Strings, Particle Physics and the Swampland

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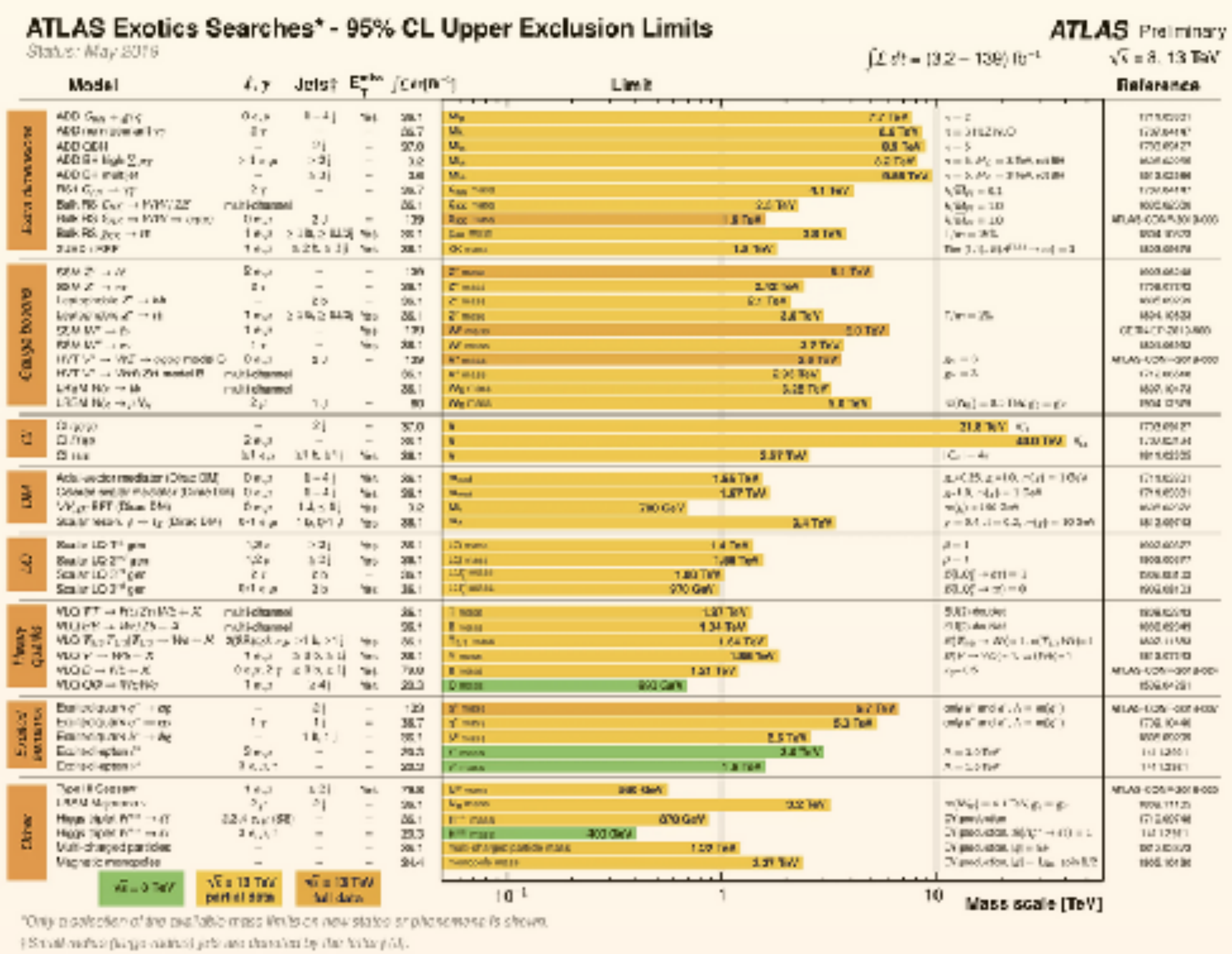
From Home, June 4 2020

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



…which direction should we take?

SUSY
(be patient)

SUSY
(non-minimal)

RPV

Technicolor

Relaxion

Composite

LED

Clockwork

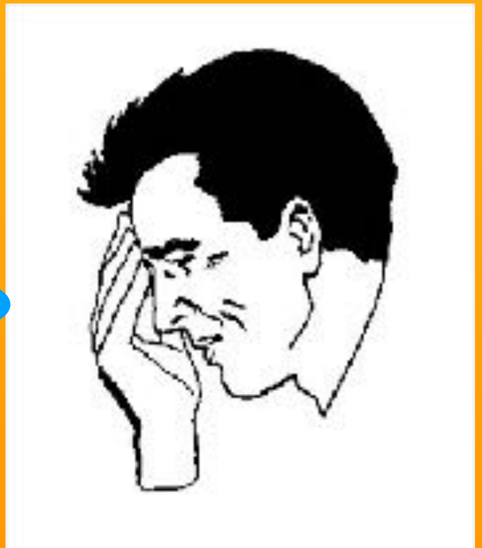
Twin H

Conformal

LST

Agravity

RS



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?

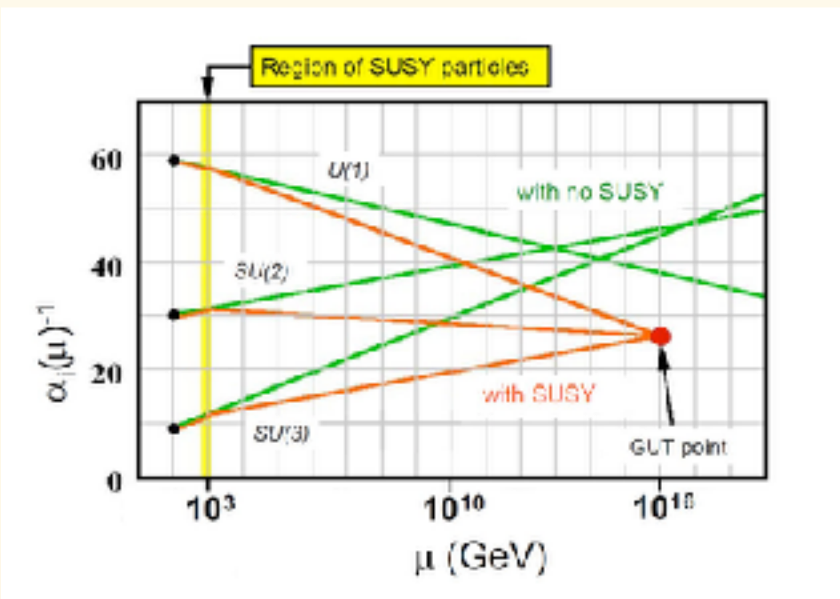
Perhaps we have to abandon some of our most cherised ideas:

** UV-IR independence

** Does Quantum Gravity really decouple?

Wilsonian view

Quantum Gravity



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, or irrelevant operators remain

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

- 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 , 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

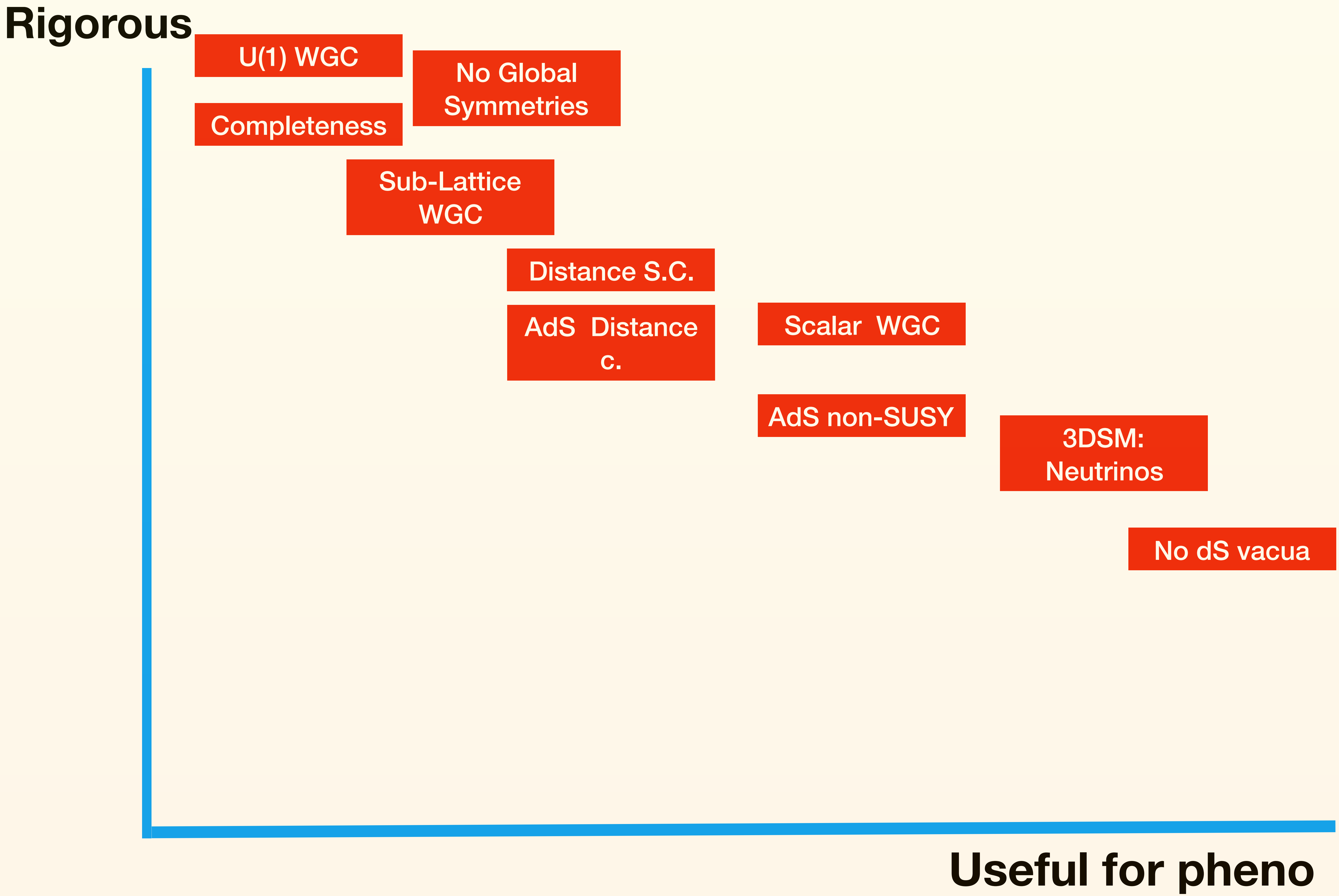
- These are conjectures, many of them suggested by black-hole quantum physics

- Other tested against string theory results

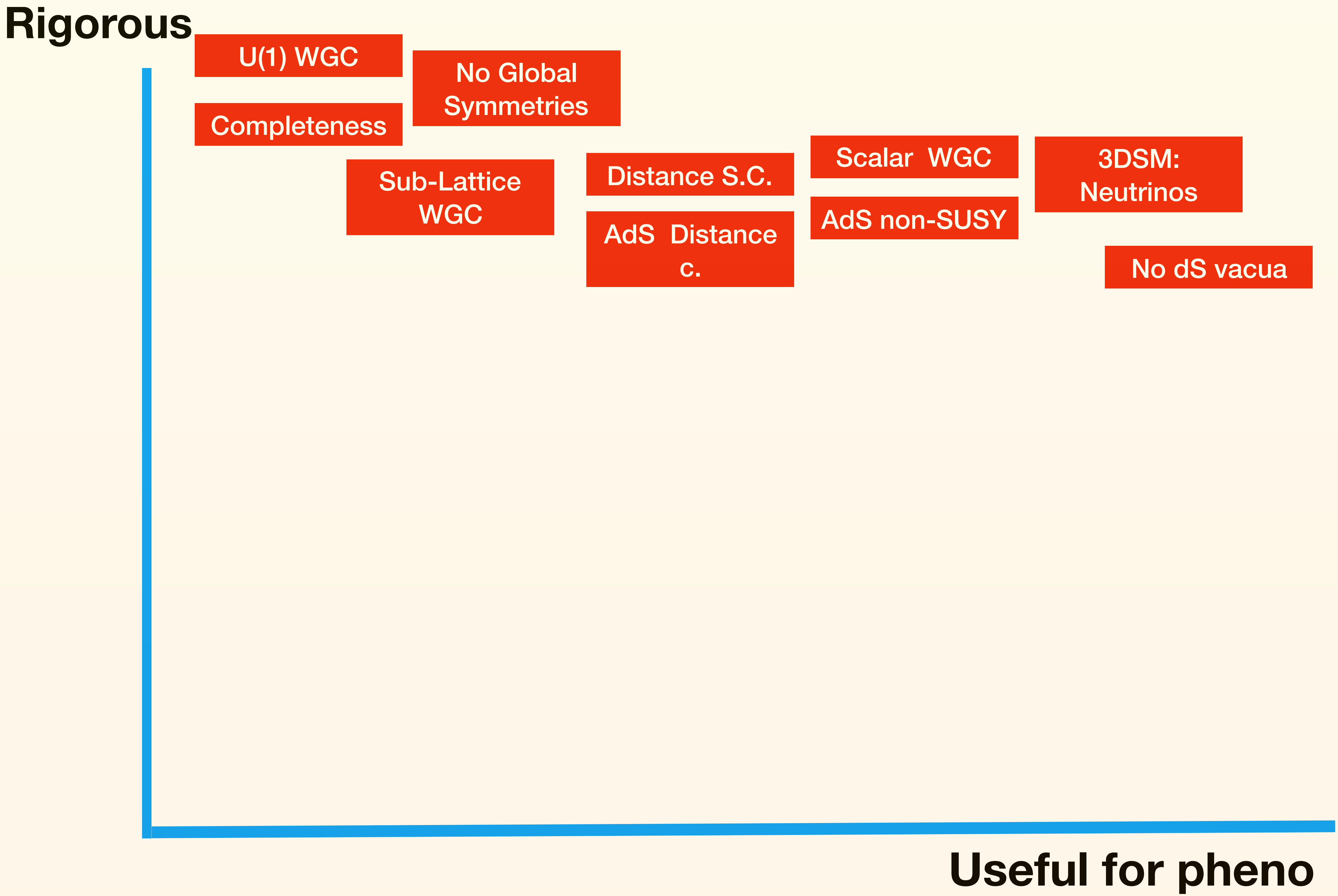
- We are thus assuming that string theory is a consistent theory of quantum gravity

Review: *Palti, arXiv:1903.06239*

Brennan, Carta, Vafa . arXiv:1711.00864



Rigorous
U(1) WGC
No Global Symmetries
Completeness
Sub-Lattice WGC
Distance S.C.
AdS Distance c.
Scalar WGC
AdS non-SUSY
3DSM: Neutrinos
No dS vacua
Useful for pheno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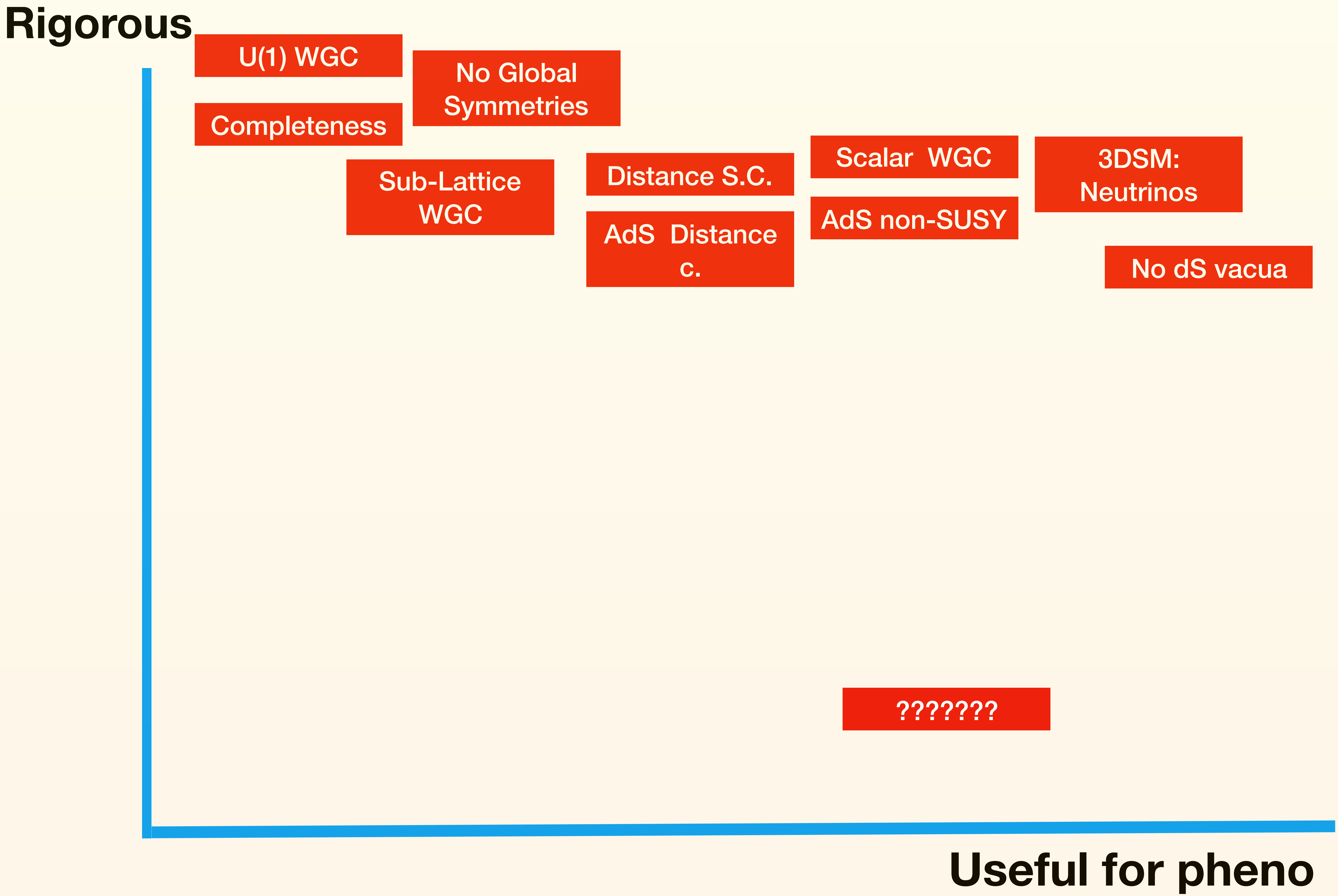
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???????
Useful for pheno

1) Overview of Swampland constraints

2) Some possible applications to Particle Physics

Some Swampland Conjectures

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

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

(Accidental global symmetries ok).

Consistent with string theory. Also discrete. *Harlow, Ooguri 2018*

2) Existence of gauge bosons implies existence of charged p.

Polchinski 2003

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

Motivated by black-hole physics: Charged BH solutions exist

3) Completeness conjecture:

Polchinski 2003

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

Motivated also by black-hole physics and string theory

4) No free parameters in the theory

All couplings are scalar fields (including masses, kinetic terms)

A fact in String theory

5) The Weak Gravity Conjecture

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

WGC for a U(1):

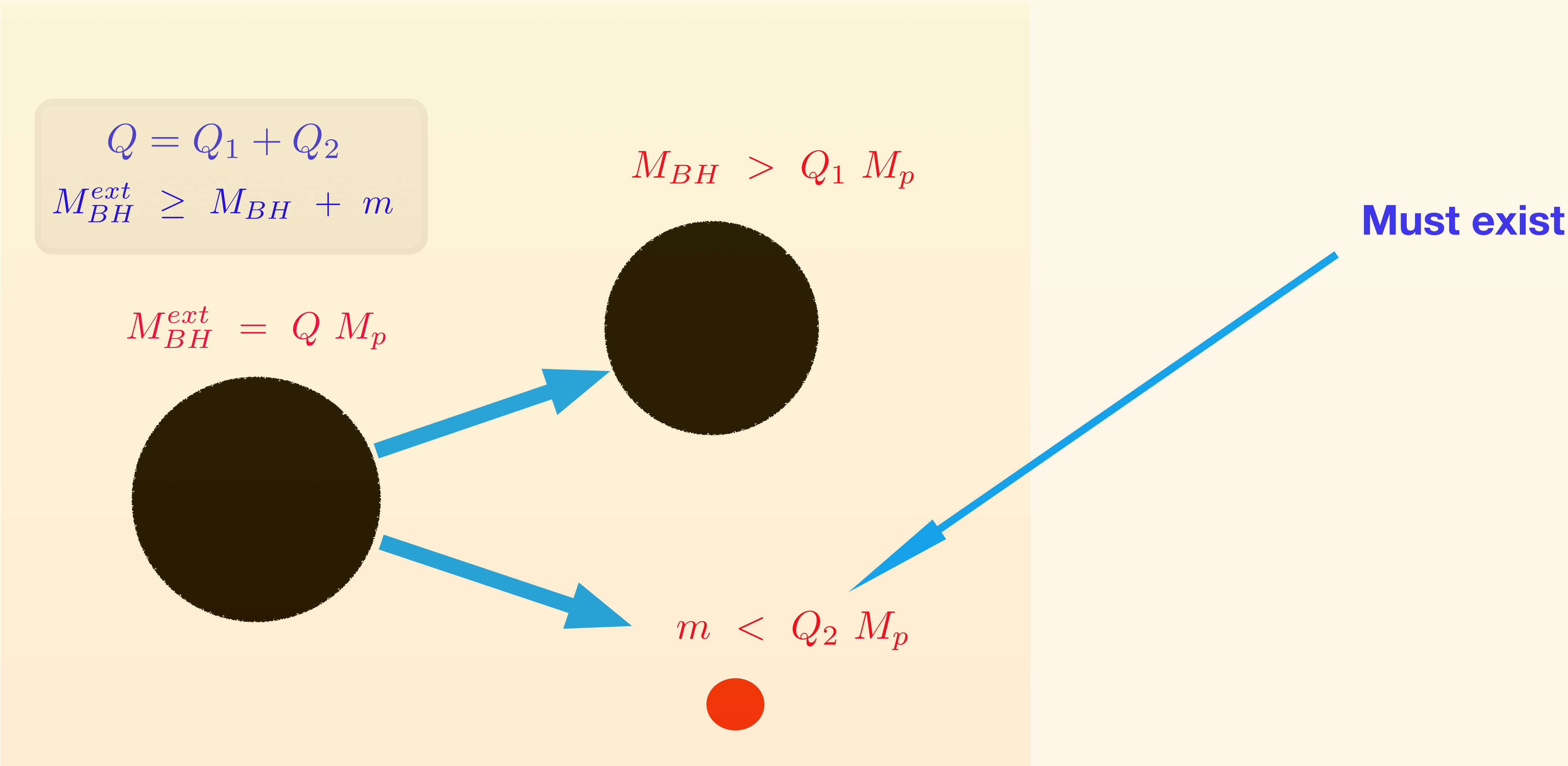
- In any UV complete U(1) gauge theory there must exist at least one charged particle with mass m such that:

$$m \leq Q\, M_p$$

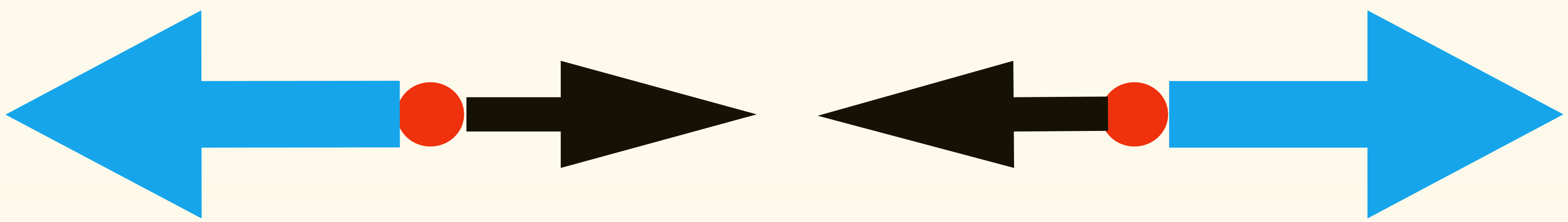
Motivated by Black-hole physics

- Extremal charged blackholes: $M_{BH}^{ext} = Q\ M_p$

- BH lore: extremal blackholes must decay. Otherwise there would be an infinite number of 'remants' looking like particles in the theory



Gravity is the weakest force



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

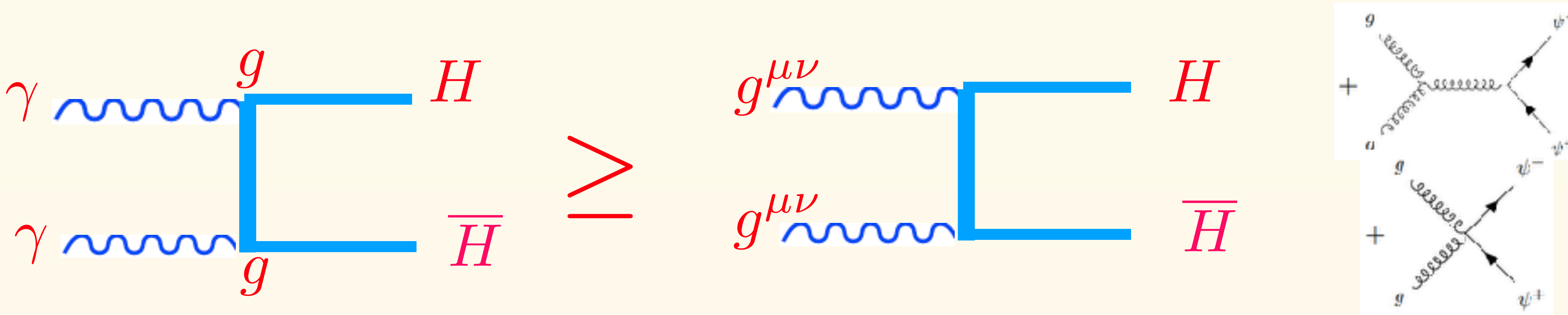
$$F_G \leq F_q \longrightarrow m \leq qM_p$$

'Weak gravity conjecture'

Alternative formulation: Pair production WGC

$H \; = \; \textit{Heavy charged particle}$ *L.I., E. Gonzalo 2020*

- Particle physicist formulation: production at threshold



If gravity weakest force: $$\left|T(\gamma\gamma \to H\overline{H})\right|^2 \geq \left|T(g^{\mu\nu}g^{\mu\nu} \to H\overline{H})\right|^2$$

$$\boxed{2\,g^2 \;\geq\; \frac{m^2}{M_p^2}}$$

Same conditions obtained

- This approach turns out to be useful for a ‘scalar WGC’ later

- Same results from pair annihilation at rest

Clash with naturality in field theory?

First observation, scalars: $m^2 \; < \; g^2 \; M_p^2$

Quadratically divergent

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!!)

Magnetic WGC for a U(1)

Arkani-hamed, Motl, Nicolis, Vafa 2006;

- Identical argument for the dual U(1) coupled to a monopole with mass M_m

$$M_m \;<\; g_{mag}\, M_p \;=\; \frac{1}{g} M_p$$

$$M_m \;\simeq\; \frac{\Lambda}{g^2}$$

$$\boxed{\Lambda \;\leq\; g M_p}$$

If there is a small gauge coupling, new thresholds must appear below the Planck scale

- In string theory the thresholds are either KK or string thresholds

- E.g. in the Heterotic string:

$$M_{string} \;=\; g\; M_p$$

Generalization to N U(1)'s

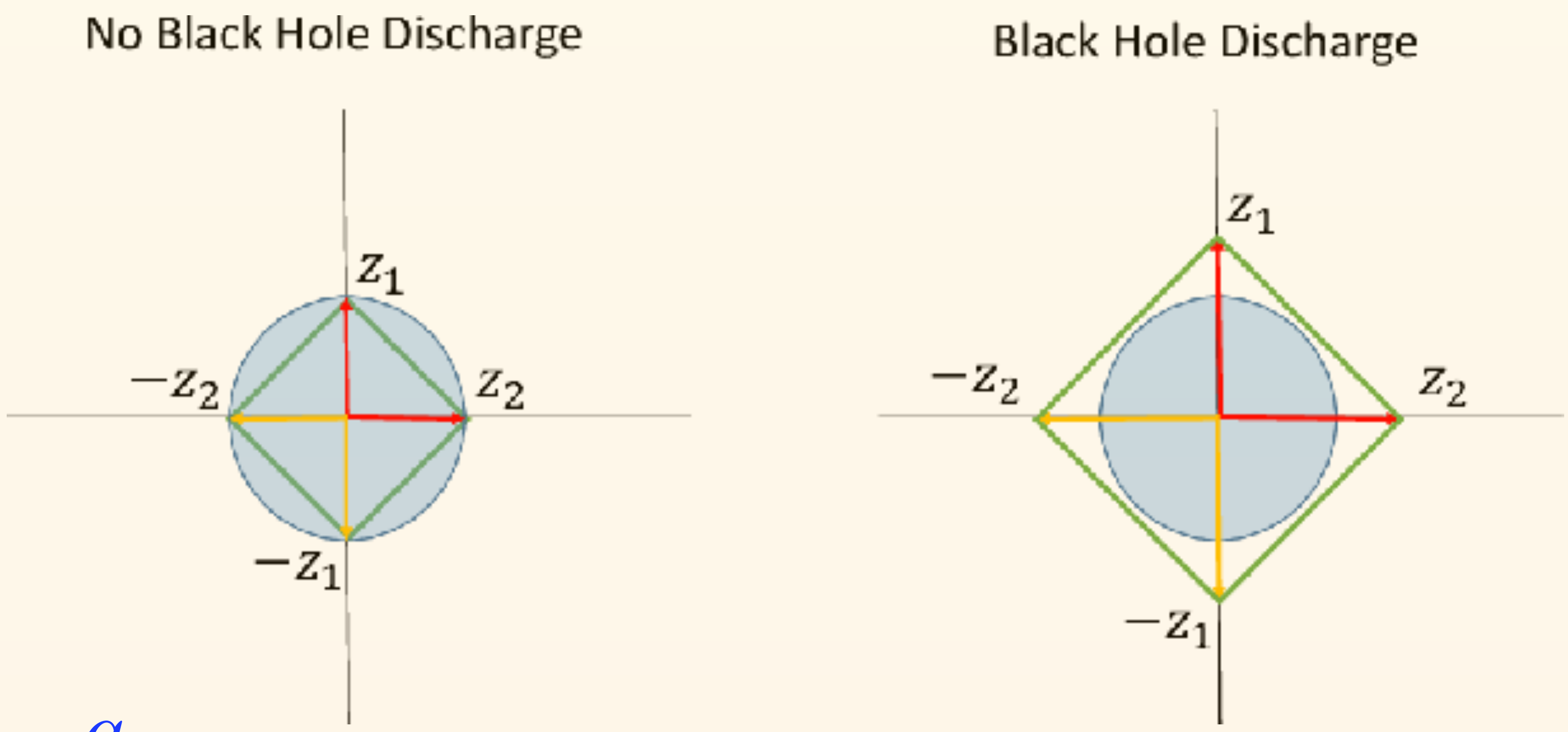
Cheung, Remmen 2014

- Slightly non-trivial: not enough to obey it for each U(1)

$$m_i \leq \sqrt{2} q_i M_p$$

$|Q_{BH}| \leq M_{BH}/\sqrt{2}$

- For extremal blackholes to decay the BH zone should be contained
- inside the 'convex hull' spanned by the $\vec{z}_i \equiv \frac{\vec{q}_i}{m_i}$
- e.g. for 2 U(1)'s



$$m_i \leq \sqrt{2} \frac{q_i}{\sqrt{N}} M_p$$

Condition stronger by $\sqrt{N}$

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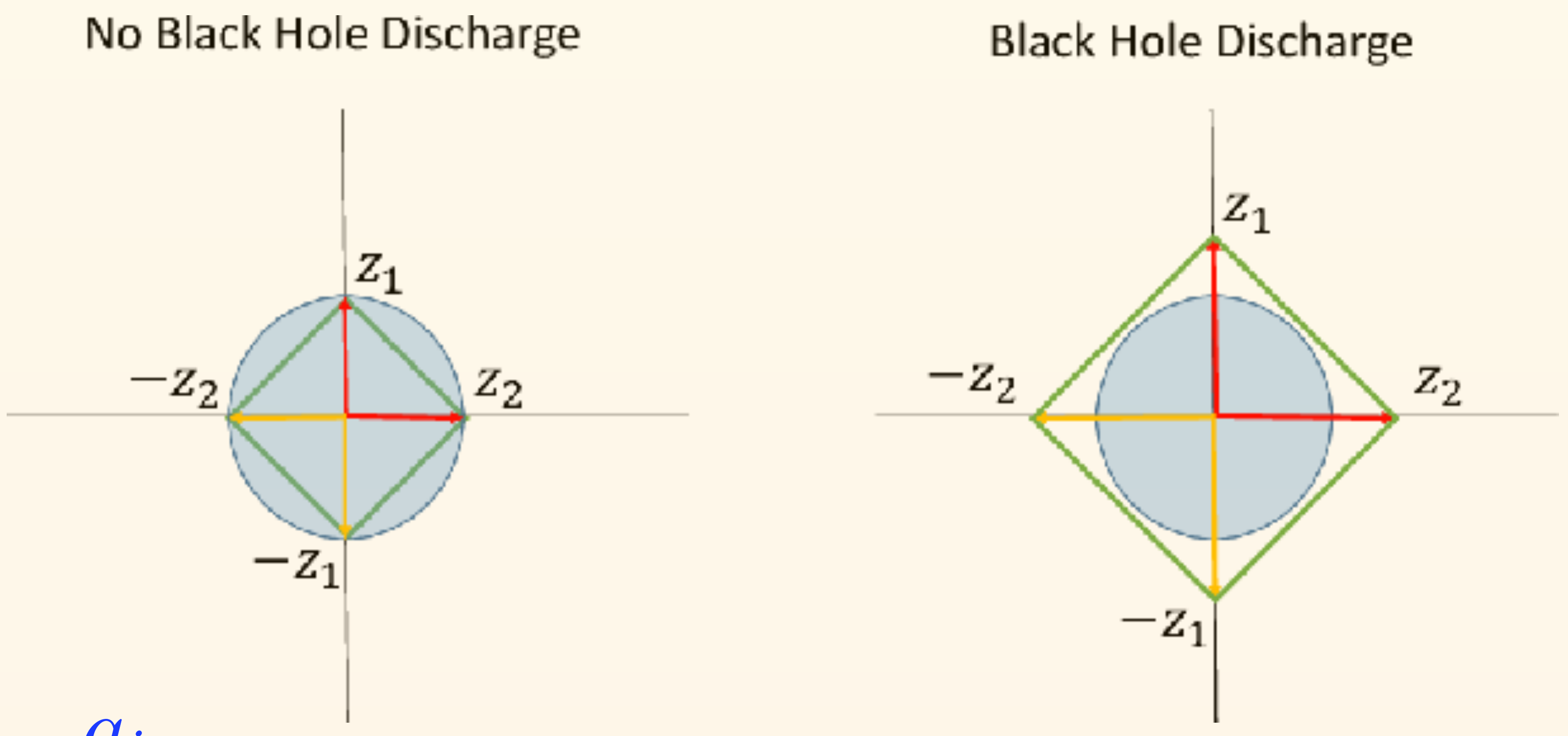

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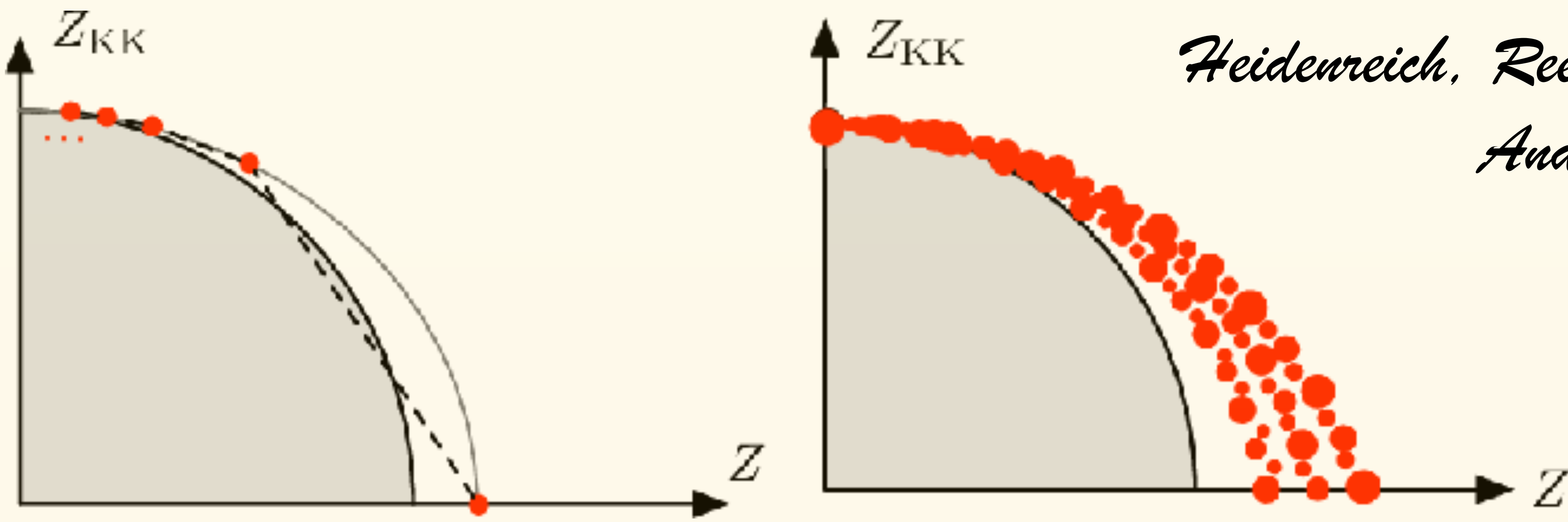
Condition stronger by $\sqrt{N}$

6) The sublattice WGC

- Simplest WGC is not what seems realised in string theory
- Upon dimensional reduction the KK U(1)'s break the WGC



Heidenreich, Reece, Rudelius 2016
Andriolo et al. 2018

- May be overcome if there are an infinite number of charged states

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

- Consistent with 'completeness conjecture'

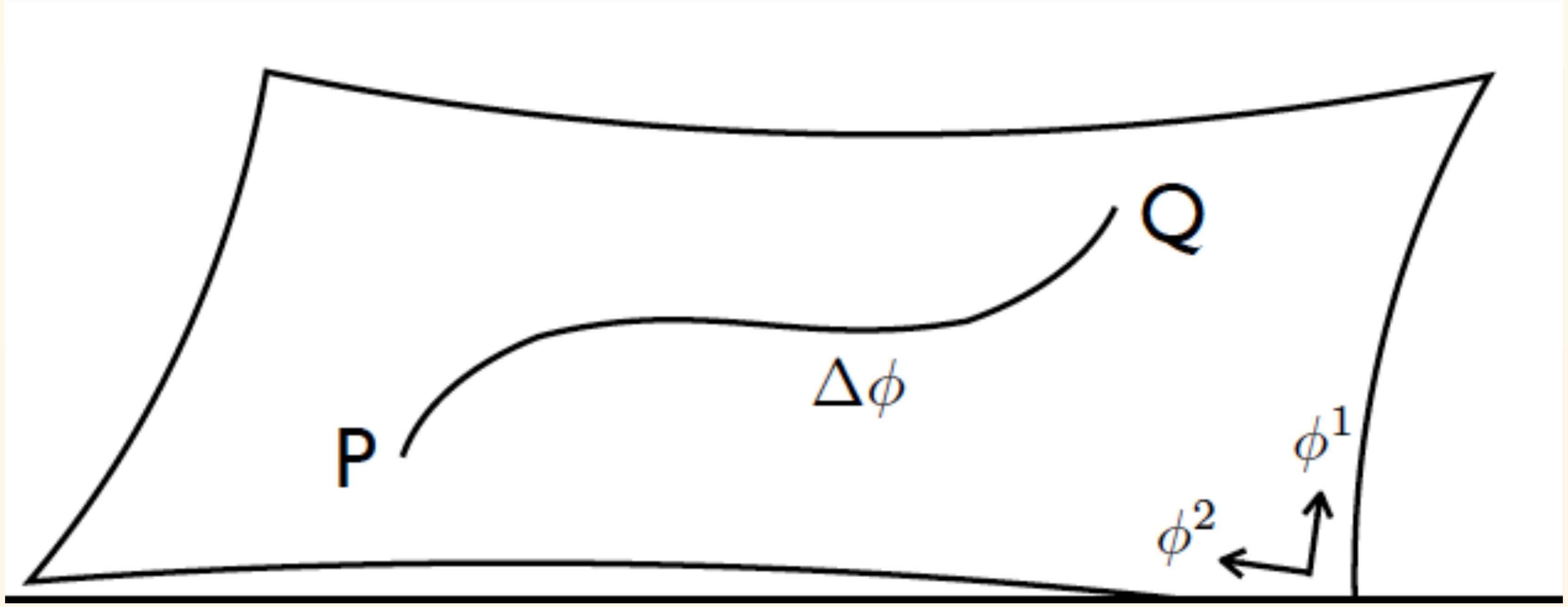
$$g^2 \longrightarrow 0 \longrightarrow A \ full \ tower \ of \ charged \ states \ becomes \ massless$$

7) Distance Swampland Conjecture

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

Ooguri, Vafa 2006

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

- Has been checked in many string theory examples

8) The Scalar WGC Conjecture

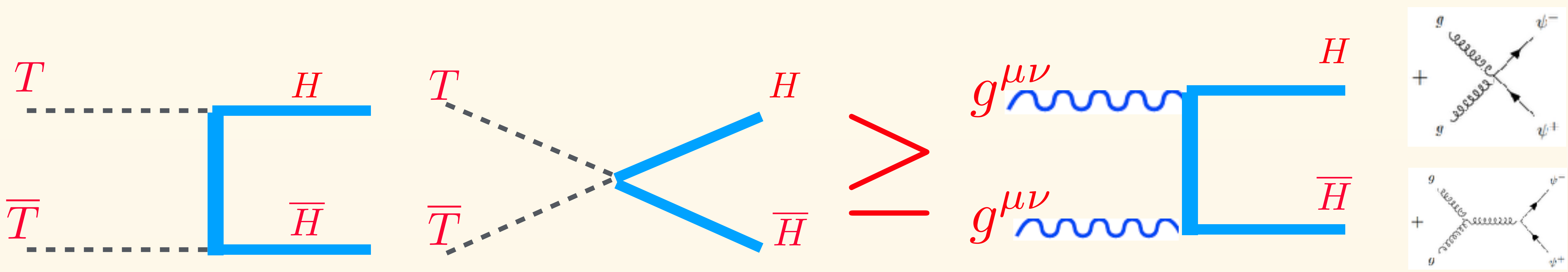
- WGC originally formulated for U(1)'s and charged particles

- Is there an analogue for moduli scalars T ?

Palti 2017

- There must exist heavy states H such that:

L.I., E.Gonzalo 2019,202



$$\mathcal{L}_T \;=\; \partial_\mu H \partial^\mu \overline{H} + \partial_\mu T \partial^\mu \overline{T} \;-\; m^2(T,\overline{T})|H|^2 \;+ ..$$

$$m^2 \;\simeq\; m_0^2 \;+\; (\partial_T m^2)T \;+\; (\partial_{\overline{T}} m^2)\overline{T} \;+\; (\partial_{\overline{T}}\partial_T)m^2)|T|^2 \;+\; ..$$

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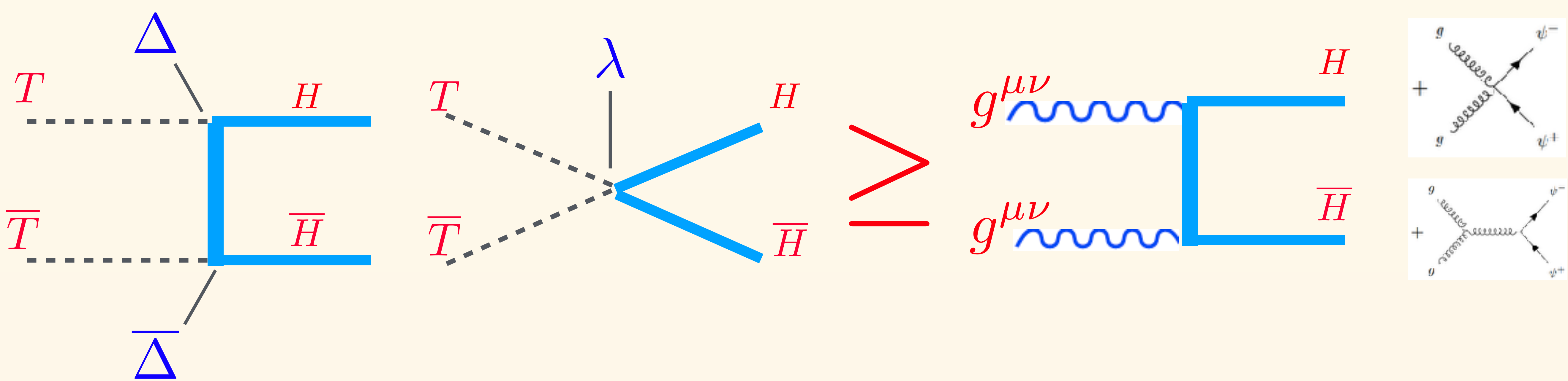

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$$\Delta = \partial_T m^2 \;,\; \overline{\Delta} = \partial_{\overline{T}} m^2 \;,\; \lambda \;=\; \partial_T \partial_{\overline{T}} m^2$$

- Scalar T coupled to gravity requires existence massive states with mass

$$g^{T\overline{T}}\left|(\partial_T m^2)(\partial_{\overline{T}} m^2) \ - \ m^2(\partial_T\partial_{\overline{T}} m^2)\right| \ \geq \ \frac{m^4}{M_p^2}$$

L.I., E. Gonzalo, 2020

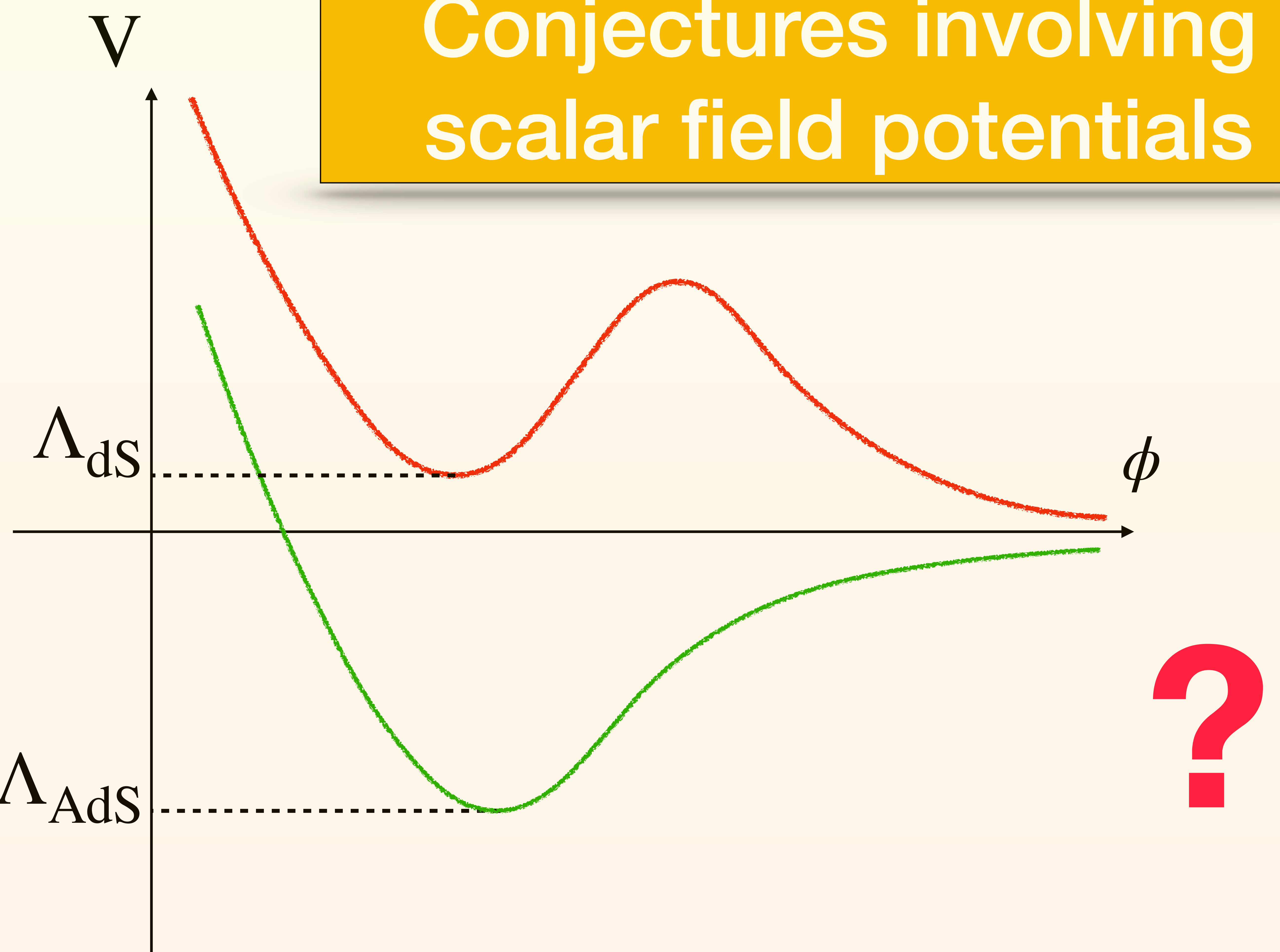
- Consider e.g. a no scale metric $g_{T\overline{T}} = \dfrac{1}{(T+\overline{T})^2}$

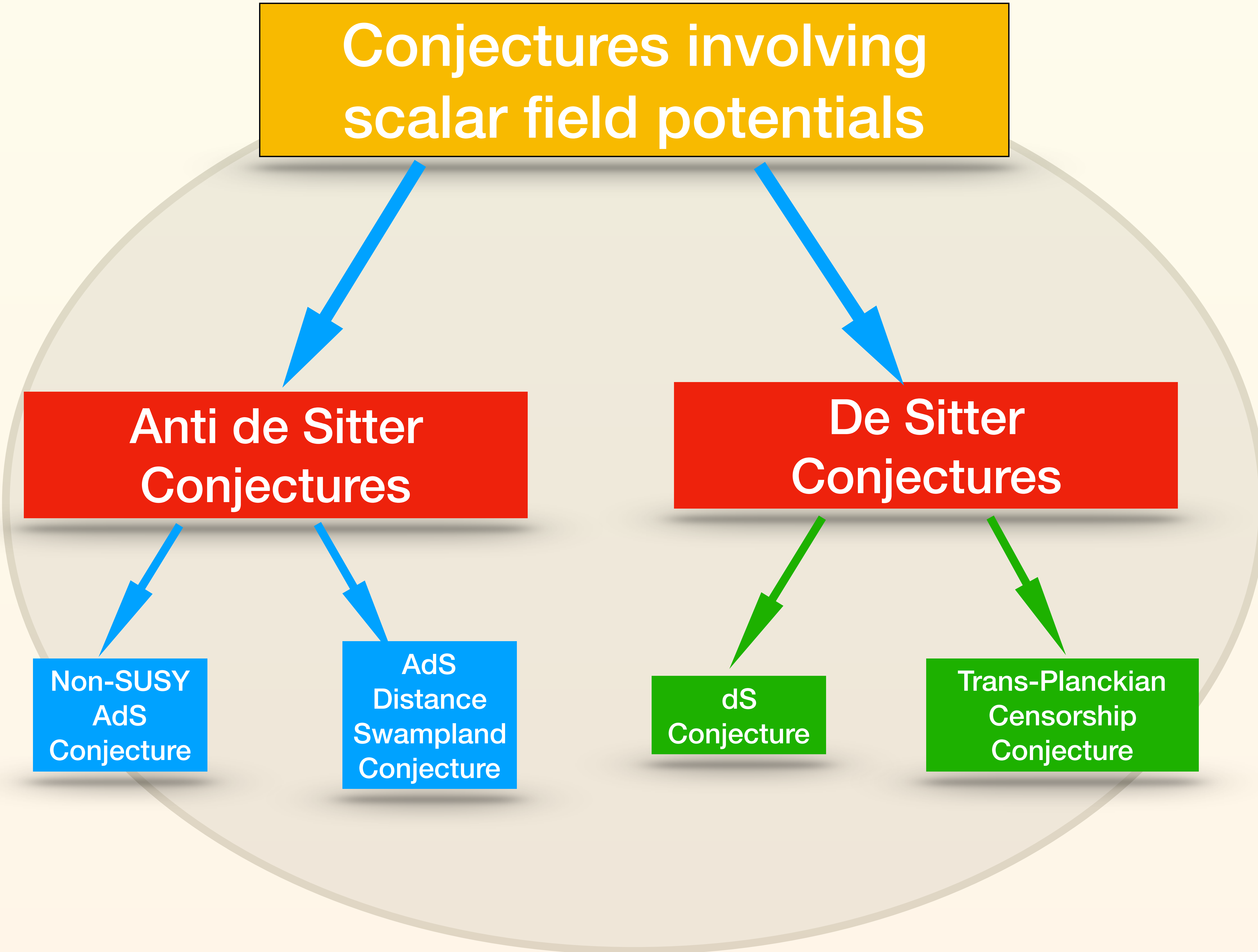
- There are solutions which saturate the SWGC, in particular:

$$m_{KK}^2 \ = \frac{1}{(T+\overline{T})} \ , \ m_w^2 \ = \ (T+\overline{T})$$

- Look like KK and winding states in a torus compactification !!
- Emergence of extra dimensions and string states to saturate the bound!
- Although we started just with a massless scalar with a no-scale metric
- Tested in CY Type II string compactifications (Dp-branes wrapping cycles
- May lead to some pheno constraints, see below

Conjectures involving scalar field potentials





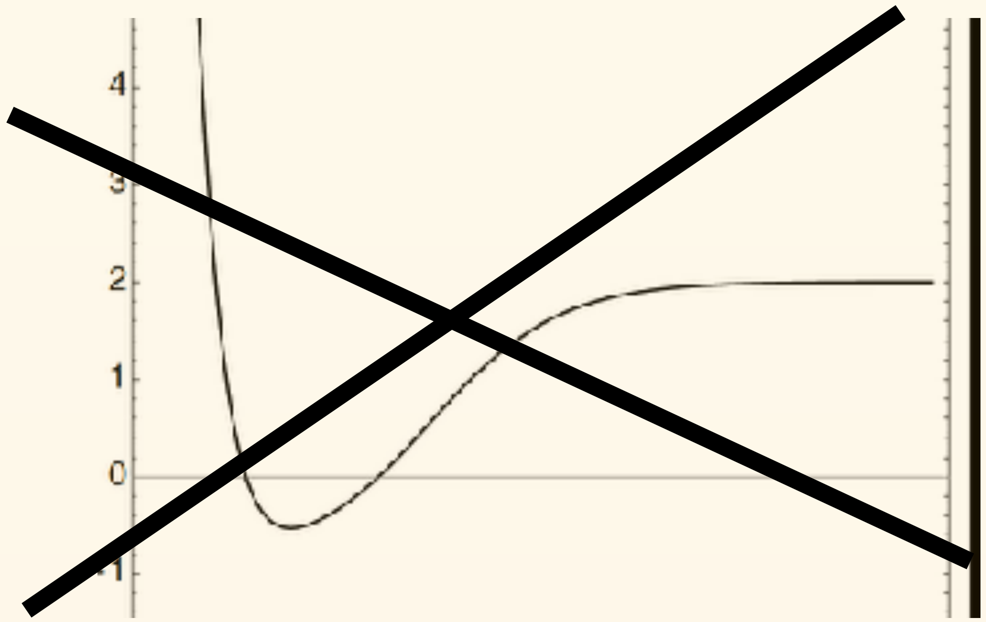
Conjectures involving scalar field potentials
Anti de Sitter Conjectures
De Sitter Conjectures
Non-SUSY AdS Conjecture
AdS Distance Swampland Conjecture
dS Conjecture
Trans-Planckian Censorship Conjecture

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



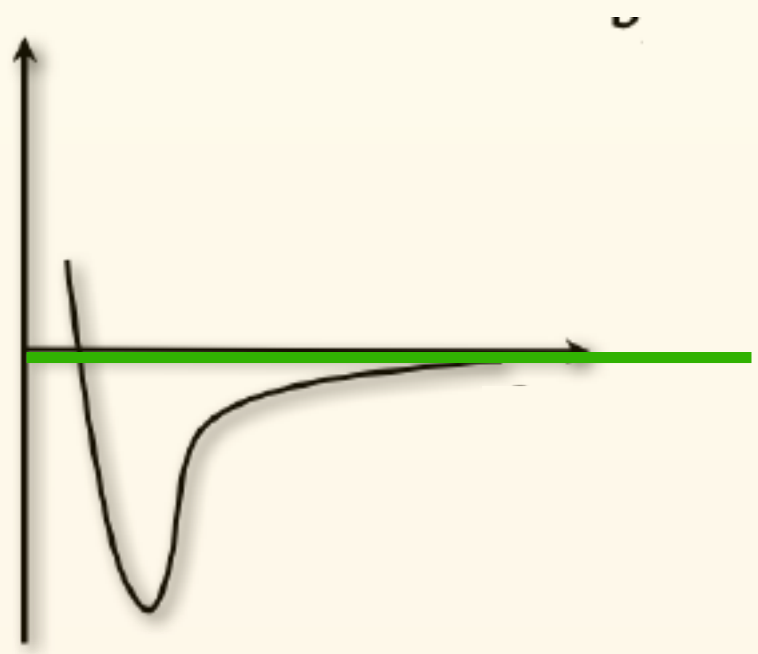
(If you find one in your theory, then it is
inconsistent with quantum gravity)

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

AdS Distance Swampland Conjecture

Lust, Palti, Vafa 2019

- One cannot go smoothly from AdS to Minkowski:



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

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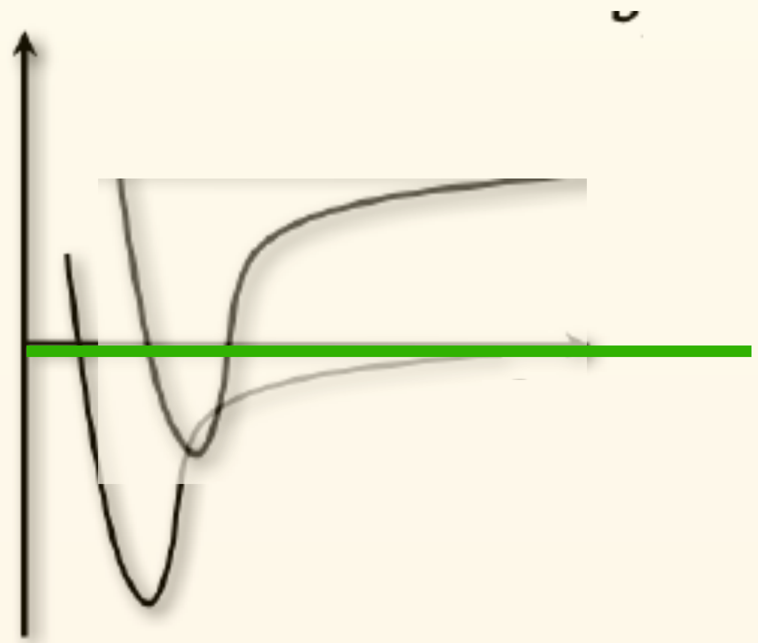

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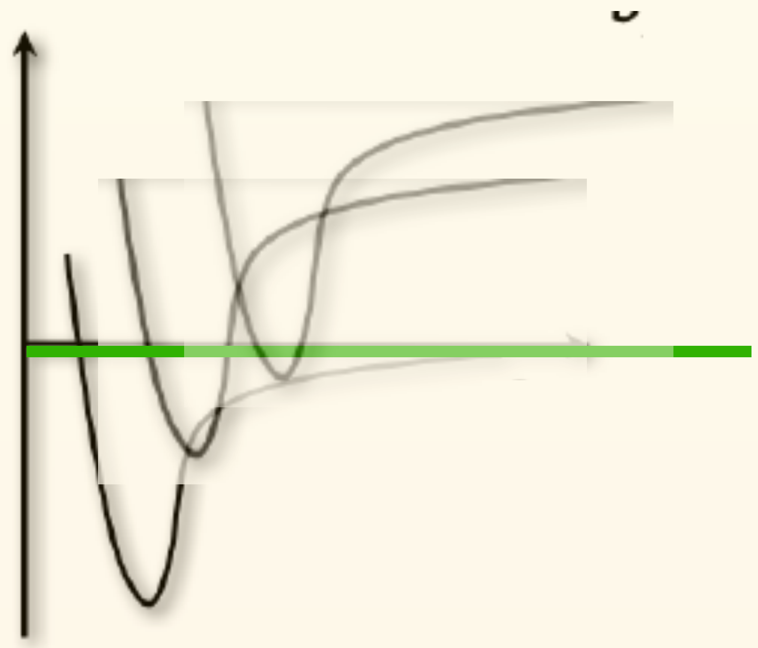

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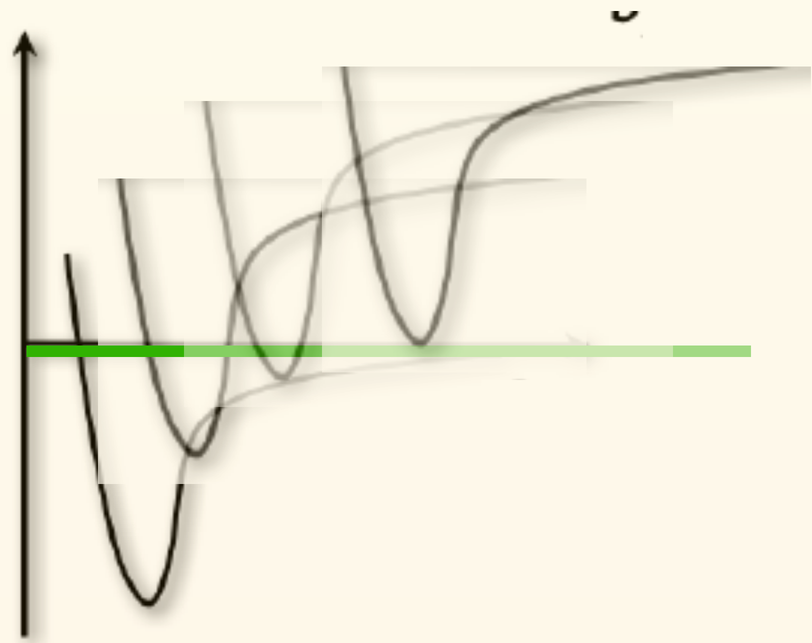

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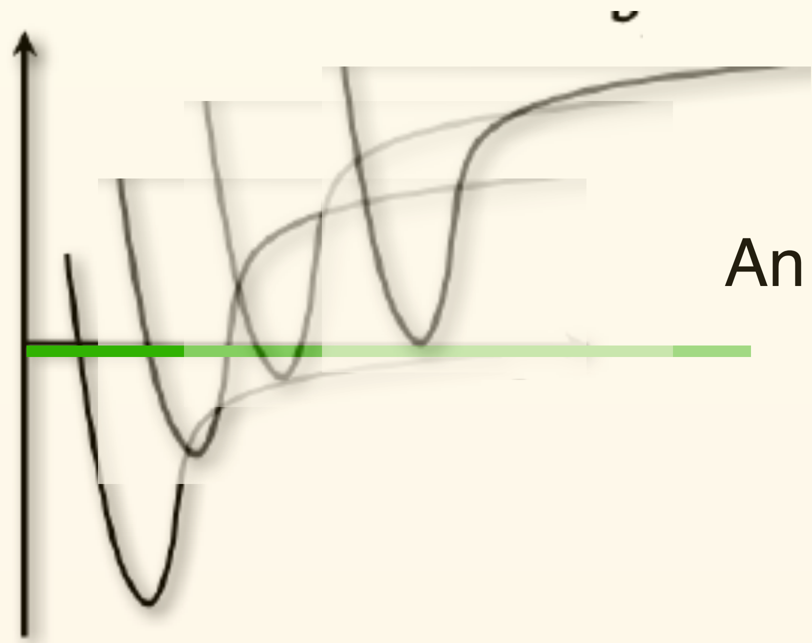


Consider family of AdS vacua with $\Lambda_{c.c.} \to 0$

An infinite tower of states with mass scale m behave as

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

Implies no separation between AdS and KK scales *Van Riet et al. 2018*

This separation of scales is crucial e.g. for the KKLT construction of dS vacua

(there is a possible counterexample still under discussion…)

De Wolfe et al., Camara et al. 2005

7) dS Swampland Conjecture

Obied, Ooguri, Spodyneiko, Vafa 2018

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

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

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.....

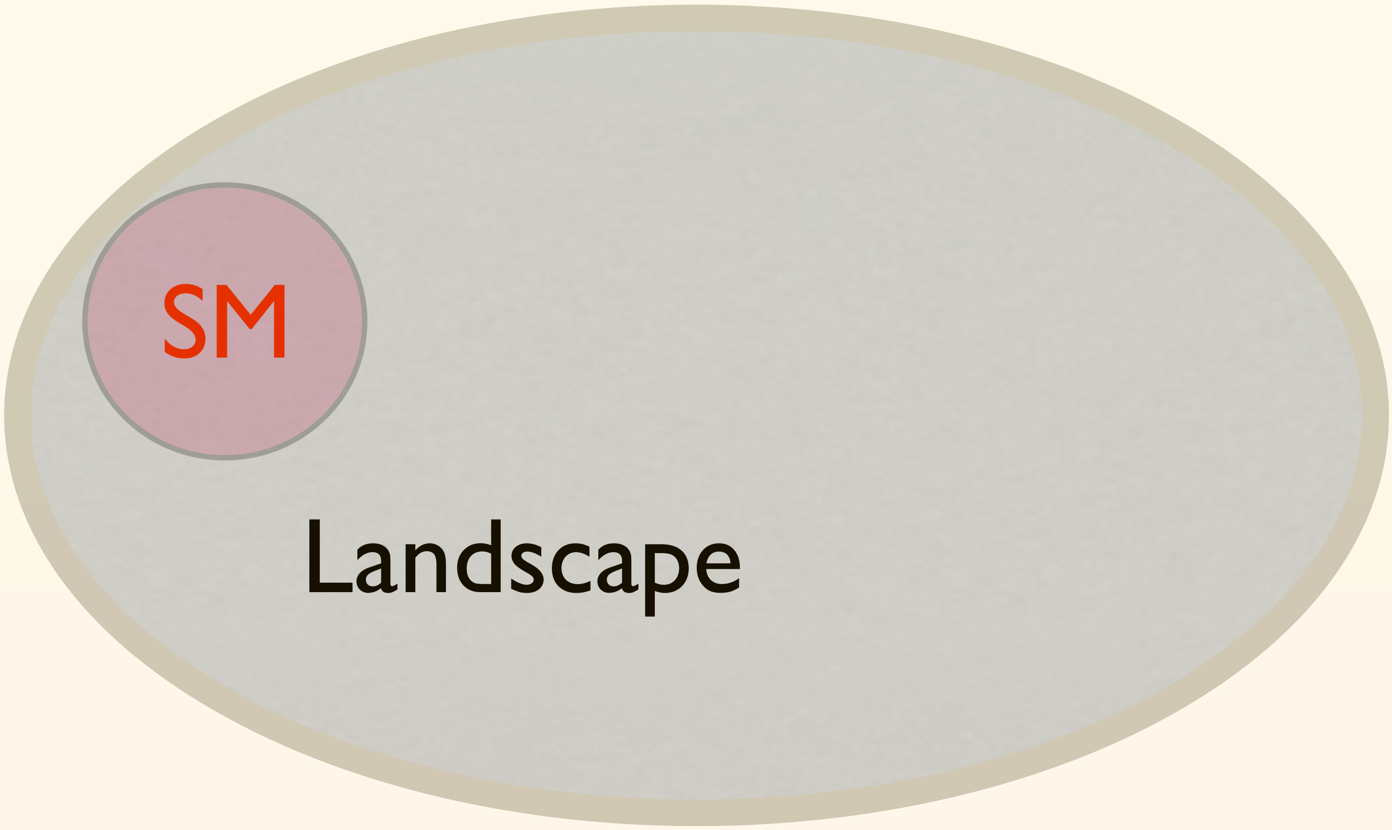
Ooguri, Palti, Shiu, Vafa 2018

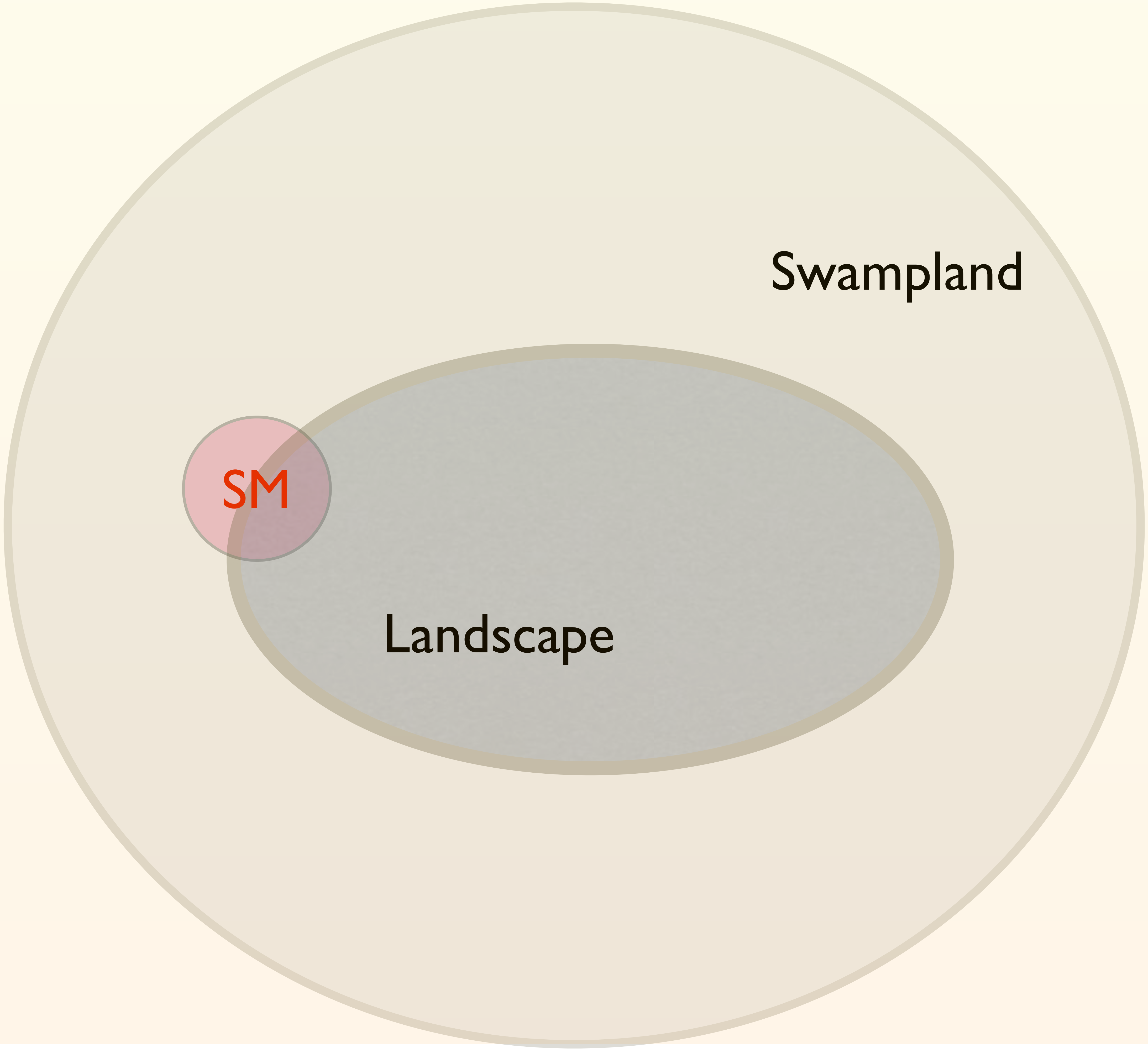
$$min(\nabla_i \nabla_j V(\phi)) \leq -\frac{\mathcal{O}(1)}{M_p^2} V(\phi)$$

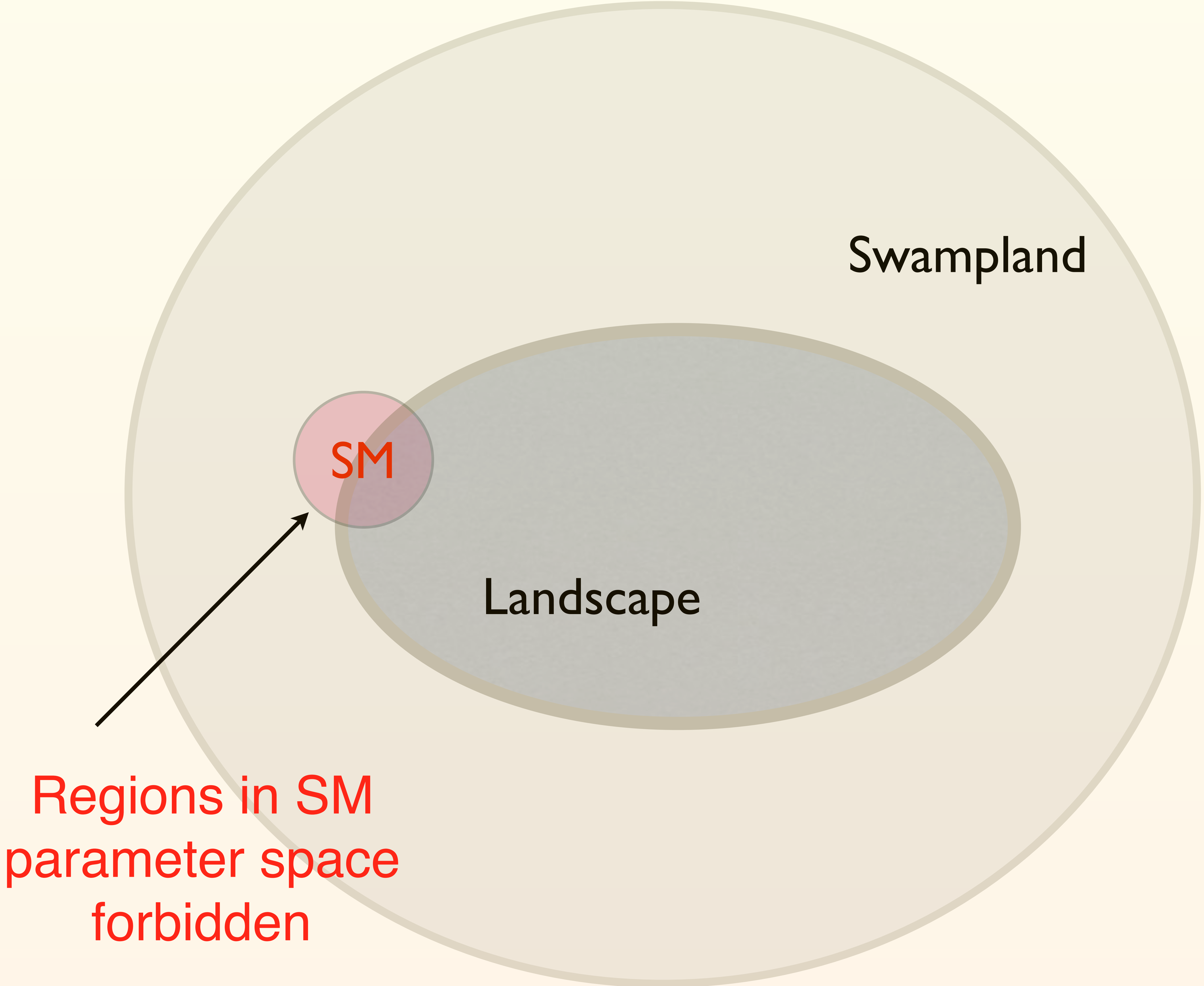
Forbids dS vacua!!!!!

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

Applications To Particle Physics


SM
Landscape


Swampland
SM
Landscape


Swampland
SM
Landscape
Regions in SM
parameter space
forbidden

1) The Standard Model and 3D AdS

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

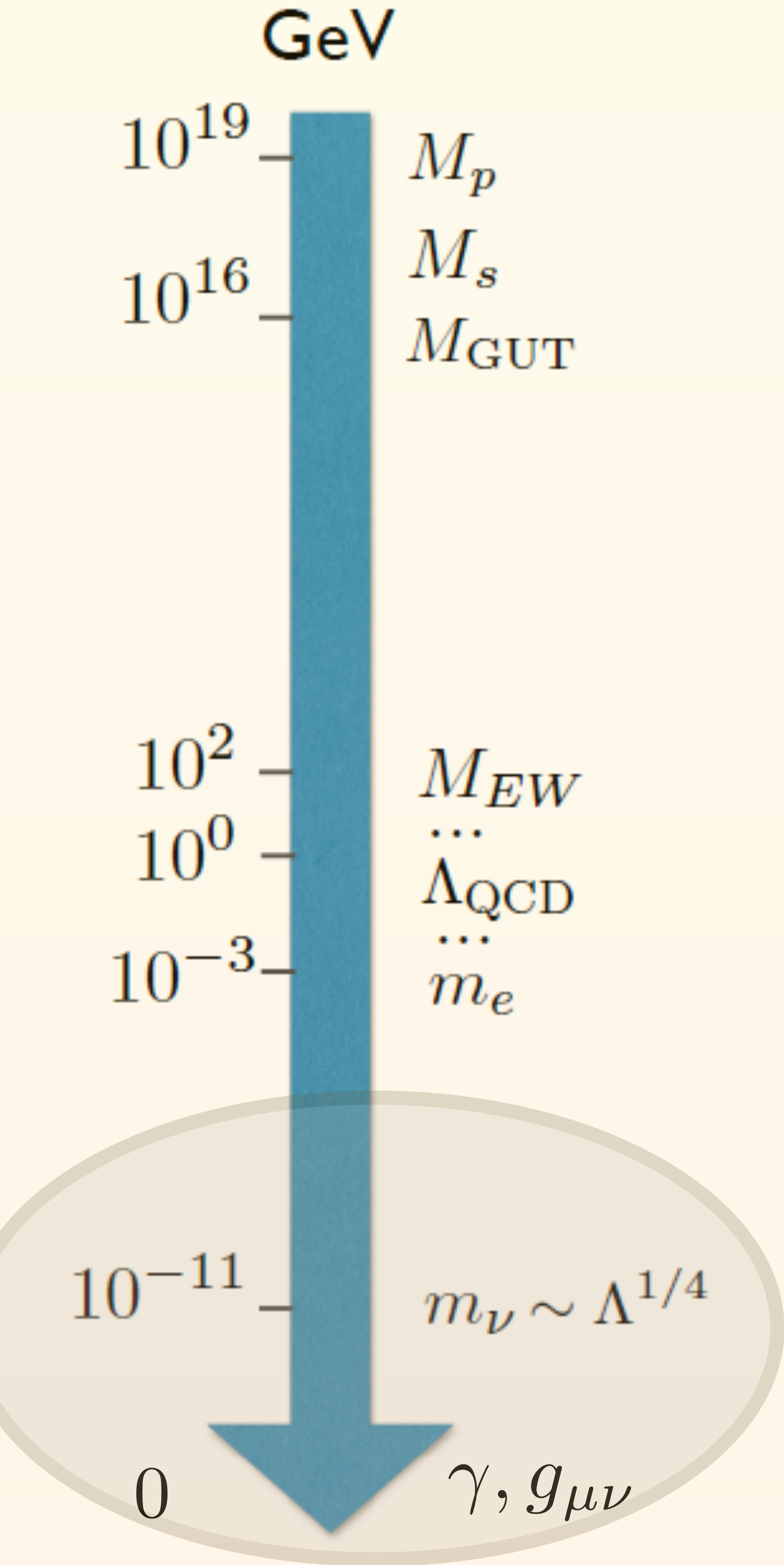
$$m_{KK} \simeq m_\nu$$

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

Conjectures forbid these vacua

Constraints on SM physics

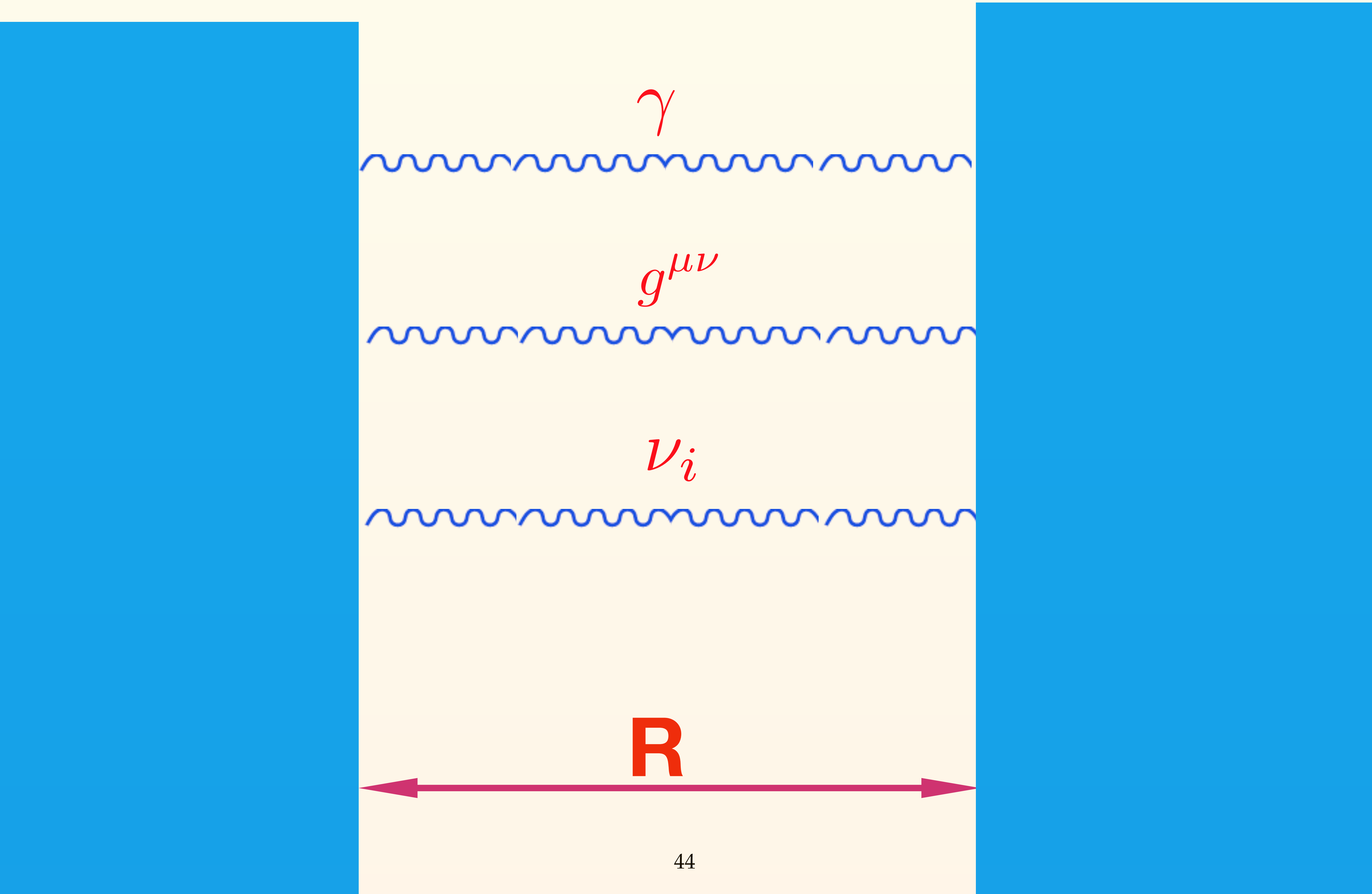
Scales in Fundamental Physics

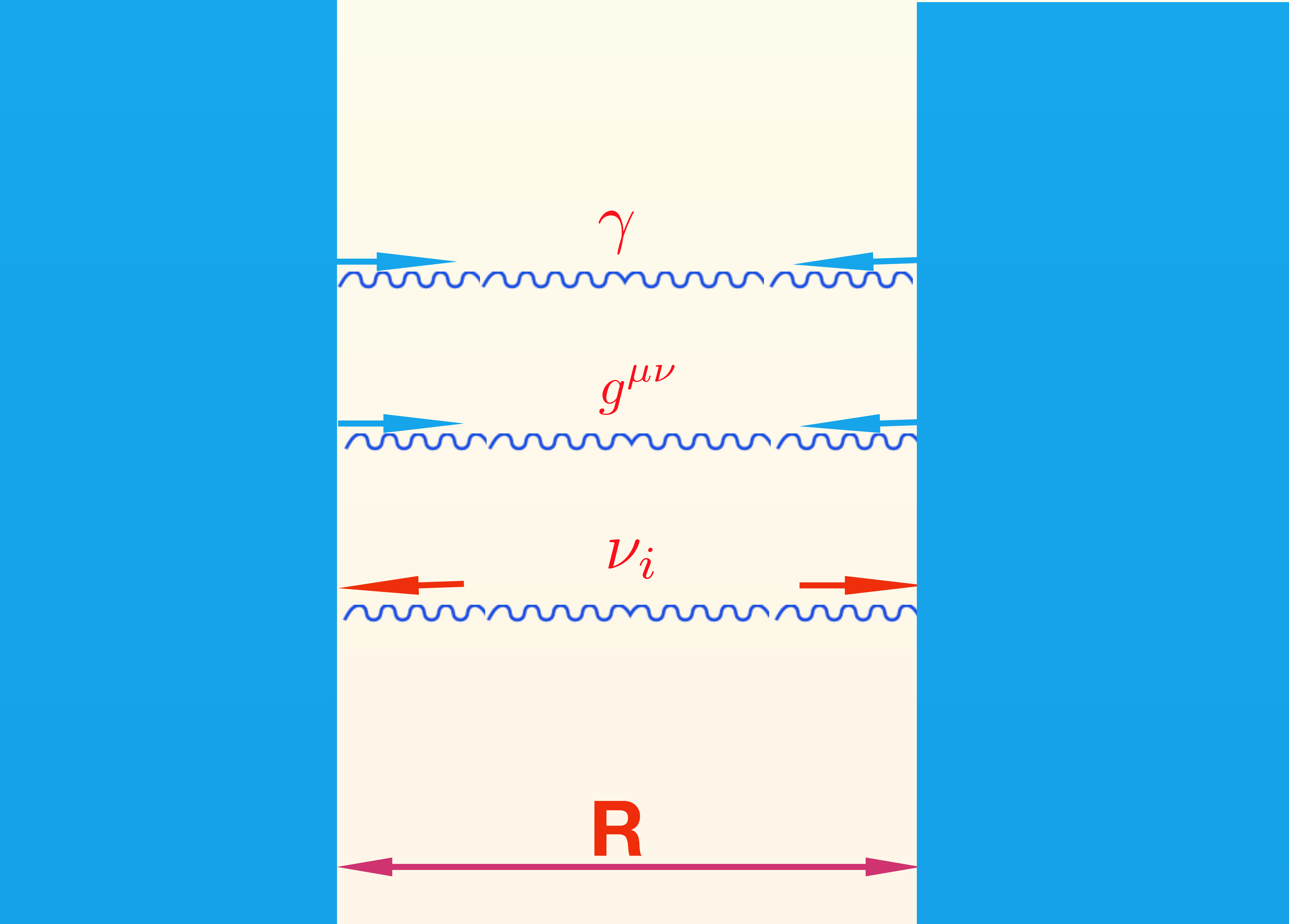


Will focus first in lightest SM sector

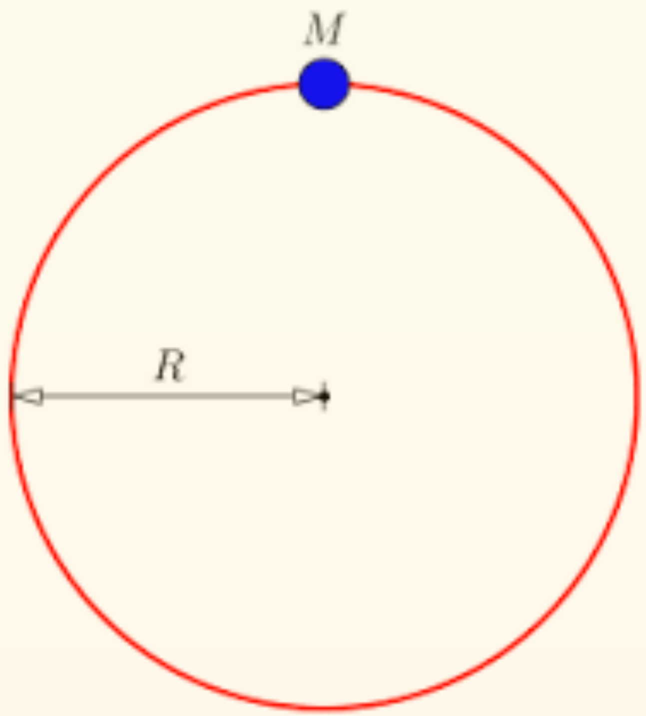
$\textit{Below electron threshold:}$

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




γ
$g^{\mu\nu}$
ν_i
R

SM compactified to 3D on a circle

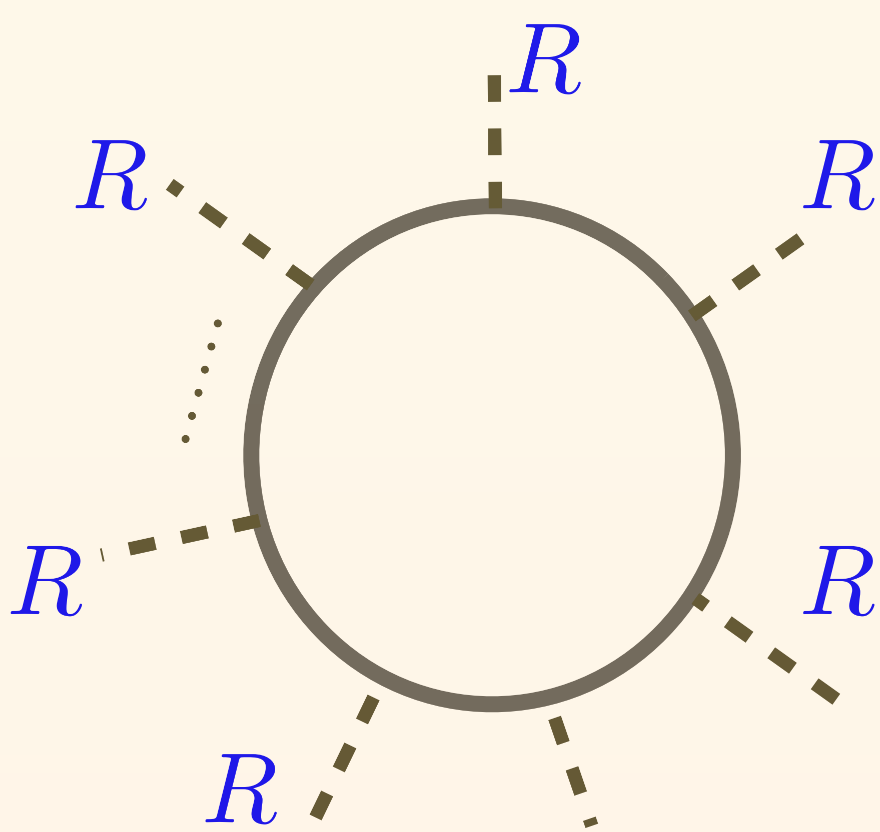


A Compact Dimension

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

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

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

Arkani-Hamed, Dubovsky, Nicolis, Villadoro, 2007

One – loop Casimir energy

The radius potential :

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

From 4D c.c.

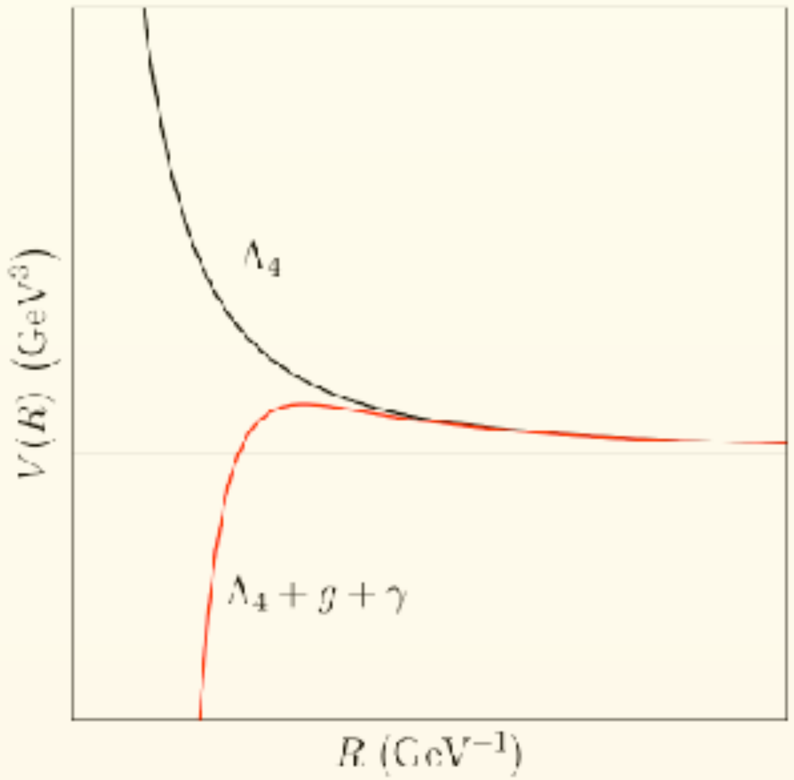
$\gamma, g_{\mu\nu}$

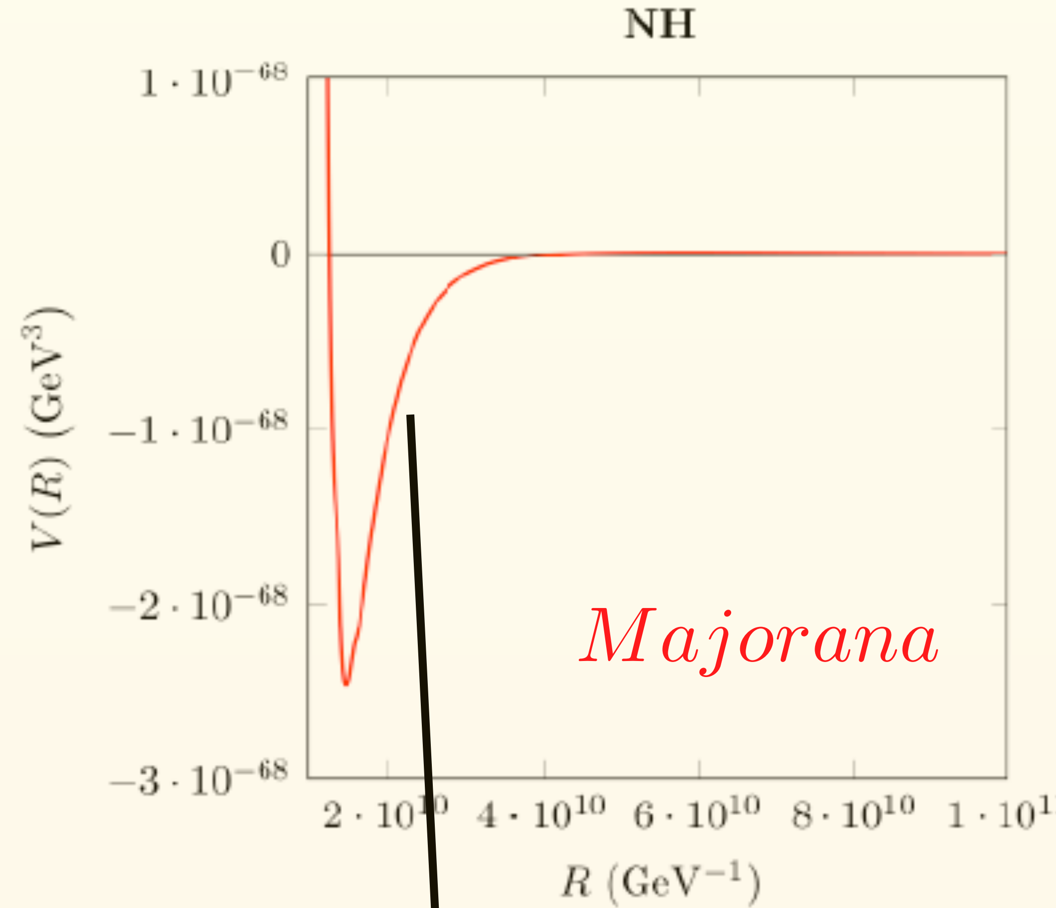
ν_i

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

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

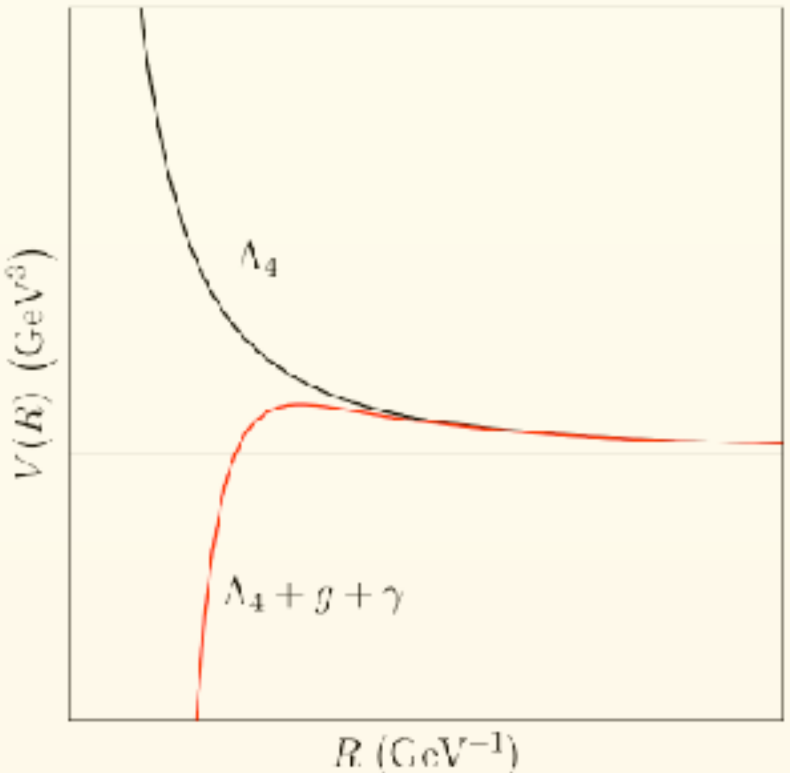
Important: Effect of heavier particles suppressed like $e^{-(m_f/m_\nu)}$

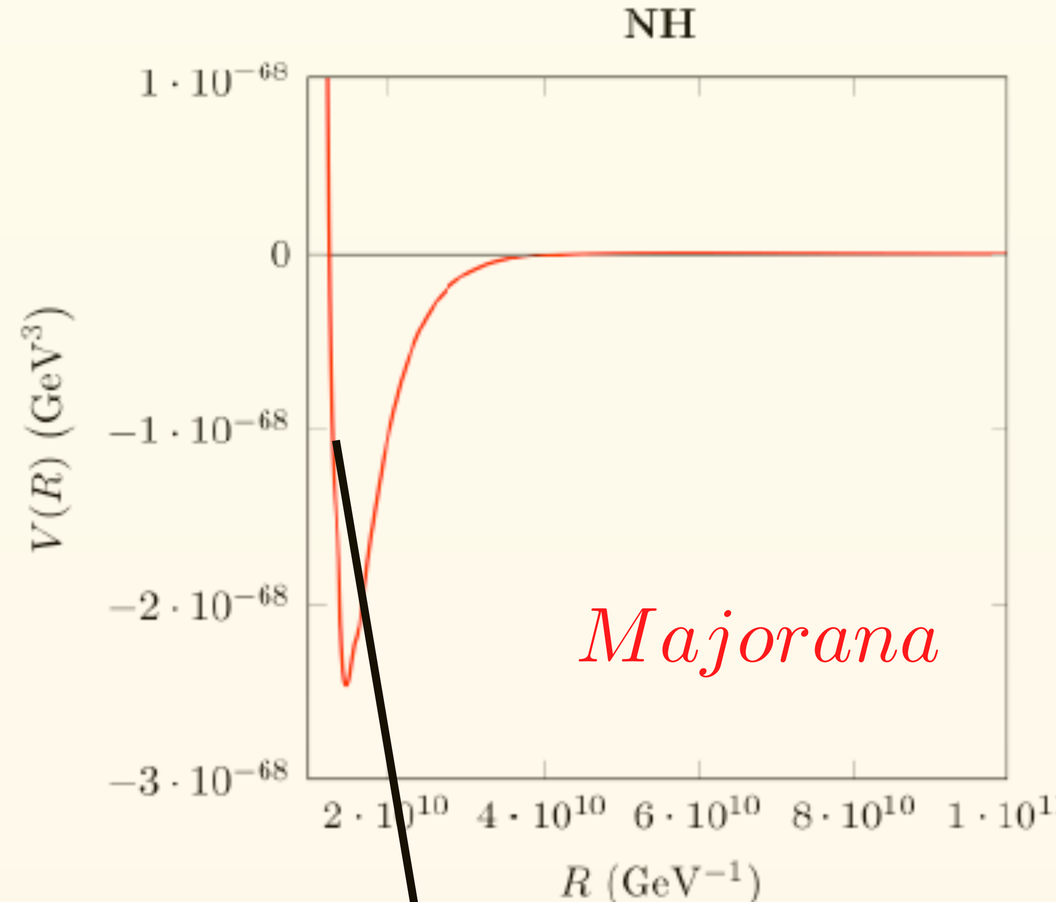




$$\underset{\gamma}{(-2} \; \underset{g_{\mu\nu}}{-\,2} \; \underset{\nu_1^M}{+\,2)} \left(\frac{1}{720\pi R^6} \right)$$

γ $\quad g_{\mu\nu}$ $\quad \nu_1^M$



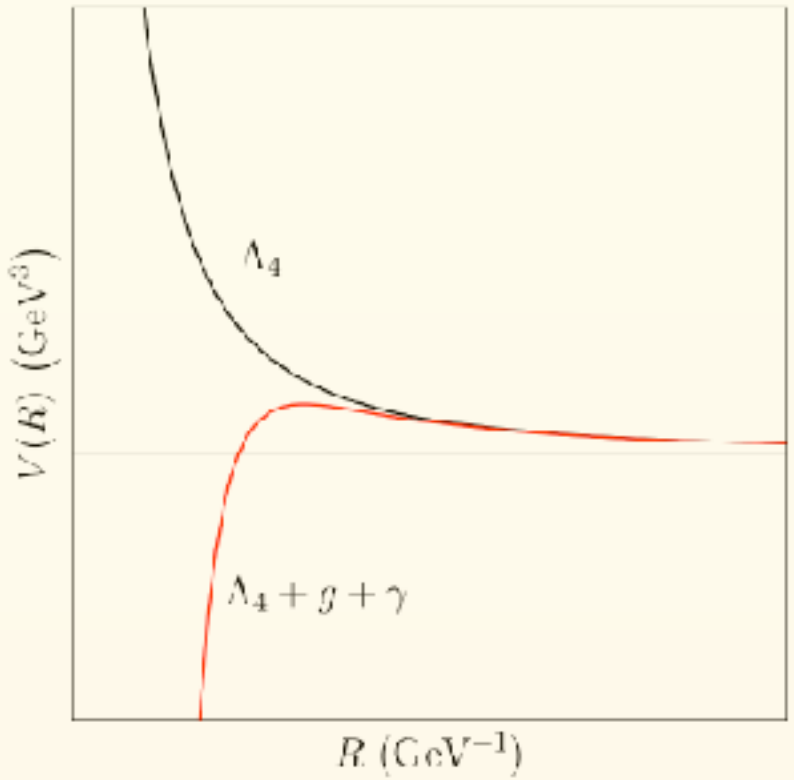


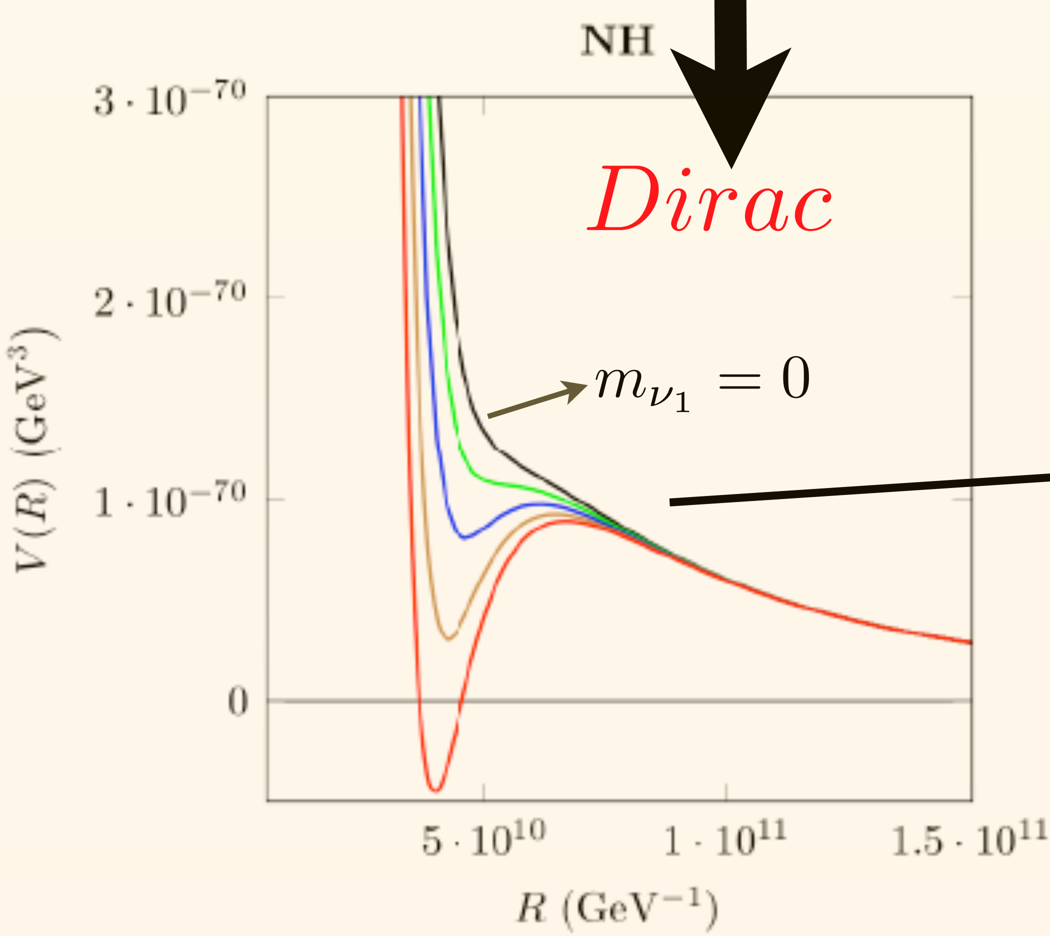
$$(-2-2+6)\left(\frac{1}{720\pi R^6}\right)$$

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

$Majorana\ \nu_1\ forbidden!!$

Ooguri,Vafa 2016

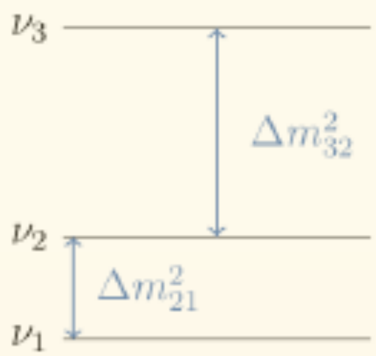


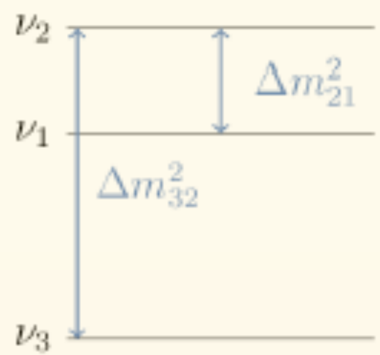


Dirac

$$(\underbrace{-2}_{\gamma} \underbrace{- 2}_{g_{\mu\nu}} \underbrace{+ 4}_{\nu_1^D}) \left(\frac{1}{720\pi R^6} \right)$$

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!!

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

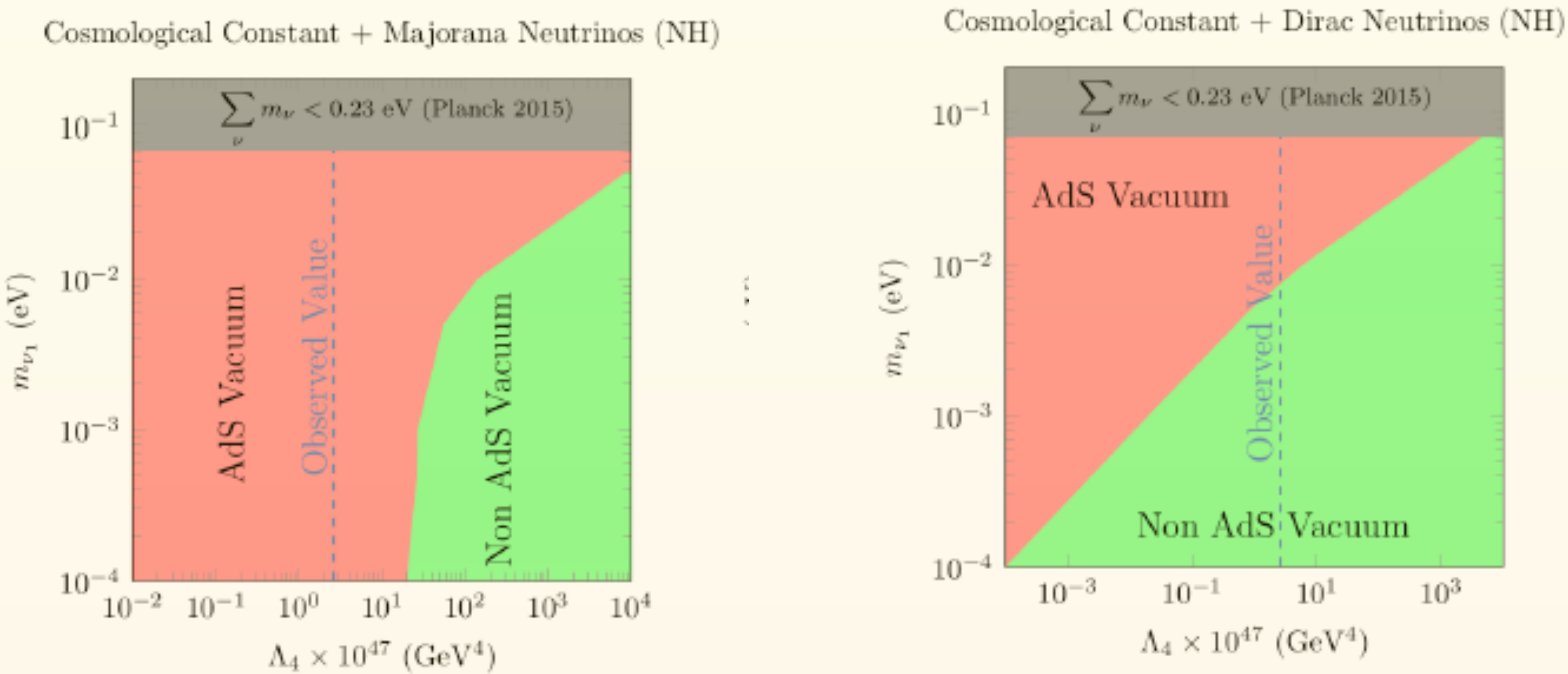
Dirac:

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

Lower bound on the cosmological constant



Majorana

Dirac

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

To avoid AdS

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

Explains coincidence!!

L.I, Martin-Lozano, Valenzuela 2017

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

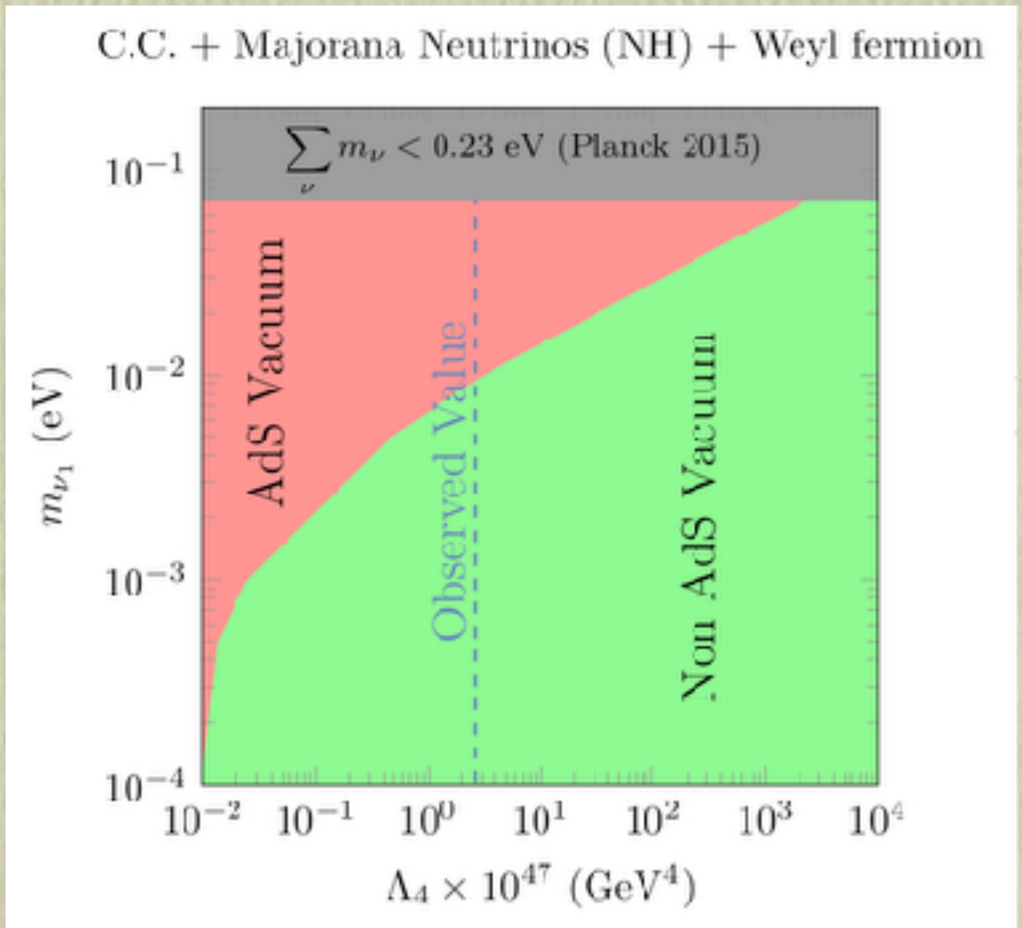
Constraints with BSM physics:

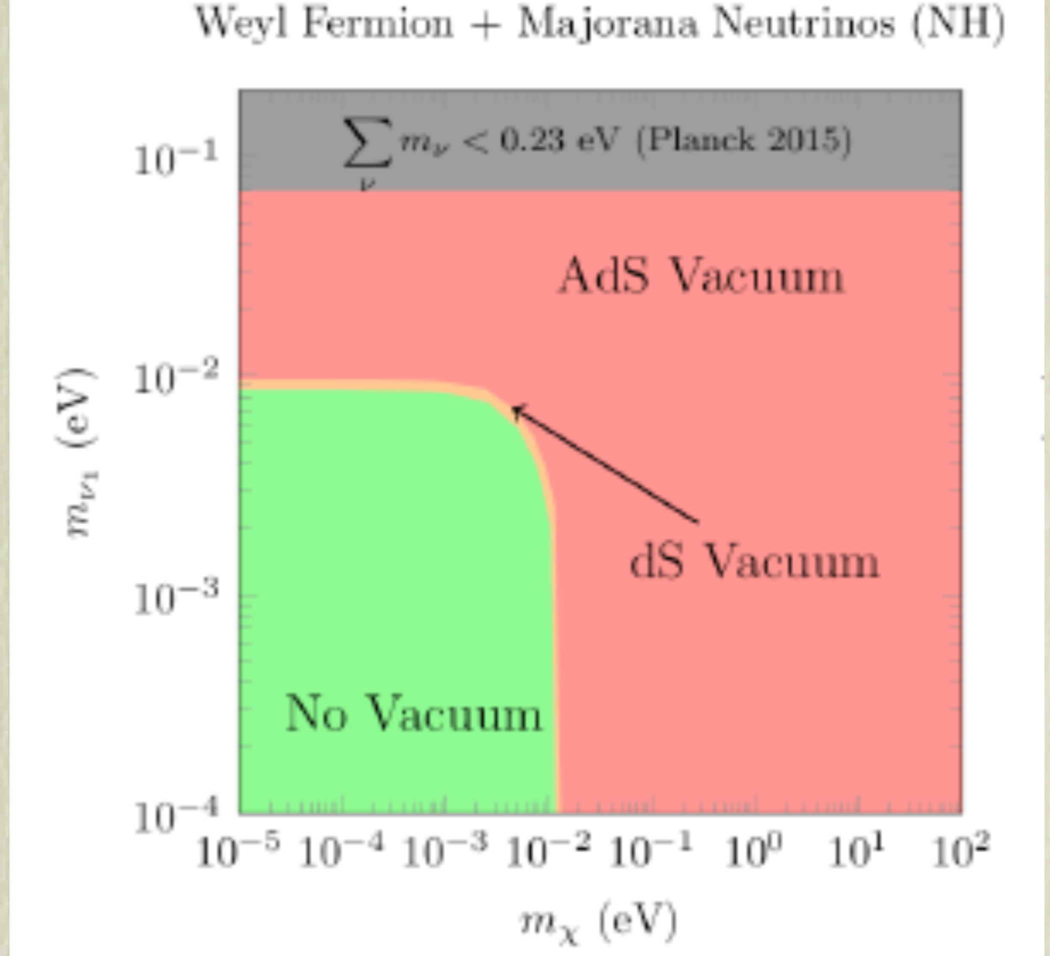
One additional very light Weyl spinor

Possitive contribution to Casimir energy

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

e.g. Majorana, NH





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

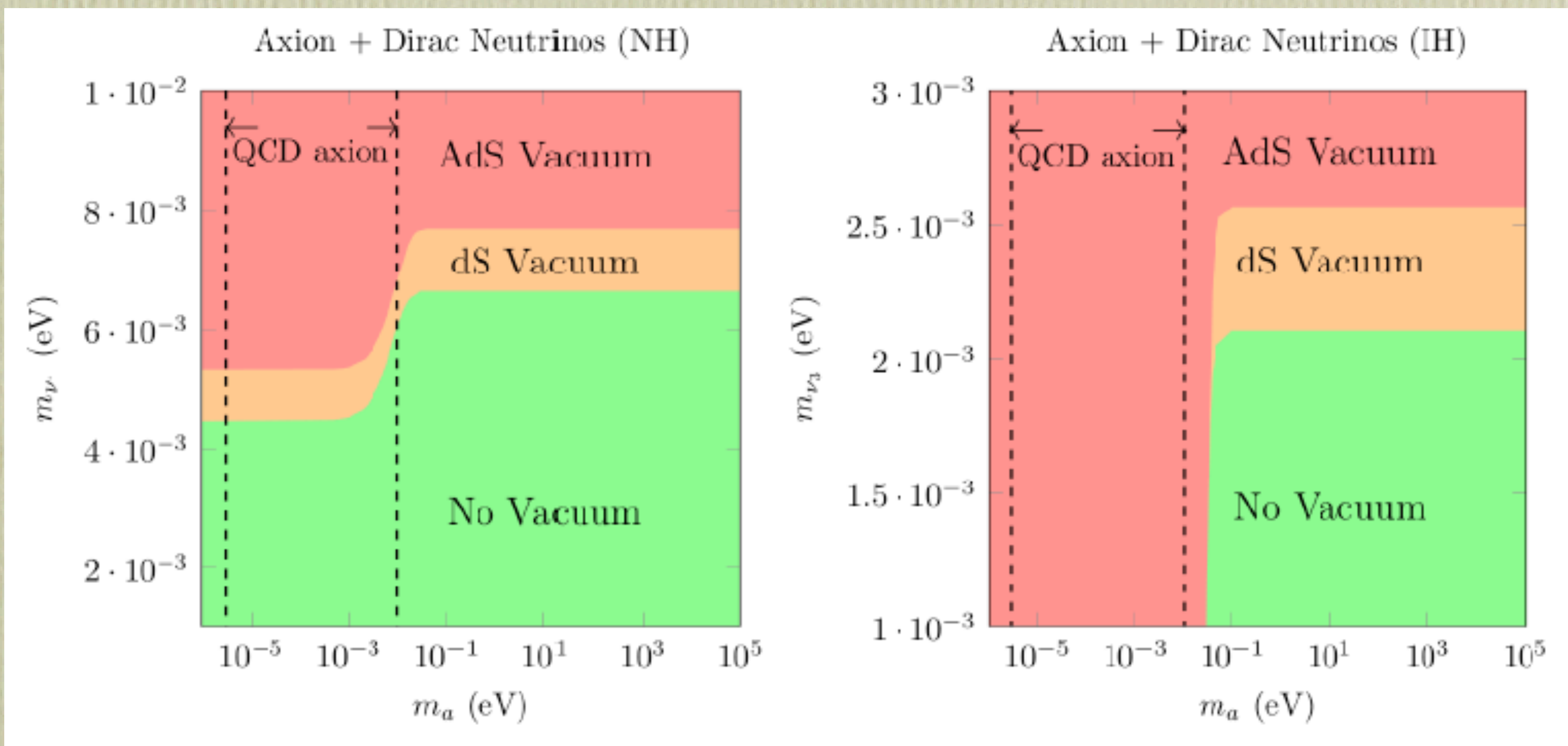
L.I,Martin-Lozano, Valenzuela 2017

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

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

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

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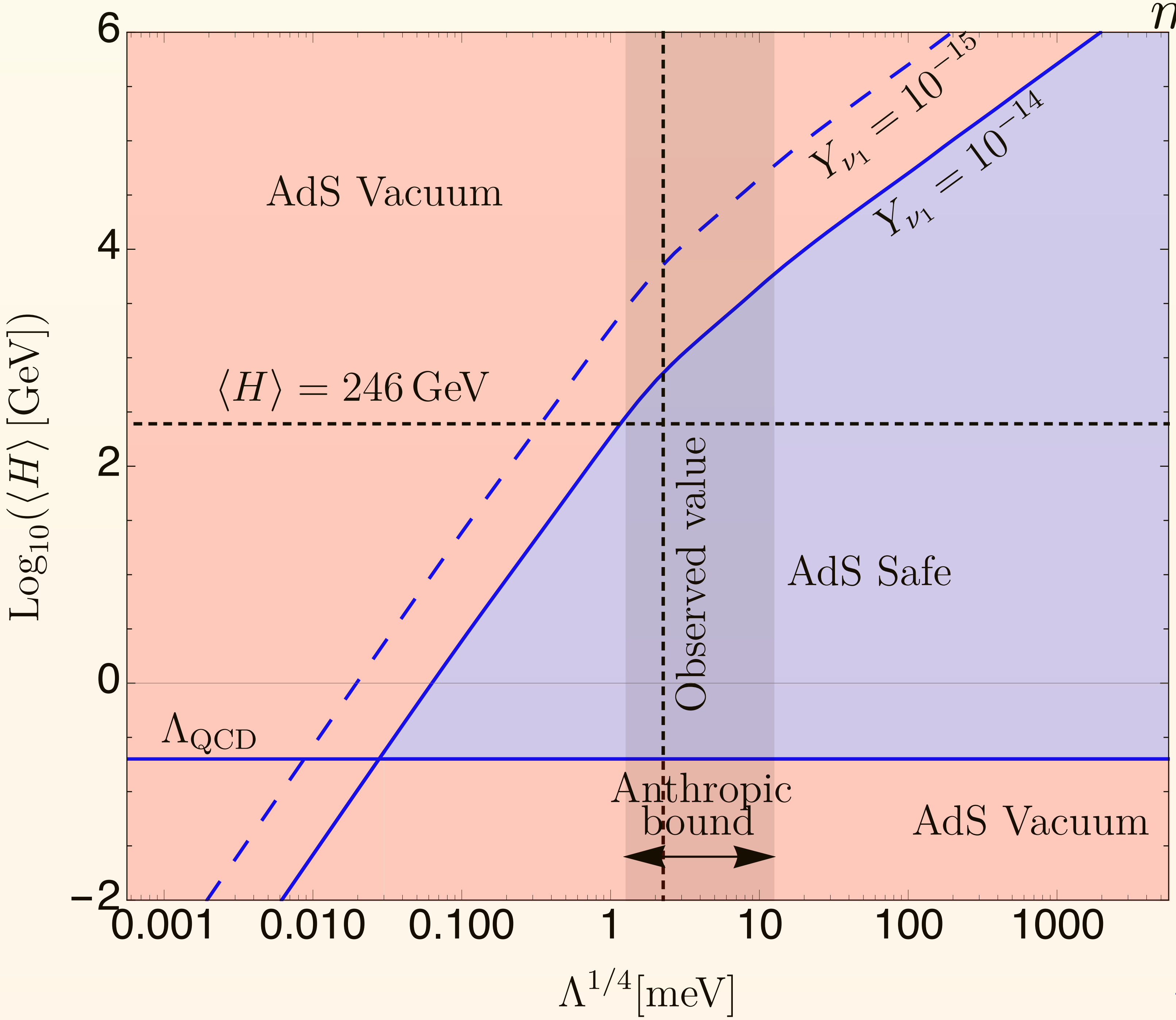


$$< H > \lesssim 1.6 \frac{\Lambda_4^{1/4}}{Y_\nu}$$

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

2) Constraints on axions

$$A^\mu \longrightarrow a(x) \ axion$$

- Axions are 0-forms

$$m \leq g \, M_p$$

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

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

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

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

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

3) Constraints from the scalar WGC

L.I., E. Gonzalo 2019, 2020

- Scalar WGC for a single massive scalar H (canonical kinetic term)

$$\left|(\partial_\phi m^2)^2 - \ m^2(\partial_\phi^2 m^2)\right| \geq \ \frac{m^4}{M_p^2}$$

- You may conjecture that it also applies to the 'modulus' scalar ϕ itself

$$m^2 \ \longrightarrow \ \partial_\phi^2 V(\phi)$$

$$\boxed{\left|(V''')^2 \ - \ V''V''''\right| \ \geq \ \frac{(V'')^2}{M_p^2}}$$

'Strong S WGC'

- The idea is that scalar interactions should be stronger than gravity

$$\left|(V''')^2 - V''V''''\right| \geq \frac{(V'')^2}{M_p^2}$$

- If this applies for any scalar, a very strong constraint !
- Note a linear potential $V = a\phi$ is always a solution
- Pure quadratic, with no other interaction is not a solution
- Some tests: $V = -cos(\phi/f)$
- Axion potential:

$$\frac{1}{f^6}\left|sin^2(\phi/f) + \cos^2(\phi/f)\right| \geq \frac{cos^2(\phi/f)}{f^4 m_p^2}$$

$$f \leq M_p$$

- Consistent with other Swampland results

L.I., E. Gonzalo 2019, 2020

- Quartic real scalar coupling: $V = \frac{m_0^2}{2}\phi^2 + \frac{\lambda}{4!}\phi^4$

$m^2(\phi) = V''$

- Constraint $|\lambda| \left|m^2(\phi) - \lambda\phi^2\right| \geq \frac{1}{M_p^2}\left|m^2(\phi)\right|^2$

- For $\phi \to 0 \longrightarrow |\lambda| \geq (m_0^2/M_p^2)$ consistent with WGC intuition

- It must be $m^2(\phi) \neq \lambda\phi^2 for\ all\ \phi$

- It would be very interesting to generalize to more realistic case of the SM (gauge couplings, top Yukawa, running…..)

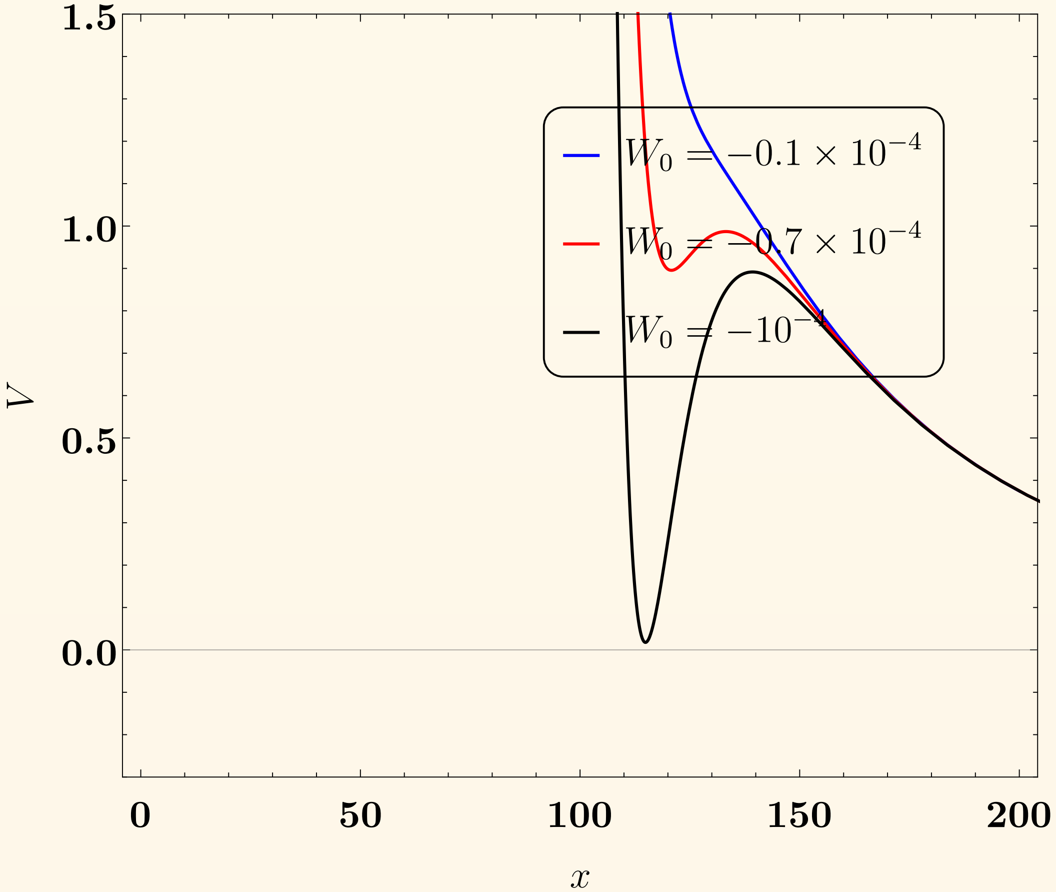
- In particular, the fact that $\lambda(h) \longrightarrow 0$ at $\sim 10^{11} GeV$ in the SM perhaps would imply interaction becomes weaker than gravity there ?

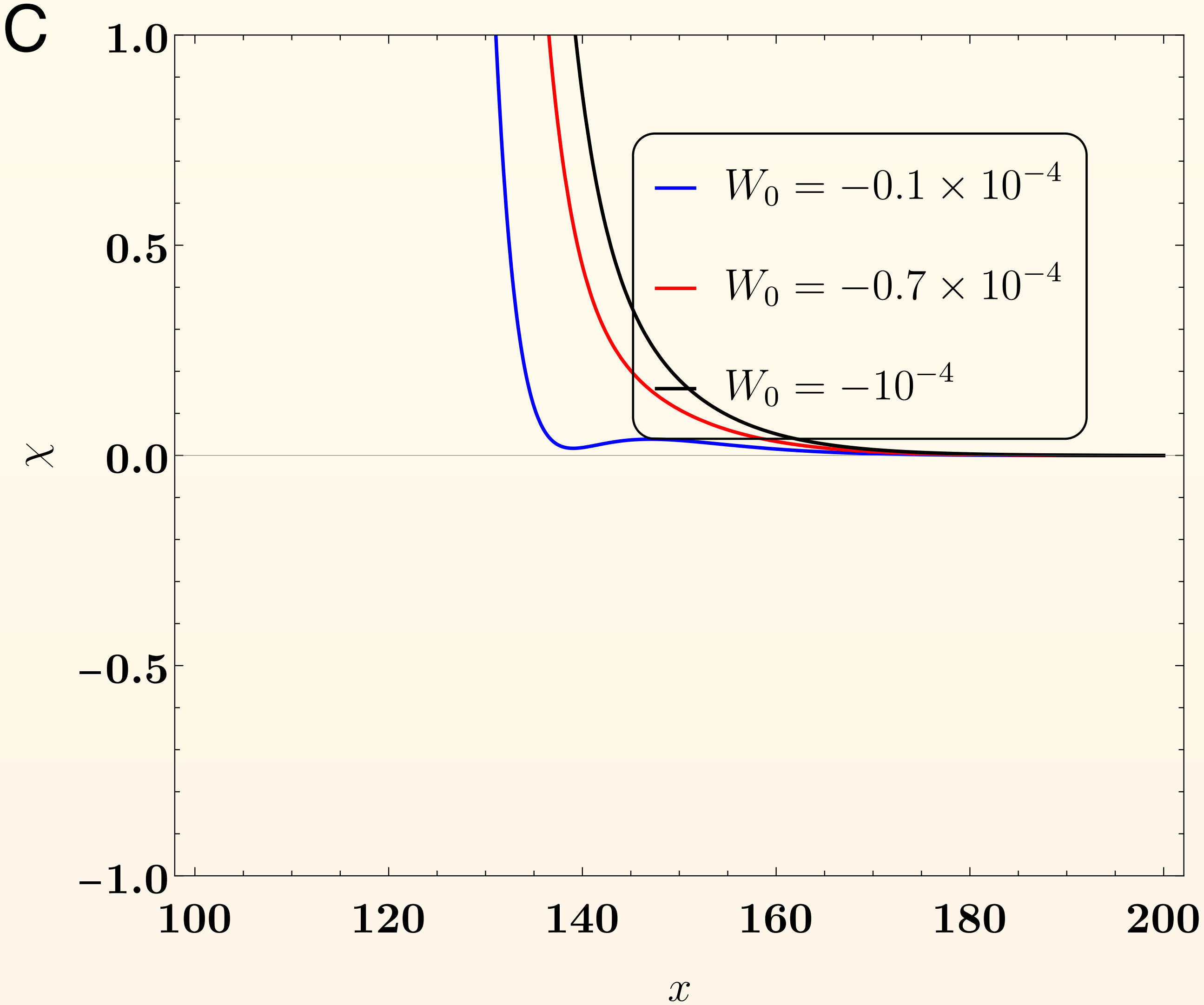
New Physics (like SUSY) at (or before) an intermediate scale

Another application:

Moduli fixing in string vacua : E.g. KKLT

Constrained but consistent with SSWGC





dS vacua

$$\chi \equiv g^{tt} \left|(V''')^2 - (V'')(V'''')\right| - \left|V''\right|^2 / M_p^2 \geq 0$$

$Violated\ if\ W_0\ made\ too\ small....$

SUSY broken at a large scale

It may violate the dS conjecture but not the SSWGC

4) Constraints from dS Swampland conjecture

- dS Swampland conjecture

Oogurі, Palti, Shiu, Vafa 2018

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

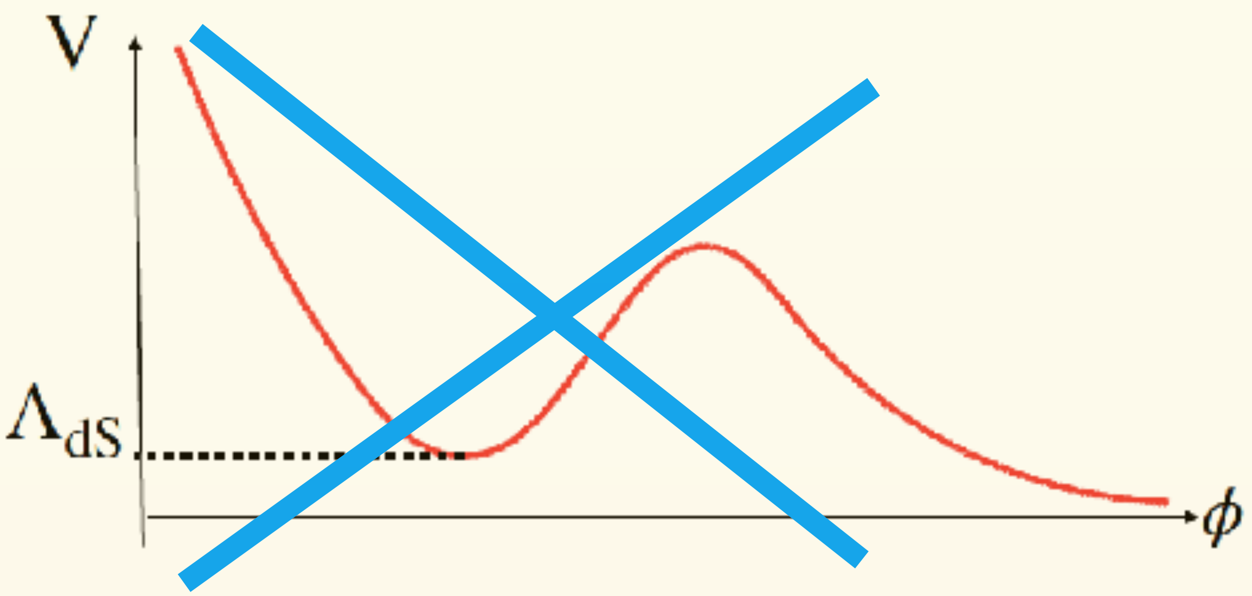
Sufficiently unstable maxima

- Minima should have $\nabla V(\phi) = 0\ ,\ min(\nabla_i \nabla_j V(\phi)) > 0$

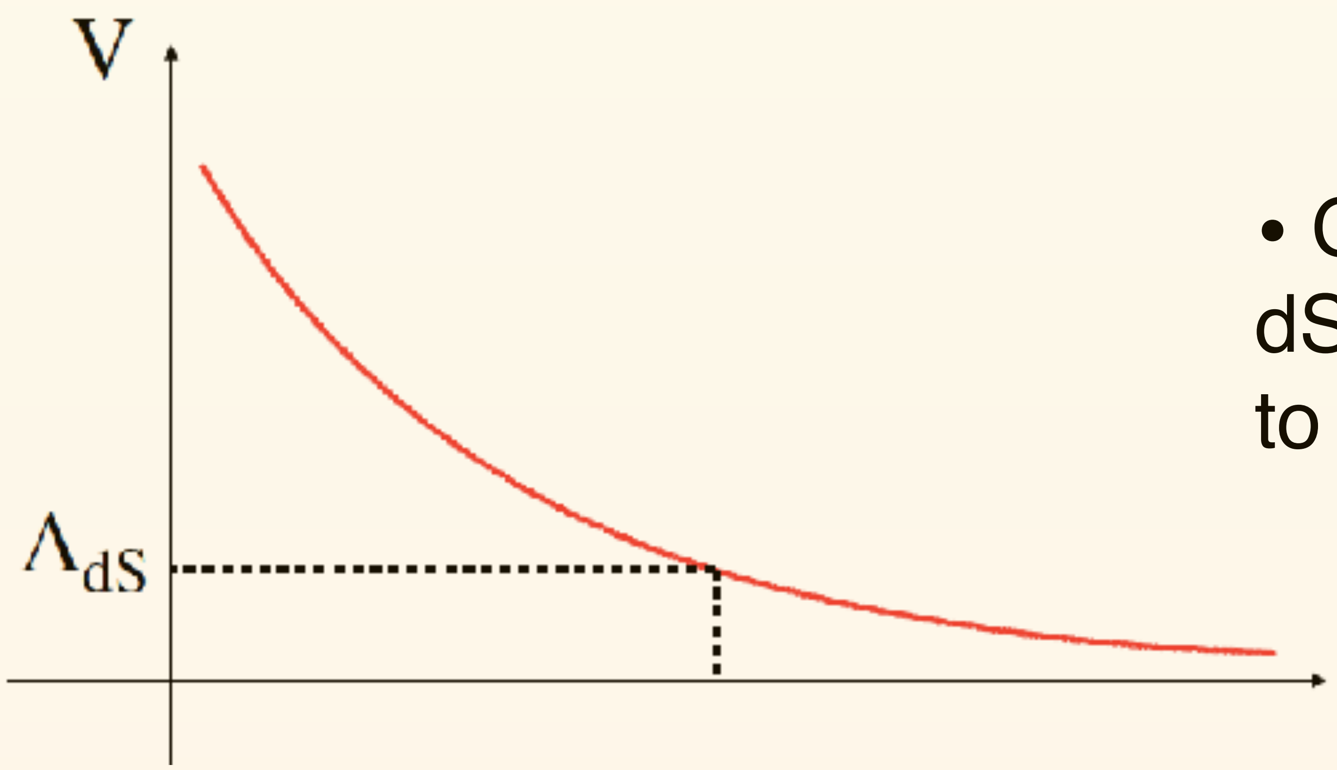
Forbids dS vacua

- It is true that (unlike AdS) finding dS minima in string theory has shown to be very difficult (some people claim impossible)

- The canonical example of KKLT is being scrutinised in detail now….. So far, it is fair to say it is alive…..



• Makes inflation very difficult…



• Quintessence ok with the dS constraint but no easy to construct viable models…

- The Trans-Planckian Censorhip Conjecture (TCC) *Bedroya,Vafa 2019*

- In cosmological expansion ‘ no length scales which exit the Hubble horizon could ever had a wavelength smaller than the Planck length’

$$a_i \; > \; a_f \, \frac{H_f}{M_p}$$

- Limits inflation strongly: $V^{1/4} \; \leq \; 10^9 GeV \;\; , \;\; r \; < \; 10^{-30}$

- For large field predicts

$$|V'| \; \geq \; \frac{2}{\sqrt{((d-1)(d-2)}} V$$

This particular constraint tested in many string compactifications

5) Other systems constrained by WGC

- Bounds on (Stuckelberg) mass of the photon

M. Reece, 2018

- Constraints on clock-work mechanism

L.I.,M. Montero, 2017

- Relaxions: constraints on the UV scale

L.I.Montero,Uranga,Valenzuela 2015

Conclusions

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

2) It is important to advance along two parallel lines:

Better understand the origin and structure of the WGC/Swampland ideas

Apply them to address pending issues in BSM physics and Cosmology

Thank you !!

Swamp

land