Constraining Particle Physics from Quantum Gravity Conjectures

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Ibanez,Martin-Lozano,IV [arXiv:1706.05392 [hep-th]]
Ibanez,Martin-Lozano,IV [arXiv: 1707.05811 [hep-th]]

BSM 2017, Hurghada, December 2017

Puzzles today

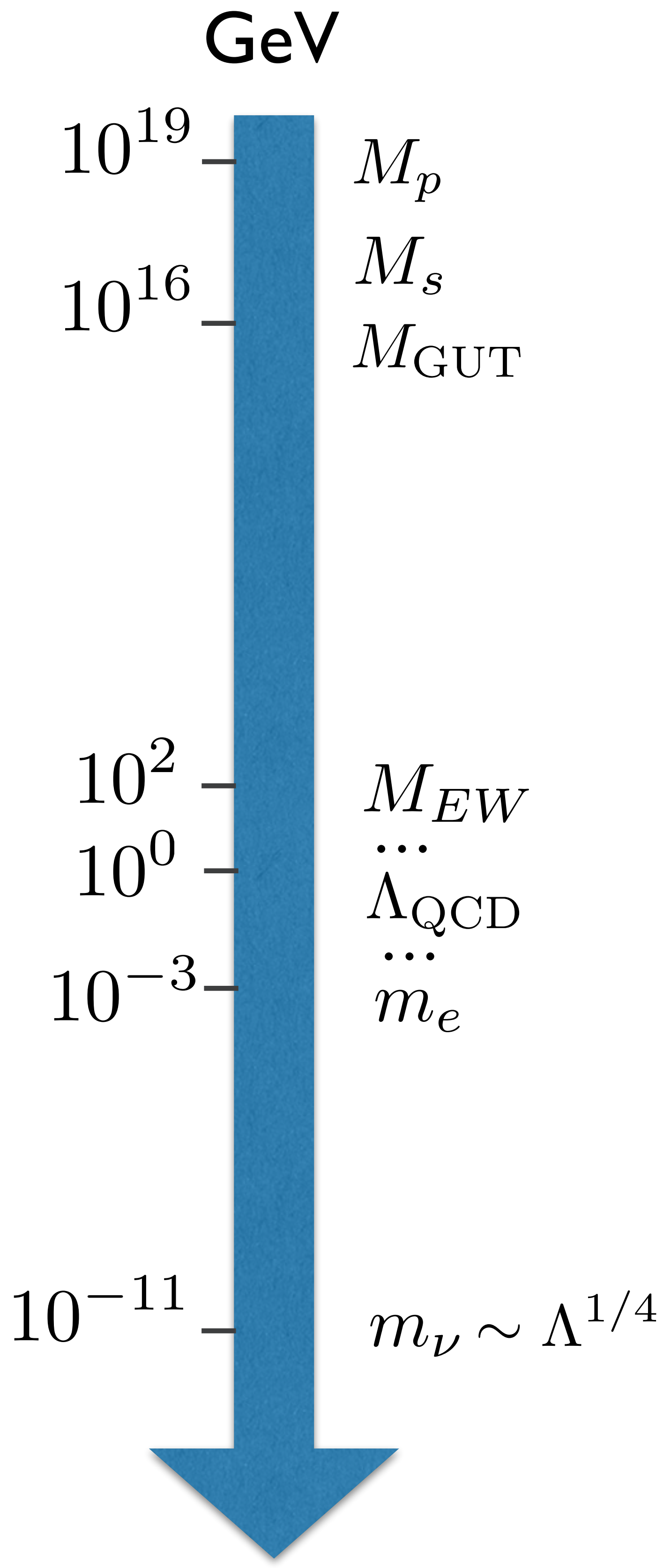
Naturalness problems:

- Cosmological constant
- EW hierarchy problem ← LHC

Based on the principle of separation of scales which follows from a quantum field theory approach

Numerical cosmological coincidence:

$$\left.\begin{array}{r} m_\nu \simeq 10^{-1}-10^{-2}\mathrm{eV} \\ \Lambda \simeq (0.24\cdot 10^{-2}eV)^4 \end{array}\right\} \Rightarrow \Lambda \simeq m_\nu^4$$



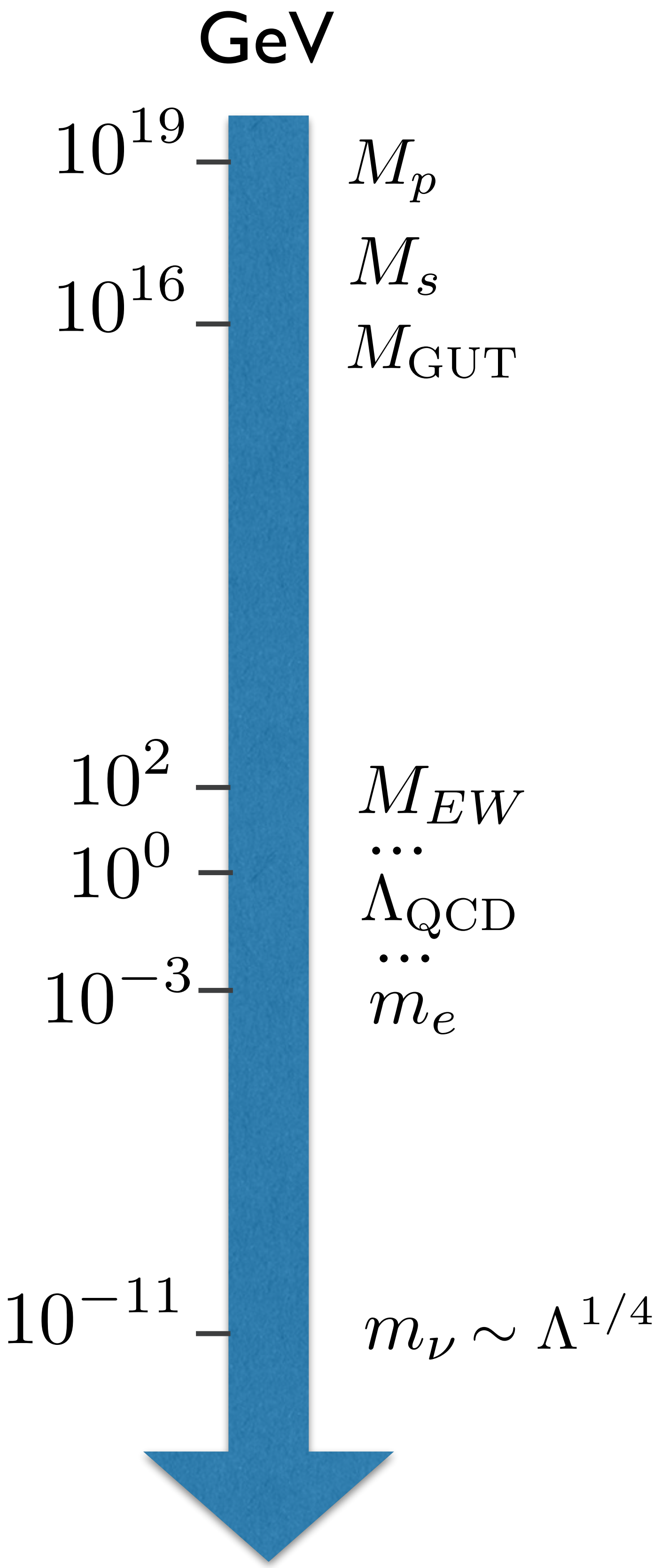
Puzzles today

Absence of new physics is also a hint!

We are forced to rethink the guiding principles of high energy physics

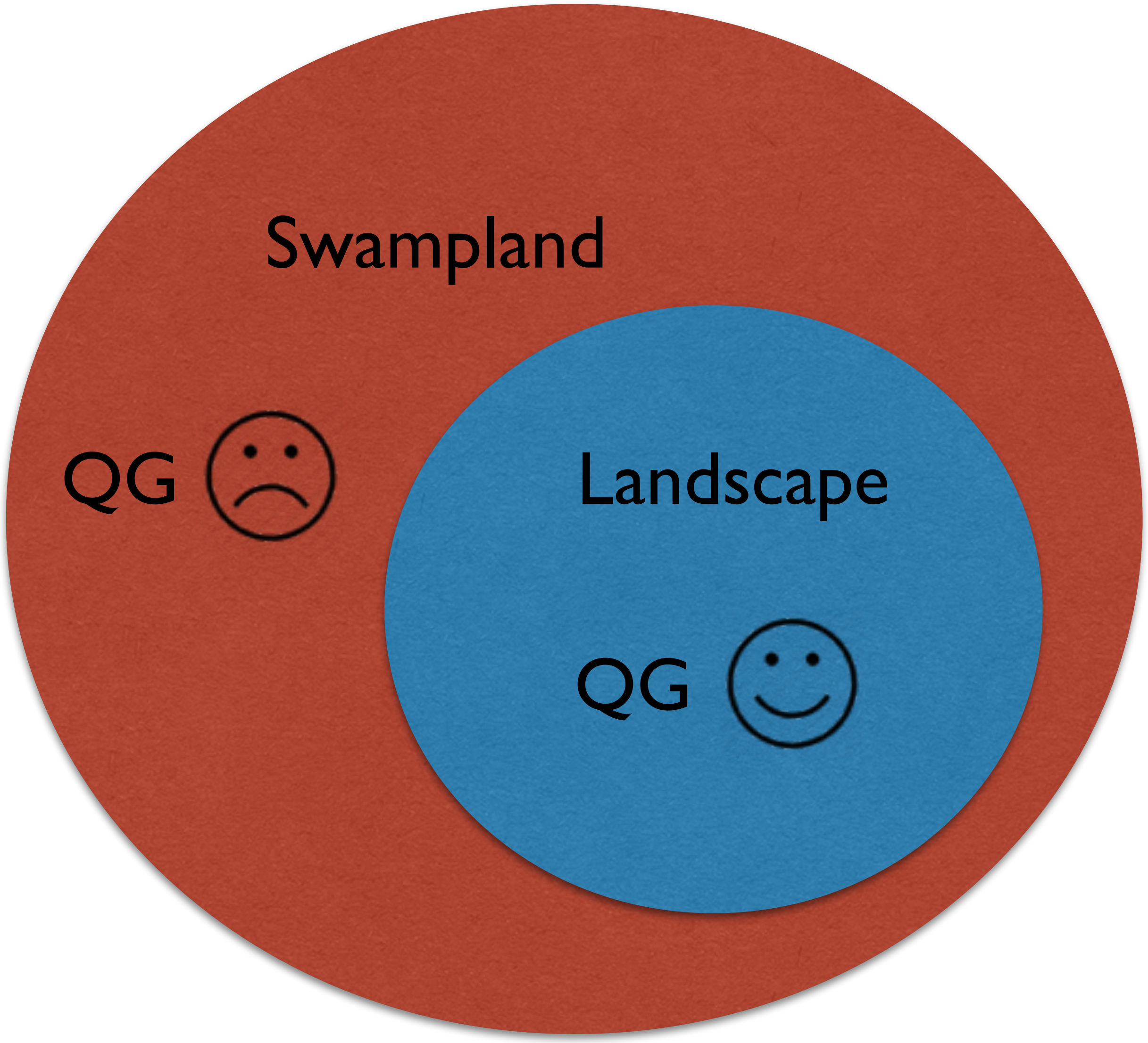
UV/IR mixing induced by gravity?

Quantum gravity constraints?



Not everything is possible in string theory/quantum gravity!!!

What are the constraints that an effective theory must satisfy to be embedded in quantum gravity?



Swampland

QG ☹

Landscape

QG ☺

QFT of scalar and fermionic fields

Anomaly
constraints

QFT of scalar and fermionic fields
+ gauge fields

example. QFT of one fermion with SU(2) global symmetry

There is a Witten anomaly when coupling the theory to a gauge field!

QFT of scalar and fermionic fields

Anomaly constraints

QFT of scalar and fermionic fields
+ gauge fields

QFT of scalar and fermionic fields
+ gauge fields
+ gravity

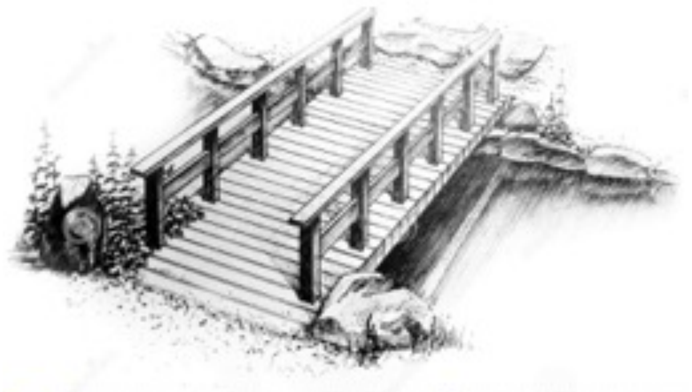
Quantum Gravity Conjectures

Motivated by observing recurrent features of the string landscape and “model building failures”, as well as black hole arguments

- Absence of global symmetries [Banks-Dixon’88]
- Completeness hypothesis [Horowitz,Strominger,Seiberg…] [Polchinski.’03]
- Weak Gravity Conjecture [Arkani-Hamed et al.’06]
- Swampland constraints about the moduli space [Ooguri-Vafa’06]

…

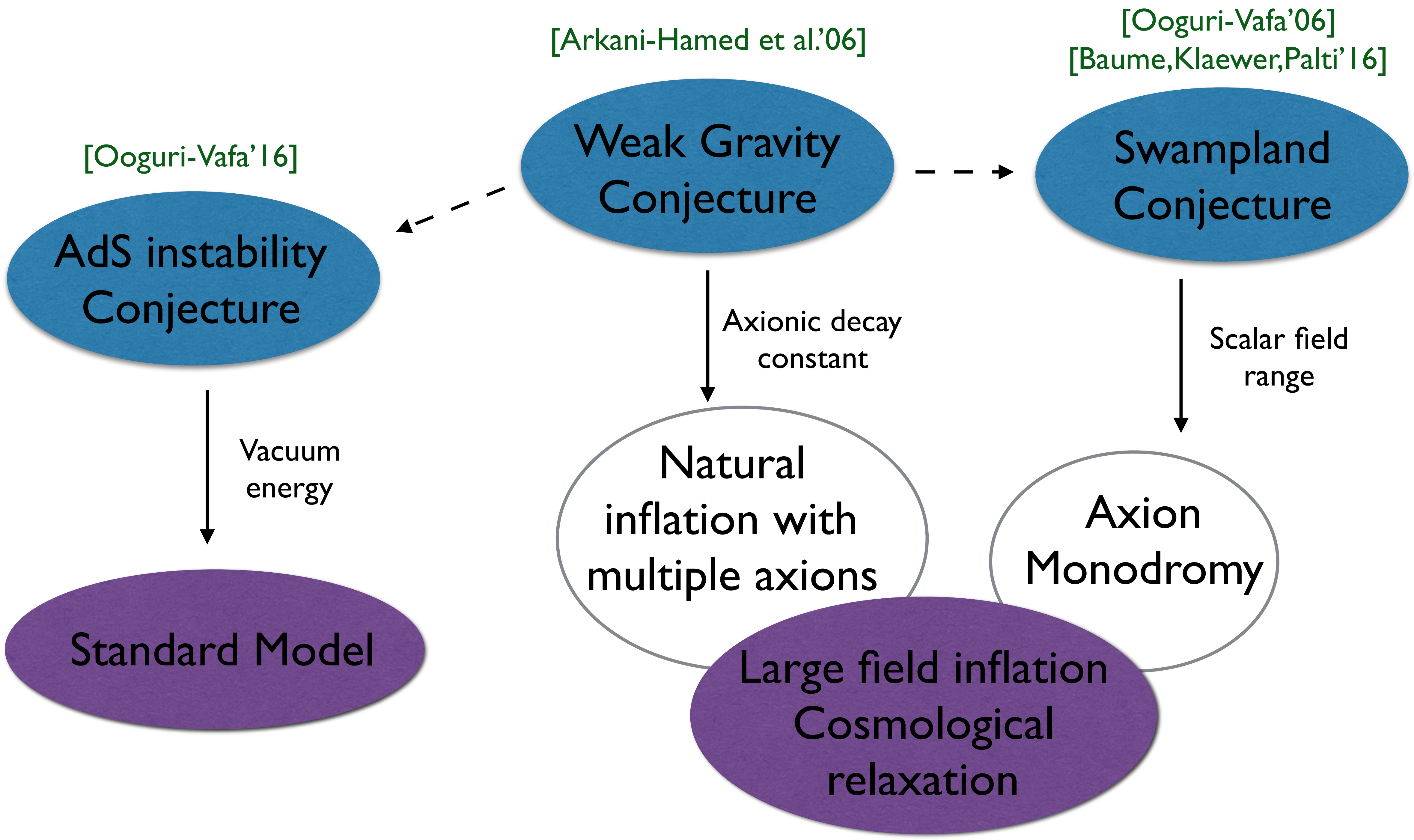
Formal ST



StringPheno

They can have significant implications in low energy physics!

Quantum Gravity Conjectures



[Arkani-Hamed et al.'06]

Weak Gravity Conjecture

[Ooguri-Vafa'06]
[Baume,Klaewer,Palti'16]

Swampland Conjecture

[Ooguri-Vafa'16]

AdS instability Conjecture

Axionic decay constant

Scalar field range

Vacuum energy

Natural inflation with multiple axions

Axion Monodromy

Standard Model

Large field inflation
Cosmological relaxation

Weak Gravity Conjecture

Weak Gravity Conjecture: [Arkani-Hamed et al.'06]

Given an abelian p-form gauge field, there must exist an electrically charged state with

$$T \leq Q$$

(tension) (charge)

in order to allow extremal black holes to decay.

ex. For 1-form gauge field: $m \leq Q = qg$ in Mp units

Evidence:

- Plethora of examples in string theory (not known counter-example)
- Relation to modular invariance of the 2d CFT [Heidenreich et al'16] [Montero et al'16]
- Relation to entropy bounds [Cottrell et al'16] [Fisher et al'17]
- Relation to cosmic censorship [Crisford et al'17]

Weak Gravity Conjecture

Weak Gravity Conjecture: [Arkani-Hamed et al.'06]

Given an abelian p-form gauge field, there must exist an electrically charged state with

$$\underset{\text{(tension)}}{T} \leq \underset{\text{(charge)}}{Q}$$

in order to allow extremal black holes to decay.

Sharpened WGC: [Ooguri-Vafa'16]

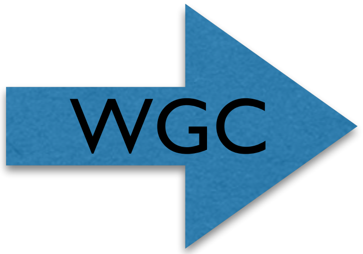
Bound is saturated only for a BPS state in a SUSY theory

Evidence:

- Perturbative spectrum of heterotic toroidal compactifications.
- Higher derivative corrections to extremal non-BPS BH in heterotic ST. [Kats et al'06]
- Robustness under dimensional reduction only if supersymmetric. [Heidenreich et al'15]

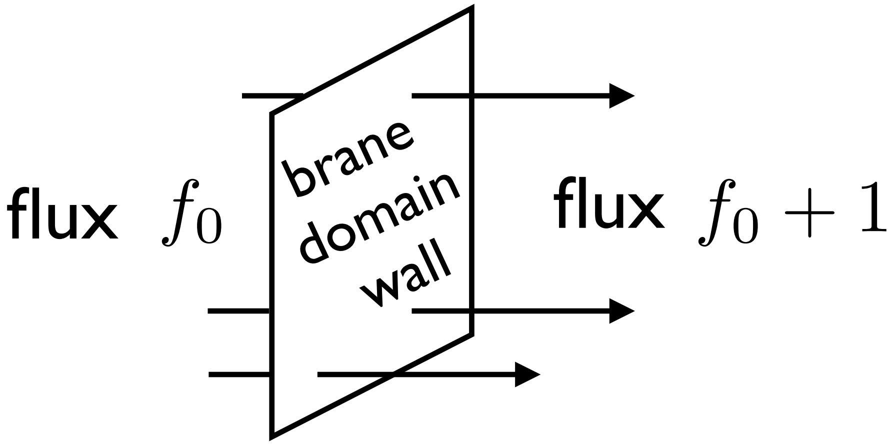
AdS Instability Conjecture

Geometry supported
by fluxes



Brane charged under
the flux with $T \leq Q$

$$f_0 \sim \int_{\Sigma_p} F_p$$

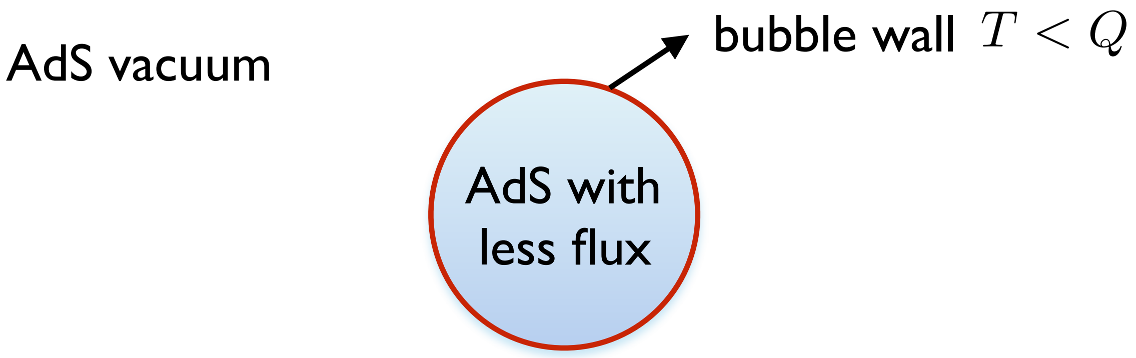


AdS Instability Conjecture

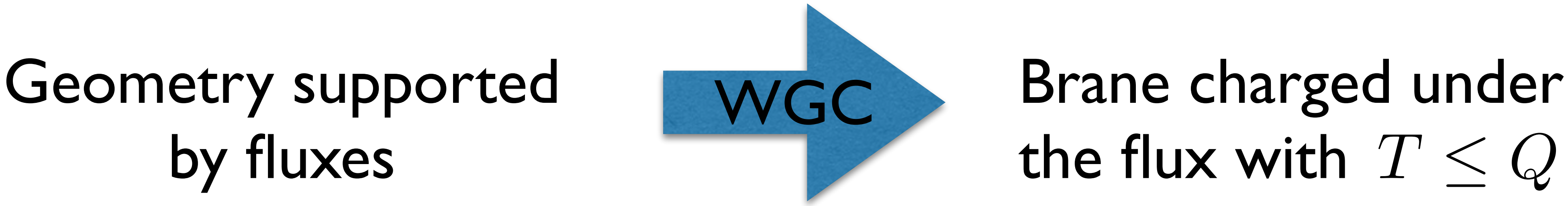
Geometry supported by fluxes → WGC → Brane charged under the flux with $T \leq Q$

[Maldacena et al.'99]

!! In AdS, a brane with $T < Q$ describes an instability



AdS Instability Conjecture



Geometry supported by fluxes

WGC

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[Maldacena et al.'99]

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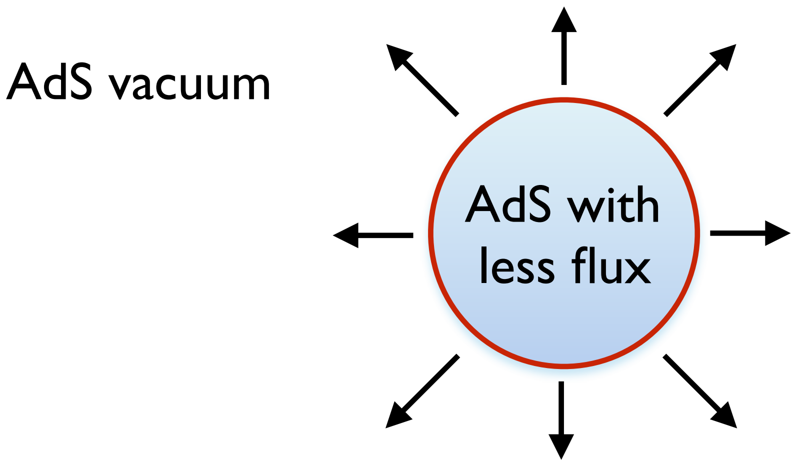
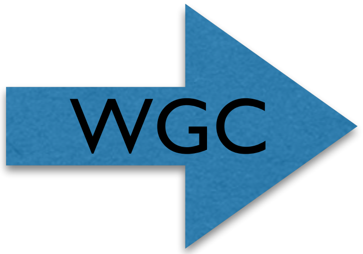


AdS vacuum

AdS with less flux

AdS Instability Conjecture

Geometry supported by fluxes



Brane charged under the flux with $T \leq Q$

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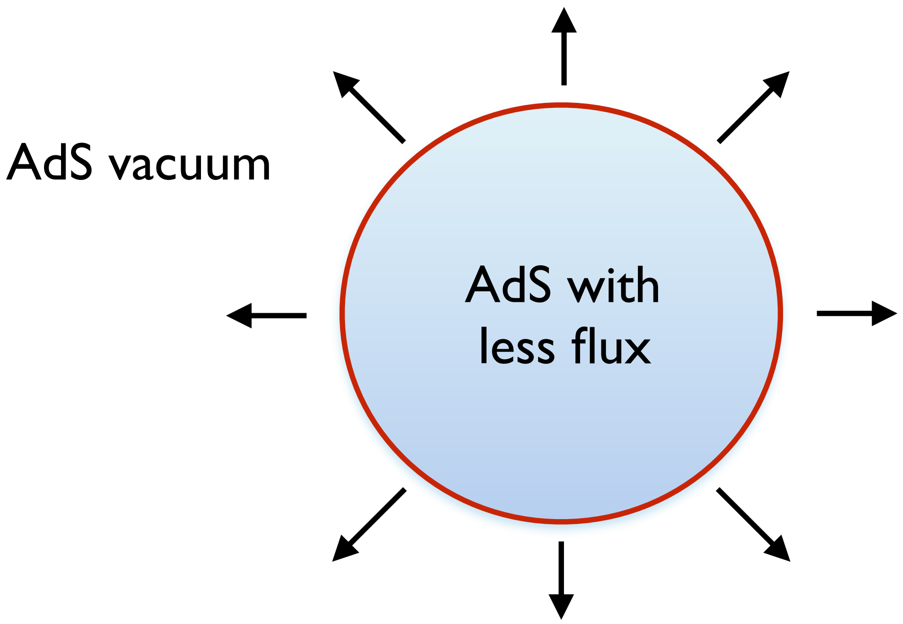
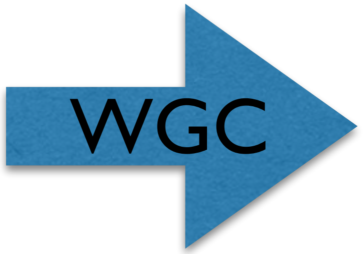


AdS Instability Conjecture

(non-susy)
Geometry supported
by fluxes



Brane charged under
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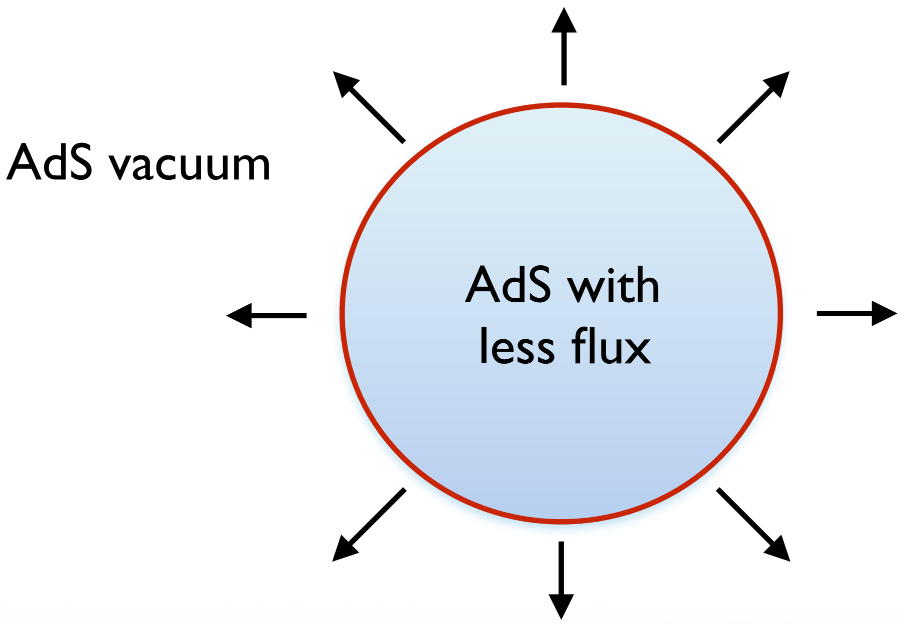


Non-susy AdS vacua supported by fluxes are at best metastable

AdS Instability Conjecture

[Ooguri-Vafa'16]

Non-susy AdS vacua supported by fluxes are at best metastable

➡ Instabilities can also appear as bubbles of nothing [Ooguri-Spodyneiko'17]

Examples: $AdS_5 \times S^5/\Gamma, AdS_5 \times \mathbb{CP}^3$

➡ Same conjecture in [Freivogel-Kleban'16]

Non-susy stable AdS vacua cannot be embedded in quantum gravity!

Implications for:

- Holography ⟶ no dual CFT
- String landscape
- Low energy physics?

Compactification of the SM to 3d

Standard Model + Gravity on S^1: [Arkani-Hamed et al.'07] (also [Arnold-Fornal-Wise'10])

$$V(R) = \underbrace{\frac{2\pi\Lambda_4}{R^2}}_{\text{tree-level}} + \underbrace{\text{Casimir energy}}_{\text{one-loop corrections}}$$

➡ suppressed by $e^{-2\pi m R}$ for $m \gg 1/R$

Depending on the light mass spectra and the cosmological constant, we can get AdS, Minkowski or dS vacua in 3d

But non-susy AdS vacua are inconsistent with quantum gravity!

Compactification of the SM to 3d

Assumption: Background independence

If our 4d SM is
consistent with QG

→

Compactifications of SM
should also be consistent

We should not get stable non-susy AdS vacua from compactifying the SM!

Compactification of the SM to 3d

Assumption: Background independence

If our 4d SM is consistent with QG → Compactifications of SM should also be consistent

!!

We should not get **stable** non-susy AdS vacua from compactifying the SM!

- There is some hidden instability
  - Instability appearing upon compactification ✗

    (periodic b.c. → no bubbles of nothing)
  - Instability already in 4 dimensions → Transfered to 3d

    ?

Compactification of the SM to 3d

As

A 4d bubble instability yields a 3d instability only if

$$R_b < l_{AdS_3}$$

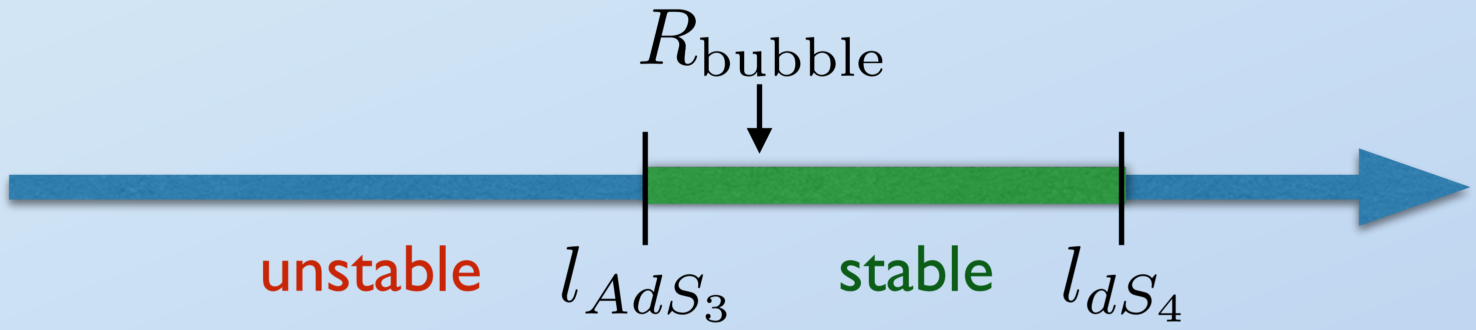
Therefore, the 3d vacuum will be **stable** if:

$$l_{AdS_3} < R_{\rm bubble} < l_{dS_4} \quad \longrightarrow \quad \text{large bubbles, nearly BPS}$$

$$(l_{dS_4} \sim 2 - 200\ l_{AdS_3})$$

W

M!



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- There is some hidden instability
  - Instability appearing upon compactification ✗

    (periodic b.c. → no bubbles of nothing)
  - Instability already in 4 dimensions → Transfered to 3d only if $R_{\text{bubble}} < l_{AdS_3}$!
- Absence of these vacua → Constraints on SM (light spectra)

Compactification of the SM to 3d

Standard Model + Gravity on S^1:

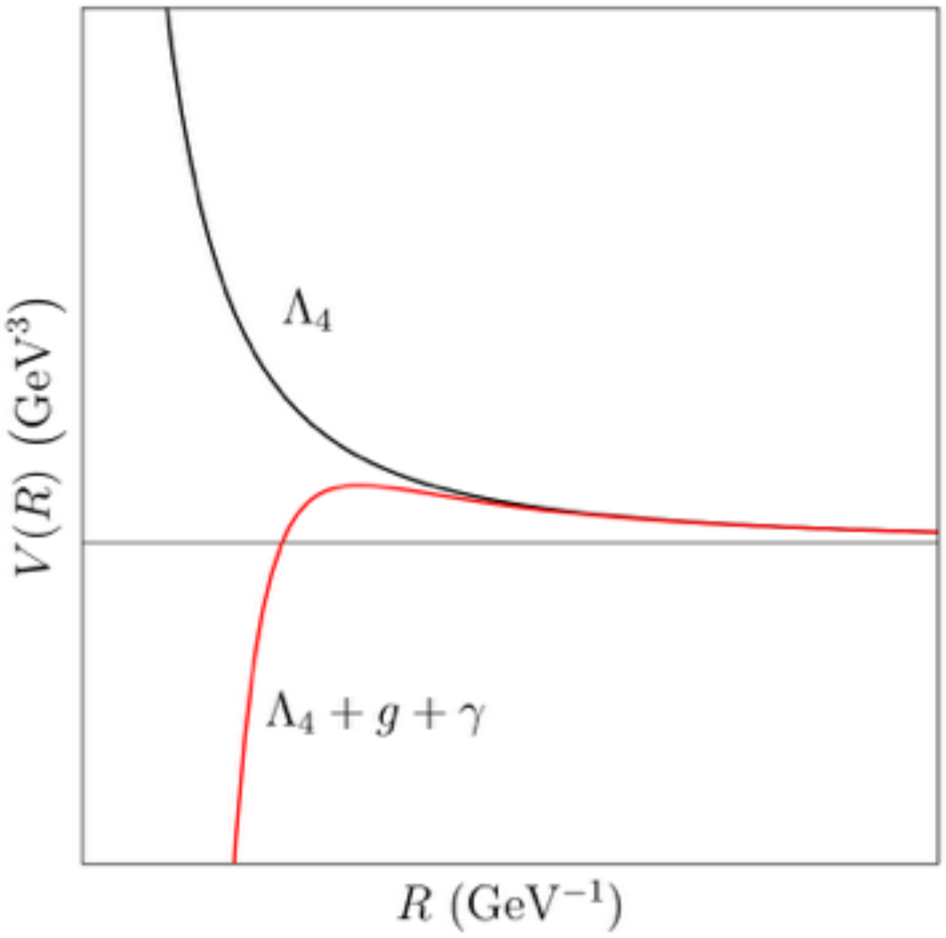
$$V(R) = \frac{2\pi\Lambda_4}{R^2} \quad + \text{Casimir energy}$$

Compactification of the SM to 3d

Standard Model + Gravity on S^1:

massless particles:
graviton, photon

$$V(R) = \frac{2\pi\Lambda_4}{R^2} - \frac{4}{720\pi R^6}$$

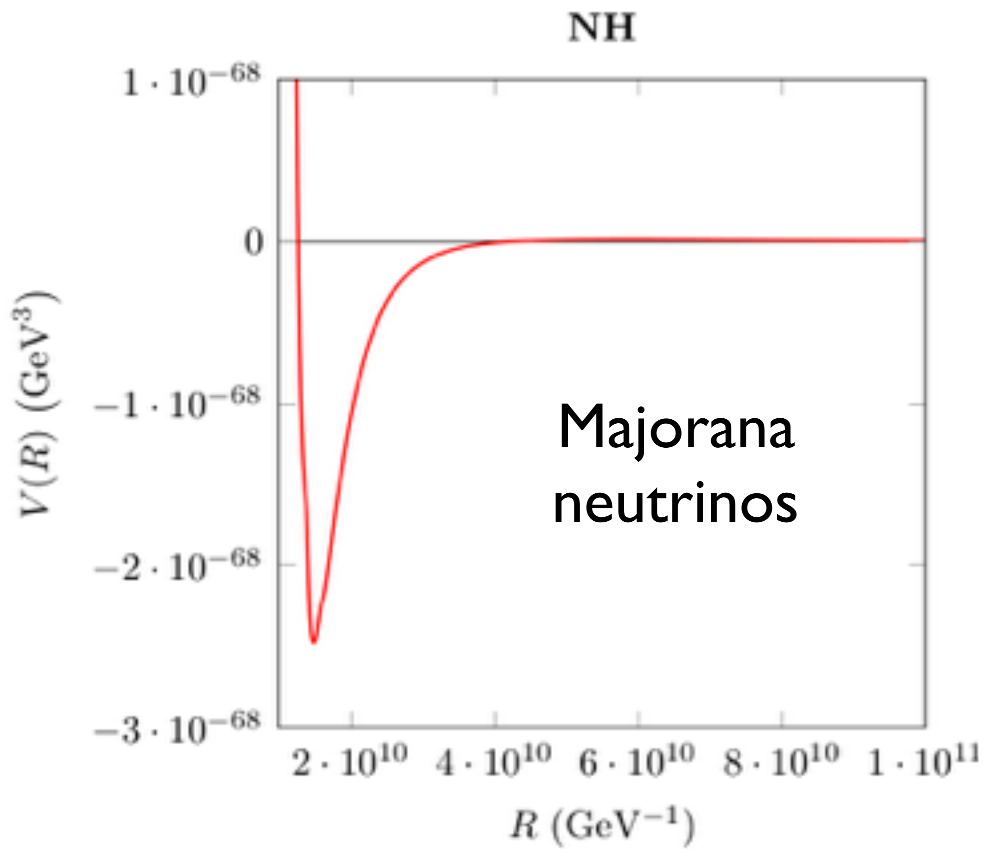


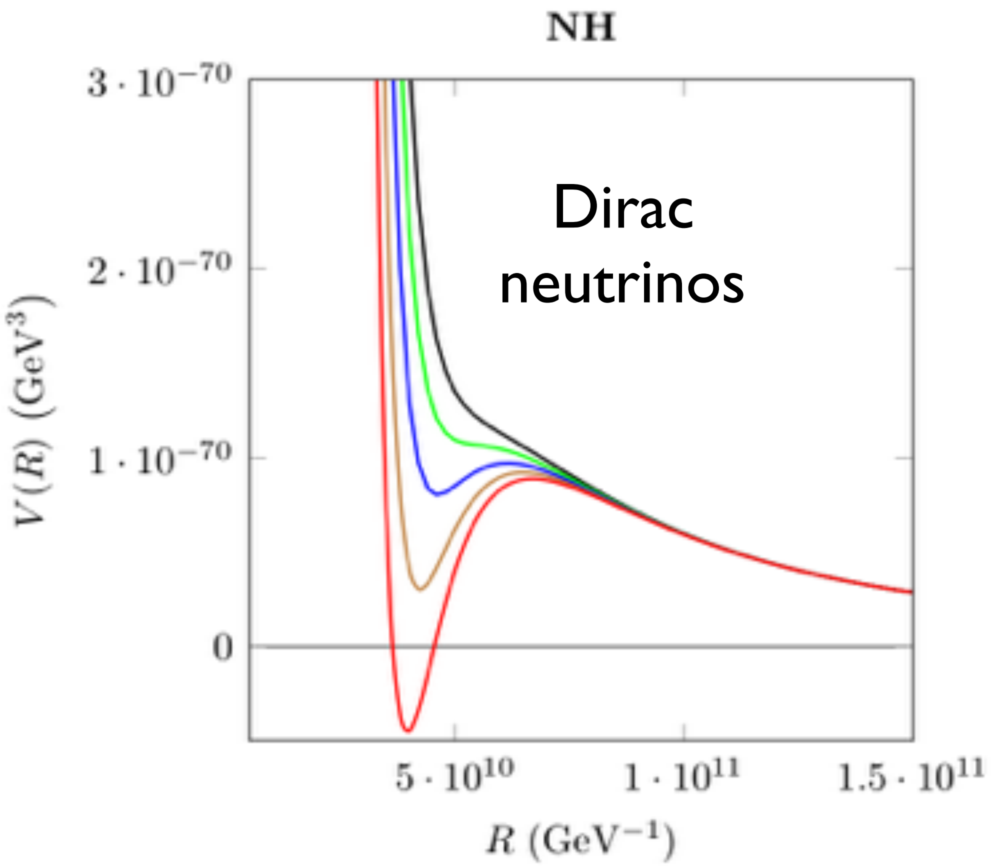
Compactification of the SM to 3d

Standard Model + Gravity on S^1:

massive particles: neutrinos,…

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





The more massive the neutrinos, the deeper the AdS vacuum

Constraints on neutrino masses

- Majorana:

There is an AdS vacuum for any value of m_ν → Majorana neutrinos ruled out!

- Dirac:

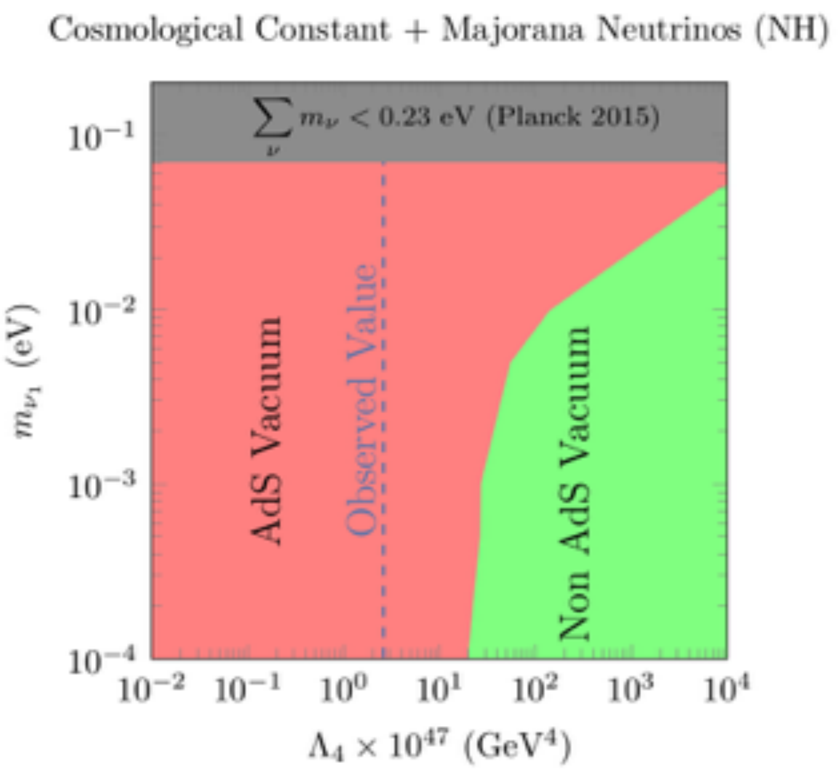
	NH	IH
No vacuum	$m_{\nu_1} < 6.7\ \text{meV}$	$m_{\nu_3} < 2.1\ \text{meV}$
dS_3 vacuum	$6.7\ \text{meV} < m_{\nu_1} < 7.7\ \text{meV}$	$2.1\ \text{meV} < m_{\nu_3} < 2.56\ \text{meV}$
AdS_3 vacuum	$m_{\nu_1} > 7.7\ \text{meV}$	$m_{\nu_3} > 2.56\ \text{meV}$

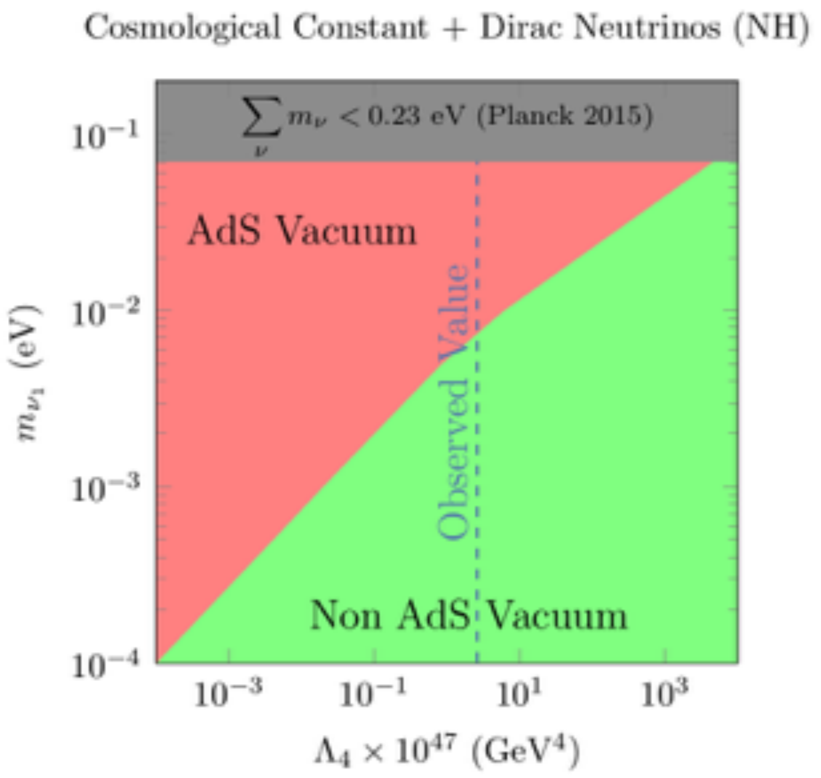
Absence of AdS vacuum requires

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

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

Lower bound on the cosmological constant


Cosmological Constant + Majorana Neutrinos (NH)


Cosmological Constant + Dirac Neutrinos (NH)

The bound for Λ_4 scales as m_ν^4 (as observed experimentally)

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

with $a(n_f) = 0.184(0.009)$, $b(n_f, m_i) = 5.72(0.29)$ for Majorana (Dirac)

First argument (not based on cosmology) to have $\Lambda_4 \neq 0$

Adding BSM physics

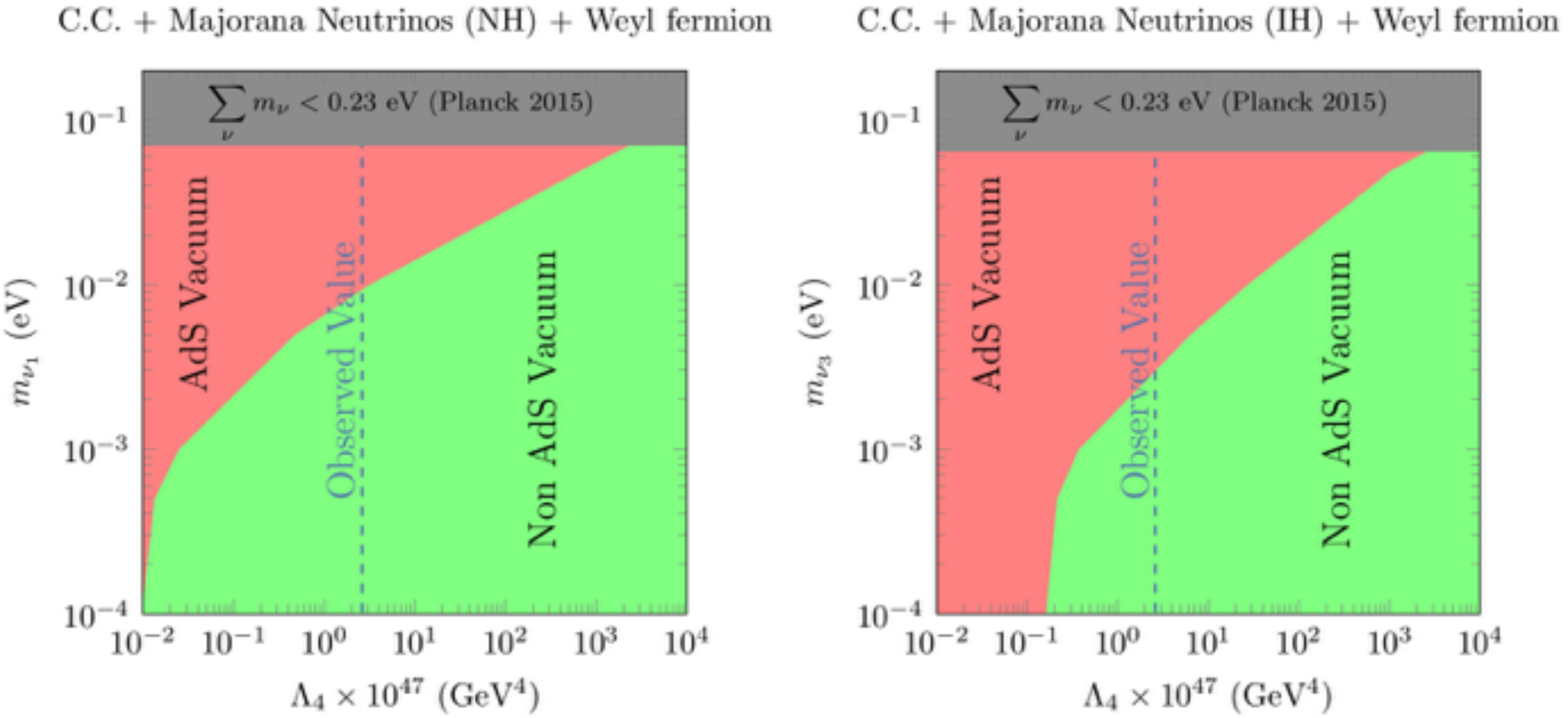
- **Light fermions**

Positive Casimir contribution ⟶ helps to avoid AdS vacuum

Majorana neutrinos are consistent if adding $m_\chi \lesssim 2\ \mathrm{meV}$

(Detection of Majorana neutrinos would imply light BSM physics!)

example. For $m_\chi = 0.1\ \mathrm{meV}$:



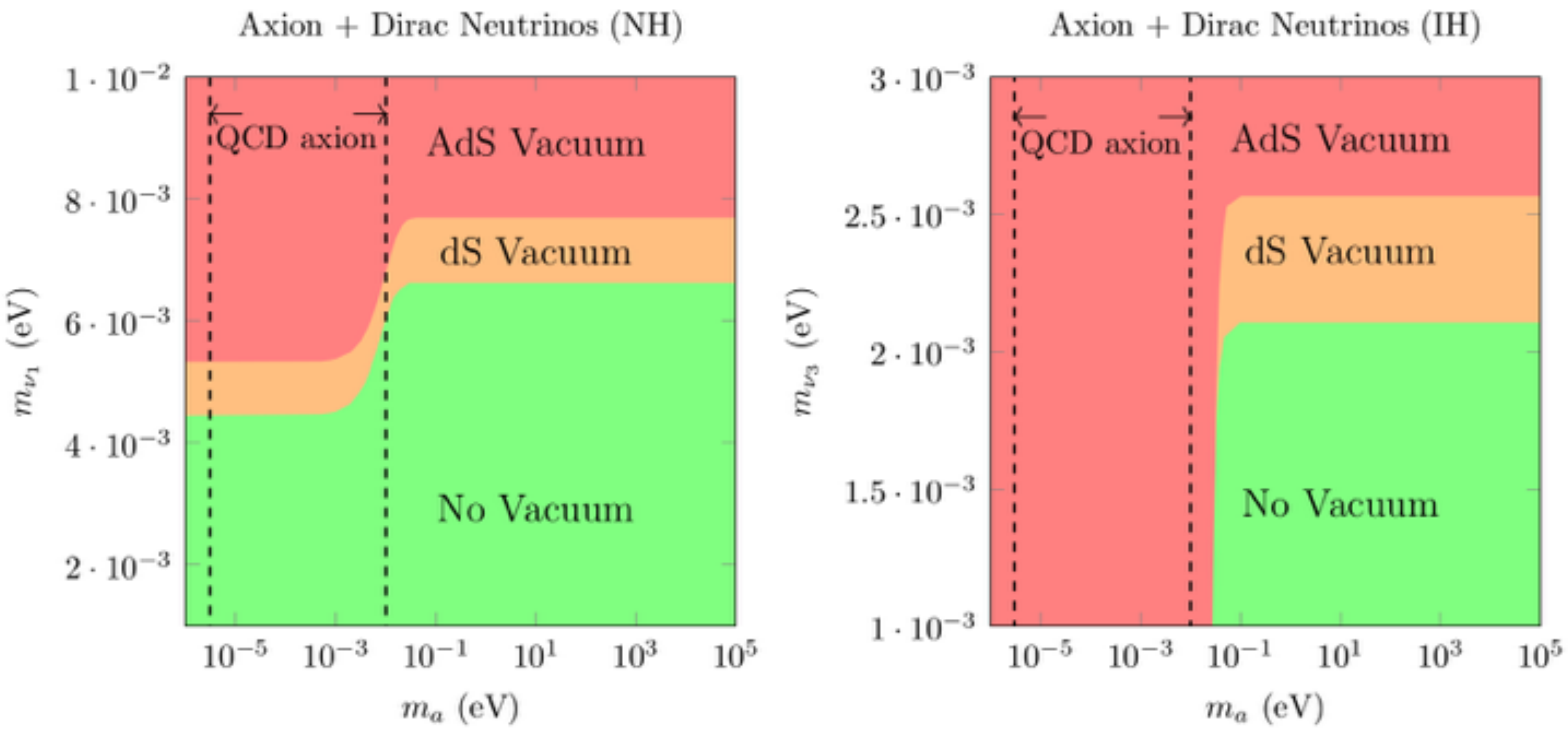
Adding BSM physics

- **Axions**

1 axion: negative contribution ⟶ bounds get stronger

(IH Dirac neutrinos with a QCD axion are also ruled out!)

Multiple axions: can destabilise AdS vacuum



Bounds on the SM + light BSM physics

Model	Majorana (NI)	Majorana (IH)	Dirac (NH)	Dirac (IH)
SM (3D)	no	no	$m_{\nu_1} \leq 7.7 \times 10^{-3}$	$m_{\nu_3} \leq 2.56 \times 10^{-3}$
SM(2D)	no	no	$m_{\nu_1} \leq 4.12 \times 10^{-3}$	$m_{\nu_3} \leq 1.0 \times 10^{-3}$
SM+Weyl(3D)	$m_{\nu_1} \leq 0.9 \times 10^{-2}$ $m_f \leq 1.2 \times 10^{-2}$	$m_{\nu_3} \leq 3 \times 10^{-3}$ $m_f \leq 4 \times 10^{-3}$	$m_{\nu_1} \leq 1.5 \times 10^{-2}$	$m_{\nu_3} \leq 1.2 \times 10^{-2}$
SM+Weyl(2D)	$m_{\nu_1} \leq 0.5 \times 10^{-2}$ $m_f \leq 0.4 \times 10^{-2}$	$m_{\nu_3} \leq 1 \times 10^{-3}$ $m_f \leq 2 \times 10^{-3}$	$m_{\nu_1} \leq 0.9 \times 10^{-2}$	$m_{\nu_3} \leq 0.7 \times 10^{-2}$
SM+Dirac(3D)	$m_f \leq 2 \times 10^{-2}$	$m_f \leq 1 \times 10^{-2}$	yes	yes
SM+Dirac(2D)	$m_f \leq 0.9 \times 10^{-2}$	$m_f \leq 0.9 \times 10^{-2}$	yes	yes
SM+1 axion(3D)	no	no	$m_{\nu_1} \leq 7.7 \times 10^{-3}$	$m_{\nu_3} \leq 2.5 \times 10^{-3}$ $m_a \geq 5 \times 10^{-2}$
SM+1 axion(2D)	no	no	$m_{\nu_1} \leq 4.0 \times 10^{-3}$	$m_{\nu_3} \leq 1 \times 10^{-3}$ $m_a \geq 2 \times 10^{-2}$
$\geq 2(10)$ axions	yes	yes	yes	yes

Bounds on the SM + light BSM physics

Model	Majorana (NI)	Majorana (IH)	Dirac (NH)	Dirac (IH)
SM (3D)	no	no	$m_{\nu_1} \leq 7.7 \times 10^{-3}$	$m_{\nu_3} \leq 2.56 \times 10^{-3}$
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$\geq 2(10)$ axions	yes	yes	yes	yes

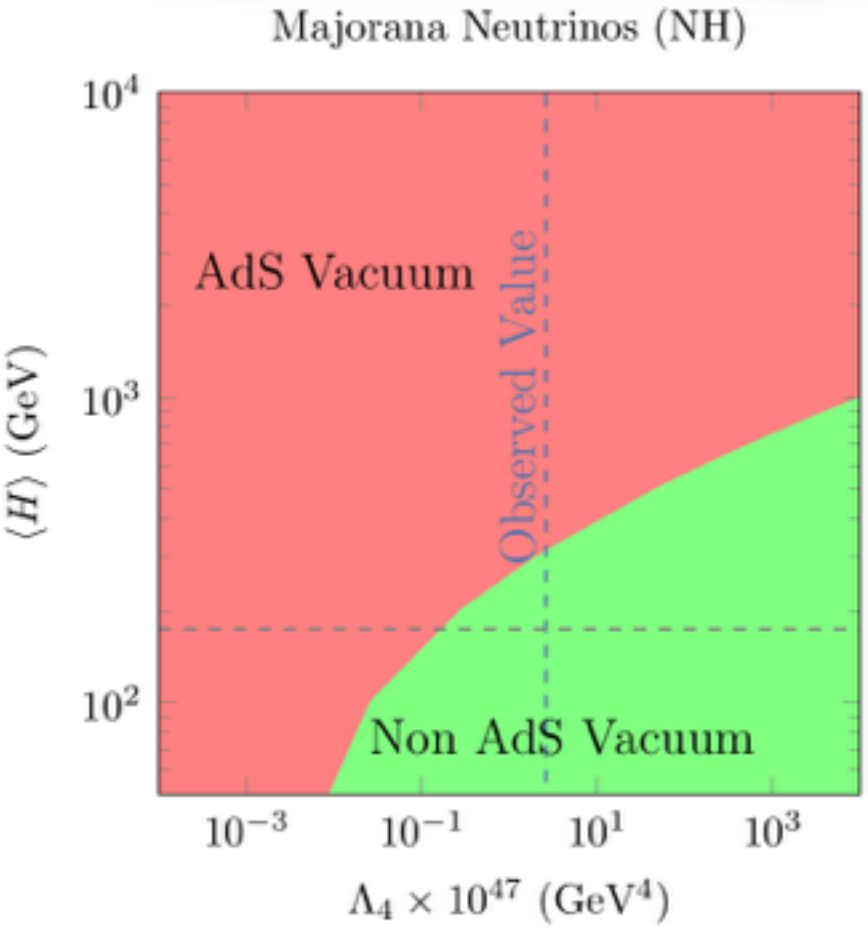
Compactifications of SM on T_2 → qualitatively similar, but a bit stronger

(see also [Hamada-Shiu'17])

Upper bound on the EW scale

Majorana case

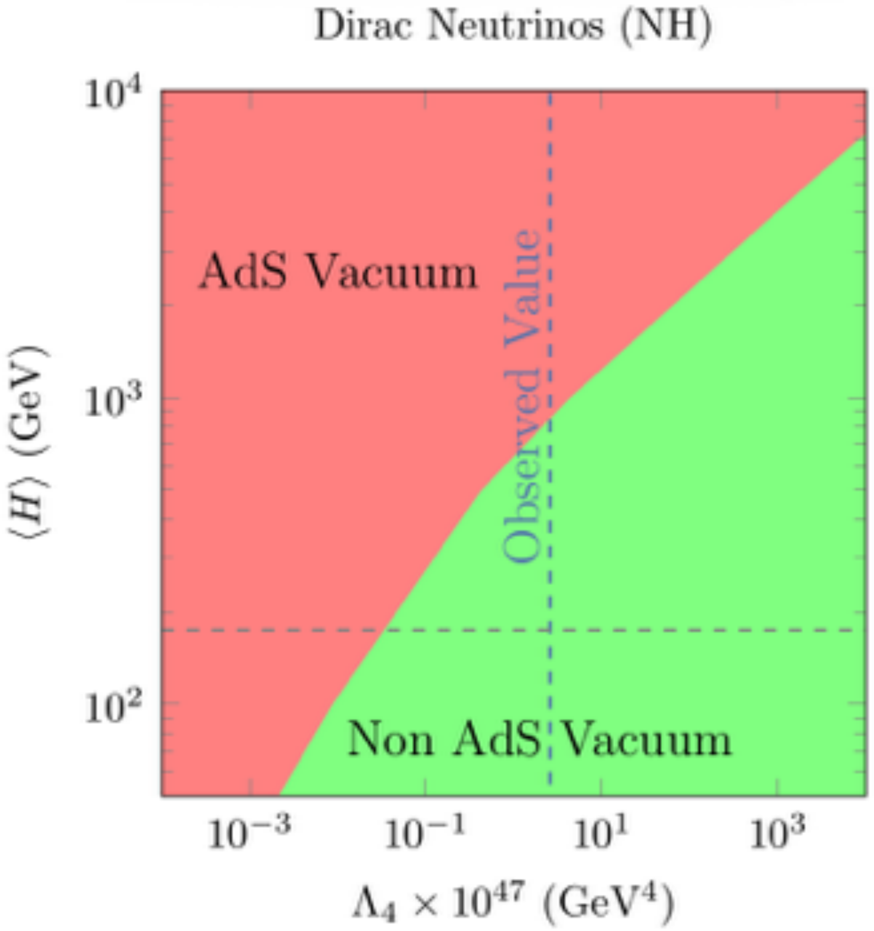
$$\langle H \rangle \lesssim \frac{\sqrt{2}}{Y_{\nu_1}} \sqrt{M \Lambda^{1/4}}$$



$M = 10^{10}$ GeV, $Y = 10^{-3}$

Dirac case

$$\langle H \rangle \lesssim 1.6 \frac{\Lambda^{1/4}}{Y_{\nu_1}}$$



$Y = 10^{-14}$

Upper bound on the EW scale

Majorana case

$$\langle H \rangle \lesssim \frac{\sqrt{2}}{Y_{\nu_1}} \sqrt{M \Lambda^{1/4}}$$

Dirac case

$$\langle H \rangle \lesssim 1.6 \frac{\Lambda^{1/4}}{Y_{\nu_1}}$$

Parameters leading to a higher EW scale do not yield theories consistent with quantum gravity

➡ No hierarchy problem

Not everything is possible in the string landscape…

Conclusions

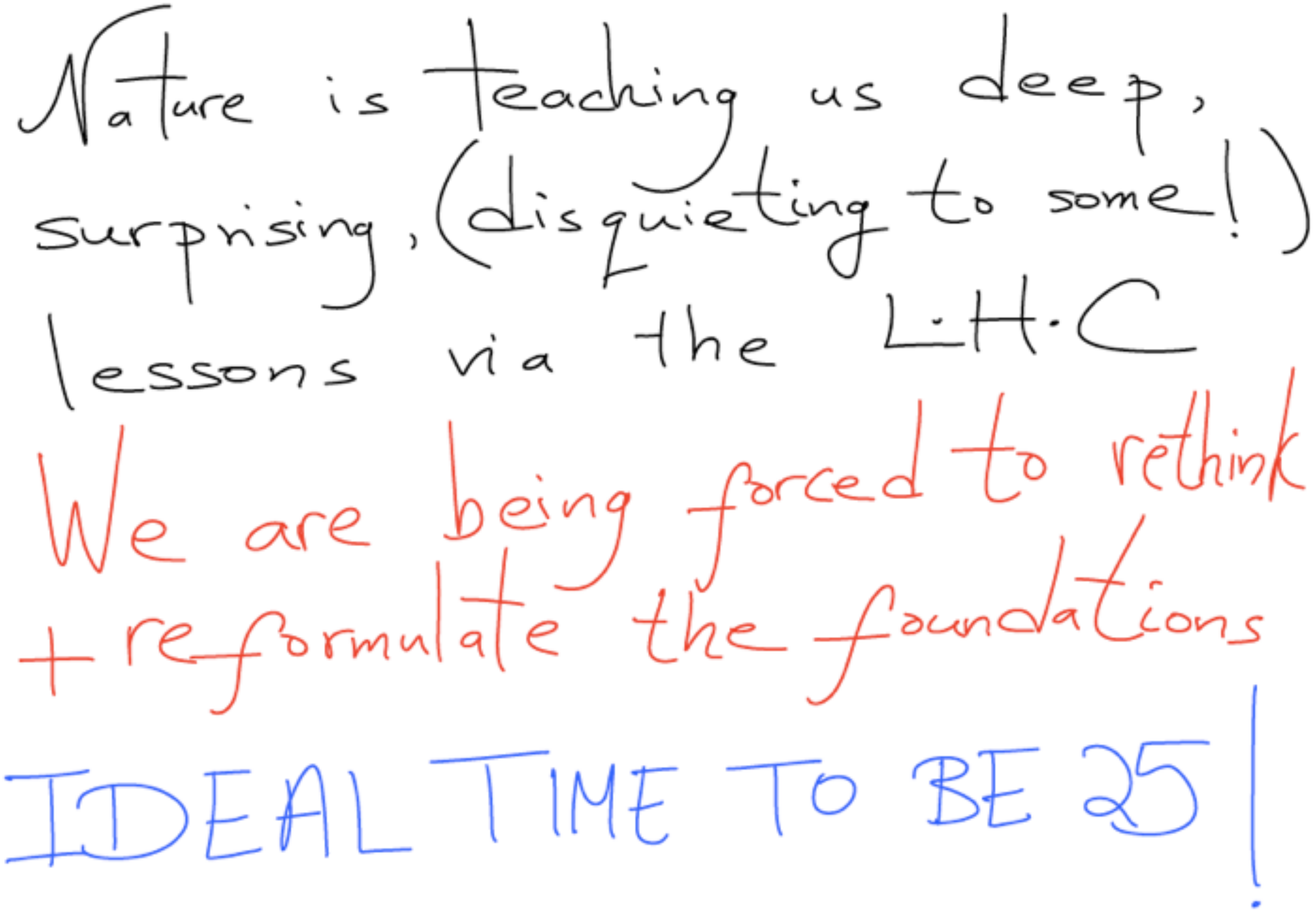
Consistency with quantum gravity implies constraints on low energy physics:

➡ **AdS Instability Conjecture + stability of 3D SM vacua:**

- Lower bound on the cosmological const. of order the neutrino masses ⟷ Upper bound on the EW scale in terms of the cosmological const.

New approach to fine-tuning or hierarchy problems?
UV/IR mixing? (see also [Luest-Palti'17])

Slide taken from Nima’s talk in PASCOS 2017:



Nature is teaching us deep, surprising, (disquieting to some!) lessons via the L·H·C

We are being forced to rethink + reformulate the foundations

IDEAL TIME TO BE 25!

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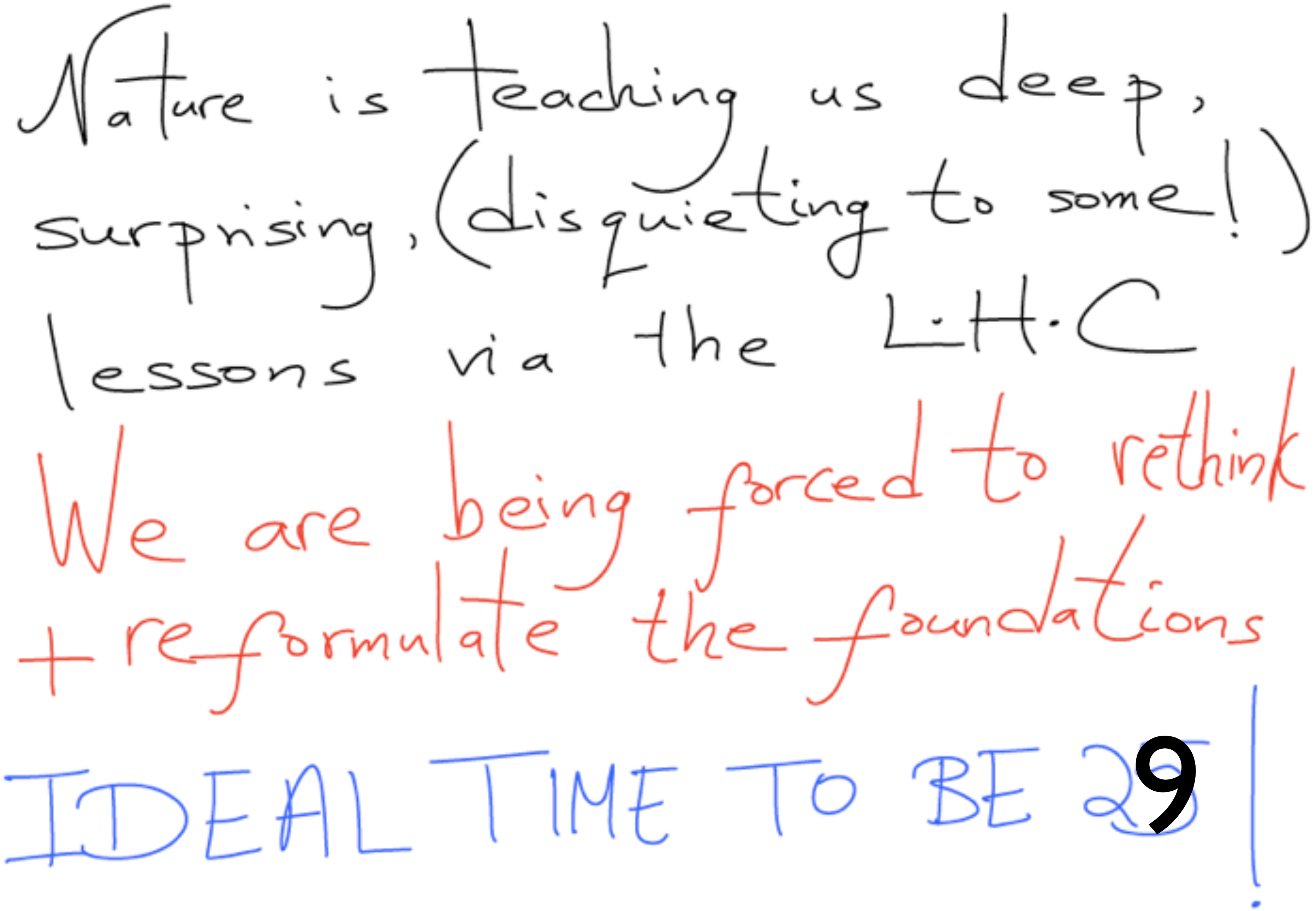

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IDEAL TIME TO BE 29!

Thank you!

back-up slides

Casimir energy

Potential energy in 3d:

$$V(R) = \frac{2\pi r^3 \Lambda_4}{R^2} + \sum_i (2\pi R) \frac{r^3}{R^3} (-1)^{s_i} n_i \rho_i(R)$$

Casimir energy density:

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

For small mR:

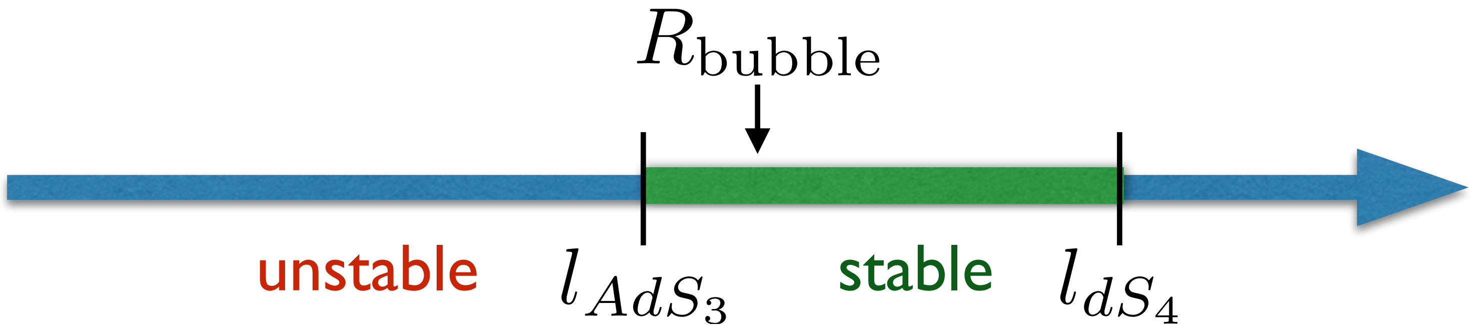
$$\rho(R) = \mp \left[\frac{\pi^2}{90(2\pi R)^4} - \frac{\pi^2}{6(2\pi R)^4}(mR)^2 + \frac{\pi^2}{48(2\pi R)^4}(mR)^4 + \mathcal{O}(mR)^6 \right]$$

Outlook

- Explore more the relation between $\Lambda, \; M_{EW}$ and the presence of lower dimensional vacua

- Gather more evidence to prove - or disprove - the conjecture

- Are the 3D vacua really stable?



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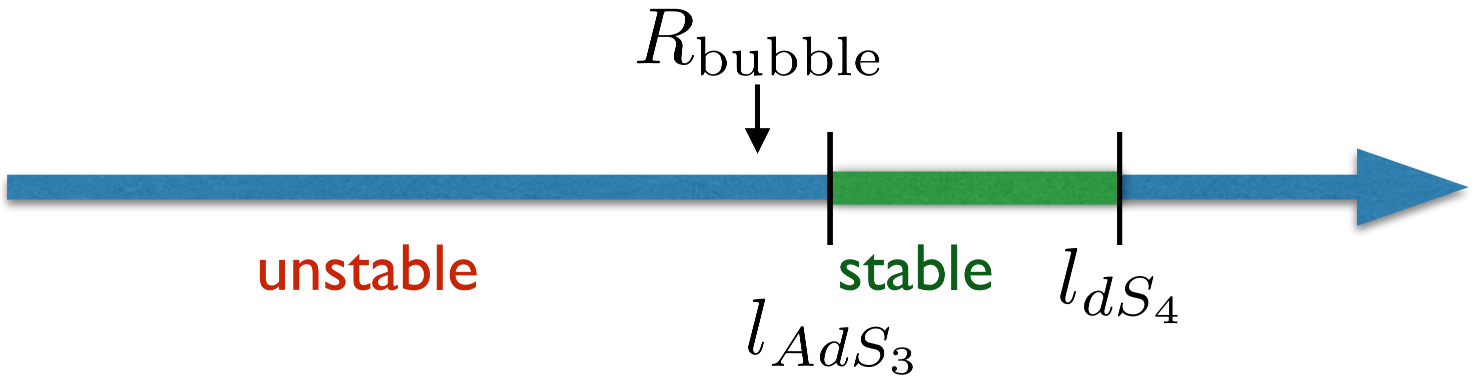
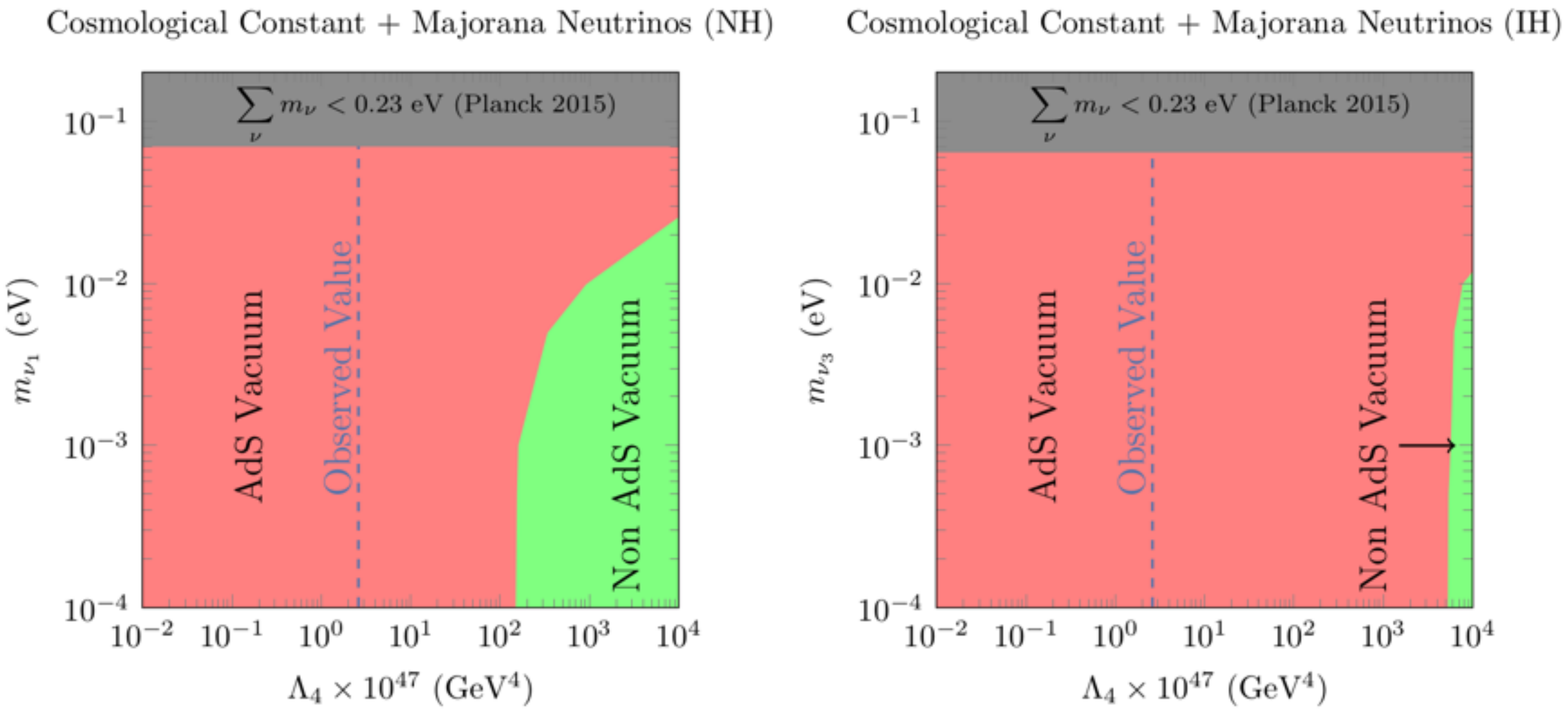
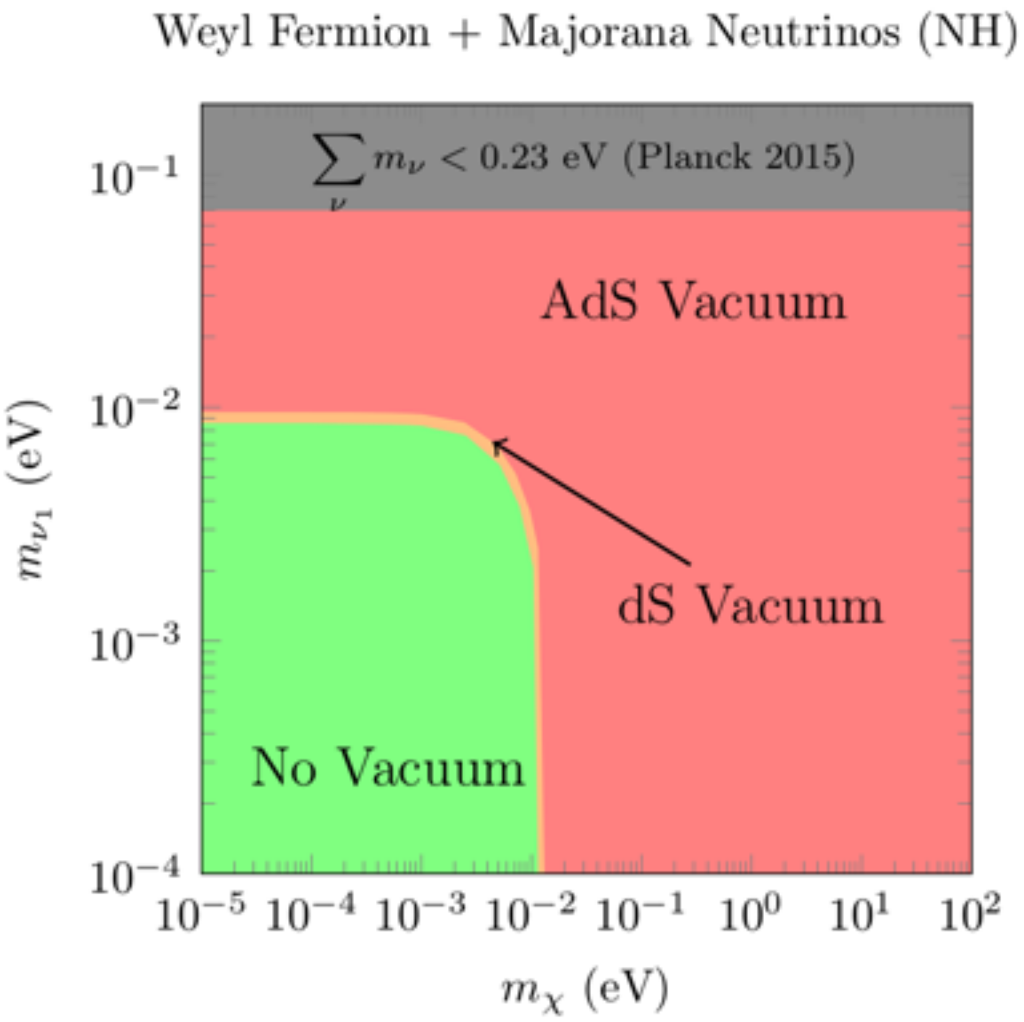


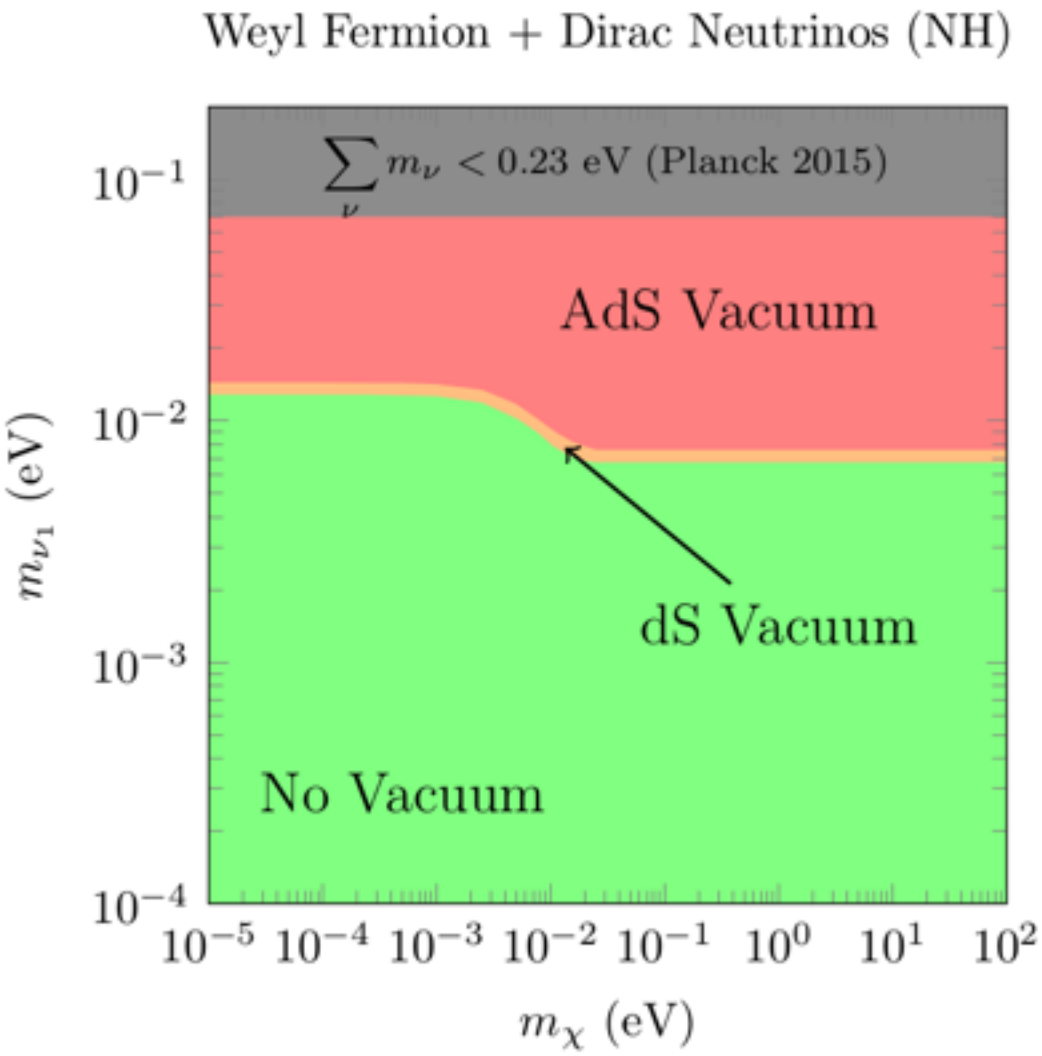
$$\left.\begin{aligned} m_\nu^{-1} \propto l_{AdS_3} &> R_{\text{bubble}} \\ R_{\text{bubble}} \sim \epsilon\, l_{dS_4} &= \epsilon\, M_p/\Lambda^{1/2} \end{aligned}\right\} \longrightarrow \quad m_\nu < \epsilon^{-1}\ \Lambda^{1/2}/M_p$$

Compactification of the SM to 2d



Adding light fermions


Weyl Fermion + Majorana Neutrinos (NH)


Weyl Fermion + Dirac Neutrinos (NH)