Light Fermions and the Swampland

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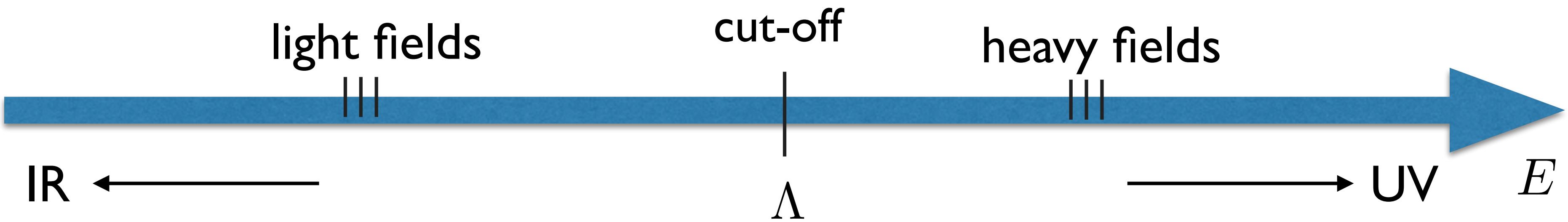
+ ongoing work with Gonzalo, Ibañez

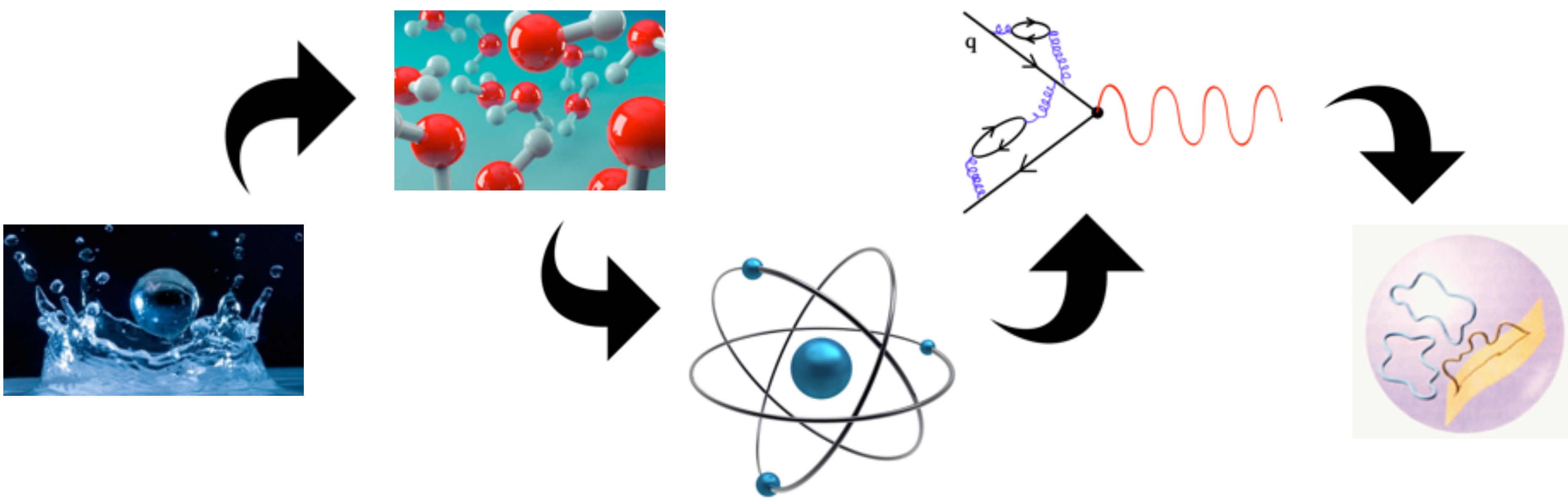
+ previous work with Martin-Lozano, Ibañez

Planck 2021

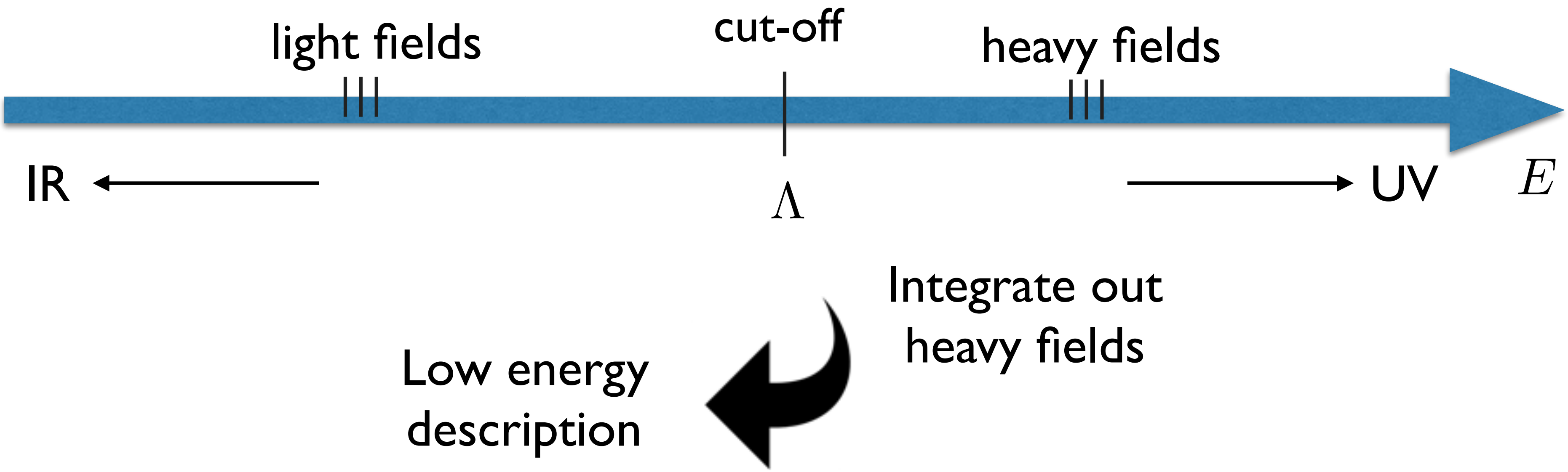
Effective field theories



Modern physics based on a Wilsonian effective field theory approach



Effective field theories

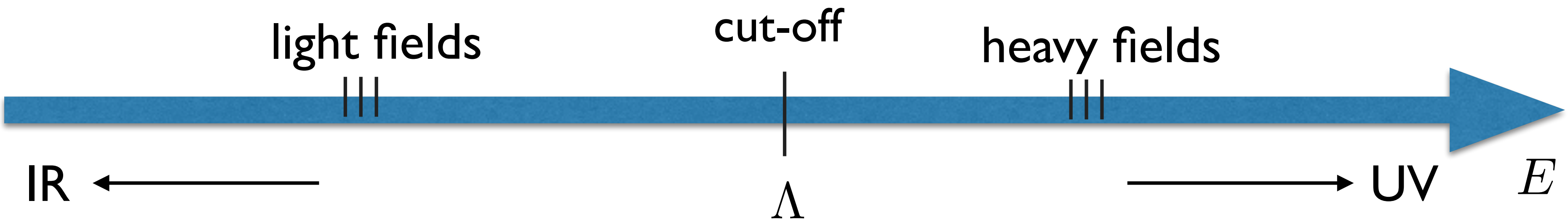


Expectation of 'separation of scales':

UV corrections become small in the IR → Not important to predict experimental results

IR effective theory not very sensitive to UV physics

Effective field theories



Low energy description

Integrate out heavy fields

Expectation of 'separation of scales':

UV corrections become small in the IR → Not important to predict experimental results

IR effective theory not very sensitive to UV physics

But this can fail…

Naturalness issues

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Proposal: Quantum Gravity is the missing piece to solve naturalness issues

(cosmological constant problem, EW hierarchy problem...)

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Space of parameters consistent with quantum gravity is smaller than expected, not every EFT is valid!

Naturalness issues

Proposal: Quantum Gravity is the missing piece to solve naturalness issues

(cosmological constant problem, EW hierarchy problem…)

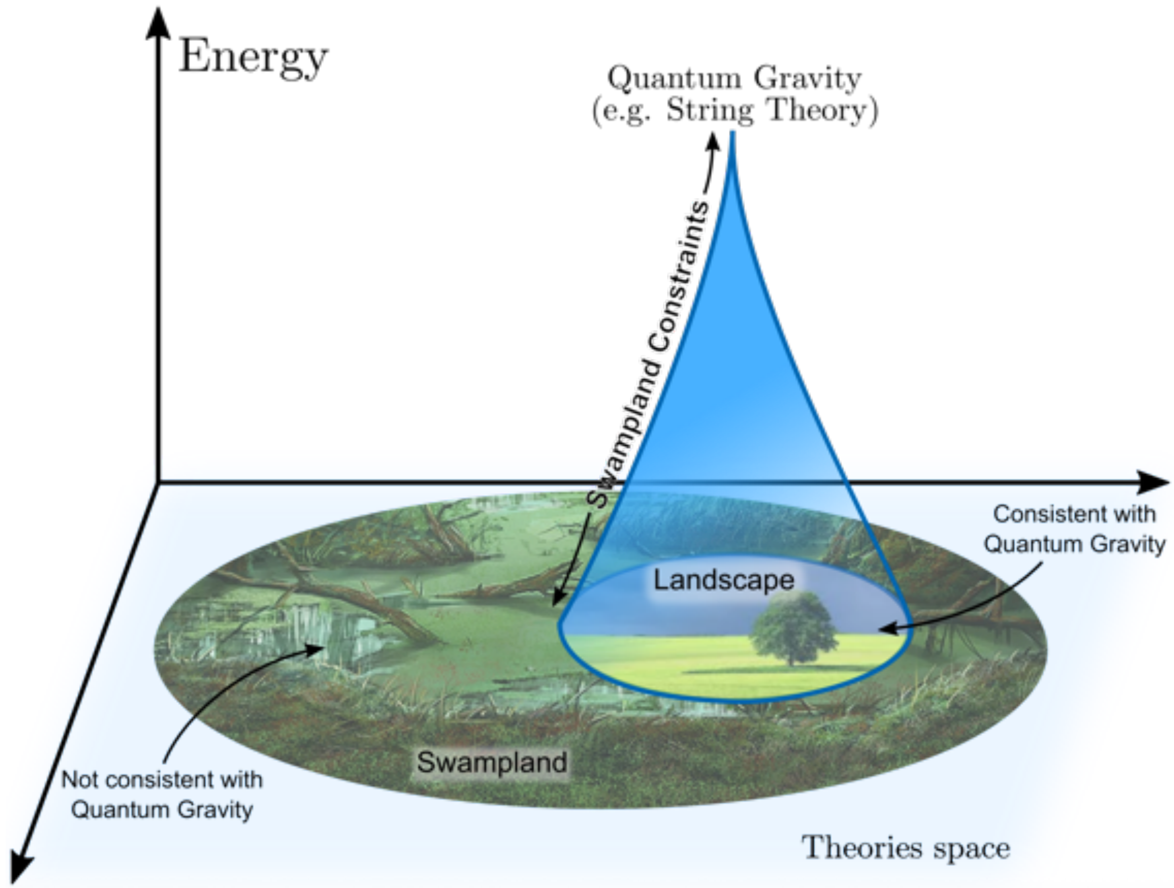
According to the Swampland program:

Space of parameters consistent with quantum gravity is smaller than expected, not every EFT is valid!

→ Swampland constraints provide IR rules to identify non-trivial correlations among parameters of the EFT

Swampland:

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



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

Goal of the Swampland program:

What are the constraints that an effective theory must satisfy to be consistent with quantum gravity?

What distinguishes the landscape from the swampland?

Swampland constraints

Constraints that any EFT must satisfy to be consistent with quantum gravity

→ UV imprint of quantum gravity at low energies

Potential phenomenological implications!

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- *Guiding principles to construct BSM models*
- *New insights to solve naturalness issues in our universe*

Swampland constraints

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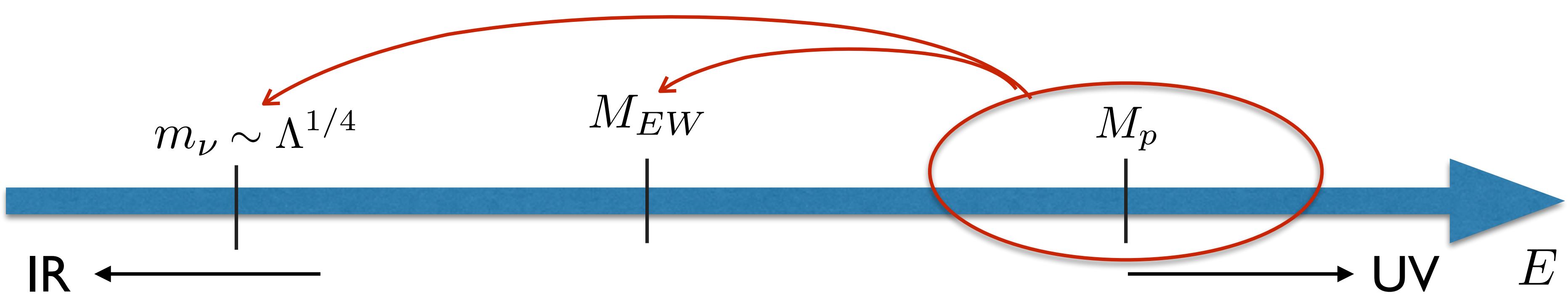
Potential phenomenological implications!

- *Guiding principles to construct BSM models*
- *New insights to solve naturalness issues in our universe*



Outline:

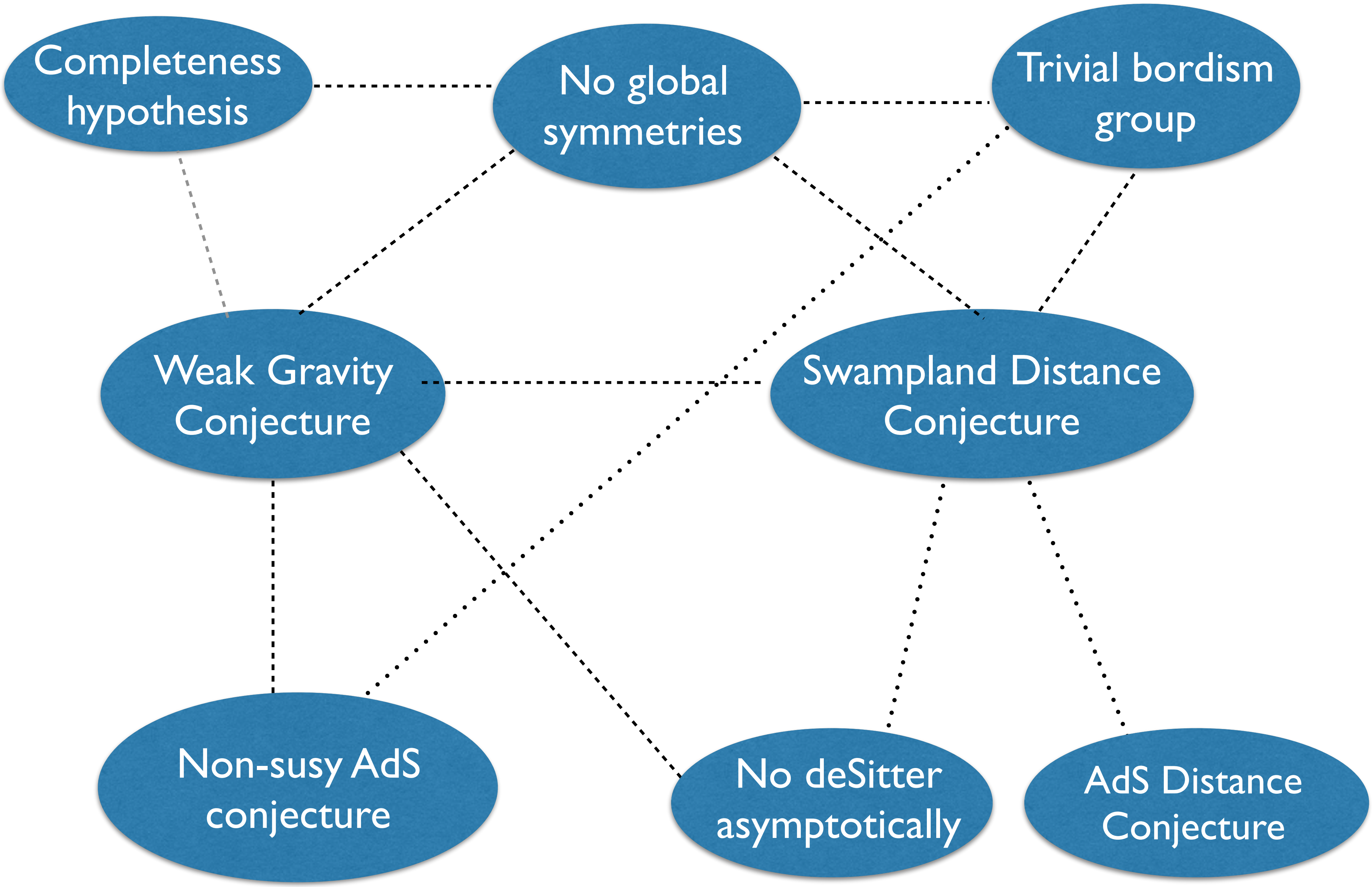
(1) Swampland conjectures

(2) Constraints on D-dim vacua (Minkowski, AdS, dS)

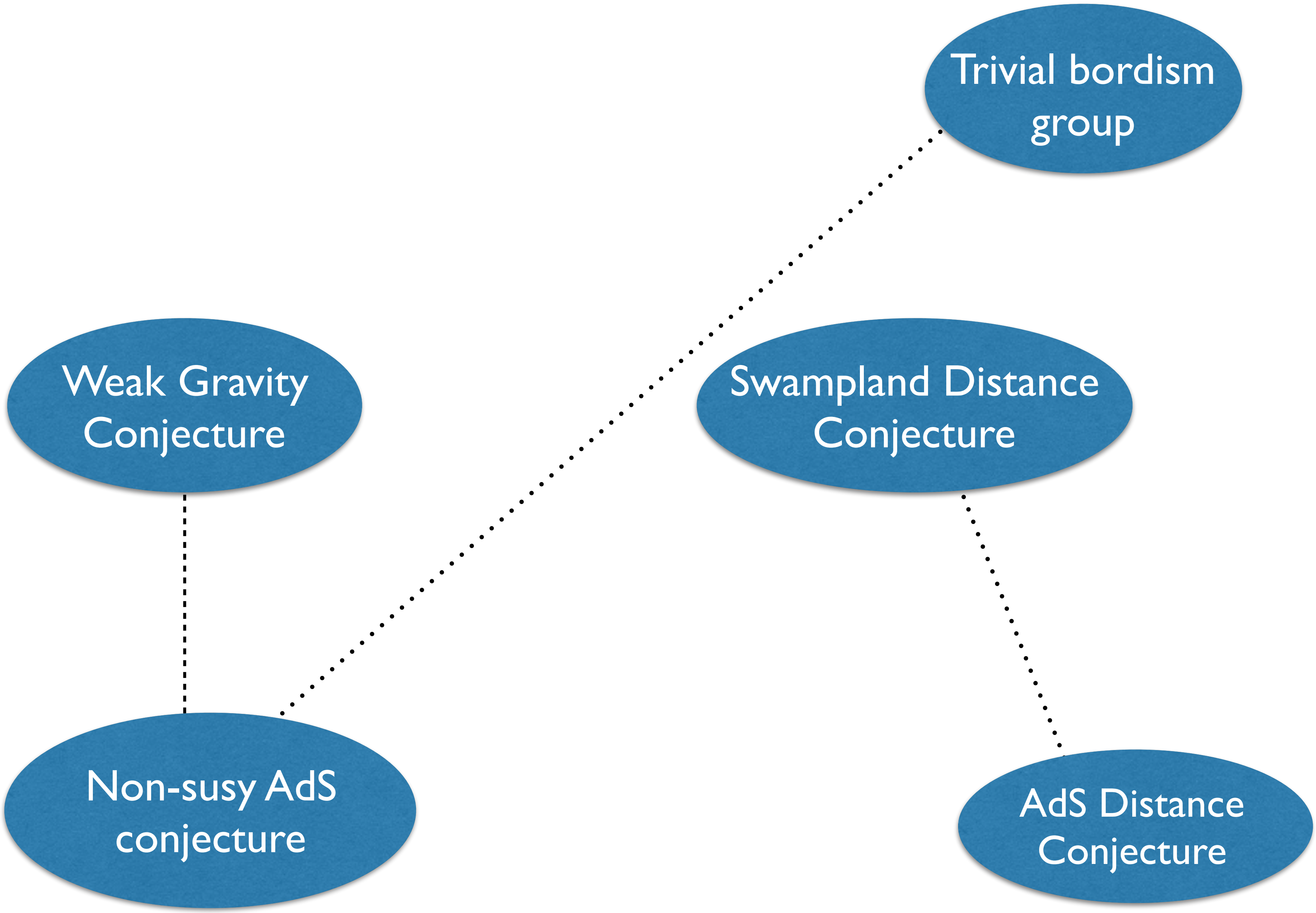
(3) Constraints on the SM of particle physics

(1) Swampland conjectures

Swampland Conjectures



Swampland Conjectures



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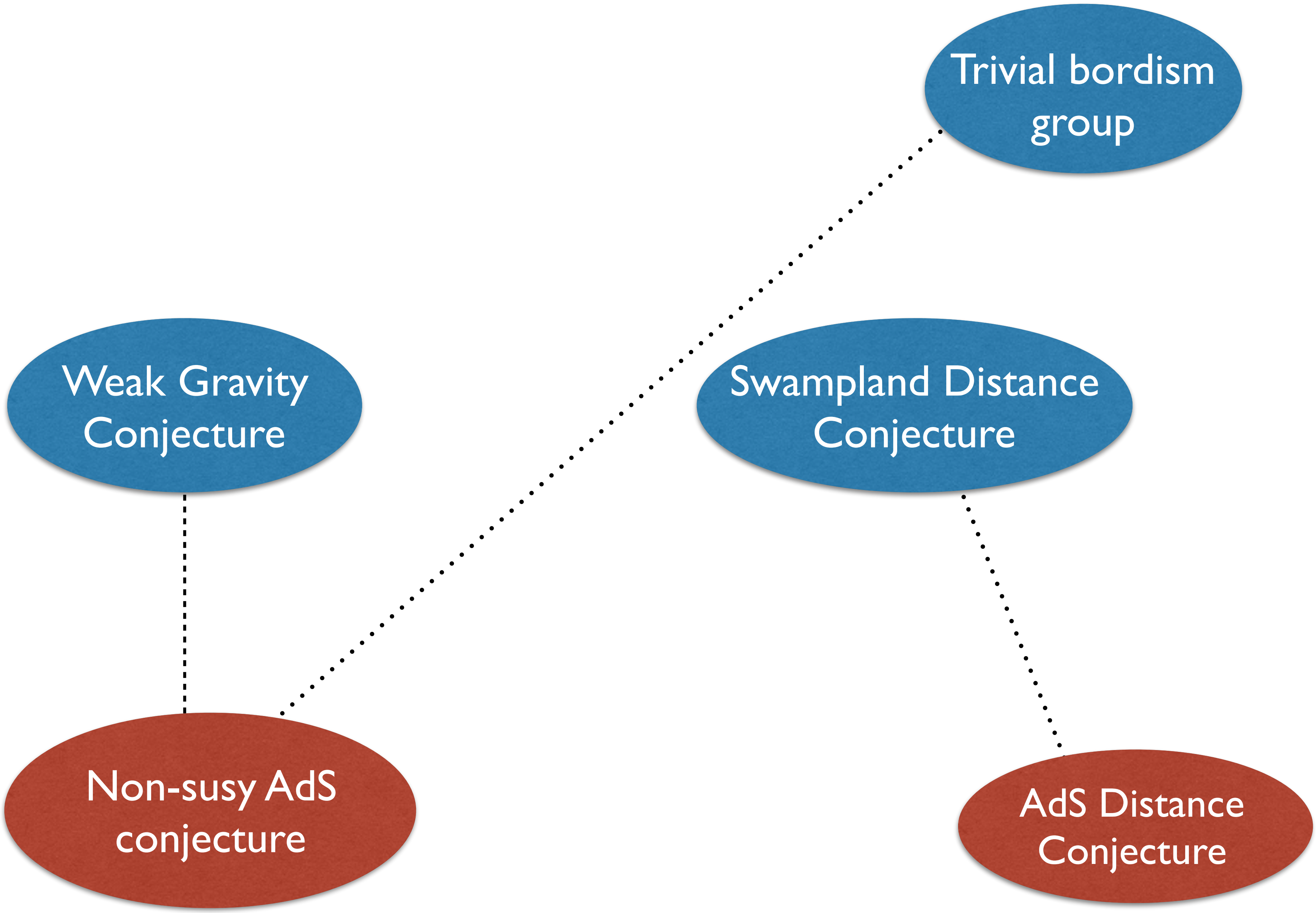


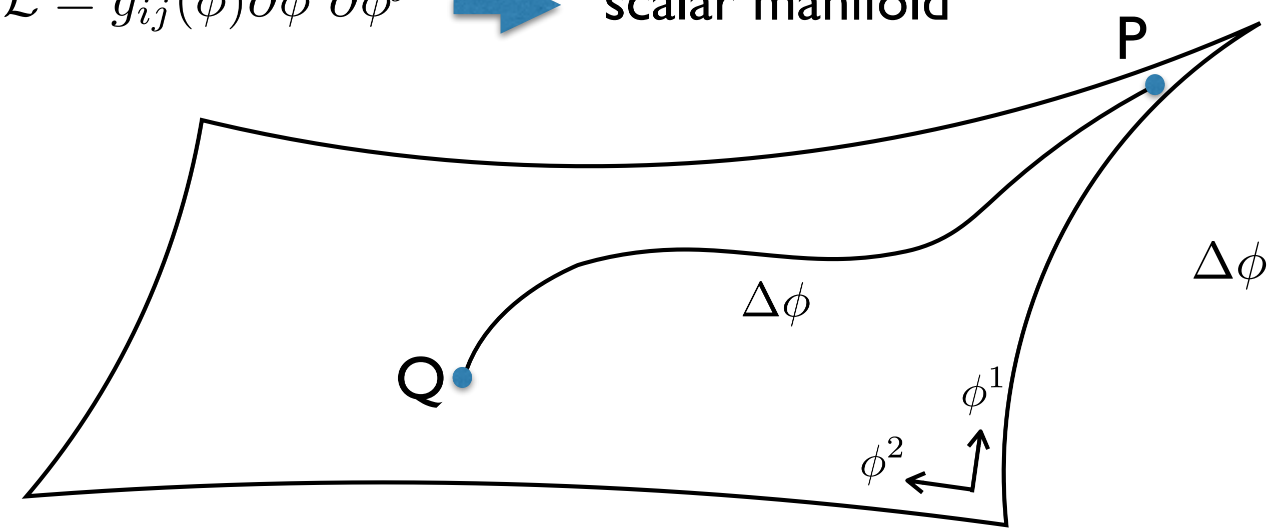
Distance Conjecture

[Ooguri-Vafa'06]

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

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

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



$\Delta\phi =$ geodesic distance between P and Q

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AdS Distance conjecture: [Luest,Palti,Vafa'19]

Generalisation to distances in the space of metric configurations:

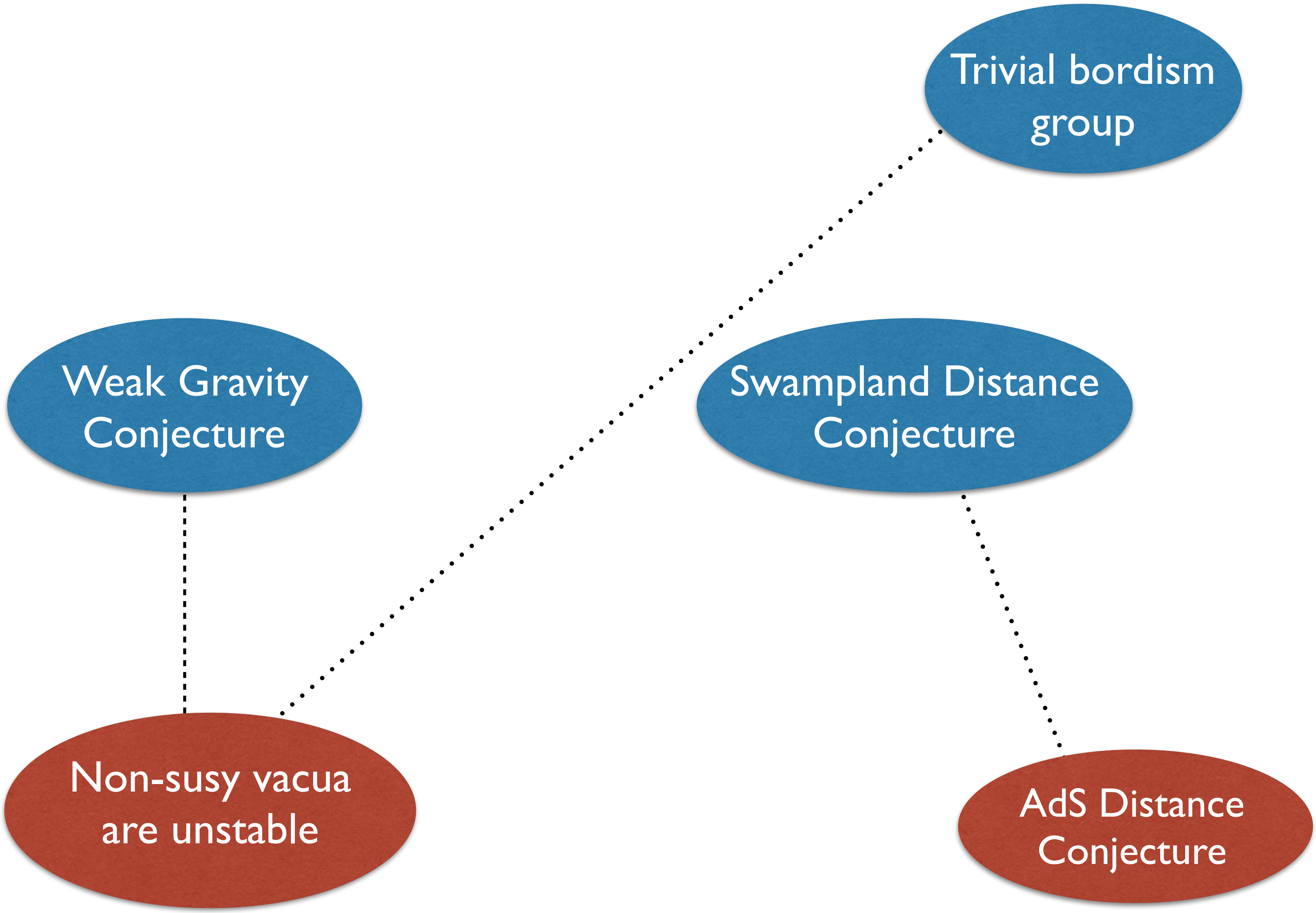
Flat space limit $\Lambda \to 0$ *is at infinite distance*

There is an infinite tower of states becoming light with a mass

$$m \sim \Lambda^{\alpha} \quad \text{as} \quad \Lambda \to 0$$

with α some positive O(1) number.

Swampland Conjectures



Non-SUSY AdS Conjecture

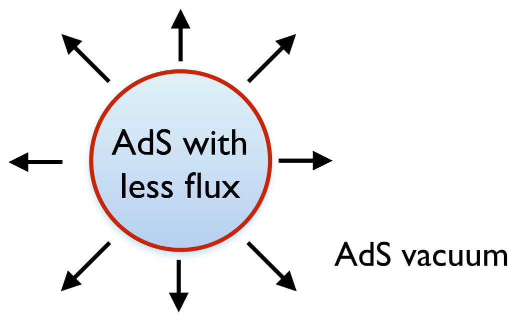
Any non-supersymmetric vacuum must at best metastable

[Ooguri-Vafa'17] [Kleban,Ferivogel'17]

Motivation:

- It follows from a sharpening of the WGC applied to a vacuum with gauge fluxes:

∃ brane with $T < Q$ → ***Bubble instability of the vacuum!***



- There is no topological obstruction for bubble of nothing instabilities if there are no global symmetries in quantum gravity.

[McNamara,Vafa'19] [Garcia-Etxebarria,Montero,Sousa,IV'20]

(2) Constraints on D-dim vacua

Strategy

D-dimensional vacuum consistent with quantum gravity

compactify on S^1

assuming background independence

(D-1)-dimensional vacuum

whose properties depend on the field spectra of D-dim theory

Is it consistent with the swampland conjectures?

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Is it consistent with the swampland conjectures?

yes

D-dim vacuum was consistent with quantum gravity

no

D-dim vacuum was inconsistent with quantum gravity

Constraints on D-dim vacua

Consistency of the D-dim vacuum with quantum gravity → The (D-1)-dim vacuum should satisfy the Swampland conj. → Constraints on the field spectra of the D-dim theory

- Constraints on SM from Non-SUSY AdS conjecture:

  [Martin-Lozano et al'17][Hamada et al'17][Gonzalo et al'18]

- We now generalise it for any D-dim vacuum and also consider the AdS Distance conjecture

Setup

(D>3)-dim Einstein gravity theory coupled to matter:

- Massless graviton + massless gauge bosons
- Massive scalars and fermions

→

n_b : bosonic d.o.f

n_f : fermionic d.o.f

n_0 : net number of massless bosons

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We compactify on a circle of radius R:

$$V(R) = \frac{2\pi\Lambda_4}{R^2} + \text{Casimir energy}\,(n_b, n_f, m_b, m_f)$$

$\frac{2\pi\Lambda_4}{R^2}$ ↓ tree-level

Casimir energy ↓ one-loop corrections

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Casimir energy ↓ one-loop corrections

Goal: Determine constraints on the field spectra to avoid V(R) to develop a minimum that would violate the AdS Swampland conjectures

Casimir potential

- Behaviour at small R: $V \to \text{sign}[(-1)^{k+1}\text{Str}(M^{2k})]\infty$

$$V(R\to 0) \approx \frac{r^{\frac{(D-1)}{(D-3)}}}{R^{\frac{(D-1)(D-2)}{(D-3)}}} \sum_{k<\frac{D}{2}} \beta_k (-1)^{k+1}\text{Str}(M^{2k})R^{2k} + \ldots$$

$$\text{Str}(M^{2k}) = \sum_b n_b m_b^{2k} - \sum_f n_f m_f^{2k}$$

$$(-1)\text{Str}(M^0) = \sum_f n_f - \sum_b n_b$$

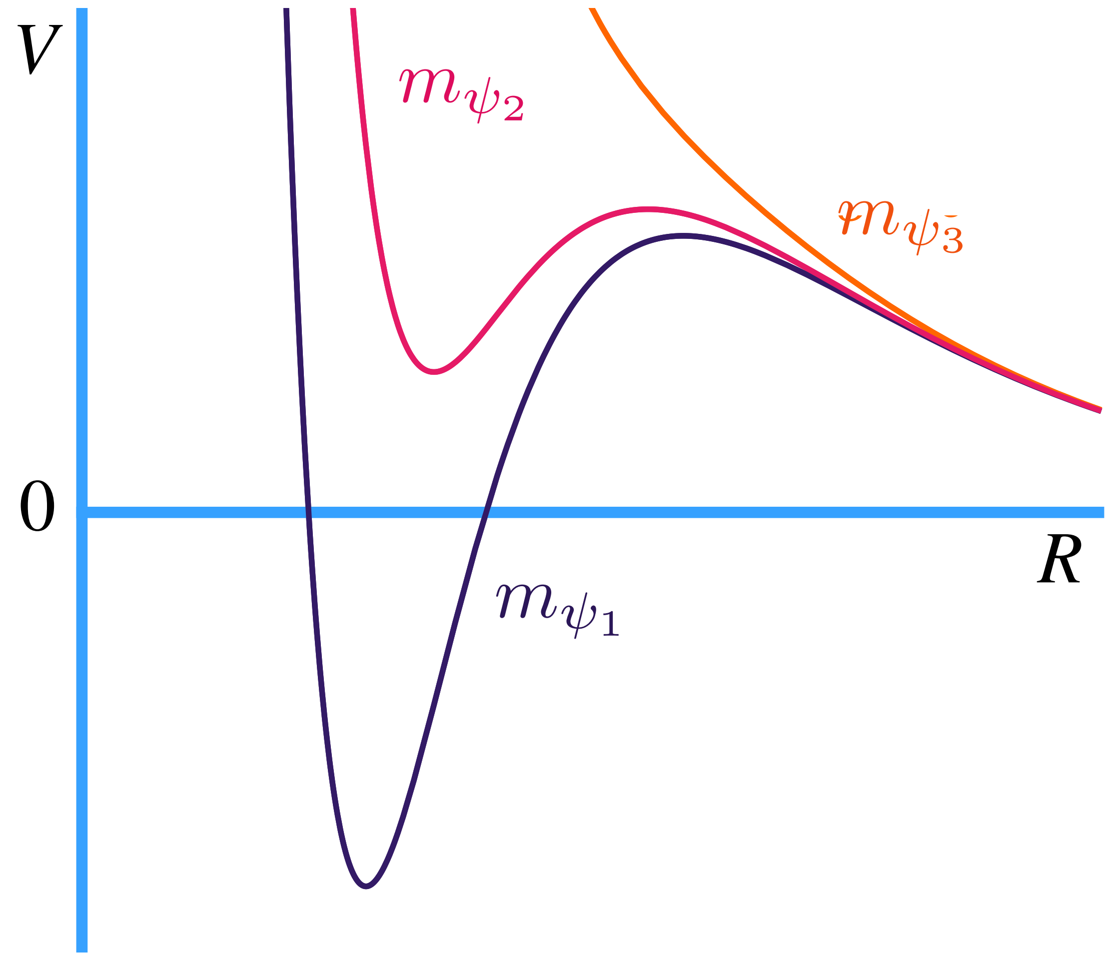
$$\text{Str}(M^2) = \sum_b n_b m_b^2 - \sum_f n_f m_f^2$$

$$\ldots$$

- Behaviour at large R: $V \to \text{sign}[n_0]0$

$$V(R\to\infty) \approx 2\pi r \left(\frac{r}{R}\right)^{\frac{2}{d-2}} \Lambda_D - n_0 \frac{(-1)^F r^{\frac{(D-1)}{(D-3)}} \beta_0}{R^{\frac{(D-1)(D-2)}{(D-3)}}}$$

Example



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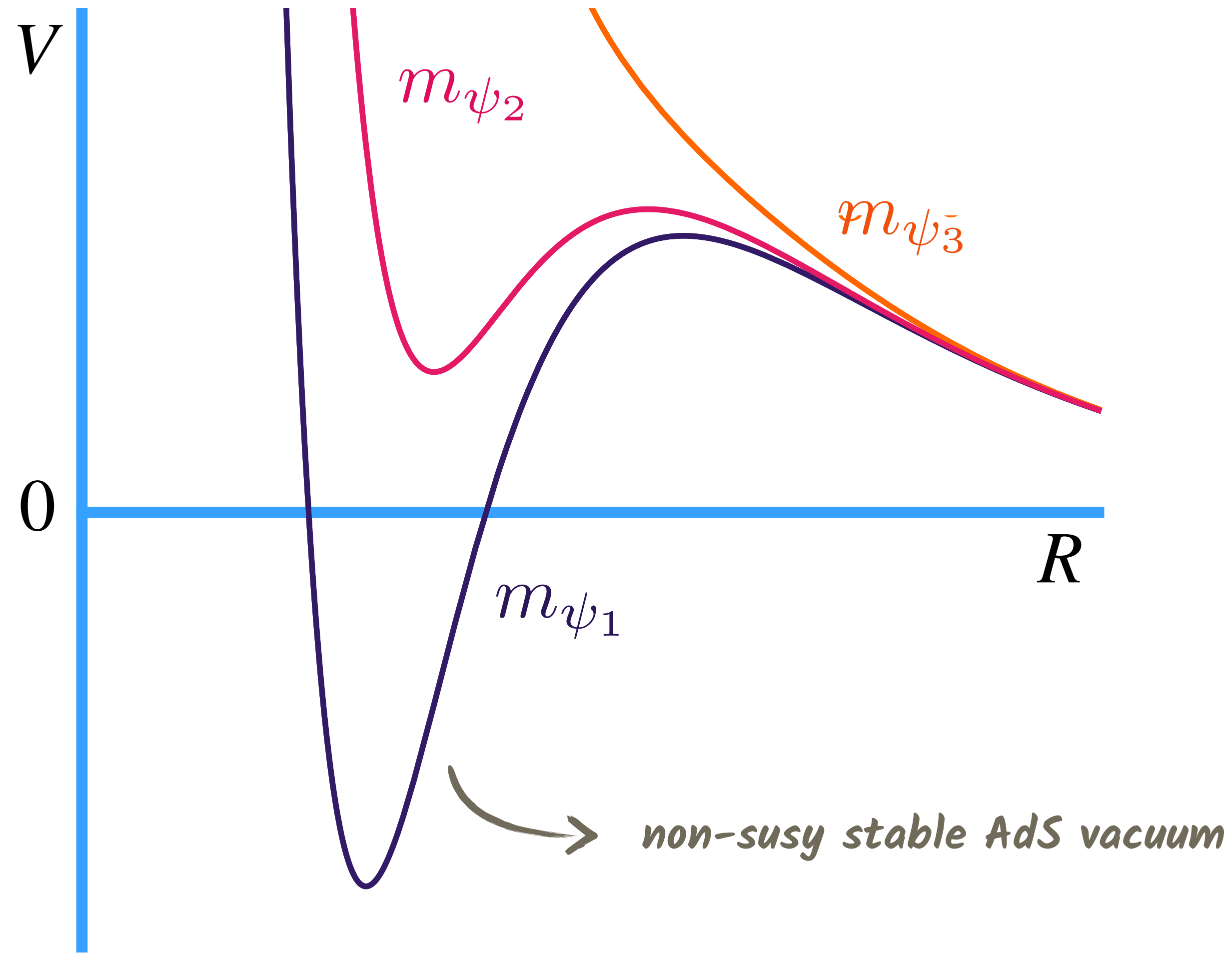

inconsistent with Non-SUSY AdS conjecture

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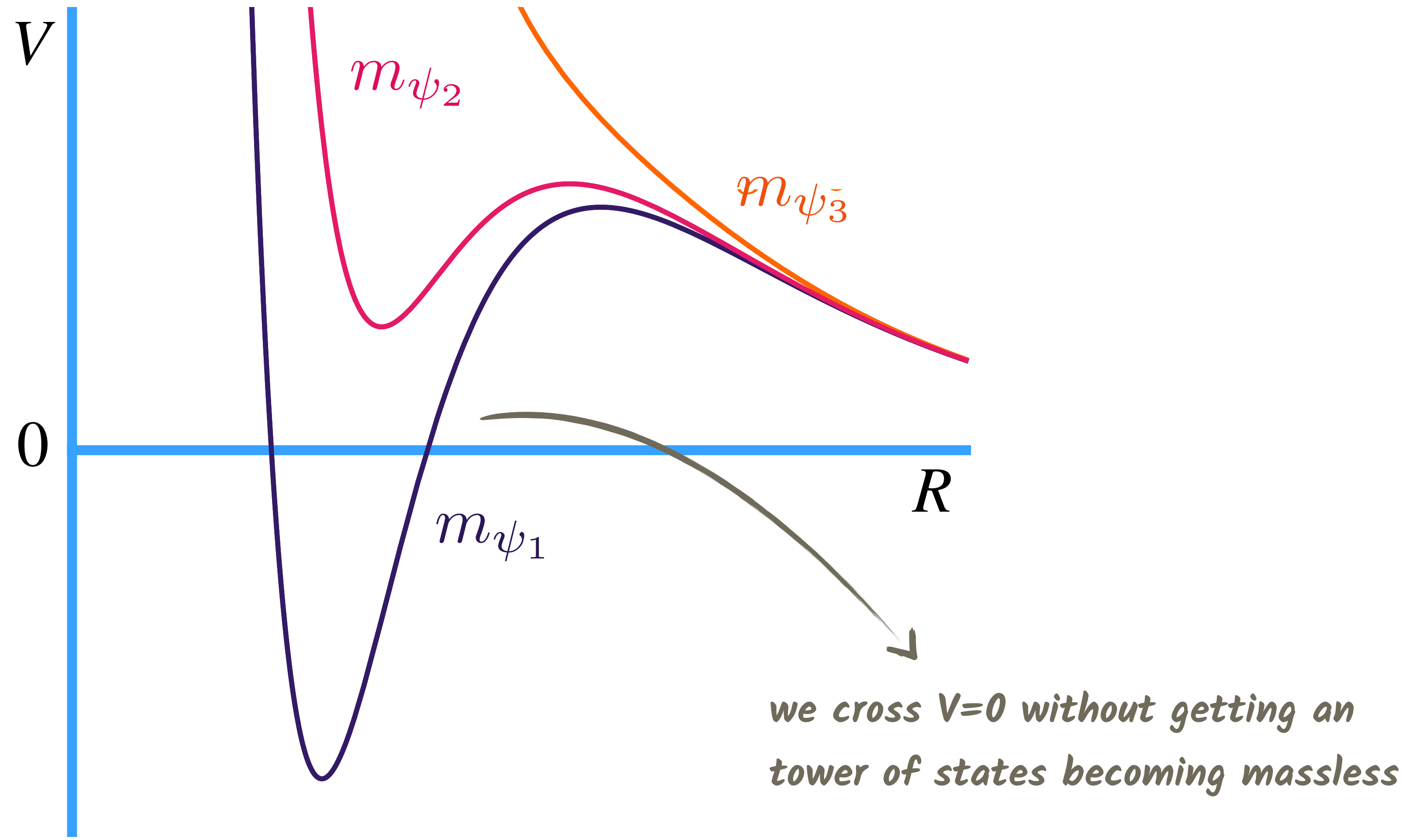


inconsistent with AdS Distance conjecture

Assumptions

- For Non-SUSY AdS conjecture:

  We assume that no D-dim non-perturbative instability gets transferred to lower dimensions, ie. $\rho_{\text{bubble}} > L_{AdS}$

- For AdS Distance conjecture:

  We assume that we can scan a family of D-dim vacua by varying the masses from $m \simeq 0$ to larger values

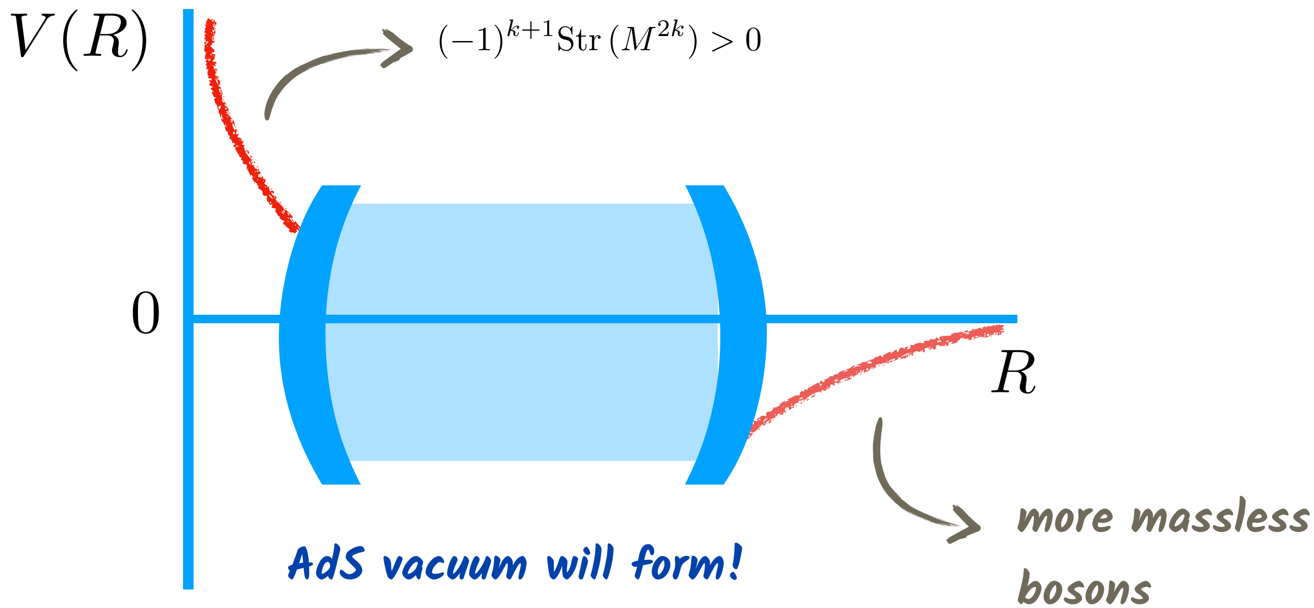
  For example, in the SM, by changing the vev of the Higgs, or the Yukawas

$$m_\nu = m_\nu^{\text{exp}} \lambda$$

→ *No assumption on vacuum stability required!*

Minkowski vacua

According to the Non-SUSY AdS conjecture:



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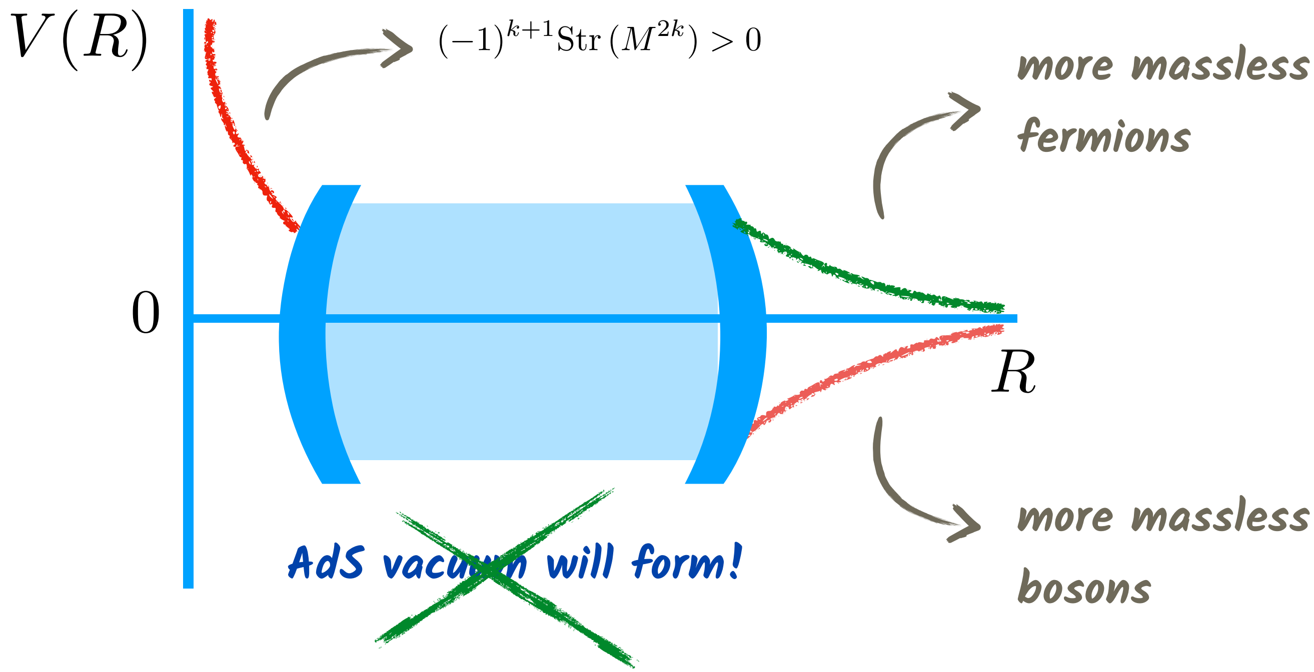

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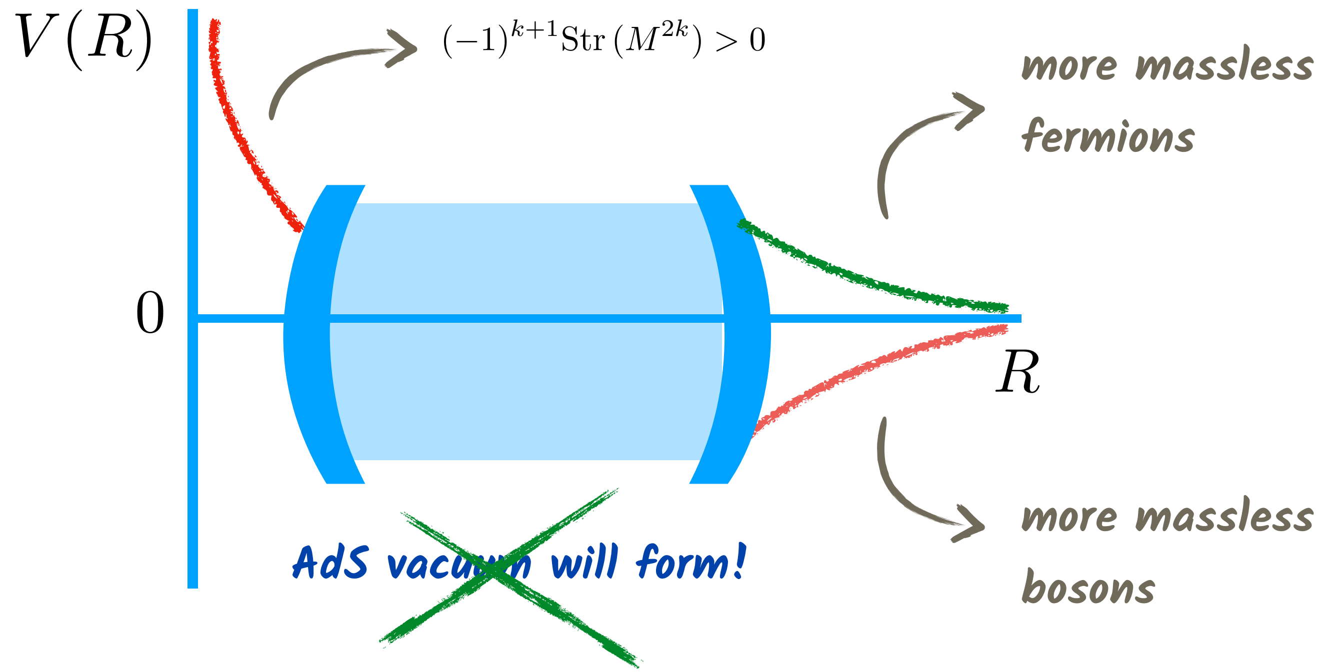
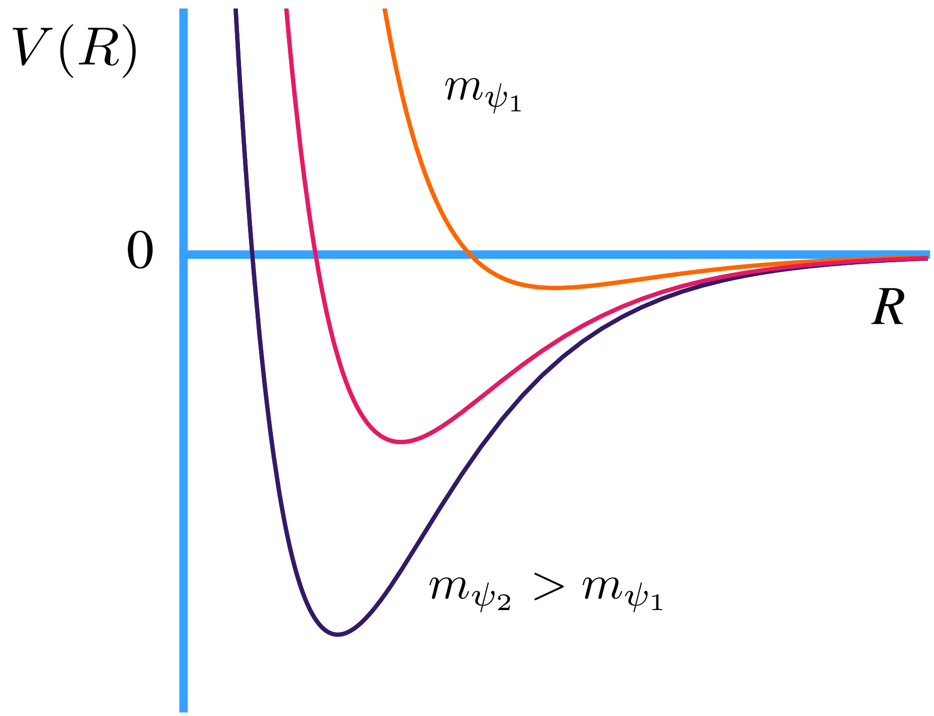


Claim 1: A D-dim Mink vacuum satisfying $(-1)^{k+1}\mathrm{Str}\,(M^{2k}) > 0$ for the first non-vanishing supertrace is inconsistent with quantum gravity unless there is a surplus of massless fermions

Minkowski vacua

According to the AdS Distance conjecture:



$R \to \infty$ as $V \to 0$

$$m_{KK} \sim \Lambda_D^{1/D} \to 0$$

KK tower of states get light!

Minkowski vacua

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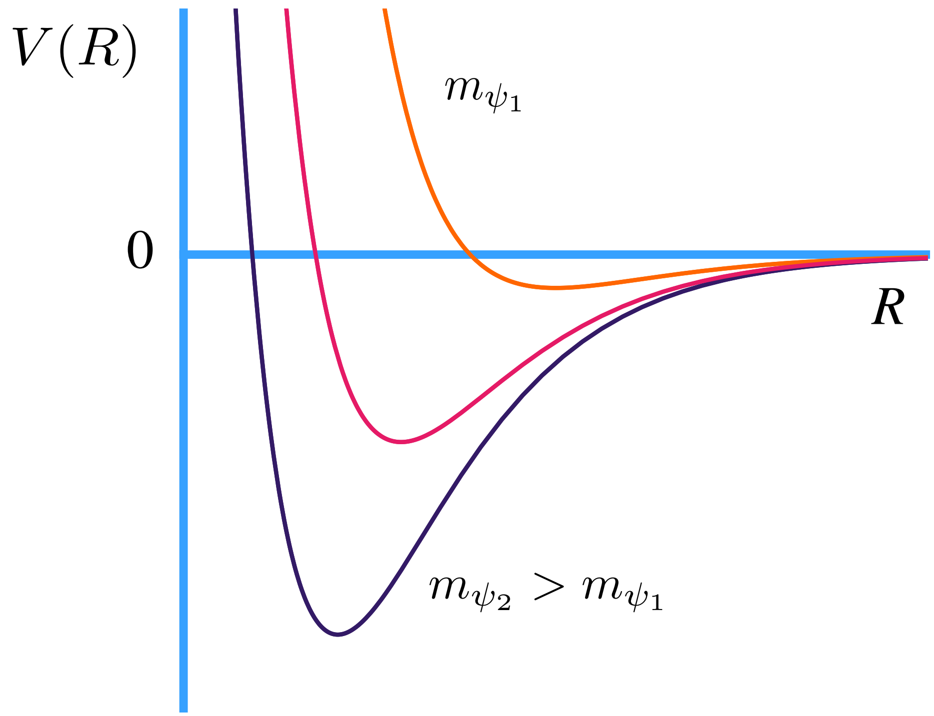


$R \to \infty$ as $V \to 0$

$$m_{KK} \sim \Lambda_D^{1/D} \to 0$$

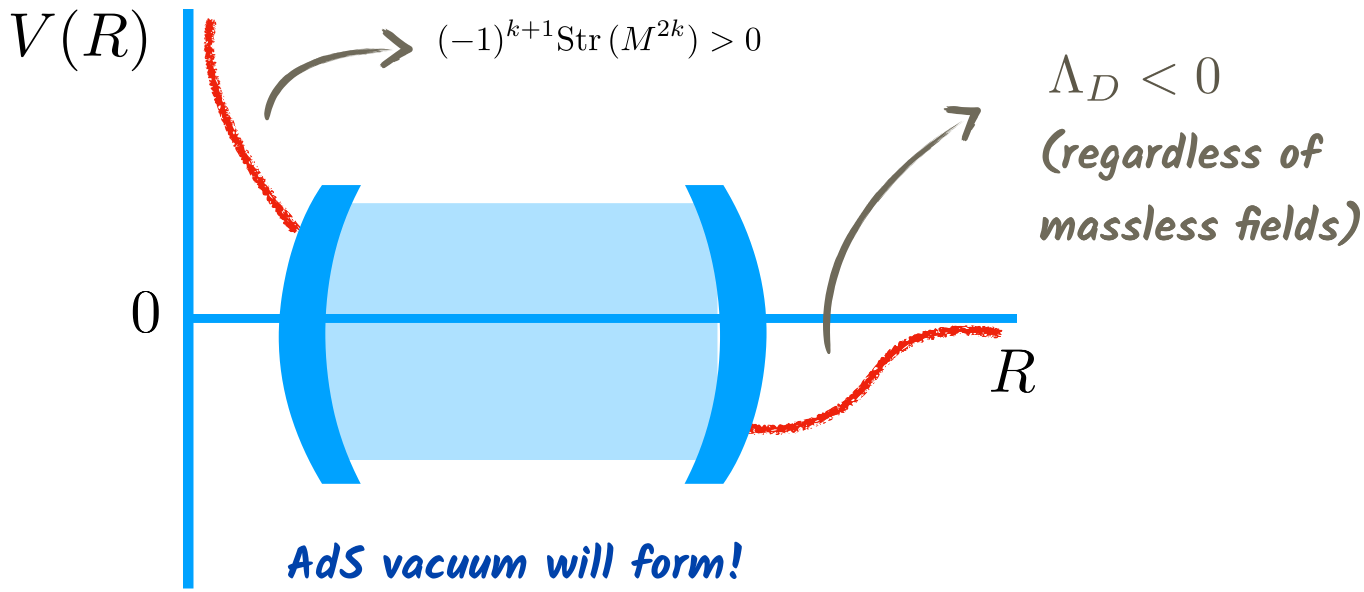
KK tower of states get light!

It is consistent with the mild (but not the strong) version of the conjecture.

$$m \sim \Lambda^{\alpha} \quad , \quad \alpha = \frac{1}{D} < \frac{1}{2}$$

AdS vacua

According to the Non-SUSY AdS conjecture:



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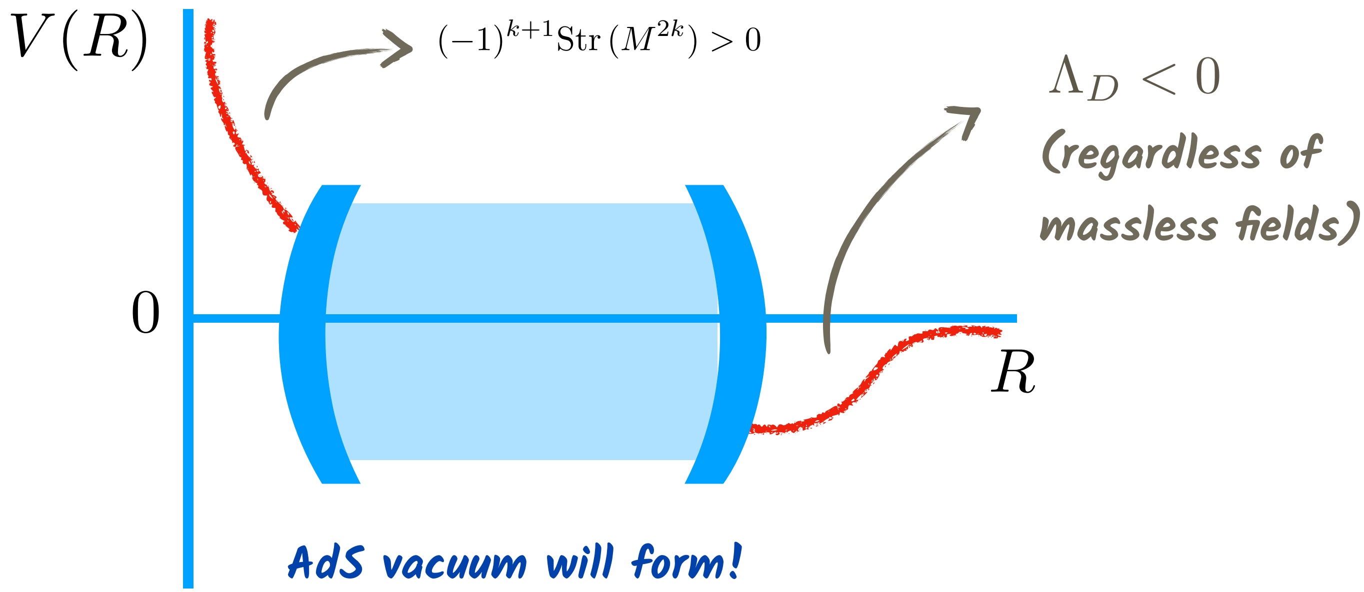

Claim 2: A D-dim AdS vacuum satisfying $(-1)^{k+1}\mathrm{Str}\,(M^{2k}) > 0$ for the first non-vanishing supertrace is inconsistent with quantum gravity.

AdS vacua

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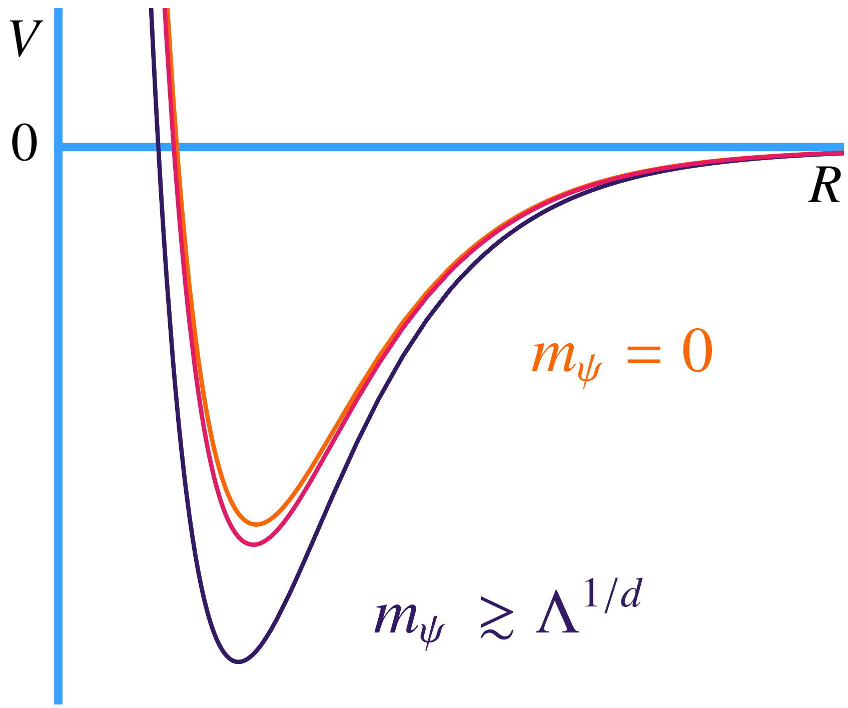

It never crosses V=0

unless $\Lambda_D \to 0$

- D-dim tower $m \sim \Lambda^\alpha \to 0$
- $m_{KK} \sim \Lambda_D^{1/D} \to 0$

(see also [Rudelius'21])

AdS vacua

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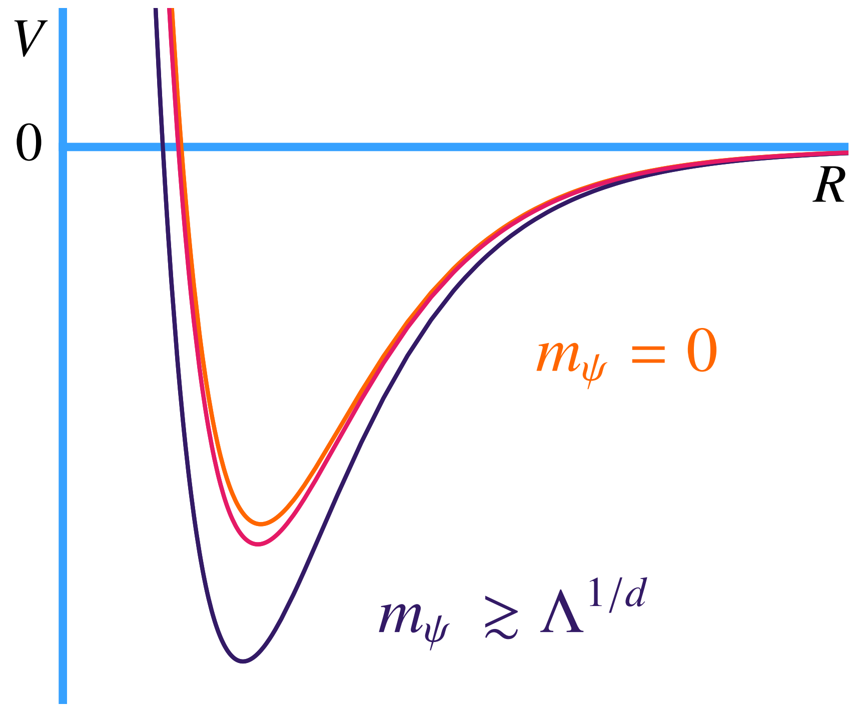

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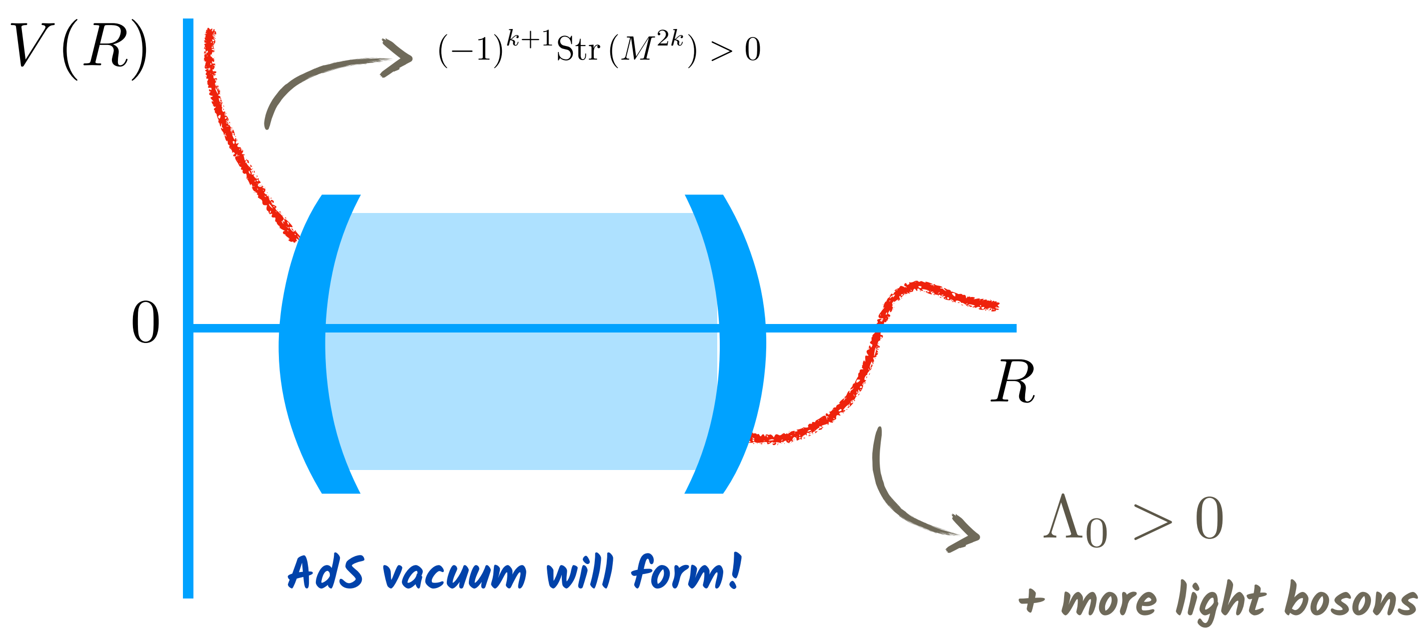
It is consistent with the conjecture

dS vacua

According to the Non-SUSY AdS conjecture:



Claim 1: A D-dim dS vacuum satisfying $(-1)^{k+1}\mathrm{Str}\,(M^{2k}) > 0$ for the first non-vanishing supertrace is inconsistent with quantum gravity unless there is a surplus of light fermions $m_f \lesssim \Lambda_D^{1/D}$

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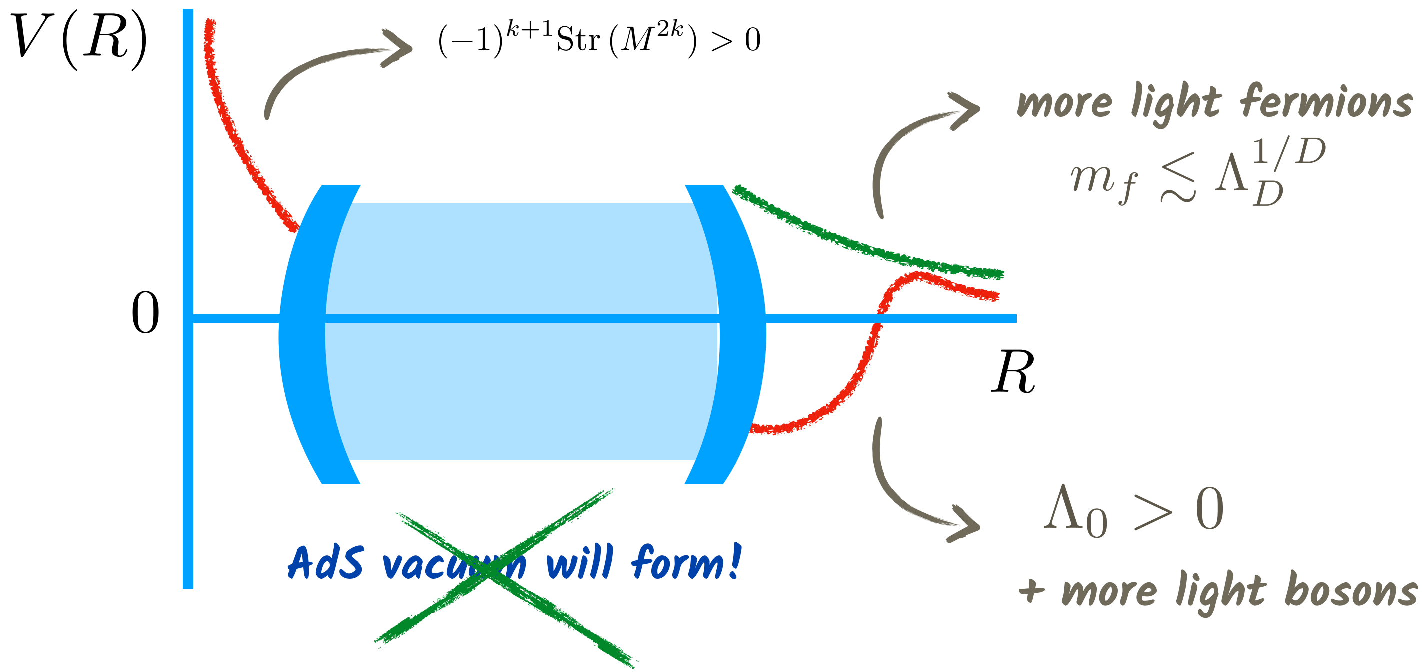

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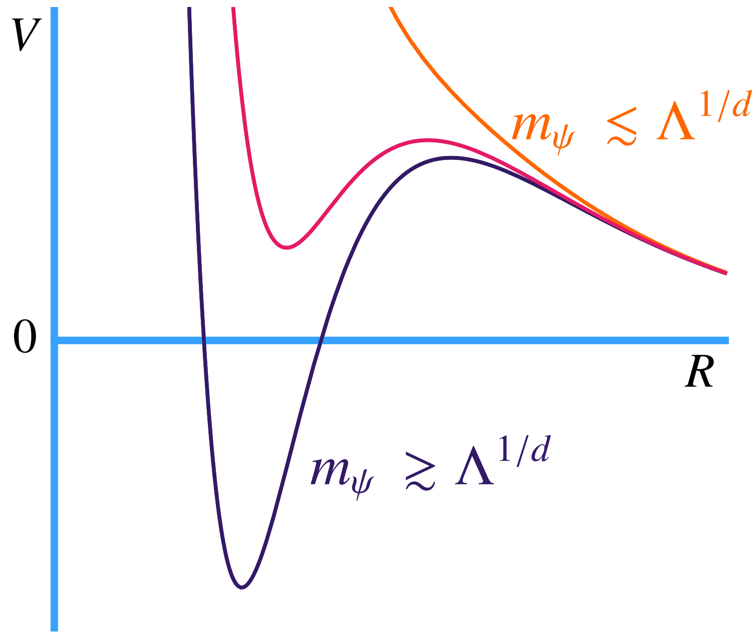


We cross V=0 at finite radius

No tower gets light!

Claim 2: A D-dim de Sitter vacuum satisfying $(-1)^{k+1}\mathrm{Str}\,(M^{2k}) > 0$ for the first non-vanishing supertrace is inconsistent with quantum gravity unless there is a surplus of light fermions:

1) with $m \lesssim \Lambda_D^{1/D}$

2) that are part of an infinite tower in D-dim scaling as $m \sim \Lambda_D^{\alpha}$

Results

- Consistency with quantum gravity implies constraints on EFTs:

Vacua	non-SUSY AdS	AdS distance
M_D	violated (unless surplus of massless fermions)	$\alpha = 1/d$
dS	violated (unless surplus of fermions $m_f \lesssim \Lambda^{1/D}$)	violated* (unless surplus fermions $m_f \lesssim \Lambda^{1/D}$)
AdS	violated	

They apply if $(-1)^{k+1}\mathrm{Str}\,(M^{2k}) > 0$ (UV/IR mixing)

e.g. non-SUSY theories $n_f > n_b$

spont. broken SUSY $n_f = n_b$, $\sum_b n_b m_b^2 > \sum_f n_f m_f^2$ (like split SUSY)

Light fermion swampland conjecture

- We can summarise the results in the following proposal:

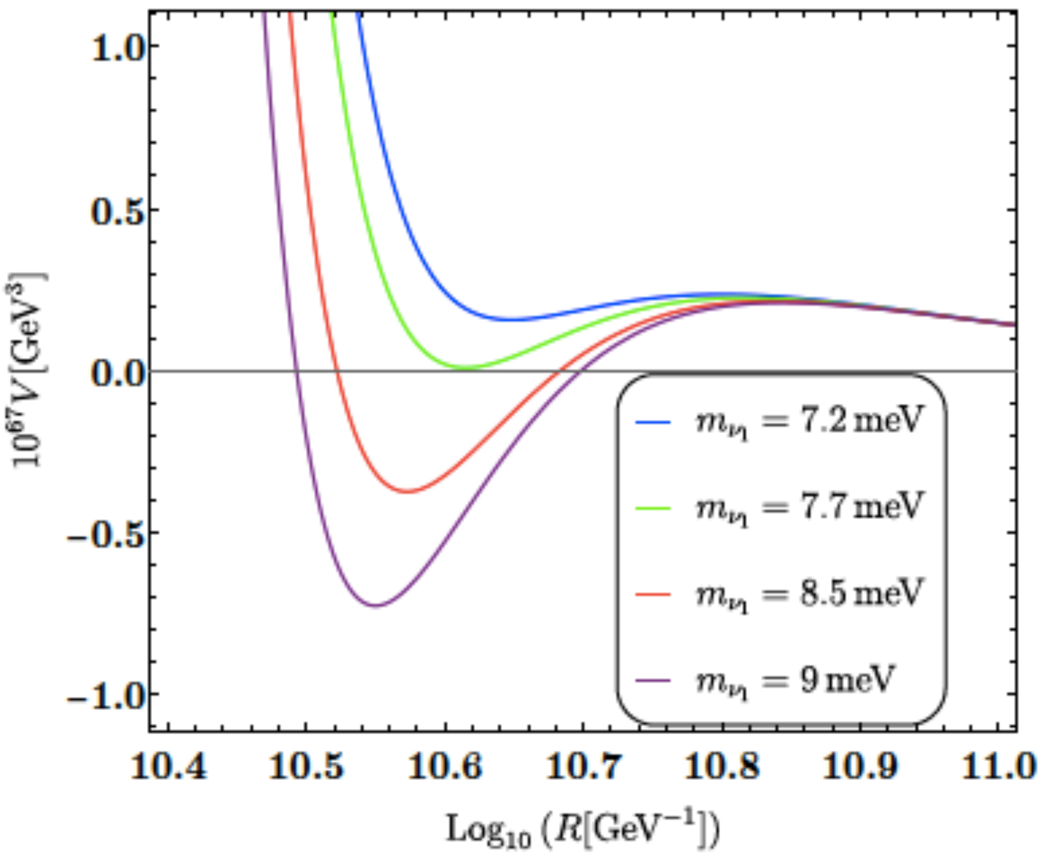
> In a SUSY broken theory coupled to gravity with $\Lambda_D \geq 0$ and positive first non-vanishing supertrace $(-1)^{k+1}\mathrm{Str}\,(M^{2k}) > 0$ there must exist a surplus of light fermions with masses $m \lesssim \Lambda_D^{1/D}$

→ Satisfied by the non-SUSY SO(16)xSO(16) heterotic string theory

More evidence?

(3) Constraints on Standard Model

Constraints on SM of Particle Physics



By varying neutrino masses, we can cross Minkowski without (apparently) having an infinite tower of states becoming massless!

Constraints on SM of Particle Physics

In the absence of additional light BSM fields:

- Non-SUSY AdS conjecture:

  Neutrinos must be Dirac with mass $m_{\nu_1} \lesssim \Lambda_4^{1/4}$

  assumption: no hidden stabilities

- AdS Distance conjecture:

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  or they must be part of an infinite tower of states scaling as $m_\nu \sim \Lambda_4^\alpha$

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More concretely, $m_{\nu_1} \leq 6.6 \text{ meV}$ for Dirac (NH)

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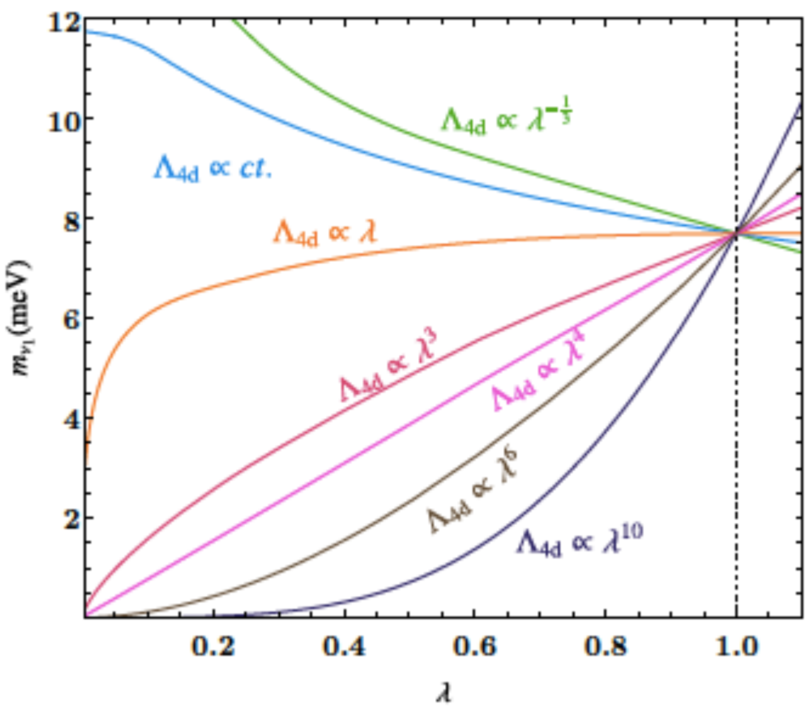
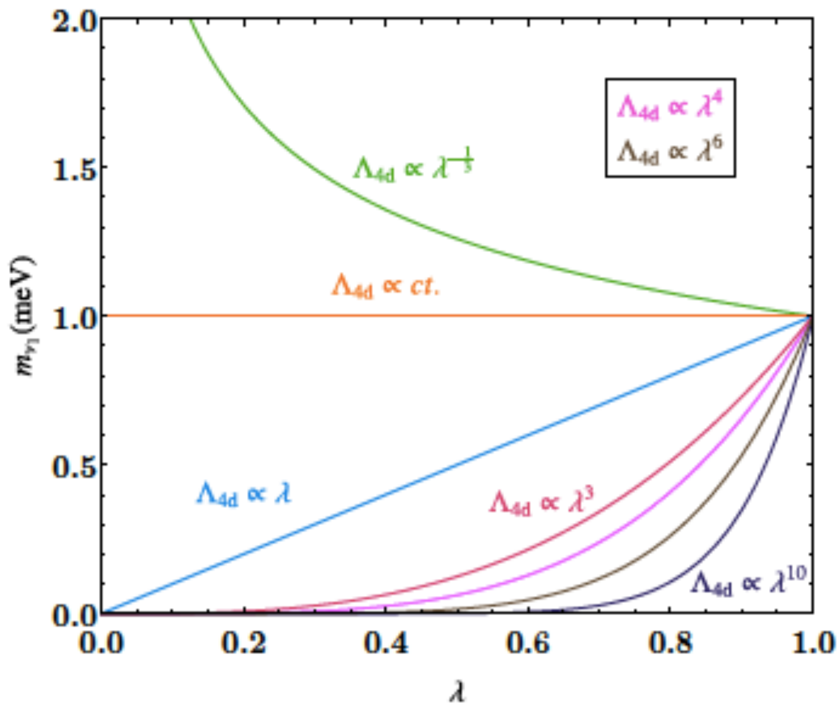
or there is light fermionic Dark Matter!

Other scannings

We can also allow for some dependence

$$\Lambda_4 = \Lambda_4^{\exp} \lambda^{\alpha}$$
$$m_\nu = m_\nu^{\exp} \lambda$$





Quintessence

What if we live in a quintessence phase instead of a dS vacuum?

de Sitter conjecture: $\frac{|\nabla V|}{|V|} \geq c$ $\qquad \mathrm{min}(\nabla_i \nabla_j V) \geq -c' V$

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Assuming SM + additional quintessence scalar field, consistency with the conjecture implies

$$\sqrt{\frac{R^2}{|V|^2}\left|\frac{\partial V}{\partial R}\right|^2 + \frac{c_\phi^2}{|1+\frac{V_{1L}}{V_{tree}}|}} > c$$

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AdS minima on the radion can be problematic!

It also forces us to forbid these AdS vacua, we recover same bounds than before.

Naturalness issues

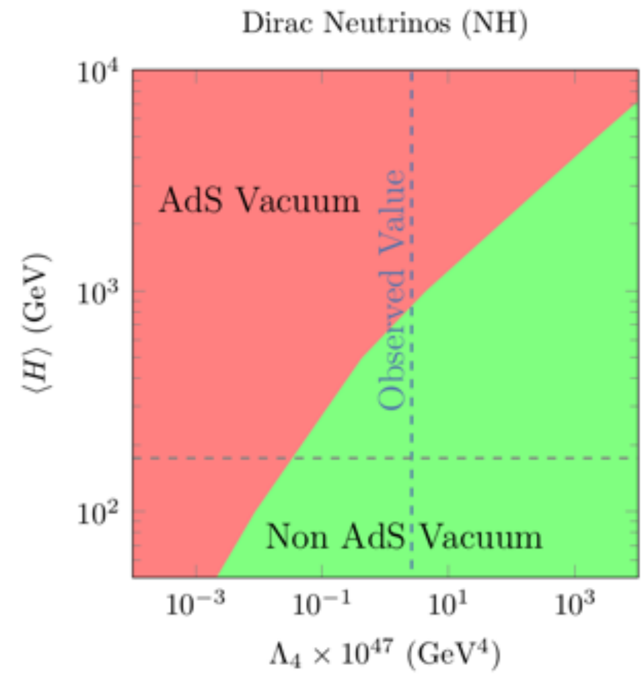
Neutrinos must be Dirac with mass

$$m_{\nu_1} \lesssim \Lambda_4^{1/4}$$

numerical coincidence observed in our universe!

[Martin-Lozano,Ibanez,IV'17]

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



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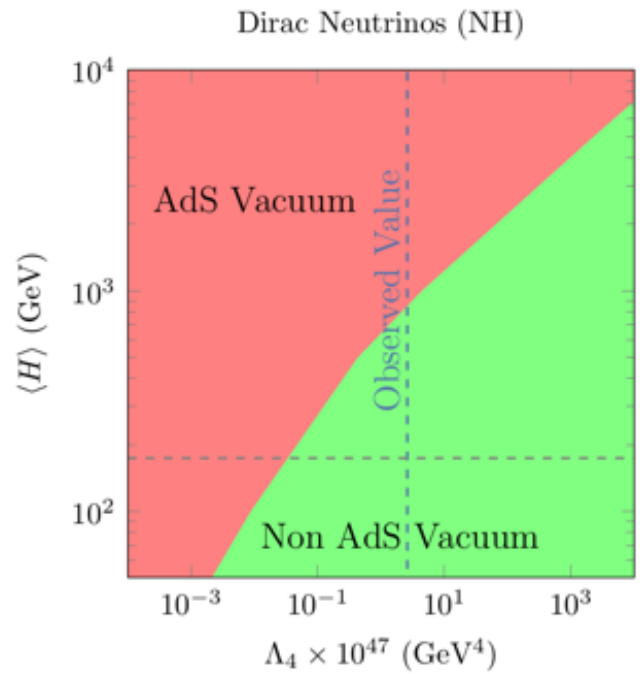
numerical coincidence observed in our universe!

[Martin-Lozano,Ibanez,IV'17]

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



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 do not yield theories consistent with quantum gravity

Solution to EW hierarchy porblem?

Conclusions

- Consistency with quantum gravity implies constraints on low energy physics:

We have explored the constraints on Mink,AdS and dS vacua arising from requiring that circle compactifications of such a theory are consistent with the AdS swampland conjectures

The conjectures are typically satisfied if there is a surplus of light fermions

$$m \lesssim \Lambda_D^{1/D}$$ (Light fermion swampland conjecture)

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  (for NH: $m_{\nu_1} \leq 6.6 \text{ meV}$) *or there is light fermionic DM*

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  New approach to hierarchy problems?

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Thank you!