Emergence in Quantum Gravity and the Fundamental Scales of Physics

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Do towers play any role in SM Physics?

quark-lepton hierarchies

smallness of neutrino masses
(need a tower around 700 TeV)

EW hierarchy

Fundamental scales determined by c.c.

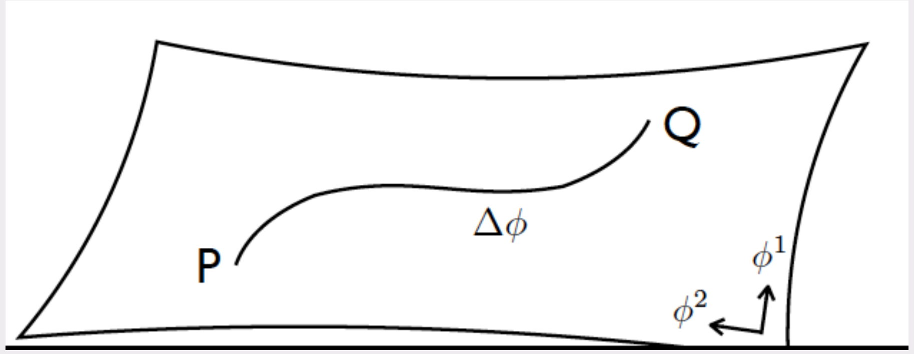
$$M_{EW} \simeq V_0^{1/8} M_p^{1/2} \qquad M_{UV} \simeq V_0^{1/24} M_p^{5/6}$$

work with A. Castellano and A. Herraez
arXiv:2302.00017, arXiv:2212.03908

(for a different view on the phenomenological role of towers see
Montero,Vafa,Valenzuela's 'dark dimension' 2022) (see Obied talk)

1) The importance of towers in QG

The Swampland Distance Conjecture:



Ooguri, Vafa 2006

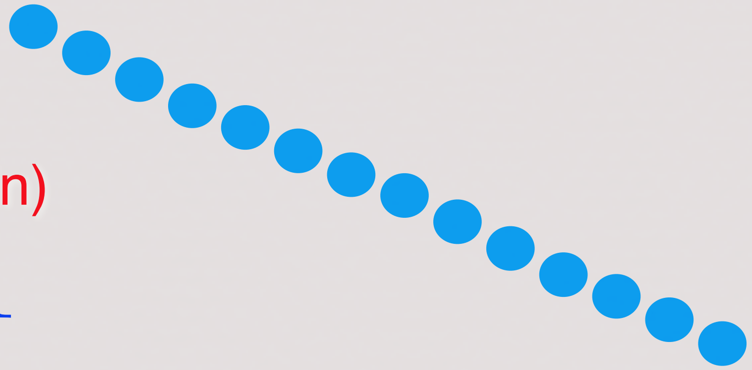
$$m(Q) \simeq m(P)e^{-\lambda\Delta\phi} \qquad \lambda \sim 1$$

as $\Delta\phi \to \infty$ exponentially massless towers of states appear:

$$m_n = n^{1/p} m_0 \quad ; \quad \Lambda_{UV} \simeq N^{1/p} m_0$$

Particles (Kaluza-Klein)

$p = 1$

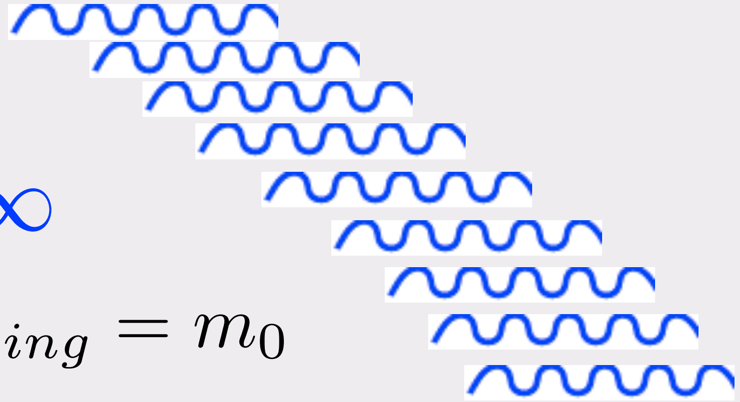


or

Strings

$p = \infty$

$\Lambda_{UV} \simeq M_{string} = m_0$



tested in many string theory vacua

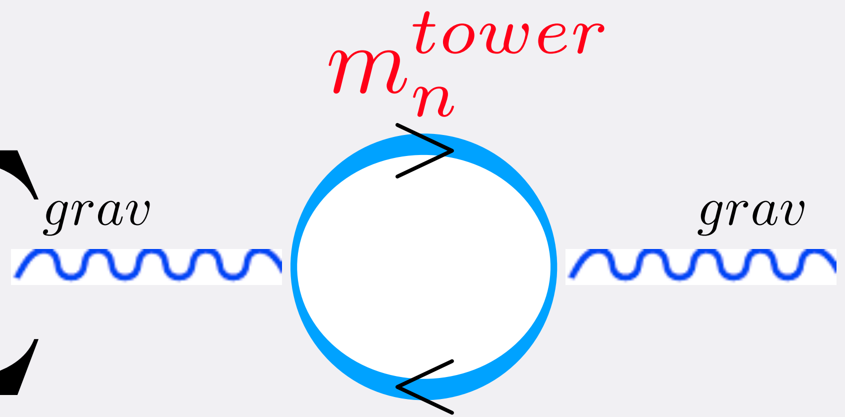
If for some reason we are in a ST vacuum with a large modulus, a tower(s) should appear

2) What is the fundamental Quantum gravity scale?

$M_{Planck}?\ M_{String}?$ In general not

It is the scale at which strong quantum gravity effects cannot be neglected:

$$\sum_{n=1}^{N}$$



$N\ =\ number\ of\ species$

- Loop corrections to Newton's constant

$$M_{Planck}^2 \longrightarrow \Lambda_{QG}^2 \simeq \frac{M_{Planck}^2}{N}$$

$\Lambda_{QG}^2\ is\ the\ `species\ scale'$

$Dvali, Redi\ (2007)$

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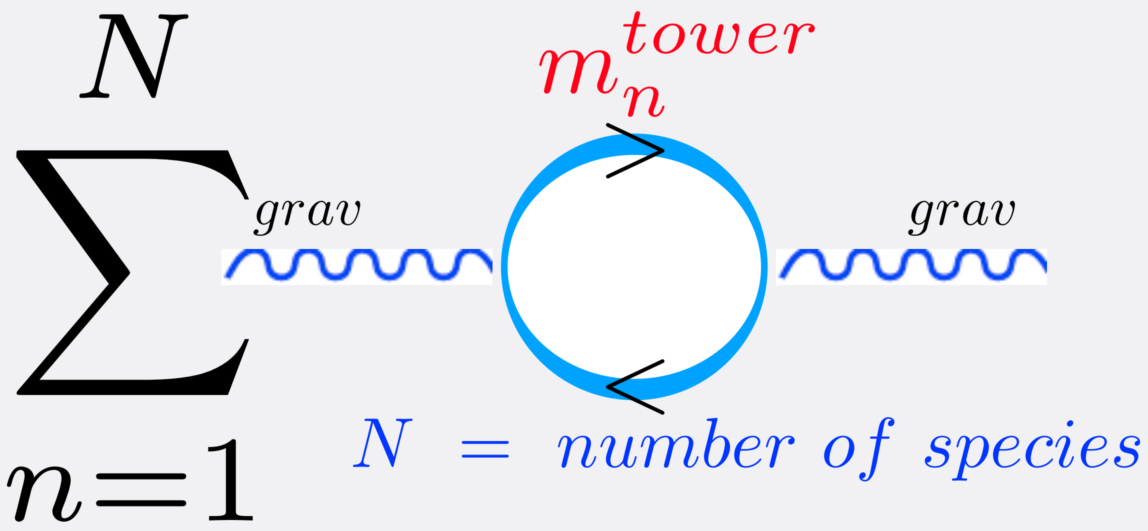

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- Loop corrections to Newton's constant

$$M^2_{Planck} \longrightarrow \Lambda^2_{QG} \simeq \frac{M^2_{Planck}}{N}$$

Λ^2_{QG} *is the 'species scale'*

Dvali, Redi (2007)

In the presence of towers with N>>1 the fundamental QG scale substantially lowered:

$$\boxed{\Lambda^3_{QG} \simeq m_0 \ M^2_{Planck}} \ll M^3_{Planck}$$

$e.g.\ extra\ dim.\ at\ m_0 \simeq 1 TeV \longrightarrow \Lambda_{QG} \simeq 10^{13}\ GeV$

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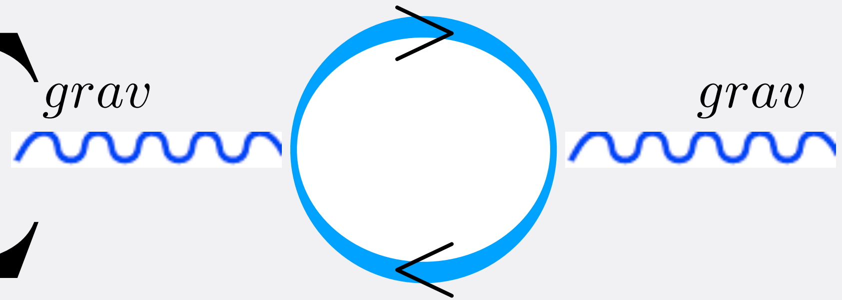

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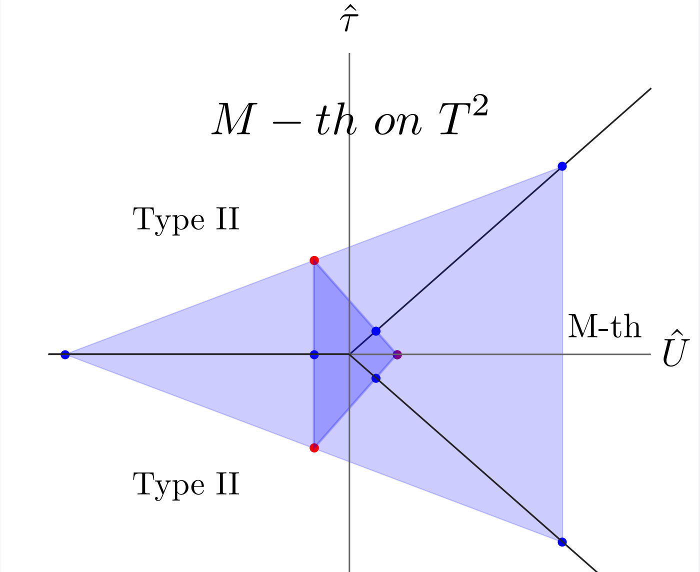
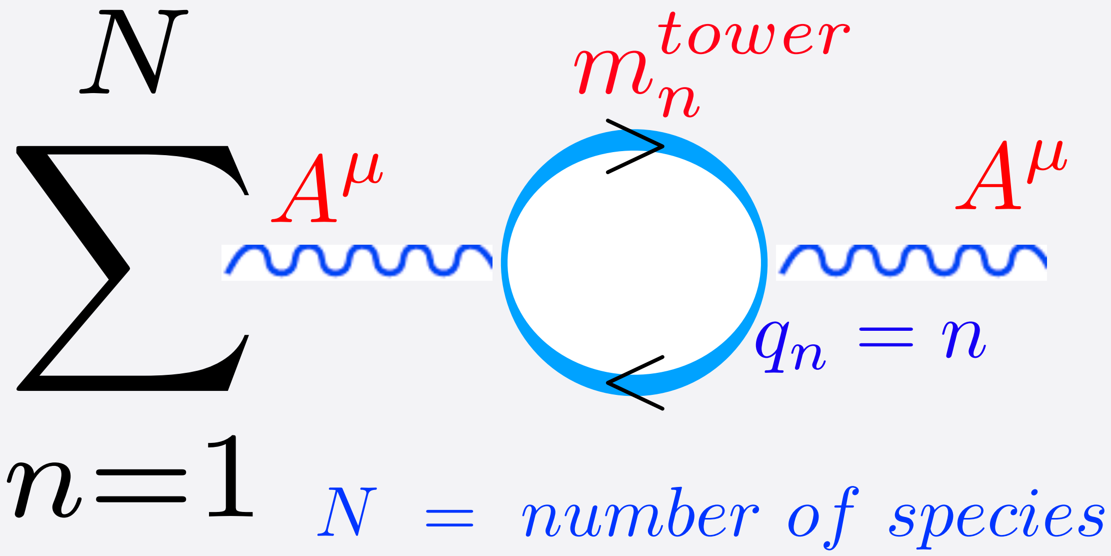
$$\Lambda_{QG}\ =\ \Lambda_{QG}(\phi_i)\ is\ moduli\ dependent!!$$



talks Castellano, Herraez, Valenzuela, Wiesner, Ruiz…..

3) Large wave-function renormalisation

Another important effect of towers!!



- Loop corrections gauge couplings

$$\frac{1}{g^2} \simeq \sum_n^N n^2 \log\left(\frac{\Lambda_{\mathrm{QG}}^2}{m_0^2\, n^2}\right) \sim N^3 \lesssim \frac{M_p^2}{m_0^2}\,,$$

→ $m_0^2 \lesssim g^2 M_p^2$

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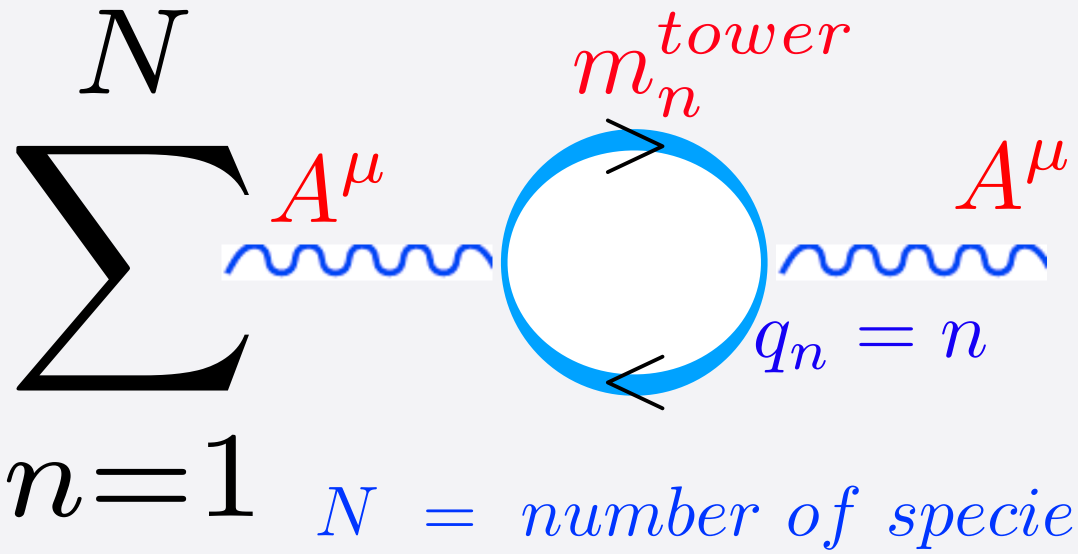

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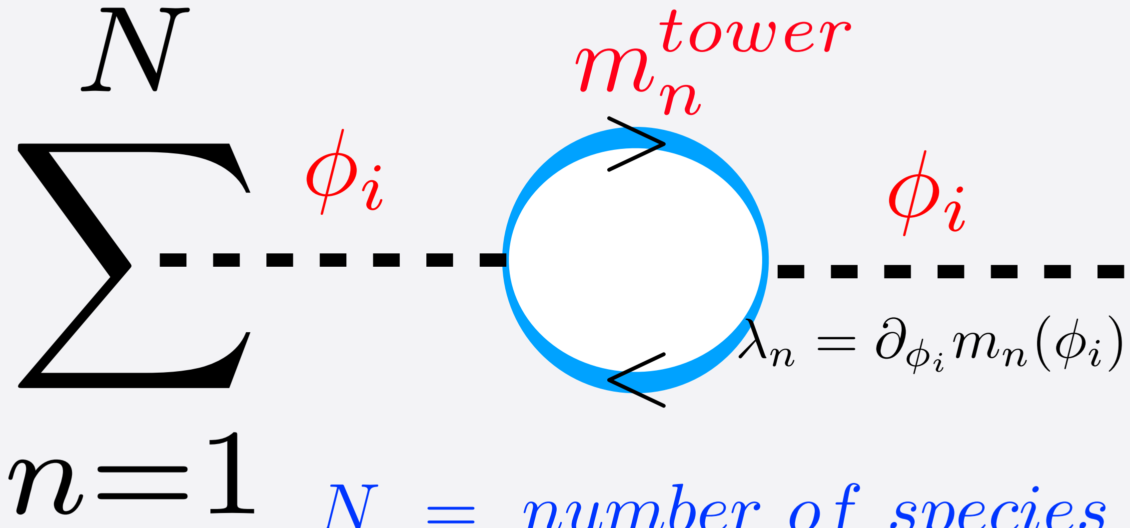
$$\uparrow$$

$$\longrightarrow \quad m_0^2 \lesssim g^2 M_p^2$$

'magnetic WGC'



$N = number\ of\ species$

- Loop corrections to moduli

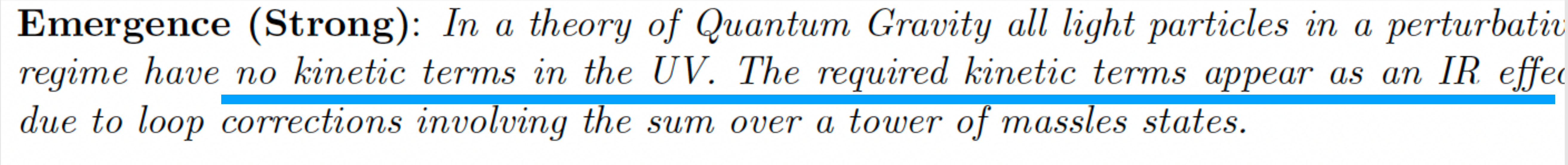
$$g_{\phi\phi} \sim \sum_{n=1}^{N} (n\partial_\phi m_0)^2 log\left(\frac{\Lambda_{QG}^2}{n^2 m_0^2}\right) \sim M_p^2 (\frac{\partial_\phi m_0}{m_0})^2$$

$$\uparrow$$

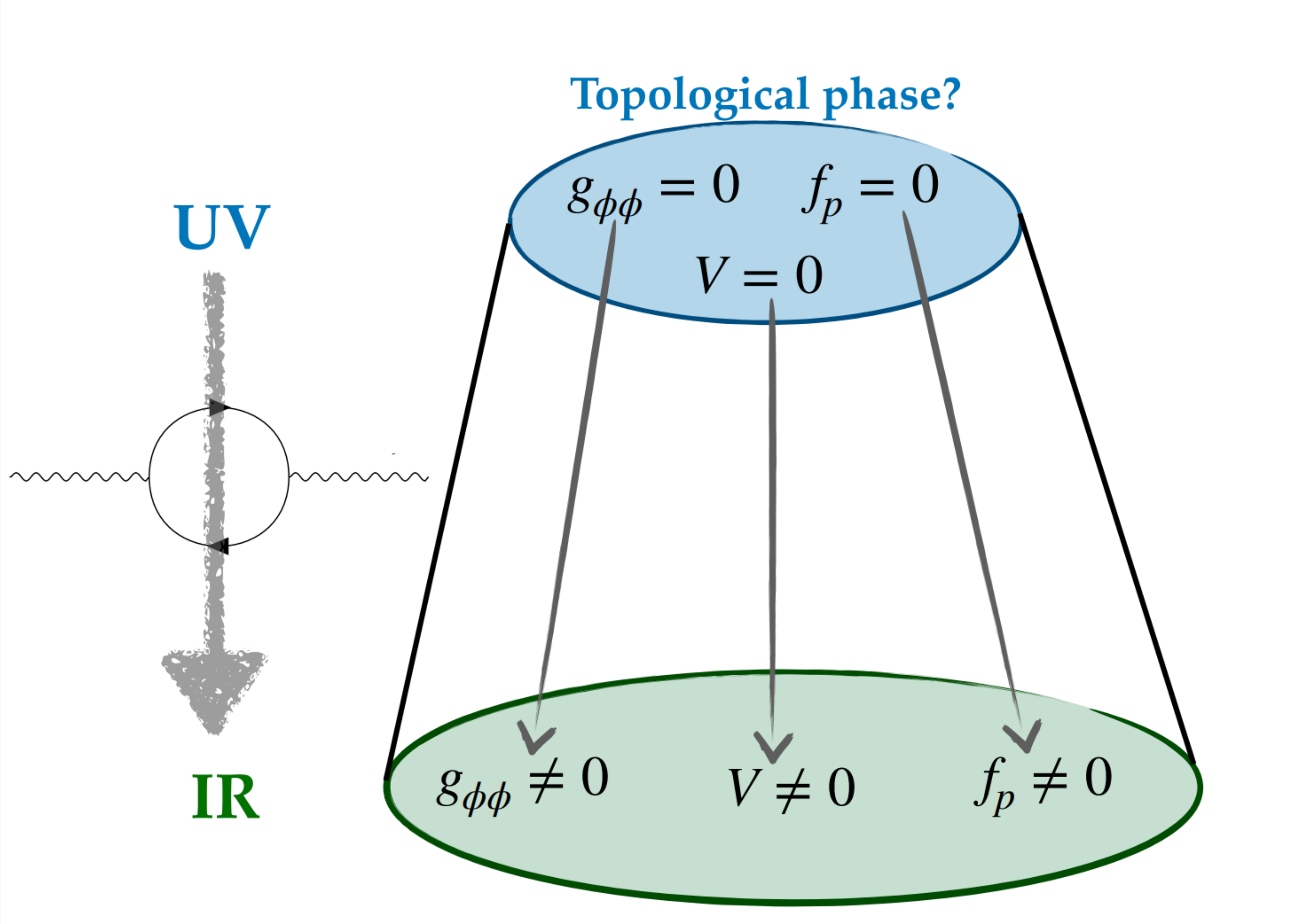
distance conjecture

These loop effects may be large for small tower scale m_0 !

Emergence Conjecture:



Emergence (Strong): *In a theory of Quantum Gravity all light particles in a perturbativ regime have no kinetic terms in the UV. The required kinetic terms appear as an IR effec due to loop corrections involving the sum over a tower of massles states.*



Harlow 2015 | Grimm, Palti, Valenzuela 2018 | Heidenreich, Reece, Rudelius 2018 | Ooguri, Palti, Shiu, Vafa 2018 | Palti 2019

Recent systematic analysis: A. Castellano, A. Herráez, L.I. arXiv: 2212.03908

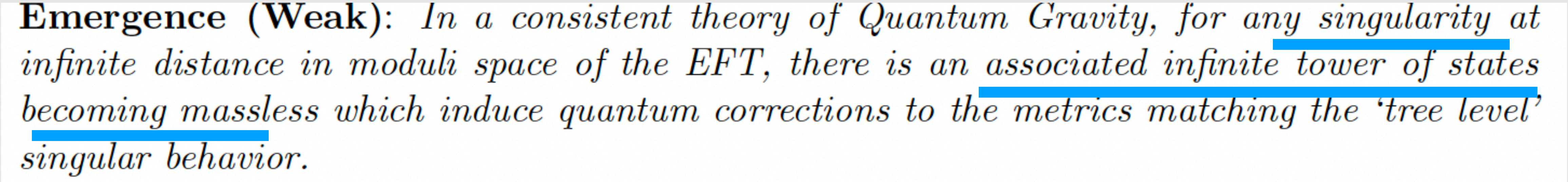
Recently tested in a number string theory examples,

A. Castellano, A. Herráez, L.I. arXiv: 2212.03908
Marchesano, Meloti 2022,
Blumenhagen et al 2023

- 4D Type IIA, IIB string theory on CY examples (kinetic terms and flux potentials)
- 6D examples from F-theory on an eliptic fibration
- 7D examples from _theory on K3
- 10D Type IIA and Type IIB strings
-

Emergence gives an understanding of the distance conjecture and the magnetic WGC

Conjecture still being checked



Emergence (Weak): *In a consistent theory of Quantum Gravity, for any singularity at infinite distance in moduli space of the EFT, there is an associated infinite tower of states becoming massless which induce quantum corrections to the metrics matching the 'tree level' singular behavior.*

Towers and the SM

5) Emergence and the SM Yukawas

- For canonical kinetic terms:

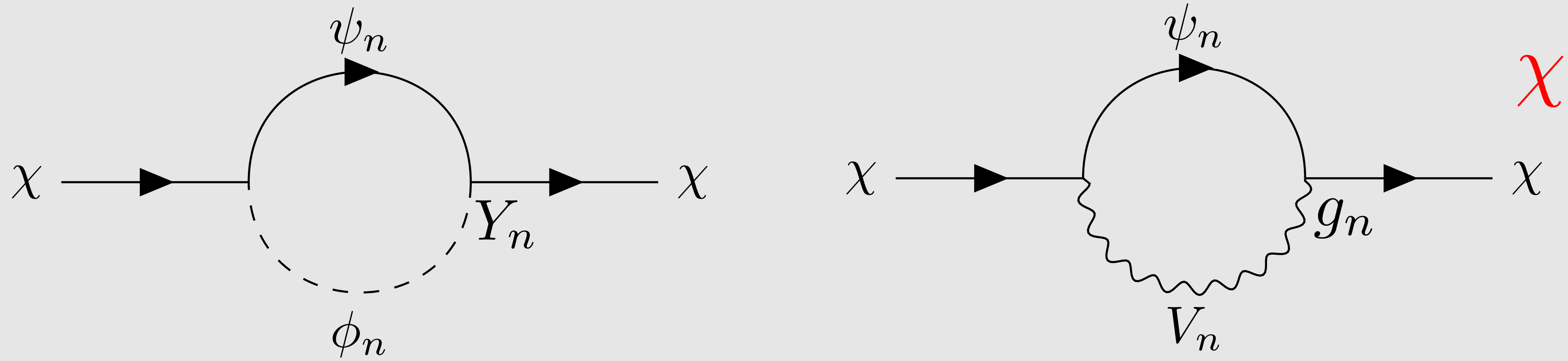
Palti 2020
Castellano, Herraez, L.I. 2022

$$Y_{ijk} = \mathcal{S}_{ijk} \left(g_{i\bar{i}} g_{j\bar{j}} g_{k\bar{k}}\right)^{-1/2}$$

emergence: $UV : \sim 0, 1$
(e.g.intersection numbers)

may be small for light towers

$$\sum_{n}^{N}$$



$\chi = q, l$

$$m_n = n m_0 \; ; \; \Lambda = N m_0 \; ; \; Y_n, g_n = n$$

$$g_{\chi\chi} \sim \sum_{n}^{N} n^2 \sim N^3 \sim \left(\frac{M_p}{m_0}\right)^2$$

suggested intersecting branes
L.I., F.Marchesano t.a.

$$g_{\chi\chi}^{-1/2} \sim \left(\frac{m_0}{M_p}\right)$$

- Light tower implies small Yukawas

- Case of additional multiple heavier towers (appropriate for SM case) :

$$m_n^{(i)} = n_i m_o^{(i)} \ ; \ \Lambda = N m_0 = N_i m_0^i \qquad N \gg N_i$$

$$g_{ii} \sim \sum_{n_i}^{N_i} \sim N_i^3 \sim \left(\frac{\Lambda}{m_0^{(i)}} \right)^3$$

$$Y_{ijk} \ \simeq \ \mathcal{S}_{ijk} \ \left(\left(\frac{m_0^{(i)}}{\Lambda} \right) \left(\frac{m_0^{(j)}}{\Lambda} \right) \left(\frac{m_0^{(k)}}{\Lambda} \right) \right)^{3/2}$$

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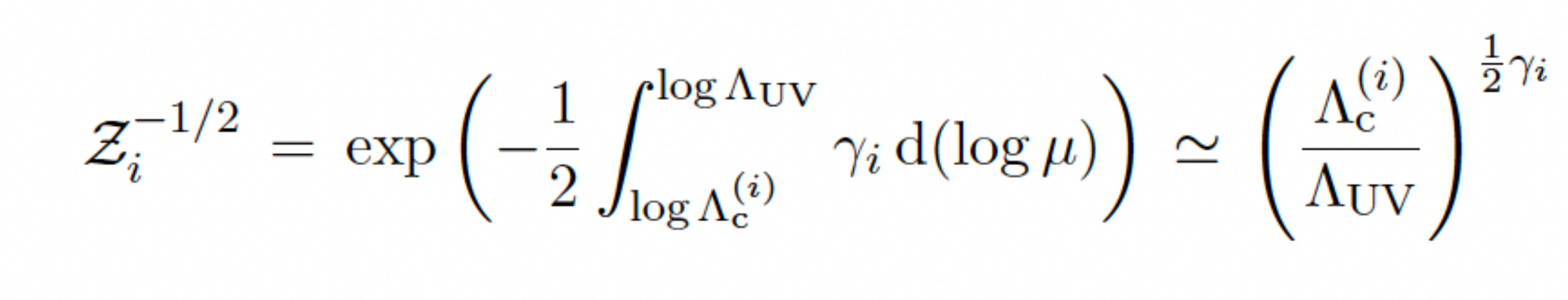
- Hierarchies somewhat analogous to ‘Superconformal Flavor Models’

Georgi et al, ‘On the proposition that all fermions are created equal’ (1983)



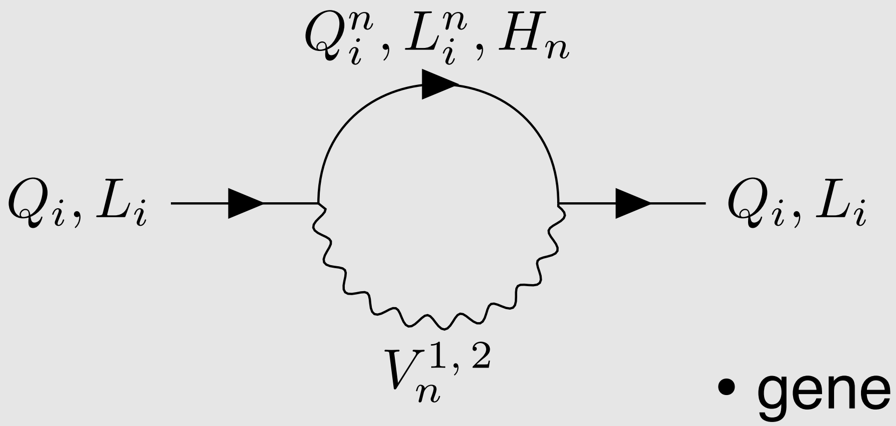
$$\mathcal{Z}_i^{-1/2} = \exp\left(-\frac{1}{2} \int_{\log \Lambda_c^{(i)}}^{\log \Lambda_{\rm UV}} \gamma_i \, {\rm d}(\log \mu) \right) \simeq \left(\frac{\Lambda_c^{(i)}}{\Lambda_{\rm UV}} \right)^{\frac{1}{2}\gamma_i}$$

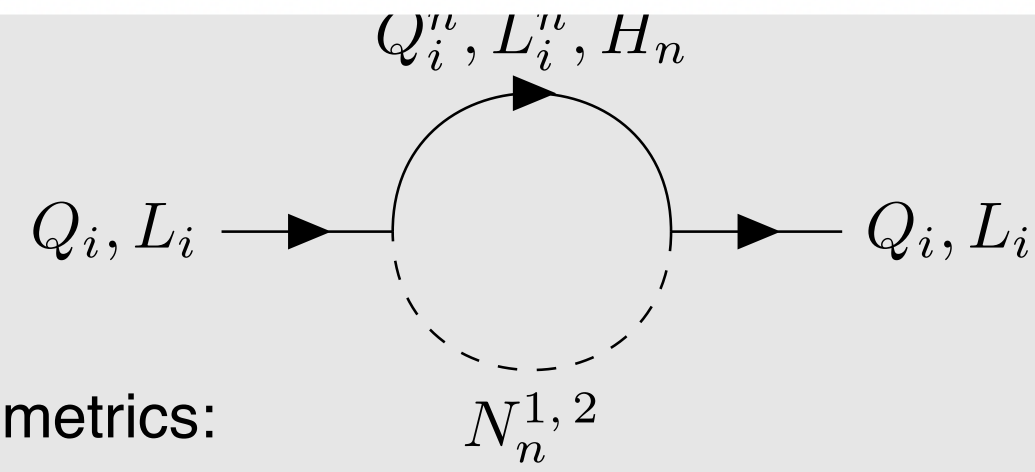
Nelson, Strassler 2000 *Poland, Simmons-Duffin 2009*

Flavour hierarchies from emerging towers

Castellano,Herraez,L.I. 2023

$$W_Y = \overline{H}\left(\mathcal{S}^U_{ij} Q^i_L U^j_R + \mathcal{S}^\nu_{ij} L^i \nu^j_R\right) + H\left(\mathcal{S}^D_{ij} Q^i_L D^j_R + \mathcal{S}^E_{ij} L^i E^j_R\right)$$





- generate metrics:

$$Y^U_{ij} \simeq \mathcal{S}^U_{ij}\left(g_{\bar{H}} g_Q^{(i)} g_U^{(j)}\right)^{-1/2}, \qquad Y^D_{ij} \simeq \mathcal{S}^D_{ij}\left(g_H g_Q^{(i)} g_D^{(j)}\right)^{-1/2}$$

$$Y^E_{ij} \simeq \mathcal{S}^E_{ij}\left(g_H g_L^{(i)} g_E^{(j)}\right)^{-1/2}, \qquad Y^\nu_{ij} \simeq \mathcal{S}^\nu_{ij}\left(g_{\bar{H}} g_L^{(i)} g_{\nu_R}^{(j)}\right)^{-1/2}$$

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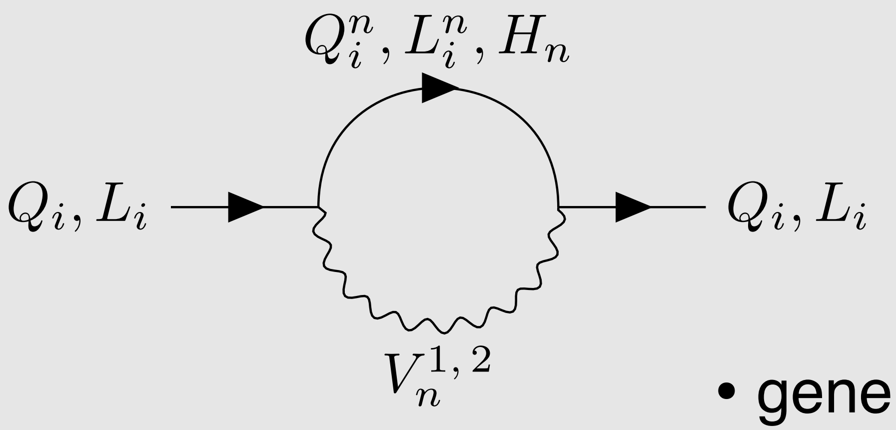

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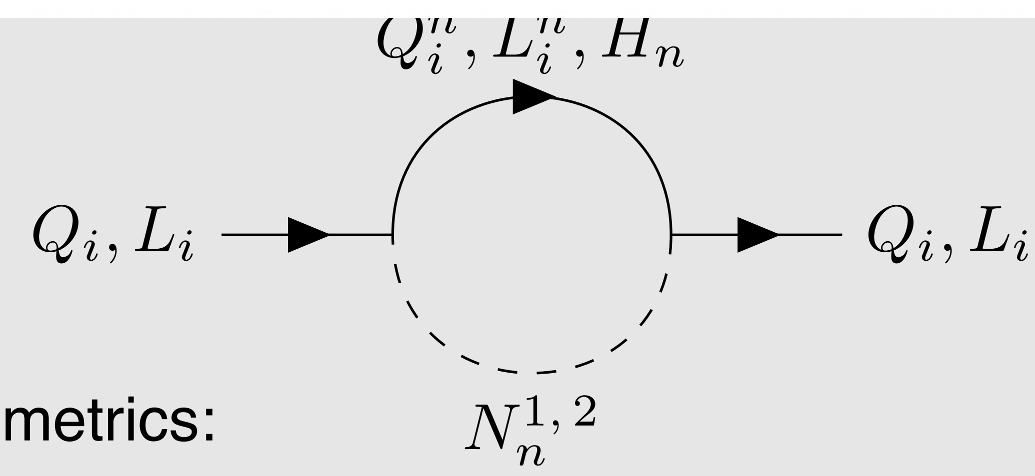

$$Y^U_{ij} \simeq \mathcal{S}^U_{ij}\left(g_{\bar{H}} g^{(i)}_Q g^{(j)}_U\right)^{-1/2}, \qquad Y^D_{ij} \simeq \mathcal{S}^D_{ij}\left(g_H g^{(i)}_Q g^{(j)}_D\right)^{-1/2}$$

$$Y^E_{ij} \simeq \mathcal{S}^E_{ij}\left(g_H g^{(i)}_L g^{(j)}_E\right)^{-1/2}, \qquad Y^\nu_{ij} \simeq \mathcal{S}^\nu_{ij}\left(g_{\bar{H}} g^{(i)}_L g^{(j)}_{\nu_R}\right)^{-1/2}$$

- Define (potentially) small parameters:

$f = Q, U, D, L, E, N$

$$\epsilon^{(i)}_f \equiv \left(g^{(i)}_{ff}\right)^{-1/2} = \left(\frac{m^{(i)}_{0f}}{\Lambda}\right)^{3/2}$$

- One can describe the observed quark and (charged) fermion masses

$$\epsilon^{(i)} \sim \frac{1}{\Lambda^{9/2}}(m^1_0, m^2_0, m^3_0)^{3/2} \sim (1, 10^{-1}, 10^{-2})$$

- The hierarchy of quarks/leptons is a reflection of (small) hierarchies of towers

6) The special rol of Dirac neutrino masses

- Recall some neutrino facts. From oscillations:

$$\Delta m^2_{21} = (7.42 \pm 0.2) \times 10^{-5}\ \mathrm{eV}^2\,, \qquad \Delta m^2_{31} = (2.51 \pm 0.028) \times 10^{-3}\ \mathrm{eV}^2$$

- Lightest neutrino mass unknown
- Do not know whether hierarchy is 'normal' or 'inverted'
- Do not know if they are Dirac or Majorana
- An intriguing coincidence: $\boxed{m_\nu \sim (V_0)^{1/4}} \sim 10^{-1} - 10^{-2}\ eV$

$cosmological\ constant$

- Why neutrino masses so small? A popular idea IF neutrinos are Majorana:

$$See - saw\ mechanism:\ m_\nu \simeq \frac{M^2_{EW}}{M_*}$$

……. does not explain why $m_\nu \sim V_0^{1/4}$ ……..

Neutrino Dirac masses and an emergent tower

$$Y_{ij}^{\nu} \; = \; \mathcal{S}_{ij}^{\nu} \left(\underset{\underset{\sim 1}{\nwarrow}}{g_{\bar{H}}} \, \underset{\underset{(1, \epsilon_L^{(2)}, \epsilon_L^{(1)})}{\uparrow}}{g_L^{(i)}} \, g_{\nu_R}^{(j)} \right)^{-1/2} \sim \left(\frac{m_{0\nu_R}^{(j)}}{M_p} \right) \epsilon_L^{(i)}$$

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Consider 3-d neutrino generation. Exp. for normal hierarchy $m_{\nu_3} \simeq \sqrt{\Delta m^2_{32}} \simeq 5\times 10^{-2} eV$

$$m_{\nu_3} \simeq M_{EW}\,\frac{m_{0\nu_R}}{M_p} \;\simeq\; 5\times 10^{-2} eV$$

→ $\boxed{m_{0\nu_R} \;\simeq 690\; TeV}$

There must be a tower at that scale

(extra dimensions)

in order to describe the observed neutrino masses (which are Dirac)

Castellano,Herraez,L.I. 2023

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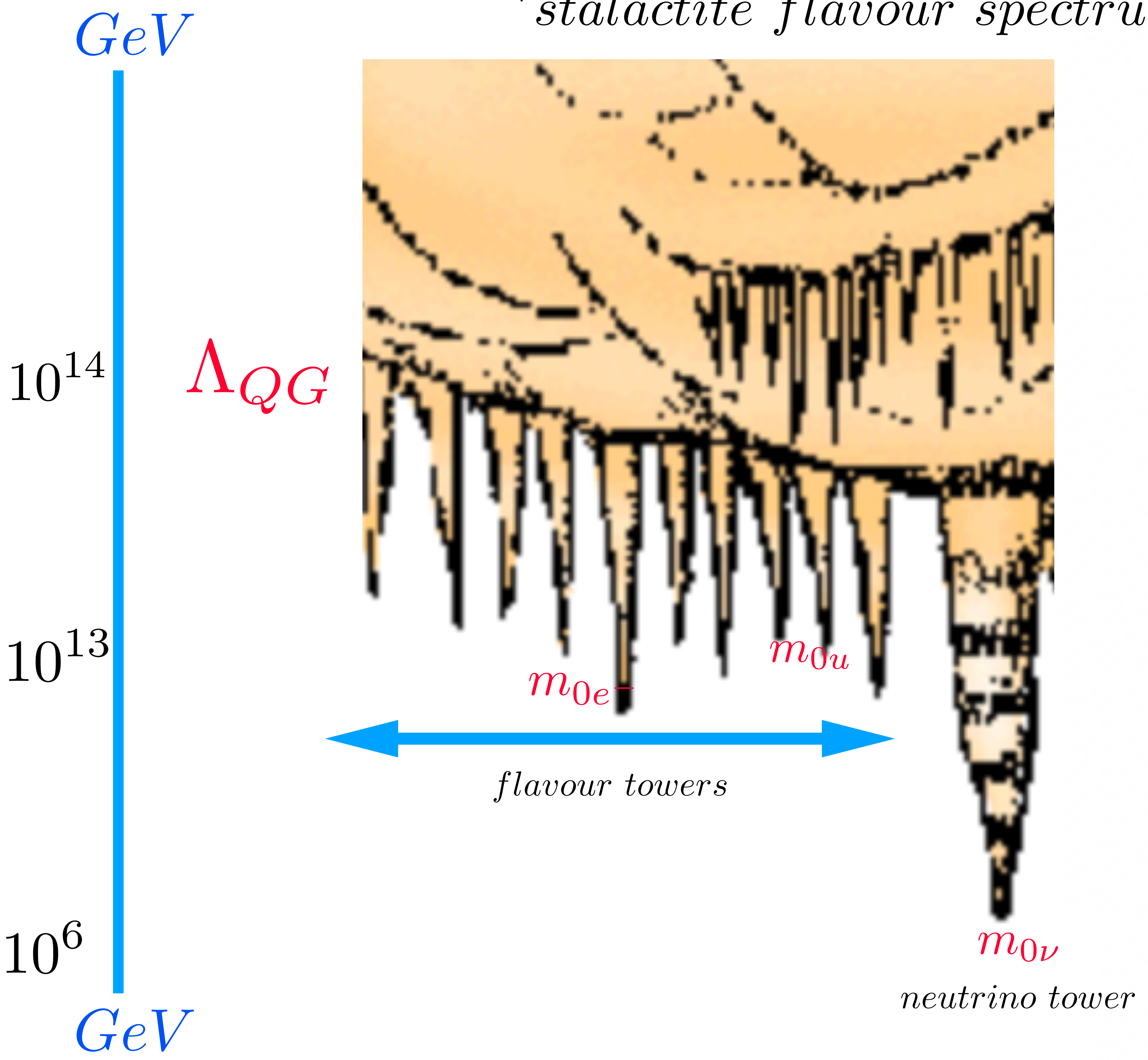
Castellano,Herraez,L.I. 2023

- Note there is a sort of see-saw: $m_{\nu} \simeq \dfrac{M_{EW}\, m_{0\nu_R}}{M_p}$

Neutrinos are light due to the existence of a tower at singlets slightly above the EW scale

'stalactite flavour spectrum'



(Note that a single large modulus may give rise to multiple towers, depending on the geometry of the internal sector of a compactification)

7) Neutrinos, the cosmological constant and the hierarchy problem

- But why such a tower related to neutrinos exist precisely at that scale?
- A Swampland constraint on neutrino masses:

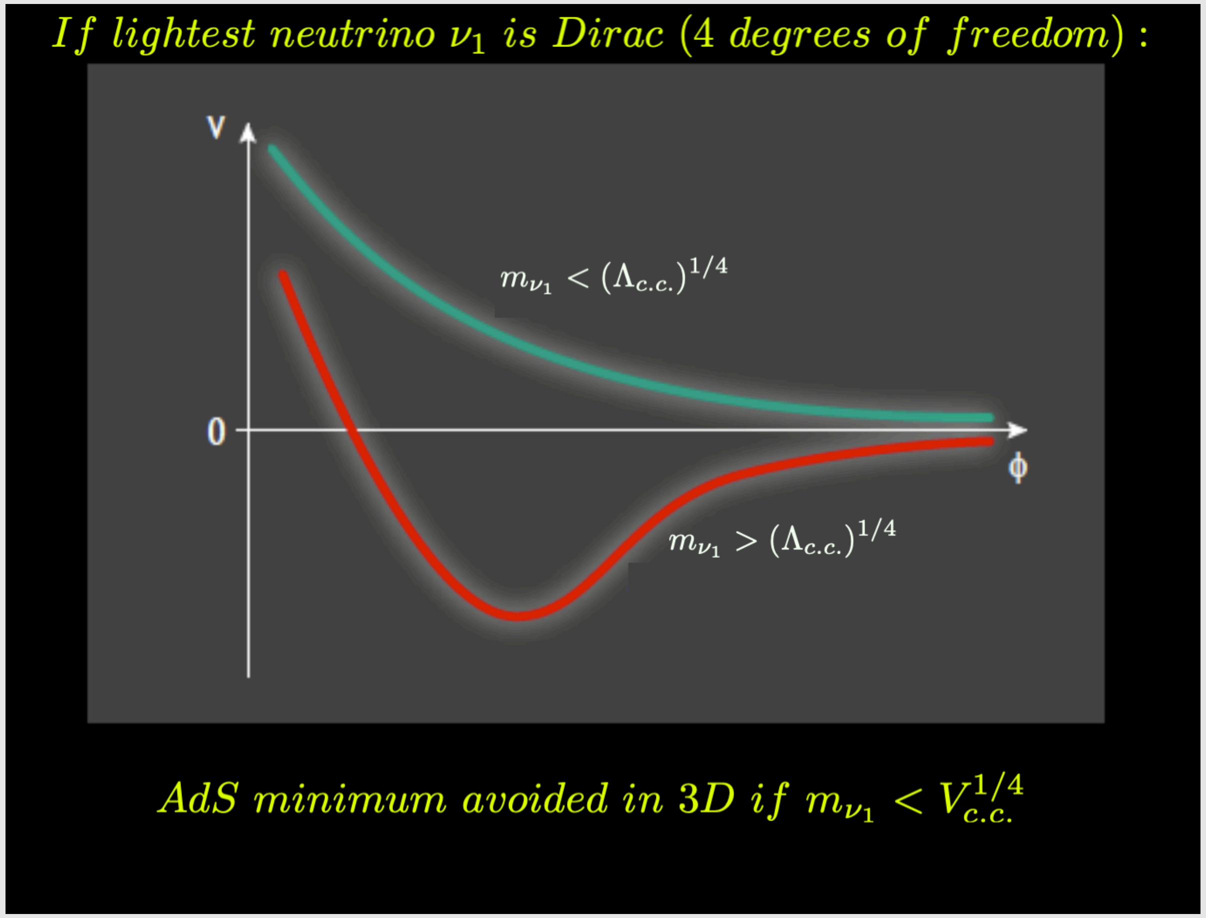
$$\boxed{m_{\nu_1} \lesssim V_0^{1/4}}$$

$lightest\ neutrino$

L.I, Martin-Lozano, Valenzuela 2017

Hamada, Shiu 2017

L.I, Gonzalo, Valenzuela 2021



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

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

(this is to avoid AdS vacua in the 3D SM, forbidden by swampland AdS conjectures)

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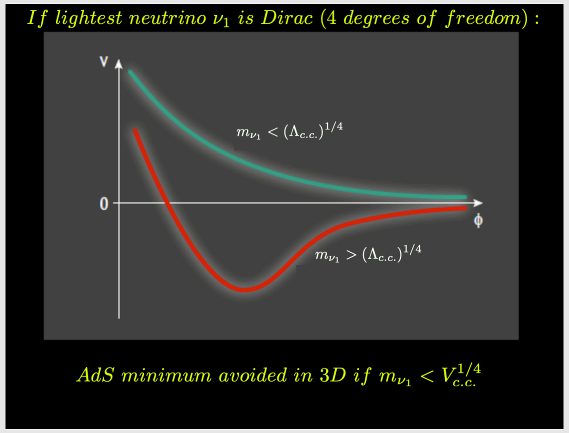


If lightest neutrino ν_1 is Dirac (4 degrees of freedom) :

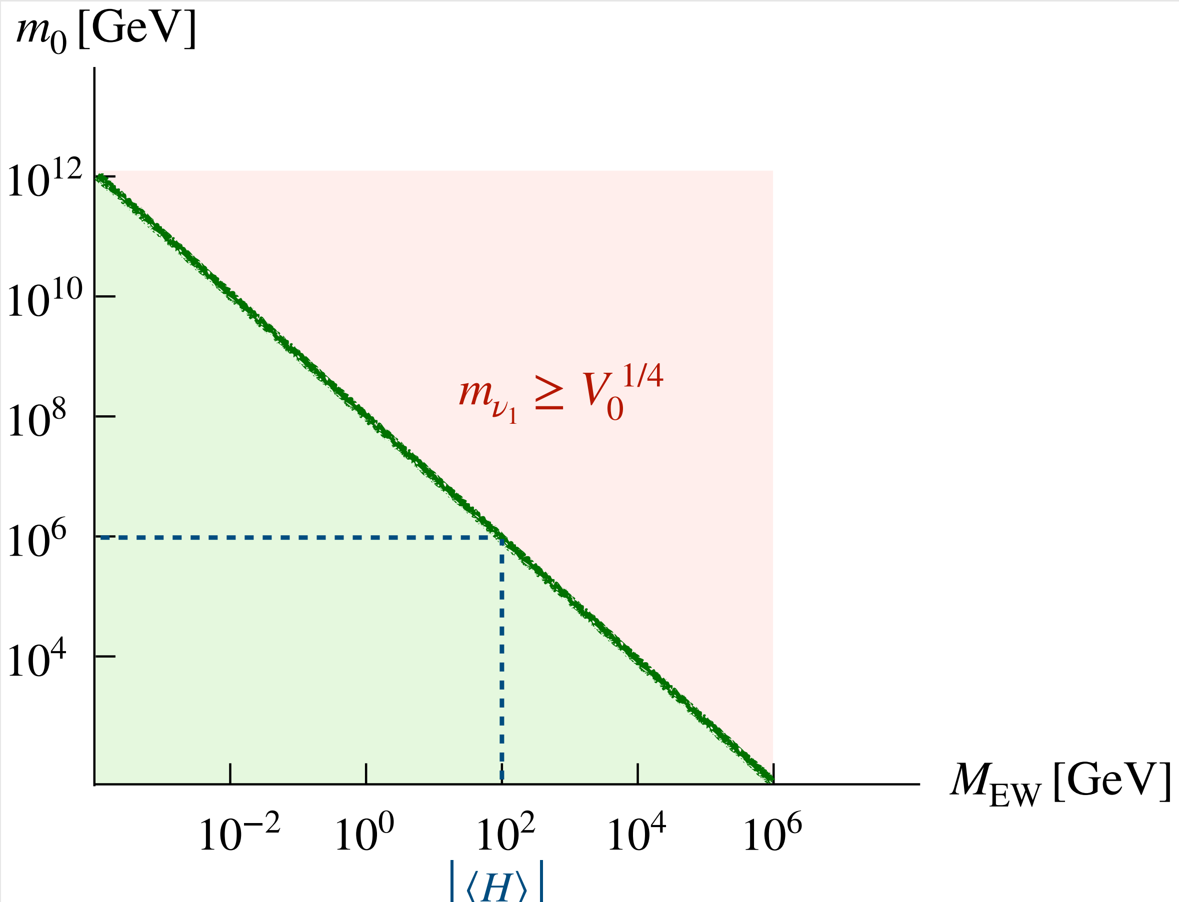
AdS minimum avoided in 3D if $m_{\nu_1} < V_{c.c.}^{1/4}$

(this is to avoid AdS vacua in the 3D SM, forbidden by swampland AdS conjectures)

$$m_{\nu_1} = Y_\nu^{(1)} M_{EW} \simeq \frac{m_{0\nu_R}}{M_p} \epsilon_L^{(1)} M_{EW} \lesssim V_0^{1/4}$$

$$\boxed{M_{EW} \lesssim \frac{V_0^{1/4} M_p}{m_{0\nu_R}} (\epsilon_L^{(1)})^{-1} \simeq 10^2\ GeV}$$

- EW scale related to the c.c.
- No EW hierarchy problem !!



Summary up to here:

- Smallness of neutrino masses due to large wave function renormalization from a tower of singlets with $m_0 \simeq 700\ TeV$

- This tower with this scale appears because it must be $m_{\nu_1} \lesssim V_0^{1/4}$
- (from AdS Swampland conjectures)

- Those conditions imply a bound on the EW scale: M_{EW} is related to the c.c. by

$$\boxed{M_{EW} \ \lesssim \ \frac{V_0^{1/4} M_p}{m_{0\nu_R}} (\epsilon_L^{(1)})^{-1} \ \simeq \ 10^2\ GeV}$$

The EW scale is related to the c.c. and there is no EW hierarchy problem

- SUSY does not seem to play any role in this scheme……

8) May SUSY play any role?

- The SUSY SM has still a number of attractive implications, even if it does not help with the hierchy problem:

  i) The Higgs mass $M_H \simeq 125\ GeV$ is consistent with SUSY with a heavy sfermion spectrum

  i) SUSY avoids SM potential to become unbounded below

- Estimate of scale of SUSY-breaking

$$m_{3/2} \sim \frac{|W|}{M_p^2} \lesssim \frac{\Lambda^3}{M_p^2} \simeq m_{0\nu_R} \simeq 700\ TeV$$

- This would also guarantee stability of the tower

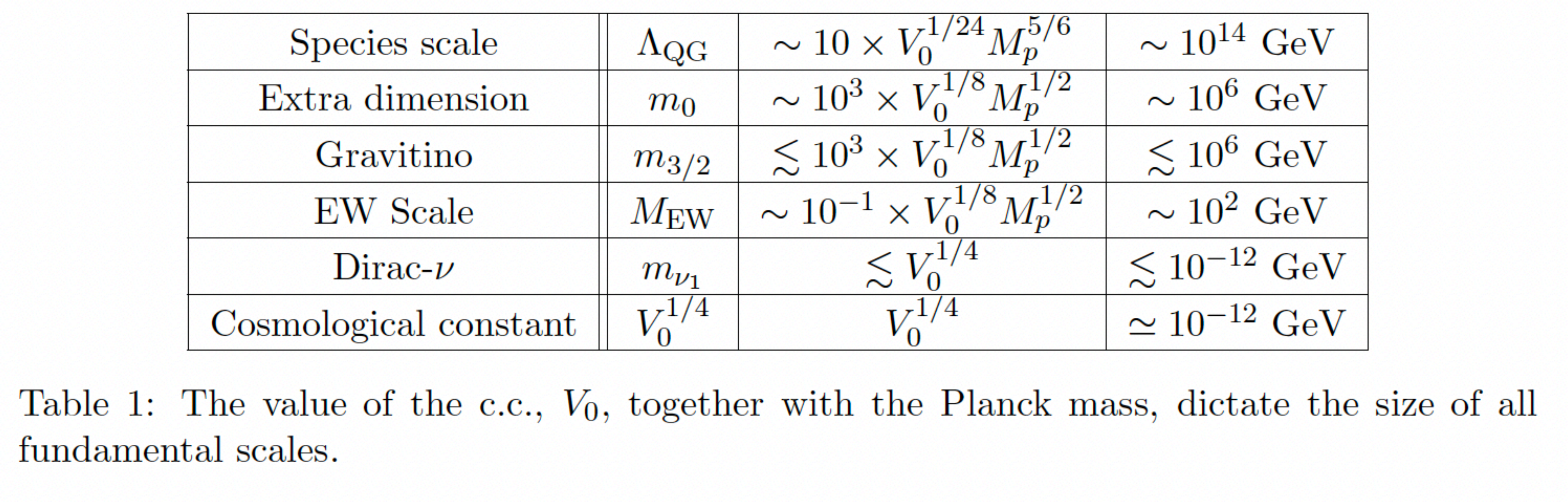
- Scale is consistent with the value of the Higgs mass. Similar to the SUSY 'Mini-Split' scenario

Arvanitaki et al.
Arkani-Hamed et al, Hall et al 2012

Is SUSY around the corner?

All fundamental scales may be written in terms of powers of the c.c. !!

$$M_{fund} \sim V_0^a M_p^{1-4a}$$



Species scale	$\Lambda_{\rm QG}$	$\sim 10 \times V_0^{1/24} M_p^{5/6}$	$\sim 10^{14}$ GeV
Extra dimension	m_0	$\sim 10^3 \times V_0^{1/8} M_p^{1/2}$	$\sim 10^6$ GeV
Gravitino	$m_{3/2}$	$\lesssim 10^3 \times V_0^{1/8} M_p^{1/2}$	$\lesssim 10^6$ GeV
EW Scale	$M_{\rm EW}$	$\sim 10^{-1} \times V_0^{1/8} M_p^{1/2}$	$\sim 10^2$ GeV
Dirac-ν	m_{ν_1}	$\lesssim V_0^{1/4}$	$\lesssim 10^{-12}$ GeV
Cosmological constant	$V_0^{1/4}$	$V_0^{1/4}$	$\simeq 10^{-12}$ GeV

Table 1: The value of the c.c., V_0, together with the Planck mass, dictate the size of all fundamental scales.

In this view it is the long wave physics which determines the scales of microphysics

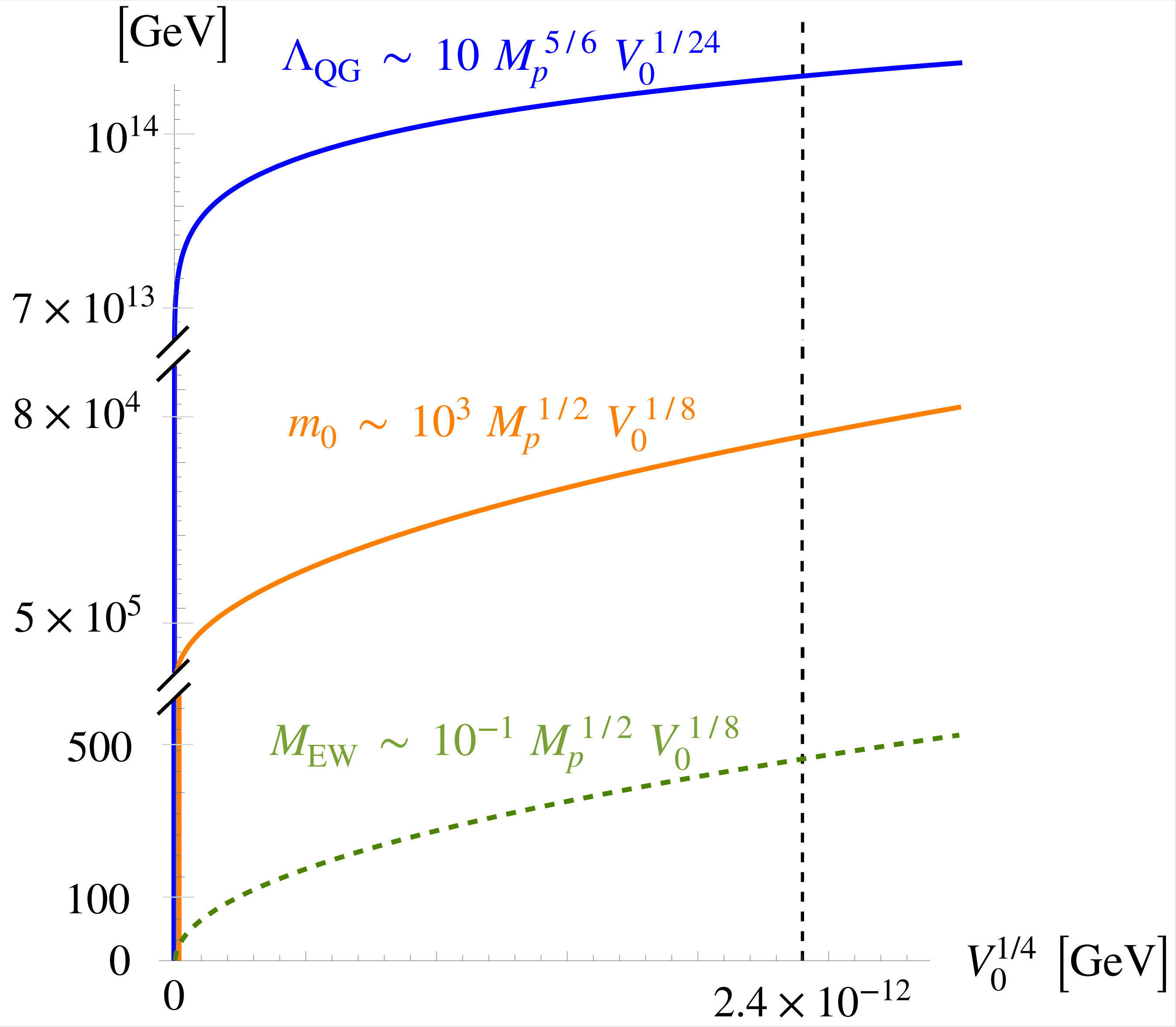
- The usual fine-tuning problems for V_0, M_{EW} :

$$V_0 \ = \ aM_a \ + bM_b \ ; \ M_{EW} \ = \ cM_c \ + dM_d \ \ , \ M_{a,b,c,d} \gg V_0$$

require: $a \simeq -b(M_b/M_a)$, $c = -d(M_d/M_c)$ with enormous precission

- No such fine tunings here if $M_{fund} \sim V_0^a M_p^{1-4a}$ with V_0 fixed to its physical value

If the c.c. goes to zero all fundamental scales would go to zero



Castellano,Herraez,L.I. 2023

A tiny positive cosmological constant is needed for the universe to develop

$V_0 = \Lambda_{c.c.}\ and\ M_{Planck}\ are\ the fundamental\ scales$

How? Why?

An intriguing idea : $T.Banks\ (2007)$

Gibbons-Hawking entropy in the dS Universe:

$$S \ \simeq \ \frac{M^2_{Planck}}{V_0^{1/2}}$$

Observed universe requires huge entropy: explains why c.c. so small

The universe has an ‘entropy budget’, which is an initial condition

Phenomenological signatures:

- Neutrinos are Dirac and the lightest neutrino has a mass

$$m_{\nu_1} \lesssim 0.007\ eV$$

$(present\ cosmological\ fits\ bounds\ m_{\nu_1} \lesssim 0.030)$

- There is a tower of singlet states which couples to neutrinos with a mass

$$m_{0\nu_R} \simeq 700\ TeV$$

- SUSY partners may be at scales

$$M_{ss} \lesssim 700\ TeV$$

Spectrum could be similar to that of ‘mini-split scenario, so that lightest sparticles may perhaps be detected at LHC or FCC

It would be interesting to fully work out the phenomenological consequences of this structure !!

Conclusions

- The ideas of Emergence of kinetic terms and the 3D AdS Swampland constraints suggest a new rationale for fundamental scales in physics

- The hierarchies of quarks and leptons appear as a
- reflection of the presence of (not too large) towers of states

- The c.c. V_0 is the fundamental scale in terms of which all
- others may be expressed:

$$M_{fund} \sim V_0^a M_p^{1-4a}$$

The EW scale is related to the c.c. and there is no EW hierarchy problem

$$\boxed{M_{EW} \ \lesssim \ \frac{V_0^{1/4} M_p}{m_{0\nu_R}} (\epsilon_L^{(1)})^{-1} \ \simeq \ 10^2 \ GeV}$$

- Neutrinos play a fundamental role: they are Dirac and force the presence of a tower of singlet states at $m_{0\nu_R} \simeq 700 \ TeV$. SUSY could perhaps be around the corner

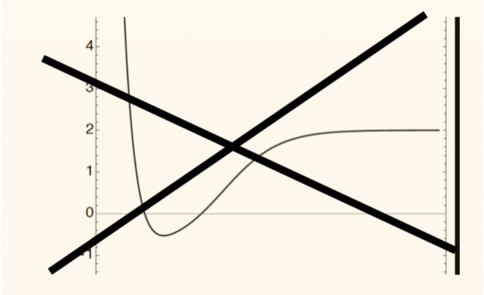
If true , many questions arise. In particular understanding in detail what is the physics which makes the c.c. to play such a fundamental role !!

Thank you !!

Back-up

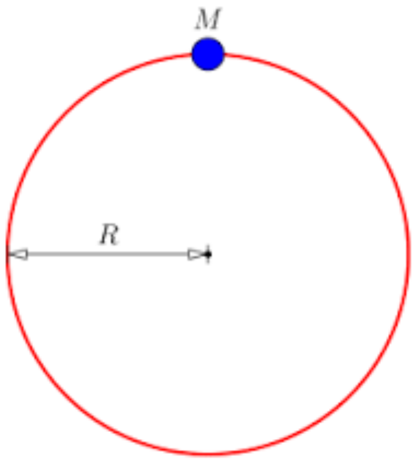
The c.c. and neutrino masses

‘**AdS non-SUSY conjecture**’ : **negative energy vacua are inconsistent in QG**

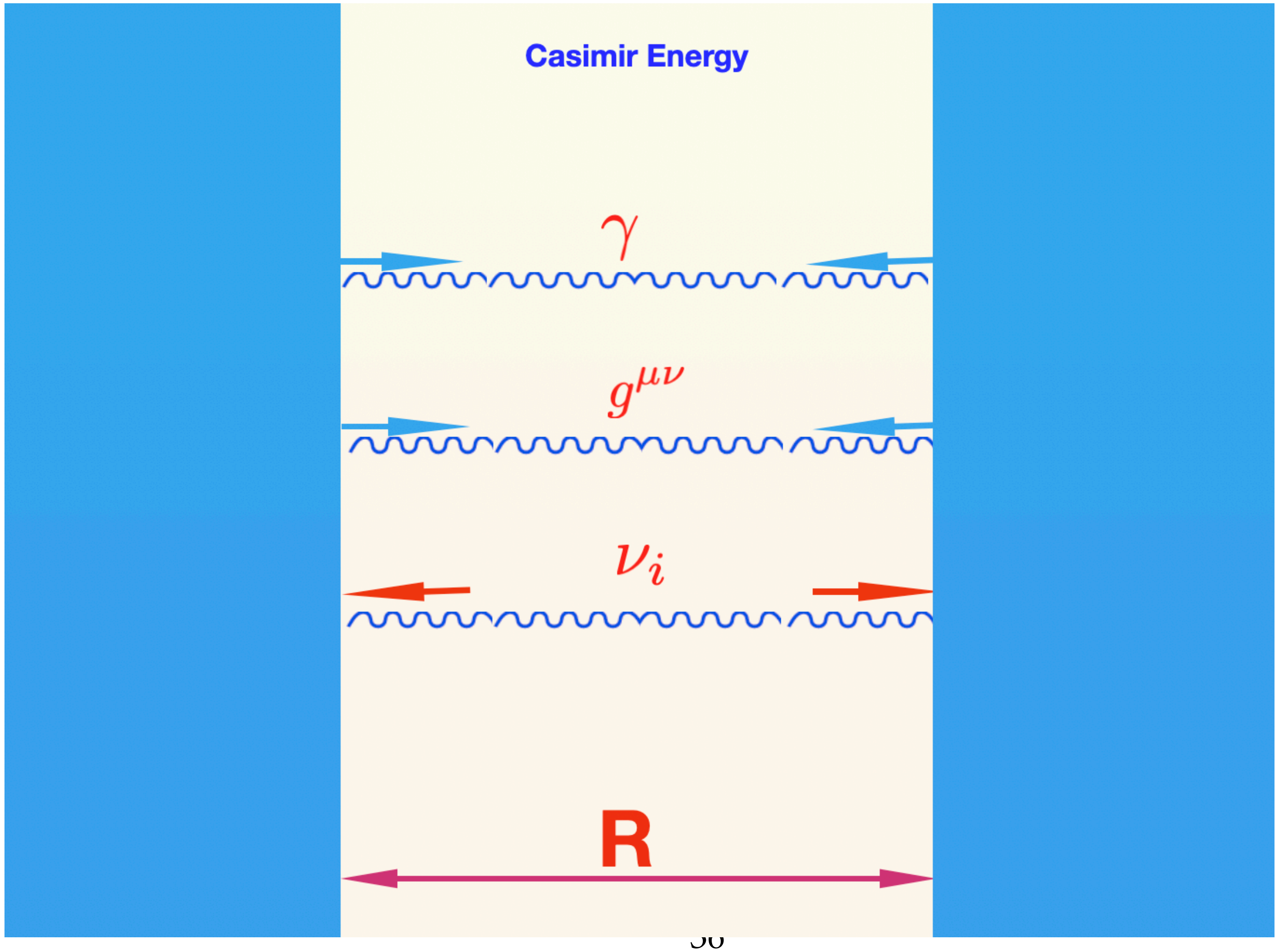


Ooguri, Vafa (2017)

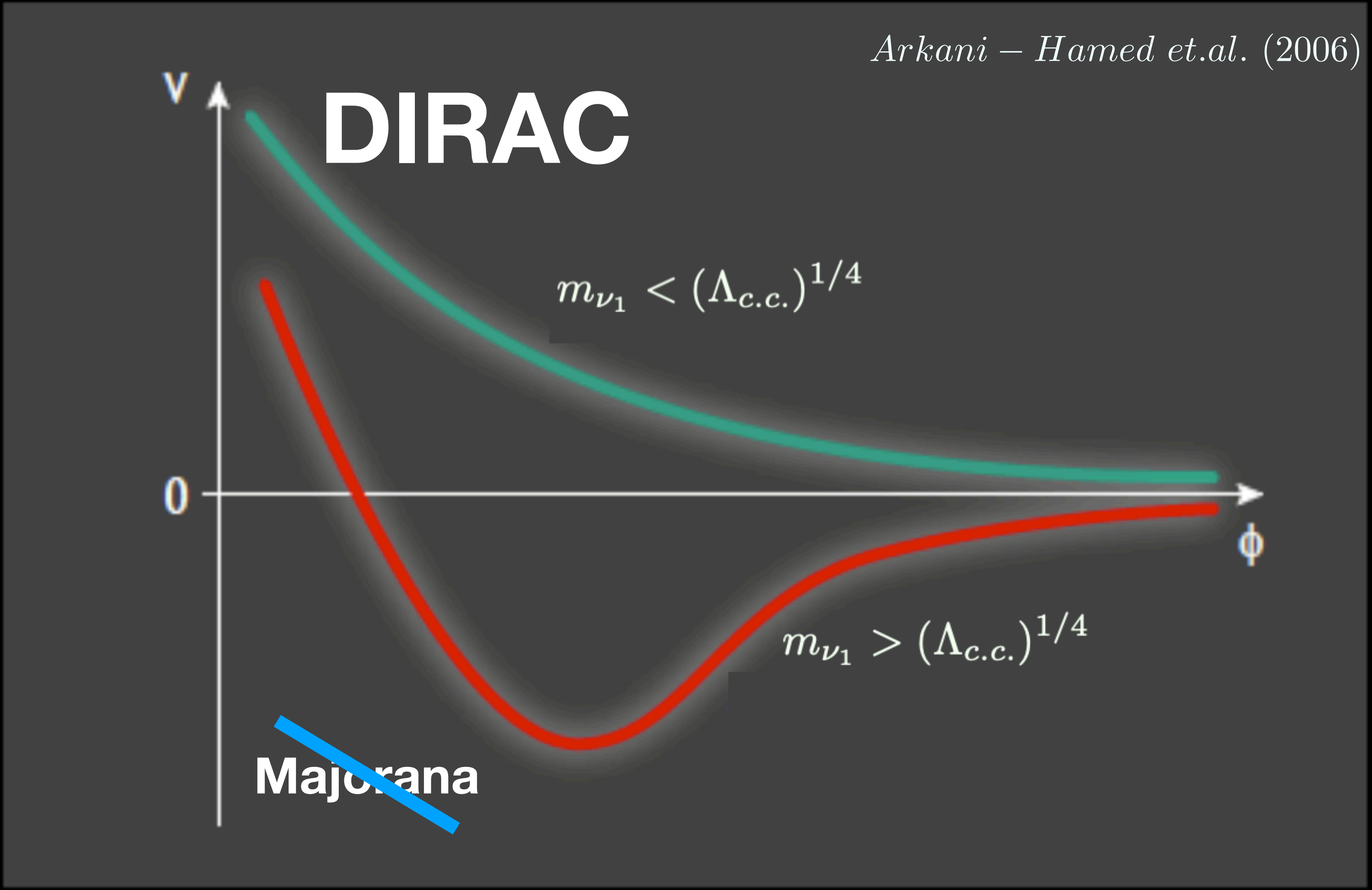
But ‘compactifying’ the SM down to 3D there ARE AdS vacua !!



A Compact Dimension



If lightest neutrino ν_1 is Dirac (4 degrees of freedom) :



Arkani – Hamed et.al. (2006)

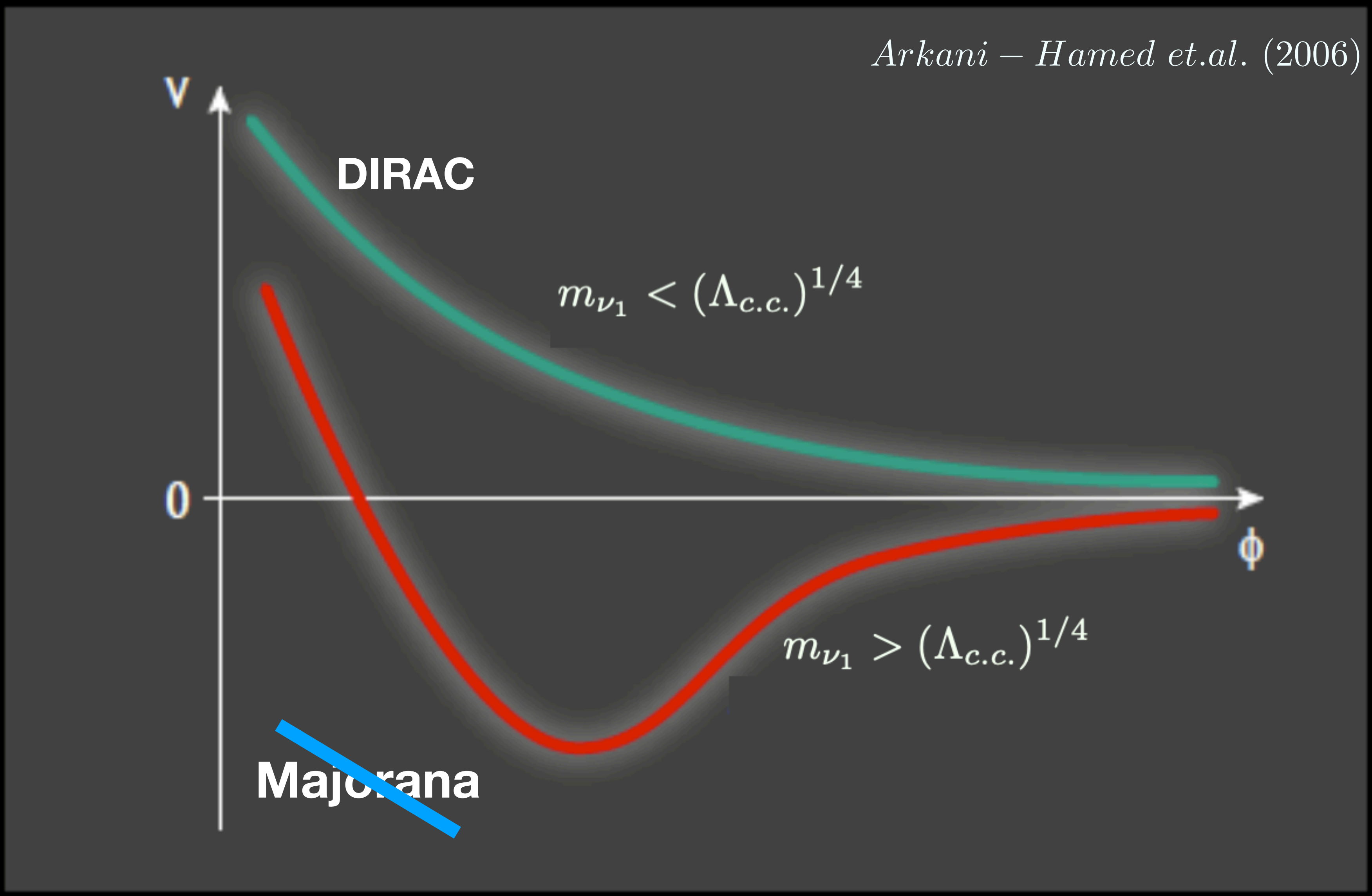
AdS minimum avoided in 3D if $m_{\nu_1} < V_{c.c.}^{1/4}$

(…and neutrinos are Dirac)

$$\boxed{m_{\nu_1} \lesssim V_{c.c.}^{1/4}}$$

(work with Irene Valenzuela)

If lightest neutrino ν_1 *is Dirac (4 degrees of freedom) :*



Arkani – Hamed et.al. (2006)

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

(…and neutrinos are Dirac)

Lust, Palti, Vafa 2019

$$\boxed{m_{\nu_1} \lesssim V_{c.c.}^{1/4}}$$

L.I, Martin-Lozano,
Valenzuela 2017
Hamada, Shiu 2017

Similar condition from ‘AdS distance conjecture

L.I, Gonzalo,
Valenzuela 2021