# A Journey through the Swampland: What is the Scale of Quantum Gravity?


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# A Journey through the Swampland

**Motivation:**

What is this journey about?


# A Journey through the Swampland

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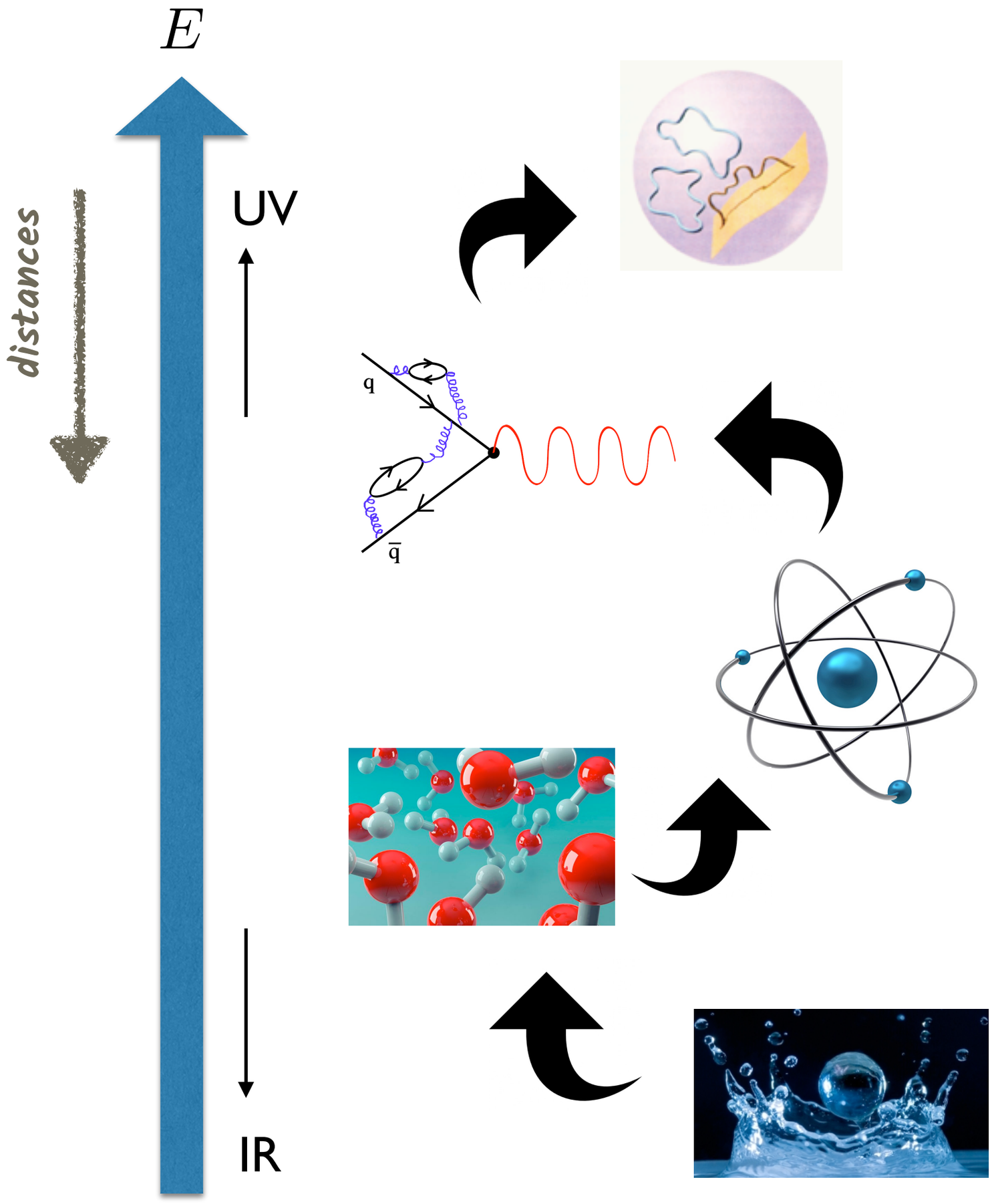
What is this journey about?

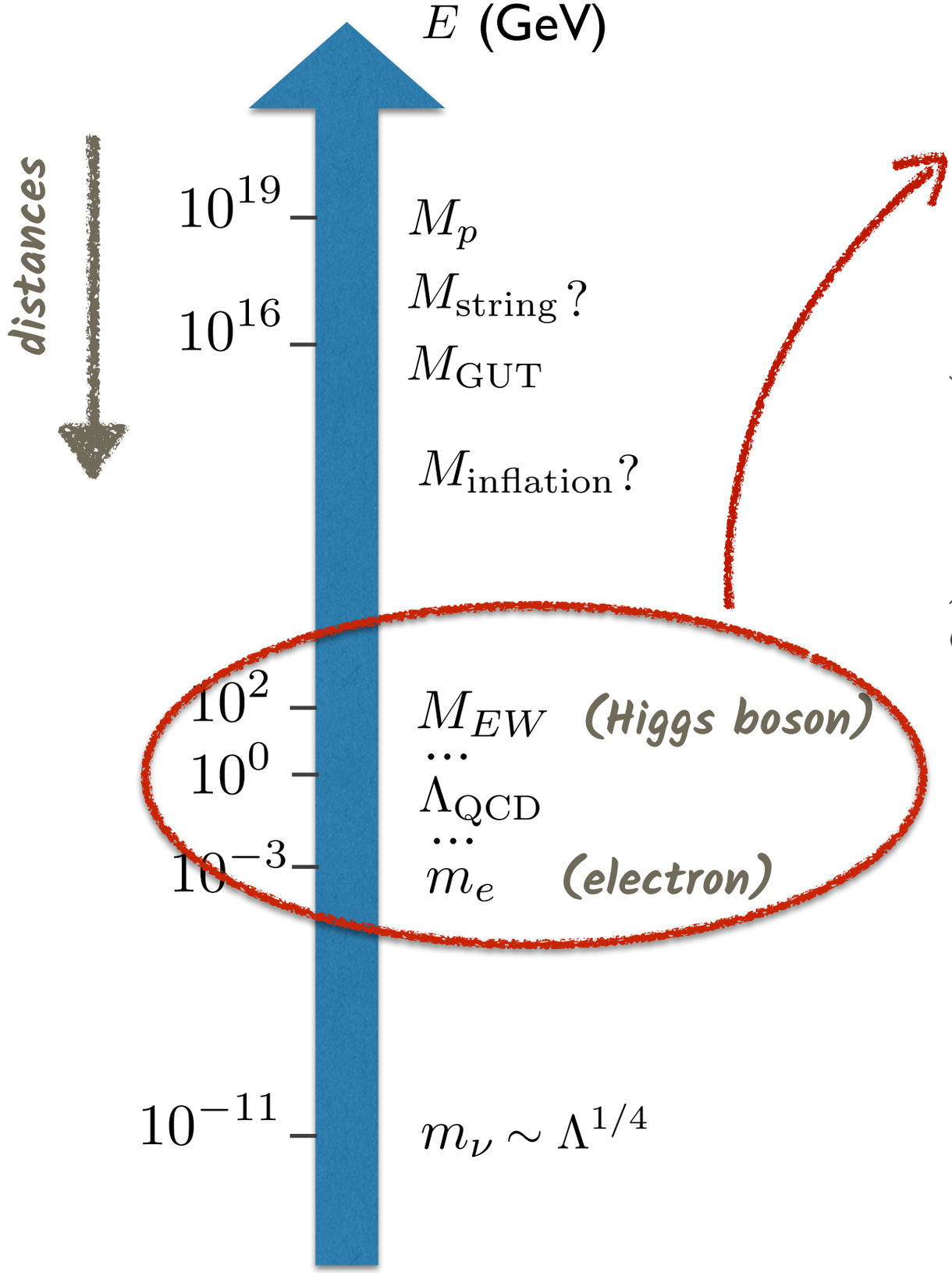
## It is about exploring the Quantum Gravity imprint at low energies




Modern physics is based on a Wilsonian effective field theory (EFT) approach

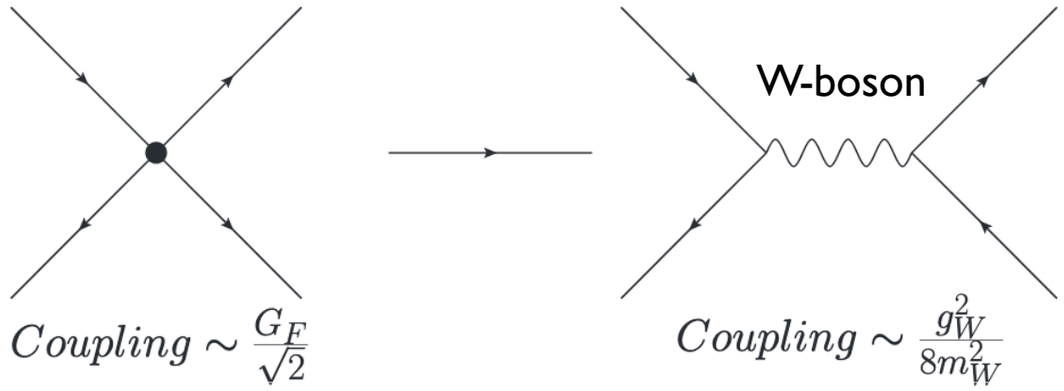
We construct EFTs that describe the physical phenomena up to some energy cut-off

These EFTs need to be UV completed at higher energies

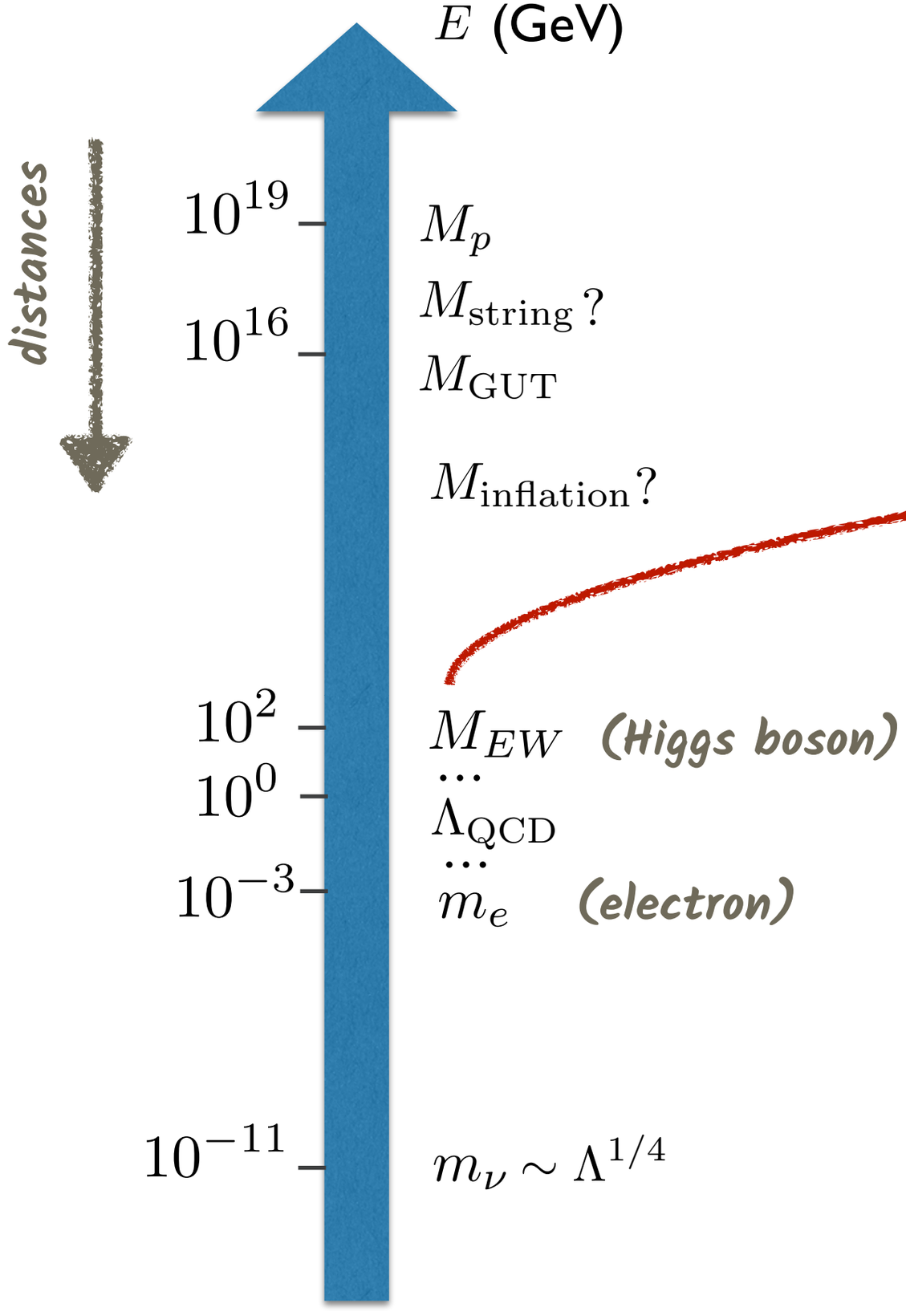



## Example: Fermi's interaction

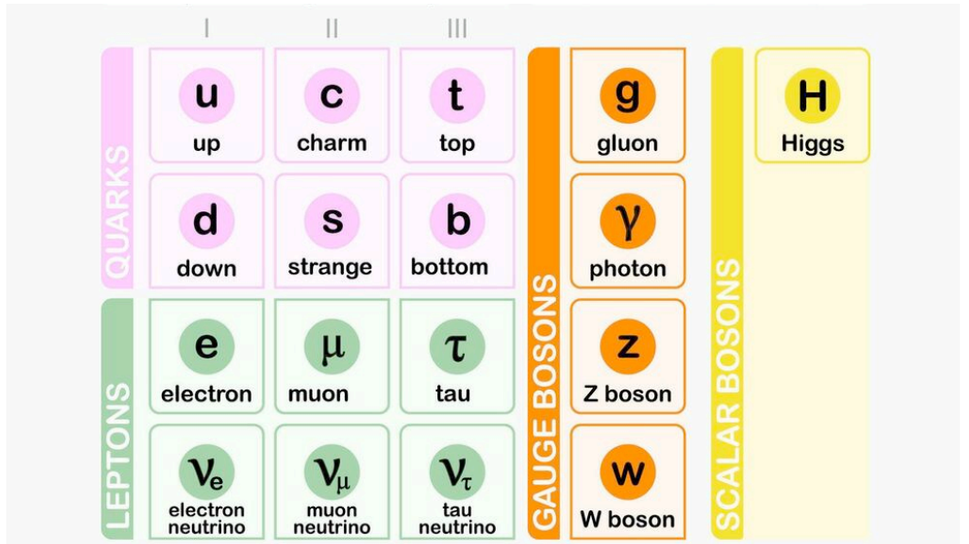
$$n \to p^+ + e^- \bar{\nu}_e$$



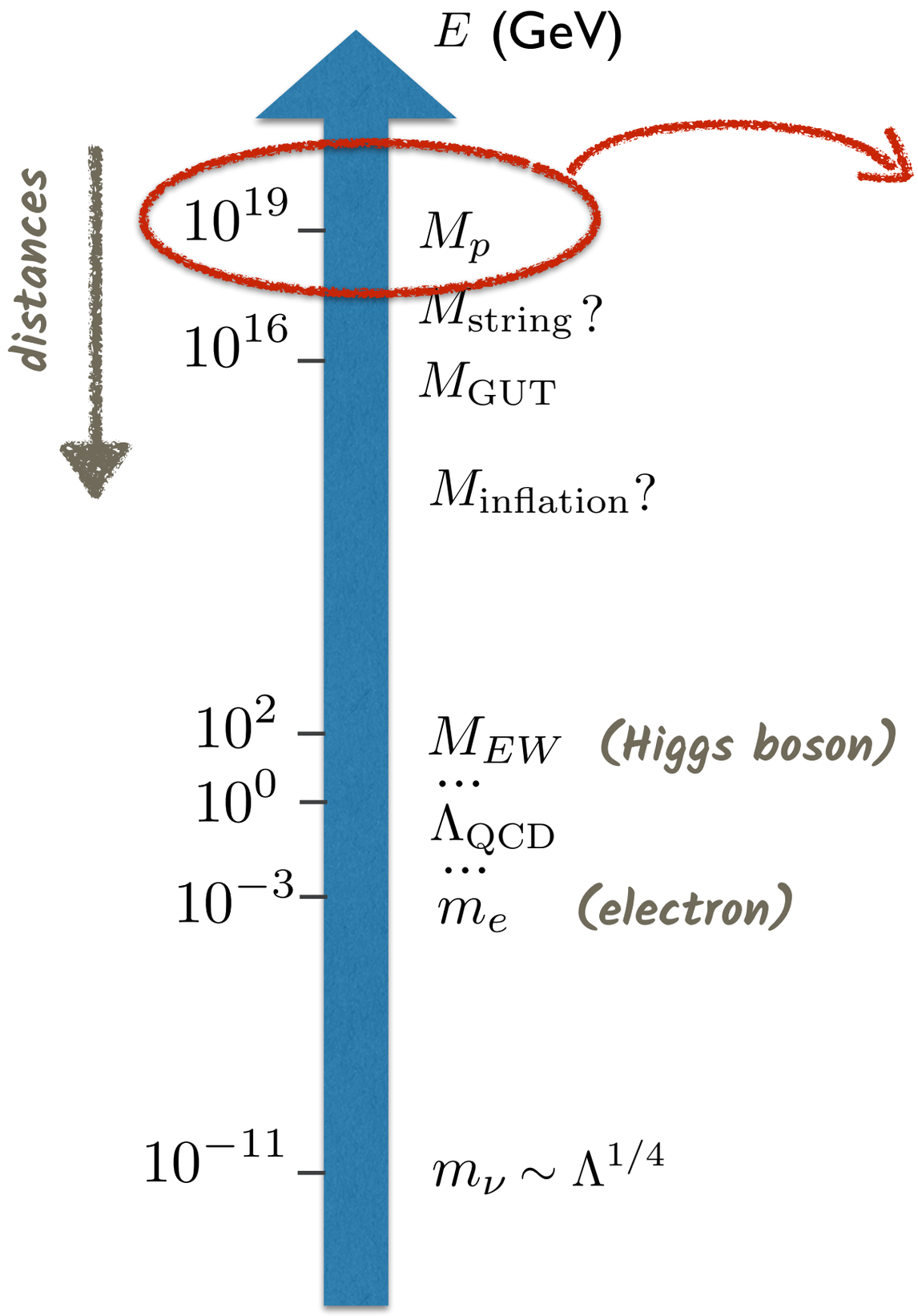

Fermi's 4-point interaction gets UV completed by QED at energies above $m_W$




## Standard Model of Particle Physics




What comes next?



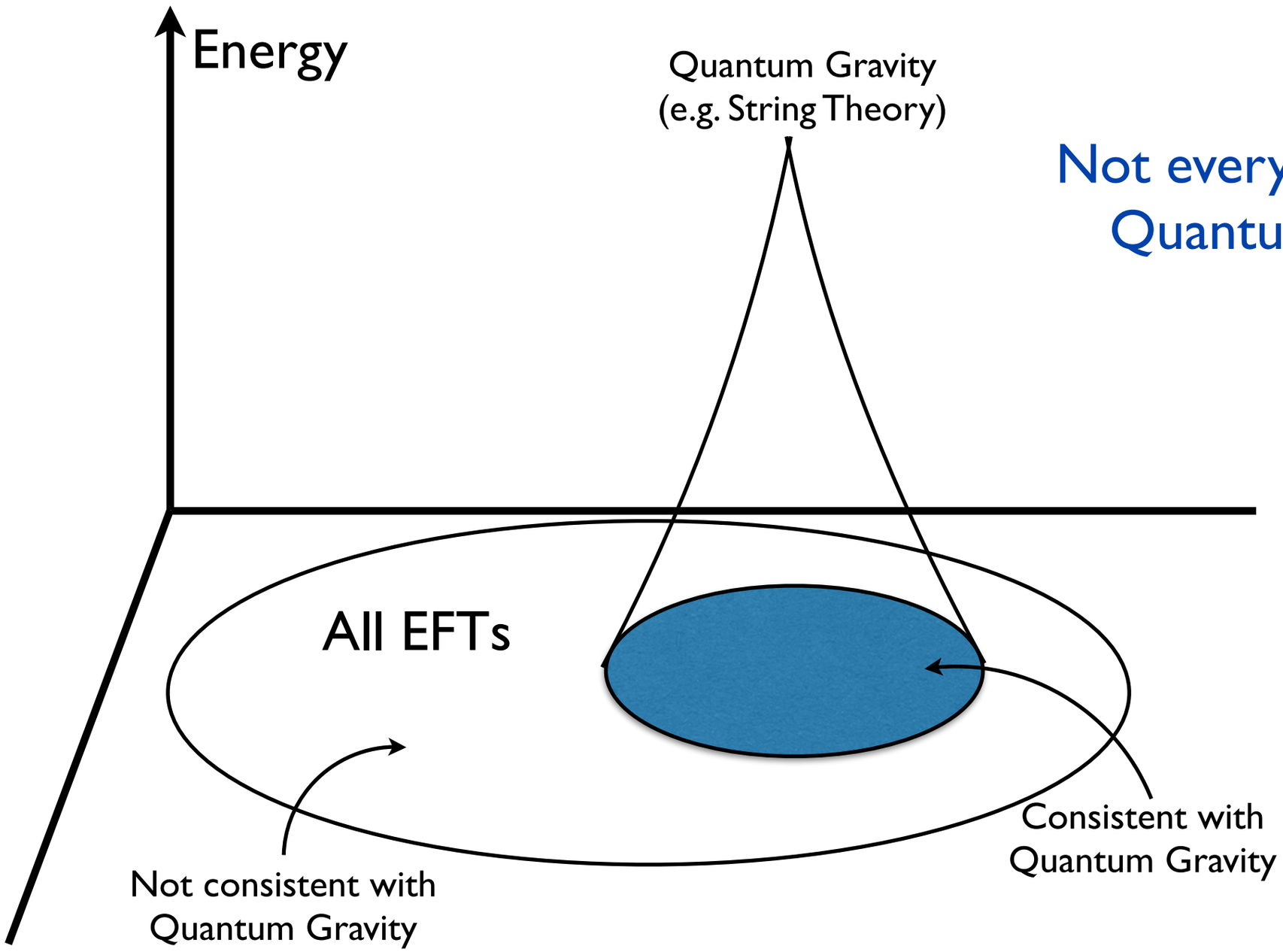

EFTs coupled to gravity need to be UV completed in a quantum graviy theory when reaching the Planck scale

i.e., when quantum gravitational effects are *typically* expected to become significant

# Can any EFT be UV completed in a consistent quantum gravity (QG) theory?

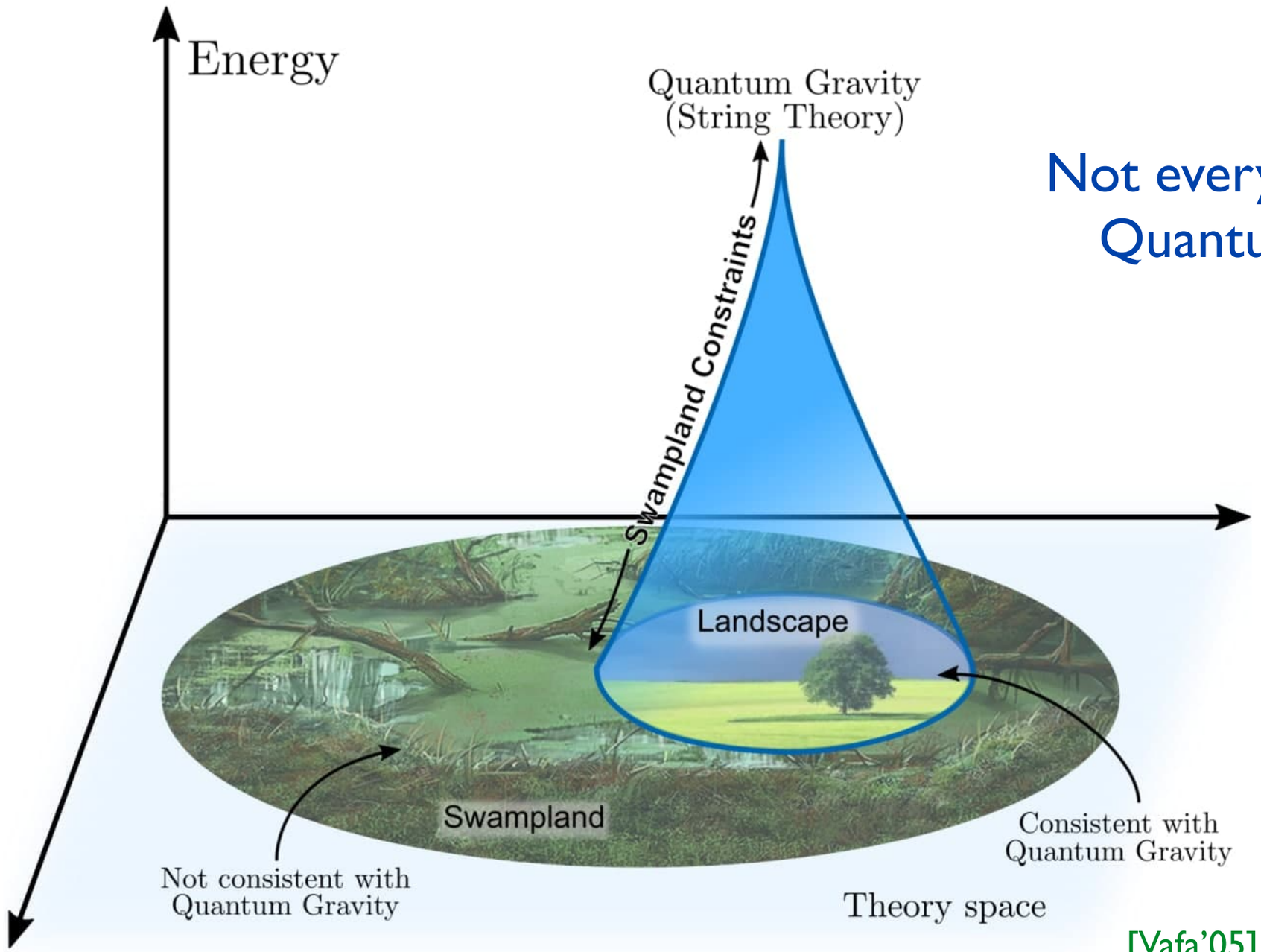
**NO**

- Gravitational anomalies
- Unitarity/causality constraints
- Constraints from black hole physics
- Concrete quantum gravity theories (like string theory) do not allow for every EFT at low energies




## Not everything goes in Quantum Gravity!

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

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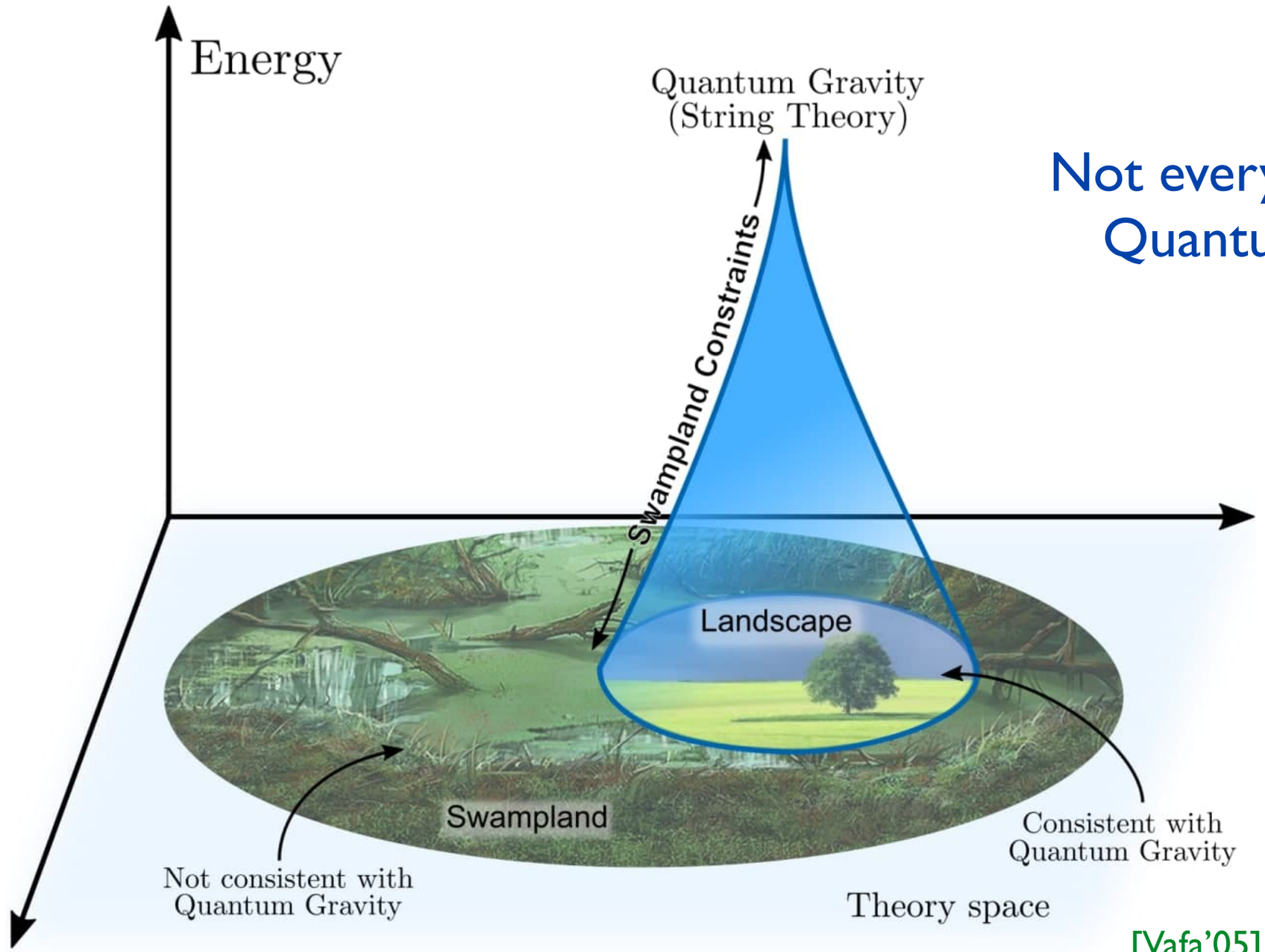
[Vafa'05]




[Vafa'05]

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## Swampland:

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

# Swampland program

What is the space of Effective Field Theories weakly coupled to Einstein gravity that can be consistently UV completed (in quantum gravity)?

$$S = \int d^4x \left( R + \mathcal{L}_{\rm EFT} + \sum_n \frac{\mathcal{O}_{n+4}}{\Lambda^{n-4}_{\rm cut-off}} \right)$$

What can it go here?

What is the quantum gravity cut-off?

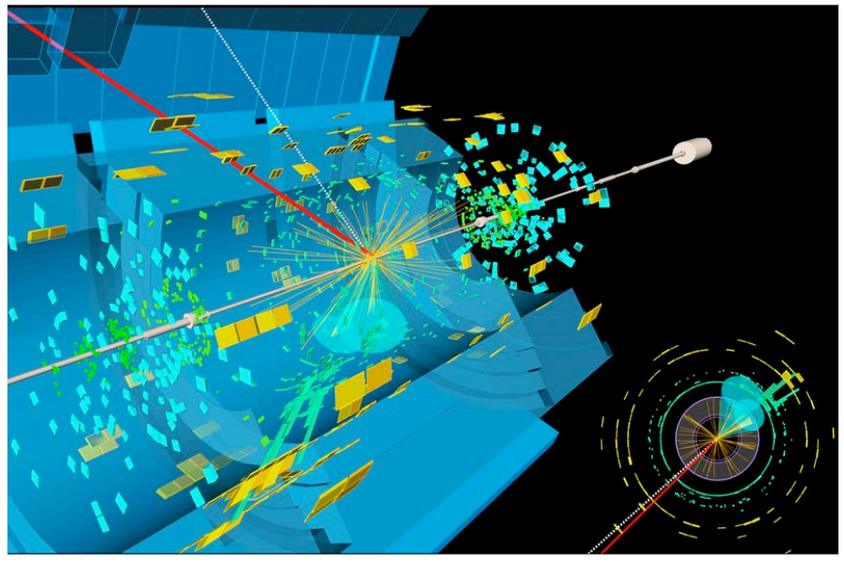
# Swampland program

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

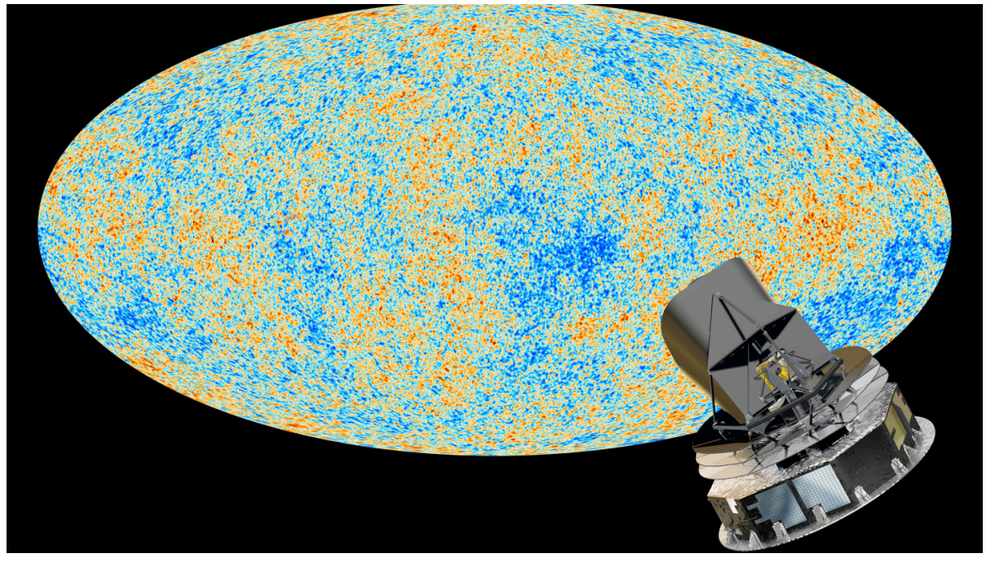
What distinguishes the landscape from the swampland?

→ UV imprint of quantum gravity at low energies

## Particle Physics



## Cosmology



quantum gravity

Golden opportunity!

UV Consistency with quantum gravity can provide new guiding principles for BSM in Particle Physics and Cosmology

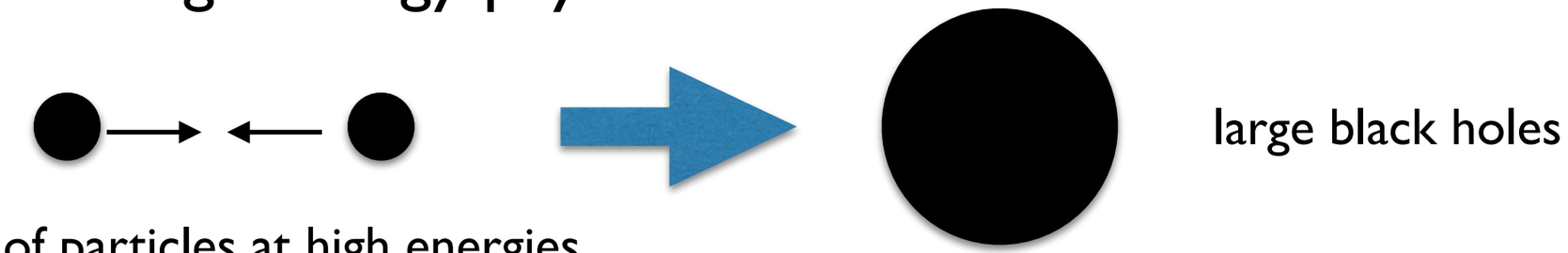
Maybe naturalness issues are a first hint of this…

# Gravity is different than other interactions

- Everything couples to gravity

- Gravity can break the notion of separation of scales (UV/IR mixing)

  Black Hole Physics makes manifest a correlation between long distances and high energy physics




scattering of particles at high energies

Even if the Planck scale is very high, consistency with Quantum Gravity can impose non-trivial constraints at low energies

e.g. constraints on inflation, dark energy, dark photons, neutrinos…

**How do we determine these consistency quantum gravity constraints?**

A consistent theory of quantum gravity

(theoretical laboratory)


Plethora of theoretical data/ models to check the constraints

**How do we determine these consistency quantum gravity constraints?**

AdS/CFT

Black Holes

String Theory

Unitarity/causality constraints

Categorical approach to symmetries

# A Journey through the Swampland

01 Identify pattern (swampland conjecture)

03 Explain it using black holes, amplitudes, holography…

05 Phenomeno-logical predictions

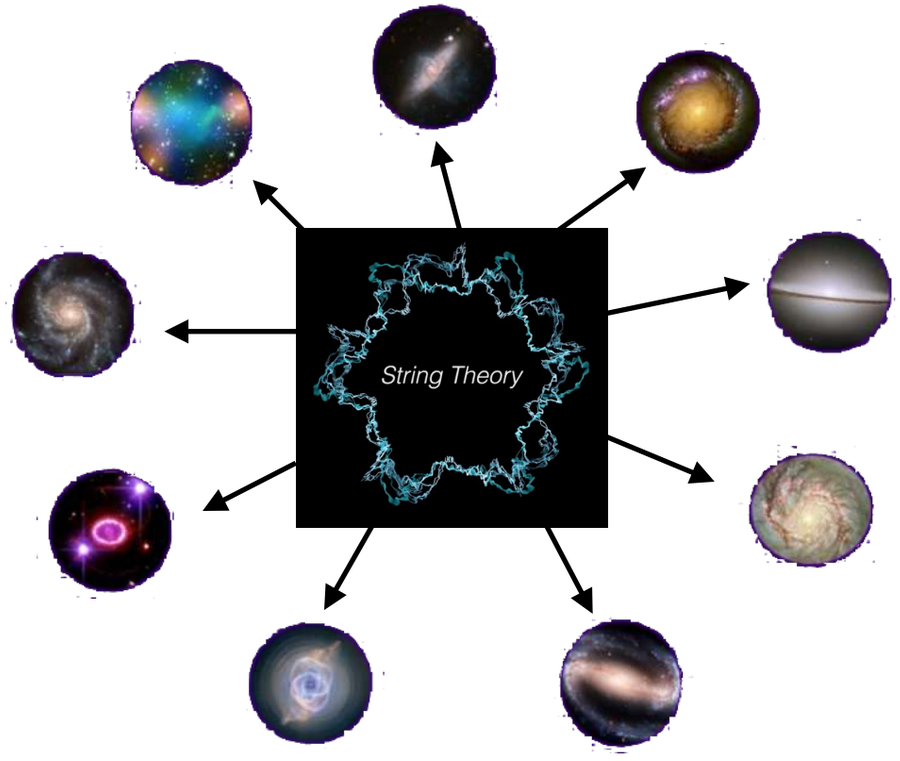
04

02 Prove it in AdS/CFT

Provide evidence in String Theory

# Change of paradigm in String Phenomenology

New approach to connect string theory to our world

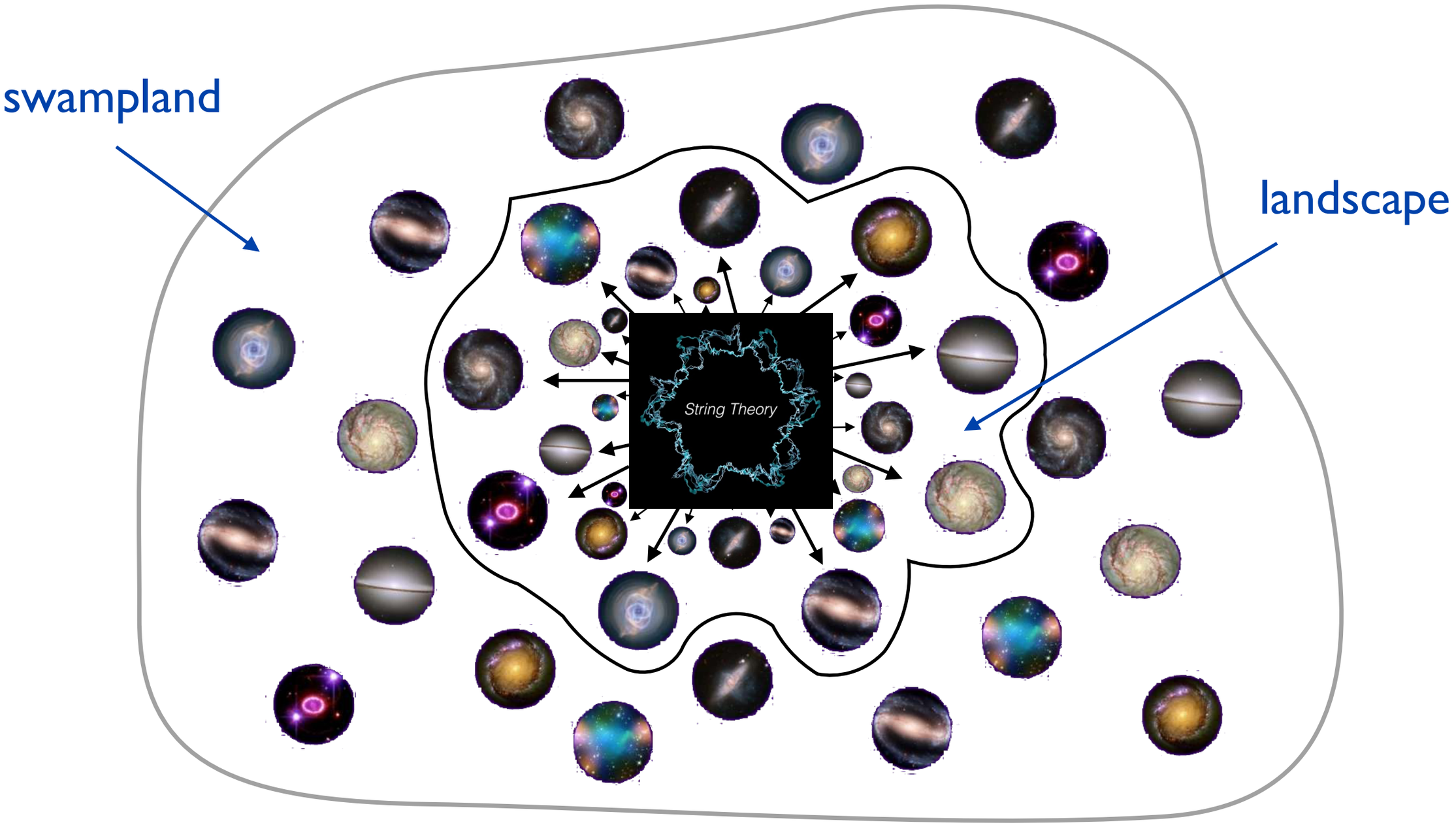


# Change of paradigm in String Phenomenology

New approach to connect string theory to our world (since 2015)

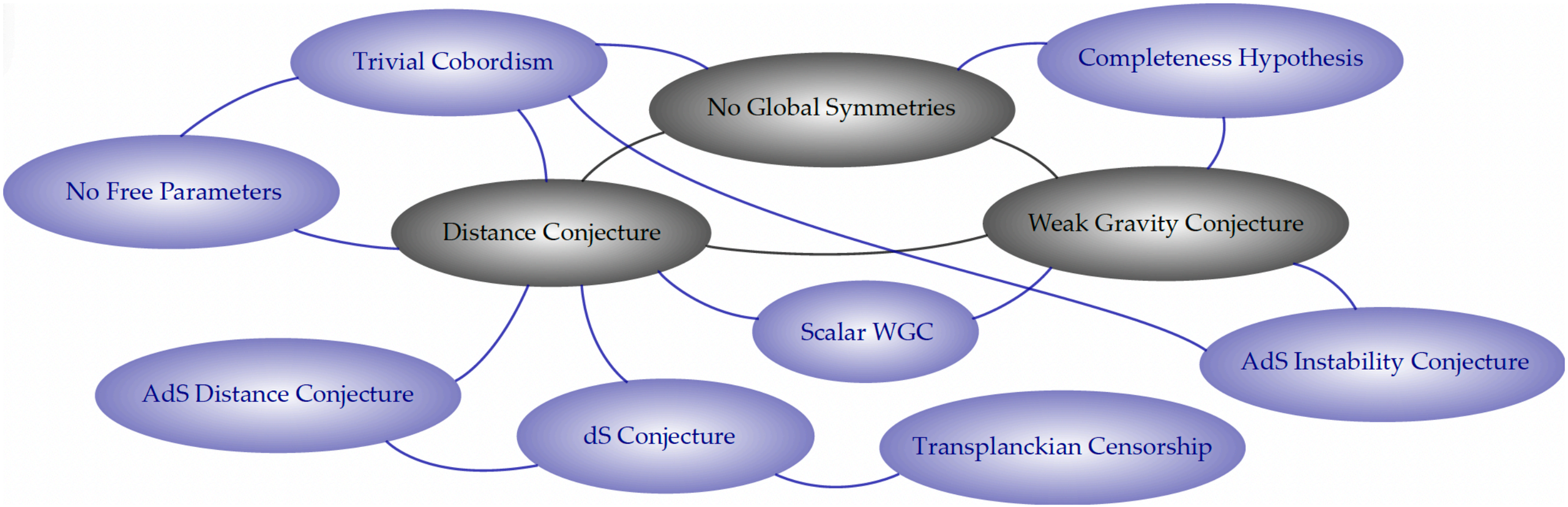
Rather than trying to identify the concrete solution that describes our universe…

… we look for universal features



# Swampland conjectures

Web of interconnected constraints:




We are now living an era of precision

# Swampland conjectures

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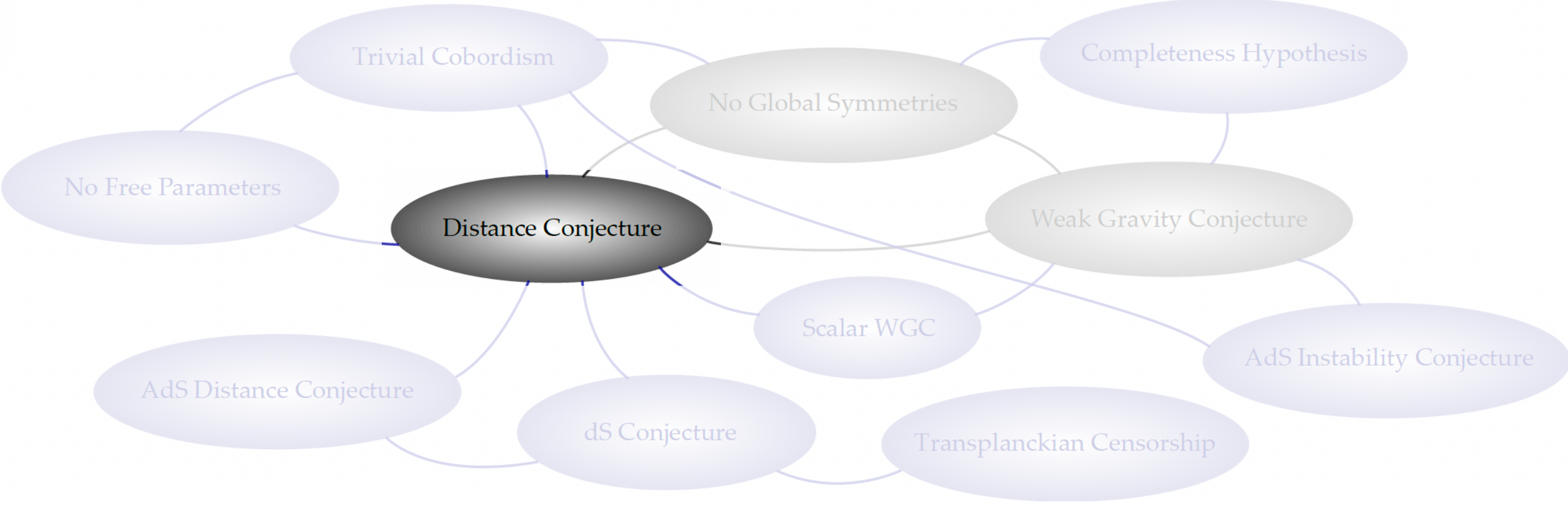


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# A Journey through the Swampland

**What is the scale of quantum gravity?**

01 Distance conjecture

03 String theory evidence

05 Future prospects

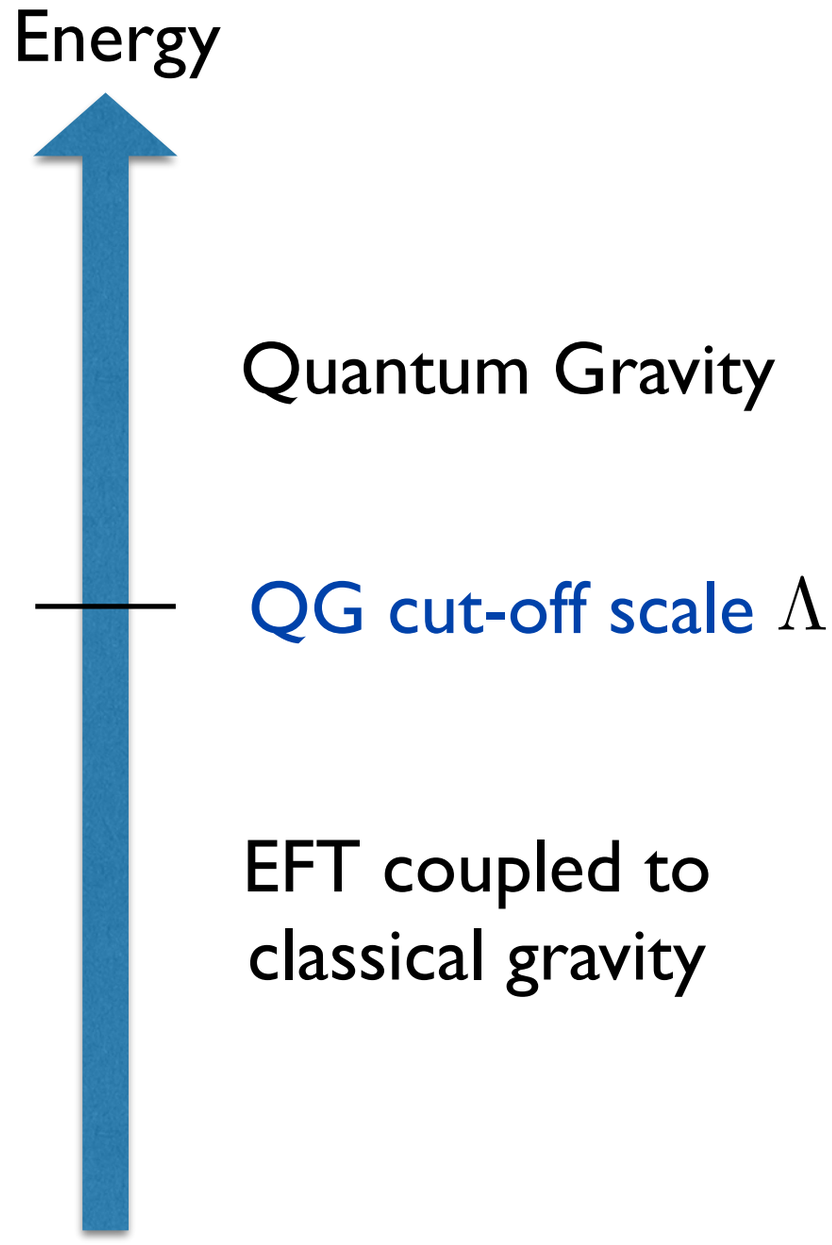
04

02 Proof in AdS/CFT

Phenomenological implications

# What is the scale of quantum gravity?

**Given an Effective Field Theory (EFT) coupled to Einstein gravity, what is the cut-off at which semiclassical gravity breaks down and how?**




Is it $M_p$ ?

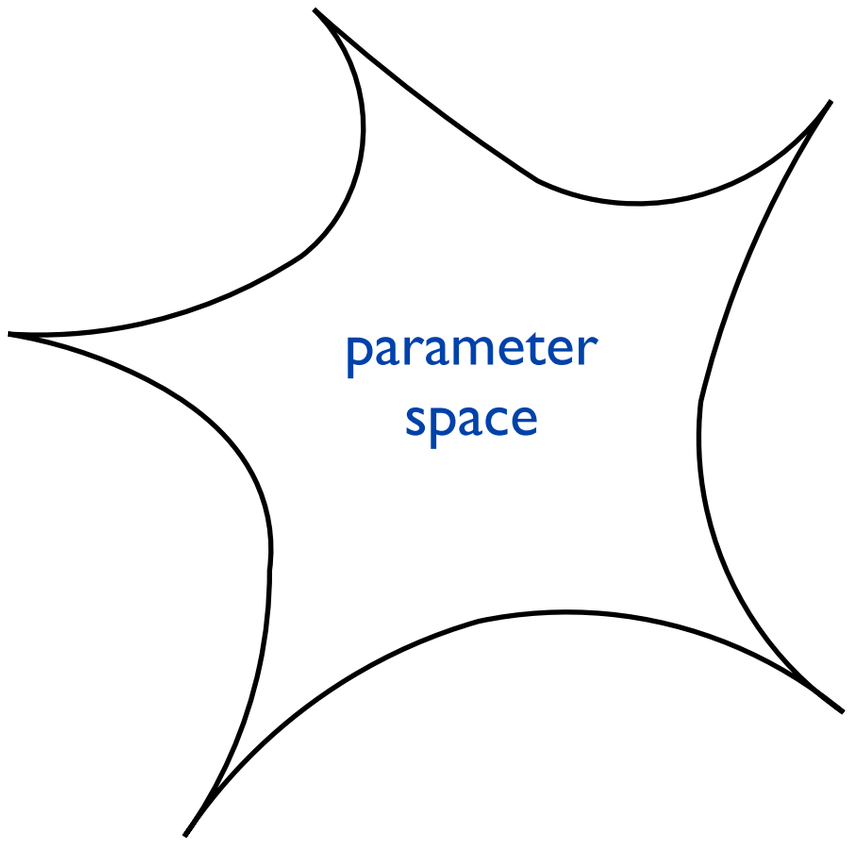
String Theory implies a cut-off

$$\Lambda < M_p$$

(for certain regions of the space of EFT parameters)

# What is the scale of quantum gravity?

String Landscape: Each point corresponds to a different (UV consistent) EFT coupled to gravity




$\mathcal{L}_{\rm EFT}(\varphi, g)$

fields

parameters

the value of these scalar vevs also parametrize the volume/size of extra dimensions

In String Theory: EFT parameters are set by vacuum expectation values of scalar fields $g(\phi)$

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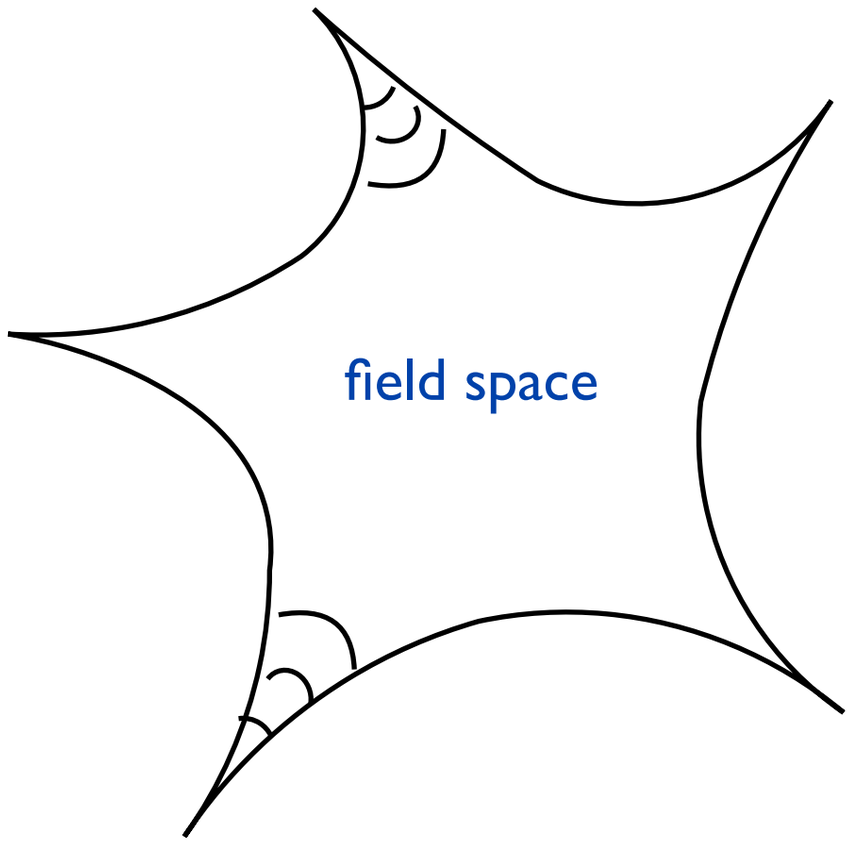


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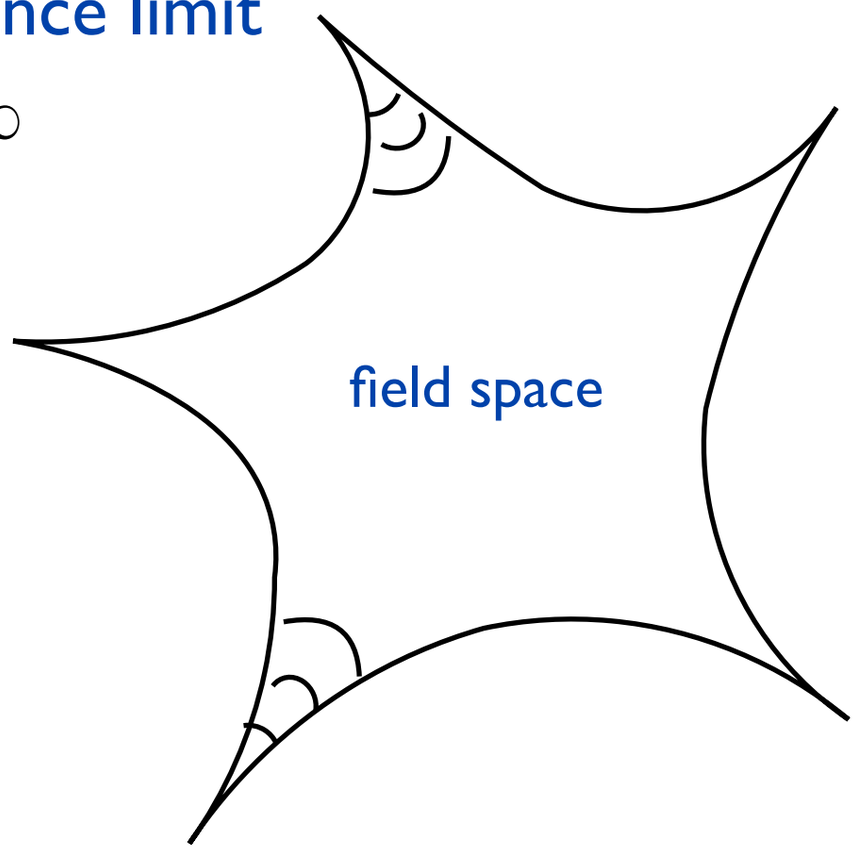
infinite distance limit

$$\phi \to \infty$$




$$\mathcal{L}_{\rm EFT}(\varphi, g)$$

fields

parameters

$$g(\phi)$$

This field space is equipped by a metric given by the kinetic term of the scalars:

$$\mathcal{L} = \frac{M_{{\rm pl},d}}{2}^{d-2} \left( R - \frac{1}{2} g_{ij}(\phi)(\partial\phi)^2 + \dots \right)$$

field metric

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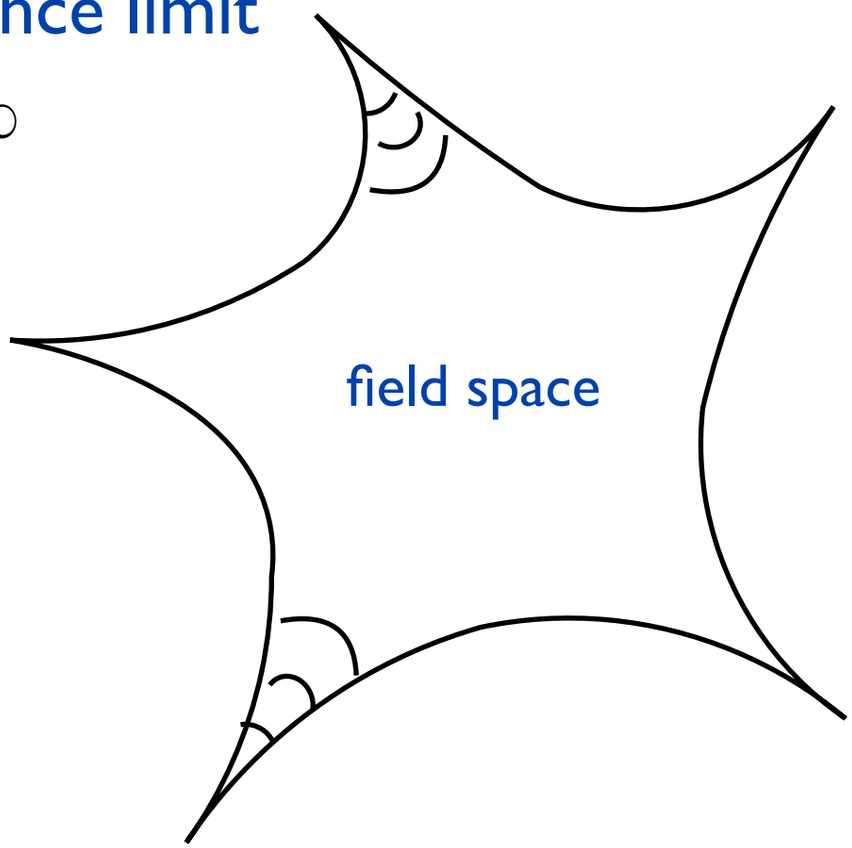


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**What is the value of the QG cut-off scale?**

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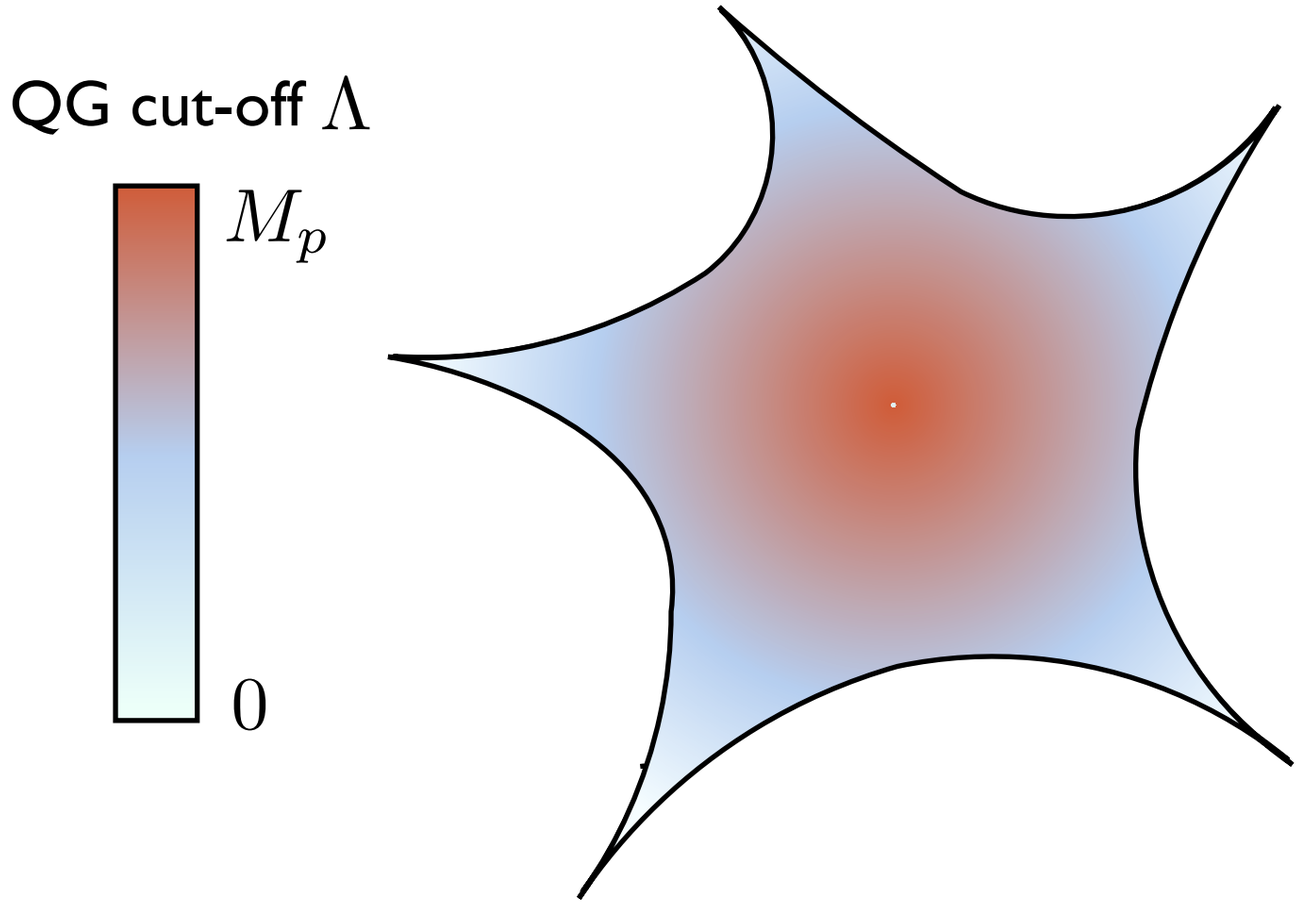



The EFT drastically breaks down at a QG cut-off scale:

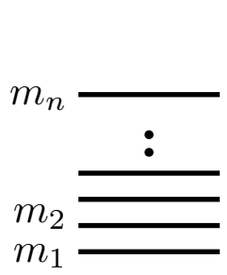
$$\Lambda \sim M_p \exp(-\lambda \Delta\phi) \ll M_p$$

as $\phi \to \infty$

**What is the value of the QG cut-off scale?**

# What is the scale of quantum gravity?

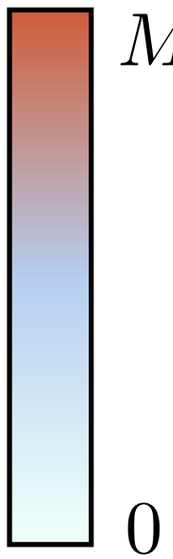
$\exists$ infinite tower of weakly-coupled states becoming all light

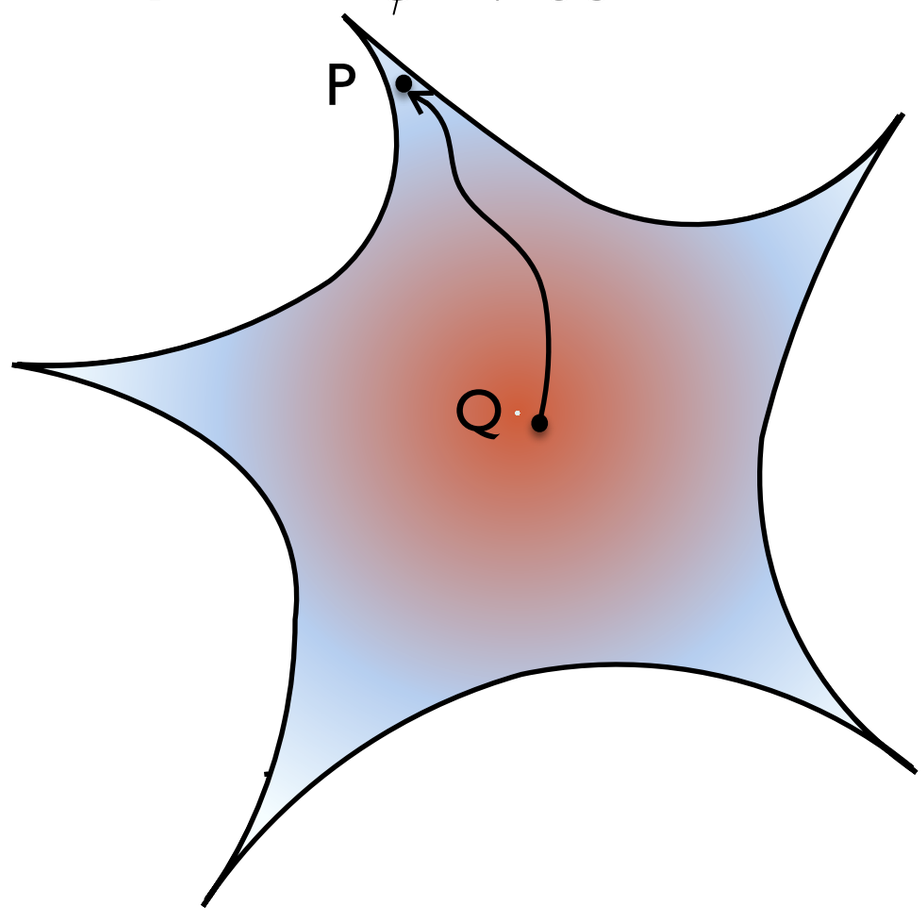



$$m(P) \sim m(Q) e^{-\alpha \Delta \phi}$$

$$\phi \to \infty$$

QG cut-off $\Lambda$

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

as $\phi \to \infty$

**What is the value of the QG cut-off scale?**

This cut-off is known as the "species scale" [Dvali'07] [Dvali,Redi'07]

[Arkani-Hamed et al'07] [Distler,Varadarajan'05] [Dimopoulos et al'05]

# Distance Conjecture

Given an EFT weakly coupled to Einstein gravity with a field space parametrized by the vevs of scalar fields:

$$\mathcal{L} = \frac{M_{\mathrm{pl},d}}{2}^{d-2} \left( R - \frac{1}{2} g_{ij}(\phi)(\partial\phi)^2 + \dots \right)$$

↳ field metric

There should be an infinite tower of states becoming exponentially light when approaching any infinite field distance boundary of the field space

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

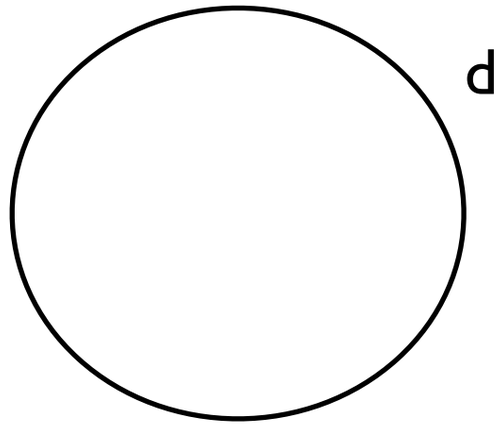
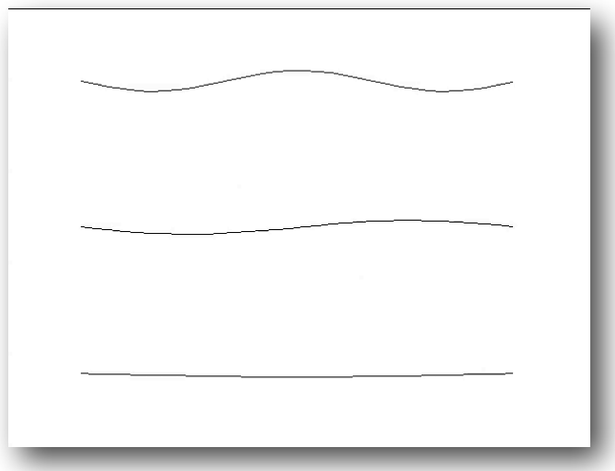
(in Planck units)

$$\Delta\phi = \int_Q^P \sqrt{g_{ij} \frac{d\phi^i}{ds} \frac{d\phi^j}{ds}} ds$$

geodesic distance (canonically normalised scalar field in Einstein frame)

# Nature of the tower

In all known examples in string theory, the tower behaves* as:

| Type | Kaluza-Klein tower | String oscillator tower |
|---|---|---|
| What happens? |  extra dimension grows |  string length grows |

*in some duality frame

# Nature of the tower

In all known examples in string theory, the tower behaves* as:

| Type | Kaluza-Klein tower | String oscillator tower |
|---|---|---|
| What happens? | decompactification limit of extra dimensions $R \to \infty$ | perturbative string limit $g_s \to 0$ |
| QG cut-off | Planck scale of a higher dimensional theory | String scale |

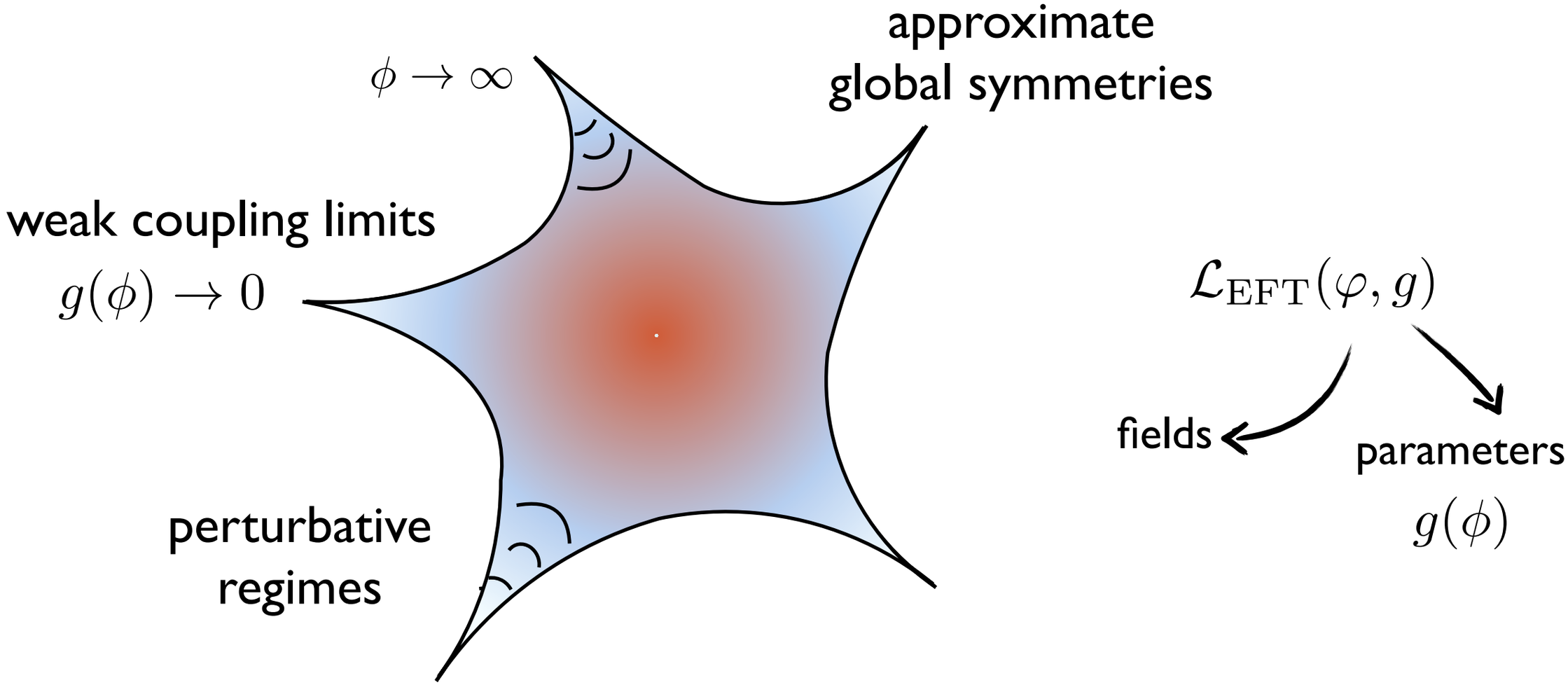
These two possibilities are encoded in the Emergent String Conjecture

[Lee, Lerche, Weigand'19]

*in some duality frame

# Extreme limits of EFT parameters

What happens with the EFT parameters in the infinite distance limits?




Approaching the boundaries of the field space correspond to taking an extreme limit of some EFT parameter

# Extreme limits of EFT parameters

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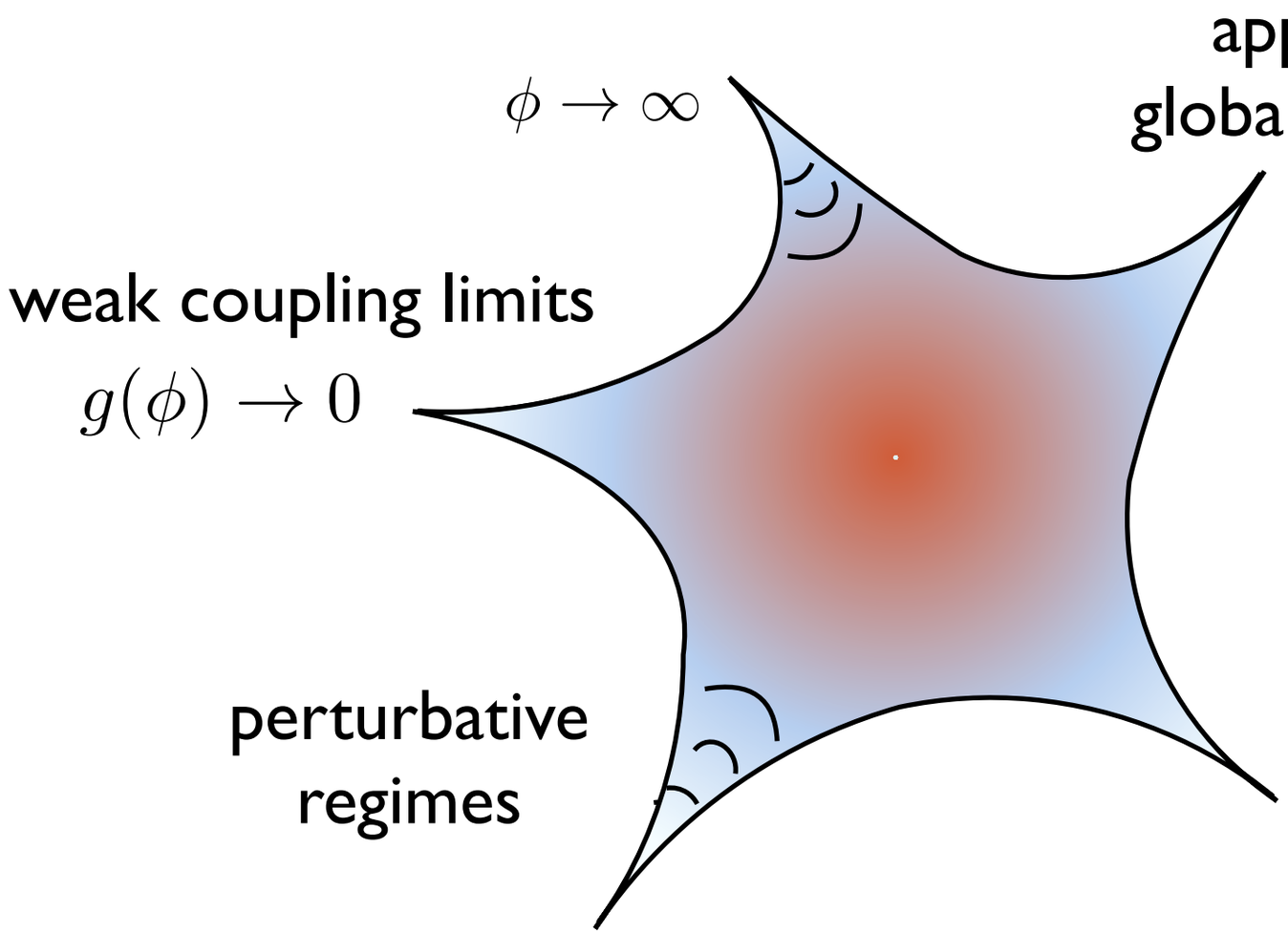


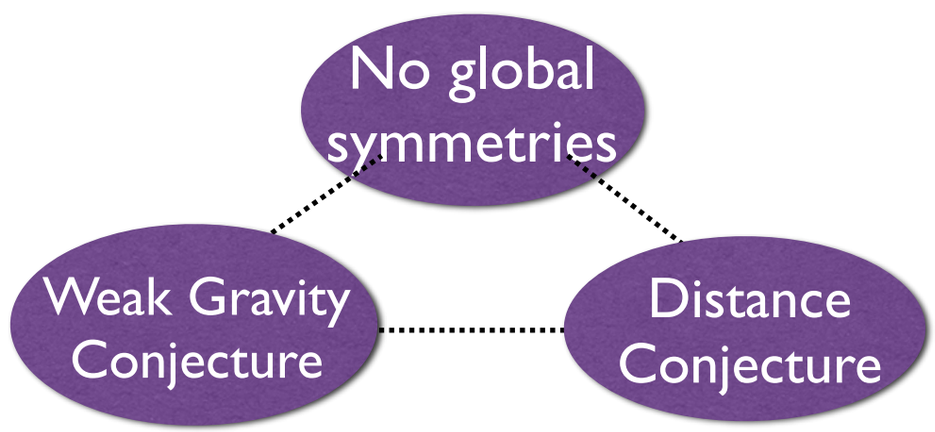

$\mathcal{L}_{\rm EFT}(\varphi, g)$

fields

parameters

$g(\phi)$

The theories at the boundaries contain features which are not consistent with QG



# Extreme limits of EFT parameters

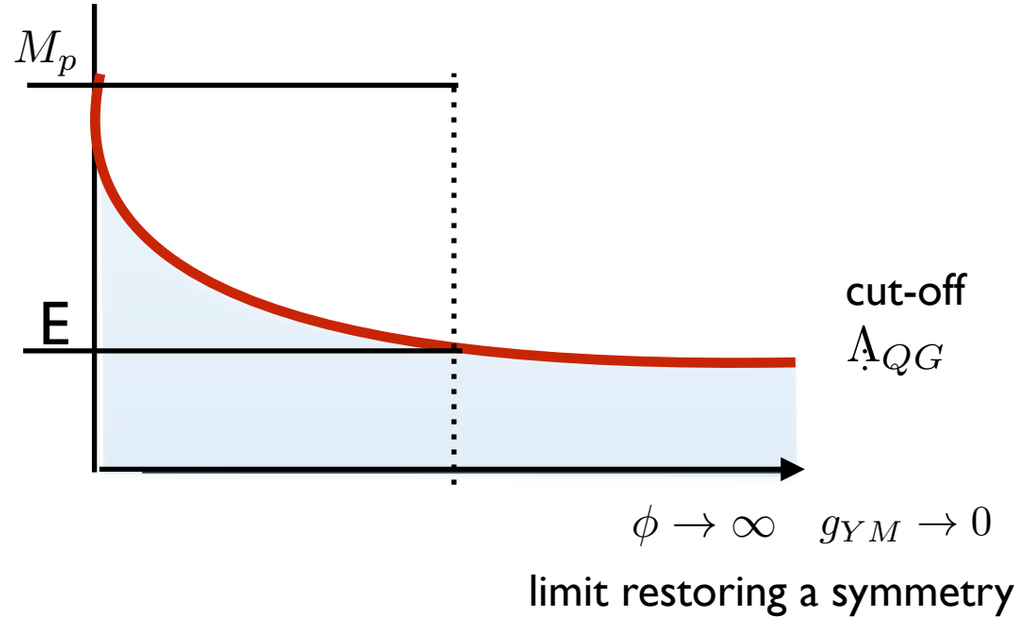
Very natural feature from string theory perspective, but surprising for the low energy EFT!

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

but still, the EFT must break down 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**

# A Journey through the Swampland

**What is the scale of quantum gravity?**

01 Distance conjecture

03 String theory evidence

05 Future prospects

04

02 Proof in AdS/CFT

Phenomenological implications

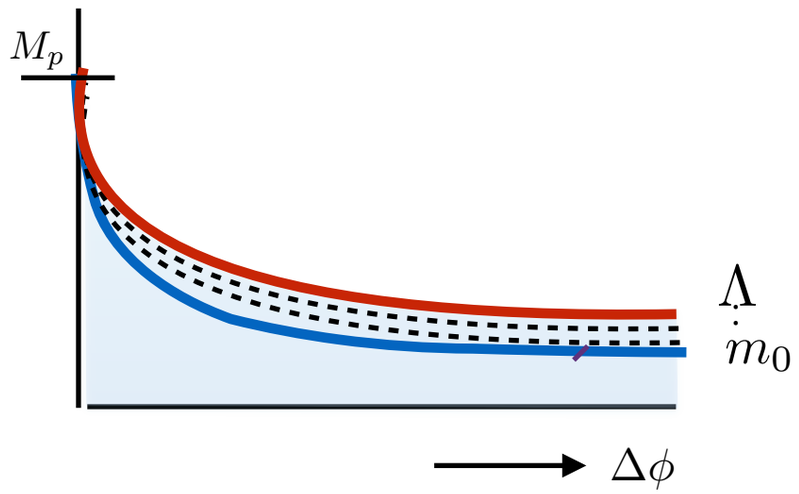
# Implications for Cosmology

In cosmology we often have new scalar fields whose dynamics drive:

- Inflation (early time acceleration of the universe)
- Quintessence (late time acceleration)
- Cosmological solutions to the EW hierarchy problem (e.g. relaxion)

Distance Conjecture implies that QG effects become significant at a scale:

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




Large field ranges are problematic since the cut-off gets reduced

# Implications for Cosmology

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

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

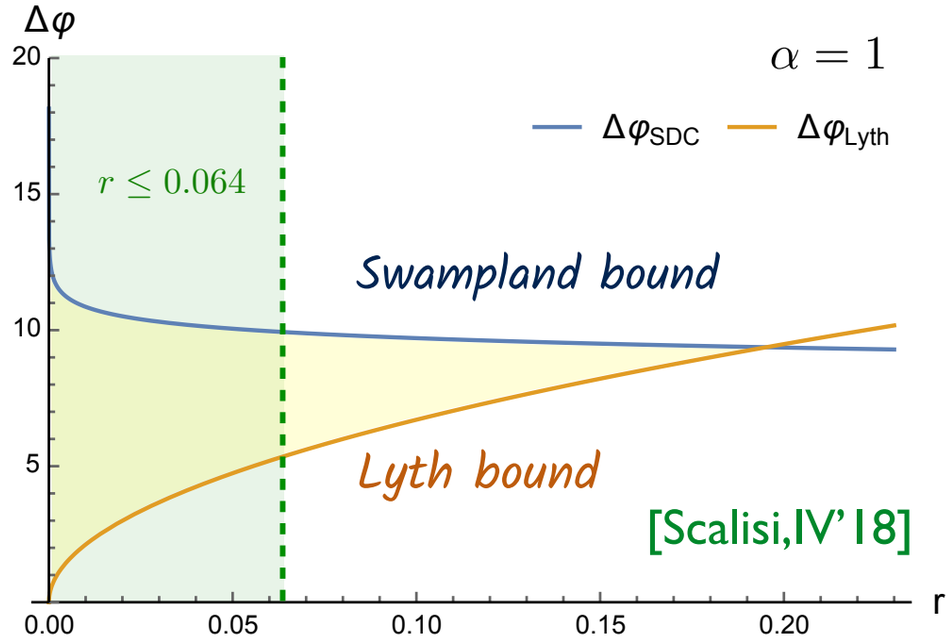
**Example:** Constraints on single field inflation

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

$$H \leq \Lambda$$

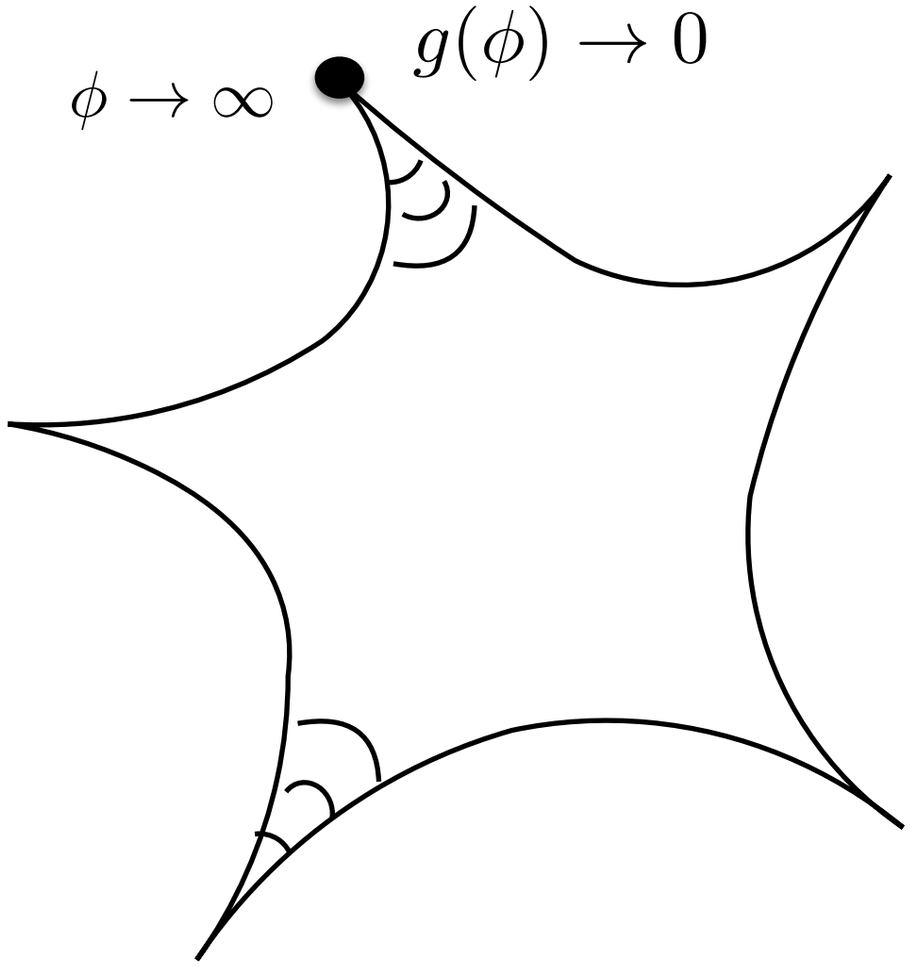
Large field inflation is not ruled out, but can be highly constrained

This triggered the revolution of the Swampland program in 2015




(constraints on multi-field inflation are more involved)

# Implications for Particle Physics




**For weak coupling limits:**

$\exists$ tower of states becoming light as the gauge coupling becomes small

➡ EFT breaks down at $\Lambda \lesssim g^k \, M_p$

with $1/3 \leq k \leq 1$

Lower bound on gauge coupling!

(gravity always remains as the weakest force)

Small gauge couplings (very weakly coupled gauge interactions) are problematic since the cut-off gets reduced

# Implications for Particle Physics

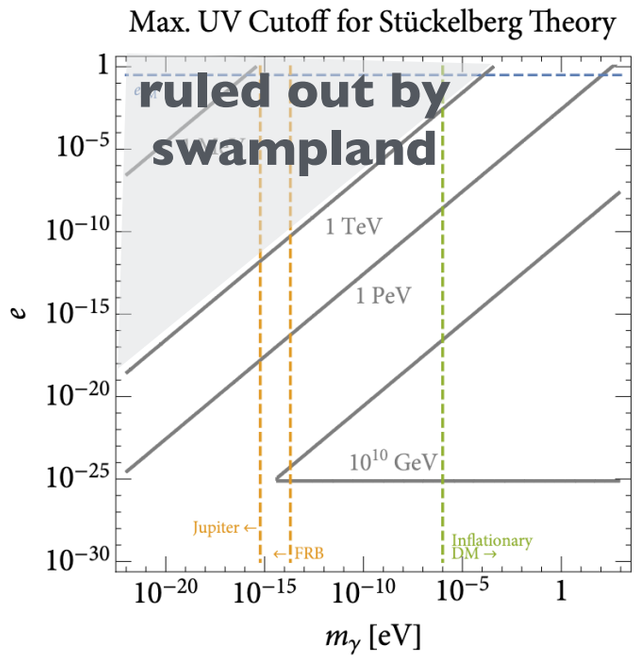
## Constraints on new forces:

- If (B-L) symmetry in the SM is gauged (there is a new gauge boson associated to it):

$$g < 10^{-24} \Rightarrow \Lambda_{\rm QG} < 10^{11}\ {\rm GeV}$$

experimental bound

- Bounds on dark photons:




[Reece'18]

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

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01 Distance conjecture

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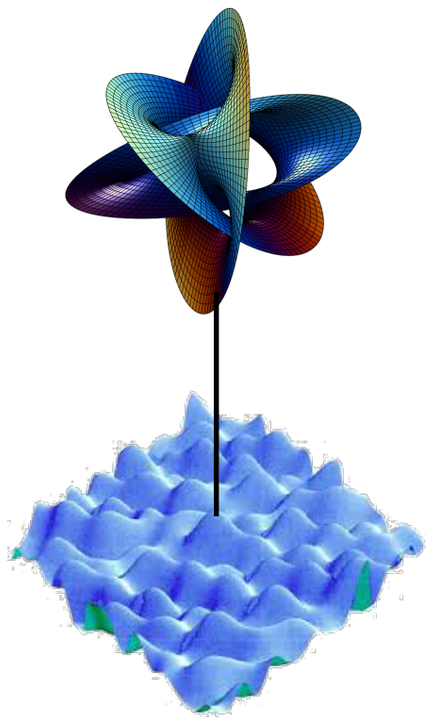
# String Theory Evidence

❖ **Plethora of works testing the conjecture in string theory compactifications to flat space:** [Grimm,Palti,IV'18] [Lee,Lerche,Weigand'19] …

Álvarez-García, Andriot, Antoniadis, Basile, Baume, Bedroya, Angius, Benakli, Blasio, Blumenhagen, Brandenberger, Huertas, Buratti, Calderón-Infante, Castellano, Cecotti, Collazuol, Collins, Cota, Cremonini, Cribiori, Dalianis, Delgado, Dierigl, Etheredge, Farakos, Fierro Freitas, Gnecci, Gonzalo, Graña, Grimm, Hamada, Heidenreich, Herráez, Horer, Ibáñez, Jafferis, Kehagias, Lanza, Lee, Lerche, Li, Long, Lust, Marchesano, Mavromatos, McNamara, Melotti, Mininno, Montella, Montero, Morittu, Ooguri, Palti, Parra Petri, Bastian, Quirant, Rajaguru, Raman, Reece, Riet, Rudelius, Ruiz, Scalisi, Schlechter, Seo, Shiu, Stout, Tarazi, Tonioni, Tran, Tringas, Uranga, Van de Heisteeg, Vafa, Valenzuela, Weigand, Wiesner, Wrase, Wu, Xu, Yau...

(M-theory and Heterotic toroidal comp., F-theory and IIB on Calabi-Yau's, M-theory on G2, Type IIA orientifolds, non-SUSY heterotic…)



The Distance conjecture can be translated to geometric properties of the extra dimensions and the behaviour of stringy states

→ Proven in large classes of string compactifications

# What is the exponential decay rate?

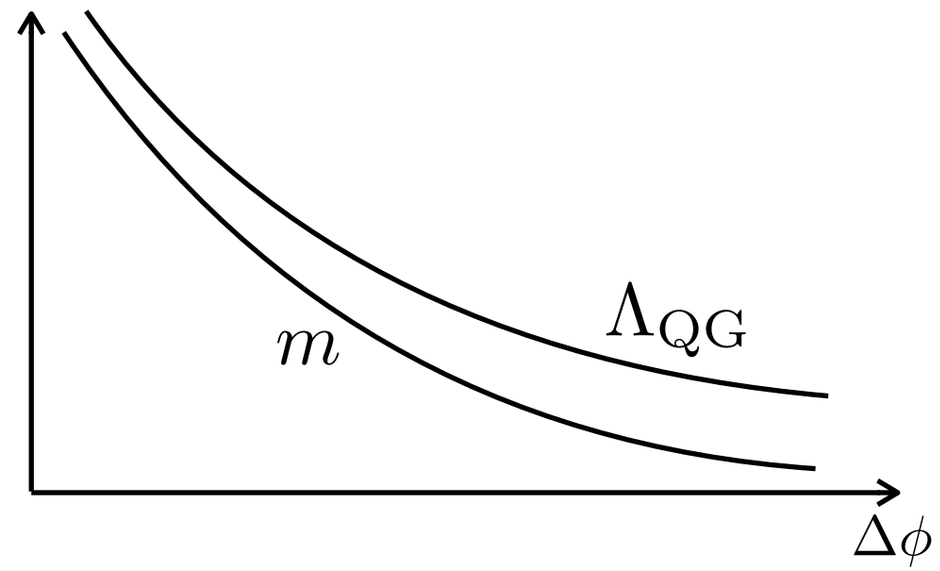
**Goal: determine the value of the exponential rates**

Mass of the tower:

$$m \sim m_0 \exp(-\alpha \Delta\phi)$$

Quantum Gravity cut-off:

$$\Lambda_{\rm QG} \sim m^\gamma \sim M_p \exp(-\lambda \Delta\phi)$$




The value of the exponential rates depend on the microscopic nature of the tower, so it is model-dependent (it depends on the type of limit)

**But...**

# What is the exponential decay rate?

There is a universal pattern relating the lightest state and the quantum gravity cut-off satisfied in all string theory examples:

[Castellano,Ruiz,IV'23]

$$G^{\phi^i\phi^j}\frac{\partial_{\phi^i} m}{m}\frac{\partial_{\phi^j}\Lambda}{\Lambda}=\frac{1}{d-2}$$

$d=$ space-time dimension

- metric in field space
- mass of the lightest state of the tower
- quantum gravity cut-off

For a single field:

$$\alpha\,\lambda=\frac{1}{d-2}$$

Since $m\leq\Lambda$ $\Rightarrow$ $m\sim m_0\exp(-\alpha\Delta\phi)$

$$\alpha_{min}=\left|\frac{\vec{\nabla}m}{m}\right|\geq\frac{1}{\sqrt{d-2}}$$

This gives a universal upper bound for that the mass of the lightest state

(it reproduces the bound proposed in [Etheredge et al'22] )

# A Journey through the Swampland

**What is the scale of quantum gravity?**

01 Distance conjecture

02 Phenomenological implications

03 String theory evidence

04 Proof in AdS/CFT

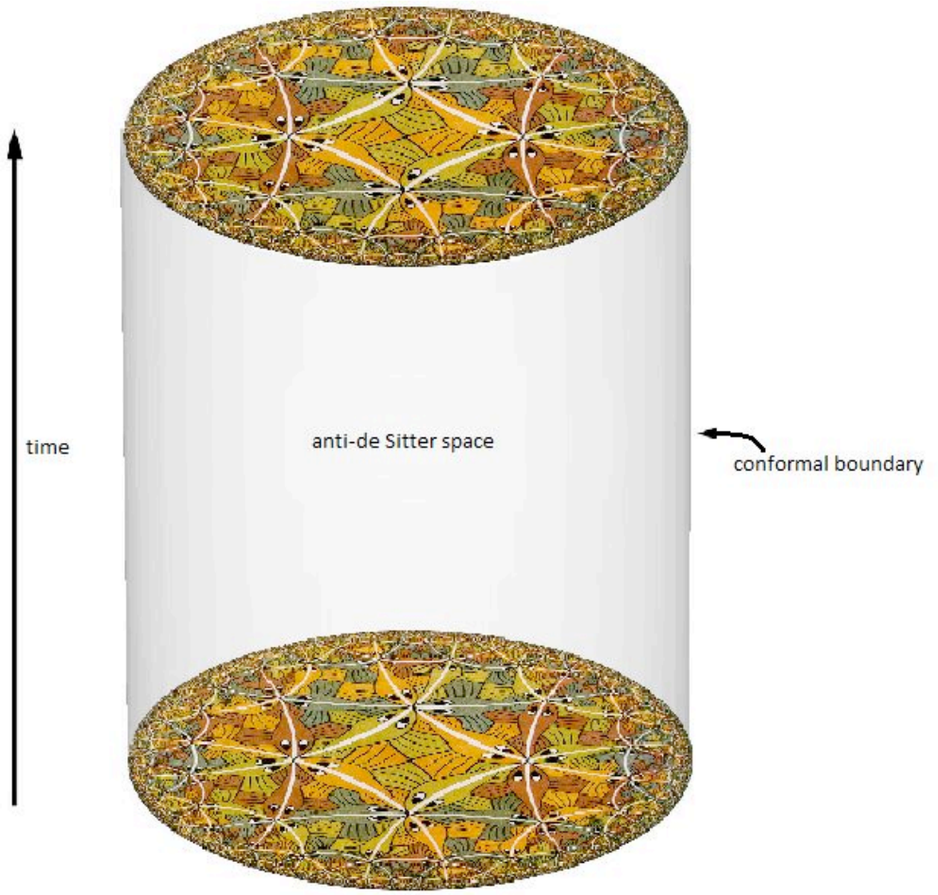
05 Future prospects

# Holographic duality

Quantum Gravity in
(d+1)-dimensional
Anti-de-Sitter (AdS) space

dual

Conformal field theory
(CFT) in d-dimensions




Can we translate the Distance conjecture to the CFT
and prove it using CFT techniques?

# CFT Distance Conjecture

**Distance Conjecture in CFT language:**

∃ infinite tower of operators saturating the unitarity bound at every infinite distance limit measured by Zamolodchikov metric in the conformal manifold, such that

$$\gamma_J \sim e^{-\alpha d(\tau,\tau')} \quad \text{as} \quad d(\tau,\tau') \to \infty$$

[Perlmutter,Rastelli,Vafa,IV'21]
[Baume,Calderon-Infante'21]

anomalous dimension

$\gamma_J = \Delta - \Delta_{\text{unitarity}}$

distance measured by Zamolodchikov metric

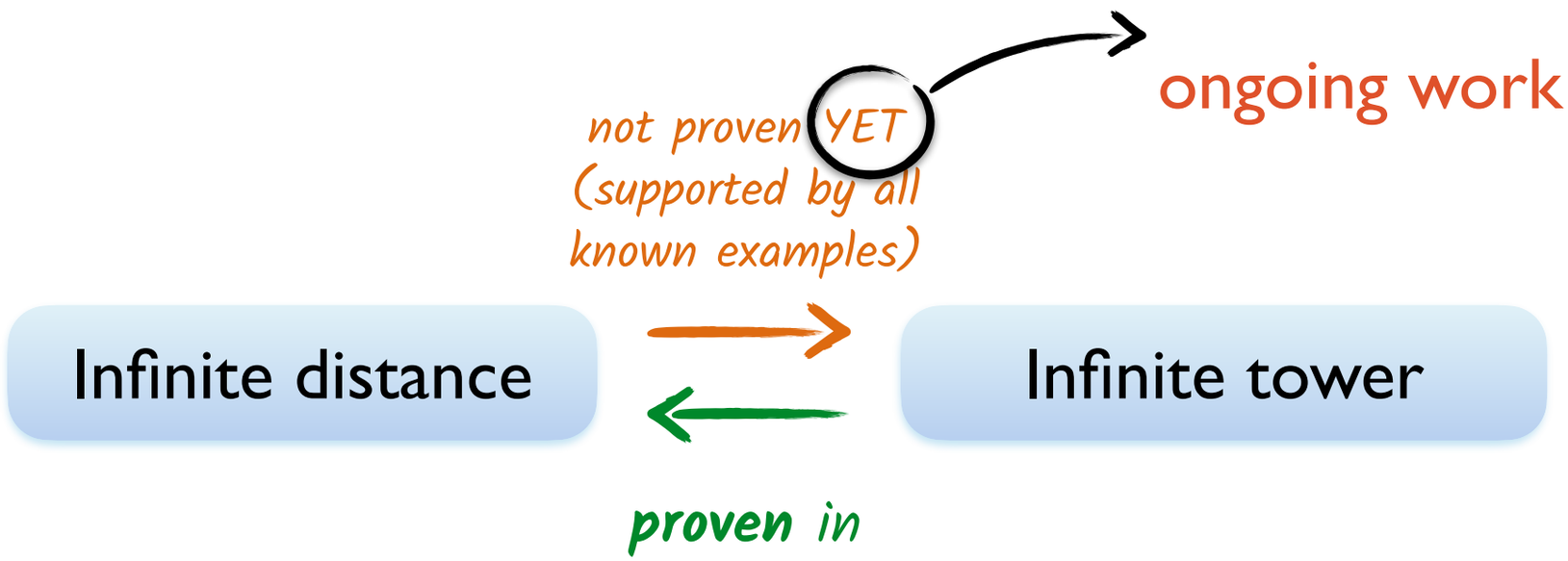
$|x-y|^{2d}\langle O_i(x)O_j(y)\rangle = g_{ij}(t^i)$

For $d=2$ : Tower of scalar modes [Kontsevich,Soibelman'00] [Ooguri,Wang'24] [Acharya,Douglas'06]

For $d\geq 3$ : Tower of higher spin modes [Perlmutter,Rastelli,Vafa,IV'21] [Baume,Calderon-Infante'21-23] [Calderon-Infante,IV'24]

# CFT Distance Conjecture

Can we prove it for any CFT? A Distance theorem?




[Baume,Calderon-Infante'23] for higher spin gap in d>2
[Ooguri,Wang'24] for scalar gap in d=2

**Lesson:** it holds for any local unitary CFT (and thus, any AdS gravity dual), regardless of having an Einstein gravity description at low energies and regardless of supersymmetry

# A Journey through the Swampland

**What is the scale of quantum gravity?**

01 Distance conjecture

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# Bottom-up Explanation

1) Can we find a bottom-up rationale for the existence of the tower of states?

❖ Black Hole physics: [Hamada,Montero,Vafa,IV'21] [Cribiori,Luest,Staudt'22]
[Calderon-Infante,Castellano,Herraez,Ibañez'23]
[Calderon-Infante,Delgado,Uranga'23] [Bedroya,Mishra,Wiesner'24]

❖ Unitarity/Causality of scattering amplitudes:

[Caron-Huot,Li'24] [Häring,Zhiboedov,24]

and much more to come!

# Extreme values of parameters

2) Can we forget about the scalar field space and formulate it purely in terms of EFT data?

What 'extreme limits" of EFT parameters imply a drop-off of the QG cut-off?

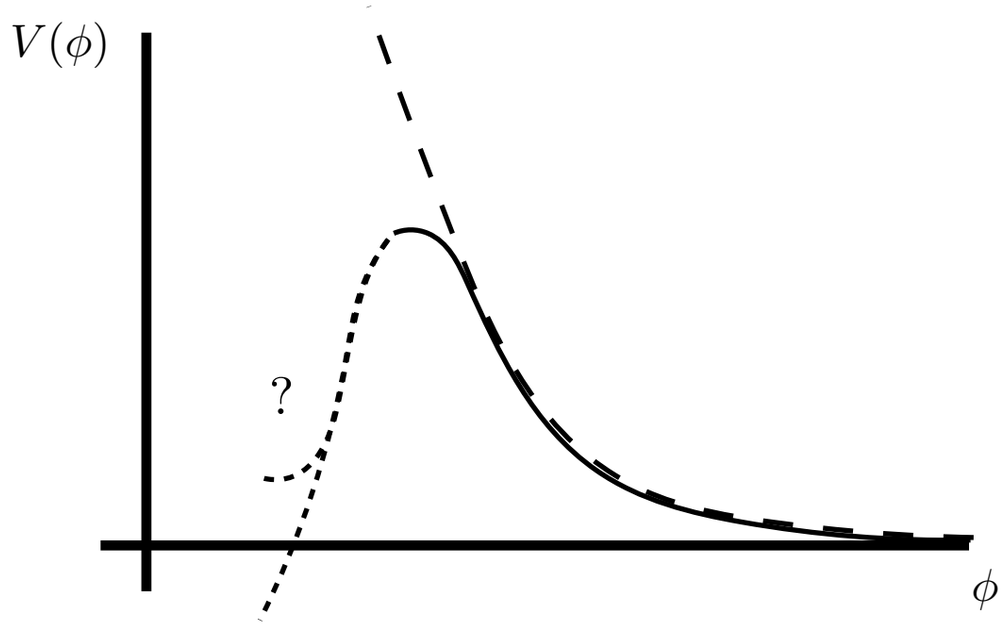
Any small parameter works?

If so… there is a very tiny quantity in our universe:

**The value of Dark Energy** $V_0 \sim 10^{-120} M_p$

# Dark Energy as an extreme limit

Indeed, in all known (non-AdS) string theory examples, the vacuum energy vanishes at the infinite distance boundaries of the field space




**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 infinite distance 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

Combining both theoretical and experimental bounds:

- The light tower of states should have a 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]

# Dark Dimension

A particular corner of large extra dimension models, motivated by the cosmological constant problem (rather than the EW hierarchy problem)

[Arkani-Hamed,Dimopoulos, Dvali'98]

QG scale: $\hat{M} \sim m^{1/3} M_P^{2/3} \sim 10^{10}\, GeV \;\neq$ TeV scale

To be further explored theoretically… [Gonzalo et al'22] [Law-Smith et al'23] [Anchordoqui et al'23-24] [Basile,Luest'24] [Heckman,Vafa,Weigand,Xu'24]

To be tested experimentally…

New ISLE at the Conrad Observatory [Aspelmeyer,Adelberger,Shayeghi,Zito…]

It will be tested in the next five years!

# Conclusions

- Consistency with Quantum Gravity can have significant implications for our universe at energies much below the Planck scale.

- We are entering an era of precision in the Swampland program: recent developments to sharpen and prove the swampland constraints.

- The Distance Conjecture implies the existence of an infinite tower of states at every infinite field distance limit, so that $\Lambda_{QG} \ll M_p$

- It implies bounds on large field ranges, weakly coupled interactions and maybe even predict the existence of a large extra dimension!

# Conclusions

- This is the end of the journey today, but it is just the tip of the iceberg, many more swampland constraints and much more work to be done.

- Both theoretical analysis and experimental data can help us to map out the boundary between the landscape and the swampland.

*Thank you!*

# back-up slides

# Experimental constraints

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

In our universe: $V^{1/4} \sim 2.31 \text{ meV}$

**Nature of the tower** (according to string theory): [Lee,Lerche,Weigand'19]

- ~~String perturbative limit~~ *ruled out exp.*
- Decompactification of n extra dimensions

**Experimental constraints:**

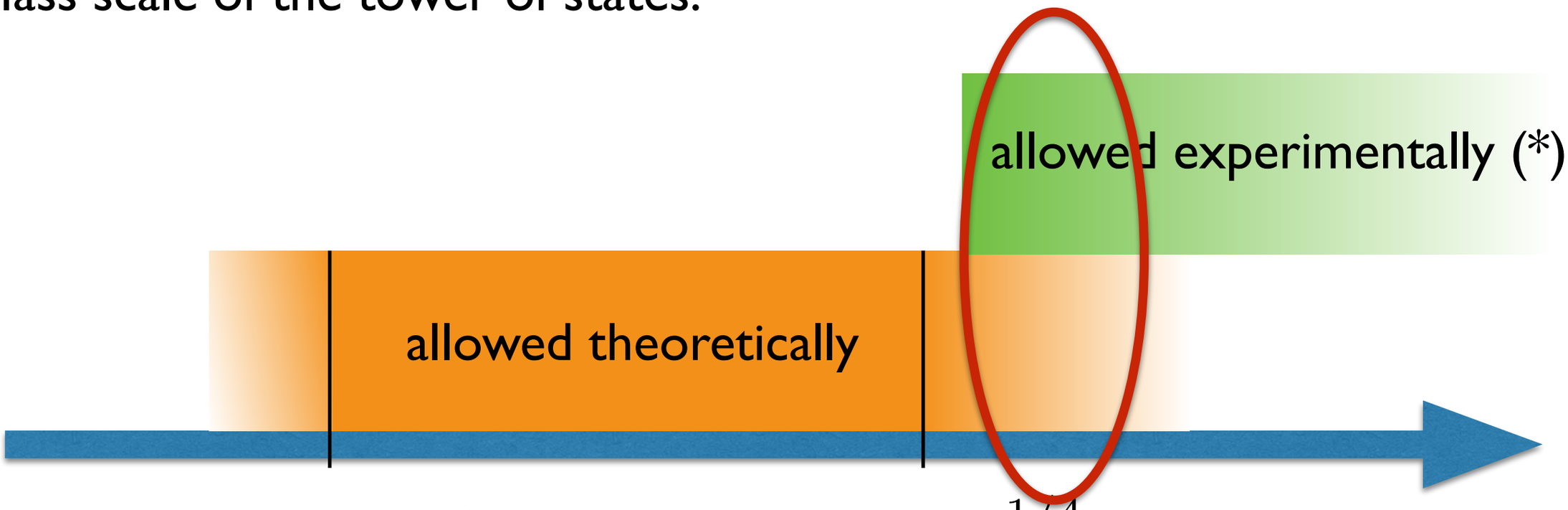
- Astrophysical bounds: $m^{-1} \leq 10^{-4}\,\mu m \quad (n=2)$ ~~$(n=2)$~~ *ruled out*

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

- Dev. from Newton's laws (n=1): $m^{-1} \leq 30\,\mu m$ [Lee et al '21]

# Dark Dimension

Mass scale of the tower of states:




Higuchi bound

Casimir contribution
(one loop quantum correction)

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

# CFT Distance conjecture

**Consider a 4d CFT:** [Perlmutter,Rastelli,Vafa,IV'21] (see also [Baume,Calderon-Infante'21])

All known infinite distance limits are weak coupling limits

$$g_{YM} \to 0 \longrightarrow \mathcal{O}_\tau = \mathrm{Tr}(F^2 + \dots) \qquad \tau = \frac{4\pi i}{g^2_{YM}} + \frac{\theta}{2\pi}$$

By perturbation theory: $ds^2 = \beta^2 \frac{d\tau d\bar{\tau}}{(\mathrm{Im}\tau)^2}$ as $\mathrm{Im}\tau \to \infty$

$\beta^2 = 24\ \mathrm{dim}G$ → gauge group getting free

$\Rightarrow \mathrm{CFT}_{\mathrm{free}} \times \mathrm{CFT}'$

Free point ⇄ Higher Spin tower [Maldacena,Zhiboedov'11]

Higher spin (HS) operators $\gamma_J \sim f(J) g^2_{YM} \sim f(J) \exp\left(-\frac{d(\tau,\tau')}{\beta}\right)$

⇔ Tower of higher spin fields in AdS with an exponential rate:

$$\alpha = \sqrt{\frac{2c}{\mathrm{dim}G}} \geq \frac{1}{\sqrt{d-2}}$$

for all examples

# Classification of Infinite Distance Limits in d>2

Exponential rate: $\alpha = \sqrt{\frac{2c}{\dim G}} = \frac{1}{\sqrt{4a/c - 2}}$ [Calderon-Infante,IV' ongoing]

Consider the full classification of 4d SCFTs with large N and simple factor for the gauge group $G = SU(N), USp(2N), SO(N)$

[Bhardwaj,Tachikawa'13] [Razamat, Sabag, Zafrir'20]

Only three values appear!

$$\alpha = \frac{1}{\sqrt{2}}, \sqrt{\frac{7}{12}}, \sqrt{\frac{2}{3}}$$

critical string  non-critical strings

because of $\frac{a}{c} = \{1, \frac{13}{14}, \frac{7}{8}\}$

They all correspond to higher spin points (a tensionless string limit in the bulk)

Do they correspond to three different types of tensionless strings?

Yes, they seem to have three different values for the Hagedorn temperature

$T_H = T_H(a/c)$ [Calderon-Infante,IV' ongoing]

| $G$ | Hypermultiplets | $c$ | $\alpha$ |
|---|---|---|---|
| $SU(N)$ | $2N$ **fund** | $\frac{1}{6}(2N^2-1)$ | $\sqrt{\frac{2}{3}}$ |
| $SU(N)$ | 1 **asym**, $N+2$ **fund** | $\frac{1}{24}(7N^2+3N-4)$ | $\sqrt{\frac{7}{12}}$ |
| $SU(N)$ | 2 **asym**, 4 **fund** | $\frac{1}{12}(3N^2+3N-2)$ | $\frac{1}{\sqrt{2}}$ |
| $SU(N)$ | 1 **asym**, $N-2$ **fund** | $\frac{1}{24}(7N^2-3N-4)$ | $\sqrt{\frac{7}{12}}$ |
| $SU(N)$ | 1 **sym**, 1 **asym** | $\frac{1}{12}(3N^2-2)$ | $\frac{1}{\sqrt{2}}$ |
| $USp(2N)$ | $4N+4$ $\frac{1}{2}$ **fund** | $\frac{1}{6}N(4N+3)$ | $\sqrt{\frac{2}{3}}$ |
| $USp(2N)$ | 1 **asym**, 4 **fund** | $\frac{1}{12}(6N^2+9N-1)$ | $\frac{1}{\sqrt{2}}$ |
| $SO(N)$ | $N-2$ **vect** | $\frac{1}{12}N(2N-3)$ | $\sqrt{\frac{2}{3}}$ |

[Bhardwaj,Tachikawa'13]

4d N=2 SCFTs

[Razamat, Sabag, Zafrir'20]

4d N=1 SCFTs

| $G$ | Theory | $c$ | $\alpha$ |
|---|---|---|---|
| $SU(N)$ | Table 2, #1 | $\frac{1}{24}(7N^2-5)$ | $\sqrt{\frac{7}{12}}$ |
| $SU(N)$ | Table 2, #5 | $\frac{1}{24}(6N^2+3N-5)$ | $\frac{1}{\sqrt{2}}$ |
| $SU(N)$ | Table 3, #4 | $\frac{1}{24}(7N^2-4)$ | $\sqrt{\frac{7}{12}}$ |
| $SU(N)$ | Table 5, #4 | $\frac{1}{24}(8N^2-3)$ | $\sqrt{\frac{2}{3}}$ |
| $USp(2N)$ | Table 12, #1 | $\frac{1}{24}(14N^2+15N-1)$ | $\sqrt{\frac{7}{12}}$ |
| $USp(2N)$ | Table 13, #9 | $\frac{1}{8}(4N^2+8N-1)$ | $\frac{1}{\sqrt{2}}$ |
| $USp(2N)$ | Table 13, #10 | $\frac{1}{24}(14N^2+21N-2)$ | $\sqrt{\frac{7}{12}}$ |
| $SO(N)$ | Table 18, #1 | $\frac{1}{48}(7N^2-21N-4)$ | $\sqrt{\frac{7}{12}}$ |
| $SO(N)$ | Table 18, #2 | $\frac{1}{48}(7N^2-15N-2)$ | $\sqrt{\frac{7}{12}}$ |
| $SO(N)$ | Table 18, #3 | $\frac{1}{24}(4N^2-9N-1)$ | $\sqrt{\frac{2}{3}}$ |

# WGC and SDC from Entropy Bounds

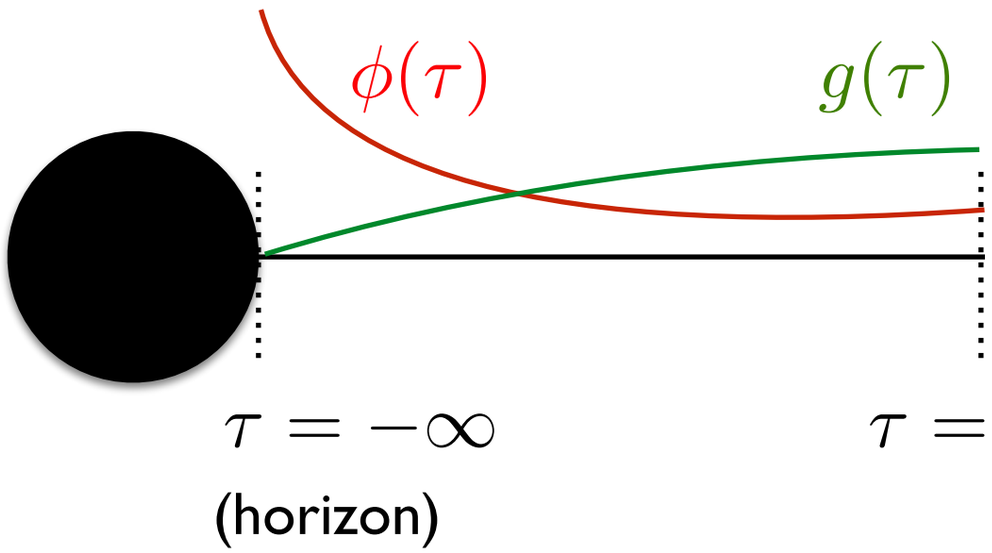
Take Einstein-Maxwell-Dilaton theory:

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

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

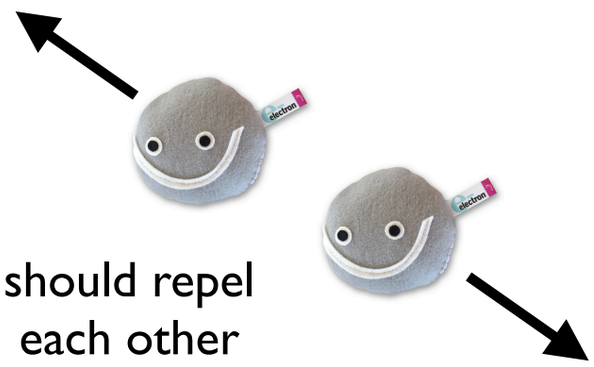
# Implications for Particle Physics

## Interplay with the Weak Gravity Conjecture:

Gravity must be the weakest force

$m_{\text{tower}} \leq qg$ in Planck units

so that $F_g = \dfrac{m^2}{r^2} \leq F_{\text{gauge}} = \dfrac{(qg)^2}{r^2}$




should repel each other

The electron satisfies this!

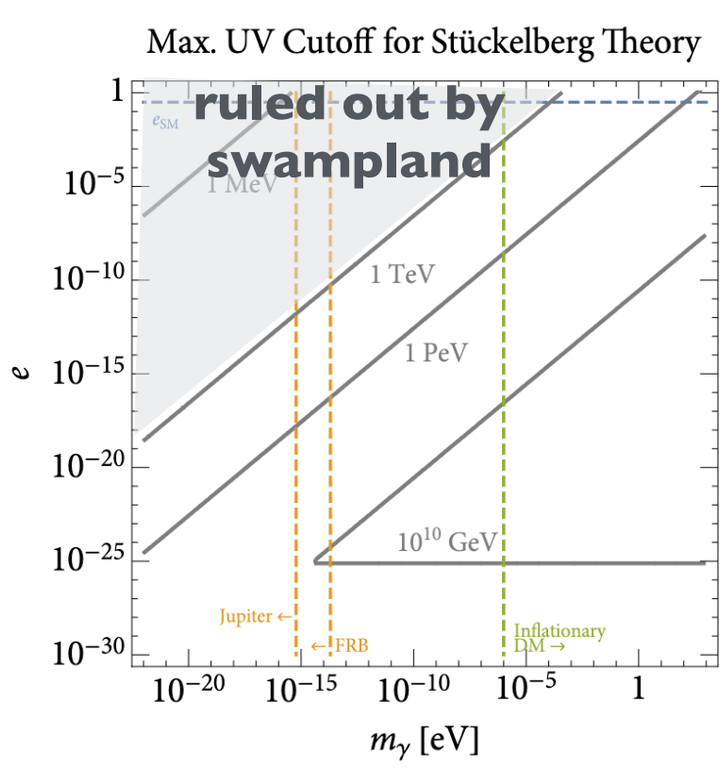
But what if we discover new weakly coupled dark photons?

# Implications for Particle Physics

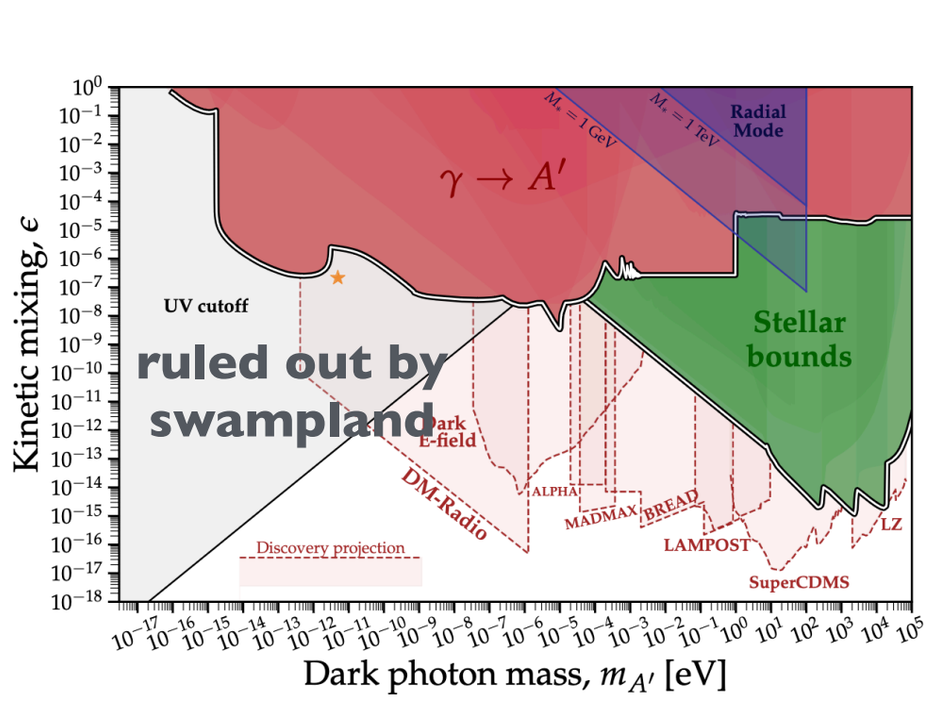
**Constraints on dark photons for dark matter:**

The quantum gravity cut-off becomes $\Lambda_{QG} \ll M_p$

for weakly coupled or very light dark photons




[Reece'18]




[Montero,Muñoz,Obied'22]