"

Neutrino's?

- Suggestive numerology $\sqrt{g M_P H} \sim 10^{-3}\, eV$
- If B-L is weakly gauged instead of spontaneously broken at high E, then lightest neutrino cannot be massless.

1. Motivation

2. Swampland bound examples

3. The Festina Lente bound.

4. Pheno applications

5. Conclusions.

This cartoon is false. But patience is a nice thing.

Stay tuned.