Quantum Gravity Constraints on Particle Physics

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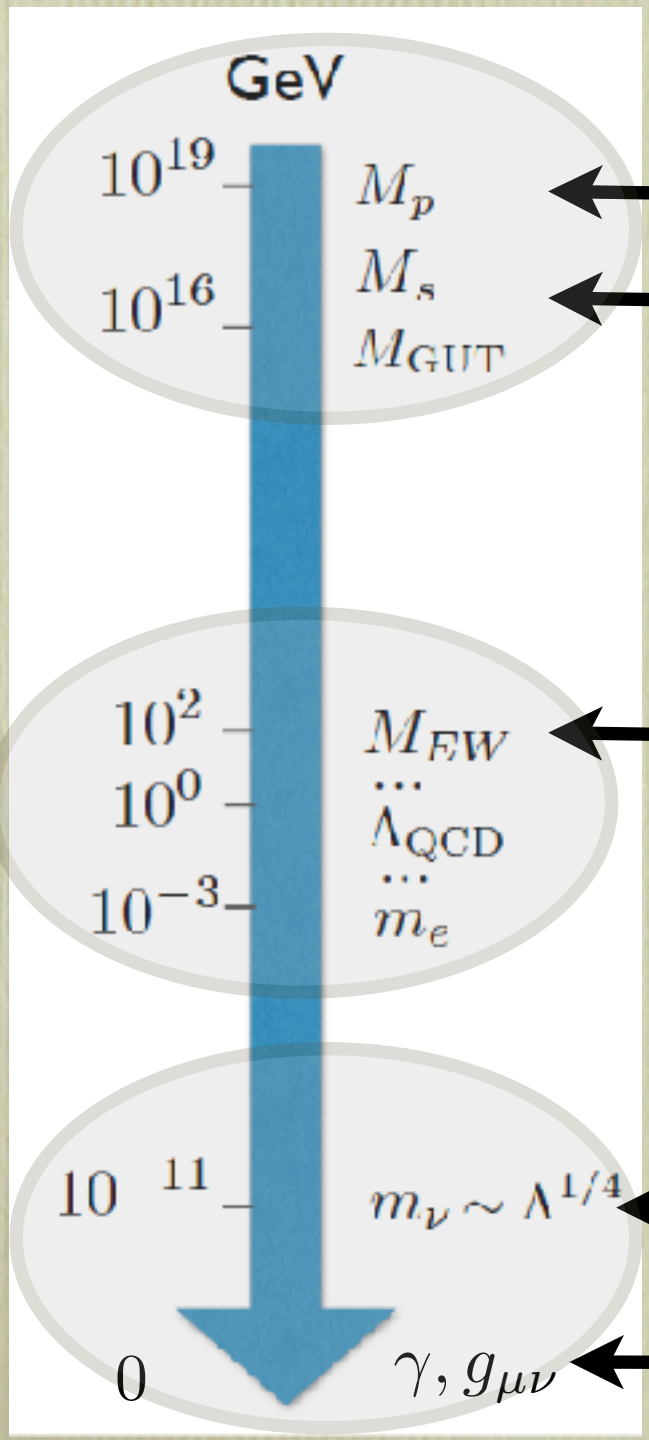
Scales in Fundamental Physics



Quantum Gravity

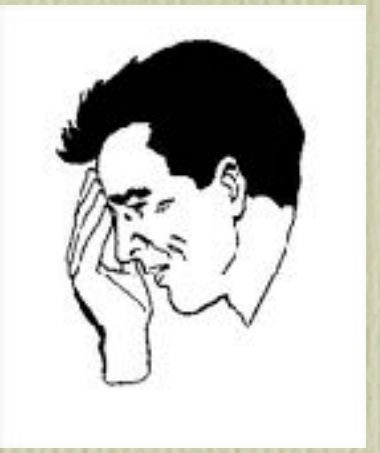
Unification/ UV completion

$EW\ scale,\ m_H = 125\ GeV$

$M_W\ not\ far\ from\ \Lambda_{QCD}$

Dirac?Majorana?One is massless? Why equal?

Only massless d.o.f.



Pressing questions

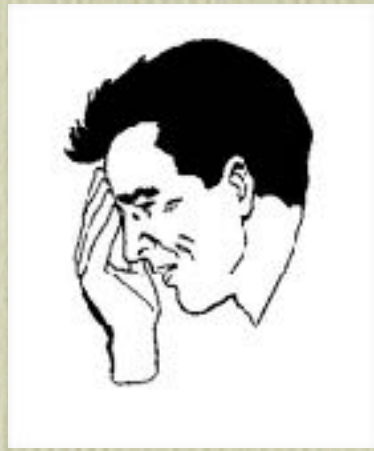
The universe accelerates. Simplest explanation a non-vanishing constant vacuum energy $\Lambda_{c.c.}$

** Why and how is the c.c. so small and non-vanishing??

$$\Lambda_{c.c.} \simeq (10^{-3} eV)^4 \qquad \Lambda_{c.c.} \sim m_\nu^4 \ ?$$

Naturality: One would expect something of oder the cut-off

$$\Lambda_{c.c.} \simeq M_{Planck}^4 \simeq (10^{30} eV)^4$$

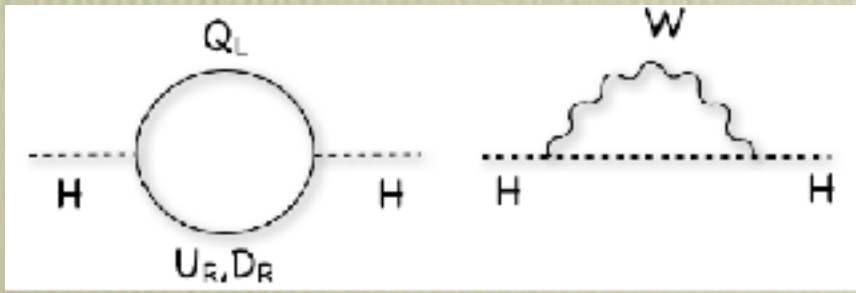


Pressing questions

** Why and how is the EW scale so small compared to the Planck/Unification scale?

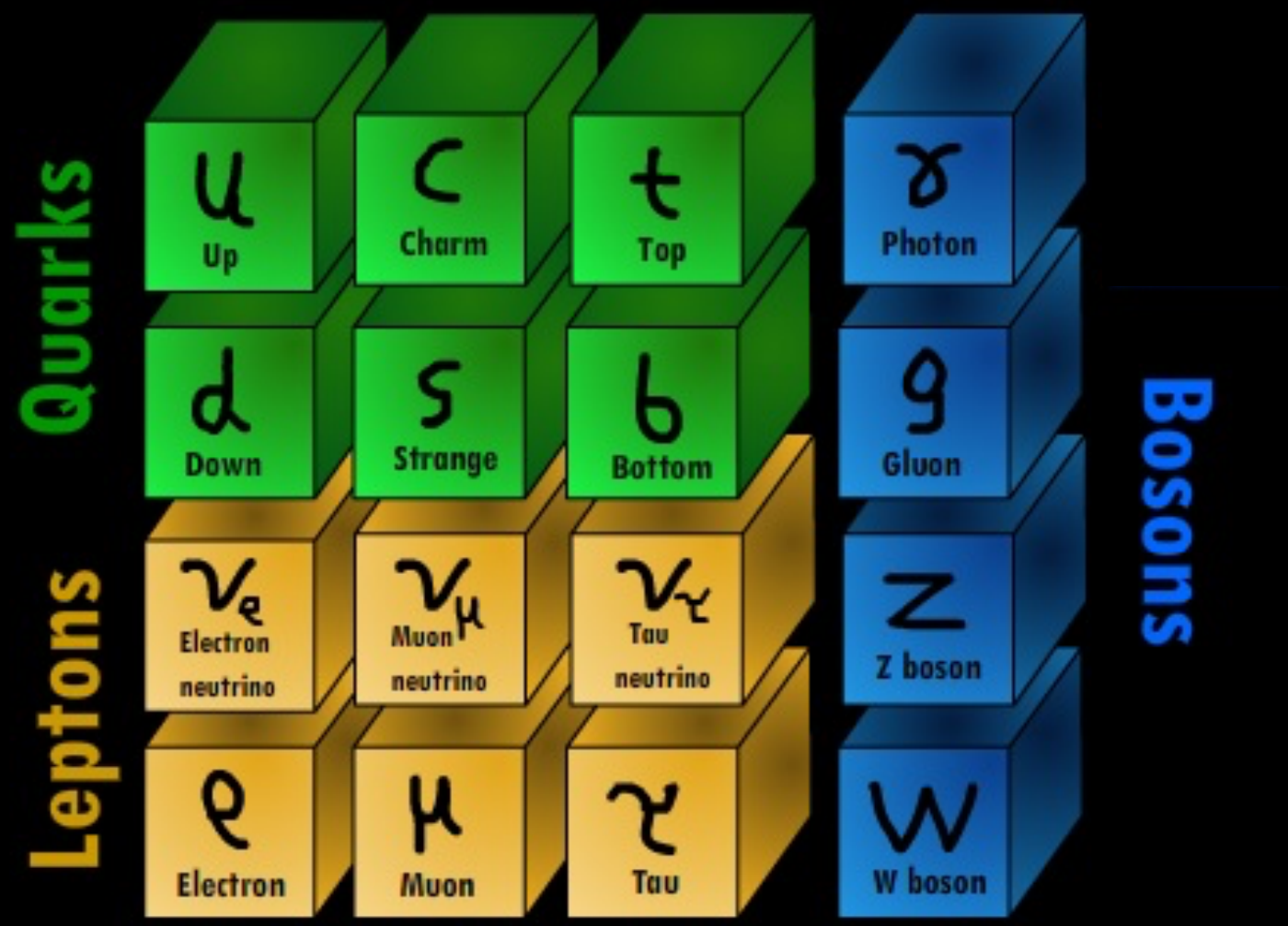
$$M_W \ll M_p$$

Naturality: Fundamental scalars like the Higgs are unprotected against quantum corrections and push

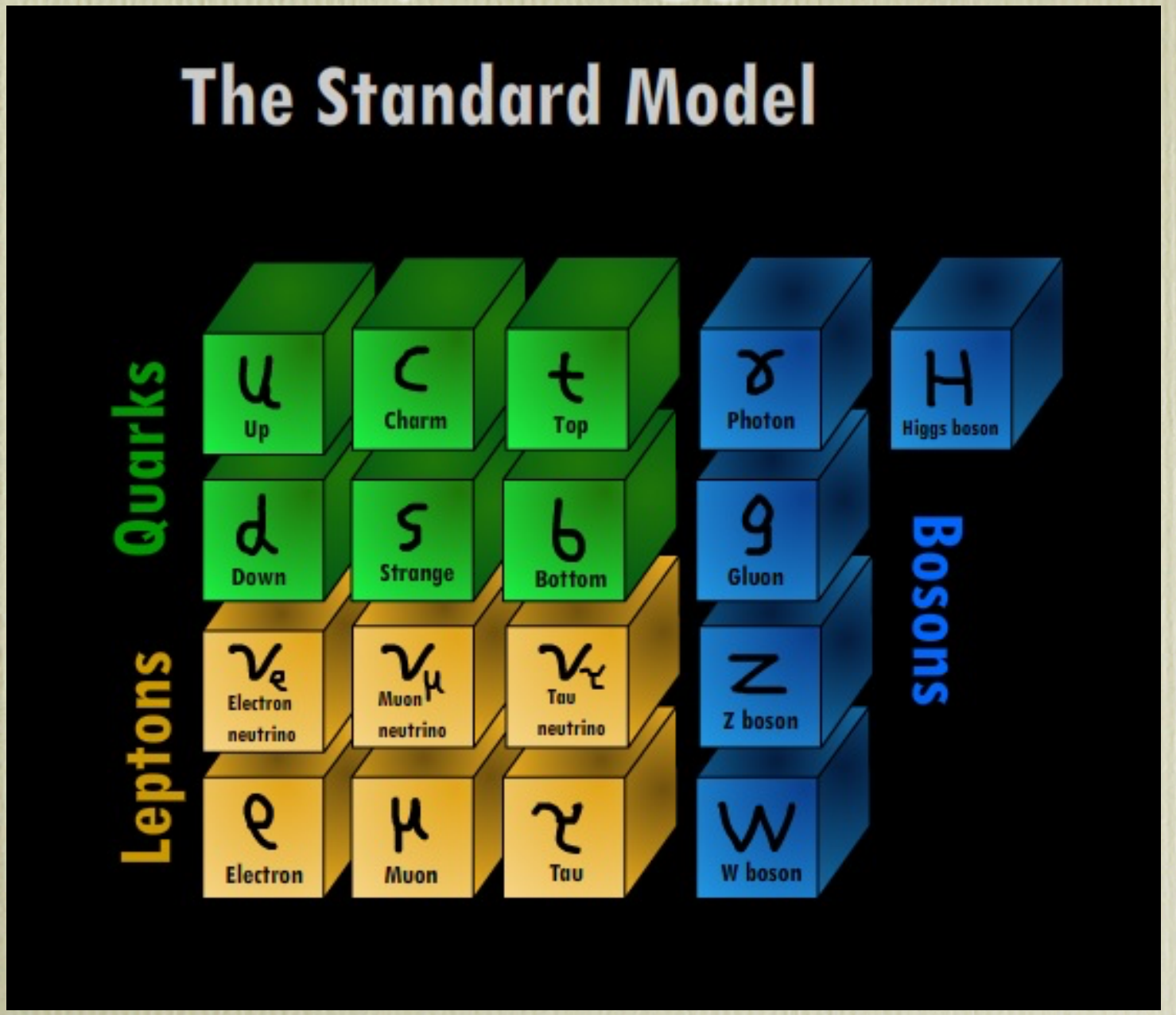


$$M_W \simeq M_p$$

The Standard Model



Why a Higgs exists at all?



Why there are 3 generations?

Naturality has been at the forefront of (almost) all our attempts to understand hierarchies in the last decades

Has the naturality criterium guided us in the right direction?

Perhaps we have to abandon some of our most cherised ideas:

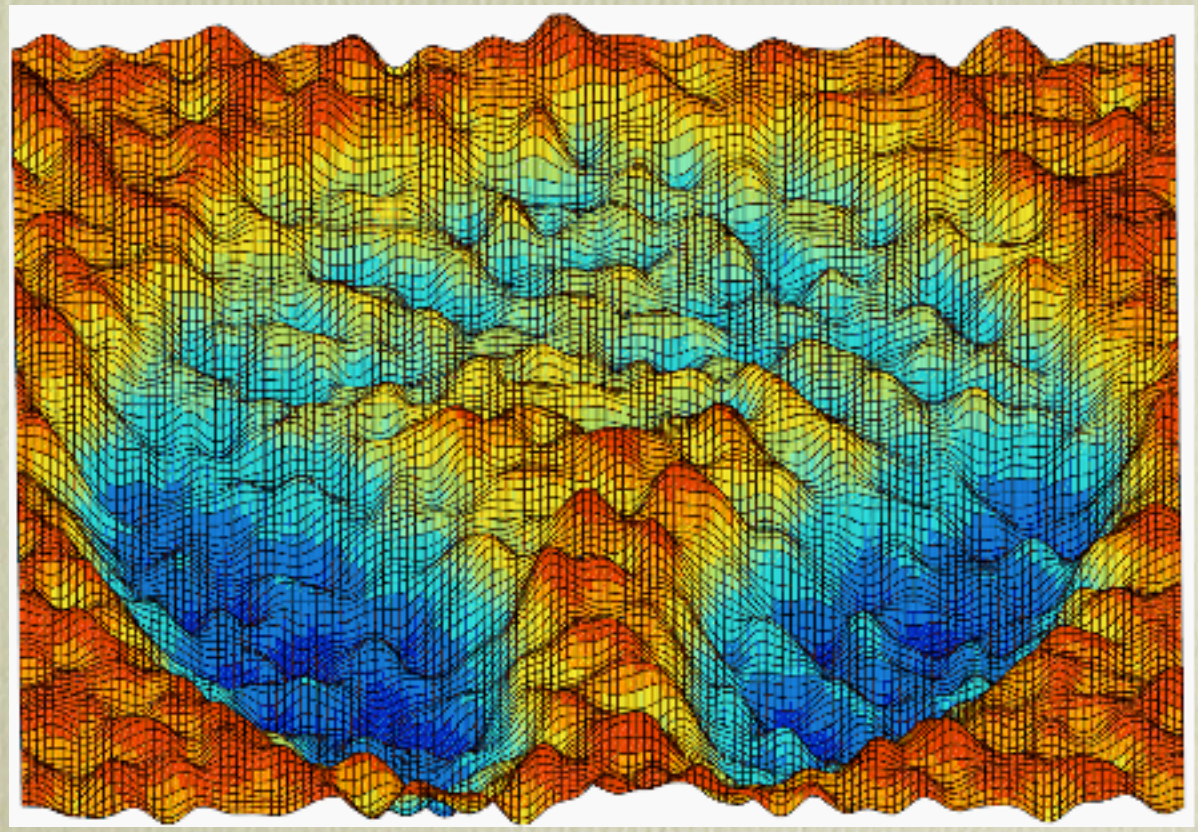
** Uniqueness of solutions: the landscape

** UV-IR independence

Leading idea for the cosmological constant problem:

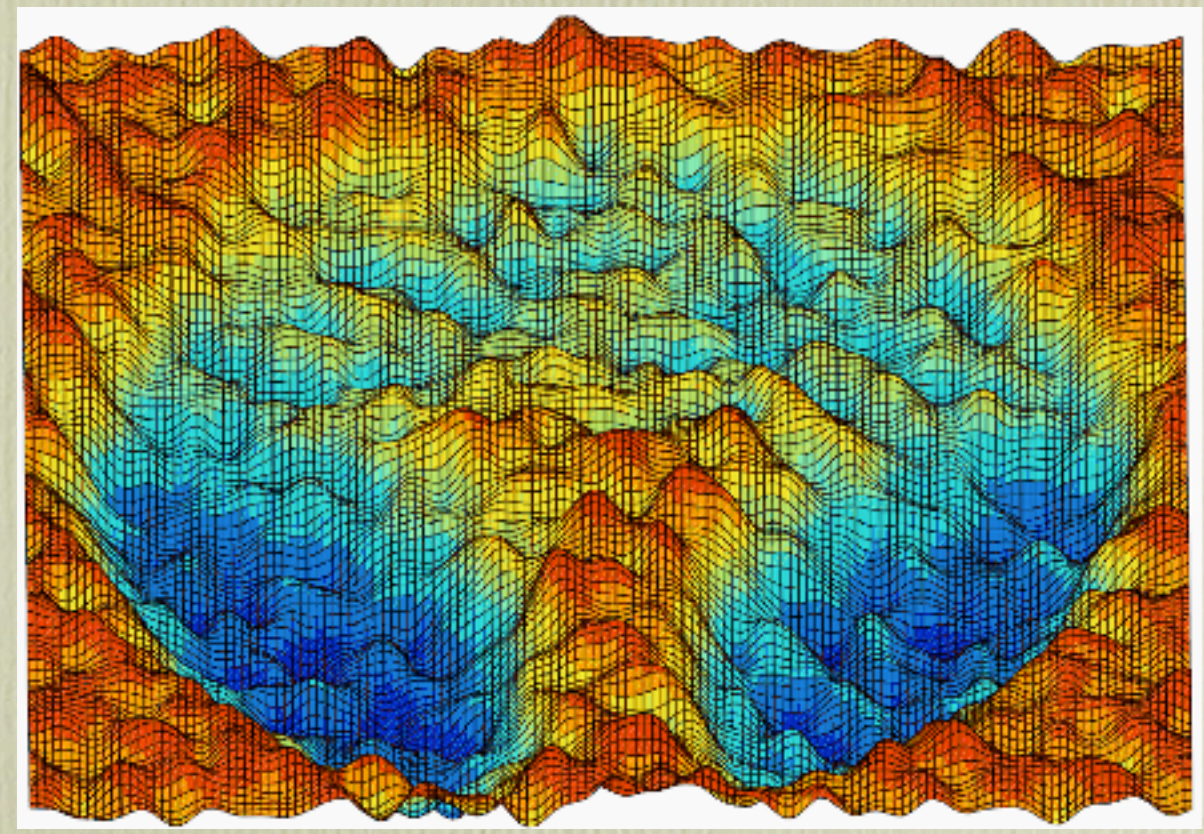
The String Landscape

10^{500} *4D String vacua estimated*



Leading idea for the cosmological constant problem:

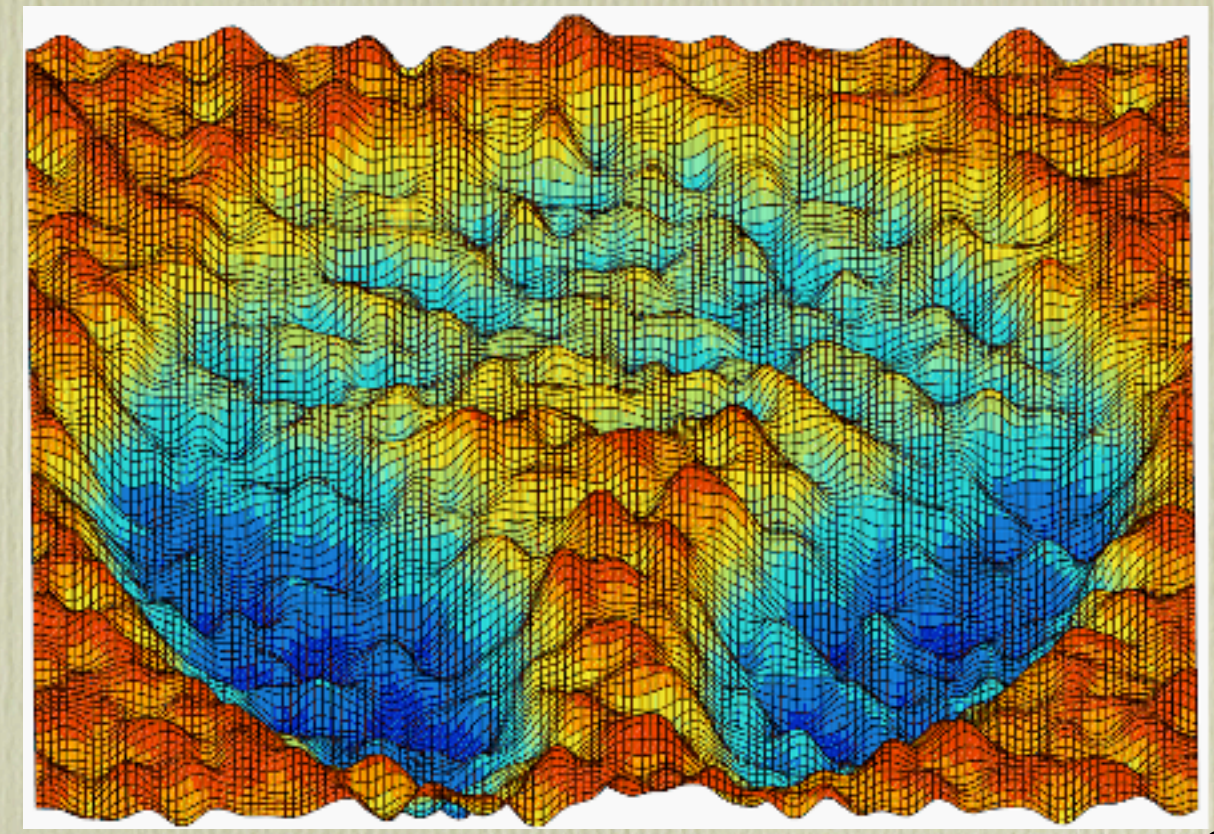
The String Landscape



$$10^{272000}\ 4D\ F-theory\ vacua\ estimated$$

Taylor, Wang 2015

The String Landscape



Quantized fluxes

$$V = \sum_a G_a |F_4^a|^2 - \Lambda_0$$

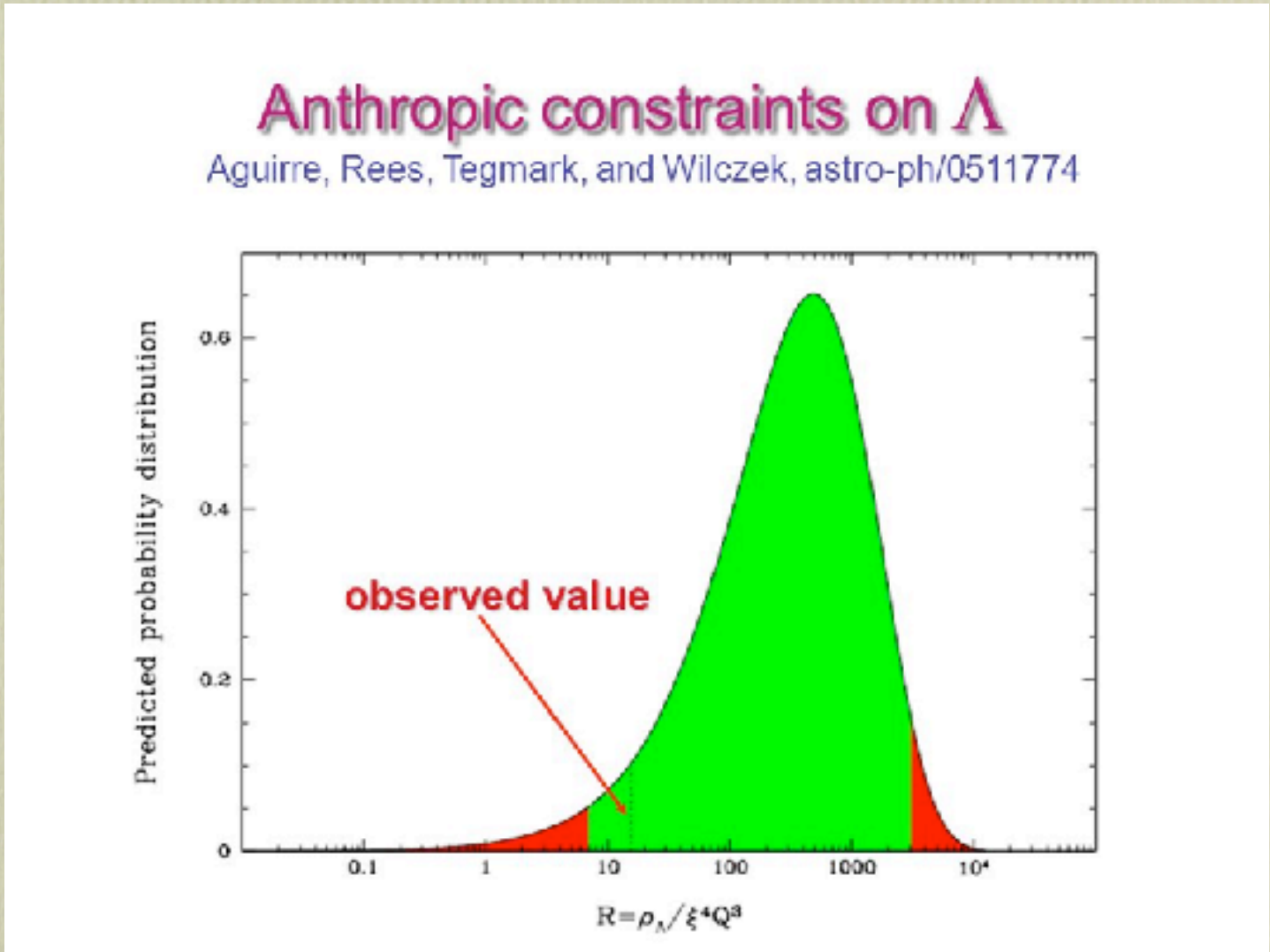
Bousso, Polchinski 2000

very likely vacua exist with small c.c. matching cosmological observations

Existence of this huge landscape combined with anthropic arguments provides for an understanding of the size of the c.c.

Galaxy formation constraints the c.c.

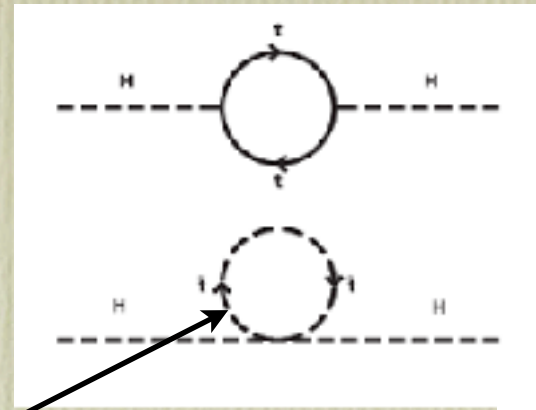
Weinberg 1987



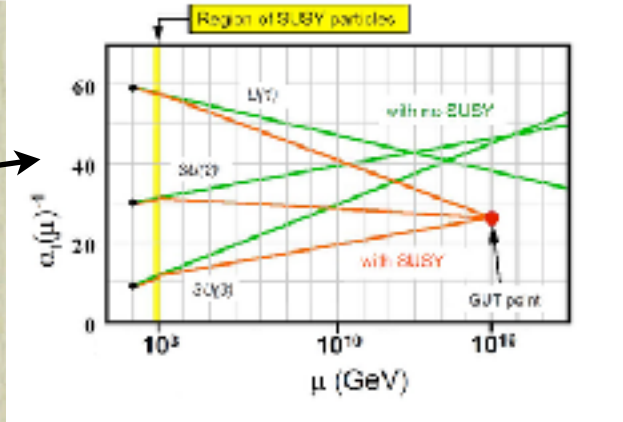
Probability distribution of the c.c.

The Electro-Weak Hierarchy Problem

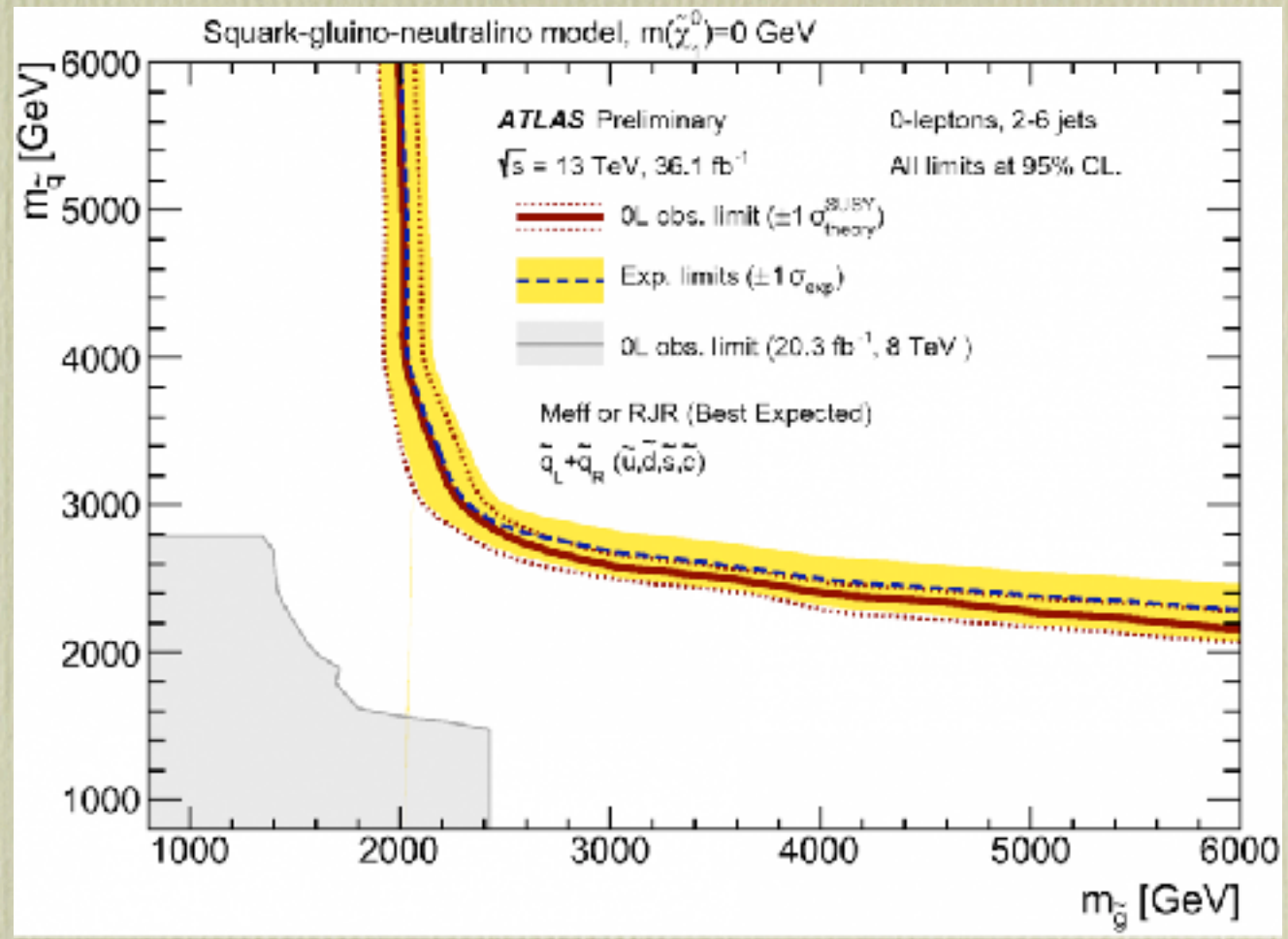
Supersymmetry:



- 1) Stabilizes the Higgs mass
- 2) Accurate gauge coupling unification
- 3) Neutralinos candidates for dark matter
- 4) Built-in in String Theory



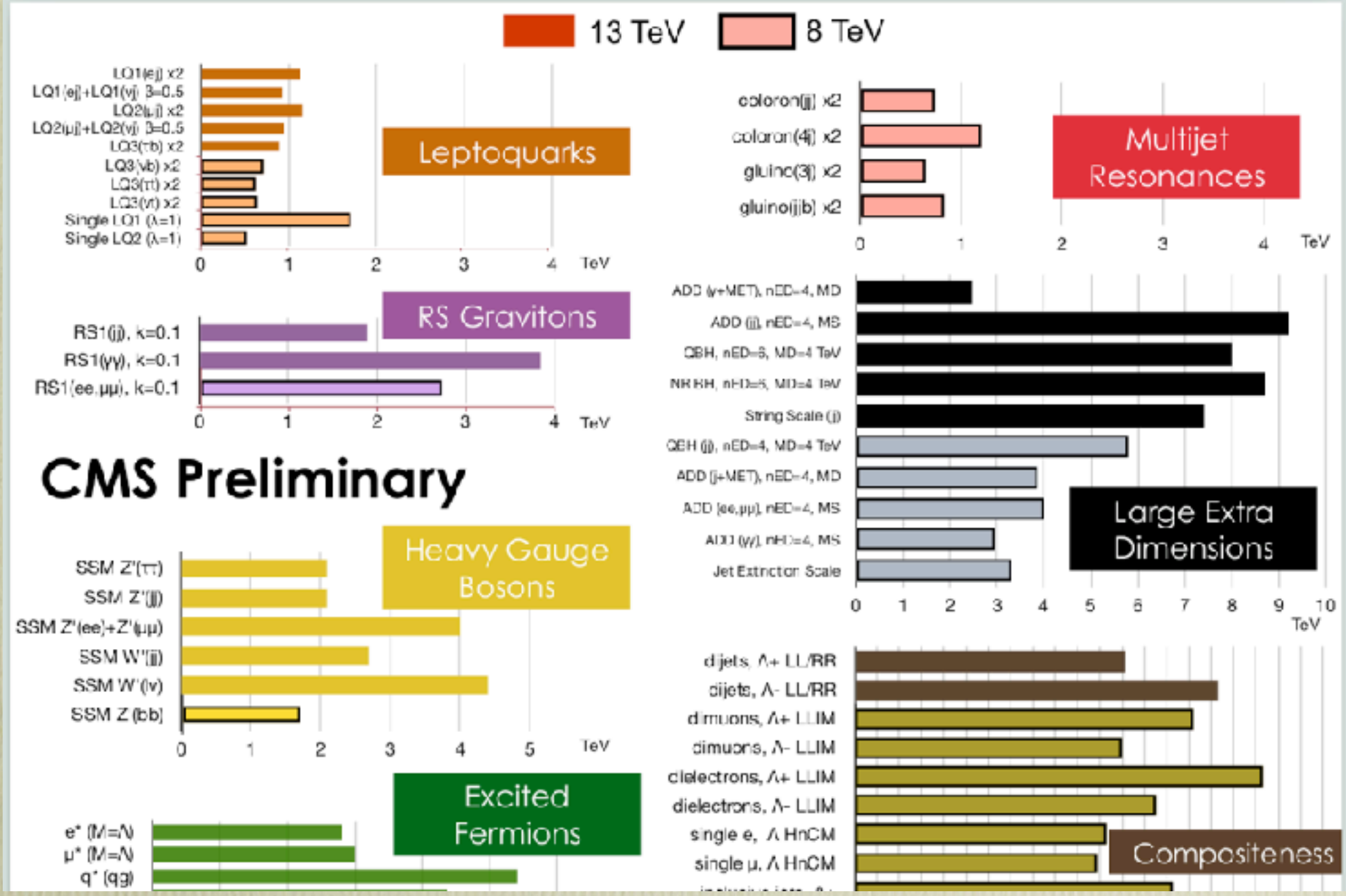
but.....no trace of SUSY so far



$$Observed\ Higgs\ mass\ m_H = 125\ GeV$$

$$suggests\ very\ heavy\ spectrum\ (if\ at\ all)$$

$$FINE-TUNING\ \simeq\ 10^{-2} - 10^{-3}$$



No hint either for alternative new physics

SUSY (or some other BSM physics) could be around the corner.

But at least some ammount of fine-tuning seems necessary

Have to reconsider the naturality criterium?

It is time

for new

ideas!!

It is time

for new

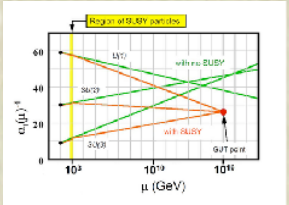
(possibly wild!!)

ideas!!

Consistency with Quantum Gravity may hold the key...

Quantum Gravity versus Particle Physics

- We normally assume that the SM is unified with quantum gravity at the Planck scale



- Also asume that no trace of such quantum gravity embedding, other than boundary conditions, e.g. coupling unification, remains

- So we can ignore quantum gravity effects at low energies

- The tacit assumption is the belief that any field theory you can think of can consistently be coupled to quantum gravity.

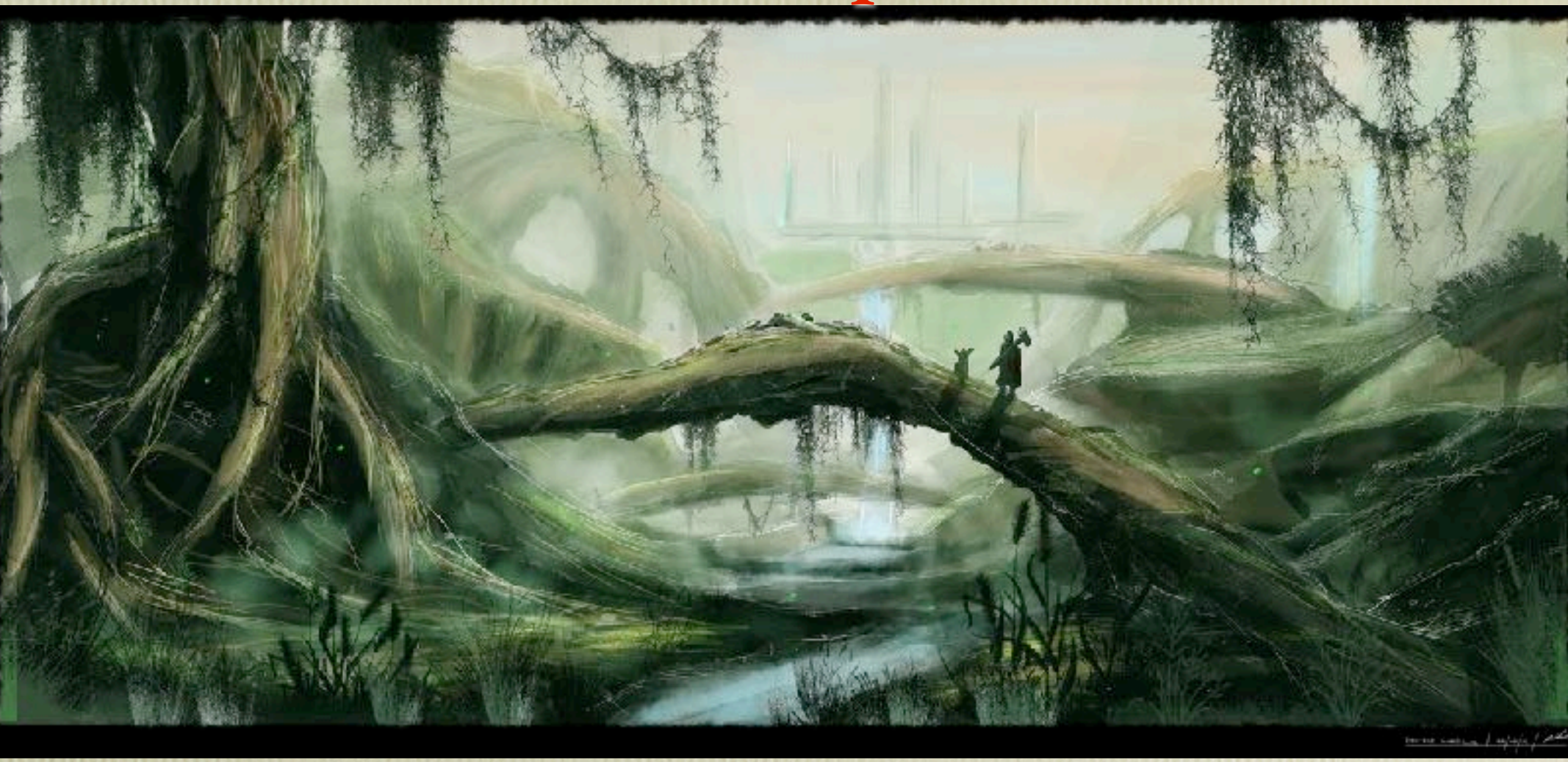
- It has been realized in the last decade that this is NOT TRUE

- Most field theories cannot be consistently coupled to quantum gravity, they belong to the

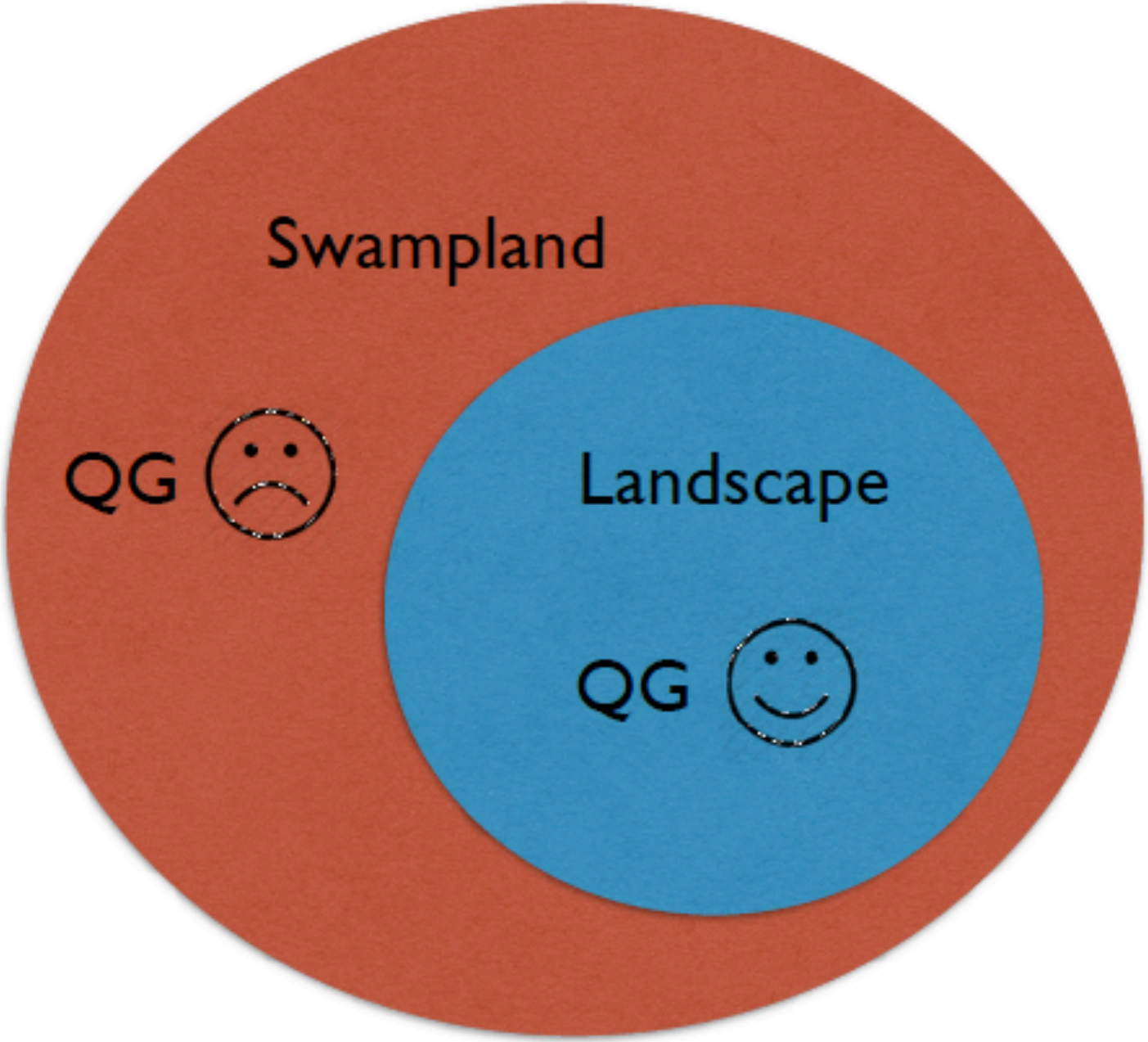
SWAMPLAND

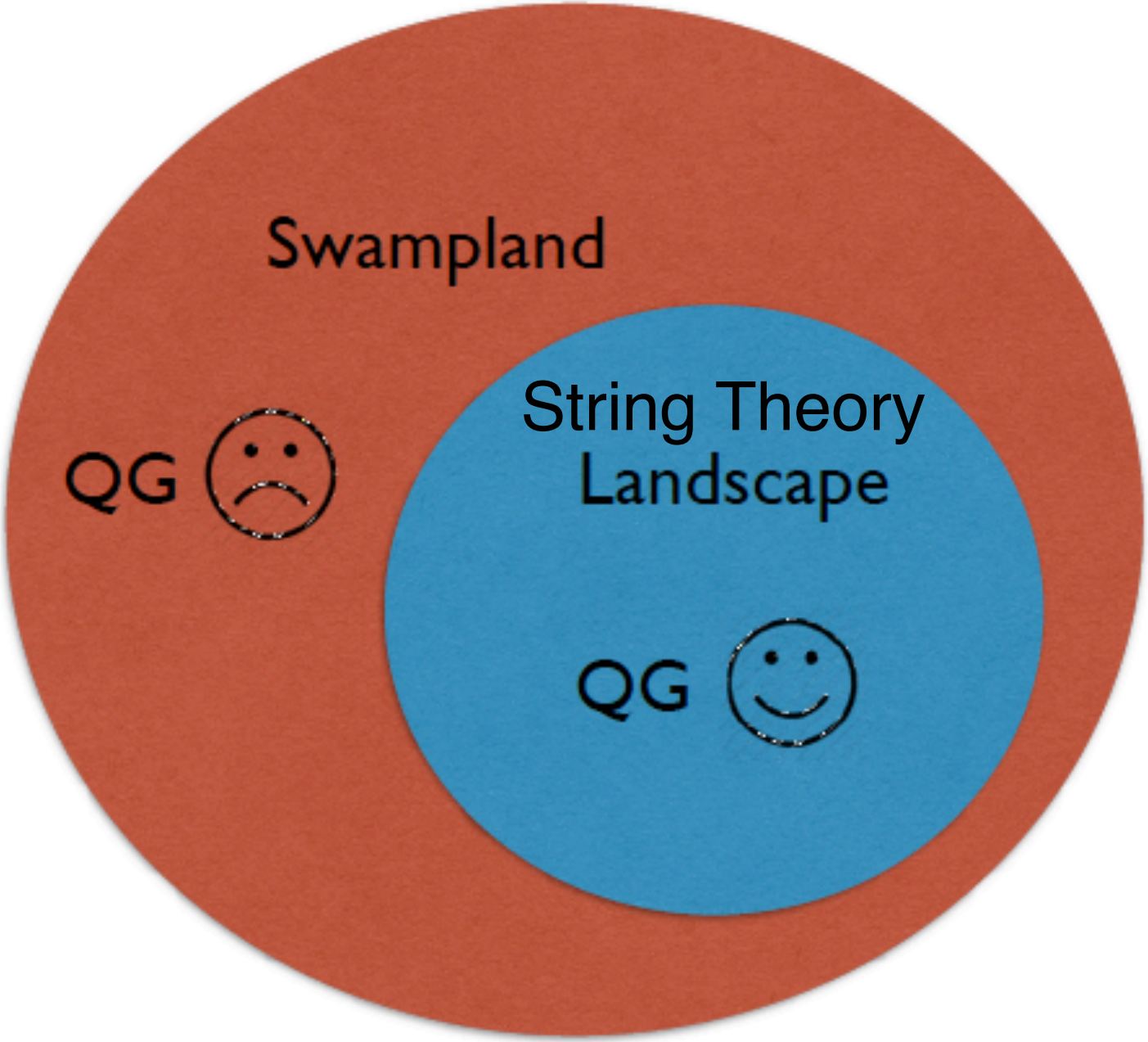
C. Vafa 2005

The Swampland

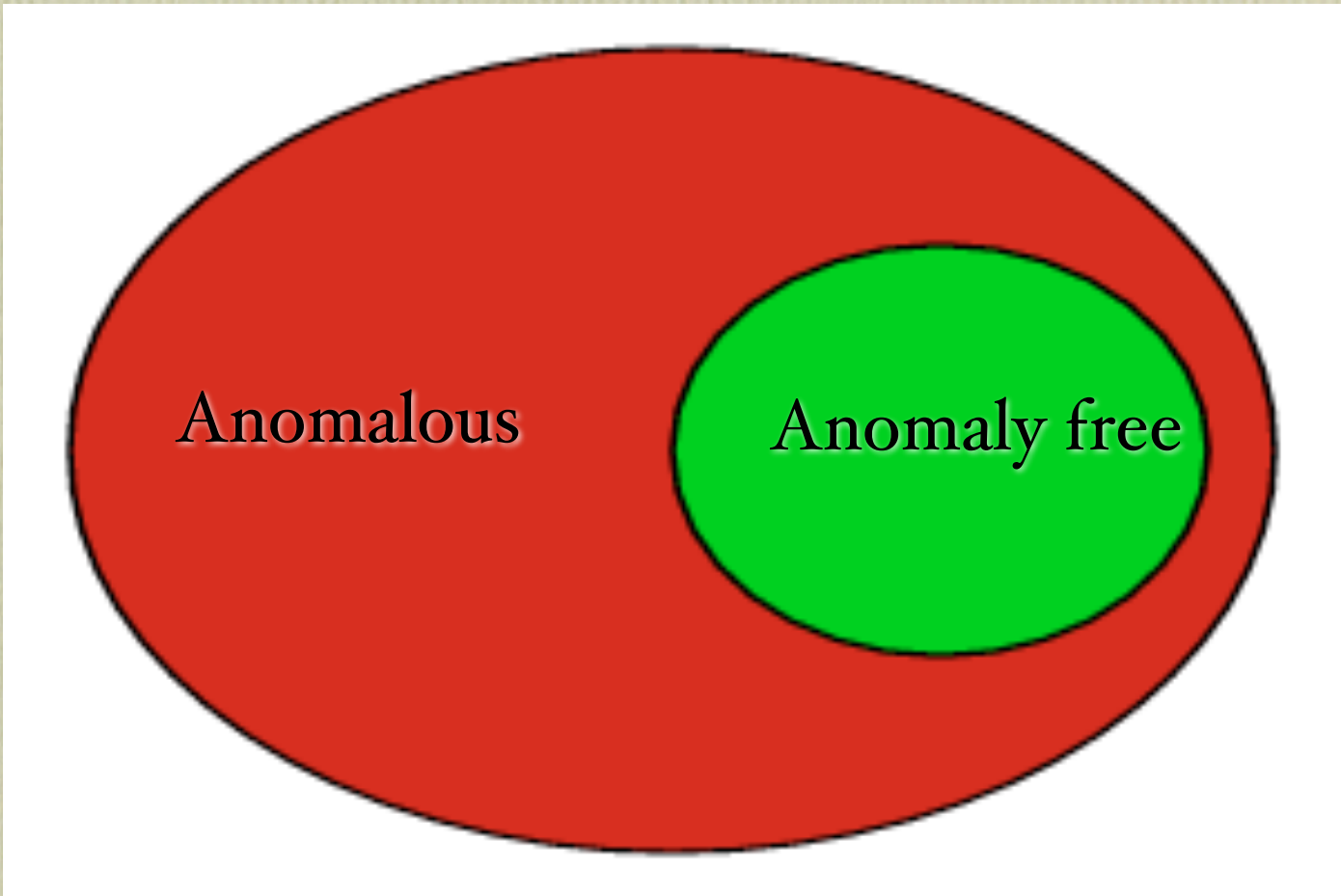


The space of field theories which cannot be embedded into a consistent theory of quantum gravity


Swampland
QG
Landscape
QG

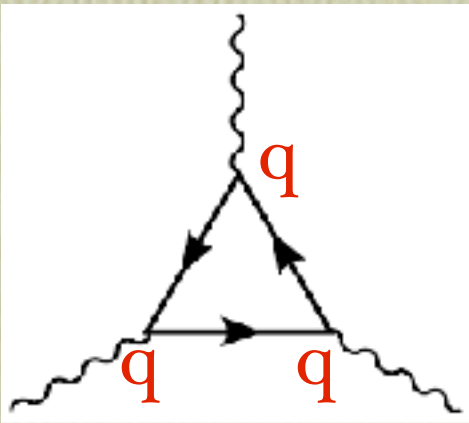

Swampland
QG
String Theory
Landscape
QG

Analogy in QFT: Anomalies



Simple example in the swampland

$A\ U(1)_X\ theory\ with\ Weyl\ fermions\ with\ charges$

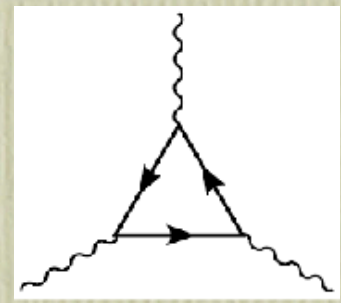


$$\psi(q=2)\ +\ 8\ \chi(q=-1)$$

$$Anomaly = 2^3 + 8(-1)^3 = 0$$

Simple example in the swampland

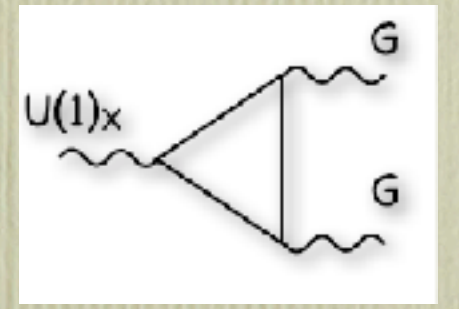
$A\ U(1)_X\ theory\ with\ Weyl\ fermions\ with\ charges$



$$\psi(q=2)\ +\ 8\ \chi(q=-1)$$

$$Anomaly = 2^3 - 8(-1)^3 = 0$$

BUT COUPLED TO QUANTUM GRAVITY.....



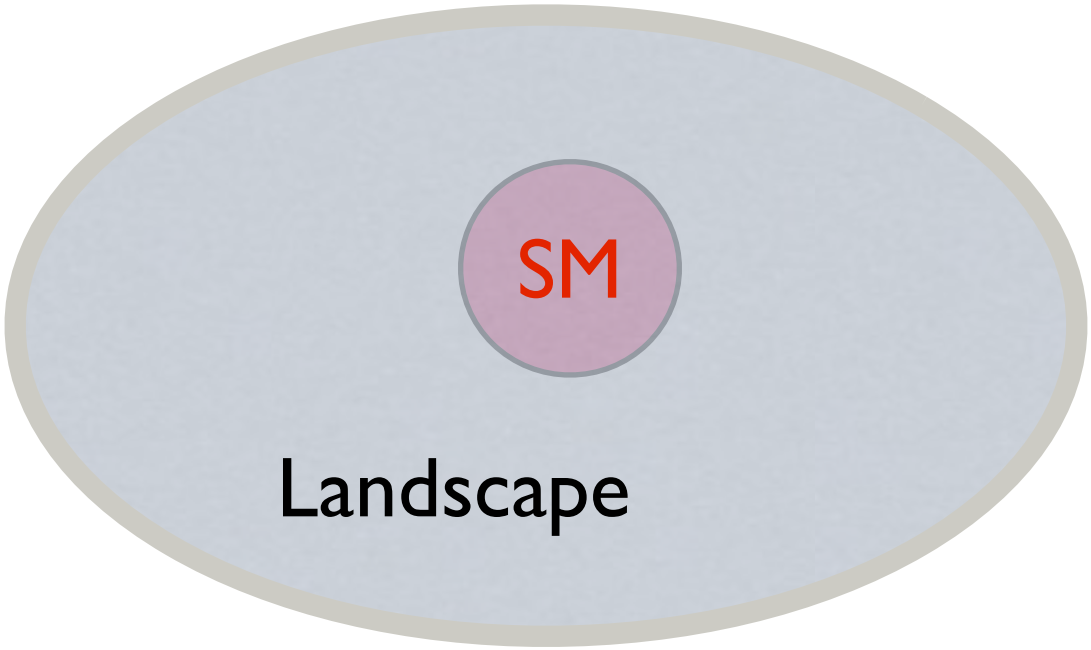
$$Anomaly(grav) = TrQ_X = 2 - 8 \neq 0$$

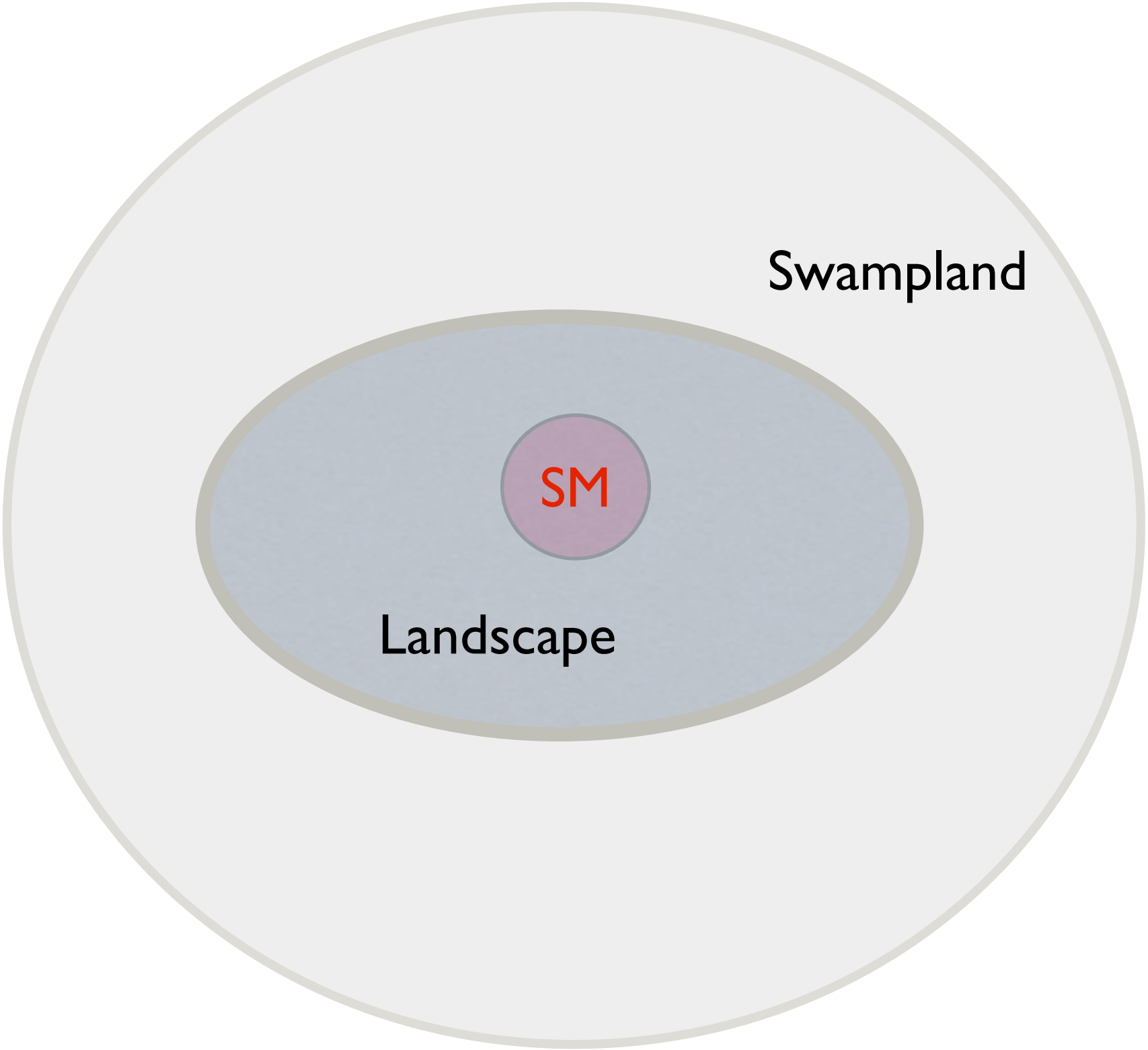
This model is in the swampland

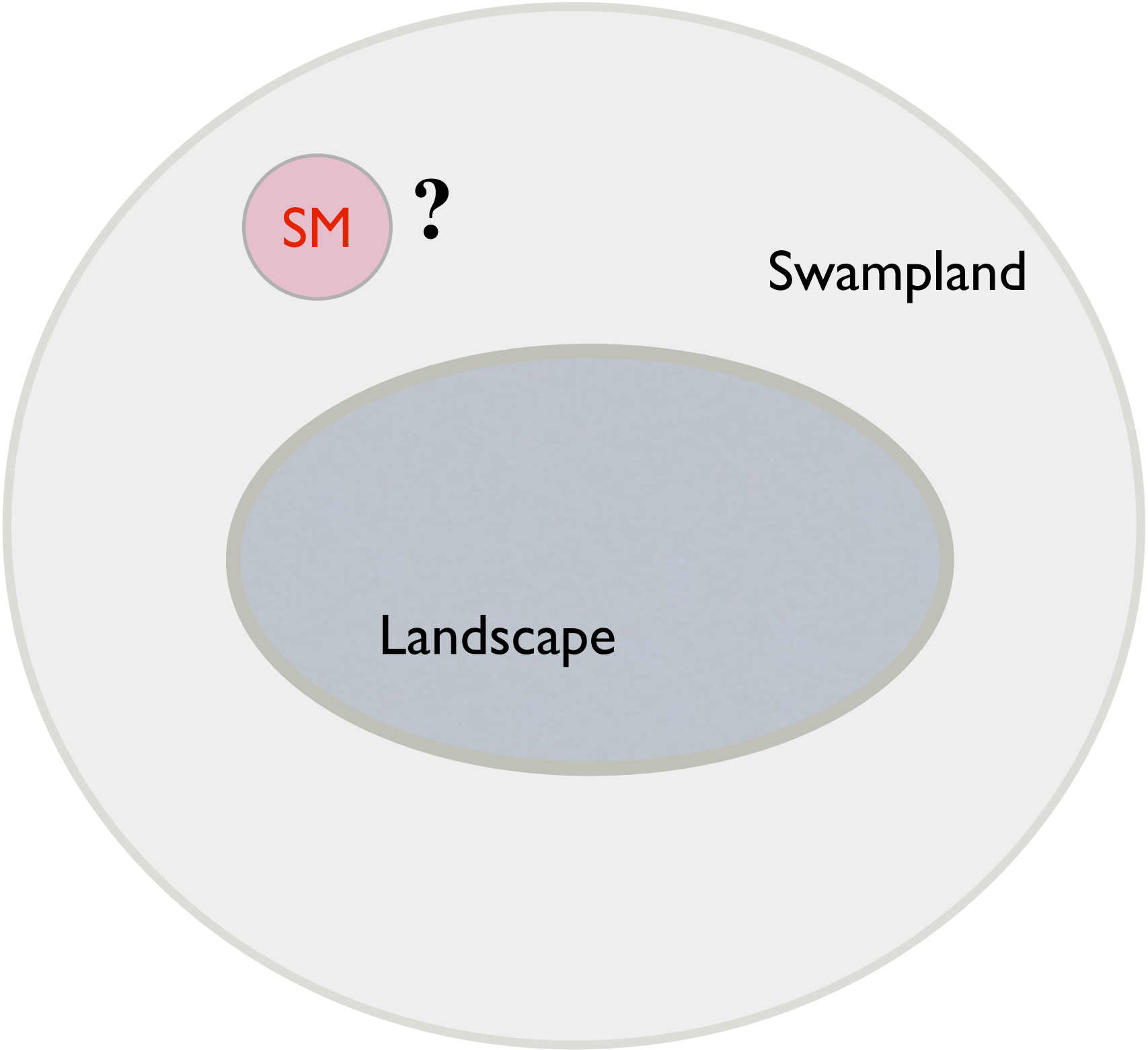
(But will not be the type of inconsistencies we will deal with....)

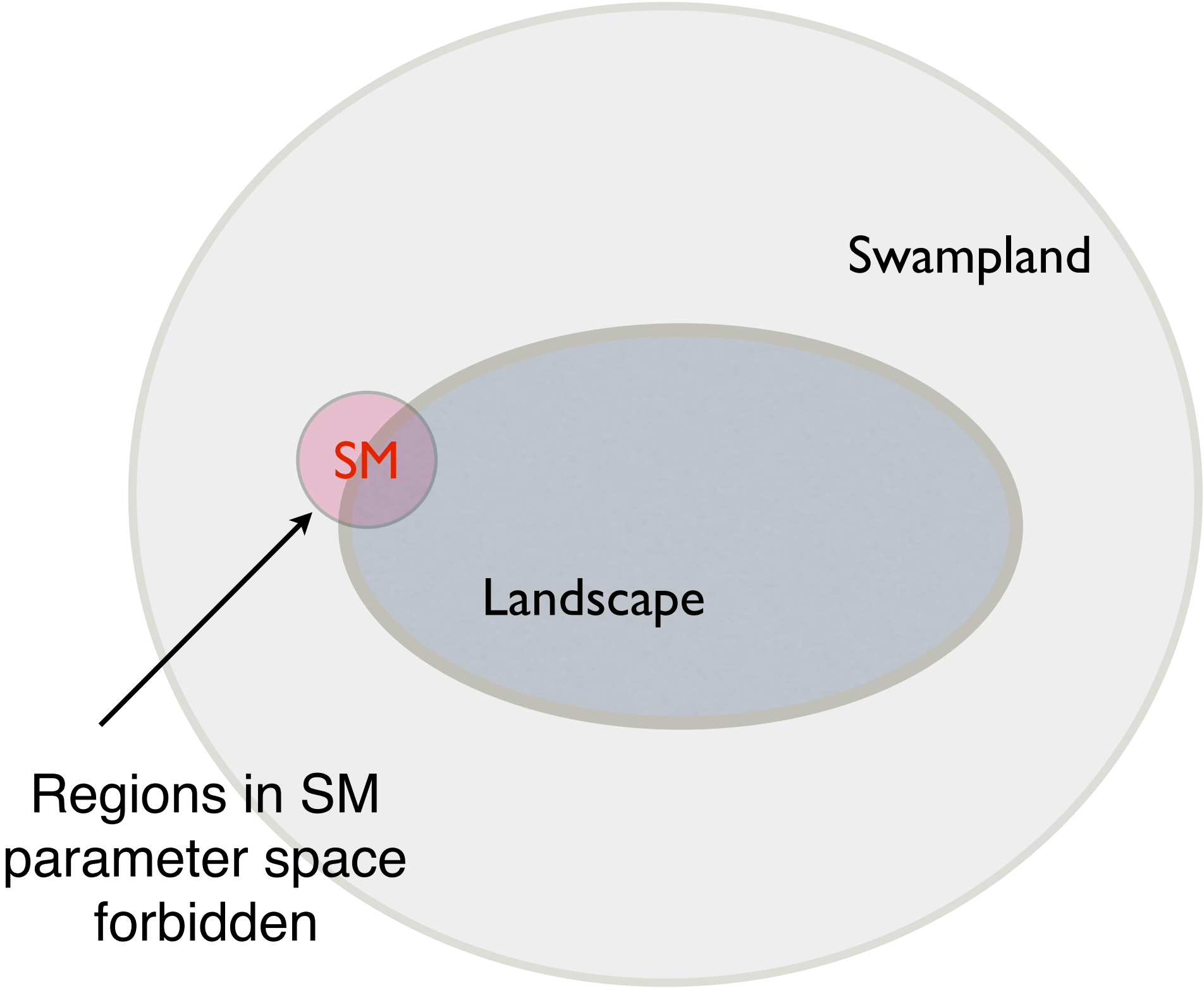
(Charge quantization in SM verifies $TrY = 0$)

SM


SM
Landscape


Swampland
SM
Landscape


SM
?
Swampland
Landscape


Swampland
SM
Landscape
Regions in SM
parameter space
forbidden

Some Swampland Criteria

- These are conjectures, many of them suggested by black-hole quantum physics

- No counterexample to these criteria has been found within string theory

Recent Review: *Brennan, Carta, Vafa . arXiv:1711.00864*

Some Swampland Conjectures

1) There are no exact global symmetries

Motivated by black-hole physics (no-hair).

Proven in string theory

2) All possible charges must appear in the full spectrum

$$\frac{1}{4g^2}\int F_{\mu\nu}F^{\mu\nu} + \frac{1}{2\kappa}\int \sqrt{G}R \quad \longrightarrow \quad \text{Inconsistent !}$$

Motivated by black-hole physics. Gauge bosons imply existence of charged particles.

3) No free parameters in the theory

All couplings are scalar fields.

e.g N=2 pure supergravity cannot exist (has no scalars)

$$N = 2: \; g^{\mu\nu}, \psi^{\mu}_{3/2}, A^{\mu}$$

Most usefull:

The Weak Gravity Conjecture

Arkani-hamed et al. 2006

Gravity as the weakest force

Arkani-hamed, Motl, Nicolis, Vafa 2006; Ooguri,Vafa 2007

"In any UV-complete theory gravity must be the weakest force"

WGC for a U(1)

- In any UV complete U(1) gauge theory there must exist at least one charged particle with mass M such that:

$$\frac{M}{M_p} \leq g$$

Generalizes to higher rank tensors and branes in ST

$$A^\mu \longrightarrow C^{\mu..\rho} \;\; ; \;\; M,\ mass \longrightarrow T,\ tension$$

$$\frac{T}{M_p} \leq g \qquad (g\ dimensionful)$$

Ooguri and Vafa 2016: *arXiv:1610.01533*

The equality is only achieved for SUSY BPS states

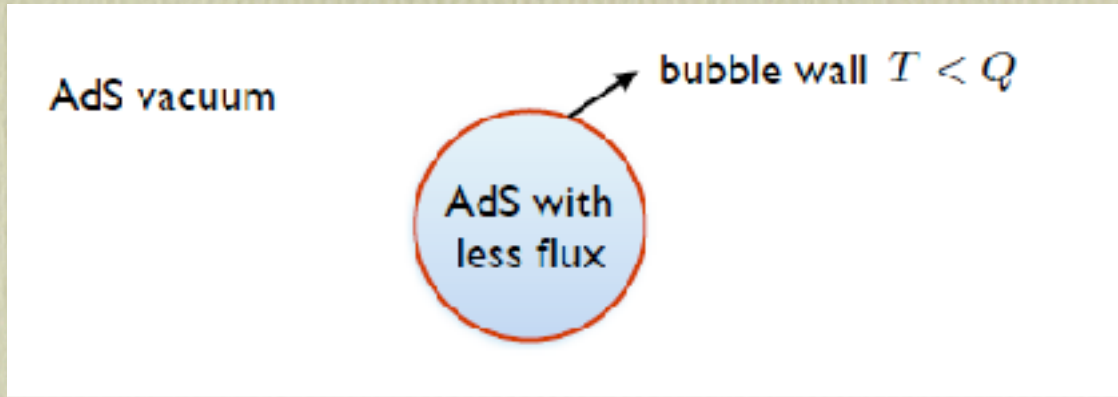
$$\frac{T}{M_p} < g$$

for non-SUSY

Strong Corolarium !!

(also Banks 2016, Freivogel, Kleban 2016)

Decay of AdS flux vacua may occur through membrane (bubble) nucleation



In non-SUSY AdS membranes with $T < Q$ necessarily nucleate instantaneously

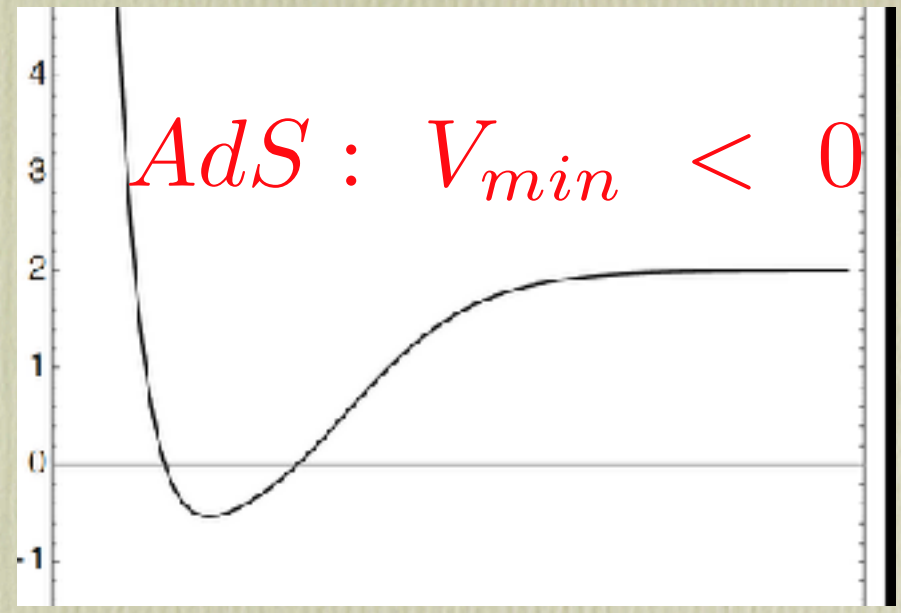
Maldacena, Michelson, Strominger 1998

Non-SUSY AdS flux vacua are unstable

This makes such theories not to have a holographic dual:

No AdS/CFT dual: not consistent with quantum gravity

AdS Phobia Conjecture:

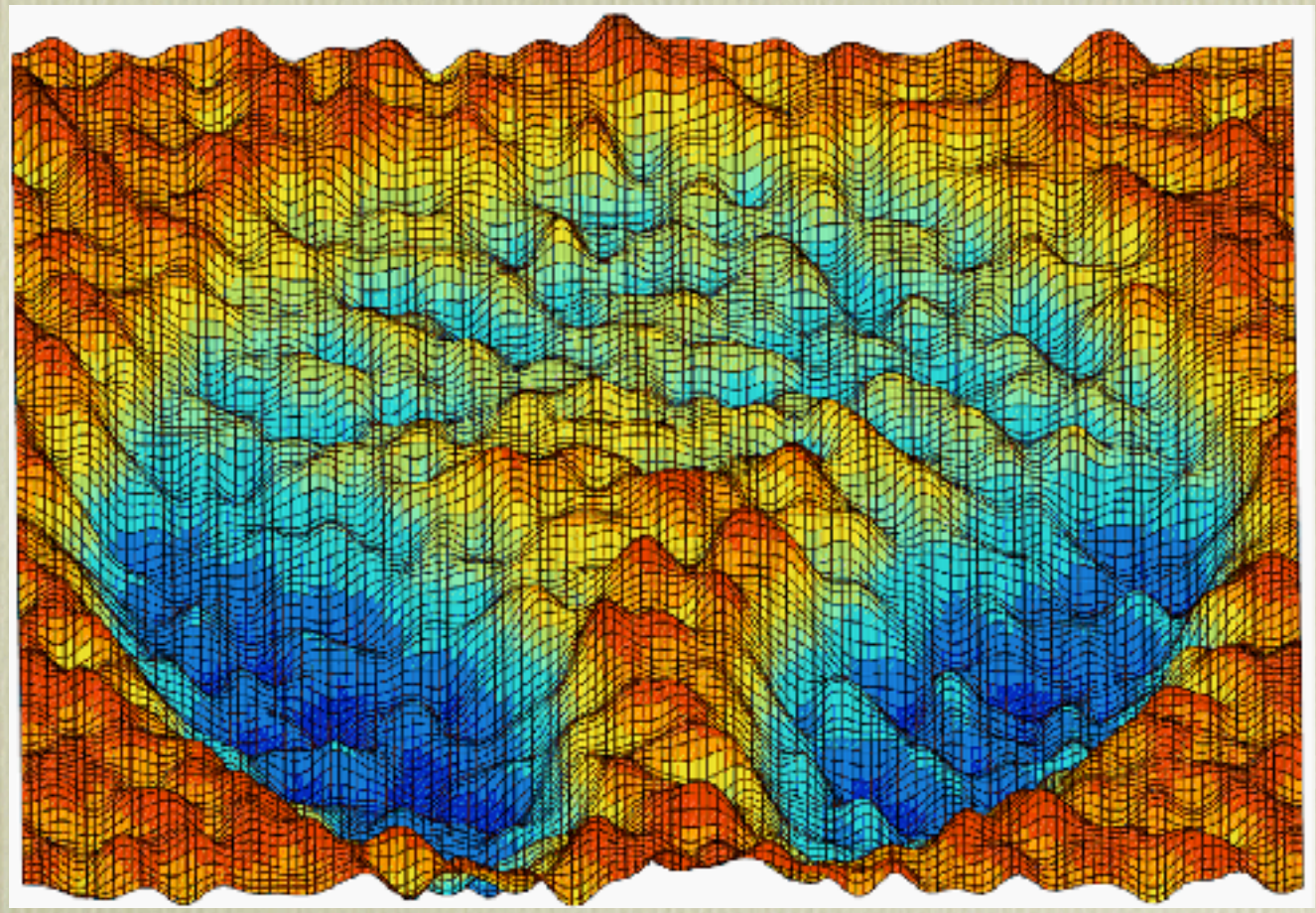


There cannot be stable non-SUSY AdS vacua in quantum gravity

(Not only for string flux vacua)

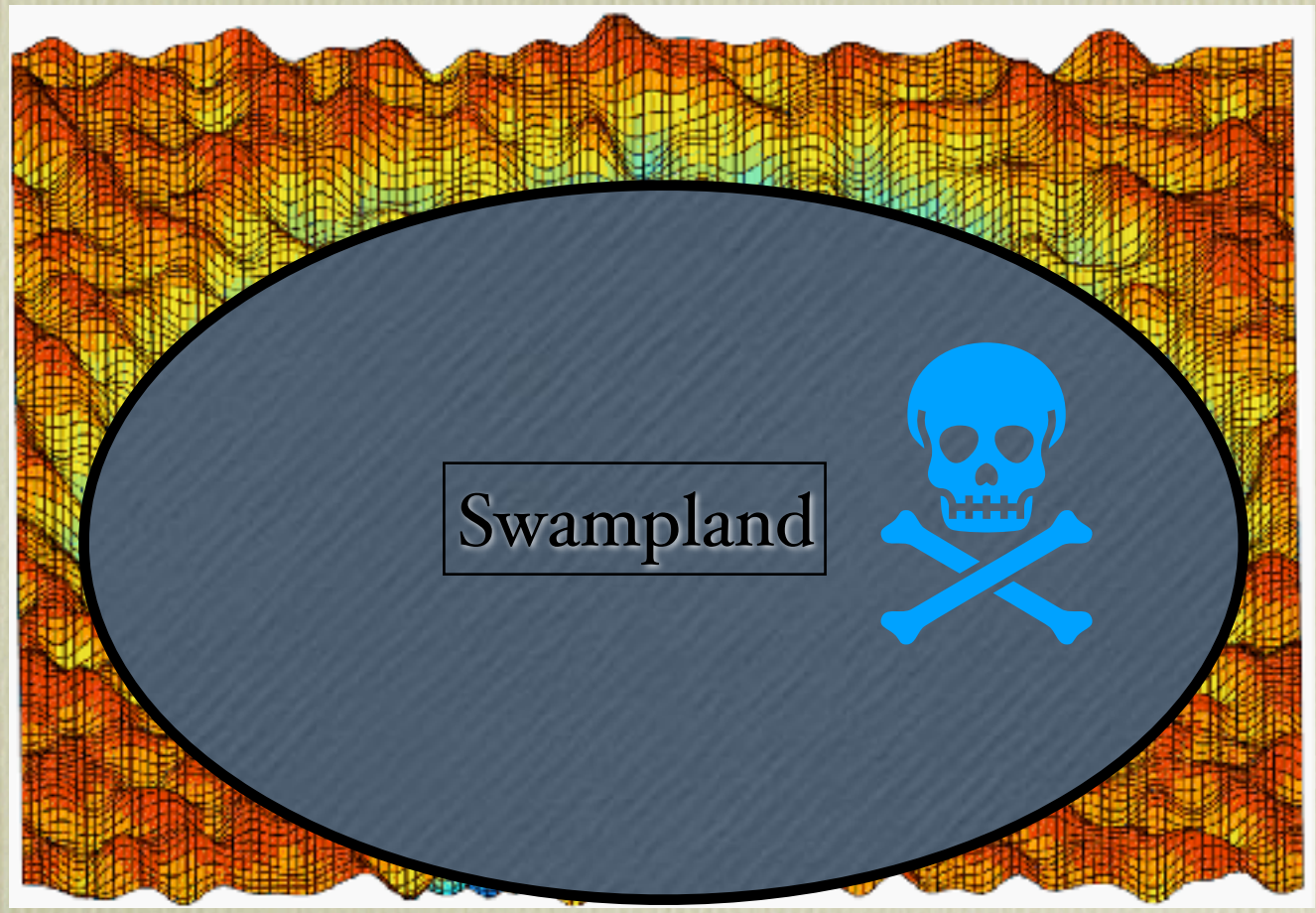
(If you find one in your theory, then it is inconsistent with quantum gravity)

General non-SUSY AdS stable vacua are in the swampland



General non-SUSY AdS stable vacua are in the swampland

(independently whether is a flux vacuum or not)



Landscape only Minkowski and de Sitter !!

(...or SUSY AdS)

AdS phobia and the SM

If we have a consistent theory, it is consistent in any background:

If SM consistent, any compactification should be consistent

The SM should not have any AdS (stable) lower dimensional vacua

Ooguri, Vafa 2016

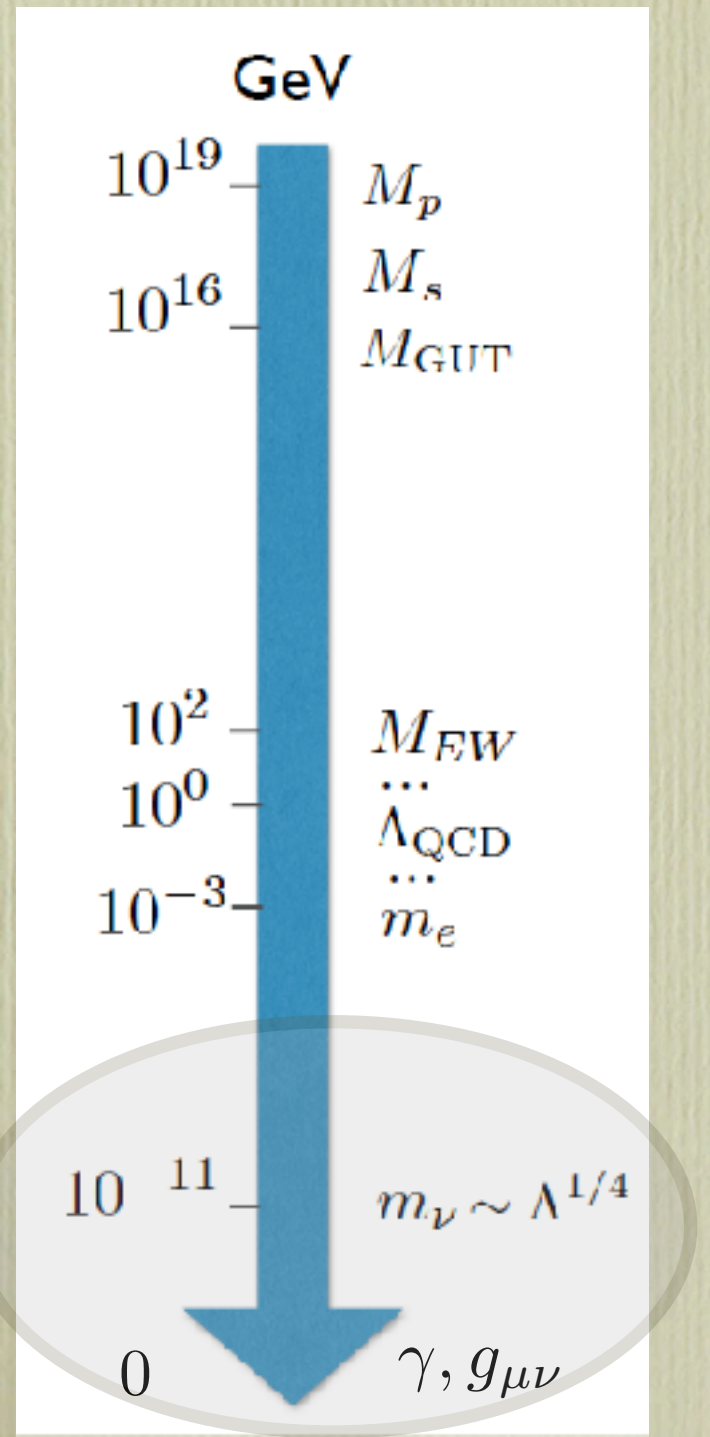
The Standard Model Landscape in lower dimensions

There is a SM landscape of vacua
(even without any string theory arguments)

Arkani-Hamed, Dubovsky, Nicolis, Villadoro 2007: hep-th:0703067:
Arnold, Fornal, Wise 2010: hep-th:1010.4302:

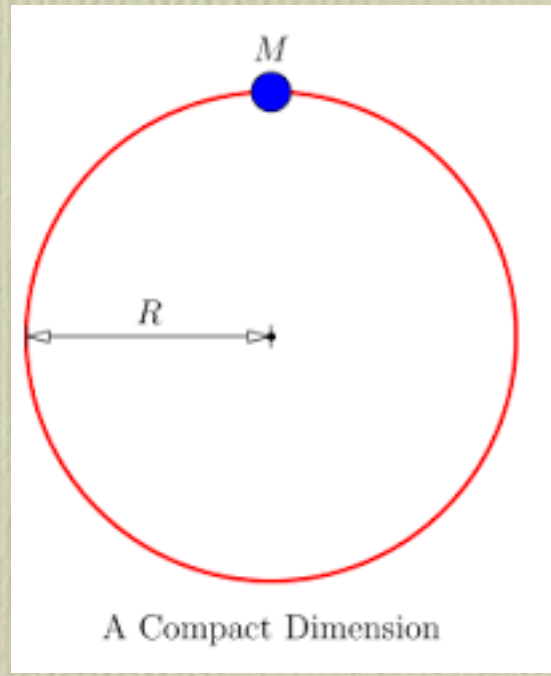
We will see AdS phobia puts constraints on neutrino masses, the c.c., the EW hierarchy and more

Scales in Fundamental Physics



Will focus first in lightest SM sector

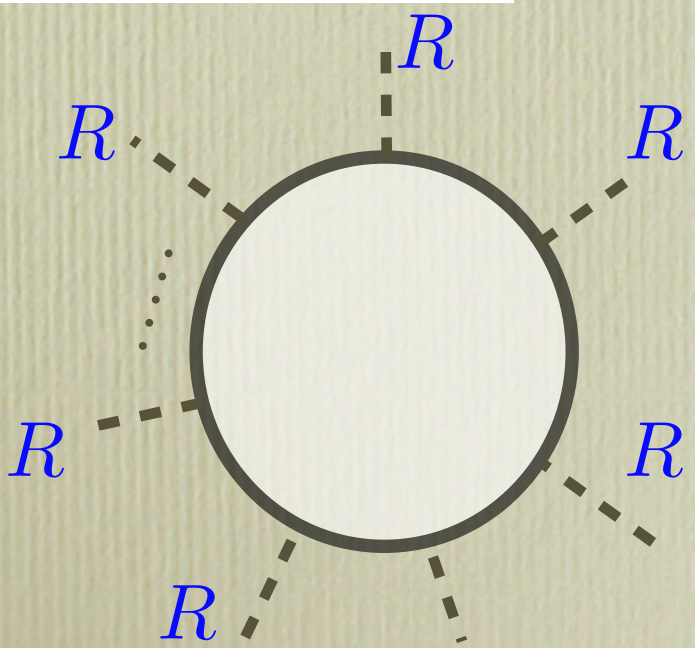
SM compactified to 3D on a circle



Radius R is a massless scalar field

For $R \gg 1/m_e$

only $\gamma,\ g^{\mu\nu},\ \nu_i$ relevant



$$V_{boson} \sim -\frac{1}{R^6}$$

$$V_{fermion} \sim \frac{1}{R^6}$$

One-loop Casimir potential

(massless fields)

The SM + gravity on a circle S^1

Consider the lightest sector : $\gamma, g_{\mu\nu}, \nu_{1,2,3}$

The radius potential :

One – loop Casimir energy

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

From 4D c.c.

$\gamma, g_{\mu\nu}$

ν_i

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

ν_i *with periodic b.c. contributes positively!!*

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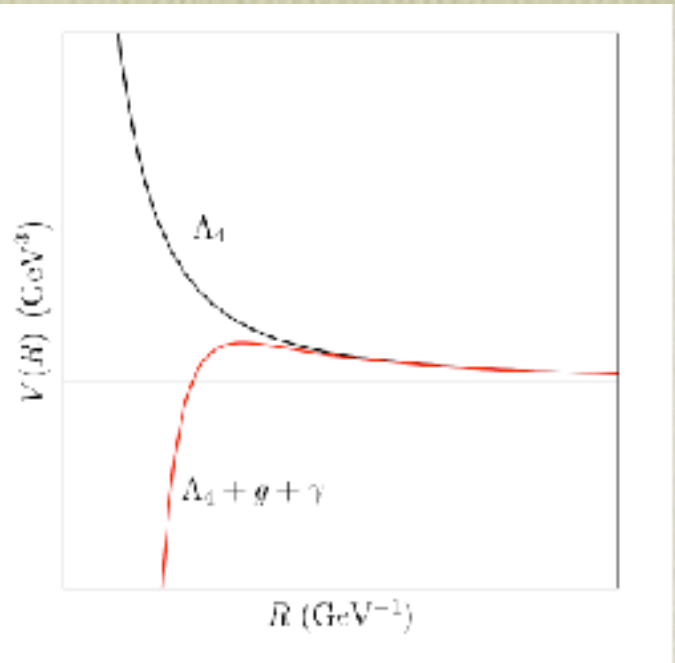
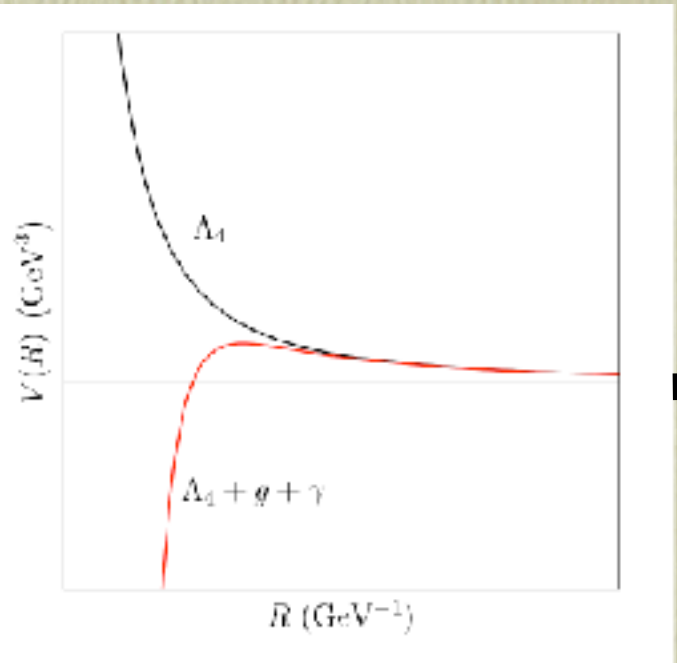
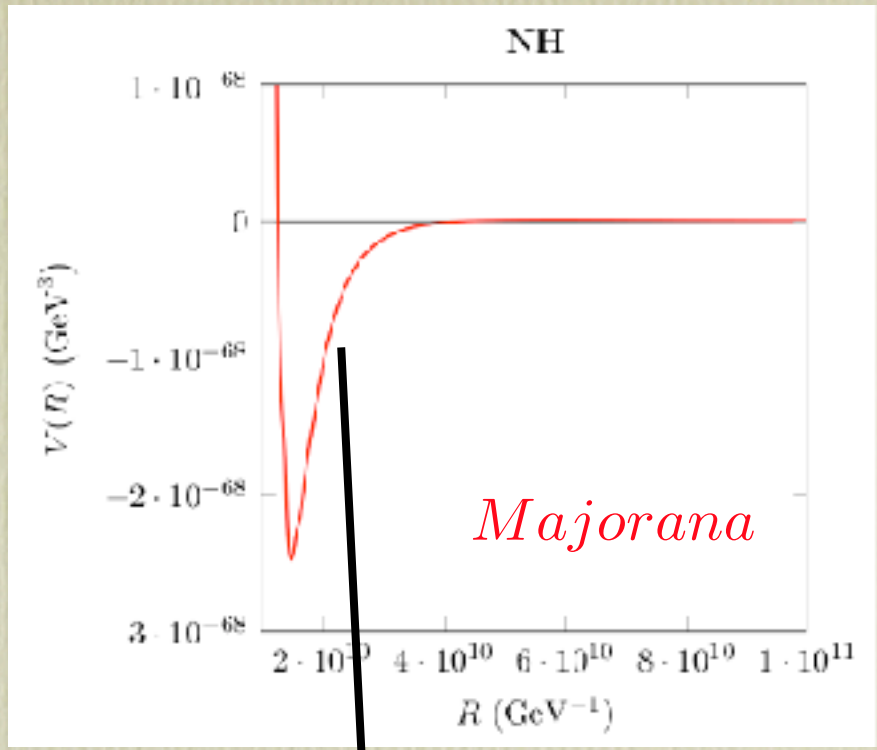
ν_i *with periodic b.c. contributes positively!!*

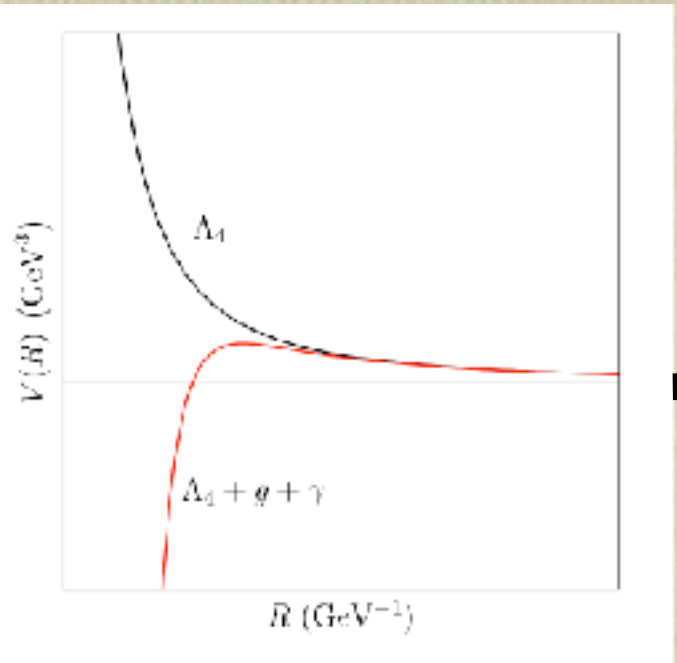
Important: Effect of heavier particles suppressed like $e^{-(m_f/m_\nu)}$

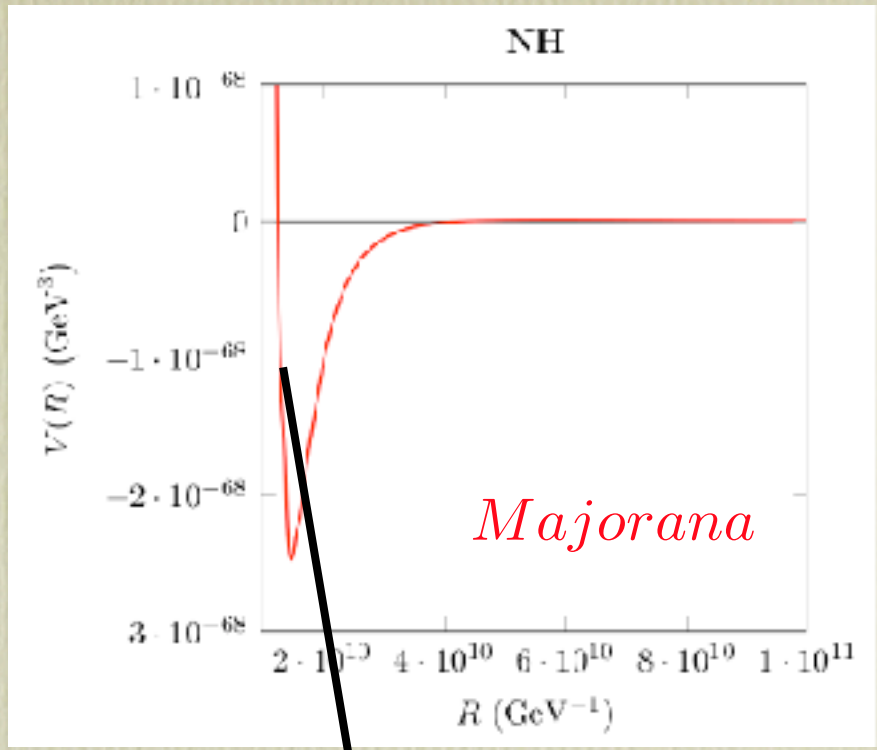

Λ_1
$\Lambda_1 + g + \gamma$
$V(R)$ (GeV^2)
R (GeV^{-1})





$$(\underbrace{-2}_{\gamma} \underbrace{-2}_{g_{\mu\nu}} \underbrace{+2}_{\nu_1^M}) \left(\frac{r^3}{720\pi R^6} \right)$$



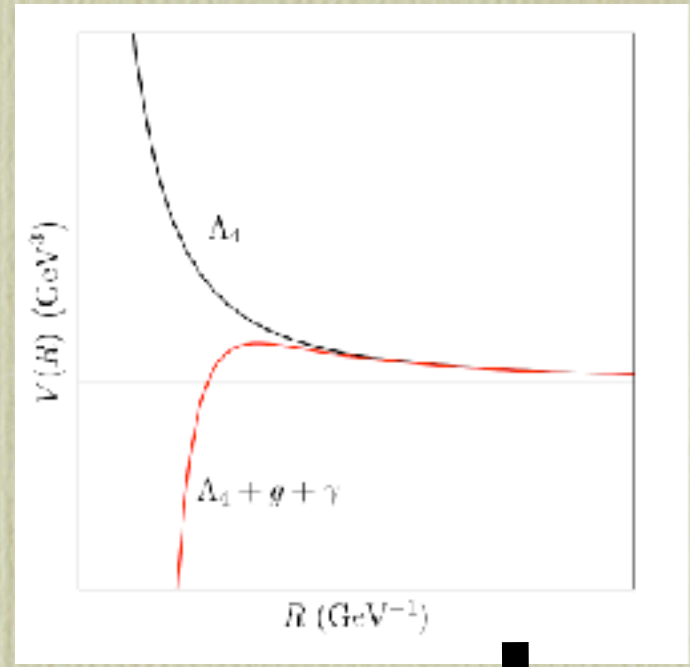


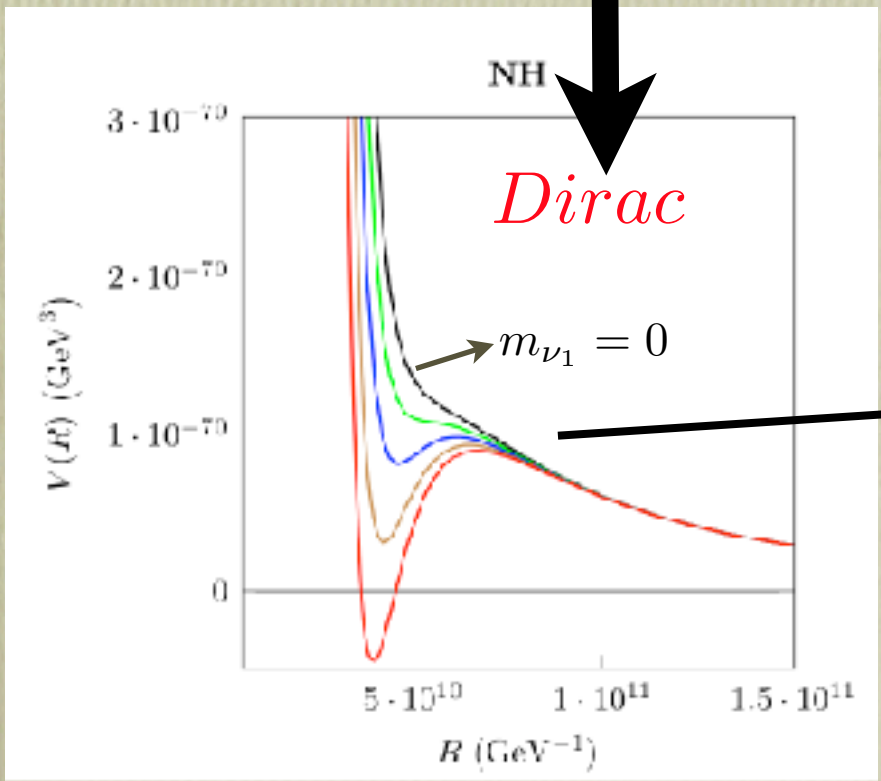
$$(-2 - 2 + 6)\left(\frac{r^3}{720\pi R^6}\right)$$

γ $\quad g_{\mu\nu}$ $\quad \nu^M_{1,2,3}$

Majorana ν_1 *forbidden!!*

Ooguri,Vafa 2016

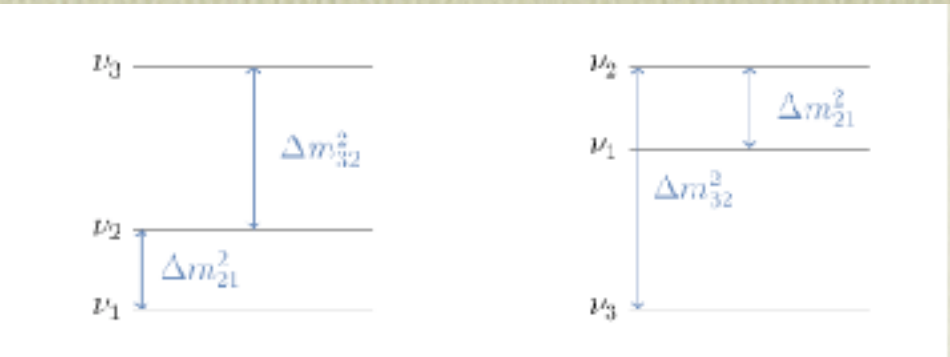




$$(-2 - 2 + 4)\left(\frac{r^3}{720\pi R^6}\right)$$

γ $\quad g_{\mu\nu}$ $\quad \nu_1^D$

Constraints on neutrino masses



$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2,$$
$$\Delta m^2_{32} = (2.44 \pm 0.06) \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NH}),$$
$$\Delta m^2_{32} = (2.51 \pm 0.06) \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IH}).$$

Majorana: ruled out!!

There is always an AdS vacuum for any m_{ν_1}

Dirac:

	NH	IH
No vacuum	$m_{\nu_1} < 6.7$ meV	$m_{\nu_3} < 2.1$ meV
dS_3 vacuum	6.7 meV $< m_{\nu_1} < 7.7$ meV	2.1 meV $< m_{\nu_3} < 2.56$ meV
AdS_3 vacuum	$m_{\nu_1} > 7.7$ meV	$m_{\nu_3} > 2.56$ meV

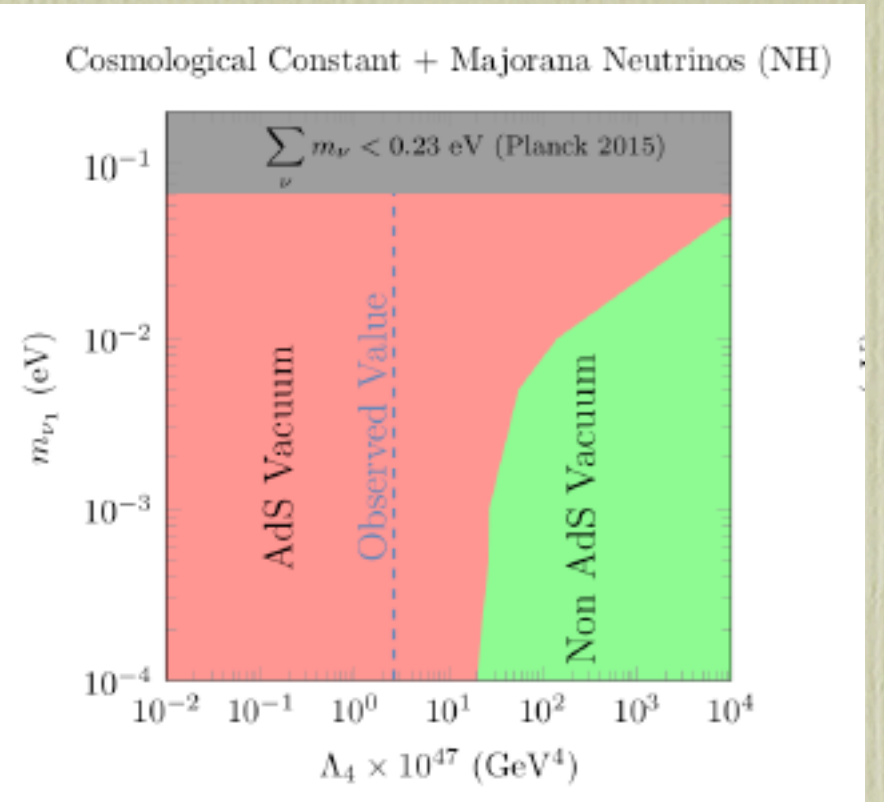
$$m_{\nu_1} < 7.7 \text{ meV (NH)}$$
$$m_{\nu_1} < 2.1 \text{ meV (IH)}$$

L.I, Martin-Lozano, Valenzuela 2017

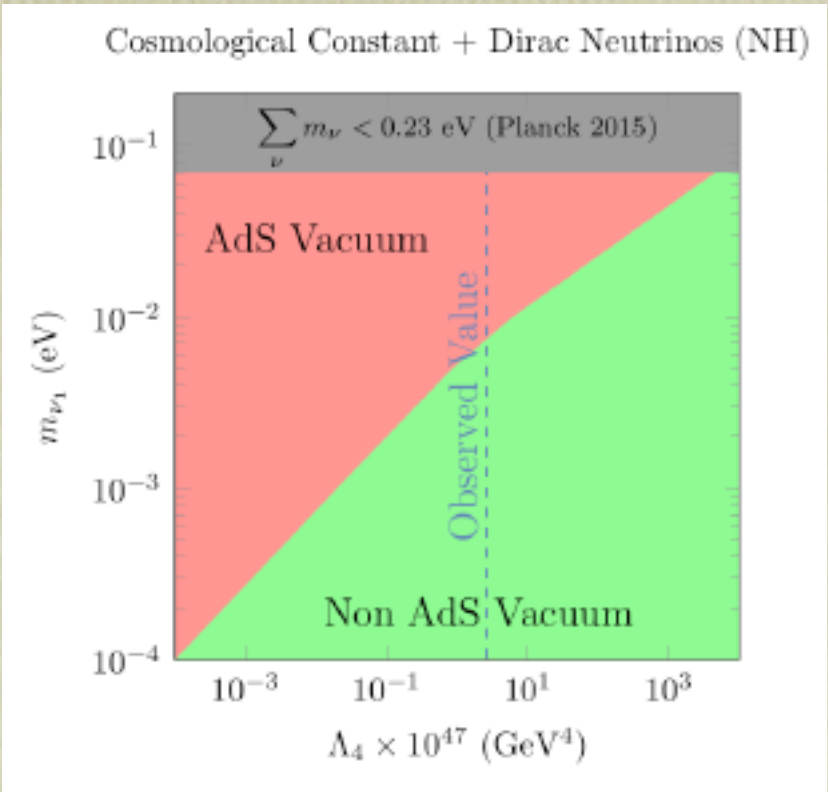
Alternative to see-saw!!

(lightest neutrino)

Lower bound on the cosmological constant



Majorana



Dirac

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

L.I, Martin-Lozano, Valenzuela 2017

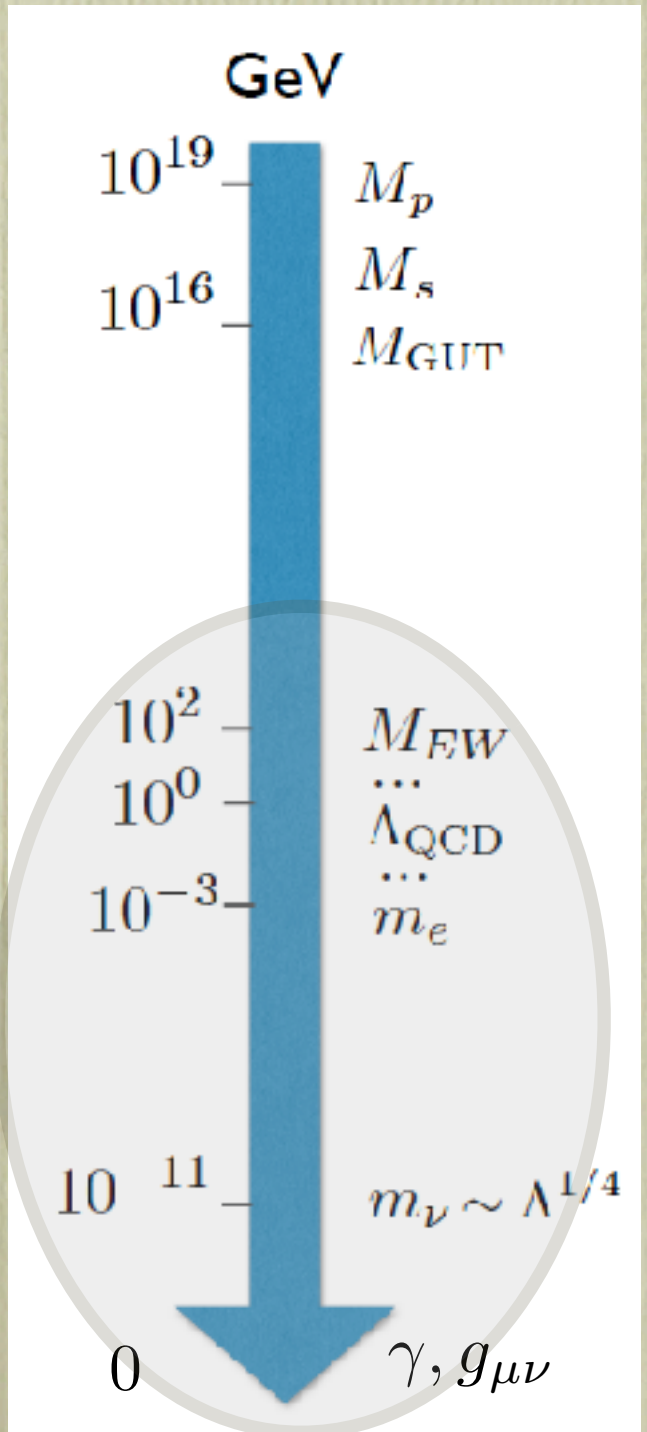
To avoid AdS

$$\Lambda_4 \gtrsim m_\nu^4$$

Explains coincidence!!

First particle physics argument for a non-vanishing c.c. (independent of cosmology)

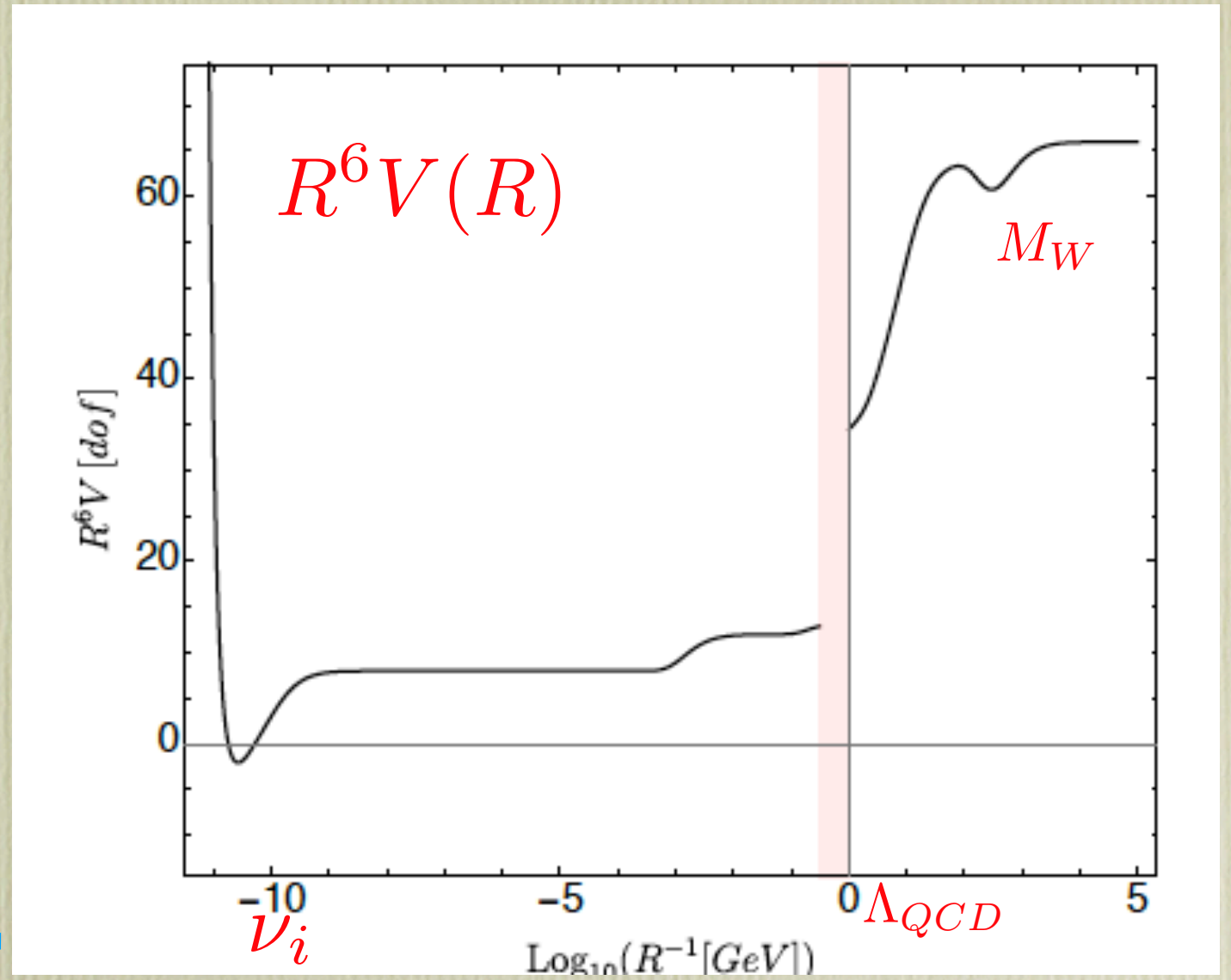
Scales in Fundamental Physics



Explore now the radius potential for

$$R \ll 1/m_e$$

The 3D SM at smaller radius R



(Normalized to d.o.f.)

Large R

Small R

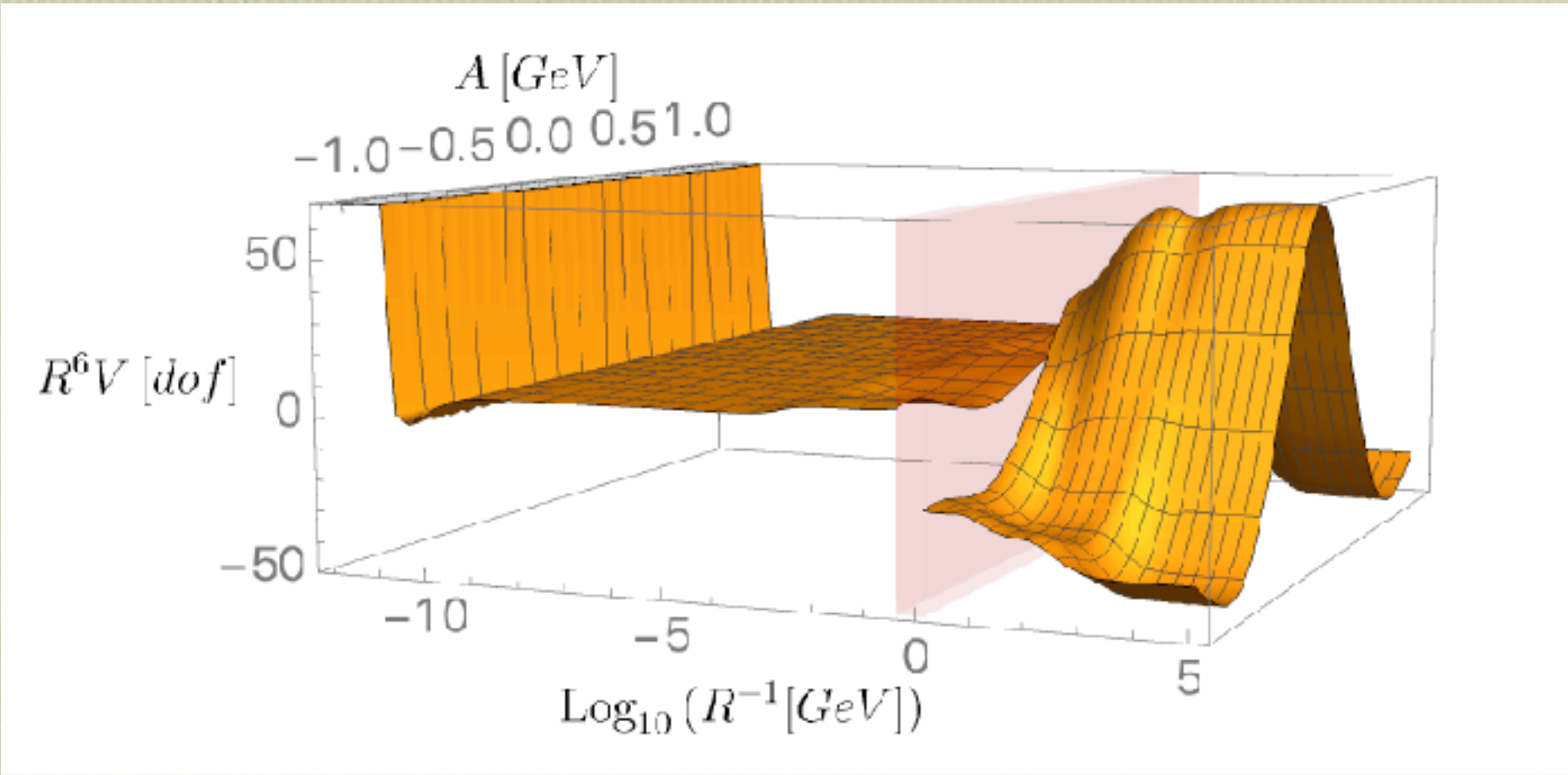
Hamada, Shiu 2017

E.Gonzalo, A.Herraez, L.I. 2018

No new minima

....but photon Wilson line degree of freedom.....

Hamada,Shiu 2017



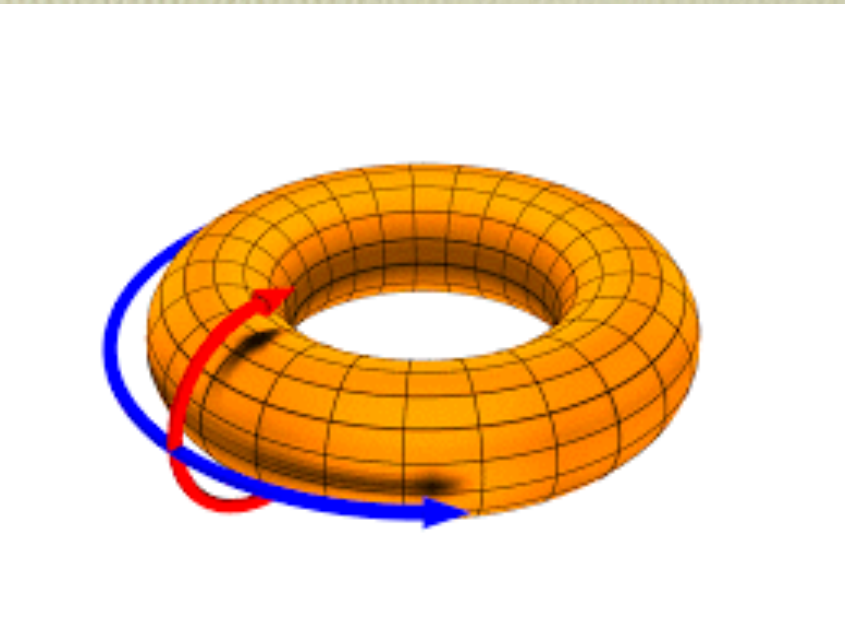
....make (??) unstable the potential: OK with WGC but lose predictions!!

Conservative: search for new SM vacua with no Wilson line d.o.f. ➡ $SM\ on\ 2D:\ T^2/Z_N$

E.Gonzalo,A.Herraez,L.I. 2018

Simplest:

New 2D SM vacua on T^2/Z_4



Project under $\pi/2$ rotations

$$y_1 \to -y_2$$

$$y_2 \to y_1$$

$$\phi(x_i, y_1, y_2) = e^{iq\alpha}\phi(x_i, -y_2, y_1)$$

$$\psi\left(x_i, y_1, y_2\right)) = e^{iq\alpha}e^{i\frac{\pi}{4}\sigma_3}\psi\left(x, -y_2, y_1\right)$$

$e^{iq\alpha} = SM\ \ gauge\ rotation$

Only 2D surviving scalar is the torus area (and the Higgs)

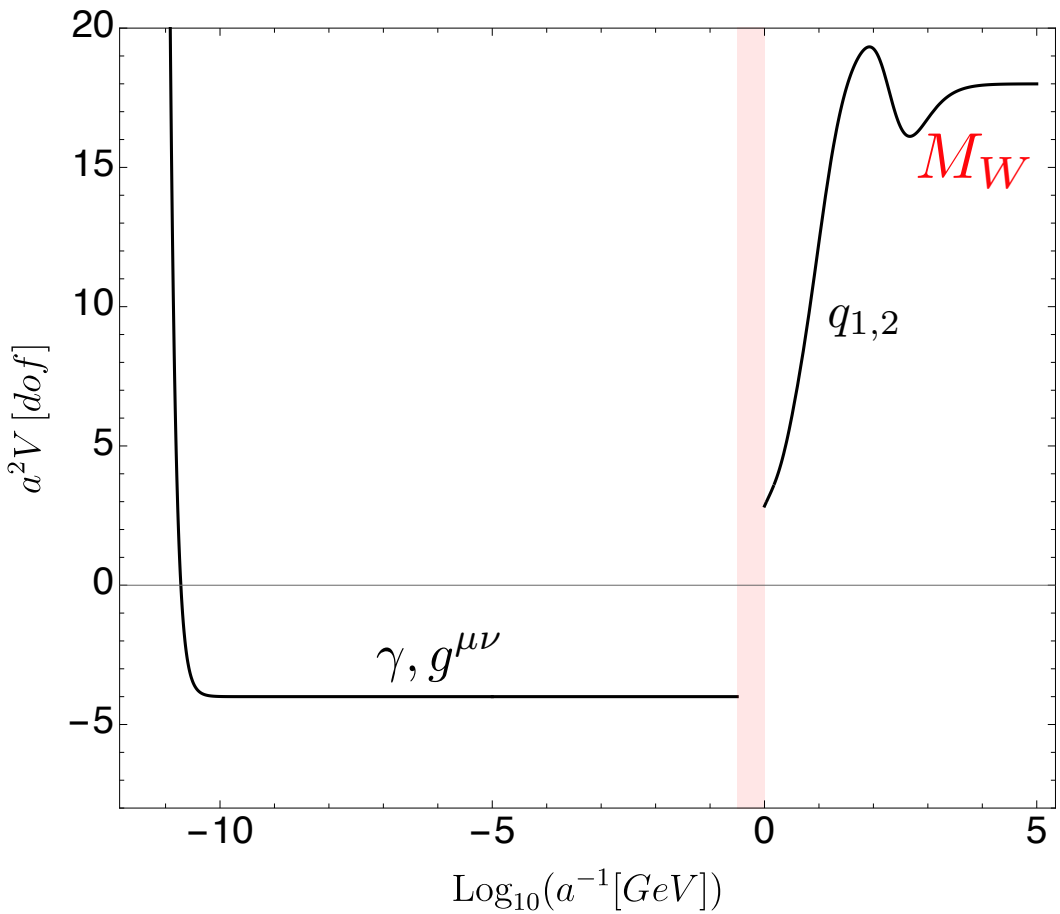
(Needed to get constraining compactifications)

A dangerous vacuum for the SM

Chose gauge action inside SU(3):

$$\Psi\left(x_i, y_1, y_2\right) = e^{i(q_3 T_3 + q_8 T_8)} e^{i\frac{\pi}{4}\sigma_3} \psi\left(x, -y_2, y_1\right)$$

The Casimir potential depends then only on 2 colours of quarks, gauge and Higgs bosons (NO leptons)



AdS minimum appears, irrespective of neutrino masses

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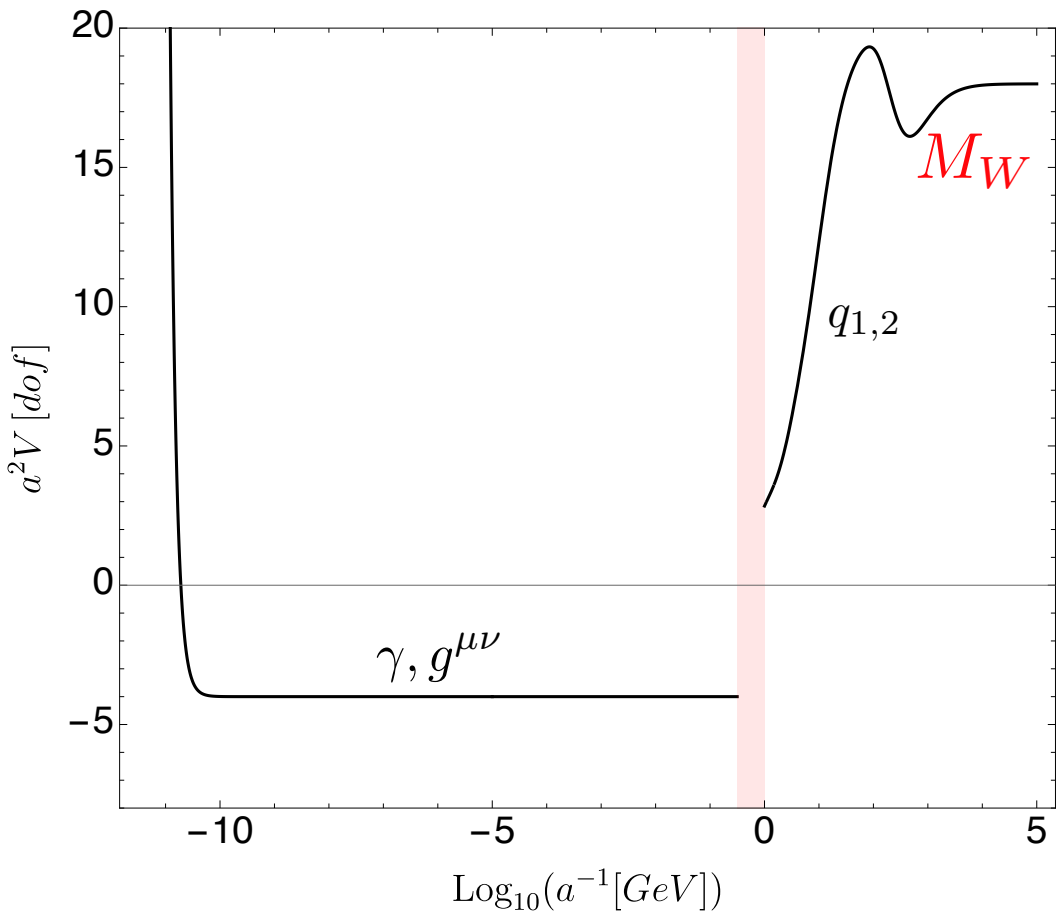
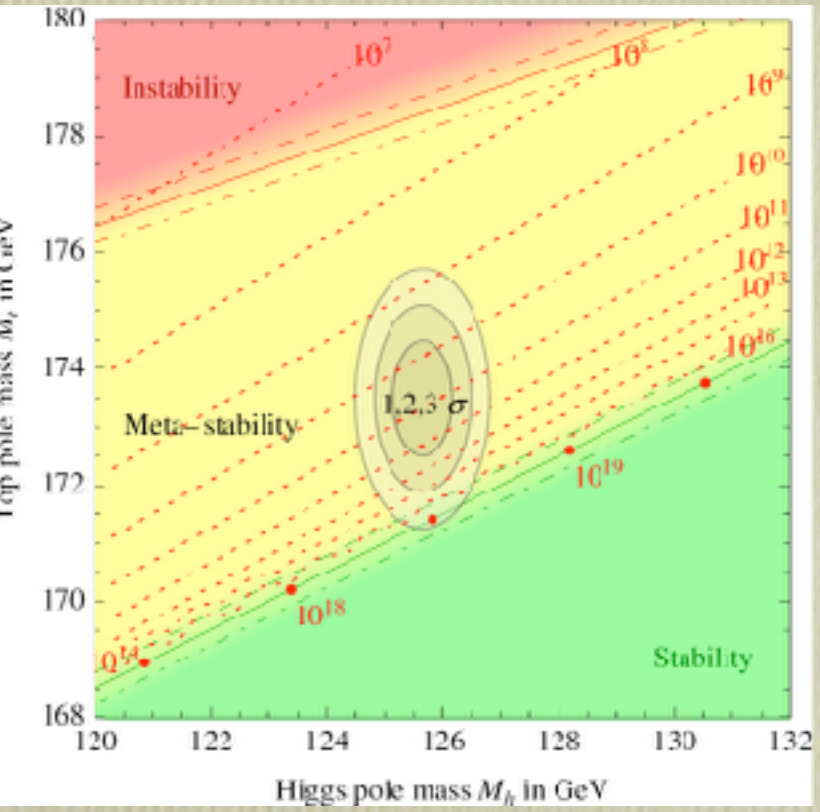


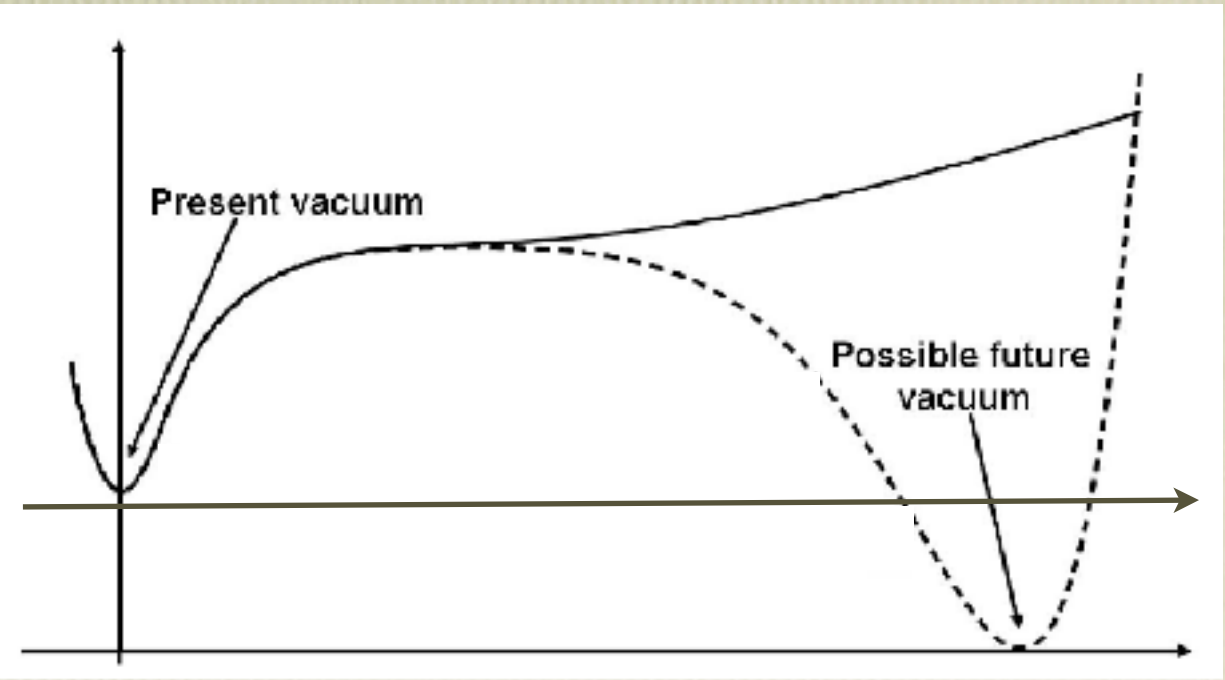
AdS minimum appears, irrespective of neutrino masses

SM IN SWAMPLAND!!

In fact we already knew that the SM in 4D may have AdS vacua:

The SM may have a second high scale minimum:

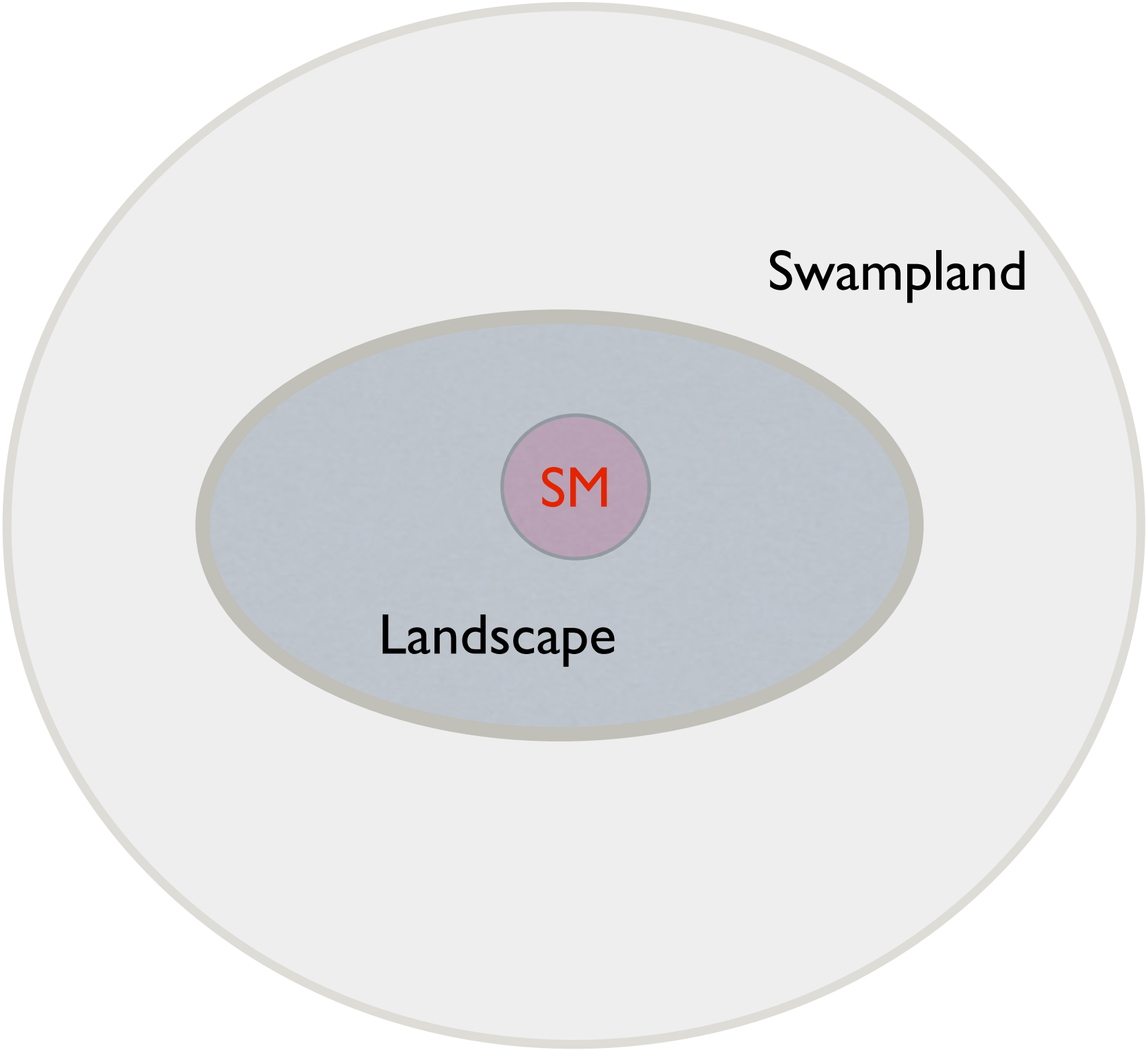


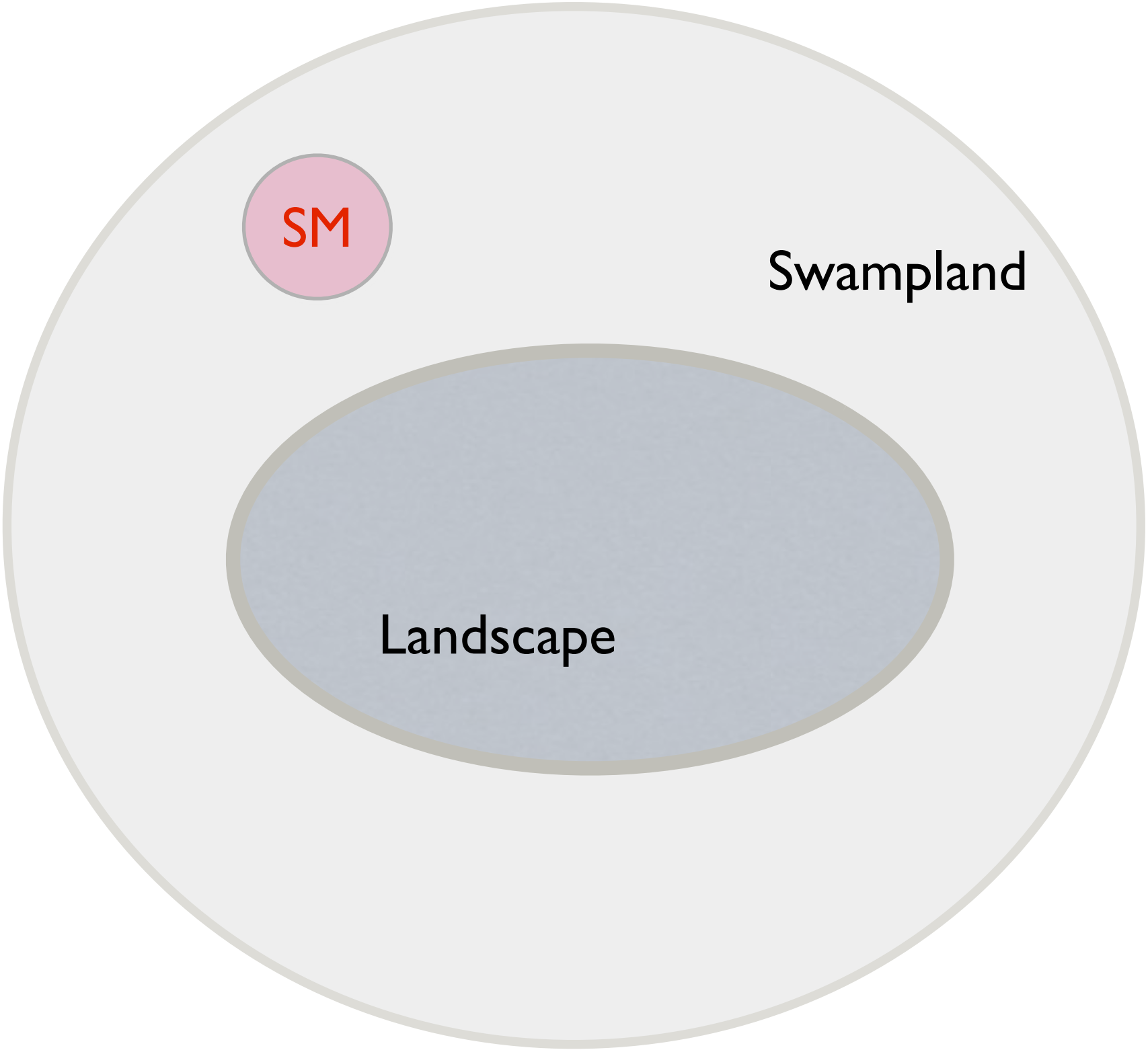


$10^{10-12} GeV$

Degrassi et al. 2013

SM in swampland unless.... NEW PHYSICS

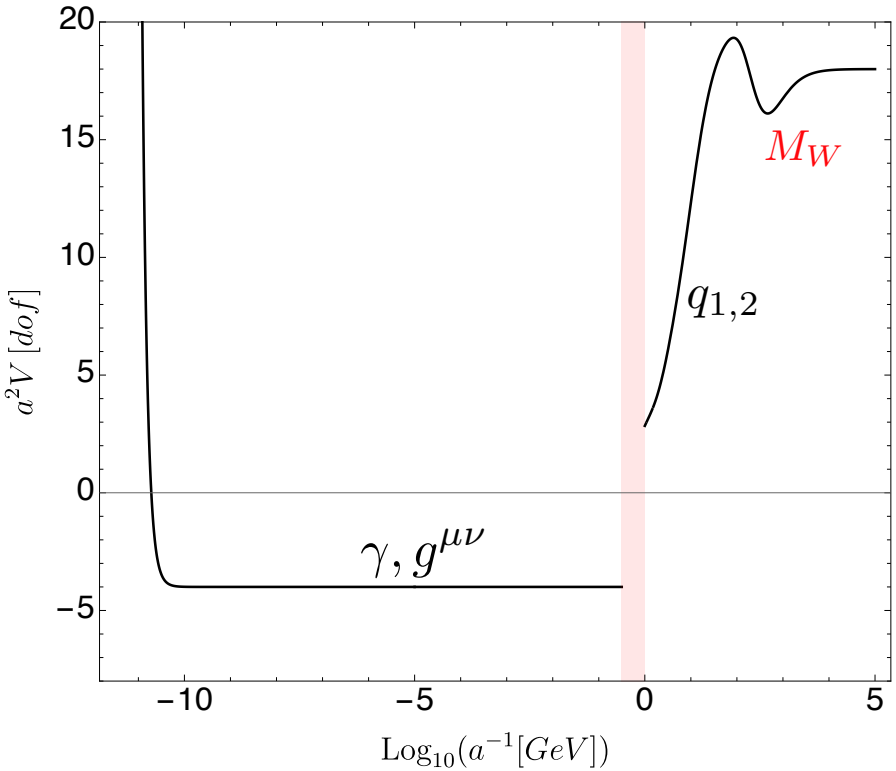

Swampland
SM
Landscape


SM
Swampland
Landscape

Does SUSY SM do any better?

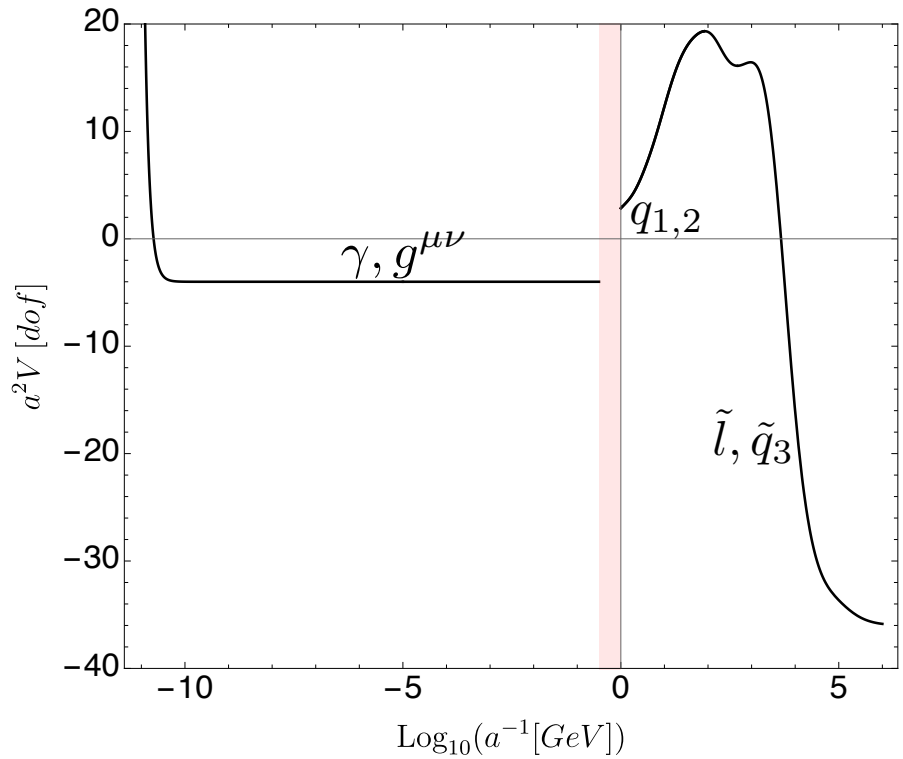
Same T^2/Z_4 compactification

SM



AdS minimum forms

MSSM

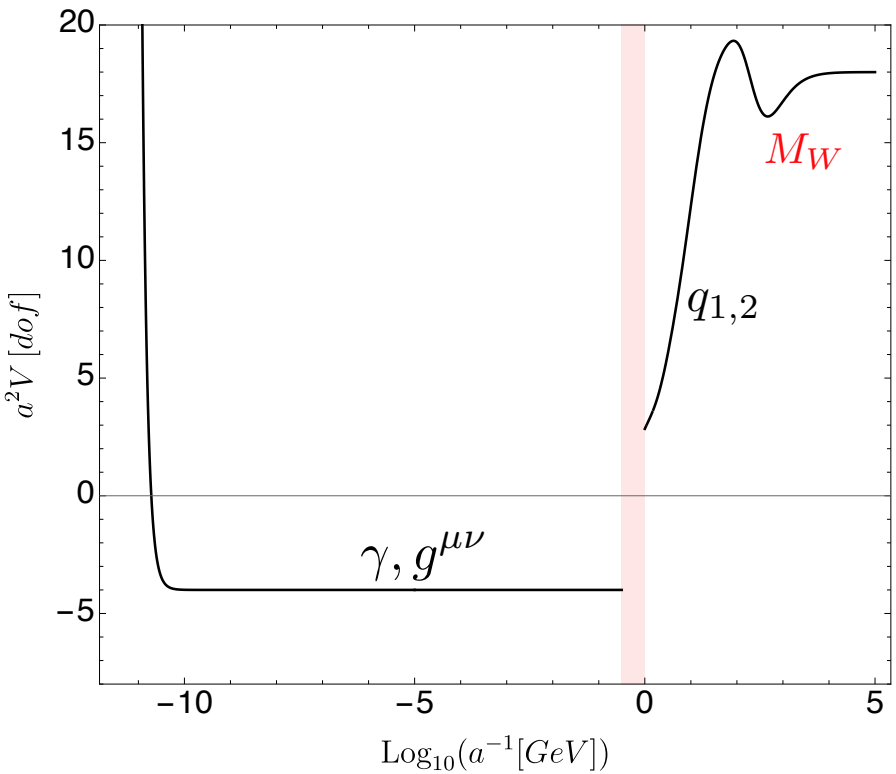


AdS minimum unstable
Due to (negative) contribution
of sleptons and some squarks

Does SUSY SM do any better?

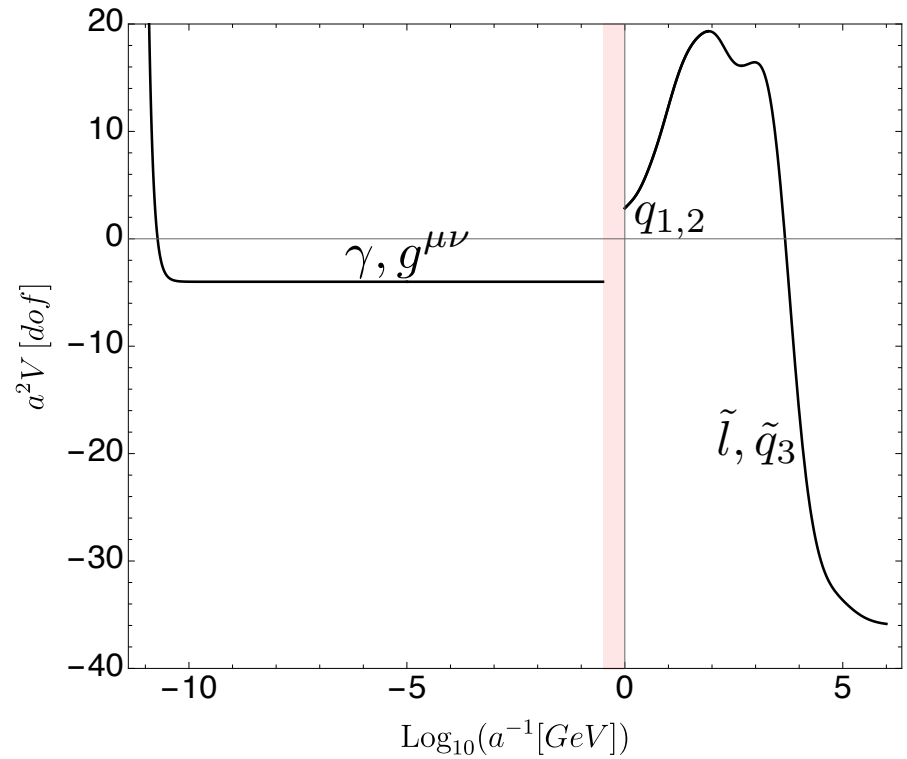
Same T^2/Z_4 compactification

SM



AdS minimum forms

MSSM

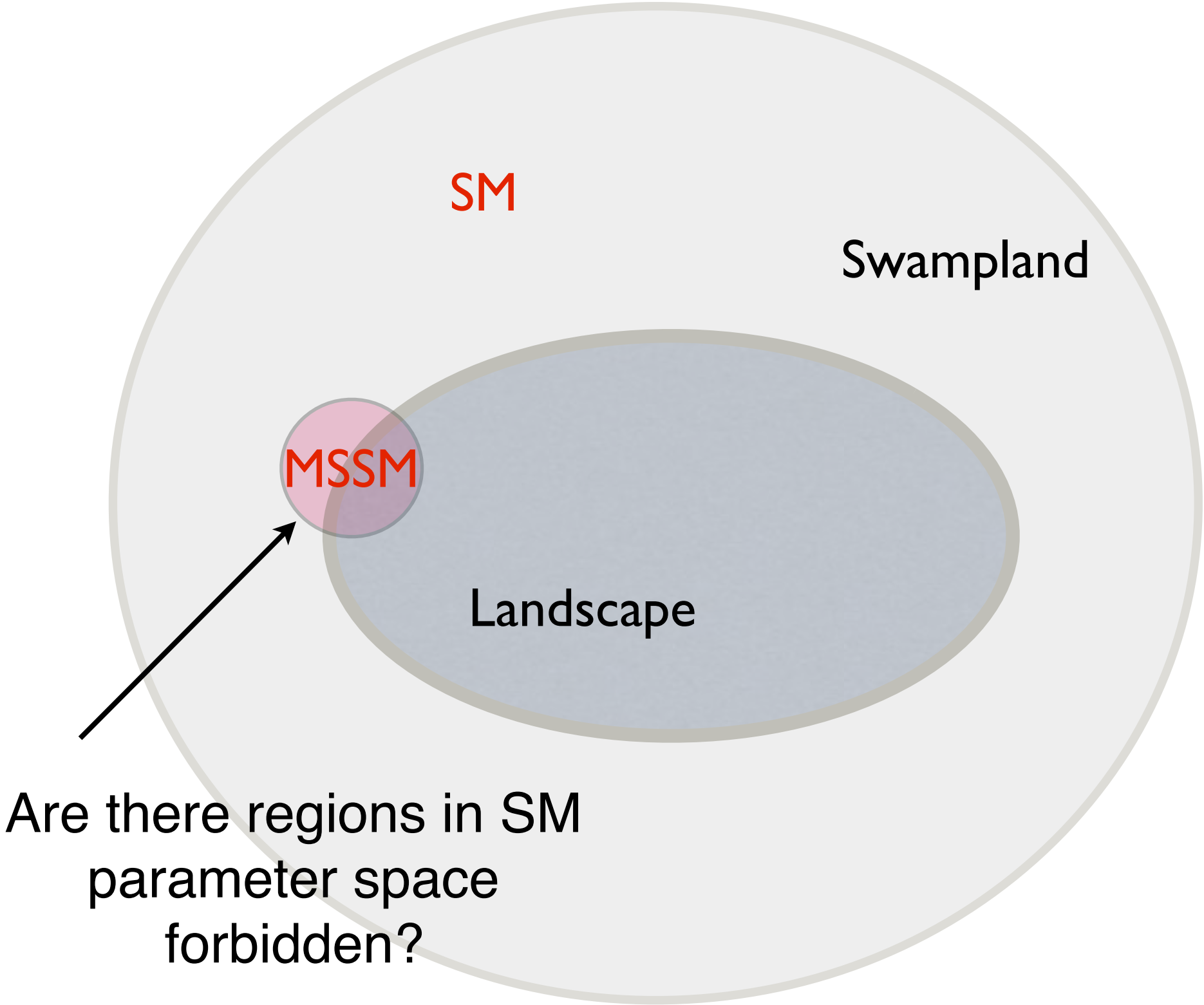


AdS minimum unstable

Due to (negative) contribution of sleptons and some squarks

The SUSY SM survives the test

E.Gonzalo, A.Herraez, L.I. 2018

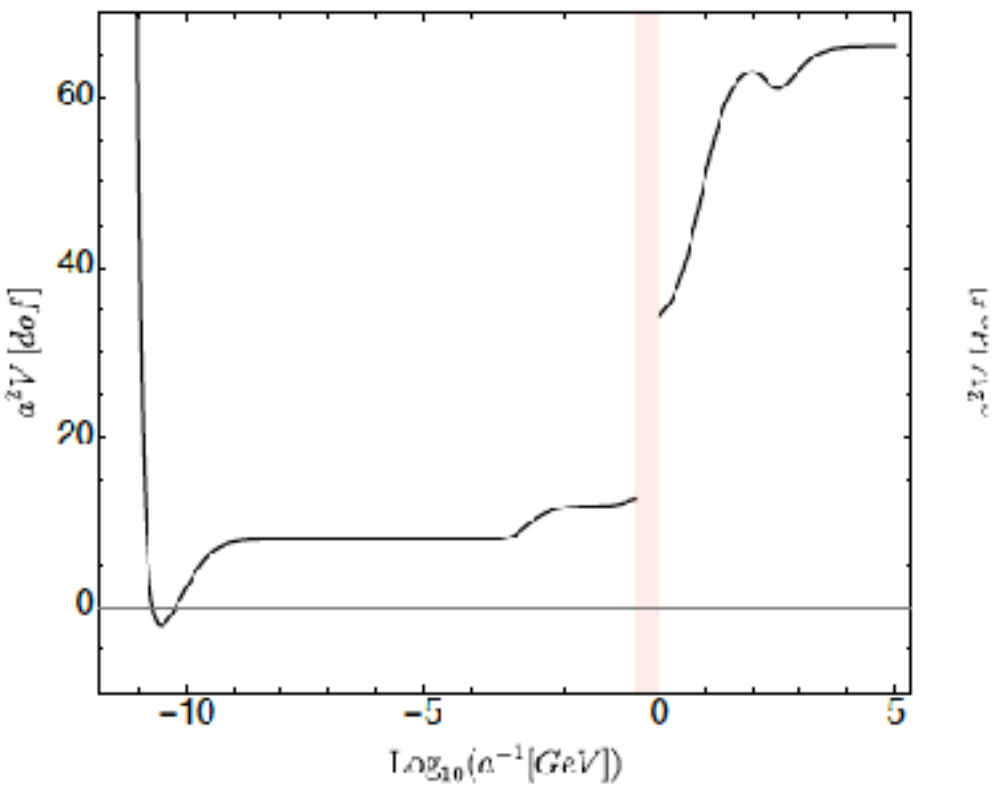

SM
Swampland
MSSM
Landscape
Are there regions in SM parameter space forbidden?

Low energy predictions and B-L

If the MSSM includes a discrete gauge subgroup of $U(1)_{B-L}$

$$\Psi(x_i, y_1, y_2) \;=\; e^{\frac{i}{8}Q_{B-L}} e^{i\frac{\pi}{4}\sigma_3} \psi(x, -y_2, y_1)$$

E.Gonzalo,A.Herraez,L.I. 2018



Predictions from absence of neutrino vacua recovered

Suggests MSSM comes along with a $U(1)_{B-L}$
(at some scale)

Hierarchy Problem, Naturality and the Swampland

A hint that WGC is at odds with naturally

A U(1) coupled to a charged scalar

$$m^2 \leq g^2 M_p^2$$

BUT: m diverges quadratically and g logaritmically!

Bizarre….

Cheung, Remmen 2014

SM without a Higgs is in the Swampland

No fermion masses

$$Below\ \Lambda_{QCD}:$$

$$U(6)_L \times U(6)_R \longrightarrow U(6)_{L+R}$$

$$36\ Godstones\ -3-1\ =\ 32\ massless\ scalars$$
$$6\ massless\ leptons\ \rightarrow\ 24\ fermionic\ d.o.f.$$

$$n_B - n_F\ =\ (32+2+2)-24\ =\ 12$$

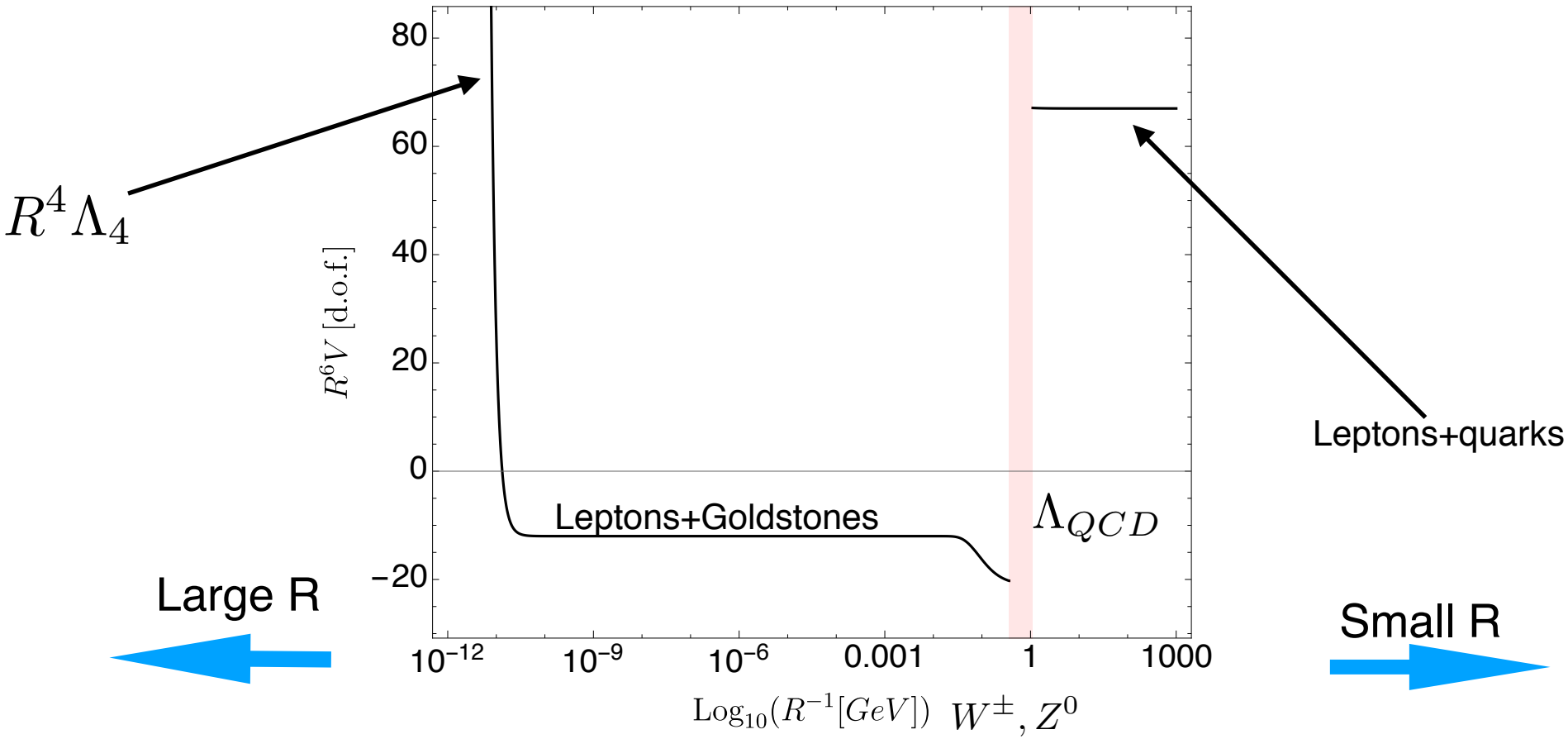
3D:

- If they all contribute to the Casimir energy,

An AdS vacuum necessarily develops!

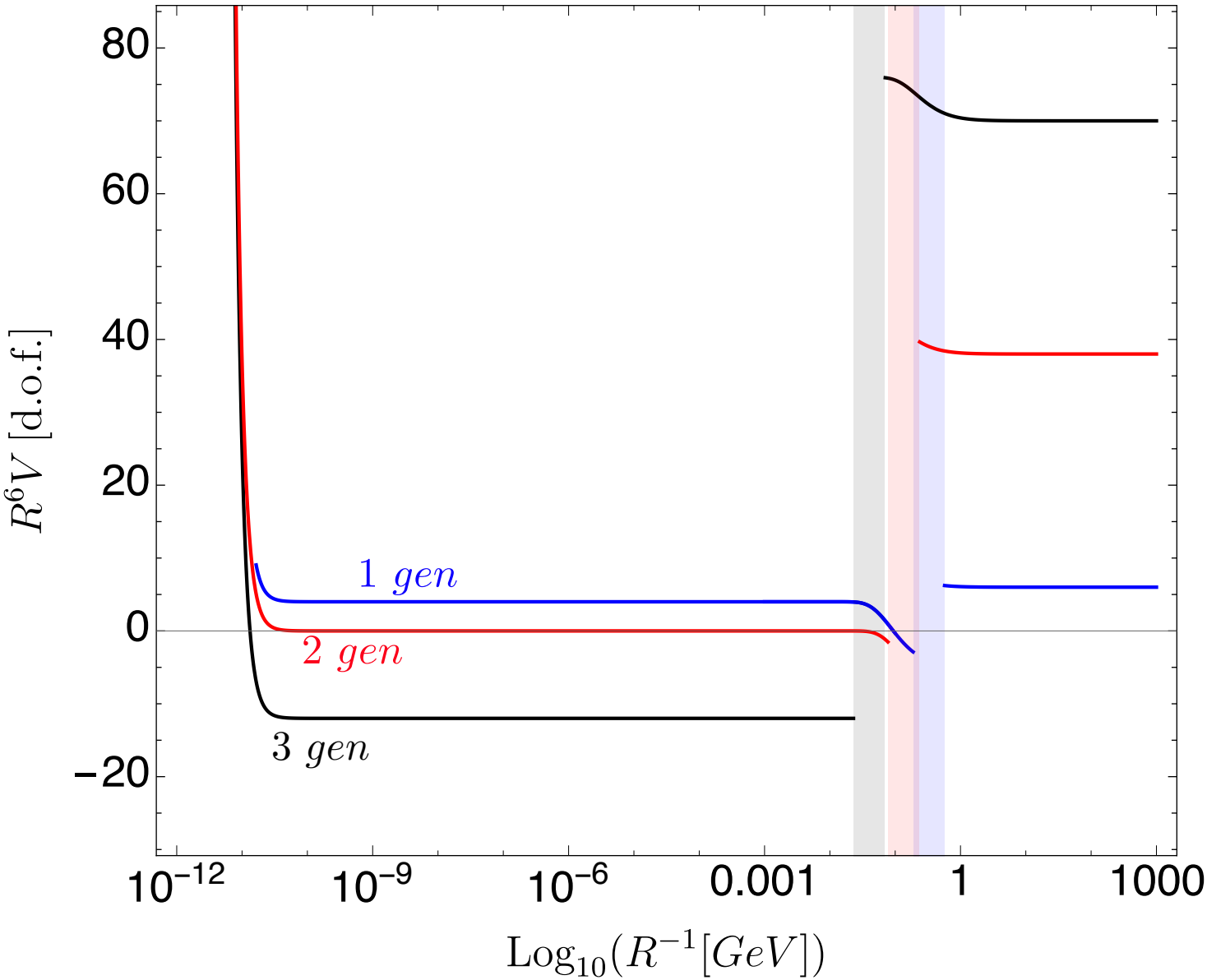
3D

SM without a Higgs



An AdS minimum forms

Higgs is needed!!

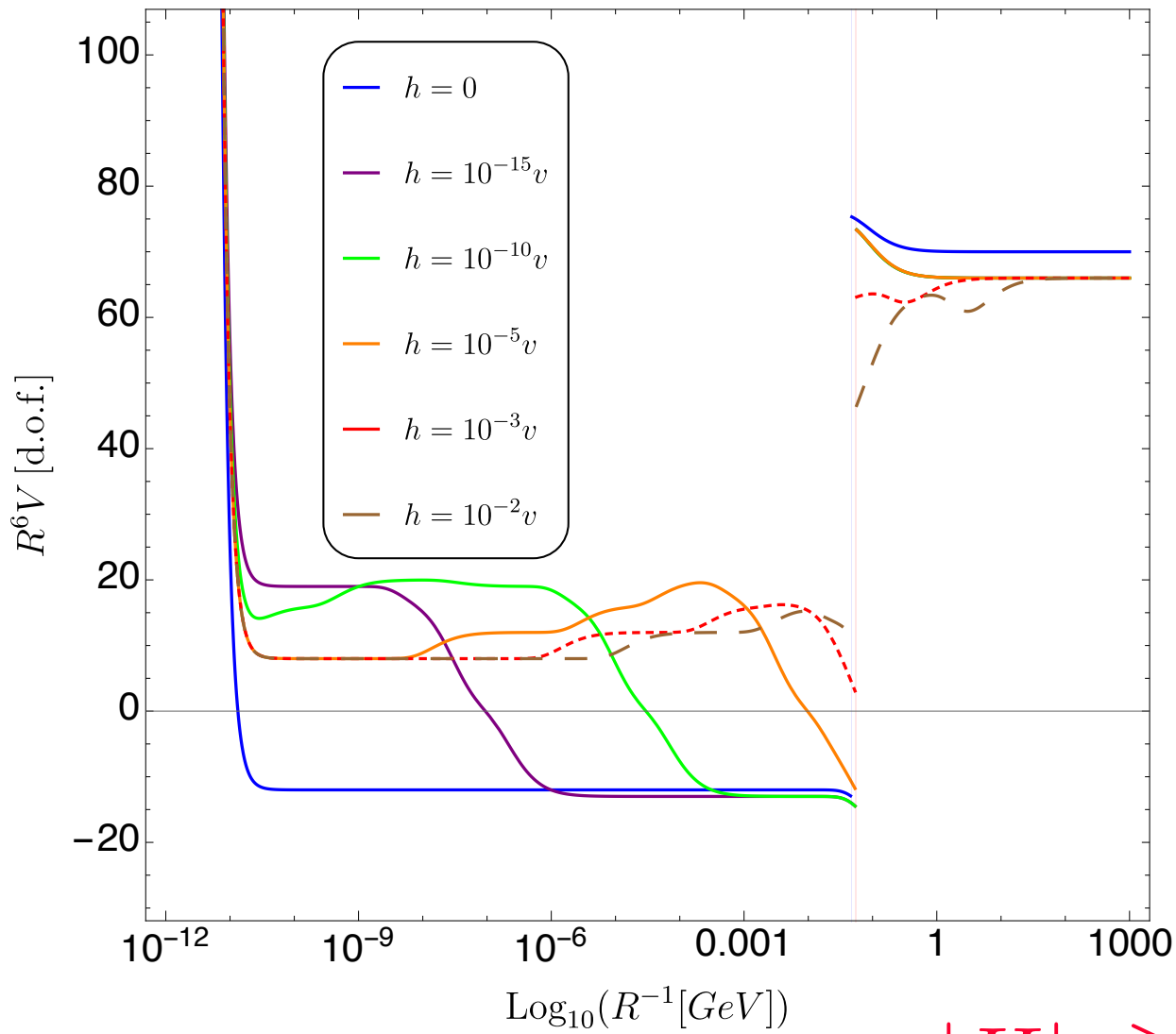


Higgs is needed….if the number of generations is 3 or more

E.Gonzalo, L.I. 2018

Lower bound on Higgs vev

As we turn the Higgs vev on, with SM Yukawa fixed, the goldstones start becoming heavy: fewer bosons



$$h =< H >$$

$$To\ avoid\ AdS\ vacua: \quad |H| \gtrsim \Lambda_{QCD}$$

Hierarchy problem and the swampland

Dirac neutrinos(NH):

$$m_{\nu_1} = Y_\nu < H >$$

$$m_{\nu_1} \lesssim 4.12 \times 10^{-3} eV = 1.6 \Lambda_4^{1/4}$$

L.I.,Martin-Lozano, Valenzuela 2017; E.Gonzalo, L.I. 2018

Hierarchy problem and the swampland

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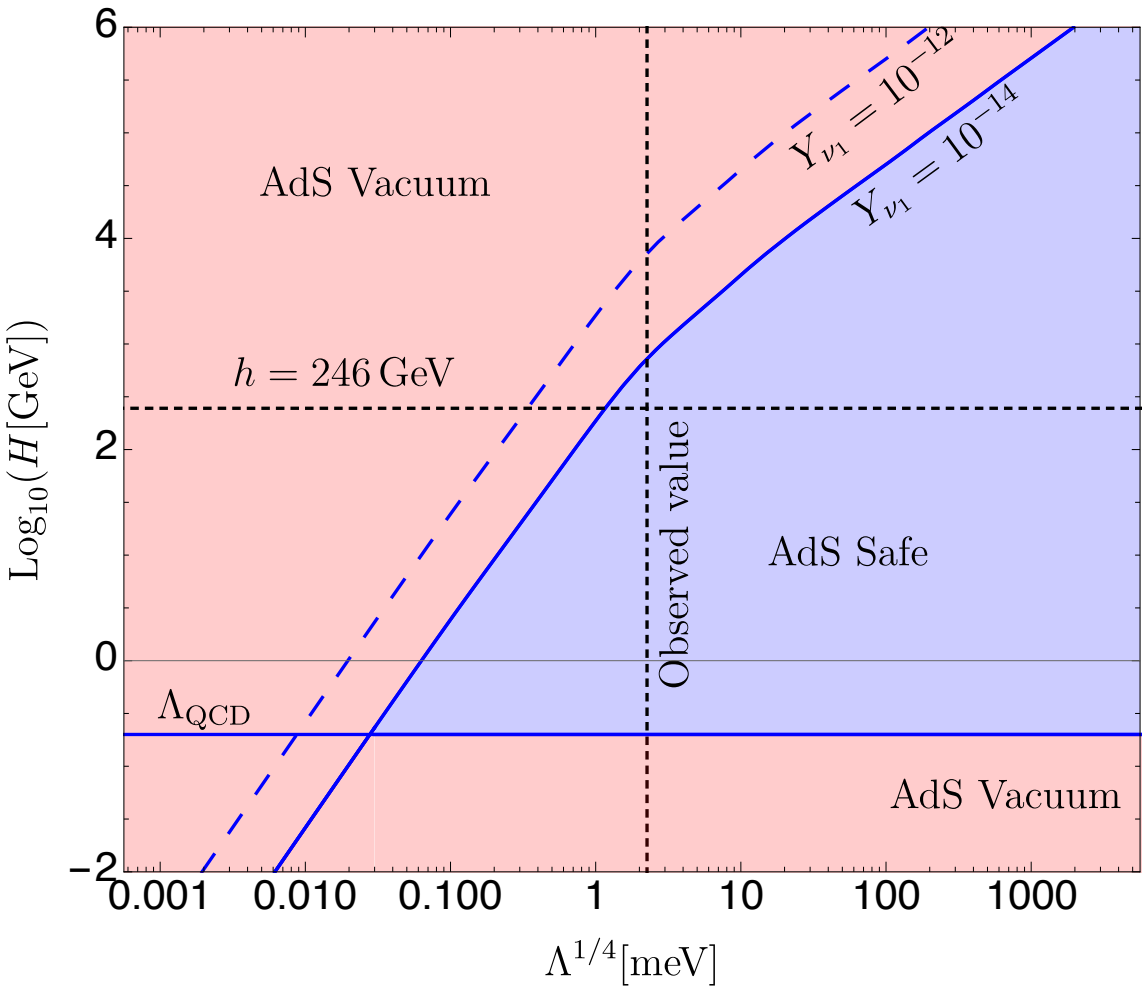


$$< H > \lesssim 1.6 \frac{\Lambda_4^{1/4}}{Y_\nu}$$

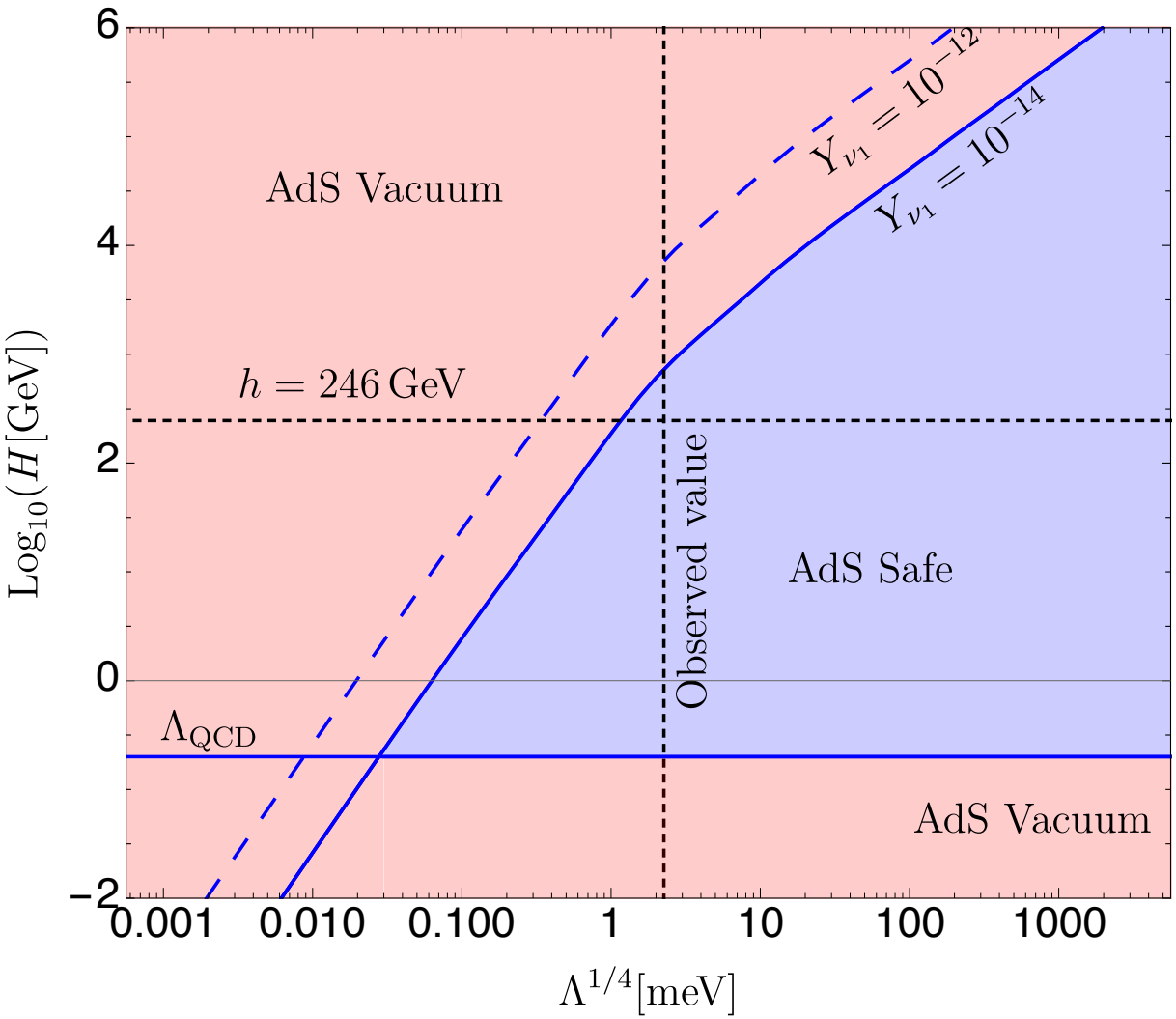
EW scales above 1 TeV in the Swampland!!

$(For\ fixed\ Y_\nu\ and\ \Lambda_4)$

L.I.,Martin-Lozano, Valenzuela 2017; E.Gonzalo, L.I. 2018

Hierarchy problem and the swampland

Dirac neutrinos(NH):



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EW scales above 1 TeV in the Swampland!!

No real fine-tuning.....

EW scale tied up to Λ_4

L.I.,Martin-Lozano, Valenzuela 2017; E.Gonzalo, L.I. 2018

Hierarchy problem and the swampland

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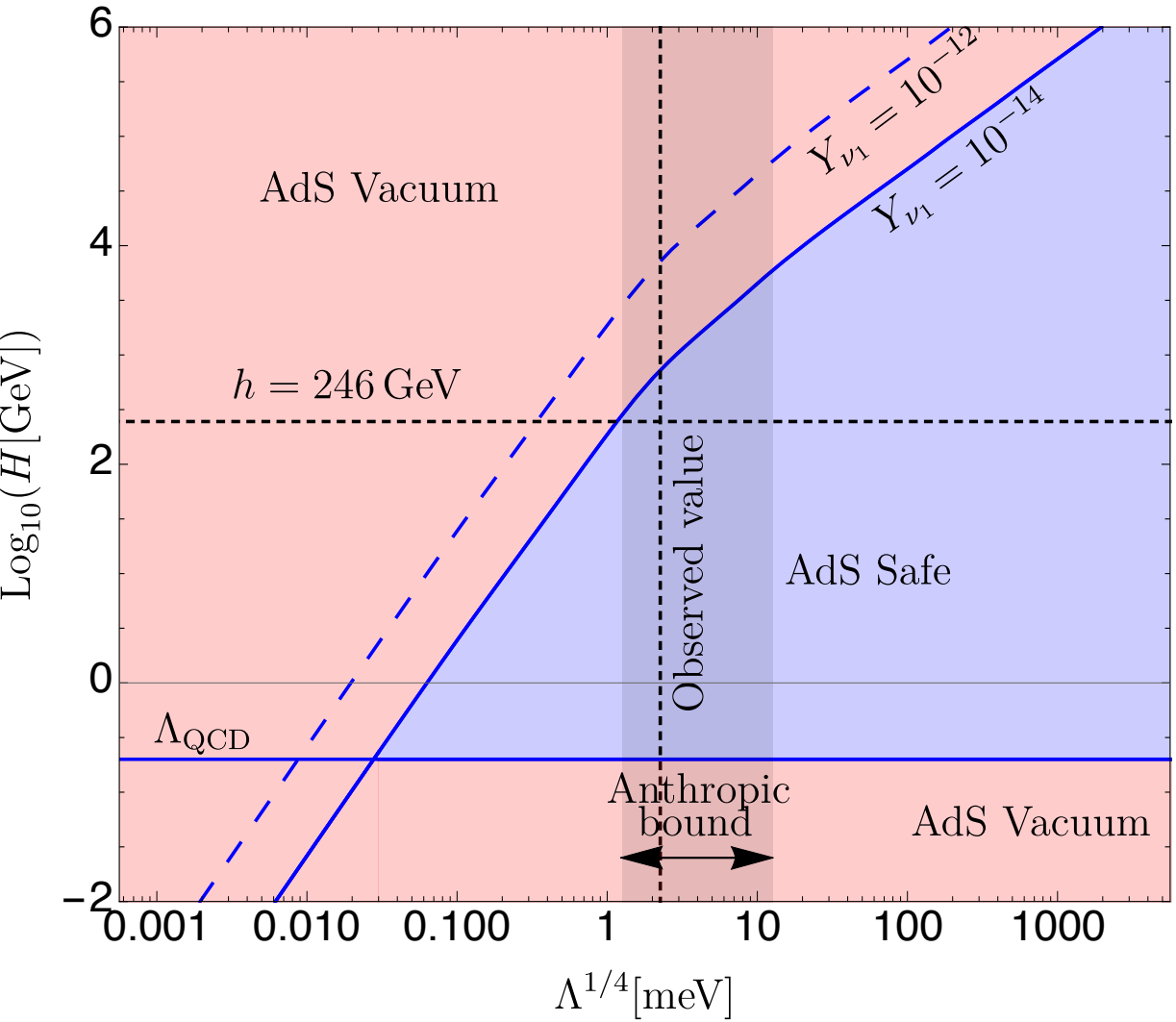

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EW scales above 1 TeV in the Swampland!!

No real fine-tuning.....

EW scale tied up to Λ_4

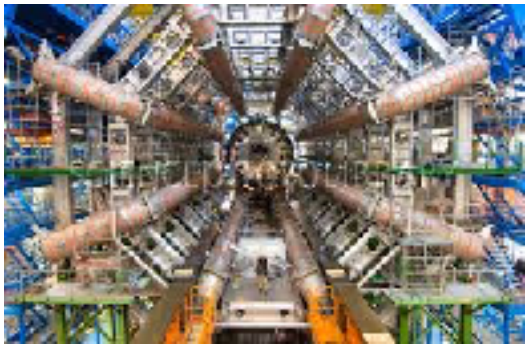
L.I.,Martin-Lozano, Valenzuela 2017; E.Gonzalo, L.I. 2018

$$H_{ex} + \Delta H \leq \frac{a\Lambda_4^{1/4}}{h_{\nu_1}}$$

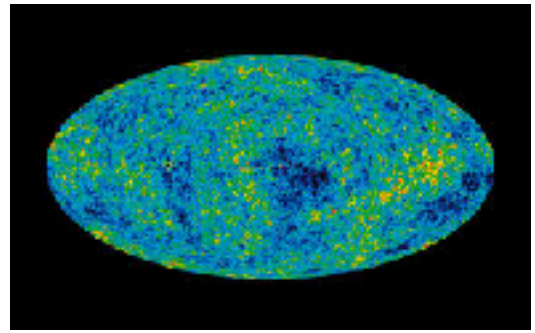
$$\frac{|\Delta H|}{|H|} \leq \frac{(a\Lambda_4^{1/4} - m_{\nu_1})}{m_{\nu_1}}$$

EW fine-tuning is related to the proximity between neutrino masses and the c.c.!

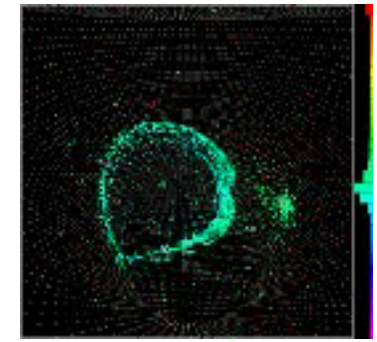
L.I.,Martin-Lozano, Valenzuela 2017; E.Gonzalo, L.I. 2018



EW fine-tuning



Dark Energy



Neutrino Physics

$$\frac{|\Delta H|}{|H|} \leq \frac{(a\Lambda_4^{1/4} - m_{\nu_1})}{m_{\nu_1}}$$

EW fine-tuning is related to the proximity between neutrino masses and the c.c.!

L.I.,Martin-Lozano, Valenzuela 2017; E.Gonzalo, L.I. 2018

- The EW stability may be explained by the requirement of no AdS neutrino vacua

- However in addition SUSY is required to avoid additional AdS vacua

- Unfortunatelly the scale of SUSY is not determined by AdS phobia

- Avoiding charge/colour-breaking (AdS) minima suggests a not too light SUSY spectrum

Summary of Q.G. Constraints

- 1) Bounds on neutrino masses: no Majorana masses (unless new physics). For Dirac (or pseudo) neutrinos:

$$m_{\nu_1} \leq 4.1 \times 10^{-3} eV \ (NH) \ ; \ m_{\nu_3} \leq 1.0 \times 10^{-3} eV \ (IH)$$

- 2) Lower bound on the cosmological constant

$$\Lambda_4 \ \gtrsim m_\nu^4$$

First argument for non-vanishing Λ_4 purely on the basis of Particle Physics

- 3) A Higgs-less SM would be in the swampland and

$$| < H > | \gtrsim \Lambda_{QCD} \qquad (if \ n_{gen} \geq 3)$$

- 4) Bounds on neutrino masses imply upper bound on the EW scale

$$\frac{|\Delta H|}{|H|} \leq \frac{(a\Lambda_4^{1/4} - m_{\nu_1})}{m_{\nu_1}}$$

- If true, this would redefine our notion of fine-tuning of the EW scale: So talking about naturalness makes sense only within the class of allowed theories

The EW scale and the c.c. scales are tied up BUT:

- 5) SM requires necessarily an extension.
- 6) A natural extension surviving all tests so far is SUSY
- 7) A MSSM extension including $U(1)_{B-L}$ is favored: extra $Z^{0'}$

Conclusions

- 1) Quantum gravity constraints effective field theories

- 2) A number of conjectures exist on those constraints. The strongest support comes from no counterexamples in String Theory

- 3) In particular, AdS-phobia OV conjecture states that no consistent non-SUSY, stable, AdS vacua can exist.

- 4) When applied to SM compactifications to 3D and 2D a number of constraints appears

It is surprising how a rather abstract condition like absence of non-SUSY AdS vacua is able to yield reasonable (not wild) constraints on actual Physics

Outlook

- Need to understand better the theoretical basis of the swampland conjectures

- Understand better the stability of the vacua

- Explore further SM vacua and constraints

- Can we say something about scale of SUSY?
- Study implications on our views on naturality. The EW fine-tuning could be a mirage!!


Thank you !!

Instituto de Física Teórica UAM-CSIC presents:

Vistas over the Swampland

Madrid, 19-21 September 2018

https://workshops.ift.uam-csic.es/swampland

Swamp lookouts

N. Arkani-Hamed (IAS - Princeton)
T. Banks (Santa Cruz & Rutgers U.)
R. Blumenhagen (MPI - Munich)
T. Crisford (DAMTP - Cambridge)
U. Danielsson (Uppsala U.)
A. Hebecker (Heidelberg U.)
M. Kleban (New York U.)
D. Lüst (LMU & MPI - Munich)
M. Montero (ITP - Utrecht)
E. Palti (MPI - Munich)
M. Reece (Harvard U.)
G. Remmen (UC - Berkeley)
T. Rudelius (IAS - Princeton)
G. Shiu (UW - Madison)
P. Soler (Heidelberg U.)
C. Vafa (Harvard U.)
I. Valenzuela (ITP - Utrecht)
T. Van Riet (KU Leuven)

Swamp rangers

L. E. Ibáñez
F. Marchesano
A. M. Uranga

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