The Swampland Program
and the Quantum Gravity Imprint at Low Energies

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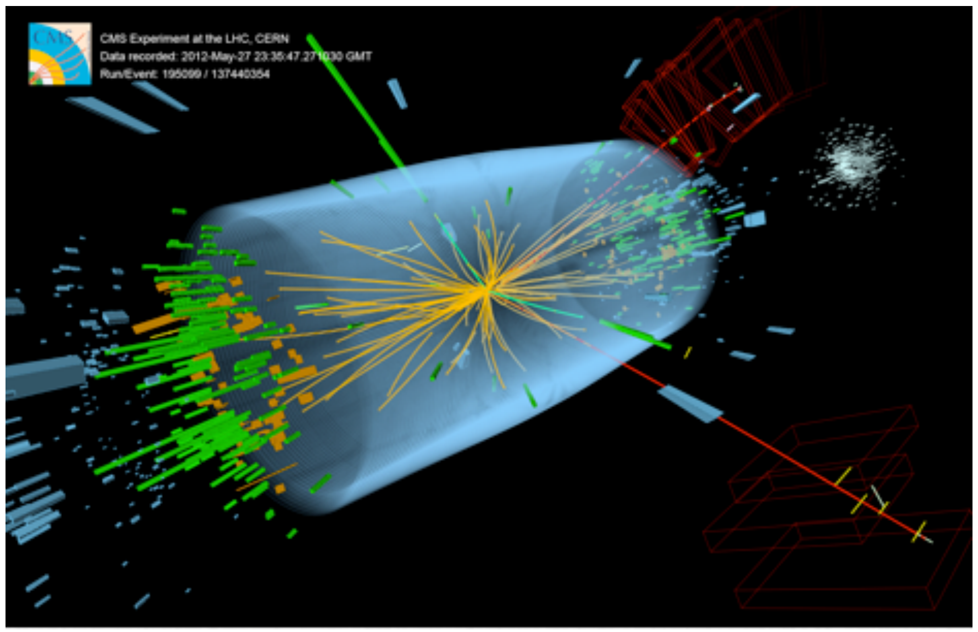
Most important thing:

Please don’t hesitate to interrupt for questions!!

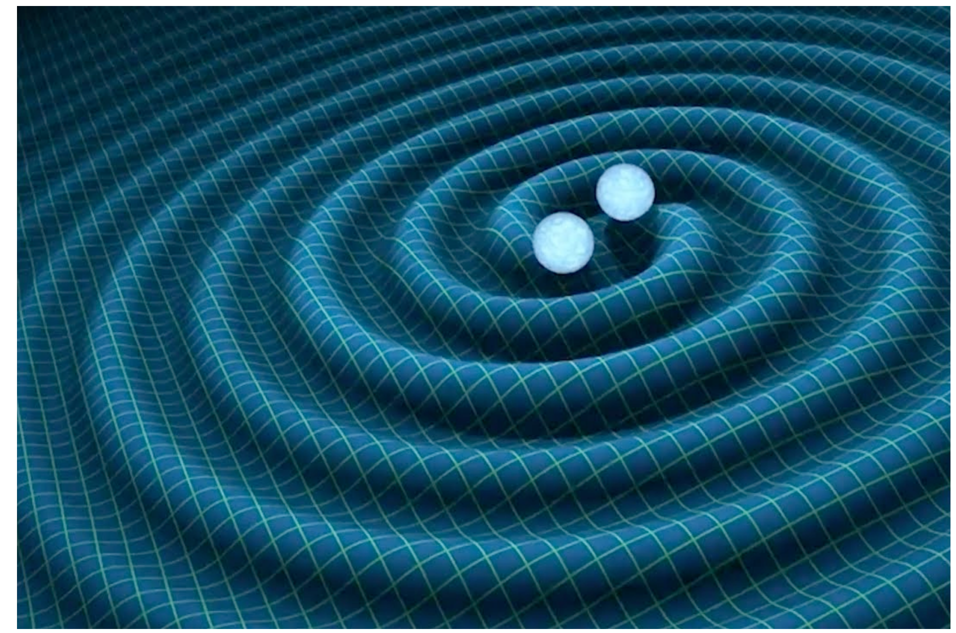
Quantum



Standard Model of Particle Physics

Quantum description of all elementary particles except for gravity

Gravity



Standard Model of Cosmology

Classic description of gravity and evolution of our universe

small distances

large distances

Quantum **Gravity**

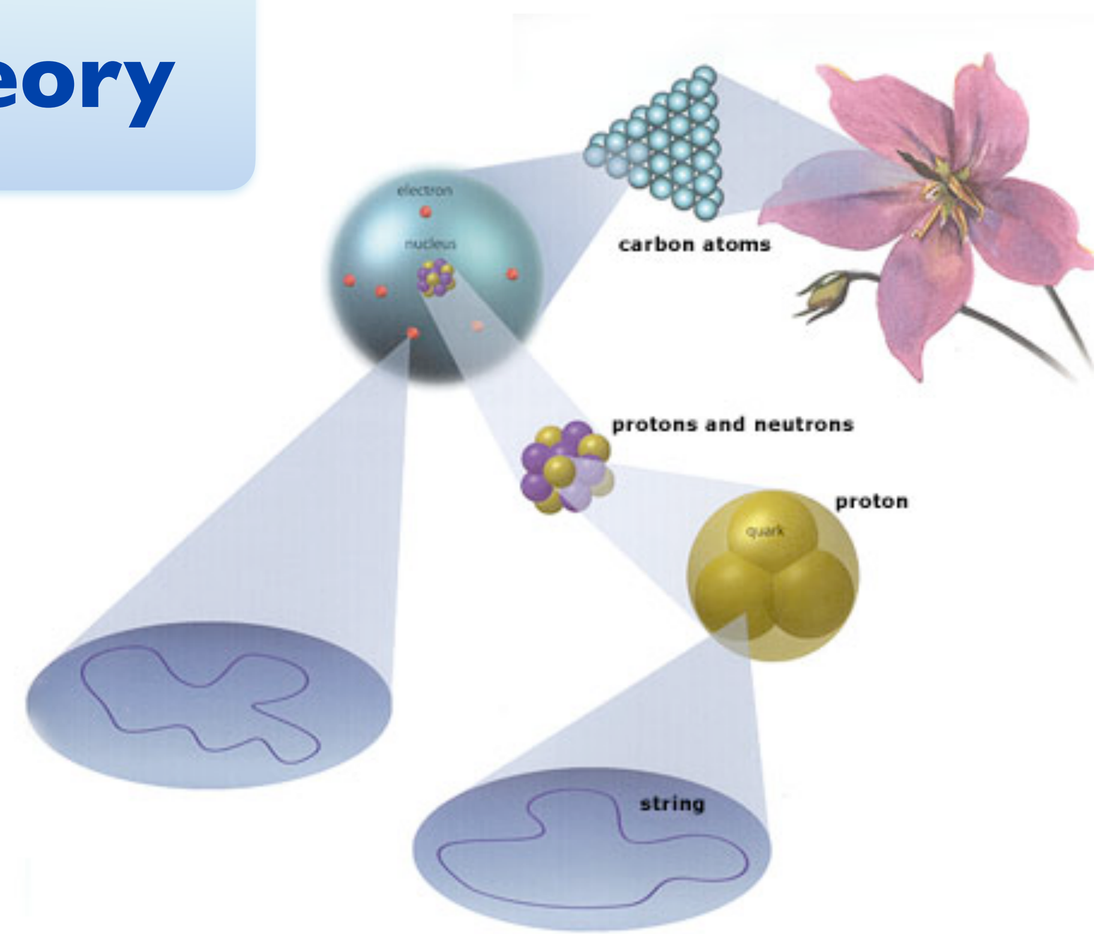
Big challenge of the century!

Quantum Gravity

Big challenge of the century!

Can we construct a consistent theory of **quantum gravity**?

Yes, for example: **String Theory**



And now what?
Can we test it experimentally?

Or is this just a mere theoretical exercise?

Does Quantum Gravity matter at low energies?

Does Quantum Gravity have any implication for the physics that can be detected with current experiments?

Does Quantum Gravity matter at low energies?

~~No, it is irrelevant since quantum gravitational effects are only important at very high energies~~

False!

Does Quantum Gravity matter at low energies?

Yes!

Gravity is different than the other interactions

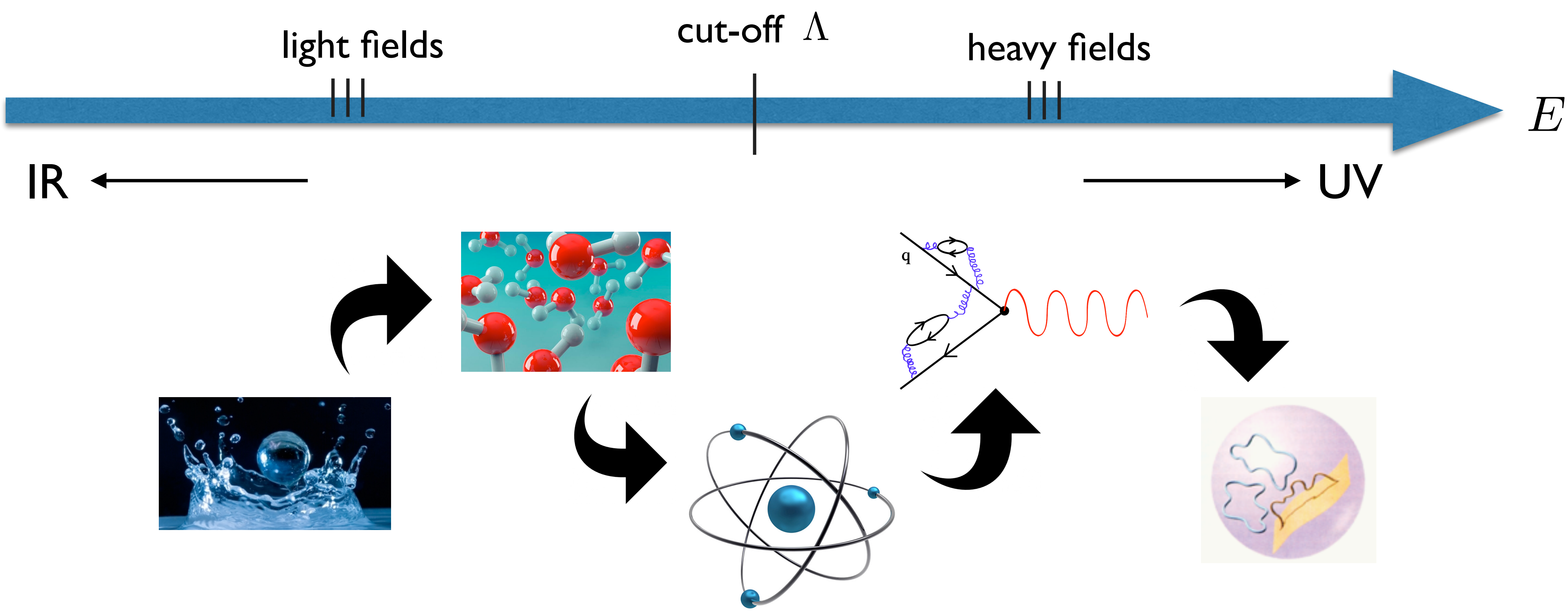
Quantum Gravity can impose non-trivial constraints at low energies and potentially shed new light into naturalness issues of our universe

Why would one expect quantum gravity to be irrelevant at low energies?

Expectation of 'separation of scales':

IR effective theory should not be very sensitive to UV physics

based on a Wilsonian effective field theory approach



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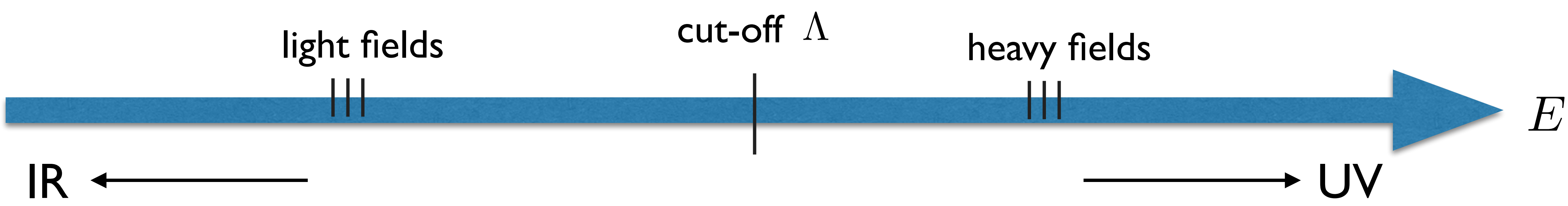


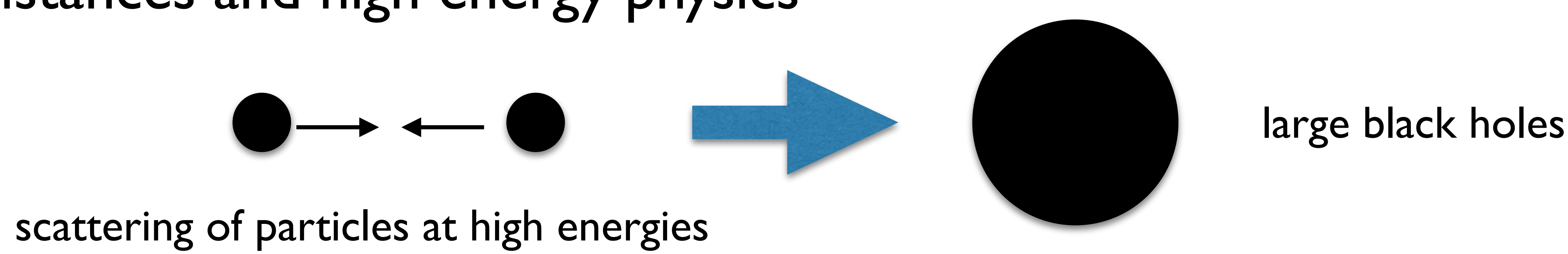
Following this, quantum gravitational effects would be expected to be important at very high energies of 10^{18} GeV

But gravity is different!

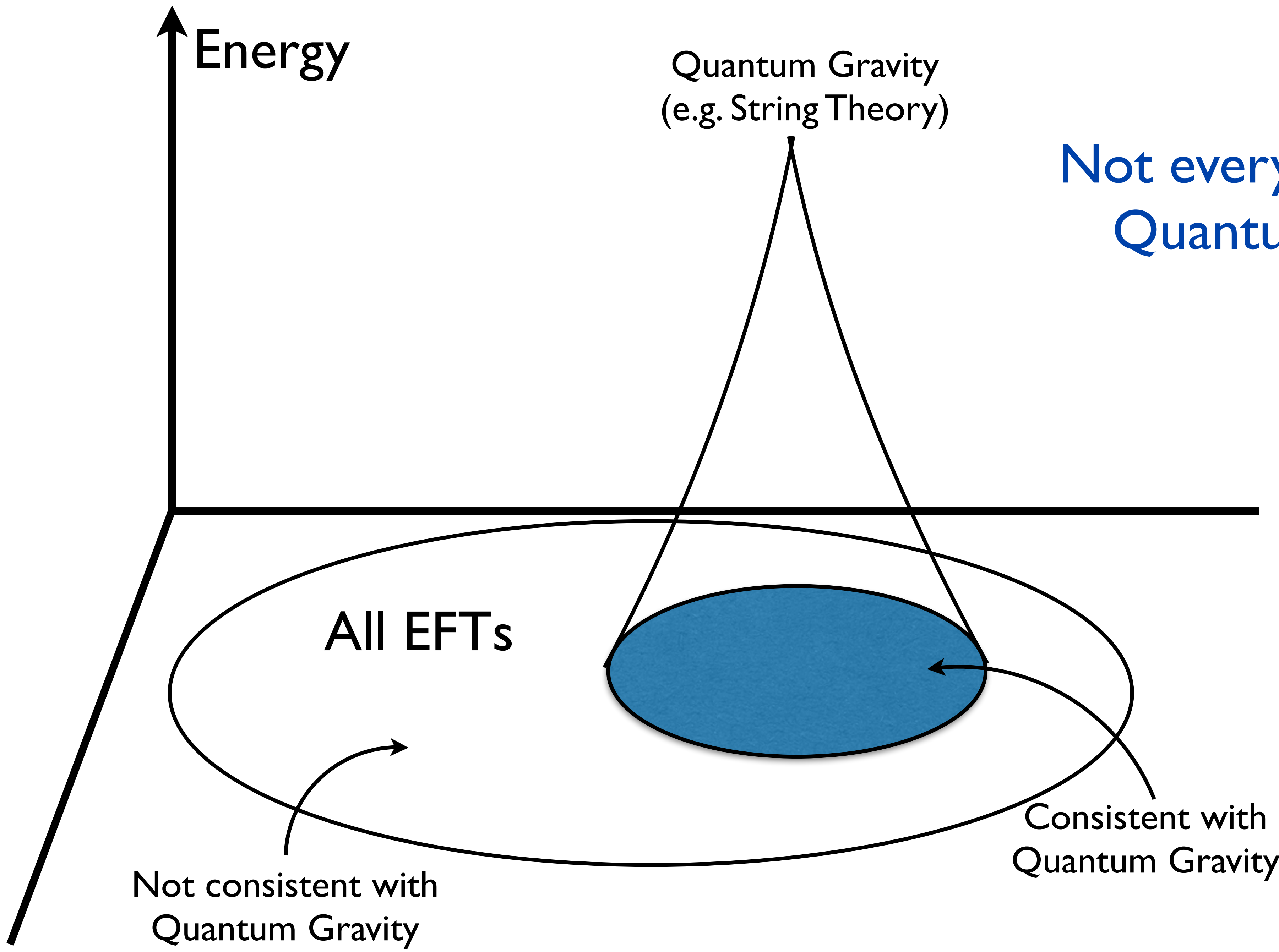
Gravity is different: UV/IR mixing

Quantum Gravity breaks with this notion of separation of scales and can impose non-trivial constraints at low energies

- Evidence from String Theory (string dualities…)
- Black Hole Physics makes manifest a correlation between long distances and high energy physics



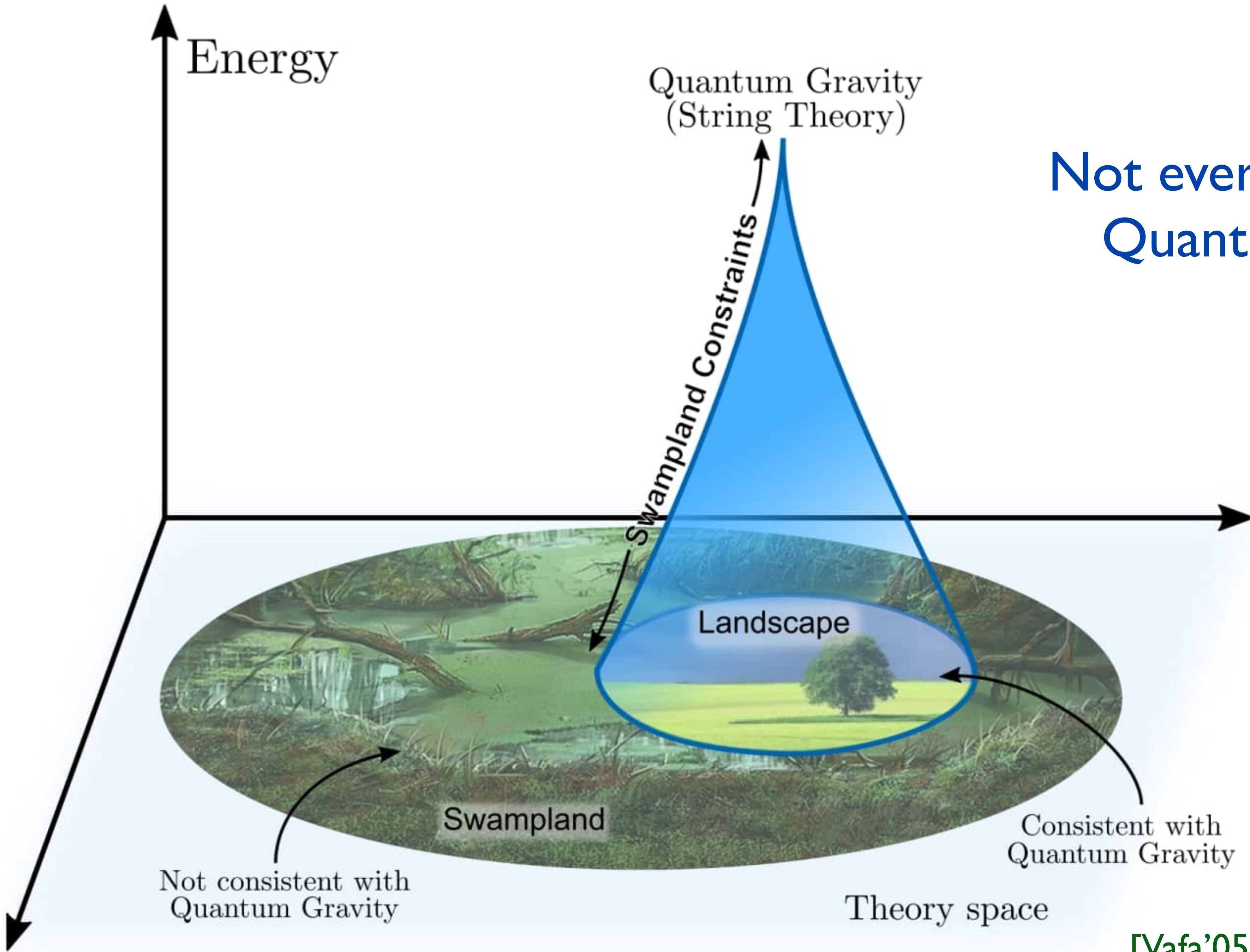
Not every EFT is compatible with quantum gravity



Not everything goes in Quantum Gravity!

Swampland Lectures/Reviews:
[Brennan,Vafa'17] [Palti'19]
[Van Beest,Calderon-Infante,Mirfendereski,IV'21]

Not every EFT can arise as the low energy limit of a consistent theory of quantum gravity (e.g. string theory)



[Vafa'05]

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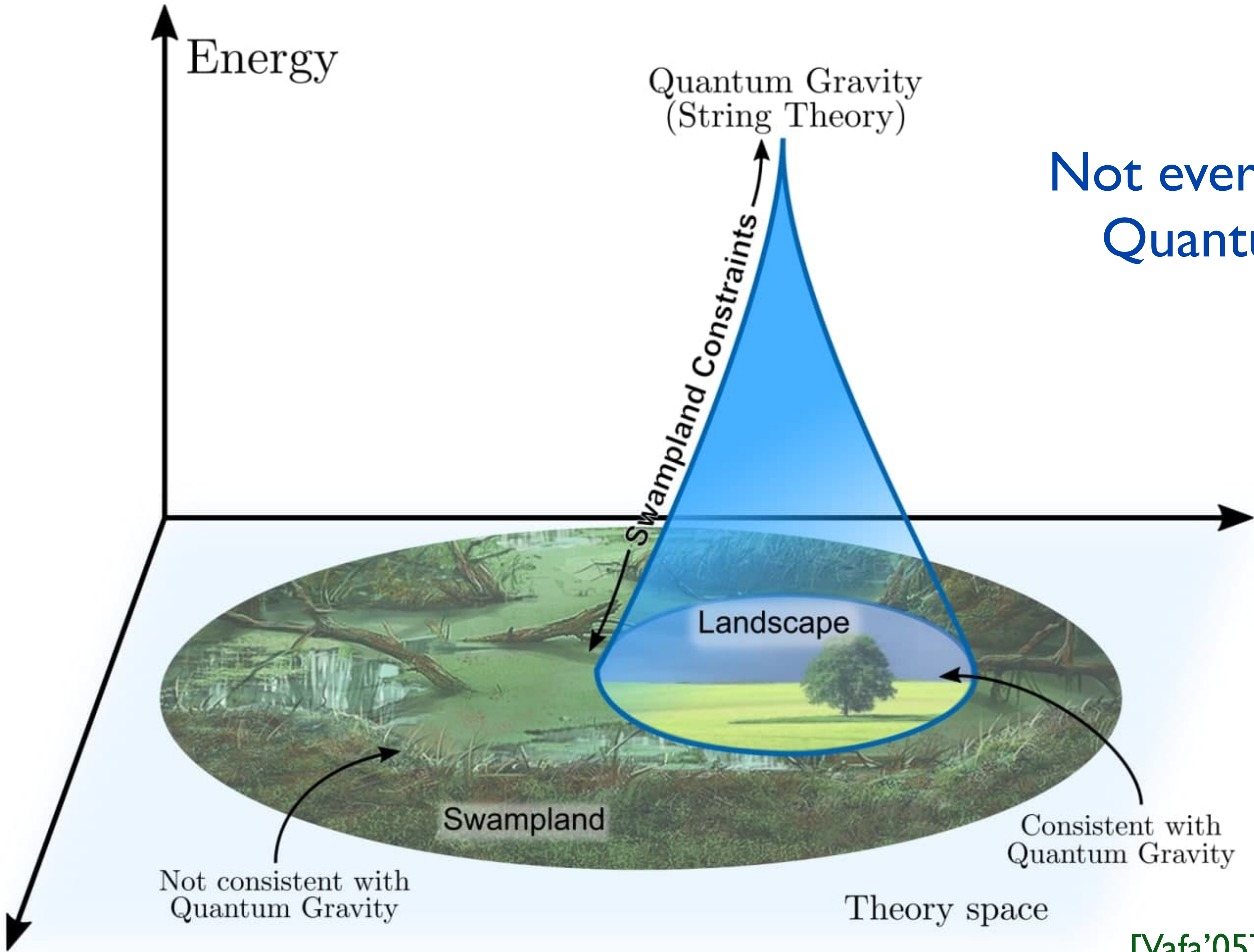

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[Vafa'05]

Swampland:

Apparently consistent (anomaly-free) quantum effective field theories that cannot be UV completed in quantum gravity

Swampland program

Goal: Determine the constraints that an effective theory must satisfy to be consistent with quantum gravity

What distinguishes the landscape from the swampland?

→ UV imprint of quantum gravity at low energies

EFT expectations can fail in the presence of gravity

- New approach to connect string theory to our world
- Potential phenomenological implications:
  - Guiding principles to construct BSM models
  - New insights to solve naturalness issues in our universe

… because not the entire space of parameters is allowed!

Swampland program

Goal: Determine the constraints that an effective theory must satisfy to be consistent with quantum gravity

What distinguishes the landscape from the swampland?

→ UV imprint of quantum gravity at low energies

EFT expectations can fail in the presence of gravity

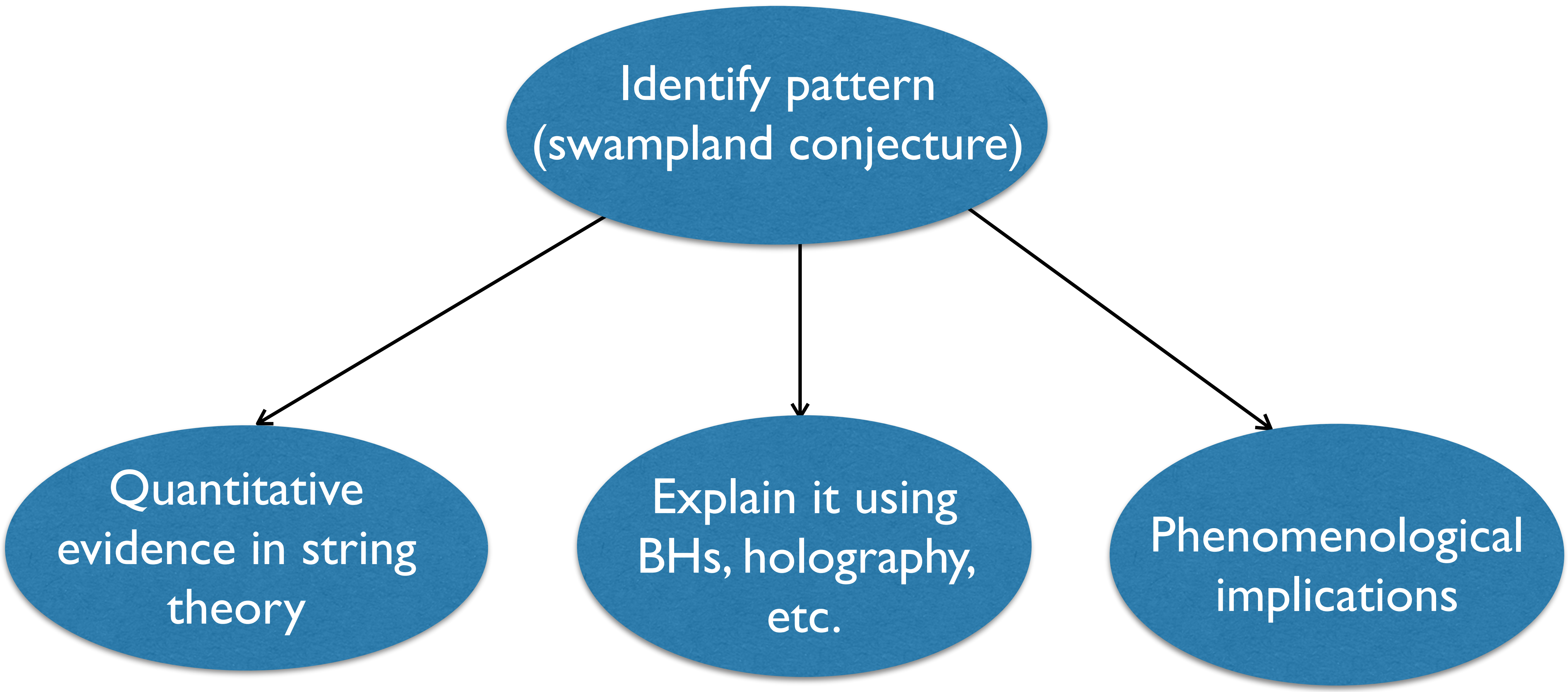
We will see an example at this talk for the cosmological constant!

- New insights to solve naturalness issues in our universe

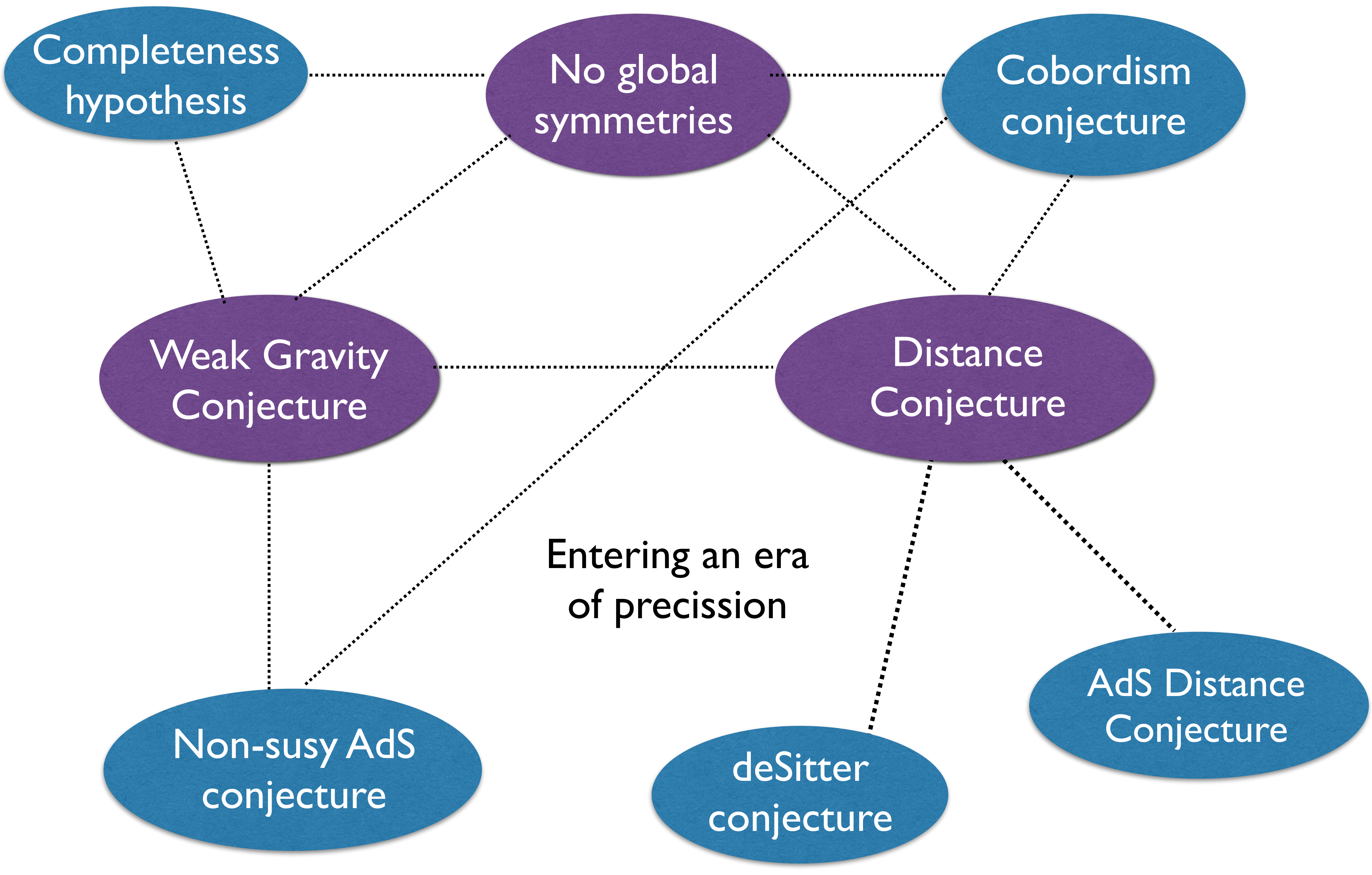
… because not the entire space of parameters is allowed!

Swampland Conjectures

Proposals for constraints that EFTs must satisfy to be consistent with QG
(mainly motivated by string theory and black hole physics)



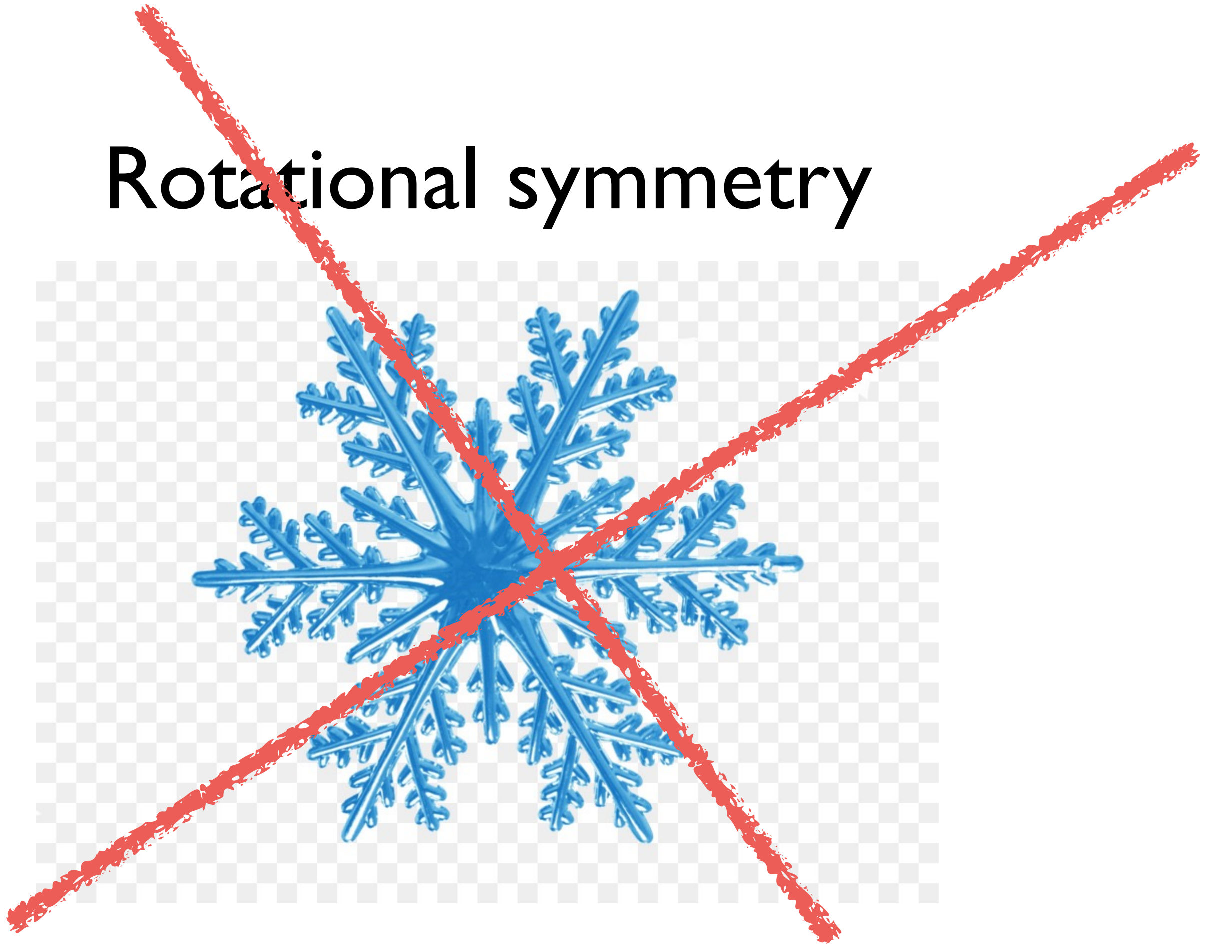
Swampland Conjectures



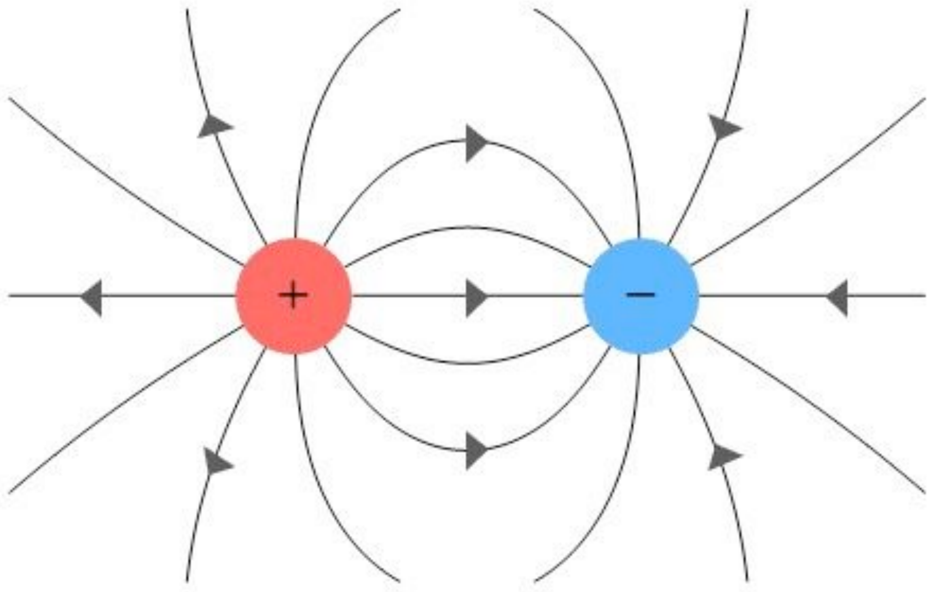
No global symmetries

Symmetries

Rotational symmetry



Electric charge



Angular momentum

Swampland conjecture: “No global symmetries”

Some kind of symmetries (known as global symmetries) cannot be exact in quantum gravity

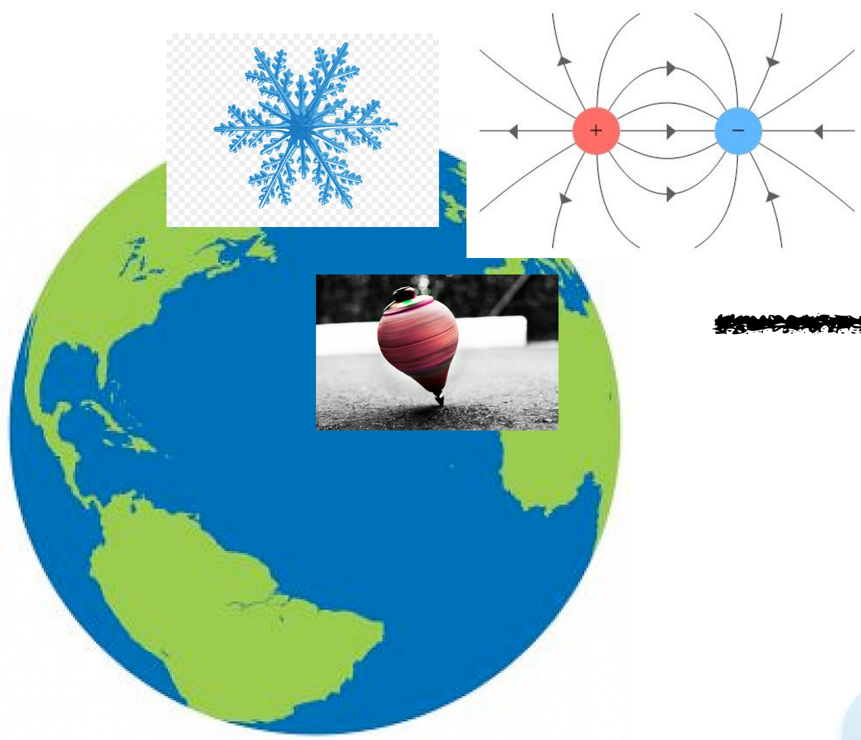
[Banks-Dixon’88] [Horowitz,Strominger,…][Susskind] [Banks,Seiberg’11]

Quantum gravitational effects break them

Symmetries

Two types of symmetries: global vs gauged

Can we measure the conserved charge from very far away?



?

Yes → Gauged symmetry

No → Global symmetry

They are broken in quantum gravity

Example in the SM of particle physics:

Consider $n \to p^+ + e^- \bar{\nu}_e$

There are two conserved charges: ~~$B - L = 1$~~ global

$Q = 0$ gauged

→ electric charge

Two possible solutions:

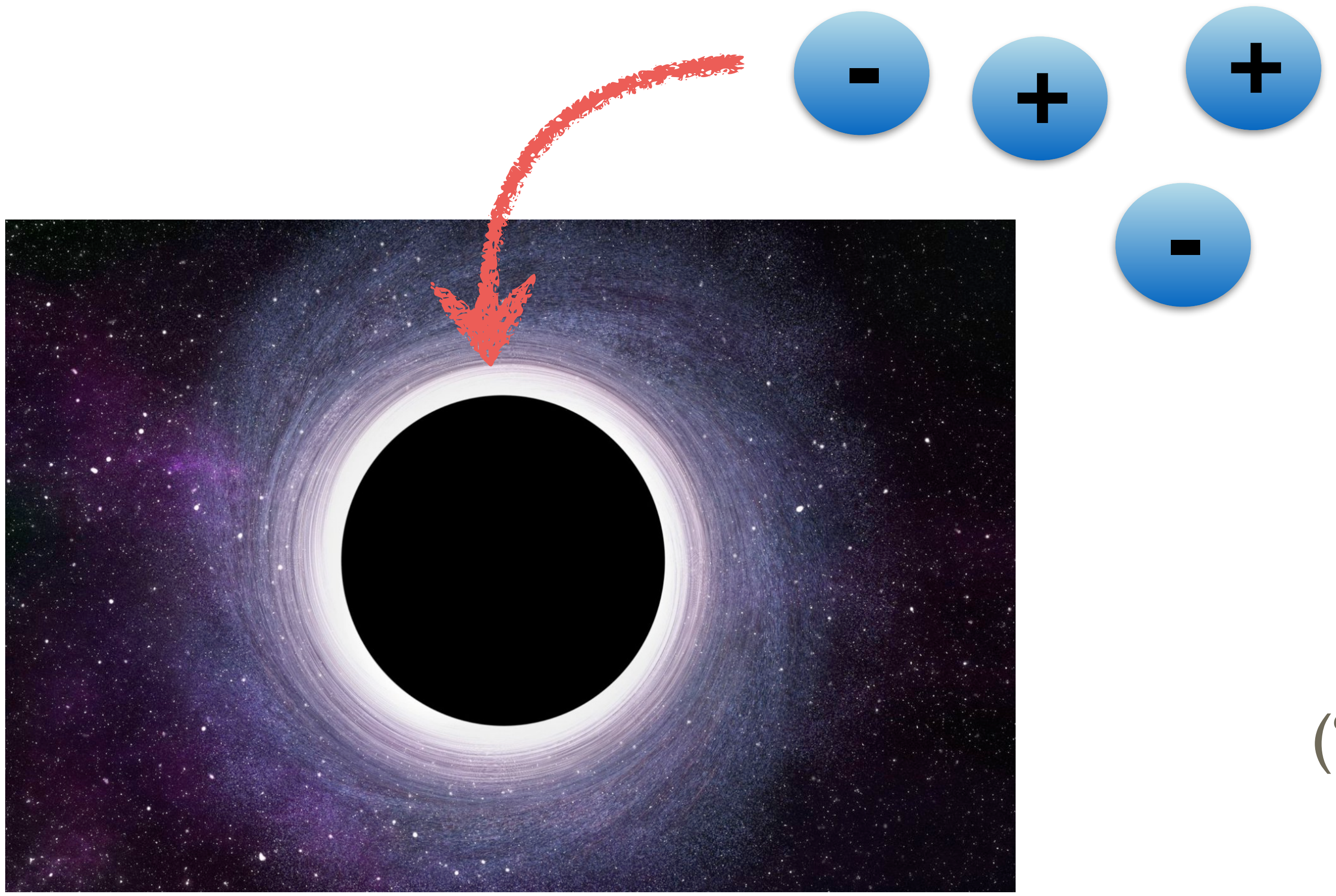
- The symmetry is exact because it is actually gauged

There is a new force (a new gauge field)

- The symmetry is broken

Proton cannot be stable

Motivation from black holes



Black holes have finite entropy

("how many different ways lead to the same black hole exterior")

Since global symmetries cannot be detected from far away,

we could have infinitely many black holes with different values of the global charge, but that look the same from far way

→ Infinite entropy constradiction!

Evidence for "No global symmetries"

- Proof in perturbative string theory [Polchinski's book]
- Proof in AdS/CFT [Harlow,Ooguri '18]
- Correlation to unitary black hole evaporation (and topology changing processes)

  [Harlow,Shaghoulian '20] [Chen,Lin '20] [Hsin et al '20] [Yonekura '20] $\cdots$

Global symmetries are not well defined in quantum gravity as the topology itself fluctuates

Implications for classifying the landscape

Recent developments: This conjecture is more constraining that expected!

- **Example:**

Absence of topological global charges (corbodism) + anomaly cancellation + supersymmetry	=	rules out some supergravity theories by constraining the rank of the gauge group

Using these general principles, we can classify all supergravities in $d>7$ that are consistent with quantum gravity

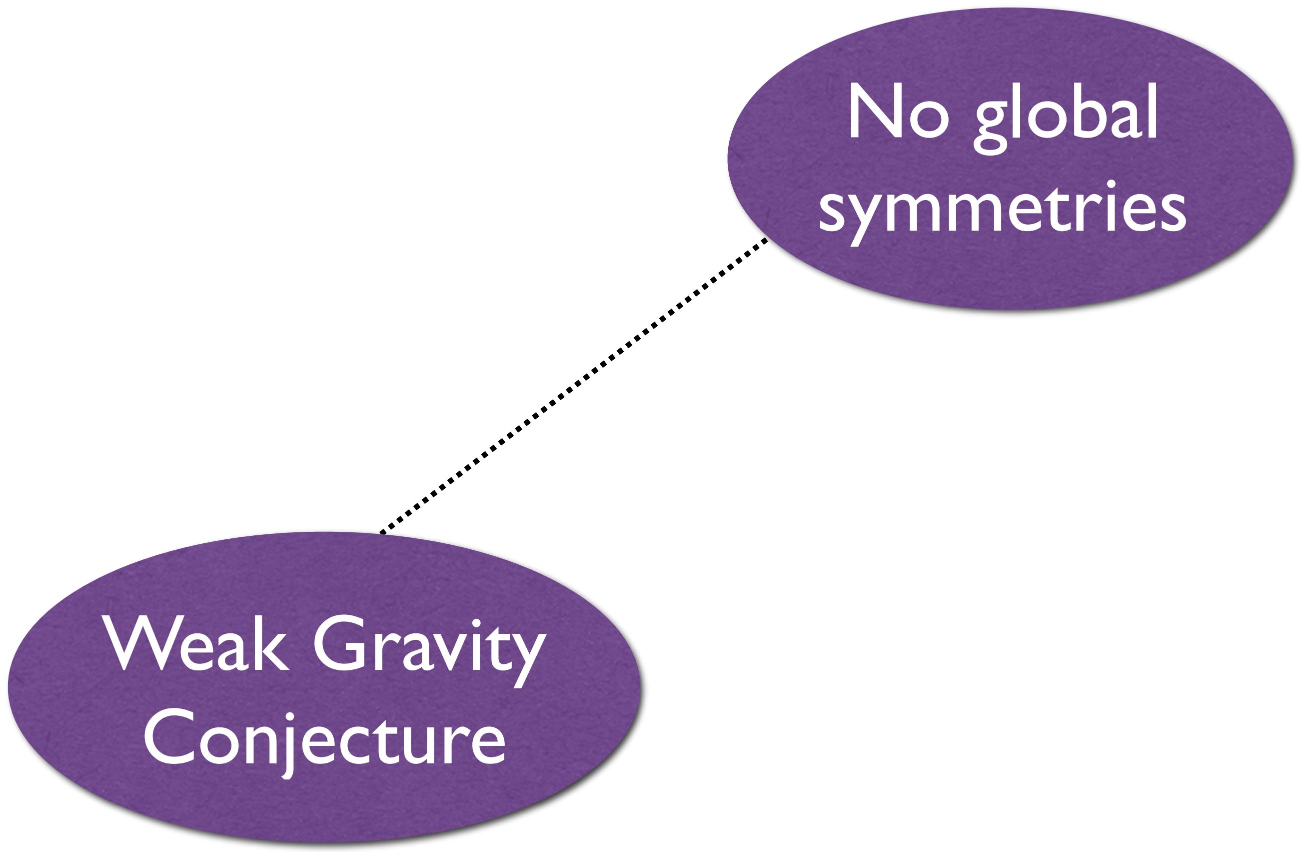
They happen to match exactly the possible string theory constructions

[Bedroya, Montero, Hamada, Vafa'21] [Hamada, Vafa'21] [Font et al'20-21] [Cvetic et al'20] [Dierigl, Heckman'20] [Montero, Vafa'20] [Kim, Shiu, Vafa'19] …[Adams et al'10….]

String universality!

No global symmetries

Open question: How much are they broken?


No global symmetries
Weak Gravity Conjecture

Weak Gravity Conjecture

[Arkani-Hamed et al'06]

There must exist a particle satisfying:

$$\frac{Q}{m} \geq 1$$

Q : charge
m : mass

so that the gravitational force acts weaker than the gauge force

$$F_e = \frac{Q^2}{r^2} \qquad F_g = \frac{m^2}{r^2}$$

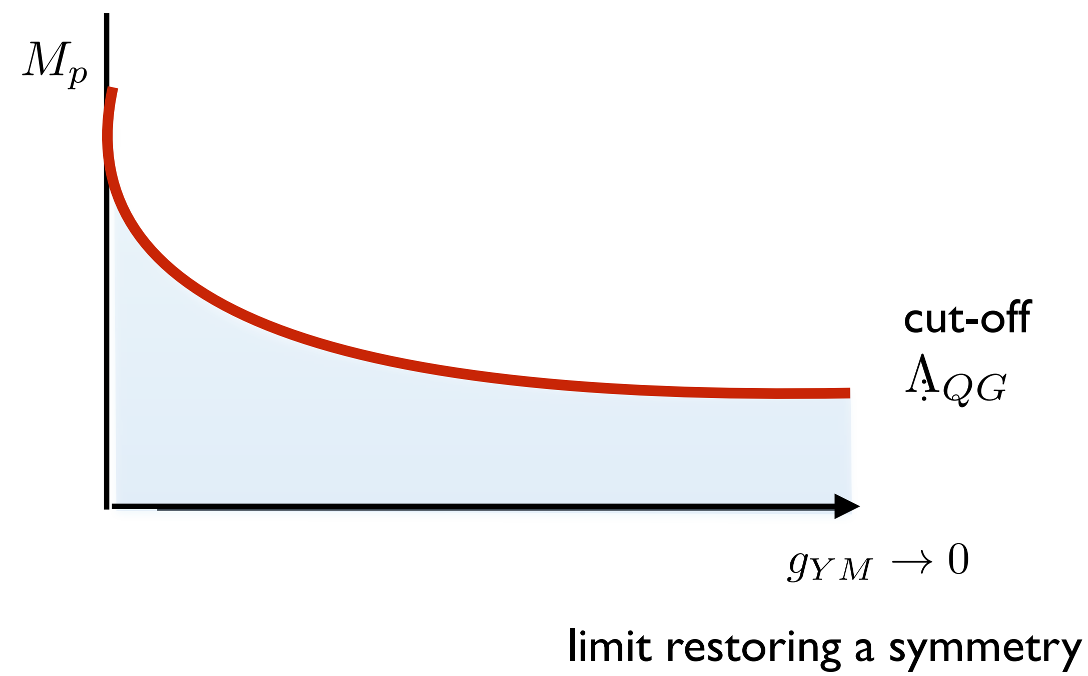
Weak Gravity Conjecture

[Arkani-Hamed et al'06]

Magnetic version:

The EFT breaks down at $\Lambda_{\rm cut-off} \sim g_{\rm YM} M_p$

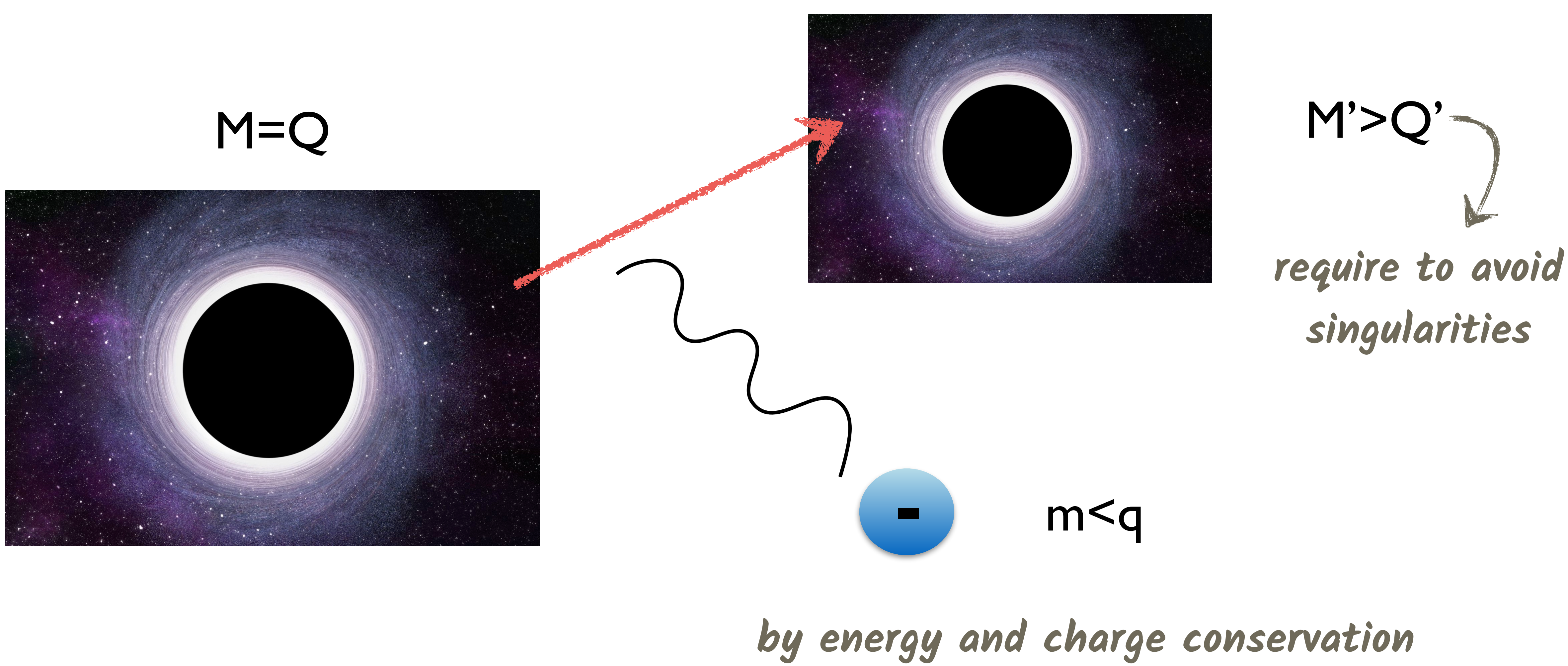
It acts as a censorship mechanism to restore a global symmetry as $g_{\rm YM} \to 0$



Plethora of quantitative tests in string theory!

Motivation from black holes

If such a particle does not exist, there would be black holes that cannot evaporate without creating singularities in space



It is satisfied in our universe:

Electron mass	10^{-23}	
Electron charge	10^{-1}	

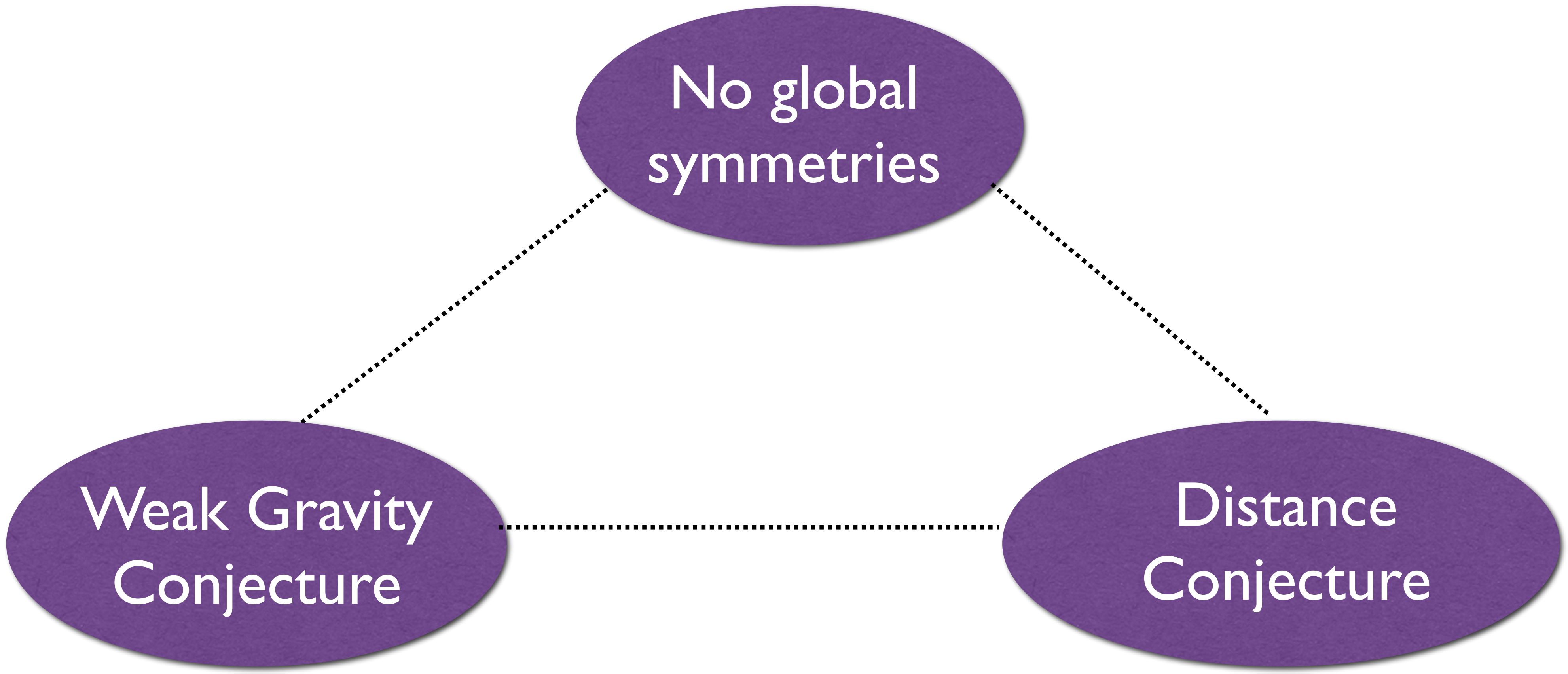
$$\left.\begin{array}{ll} \text{Electron mass} & 10^{-23} \\ \text{Electron charge} & 10^{-1} \end{array}\right\} \quad m \leq Q \quad ✓$$

(in Planck units, i.e. Mp=1)

It is not random, it has a quantum gravity explanation!

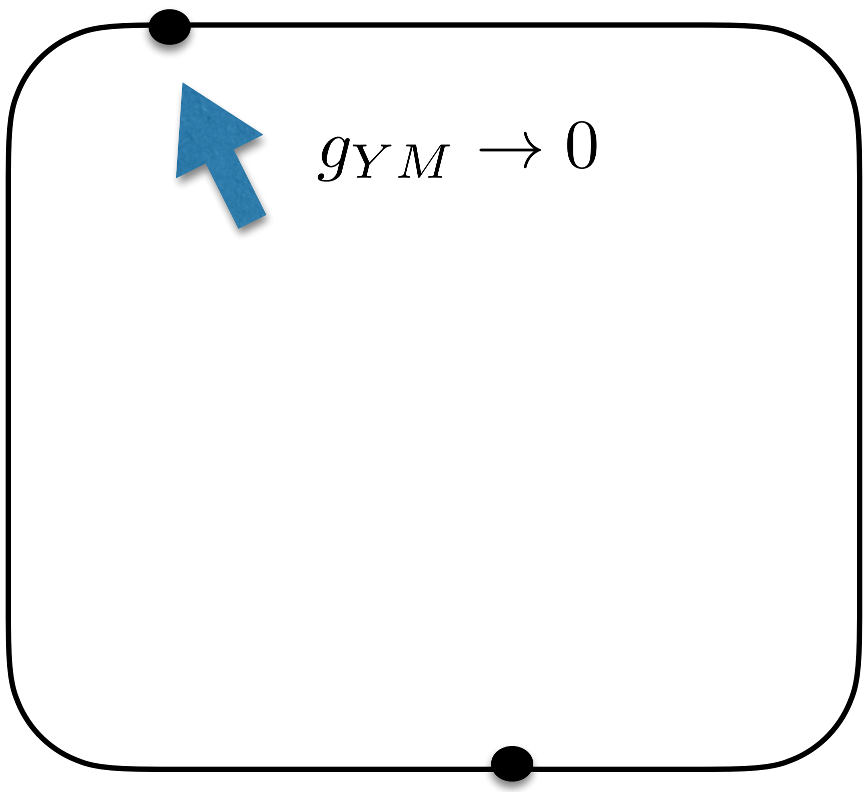
Important implications for Beyond Standard Models of Particle Physics:

Hidden forces that are very weakly coupled are disfavoured in quantum gravity, since the QG cut-off gets low if gauge couplings are small


No global symmetries
Weak Gravity Conjecture
Distance Conjecture

Approximate global symmetries

Parameter space:

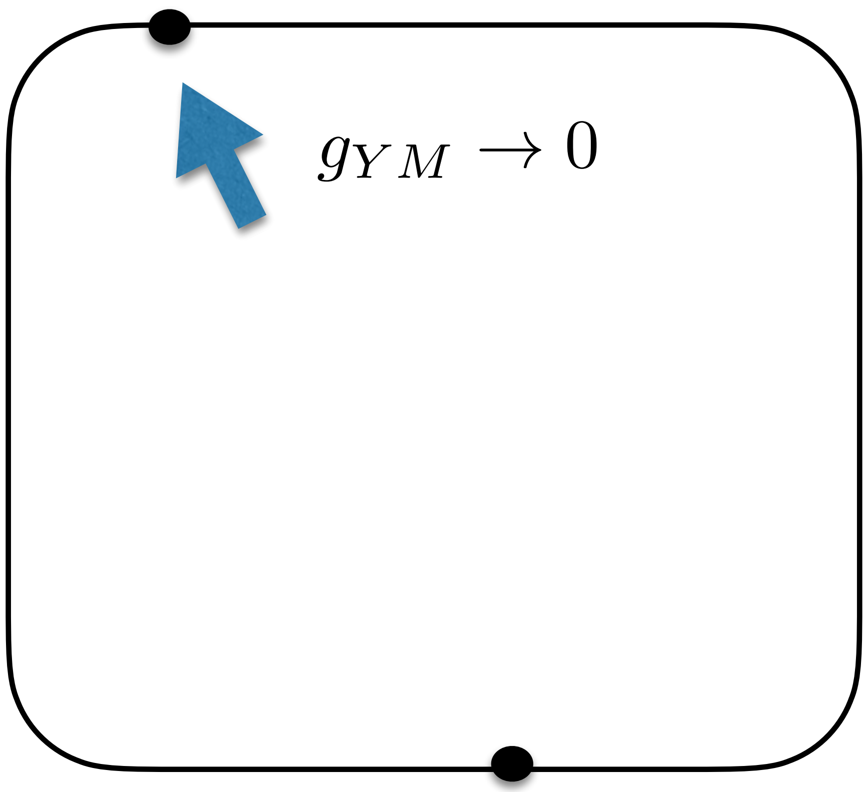


Assume some global symmetry can be restored in a continuous way at some special points of the parameter space

e.g. by sending gauge coupling $g_{YM} \to 0$
we restore a U(1) global symmetry

Approximate global symmetries

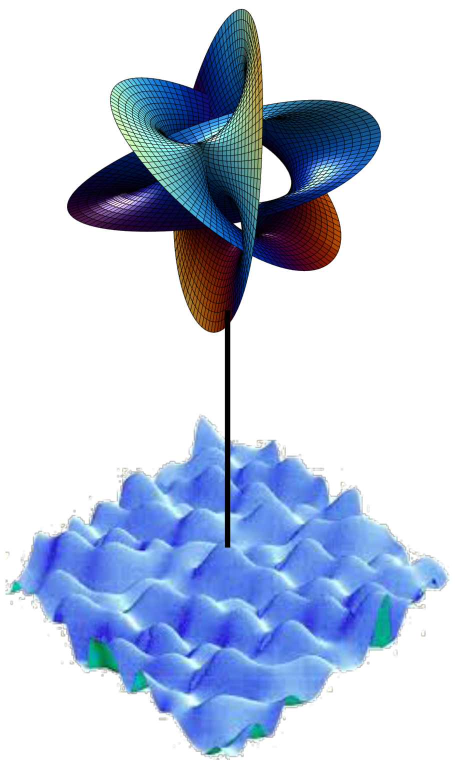
Parameter space:



String Theory has no free parameters:

All masses/couplings are given by vacuum expectation values of scalar fields that fix the size/shape of extra dimensions

(like the Higgs boson)



Approximate global symmetries

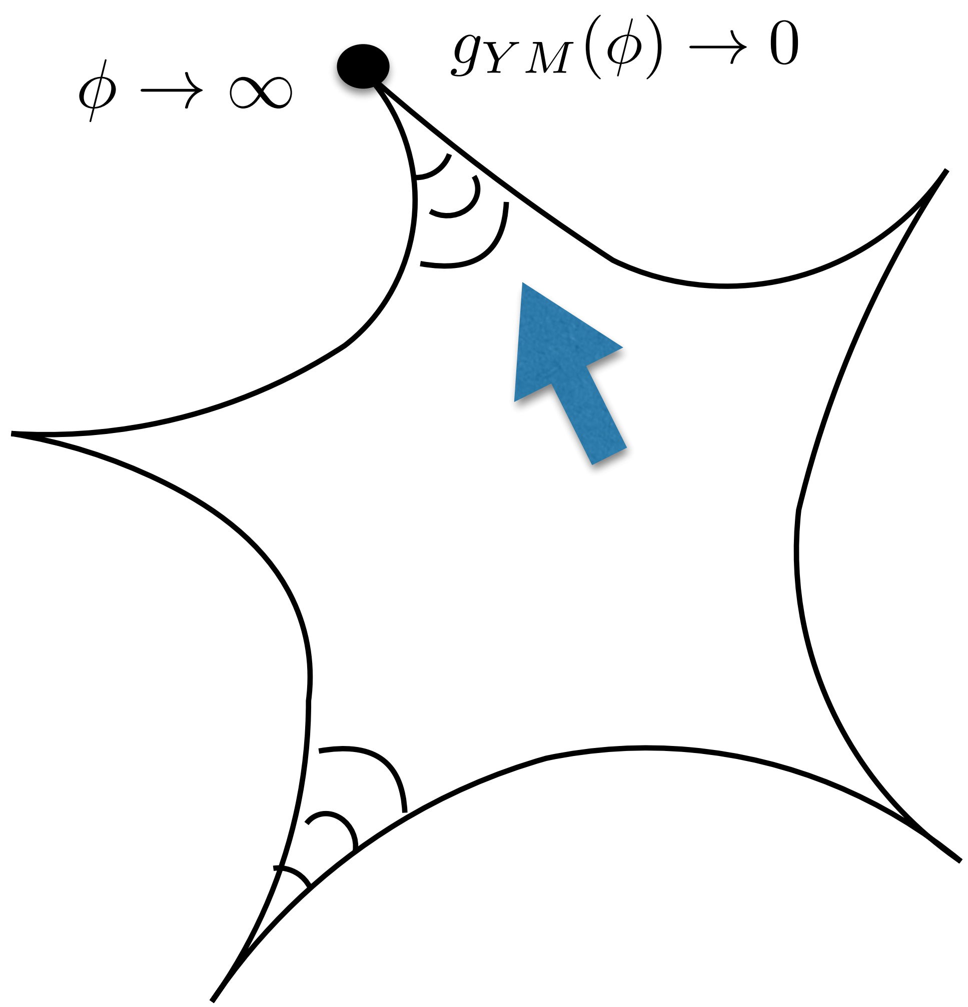
Parameter space:

=

Scalar field space in String Theory

$$\mathcal{L} = g_{ij}(\phi)\partial\phi^i\partial\phi^j$$

↳ field metric



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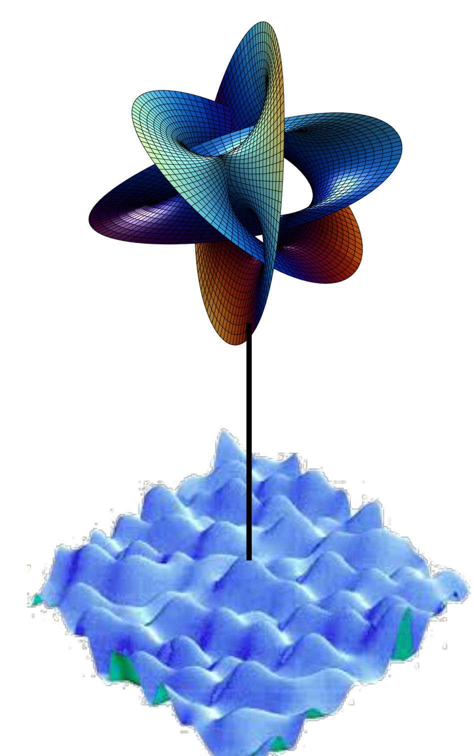

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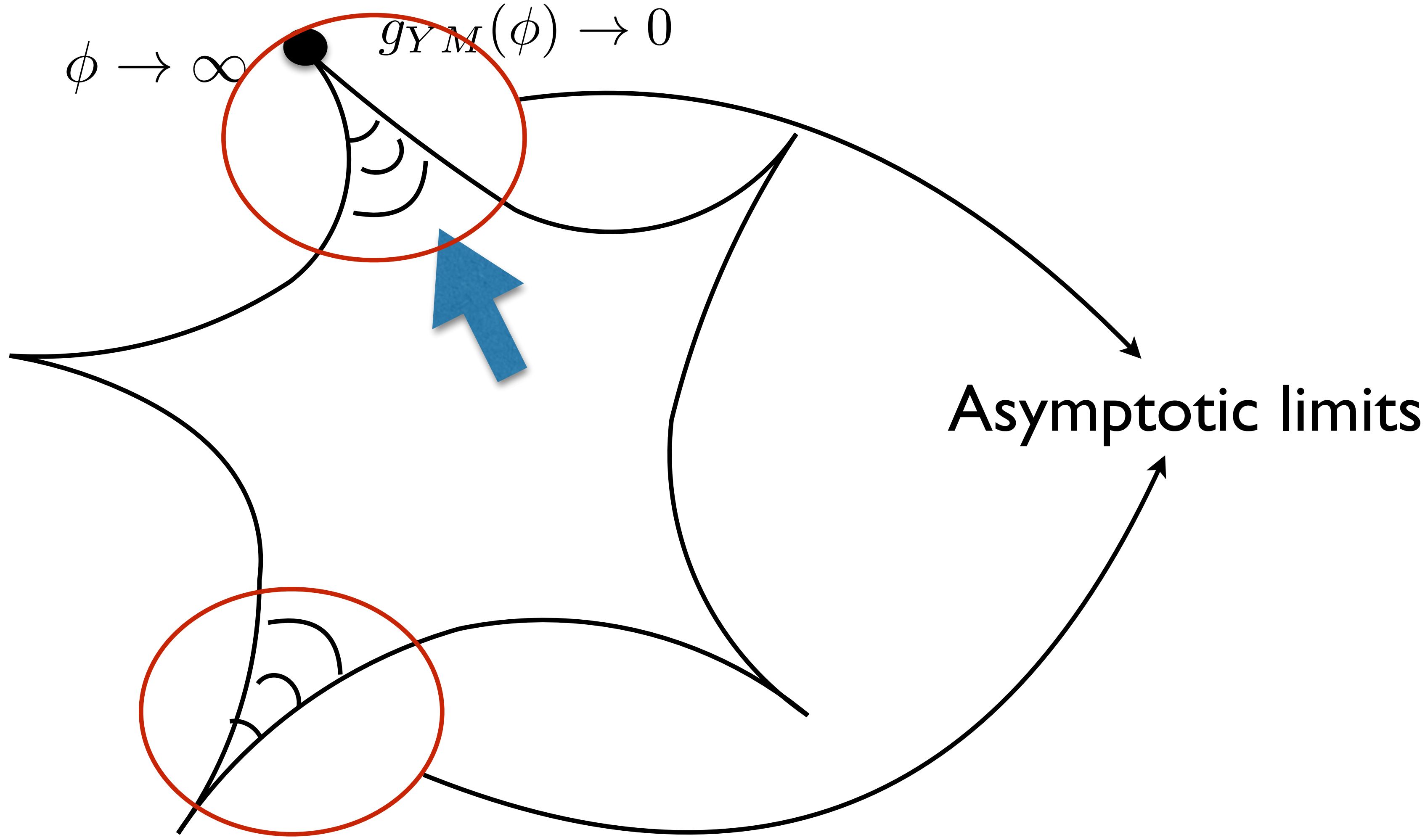


Examples: large volume, weak coupling…

Global symmetries not allowed in quantum gravity → They can only be restored at infinite field distance (asymptotic limits)

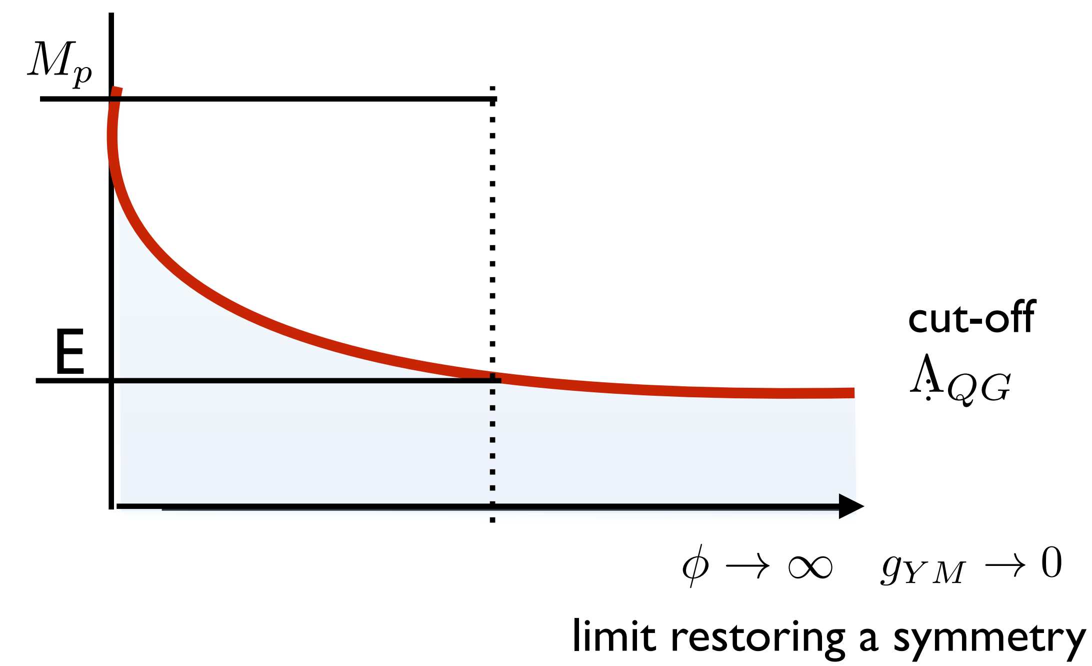
Asymptotic limits in moduli spaces

These limits seem under control from the point of view of QFT

but still, the EFT must break down when approaching the boundary by quantum gravity effects

Approximate global symmetries,
Weakly coupled gauge theories,
Large field ranges…

…come at a price.



There is new light physics that forces the cut-off to go to zero
and acts as a censorship mechanism to restore global symmetries.

Swampland Distance Conjecture

There is an infinite tower of states becoming exponentially light at every infinite field distance limit of the moduli space

$$m \sim m_0 e^{-\alpha\Delta\phi} \quad \text{when} \quad \Delta\phi \to \infty$$

[Ooguri-Vafa'06]

This signals the breakdown of the effective theory:

$$\Lambda_{QG} \sim M_p \exp(-\alpha\Delta\phi) \quad \Rightarrow \quad \Delta\phi \lesssim \frac{1}{\alpha}\log\left(\frac{M_p}{\Lambda}\right)$$

Upper bound on field range!

If the tower is charged under a gauge field:

$$m \sim g \to 0 \quad \Rightarrow \quad \Lambda \lesssim g M_p$$

Lower bound on gauge field!

same than WGC

Swampland Distance Conjecture

There is an infinite tower of states becoming exponentially light at every infinite field distance limit of the moduli space

$$m \sim m_0 e^{-\alpha \Delta\phi} \quad \text{when} \quad \Delta\phi \to \infty$$ [Ooguri-Vafa'06]

Evidence:

- Plethora of quantitative tests in string theory

  [Grimm, Palti, IV'18] [Grimm,Palti,Li'18] [Gendler,IV'20] [Lee,Lerche,Weigand'18-21] [Corvilain, Grimm, IV'18] [Baume,Marchesano,Wiesner'19] [Lanza,Marchesano,Martucci, IV'20-21] [Klaewer,Lee,Weigand,Wiesner'22] …

- Bottom-up arguments based on black hole physics [Hamada,Montero,Vafa, IV'21]

Very natural from string theory perspective, but surprising from EFT!

Swampland Distance Conjecture

There is an infinite tower of states becoming exponentially light at every infinite field distance limit of the moduli space

$$m \sim m_0 e^{-\alpha\Delta\phi} \quad \text{when} \quad \Delta\phi \to \infty$$

[Ooguri-Vafa'06]

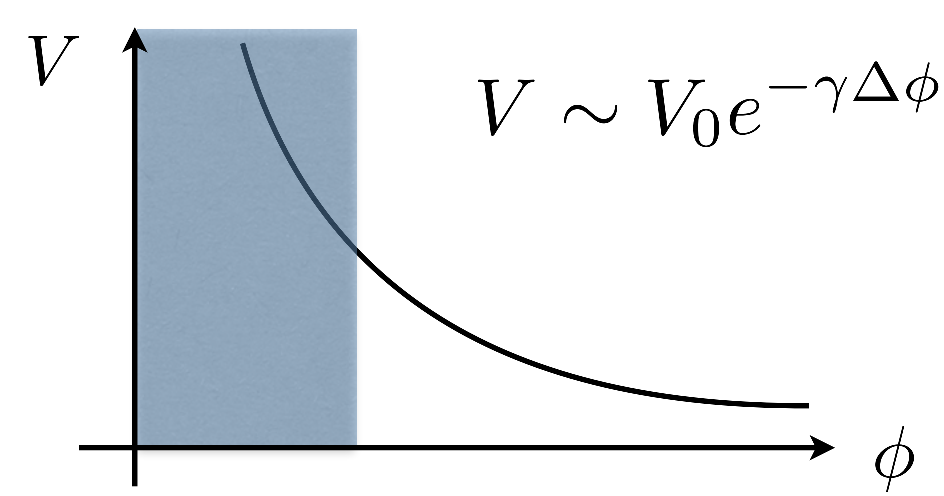
Refinement motivated by string theory: (still to be understood better!)

❖ If there is a potential energy:

$$m \sim V_0^{1/\alpha} \to 0$$

Universal asymptotic runaway behaviour of the potential

[Dine-Seiberg] [Ooguri et al'18]



Our universe

$$m \sim V_0^{1/\alpha} \to 0$$

Could it be the case of our universe?

Possible scenario:

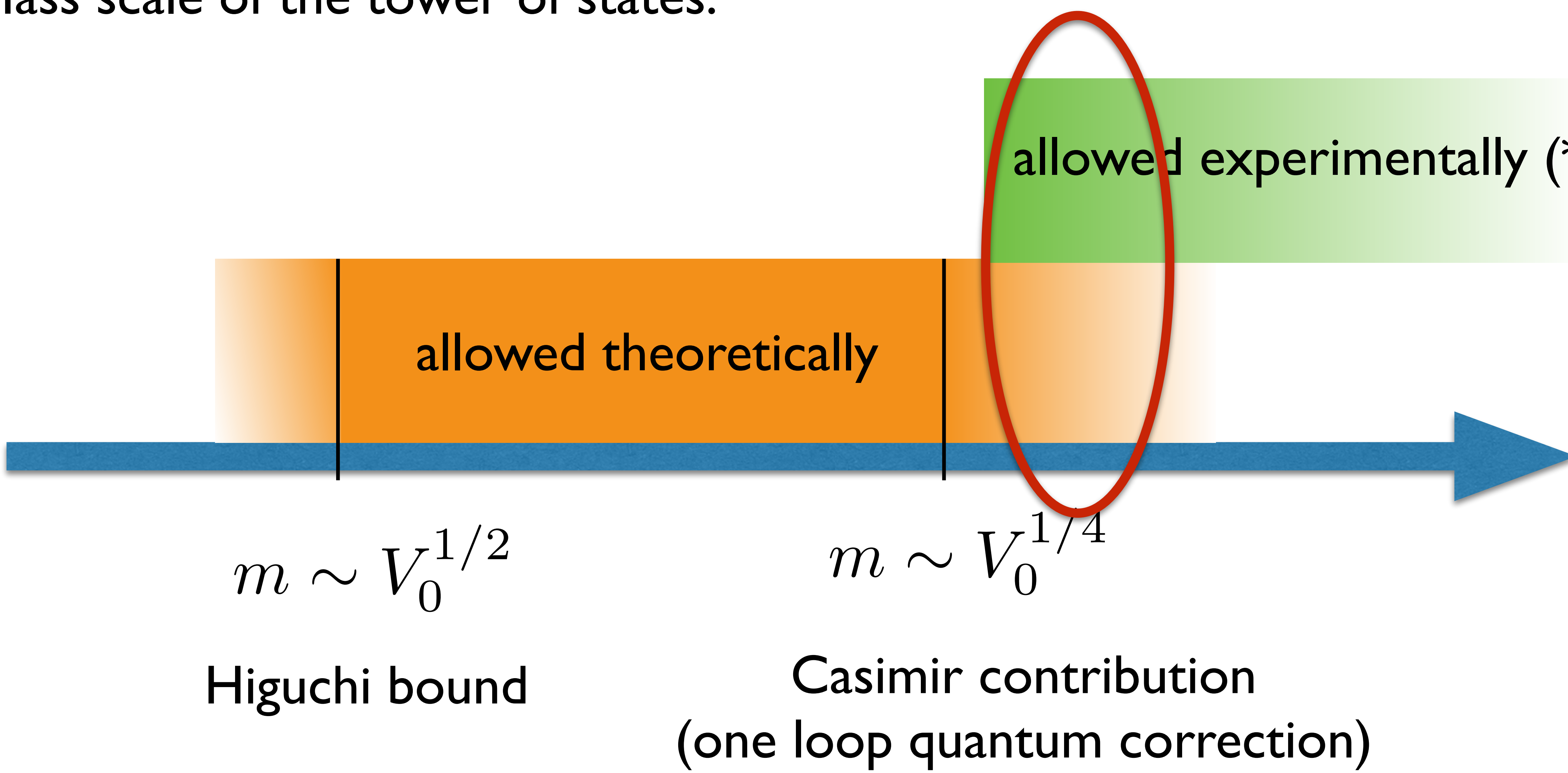
The smallness of our vacuum energy is not due to a fine-tuning of contributions in a landscape, but is a signal of being near an asymptotic limit where it naturally goes to zero

But then:

There should be a light tower of states whose mass is correlated to the cosmological constant

Dark Dimension

Mass scale of the tower of states:



(*) astrophysical bounds and deviations from Newton's law

Dark Dimension

If we live in an asymptotic limit:

- the cosmological constant would be naturally small
- there should be a light tower of states of mass:

$$m \sim V_0^{1/4} \sim \mathcal{O}(meV)$$

→ neutrino scale!

Tower of right handed neutrinos?

(it could explain coincidence between neutrino masses and cosmological constant)

implying one large extra dimension $l \sim 0.1 - 10 \mu m$

The Dark Dimension [Montero,Vafa,IV'22]

Conclusions

❖ Consistency with Quantum Gravity can have important implications for our universe that we are only starting now to discover.

❖ Not every EFT is consistent with Quantum Gravity, unless it satisfies the swampland constraints.

❖ Approximate global symmetries, weakly coupled gauge theories and large field ranges are disfavoured in Quantum Gravity.

❖ Swampland constraints motivated by string theory suggest

$$V_0 \sim m_{\text{tower}}^{\alpha} \quad \text{as} \quad V_0 \to 0$$

which would imply one mesoscopic extra dimension of

$$l \sim 0.1 - 10 \mu m \quad \text{in our universe.}$$

Thank you!

Online series of Swampland seminars / open mic discussions

on Mondays at 10:30 am ET (4:30 pm CET)

You can subscribe here: https://sites.google.com/view/swamplandseminars/

Everybody is welcome! :)

back-up slides

Dark Dimension

Is $V^{1/2} \lesssim m \lesssim V^{1/4} \sim 2.31meV$ compatible with experimental constraints?

$$\Rightarrow \quad m^{-1} \gtrsim O(10)\,\mu m$$

- **Nature of the tower:** ~~String perturbative limit~~ ruled out exp.

  Decompactification of n extra dimensions

- **Experimental constraints:**

  Astrophysical bounds: $m^{-1} \leq 10^{-4}\,\mu m$ ~~$(n=2)$~~ ruled out

  [Hannestad and Raffelt '03] $m^{-1} \leq 44\,\mu m$ $(n=1)$

  Dev. from Newton's laws (n=1): $m^{-1} \leq 30\,\mu m$

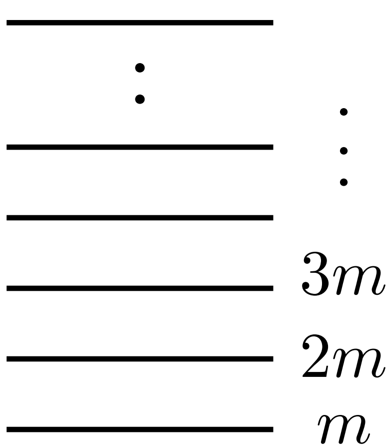
  [Lee et al '21]

Only n=1 (one large extra dimension) is marginally compatible!

Pattern in string theory:

In all known string theory examples so far, it occurs that

$$V_0 \sim m_{\rm tower}^{\alpha} \quad \text{in Planck units,} \quad \text{as} \quad V_0 \to 0$$



Notice! It can go against field theory expectations

$$V \sim m^{\alpha} < \Lambda_{QG}^4$$

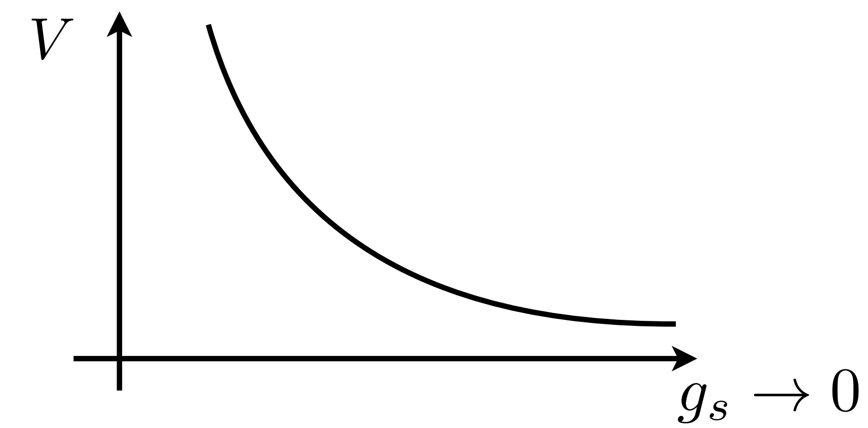
first state of the tower!

Interesting opportunity!

Failure of EFT expectation

Non-SUSY example

Recall: SO(16)xSO(16) non-SUSY (tachyon-free) heterotic string theory:



Positive runaway on the dilaton

Tower of string modes becoming light in the weak coupling limit, starting at

$$m \sim M_s$$

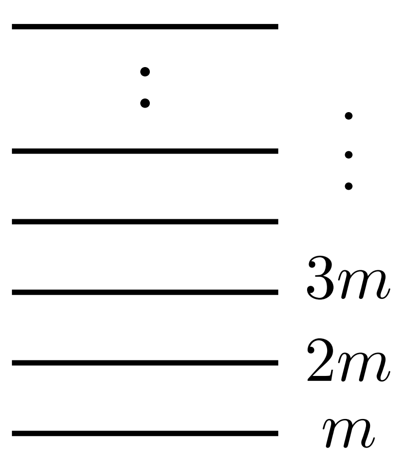
$$V_{\text{1-loop}} \sim -\sum_i (-1)^{F_i} \int_{\Lambda_{UV}^{-2}}^{\infty} \frac{ds}{s^6} \exp\left(-\frac{m_i^2 s}{2}\right) \quad \Rightarrow \quad V \sim m^{10}$$

Contribution of massive string excitations is cut-off at Ms due to modular invariance

Failure of EFT expectation

It is very important to integrate out the entire infinite tower of states

The result is drastically different than if integrating out only a finite number of them



- If integrating out the infinite tower:

$$V_0 \sim m_1^d$$ first light state of the tower!

- If integrating a finite number of fields below a cut-off:

$$V_0 \sim m_{\text{heavy}}^d$$ the heavy states dominate

Pattern in string theory:

In all known string theory examples so far, it occurs that

$$V_0 \sim m_{\text{tower}}^{\alpha} \quad \text{in Planck units,} \quad \text{as} \quad V_0 \to 0$$

The presence of a tower of states becoming light forces the vacuum energy to become small

No fine-tuning or naturalness problem for the cosmological constant

Caveat: $V_0 = \lambda m^{\alpha}$ → model dependent

One could try to fine-tune λ to decouple them,
but naturally V_0 remains small

Approximate global symmetries,
Weakly coupled gauge theories,
Large field ranges…

…come at a price.

(Swampland) Distance Conjecture (SDC):

There is an infinite tower of states becoming exponentially light at every infinite field distance limit of the moduli space

$$m(P) \sim m(Q)e^{-\alpha\Delta\phi} \quad \text{when} \quad \Delta\phi \to \infty$$

(geodesic distance)

[Ooguri-Vafa'06]

[Arkani-Hamed et al'06]

Weak Gravity Conjecture (WGC):

Given a gauge theory, there must exist an electrically charged state with

$$\frac{Q}{M} \geq \left(\frac{Q}{M}\right)_{\text{extremal}} = \mathcal{O}(1)$$

Q=q g : charge
m : mass in Planck units

Strong version: *there is a sublattice/tower of superextremal states*

[Montero et al.'16][Heidenreich et al.'15-16][Andriolo et al'18]

UV cut-off goes to zero due to new light states

$$\Lambda \sim gM_p$$

$$\Lambda \sim M_p \exp(-\alpha\Delta\phi)$$

Phenomenological implications of WGC and SDC

- WGC: constrains EFTs with tiny gauge couplings $\Lambda \sim g M_p$
  or large axionic decay constants (since $f = 1/g_{\rm axion}$)

- SDC: constrains EFTs with large field ranges

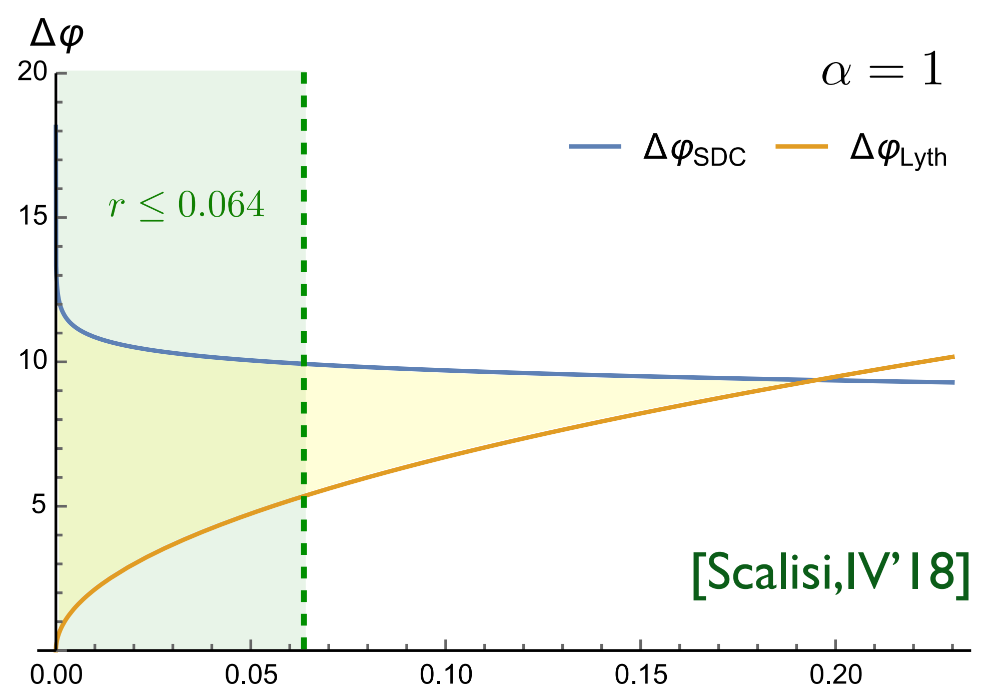
$$\Lambda \sim M_p \exp(-\alpha \Delta\phi) \quad \Rightarrow \quad \Delta\phi \leq \frac{1}{\alpha} \log \frac{M_p}{\Lambda}$$

Example: Constraints on inflation

$$\Delta\phi \leq \frac{1}{\alpha} \log \frac{M_p}{H} \quad = \frac{1}{\alpha} \log \sqrt{\frac{2}{\pi^2 A_s r}}$$

$H \leq \Lambda$

Opposite scaling than Lyth bound!



Large field inflation is not ruled out but constrained

Cosmological signatures of the tower?

Evidence for WGC and SDC

❖ String theory compactifications: Plethora of quantitative tests!

- Systematic approach according to the level of supersymmetry
- Interesting connections to mathematics

[Grimm, Palti, IV'18]
[Grimm,Palti,Li'18]
[Lee,Lerche,Weigand'18-19]
…

❖ AdS/CFT:

- WGC proven for AdS3 using modular invariance of the CFT [Heidenreich et al'16] [Montero et al'16]
- WGC from QI theorems and entanglement entropy [Montero'18]
- SDC formulated in terms of a CFT Distance conjecture [Perlmutter et al'20]

❖ Black hole arguments:

- WGC follows from requiring black holes to decay [Arkani-Hamed et al'06]
- WGC/SDC follows from entropy bounds associated to small BHs [Hamada et al'21]
- Connection between WGC and weak cosmic censorship [Crisford et al'17]

❖ Using positivity/unitarity bounds: lead to mild versions of the WGC

[Cheung et al'18][Hamada et al'18]…

WGC and SDC from Entropy Bounds

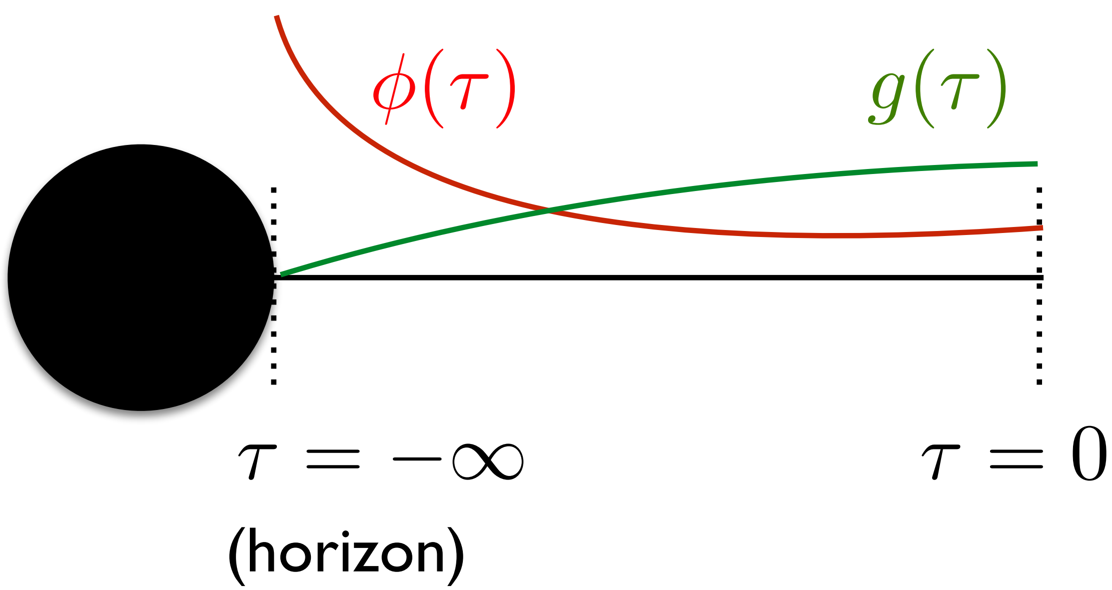
Take Einstein-Maxwell-Dilaton theory:

$$S = \int d^4x\sqrt{-g}\left[R + 2|d\phi|^2 + \frac{1}{2g(\phi)^2}|F|^2\right] \quad \text{s.t.} \quad g(\phi) \to 0 \quad \text{as} \quad \phi \to \infty$$

There are electrically charged BH solutions with classical zero area (small BHs)

If $g(-\infty) \to 0$ then $A(-\infty) \to 0$: Small BH

BH induces a running of the scalar field and gauge coupling as approaching the horizon leading to:



large field range!
small gauge coupling!

WGC and SDC from Entropy Bounds

Small BHs lead to a violation of the Bekenstein bound, unless the EFT cutoff decreases as dictated by the SDC / WGC

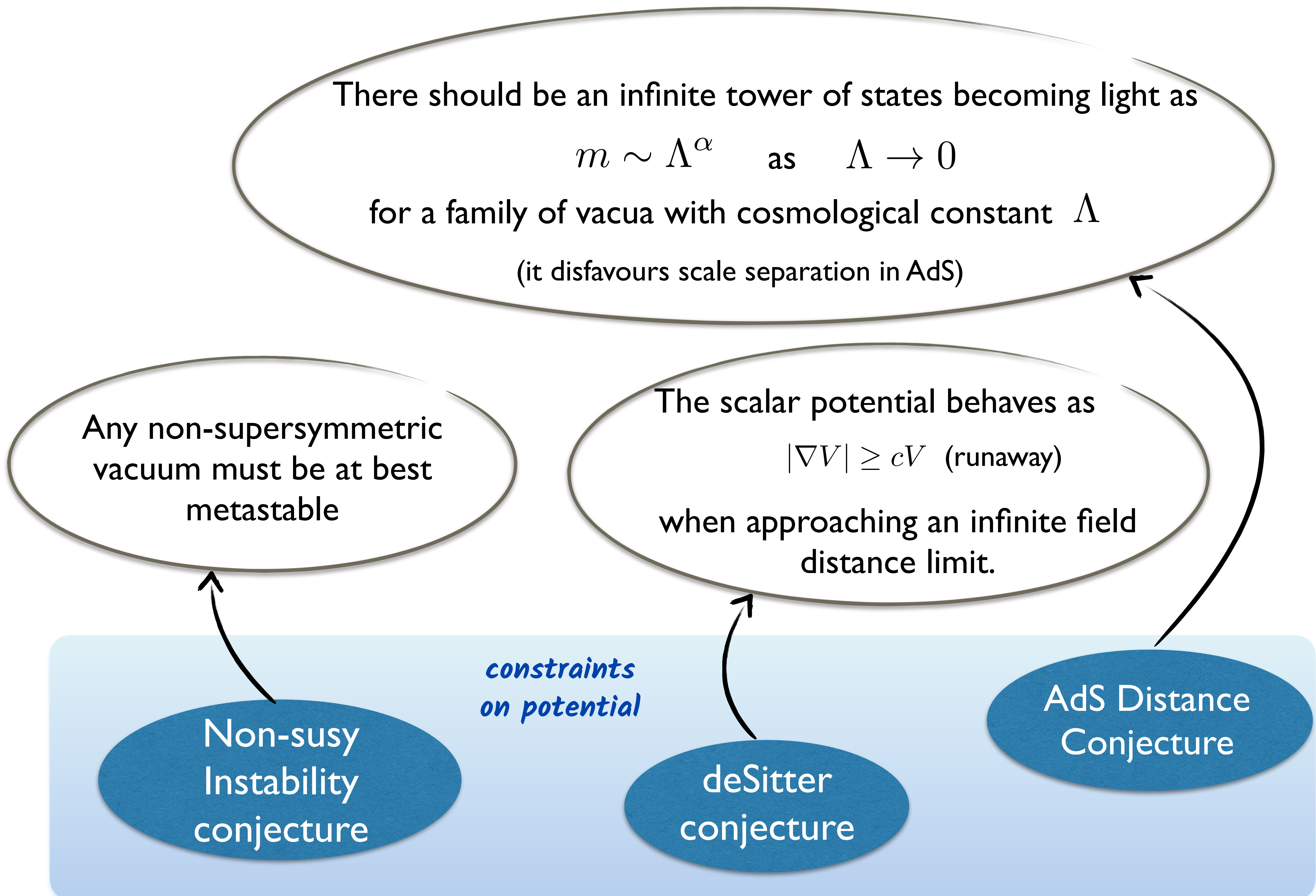
Entropy Bound: A region of size L cannot have more entropy than a Schwarzschild black hole of the same area $A = L^2$

$$N_{\text{species}} = Q_{\max} \lesssim L^2 = A$$

Using extremality condition and that EFT breaks down at $|d\phi|^2 \sim \Lambda^2$

→ $\Lambda \lesssim g$ in Planck units

due to an infinite tower of states



There should be an infinite tower of states becoming light as
$m \sim \Lambda^\alpha$ as $\Lambda \to 0$
for a family of vacua with cosmological constant Λ
(it disfavours scale separation in AdS)
Any non-supersymmetric vacuum must be at best metastable
The scalar potential behaves as
$|\nabla V| \geq cV$ (runaway)
when approaching an infinite field distance limit.
constraints on potential
Non-susy Instability conjecture
deSitter conjecture
AdS Distance Conjecture

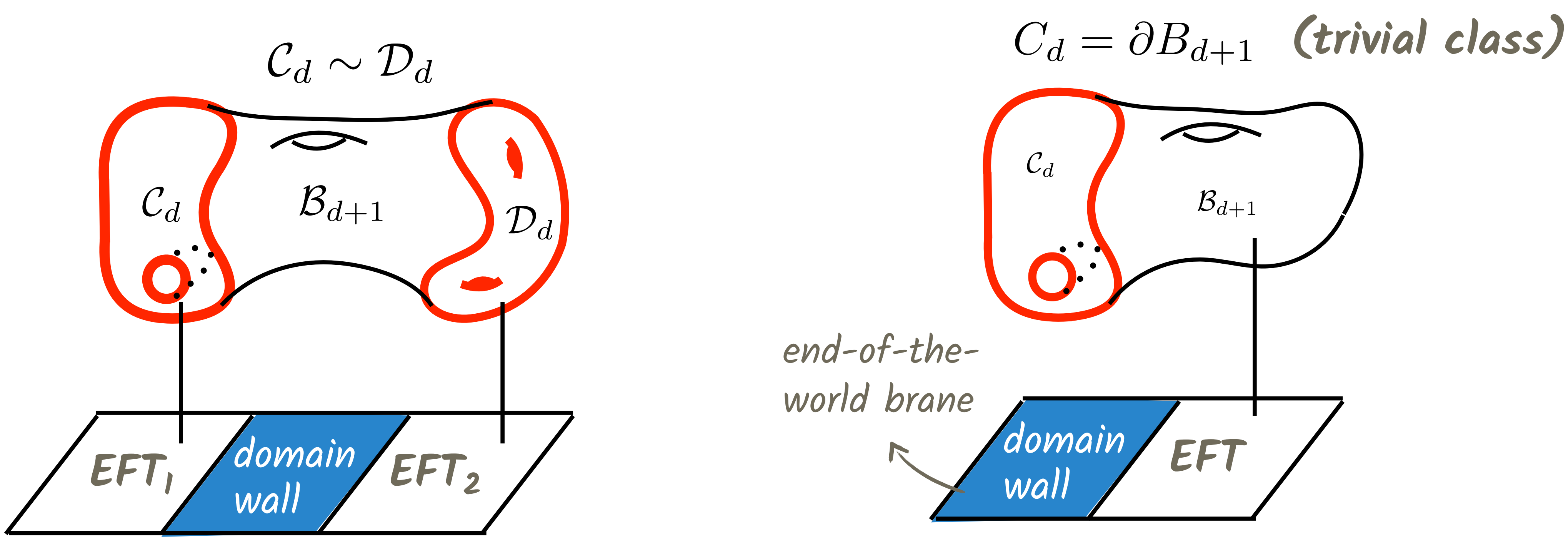
Cobordism conjecture

The cobordism group of a quantum gravity theory must be trivial:

$$\Omega_k^{QG} = 0$$ [McNamara, Vafa'19]

k : internal dimension
D : total dimension

to avoid a (D-k-1)-form global symmetry with charges $[M] \in \Omega_k^{QG}$



It implies all theories of same dimension are connected by finite energy domain walls, and predicts the existence of new defects in string theory!