Constraints on SM from AdS conjectures

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Based on: 2104.06415 and 21xx.xxxxx with L. Ibáñez and I. Valenzuela.

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Plan for the talk

1. **Light Fermion Conjecture.** Study Non AdS Instability and AdS Distance on a generic setup in:
   - Minkowski
   - dS
   - AdS
2. **Constraints on Neutrinos.**
   - dS
   - Quintessence

Set up

- We start with an EFT in D-dim and compactify it on a circle.
- Theory in $D-1$ is inconsistent $\rightarrow$ original theory in D-dim was inconsistent.
- Useful in the past to test and refine conjectures [4][5].

Spectra in D-dimensions

- **Massless**: $g_{\mu\nu}$, $U(1)^B$ gauge bosons, F massless fermionic d.o.f.
- **Massless + Massive**: n_f fermionic d.o.f. and n_b bosonic.

[4] B. Heidenreich et al '15, [5]T. Rudelius '21.

Set up

Non-susy (AdS) Instability Conjecture [6]

Any non-supersymmetric (AdS) vacuum is metastable at best.

AdS Distance Conjecture [7]

As $\Lambda_D \to 0$ a tower $m_n^{(D)} \sim |\Lambda_D|^{\alpha_D} M_D^{1-2\alpha_D}$ becomes light.

- **Mild version**: α_D to be a positive and $\mathcal{O}(1)$ number .
- **Strong version**: $\alpha_D = 1/2$ for AdS susy vacua.
- **Stronger version**: $\alpha_D > 1/2$ for non-susy AdS and also holds in dS space with $\alpha_D < 1/2$.

[6] H. Ooguri and C. Vafa '16, [7] D. Lust, E. Palti and C. Vafa '19

Idea and Assumptions

- Under which conditions of the D-dim spectra, the effective potential of the radion generates a d-dim AdS vacuum.
- Assumptions:
  1. For the Non AdS Instability we need to assume that the vacua would be non susy and stable. Wilson lines [8] may give rise to non-perturbative instabilities. Assume they are killed by nucleation dynamics or by orbifolding [9].
  2. For the AdC we assume that we can scan on masses.

[8] G. Shiu, Y.Hamada '18, [9] E.G., A. Herráez and L. Ibáñez '18

Some Formulas

$$G_{MN} = \begin{bmatrix} (R/r)^{\frac{-2}{(D-3)}} g_{\mu\nu} & 0 \\ 0 & (R/r)^2 \end{bmatrix}$$

$$V = 2\pi r \left(\frac{r}{R}\right)^{\frac{2}{D-3}} \Lambda_D + V_{1L}$$

$$V_{1\mathrm{L}} = \pm 2\pi r^{\frac{(D-1)}{(D-3)}} \sum_{i=b,f} \frac{n_{b_i,f_i}\, 2m_i^D}{(2\pi)^{\frac{D}{2}} R^{\frac{2}{(D-3)}}} \times \sum_{n=1}^{\infty} \frac{K_{D/2}(2\pi n m_i R)}{(2\pi n m_i R)^{D/2}}.$$

Important:

- The sign of the tree-level term is positive for dS and negative for AdS.
- The sign of the one-loop correction is positive for fermions and negative for bosons.

IR vs UV w.r.t. Λ

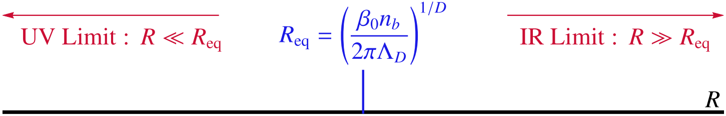


Figure: We introduce the relevant scale of the problem as the scale where the one-loop correction of the massless sector equals the tree-level term

Important:

- The sign of the tree-level term is positive for dS and negative for AdS.
- The sign of the one-loop correction is positive for fermions and negative for bosons.

Who dominates in the UV?

In the region $R \ll (2\pi n m_i)^{-1}$ the potential of a single degree of freedom is given by:

$$V_{1L} \approx \frac{(-1)^F r^{\frac{(D-1)}{(D-3)}}}{R^{\frac{(D-1)(D-2)}{(D-3)}}} \sum_{k<\frac{D}{2}} (-1)^{k+1} \beta_k (mR)^{2k}.$$

Summing over all degrees of freedom:

$$V(R \to 0) \approx \frac{r^{\frac{(D-1)}{(D-3)}}}{R^{\frac{(D-1)(D-2)}{(D-3)}}} \sum_{k<\frac{D}{2}} \beta_k (-1)^{k+1} \mathrm{Str}(M^{2k}) R^{2k} + \dots$$

where

$$\mathrm{Str}(M^{2k}) = \sum_b n_b m_b^{2k} - \sum_f n_f m_f^{2k} \; .$$

Who dominates in the UV?

Important:

In the UV the sign is determined by the first non-zero supertrace.

$$V \propto (-1)^{k+1}\mathrm{Str}(M^{2k})$$

- First supertrace with $k = 0$: $(-1)\mathrm{Str}(M^0) = \sum_f n_f - \sum_b n_b$.
- If this term cancels out then the sign of the potential is rather determined by $\mathrm{Str}(M^2) = \sum_b n_b m_b^2 - \sum_f n_f m_f^2$, and so on.

Who dominates in the IR?

- $R \gg (2\pi n m_i)^{-1}$: Modified Bessel functions decay exponentially.

Important:

- In the deep IR the cosmological constant dominates unless we started in Minkowski.
- Unless there is a surplus of massless fermions in the spectra, bosons dominate in the not-so-deep IR.

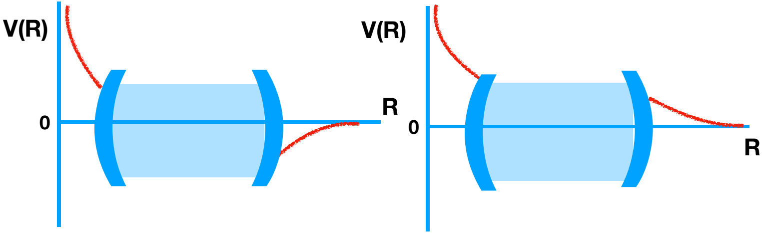
Minkowski

UV Limit : $R \ll R_{\rm eq}$

$$R_{\rm eq} = \left(\frac{\beta_0 n_b}{2\pi\Lambda_D}\right)^{1/D}$$

IR Limit : $R \gg R_{\rm eq}$

R



$\mathcal{S}tr\ >\ 0\ ;\ \ no\ m_\psi = 0$

A

$\mathcal{S}tr\ >\ 0\ ;\ \ \text{surplus}\ \psi\ ,\ \ m_\psi = 0$

B

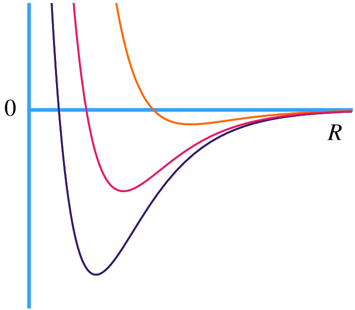
Non Susy AdS Instability Conjecture for M_D

Claim 1:

A D-dim Minkowski theory satisfying $(-1)^{k+1}\mathrm{Str}\,(M^{2k}) > 0$ for the first non-vanishing supertrace is inconsistent with QG unless there is a surplus of massless fermions.

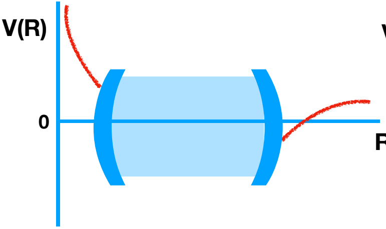
- In the SM we have 48 d.o.f. from Weyl fermions and 12 gauge bosons.
- If neutrinos are massive then a non-zero positive cosmological constant is required! More on this later.

AdS Distance Conjecture for M_D



- Non-susy AdS vacua are not problematic per se. Only if $\Lambda_d \to 0$ and no tower becomes light.
- $M_{KK} \propto n\Lambda^{\frac{1}{d}}$ so disagreement only with the stronger version of the conjecture $\alpha \geq \frac{1}{2}$.

dS



$\mathcal{S}tr \ > \ 0 \ ; \ $ no surplus of ψ *with* $m_\psi \lesssim \Lambda_D^{1/D}$

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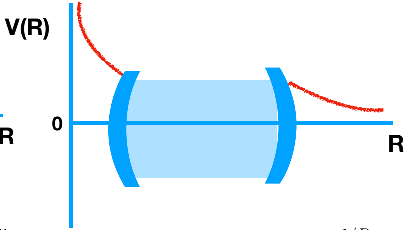


$\mathcal{S}tr \ > \ 0 \ ; \ $ surplus ψ , $m_\psi \lesssim \Lambda_D^{1/D}$

B

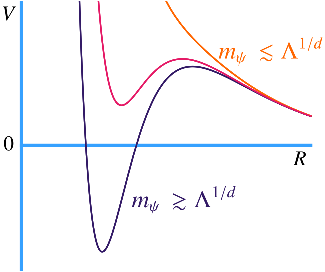
Non Susy AdS Instability Conjecture for dS_D

Claim 2:

A D-dim de Sitter vacua satisfying $(-1)^{k+1}\mathrm{Str}\,(M^{2k}) > 0$ for the first non-vanishing supertrace is inconsistent with QG unless there are enough light fermions with mass $m \lesssim \Lambda_D^{1/D}$.

- dS_D can be unstable, but assume AdS_d vacua is nevertheless stable.
- We will see the particular implications for SM neutrinos later.

AdS Distance Conjecture for dS_D



Claim 3:

dS_D with first $(-1)^{k+1}\mathrm{Str}\,(M^{2k}) > 0$ is inconsistent unless there is a surplus of light fermions that either:

1. Are light $m \lesssim \Lambda_D^{1/D}$ or
2. Are part of an infinite tower $m_f \sim \Lambda_D^{\alpha}$.

AdS

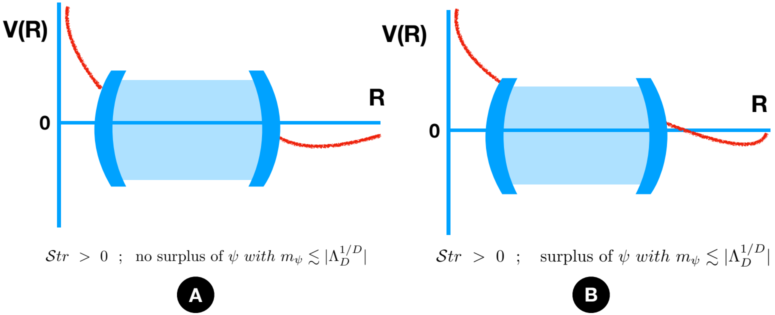


Figure: In the IR the potential always approached zero from below so massless fermions cannot save the day.

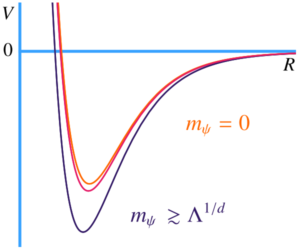
Non Susy AdS Instability Conjecture for AdS_D

Claim 4:

A D-dim AdS vacuum satisfying $(-1)^{k+1}\mathrm{Str}\,(M^{2k}) > 0$ for the first non-vanishing k is inconsistent with quantum gravity.

- Either $(-1)^{k+1}\mathrm{Str}\,(M^{2k}) \leq 0$, the higher dimensional instability can be inherited or some new instability appears.

AdS Distance Conjecture for AdS_D



- The only way in which V_0 can vanish is if we consider scannings which affect Λ_D.
- Already in D-dim a tower is required since both $\Lambda_D, \Lambda_d \to 0$. Regardless α_D the KK comes down with $\alpha_d = \frac{1}{d}$.
- AdS vacua seem consistent with the mild but not the strong version of AdC upon circle compactification.

Conclusions of first part

- Supported by Non-Susy Instability in *dS* and *Mink* and also from AdC in *dS*.

Light Fermion Swampland Conjecture

In a SUSY-broken theory with $\Lambda_D \geq 0$ and positive first non-vanishing supertrace $(-1)^{k+1}\mathcal{S}trM^{2k}$, which is consistent with quantum gravity, there must exist a surplus of light fermions with masses $m \lesssim \Lambda_D^{1/D}$

- Would be interesting to test the conjecture in non-SUSY dS_D and M_D. Heterotic $SO(16) \times SO(16)$ is *almost* a test.
- Look for rationale, heuristic argument behind the conjecture.

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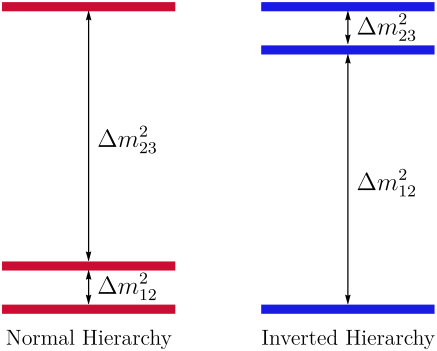
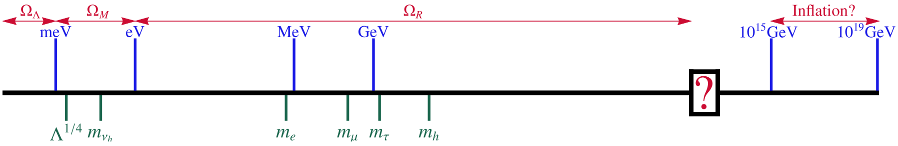
Dirac vs Majorana

- Check 3 different Swampland conjectures on the SM plus additional sterile neutrinos with:
  1. Dirac neutrinos (12 light d.o.f.)
  $$\mathcal{L}_{\rm D} = -m_A^D \overline{\nu^A} \nu^A$$
  2. Majorana neutrinos (6-12 light d.o.f depending on how large M is)
  $$\mathcal{L}_M = -\frac{m_A^D}{2}(\overline{N_R^A}\nu_L^A + \overline{\nu_L^c}N_R^c) - \frac{M_{AB}}{2}\overline{N_{RA}^c}N_{RB} + h.c.$$
- We will see that See-Saw scenarios $M \gg m_D$ lead to inconsistencies with QG.

Hierarchy and Absolute Scale

- We can say things not only about the nature but also about the absolute scale and the ordering.
- Why do the scale of neutrino masses and dark energy coincide?





AdS Instability Conjecture

Non-susy (AdS) Instability Conjecture [6]

Any non-supersymmetric (AdS) vacuum is metastable at best.

- Radion effective potential has 3d AdS vacua.
- Avoided if neutrinos are (Pseudo-)Dirac with $m_{\nu_l} \lesssim \Lambda_{4d}^{1/4}$ [6-10].
- Need to assume they are stable and this requires UV information.
- Idea: check other swampland conjectures which require only IR information.

[6] H. Ooguri and C. Vafa '16,
[10] L. Ibáñez,V. Martin-Lozano, I. Valenzuela '17,
[8] G. Shiu, Y.Hamada '18,
[9] E.G., A. Herráez and L. Ibáñez '18

AdS Distance Conjecture

AdS Distance Conjecture

As $\Lambda_D \to 0$ a tower $m_n^{(D)} \sim |\Lambda_D|^{\alpha_D} M_D^{1-2\alpha_D}$ becomes light.

- **Mild version**: α_D to be a positive constant.
- **Strong version**: $\alpha_D = 1/2$ for AdS susy vacua.
- **Stronger version**: $\alpha_D > 1/2$ for non-susy AdS and also holds in dS space with $\alpha_D \leq 1/2$.

- Radion effective potential vacua depend on m_ν.
- According to the conjecture, if in a certain direction of field space (i.e Higgs field, Yukawa) $\Lambda_3 \to 0$, then some tower of states $m \sim |\Lambda_3|^\alpha = |V_0|^\alpha$ also become light.

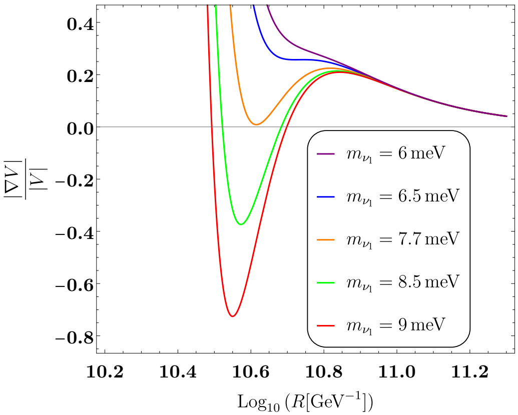
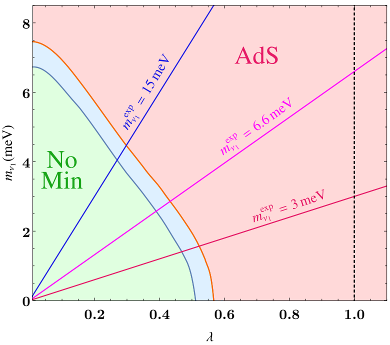


Figure: NH Dirac. If we change the mass of the neutrinos the vacuum smoothly goes from AdS to dS. When $\Lambda_{3d} \to 0$ a tower of states should become massless at a **finite** value of R.

Assumptions

1. There is a family of 4d-dimensional vacua exhibiting different values for the masses of the neutrinos $m_{\nu_i} = m_{\nu_i}^{\text{exp}}\lambda$ (i.e. change the vev of the Higgs, or the Yukawas).
2. The point where all neutrinos are massless is part of the landscape: we can increase their masses until we reach (if so) some inconsistency.

Normal Hierarchy



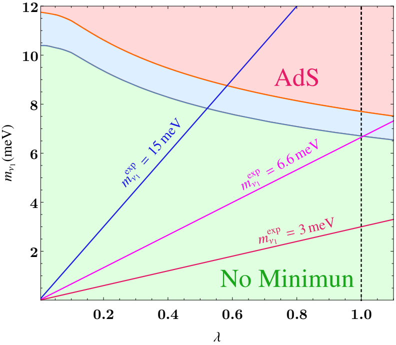


Figure: Left: Majorana. We are not able to reach $\lambda = 1$ without crossing lines. Right: Dirac: We can only reach $\lambda = 1$ without crossing lines for $m_{\nu_l} \leq 6.6$ meV. **Remark**: Constraints from neutrino oscillations are essential.

Other scannings

- Festina Lente [11]: $\left(\frac{g^2 q^2 M_p^2 \Lambda}{3\Omega_\Lambda}\right)^{1/4} < m$ for every charged particle in the spectrum so that large charge black holes evaporate back to empty dS space.
- If $m_\nu, m_e \propto \lambda$ then Λ could also change if we scan along the Higgs.
- FL requires $\Lambda \propto \lambda^\alpha$ with $\alpha > 4$.
- To also preserve $m_\nu \lesssim (\Lambda_{4d} M_p^2)^{\frac{1}{4}}$ the only scanning that is in agreement with Non AdS, AdC and Festina Lente is $\alpha = 4$.

[11] M. Montero, T. Van Riet and G. Venken

Other scannings

1. Non AdS + AdC: The mass of lightest neutrino is bounded from above $m_\nu \lesssim (\Lambda_{4d} M_p^2)^{\frac{1}{4}}$. For NH Dirac neutrinos the bound on the lightest neutrino is $m_{\nu_l} \leq 6.6$ meV.

2. The only consistent scanning with Non-AdS+AdC+FL seems to be with $\alpha = 4$ so perhaps neutrinos are somehow part of a tower.

Quintessence

- Perhaps the SM is not a dS vacua, but a quintessence runaway.
- Neutrino bounds?
- Refined dS/AdS conjecture [12,13,7]:

In a consistent theory of quantum gravity the scalar potential must verify either:

$$M_p \frac{|\nabla V|}{|V|} \geq c \qquad \text{or} \qquad (M_p)^2 \text{min}(\nabla_i \nabla_j V) \leq -c' V$$

[12] G. Obied, H. Ooguri, L. Spodyneiko and C. Vafa '18
[13] H. Ooguri, E. Palti, G. Shiu and C. Vafa '19
[7] D. Lust, E. Palti and C. Vafa '19

- The dS/AdS conjecture for our theory is:

$$\sqrt{\frac{R^2}{|V|^2}\left(\left|\frac{\partial V}{\partial R}\right|\right)^2 + \frac{c_V^2}{|1+\frac{V_{1L}}{V_{\text{tree}}}|}} > c$$

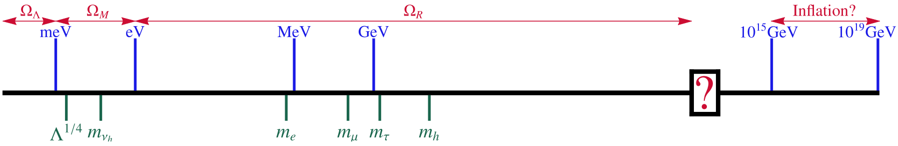
- Minima along radion direction satisfy $|V_{1L}| > V_{\text{tree}}$ so they can violate the bound (results depend on $c_V/c > 1$).
- First part of dSC + dark energy data requires $c_V = \left|\frac{U'}{U}\right| M_p \lesssim 0.6$.

RESULTS for $c_V = 0.6$:

- NH Dirac neutrinos require $m_{\nu_l} \leq 6.5$ meV for $c = 0.6$.
- Dirac IH require $c \lesssim 0.03$ and Pure Majorana require $c \lesssim 0.002$ (Strong Tension!)

Conclusions

- We obtain similar upper bounds on neutrino masses from three AdS Swampland (Non AdS, AdS Distance and AdS/dS) Conjectures.
- For NH Dirac we find $M < 0.069$ eV. Planck '18: $M < 0.12$ eV and could be lowered to our bound in the next ~ 20 years.
- The simplest See-Saw explanation of why active neutrinos are so light seems inconsistent.
- Perhaps QG provides a deeper explanation of why $m_\nu \sim \rho_{\Lambda_{4d}}^{1/4}$.




THANK YOU
FOR VISITING
THE SWAMP

Quintessence

- dSC is in strong tension with Single-Field Inflation, Quintessence.
- First part of dSC + dark energy data requires $c_V = \left|\frac{U'}{U}\right| M_p \lesssim 0.6$ [14] and $m_\phi^2 = \frac{\partial^2 U}{\partial \phi^2} \sim \sqrt{\frac{\rho_\phi^0}{M_P^2}} \sim 10^{-42}$GeV. [15]
- We assume dark energy is a canonical field with potential $U(\phi)$.
- After dimensional reduction:

$$V_{\text{tree}} = 2\pi r \left(\frac{r}{R}\right)^2 U(\phi)$$

- We have one additional massless bosonic degree of freedom in Casimir energy ($m_\phi \sim 10^{-42}$GeV $\ll \rho_\phi^{1/4} \sim 10^{-12}$GeV).

[14] P. Agrawal, G.Obied, P.J. Steinhardt, C. Vafa '18
[15] S. Tsujikawa '13