
Massless towers of states, field distances and the Swampland



Irene Valenzuela

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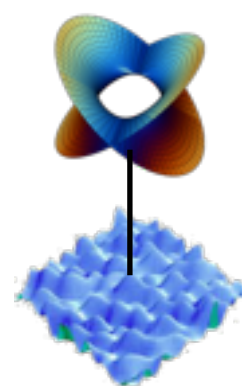
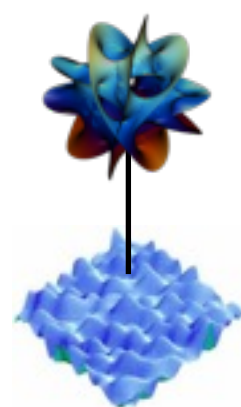
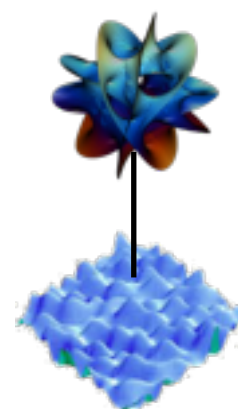
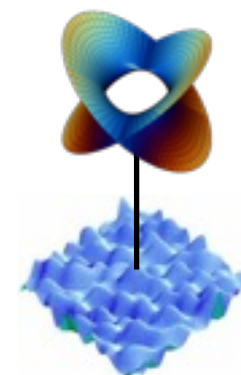
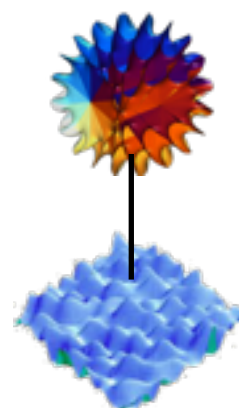
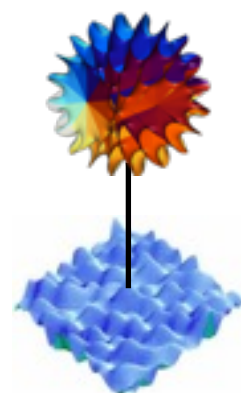
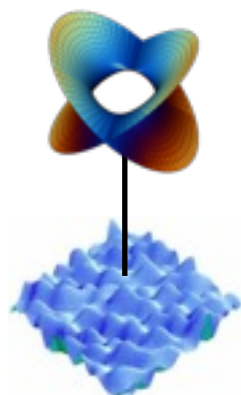
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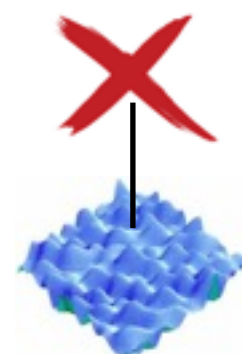
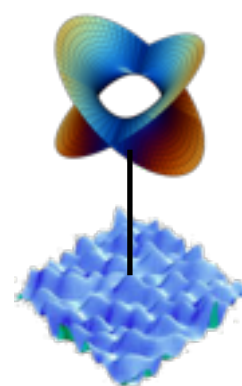
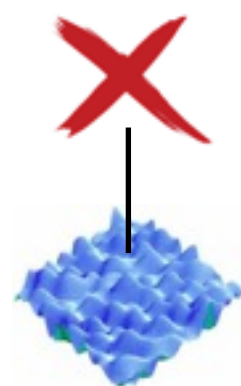
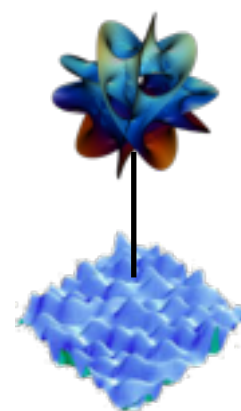
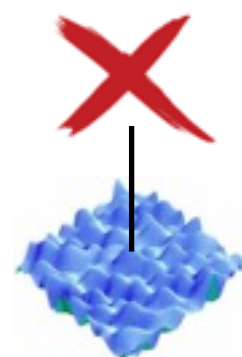
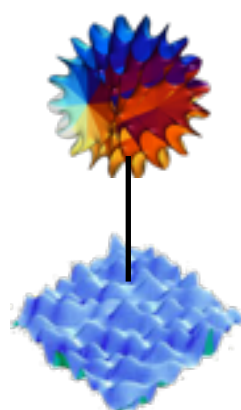
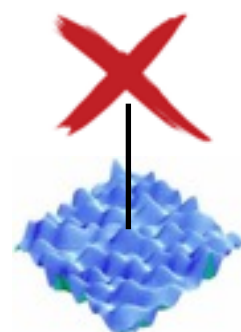
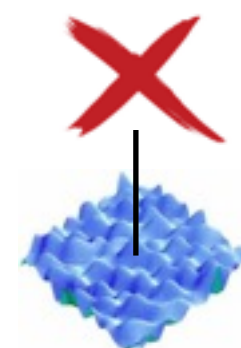
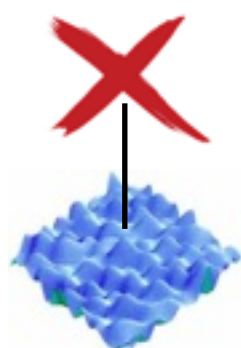
Grimm, Palti, IV [[arXiv:1802.08264](https://arxiv.org/abs/1802.08264) [hep-th]]

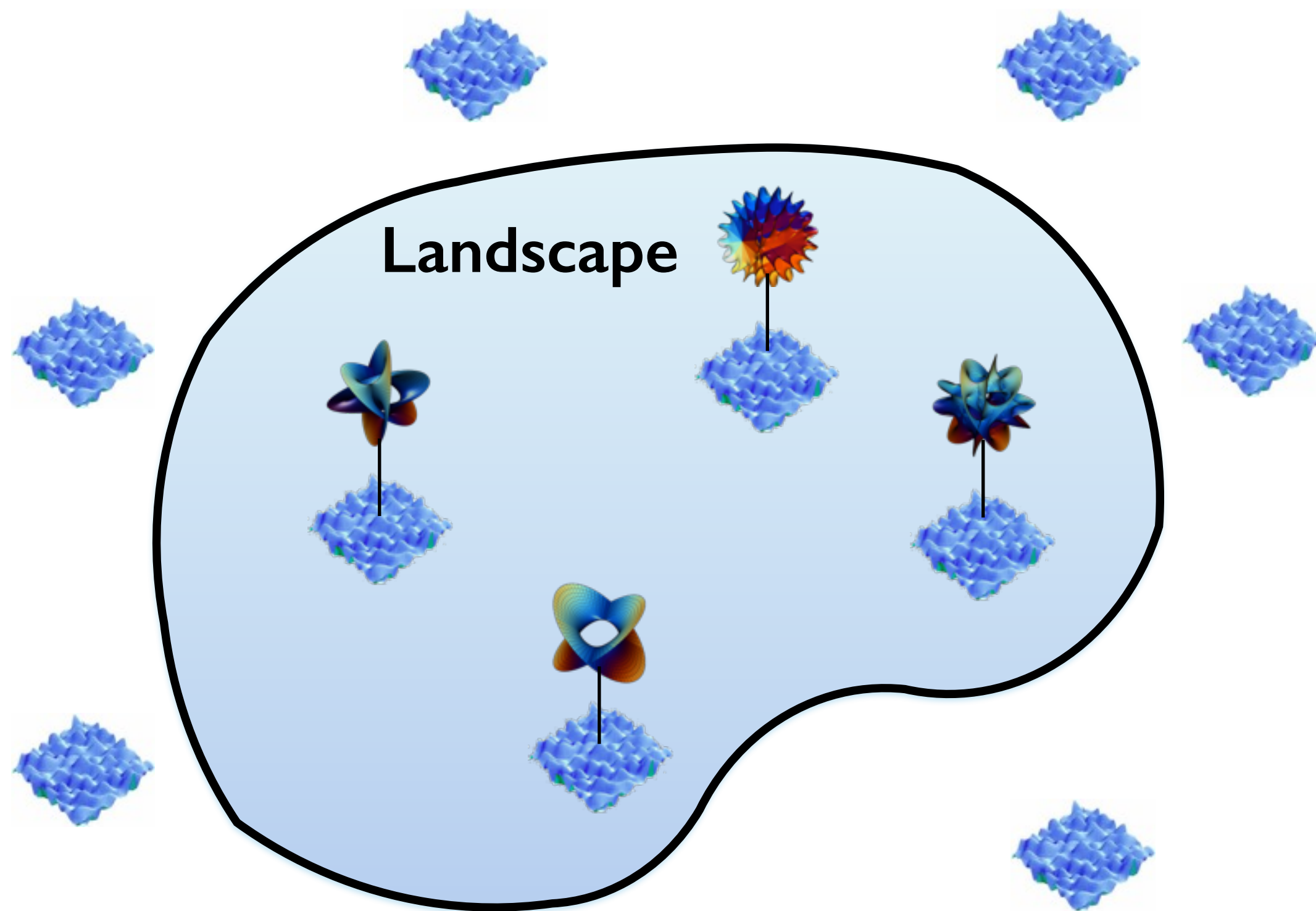
String Pheno 2018, Warsaw (Poland)

Swampland:

Apparently consistent (anomaly-free) quantum **effective field theories** that **cannot** be UV embedded in **quantum gravity**
(they cannot arise from string theory)



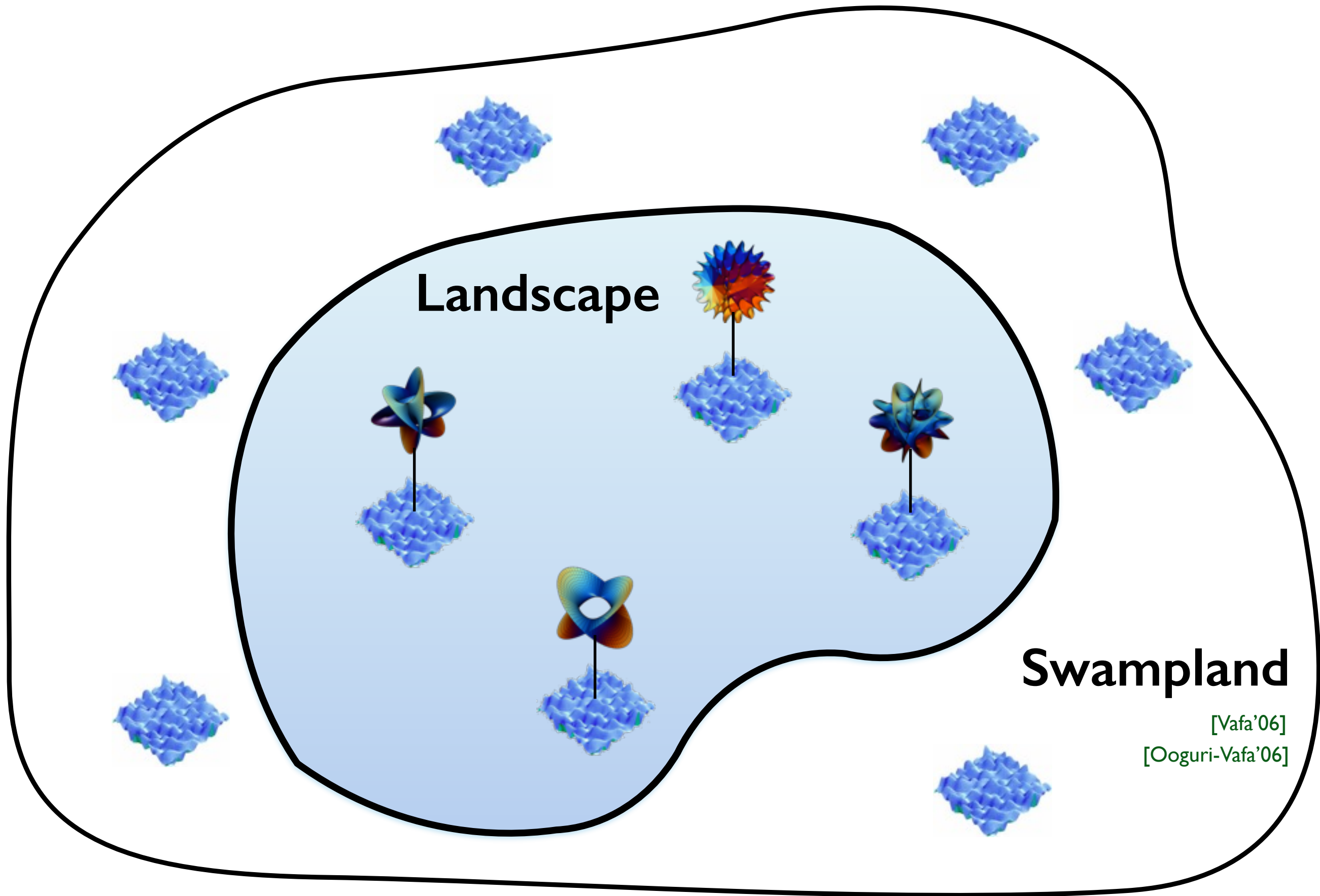




Landscape

Swampland

[Vafa'06]
[Ooguri-Vafa'06]



Not consistent with
quantum gravity

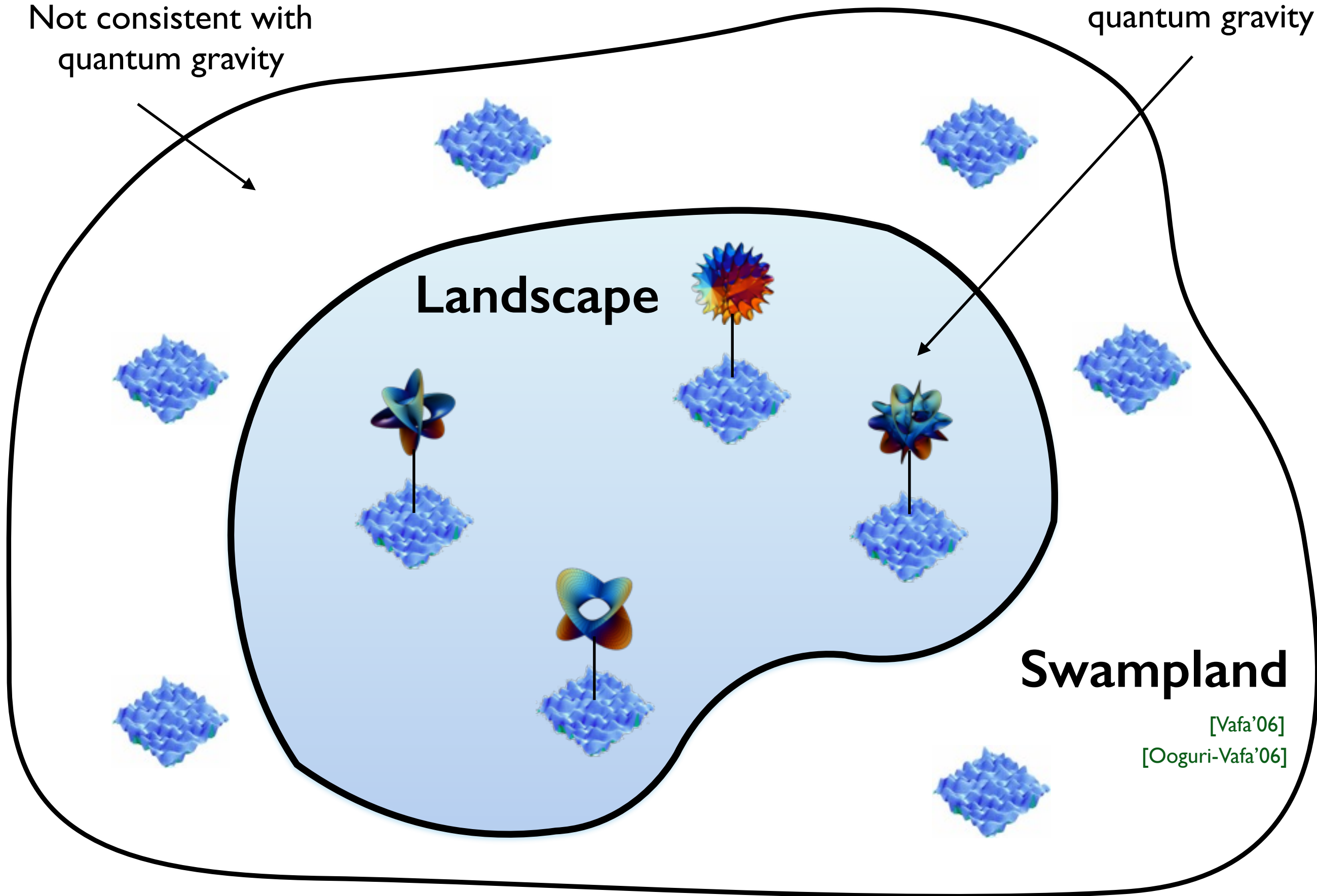
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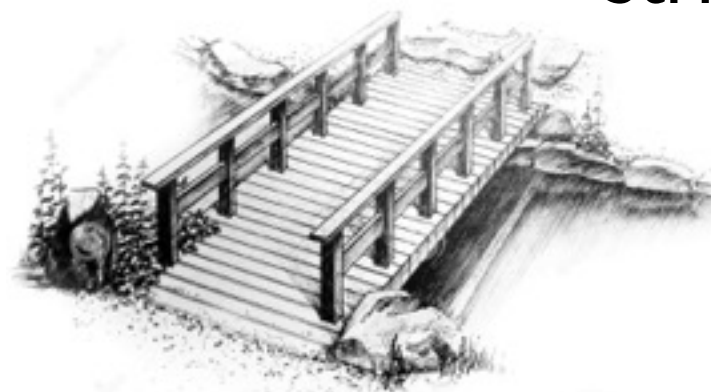
[Vafa'06]

[Ooguri-Vafa'06]



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

Additional QG constraints = UV imprint at low energies
= Quantum Gravity/String Theory predictions!



String Theory

Phenomenology

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

What distinguishes the landscape from the swampland?

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







What distinguishes the landscape from the swampland?



Absence of gravitational anomalies are not enough to ensure quantum consistency of gravity

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]
-  No stable non-susy AdS vacua [Ooguri-Vafa'16]
-  No deSitter vacuum? (see Thomas's talk)

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- } Large field inflation
- Particle physics and c.c.

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

Quantum Gravity Conjectures

Absence of non-susy AdS vacua at lower dimensional compactifications of the SM implies:

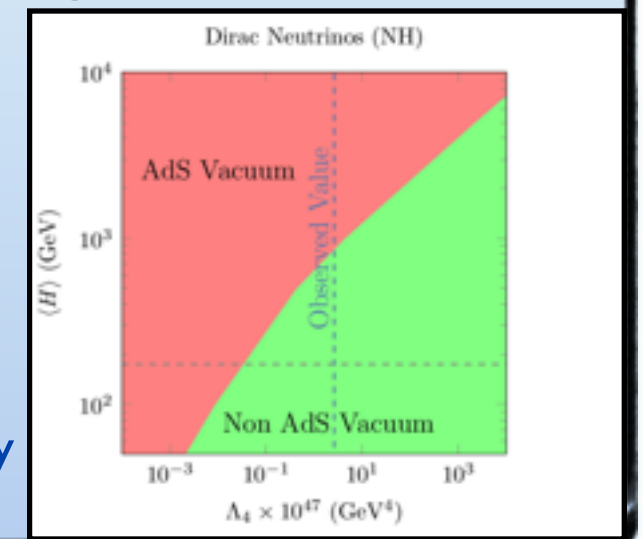
[Ibanez, Martin-Lozano, IV'17]

📌 Upper bound on neutrino masses in terms of the cosmological constant

$$\sum_i m_{\nu_i}^4 \lesssim \mathcal{O}(\Lambda_4) \longrightarrow \langle H \rangle \lesssim 1.6 \frac{\Lambda^{1/4}}{Y_{\nu_1}}$$

➡ Upper bound on EW scale! New approach to hierarchy problems?

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



📌 No stable non-susy AdS vacua [Ooguri-Vafa'16]

➡ Particle physics and c.c.

📌 No deSitter vacuum? (see Thomas's talk)

[Ibanez, Martin-Lozano, IV'17]
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(see Alvaro and Eduardo's talks)

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They can have significant implications in low energy physics!

- UV sensitive effective theories
- Naturalness issues

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Very important to gather more evidence to prove (or disprove) them
→ doable task

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Swampland Distance Conjecture

- ➤ Definition and implications
- ➤ Test in the complex structure moduli space of Type IIB CY compactifications
- ➤ General insights

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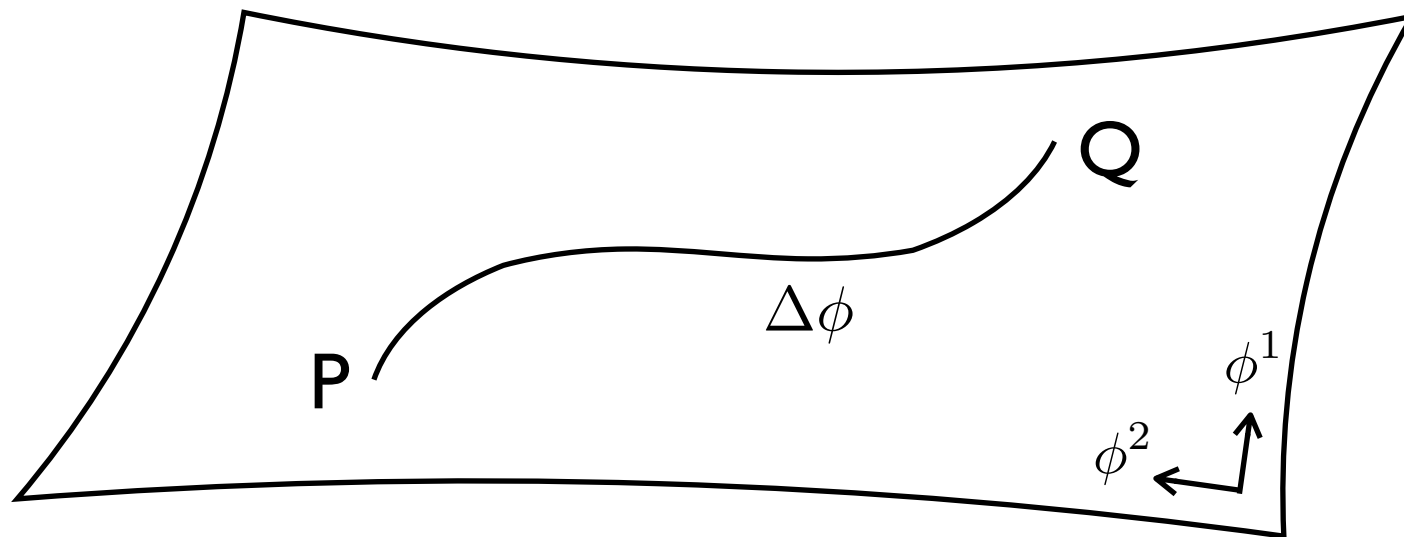
Swampland Distance Conjecture [Ooguri-Vafa'06]

An effective theory is valid only for a **finite scalar field variation** $\Delta\phi$
because an **infinite tower of states** become **exponentially light**

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

Consider the moduli space of an effective theory:

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



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

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

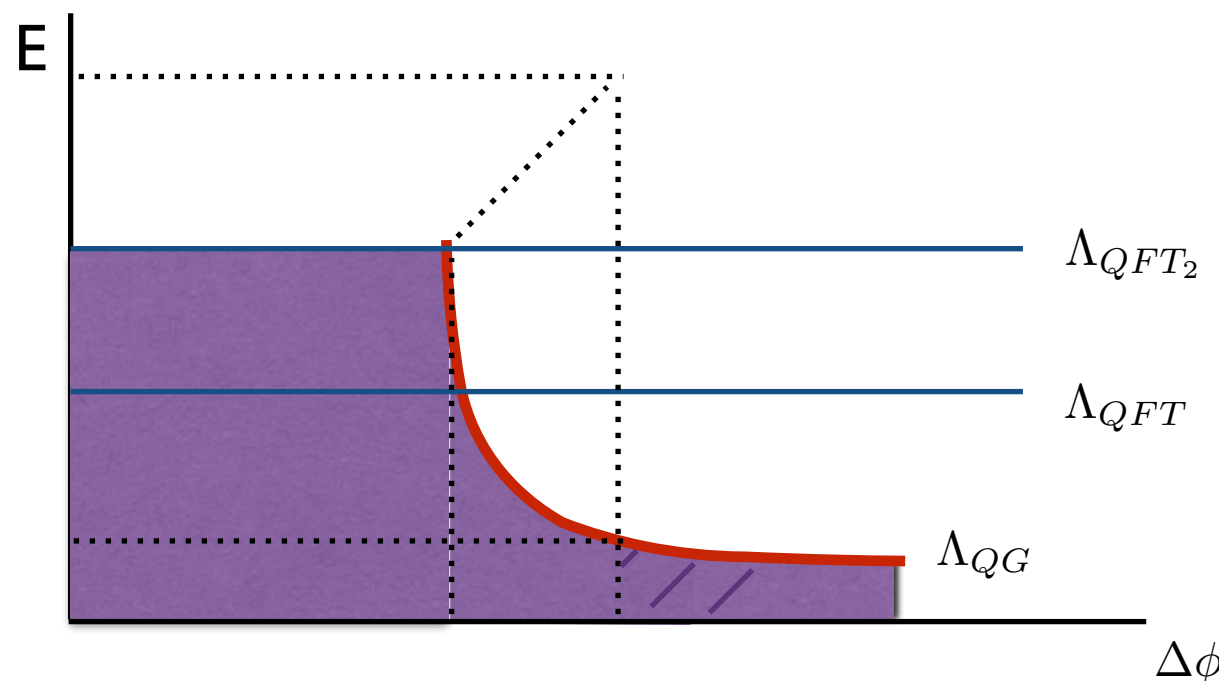
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This signals the breakdown of the effective theory:

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



Swampland Distance Conjecture

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

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

Phenomenological implications:

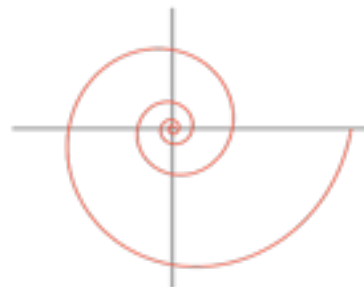
- Large field inflation
- Cosmological relaxation of the EW scale

• 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: [Ooguri-Vafa'06] (see Daniel, Florian and David's talks)
[Klaewer,Palti'16]

➔ $\lambda \sim 1 \rightarrow \Delta\phi \lesssim \mathcal{O}(1)M_p$

Caveats!



non-geodesics?
mass hierarchies?

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,Mayrhofer,Shukla'18][Blumenhagen et al.'18]

- Model-independent understanding missing...
- Very little is known about the tower of particles...
- What is the underlying QG obstruction?

Swampland Distance Conjecture

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[Grimm,Palti,IV'18]

Focus: Complex structure moduli space of IIB CY_3 compactifications
(4d $N=2$ string theory moduli space preserving special Kahler geometry)



natural testing ground for QG

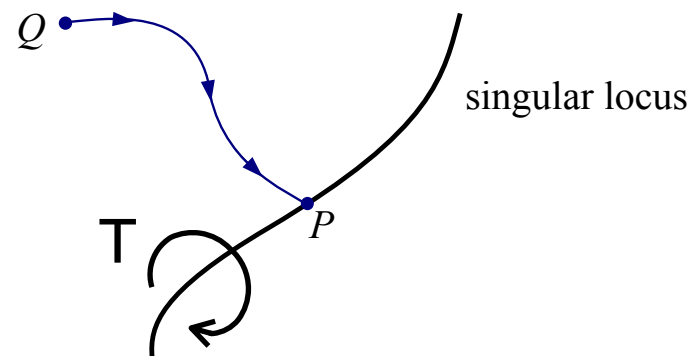
Aim: Prove the conjecture for any infinite distance path!

Swampland Distance Conjecture

- Definition and implications
- Test in the complex structure moduli space of Type IIB CY compactifications
- General insights

Complex structure moduli space of IIB CY compactifications

Prime example of a field space capturing information about ‘quantum gravity’



Infinite geodesic distances can occur only if approaching a singularity

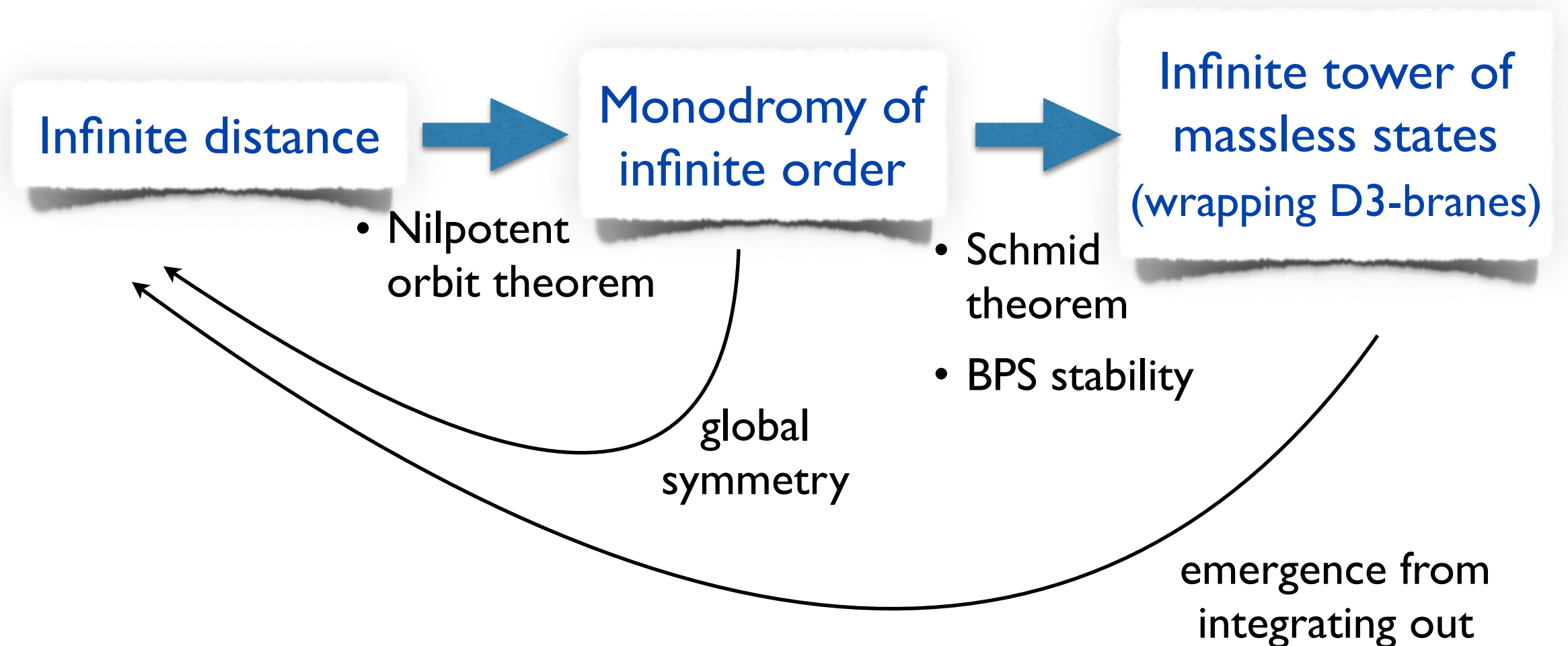
Massless BPS states (wrapping D3-branes) arise at the singularities

Candidates for SDC tower!

Two types:

- Infinite distance singularities: any trajectory approaching P has infinite length
- Finite distance singularities: at least one trajectory approaching P has finite length

Aim: Identify infinite tower of exponentially massless BPS states at any infinite distance singularity

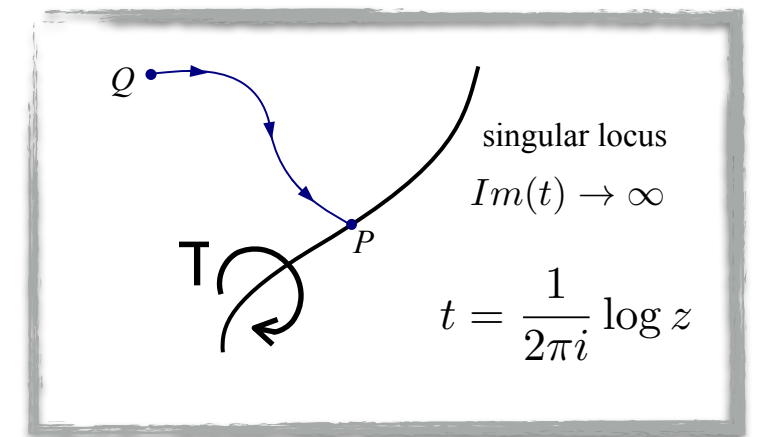


[Grimm,Palti,IV'18]

Focus on points belonging to a single singular divisor ✓

Nilpotent orbit theorem

- Distances given by: $d_\gamma(P, Q) = \int_\gamma \sqrt{g_{I\bar{J}} \dot{x}^I \dot{x}^{\bar{J}}} ds$ $g_{I\bar{J}} = \partial_{z^I} \partial_{\bar{z}^{\bar{J}}} K$
 $K = -\log \left(-i^D \int_{Y_D} \Omega \wedge \bar{\Omega} \right)$

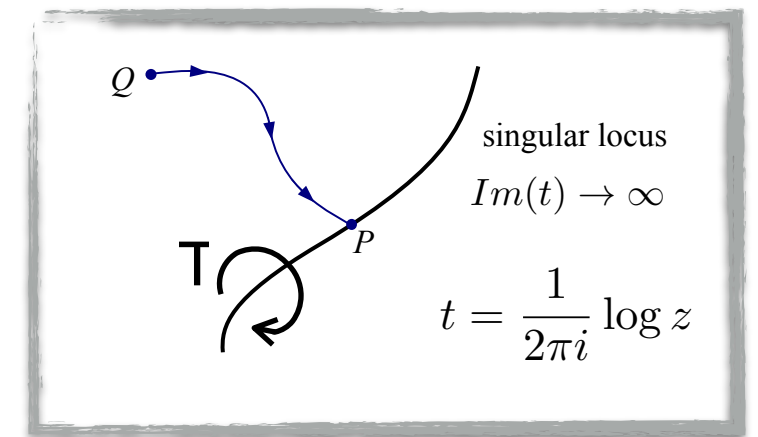


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- Periods of the (D,0)-form: $\Pi^{\mathcal{I}} = \int_{\Gamma_{\mathcal{I}}} \Omega$

transform under **monodromy** $\Pi(e^{2\pi i z}) = T \cdot \Pi(z)$
 (remnant of higher dimensional gauge symmetries)

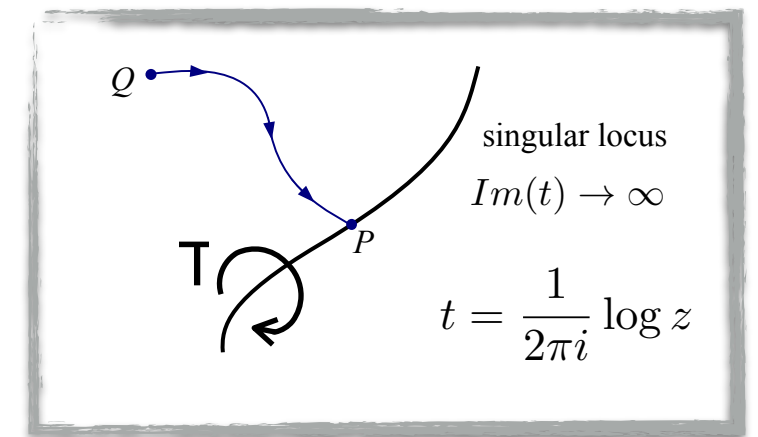


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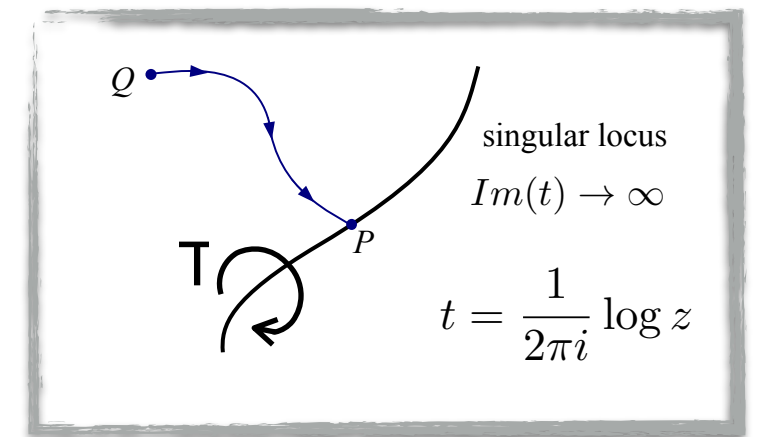
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 (no k s.t. $T^k = I$)

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Nilpotent orbit theorem:

[Schmid'73]

$$\Pi(t, \eta) = \exp(tN) a_0(\eta) + \mathcal{O}(e^{2\pi i t}, \eta) \quad \Rightarrow \quad g_{t\bar{t}} = \frac{d}{\text{Im}(t)^2} + \dots$$

It gives local expression for the periods near singular locus!

$$\Pi(t, \eta) = (1 + tN + \dots + t^d N^d) a_0(\eta) + \mathcal{O}(e^{2\pi i t}, \eta)$$

Infinite distances - Infinite states

I) Infinite distances only if monodromy is of infinite order

Theorem: P is at infinite distance $\longleftrightarrow Na_0 \neq 0$
[Wang'97, Lee'16]
 $d_\gamma(P, Q) = \sqrt{d} \log(\text{Im } t)|_Q^P \rightarrow \infty$

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

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

$$\begin{array}{c} q_m \\ \vdots \\ q_1 \\ q_0 \end{array} \begin{array}{c} \text{-----} \\ \text{-----} \\ \text{-----} \\ \text{-----} \end{array} \quad \curvearrowright \quad q_m = T^m q \quad m \in \mathbb{Z}$$

If T is of infinite order \longrightarrow Starting with one state, we generate infinitely many!

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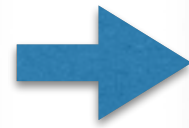
3) Universal local form of the metric gives the exponential mass behaviour

$$Z = \frac{1}{t^{d/2}} \sum_{j=1}^d (q \cdot N^j a_0) t^j + \mathcal{O}(e^{2\pi i t}) \quad \longrightarrow \quad \frac{M_q(P)}{M_q(Q)} \simeq \exp \left(-\frac{1}{\sqrt{2d}} d_\gamma(P, Q) \right)$$

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

Infinite distances - Infinite states

Infinite massless monodromy orbit at the singularity



Infinite tower of states becoming exponentially light

Swampland Distance Conjecture ✓

Swampland Distance Conjecture (SDC) is reduced to prove the existence of an infinite massless monodromy orbit at the singularity

$$\begin{aligned} \exists q \quad \text{s.t.} \quad & q^T N^j a_0 = 0, \quad j \geq d/2 \quad (\text{Massless}) \\ & Nq \neq 0 \quad (\text{Infinite orbit}) \end{aligned}$$

Tool: mathematical machinery of mixed hodge structure
(introduce finer split of cohomology at the singularity adapted to N)

[Deligne][Schmid][Cattani,Kaplan,Schmid][Kerr,Pearlstein,Robles'17]

(Subtleties regarding stability of BPS states: need to mod out states with $q^T N^j a_0 = 0, \forall j$)

BPS states and stability

How many BPS states are when approaching singularity?

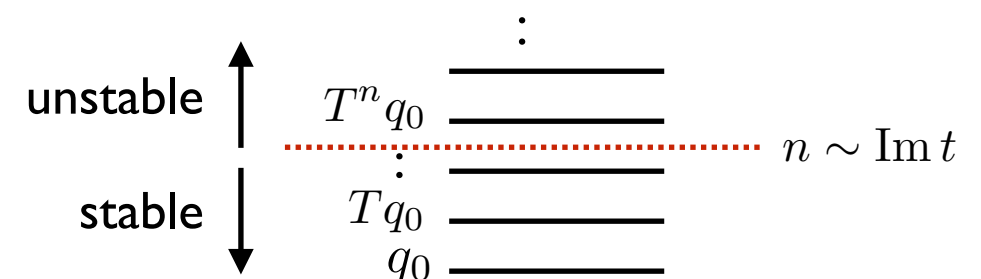
Do they cross a wall of marginal stability upon circling the monodromy locus?

Consider: $\mathbf{q}_C = \mathbf{q}_B + \mathbf{q}_{\bar{A}} \rightarrow M_{\mathbf{q}_C} \leq M_{\mathbf{q}_B} + M_{\mathbf{q}_{\bar{A}}}$

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

Upon circling the monodromy locus n times:

$$\varphi_I \rightarrow \varphi_I - \frac{n}{\pi \text{Im} t} + \mathcal{O}\left(\frac{1}{(\text{Im} t)^2}\right)$$



Charge states $\mathbf{q} = T^n \mathbf{q}_0$ with $n \ll \text{Im} t$ are stable (grade does not change)
(states higher up in the tower are unstable)

Number of BPS states: $n \sim \text{Im}(t) \sim e^{d_\gamma(P,Q)}$

(grows when approaching the singularity and diverges there)

Swampland Distance Conjecture

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Global symmetries

 SDC as a quantum gravity obstruction to restore a global continuous axionic shift **symmetry** at the singular point

$$K = -\log[p_d(\text{Im } t) + \mathcal{O}(e^{2\pi i t})]$$

At infinite distance singularities: $\text{Re } t \rightarrow \text{Re } t + c, \quad c \in \mathbb{R} \quad \text{when } \text{Im } t \rightarrow \infty$

$\text{Re } t$ = axion with decay constant $f^2 = g_{t\bar{t}} \rightarrow 0$

(also, gauge coupling of dual 2-form gauge field goes to zero)

—————→ analogous to WGC

Global symmetries

SDC = Magnetic Scalar WGC

- Magnetic version:

WGC: $\Lambda < g M_p$ If $g \rightarrow 0$ global symmetry is restored

How small can the gauge coupling be?

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

How large can the field variation be?

- Electric version:

$$\underbrace{g^{ij} (\partial_i m) (\partial_j m)}_{\text{charge}} M_p^2 \geq \underbrace{m^2}_{\text{mass}} \quad \Rightarrow \quad \text{satisfied for long distance if mass is exponential in } \phi \text{ [Palti'17]}$$

Emergence from integrating out the states

These moduli spaces are
'quantum in nature'



geometry incorporates information
about integrating out BPS states

Conifold singularity: log-divergence of gauge coupling from integrating
[Strominger'95] out a single BPS D3-state

Similar computation at infinite distance singularities! [Grimm,Palti,IV'18]

One-loop corrections from integrating out the tower of BPS states
→ matches geometric result (generates the log. infinite distance)

At infinite distance
singularities:

$$g_{t\bar{t}} = \frac{d}{\text{Im}(t)^2} + \dots$$

$$d_\gamma(P, Q) = \int_Q^P \sqrt{g_{t\bar{t}}} |dt| \sim \frac{\sqrt{2}}{2} \log(\text{Im } t)|_Q^P$$

Emergence from integrating out the states

$$\begin{array}{c}
 \text{---} \Lambda_{UV} = \Lambda_{\text{Species}} \\
 \vdots \\
 \text{---} m_2 \\
 \vdots \\
 \text{---} m_1 \\
 \text{---} m_0 = \Lambda_0 \\
 \vdots \\
 \text{---} m_\phi = 0
 \end{array}$$

Δm {

Original theory:

$$\mathcal{L} = \underbrace{\frac{1}{2} (\partial\phi)^2}_{\text{light field}} + \sum_{i=1}^S \left[\underbrace{\frac{1}{2} (\partial h_i)^2 + \frac{1}{2} m_i (\phi)^2 h_i^2}_{\text{tower of massive fields}} \right]$$

integrate them out!

$m_k = m_0 + k\Delta m$

We have to integrate out the tower of particles up to the UV cut-off of the original theory!

UV cut-off = Species bound

$$\Lambda_{UV} = \frac{M_p}{\sqrt{S}} \quad [\text{Dvali'07}]$$

↳ number of fields below Λ_{UV}


$$\left. \begin{array}{l}
 S = \frac{\Lambda_{UV}}{\Delta m(\phi)} \\
 \Delta m(\phi) \sim \phi^{-d/2}
 \end{array} \right\} \Rightarrow \Lambda_{UV}(\phi) \sim \Delta m(\phi)^{1/3} \sim \phi^{-d/6}$$

Field dependent UV cut-off!

At the singularity: $S \rightarrow \infty \Rightarrow \Lambda_{UV} \rightarrow 0$ (growth of S matches with stability of BPS states!)

Emergence from integrating out the states

$$\begin{array}{c}
 \text{---} \Lambda_{UV} = \Lambda_{\text{Species}} \\
 \vdots \\
 \text{---} m_2 \\
 \text{---} m_1 \\
 \Delta m \left\{ \text{---} m_0 = \Lambda_0 \right. \\
 \text{---} m_\phi = 0
 \end{array}$$

 Original theory:

$$\mathcal{L} = \underbrace{\frac{1}{2} (\partial\phi)^2}_{\text{light field}} + \sum_{i=1}^S \left[\underbrace{\frac{1}{2} (\partial h_i)^2 + \frac{1}{2} m_i (\phi)^2 h_i^2}_{\text{tower of massive fields}} \right]$$

$m_k = m_0 + k\Delta m$



integrate them out! \longrightarrow

 Quantum correction to the field metric \longrightarrow matches geometric result

$$\delta g_{\phi\phi} \propto \sum_{k=1}^S (\partial_\phi m_k)^2 \sim \frac{d}{\phi^2} \quad \longrightarrow \quad d(\phi_1, \phi_2) \sim \sqrt{d} \log \left(\frac{\phi_2}{\phi_1} \right)$$

 Quantum correction to the gauge kinetic function \longrightarrow matches geometric result

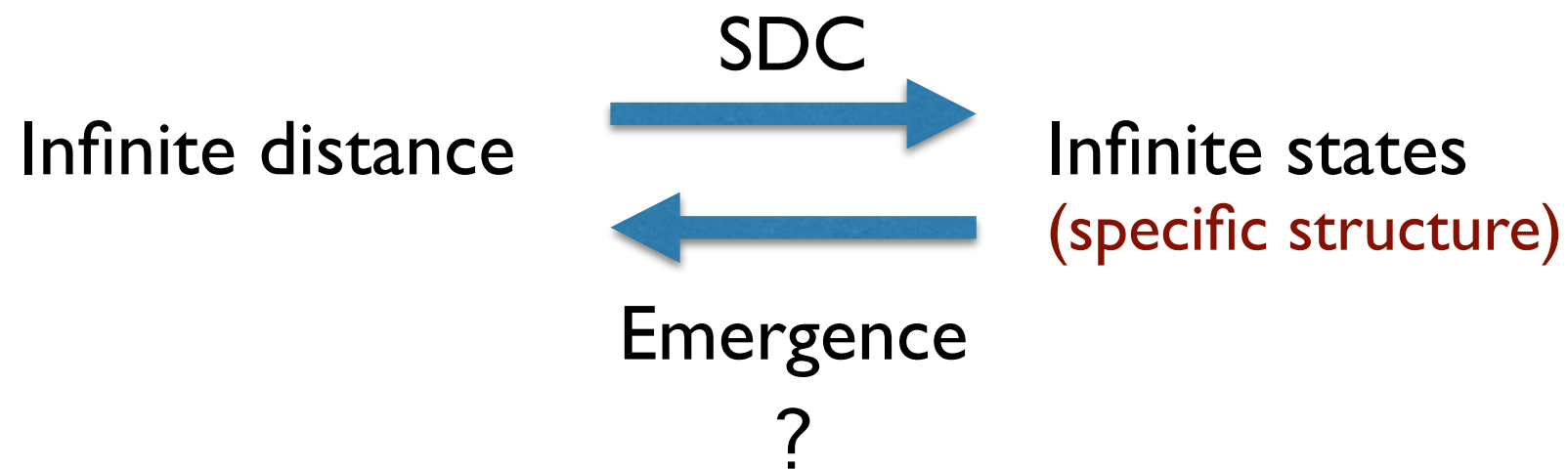
$$g_{YM}^2 \sim \phi^{-n} \sim m_0^{2n}$$

 UV cut-off decreases exponentially fast in the proper field distance $\Lambda \sim M_p e^{-\lambda d(\phi_1, \phi_2)}$
 \longrightarrow effective theory completely breaks down **SDC!** 

Emergence from integrating out the states

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

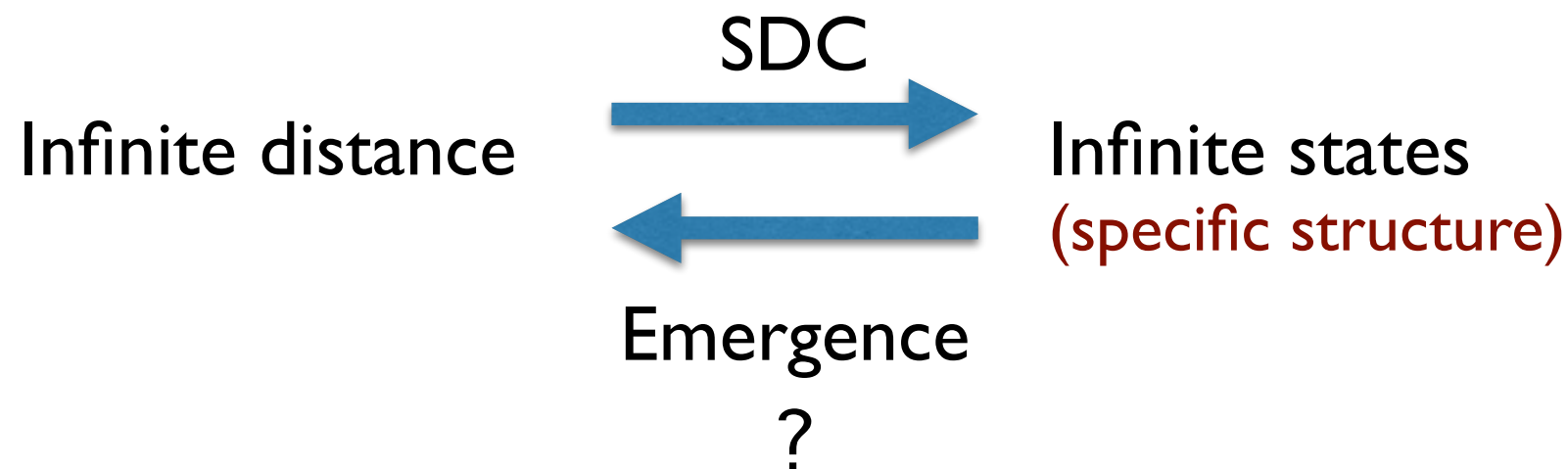
Can this be a general feature for any moduli space?



Emergence from integrating out the states

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

Can this be a general feature for any moduli space?



Comments:

$m(\phi)$ does not matter much as long as $S(\phi) \neq \text{const.}$ and diverges consistently with species bound of a tower of particles with

$$\frac{\partial_\phi m}{m} \gtrsim \mathcal{O}\left(\frac{1}{\phi}\right) \quad \text{when } \phi \rightarrow \infty$$

└──────────┘
 ↓
 different species

(see Pierre's talk)

(see also [Heidenreich,Reece,Rudelius'18])

Emergence from integrating out the states

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

Can this be a general feature for any moduli space?

This limits correspond to restoring a continuous global symmetry, so **global symmetries would also be emergent** from integrating out infinitely many states!

(emergence is continuous)

$$\Lambda_{UV} = \frac{M_p}{\sqrt{S}} \longrightarrow 0 \quad \text{when } S \rightarrow \infty \quad \text{unless } M_p \rightarrow \infty$$

Global symmetries only possible if gravity decouples

Summary

Swampland Distance Conjecture:

Upper bound on the scalar field range: [Implications for inflation!](#)

- ✓ Test in the complex structure moduli space of CY IIB compactifications
 - Infinite order monodromy as generator of the infinite tower
 - Emergence of infinite field distance and global symmetry

➡ Generalizations:

- 📍 Our results are valid for any CY (model-independent)
(but only for infinite distance points that belong to a single singular divisor)
- 📍 Other moduli spaces?

Summary

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

Knowledge of Swampland is essential for UV sensitive theories and might also be important for naturalness issues.

- Very important to gather more evidence to prove or disprove the conjectures

→ doable and exciting task!

Summary

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

Knowledge of Swampland is essential for UV sensitive theories and might also be important for naturalness issues.

- Very important to gather more evidence to prove or disprove the conjectures

→ doable and exciting task!

Thank you!

back-up slides

Infinite tower of states

Tool: mathematical machinery of **mixed hodge structure**

Problem: ‘Normal’ Hodge decomposition no longer useful when

approaching a singularity $H^3(Y_3, \mathbb{C}) = H^{3,0} \oplus H^{2,1} \oplus H^{1,2} \oplus H^{0,3}$

Idea: Introduce **finer split of cohomology** at the singularity adapted to this ‘limiting’ Hodge decomposition

$$h^{p,3-p} = \sum_q \dim I^{p,q}$$

$$H^{3,0} \rightarrow \{I^{3,3}, I^{3,2}, I^{3,1}, I^{3,0}\}$$

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

[Kerr,Pearlstein,Robles'17]

The subspaces capture non-trivial information about the nilpotent monodromy operator,

$$NI^{p,q} \subset I^{p-1,q-1}$$

For a CY: $a_0 \in I^{3,d}, \quad d = 0, 1, 2, 3$

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:

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

For small mR:

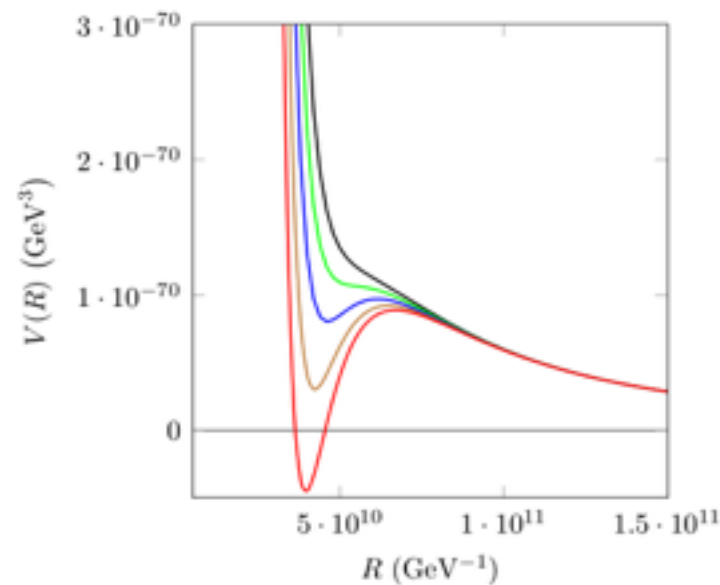
$$\rho(R) = \mp \left[\frac{\pi^2}{90(2\pi R)^4} - \frac{\pi^2}{6(2\pi R)^4} (mR)^2 + \frac{\pi^2}{48(2\pi R)^4} (mR)^4 + \mathcal{O}(mR)^6 \right]$$

Compactifications of the Standard Model

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

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

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



We can get AdS, Minkowski or dS vacua
in lower dimensions!

(depending on light spectra of SM and value of c.c.)

Compactifications of the Standard Model

Problem:

AdS minimum appears if:

- Neutrinos are Majorana
- Neutrinos have a Dirac mass: $\sum_i m_{\nu_i}^4 \gtrsim \mathcal{O}(\Lambda_4)$

For our c.c:

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

[Ibanez,Martin-Lozano,IV'17]

Assuming Ooguri-Vafa AdS conjecture + background independence:

We should not get stable non-susy AdS vacua from compactifying the SM !!!

Compactifications of the Standard Model

Solution:

Make the minimum unstable

- 📌 Include Wilson Lines to generate a runaway for small R [Hamada-Shiu'17]

→ not valid in orbifolds

- 📌 Assume existence of 4d bubble instability which is transferred to lower dimensions

→ not valid if $R_{\text{bubble}} > l_{AdS_3}$

[Ibanez, Martin-Lozano, IV'17]

Impose absence of AdS vacua

Constraints on light spectra of SM!

- 📌 Upper bound on neutrino masses in terms of the cosmological constant

$$\Lambda_4 \gtrsim \mathcal{O}(m_\nu^4)$$

(Upper bound on EW scale!)

- 📌 SM by itself ruled out → MSSM survives
[Gonzalo, Herraez, Ibanez'18]

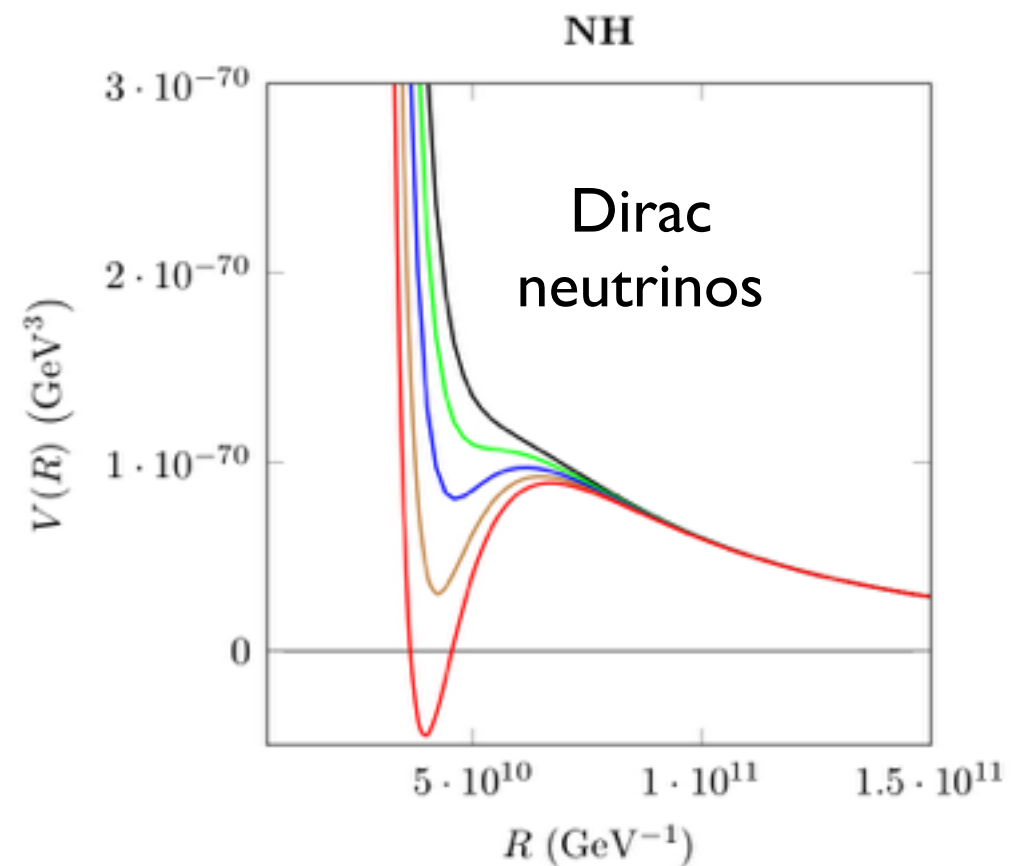
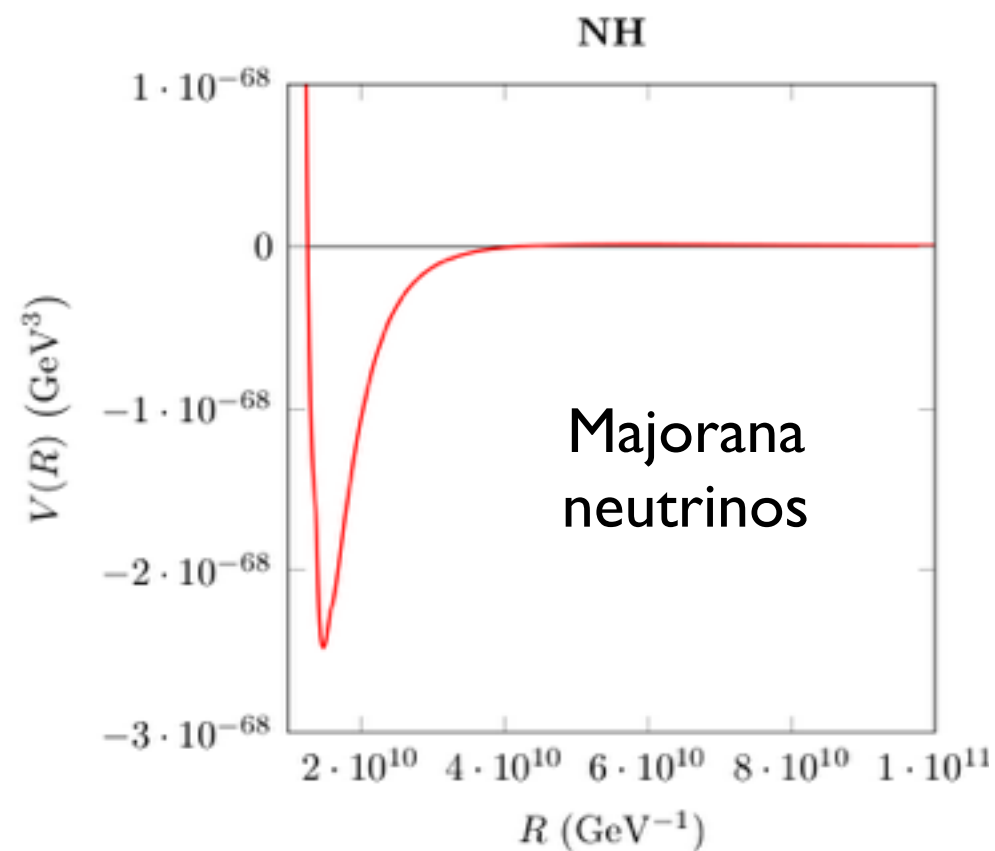
Compactification of the SM to 3d

Standard Model + Gravity on S^1 :

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

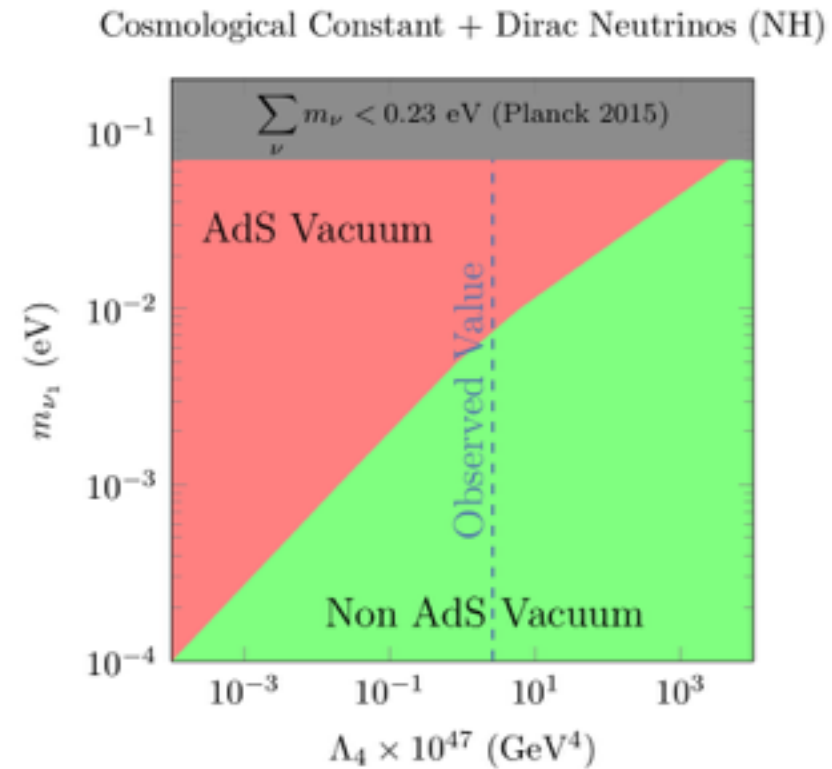
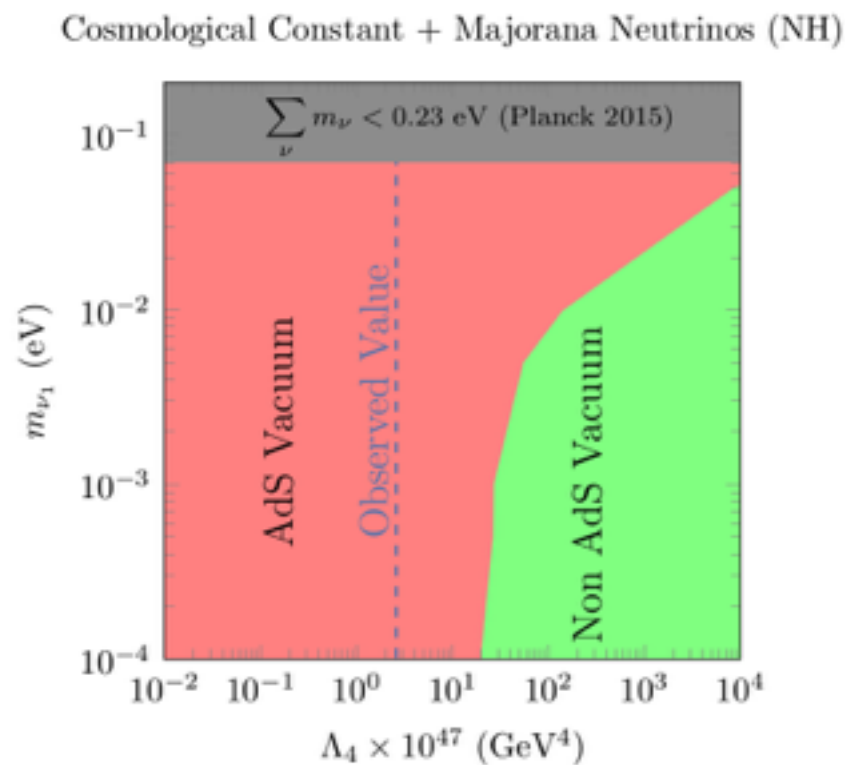
graviton, photon

massive particles:
neutrinos,...



The more massive the neutrinos, the deeper the AdS vacuum

Lower bound on the cosmological constant



The bound for Λ_4 scales as m_ν^4

(as observed experimentally)

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

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

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

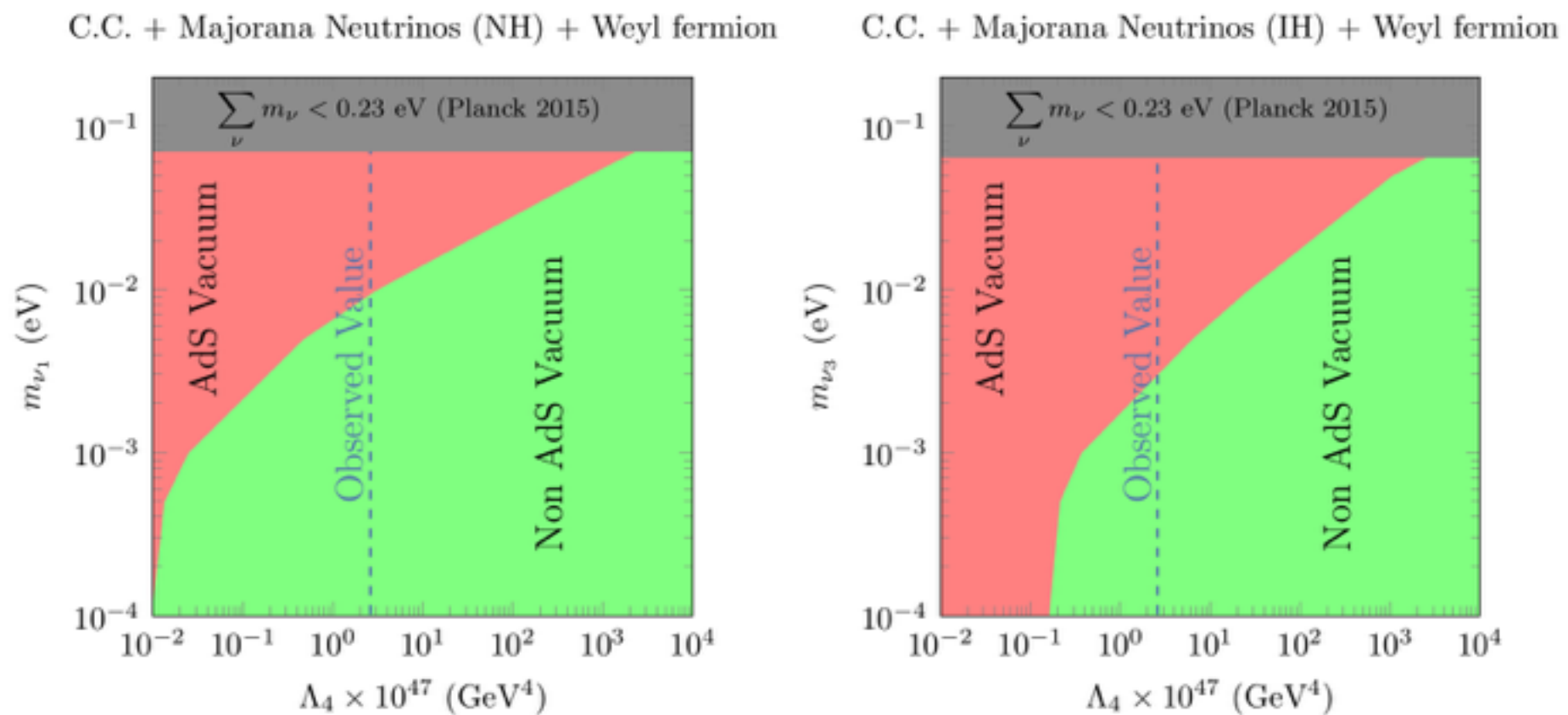
Adding BSM physics

► Light fermions

Positive Casimir contribution \longrightarrow helps to avoid AdS vacuum

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

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

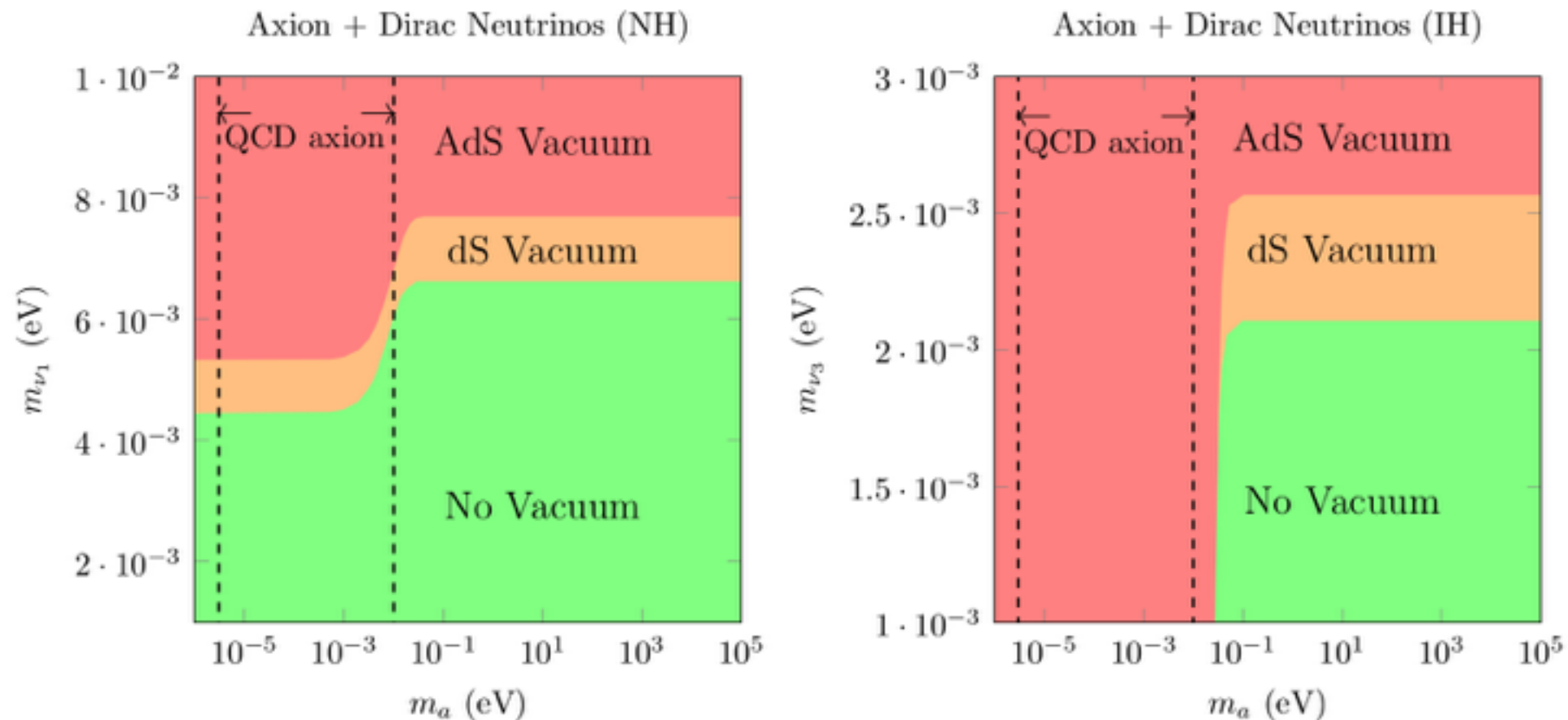


Adding BSM physics

► Axions

1 axion: negative contribution \longrightarrow 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])