Swampland Conjectures and Some Physics Implications

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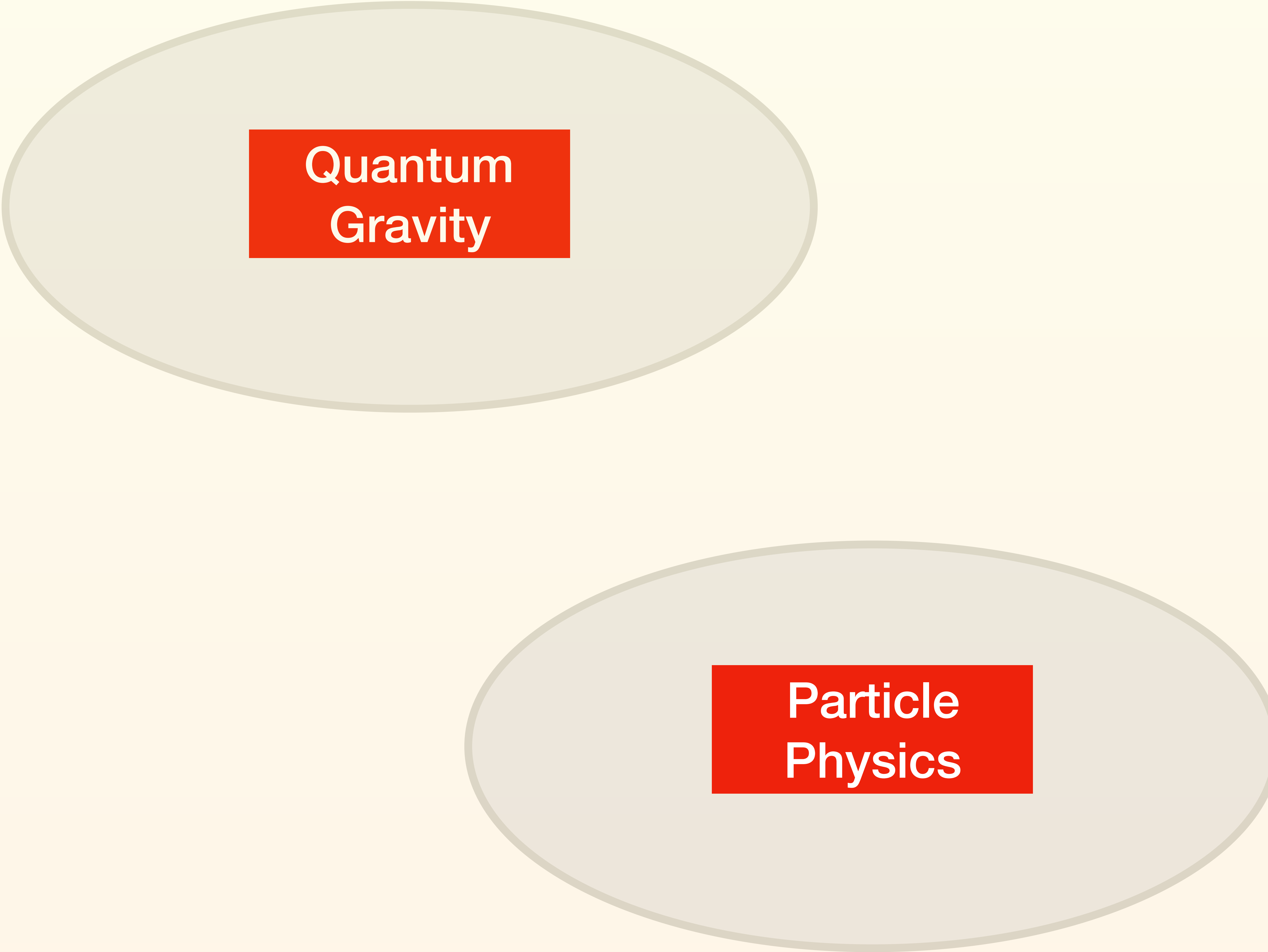
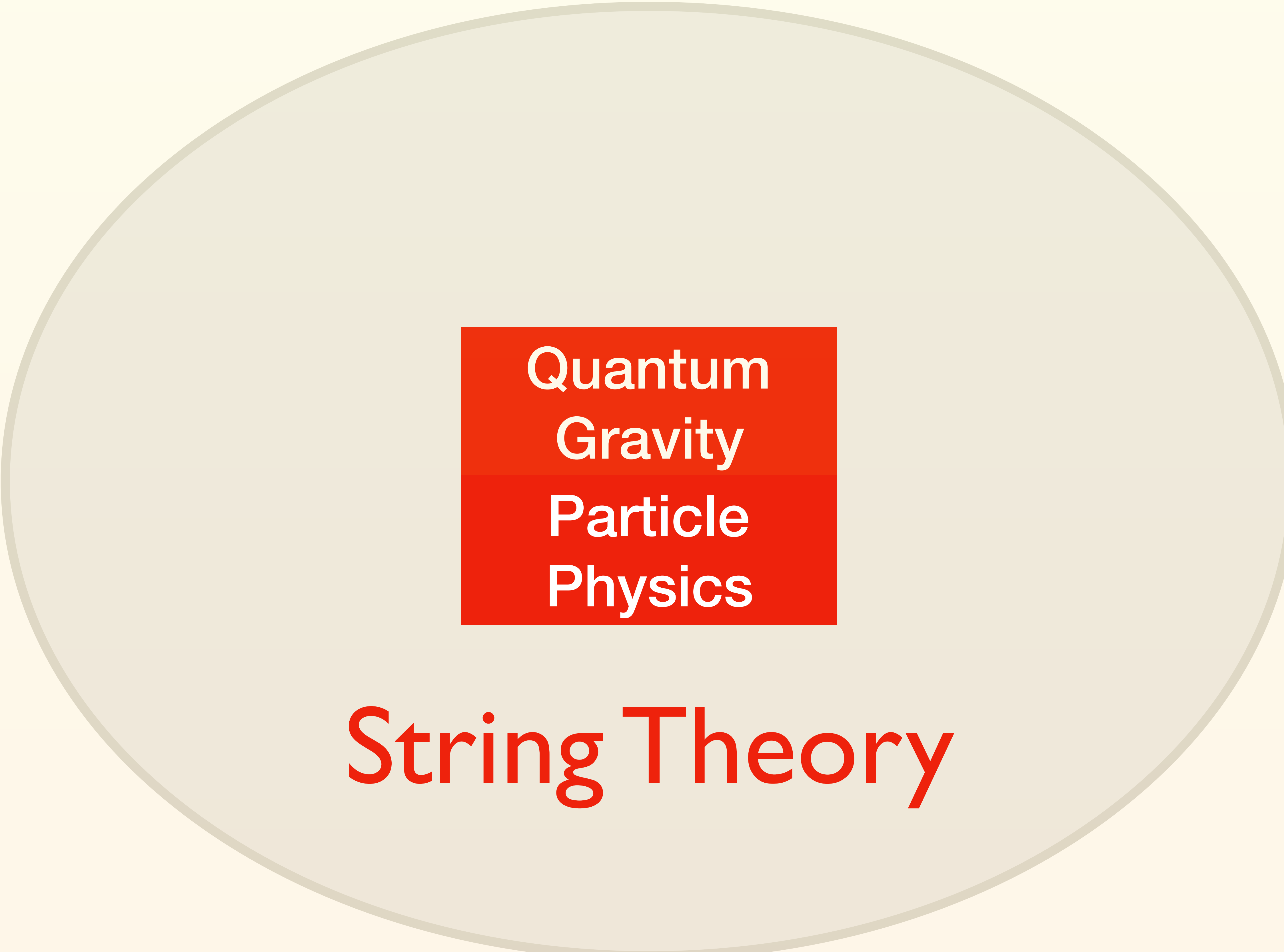
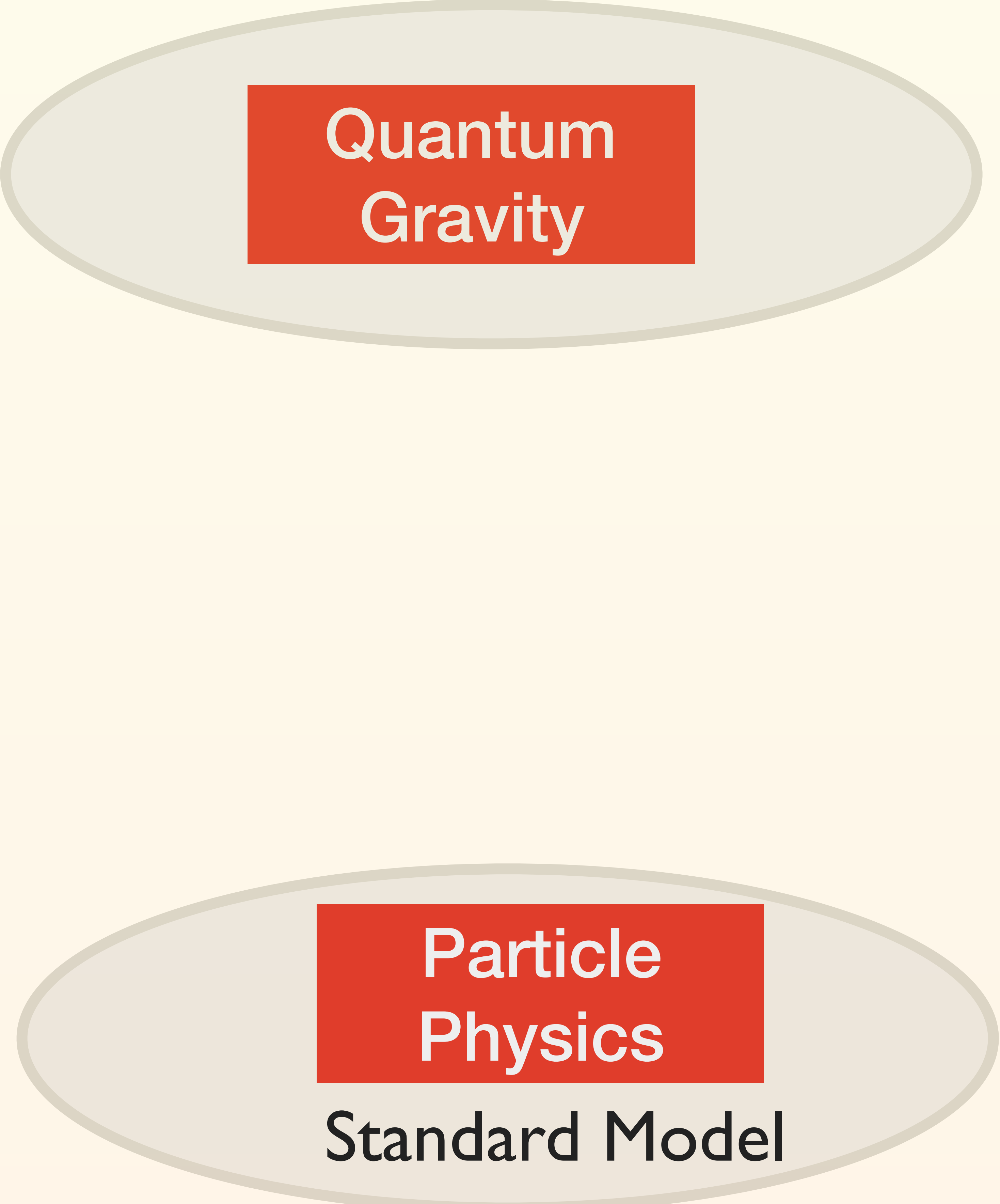

Quantum Gravity
Particle Physics


Quantum Gravity
Particle Physics
String Theory

Wilsonian view

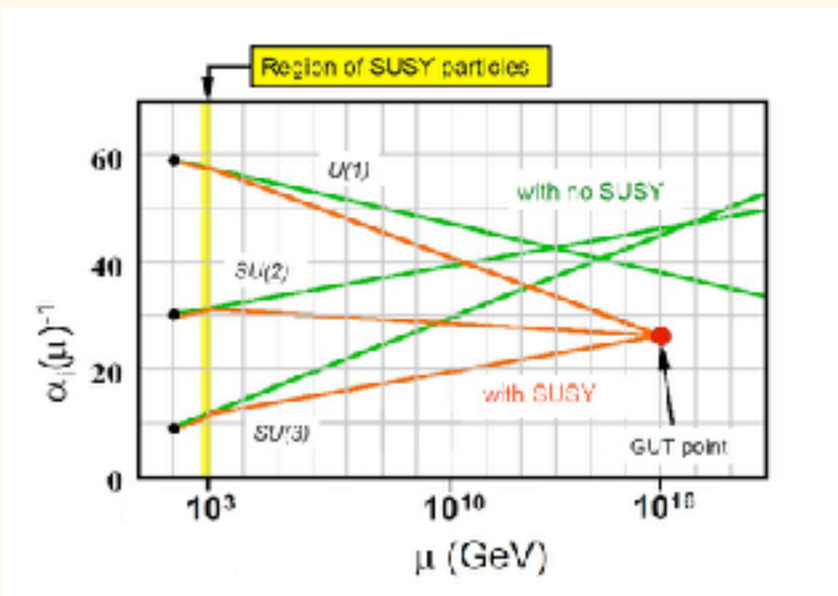


Wilsonian view

Quantum Gravity

- 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, or irrelevant operators remain

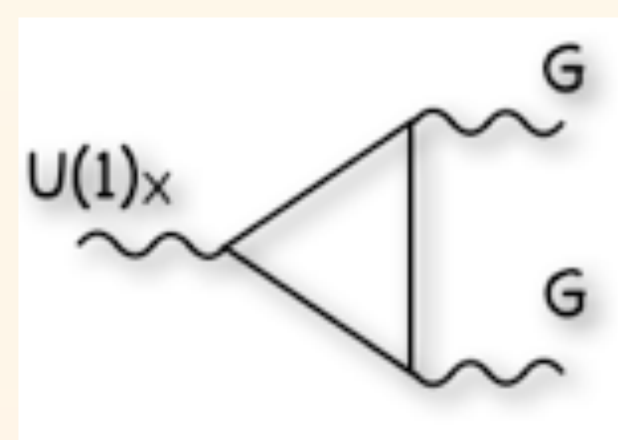


$$irrelevant\ operators\ \frac{\phi^{n+4}}{M_p^n}$$

- So we can ignore quantum gravity effects at low energies

Particle Physics

Exception:



- 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 , e.g

$$\int dx^4 \sqrt{g}\, g_{\mu\nu}\partial^\mu\phi\partial^\nu\phi^* \neq \int dx^4\, \delta_{\mu\nu}\partial^\mu\phi\partial^\nu\phi^*$$

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

SWAMPLAND

Vafa 2005

Ooguri and Vafa 2006

The Swampland

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

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

Review: Brennan, Carta, Vafa , arXiv:1711.00864

8 Swampland Conjectures

1) There are no exact global symmetries

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

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

4) The Weak Gravity Conjecture

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

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

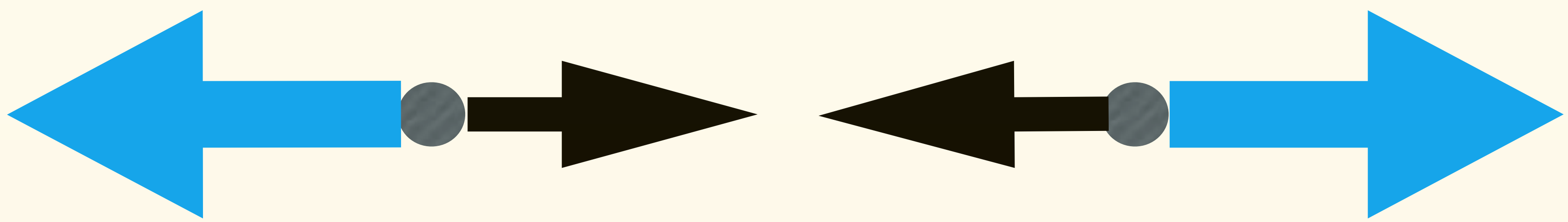
WGC for a U(1)

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

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

Generalised to 0-forms (axions) and n-forms n>1

Consider two particles with mass m and charge q :



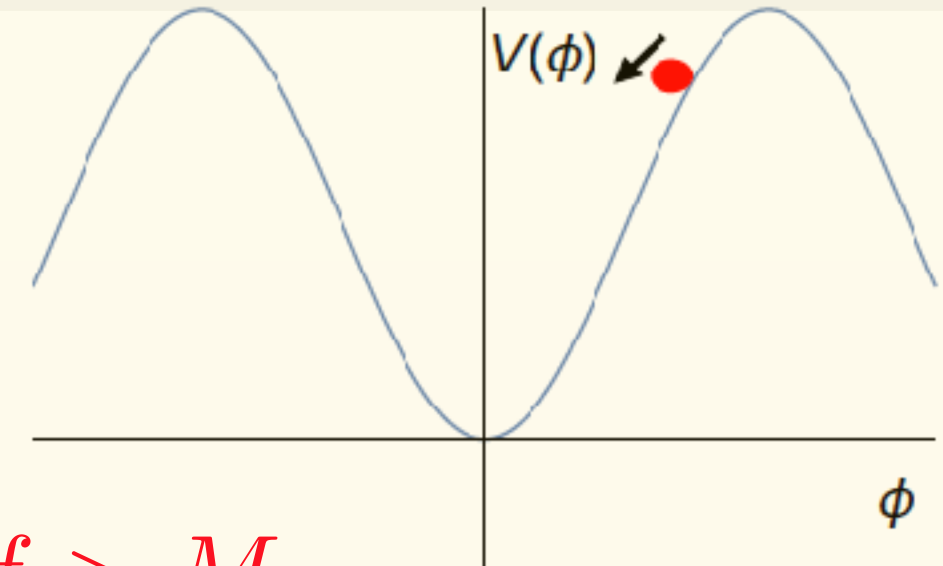
$$F_G = \frac{1}{M_p^2}\frac{m^2}{r^2} \qquad\qquad F_q = \frac{q^2}{r^2}$$

$$\boxed{F_G \leq F_q \longrightarrow m \leq qM_p}$$

e.g. electron

E.g., applications of the WGC to Cosmology

$Axion\ inflation:$



$$V(\phi) = \Lambda^4 (1 - \cos\frac{\phi}{f}) + \ldots$$

$Inflation\ needs\ f > M_p$

$$m \leq g\, M_p$$

$$\gamma \longrightarrow Axion \qquad m \longrightarrow S_{inst}, \quad g \longrightarrow \frac{1}{f}$$

$$S_{inst} \leq \frac{1}{f} M_p$$

$$Potential\ under\ control\ S_{inst} > 1 \Longrightarrow f \lesssim M_p$$

$Natural\ inflation,\ N - flation, ...inconsistent\ with\ WGC$

Heidenreich, Reece, Rudelius 2015
Montero, Uranga, Valenzuela 2015

Also constraints on relaxions

Generalizes to higher rank tensors and branes in ST

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

$$\boxed{\frac{T}{M_p} \leq g}$$

$(g\ dimensionful)$

Ooguri and Vafa 2016: *arXiv:1610.01533*

The equality is only achieved for SUSY BPS states

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

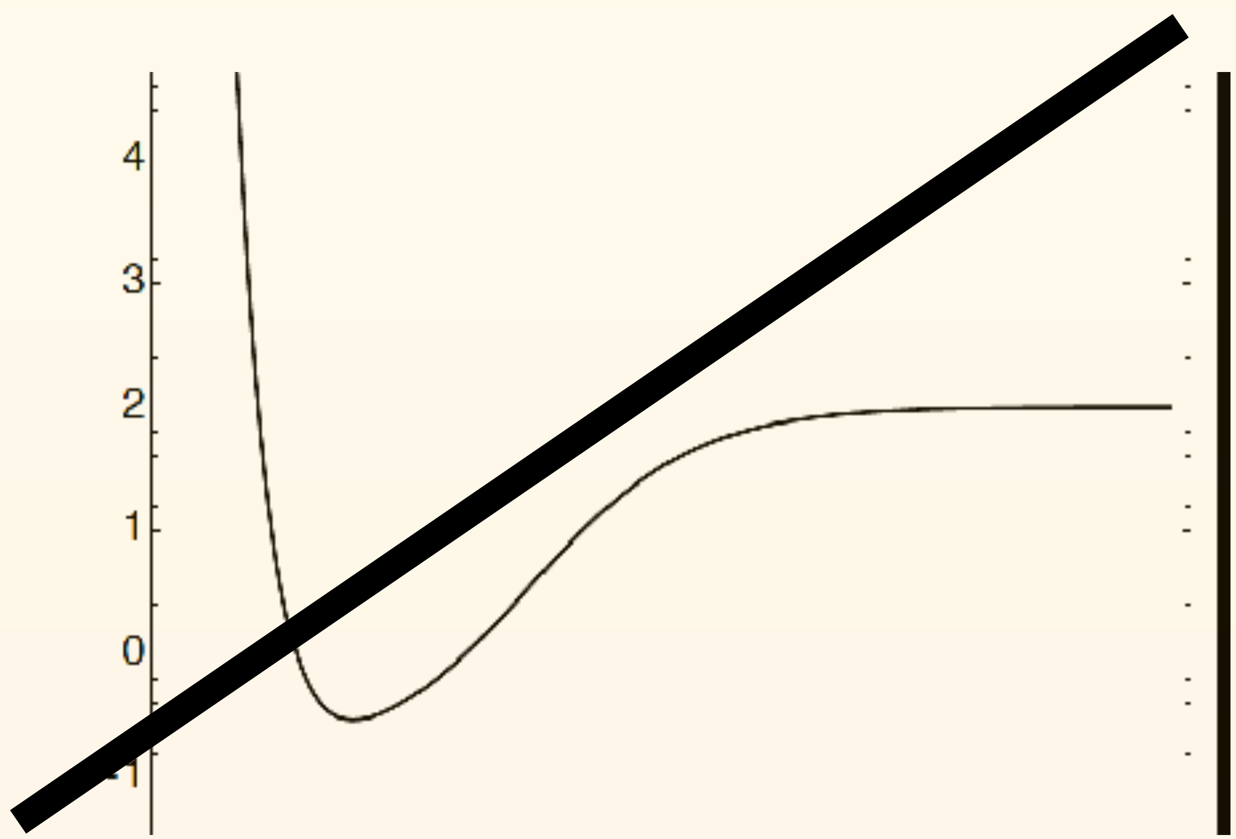
for non-SUSY

Strong Corolarium !!

(also Banks 2016, Freivogel, Kleban 2016)

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

Non-SUSY AdS flux vacua are unstable and cannot have CFT dual

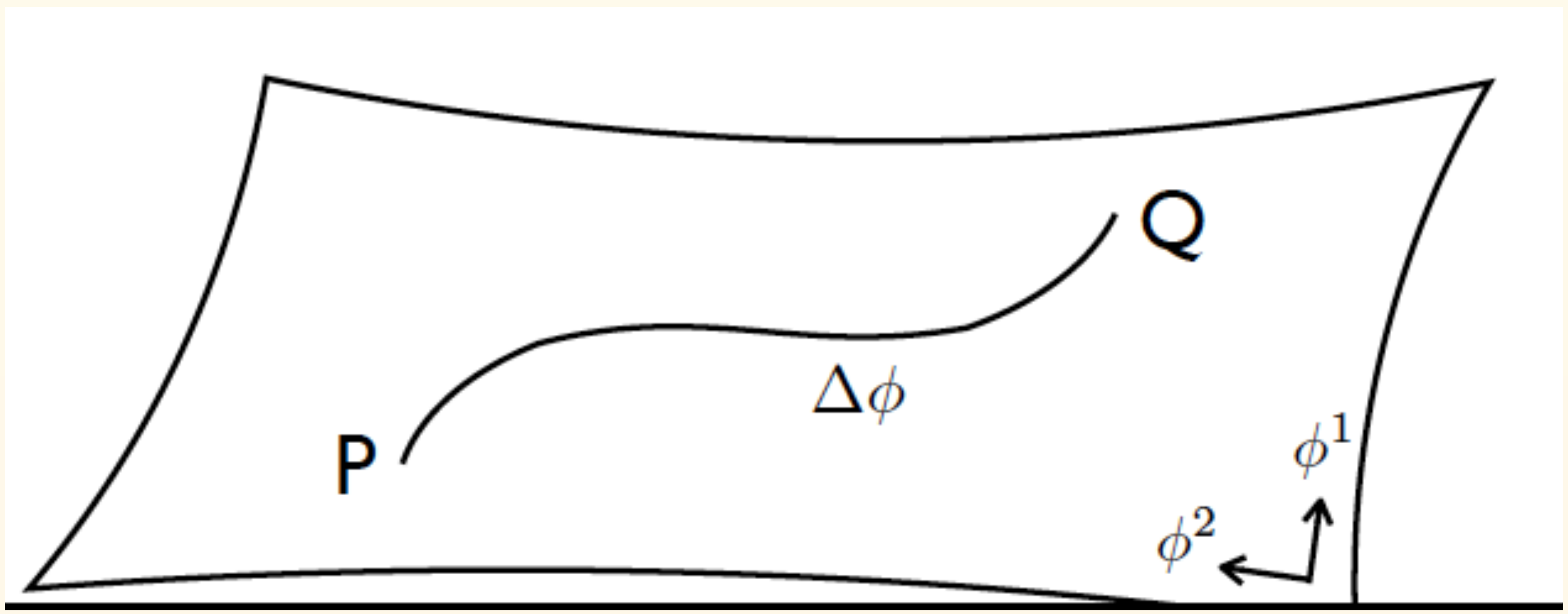


(If you find one in your theory, then it is inconsistent with quantum gravity)

Caveat: often not obvious how to be sure of full stability....

6) Distance Swampland Conjecture

Moduli space of scalars: as we move In moduli space by $\Delta\phi$ a tower of states becomes exponentially massless



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

The effective field theory becomes inconsistent

Relevant for inflation, relaxions…..

$For\ N \geq 2\ one\ transits\ to\ another\ dual\ theory\ \ : emergence\,?$

(integrating out the tower yield precisely the right moduli metric….)

Grimm, Palti, Valenzuela 2018
Heidenreich, Reece, Rudelius 2017

$For\ N < 2\ ....$

7) dS Swampland Conjecture

Obied, Ooguri, Spodyneiko, Vafa 2018

Any scalar potential $V(\phi)$ in a consistent theory of quantum gravity must obey

$$\boxed{|\nabla V(\phi)| \;\geq\; \frac{\mathcal{O}(1)}{M_p} V(\phi)}$$

7) dS Swampland Conjecture

Any scalar potential $V(\phi)$ in a consistent theory of quantum gravity must obey

$$|\nabla V(\phi)| \geq \frac{\mathcal{O}(1)}{M_p} V(\phi)$$

or else.....

Ooguri, Palti, Shiu, Vafa 2018

$$min(\nabla_i \nabla_j V(\phi)) \leq -\frac{\mathcal{O}(1)}{M_p^2} V(\phi)$$

Forbids dS vacua!!!!!

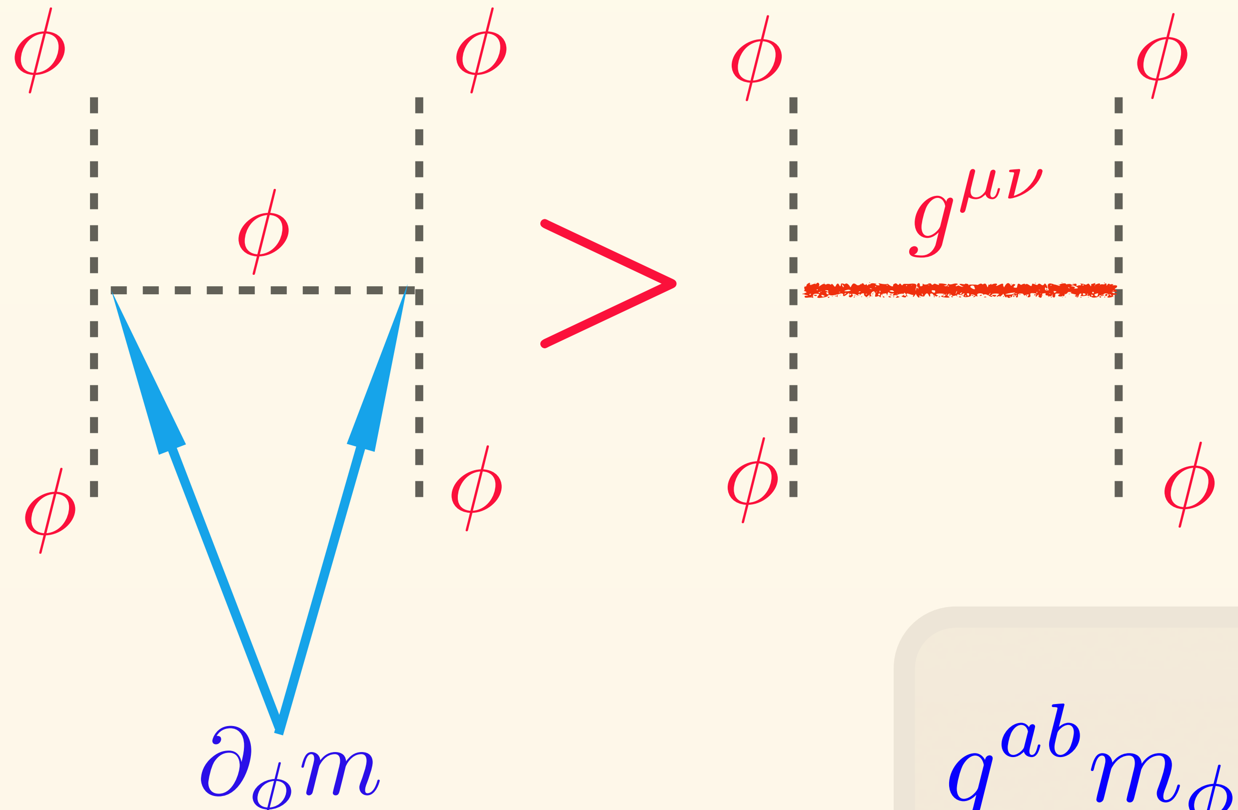
Suggests runaway dS potential rather than minima.....

Important implications for cosmology....quintessence?

8) Scalar Weak Gravity Conjecture

Palti 2017

Scalar interactions must be stronger than gravity:



$$g^{ab} m_{\phi_a} m_{\phi_b} \geq \frac{m^2}{M_p^2}$$

Yet to be tested…but very constraining…

Status

- Good string theory evidence for U(1) WGC AdS and distance swampland conjectures. Examples are perturbative and have $N \geq 2$

- Weaker evidence for dS conjecture

- Subject very controversial since it would imply 1) that the dS minima found up to now are inconsistent and 2) standard single field inflation problematic

- We would like to

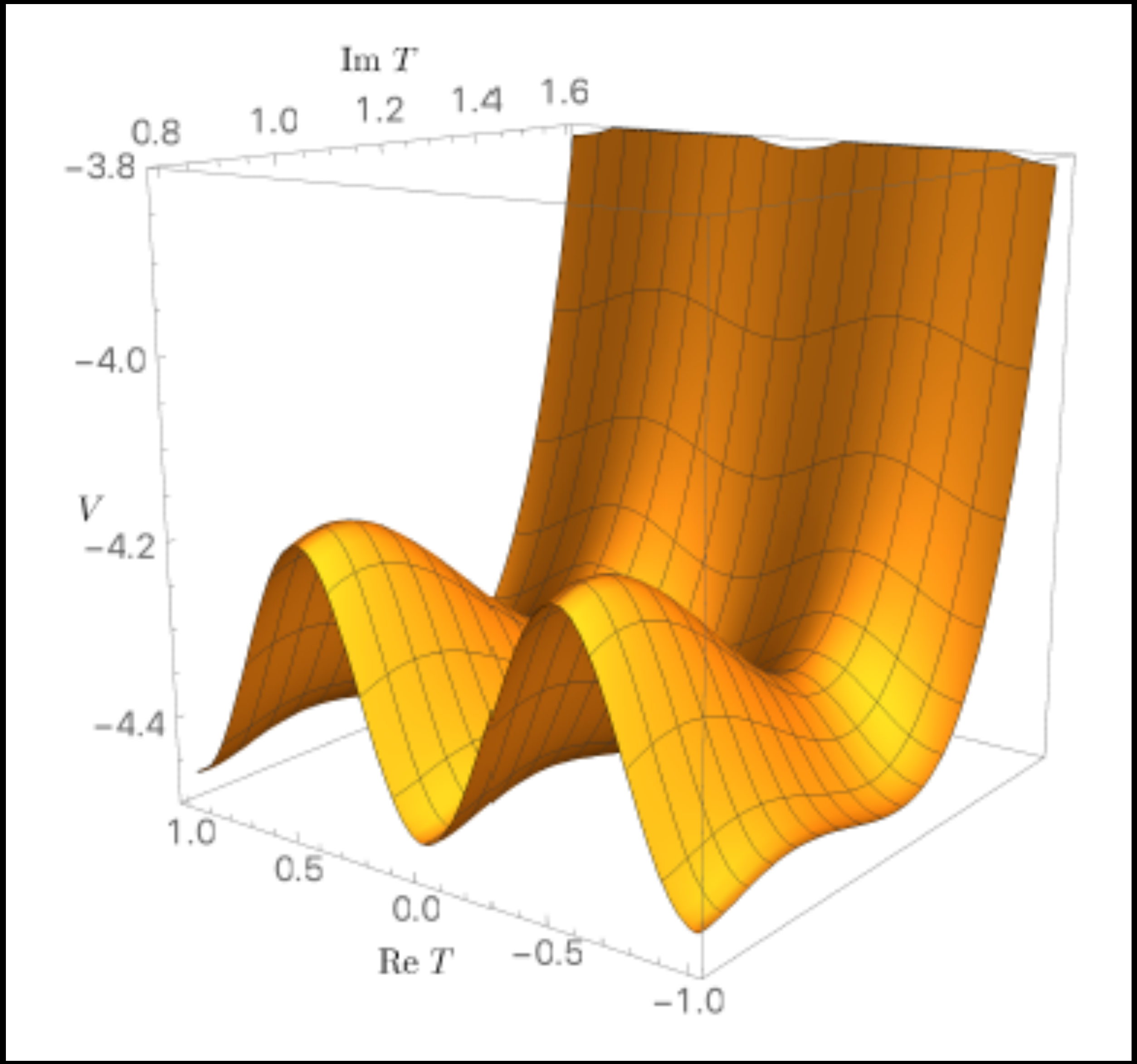
  1) Test conjectures beyond N=2 and perturbation theory
  2) Check dS conjecture in String Theory
  3) Applications to Cosmology and Particle Physics

We are going to consider:

- Modular symmetries and the Swampland conjectures: study large moduli behaviour in non-perturbative string vacua. Check dS conjecture.

- Application to SM physics. Application of AdS or SWGC to 3D SM gives constraints on neutrino masses, cosmological constant And the hierarchy problem.

Modular Symmetries and the Swampland Conjectures



- Recent String Theory tests of Swampland Conjectures are perturbative

- That is the case of e.g. the dS or the Swampland Distance conjectures (SDC)

- We propose to exploit the modular symmetries of the moduli effective action to check Swampland constraints beyond perturbation theory

- Such symmetries are part of string dualities and appear generically in any string compactification.

- Present also in instanton induced superpotentials

Modular invariance in 4D heterotic vacua

- Simplest examples: tori/$Z_N$orbifolds: $Kahler \;\; T_j = \theta_i + it_j$
- $$T \to \frac{aT+b}{cT+d} \;,\;\; a,b,c,d \in \mathbf{Z}, ad-bc = 1$$
- N=1 supergravity Kahler potential:

Ferrara, Lust, Theisen 1989
Cvetic, Font, Ibañez, Lust, Quevedo 1991

$$G \;=\; -3log(T-T^*) \;+\log|W(T)|^2$$

- Invariant if $\qquad W \;\longrightarrow\; \dfrac{W(T)}{(cT+d)^3}$
- Most general superpotential must have modular weight (-3)

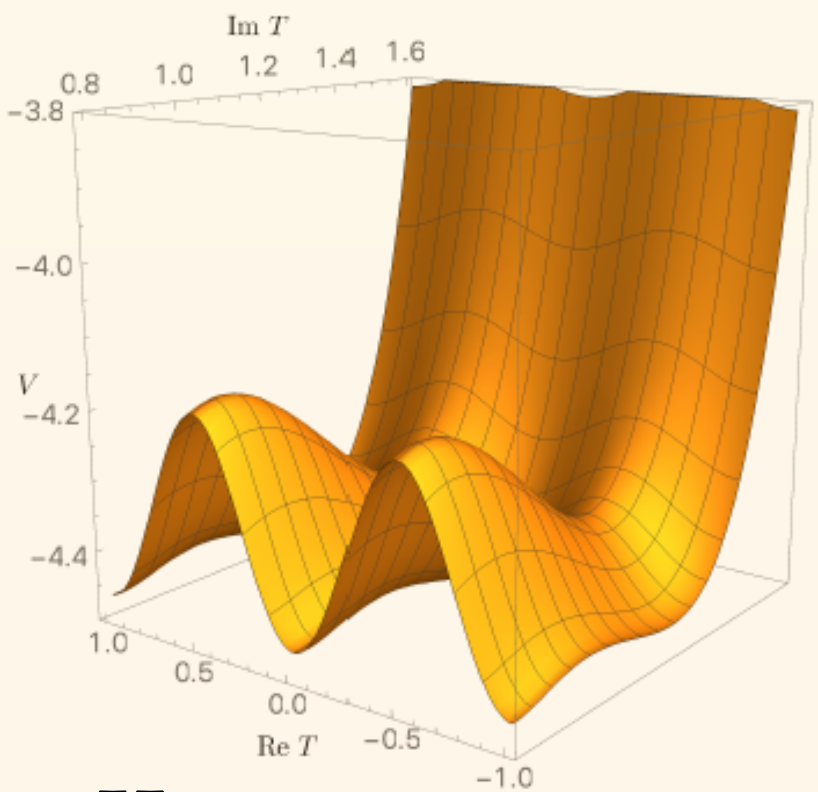
Cvetic, Font, Ibañez, Lust, Quevedo 1991

- Most general W: (without singularities inside fundamental domain)

$$W(T) = \frac{H(T)}{\eta(T)^6} \quad ; \; H(T) = j(T)^{n/3}(j(T) - 1728)^{m/2}\mathcal{P}(j(T))$$

- H(T) not singular and

$$\eta(T)^{-1} = q^{-1/24}(1 + q + 2q^2 + ...) \quad , \; q = e^{i2\pi T}$$



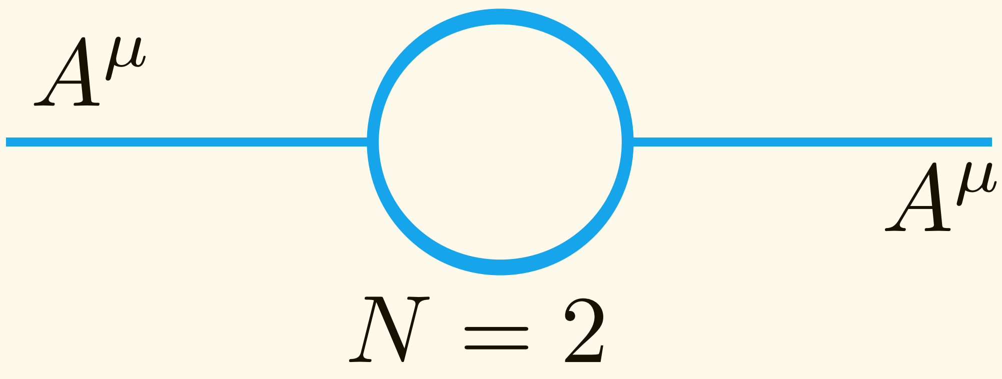
$E.g.\ H = 1$

Diverges for large ImT

Continuous (global) shift symmetry only recovered at infinite ImT

Such type of superpotentials arise in string theory

- 4D, N=1 Heterotic Z_N orbifolds



Threshold Corrections

Dixon, Kaplunovsky, Louis 1991
Antoniadis, Narain, Taylor 1991

$$f_a = S - \frac{1}{16\pi^2}\sum_{i=1}^{3} b_{a,i}^{N=2}\log\left[\eta(T_i)^4\eta(U_i)^4\right]$$

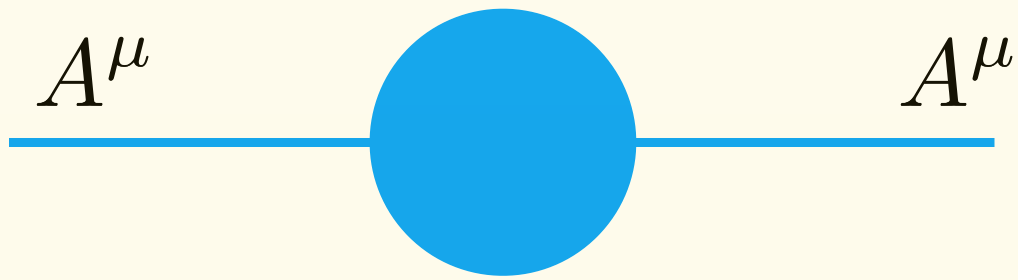
$E.g.\ Z_2 \times Z_2$

$$W_{E_8} = \Lambda^3 e^{\frac{3f_{E_8}}{2\beta_{E_8}}} = \Lambda^3 e^{\frac{3S}{2\beta_{E_8}}}\prod_{i=1}^{3}\frac{1}{\eta(T_i)^2}\frac{1}{\eta(U_i)^2}$$

Font, Ibañez, Lust, Quevedo 1990

Also in Type IIB and Horava-Witten duals

Threshold Corrections



Dixon, Kaplunovsky, Louis 1991
Antoniadis, Narain, Taylor 1991

$$\Delta_a \;=\; b_a \int_\Gamma \frac{d^2\tau}{\tau_2} \left(Z_{\rm torus}(\tau, \bar\tau) - 1 \right) \, ,$$

$$Z_{\rm torus} \;=\; \sum_{m_{1,2}, n_{1,2} \in \mathbf{Z}} e^{2\pi i \tau \, (m_1 n_1 + m_2 n_2)} e^{-\pi \tau_2 \, M^2} \, ,$$

$$M^2 \;=\; \frac{1}{4 \, ({\rm Im}\, T)({\rm Im}\, U)} \, | \, n_2 T U + n_1 T - m_1 U + m_2 \, |^2 \, .$$

(Modular invariant, under redefinition of integers)

$$e.g. \;\; fixed \; U, n_i = m_1 = 0 \longrightarrow \;\; M^2 \simeq \frac{m_2^2}{ImT} \simeq m_2^2 e^{-\sigma}$$

Tower of exponentially massless KK states: origin of divergence

Gonzalo, L.I., Uranga 2018

Dual pictures

Picture	Modulus	Duality group	Objects
Heterotic	$\int_{\mathbf{T}^2} B_2 + i\, R_9 R_{10}$	Kähler T-duality	Mix of
	$R_{10}/R_9 e^{i\theta}$	Complex structure	wrapped F1 / KK
Type I	$\int_{\mathbf{T}^2} C_2 + i\, R_9 R_{10}/g_s$	Kähler T-duality	Wrapped D1
	$R_{10}/R_9 e^{i\theta}$	Complex structure	KK
Type IIB	$C_0 + i\, 1/g_s$	S-duality	D(−1)
orientifold	$R_9/R_{10}\, e^{i\theta}$	Complex structure	Wrapped F1
Type I'	$\int_{\mathbf{S}^1} C_1 + i\, R_9/g_s$	Hidden HW	D0
orientifold	$\int_{\mathbf{S}^1 \times I} B_2 + i\, R_9 R_{10}$	Kähler T-duality	F1 winding
Horava-Witten	$R_{11}/R_9\, e^{i\theta}$	Complex structure	KK
orientifold	$\int_{\mathbf{T}^2 \times I} C_3 + i R_9 R_{10} R_{11}$	Kähler T-duality	wrapped M2

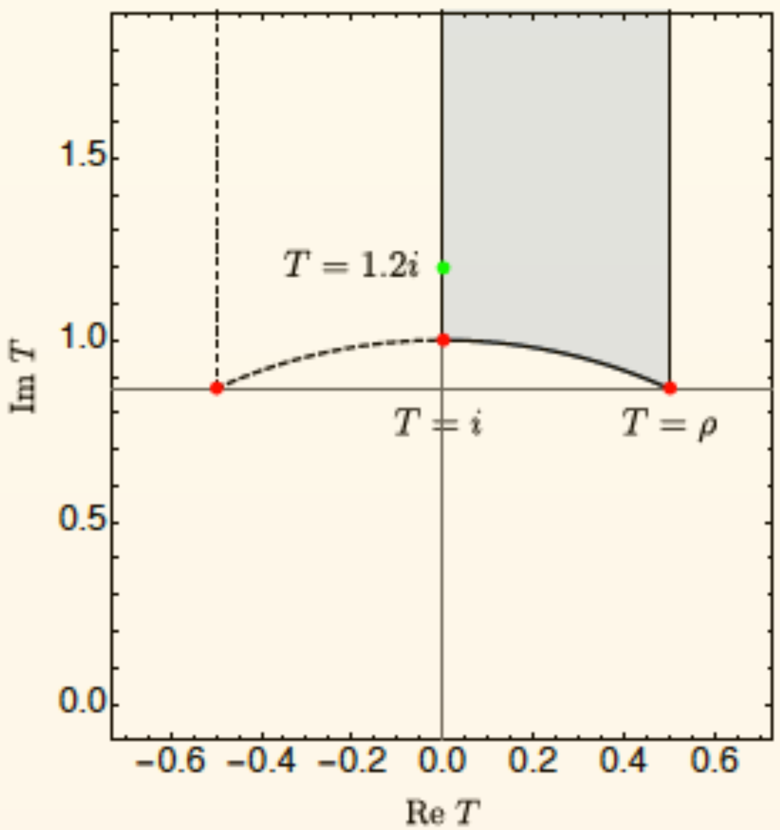
Table 1: Dual pictures and some of their ingredients. Despite similar notation for the compactification radii, they in general have meaning adapted to the corresponding picture.

Gonzalo, L.I., Uranga 2018

For more general superpotentials

$$W = \frac{H(T)}{\eta(T)^6}$$

$$V(T,T^*) = \frac{1}{8T_I^3|\eta|^{12}}\left\{\frac{4T_I^2}{3}\left|\frac{dH}{dT}+\frac{3}{2\pi}H\hat{G}_2\right|^2 - 3|H|^2\right\}$$



- Extrema on boundary of fundamental region
- Examples of Minkowski and AdS vacua, SUSY and non-SUSY
- No example of dS minima found
- Potentials diverge at large ImT (where a continuous global shift symmetry would be recovered)
- In string examples divergence corresponds to a tower of KK(winding) charged particles becoming massless
- Extrema close to self-dual points

There are examples of dS maxima

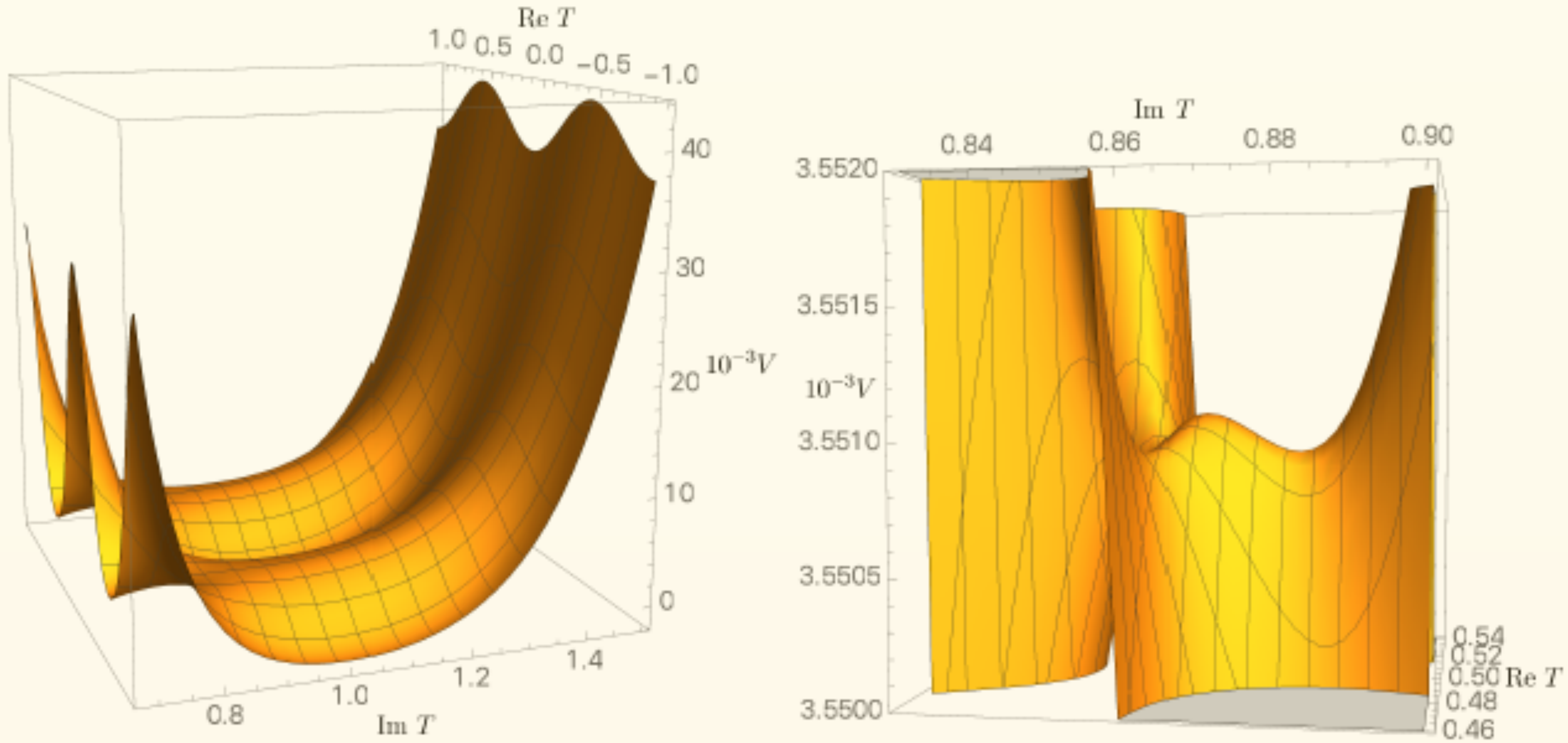
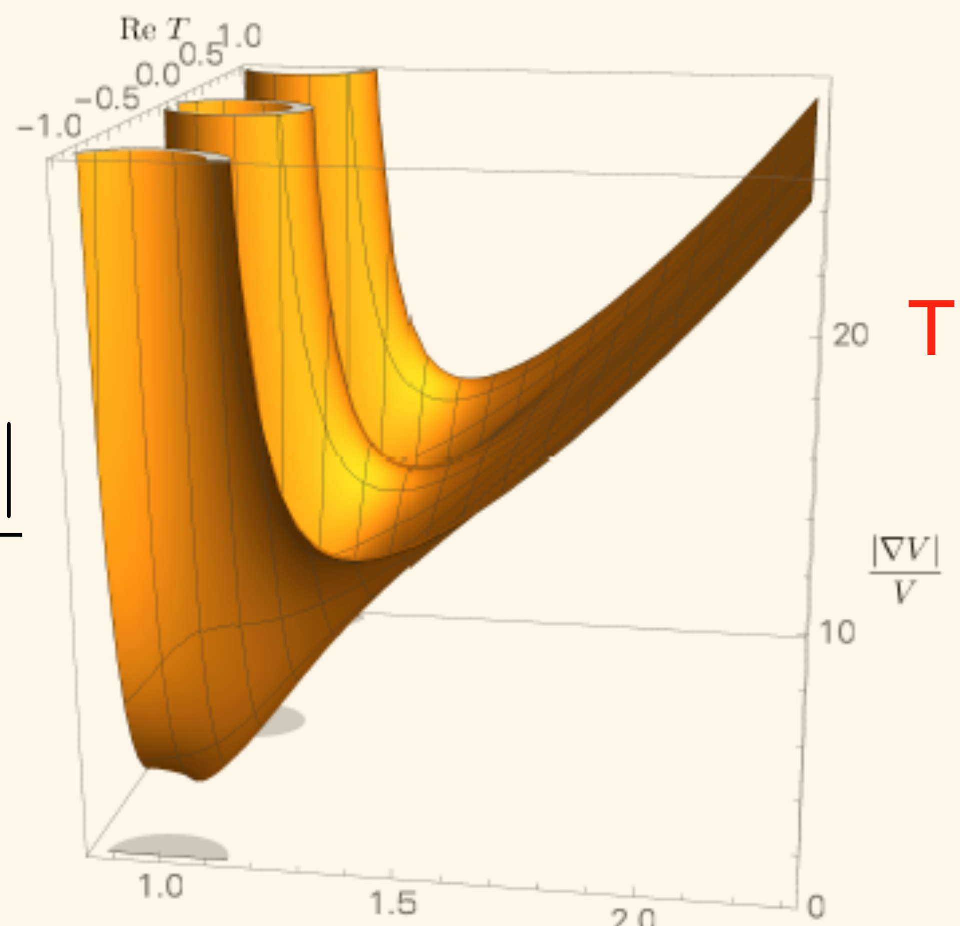


Figure 3: Left: Scalar potential for $W = j^{1/3}/\eta^6$ (i.e. $n = 1$, $m = 0$, $\mathcal{P} = 1$): Right: A zoom around its dS maximum.

$$\frac{|\nabla V|}{V}$$



The ‘refined’ dS swampland conjecture is obeyed

Gonzalo, L.I., Uranga 2018

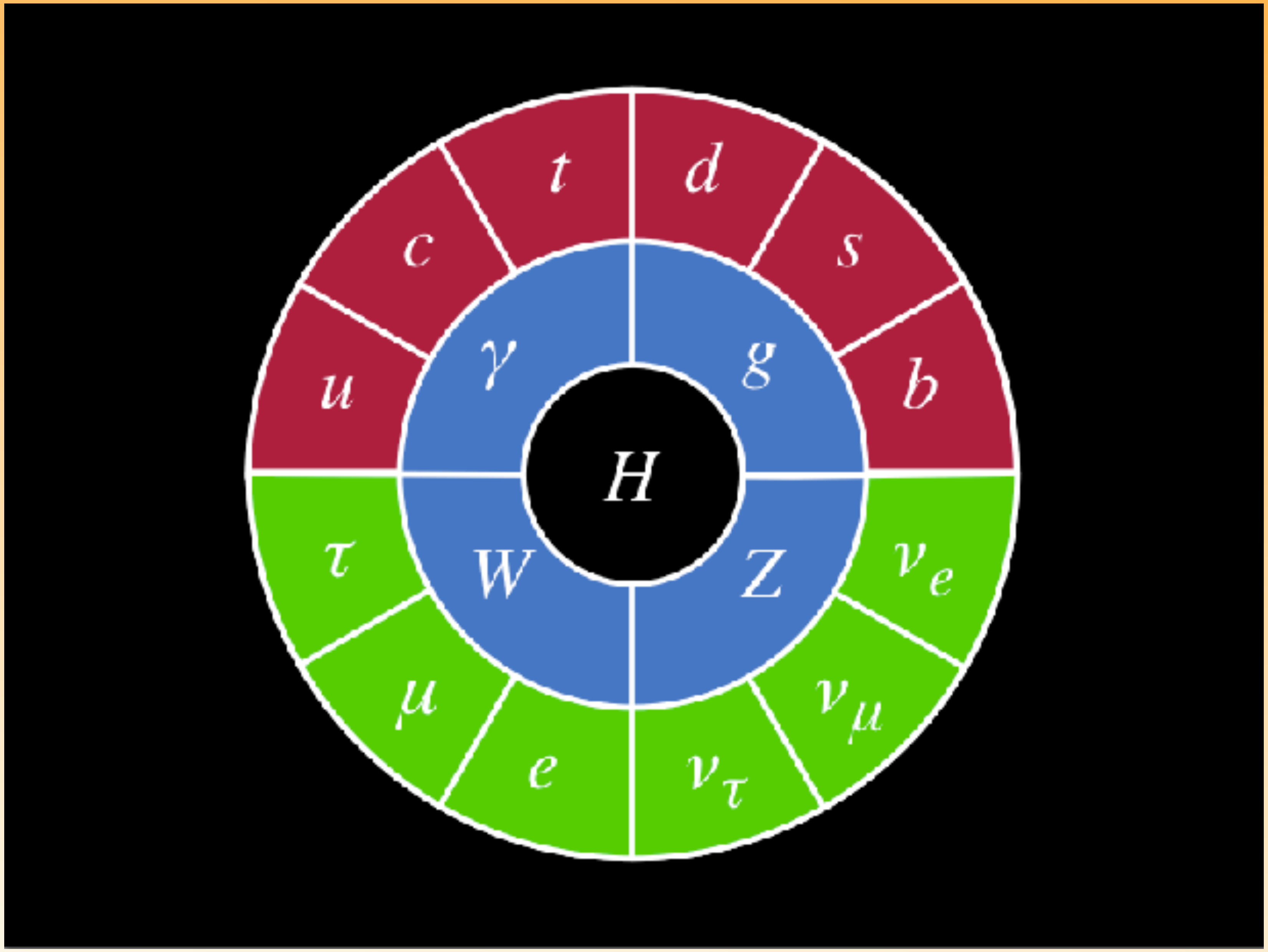
Partial summary

- In non-perturbative string vacua dynamics forbids reaching points in which global symmetries are recovered

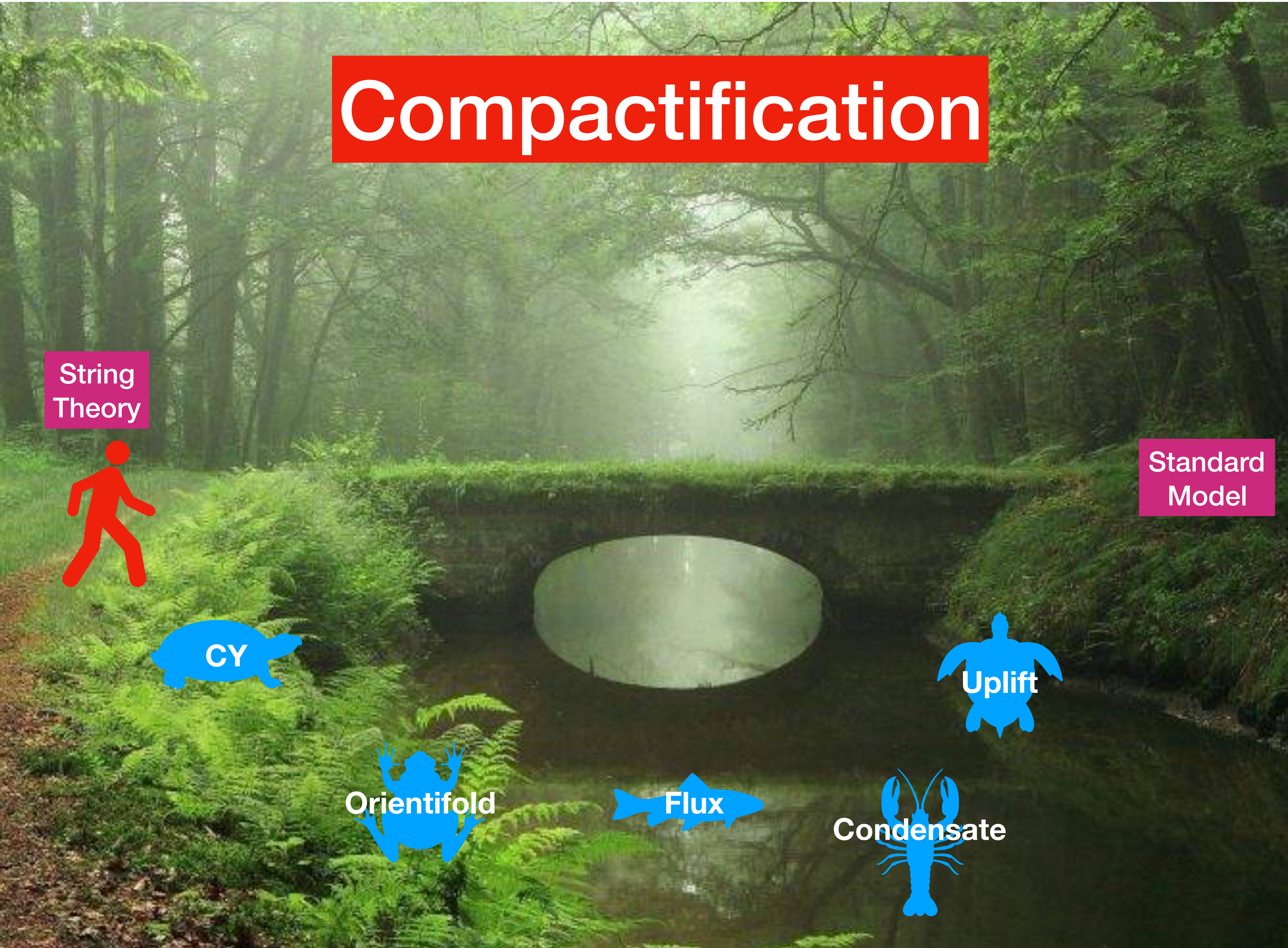
- Results consistent with: absence of global symmetries, distance swampland conjecture and (refined) swampland conjecture: no dS in (these simple models least)

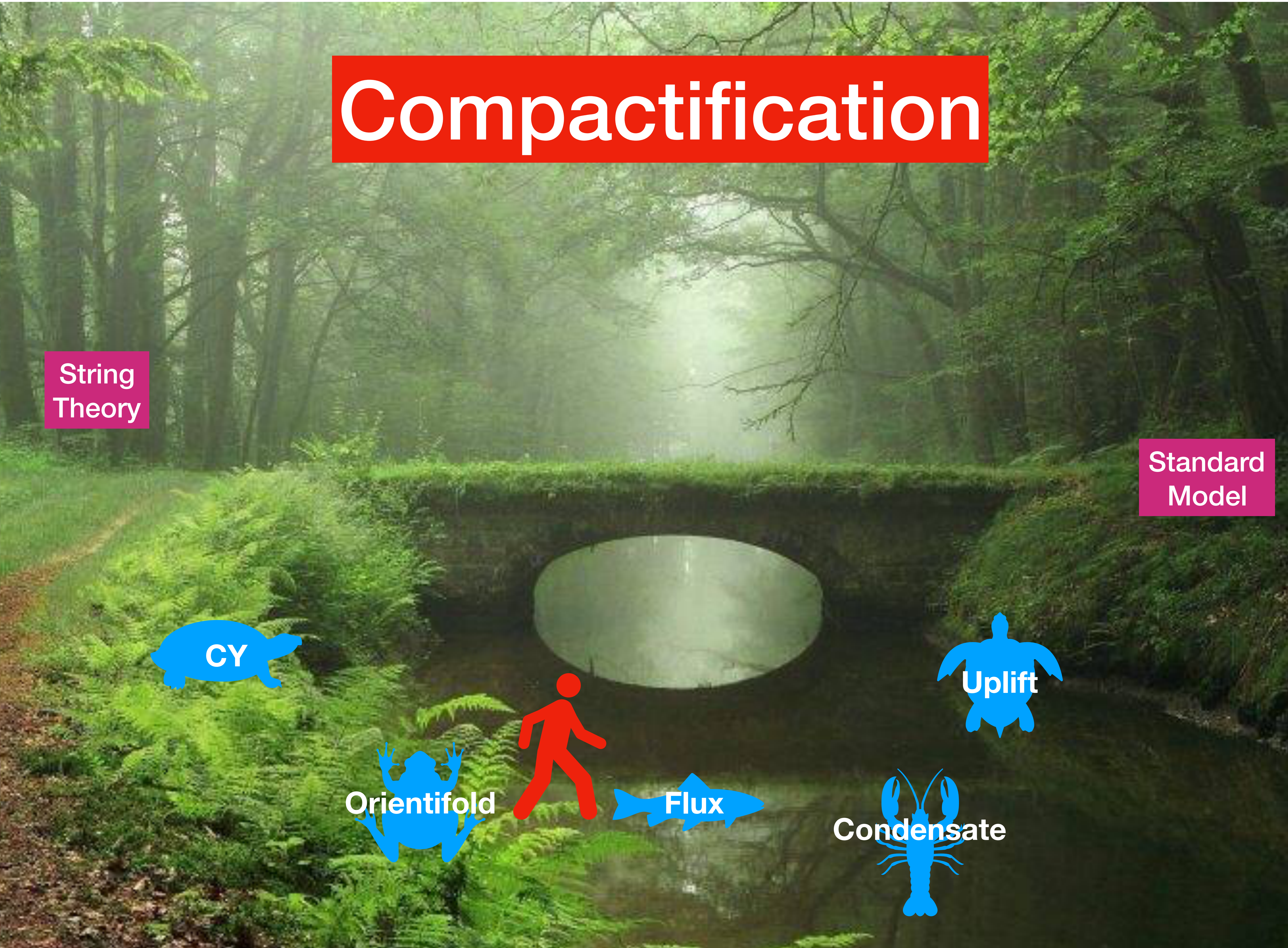
- Extrema close to self-dual points: the usual procedure in string compactifications of taking a large volume + weak coupling limit may be Problematic

Implications for the SM?

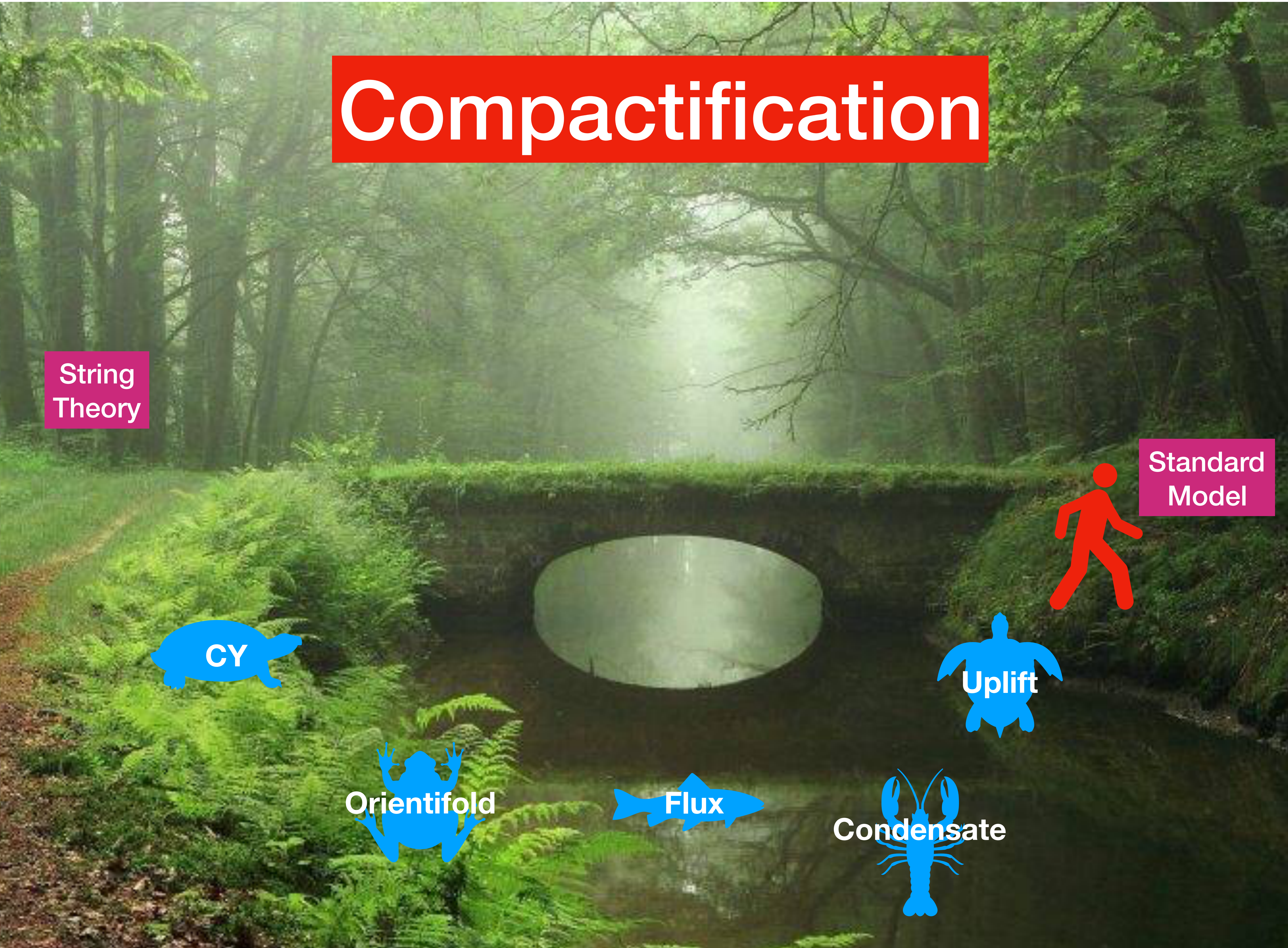


Compactification



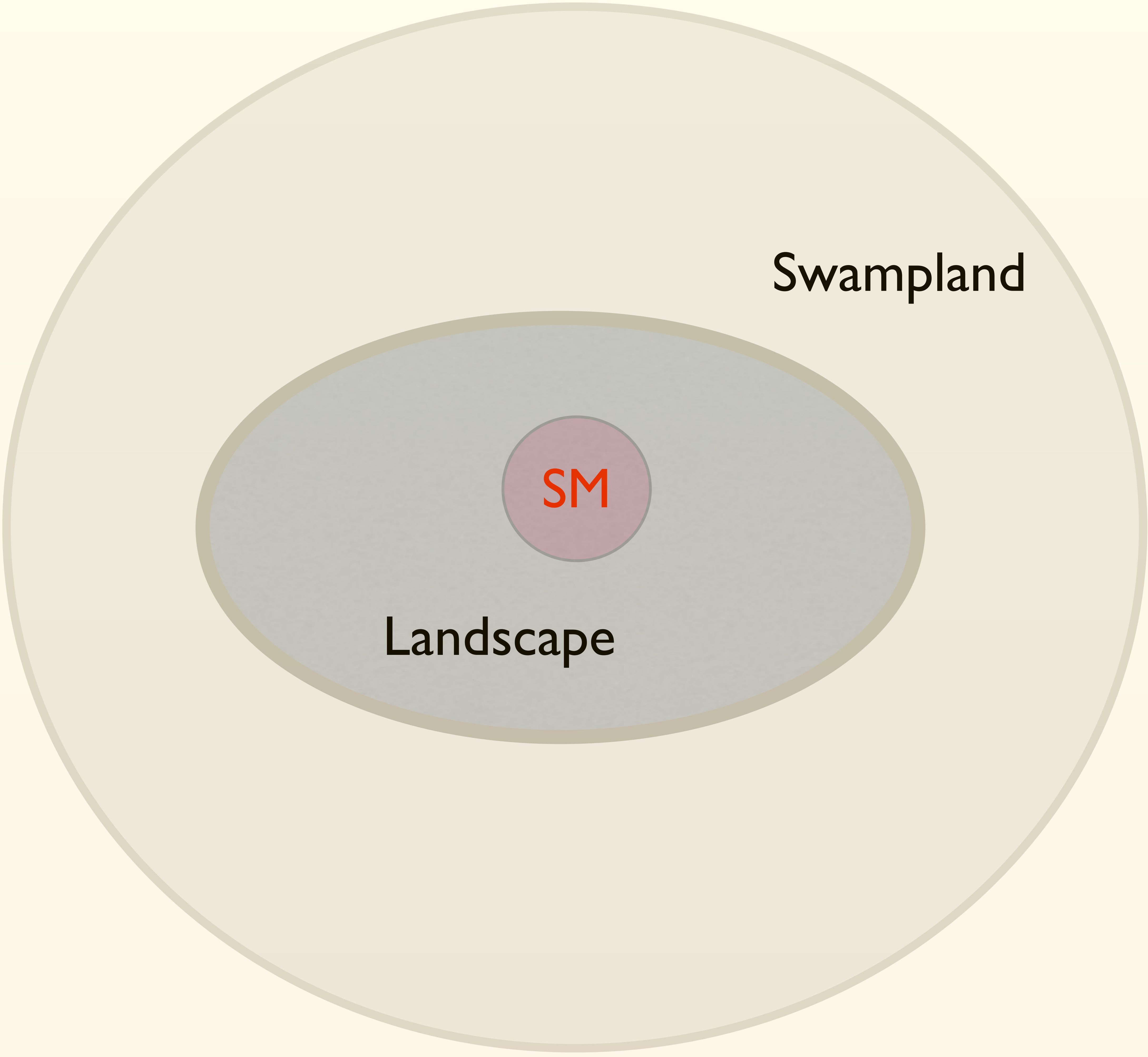

Compactification
String Theory
Standard Model
CY
Uplift
Orientifold
Flux
Condensate

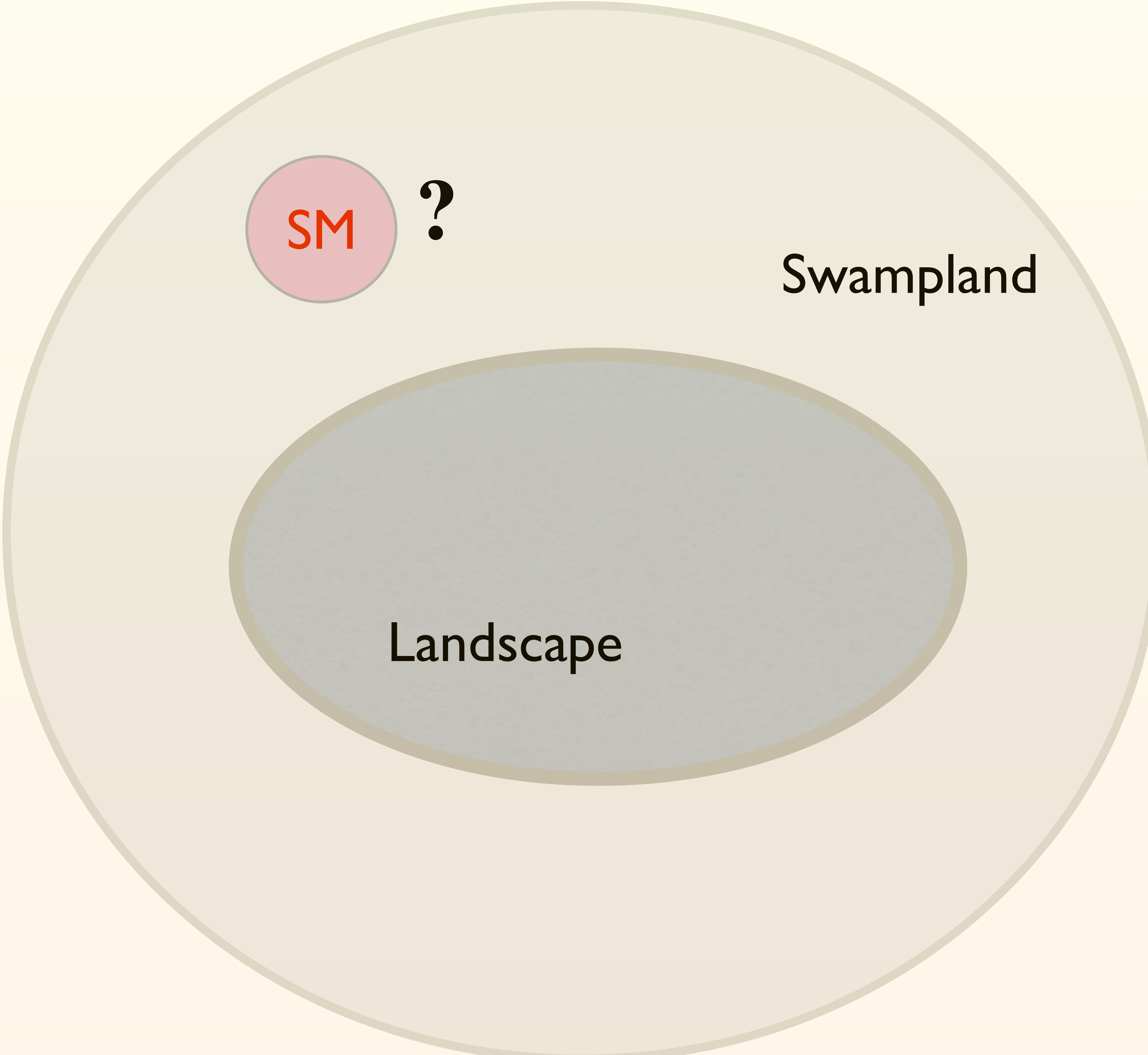
Compactification



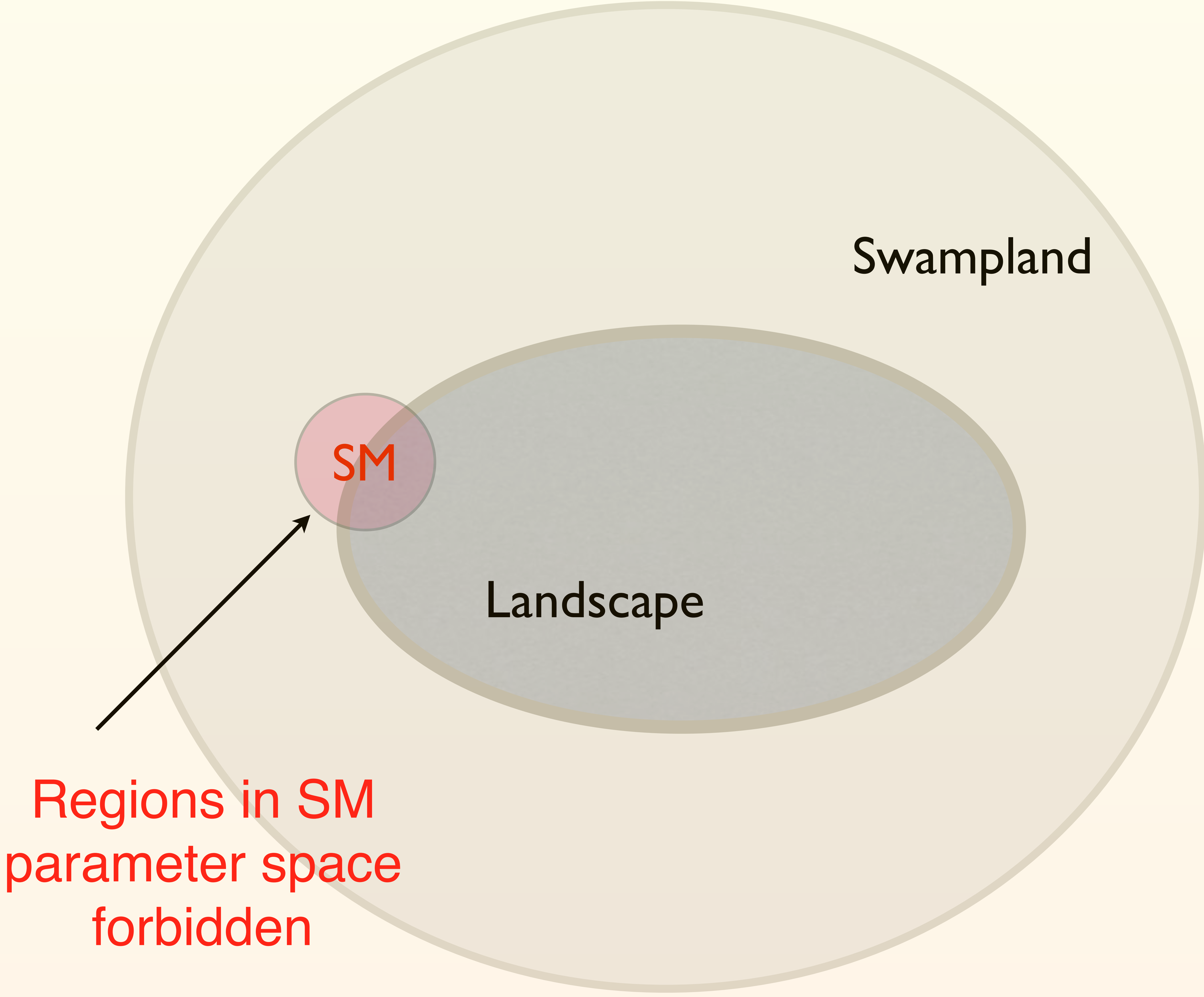
Swampland constraints

Swampland constraints


Swampland
SM
Landscape



SM
?
Swampland
Landscape


Swampland
SM
Landscape
Regions in SM
parameter space
forbidden

Consequences for the SM

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

If SM consistent, any compactification should be consistent

Ooguri, Vafa 2016

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

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

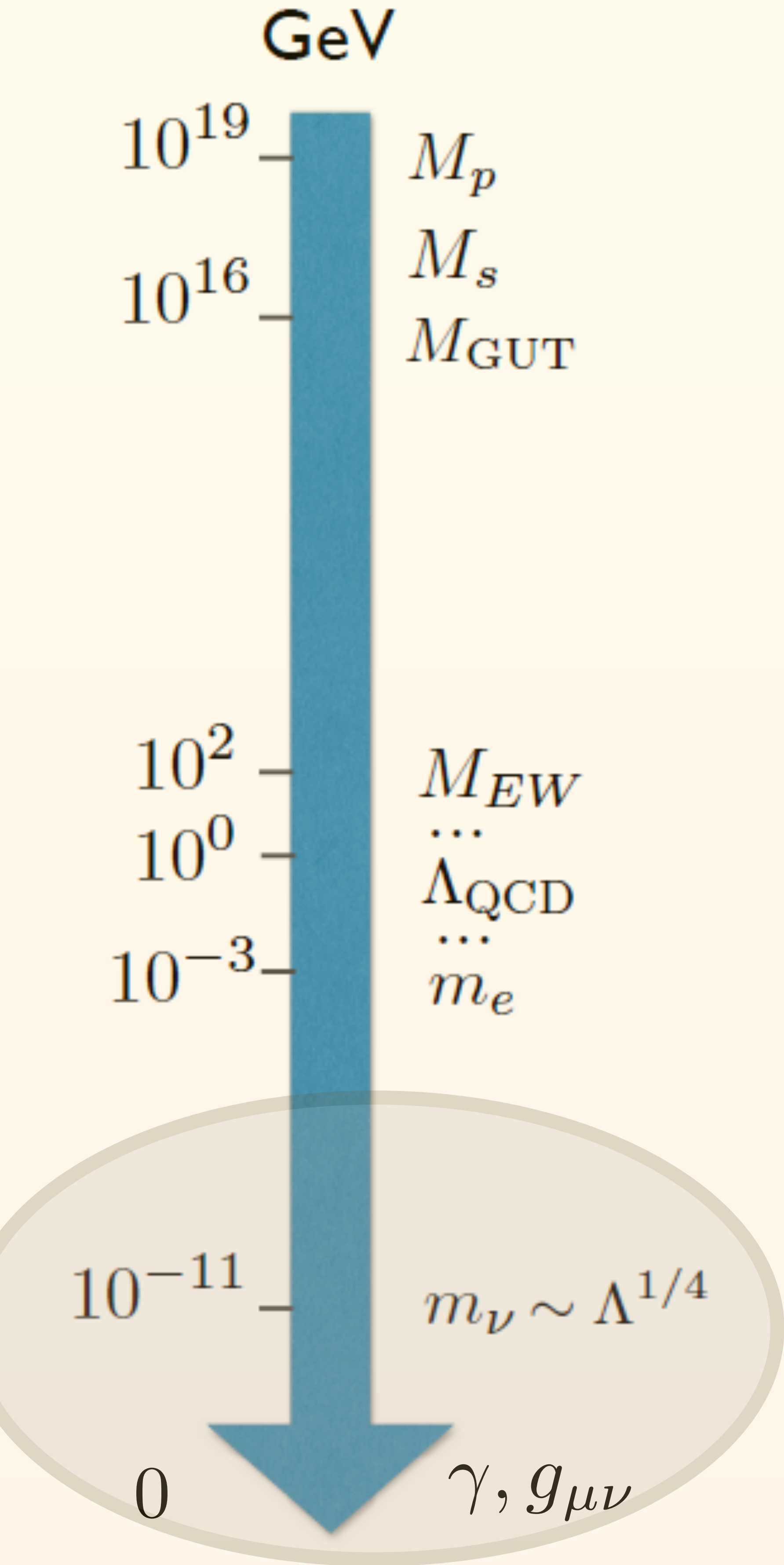
Arnold, Fornal, Wise 2010

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

Scalar WGC yields essentially same conditions

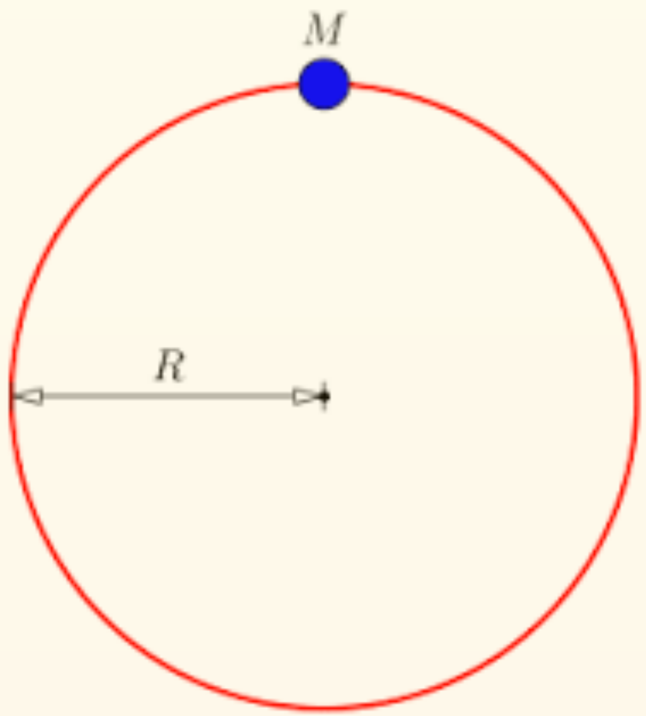
Gonzalo, L.I., 2019, to appear

Scales in Fundamental Physics

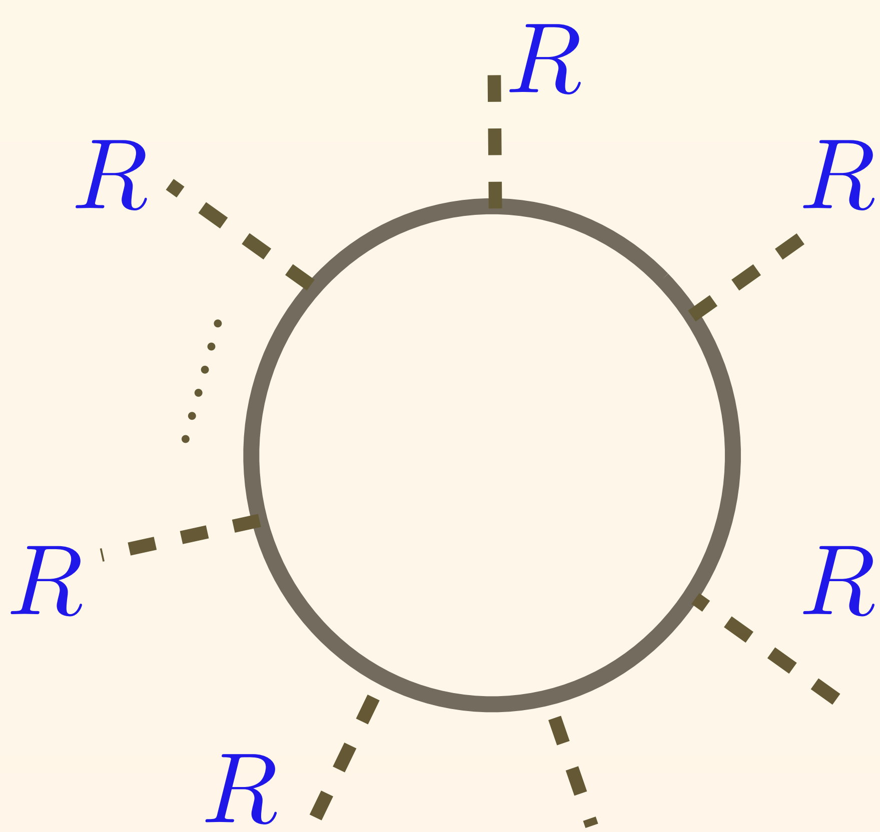


Will focus first in lightest SM sector

SM compactified to 3D on a circle



A Compact Dimension



$$Radius\ R\ is\ a\ massless\ scalar\ field$$

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)

$The\ SM\ +\ gravity\ on\ a\ circle\ S^1$

Arkani-Hamed, Dubovsky, Nicolis, Villadoro, 2007

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

$The\ radius\ potential:$

$One-loop\ Casimir\ energy$

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

$From\ 4D\ c.c.$

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

ν_i

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

$\nu_i\ with\ periodic\ b.c.\ contributes\ positively!!$

$The\ SM\ +\ gravity\ on\ a\ circle\ S^1$

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

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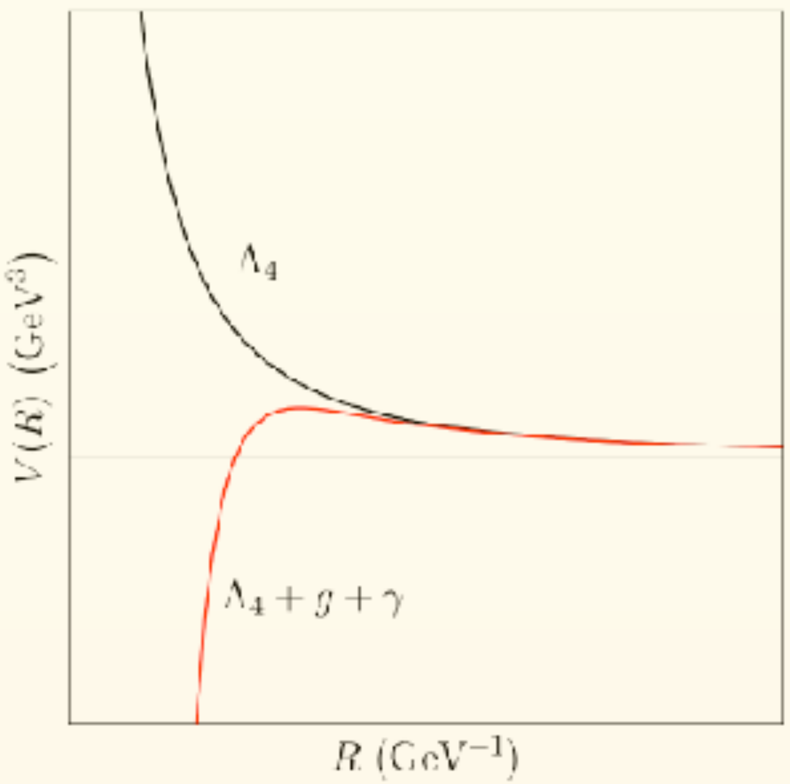
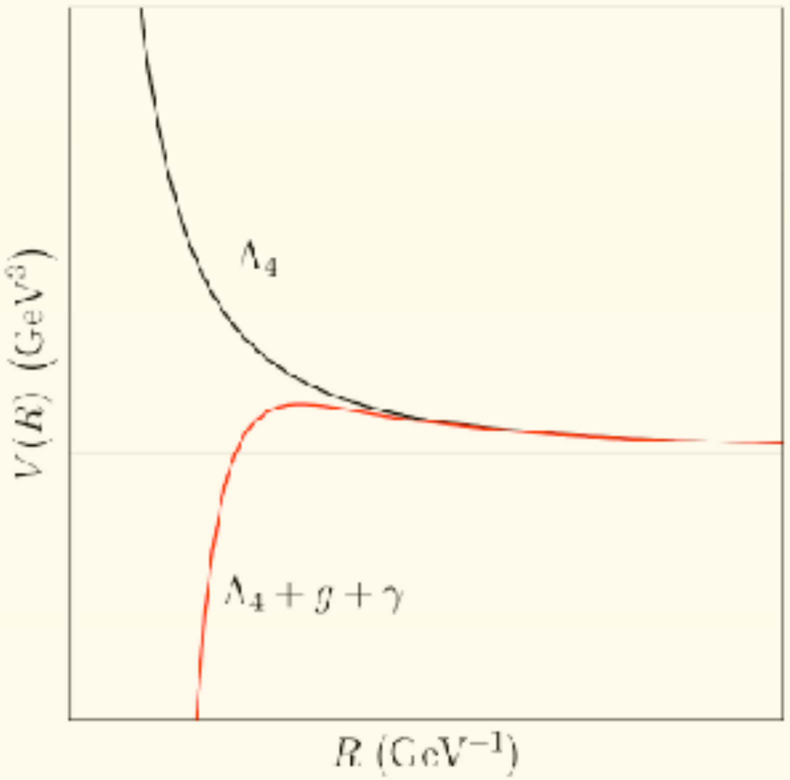
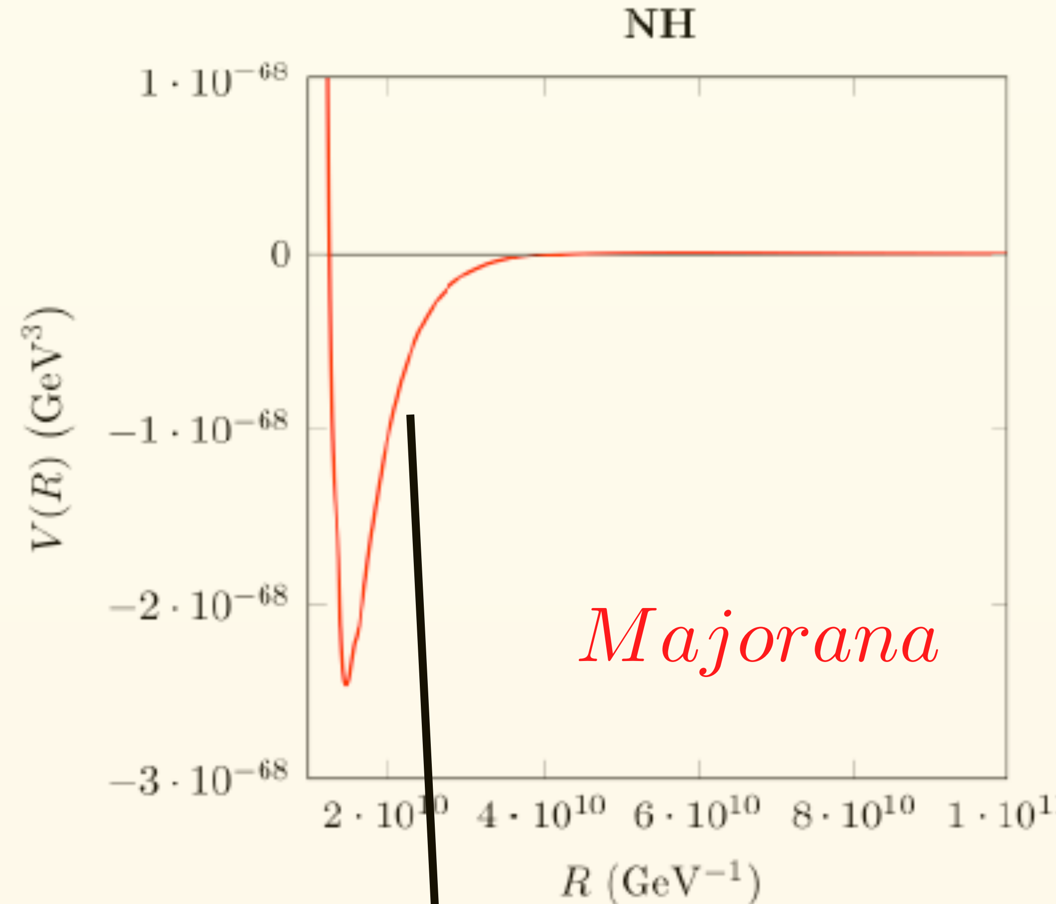
$\nu_i\ with\ periodic\ b.c.\ contributes\ positively!!$

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

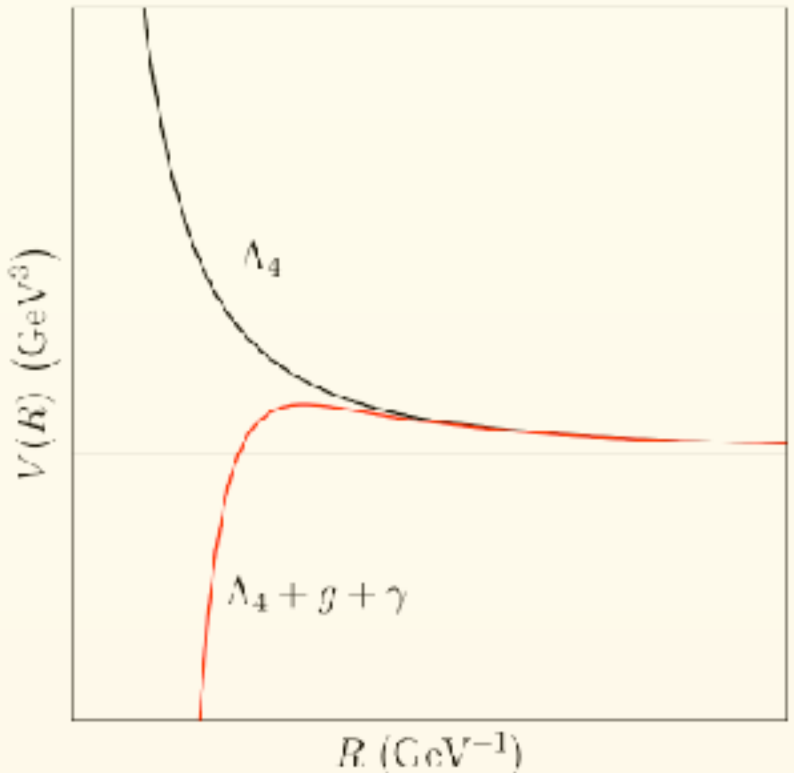


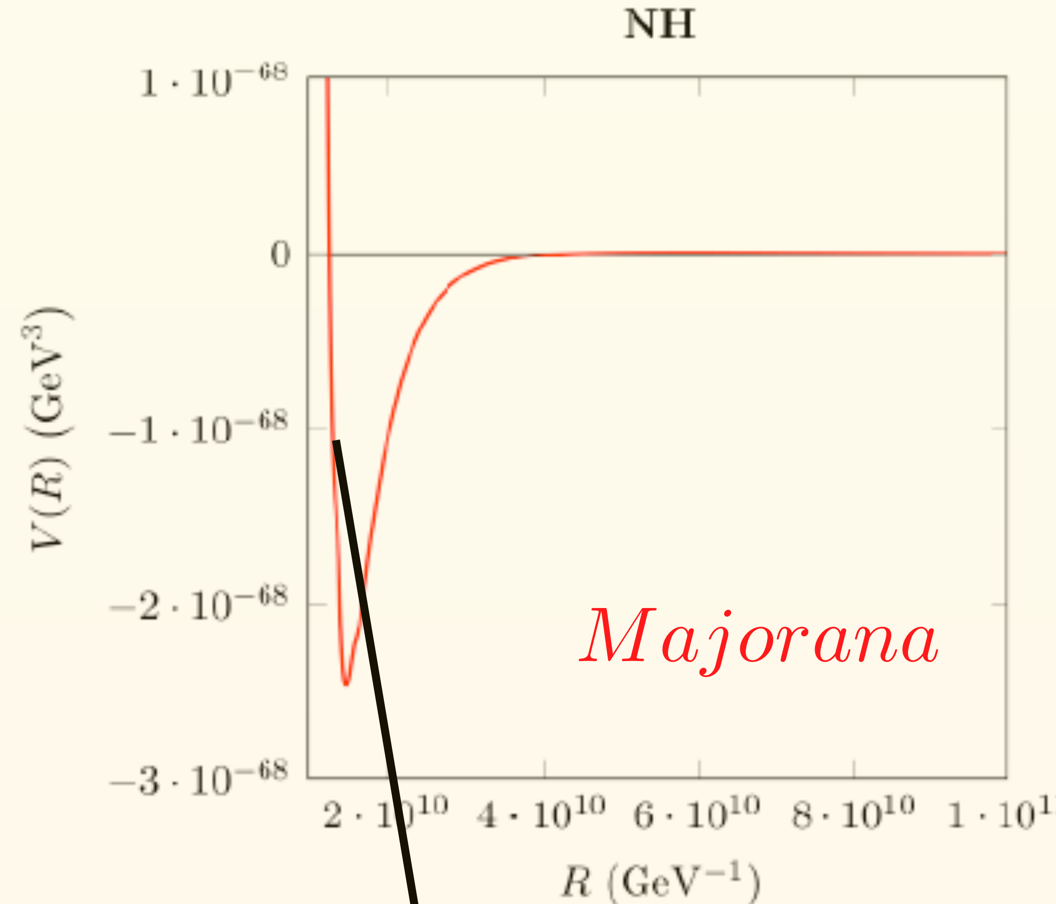
Λ_4
$\Lambda_4 + g + \gamma$
$V(R)$ (GeV^3)
R (GeV^{-1})





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

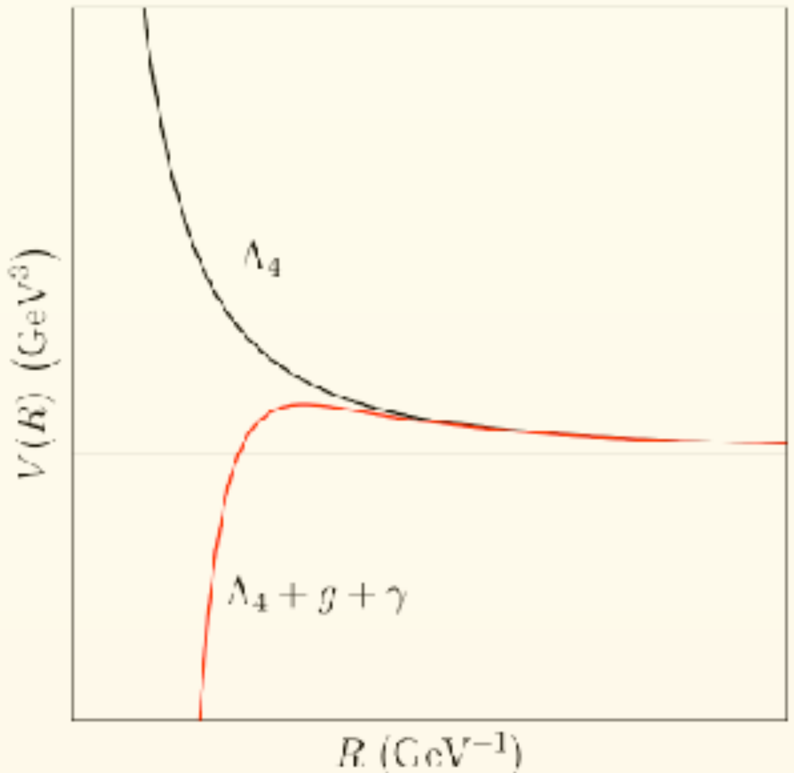


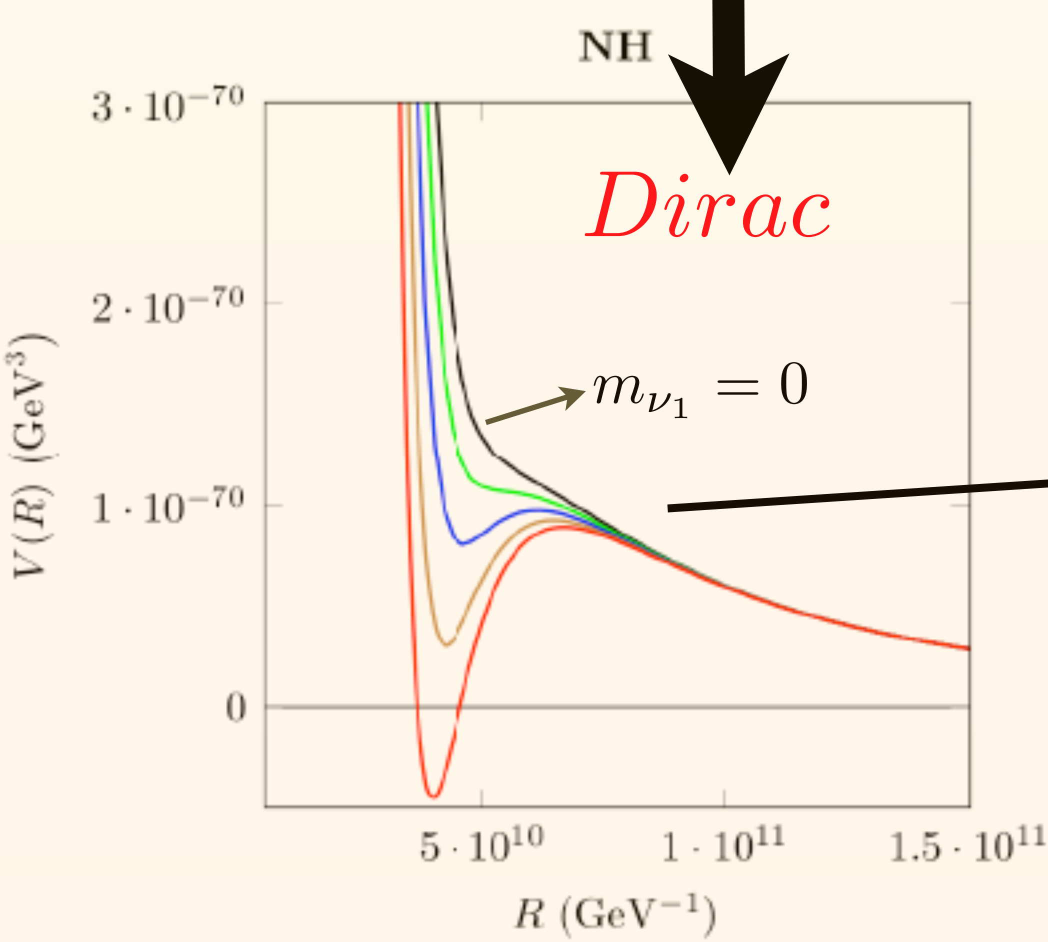


$$(\underbrace{-2}_{\gamma} \underbrace{-\,2}_{g_{\mu\nu}} \underbrace{+\,6}_{\nu^M_{1,2,3}})\left(\frac{r^3}{720\pi R^6}\right)$$

$$Majorana\ \nu_1\ forbidden!!$$

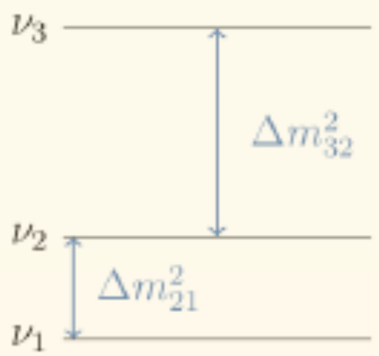
Ooguri,Vafa 2016

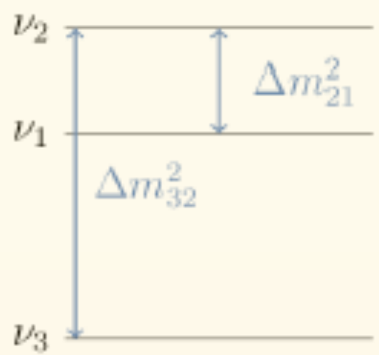




$$(\underbrace{-2}_{\gamma} \underbrace{-\,2}_{g_{\mu\nu}} \underbrace{+\,4}_{\nu_1^D})\left(\frac{r^3}{720\pi R^6}\right)$$

Constraints on neutrino masses





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

Majorana: ruled out!!

$$\textit{There is always an AdS vacuum for any } m_{\nu_1}$$

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

$$m_{\nu_1} < 7.7\ \text{meV (NH)}$$
$$m_{\nu_3} < 2.1\ \text{meV (IH)}$$

L.I, Martin-Lozano, Valenzuela 2017

Hamada, Shiu 2017

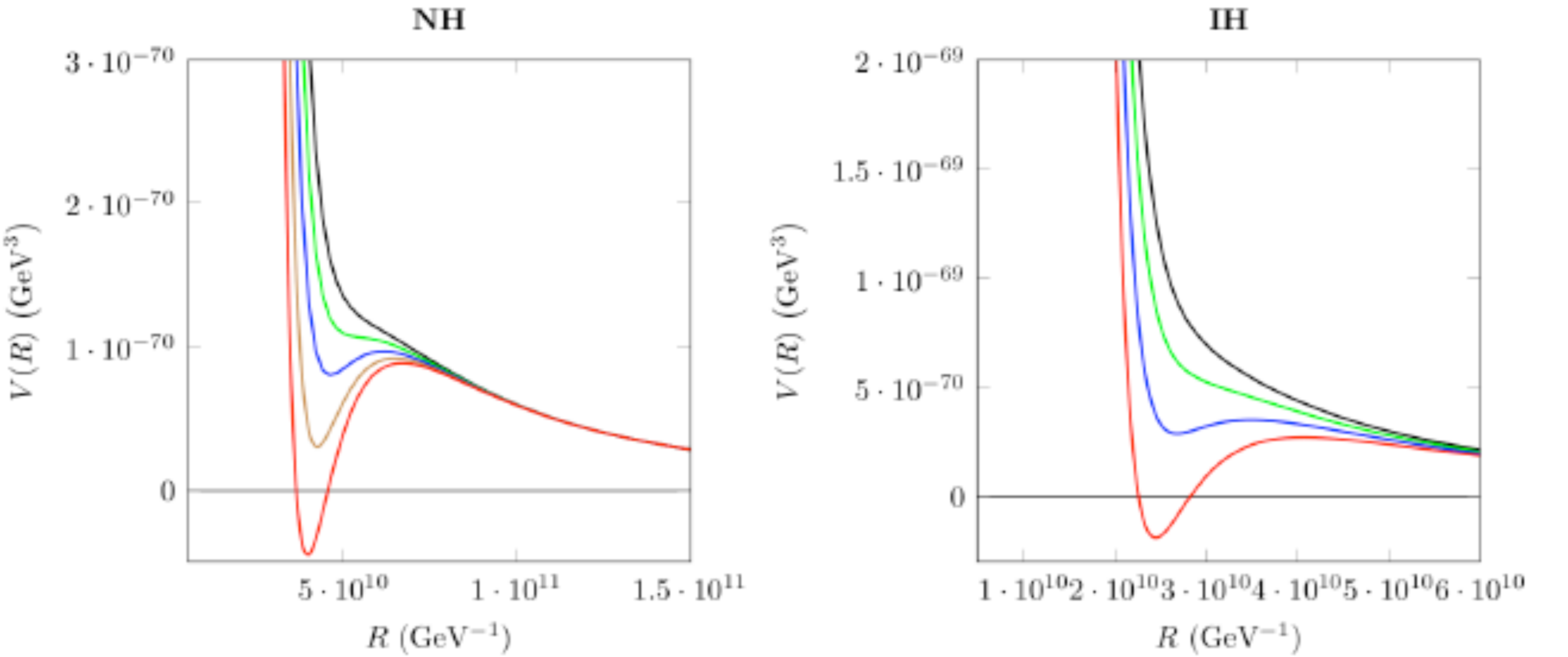
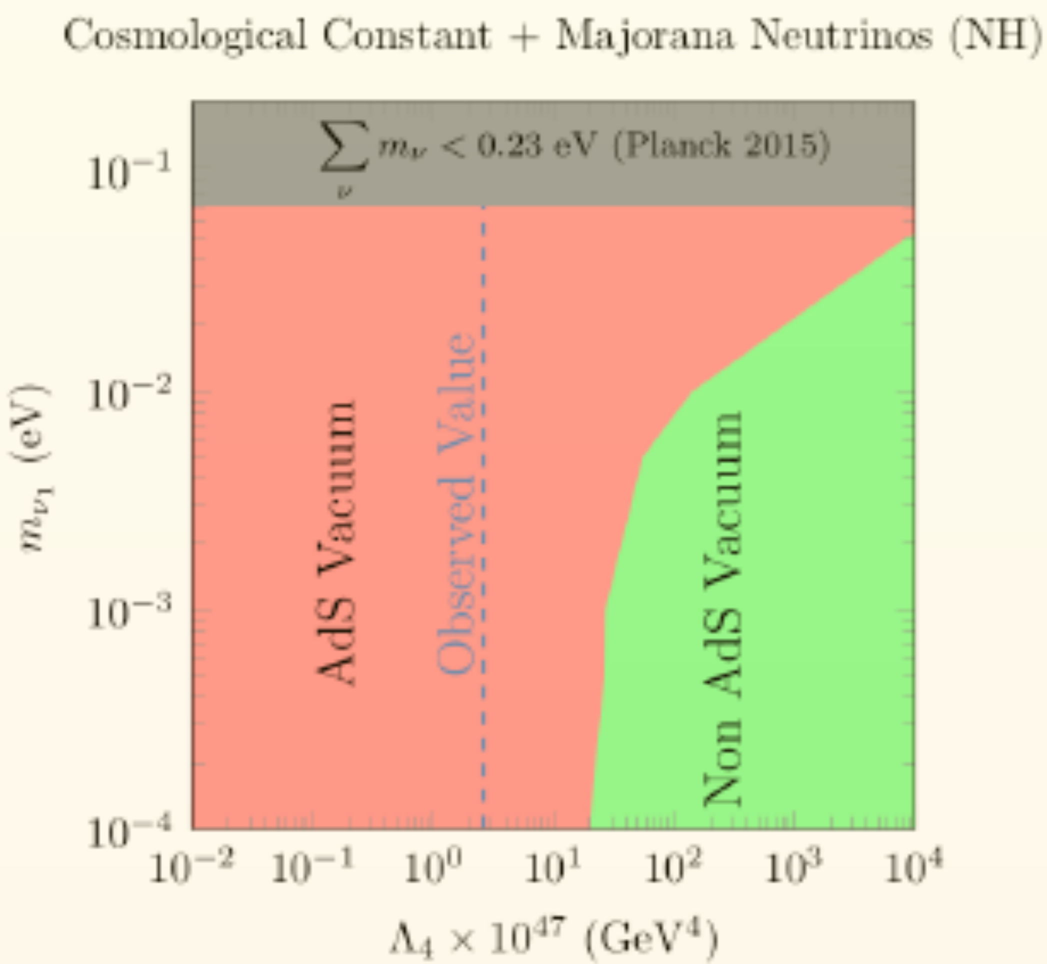


Figure 4: Radion effective potential for Dirac neutrinos when considering normal hierarchy (left) and inverted hierarchy (right). For the case of NH the different lines correspond to several values for the lightest neutrino mass: $m_{\nu_1} = 6.0$ meV (black), 6.5 meV (green), 7.0 meV (blue), 7.5 meV (brown) and 8.0 meV (red). In the case of IH the different colours correspond to the lightest neutrino masses: $m_{\nu_3} = 1.5$ meV (black), 2.0 meV (green), 2.5 meV (blue), 3.0 meV (red).

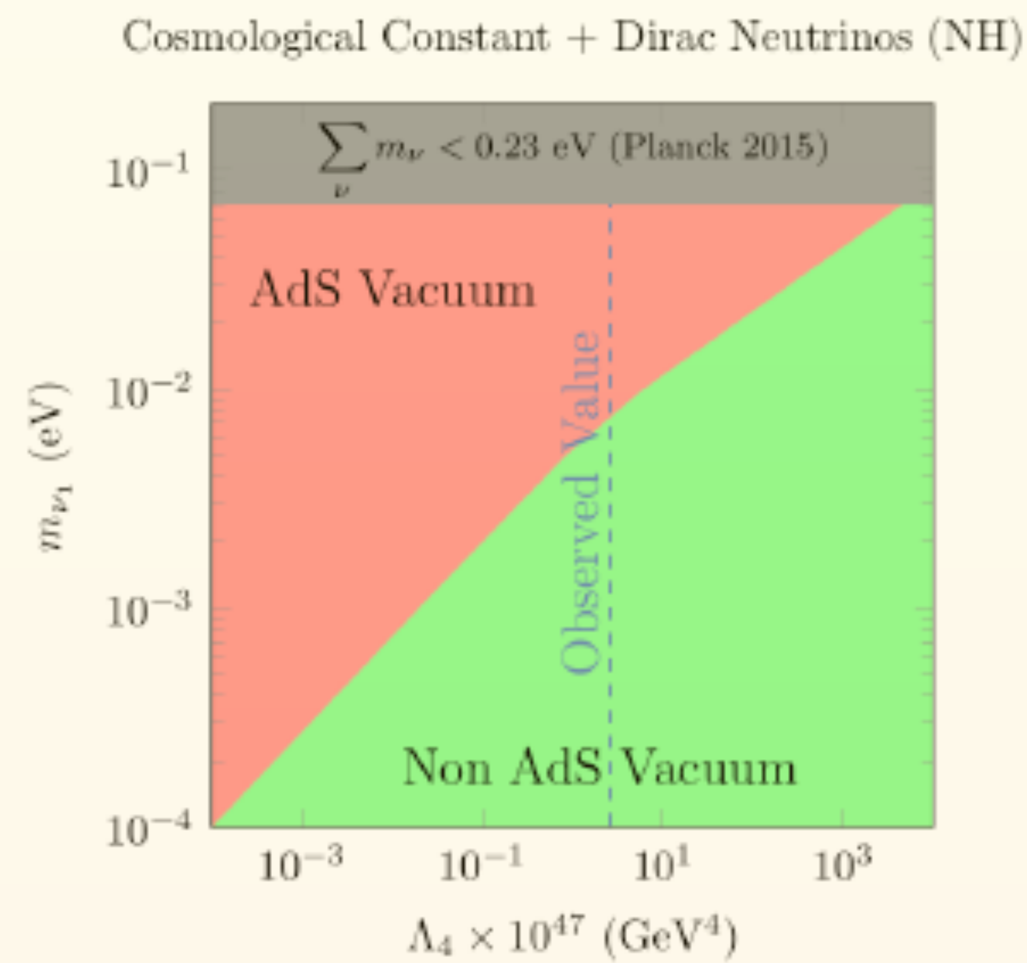
No big differences between normal and inverted hierarchy

$R_{min} \simeq 1/m_\nu \simeq 10^{-5} meters$ $\quad$ $l_{AdS_3} \simeq 4 \times 10^{25} m. \simeq l_{dS_4}$

Lower bound on the cosmological constant



Majorana



Dirac

To avoid AdS

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

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

Explains coincidence!!

L.I, Martin-Lozano, Valenzuela 2017

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

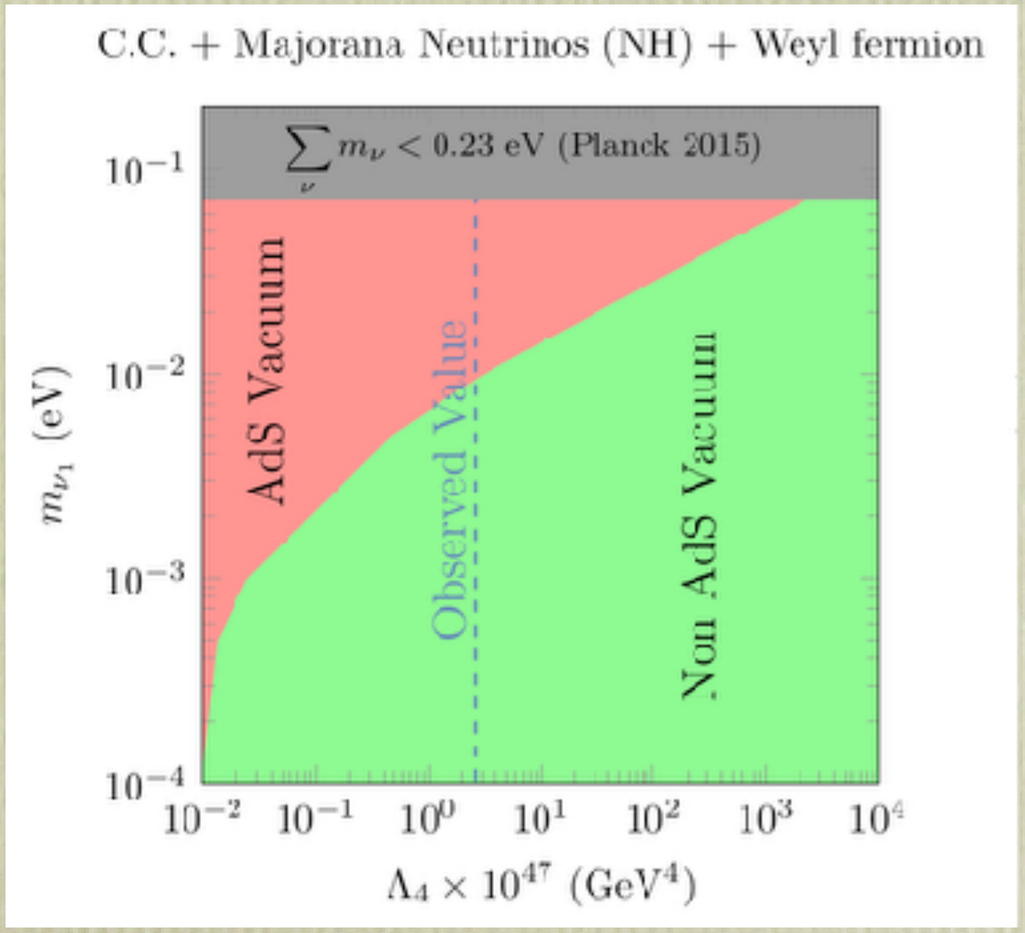
Constraints with BSM physics:

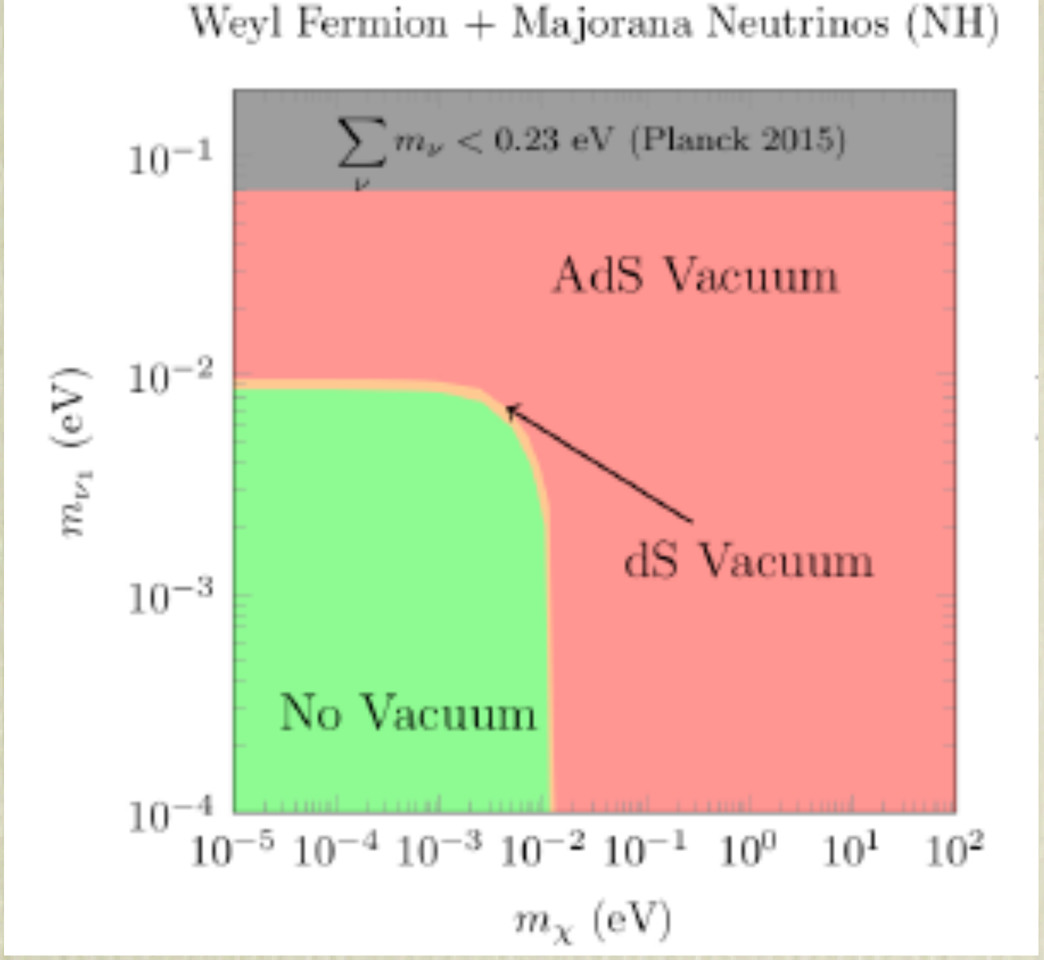
One additional very light Weyl spinor

→ Possitive contribution to Casimir energy

(e.g. axino, hidden sector fermion,...)

e.g. Majorana, NH





$$Majorana\ neutrinos\ possible\ for\ m_\psi, m_{\nu_1} \leq 10^{-2}\ eV$$

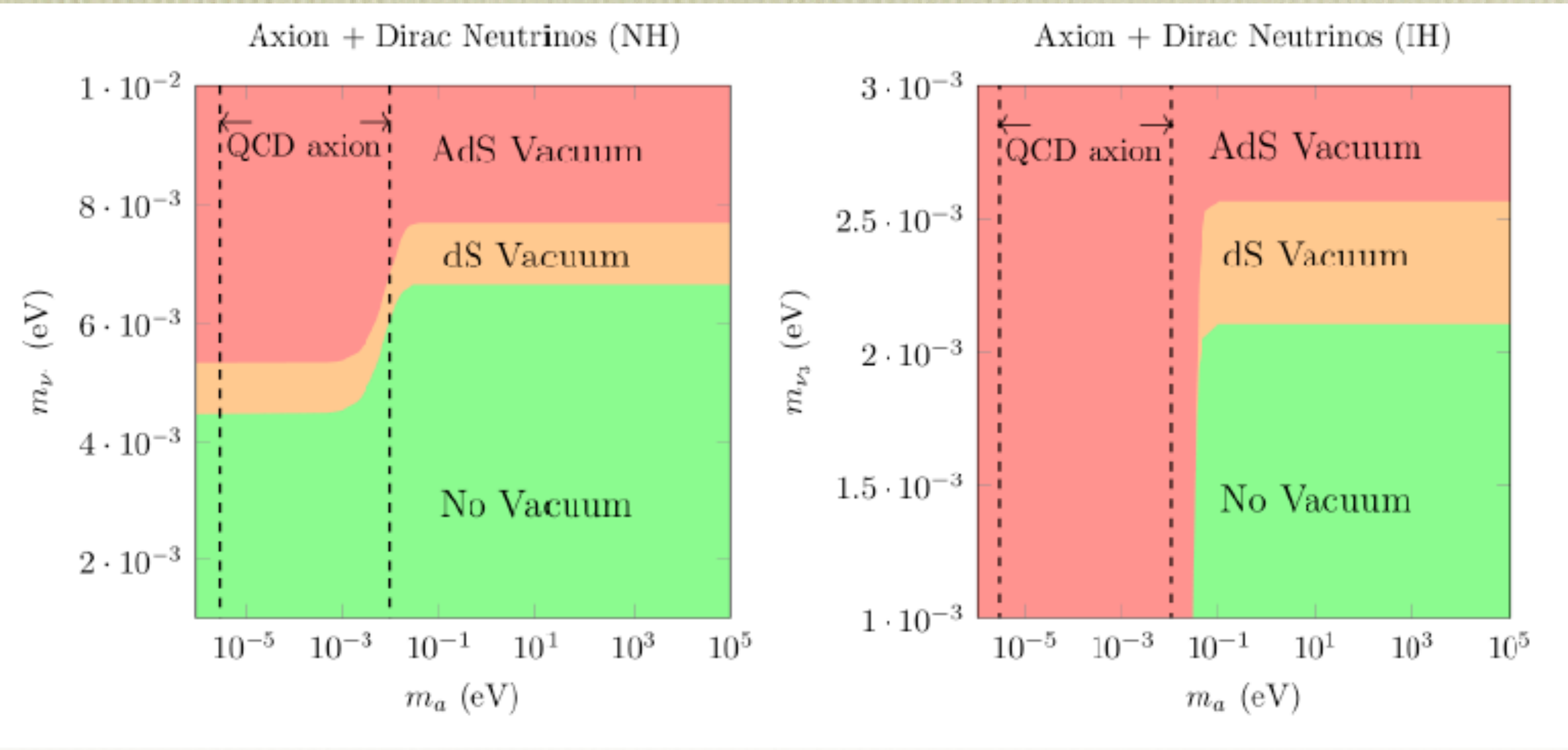
L.I,Martin-Lozano, Valenzuela 2017

2) One additional very light scalar (e.g. axion)

Negative contribution to Casimir energy

Majorana : AdS minima deeper Ruled out

Dirac:



IH Dirac neutrinos incompatible with QCD axion

$The\ SM\ +\ gravity\ on\ a\ torus\ T^2$

Arnold, Fornal, Wise 2010

$$V(a,\tau) = (2\pi a)^2\Lambda_4 + \sum_a (-1)^{F_a} n_a V^{(1)}_{2D-C}[a,\tau_1,\tau_2,m_a],$$

with $V^{(1)}_{2D-C}[a,\tau_1,\tau_2,m_a]$ defined by

$$V^{(1)}_{2D-C}[a,\tau_1,\tau_2,m_a] = -\frac{1}{(2\pi a)^2}\left[\frac{2(am)^{3/2}}{\tilde{\tau}^{1/4}}\sum_{p=1}^{\infty}\frac{1}{p^{3/2}}K_{3/2}(2\pi apm_a\sqrt{\tilde{\tau}_2}) + 2\tilde{\tau}_2(am)^2\sum_{p=1}^{\infty}\frac{1}{p^2}K_2\left(\frac{2\pi apm_a}{\sqrt{\tilde{\tau}_2}}\right) + 4\sqrt{\tilde{\tau}_2}\sum_{n,p=1}^{\infty}\frac{1}{p^{3/2}}(n^2+\frac{(am)^2}{\tilde{\tau}_2})^{3/4}\cos(2\pi pn\tilde{\tau}_1)K_{3/2}(2\pi p\tilde{\tau}_2\sqrt{n^2+\frac{(am)^2}{\tilde{\tau}_2}})\right],$$

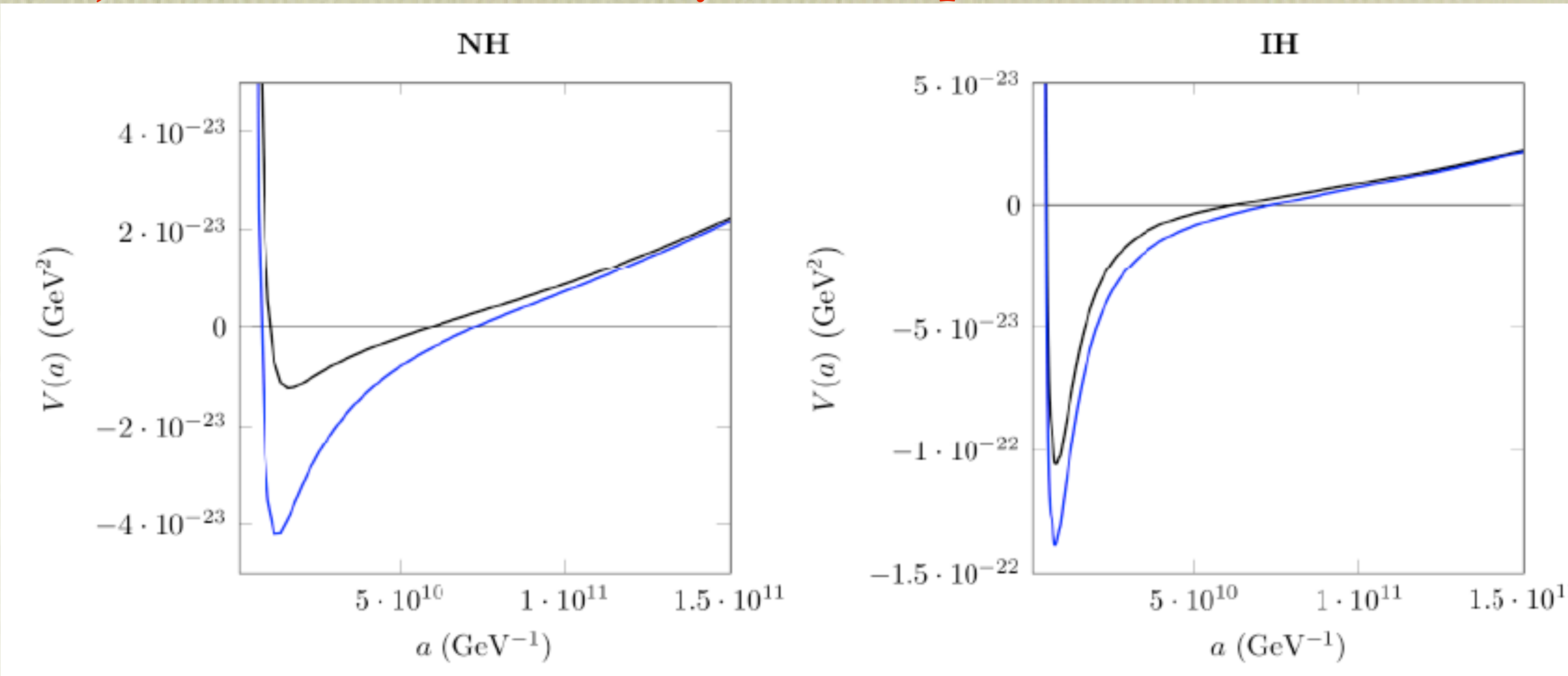
where the 2D torus is parametrized as

$$t_{ij} = \frac{a^2}{\tau_2}\begin{pmatrix} 1 & \tau_1 \\ \tau_1 & |\tau|^2 \end{pmatrix}.$$

stationary points in the case of the 2D torus are $\tau = 1$ and $\tau = 1/2 + i\sqrt{3}/2$.

Results similar to 3D but numerically a bit stronger

Majorana: AdS vacua always develop. Ruled out



L.I,Martin-Lozano, Valenzuela 2017

Dirac: slightly stronger constraints

	NH	IH
No vacuum	$m_{\nu_1} < 4.12$ meV	$m_{\nu_3} < 1.0$ meV
AdS$_3$ vacuum	$m_{\nu_1} > 4.12$ meV	$m_{\nu_3} > 1.0$ meV

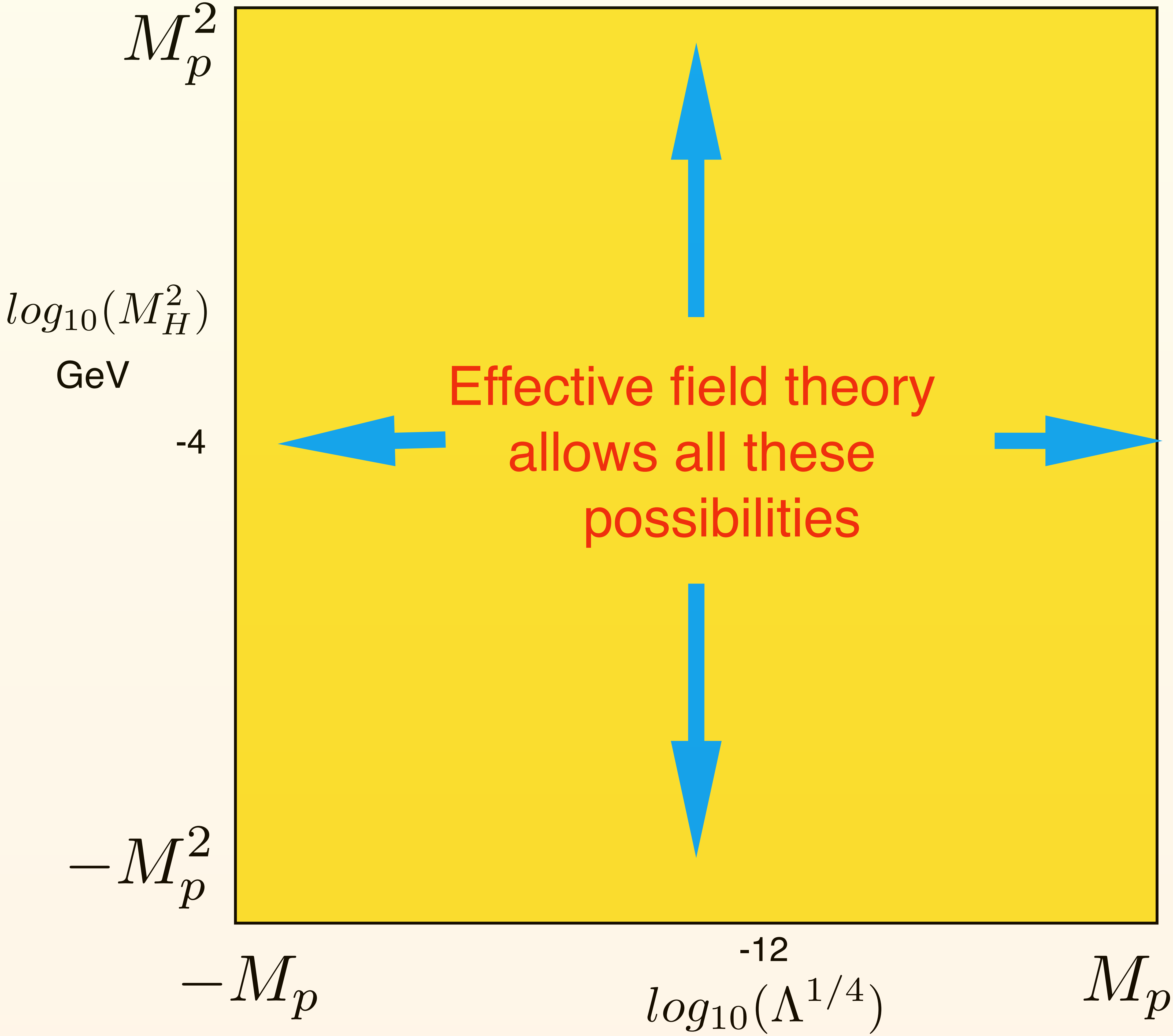
Similar results in T^2/Z_{2N} (in which W.L. can be projected out)

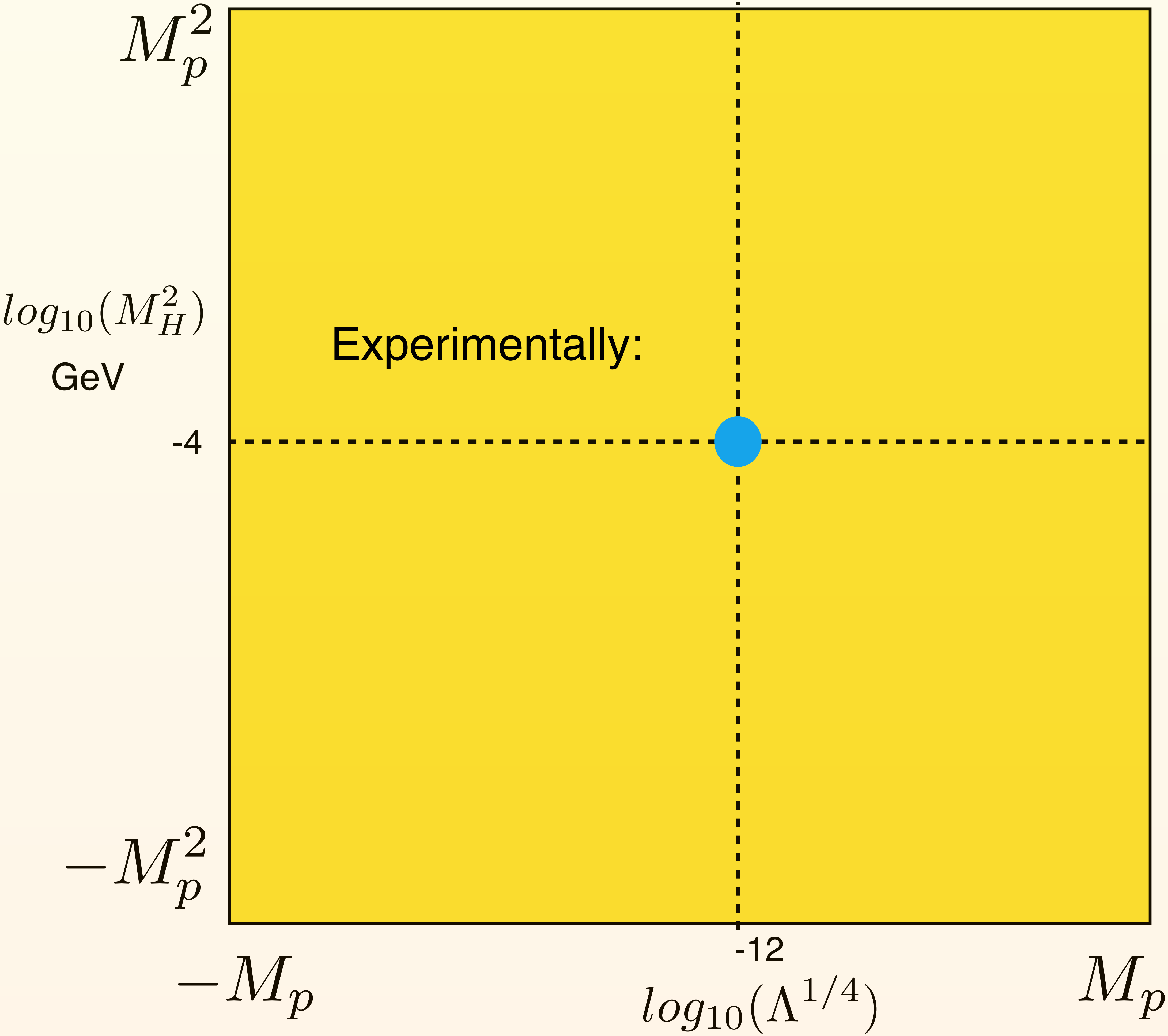
Gonzalo,Herraez,L.I. 2018

Hierarchy Problem, Naturality and the Swampland

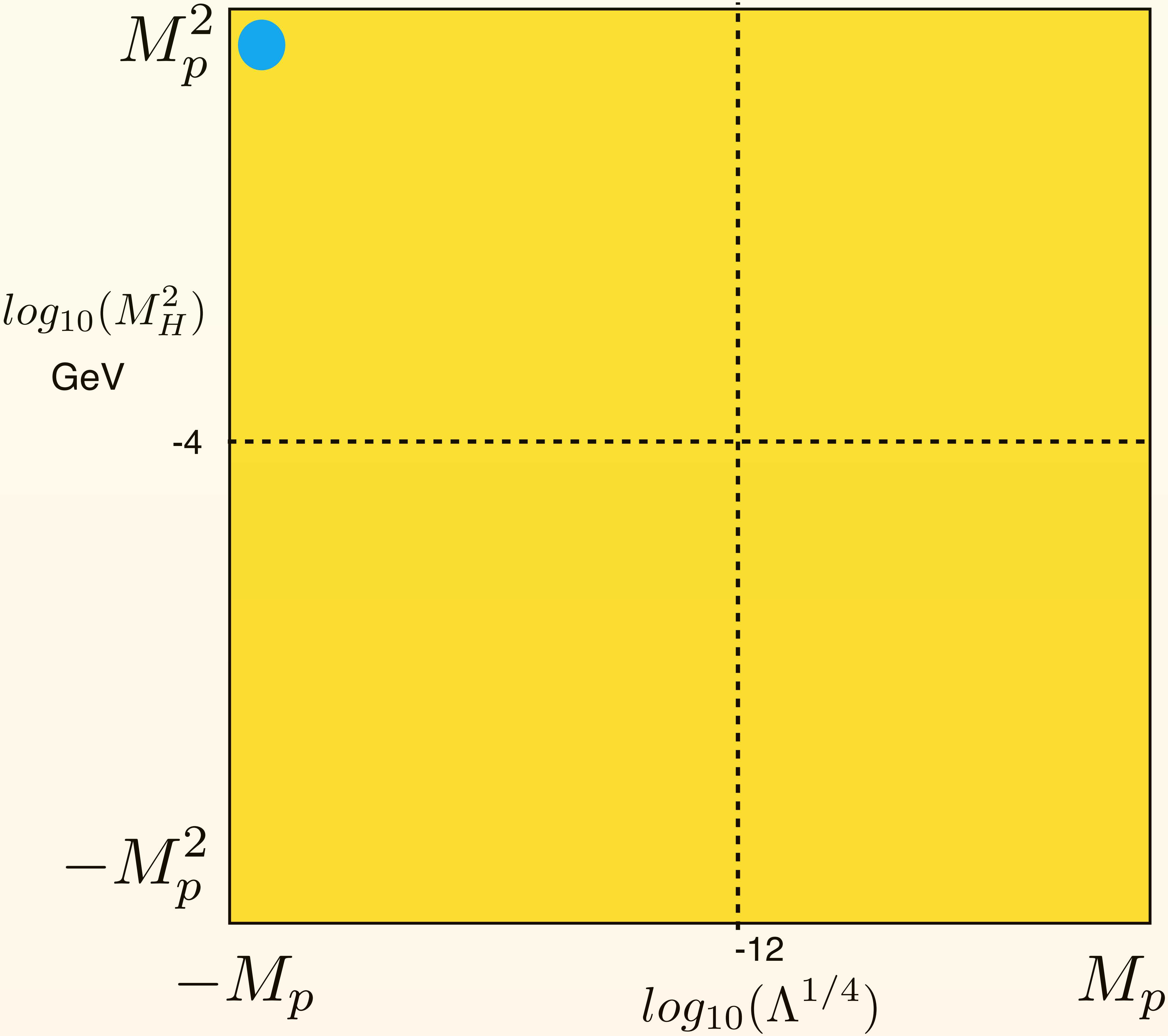
The two most offending physical quantities:

$$The\ m_H^2 - \Lambda_4\ plane$$


M_p^2
$log_{10}(M_H^2)$
GeV
-4
Effective field theory
allows all these
possibilities
$-M_p^2$
-12
$-M_p$
$log_{10}(\Lambda^{1/4})$
M_p

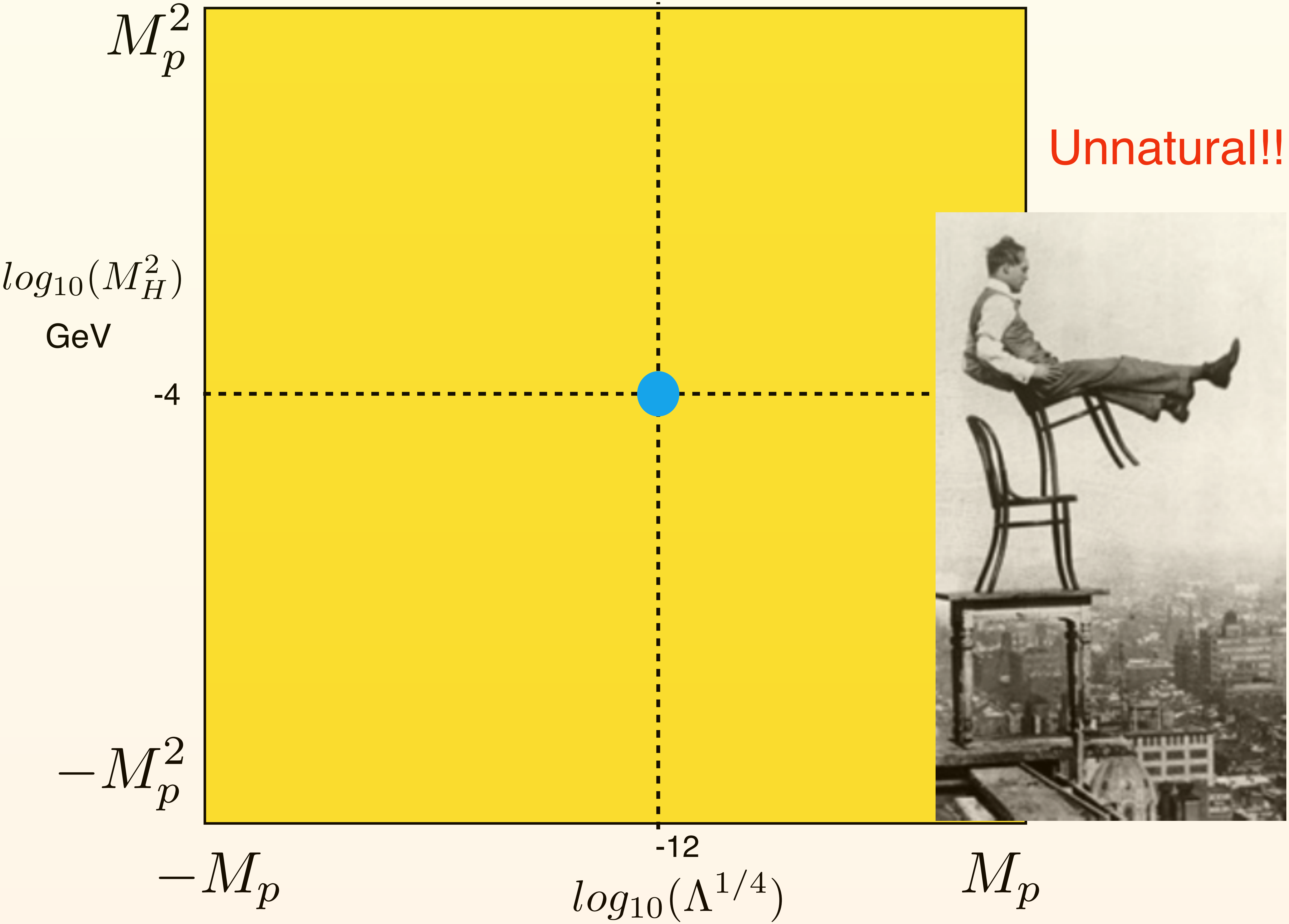


M_p^2
$log_{10}(M_H^2)$
GeV
Experimentally:
-4
$-M_p^2$
-12
$-M_p$
$log_{10}(\Lambda^{1/4})$
M_p

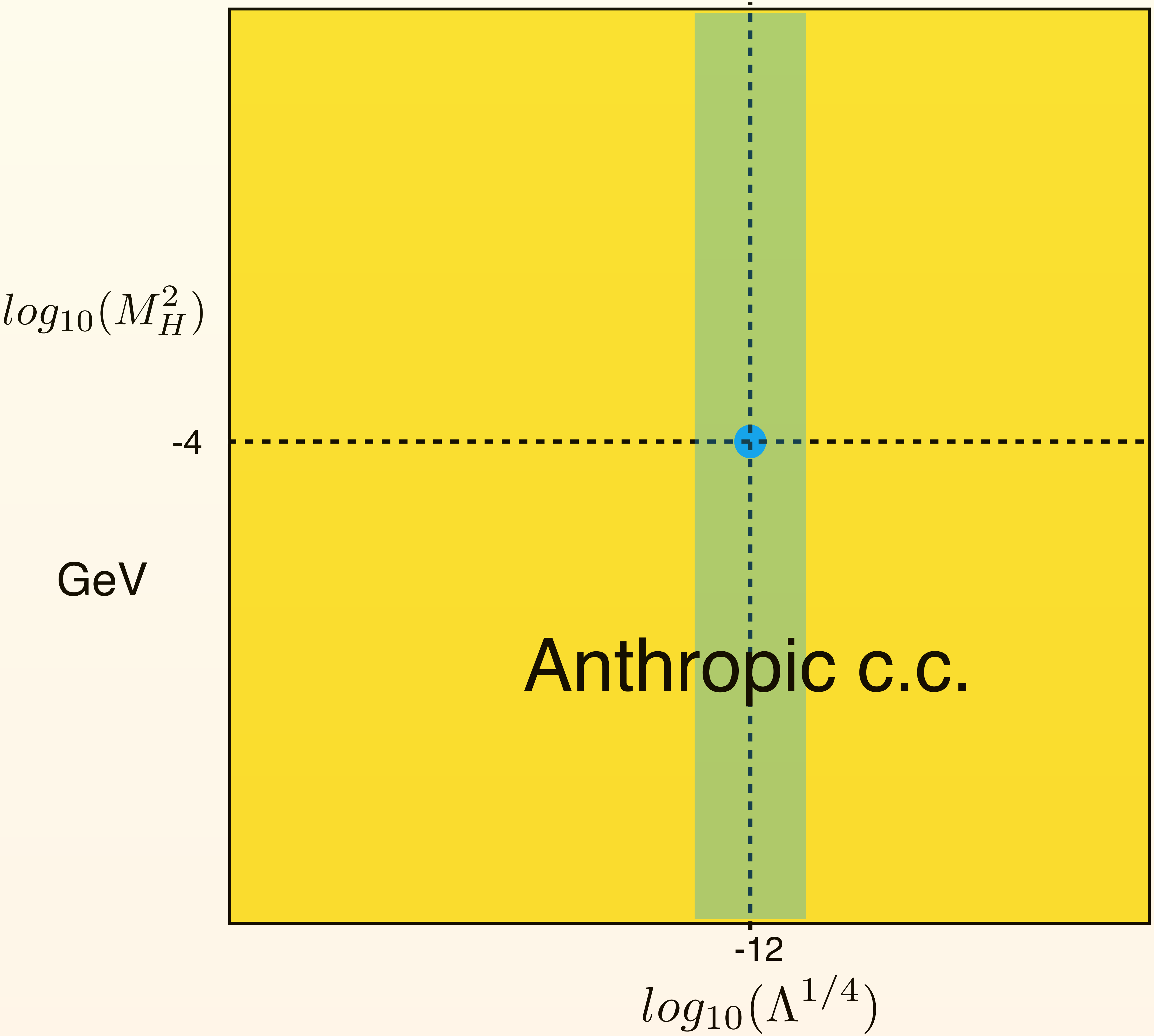


Quantum Effects!

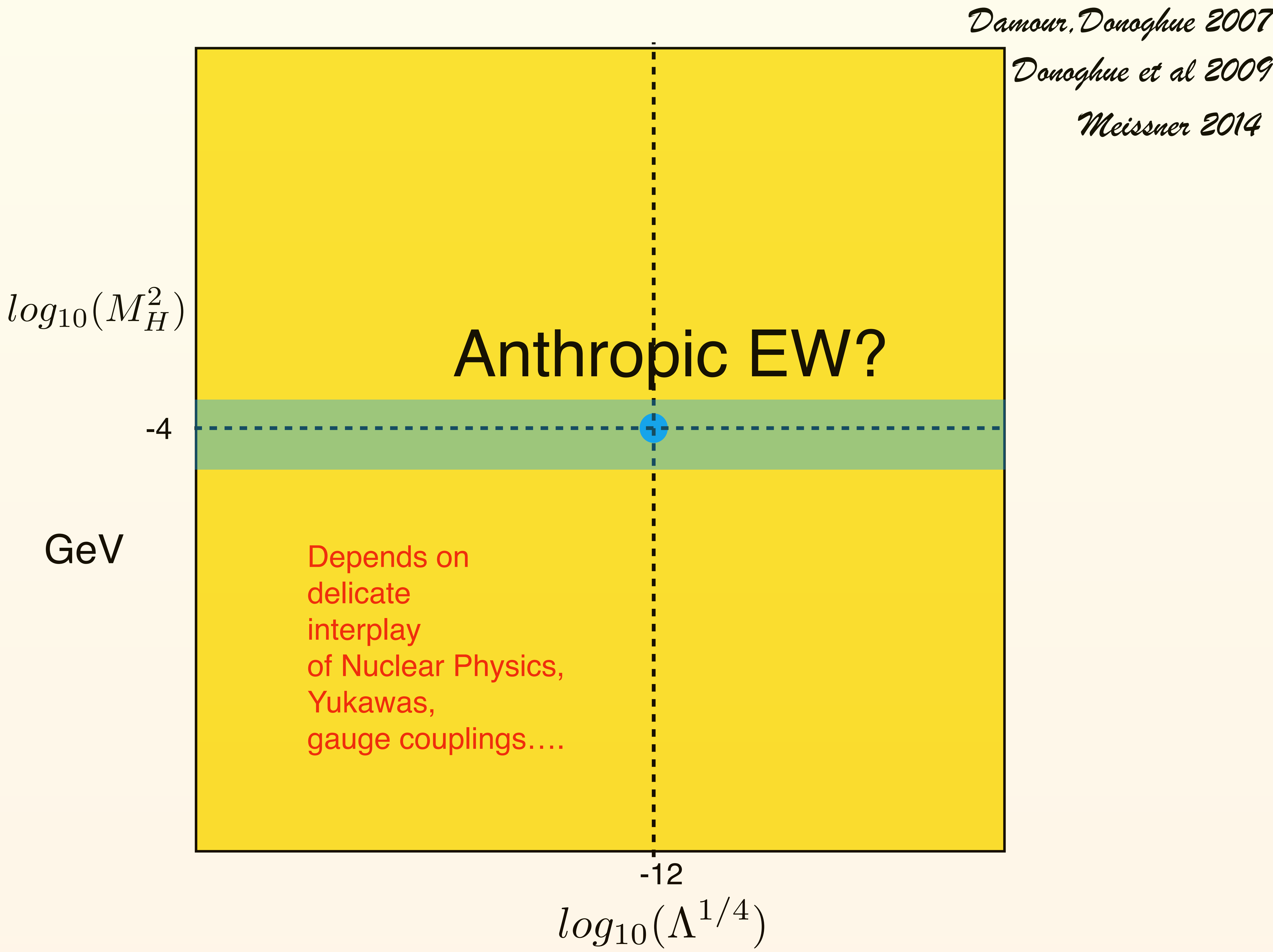
m_H^2 and Λ_4 unstable



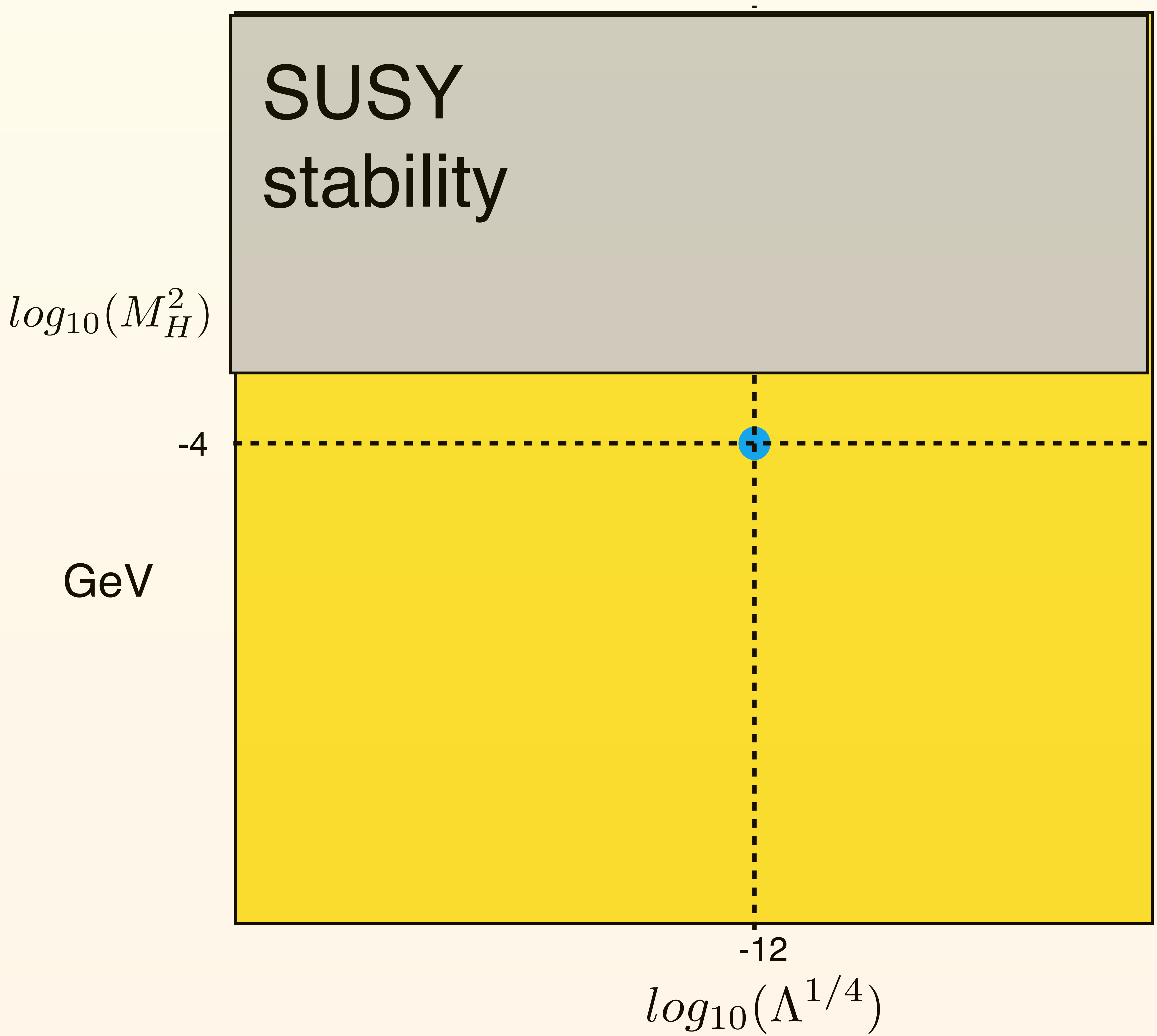
M_p^2
$log_{10}(M_H^2)$
GeV
-4
$-M_p^2$
-12
$-M_p$
$log_{10}(\Lambda^{1/4})$
M_p
Unnatural!!

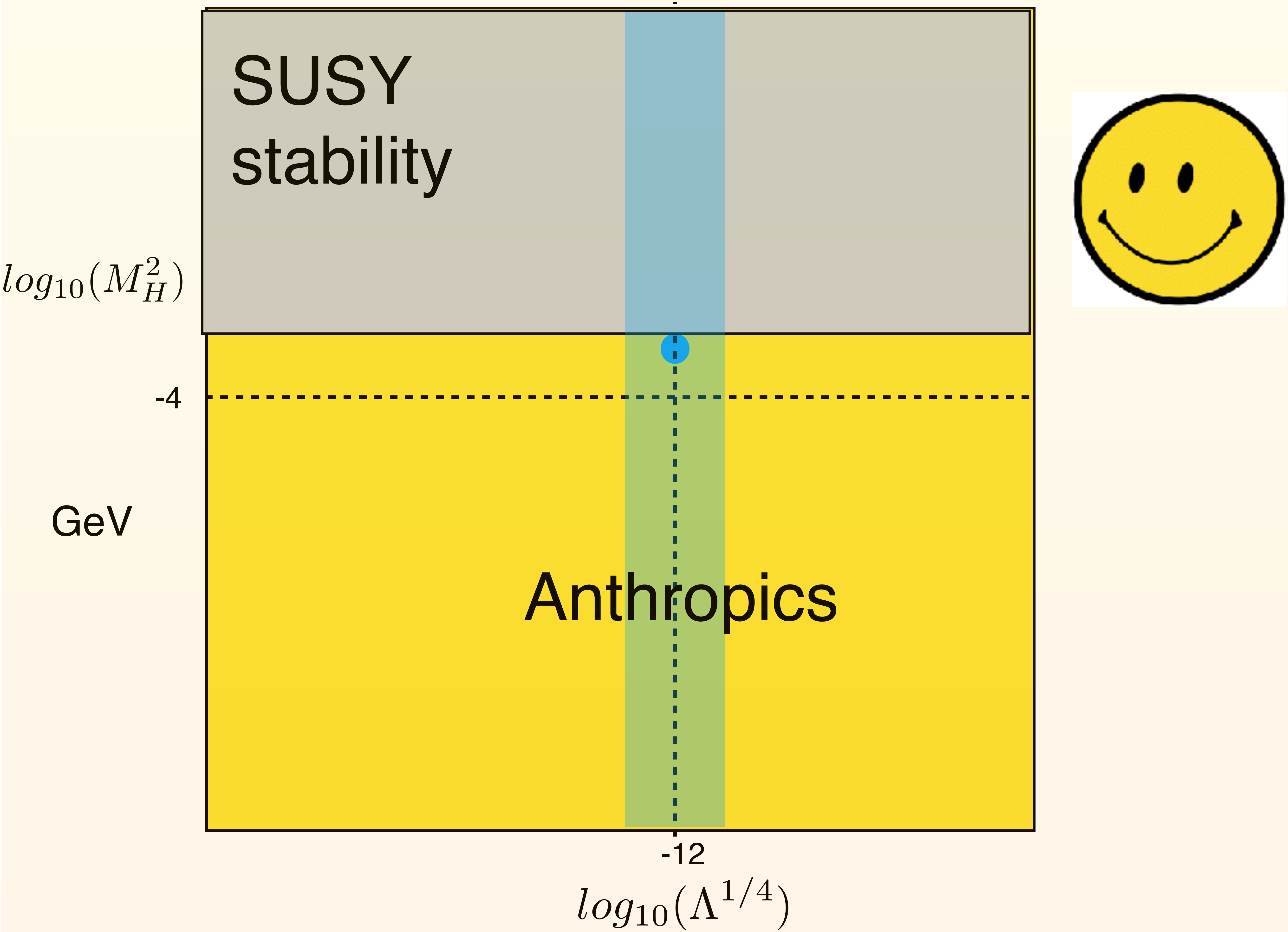


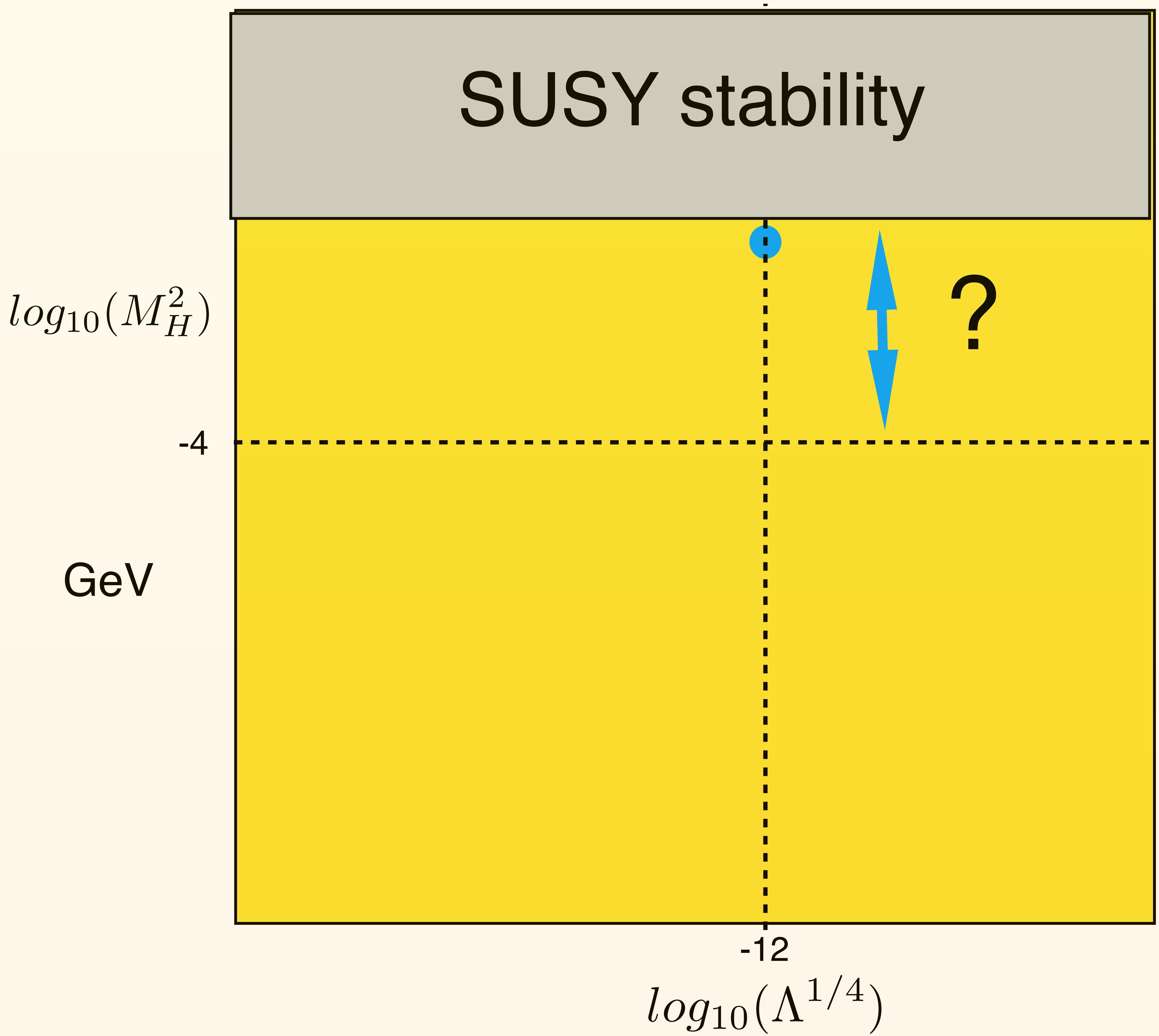
$log_{10}(M_H^2)$
GeV
-4
Anthropic c.c.
-12
$log_{10}(\Lambda^{1/4})$



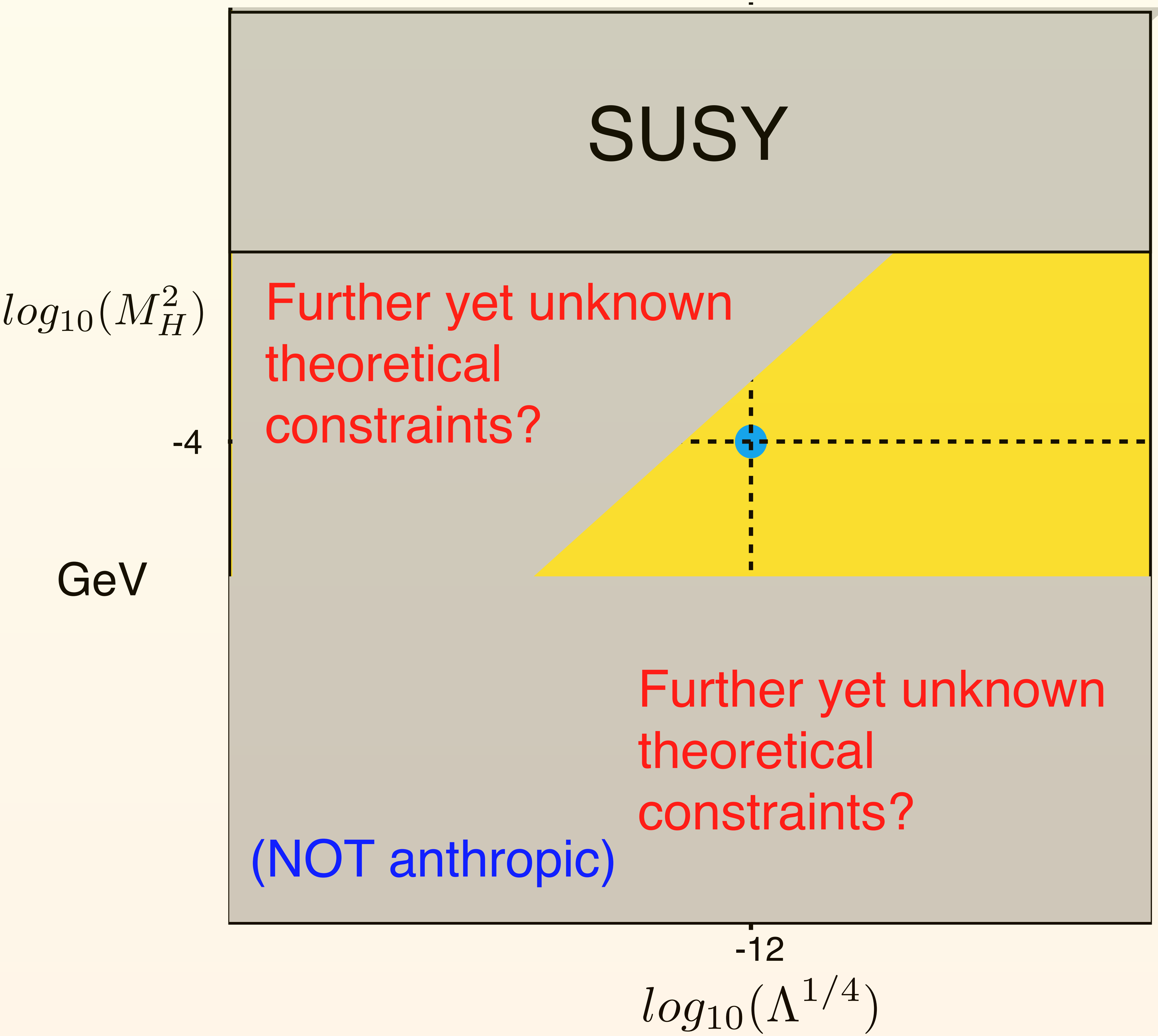
Damour, Donoghue 2007
Donoghue et al 2009
Meissner 2014
$log_{10}(M_H^2)$
GeV
-4
Anthropic EW?
Depends on
delicate
interplay
of Nuclear Physics,
Yukawas,
gauge couplings….
-12
$log_{10}(\Lambda^{1/4})$


SUSY
stability
$log_{10}(M_H^2)$
GeV
-4
-12
$log_{10}(\Lambda^{1/4})$


SUSY
stability
$log_{10}(M_H^2)$
-4
GeV
Anthropics
-12
$log_{10}(\Lambda^{1/4})$



Unnatural again!!


SUSY
Further yet unknown theoretical constraints?
Further yet unknown theoretical constraints?
(NOT anthropic)
$log_{10}(M_H^2)$
-4
GeV
-12
$log_{10}(\Lambda^{1/4})$

A LOWER BOUND ON THE HIGGS VEV

(For fixed Yukawa couplings)

SM without a Higgs is in the Swampland

No lepton masses, quarks dynamical mass

$$Below\ \Lambda_{QCD}: \quad 4n_g^2\ Goldstone\ bosons$$

$$U(2n_g)_L \times U(2n_g)_R \longrightarrow U(2n_g)_{L+R}$$

$$(N_F - N_B) = \overset{\text{Leptons}}{8n_g} - (\overset{\text{GB}}{4n_g^2} - 1 - \overset{\text{W,Z}}{3} + \overset{g^{\mu\nu}}{2} + \overset{\gamma}{2}) = 4n_g(2 - n_g)$$

$$Above\ \Lambda_{QCD}: \quad Quarks\ deconfine$$

$$(N_F - N_B) = \overset{\text{quark/leptons}}{32n_g} - \overset{\text{Gauge}}{24} - \overset{g^{\mu\nu}}{2}$$

SM without a Higgs is in the Swampland

No lepton masses, quarks dynamical mass

$$Below\ \Lambda_{QCD}: \quad 4n_g^2\ Goldstone\ bosons$$

$$U(2n_g)_L \times U(2n_g)_R \longrightarrow U(2n_g)_{L+R}$$

$$(N_F - N_B) = \overset{\text{Leptons}}{8n_g} - (\overset{\text{GB}}{4n_g^2} - 1 - \overset{\text{W,Z}}{3} + \overset{g^{\mu\nu}}{2} + \overset{\gamma}{2}) = 4n_g(2 - n_g) \quad <0$$

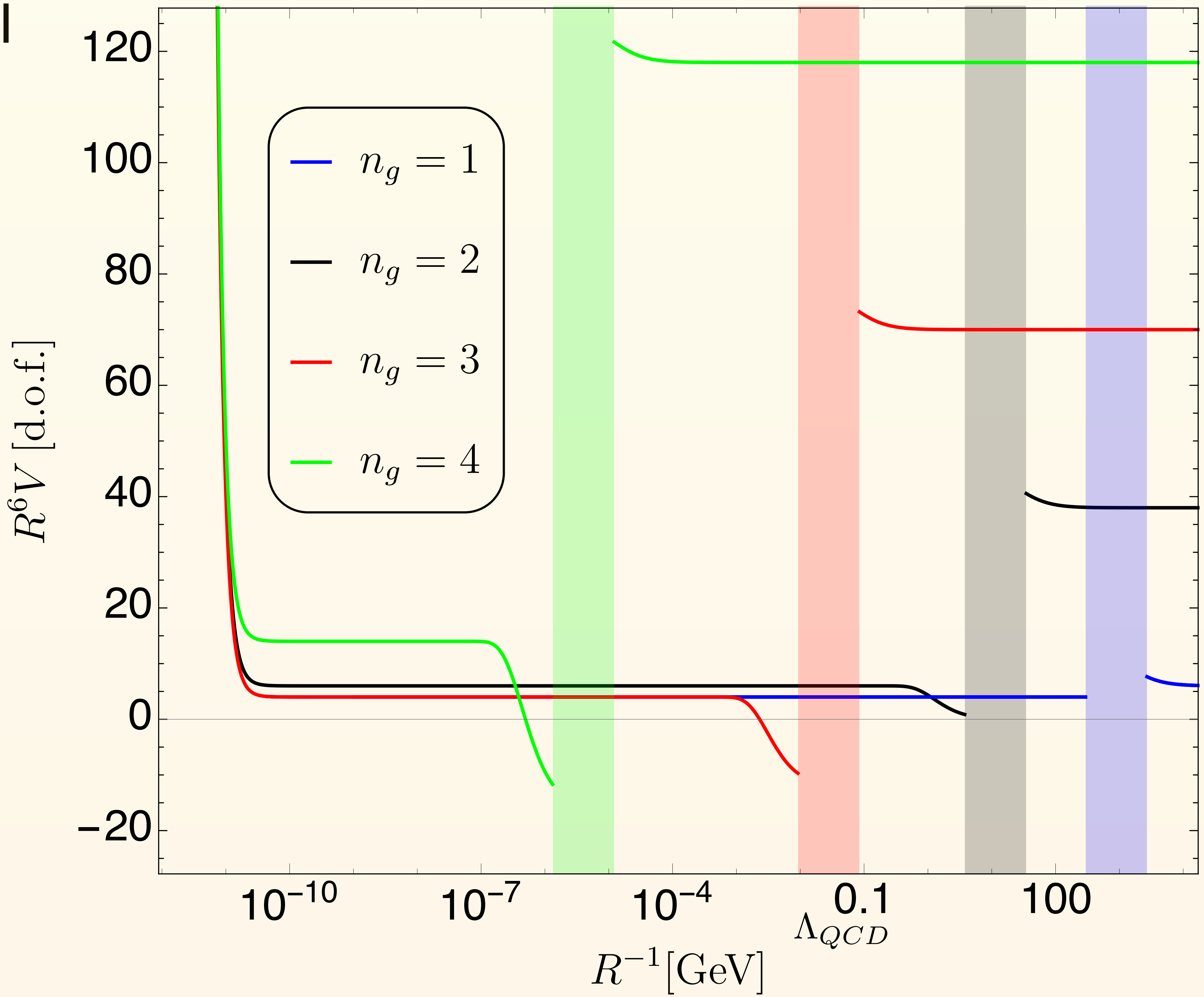
$$Above\ \Lambda_{QCD}: \quad Quarks\ deconfine$$

$$(N_F - N_B) = \overset{\text{quark/leptons}}{32n_g} - \overset{\text{Gauge}}{24} - \overset{g^{\mu\nu}}{2} \quad >0$$

- An AdS vacuum necessarily develops for $n_g \geq 3$

E.Gonzalo, L.I. 2018

3D potential

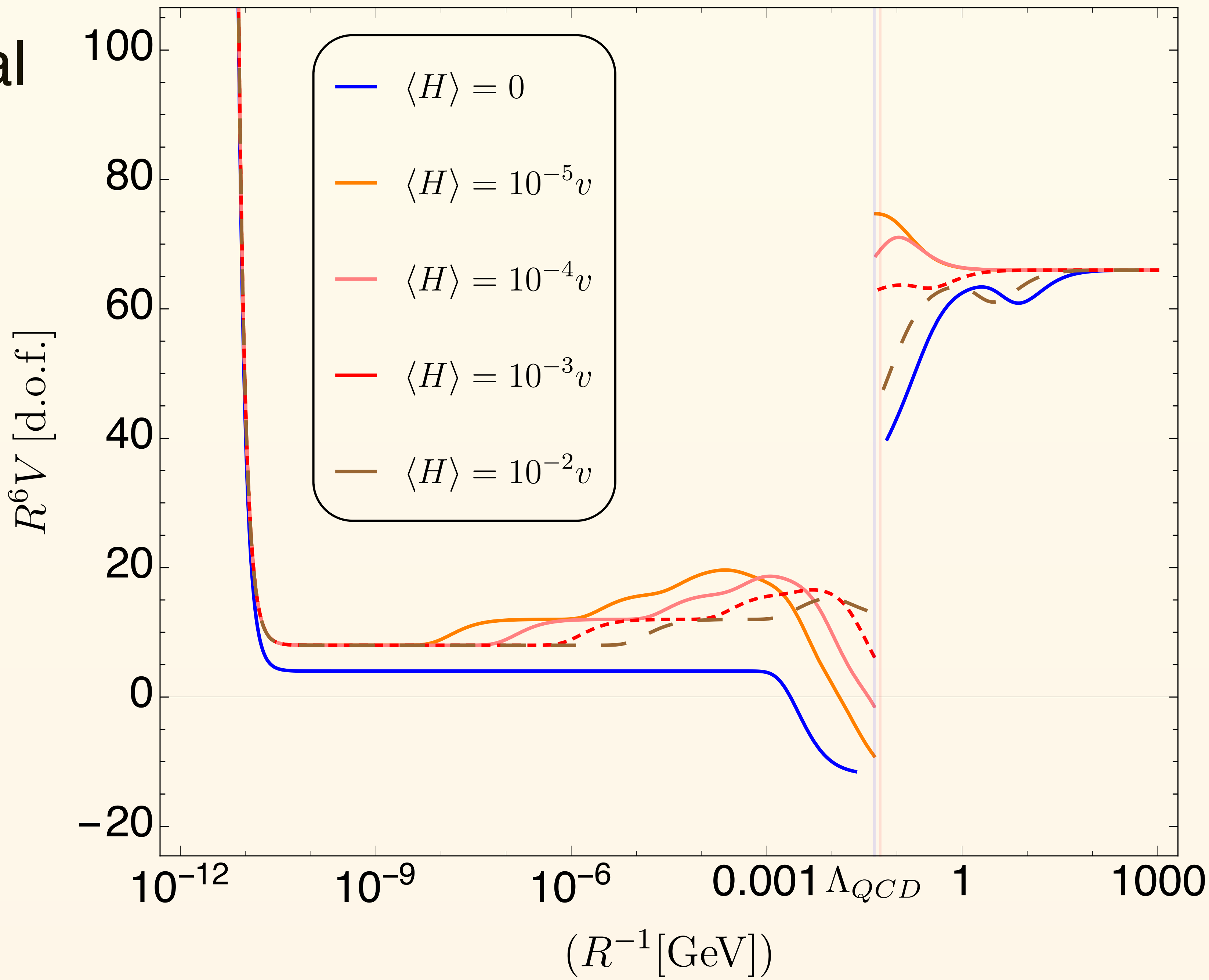


Higgs is needed….if the number of generations is 3 or more

3 generations: Lower bound on Higgs vev

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

3D potential



$$h = \langle H \rangle$$

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

Hierarchy problem and the swampland

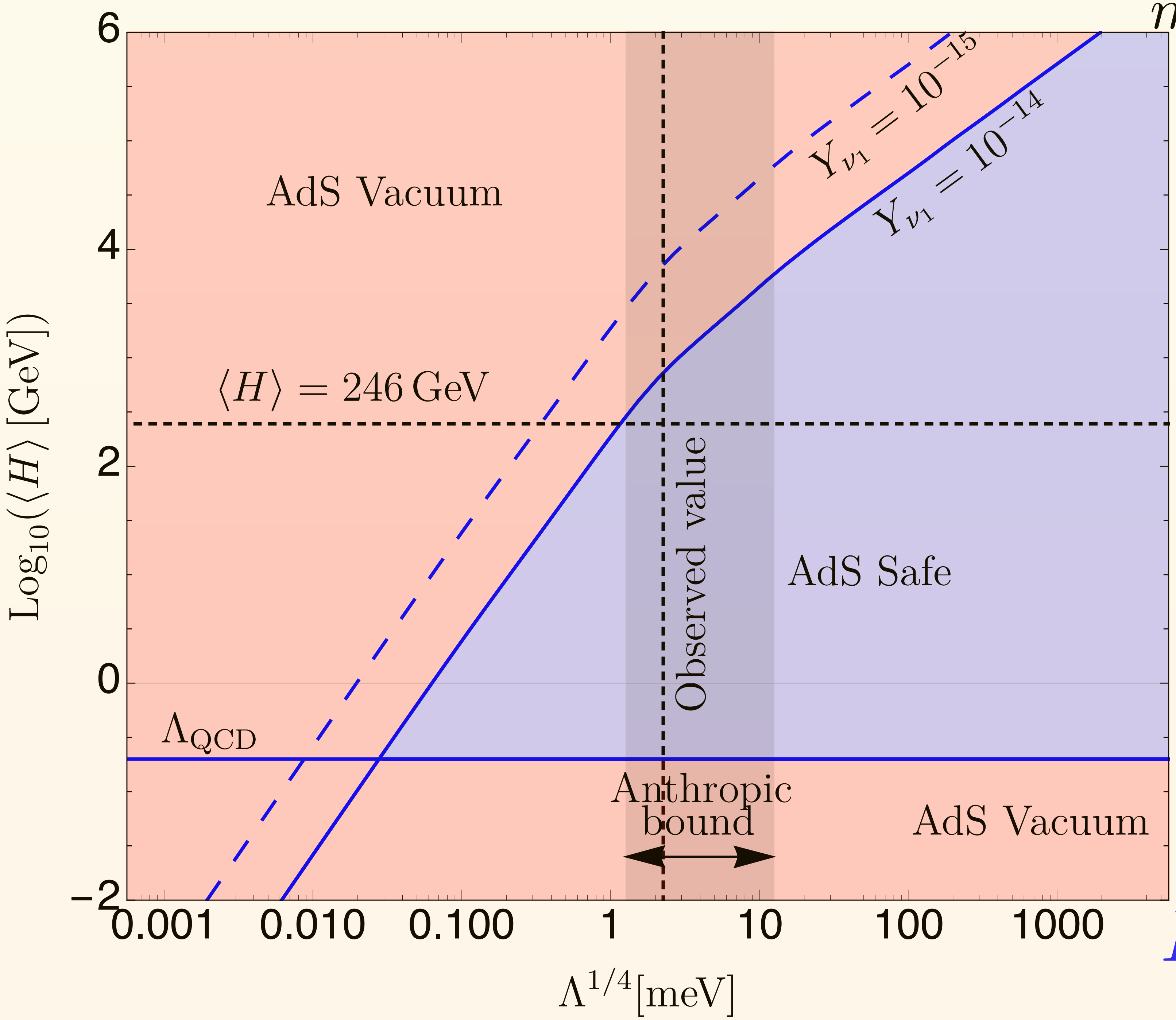
Dirac neutrinos(NH):

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

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

Hierarchy problem and the swampland

Dirac neutrinos(NH):



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

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

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

EW scales above 1 TeV in the Swampland!!

No real fine-tuning......

EW scale tied up to Λ_4

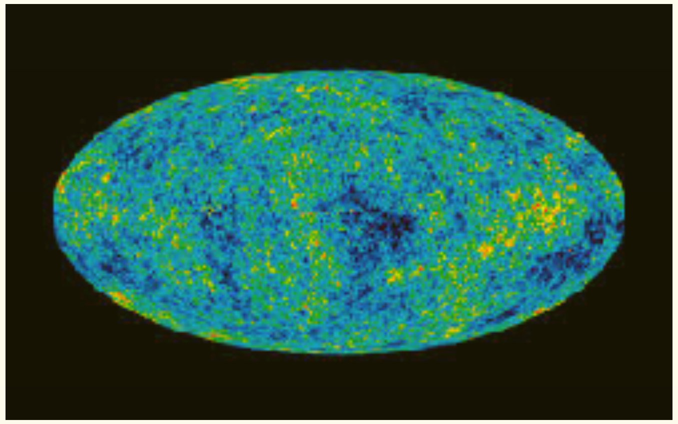
L.I.,Martin-Lozano, Valenzuela 2017; E.Gonzalo, L.I. 2018

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

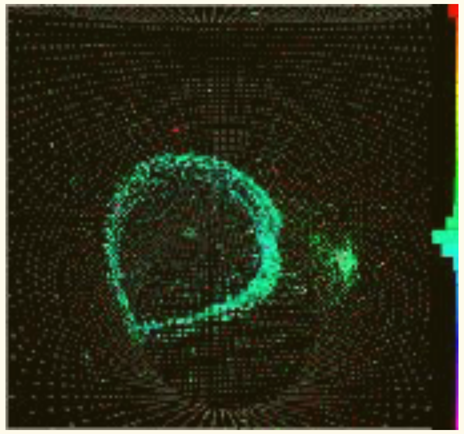
$$\frac{|\Delta H|}{|H|} \leq \frac{(a\Lambda_4^{1/4} - m_{\nu_1})}{m_{\nu_1}}$$

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



Dark Energy

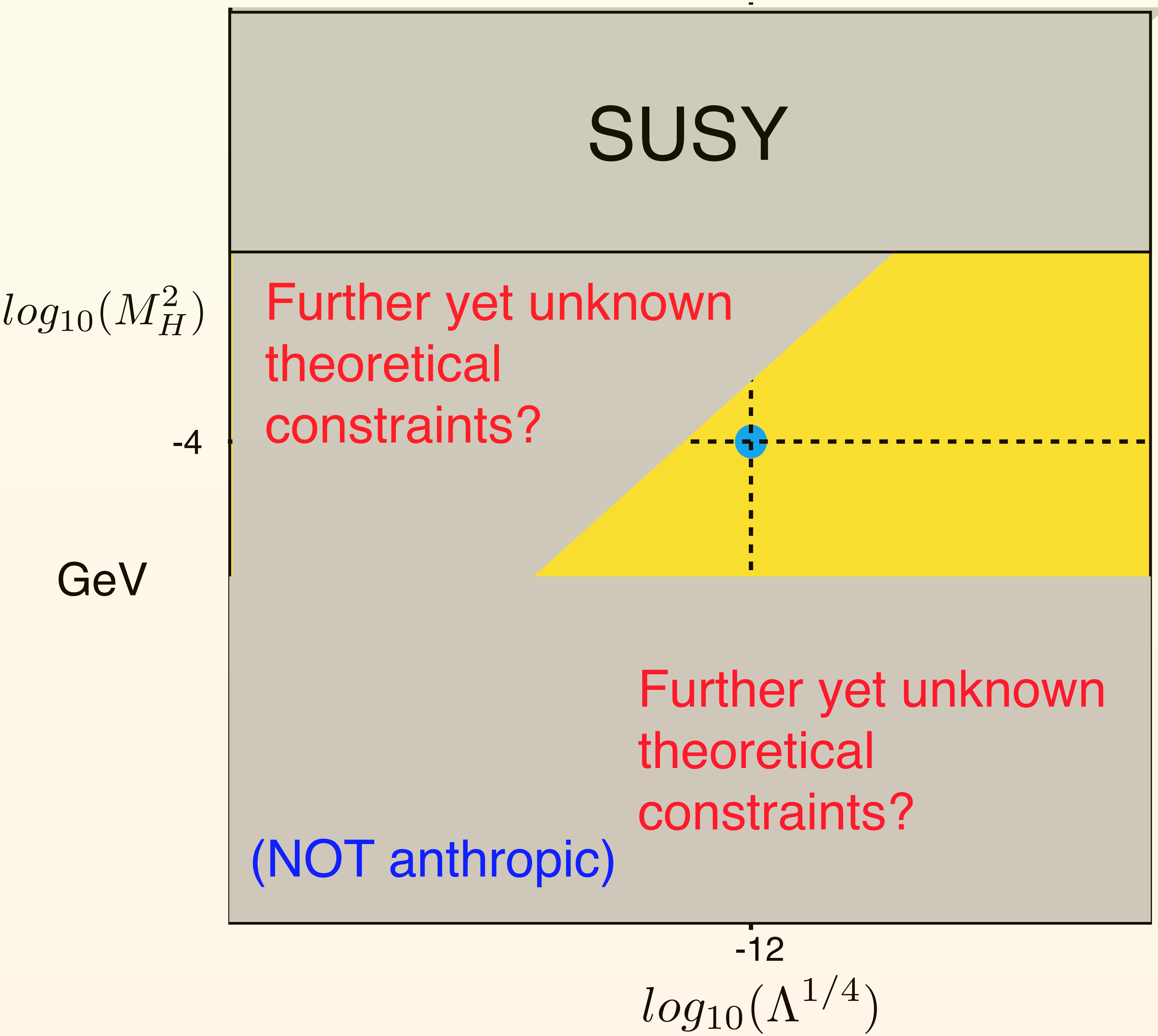


Neutrino Physics

EW fine-tuning

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

Surprising connection of neutrino physics with the hierarchy prolem!


SUSY
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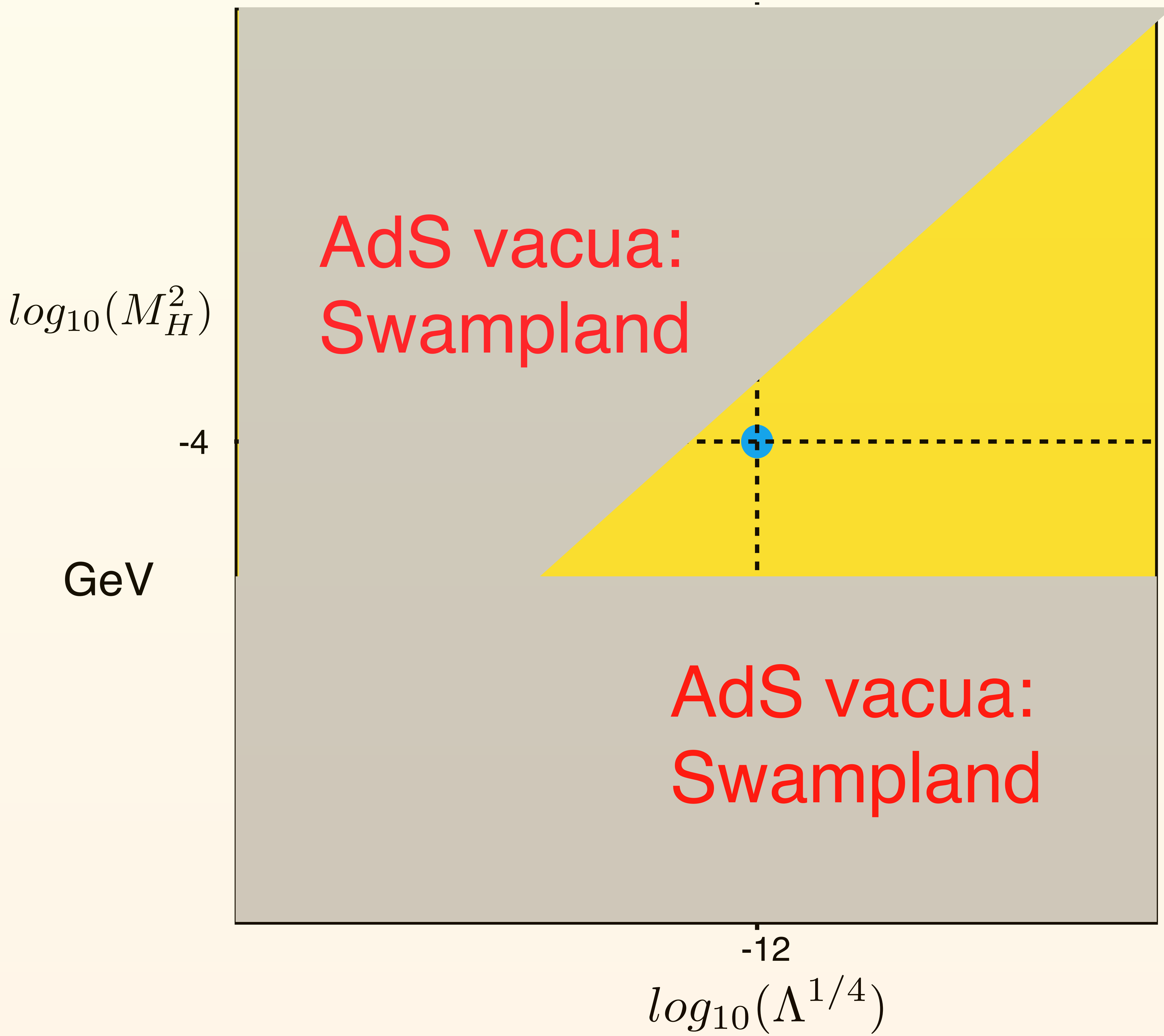
AdS vacua:
Swampland
$log_{10}(M_H^2)$
-4
GeV
AdS vacua:
Swampland
-12
$log_{10}(\Lambda^{1/4})$

Conclusions

1) Quantum gravity constraints effective field theories and may affect SM physics and cosmology in ways not previously foreseen

2) These ideas are still under construction and are based on conjectures motivated by blackhole physics and String Theory

3) Different levels of confidence

- No global symmetries————————————————>*****
- Weak gravity conjecture for U(1)————————->*****
- Generalization to axions and higher forms————->****
- Swampland distance conjecture—————————>****
- No non-SUSY AdS vacua————————————>***
- dS conjectured (refined)—————————————>**
- Scalar WGC——————————————————->**

4) Modular symmetries of string compactifications give non-perturbative information on swampland conjectures. Potential diverges at large moduli, forbidding the recovery of global symmetries.

5) One modulus modular invariant potentials verify swampland criteria. No dS minima found.

6) Application of AdS or scalar WGC to 3D SM constraints neutrino masses, the c.c. and the Higgs vev, giving a new approach to the hierarchy problem. The EW fine-tuning related to the proximity of lightest neutrino mass and c.c. scale.

Thank you !!