The Dark Dimension and the Swampland

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Outline

- Brief overview of the Swampland program
- Quantum gravity requires new physics (tower of new states becoming light) for extreme/small values of EFT parameters
- Applied to dark energy, it motivates the Dark Dimension scenario:

$$\exists \ m_{\rm tower} \sim V_0^{1/4} \sim \mathcal{O}(meV)$$

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

[Montero, Vafa, IV'22]

Swamplands program

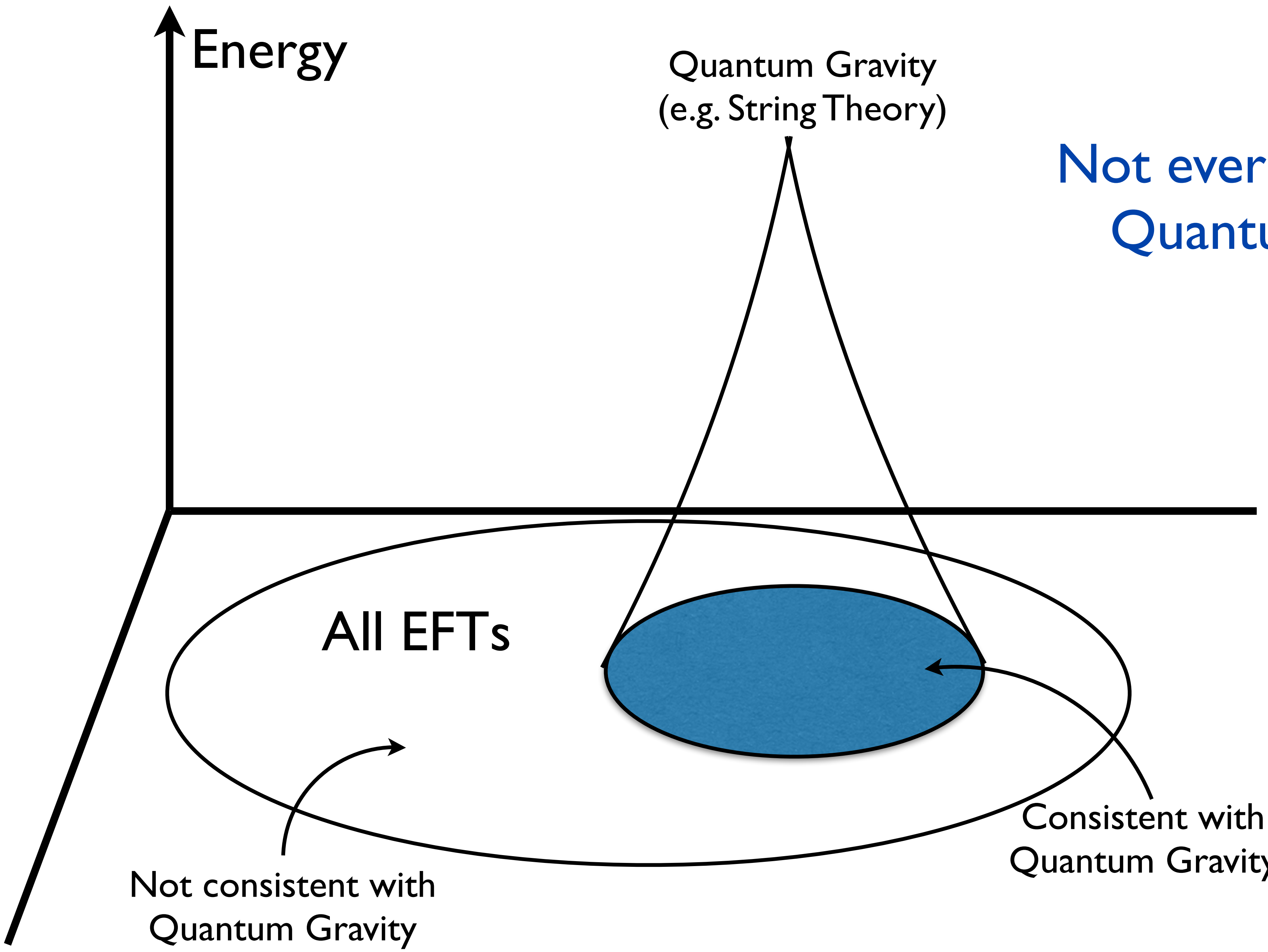
What is the space of Effective Field Theories weakly coupled to Einstein gravity that can be consistely UV completed (in quantum gravity)?

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

Not every EFT can be UV completed!

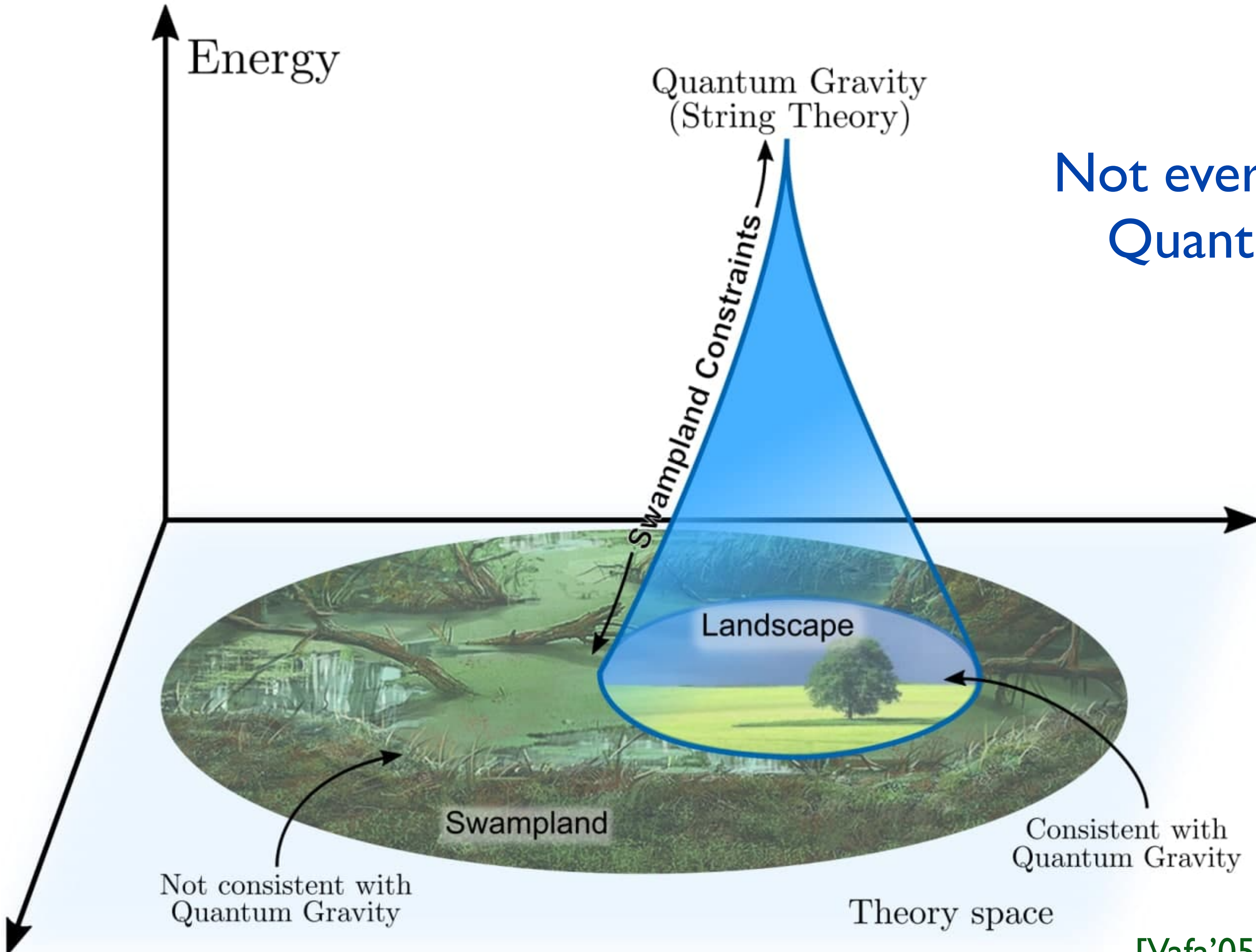
What can it go here?

What is the quantum gravity cut-off?



Not everything goes in Quantum Gravity!

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



[Vafa'05]

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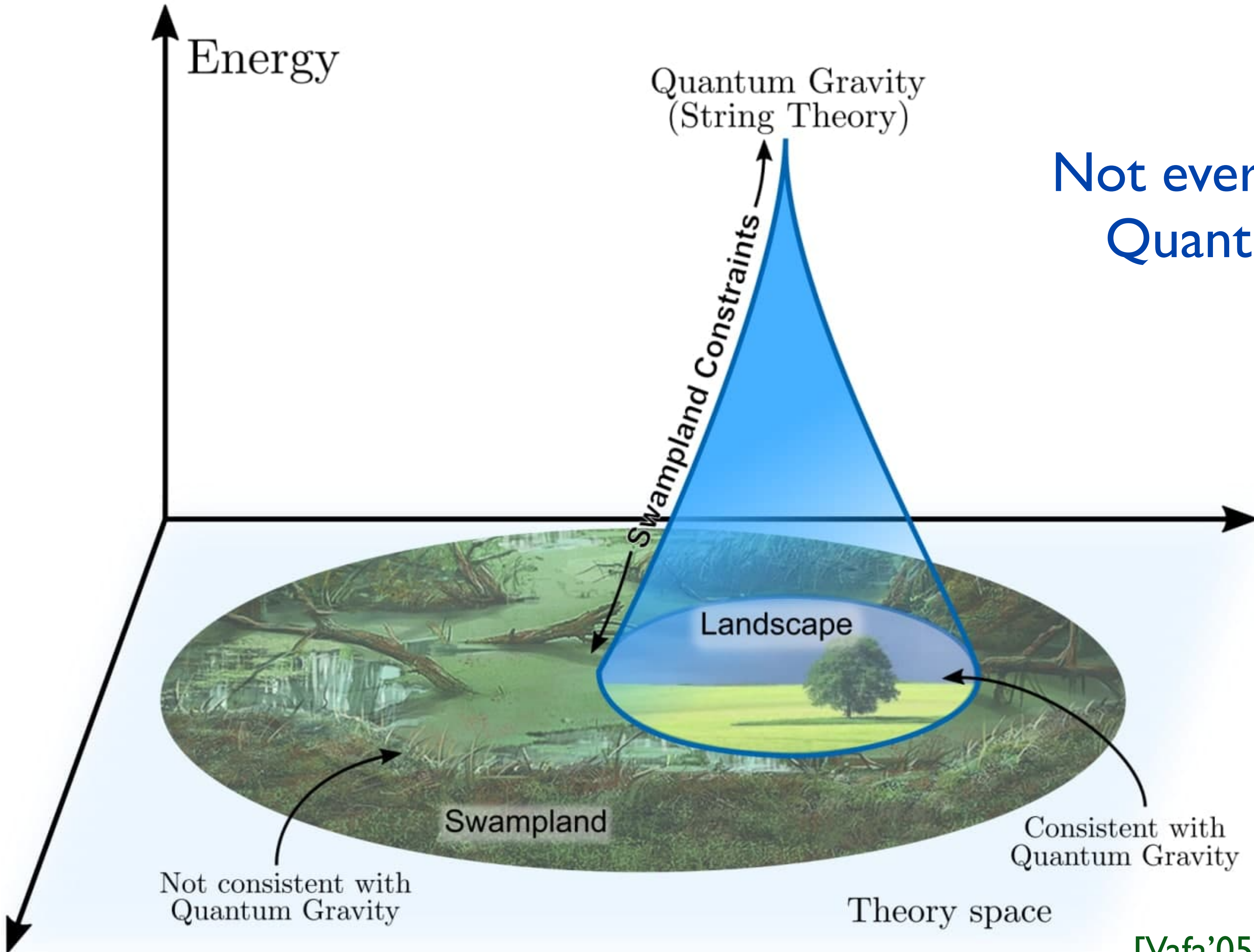

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Swampland:

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?

→ Universal UV imprint of quantum gravity at low energies

(New approach to connect string theory/quantum gravity to our world)

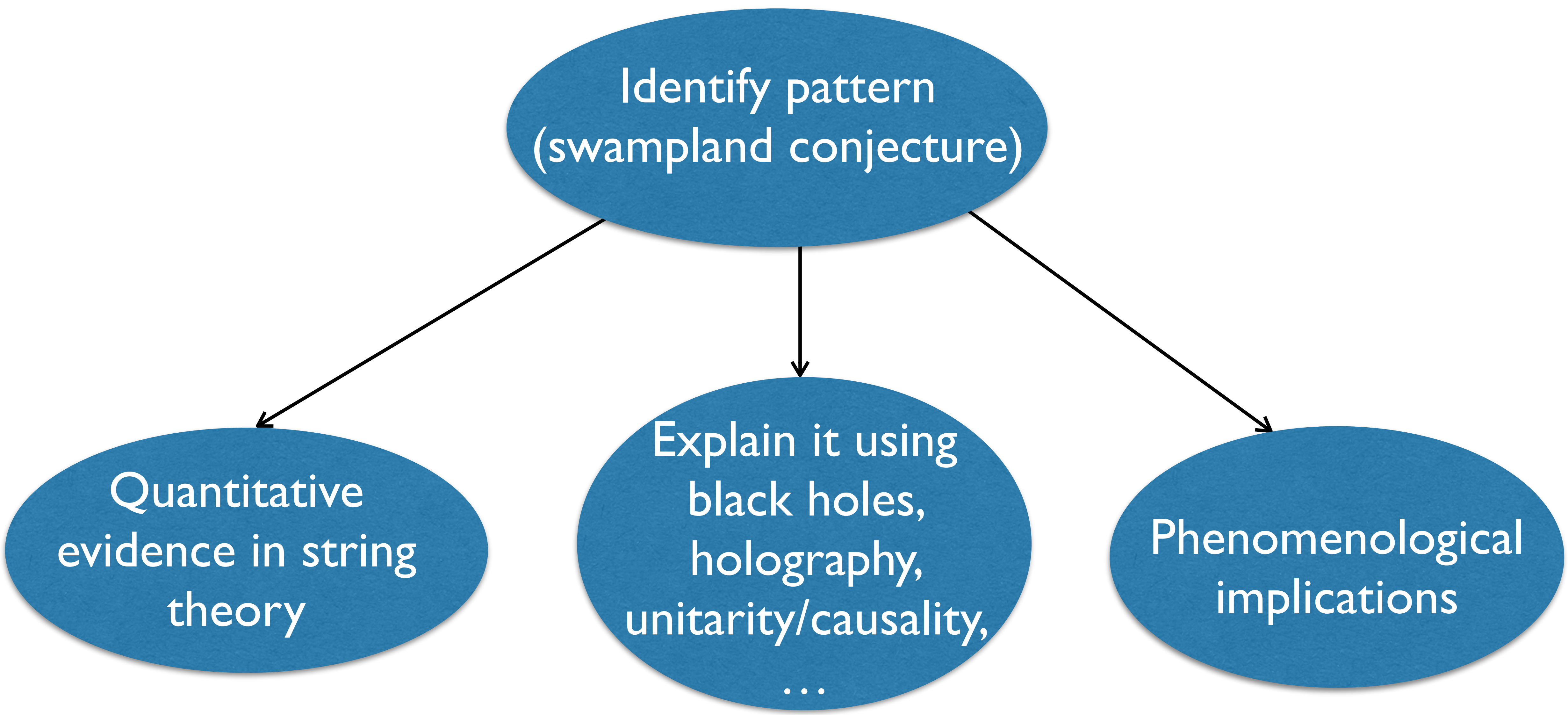
Potential phenomenological implications:

New guiding principles to construct BSM models of Particle Physics and Cosmology

Swampland conjectures

Proposals for constraints that EFTs must satisfy to be consistent with QG

They are mainly motivated by string theory and black hole physics, but we expect them to be general features of quantum gravity (even beyond string theory)



Failure of EFT expectations

These swampland constraints often look surprising from a low energy EFT perspective:

"What seems natural from UV perspective, might look unnatural from the IR perspective"

golden opportunity!

Can we bring new insights to solve naturalness issues in our universe?

Quantum gravity could be the missing piece behind naturalness issues since…

1) Not the entire space of parameters is consistent (constraints/correlations because of quantum gravity consistency in the UV)
2) Quantum Gravity does not preserve decoupling / separation of energy scales (it can induce UV/IR mixing)

Today I will focus in one example of interest for dark energy

Naturalness

In QFT, how can we get small values for a parameter in the EFT?

- Fine-tuning
- Protected by an approximate symmetry

How does this change in the presence of gravity?

Most important Swampland constraint: **No exact global symmetries**

Evidence:

- 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]

[Bah,Chen,Maldacena'22]

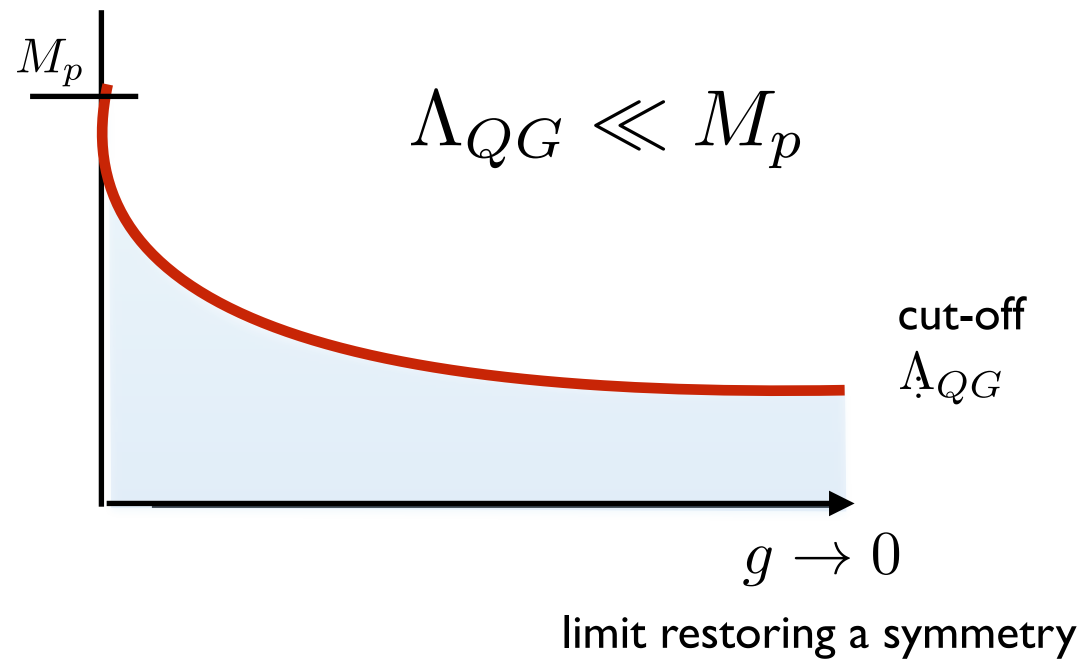
Approximate symmetries

What about approximate symmetries?

Consider a parameter g in the EFT, such that a global symmetry is restored if $g = 0$

The EFT must break down when taking the limit $g \to 0$ by quantum gravity effects

The smaller g is, the lower the quantum gravity cut-off gets



We can have approximate symmetries in the IR, but they imply a drop-off of the QG cut-off

Approximate symmetries

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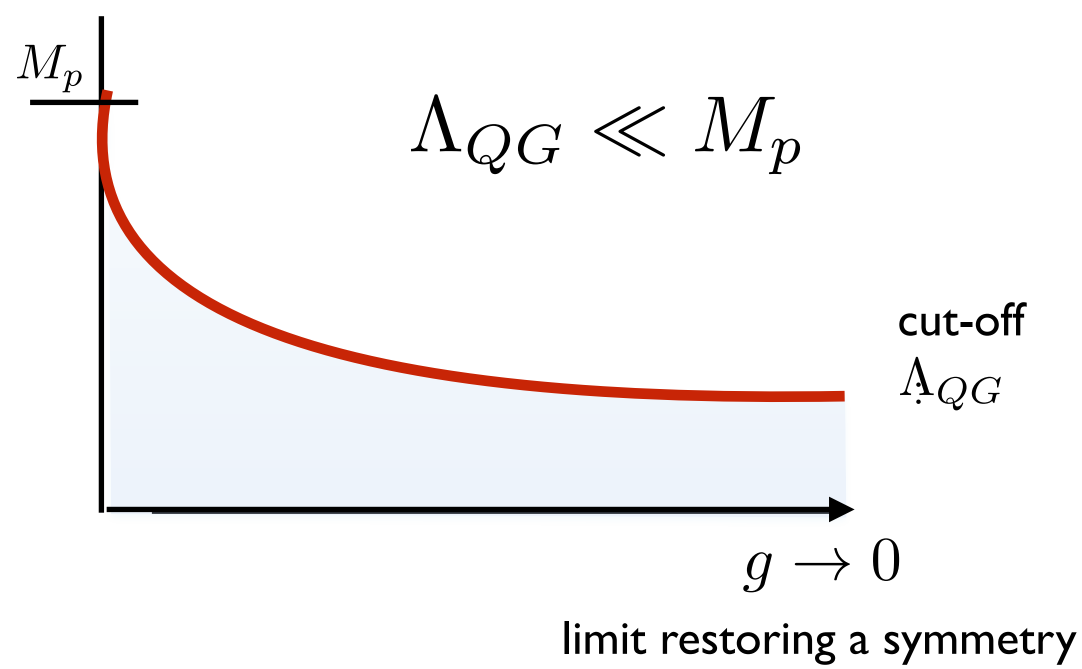


tower of states

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

Asymptotic limits

Why? From string perspective:

All continuos EFT parameters are set by vacuum expectation values of scalar fields (that fix the size/shape of extra dimensions)

$g = g(\phi)$ (like the Higgs boson parametrizes the masses $m(H) = y\langle H \rangle$)

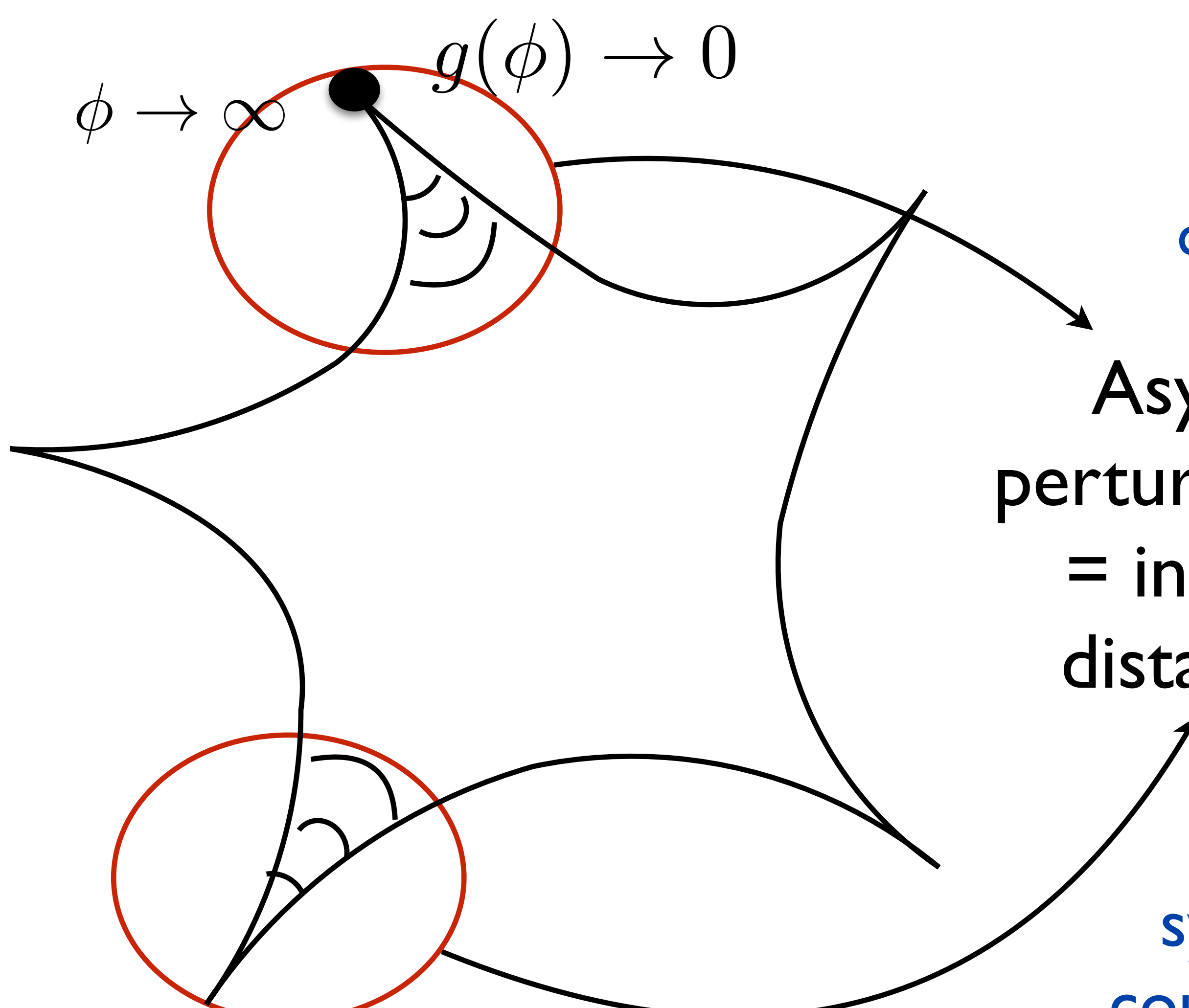
Parameter space:

=

Scalar field space in String Theory

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

↳ field metric



Computational perturbative control of the EFT

Asymptotic/ perturbative limits = infinite field distance limits

We get approx. symmetries, weak coupling, etc. in these corners

Swampland Distance Conjecture

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

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

[Ooguri-Vafa'06]

$$\Delta\phi = \int_Q^P \sqrt{g_{ij}\frac{d\phi^i}{ds}\frac{d\phi^j}{ds}}ds \equiv$$ geodesic distance (canonically normalised scalar field in Einstein frame)

Evidence:

- One (if not the most) basic feature of string theory (behind all famous string dualities)
- Plethora of quantitative tests in string theory $\sim \mathcal{O}(100)$ in 6 years

  starting in [Grimm, Palti, IV'18] [Lee,Lerche,Weigand'18-21] $\cdots$

- Bottom-up arguments based on black hole physics [Hamada,Montero,Vafa, IV'21]
- Towards a proof in the CFT dual to AdS vacua [Perlmutter,Rastelli,Vafa,IV'21] [Baume,Calderon-Infante'21-23]

Asymptotic Towers of States

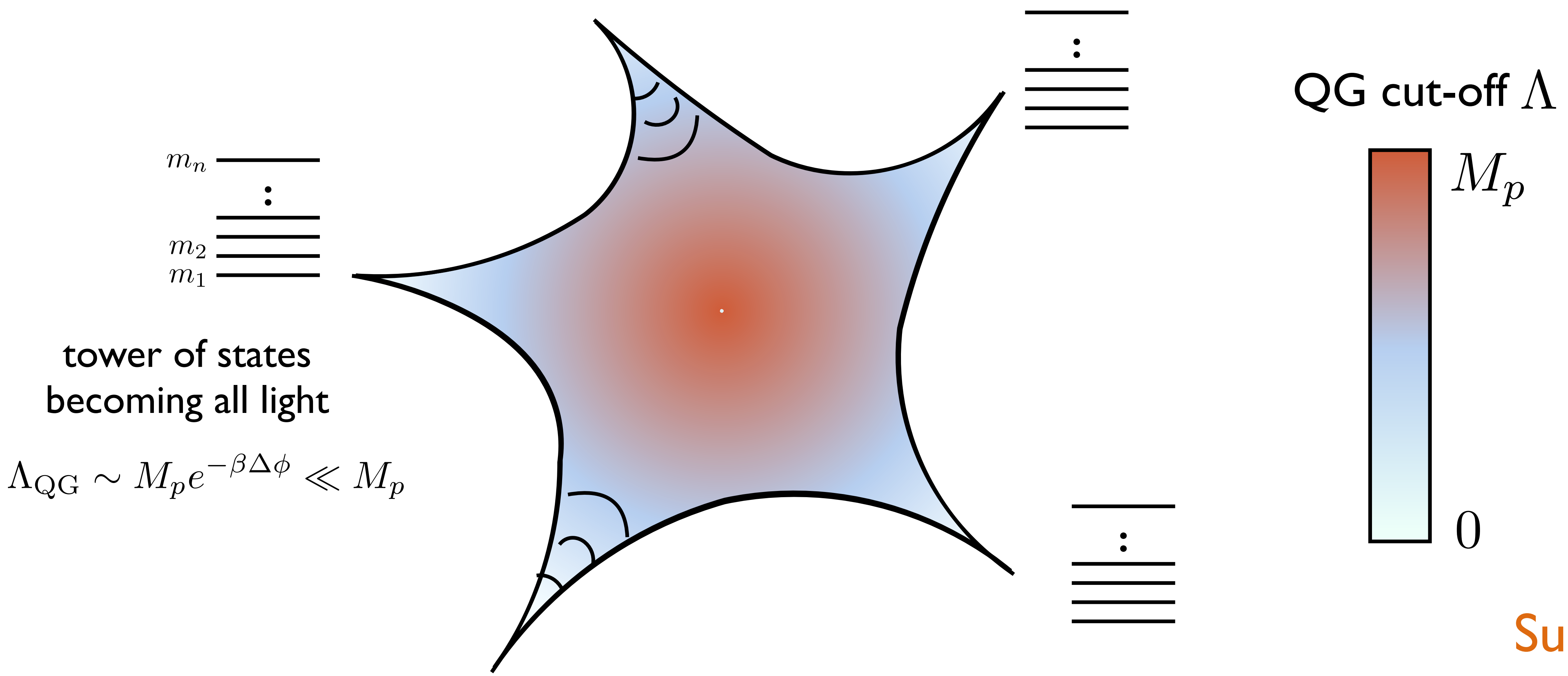
Making an EFT parameter parametrically small such that we recover an approximate symmetry

↓

Approaching an infinite distance boundary of the field space of string theory

↓

Existence of a light tower of states



Surprising!

Implications

A lot of research in Swampland program is devoted to make this precise, find new avenues to prove the existence of the tower, and quantify how light it becomes

From string theory evidence: $m_{\text{tower}} \sim m_0 e^{-\alpha\Delta\phi}$; $\alpha \geq \frac{1}{\sqrt{d-2}} = \frac{1}{\sqrt{2}}$

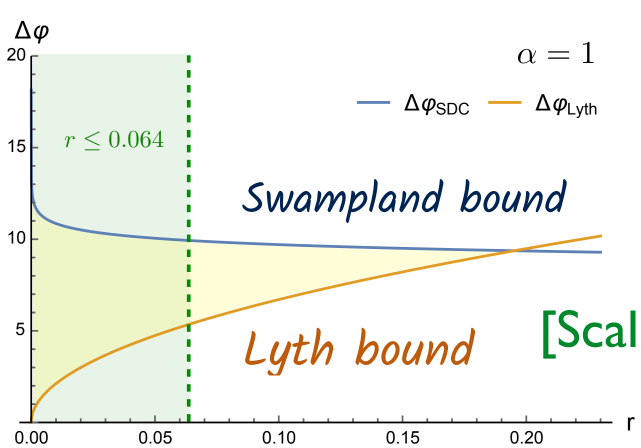
Nature of the tower: either Kaluza-Klein fields or string modes

[Lee,Weigand,Wolfgang'19] [Etheredge et al'22] [Castellano,Ruiz,IV'23]

Bounds for the scalar field range

(for inflation, cosmological relaxation…)

$$\Delta\phi \lesssim \frac{1}{\tilde{\alpha}} \log\left(\frac{M_p}{\Lambda_{QG}}\right)$$



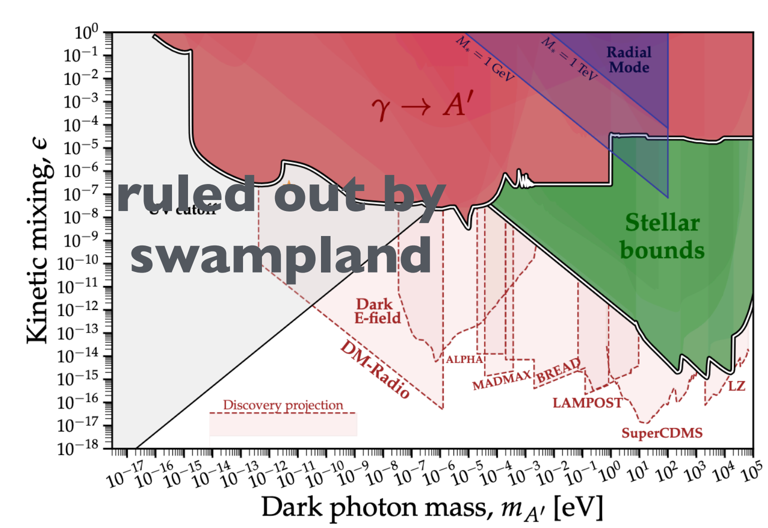
[Scalisi,IV'18]

Bounds for the value of gauge couplings

(dark photons, weakly coupled dark matter…)

$$g \gtrsim \left(\frac{\Lambda_{QG}}{M_p}\right)^{\tilde{\alpha}}$$

(Weak Gravity Conjecture)



[Reece'18]

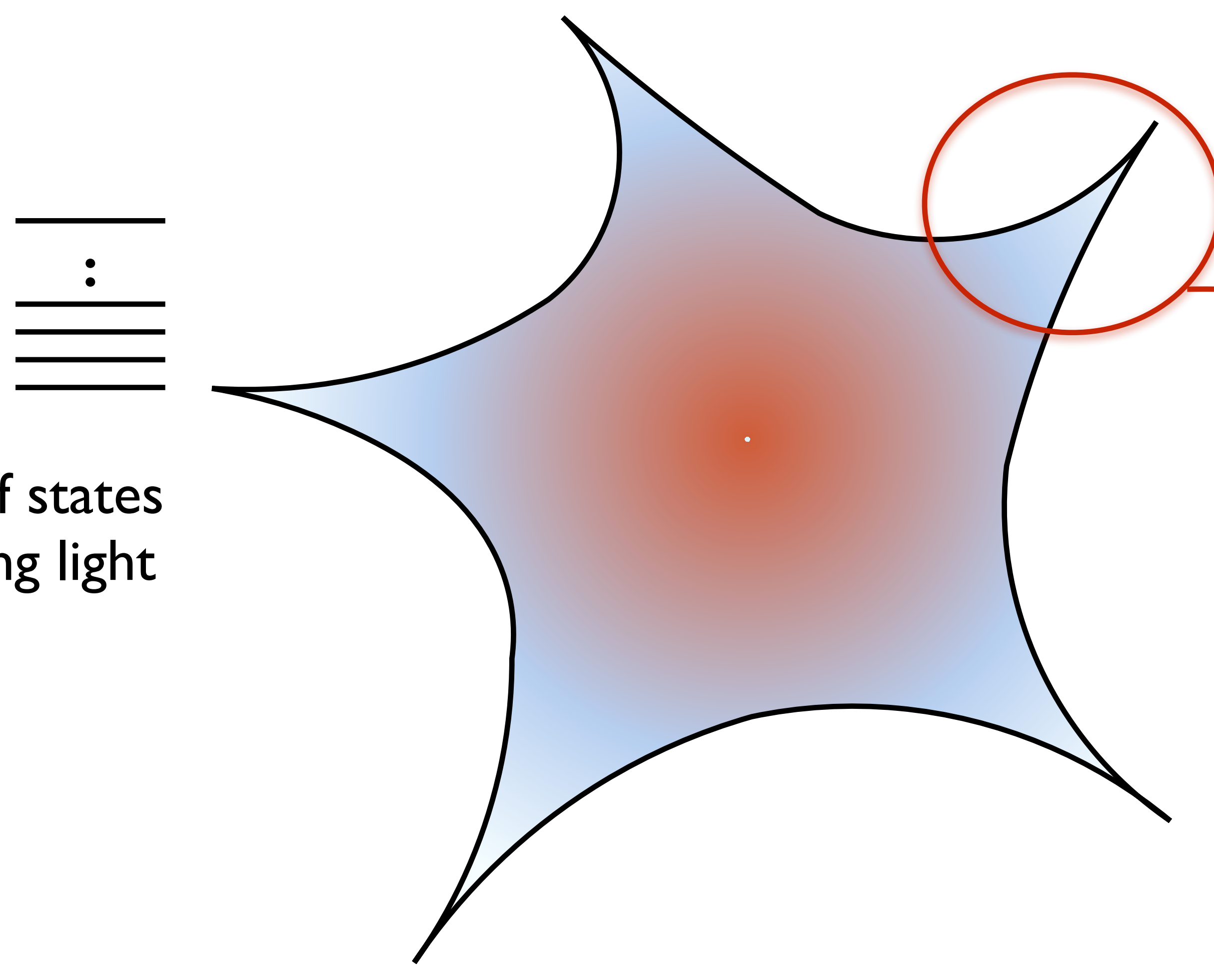
[Montero,Muñoz, Obied'22]

Dark energy

What about the smallest parameter we have in our universe?

The vacuum energy / dark energy: $V_0 \sim 10^{-122} M_p^4$

Could it be that the smallness of our vacuum energy is a signal that we live in these asymptotic regions?



tower of states becoming light

The vacuum energy (if positive) also goes to zero (in Planck units) at the infinite distance boundaries

$$V_0 \sim M_p^4 \exp(-\gamma \Delta\phi) \ll M_p^4$$

[Ooguri et al'18]

[Luest,Palti,Vafa'19]

[Montero,Vafa,IV'22]

…

Dark energy

Possible scenario:

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

Motivation:

- Our universe contains weakly coupled sectors and approximate symmetries (B-L,…) → asymptotic limit

- The limit $V_0 \to 0$ is at infinite distance in the space of metric configurations (generalization of the Distance conjecture) [Luest,Palti,Vafa'19]

$$\textit{Distance} \sim \log|V_0|$$

$$m \sim \exp(-\alpha\,\text{distance}) \sim V_0^{\alpha} \quad \text{as} \quad V_0 \to 0$$

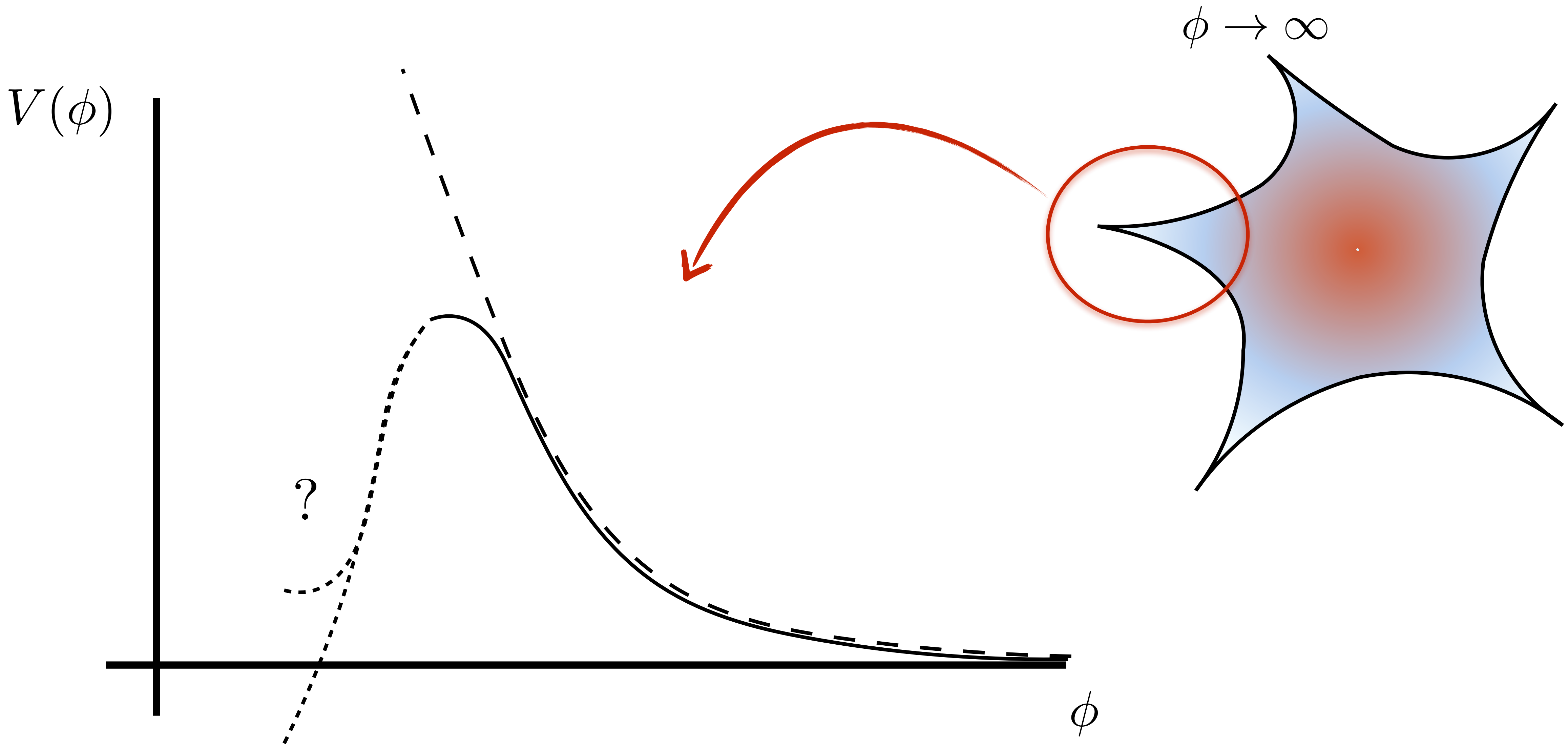
Dark energy

Possible scenario:

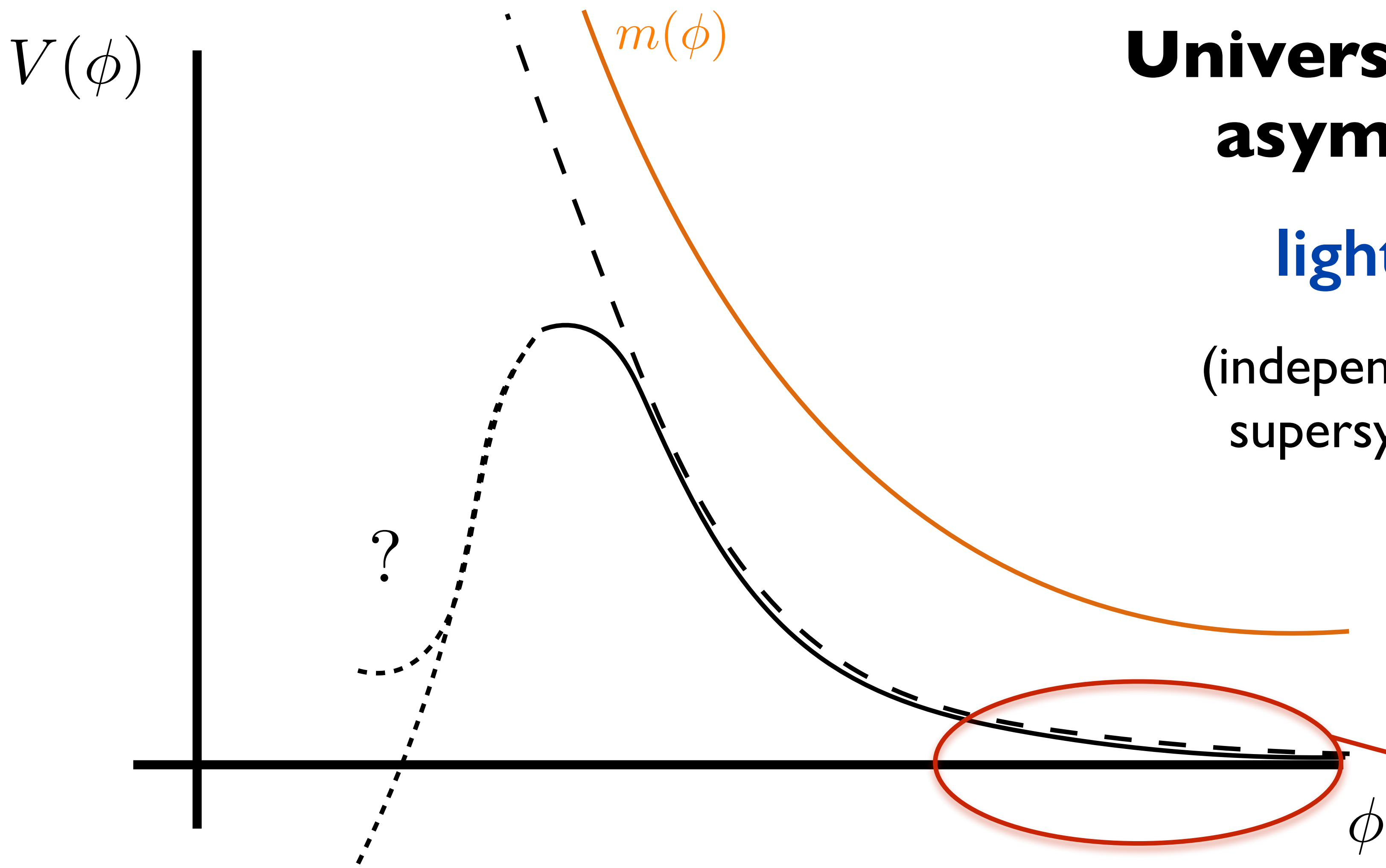
The smallness of our vacuum energy is not due to a huge fine-tuning of contributions in a landscape, but is a signal of being near an asymptotic limit where it naturally goes to zero

Let us assume this, and explore the consequences of this scenario

Asymptotic vacuum energy



Asymptotic vacuum energy



Universal consequence of asymptotic regimes:

light tower of states

(independently of whether we have supersymmetry at high energies)

$$V_0 \sim M_p^4 \exp(-\gamma \Delta\phi)$$

Known as Dine-Seiberg problem or deSitter Swampland conjectrue [Ooguri et al'18]

First lesson: Universe cannot accelerate forever

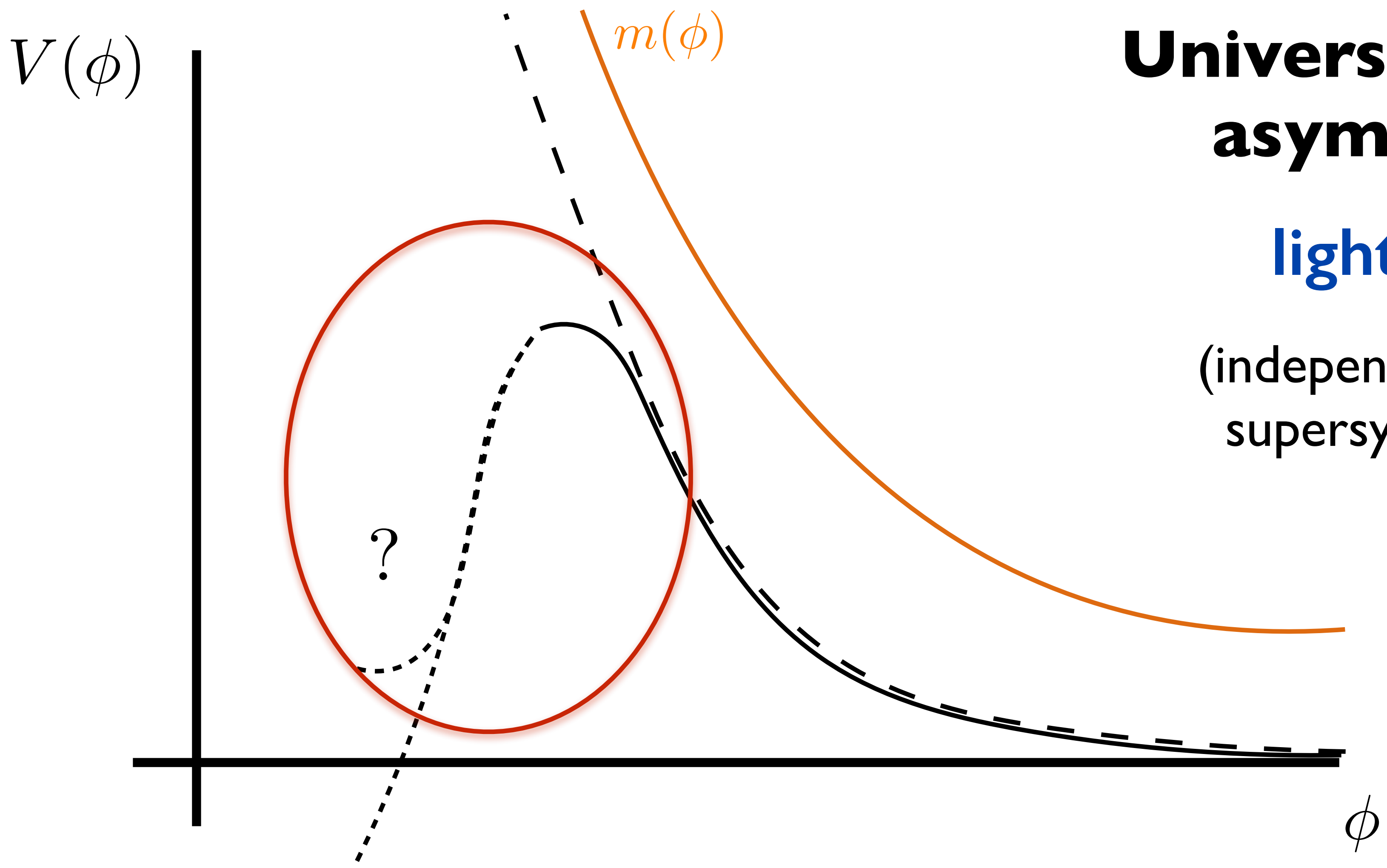
[Bedroya,Vafa'21][Rudelius'22]

$$m_{\text{tower}} \geq H = V_0^{1/2} \quad \Rightarrow \quad \gamma = \frac{|\nabla V_0|}{V_0} \geq \frac{|\nabla m_{\text{tower}}|^2}{m_{\text{tower}}^2} \geq \sqrt{2}$$

too steep!

(it deccelerates at parametrically late times)

Asymptotic vacuum energy



Universal consequence of asymptotic regimes:

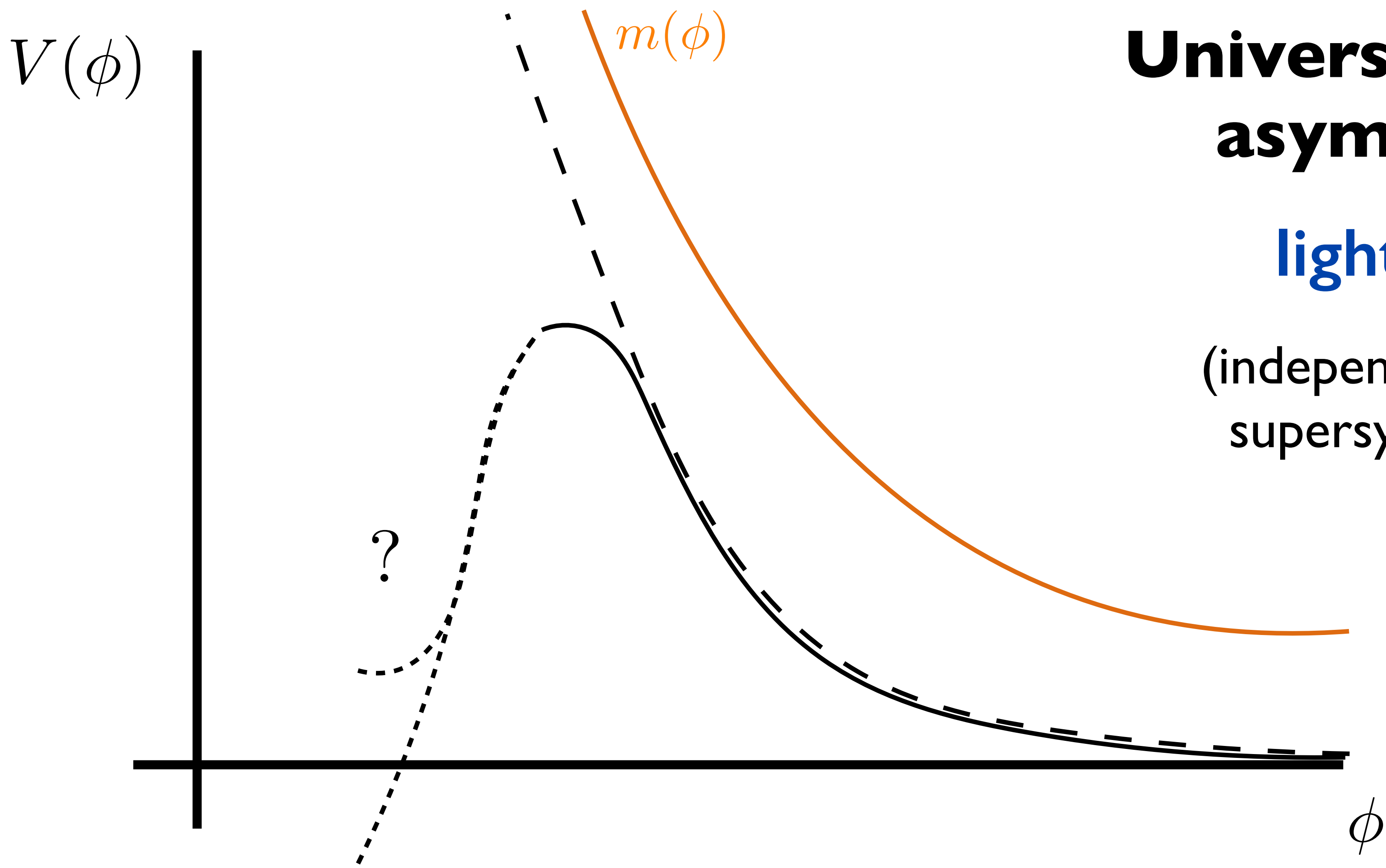
light tower of states

(independently of whether we have supersymmetry at high energies)

Under debate whether one can generate a dS minimum

(recent technical progress done here…)

Asymptotic vacuum energy



Universal consequence of asymptotic regimes:

light tower of states

(independently of whether we have supersymmetry at high energies)

Second lesson: The tower is still there regardless of what happens with the potential at smaller values of ϕ (as long as we keep perturbative control of the EFT)

$$V_0 \sim m_{\text{tower}}^{\alpha} \qquad \text{in Planck units}$$

Relation between dark energy and the light tower

$$V_0 = V_{class} + V_{loop} + \ldots \sim m_{\rm tower}^{\alpha}$$ in Planck units, as $V_0 \to 0$

The exponent α is model-dependent, but we can bound it (assuming no extreme fine-tunings)

$\alpha \geq 2$ Higuchi bound: $m_{\rm tower} \geq H = V_0^{1/2}$ since it contains higher spin fields

$\alpha \leq d = 4$ Even if classical piece is small, there is a one-loop quantum contribution $V_{loop} \sim m_{\rm tower}^d$ (if non-susy) so $V_0 \gtrsim m_{\rm tower}^d$

d → dimension of space-time

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

One could try to fine-tune λ to decouple them, but naturally V_0 and $m_{\rm tower}$ are correlated

Relation between dark energy and the light tower

Satisfied in known string theory examples:

- ☑ All known families of holographic AdS vacua (even DGKT)
- ☑ KKLT-like proposals for dS in string theory
- ☑ AdS/dS proposals using Casimir energies: $V_0 \sim m^d$
- ☑ Positive runaway potentials in 4d N=1 theories and non-SUSY theories

Relation between dark energy and the light tower

If we live near these asymptotic corners of the landscape where $V_0 \ll M_p$:

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

If we do not invoke extra fine-tunings:

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

$$2 \leq \alpha \leq d \quad \Rightarrow \quad V^{1/2} \lesssim m \lesssim V^{1/4}$$

Higuchi bound ($2 \leq \alpha$)

no fine-tuning ($\alpha \leq d$)

$d =$ space-time dimension

Let's take this correlation seriously (rather than trying to fine-tune it away) and see what it implies for our universe!

Experimental constraints

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

In our universe: $V^{1/4} \sim 2.31 \text{ meV} \sim (88\mu m)^{-1}$

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:

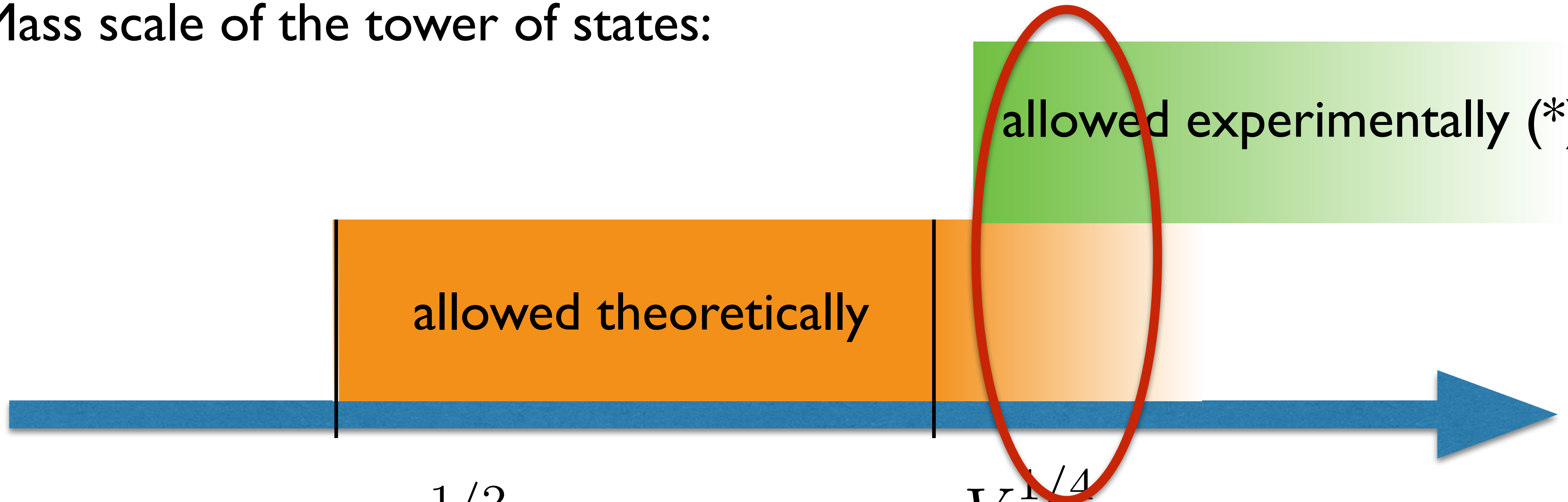
- Astrophysical bounds: $m^{-1} \leq 10^{-4}\,\mu m$ ~~$(n=2)$~~ *ruled out*

  [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]

Experimental constraints

Mass scale of the tower of states:



$m \sim V_0^{1/2}$ $\qquad$ $m \sim V_0^{1/4}$

Higuchi bound

Casimir contribution
(one loop quantum correction)

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

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

Dark Dimension Scenario

If our universe lives near an infinite distance limit $V_0 \to 0$,

there should be a light tower of states of mass: (if avoiding extra fine-tunings)

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

→ 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]

(This tower also helps to avoid violation of the AdS Distance conjecture upon compactification of the Standard Model) [Gonzalo,Ibanez,IV'21]

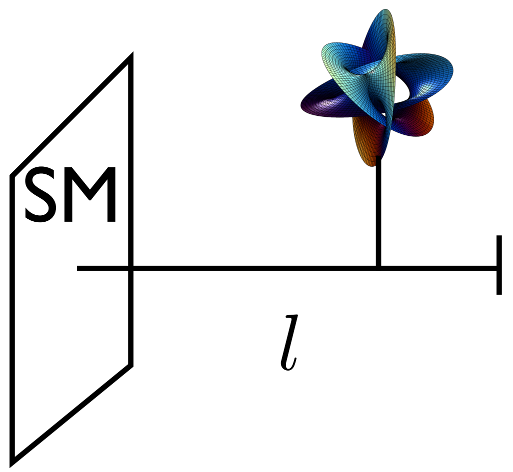
Dark Dimension Scenario

[Arkani-Hamed,Dimopoulos, Dvali'98]

This scenario is an example of the Large Extra Dimension models (ADD)

although the scale is different than usual, since it was motivated by the smallness of the cosmological constant and not by the EW hierarchy problem:

QG cut-off: $\hat{M}_5 \sim m^{1/3} M_P^{2/3} \sim 10^{10}\, GeV$



Open challenges: We do not have a concrete string theory embedding including the SM!

(challenge: engineer hierarchy with respect to SM fields, SUSY breaking scale, etc.)

Dark Dimension Scenario

Proposals for dark matter: [Gonzalo et al'22] [Law-Smith et al'23] [Anchordoqui et al'23]

↓

KK gravitons act as dark matter candidates

It will be tested in future experiments that will improve the precision measurements on deviations from Newton's law

New ISLE at the Conrad Observatory

[Aspelmeyer,Adelberger,Shayeghi,Zito…]

Conclusions

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

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

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

  → new towers of states become light yielding $\Lambda_{QG} \ll M_p$

Conclusions

- Swampland constraints motivated by string theory suggest

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

and imply that the universe cannot accelerate forever.

- This motivate an scenario in which the smallness of our vacuum energy is tied to the existence of one mesoscopic extra dimension of

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

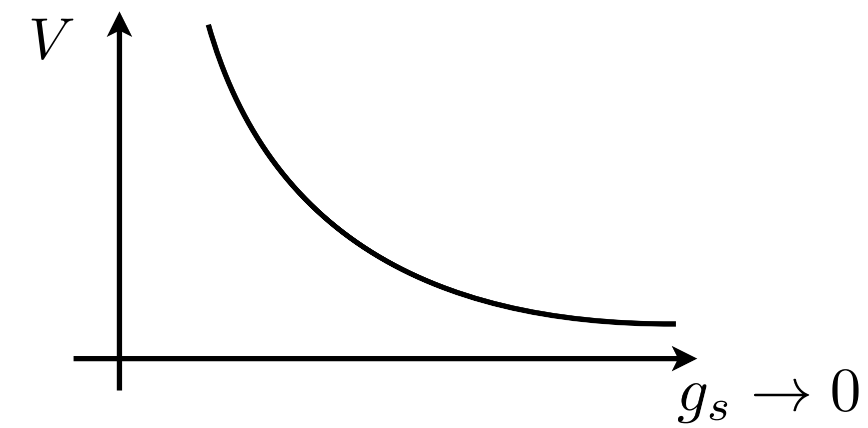
We named it the Dark Dimension.

Thank you!

back-up slides

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

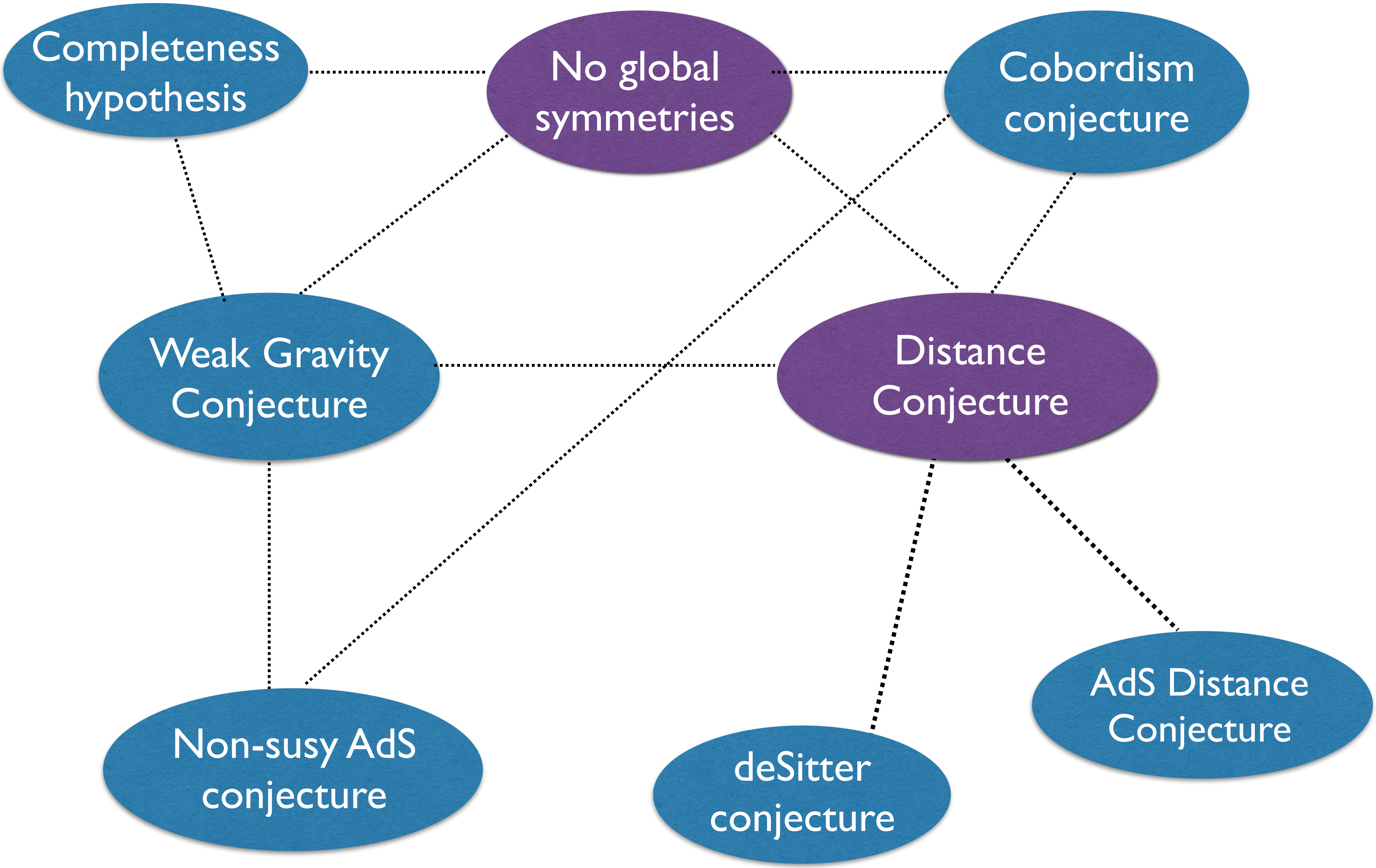
$$m \sim M_s$$

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

$$\Rightarrow \quad V \sim m^{10}$$

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

Swampland Conjectures



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

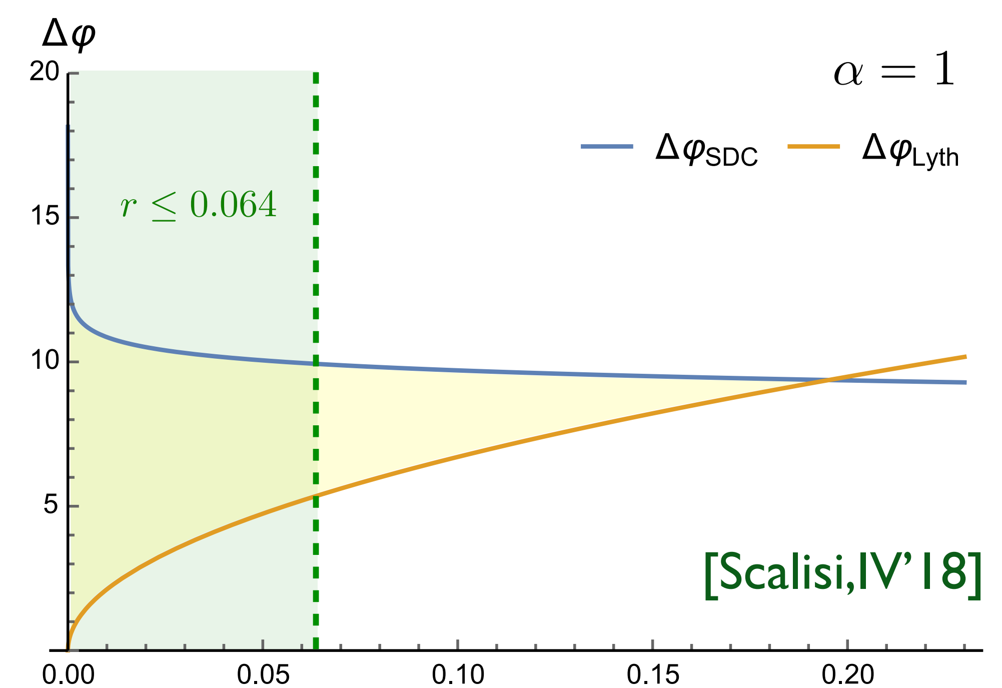
$$\Lambda \sim M_p \exp(-\alpha \Delta\phi) \quad \rightarrow \quad \Delta\phi \leq \frac{1}{\alpha} \log \frac{M_p}{\Lambda}$$

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

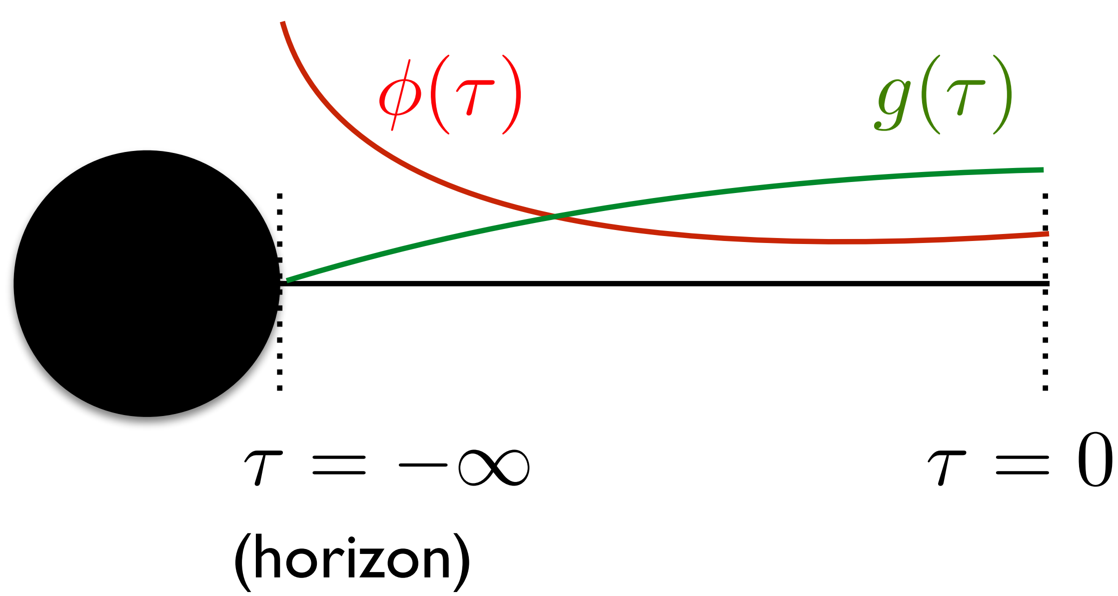
Take Einstein-Maxwell-Dilaton theory:

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

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

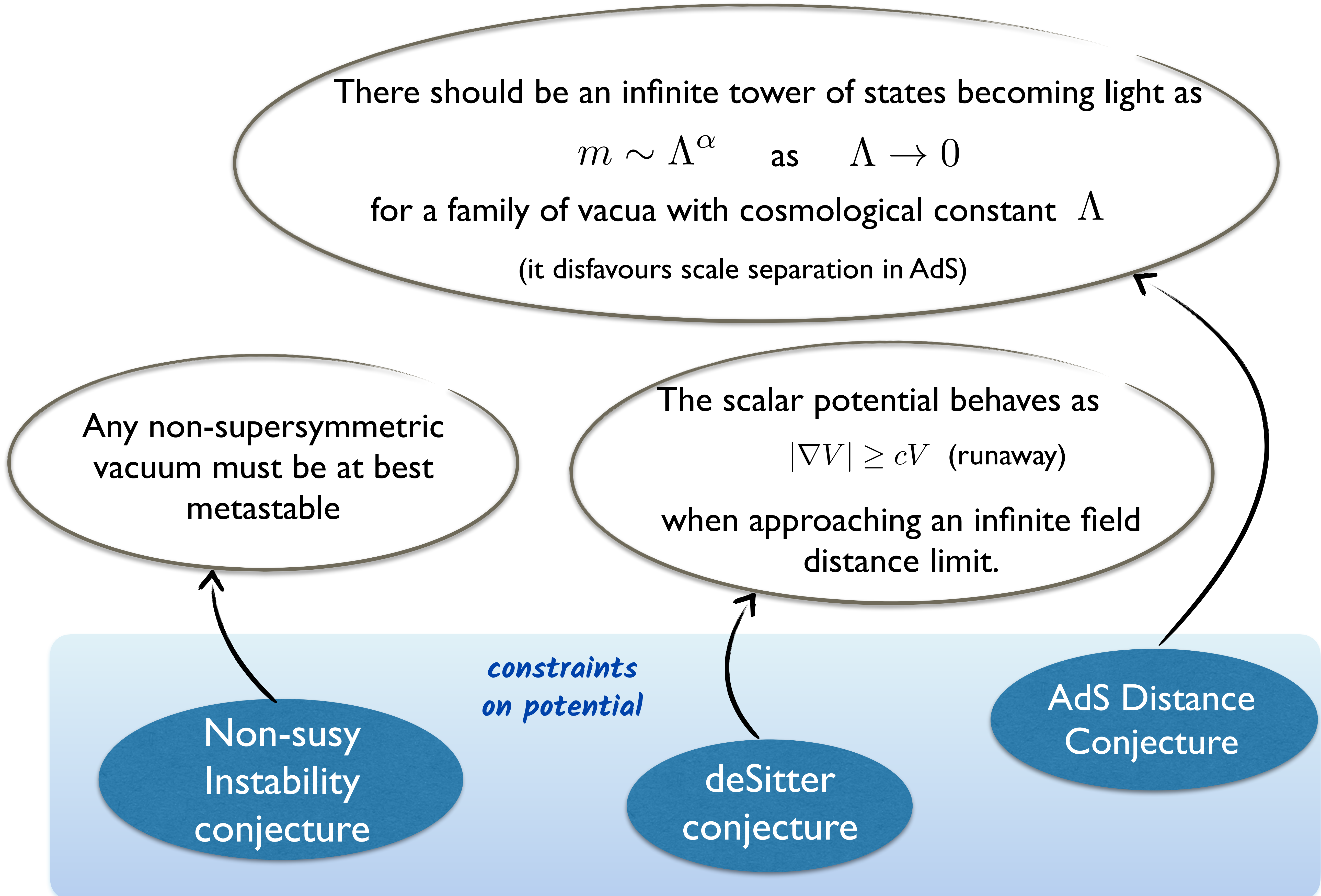
Entropy Bound: A region of size L cannot have more entropy than a Schwarzschild black hole of the same area $A = L^2$

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

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