Quantum Gravity Constraints on Particle Physics and Cosmology

Irene Valenzuela

Utrecht University

Ibanez,Martin-Lozano,IV [arXiv:1706.05392 [hep-th]]

Ibanez,Martin-Lozano,IV [arXiv: 1707.05811 [hep-th]]

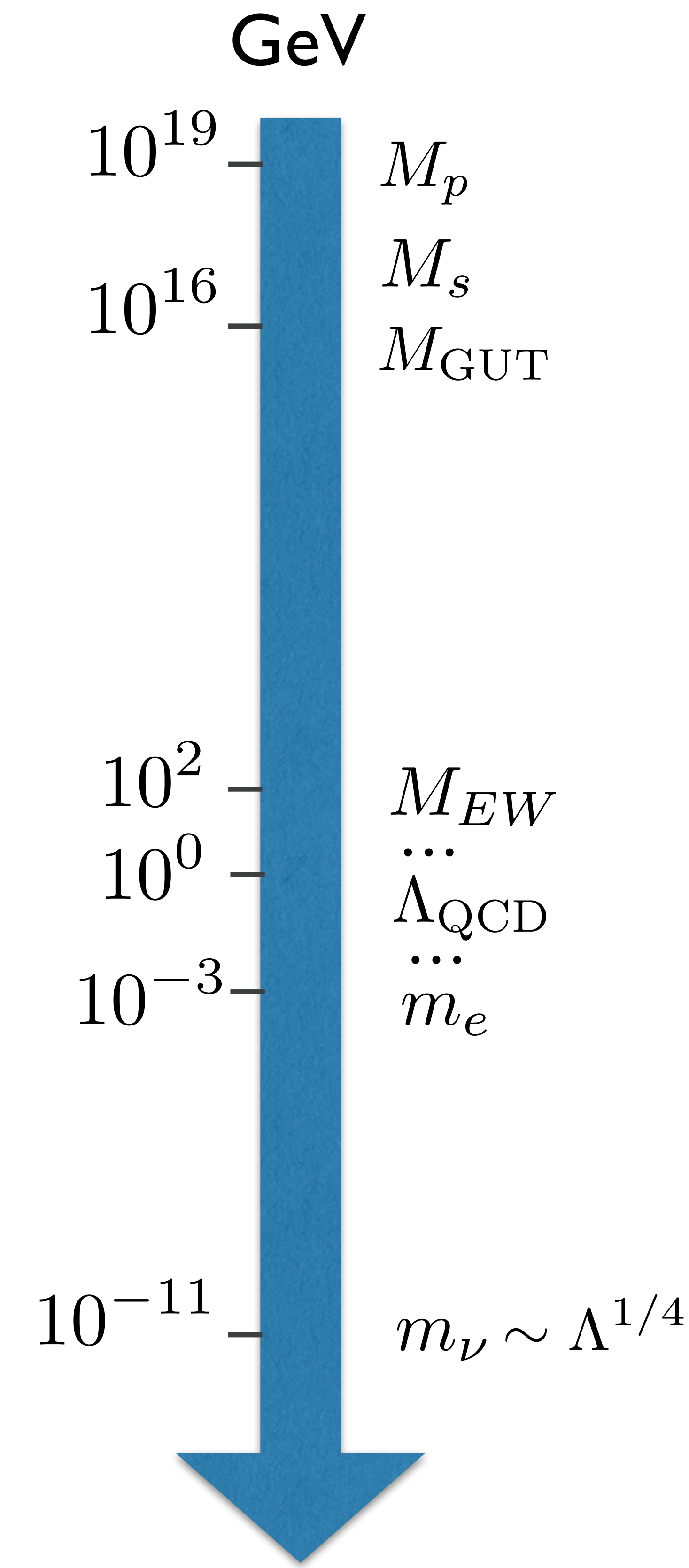
Grimm,Palti,IV [arXiv:1802.08264 [hep-th]]

Planck conference, Bonn, May 2018

Successful Standard Model of Particle Physics and Cosmology!

Expectation of 'separation of scales':

IR effective theory not very sensitive to UV physics



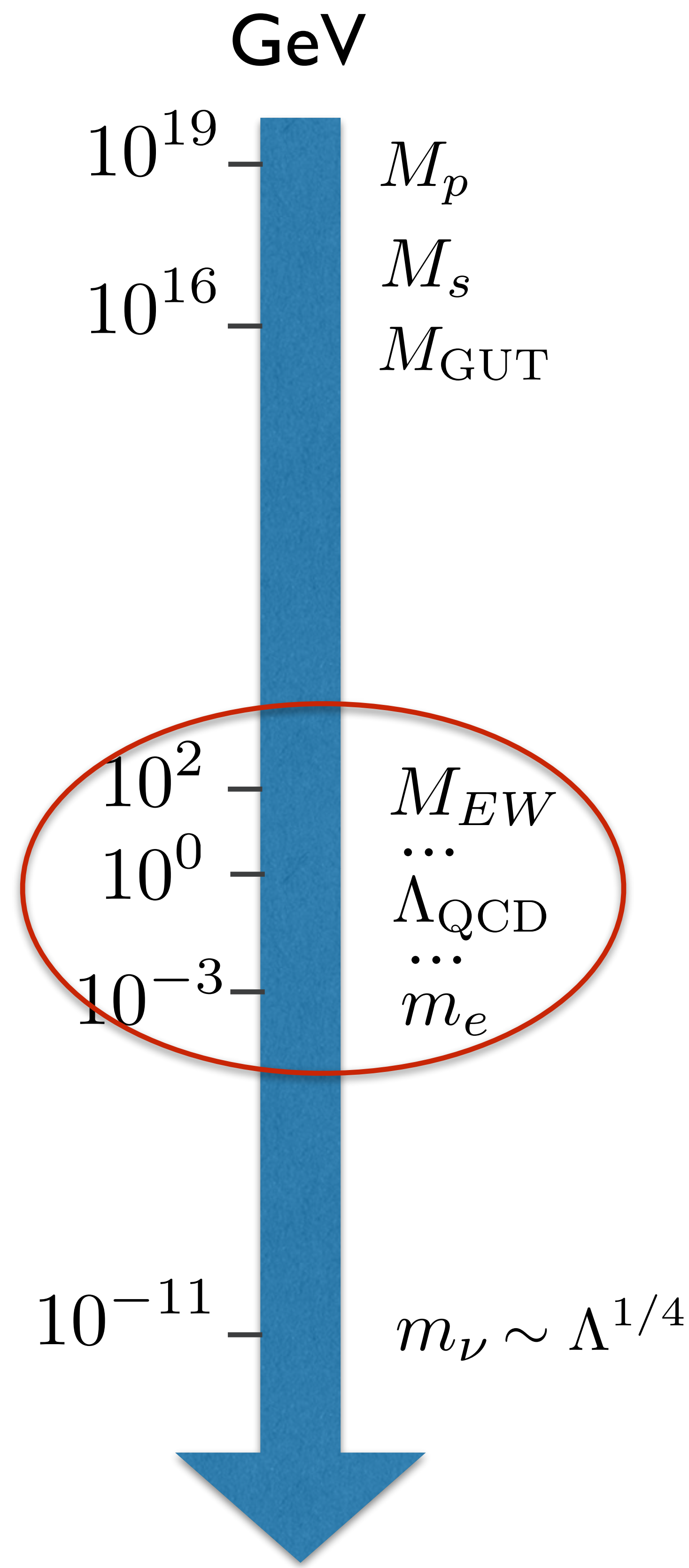
Successful Standard Model of
Particle Physics and Cosmology!

Expectation of 'separation of scales':

IR effective theory not very
sensitive to UV physics

Shall we care about Quantum Gravity?

Any implication for low energy physics?



Successful Standard Model of
Particle Physics and Cosmology!

Expectation of 'separation of scales':

IR effective theory not very
sensitive to UV physics

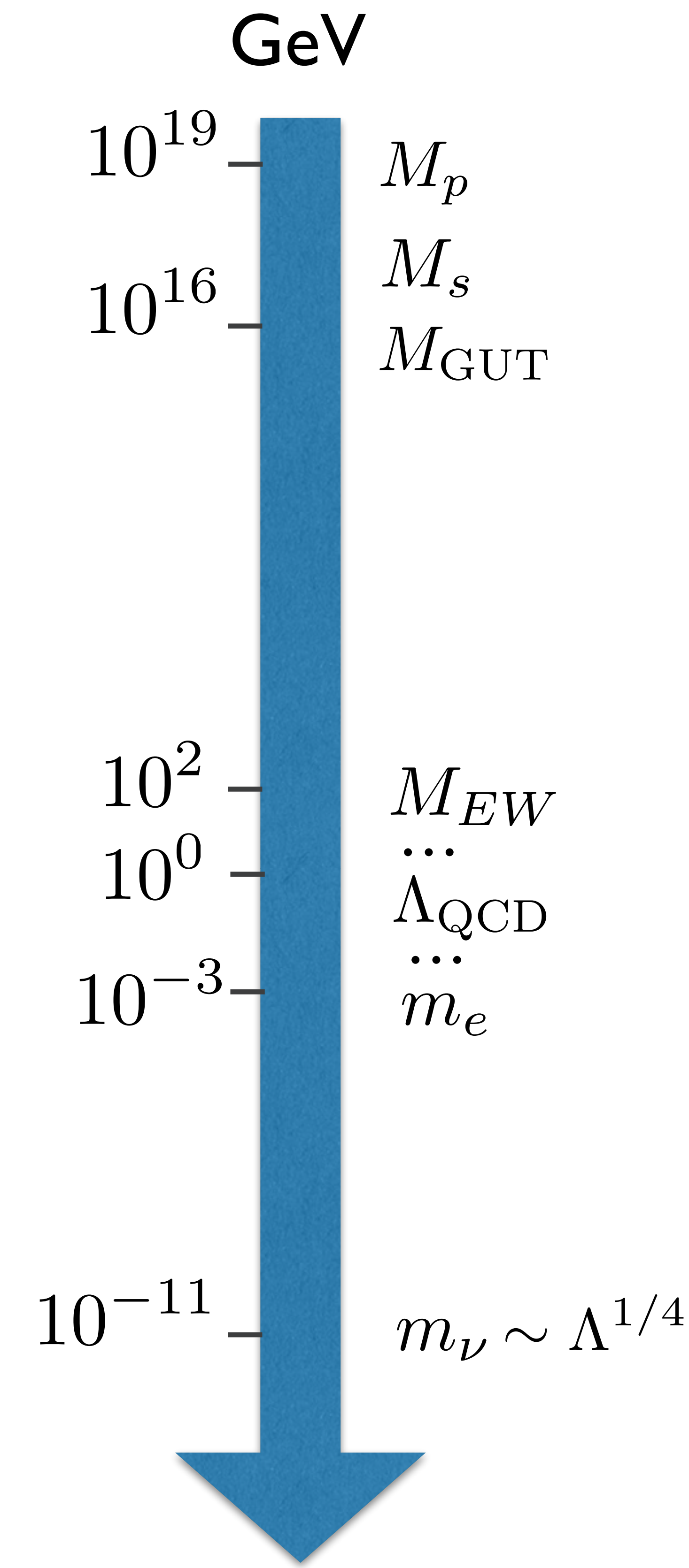
This picture can fail!

UV sensitive theories:

- Large field inflation / Relaxion

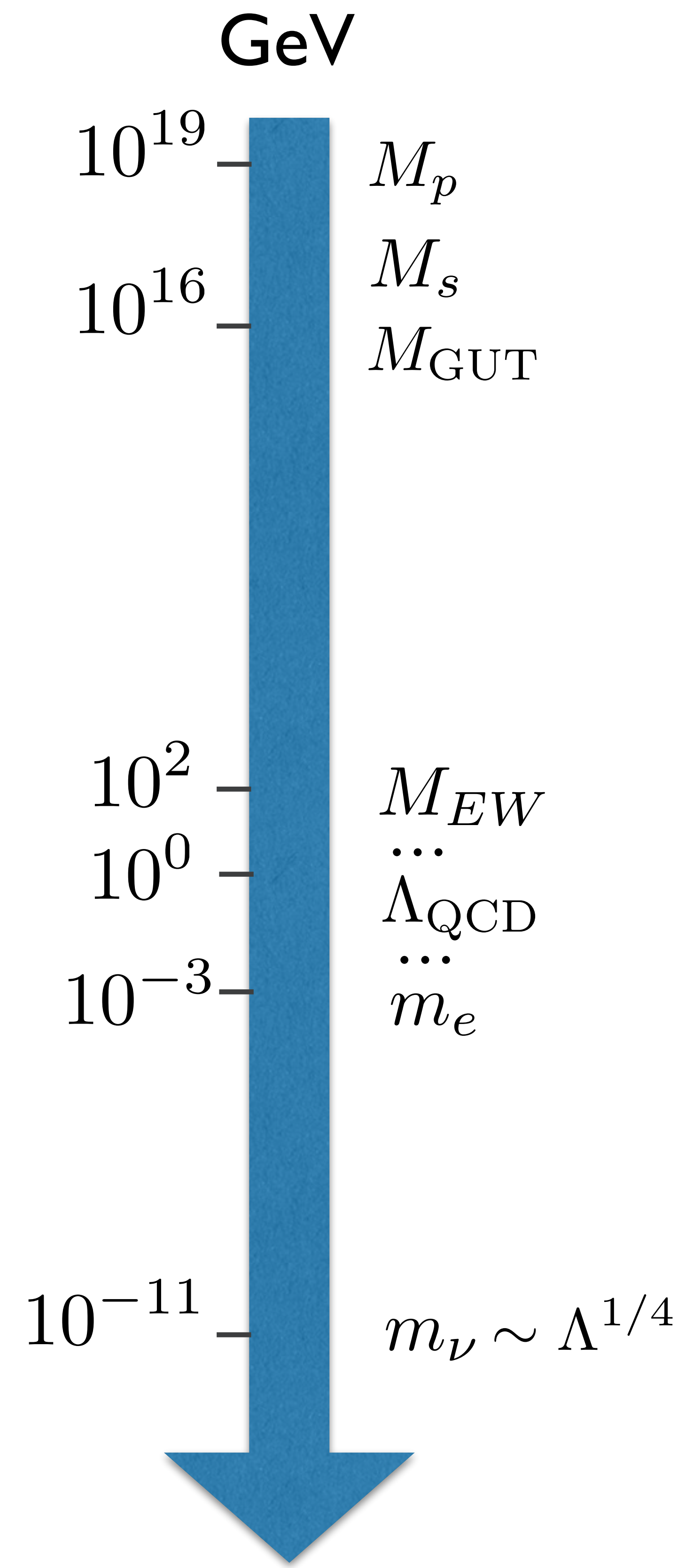
Naturalness problems:

- Cosmological constant
- EW hierarchy problem



Absence of new physics is also a hint!

Naturalness might not be good guiding principle to progress in high energy physics… new ideas?

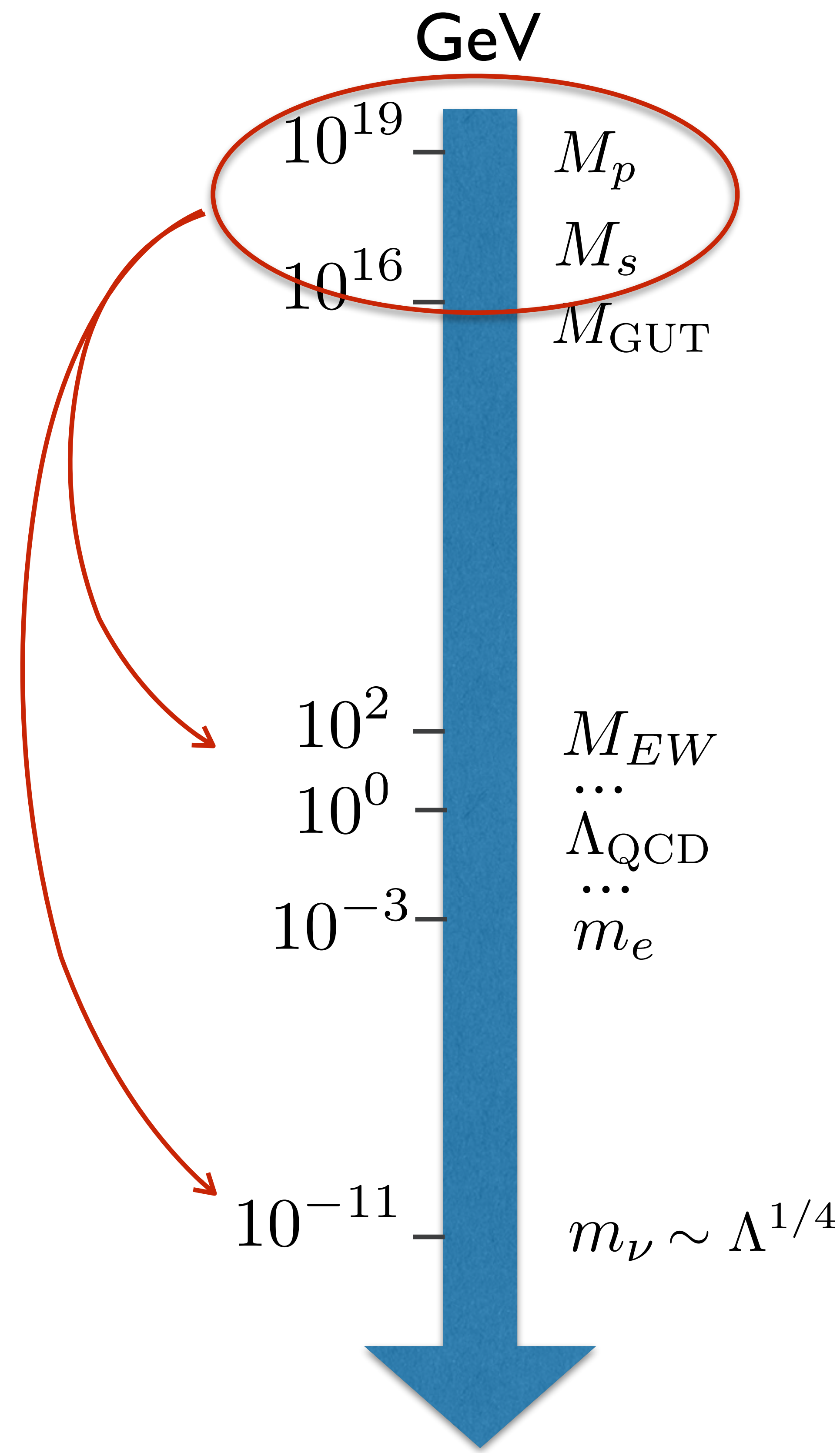


Absence of new physics is also a hint!

Naturalness might not be good guiding principle to progress in high energy physics… new ideas?

UV/IR mixing induced by gravity?

Quantum gravity constraints?

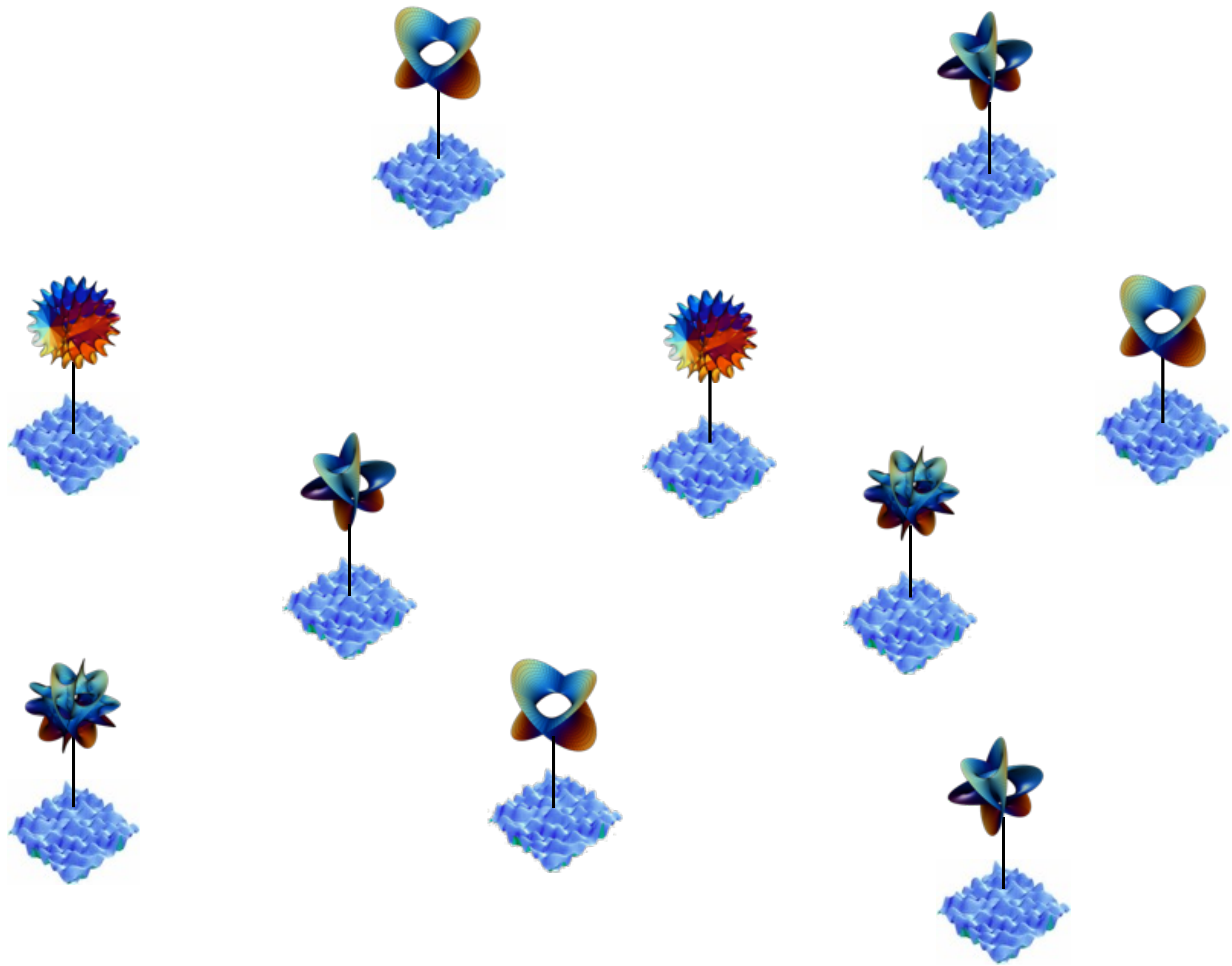


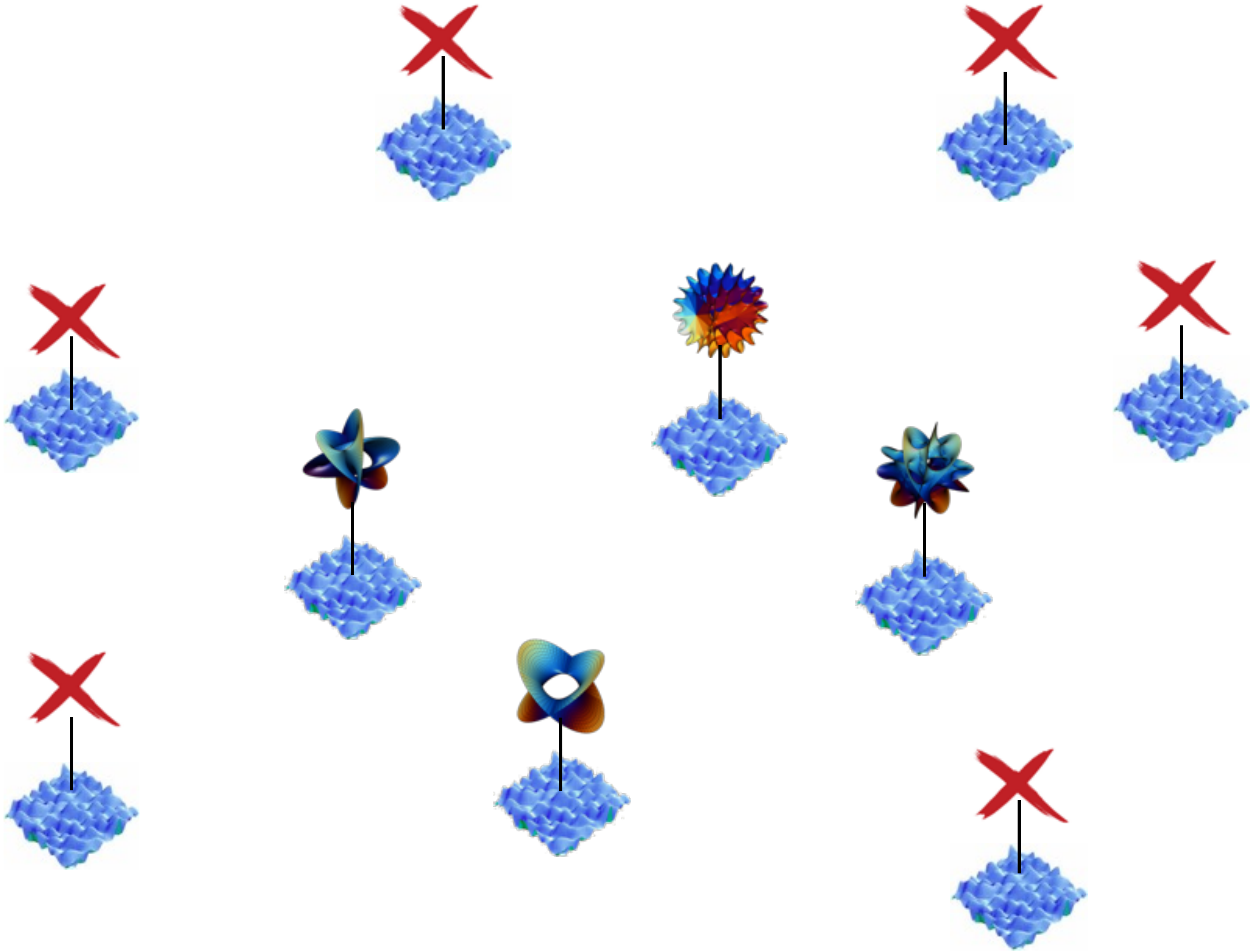
Not everything is possible in string theory/quantum gravity!!!

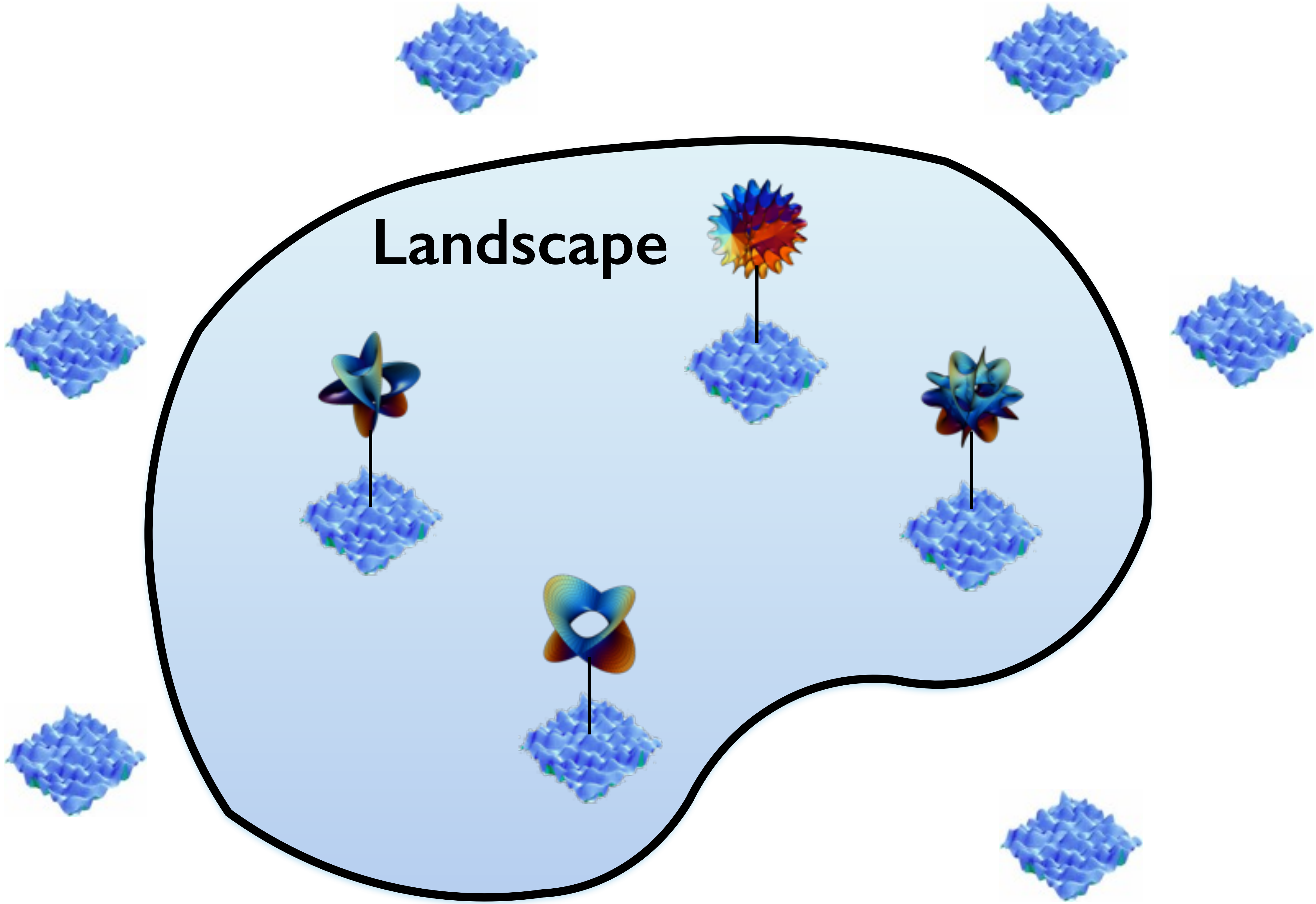
There are additional constraints that any effective QFT must satisfy to be consistent with quantum gravity

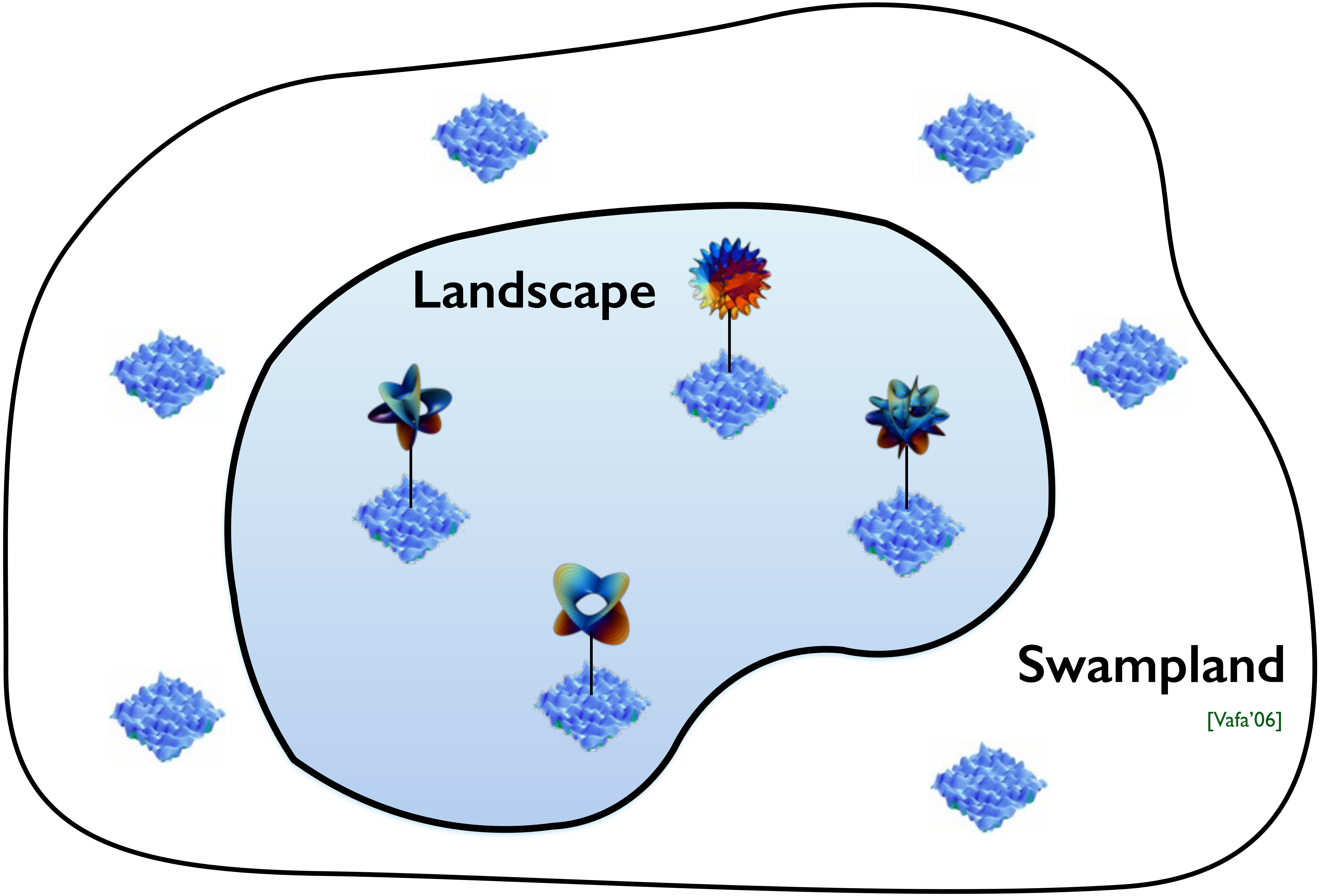
→ UV imprint of quantum gravity at low energies

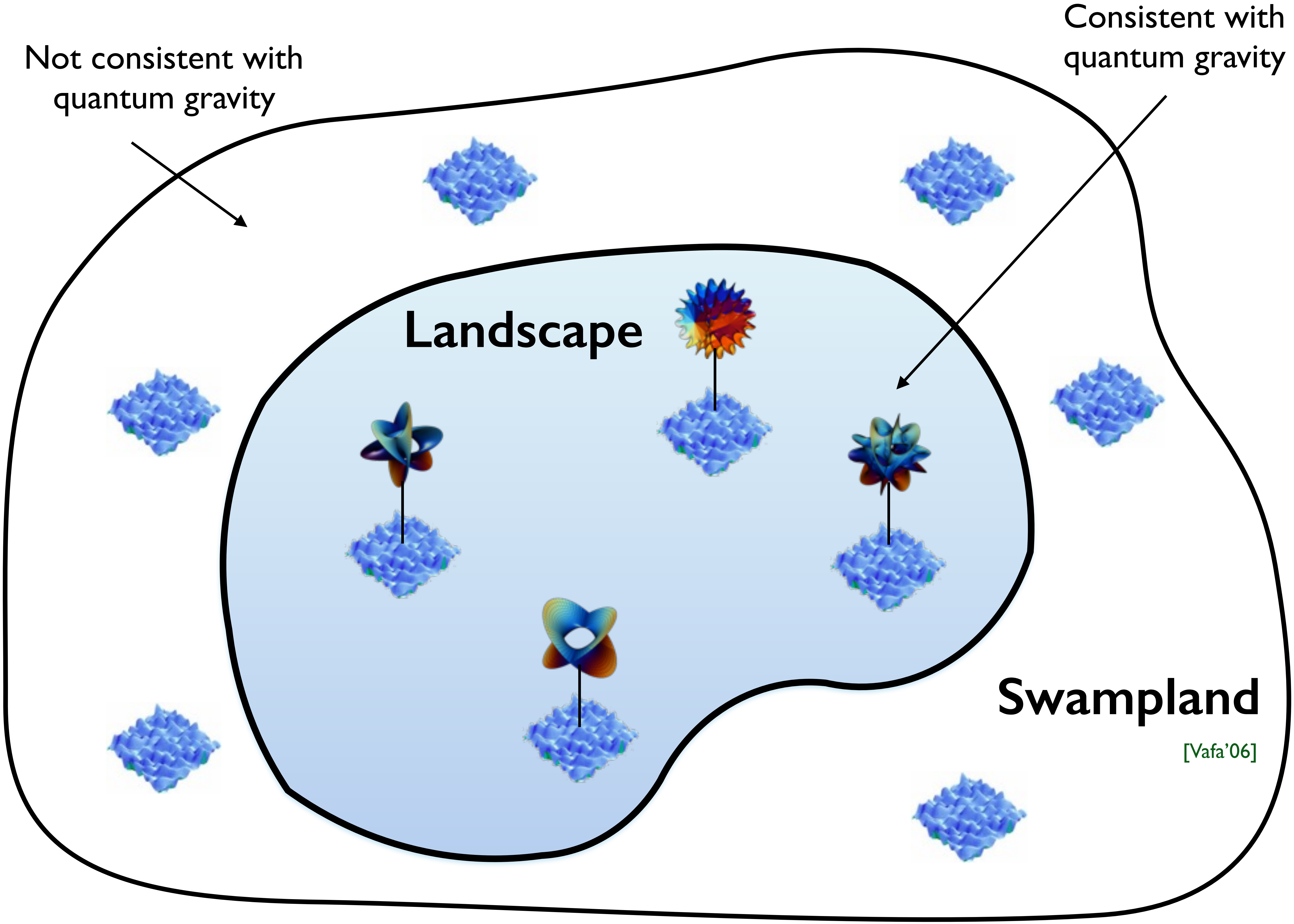
String Landscape






Landscape


Landscape
Swampland
[Vafa'06]


Not consistent with
quantum gravity
Consistent with
quantum gravity
Landscape
Swampland
[Vafa'06]

Swampland

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

What distinguishes the landscape from the swampland?

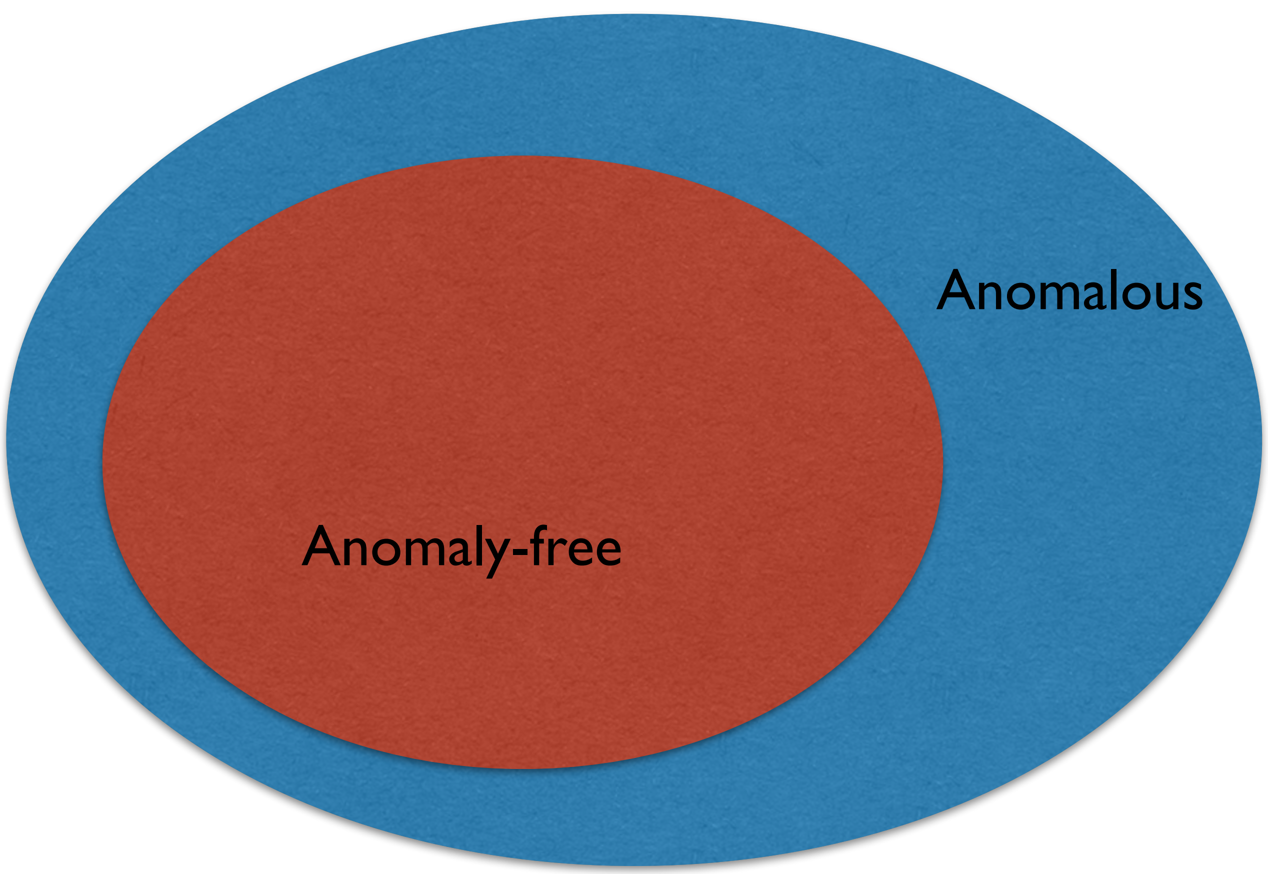
First guess: Anomalies

QFT of scalars
and fermions

First guess: Anomalies

QFT of scalars and fermions → QFT of scalars and fermions + gauge fields

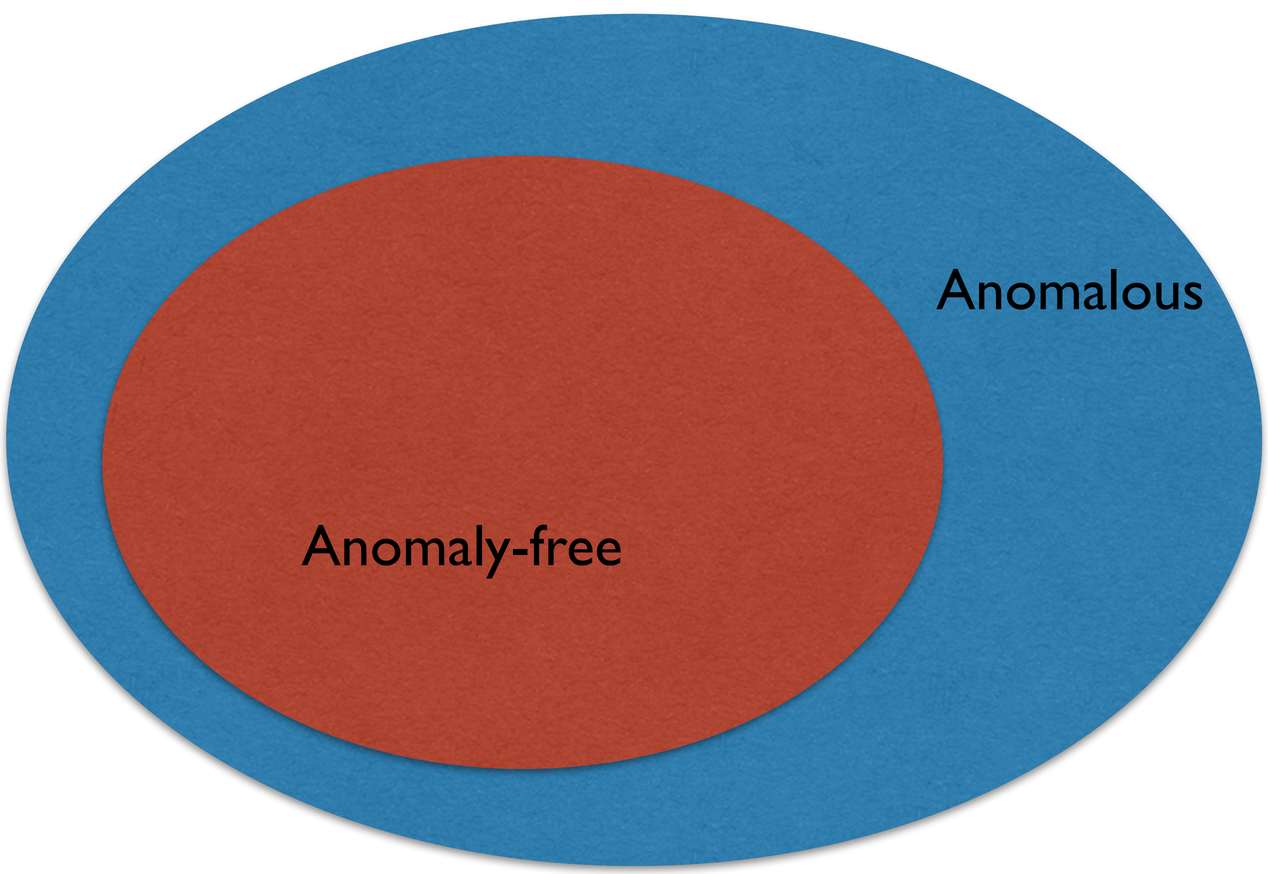
Anomaly constraints



First guess: Anomalies

QFT of scalars and fermions → QFT of scalars and fermions + gauge fields

Anomaly constraints



Example: QFT of one fermion with SU(2) global symmetry

↓

There is a Witten local anomaly when coupling the theory to a gauge field!

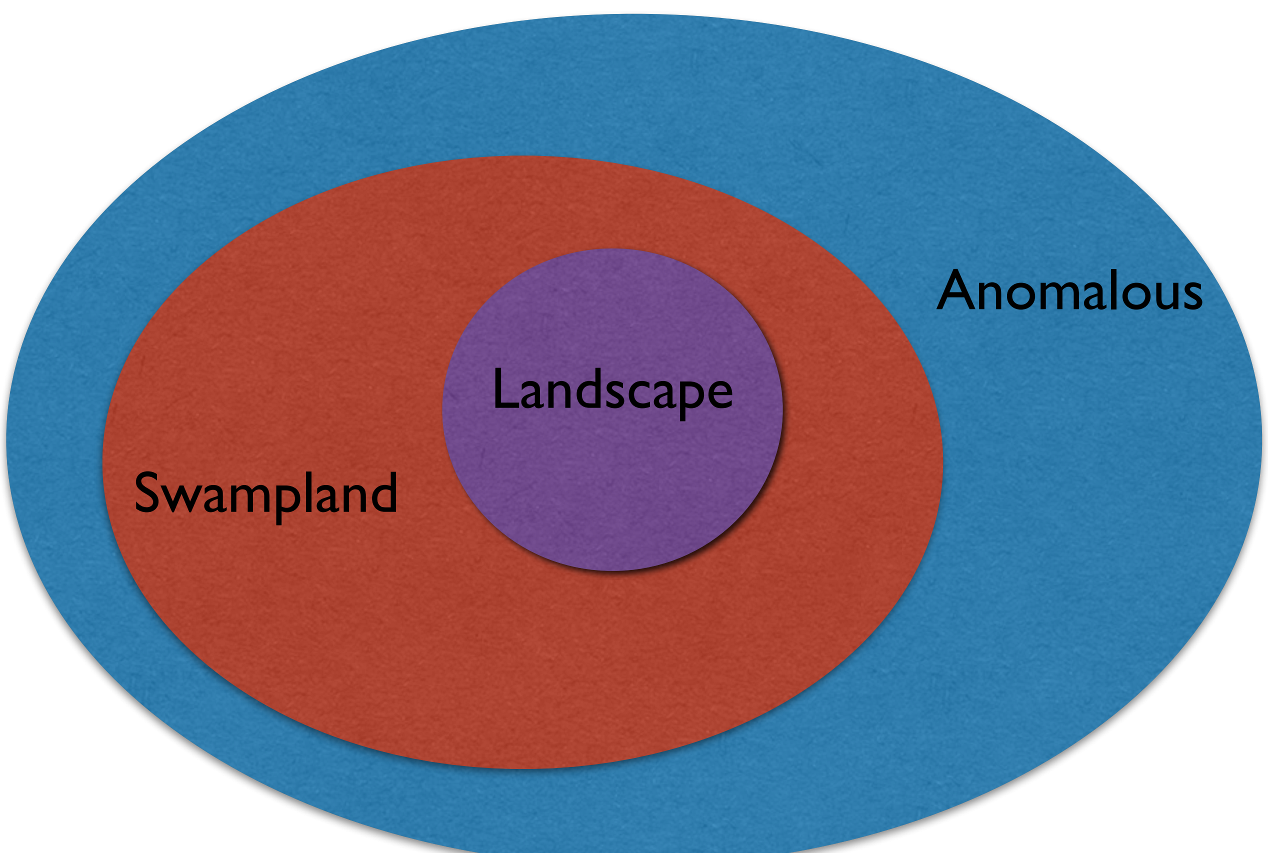
First guess: Anomalies

QFT of scalars and fermions

Anomaly constraints

QFT of scalars and fermions + gauge fields

QFT of scalars and fermions + gauge fields + gravity



First guess: Anomalies

QFT of scalars
and fermions

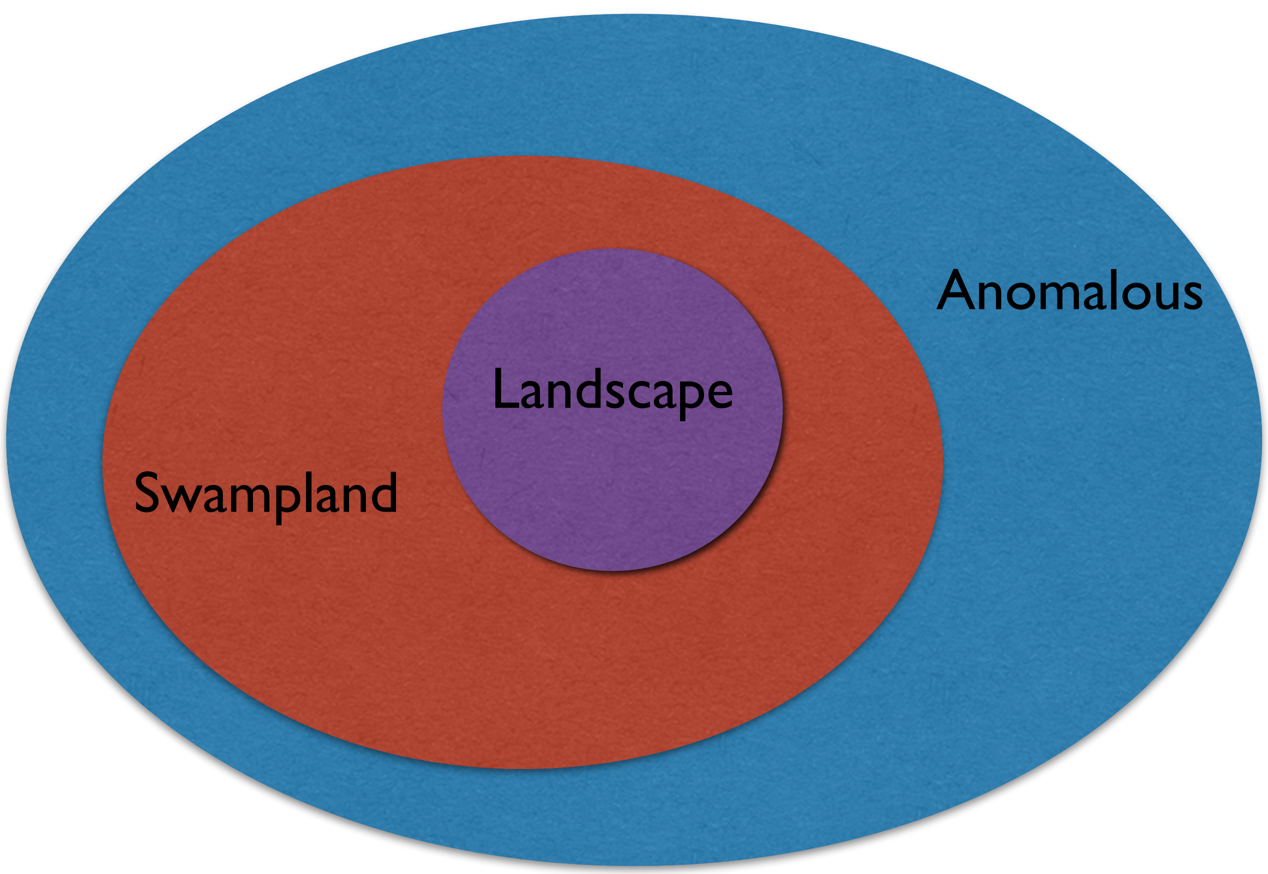
Anomaly
constraints

QFT of scalars
and fermions
+ gauge fields

Gravitational anomalies
are not enough

QFT of scalars
and fermions
+ gauge fields
+ gravity

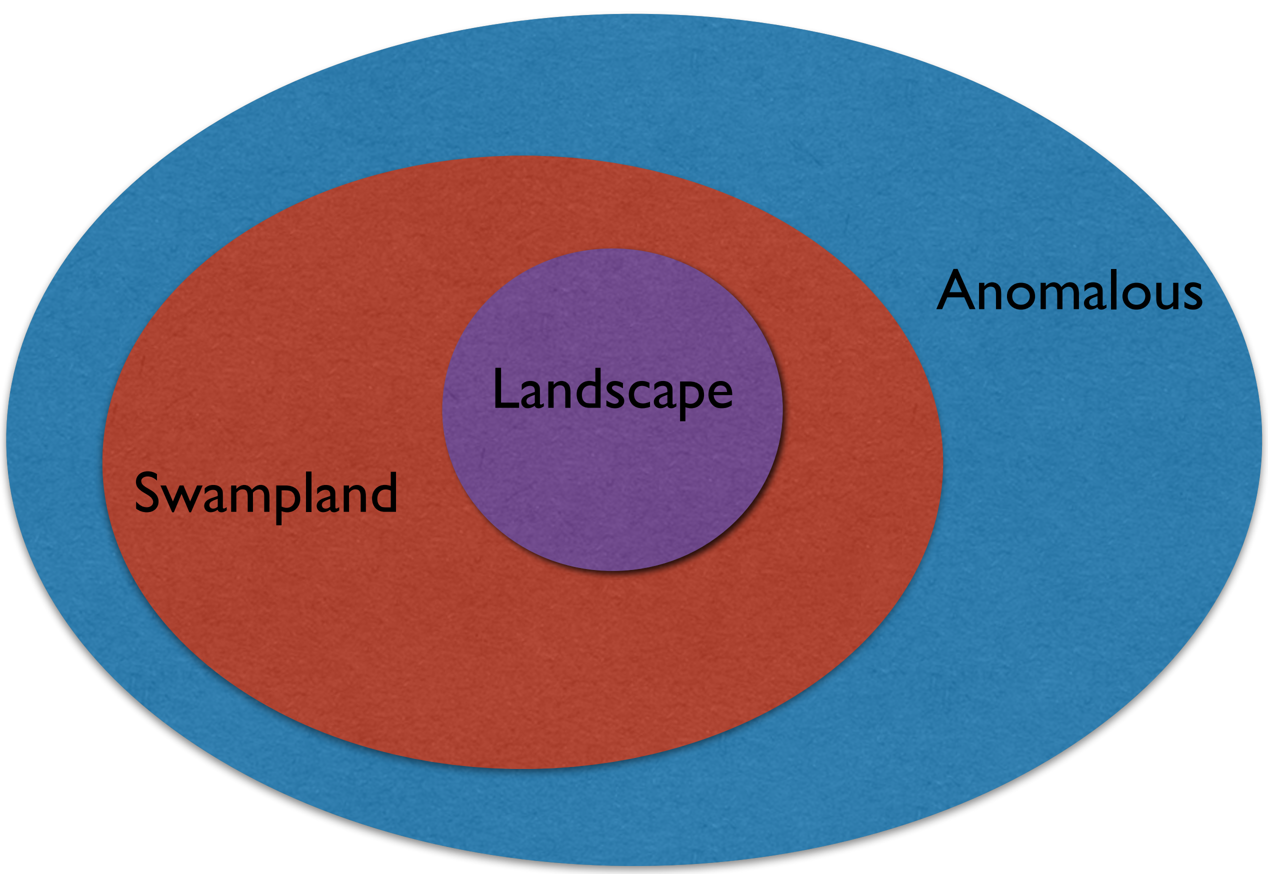
Additional QG constraints?



Not every apparently consistent (anomaly-free) effective theory can be UV embedded in quantum gravity

Additional QG constraints = UV imprint at low energies

= Quantum Gravity/String Theory predictions!



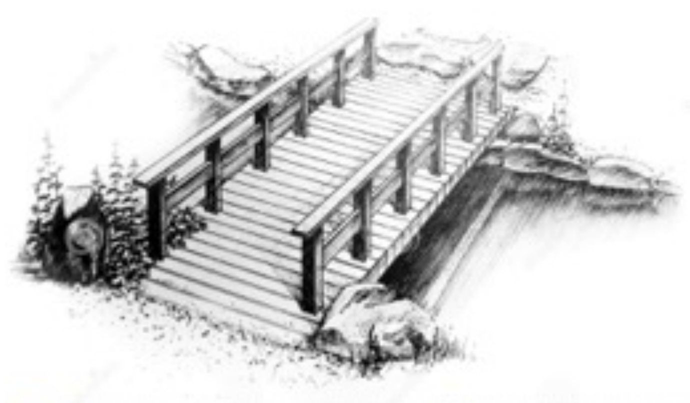
Quantum Gravity Conjectures

Motivated by observing recurrent features of the string landscape
as well as black hole physics

- Absence of global symmetries [Banks-Dixon'88] [Horowitz,Strominger,Seiberg…]
- Completeness hypothesis [Polchinski.'03]
- Weak Gravity Conjecture [Arkani-Hamed et al.'06]
- Swampland Distance Conjecture [Ooguri-Vafa'06]

…

String Theory



Phenomenology

They can have significant implications in low energy physics!

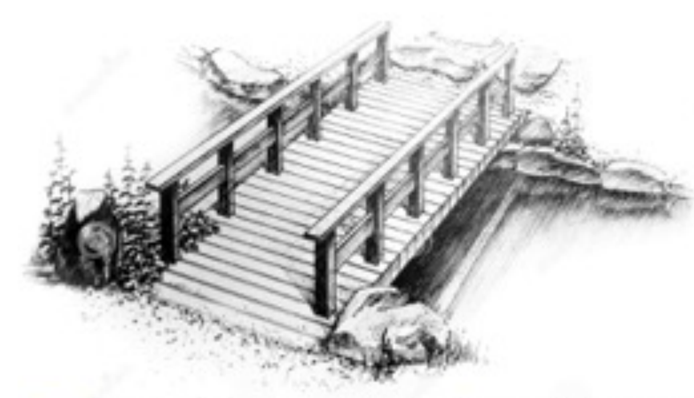
Quantum Gravity Conjectures

Motivated by observing recurrent features of the string landscape as well as black hole physics

- Absence of global symmetries [Banks-Dixon'88] [Horowitz,Strominger,Seiberg…]
- Completeness hypothesis [Polchinski.'03]
- Weak Gravity Conjecture [Arkani-Hamed et al.'06]
- Swampland Distance Conjecture [Ooguri-Vafa'06]

…

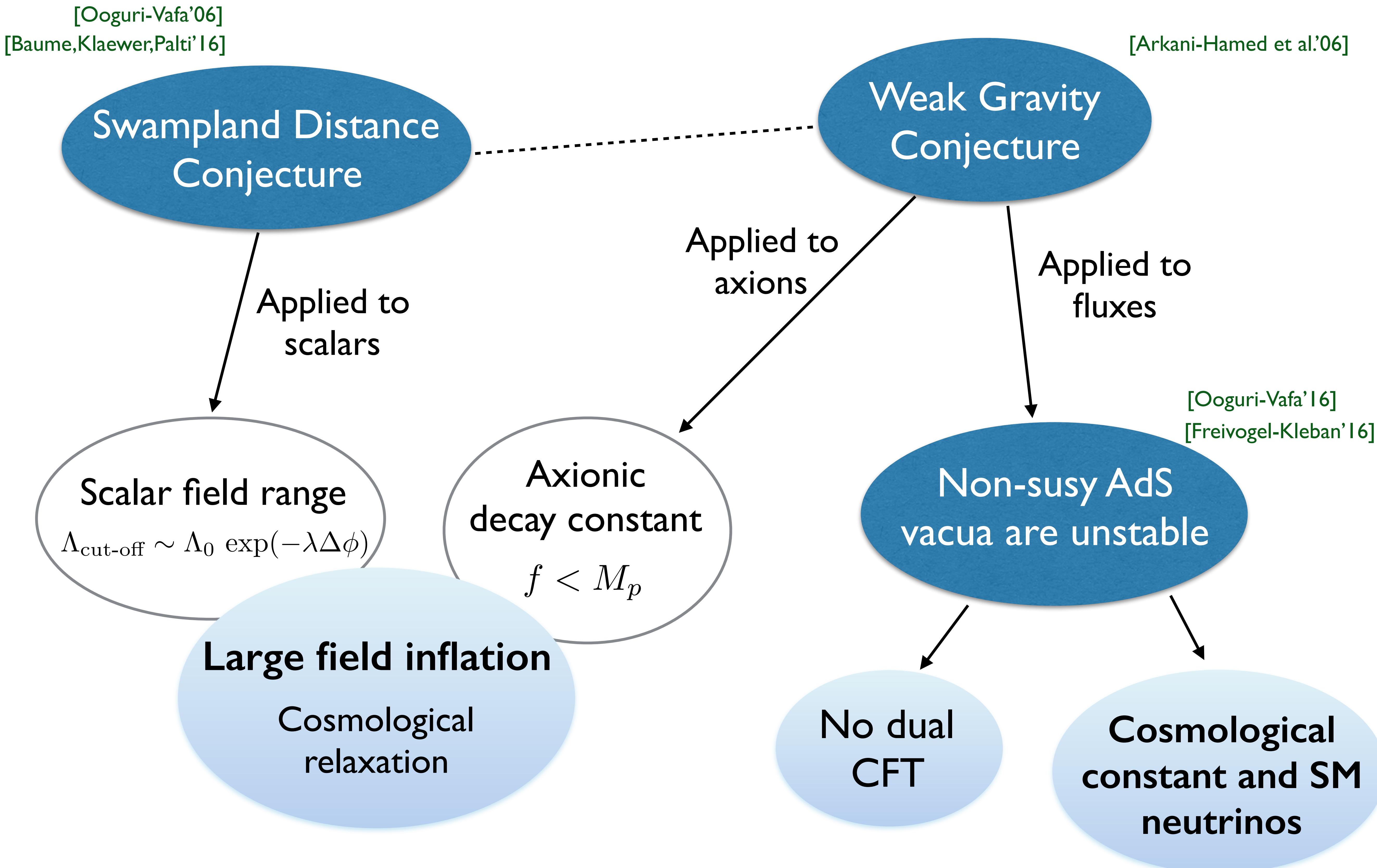
String Theory



Phenomenology

They can have significant implications in low energy physics!

Quantum Gravity Conjectures



1) Weak Gravity Conjecture

↳ Instability of non-susy vacua

Weak Gravity Conjecture

[Arkani-Hamed et al.'06]

Given an abelian gauge field, there must exist an electrically charged particle with

$$m \leq Q$$

(mass) $\leq$ (charge)

so gravity acts weaker than the gauge force.

Weak Gravity Conjecture

[Arkani-Hamed et al.'06]

Given an abelian gauge field, there must exist an electrically charged particle with

$$m \leq Q$$

(mass) $\leq$ (charge)

so gravity acts weaker than the gauge force.

Evidence:

- Trouble with stable black hole remnants [Arkani-Hamed et al.'06] [Aalsma,van de Schaar'18]
- Plethora of examples in string theory (not known counter-example)
- Relation to modular invariance of the 2d CFT [Heidenreich et al'16] [Montero et al'16]
- Relation to entropy bounds [Cottrell et al'16] [Fisher et al'17] [Cheung et al'18]
- Relation to cosmic censorship [Crisford et al'17]

Weak Gravity Conjecture for fluxes

Given a p-form gauge field, there must exist an electrically charged state with

$$T \leq Q$$

T : tension (mass)

Q : charge

[Arkani-Hamed et al.'06]

Sharpened WGC: Bound is saturated only for a BPS state in a SUSY theory

[Ooguri-Vafa'17]

Non-susy vacuum supported by internal fluxes

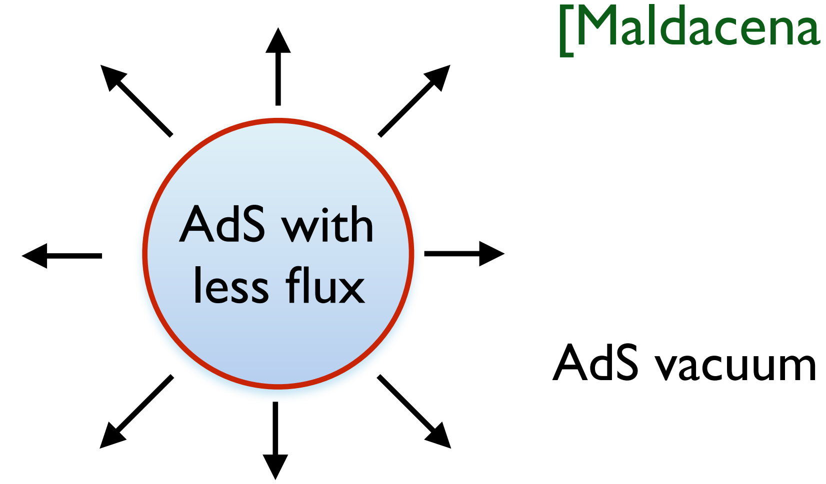
$$f_0 \sim \int_{\Sigma_p} F_p$$

WGC

Brane (domain wall) with $T < Q$

Instability of the vacuum!

[Maldacena et al.'99]



Weak Gravity Conjecture for fluxes

Given a p-form gauge field, there must exist an electrically charged state with

$$T \leq Q$$

T : tension (mass)

Q : charge

[Arkani-Hamed et al.'06]

Sharpened WGC: Bound is saturated only for a BPS state in a SUSY theory

[Ooguri-Vafa'17]

Non-susy vacuum supported by internal fluxes

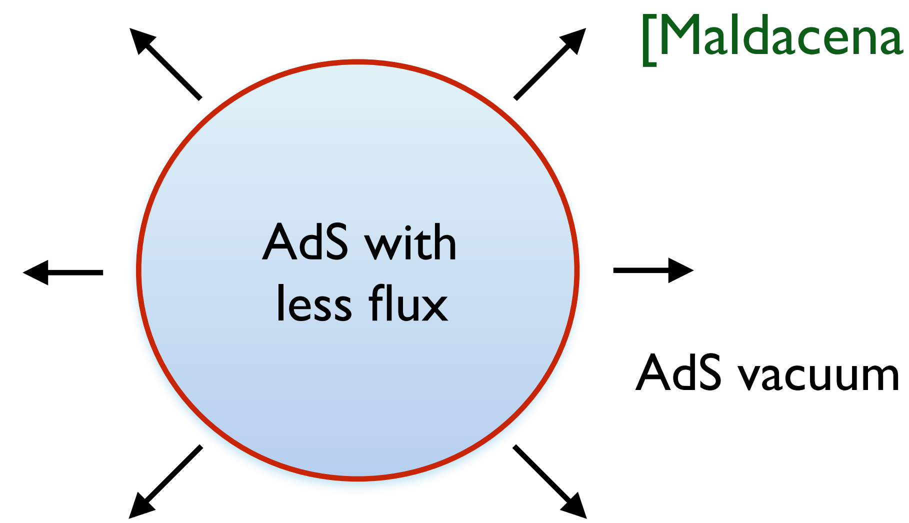
$$f_0 \sim \int_{\Sigma_p} F_p$$

WGC

Brane (domain wall) with $T < Q$

Instability of the vacuum!

[Maldacena et al.'99]



Weak Gravity Conjecture for fluxes

Given a p-form gauge field, there must exist an electrically charged state with

$$T \leq Q$$

T : tension (mass)

Q : charge

[Arkani-Hamed et al.'06]

Sharpened WGC: Bound is saturated only for a BPS state in a SUSY theory

[Ooguri-Vafa'17]

Non-susy vacuum supported by internal fluxes

$$f_0 \sim \int_{\Sigma_p} F_p$$

WGC

Brane (domain wall) with $T < Q$

Instability of the vacuum!

[Maldacena et al.'99]

Non-susy AdS vacua (supported by fluxes) are unstable

Non-susy AdS vacua are at best metastable

[Ooguri-Vafa'16]
[Freivogel-Kleban'16]

Non-susy stable AdS vacua are in the Swampland!

!! Even if no supported by fluxes, there can be other instabilities (like bubbles of nothing)

Examples: $AdS_5 \times S^5/\Gamma, AdS_5 \times \mathbb{CP}^3$ [Ooguri-Spodyneiko'17]

Implications:

→ **AdS/CFT:** Unstable AdS vacua have no dual CFT

Non-susy CFT cannot have a gravity dual which is Einstein gravity AdS

→ **Low energy physics?**

Compactification of the SM to 3d

Standard Model + Gravity on S^1: [Arkani-Hamed et al.'07] (also [Arnold-Fornal-Wise'10])

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

one-loop corrections → exponentially suppressed for $m \gg 1/R$

Depending on the light mass spectra and the cosmological constant, we can get AdS, Minkowski or dS vacua in 3d

We should not get stable non-susy AdS vacua from compactifying the SM !!!
(background independence)

Compactification of the SM to 3d

Standard Model + Gravity on S^1: [Arkani-Hamed et al.'07] (also [Arnold-Fornal-Wise'10])

$$V(R) = \frac{2\pi\Lambda_4}{R^2} + \text{Casimir energy}$$

$\downarrow$ tree-level

$\downarrow$ one-loop corrections ➡ exponentially suppressed for $m \gg 1/R$

[Ibanez,Martin-Lozano,IV'17]

We impose the absence of non-susy stable 3d AdS vacua ➡ Constraints on light spectra of SM

Assumption: 4d instabilities are not transferred to 3d

$R_{\mathrm{buble}} > l_{AdS_3}$ (large bubbles)

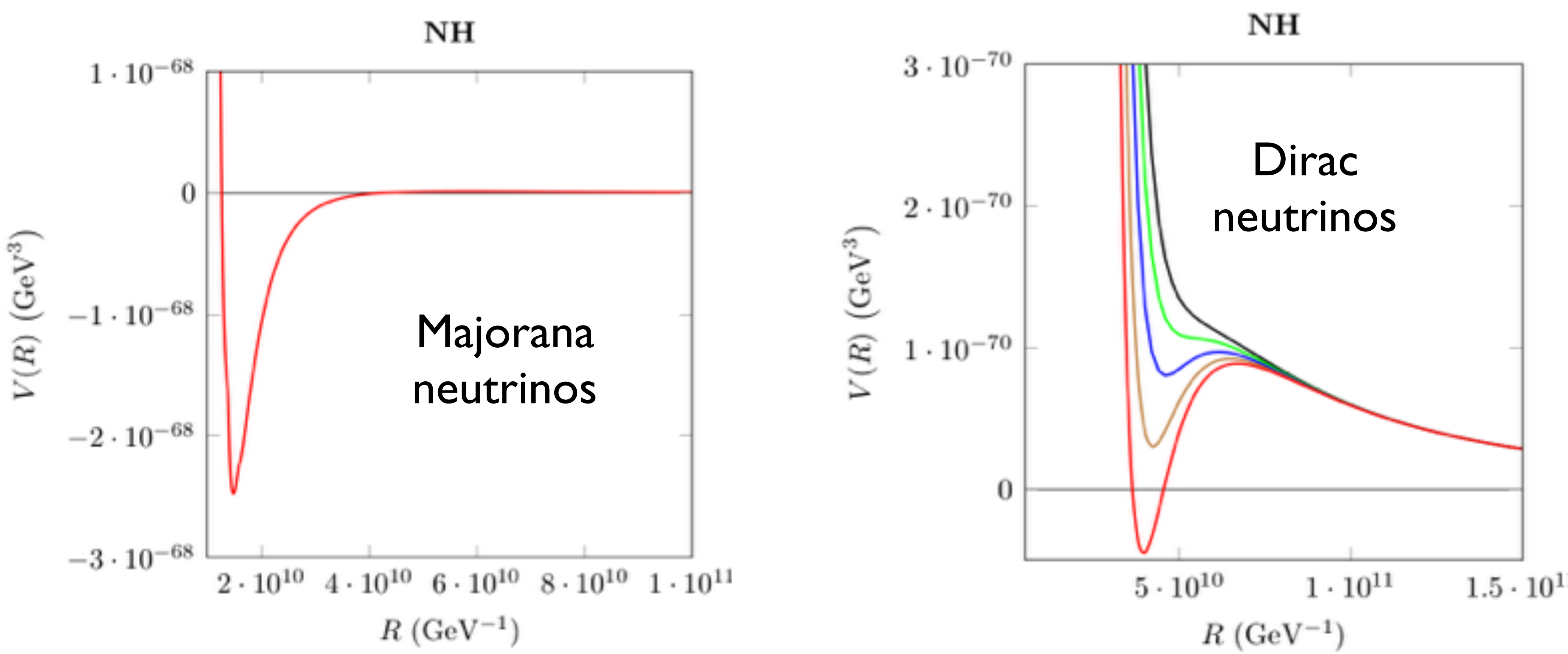
Compactification of the SM to 3d

Standard Model + Gravity on S^1:

graviton, photon

massive particles: neutrinos,…

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



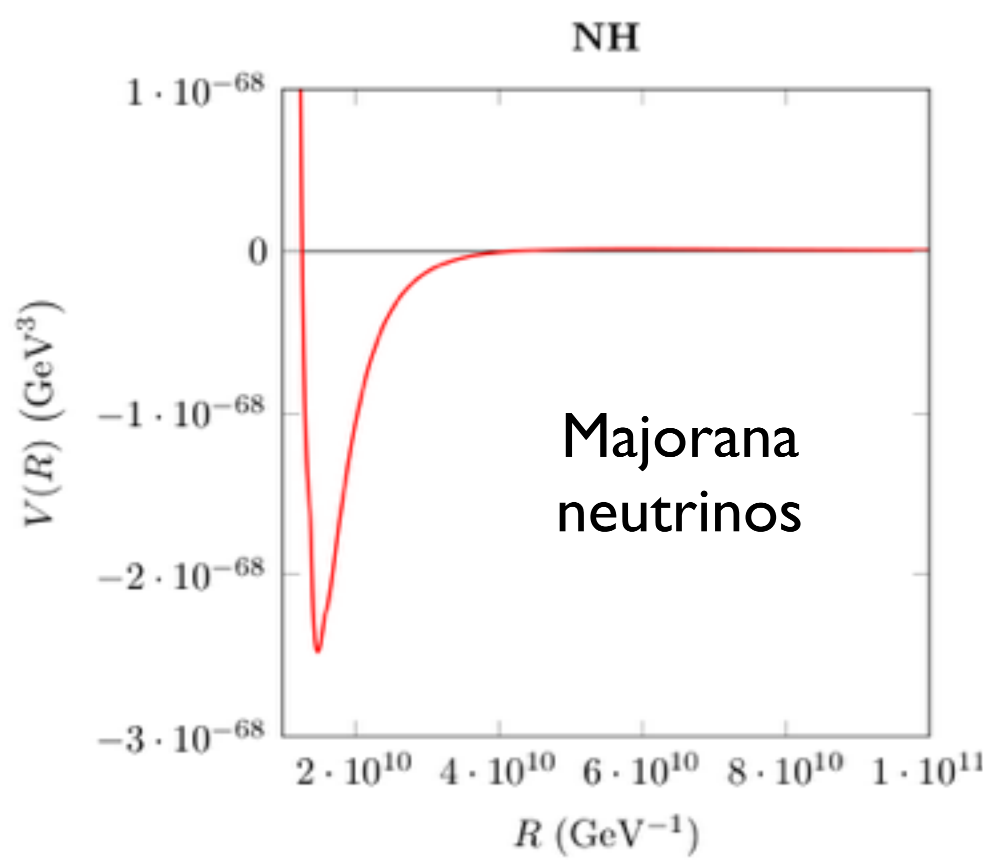
The more massive the neutrinos, the deeper the AdS vacuum

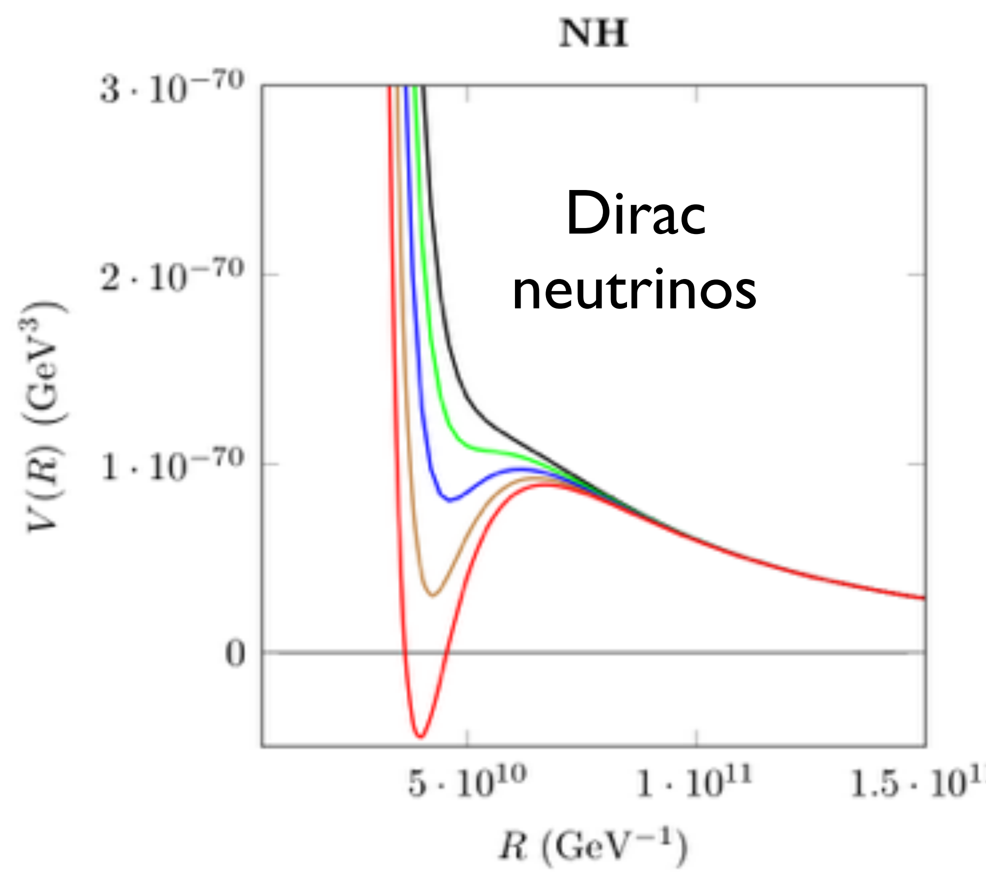
[Ibanez,Martin-Lozano,IV'17] (see also [Hamada-Shiu'17])

Compactification of the SM to 3d

Standard Model + Gravity on S^1:

Absence of AdS vacua implies:





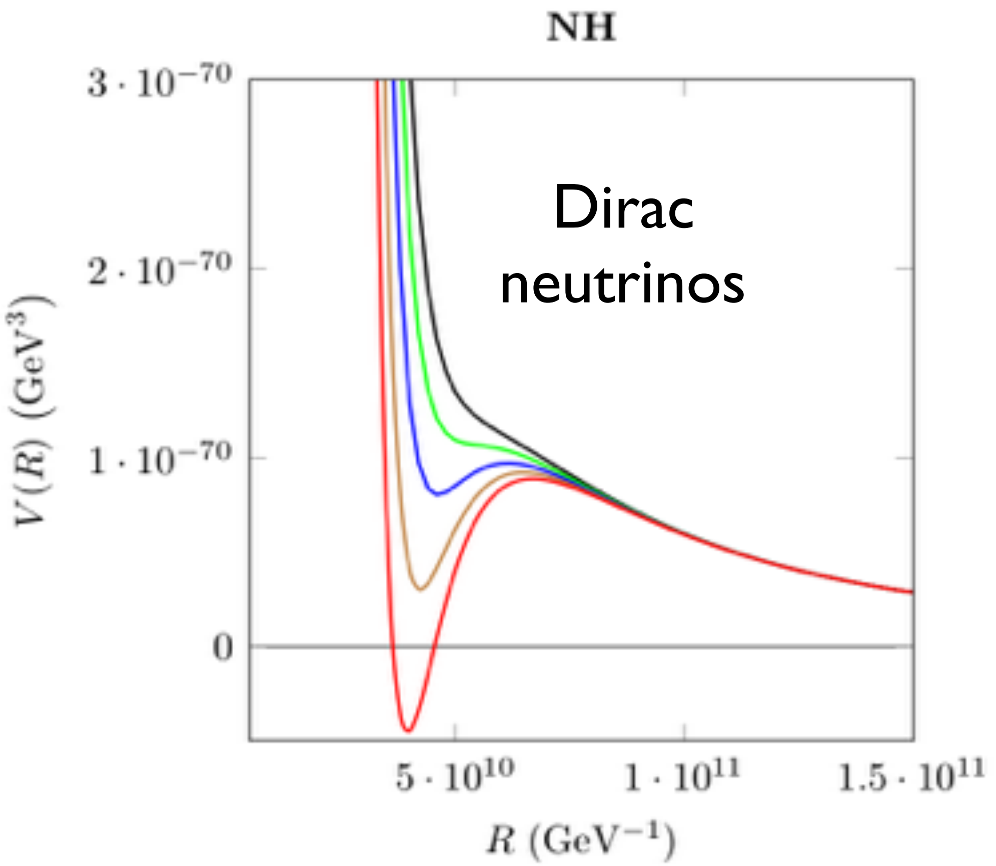
The more massive the neutrinos, the deeper the AdS vacuum

Compactification of the SM to 3d

Standard Model + Gravity on S^1:

Absence of AdS vacua implies:

Majorana neutrinos ruled out!



The more massive the neutrinos, the deeper the AdS vacuum

Compactification of the SM to 3d

Standard Model + Gravity on S^1:

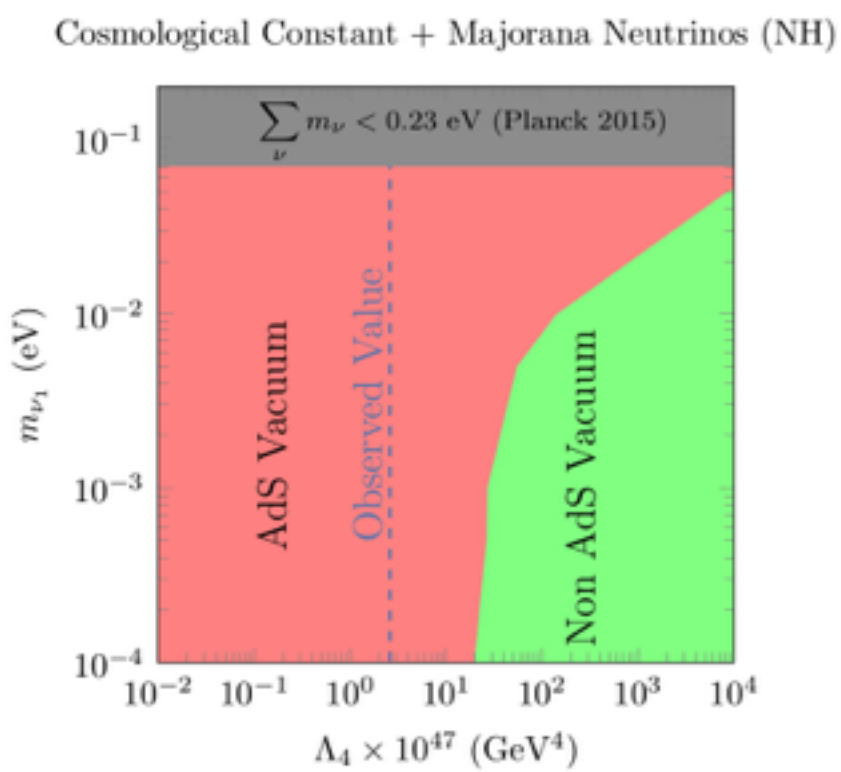
Absence of AdS vacua implies:

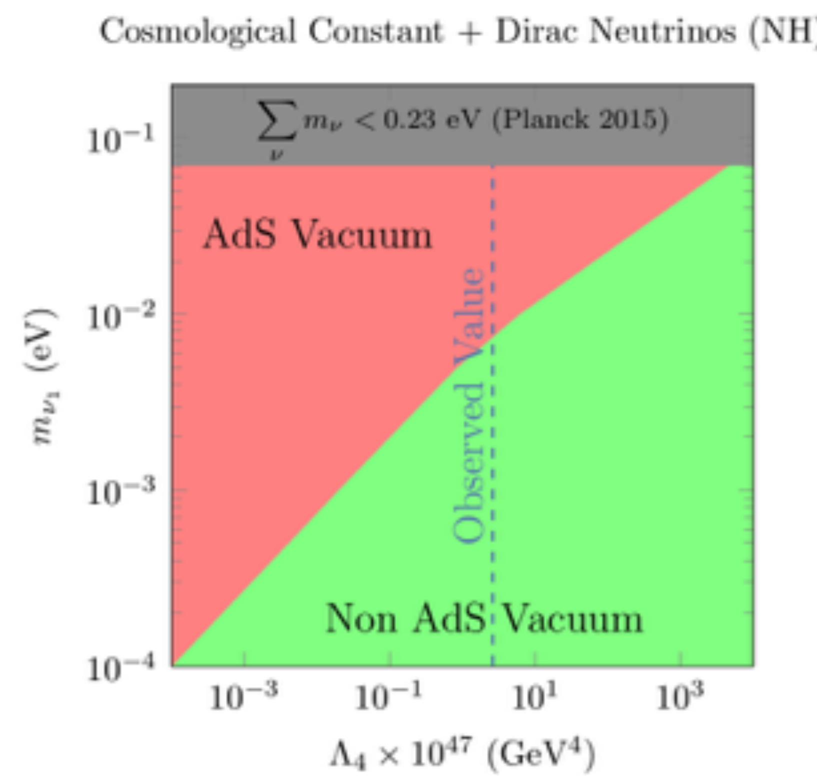
Majorana neutrinos ruled out!

Upper bound for Dirac mass!

$$m_{\nu_1} < 7.7 \text{ meV (NH)}$$
$$m_{\nu_1} < 2.1 \text{ meV (IH)}$$

Lower bound on the cosmological constant





The bound for Λ_4 scales as m_ν^4 (as observed experimentally)

$$\Lambda_4 \geq \frac{a(n_f)30(\Sigma m_i^2)^2 - b(n_f, m_i)\Sigma m_i^4}{384\pi^2}$$

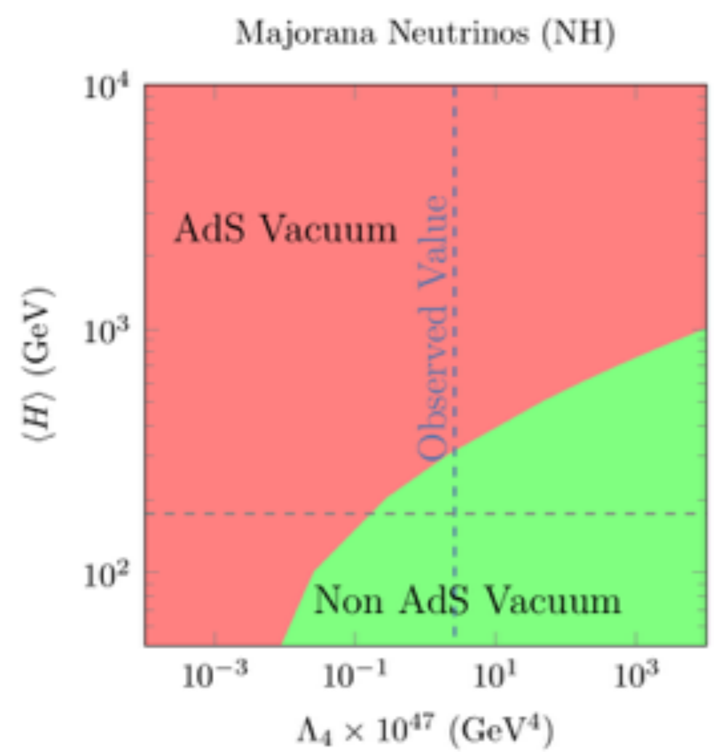
with $a(n_f) = 0.184(0.009)$, $b(n_f, m_i) = 5.72(0.29)$ for Majorana (Dirac)

First argument (not based on cosmology) to have $\Lambda_4 \neq 0$

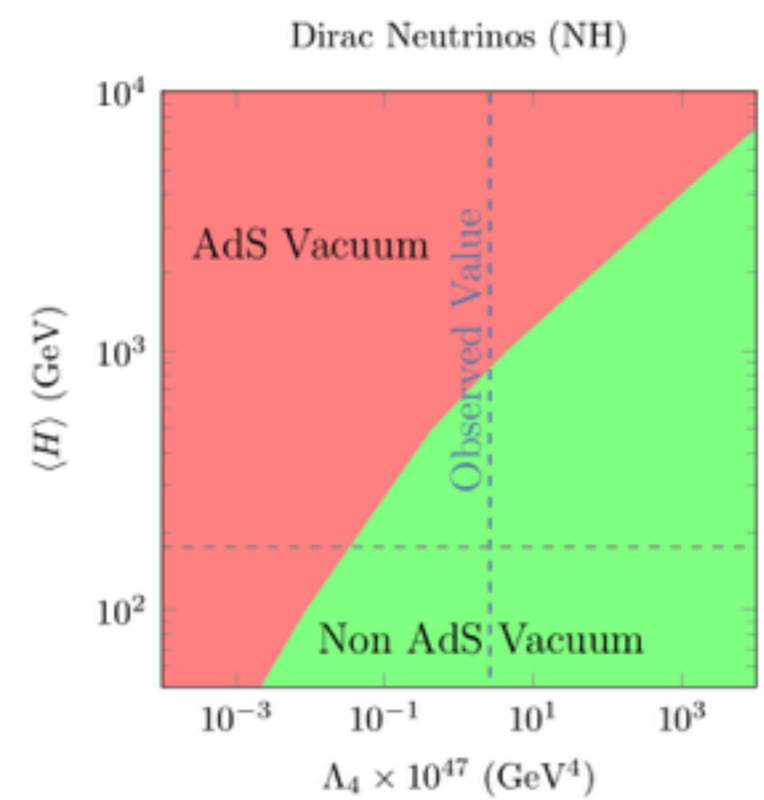
Upper bound on the EW scale

<u>Majorana case:</u> $\langle H \rangle \lesssim \frac{\sqrt{2}}{Y_{\nu_1}} \sqrt{M \Lambda^{1/4}}$

<u>Dirac case:</u> $\langle H \rangle \lesssim 1.6 \frac{\Lambda^{1/4}}{Y_{\nu_1}}$



$M = 10^{10}$ GeV, $Y = 10^{-3}$



$Y = 10^{-14}$

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

→ No EW hierarchy problem

Generalisations

- BSM extensions: New light particles, supersymmetry…

  [Ibanez,Martin-Lozano,IV'17] [Gonzalo,Herraez,Ibanez'18]

  - Majorana neutrinos are consistent if adding $m_\chi \lesssim 2\ \mathrm{meV}$
  - IH Dirac neutrinos are ruled out in the presence of QCD axion

- 2d compactifications: Toroidal, orbifolds…

  - Toroidal: similar bounds [Ibanez,Martin-Lozano,IV'17]
  - Toroidal orbifolds: SM itself is ruled out, MSSM survives

  [Gonzalo,Herraez,Ibanez'18]

  (see Alvaro's talk)

2) Swampland Distance Conjecture

Swampland Distance Conjecture [Ooguri-Vafa'06]

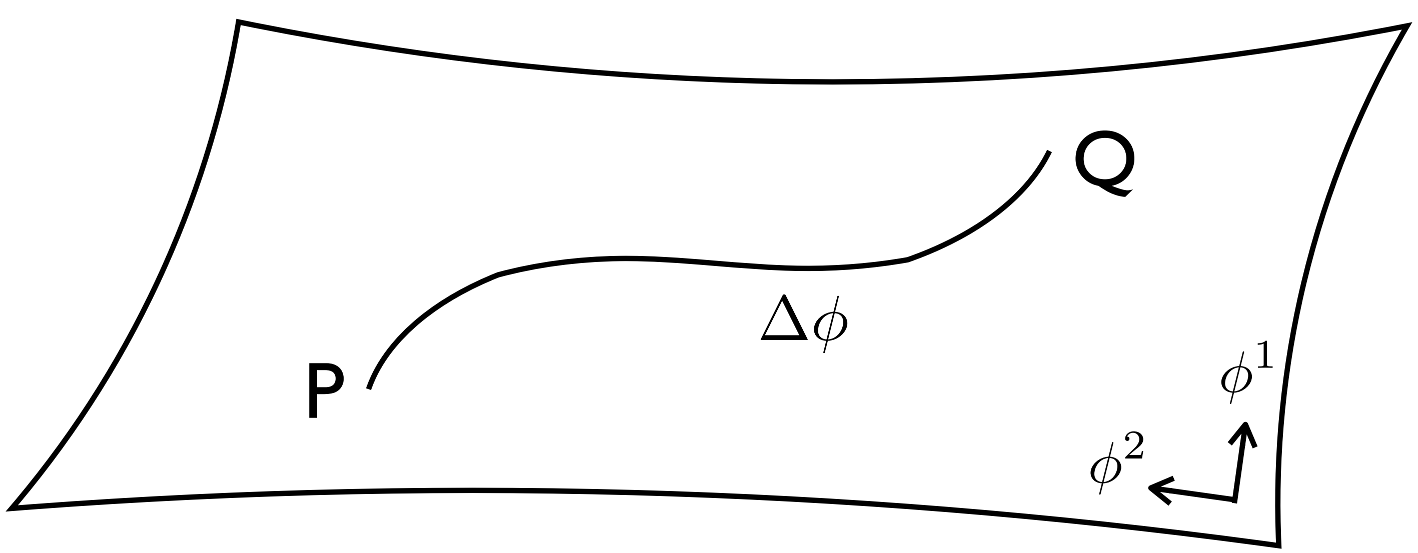
An effective theory is valid only for a finite scalar field variation $\Delta\phi$

because an infinite tower of states become exponentially light

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

Consider the moduli space of an effective theory:

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



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

$$m(P) \lesssim m(Q) e^{-\lambda\Delta\phi}$$

Swampland Distance Conjecture [Ooguri-Vafa'06]

An effective theory is valid only for a finite scalar field variation $\Delta\phi$

because an infinite tower of states become exponentially light

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

This signals the breakdown of the effective theory:

$$\Lambda_{\text{cut-off}} \sim \Lambda_0 \, \exp(-\lambda \Delta\phi)$$

Swampland Distance Conjecture [Ooguri-Vafa'06]

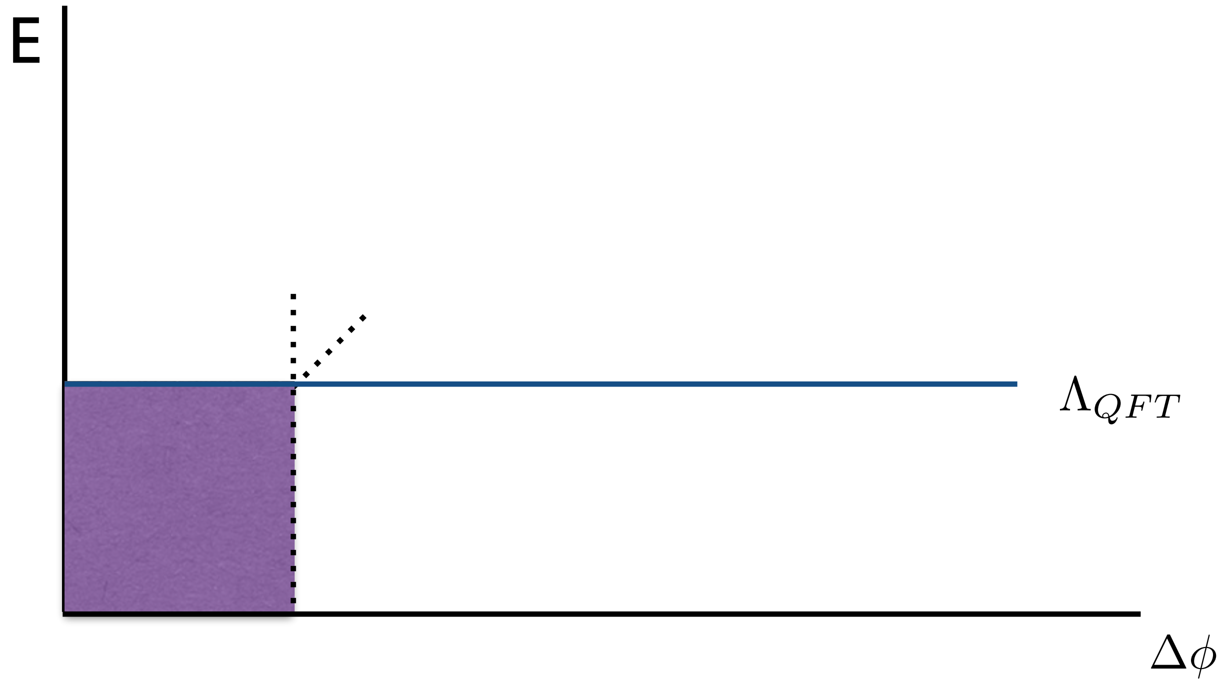
An effective theory is valid only for a finite scalar field variation $\Delta\phi$

because an infinite tower of states become exponentially light

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

This signals the breakdown of the effective theory:

$$\Lambda_{\text{cut-off}} \sim \Lambda_0 \, \exp(-\lambda\Delta\phi)$$



Swampland Distance Conjecture [Ooguri-Vafa'06]

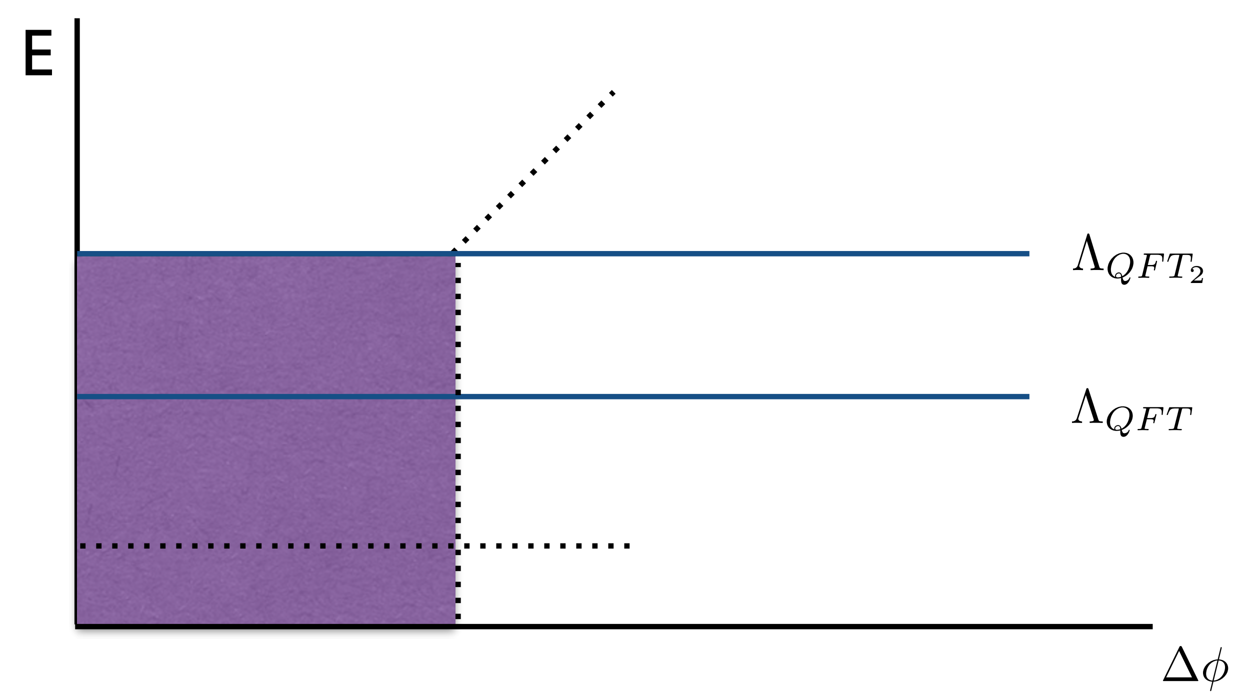
An effective theory is valid only for a finite scalar field variation $\Delta\phi$

because an infinite tower of states become exponentially light

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

This signals the breakdown of the effective theory:

$$\Lambda_{\text{cut-off}} \sim \Lambda_0 \, \exp(-\lambda\Delta\phi)$$



Swampland Distance Conjecture [Ooguri-Vafa'06]

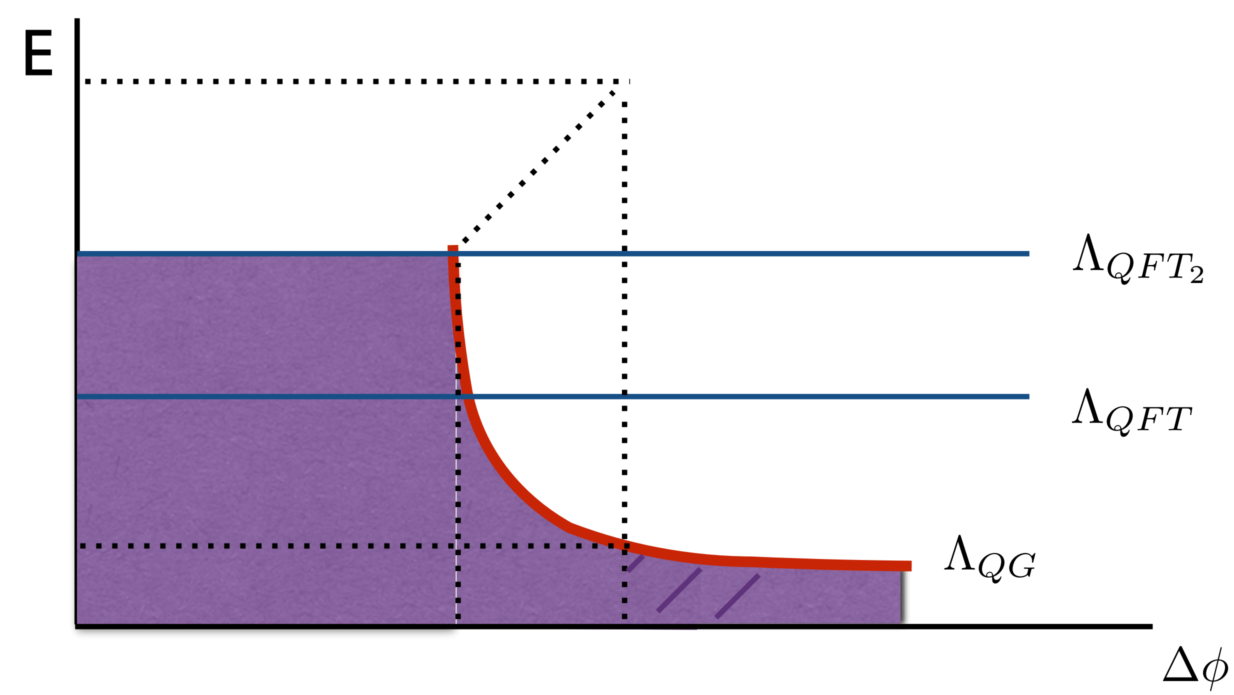
An effective theory is valid only for a finite scalar field variation $\Delta\phi$

because an infinite tower of states become exponentially light

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

This signals the breakdown of the effective theory:

$$\Lambda_{\text{cut-off}} \sim \Lambda_0 \, \exp(-\lambda\Delta\phi)$$



Swampland Distance Conjecture

It gives an upper bound on the scalar field range
described by any effective field theory with finite cut-off

- It applies to any scalar (also axions realising axion monodromy in IIB string theory upon taking into account back-reaction on kinetic term)

[Baume,Palti'16] [I.V.,'16]

- Examples compatible with the Refined SDC: [Klaewer,Palti'16]

→ exponential drop-off of the cut-off at the Planck scale

$$\Delta\phi \lesssim M_p$$

Swampland Distance Conjecture

Phenomenological implications:

- **Large field inflation:** requires large field range $\sim \mathcal{O}(M_p)$ and and high energy

  $\longrightarrow$ at the edge of validity

- **Cosmological relaxation of the EW scale:** usually requires huge field ranges

  $\longrightarrow$ seems incompatible with quantum gravity

Swampland Distance Conjecture

Phenomenological implications:

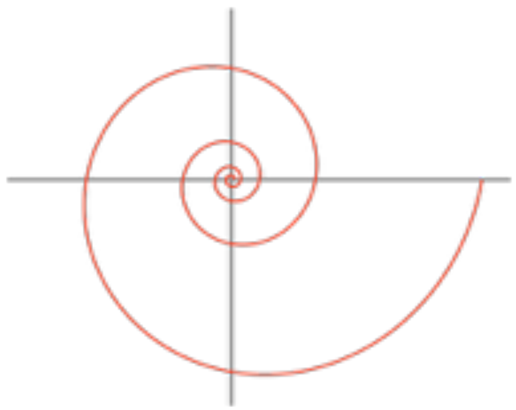
- **Large field inflation:** requires large field range $\sim \mathcal{O}(M_p)$ and and high energy

  $\longrightarrow$ at the edge of validity

- **Cosmological relaxation of the EW scale:** usually requires huge field ranges

  $\longrightarrow$ seems incompatible with quantum gravity

Caveat! This is only valid for geodesics in field space



What otherwise?

Swampland Distance Conjecture

Evidence: based on particular examples in string theory compactifications

[Ooguri,Vafa'06] [Baume,Palti'16] [I.V.,'16] [Bielleman,Ibanez,Pedro,I.V.,Wieck'16] [Blumenhagen,I.V.,Wolf'17] [Hebecker,Henkenjohann,Witkowski'17] [Cicoli,Ciupke,Mayhrofer,Shukla'18][Blumenhagen et al.'18]

Systematic analysis in the complex structure moduli space of Type IIB Calabi-Yau string compactifications

(model-independent) [Grimm,Palti,IV.'18]

Identify infinite tower of exponentially massless BPS states (wrapping D3-branes) at infinite distance singularities

(see Thomas's talk)

Swampland Distance Conjecture

[Grimm,Palti,IV.'18]

- Infinite field distance is emergent from integrating out the infinite tower of states (see also [Heidenreich,Reece,Rudelius'18])

- SDC as a quantum gravity obstruction to restore a global axionic symmetry at the singular point

WGC: $\Lambda < gM_p$ If $g \to 0$ global symmetry is restored

How small can the gauge coupling be?

SDC: $\Lambda \sim M_p \exp(-\lambda \Delta\phi)$ If $\Delta\phi \to \infty$ global symmetry is restored

How large can the field variation be?

Summary

- String Landscape vs Swampland

  Not every EFT can be UV embedded in String Theory

  ⤷ Quantum Gravity Constraints

Summary

- String Landscape vs Swampland

  Not every EFT can be UV embedded in String Theory

  ⤷ Quantum Gravity Constraints

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

  1) <u>AdS Instability Conjecture + stability of 3D SM vacua:</u>

     Upper bound on the EW scale in terms of the cosmological const.

     New approach to fine-tuning or hierarchy problems? UV/IR mixing?

  2) <u>Swampland Distance Conjecture:</u>

     Upper bound on the scalar field range. Implications for inflation!

Summary

- String Landscape vs Swampland

  Not every EFT can be UV embedded in String Theory

  ↳ Quantum Gravity Constraints

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

  1) AdS Instability Conjecture + stability of 3D SM vacua:

  Upper bound on the EW scale in terms of the cosmological const.

  New approach to fine-tuning or hierarchy problems? UV/IR mixing?

  2) Swampland Distance Conjecture:

  Upper bound on the scalar field range. Implications for inflation!

- We need more evidence for these conjectures!

Thank you!

back-up slides

Casimir energy

Potential energy in 3d:

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

Casimir energy density:

$$\rho(R) = \mp \sum_{n=1}^{\infty} \frac{2m^4}{(2\pi)^2} \frac{K_2(2\pi R m n)}{(2\pi R m n)^2}$$

For small mR:

$$\rho(R) = \mp \left[\frac{\pi^2}{90(2\pi R)^4} - \frac{\pi^2}{6(2\pi R)^4} (mR)^2 + \frac{\pi^2}{48(2\pi R)^4} (mR)^4 + \mathcal{O}(mR)^6 \right]$$

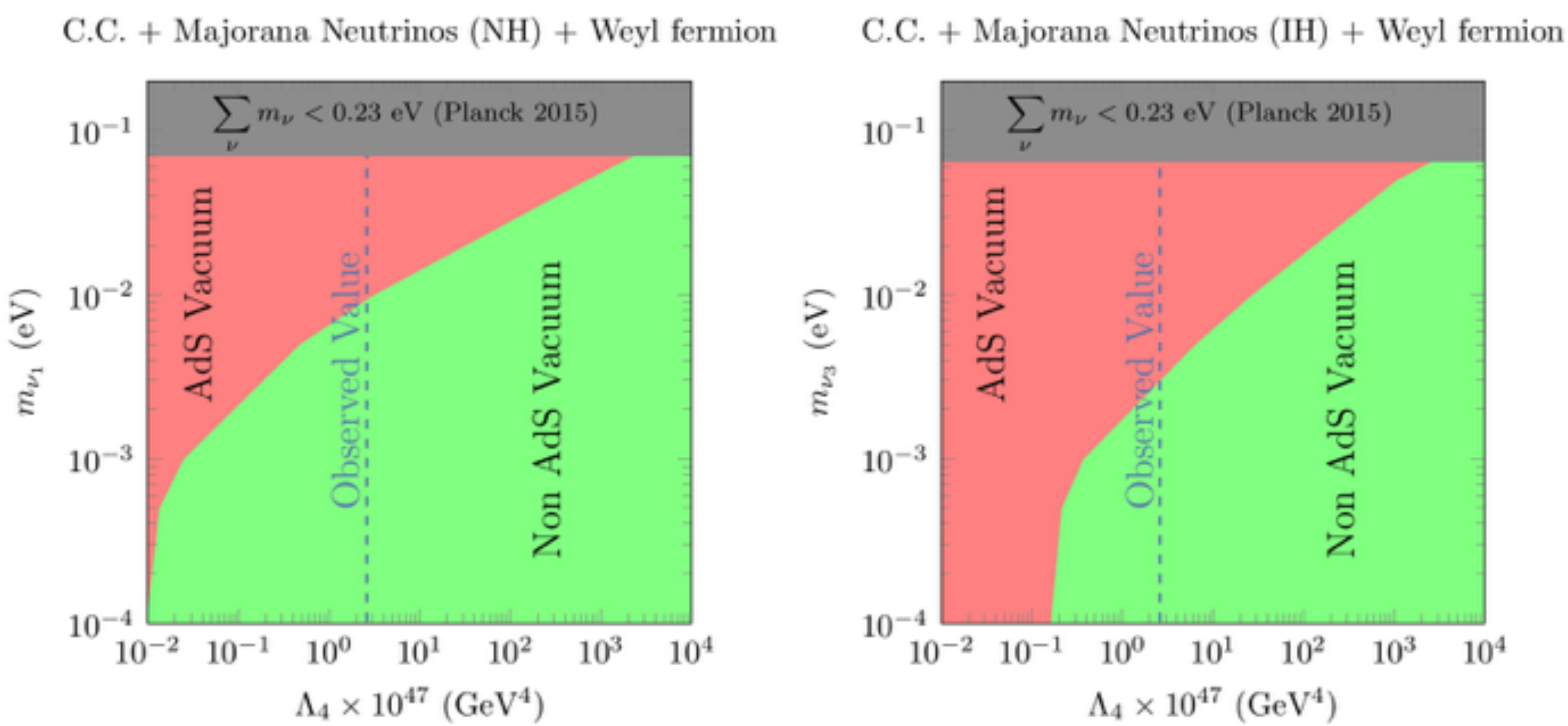
Adding BSM physics

- **Light fermions**

Positive Casimir contribution $\longrightarrow$ helps to avoid AdS vacuum

Majorana neutrinos are consistent if adding $m_\chi \lesssim 2\ \mathrm{meV}$

example. For $m_\chi = 0.1\ \mathrm{meV}$:

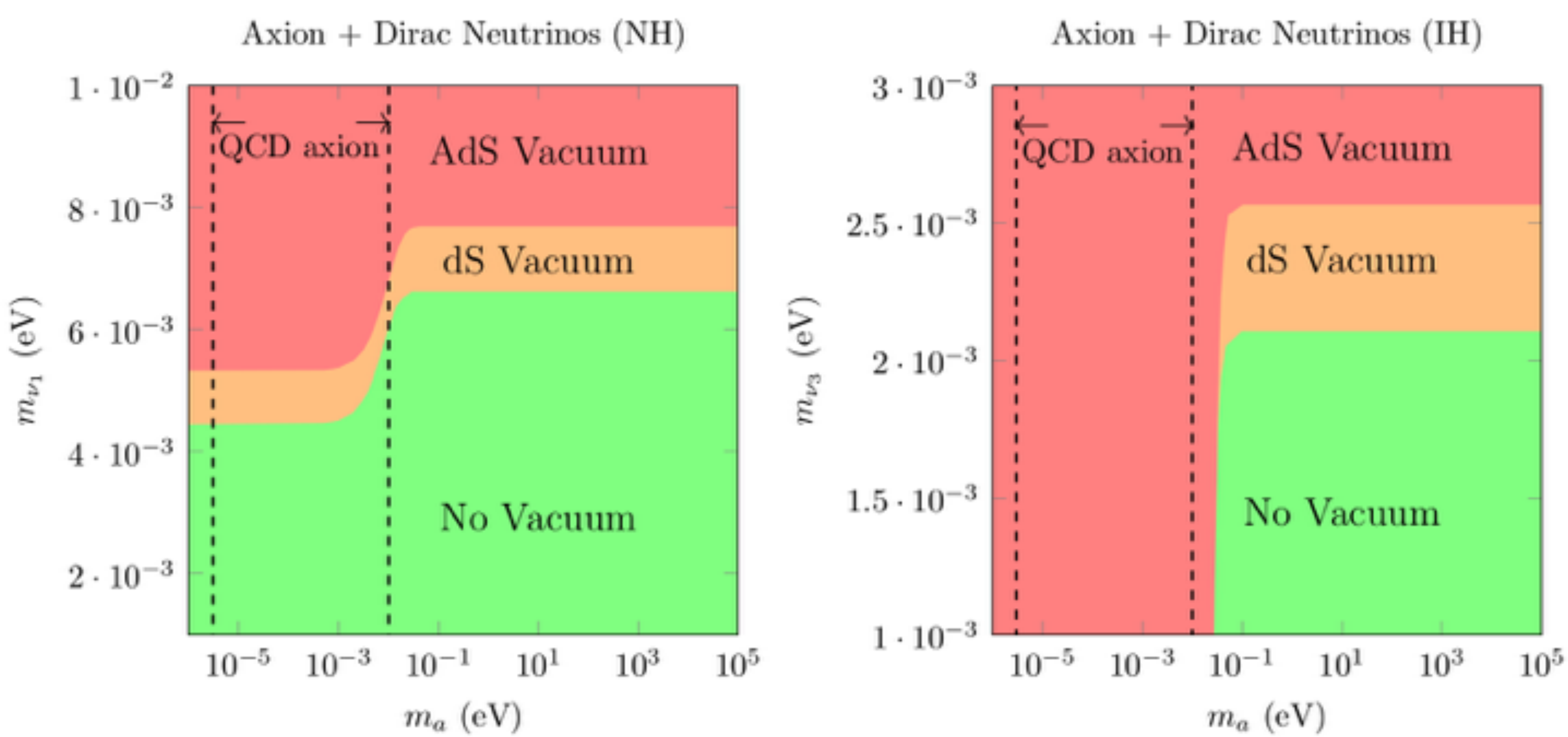


Adding BSM physics

- **Axions**

1 axion: negative contribution ⟶ bounds get stronger

Multiple axions: can destabilise AdS vacuum



Bounds on the SM + light BSM physics

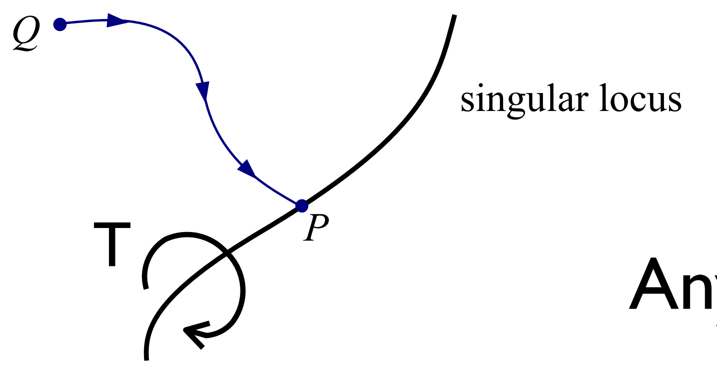
Model	Majorana (NI)	Majorana (IH)	Dirac (NH)	Dirac (IH)
SM (3D)	no	no	$m_{\nu_1} \leq 7.7 \times 10^{-3}$	$m_{\nu_3} \leq 2.56 \times 10^{-3}$
SM(2D)	no	no	$m_{\nu_1} \leq 4.12 \times 10^{-3}$	$m_{\nu_3} \leq 1.0 \times 10^{-3}$
SM+Weyl(3D)	$m_{\nu_1} \leq 0.9 \times 10^{-2}$ $m_f \leq 1.2 \times 10^{-2}$	$m_{\nu_3} \leq 3 \times 10^{-3}$ $m_f \leq 4 \times 10^{-3}$	$m_{\nu_1} \leq 1.5 \times 10^{-2}$	$m_{\nu_3} \leq 1.2 \times 10^{-2}$
SM+Weyl(2D)	$m_{\nu_1} \leq 0.5 \times 10^{-2}$ $m_f \leq 0.4 \times 10^{-2}$	$m_{\nu_3} \leq 1 \times 10^{-3}$ $m_f \leq 2 \times 10^{-3}$	$m_{\nu_1} \leq 0.9 \times 10^{-2}$	$m_{\nu_3} \leq 0.7 \times 10^{-2}$
SM+Dirac(3D)	$m_f \leq 2 \times 10^{-2}$	$m_f \leq 1 \times 10^{-2}$	yes	yes
SM+Dirac(2D)	$m_f \leq 0.9 \times 10^{-2}$	$m_f \leq 0.9 \times 10^{-2}$	yes	yes
SM+1 axion(3D)	no	no	$m_{\nu_1} \leq 7.7 \times 10^{-3}$	$m_{\nu_3} \leq 2.5 \times 10^{-3}$ $m_a \geq 5 \times 10^{-2}$
SM+1 axion(2D)	no	no	$m_{\nu_1} \leq 4.0 \times 10^{-3}$	$m_{\nu_3} \leq 1 \times 10^{-3}$ $m_a \geq 2 \times 10^{-2}$
$\geq 2(10)$ axions	yes	yes	yes	yes

Compactifications of SM on T_2 $\longrightarrow$ qualitatively similar, but a bit stronger

(see also [Hamada-Shiu'17])

Systematic analysis in the complex structure moduli space of Type IIB Calabi-Yau string compactifications

[Grimm,Palti,IV.'18]



Infinite distance locus:

Any trajectory approaching P has infinite length

Infinite tower of states: BPS D3 branes

The mass decreases exponentially fast in the field distance
(due to the universal behaviour of the metric near these points)

Key ingredient:

Monodromy transformation

Field distance

Monodromy orbit of states

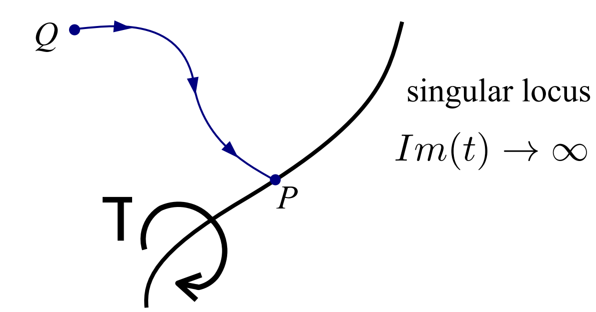
Nilpotent orbit theorem

Distances given by: $d_\gamma(P,Q) = \int_\gamma \sqrt{g_{IJ}\dot{x}^I\dot{x}^J}ds$

$$g_{I\bar{J}} = \partial_{z^I}\partial_{\bar{z}^J}K$$

$$K = -\log\left(-i^D\int_{Y_D}\Omega\wedge\bar{\Omega}\right)$$

Periods of the (D,0)-form: $\Pi^{\mathcal{I}} = \int_{\Gamma_{\mathcal{I}}}\Omega$



transform under monodromy $\Pi(e^{2\pi i z}) = T\cdot\Pi(z)$

(remnant of higher dimensional gauge symmetries)

Nilpotent orbit theorem

Distances given by: $d_\gamma(P,Q) = \int_\gamma \sqrt{g_{IJ}\dot{x}^I \dot{x}^J} ds$

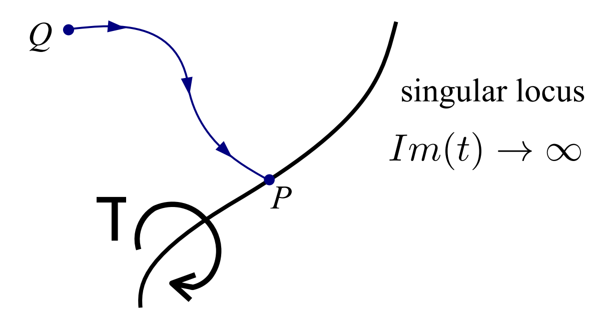
$$g_{I\bar{J}} = \partial_{z^I} \partial_{\bar{z}^J} K$$

$$K = -\log\left(-i^D \int_{Y_D} \Omega \wedge \bar{\Omega}\right)$$

Periods of the (D,0)-form: $\Pi^{\mathcal{I}} = \int_{\Gamma_{\mathcal{I}}} \Omega$

transform under monodromy $\Pi(e^{2\pi i z}) = T \cdot \Pi(z)$

(remnant of higher dimensional gauge symmetries)



Nilpotent orbit theorem: [Schmid'73]

$$\Pi(t,\eta) = \exp(tN)\, a_0(\eta) + \mathcal{O}(e^{2\pi i t}, \eta)$$

$$t = \frac{1}{2\pi i} \log z$$

$N = \log T \longrightarrow$ Nilpotent matrix

It gives local expression for the periods near singular locus!

Infinite distances - Infinite towers

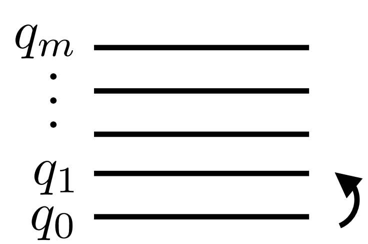
1) Infinite distances only if monodromy is of infinite order

Theorem: P is at infinite distance $\Longleftrightarrow$ $Na_0 \neq 0$

[Wang'97, Lee'16]

2) Monodromy can be used to populate an infinite orbit of BPS states

Mass given by central charge: $Z = e^K q \cdot \Pi \qquad q = (q_e^I, q_I^m)$



$$q_m = T^m q \qquad m \in \mathbb{Z}$$

3) Universal local form of the metric gives the exponential mass behaviour

$$\frac{M_q(P)}{M_q(Q)} \simeq \exp\left(-\frac{1}{\sqrt{2d}}\, d_\gamma(P,Q)\right)$$

Infinite distances - Infinite towers

Infinite massless monodromy orbit at the singularity

Infinite tower of states becoming exponentially light

Massless: $q^T N^j a_0 = 0\,, \quad j \geq d/2$

Infinite orbit: $Nq \neq 0$

Swampland Distance Conjecture ✓

Tool: mathematical machinery of mixed hodge structure

(finer split of cohomology at the singularity adapted to N)

[Deligne][Schmid][Cattani,Kaplan,Schmid]

[Kerr,Pearlstein,Robles'17]

Emergence from integrating out the states

Famous story: periods near conifold have log-divergence from integrating out a single BPS D3-state

[Strominger'95]

We perform similar analysis at infinite distance singularities:

One-loop corrections from integrating out the tower of BPS states

→ matches geometric result

Emergence from integrating out the states

Famous story: periods near conifold have log-divergence from integrating out a single BPS D3-state

[Strominger'95]

We perform similar analysis at infinite distance singularities:

One-loop corrections from integrating out the tower of BPS states

→ matches geometric result

- Corrections to the field metric:

$$d(\phi_1, \phi_2) \simeq C \int_{\phi_1}^{\phi_2} \sqrt{\sum_{i=1}^{S} (\partial_\phi m_i)^2} d\phi \simeq C \int_{\phi_1}^{\phi_2} \frac{d}{\sqrt{12c}} \frac{1}{\phi} d\phi = C \frac{d}{\sqrt{12c}} \log\left(\frac{\phi_2}{\phi_1}\right)$$

Emergence from integrating out the states

Famous story: periods near conifold have log-divergence from integrating out a single BPS D3-state

[Strominger'95]

We perform similar analysis at infinite distance singularities:

One-loop corrections from integrating out the tower of BPS states

→ matches geometric result

- Corrections to the field metric:

$$d(\phi_1, \phi_2) \simeq C \int_{\phi_1}^{\phi_2} \sqrt{\sum_{i=1}^{S} (\partial_\phi m_i)^2 d\phi} \simeq C \int_{\phi_1}^{\phi_2} \frac{d}{\sqrt{12c}} \frac{1}{\phi} d\phi = C \frac{d}{\sqrt{12c}} \log\left(\frac{\phi_2}{\phi_1}\right)$$

- Corrections to the gauge kinetic function:

$$\mathrm{Im}\, \mathcal{N}_{IJ}^{IR} \simeq \mathrm{Im}\, \mathcal{N}_{IJ}^{UV} - \sum_{k}^{S} \left(\frac{8\, q_{k,I} q_{k,J}}{3\pi^2} \log \frac{\Lambda_{UV}}{m_k} \right) \rightarrow g_{YM}^2 \sim \phi^{-n} \sim m_0^{2n}$$

(unlike conifold $g_{YM}^2 \sim 1/\log(m_0)$)

Emergence from integrating out the states

Famous story: periods near conifold have log-divergence from integrating out a single BPS D3-state

[Strominger'95]

We perform similar analysis at infinite distance singularities:

One-loop corrections from integrating out the tower of BPS states

→ matches geometric result

- Corrections to the field metric:

$$d(\phi_1,\phi_2) \simeq C\int_{\phi_1}^{\phi_2}\sqrt{\sum_{i=1}^{S}(\partial_\phi m_i)^2}d\phi \simeq C\int_{\phi_1}^{\phi_2}\frac{d}{\sqrt{12c}}\frac{1}{\phi}d\phi = C\frac{d}{\sqrt{12c}}\log\left(\frac{\phi_2}{\phi_1}\right)$$

- Corrections to the gauge kinetic function:

$$\mathrm{Im}\,\mathcal{N}_{IJ}^{IR} \simeq \mathrm{Im}\,\mathcal{N}_{IJ}^{UV} - \sum_{k}^{S}\left(\frac{8\,q_{k,I}q_{k,J}}{3\pi^2}\log\frac{\Lambda_{UV}}{m_k}\right) \rightarrow g_{YM}^2 \sim \phi^{-n} \sim m_0^{2n}$$

(unlike conifold $g_{YM}^2 \sim 1/\log(m_0)$)

Infinite distance and weak coupling emerge from integrating out an infinite tower of states!

Emergence from integrating out the states

Famous story: periods near conifold have log-divergence from integrating out a single BPS D3-state

[Strominger'95]

We perform similar analysis at infinite distance singularities:

> One-loop corrections from integrating out the tower of BPS states
>
> $\Rightarrow$ matches geometric result

$$\Lambda_{UV} = \Lambda_{\text{Species}}$$

$$\vdots$$

$$m_2$$

$$\Delta m \begin{cases} m_1 \\ m_0 = \Lambda_0 \end{cases}$$

$$m_\phi = 0$$

$$\left.\begin{aligned} \Lambda_{UV} &= \frac{M_p}{\sqrt{S}} \\ S &= \frac{\Lambda_{UV}}{\Delta m(\phi)} \end{aligned}\right\} \Rightarrow \Lambda_{UV}(\phi) \sim \Delta m(\phi)^{1/3}$$

Field dependent UV cut-off!

UV cut-off decreases exponentially fast in the proper field distance

BPS states and stability

Does a BPS state cross a wall of marginal stability upon circling the monodromy locus?

Consider:

$$\mathbf{q}_C = \mathbf{q}_B + \mathbf{q}_{\bar{A}} \quad \Rightarrow \quad M_{\mathbf{q}_C} \leq M_{\mathbf{q}_B} + M_{\mathbf{q}_{\bar{A}}}$$

Wall of marginal stability: $\varphi(B) - \varphi(A) = 1$ with $\varphi(A) = \frac{1}{\pi}\mathrm{Im}\log Z_{\mathbf{q}_A}$

Upon circling the monodromy locus:

$$\varphi_{\mathrm{I}} \to \varphi_{\mathrm{I}} + \mathcal{O}\left(\frac{1}{Im\,t}\right) , \quad \varphi_{\mathrm{II}} \to \varphi_{\mathrm{II}} + 2 + \mathcal{O}\left(\frac{1}{Im\,t}\right)$$

Type I state can only decay to I-II or II-II states!

Stable massless states: $\mathcal{M}_Q = \mathcal{M}/\mathcal{M}_{\mathrm{II}}$

Under n monodromy transformations: $\varphi_{\mathrm{I}} \to \varphi_{\mathrm{I}} - \dfrac{n}{\pi \mathrm{Im}\, t}$ $\Rightarrow$ Number of BPS states $n \sim Im\,(t)$