Swampland and Naturalness

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CERN

IFT UAM-CSIC

"New approaches to naturalness"
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European Research Council
Established by the European Commission

MOTIVATION

Ferdi Rizkiyanto

MOTIVATION

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In this talk:

Requiring consistency with quantum gravity principles can have implications at low energies.

(Swampland program)

OUTLINE

❖ Generic ideas/expectations

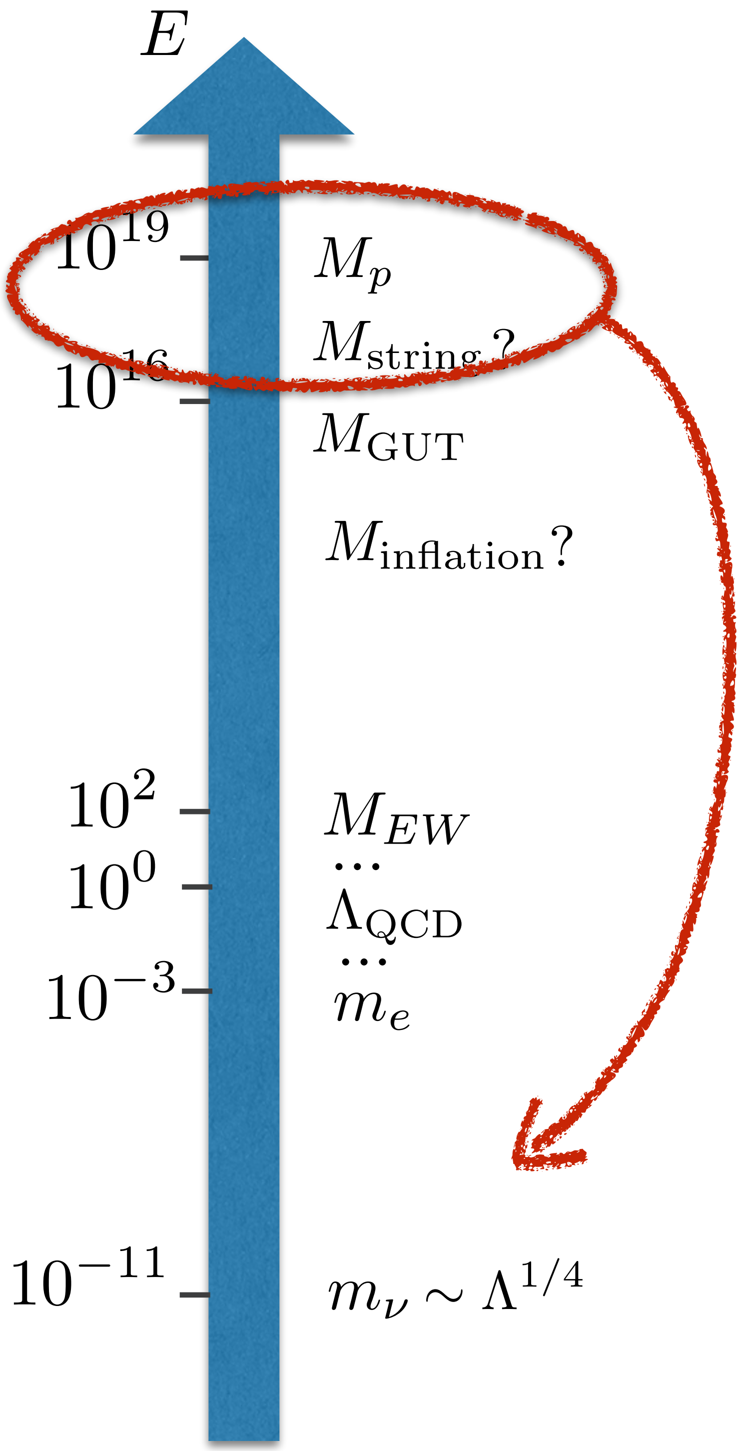
- UV/IR mixing of gravity
- Not everything goes (not every EFT can be consistently coupled to quantum gravity)

❖ Explicit examples of 'unnatural parameters' from IR perspective

- Breaking of global symmetries
- Light scalars and Weak Gravity Conjecture
- Dynamical parameters and Distance Conjecture
- Small vacuum energy and dark dimension
- AdS vacua from SM and neutrino masses

GENERIC ARGUMENTS

UV/IR mixing by gravity



E

10^{19} M_p

$M_{\text{string}}?$

10^{16} M_{GUT}

$M_{\text{inflation}}?$

10^{2} M_{EW}

$\cdots$

10^{0} Λ_{QCD}

$\cdots$

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10^{-11} $m_\nu \sim \Lambda^{1/4}$

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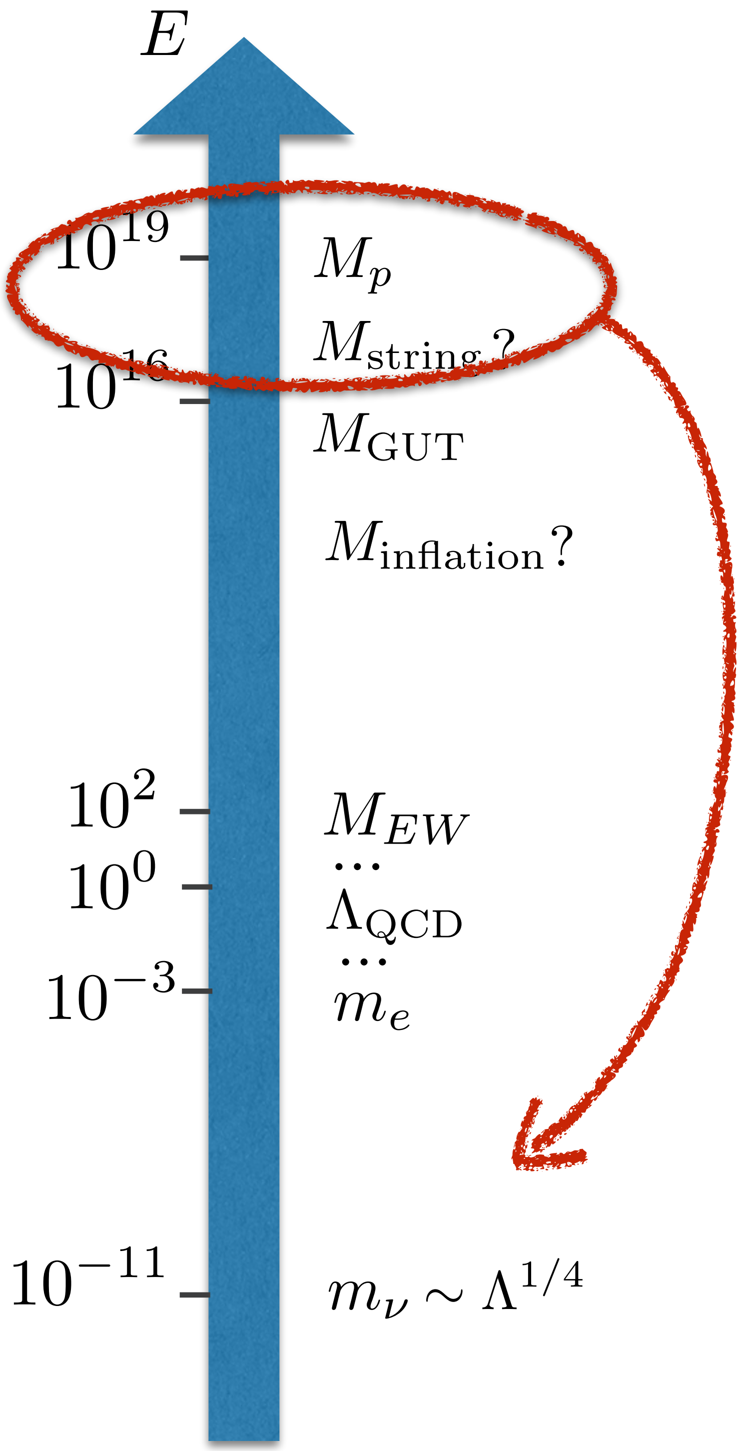

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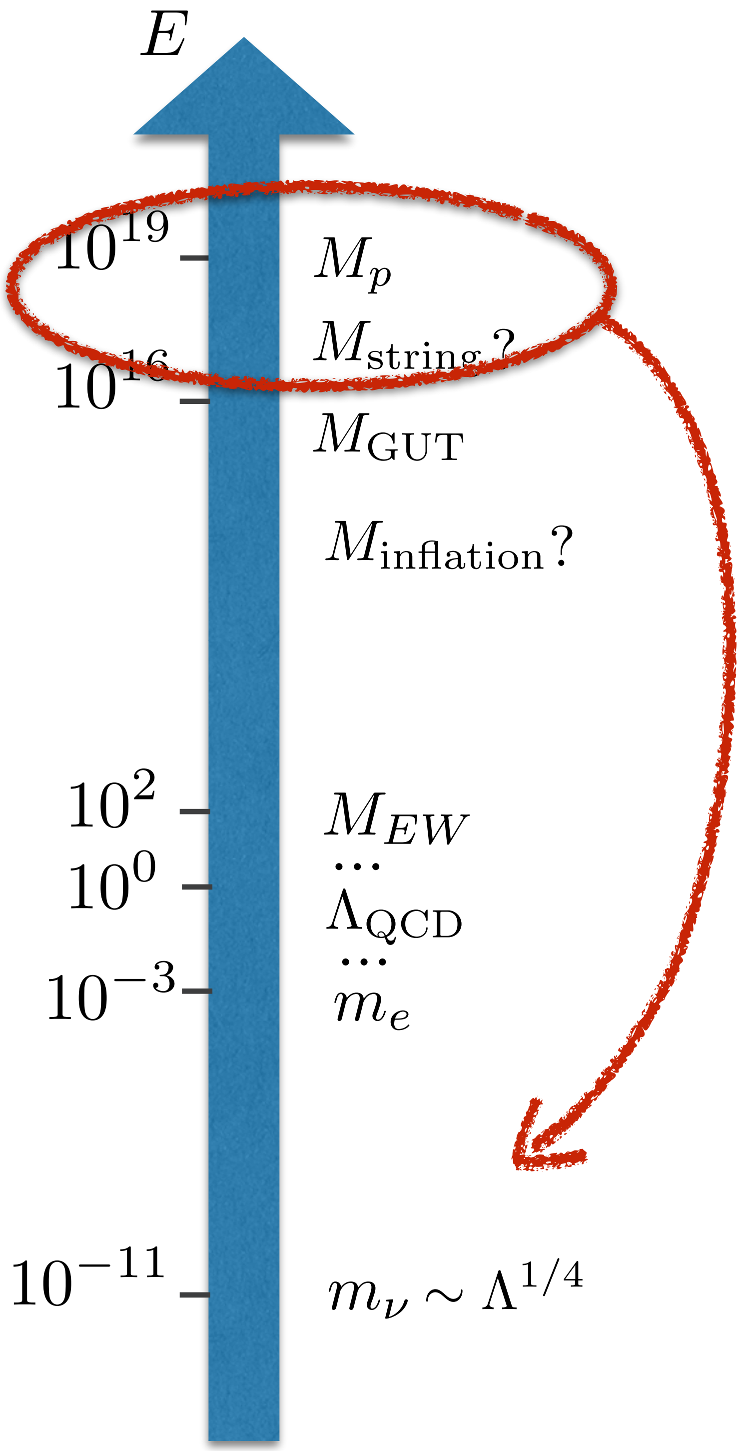

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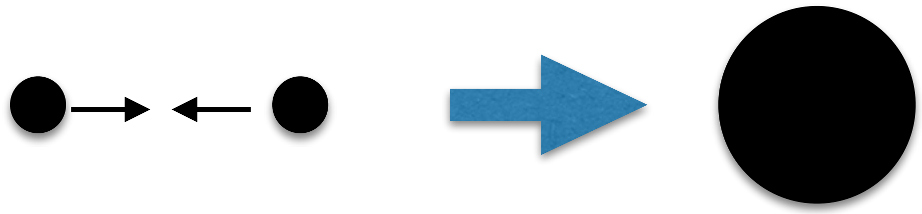

large black holes

scattering of particles at high energies

GENERIC ARGUMENTS

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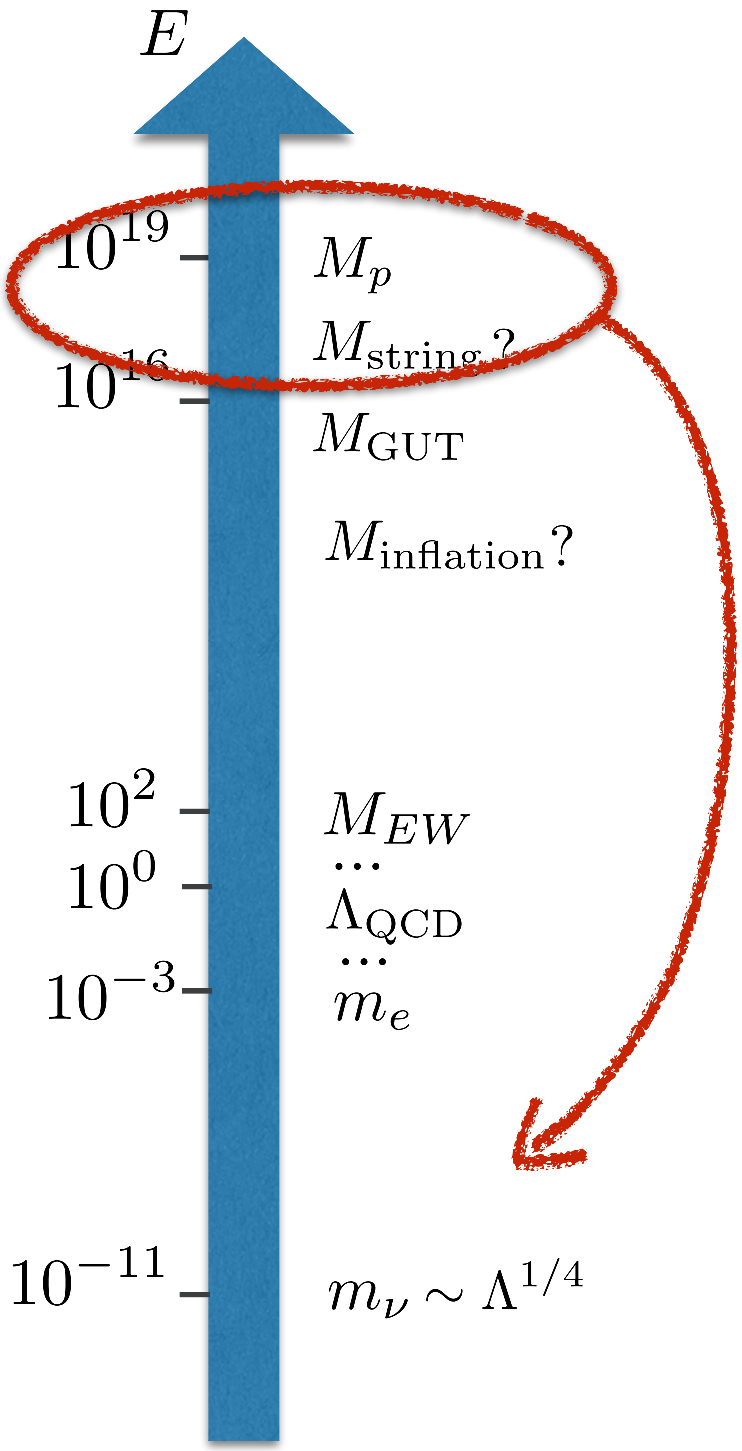
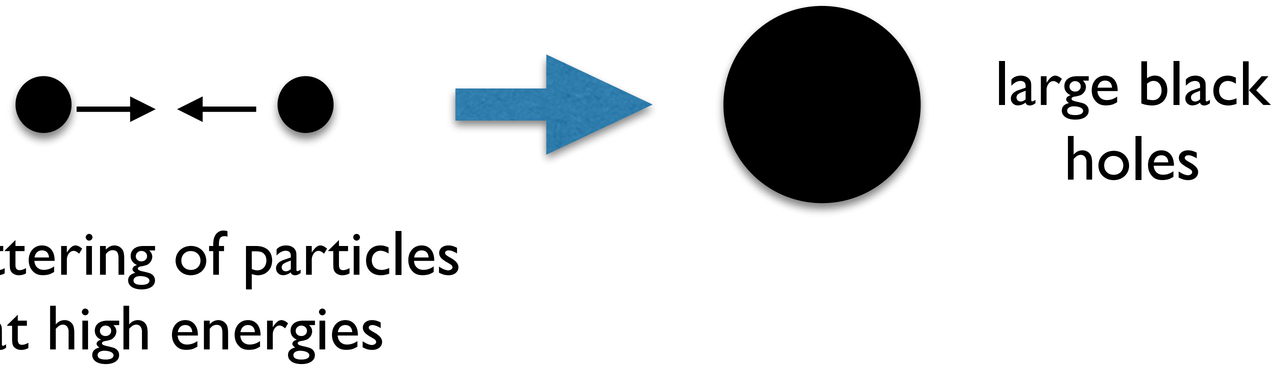


- **Black Hole Physics** makes manifest a correlation between high and low energy physics (UV/IR mixing)



- Evidence from **String Theory** (dualities, modular invariance…)

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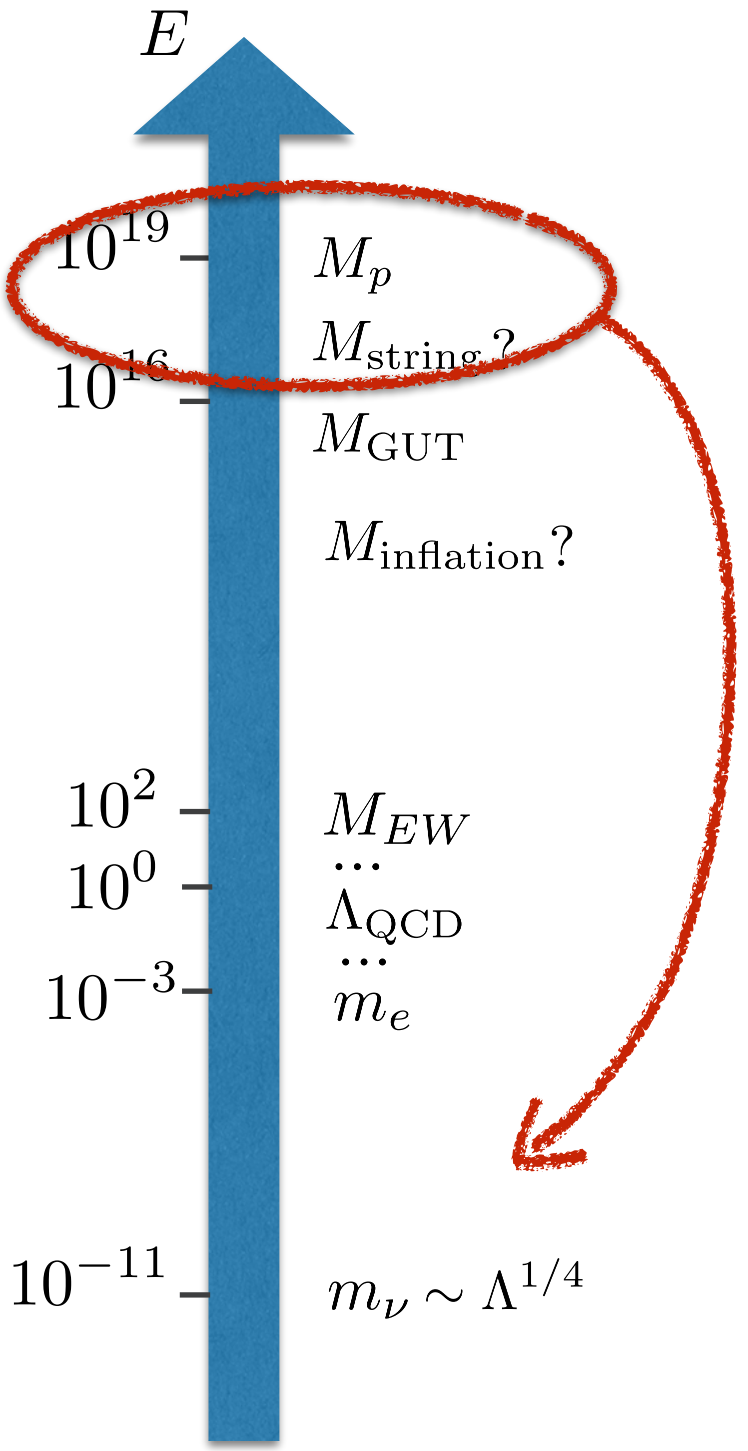

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Naturalness issues are an opportunity.

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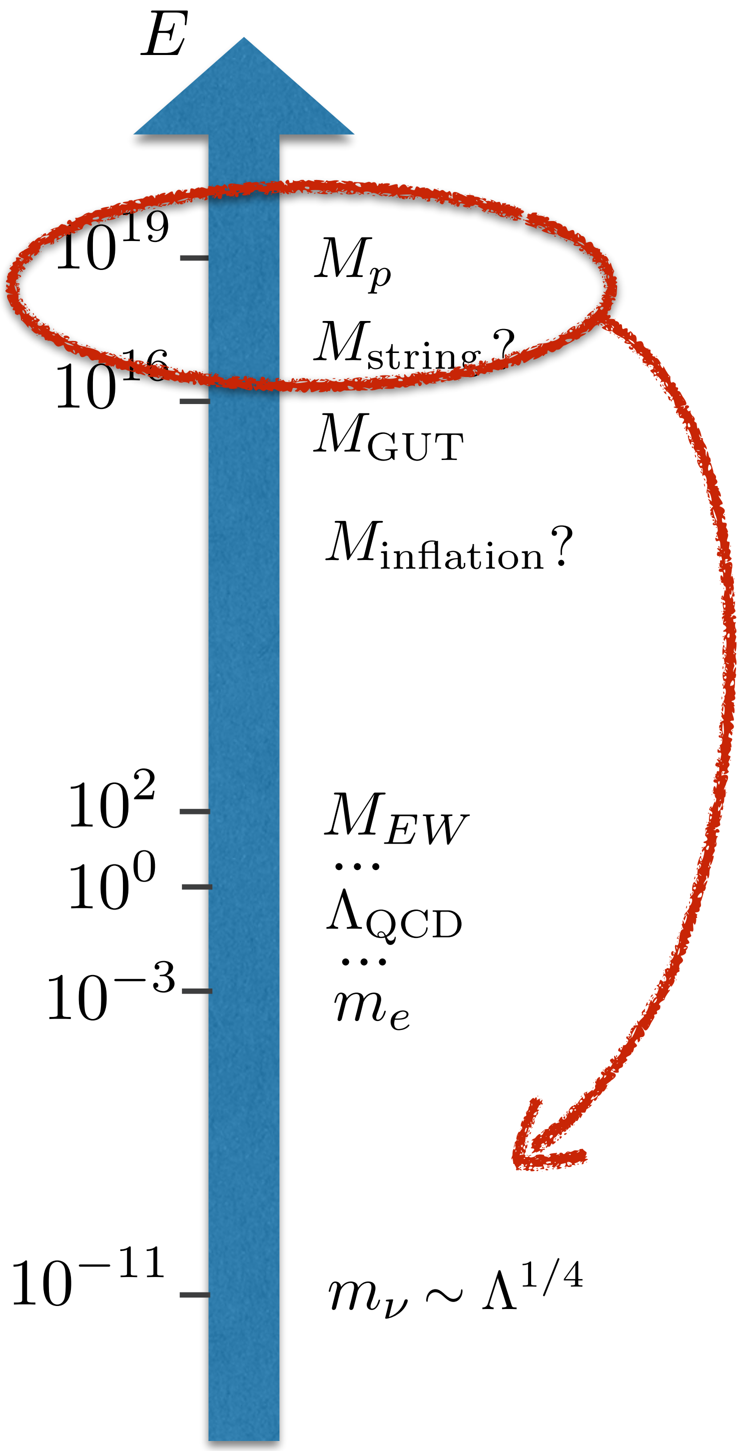

Using terminology of James Wells' talk:

(as I understood it)

- Intrinsic hierarchy problem gets solved

Once gravity kicks in, rules are different
(in fact, string theory implies infinity many states,
but divergences are cured by UV/IR mixing)

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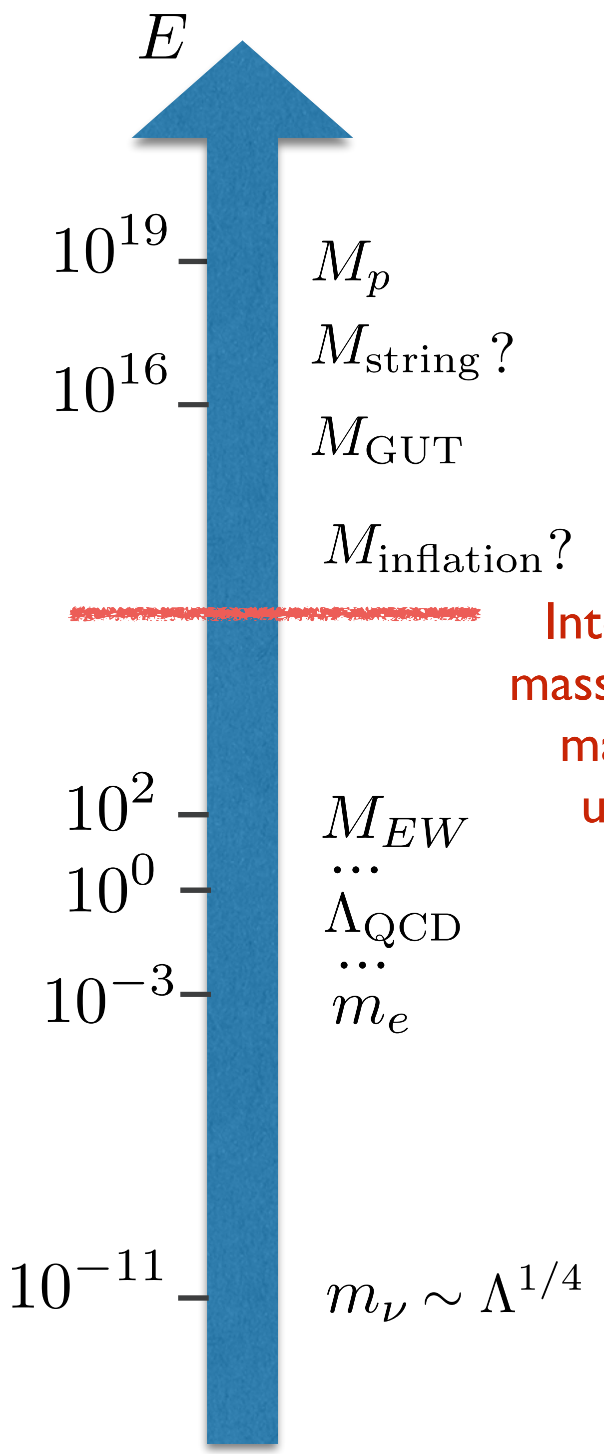

Intermediate
mass thresholds
make Higgs
unnatural

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Once gravity kicks in, rules are different
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but divergences are cured by UV/IR mixing)

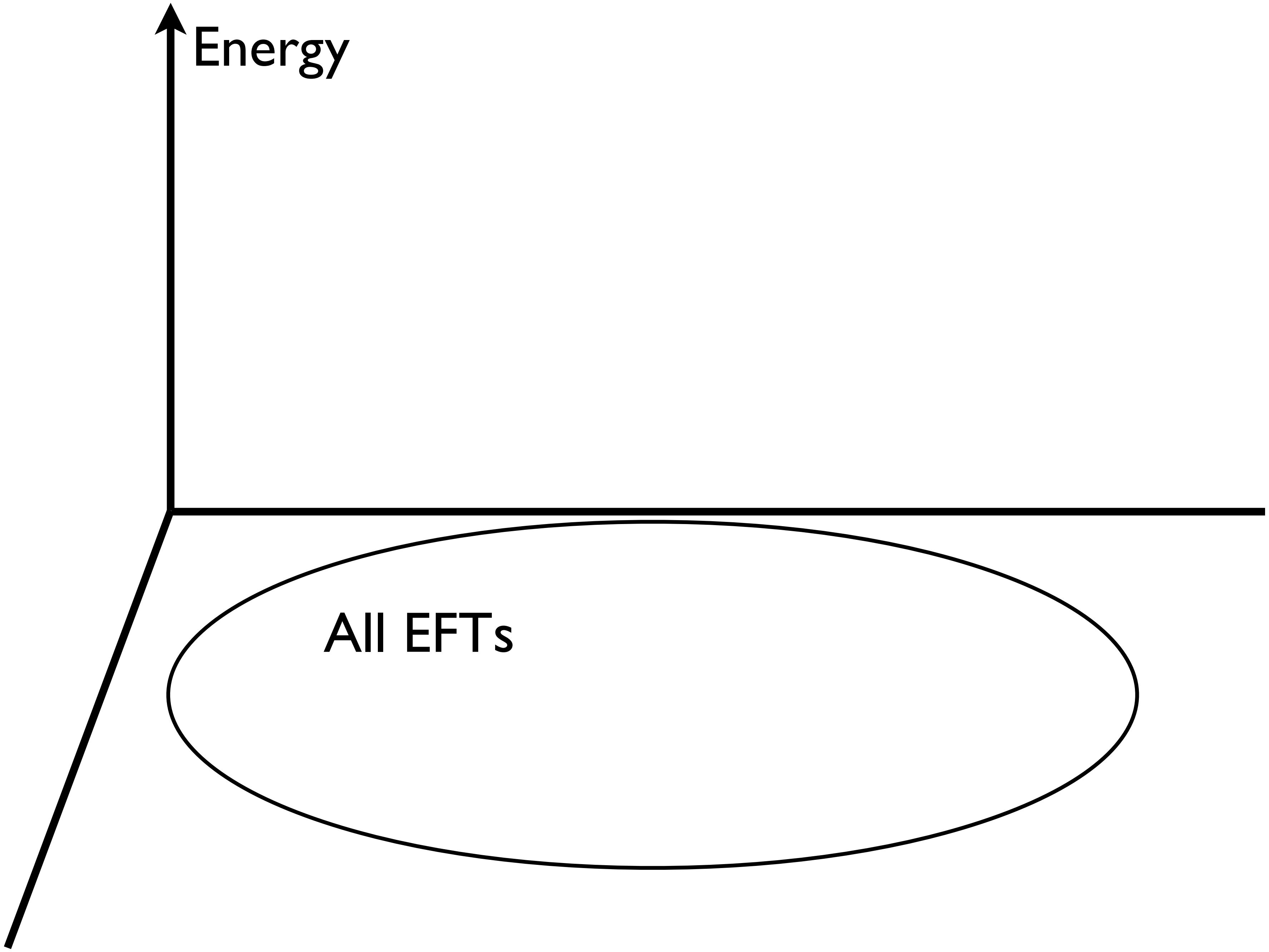
- However, extrinsic hierarchy problem can still be there

At low energies, we get QFT coupled to Einstein gravity and Wilsonian paradigm seems to hold

GENERIC ARGUMENTS

Not everything goes

Not every low energy EFT coupled to gravity can be UV completed (in a quantum gravity theory)



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[Brennan,Vafa'17] [Palti'19]
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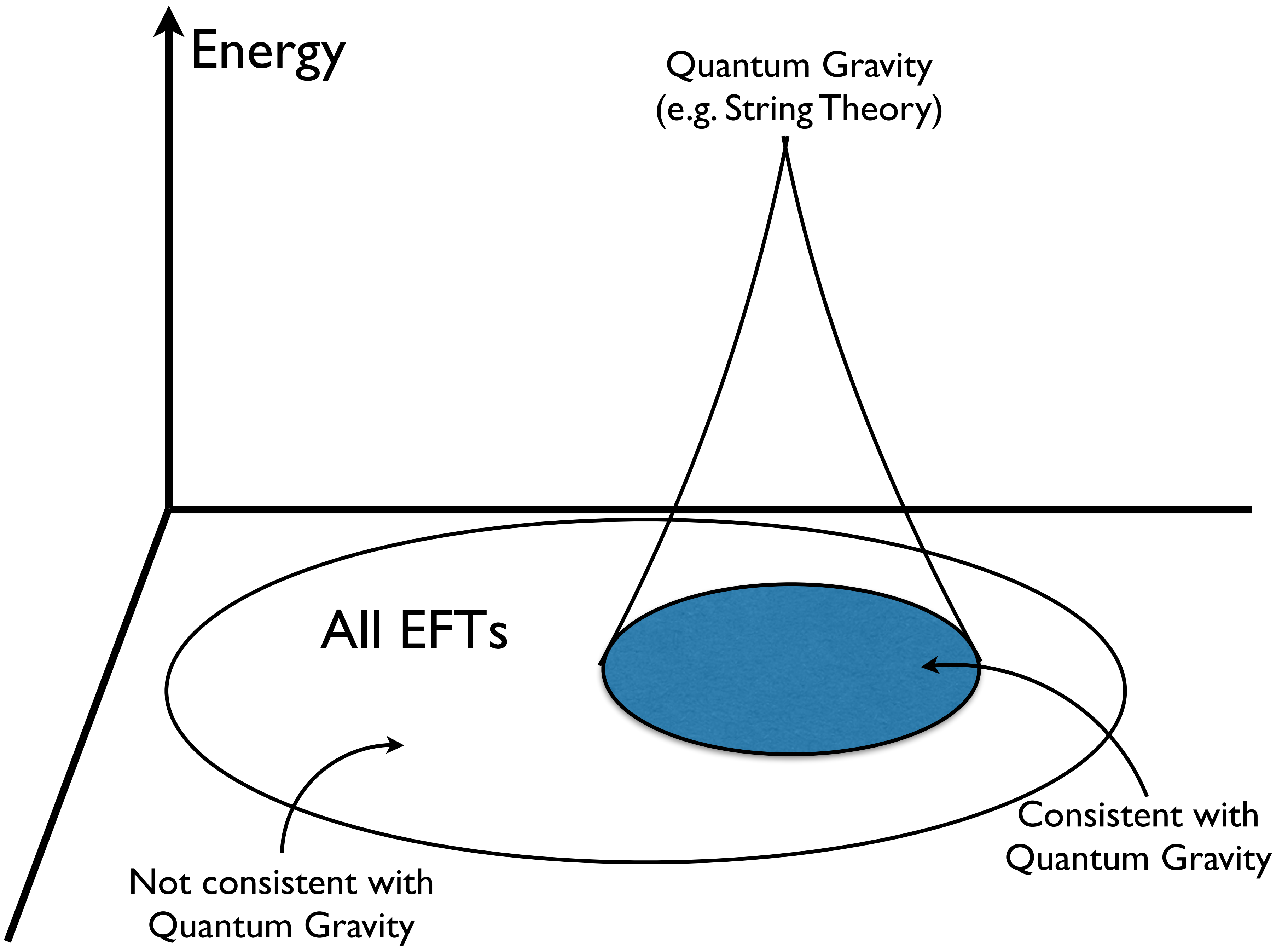

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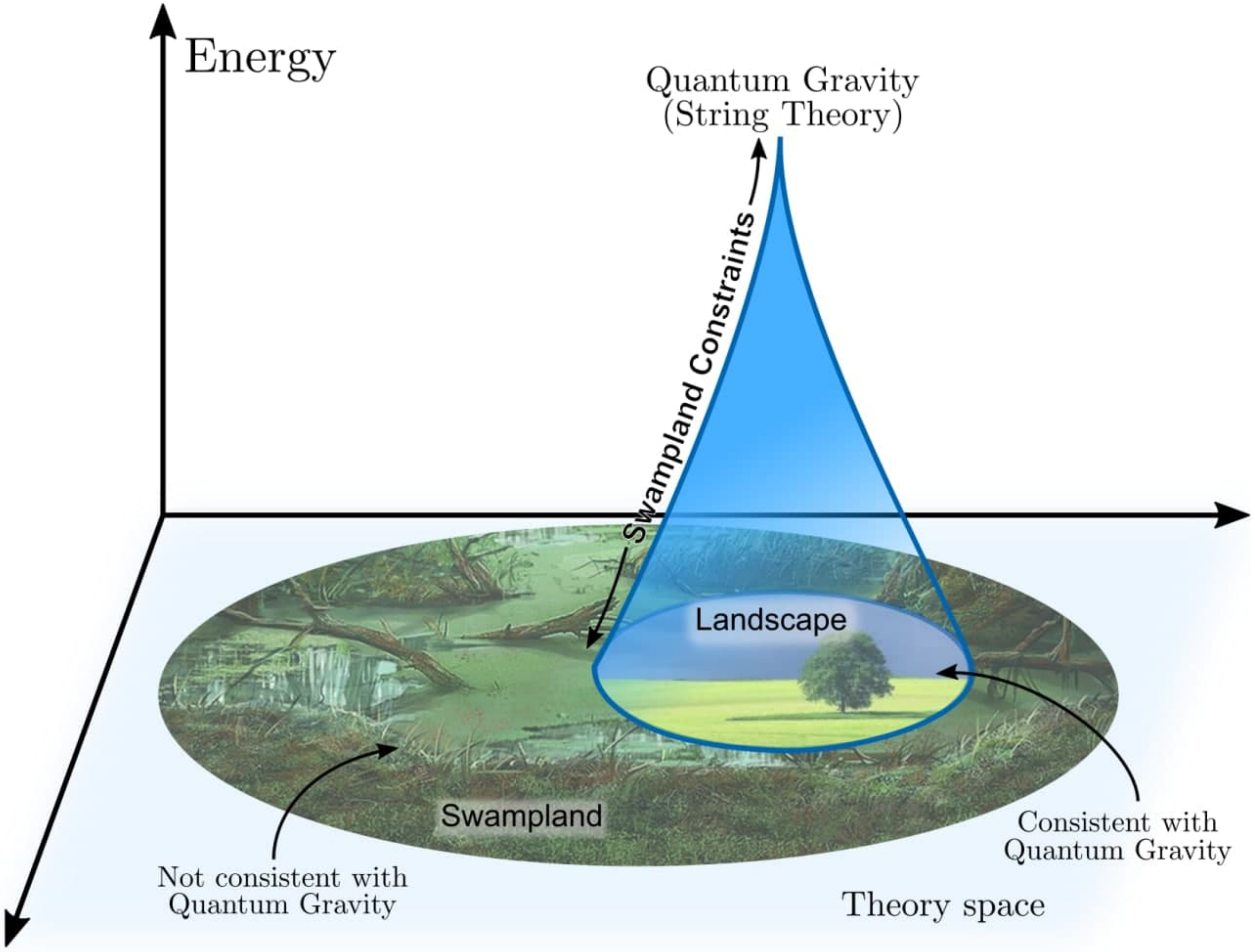

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[Vafa'05]

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Determine the constraints that an EFT must satisfy to be consistent with a UV completion in quantum gravity (QG)

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What can it go here?

What is the quantum gravity cut-off?

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Using:

- String Theory as a theoretical laboratory of QG to extract universal features
- Bottom-up arguments based on black hole physics, holography, scattering amplitudes/bootstrap,…

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Following James Wells' talk again:

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→ not the entire space of parameters is allowed

Let's understand the space of parameters/theories that are UV consistent before concluding that something is 'unnatural'

Maybe this can solve the extrinsic hierarchy problem!

EXPLICIT EXAMPLES

1) Breaking of global symmetries
2) Light scalars and Weak Gravity Conjecture
3) Dynamical parameters and Distance Conjecture
4) Small vacuum energy and dark dimension
5) AdS vacua from SM and neutrino masses

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Global symmetries	Gauged symmetries
B-L in the SM	Electric charge
Continuous scalar shift symmetry	Modular symmetries, dualities
Flavour symmetries	Discrete shift symmetry of a fundamental axion

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Evidence: String Theory + black hole arguments + proof in AdS/CFT

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Immediate consequence:

We cannot invoke the existence of UV global symmetries to avoid undesired higher dimensional operators

EXPLICIT EXAMPLES

1) Breaking global symmetries

But we can get approximate symmetries in the IR

$$S = \int d^4x \left(R + \underbrace{\mathcal{L}_{\mathrm{EFT}}}_{\text{EFT-preserving symmetry}} + \overbrace{\sum_n \frac{\mathcal{O}_{n+4}}{\Lambda^{n-4}_{\mathrm{cut-off}}}}^{\text{operators breaking the symmetry}} \right)$$

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operators breaking the symmetry

EFT-preserving symmetry

We can learn a lot from understanding how symmetries are broken

1) How much are they broken?

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[Daus et al '20] [ongoing ;)]

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- Non-invertible symmetries : broken by quantum effects in gravity

… but only at loop order $L \geq 1$!! [Kaidi,Tachikawa,Zhang '24]

[Heckman,McNamara,Montero,Sharon,Vafa,IV, '24]

EXPLICIT EXAMPLES

1) Breaking global symmetries

2) There can be correlations to ensure all symmetries are broken

$$\mathcal{L} = \phi\, \mathrm{Tr}(F \wedge F) + \dots$$

d=dimension space-time

$j = \mathrm{Tr}(F \wedge F)$ Chern-Weyl current of a (d-5)-form global symmetry which is gauged thanks to the coupling to the axion

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The other linear combinations remain as global symmetries and must be broken by quantum gravity consistency

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Can this ameliorate the QCD axion quality problem?

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2) Light scalars, weak couplings and the Weak Gravity Conjecture

Weak Gravity Conjecture: [Arkani-Hamed et al'06]

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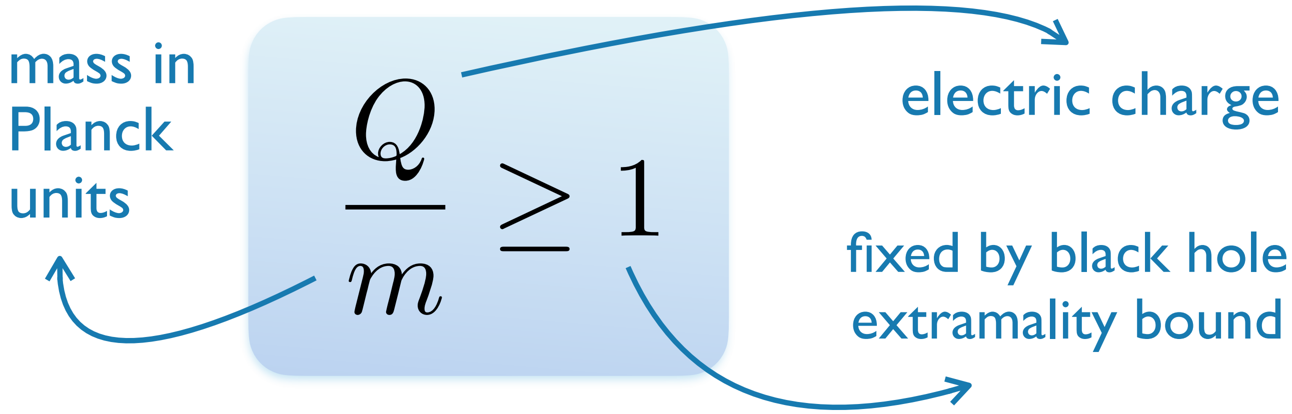
Given an EFT with a long-range gauge interaction and gravity, there must exist a particle satisfying:



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

mass in Planck units

electric charge

fixed by black hole extramality bound

so that the gravitational force acts weaker than the gauge force

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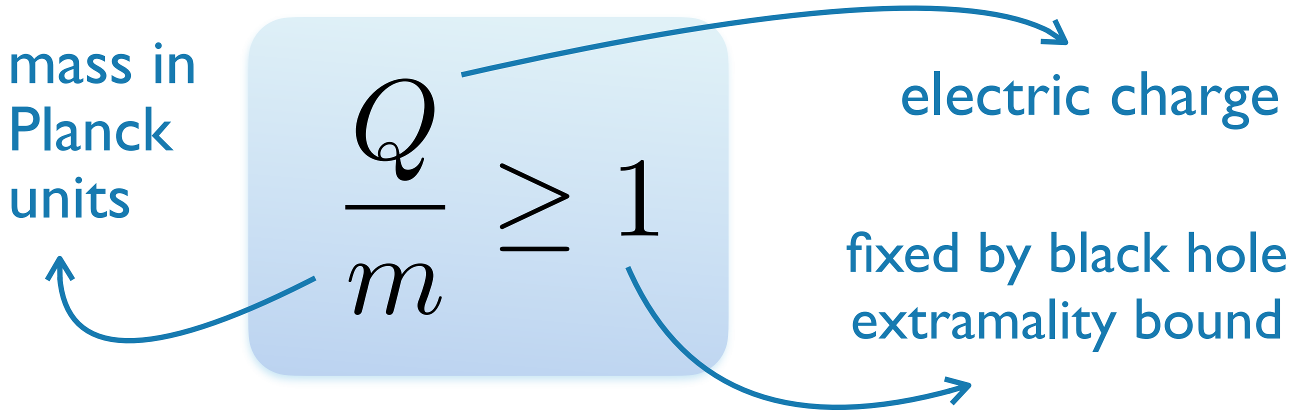

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Satisfied by the electron in the SM, but puts constraints on BSM with weakly coupled dark photons

Moreover, the EFT breaks down at $\boxed{\Lambda_{\mathrm{cut-off}} \sim g M_p}$ (from applying WGC to magnetic gauge field)

2) Light scalars, weak couplings and the Weak Gravity Conjecture

Is this “natural” for a scalar? $Q \geq m$

quadratic divergences

logarithmic running (recall $Q = qg$)

How is this satisfied in explicit string theory examples?

- At weak coupling $(g \ll 1)$ there is a tower of infinitely many particles satisfying WGC → changes scaling of quantum corrections [Grimm, Palti, IV’18] [Heidenreich et al’18]

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$$\frac{1}{g_{IR}^2} = \frac{1}{g_{UV}^2} - \sum_k^N \left(\frac{8q_k^2}{3\pi^2}\log\frac{\Lambda_{UV}}{m_k}\right) \left\{ \begin{array}{l} (\delta g)^{-2} \sim N \log m_0 \\ (\delta g)^2 \sim m^2 \end{array} \right.$$

$(\delta g)^{-2} \sim N \log m_0$ for N fields (logarithmic running)

$(\delta g)^2 \sim m^2$ for infinite tower $m_k = k\, m$ (power law!) $k = 0, 1, \ldots, \infty$

consistent with $Q \geq m$ across the RG flow

using $\Lambda_{UV} = \frac{M_p}{\sqrt{N}}$ (species scale) [Dvali'07]

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- For $g \sim \mathcal{O}(1)$ we can have just a few WGC-states, but examples under control are typically supersymmetric

Open question whether they can be scalars with $m < \Lambda_{UV}$

EXPLICIT EXAMPLES

3) Dynamical parameters and Distance Conjecture

Every continuous parameter is dynamical:
it is set by the vacuum expectation value of scalar fields

$m(\phi), g(\phi)\ldots$

parametrize size/form extra dimensions in string theory

Universal lesson from string theory, also necessary to avoid (-1)-form global symmetries

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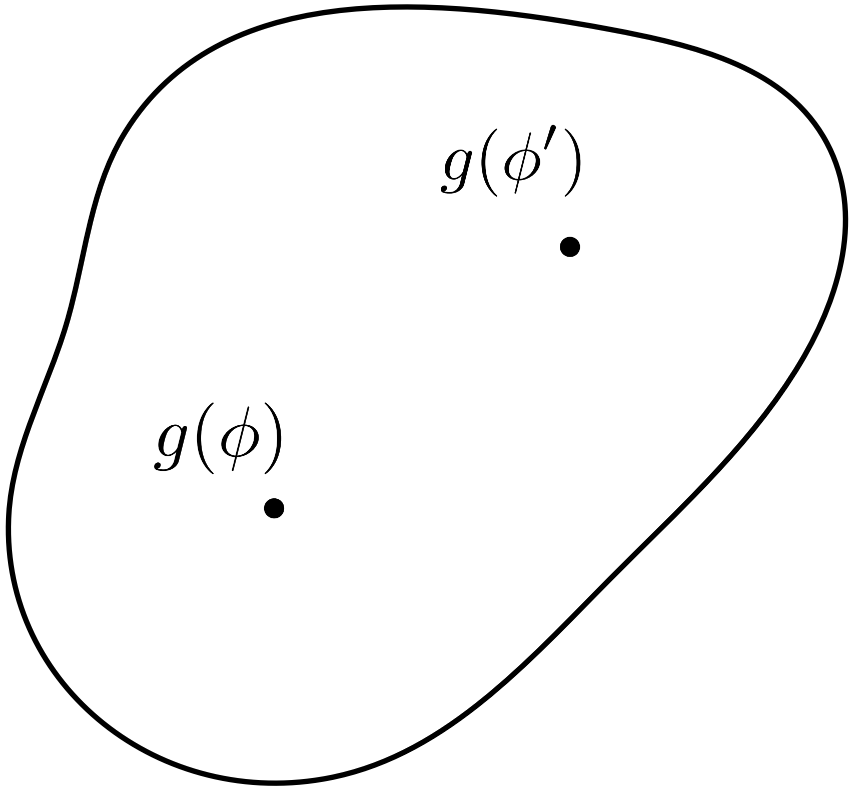

parameter space of the EFT
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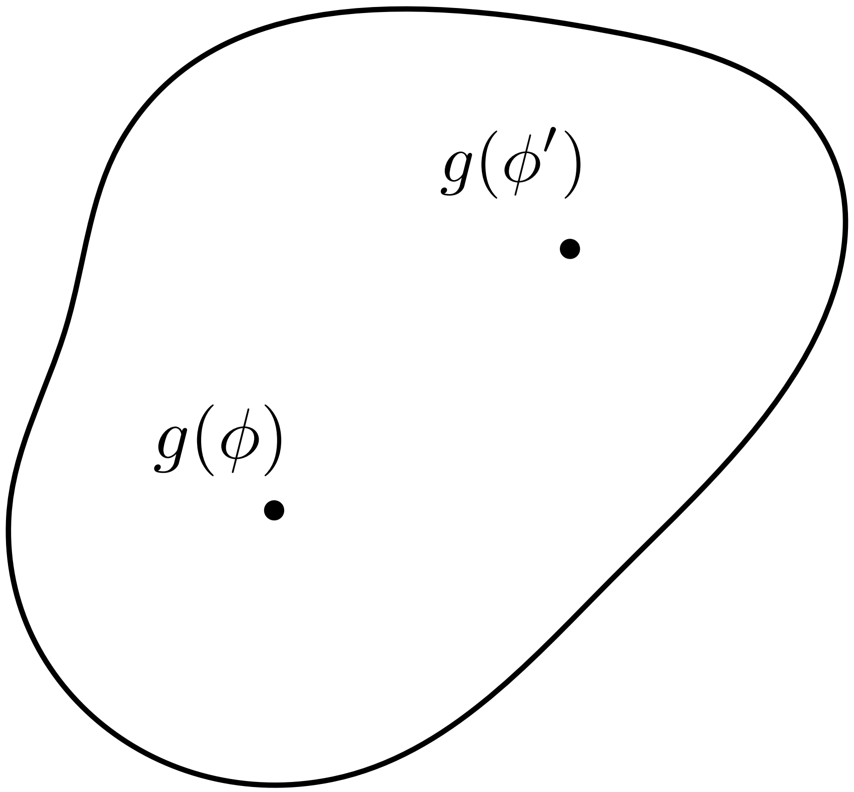
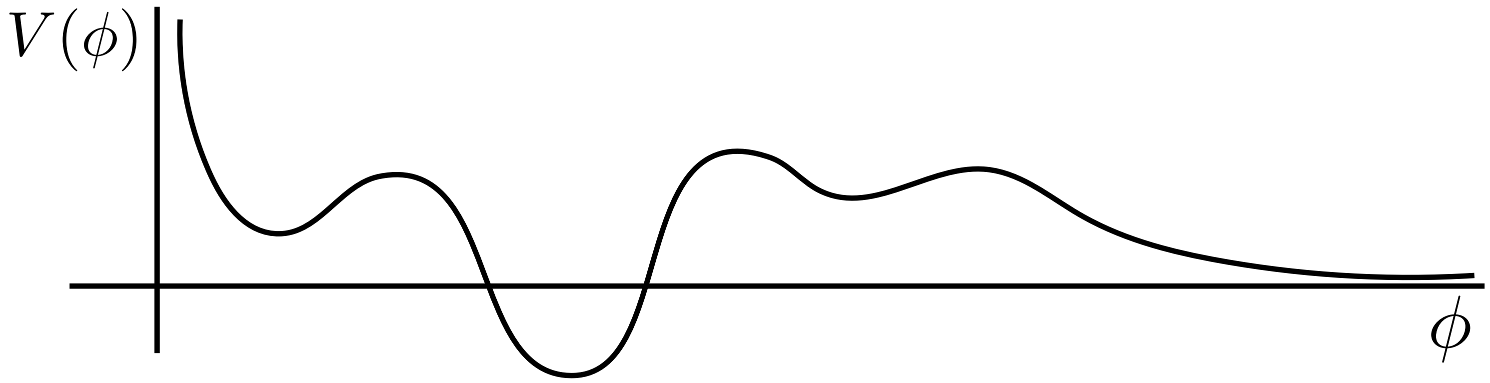


Big challenge!

parameter space of the EFT
=
scalar field space of string theory

Naturalness issues get translated to finding a dynamical mechanism that stabilizes the scalars precisely at the values required to reproduce observations



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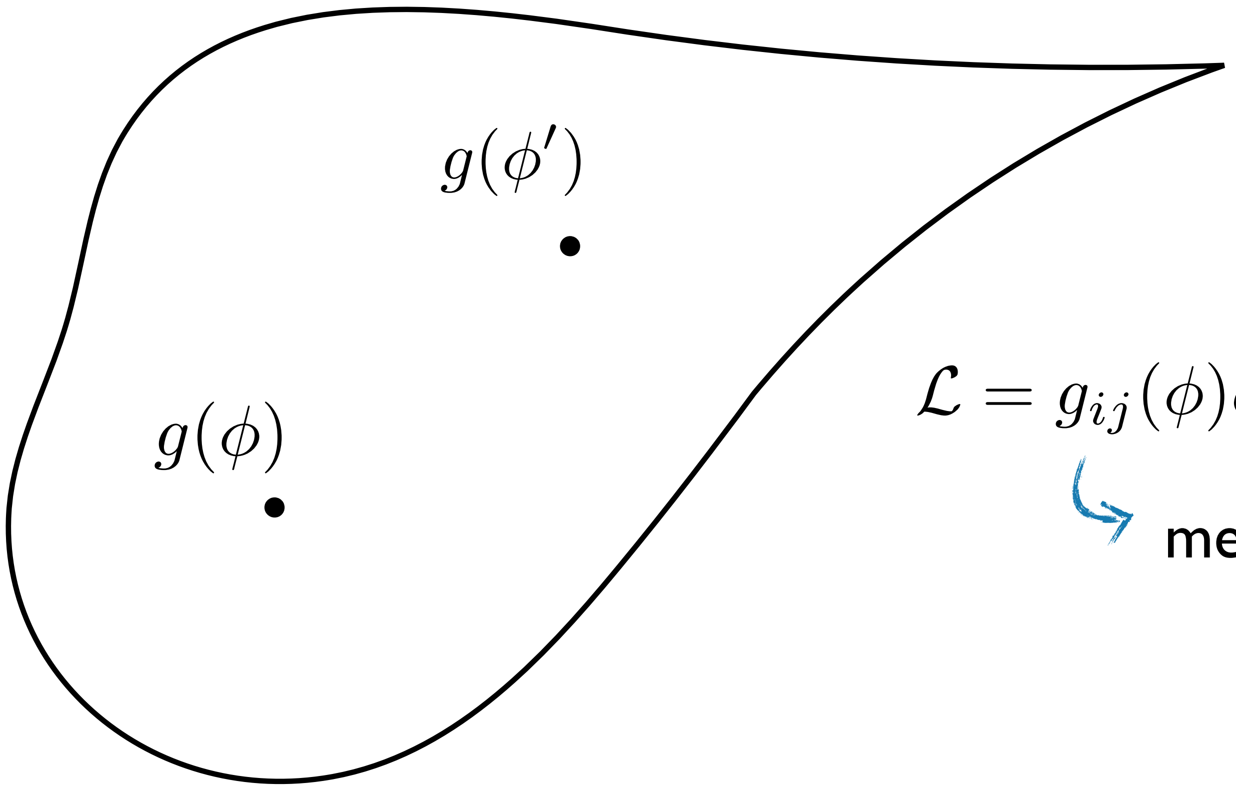
Global symmetries, vanishing couplings or large hierarchies occur at infinite distance in this field space



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

metric in the field space

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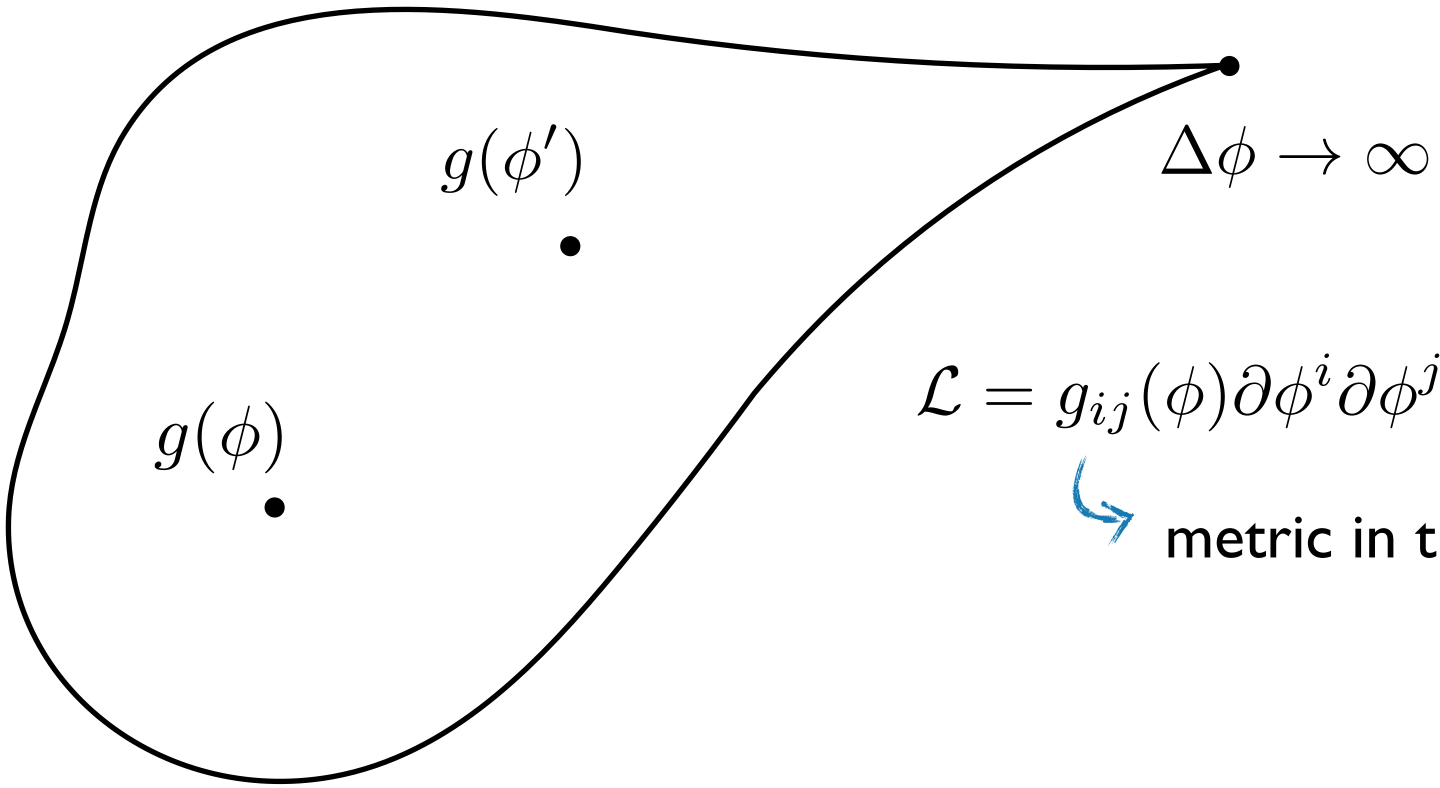

$$\mathcal{L} = g_{ij}(\phi)\partial\phi^i\partial\phi^j \qquad \Delta\phi = \int \sqrt{g_{ij}d\phi^i d\phi^j}$$

↳ metric in the field space

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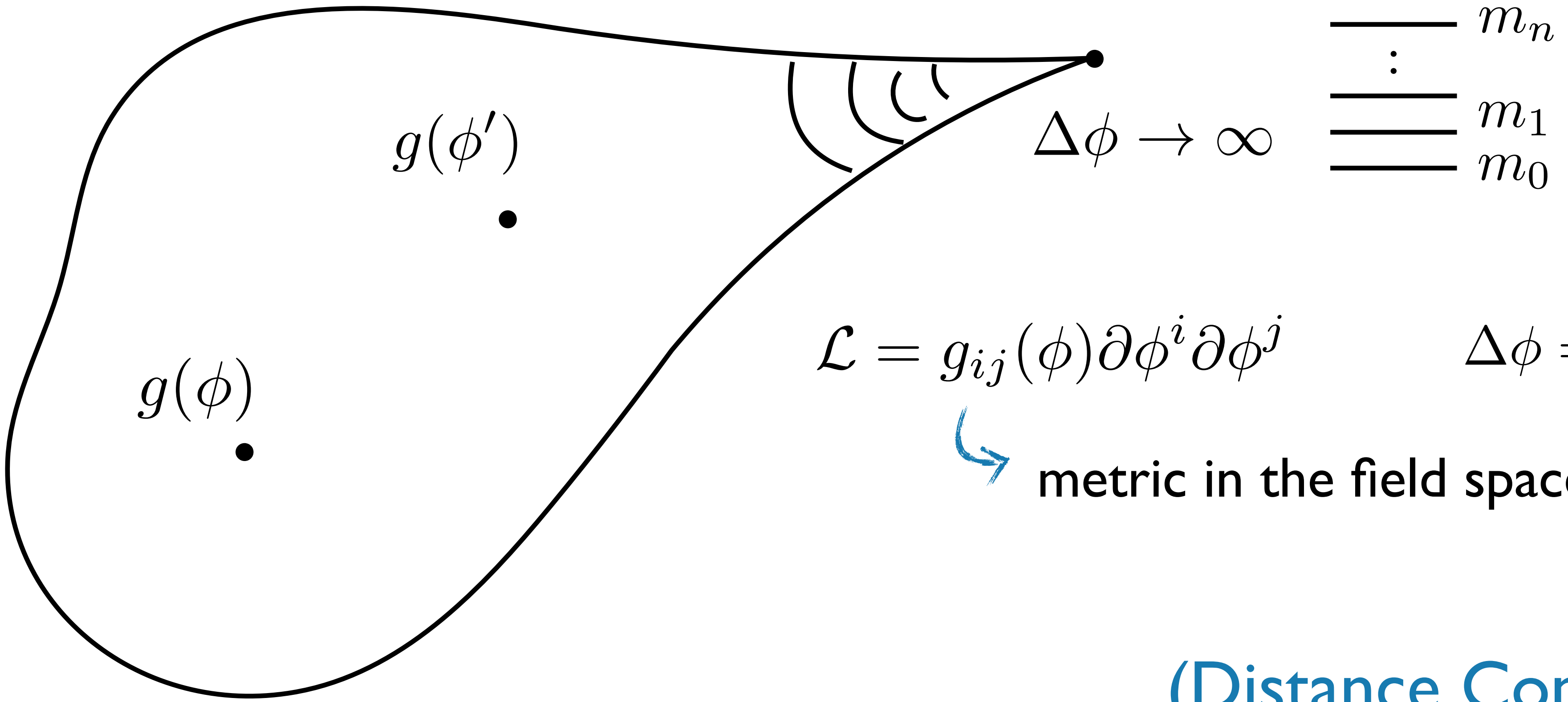
Universal features:

Global symmetries, vanishing couplings or large hierarchies occur at infinite distance in this field space



$$\mathcal{L} = g_{ij}(\phi)\partial\phi^i\partial\phi^j \qquad \Delta\phi = \int \sqrt{g_{ij}d\phi^i d\phi^j}$$

↳ metric in the field space

(Distance Conjecture)

There is an infinite tower of states becoming exponentially light at every infinite field distance limit [Ooguri-Vafa'06]

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

EXPLICIT EXAMPLES

3) Dynamical parameters and Distance Conjecture

In all string theory models that are known, the tower is (in some duality frame) either a: [Lee,Lerche,Weigand'19]

- Kaluza-Klein tower ➡ decompactification of extra dimensions
- Oscillator modes of a string ➡ perturbative string limit

EXPLICIT EXAMPLES

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- Oscillator modes of a string → perturbative string limit

Example: One large extra dimension (from (d+1)- to d-dimensions)

KK tower: $m_{\mathrm{KK}} = \frac{M_{\mathrm{pl},d+1}}{r} = M_{\mathrm{pl},d} \exp(-\sqrt{\frac{d-1}{d-2}}\Delta\phi)$

$$S = \frac{M_{\mathrm{pl},d}^{d-2}}{2}\int d^d x \left(R - \frac{1}{2}\sqrt{\frac{d-1}{d-2}}\frac{(\partial r)^2}{r^2} + \dots\right) = \frac{M_{\mathrm{pl},d}^{d-2}}{2}\int d^d x \left(R - \frac{1}{2}(\partial\phi)^2 + \dots\right)$$

As $r \to \infty$ KK tower becomes exponentially light in terms of canonically normalised radius

EXPLICIT EXAMPLES

3) Dynamical parameters and Distance Conjecture

Take-home message:

Quantum gravity consistency requires this behaviour of Kaluza-Klein theory to be generic whenever any scalar field vev gets large

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

depends on nature of the tower

$$\frac{1}{\sqrt{2}} \leq \alpha \leq \sqrt{\frac{3}{2}} \quad \text{in 4d}$$

[Etheredge et al'22]

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[Etheredge et al'22]

QFT breaks down at a cut-off scale known as the species scale Λ [Dvali'07]

If KK tower: $\Lambda = M_{\rm pl,D} \ll M_{\rm pl,d}$

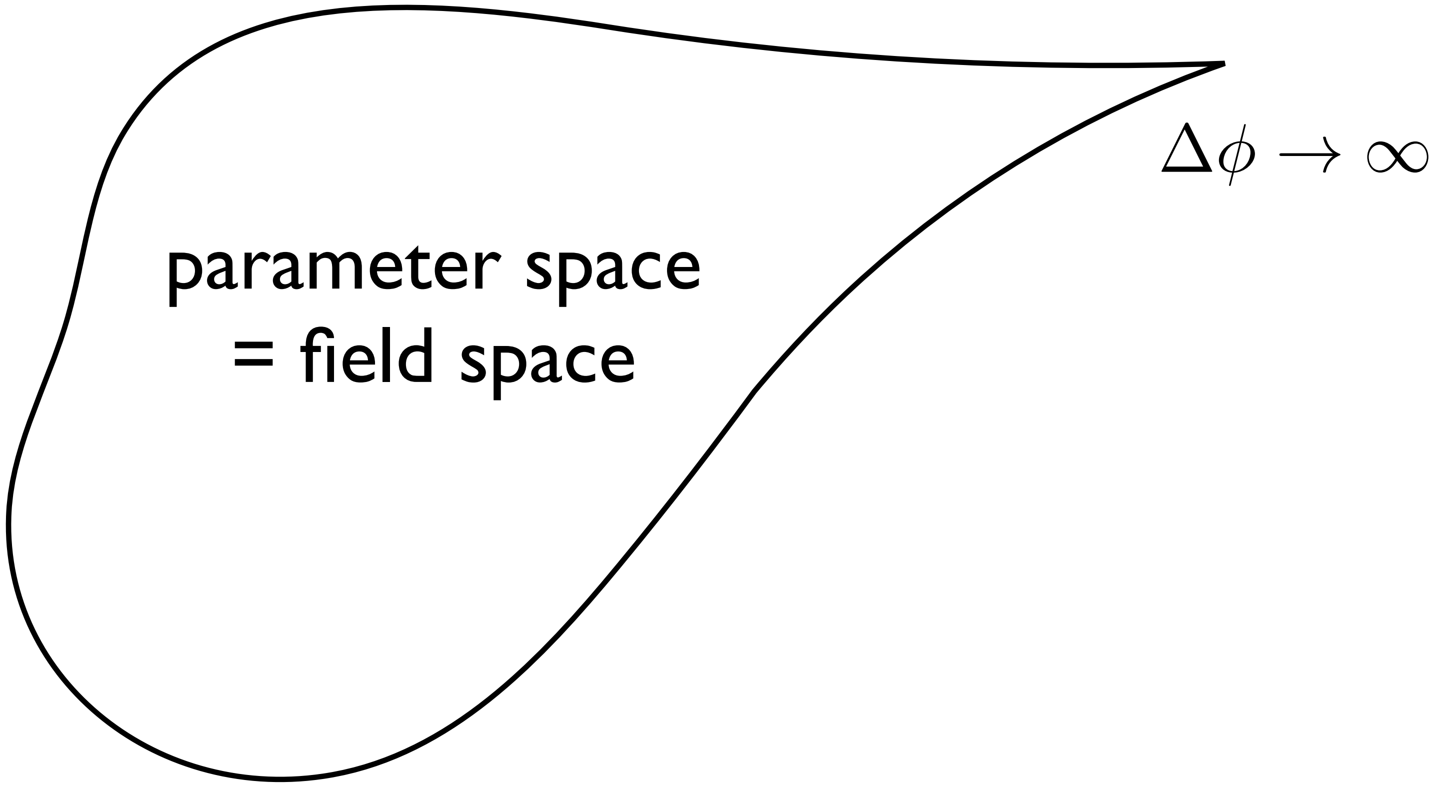
If string tower: $\Lambda \simeq M_{\rm str} \ll M_{\rm pl,d}$

$$\frac{\vec{\nabla} m}{m} \cdot \frac{\vec{\nabla}\Lambda}{\Lambda} = \frac{1}{2}$$

[Castellano,Ruiz,IV'23]

EXPLICIT EXAMPLES

3) Dynamical parameters and Distance Conjecture



EXPLICIT EXAMPLES

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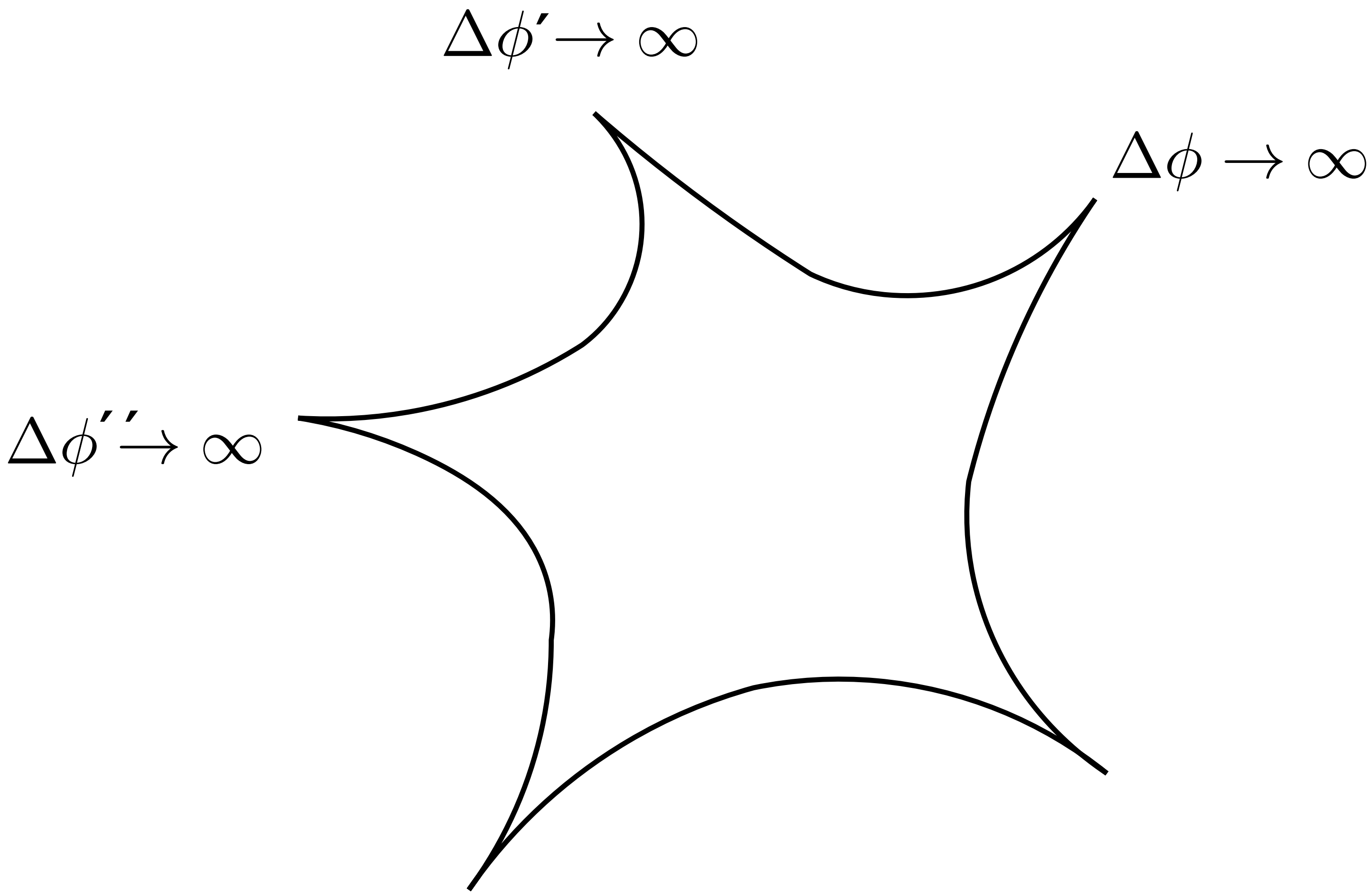
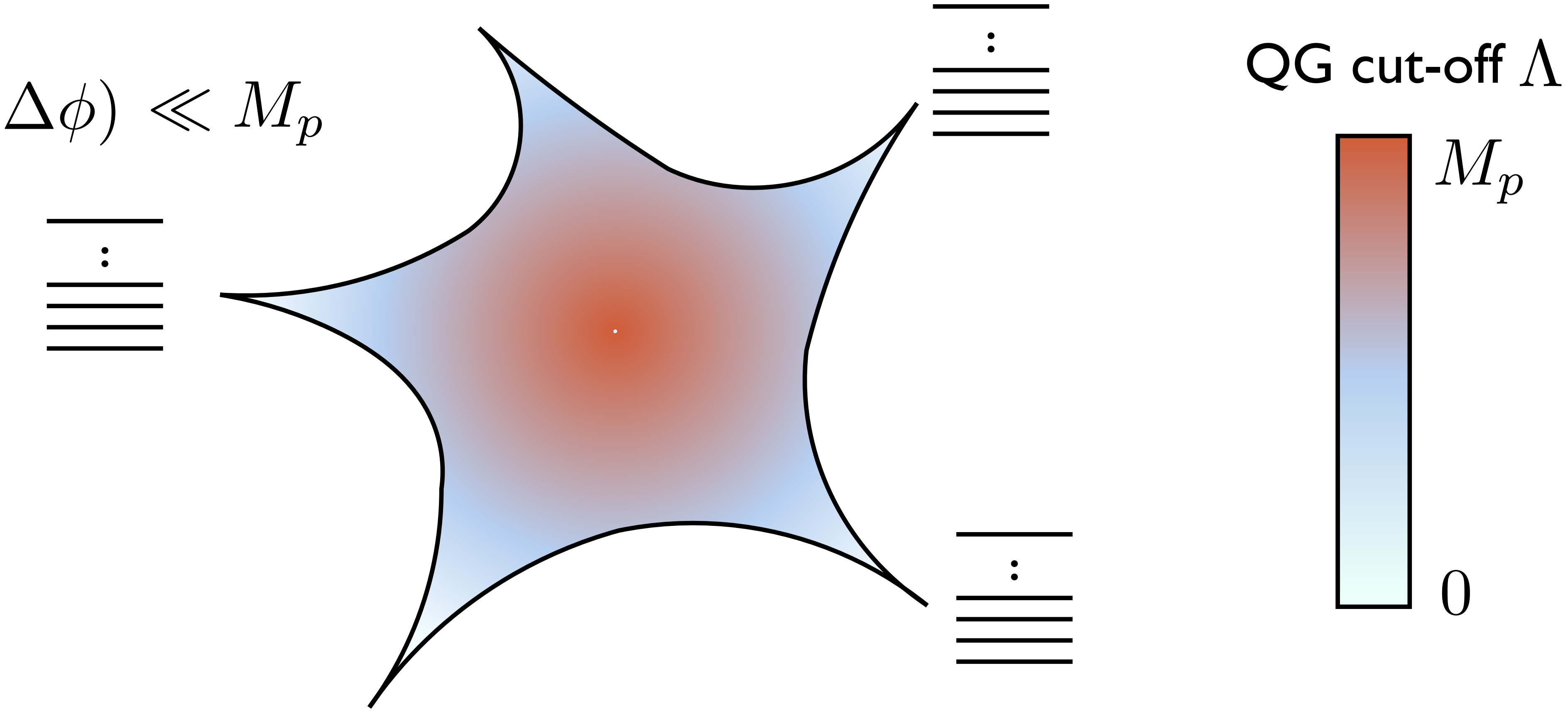


3) Dynamical parameters and Distance Conjecture

The cut-off Λ is field dependent and becomes parametrically smaller than M_p at the infinite field distance boundaries

$$\Lambda \sim M_p \exp(-\lambda\Delta\phi) \ll M_p$$



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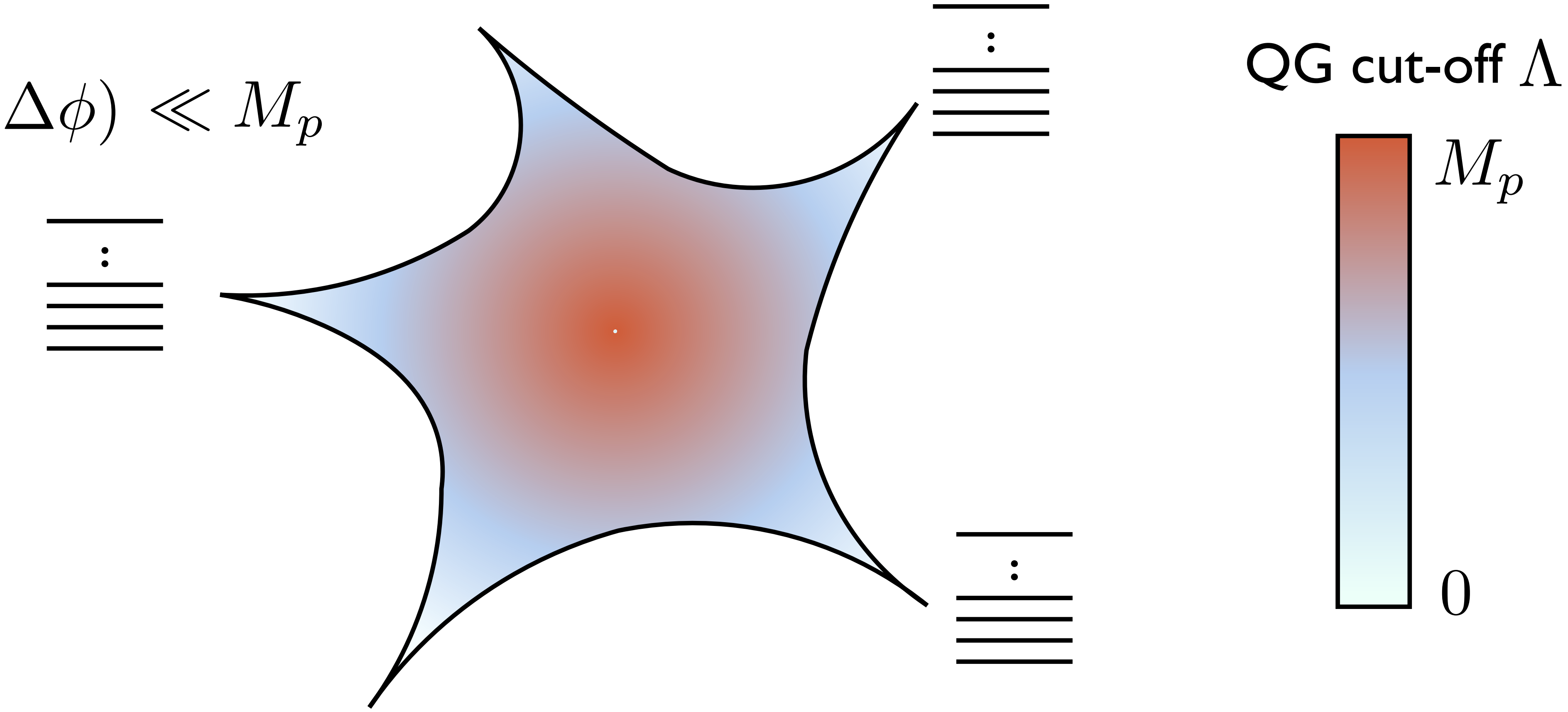

$$S = \int d^4x \left(R + \mathcal{L}_{\rm EFT}[g(\phi), m(\phi), \ldots] + \sum_n \frac{\mathcal{O}_{n+4}}{\Lambda^{n-4}(\phi)} \right)$$

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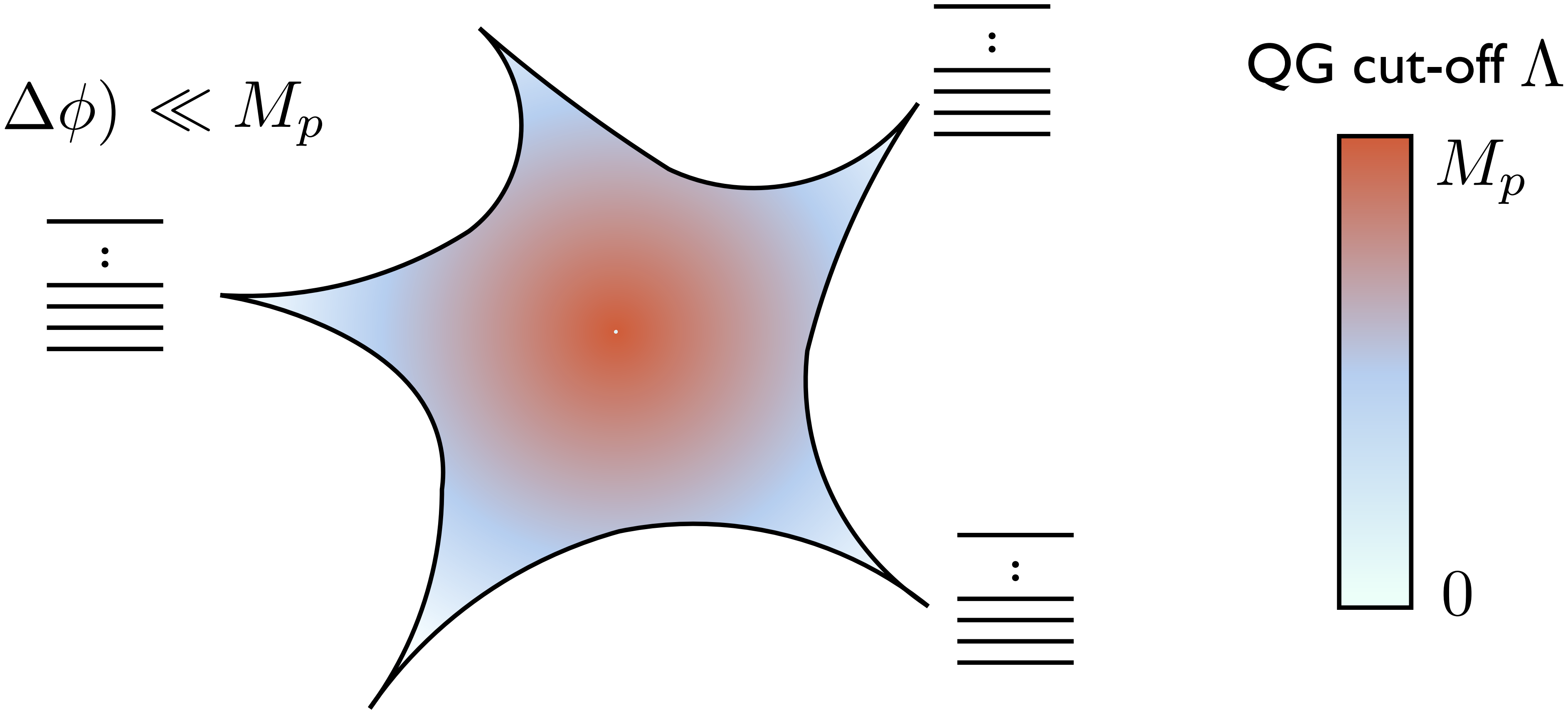
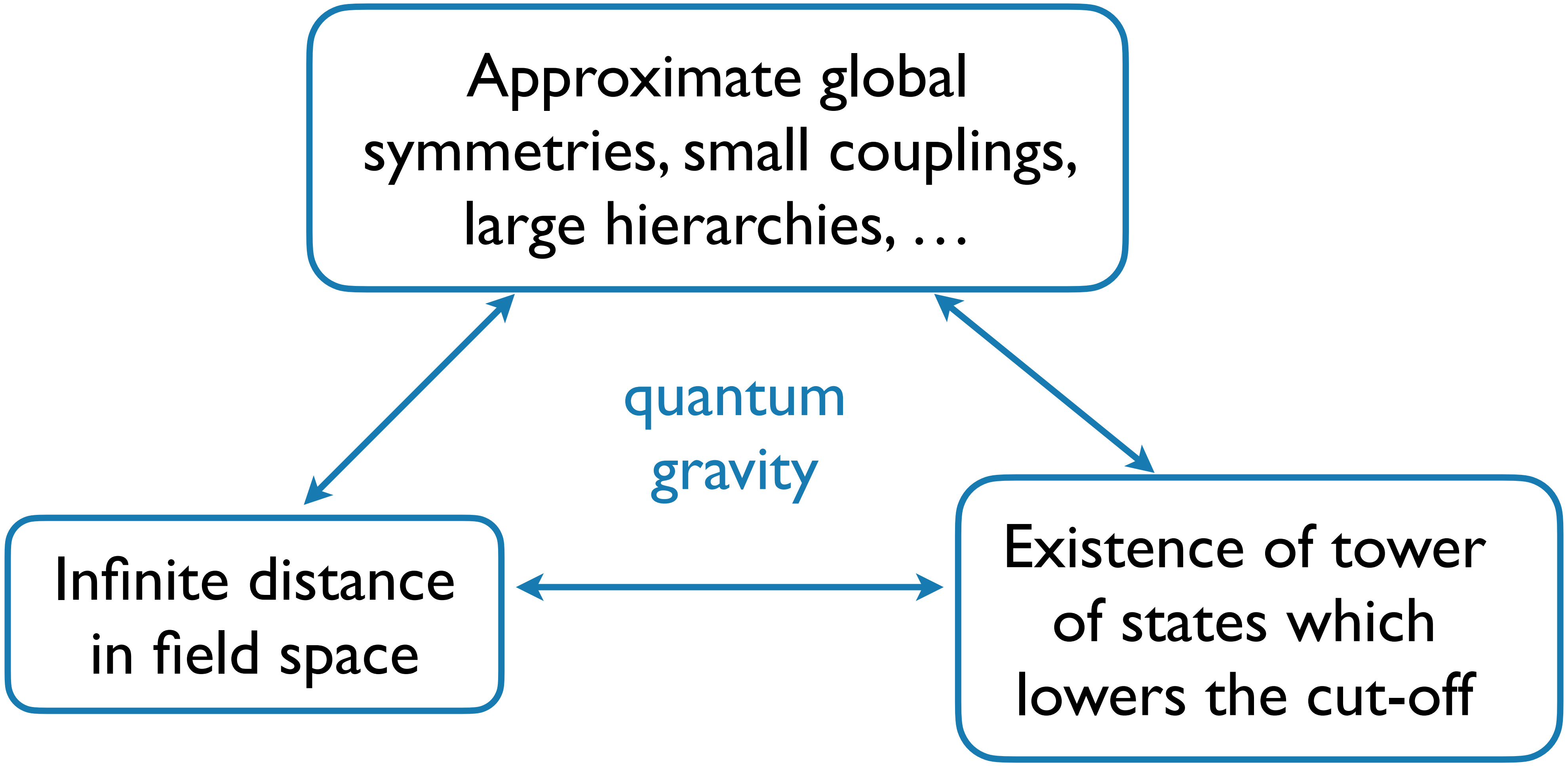


$$S = \int d^4x \left(R + \mathcal{L}_{\text{EFT}}[g(\phi), m(\phi), \dots] + \sum_n \frac{\mathcal{O}_{n+4}}{\Lambda^{n-4}(\phi)} \right)$$

given this

we can determine this (sometimes)

3) Dynamical parameters and Distance Conjecture



Approximate global symmetries, small couplings, large hierarchies, …

quantum gravity

Infinite distance in field space

Existence of tower of states which lowers the cut-off

EXPLICIT EXAMPLES

3) Dynamical parameters and Distance Conjecture

Implications:

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1) Bound on the maximum scalar field range that can be accommodated in a given EFT as a function of the Quantum Gravity cut-off

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

Constraints on large field inflation, cosmological relaxation, …

[Ibanez et al'15] [Scalisi,IV18] , …

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Constraints on large field inflation, cosmological relaxation, …

[Ibanez et al'15] [Scalisi,IV18] , …

2) Bound on how small gauge couplings can be $\Lambda \lesssim g^k M_p$ $\quad 1/3 \leq k \leq 1$

Constraints on weakly coupled dark photons, Stuckelberg couplings, …

[Reece'18] [Montero,Muñoz,Obied'22] , …

EXPLICIT EXAMPLES

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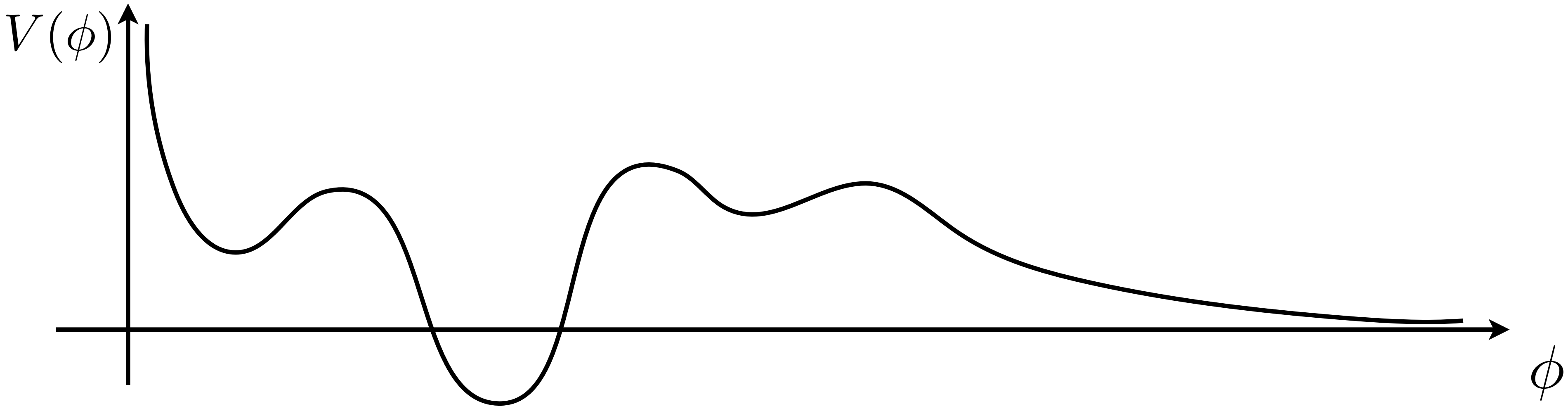
Vacuum energy (if positive an below Λ) vanishes asymptotically (at infinite field distance)



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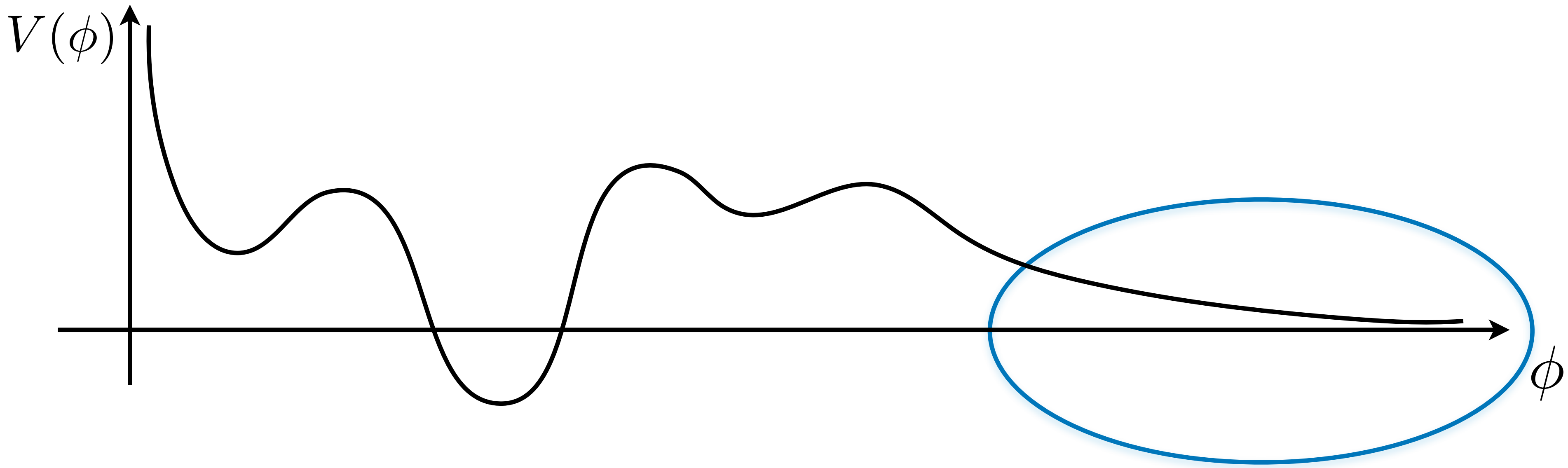

how come? it looks "unnatural"

string theory contains infinitely many massive states!

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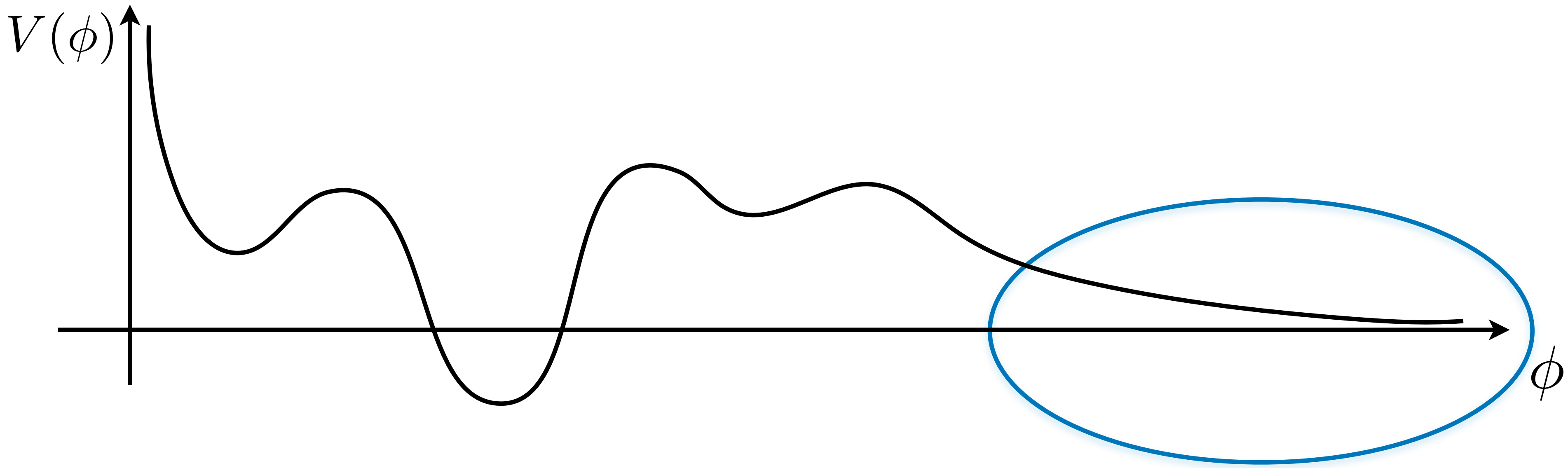

how come? it looks "unnatural"

regardless of supersymmetry

string theory contains infinitely many massive states!

Asymmptotically (at parametrically late times) the universe becomes nearly flat (Minkowski)

[Obied et al'18] [Dvali's work]

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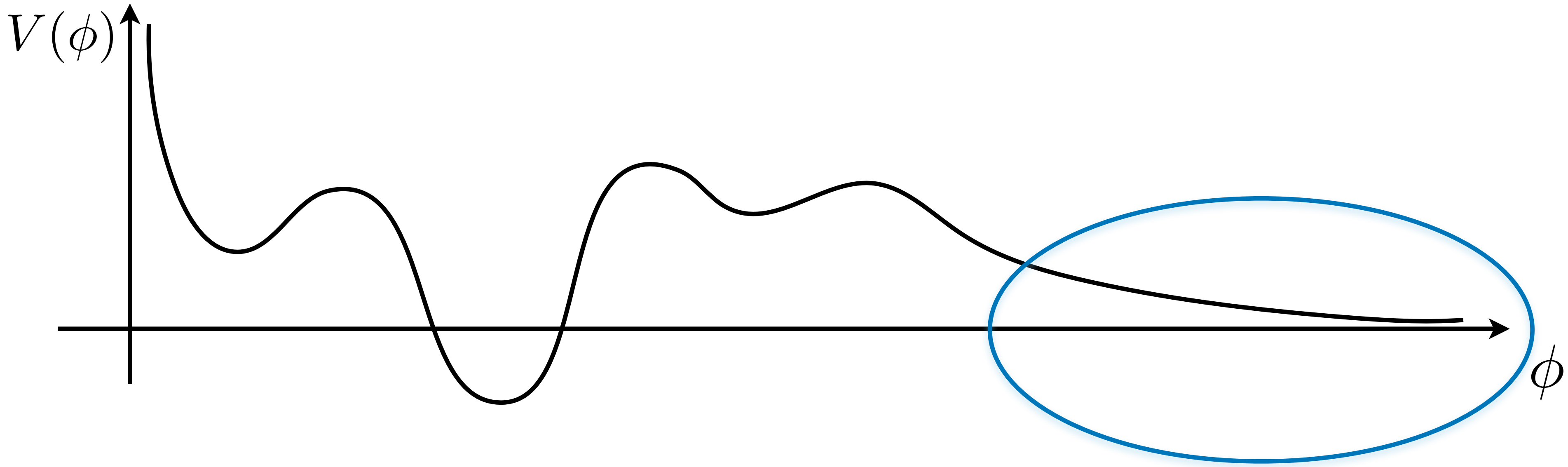

how come? it looks “unnatural”

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string theory contains infinitely many massive states!

e.g. Non-SUSY heterotic string theory $V = \cancel{V_{\text{tree}}} + V_{\text{one loop}} + \dots$

0

$\sim \exp(-\gamma\phi)$

(conformal invariance of the string worldsheet)

(“Casimir energy” of string states)

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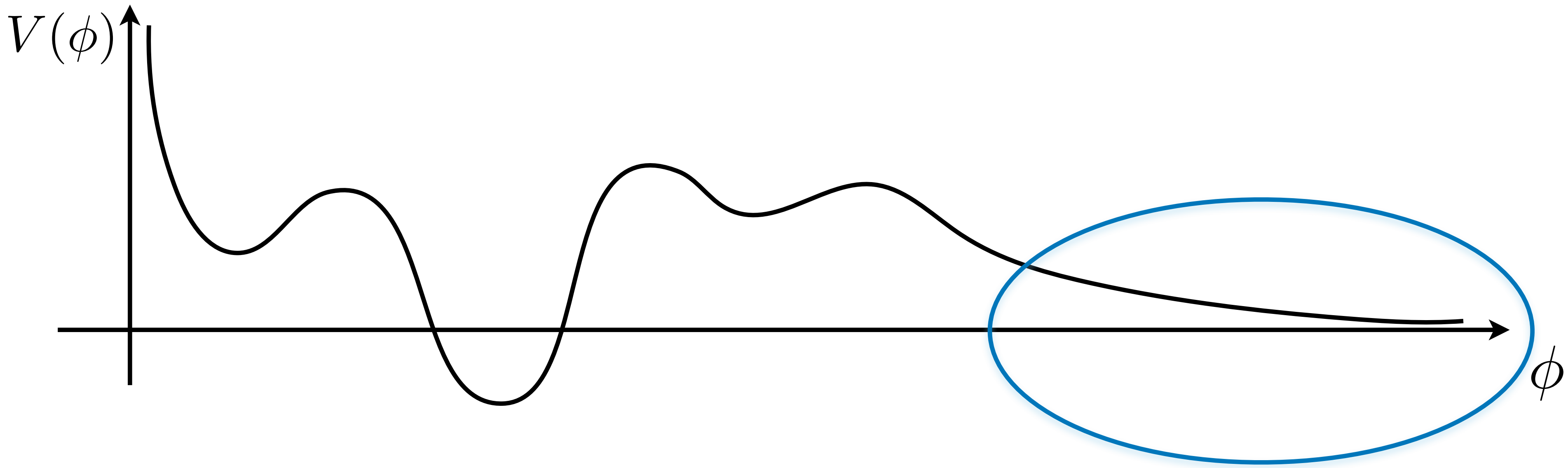

how come? it looks "unnatural"

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string theory contains infinitely many massive states!

It is crucial to integrate out the infinite towers of states to obtain a finite result that it is smaller than expected if you only considered quantum corrections form a finite number of fields

[see Steven's talk]

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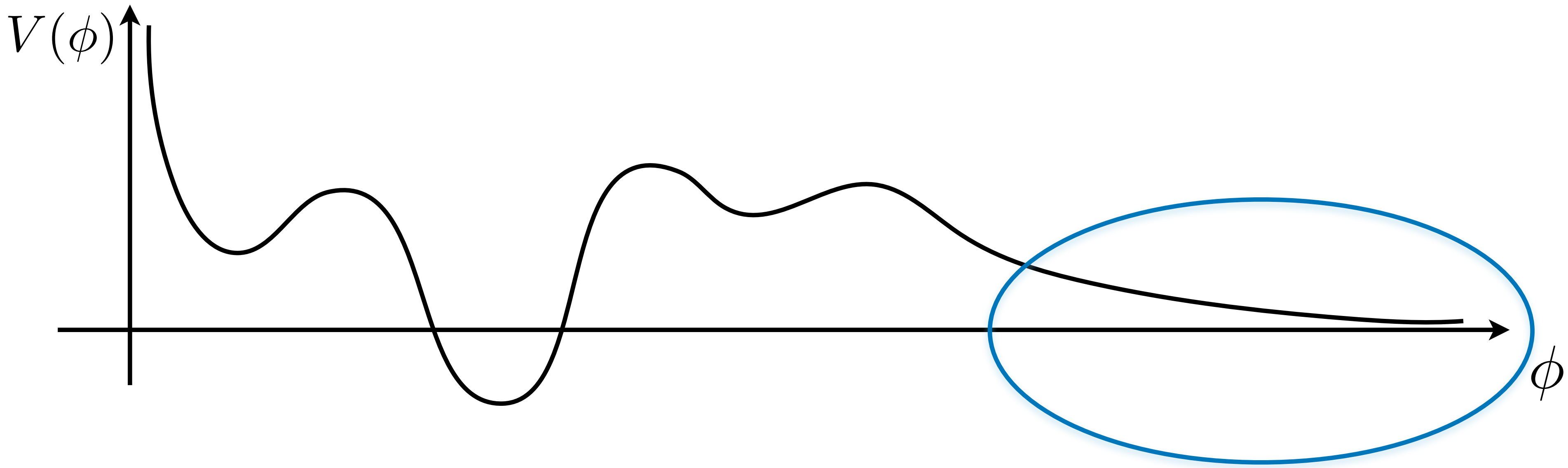

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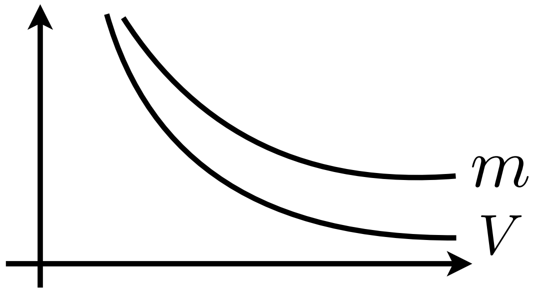
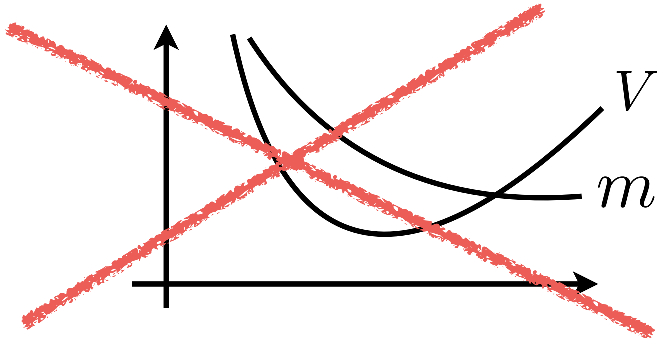
string theory contains infinitely many massive states!

This is a universal result in string theory and can also be motivated by the Swampland Distance conjecture (i.e. the existence of the tower of states)





[Ooguri et al'18]
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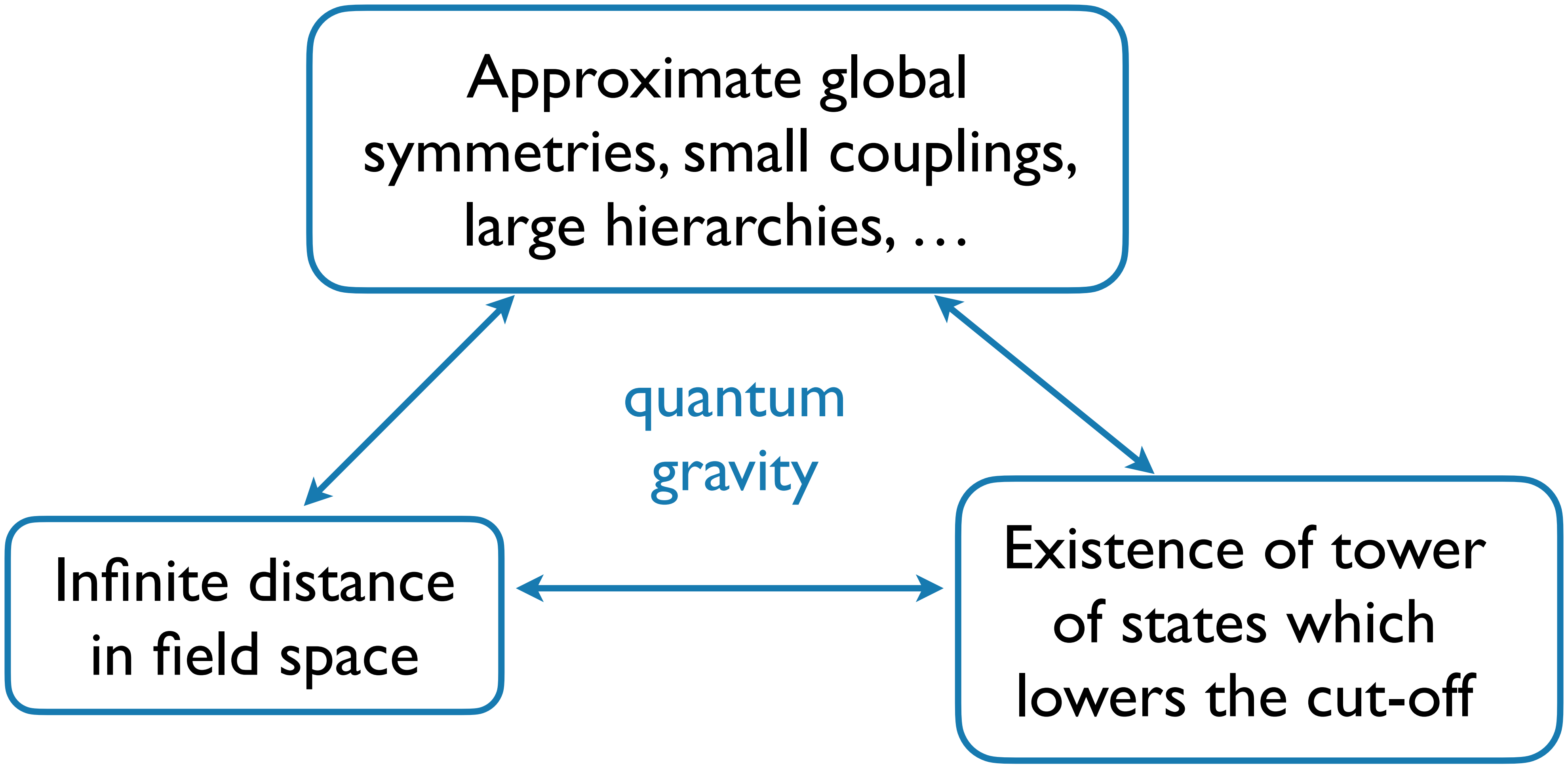

Approximate global symmetries, small couplings, large hierarchies, …

quantum gravity

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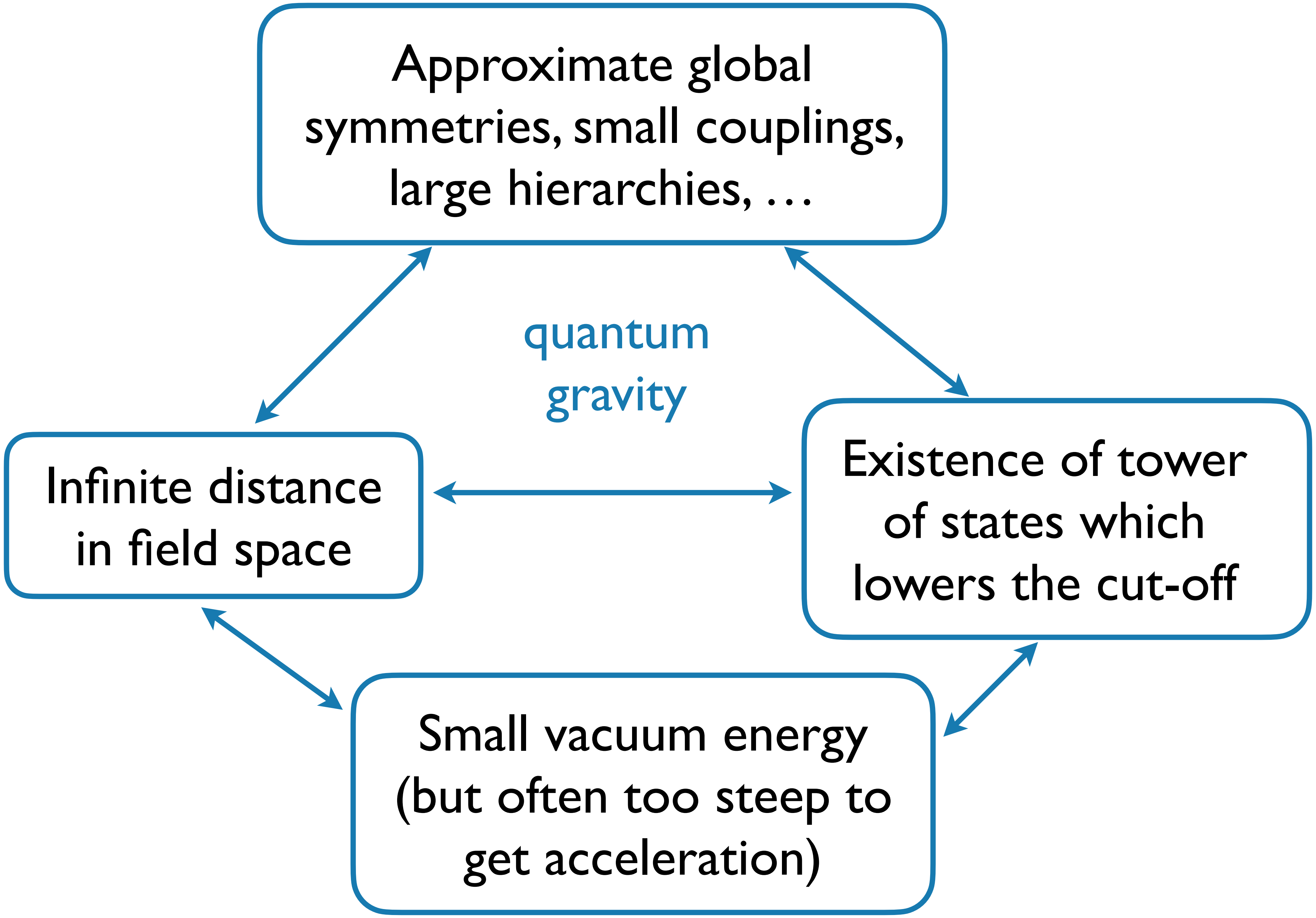

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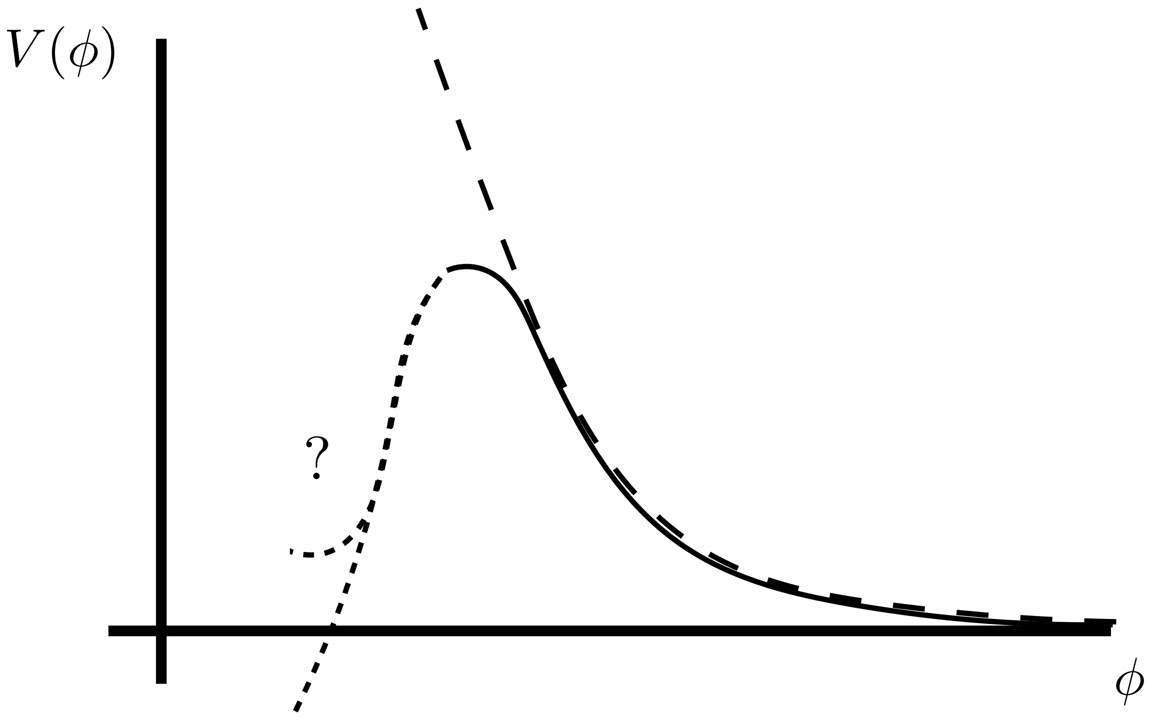
Small vacuum energy (but often too steep to get acceleration)

EXPLICIT EXAMPLES

4) Small vacuum energy and dark dimension

Could it be that the dark energy (vacuum energy) in our universe is small



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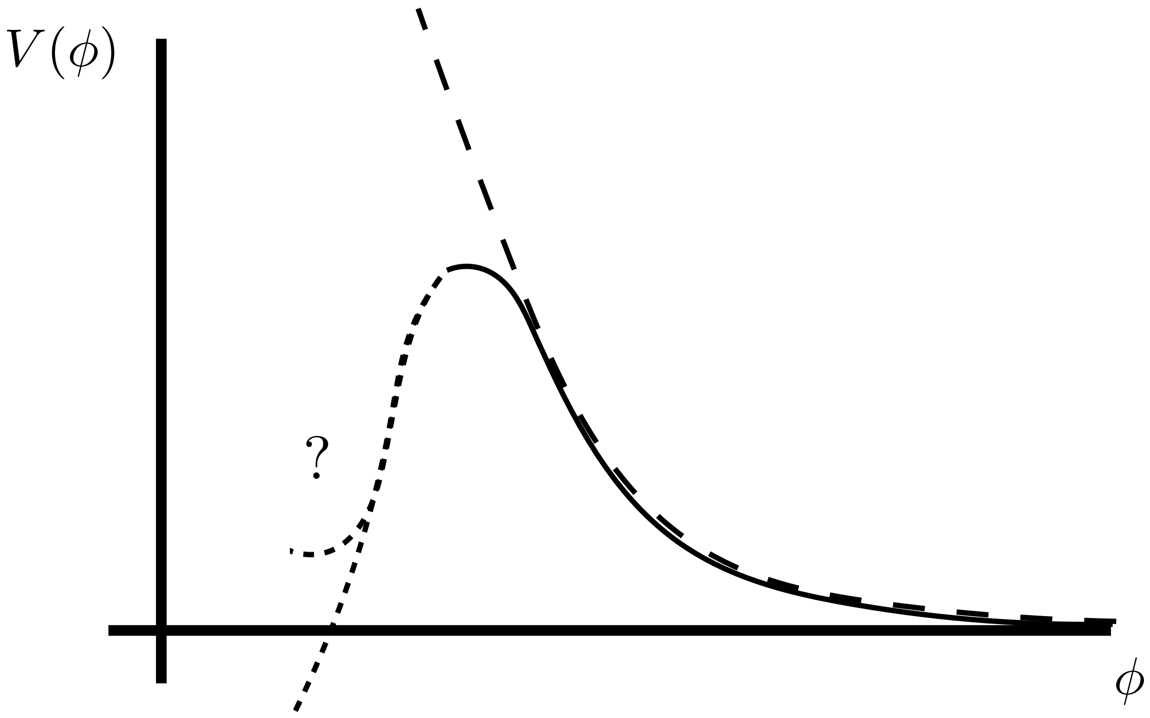

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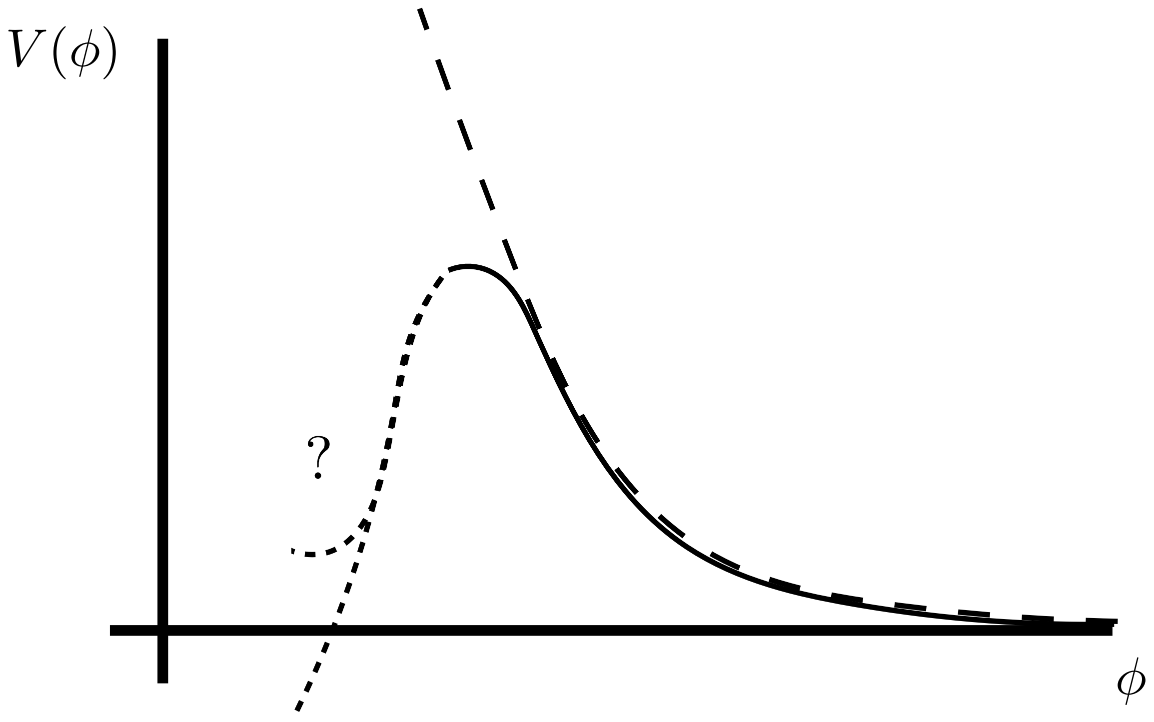

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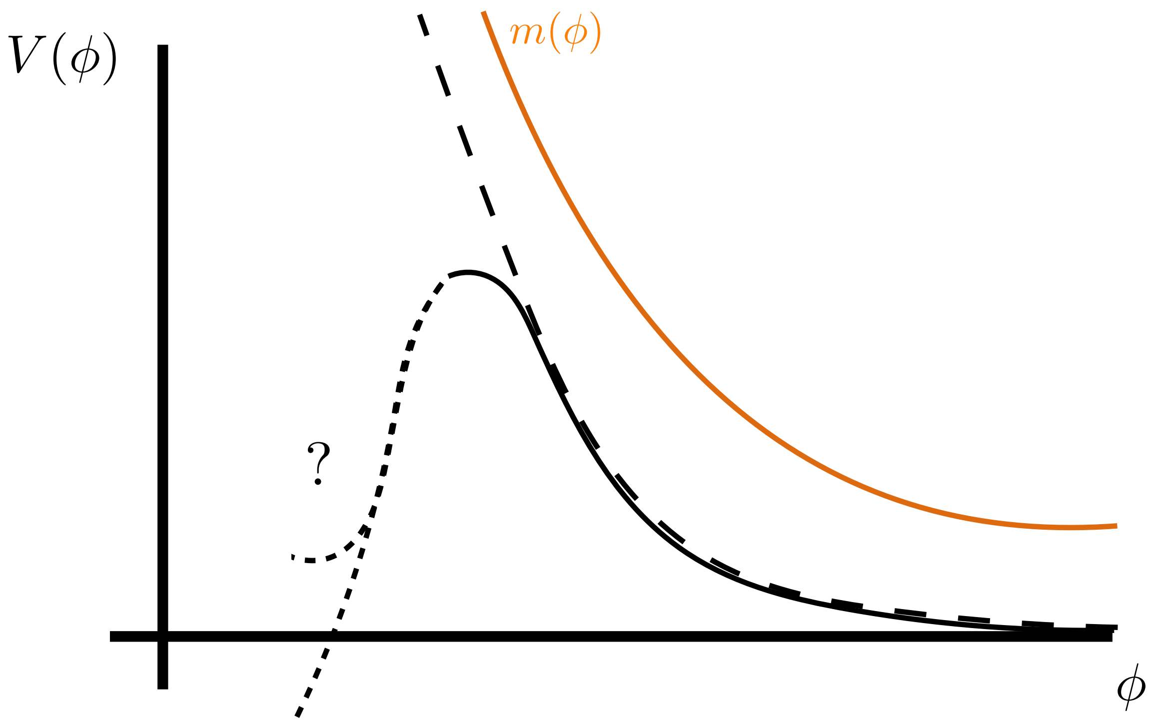
If so, one thing is clear: There should be a tower of states becoming light



4) Small vacuum energy and dark dimension

Combining:

Theoretical bounds

$$V^{1/2} \lesssim m \lesssim V^{1/4}$$

Higuchi bound

no fine-tuning of quantum corrections

+

Experimental bounds on deviations of Newton's law and astrophysical bounds

4) Small vacuum energy and dark dimension

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The first state of the tower should have a mass:

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

→ neutrino scale!

Tower of right handed neutrinos?

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Tower of right handed neutrinos?

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

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

currently testing it in New ISLE at the Conrad Observatory

[Aspelmeyer,Adelberger, Shayeghi,Zito…]

5) AdS SM vacua and neutrino masses

There is another instance in which a tower with $m_{\text{tower}} \sim \Lambda_{cc}^{1/4}$ seems necessary to comply with Swampland constraints

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Take Standard Model + gravity and compactify to 3d on a circle:

graviton, photon

massive particles: neutrinos,…

$$V(R) = \frac{2\pi\Lambda_4}{R^2} - \frac{4}{720\pi R^6} + \sum_i \frac{(2\pi R)}{R^3}(-1)^{s_i} n_i \rho_i(R)$$

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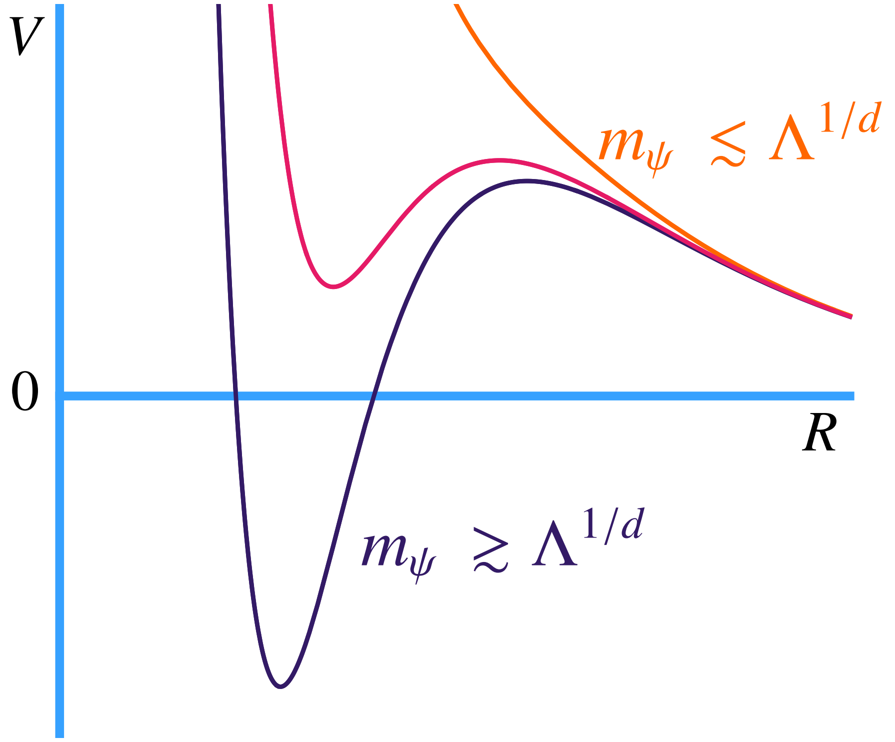

Depending on the value of Dirac neutrino masses, we get 3-dimensional AdS, Minkowski or dS vacua.

[Arkani-Hamed et al'07]

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[Martin-Lozano,Ibanez,IV'17] [Gonzalo et al'18-21]

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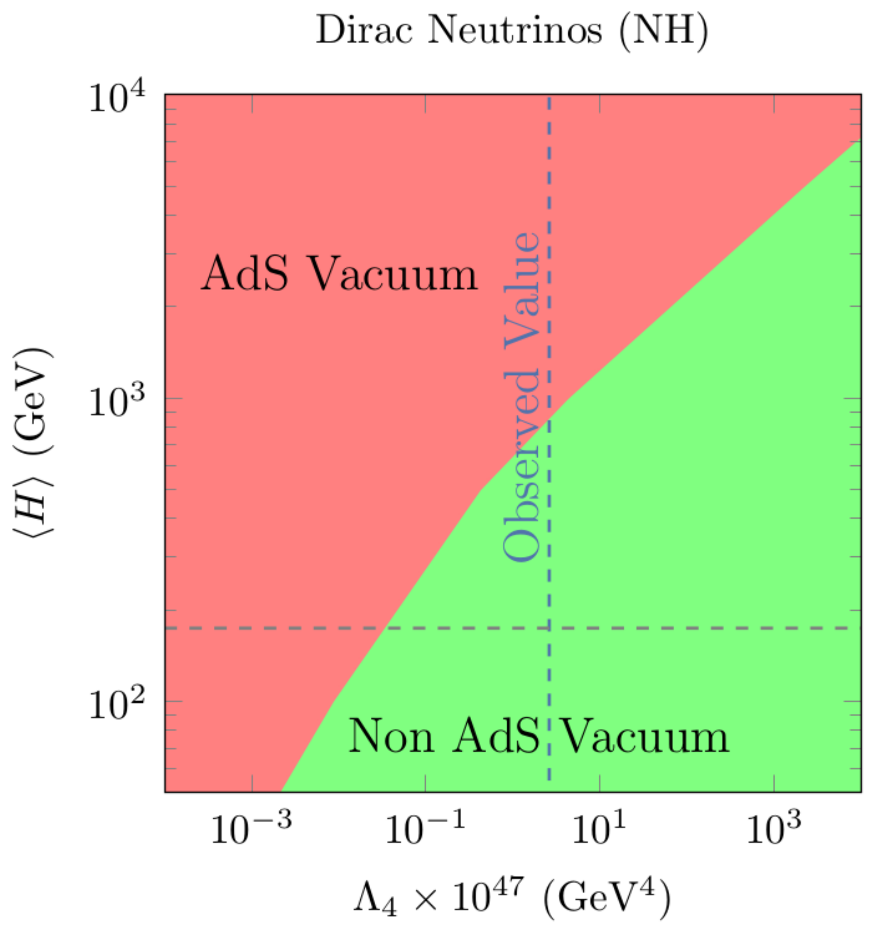
We can translate the bound on neutrino masses to an upper bound on the EW scale in terms of the cosmological constant:

$$\langle H \rangle \lesssim 1.6 \frac{\Lambda^{1/4}}{Y_{\nu_1}}$$

Parameters leading to a higher EW scale would not yield theories consistent with quantum gravity



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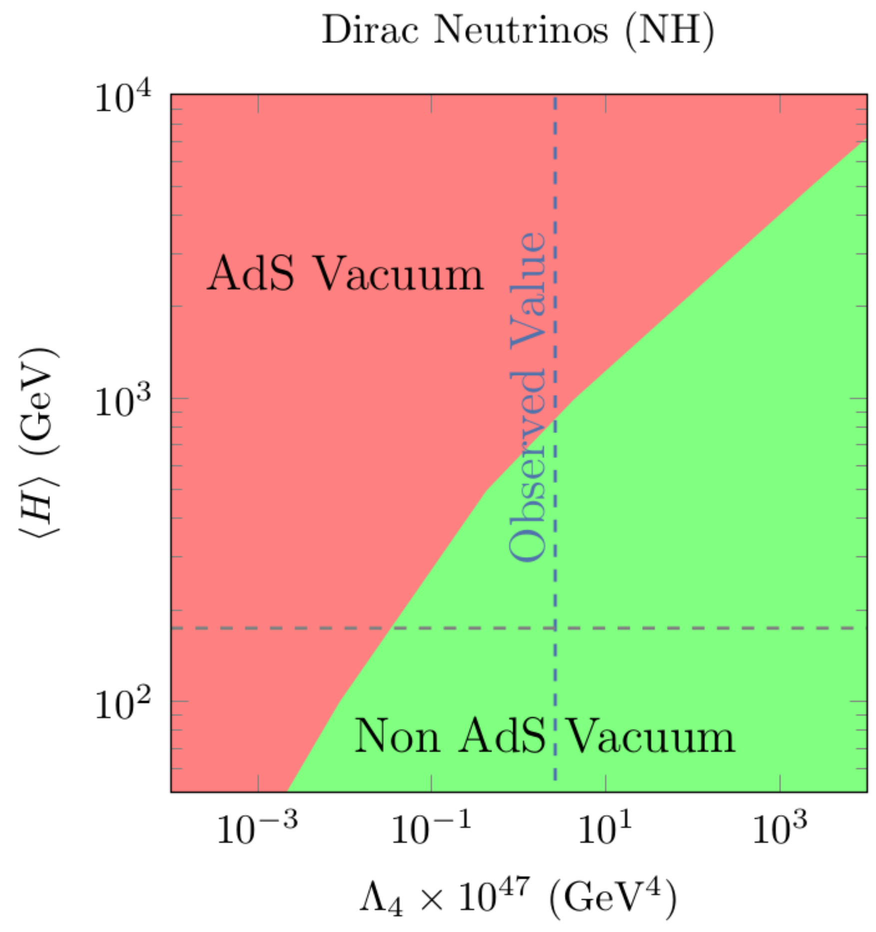
Potential loopholes. But proof of principle that space of parameters consistent with quantum gravity can be smaller than expected, not everything goes!



CONCLUSIONS

Requiring quantum gravity UV consistency can have implications at low energies and potentially shed new light into naturalness problems.

- We saw examples of Swampland constraints that imply ‘surprising’ or ‘unnatural’ results from an IR perspective, but they are natural from the UV complete theory
- None of them clearly solves the concrete naturalness issues of our universe (EW hierarchy problem, cosmological constant problem, etc.)

  but they provide interesting avenues to pursue.

- This is only the beginning. What other guiding principles for BSM can we learn from quantum gravity?

  Can we make the UV/IR mixing more manifest?

Thank you!

Thank you!

Online series of Swampland seminars / open mic discussions

on Tuesdays at 11 am ET (5 pm CET)

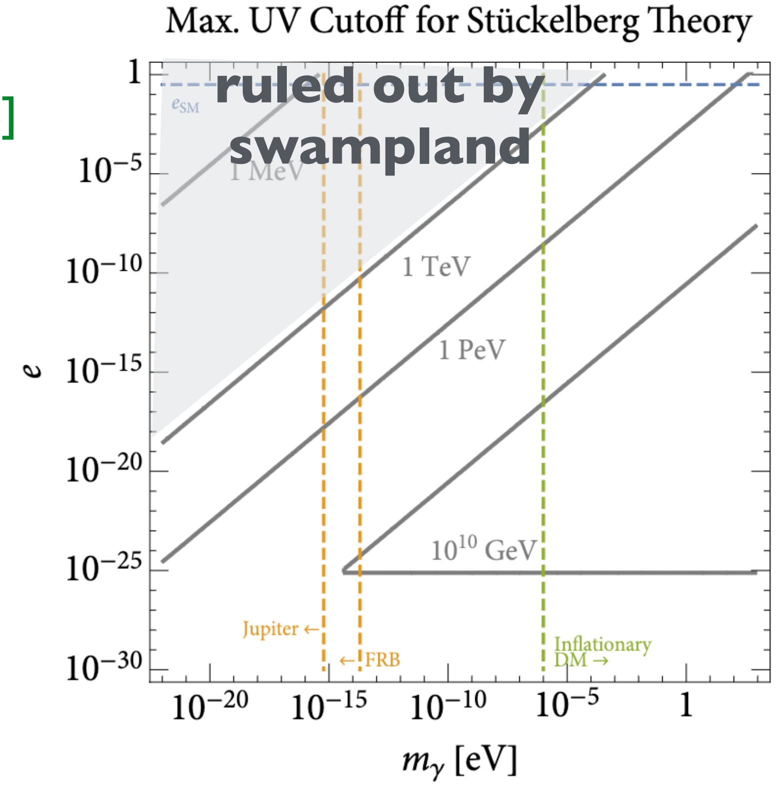
You can subscribe here: https://web.lists.fas.harvard.edu/mailman/lists/hetg-swampland.lists.fas.harvard.edu/

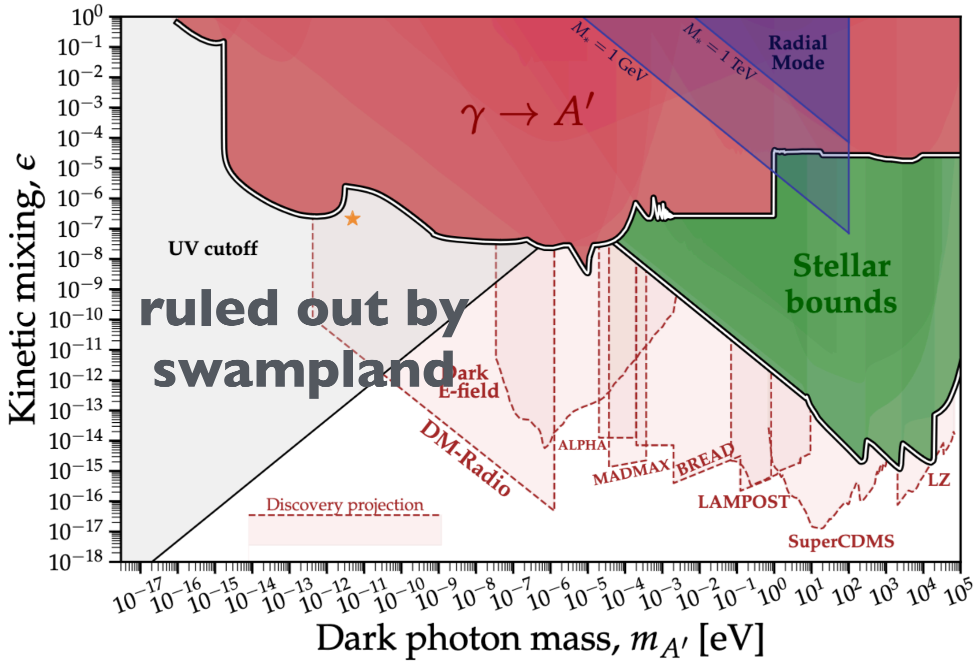
Everybody is welcome! :)

back-up slides

How does the tower/cut-off behaves in terms of EFT data?

[Reece'18]





[Montero,Muñoz,Obied'22]

For weak coupling limits:

$$\exists \text{ tower with } \quad m \leq \overbrace{\gamma_{\rm BH}}^{\mathcal{O}(1)\ \textit{factor}} \underbrace{q}_{\textit{quantized charge}}\, \underbrace{g_{\rm YM}}_{\textit{gauge coupling}} M_p$$

(Weak Gravity Conjecture)

[Arkani-Hamed et al'06]

➡ EFT breaks down at $\Lambda \lesssim g_{YM} M_p$

Lower bound on gauge coupling!

It can rule out some BSM proposals

and been tested experimentally

Consistency under dimensional reduction

Background independence of quantum gravity implies that:

If we start with a theory consistent with QG → Compactifications of that theory should also be consistent

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Take a 4-dimensional theory, and compactify one dimension on a circle of radius R. The 3-dimensional EFT contains a new scalar with potential:

$$V(R) = \underbrace{\frac{2\pi\Lambda_4}{R^2}}_{\text{tree-level}} + \underbrace{\text{Casimir energy}}_{\text{one-loop corrections}}(n_b, n_f, m_b, m_f)$$

n_b : *bosonic d.o.f*

n_f : *fermionic d.o.f*

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n_b : *bosonic d.o.f*

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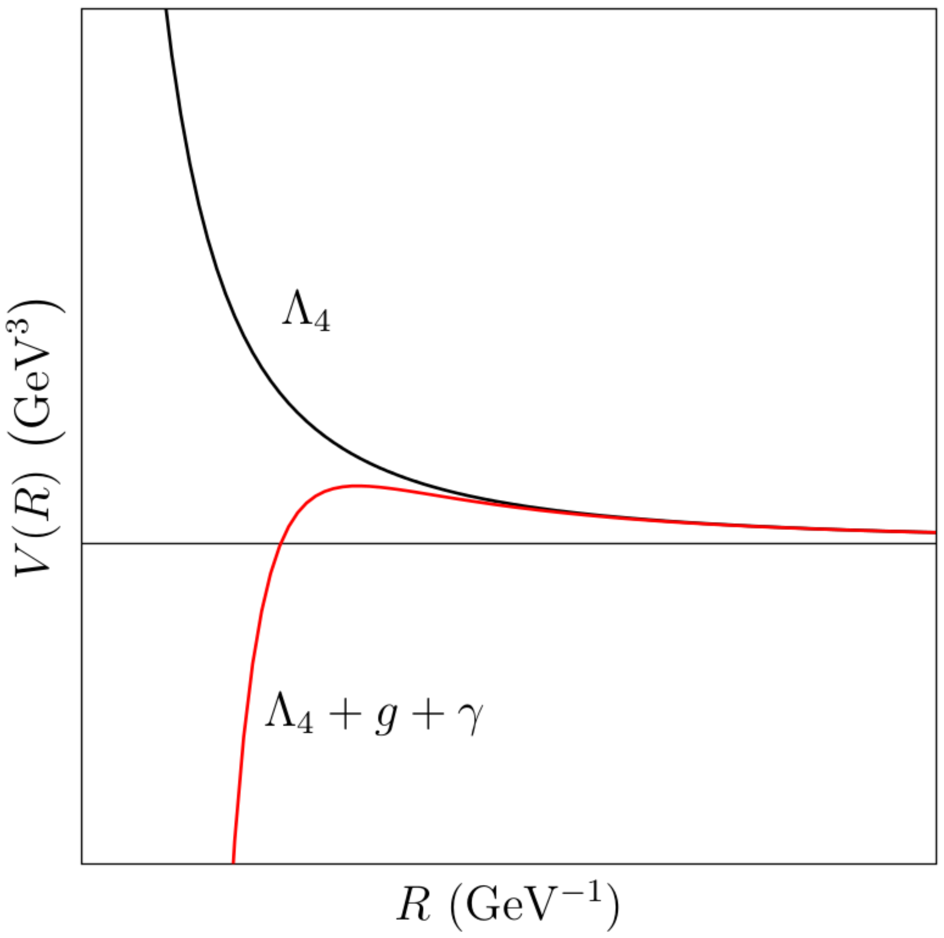
Goal: Determine constraints on the 4d field spectra that guarantee that V(R) is consistent with Swampland conjectures

Compactification of the SM to 3d

Standard Model + Gravity on S^1:

massless particles: graviton, photon

$$V(R) = \frac{2\pi\Lambda_4}{R^2} - \frac{4}{720\pi R^6}$$



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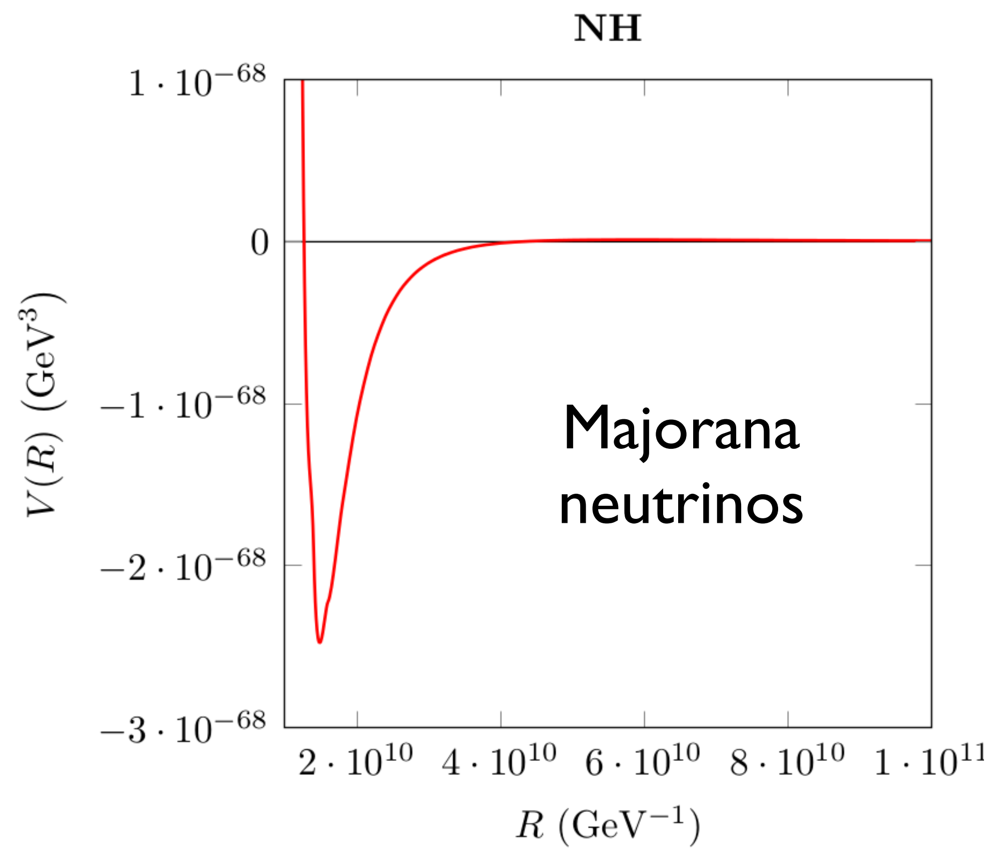
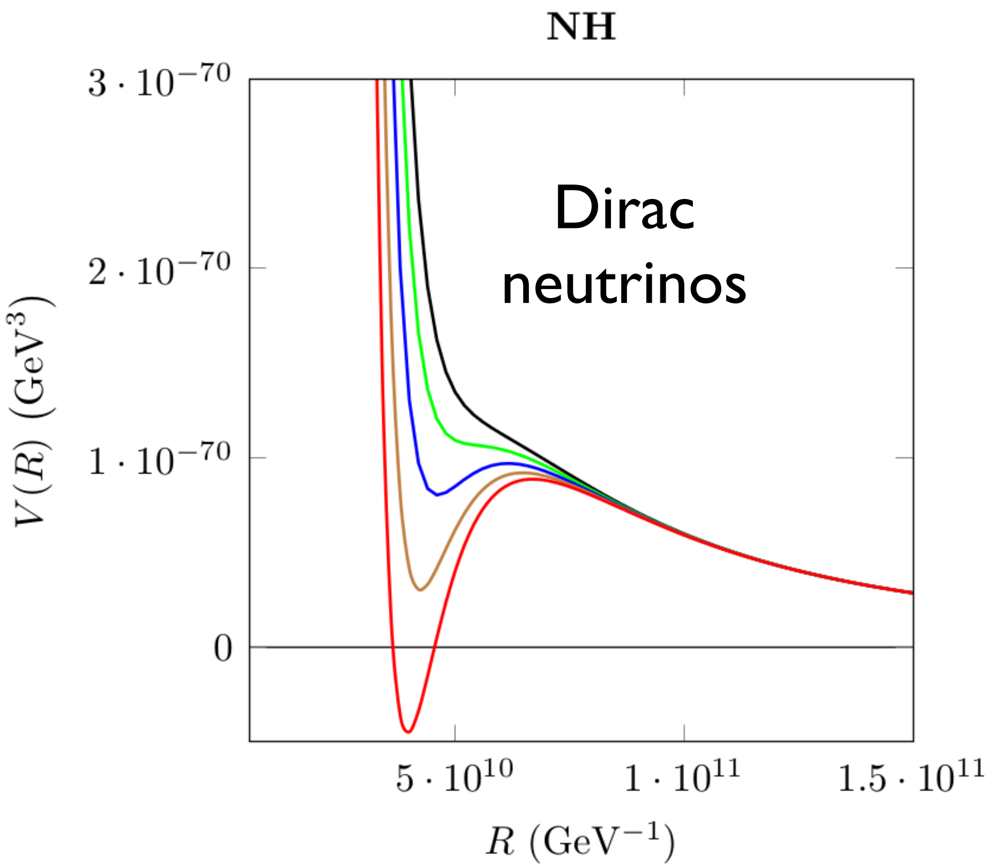




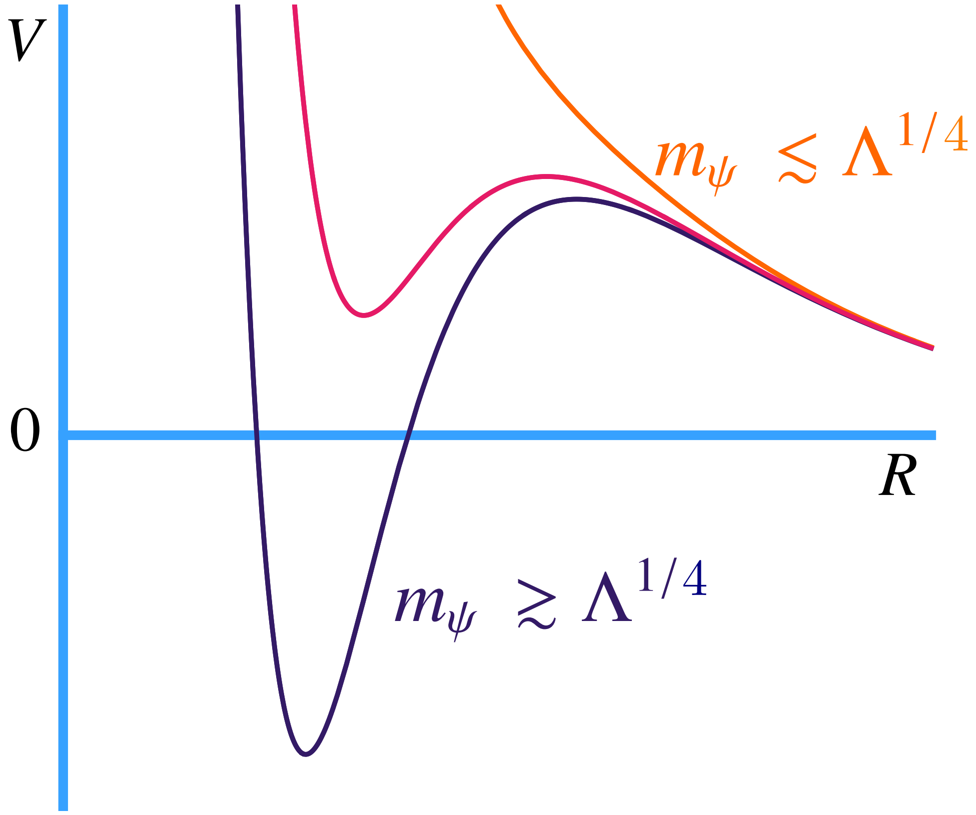
The more massive the neutrinos, the deeper the AdS vacuum

[Ibanez,Martin-Lozano,IV'17] (see also [Hamada-Shiu'17])

Compactification of the SM to 3d

Results:

- Depending on the value of Dirac mass for the neutrinos, we get 3-dimensional AdS, Minkowski or dS vacua.
- By scanning a family of 4d theories with different values of the neutrino masses (e.g. by scanning the Higgs vev), we can cross the flat space limit.



We cross the flat space limit when neutrino masses:

$$m_\nu \sim \Lambda_{\rm cc}^{1/4}$$

Compactification of the SM to 3d

According to the Generalized (AdS) Distance Conjecture, there should be a tower of states becoming light in the flat space limit

Two possible resolutions:

1) There is a surplus of light fermions with $m \lesssim \Lambda_{cc}^{1/4}$

   (larger masses are obstructed by quantum gravity consistency)

2) There is an infinite tower of states in 4d scaling as $m_{\text{tower}} \sim \Lambda_{cc}^{1/4}$

The KK tower of the Dark Dimension ensures that compactifications of the SM are consistent with the Swampland conjectures

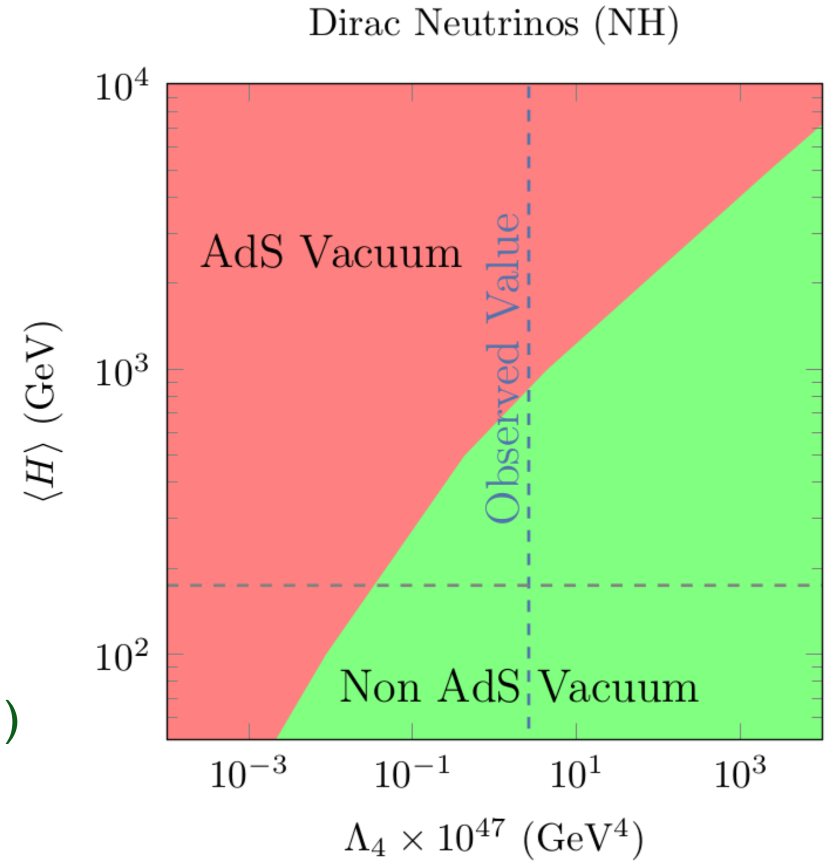
Naturalness issues

We can translate the bound on neutrino masses to an upper bound on the EW scale in terms of the cosmological constant:

$$\langle H \rangle \lesssim 1.6 \frac{\Lambda^{1/4}}{Y_{\nu_1}}$$

[Martin-Lozano,Ibanez,IV'17]

(see also [Gonzalo et al'18-21] [Rudelius'21]…)



Parameters leading to a higher EW scale do not yield theories consistent with quantum gravity

Solution to EW hierarchy porblem?

Space of parameters consistent with quantum gravity is smaller than expected, not everything goes!

We need to revisit the logic of naturalness

String Theory Evidence

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

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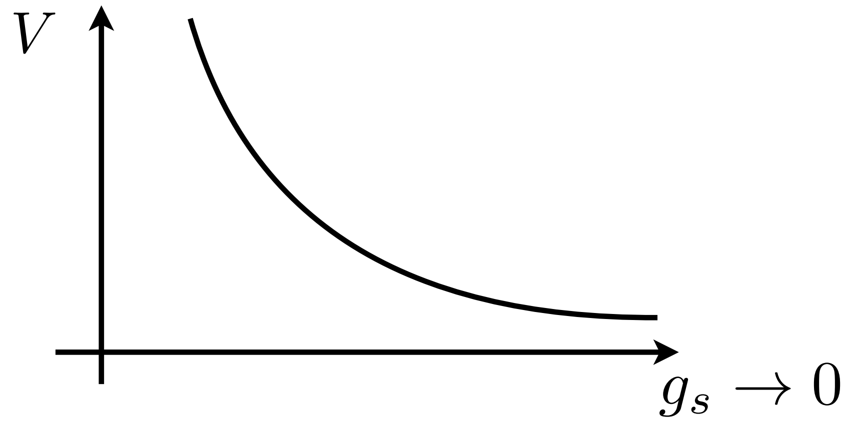
☑ Non-SUSY string theories with positive runaways

☑ KKLT-like proposals for dS in string theory [Blumenhagen et al'22]

Failure of EFT expectation

Non-SUSY example

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



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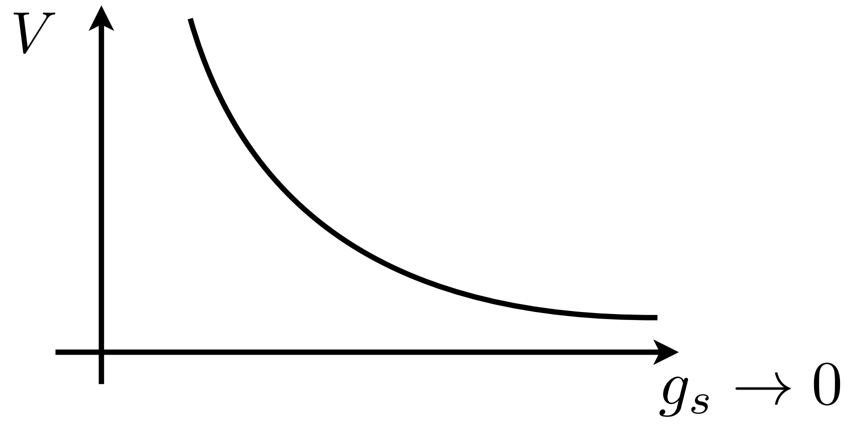

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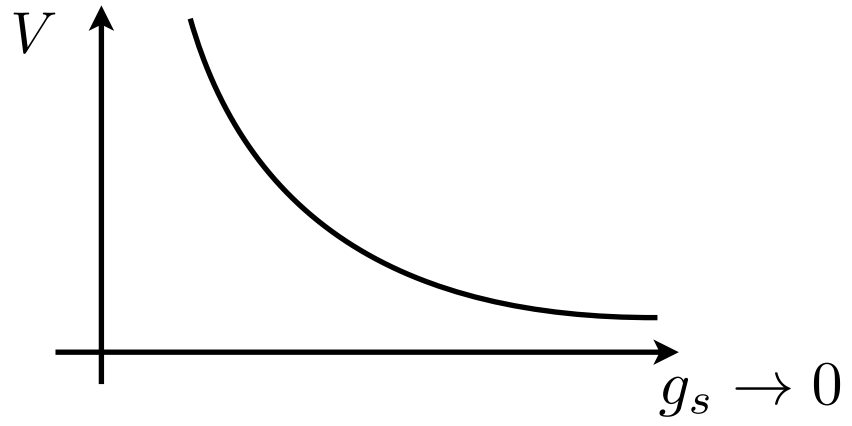

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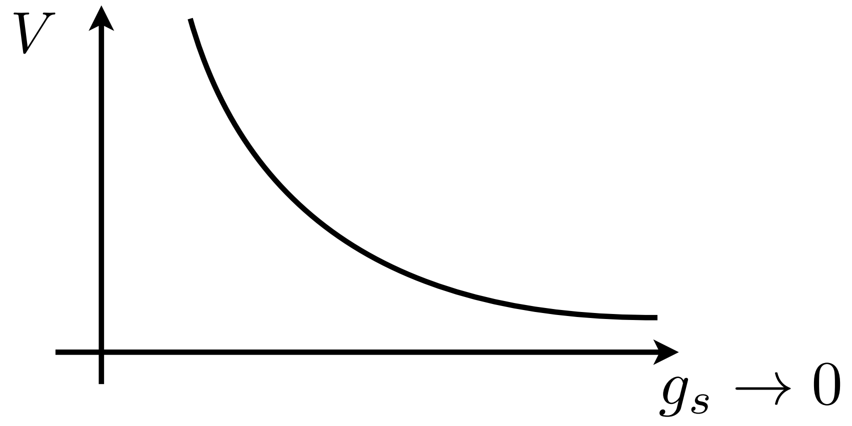

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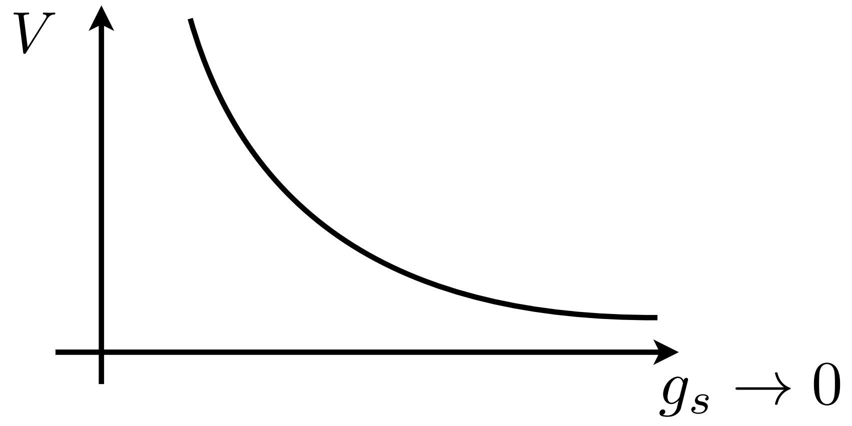

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Contribution of massive string excitations is cut-off at Ms due to modular invariance

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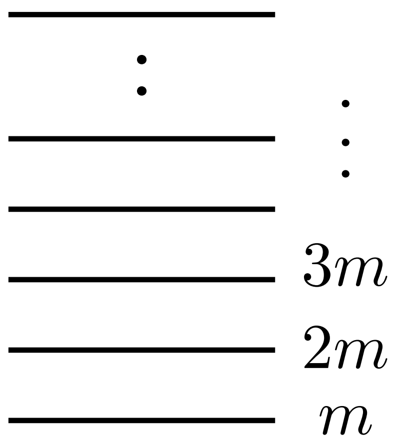

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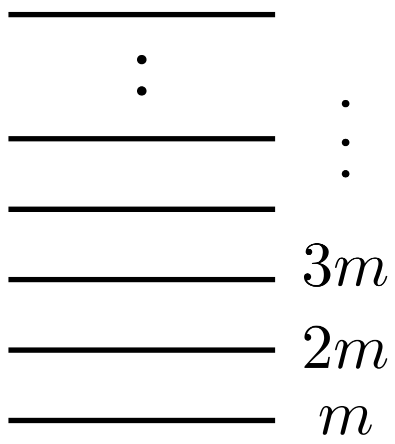

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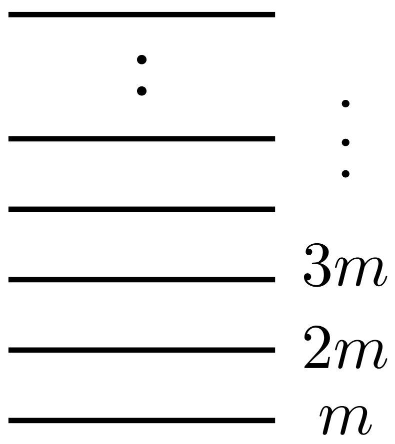

- If integrating out the infinite tower:

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

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

Experimental constraints

Is a tower with $V^{1/2} \lesssim m \lesssim V^{1/4}$

compatible with experimental constraints?

In our universe: $V^{1/4} \sim 2.31 \text{ meV}$ → $m^{-1} \gtrsim O(10)\, \mu m$

Experimental constraints:

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

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

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

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

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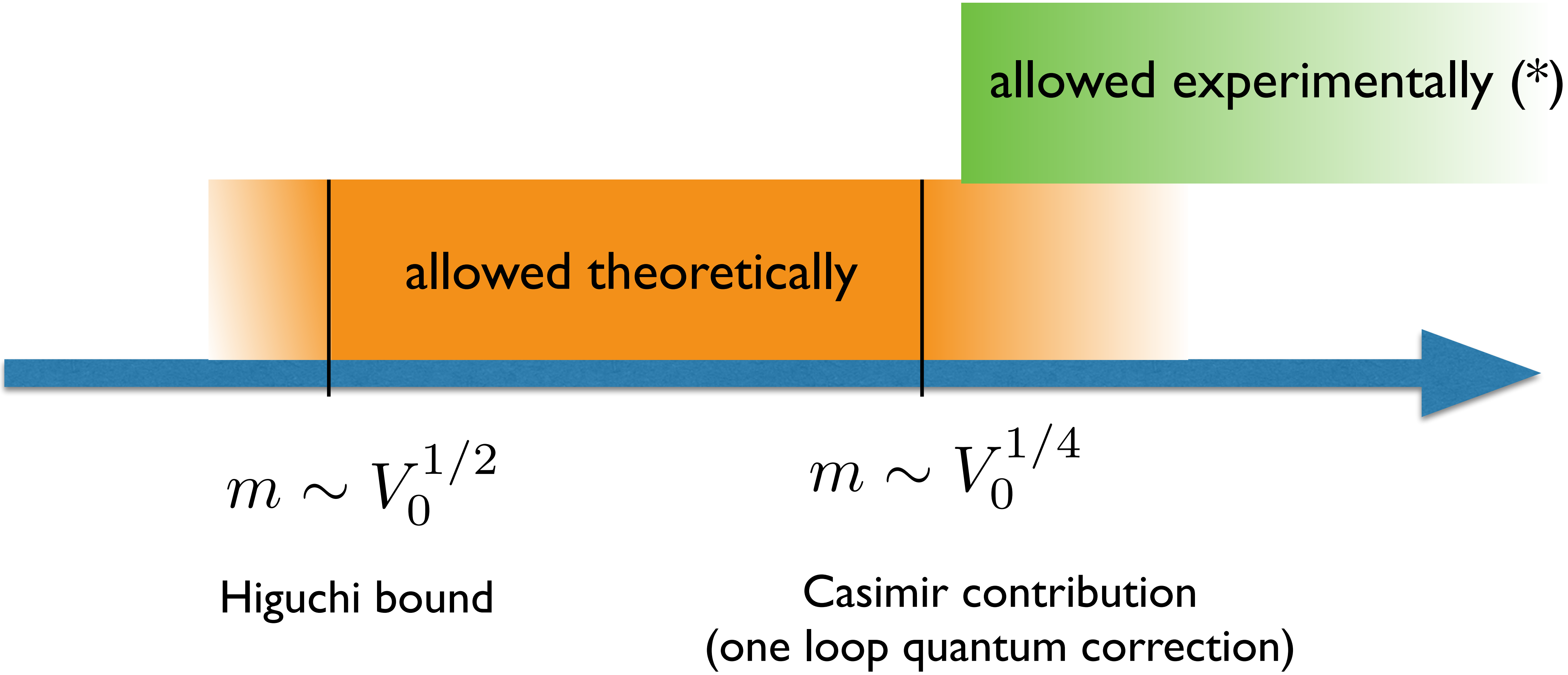

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Casimir contribution
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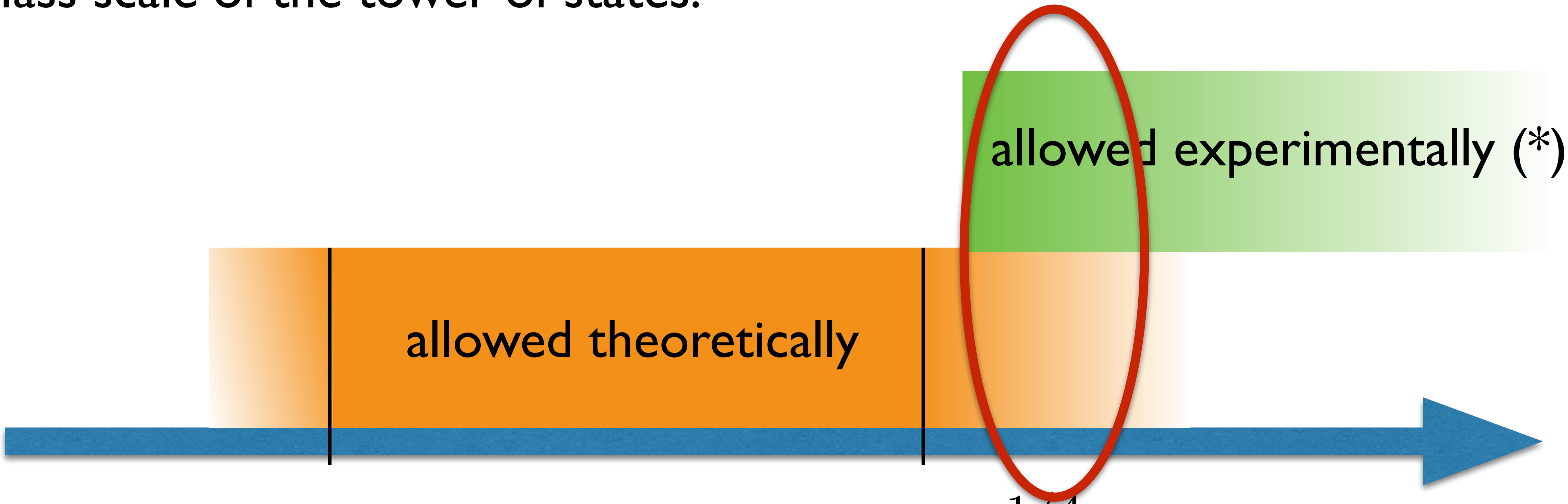

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- Systematic approach according to the level of supersymmetry
- Interesting connections to mathematics

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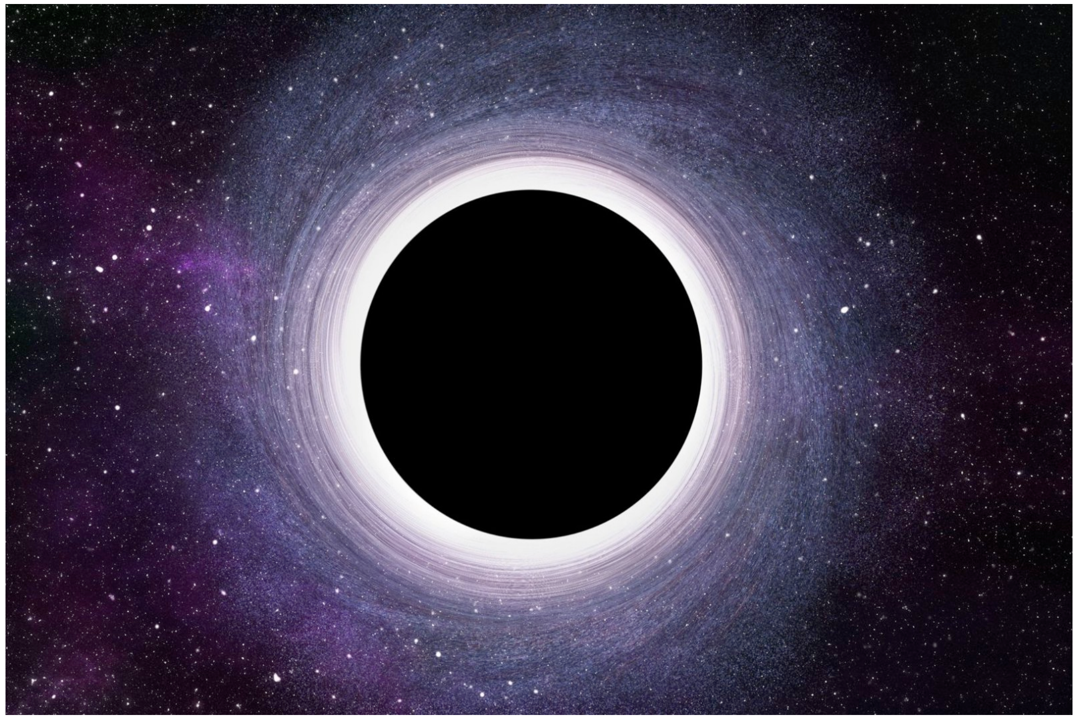
❖ Using positivity/unitarity bounds: lead to mild versions of the WGC

[Cheung et al'18][Hamada et al'18]…

Motivation from black holes



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

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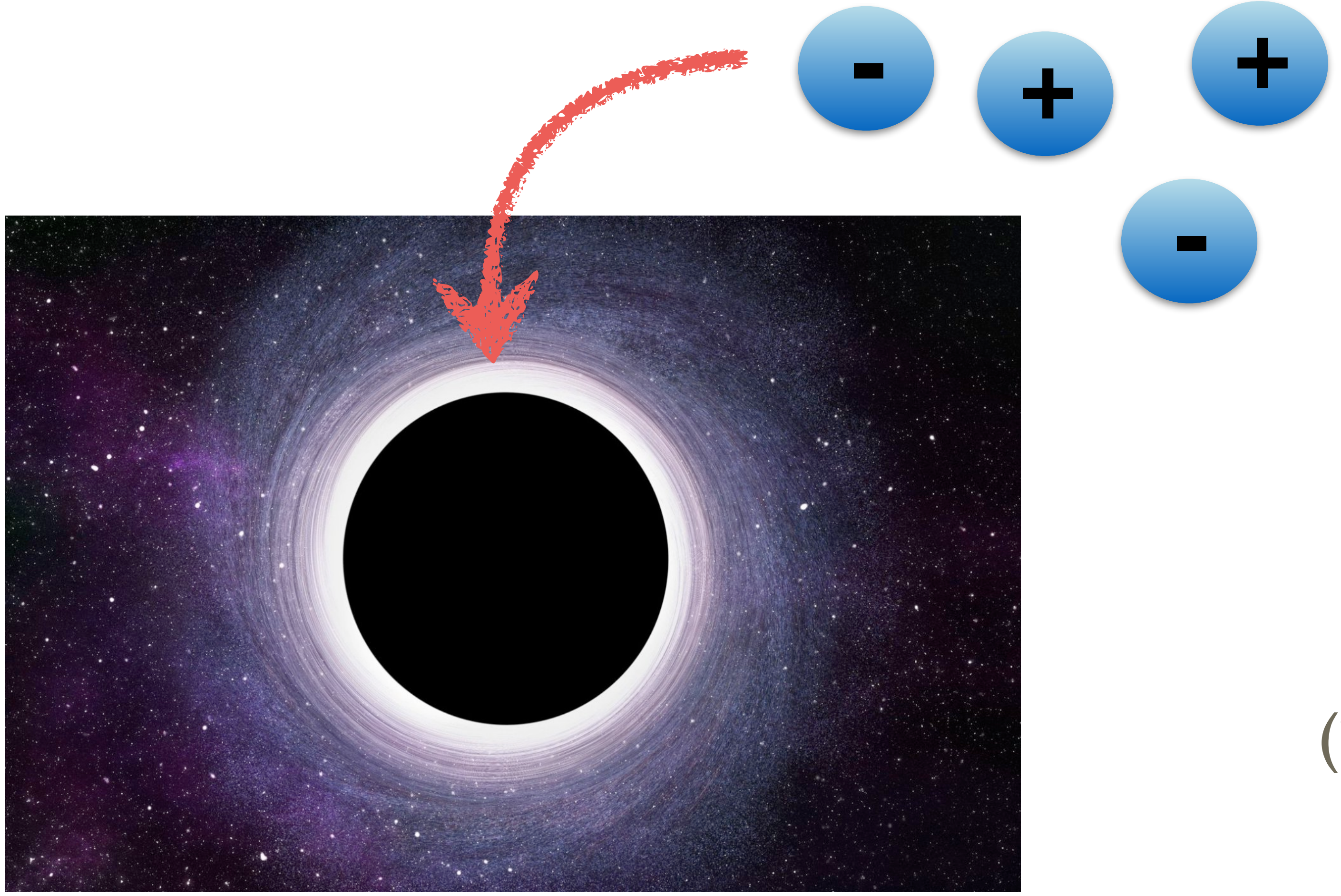

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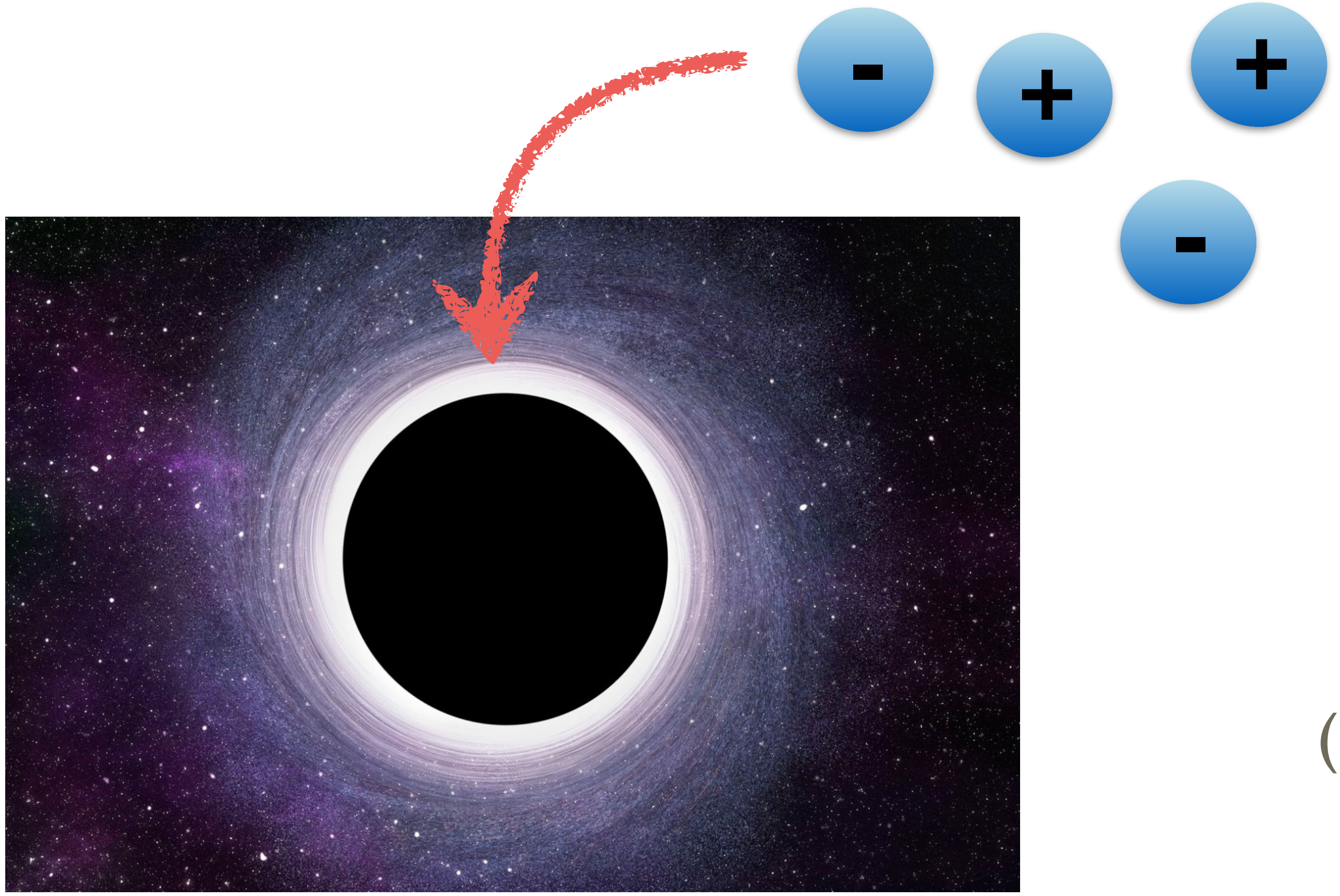

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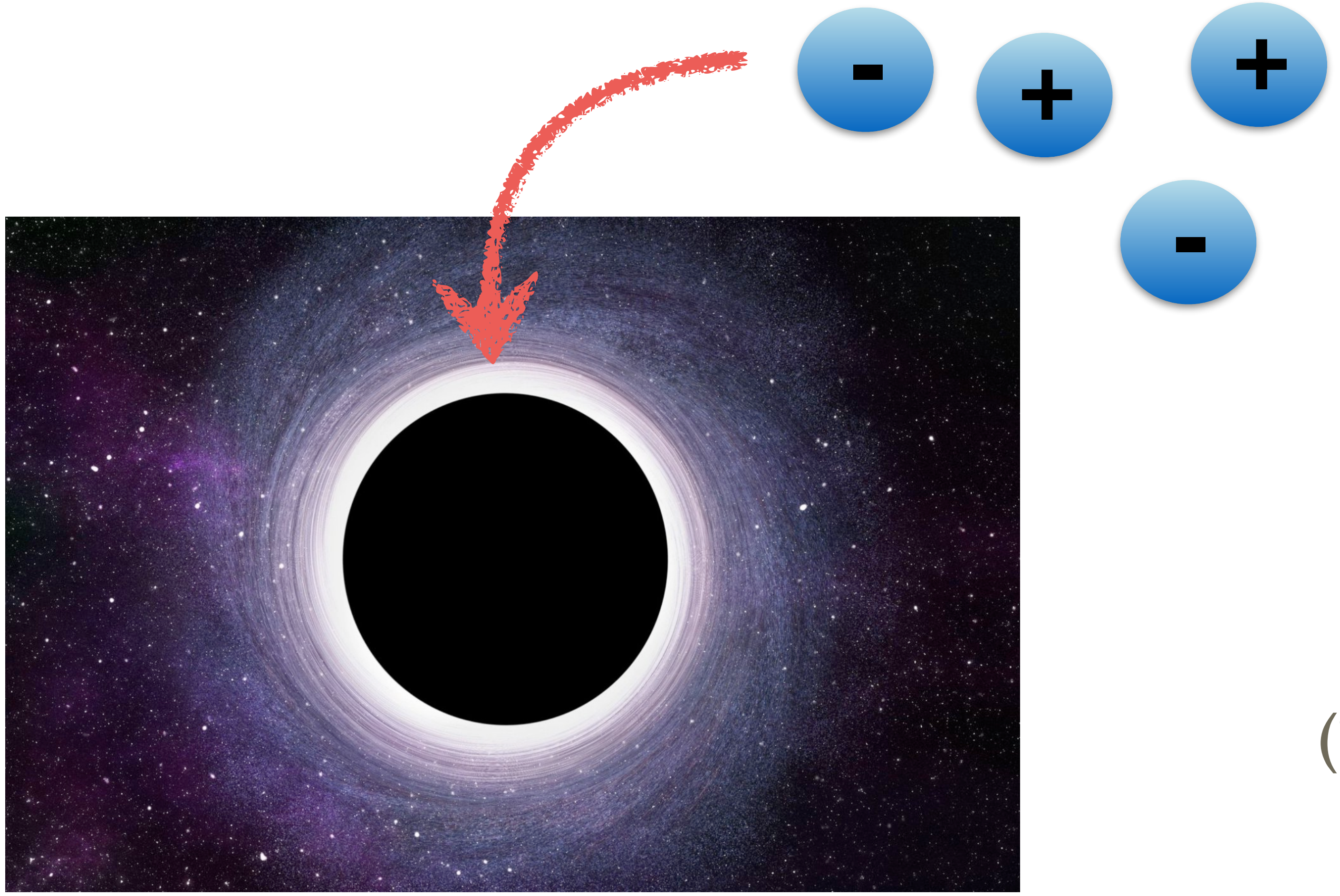

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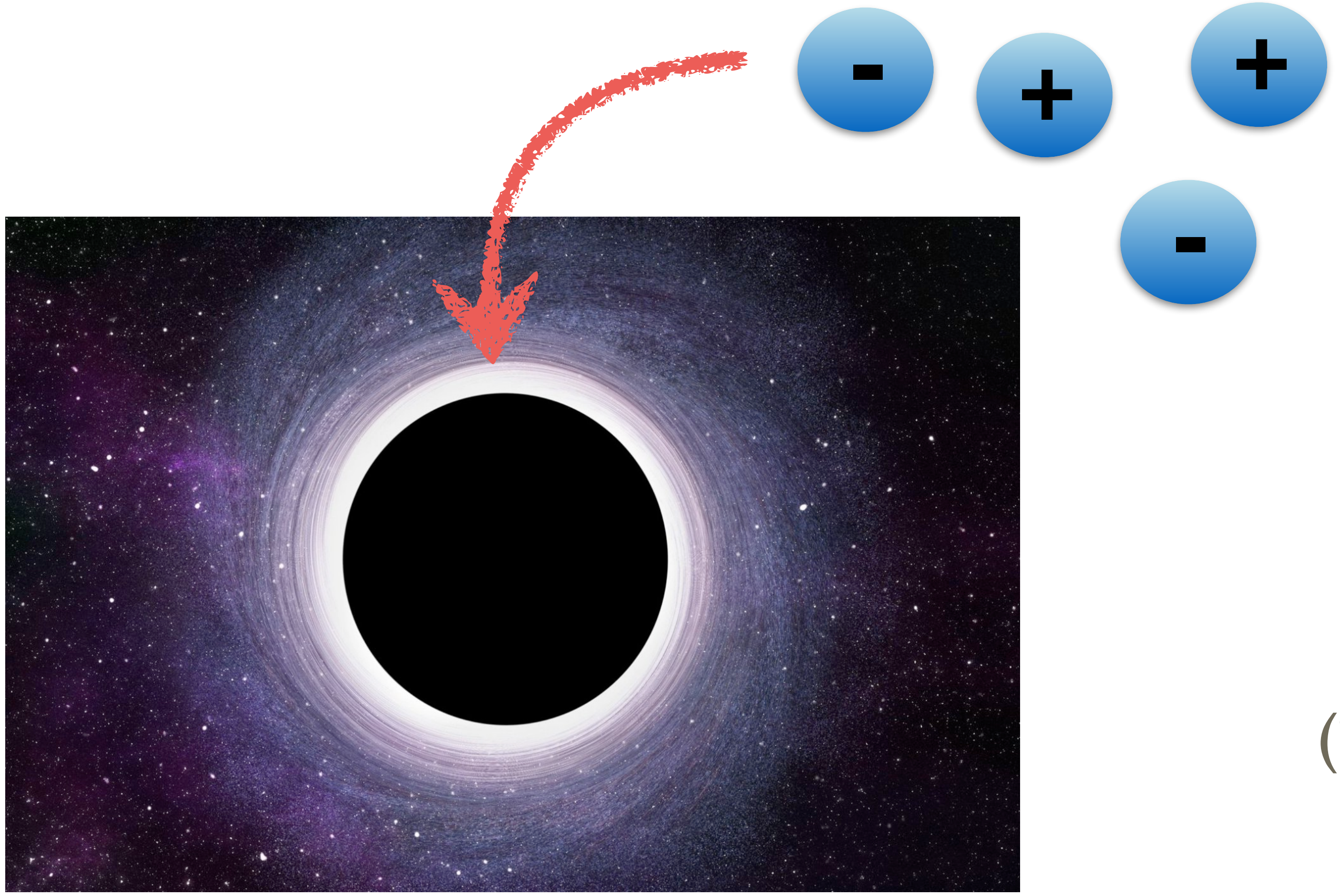

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→ Infinite entropy constradiction!

Evidence for “No global symmetries”

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

Implications for Cosmology

Maximum scalar field range that can be accommodated in a given EFT as a function of the Quantum Gravity cut-off

$$\Delta\phi \lesssim \frac{1}{\lambda} \log\left(\frac{M_p}{\Lambda}\right)$$

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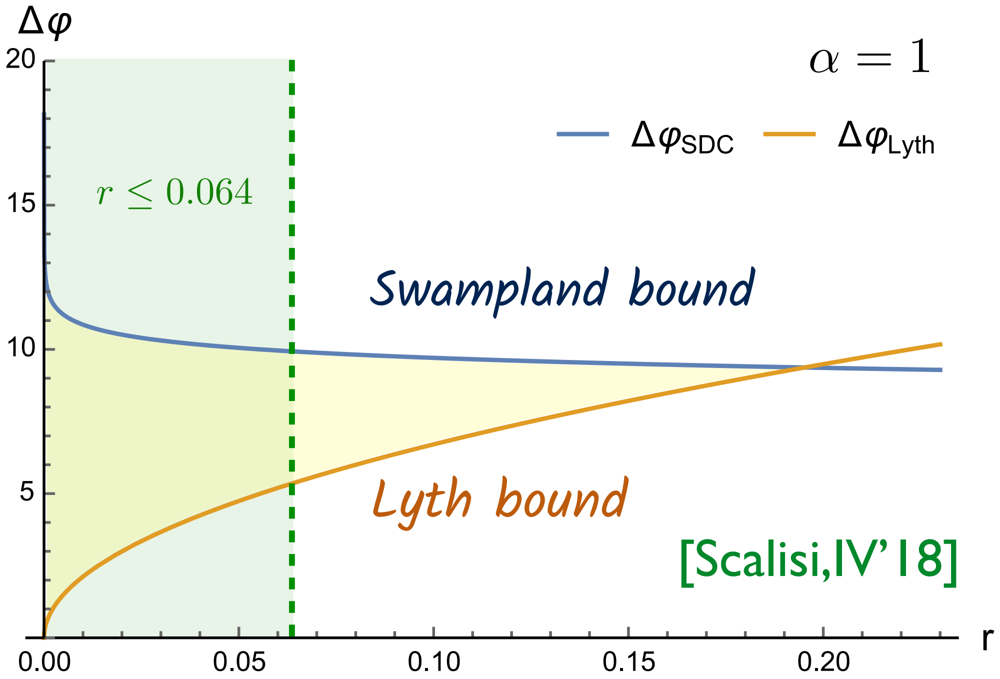

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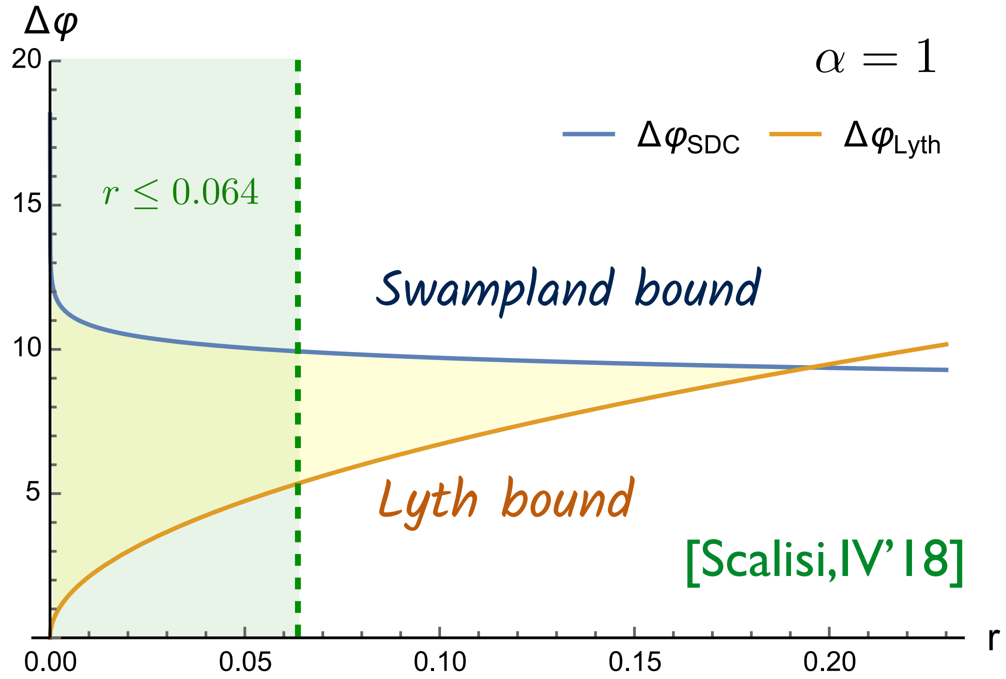

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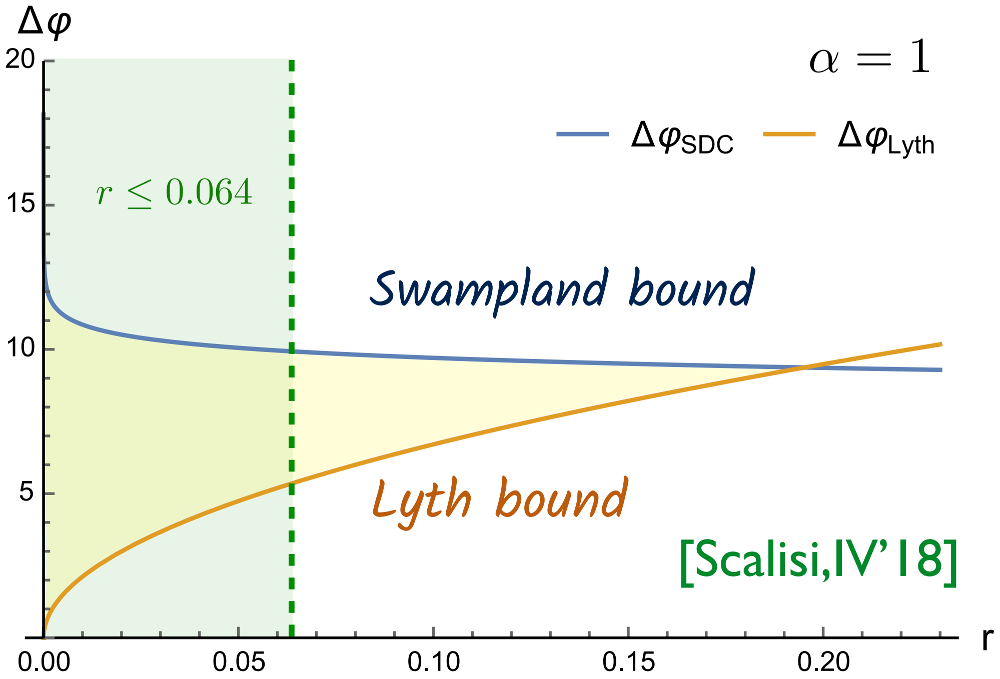

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This triggered the revolution of the Swampland program in 2015

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Implications for Particle Physics

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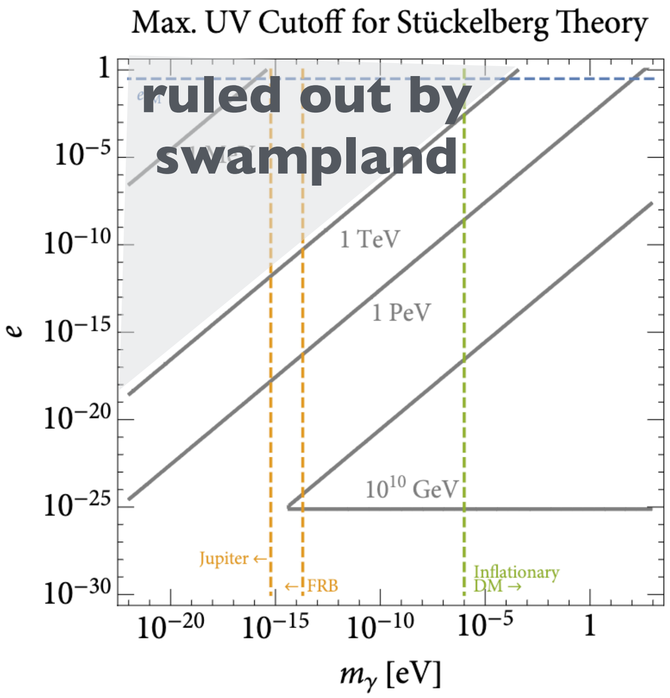
ruled out by swampland

[Reece'18]

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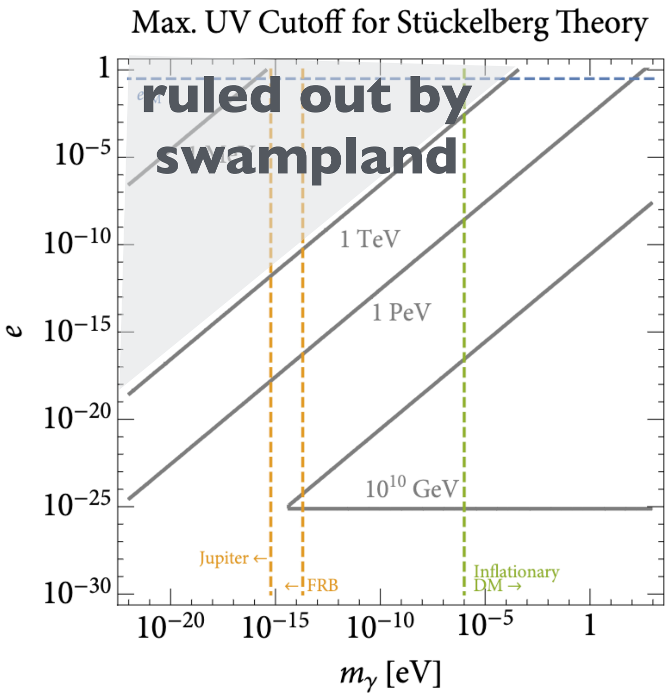

[Reece'18]

$\Lambda_{QG} \ll M_p$ for weakly coupled or very light dark photons