The Quantum Gravity Swampland and Particle Physics

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EXCELENCIA SEVERO OCHOA

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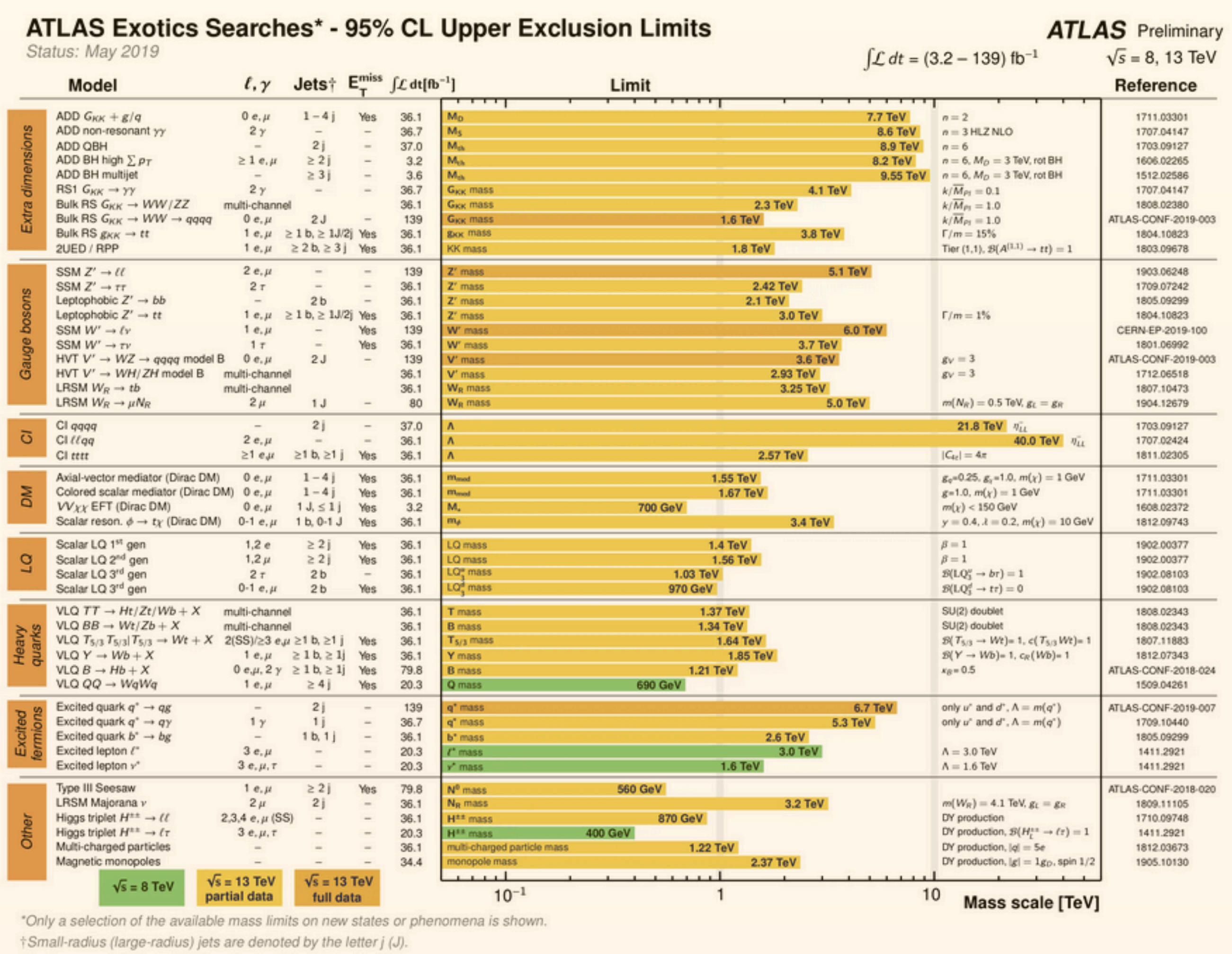
Particle Physics after LHC runs

1) The Higgs is an amazing success

2) No sign so far of SUSY....

3) ....nor any other new Physics



The Naturality Crisis

Has the naturality criterium guided us in the right direction?

Should we abandon some of our most cherised ideas:

** UV-IR independence

** Does Quantum Gravity really decouple?

There are hints of IR-UV connections in the presence of Quantum Gravity

Dualities in String Theory connect light (IR) to heavy (UV) modes

Scattering of BH's at high energy (UV) give rise to large BH's (IR)

Holography (Bekenstein) seems to imply UV-IR connections in any EFT:

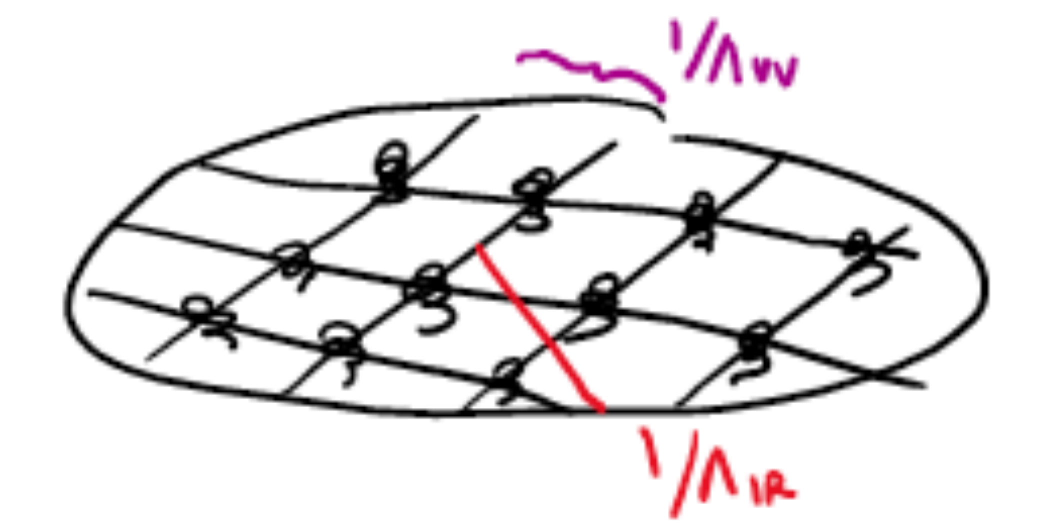
Holography and IR-UV connection

- Such UV-IR connection suggested by the covariant entropy bound (Bousso 1999) as applied to a spherical surface

- Beckenstein 1981: ‘ The entropy in a region of space is bounded by the BH entropy that can be stored in a region of the same size’

EFT with UV cut-off Λ_{UV}

Sphere of radius $L = 1/\Lambda_{IR}$



- Maximal field theoretical entropy (extensive):

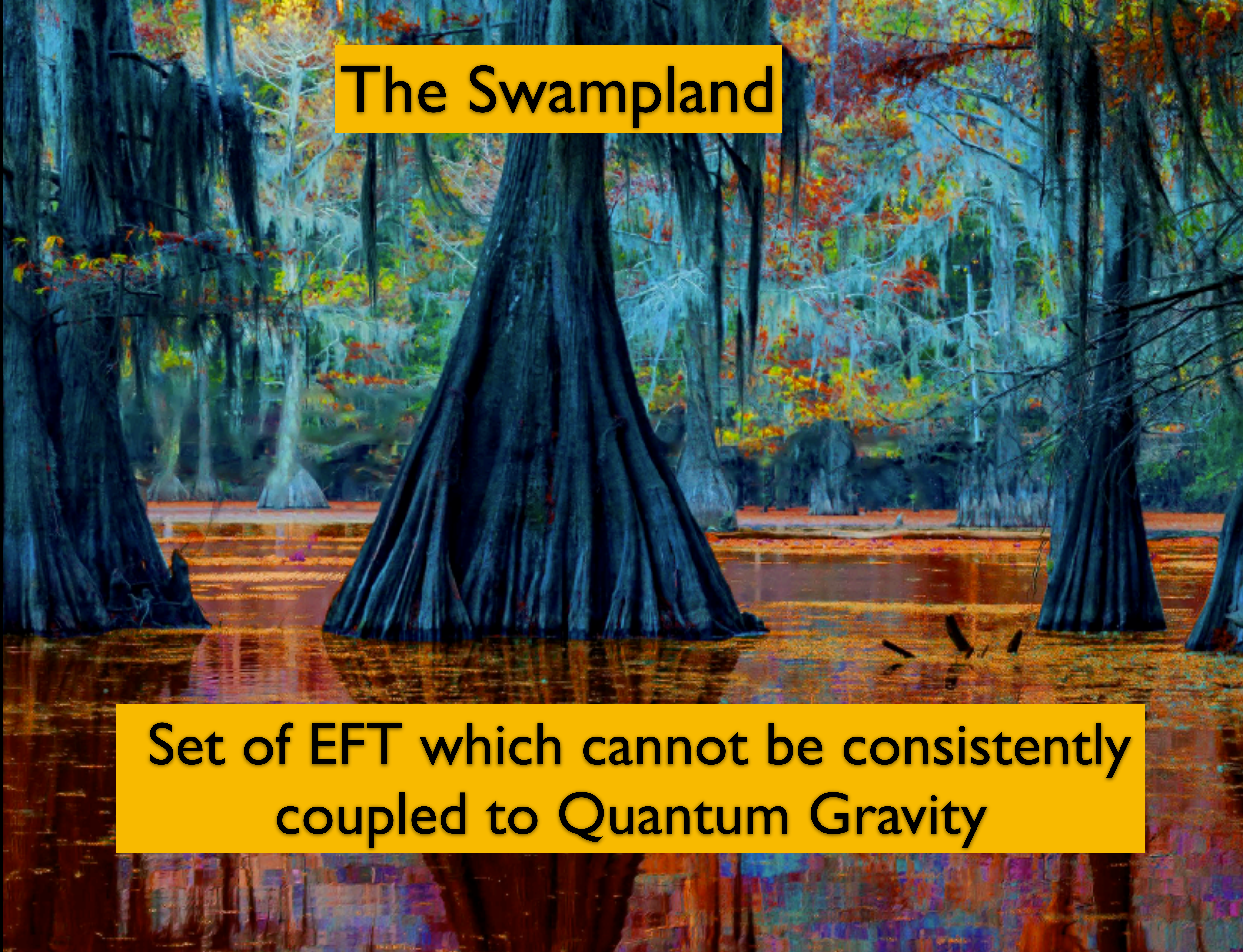
$$S_{EFT} \sim (\Lambda_{UV} L)^3$$

- Blackhole entropy (like the surface) $S_{BH} \sim L^2 M_p^2$

$$S_{EFT} \leq S_{BH} \Longrightarrow \boxed{\Lambda_{UV} \lesssim (\Lambda_{IR})^{1/3} M_p^{2/3}}$$

Correlation between UV and IR cut-offs

Cohen, Kaplan, Nelson (1999), Cohen, Kaplan (2019), Banks, Drapper (1919)



The Swampland

Set of EFT which cannot be consistently coupled to Quantum Gravity

Swampland Program

- 1) Understand how Quantum Gravity may affect EFT's below the Planck scale
- 2) See if these QG effects may address some of the fundamental questions of Particle Physics and Cosmology
- 3) Improving in this way our understanding of QG itself

Methodology

- One asumes that String Theory is a consistent theory of QG.

- One identifies general properties/patterns of QG/ST vacua

- Often these properties are formulated in terms of a conjecture which one tries to test against:

  - large sets of known string vacua
  - known semiclasical properties of Black-Holes

- One tries to derive consequences for the observed universe

Reviews:
Palti, arXiv:1903.06239
van Beest, Calderon, Mirfendereski and Valenzuela arXiv:2102.01111
Graña, Herráez arXiv:2107.00087
Harlow, Heidenreich, Reece, Rudelis arXiv:2201.08380

Some Swampland Conjectures

1) There are no exact global symmetries *Banks,Dixon 1988*

Motivated by black-hole physics (no-hair).
Consistent with string theory. Also discrete. *Harlow,Ooguri 2018*

- Recently extended to 'generalized symmetries' and to topological symmetries ('Cobordism Conjecture') *McNamara,Vafa 2019*

Montero,Vafa 2020

2) Completeness conjecture: *Polchinski 2003*

Particles of all possible charges must exist
(not necessarily light!!)

Shown this is connected to the absence of topological symmetries. Evidence in String Theory.

3) The Weak Gravity Conjecture

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

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:

$$m \leq Q\, M_p$$

Gravity weaker than Coulomb: $F_G \leq F_q \longrightarrow m \leq q M_p$

Clash with naturality in field theory?

First observation, charged scalars:

$$\underbrace{m^2}_{\text{Quadratically divergent}} < \underbrace{g^2\ M_p^2}_{\text{Logarithmically divergent}}$$

U(1) with a scalar:

Cheung, Remmen 2014

$$\delta m^2 \simeq \frac{\Lambda^2}{(4\pi)^2}\left(a\ g^2 + b\ \lambda\right) < g^2\ M_p^2$$

$$if \quad g^2/\lambda \to 0 \qquad \longrightarrow \Lambda^2 < (4\pi)^2 \left(\frac{g^2}{b\lambda}\right) M_p^2$$

Can lower the cut-off arbitrarily ! Address hierarchy problem…

Things are a bit more complex: $g^2 \longrightarrow 0\ limit\ is\ singular\ !$

(Also expected, since as $g^2 \to 0$ one recovers a global symmetry!!)

4) The (sub)lattice WGC

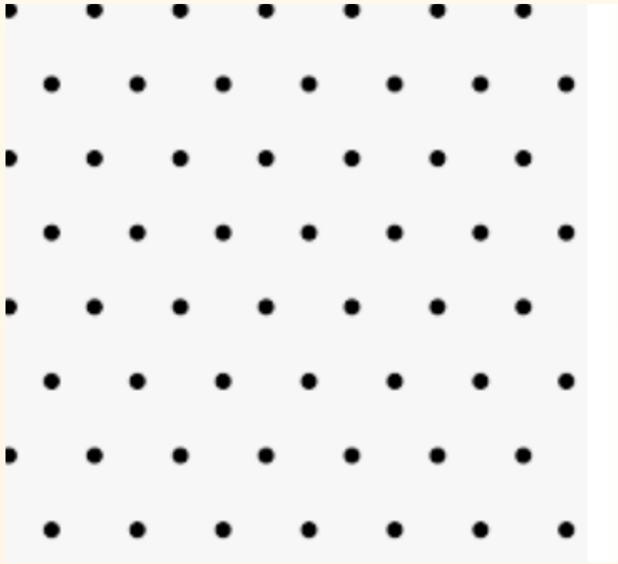
- Simplest WGC is not what seems realised in string theory

Heidenreich, Reece, Rudelius 2016

Andriolo et al. 2018

- Sublattice conjecture: for any point in the gauge lattice there is a superextremal charged particle

- Consistent with 'completeness conjecture'

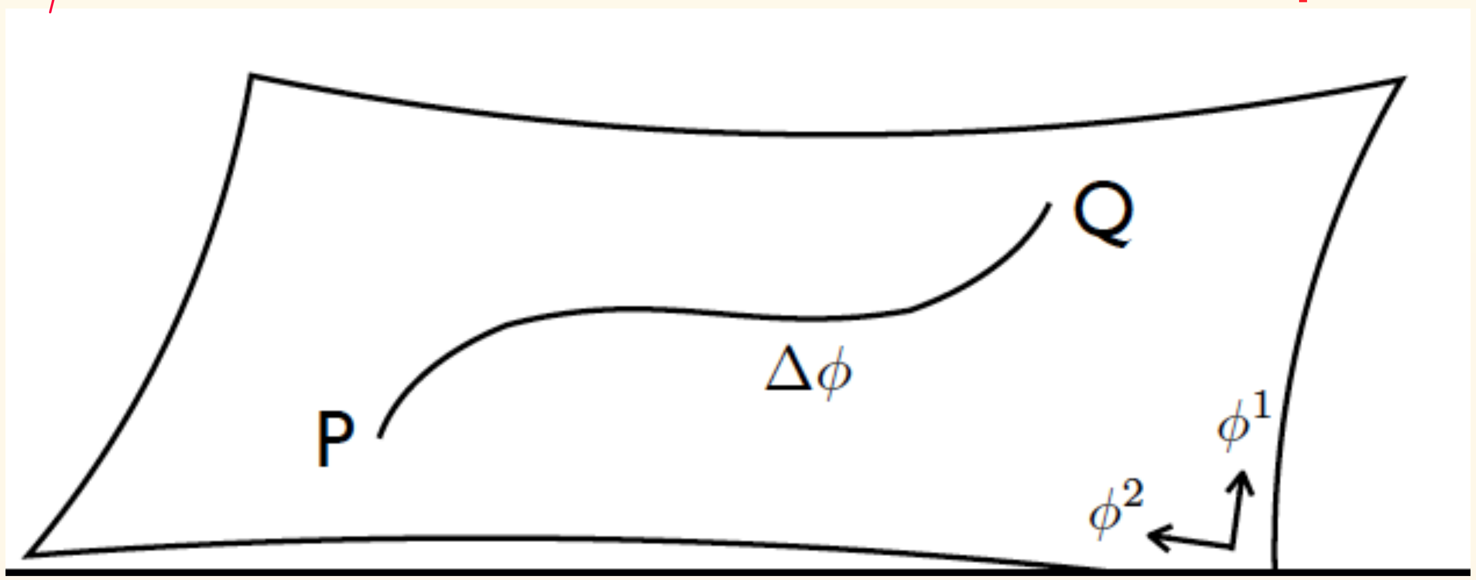


$$g^2 \longrightarrow 0 \longrightarrow A\ full\ tower\ of\ charged\ states\ becomes\ massless$$

5) Distance Swampland Conjecture

- Towers of massless fields as $g^2 \to 0$ is an example of a more general phenomenon:

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



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

Ooguri, Vafa 2006

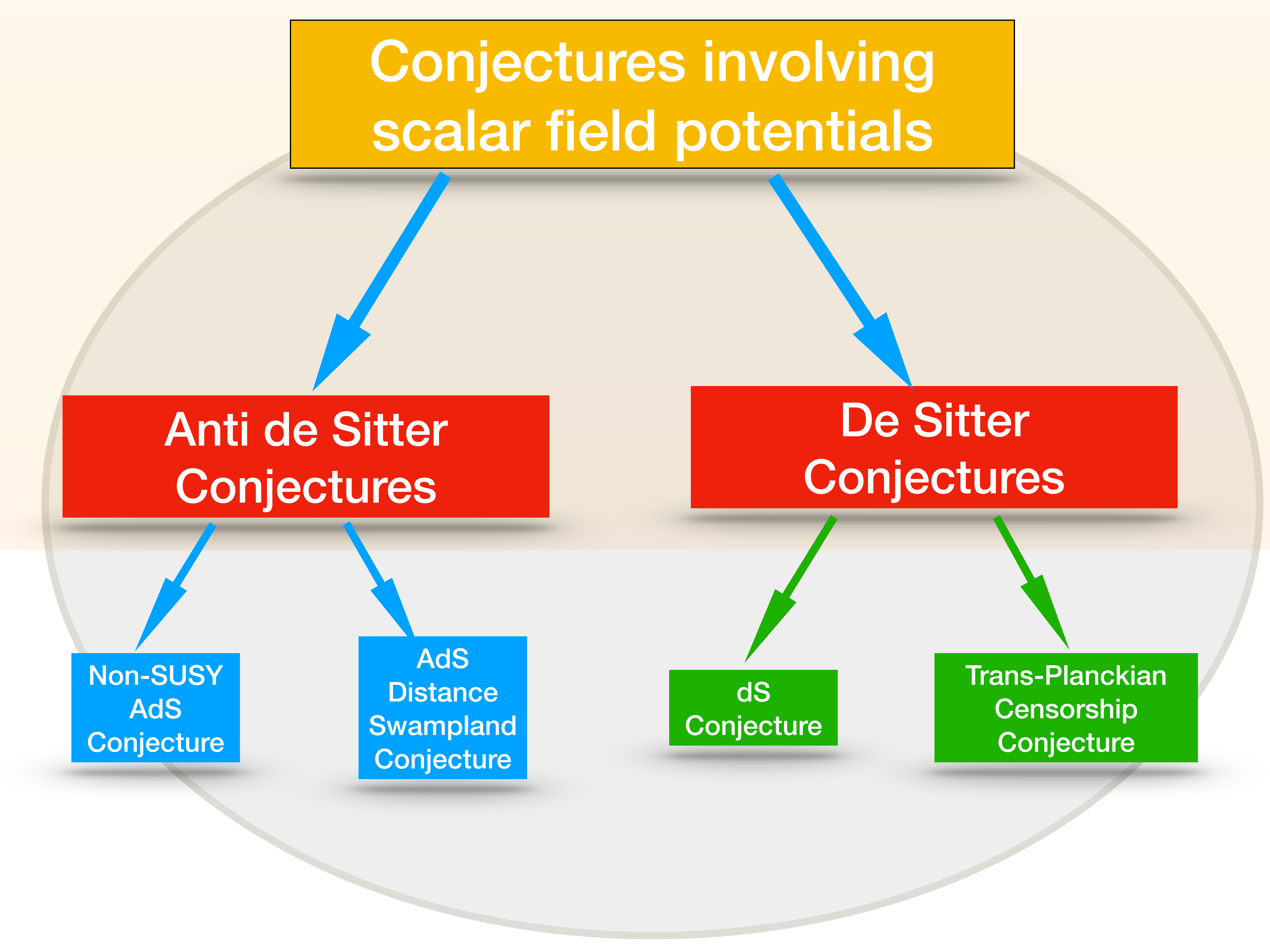
Grim, Palti, Valenzuela 2019
Gendler, Valenzuela 2021

The effective field theory becomes inconsistent

- Has been checked in many string theory examples

7-b) Emergent string conjecture: this tower is either a KK or a string tower

Lee, Lerche, Weigand2019

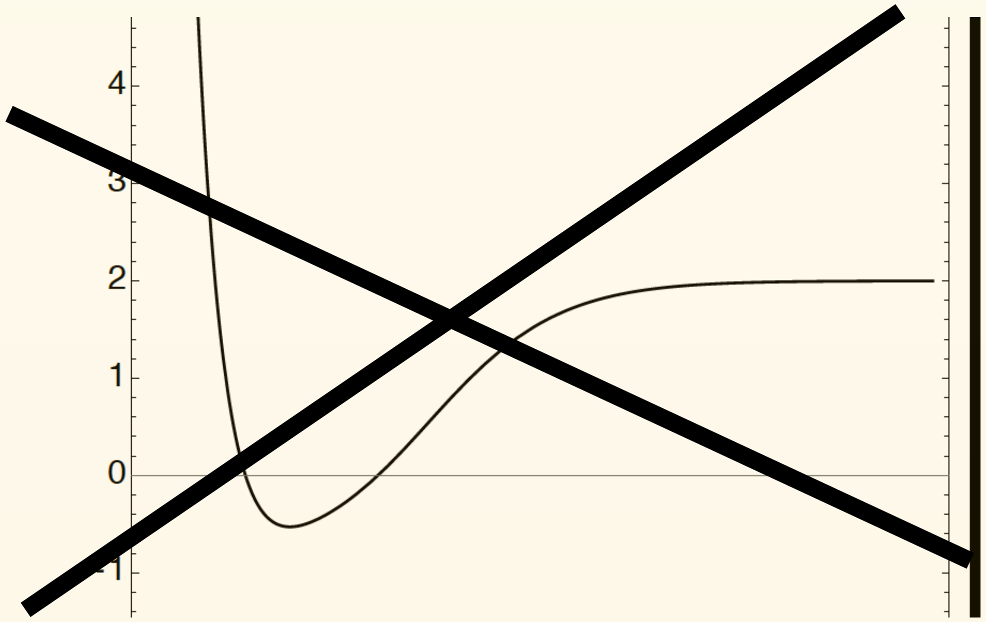

Conjectures involving scalar field potentials
Anti de Sitter Conjectures
De Sitter Conjectures
Non-SUSY AdS Conjecture
AdS Distance Swampland Conjecture
dS Conjecture
Trans-Planckian Censorship Conjecture

6) Non-SUSY AdS conjecture

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

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

Ooguri,Vafa 2016



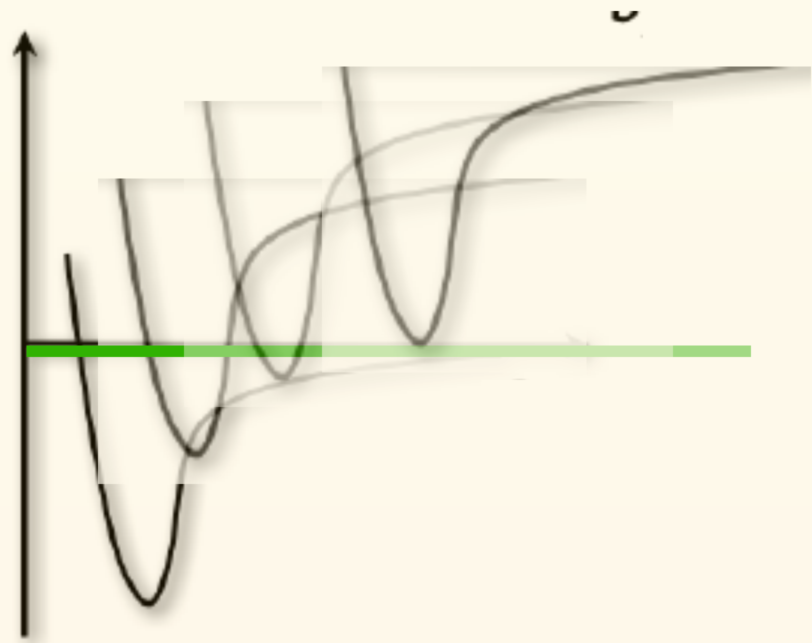
(If you find one in your theory, then it is
inconsistent with quantum gravity)

- True within known flux string vacua. No counterexample found.

7) AdS Distance Swampland Conjecture

Lust, Palti, Vafa 2019

- One cannot go smoothly from AdS to Minkowski:



Consider family of AdS vacua with $\Lambda_{c.c.} \rightarrow 0$

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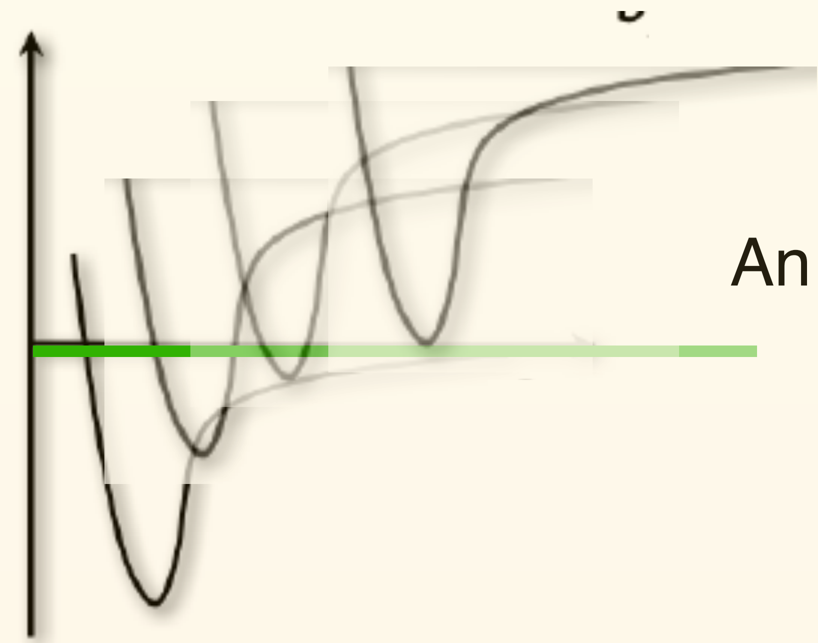


Consider family of AdS vacua with $\Lambda_{c.c.} \rightarrow 0$

An infinite tower of states with mass scale m behave as

$$m \simeq |\Lambda_{cc}|^{\alpha} \longrightarrow 0$$

There is good evidence from AdS string vacua

- Also conjectured to be true for dS vacua

(not tested in string theory in which no(?) dS vacua have been found as yet)

A stronger version states that: $\alpha \geq \frac{1}{2}$ $(for\ AdS)$ $\alpha \leq \frac{1}{2}$ $(for\ dS)$

8) dS Swampland Conjecture

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

$$|\nabla V(\phi)| \geq c\ V(\phi)$$

or else..... $min(\nabla_i \nabla_j V(\phi) \leq -c' \ V(\phi)$

Ooguri, Palti, Shiu, Vafa 2018

→ No long-lived dS vacua

Weaker: 'Asymptotic dS conjecture': only true at large distance in i moduli space. Well tested in ST

This is conjectured to apply also to AdS:

$$|\nabla V(\phi)| \geq c\ |V(\phi)|$$

9) 'Festina Lente'(dS)

Montero, van Riet, Venke 2019

- Suggested by impossing decay through Schwinger pair creation of Nariai charged extremal dS BH's.

- Any charged particle must obey

$$\boxed{(2g^2\ V_0)^{1/4}\ <\ m}\ <\ \sqrt{2}gM_p$$

Fulfilled by the SM:

$$m_e^4 \sim 10^{-12}GeV\ \gg\ 2e^2V_0 \sim 10^{-48}GeV$$

- Extremely strong conditions, see later

Some Applications To Particle Physics

1) Constraints on neutrino masses

We seem to live in a dS space with $\Lambda = (2.4 \times 10^{-3} eV)^4$

However compactifying the SM on a circle of radius R
one may get AdS 3D vacua with

Arkani-Hamed, Dubovsky, Nicolis, Villadoro, 2007

$$m_{KK} \simeq m_\nu$$

1) non-SUSY AdS stable vacua are in the Swampland
2) AdS Distance conjecture

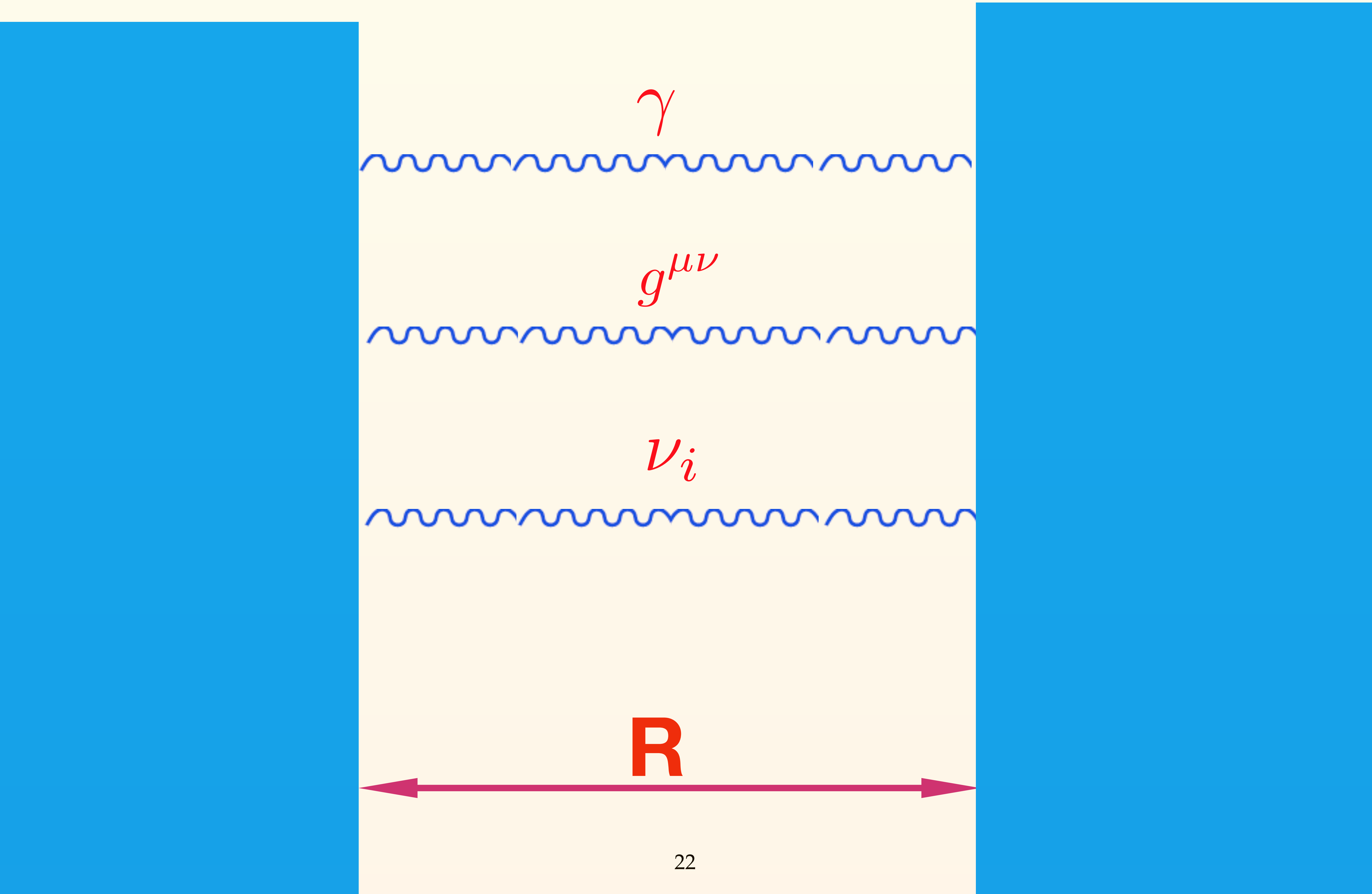
Conjectures forbid these vacua

Constraints on SM physics

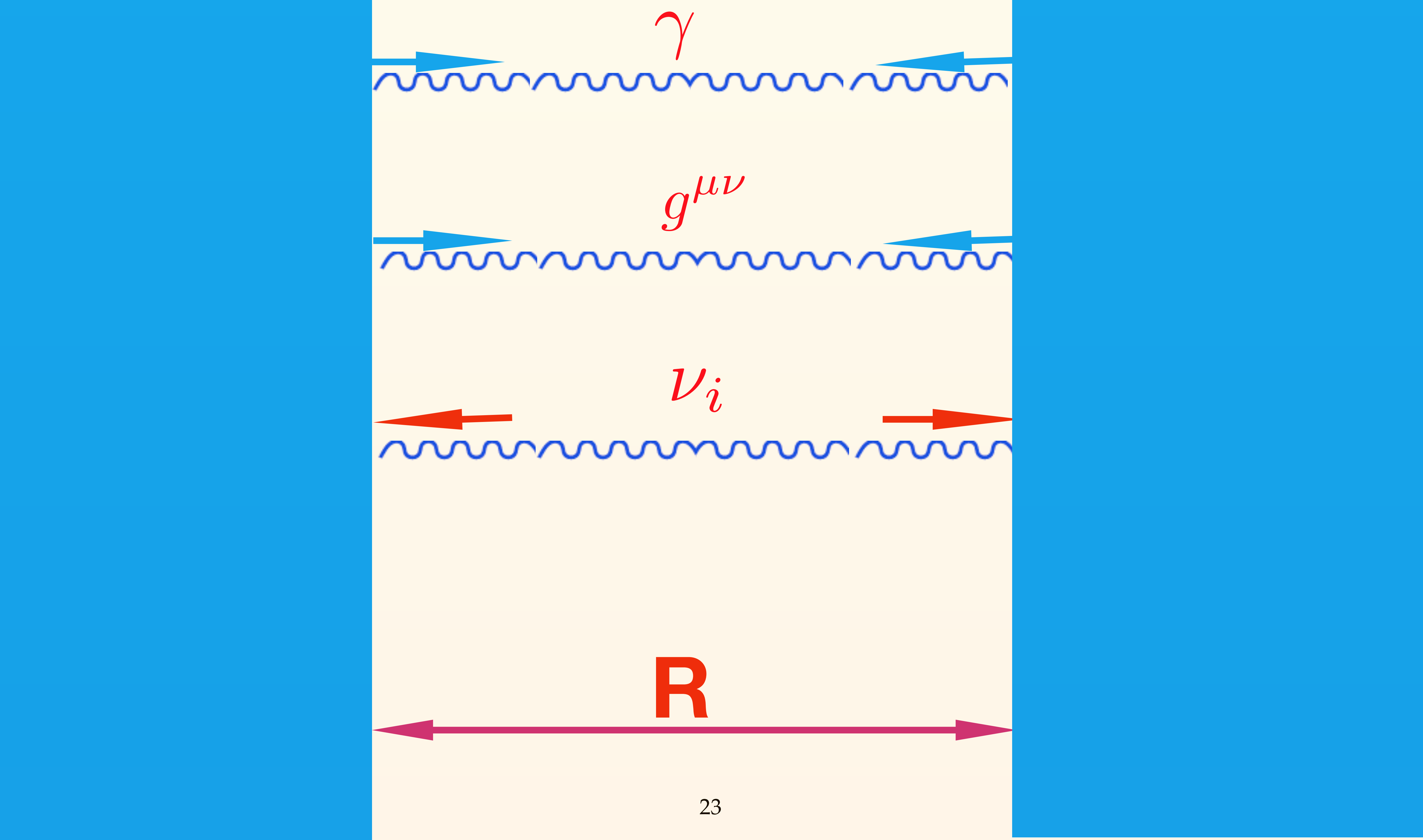
L.I., Martin-Lozano, Valenzuela 2017 *E. Gonzalo, L.I, Valenzuela 2021*

$Below\ electron\ threshold:$

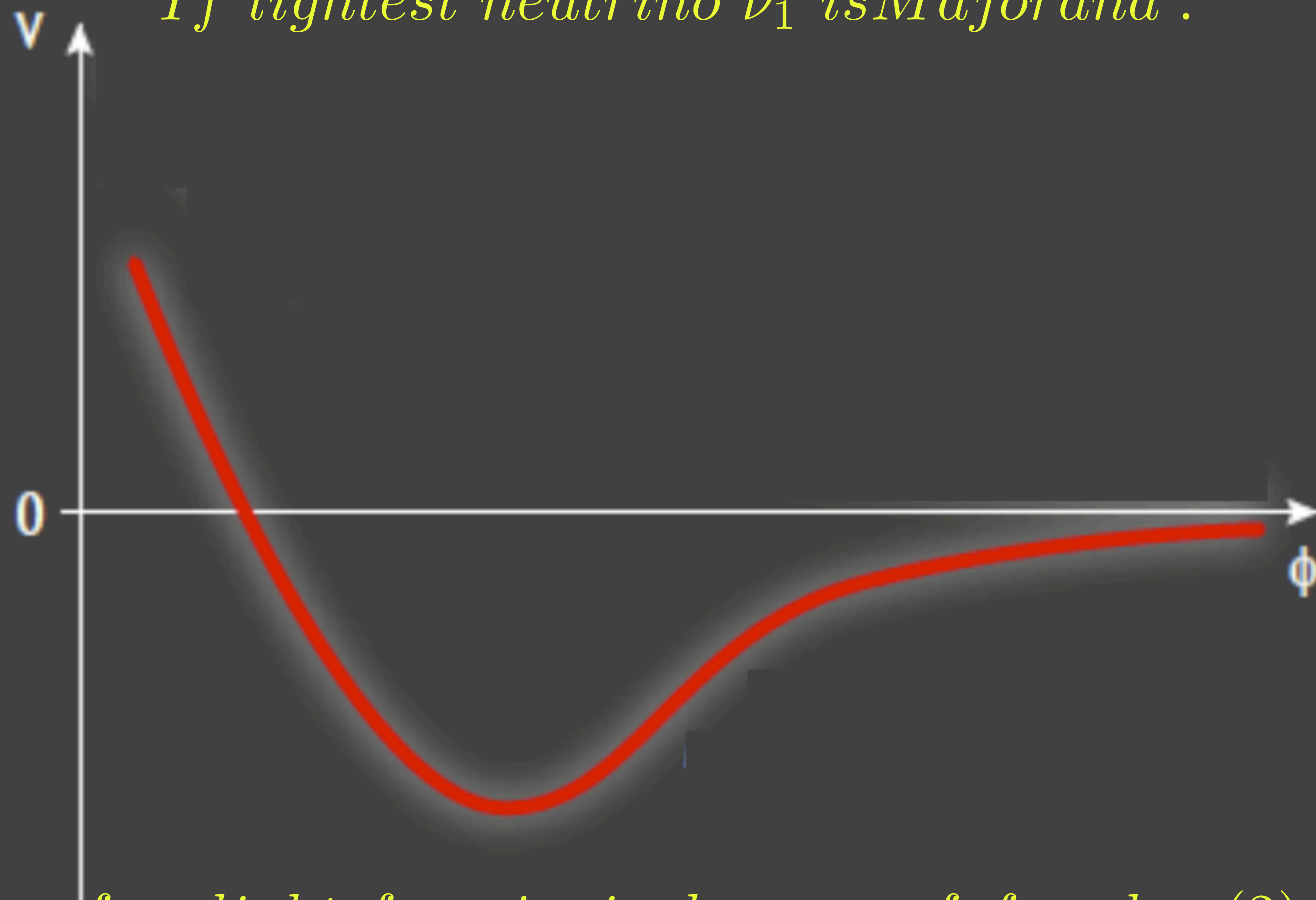
$m_e/m_\nu \ \simeq \ 10^8 : large\ region\ of\ energies\ with\ only\ \gamma, g^{\mu\nu}, \nu_i$



Casimir Energy



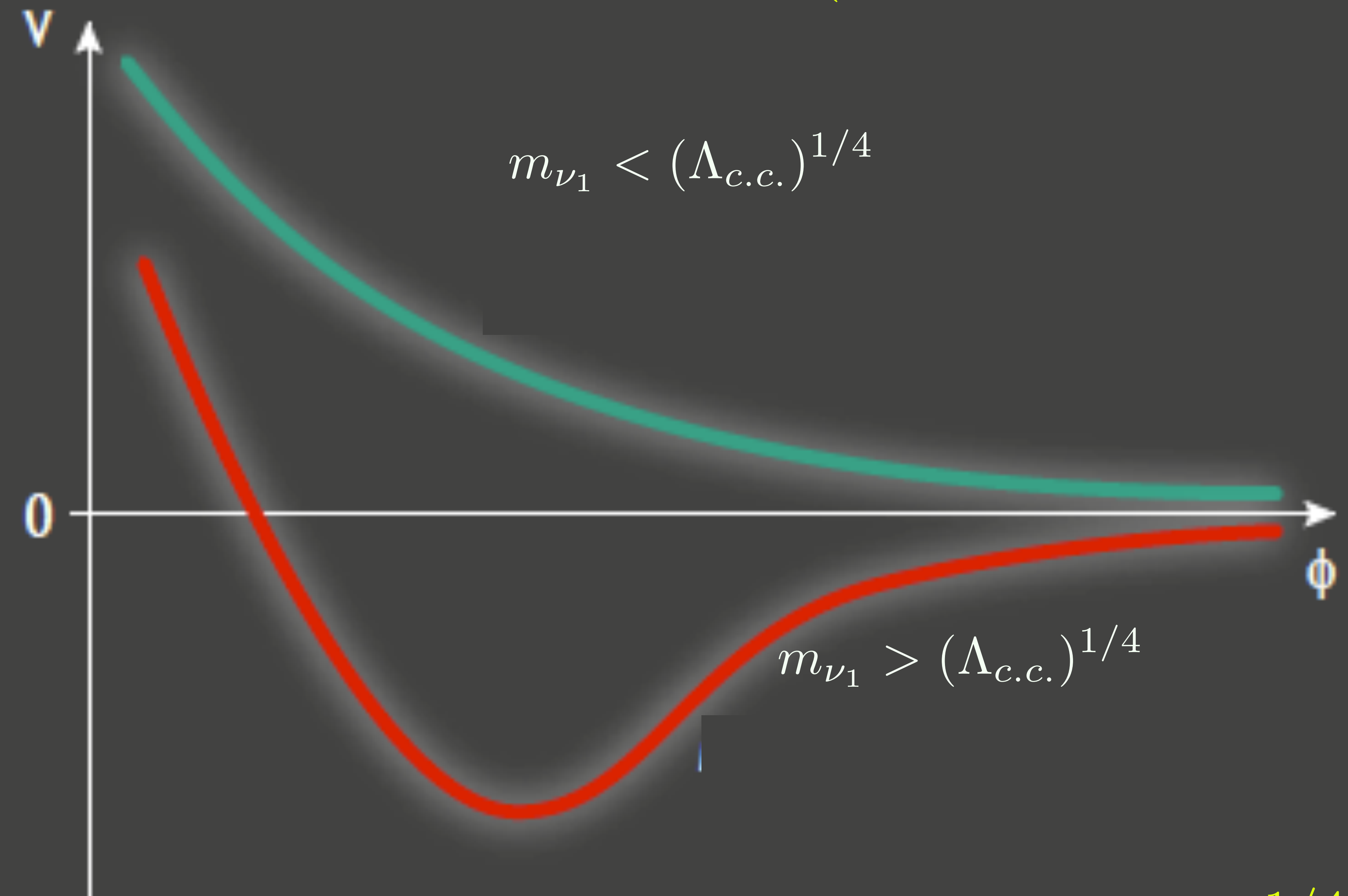
If lightest neutrino ν_1 isMajorana:



too few light fermionic degrees of freedom(2)

Majorana ν_1 excluded

$If\ lightest\ neutrino\ \nu_1\ is\ Dirac\ (4\ degrees\ of\ freedom):$



$AdS\ minimum\ avoided\ in\ 3D\ if\ m_{\nu_1} < V_{c.c.}^{1/4}$

** Neutrinos must be Dirac and have a mass: $m_{\nu_1} \lesssim 0.007\ eV$

** This would give an explanation for the remarkable experimental coincidence:

$$m_\nu \ \sim \ V_{c.c.}^{1/4}$$

** Bound not far away from cosmological results from CMB and galaxy surveys (combined with neutrino oscilation data):

$$m_{\nu_1} \ < \ 0.02\ eV \ \ (95\%c.l.)$$

$(O.Mena\ et\ al.\ 2021)$
$(GAMBIT\ col.\ (2020))$

** Majorana neutrinos are allowed if there is e.g. some hidden sector very light fermions with neutrino-like masses

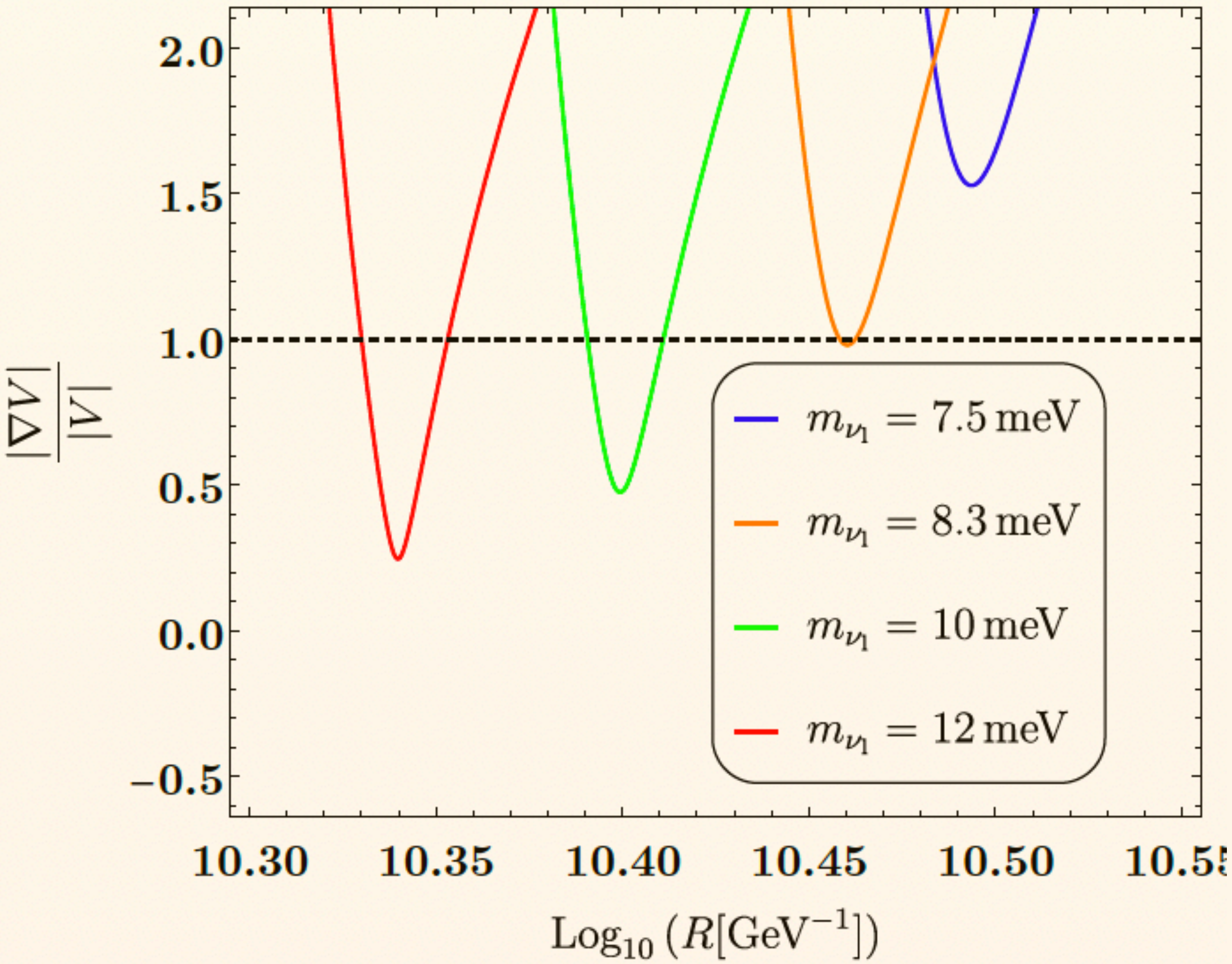
Quintessence

** In the pressence of a quintessence scalar, the 2-field potential in 3D has no stable AdS minima and the AdS conjectures cannot be applied directly.

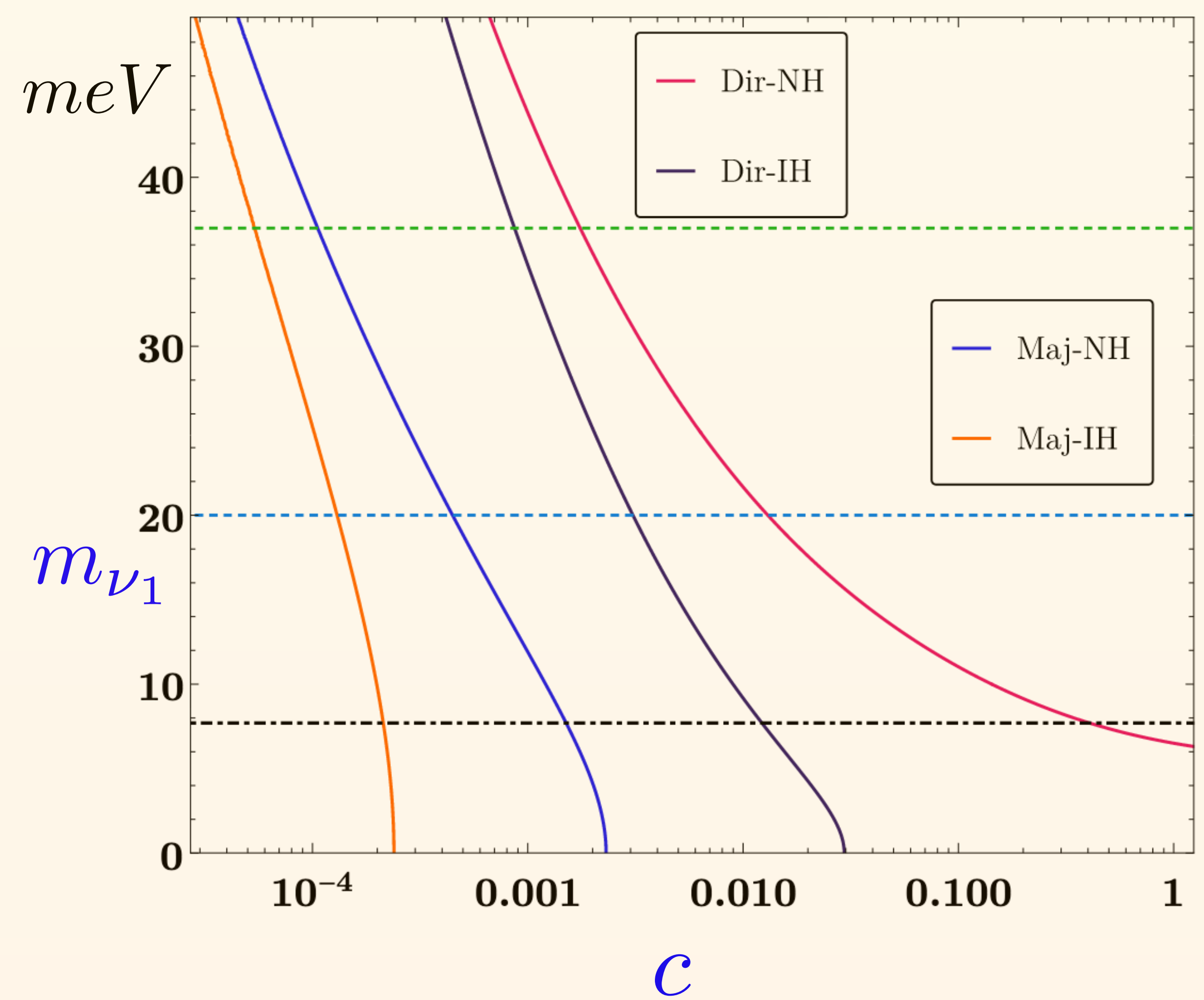
** One may obtain however similar bounds from the ‘refined’ dS conjecture which states that for large fields, even for negative AdS potentials

$$\frac{|\nabla V|}{|V|} \geq c \quad , \quad c \sim 1$$

E. Gonzalo, L.I. Valenzuela 2021



$c_Q = |U'|/|U| \sim 0.6,\ m_\phi \sim 10^{-42} GeV$



2) Some 'Festina Lente' implications

- Any charged particle in dS must obey

Montero, van Riet, Venke 2019
Montero, van Riet, Vafa, Venke 2022

$$\boxed{(2g^2\ V_0)^{1/4}\ <\ m}$$

- Improves the c.c. problem by 84 orders of magnitude!:

$$V_0\ <\ \frac{m_e^4}{2g^2}\ \sim\ (MeV)^4\ \sim\ 10^{-84}M_p^4$$

- EW interaction must be in broken phase since

$$< H_0 >= \frac{m_e}{Y_e}\ >\ 0.1\ MeV$$

- Limits inflation strongly: Higgs must have large vevs during inflation…

  - Any non-Abelian theory must be confining or broken !!
    (off diagonal generators are charged particles)

3)Hierarchy problem and the swampland

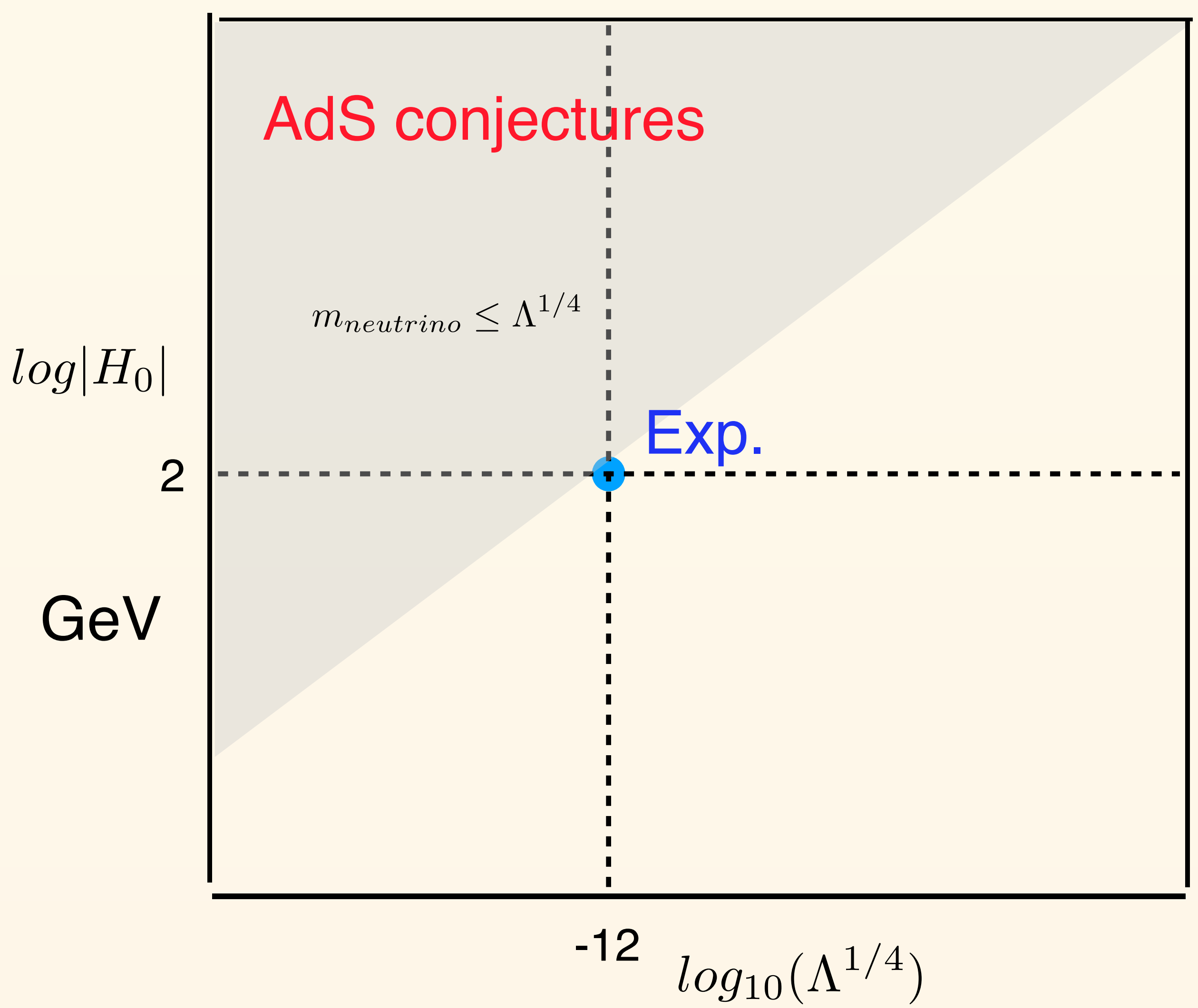
Dirac neutrinos(NH):

$(fixed\ Yukawa\ couplings)$

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

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

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



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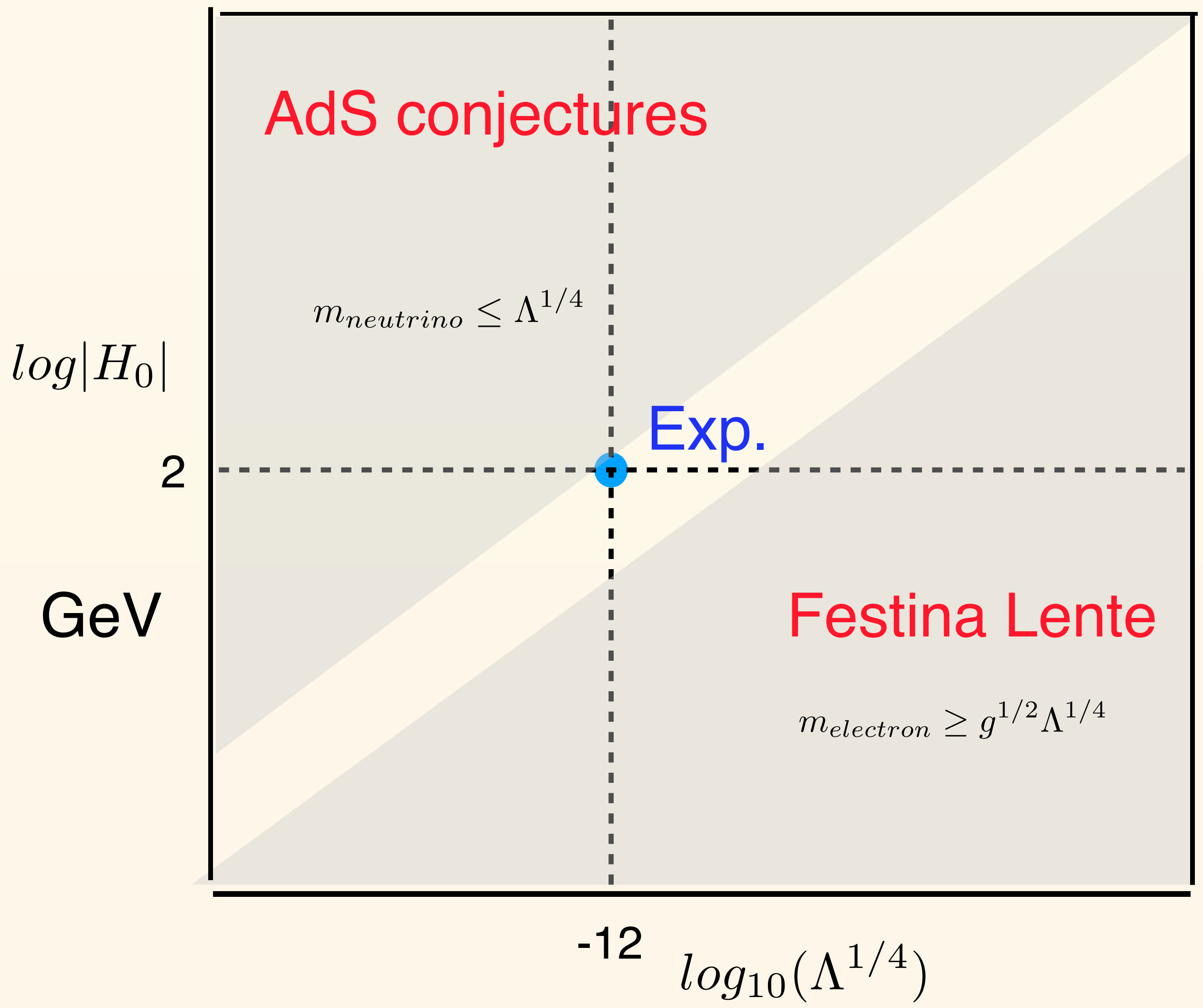


Festina Lente:

$$m_e = Y_e < H >$$

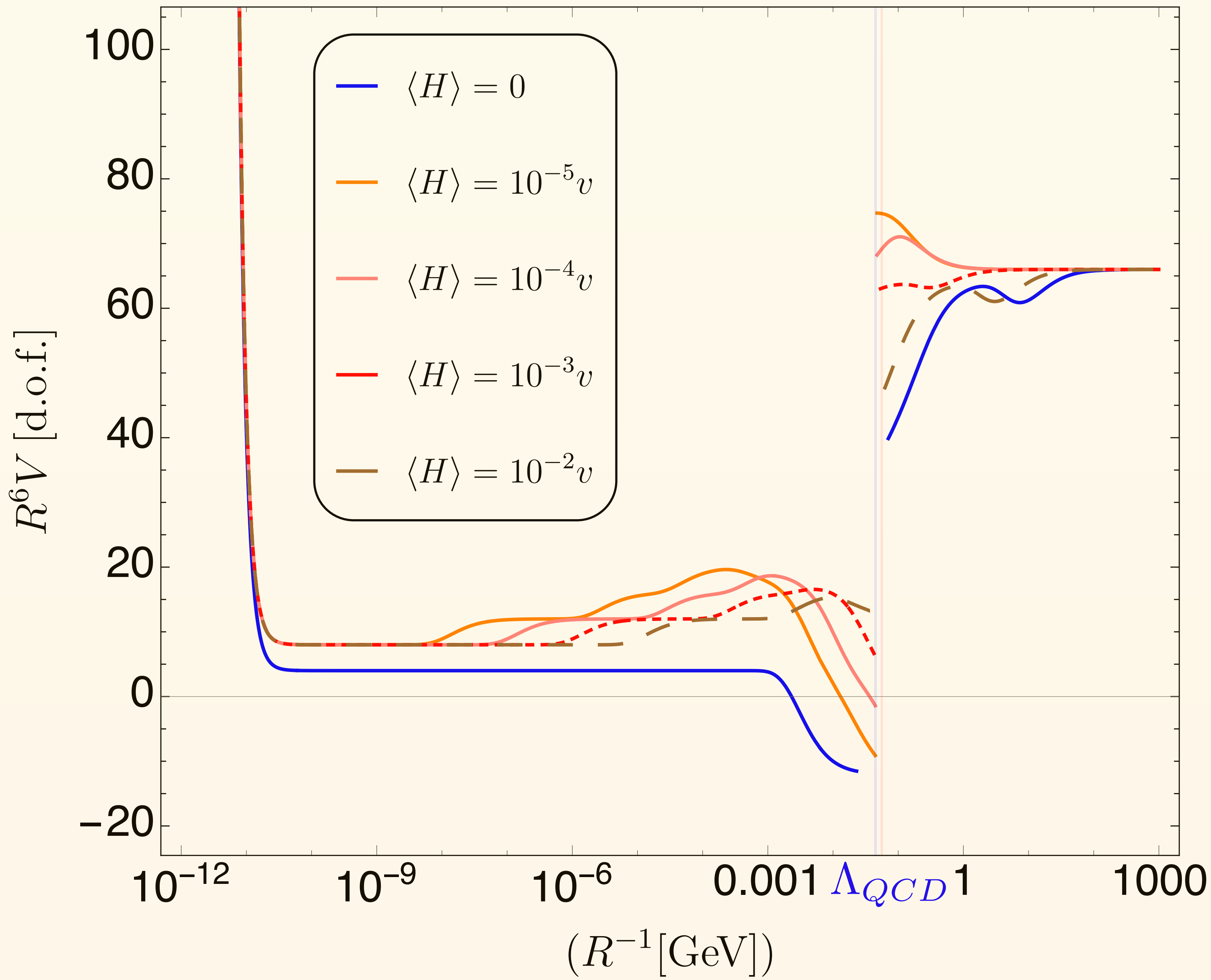
$$< H > \geq e^{1/2} \frac{\Lambda_4^{1/4}}{Y_e}$$

c.c. problem improved by many orders of magnitude:

'Festina lente': $\Lambda_{c.c.} \leq \frac{m_e^4}{g^2} \sim (MeV)^4 \ll M_p^4$

Additional lower bound on Higgs vev

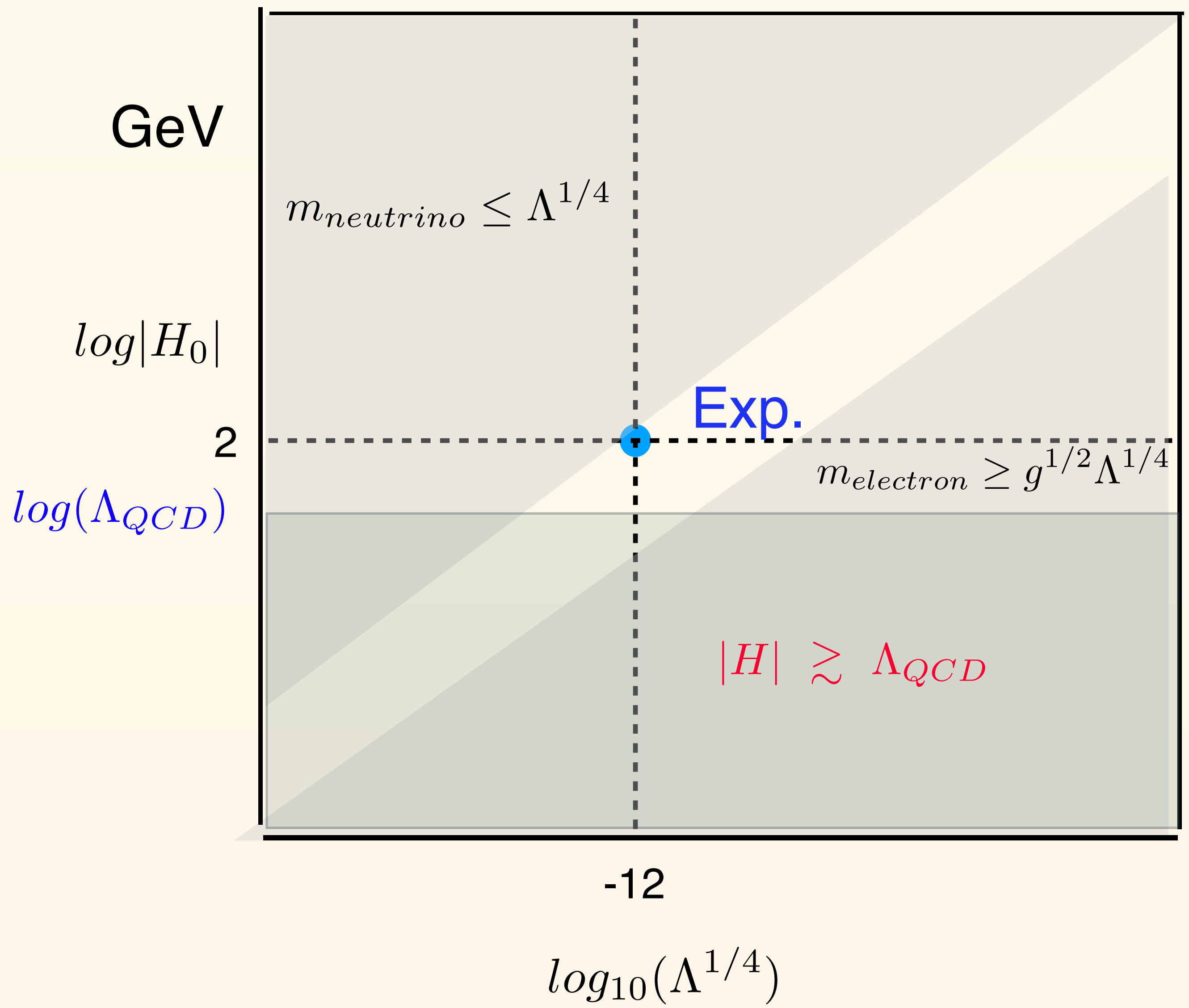
3D SM Casimir radion potential: AdS vacua develop, due to an excess of pseudo-Goldstone bosons below Λ_{QCD}



E. Gonzalo, L. I. (2018)

AdS vacua dissapear if $$|H| \gtrsim \Lambda_{QCD}$$

Swampland conditions strongly constraint the $|H_0| - \Lambda_{c.c.}$ plane



….and suggest a correlation $M_{EW} \sim \Lambda_{c.c.}^{1/4}$

4) Towers of states and holography

dS distance conjecture: $M_{tower} \lesssim V_0^{\tilde{\alpha}} M_p^{1-4\tilde{\alpha}} \quad as \ V_0 \to 0$

Smallness of V_0 suggests there could be possible towers in our universe

At what scale?

May be derived from holography: $\Lambda_{UV} \lesssim \Lambda_{IR}^{1/3} M_p^{2/3}$ Castellano, Herraez, L.I (2021)

Natural infrared cut-offs: $\Lambda_{IR} \sim V_0^r$

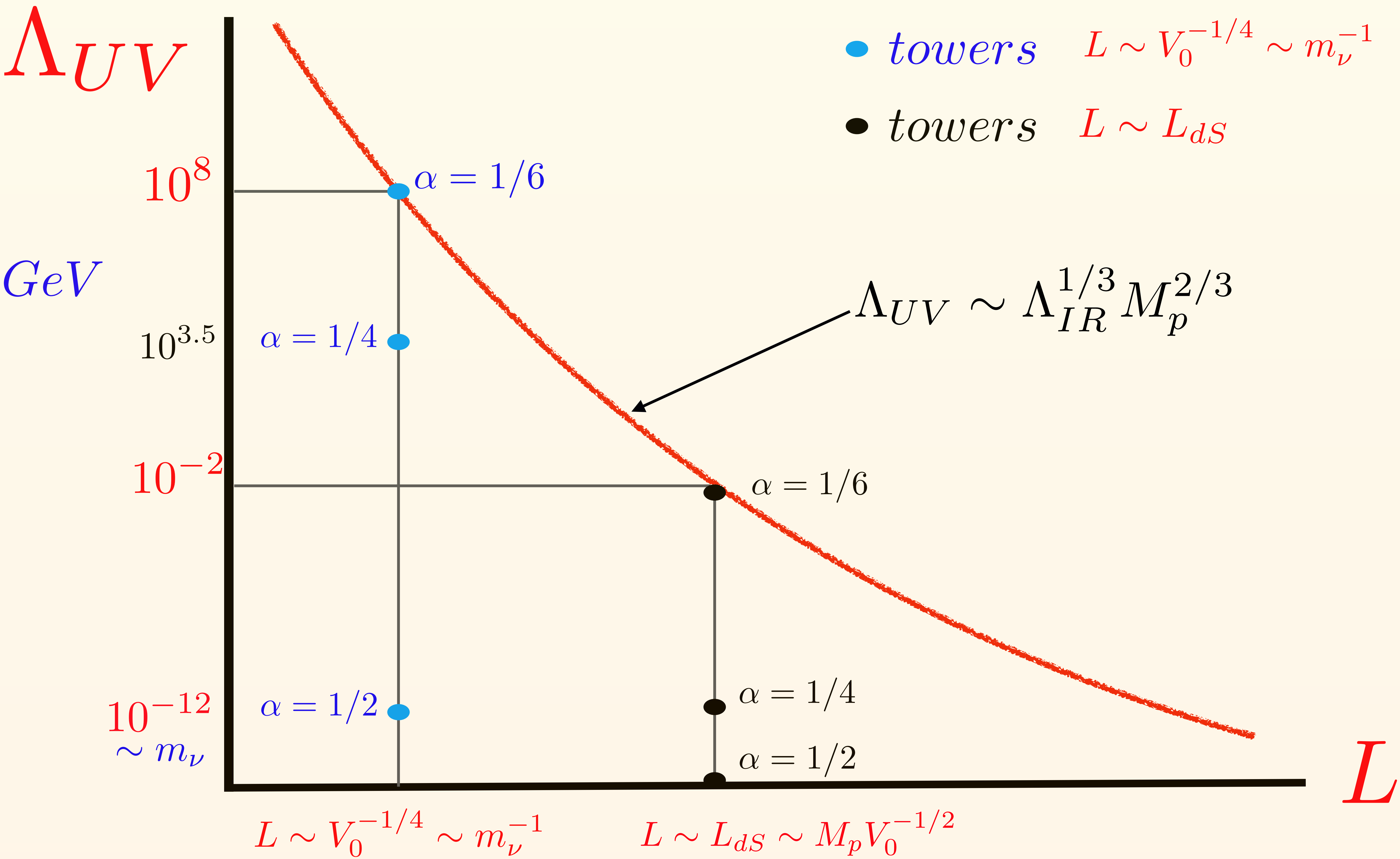
$r = 1/2 \ (dS \ horizon)$

$r = 1/4 \ (scale \ of \ potential)$

Scale of a (e.g. KK) tower is related to Λ_{UV} by: $M_{tower} \sim \Lambda_{UV}^{6\alpha} \quad \alpha = 1/2 - 1/6$

one recovers from holography $M_{tower} \lesssim V_0^{\tilde{\alpha}} M_p^{1-4\tilde{\alpha}} \quad with \ \tilde{\alpha} = 2r\alpha$

Smallness of V_0 suggests there could be possible towers in our universe



	Λ_{IR}	$\Lambda_{UV}\ (\forall\alpha)$	M_{tower}	$\alpha = 1/2$	$\alpha = 1/4$	$\alpha = 1/6$
$\Lambda_{IR}^{(1)} = \frac{V_0^{1/2}}{M_p}$	$=10^{-30}$ eV	10^{-2} GeV	M_{tower}	10^{-30} eV	10^{-3} eV	10^{-2} GeV
$\Lambda_{IR}^{(2)} = V_0^{1/4}$	$=10^{-3}$ eV	10^{8} GeV	M_{tower}	10^{-3} eV	$10^{3.5}$ GeV	10^{8} GeV

UV cut-off at $\Lambda_{UV} \sim 10^8\ GeV$

$$\alpha = 1/2 \longrightarrow M_{tower} \sim m_\nu \sim \Lambda_0^{1/4}$$

$$\alpha = 1/4 \longrightarrow M_{tower} \sim V_0^{1/8} M_p^{1/2} \sim TeV$$

Towers of light states at interesting scales may be present

$$\alpha = \frac{1}{2} \quad in\ particular\ M_{KK} \sim m_\nu$$

Castellano,Herraez,L.I (2021)

$$Different\ motivation\ and\ \Lambda_{UV}\ compared\ to\ LED\ !$$

Montero,Vafa,Valenzuela (2022)
'Dark Dimension'

M.Merian
(1621)

M.Merian
(1621)

The upside-down universe

$$\boxed{\Lambda_{UV} \lesssim (\Lambda_{IR})^{1/3} M_p^{2/3}}$$

- Since both are related, Λ_{UV} and Λ_{IR} are equally fundamental
  - So we should perhaps ask instead e.g. why $m_H \gg \Lambda_{c.c.}^{1/4}$?
    - If there is a KK tower beyond the SM with $\alpha = 1/4$

$$M_{IR} \sim V_0^{1/4} \sim 10^{-12} GeV$$

$$M_H < M_{KK} \sim V_0^{1/8} M_p^{1/2} \sim 3\ TeV$$

Castellano, Herraez, L.I (2021)

$$M_{UV} \sim V_0^{1/12} M_p^{2/3} \sim 2.4 \times 10^8 GeV$$

- Scales derived from the c.c. and not viceversa!!

- Reminiscent of T. Banks 2000 ideas in hep-th/0007146

Conclusions

- Quantum Gravity constraints effective field theories and may affect SM physics and cosmology in ways not previously foreseen

- We have described several possible phenomenological implications like

  - Bound on lightest neutrino: $m_{\nu_1} \lesssim \Lambda_{c.c.}^{1/4}$ (should have 4 d.o.f., e.g. Dirac)

  - Hierarchies of EW and c.c. scales very constrained

  - The c.c. problem drastically improved (FL): $\Lambda_{c.c.} \lesssim m_e^4$

  - Smallness of $\Lambda_{c.c.}$ suggests the possible existence of towers of light particles in our universe in a range

$$10^{-3} eV \lesssim M_{tower} \lesssim 10^{8}\ GeV$$

- Some of the Swampland conjectures are on very solid grounds (global symmetries, completeness, WGC, distance conjecture….)

- Much work is needed to better establish (or not) others like the AdS and dS conjectures, as well as FL. These are in fact the ones which have more phenomenological applicability.

- Much work is needed both in the formal and phenomenological sides in order to progress in understanding how QG affects the EFT’s which are relevant for the SM and cosmology

Thank you !!