Swampland constraint on Neutrino

Yu Nakayama（中山優）
In collaboration with T. Harada （原田大雅）

e-Print: 2203.07587
Published in MPLA

Linde's classification

When I was a student, Linde came to Japan Physical Society Annual meeting, and gave a talk.

According to him, there are two types of problems:

1. Problems that can be solved by Anthropic principle

   (e.g. Cosmological constant problem)

2. Problems that cannot be solved by Anthropic principle

   (e.g. Strong CP problem, neutrino mass)

Life is short so you may lose your precious time by working on problems 1

(But today, I show the boundary is not so obvious…)

Anthropic explanation?

CC problem:

- If the cosmological constant is not as it is today, our civilization does not exist
- Weinberg tried to use this idea to disprove anthropic explanation → But observation finds non-zero CC just within anthropic bound

Strong CP problem

- CP violations in strong force would not forbid civilizations)

Neutrino mass

- Why is the mass of neutrino so small? Or why does it have non-zero mass?

Neutrino mass

Neutrino

- Neutrino can have two types of mass
  - Majorana type:

$$L_M = m\nu^\alpha \nu_\alpha + m\bar{\nu}_{\dot{\alpha}}\bar{\nu}^{\dot{\alpha}}$$

  - Dirac type (needs partner)

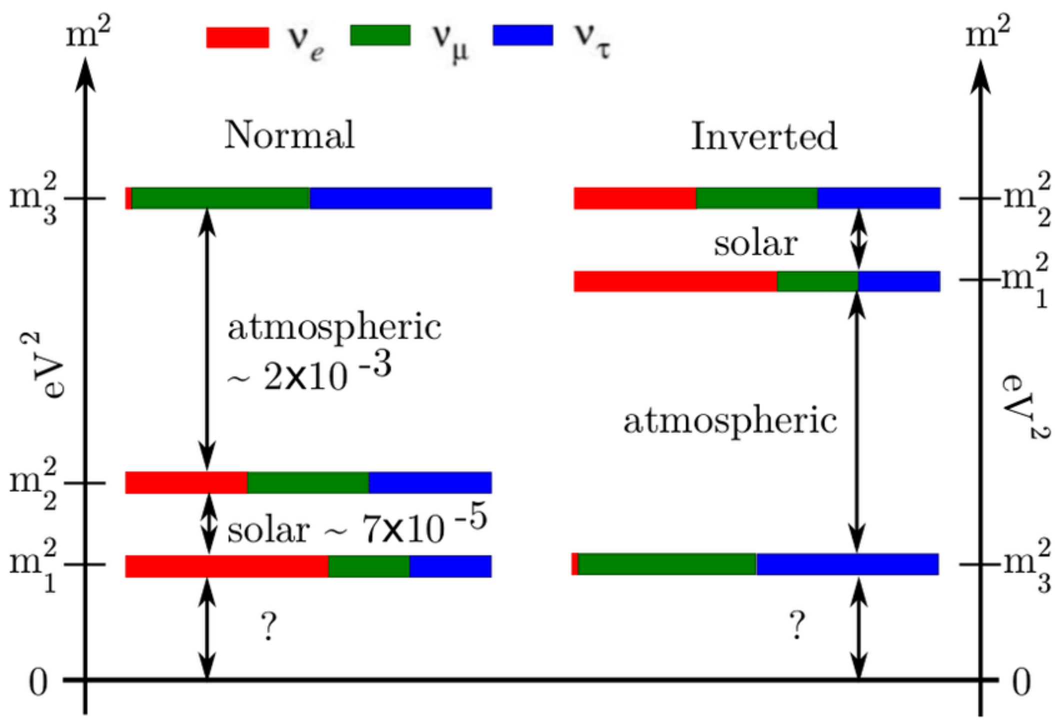
$$L_D = m\nu^\alpha \lambda_\alpha + m\bar{\lambda}_{\dot{\alpha}}\bar{\nu}^{\dot{\alpha}}$$

- You may have both (e.g. Seesaw), but today we do not consider heavy neutrinos

- Majorana breaks B-L, but Dirac may preserve it

Neutrino mass and generations

- Three generations of neutrinos are observed
- Super Kamiokande and other experiments found neutrino oscillation and their mass is different (→ at least, two families are massive)



What is this number?

$$m_1^2 - m_2^2 = 7 \times 10^{-5} \mathrm{eV}^2$$

$$\Lambda_{cc} = 3 \times 10^{-11} \mathrm{eV}^4$$

Is there any possible connection between CC and neutrino mass?

→ Yes, swampland constraint may explain the relation

Swampland conjecture

高美湿地

Landscape and Swampland

- Landscape: low-energy EFT coupled with gravity that can be embedded in consistent quantum gravity

- Swampland: otherwise (seemingly good EFT but cannot be embedded in consistent quantum gravity)
- Practically, consistent quantum gravity = string theory
- But we haven't solved string theory, so the boundary between the two is not clear

Some proposed swampland criteria

- No (continuous) global symmetry conjecture
- Weak Gravity Conjecture (Huang, Noumi…)
- De Sitter Conjecture (Vafa…)
- AdS Conjecture (Ooguri-Vafa)
  - In consistent theory of quantum gravity, there is no non SUSY (meta)stable AdS solution
- AdS distance conjecture
  - In consistent theory of quantum gravity, if we can (effectively) vary parameters, then Minkowski limit (from AdS side) must accompany infinite tower of light states

Landscape and Swampland

- Our universe is in the landscape
  - No predictive power?

- But the philosophy of landscape/swampland is that not only THE solution, but also the other solution of our low-energy EOM (e.g. compactified universe) must be in the landscape

(We do NOT say solution is bad)

Swampland constraint on Neutrino mass

Compactification of SM + gravity

- By definition, standard model of particle physics must be consistent with swampland criteria

- Our universe must be a constraint on the swampland criteria

- However, our universe may admit other solutions than our universe → non-trivial constraint (prediction!) on particle physics
- We focus on circle compactification of SM

Circle compactification of SM model

- SM (+ gravity + CC + neutrino mass) compactified on circle with radius R (radion)

- If particles have symmetries boundary conditions can be twisted by $\theta_p : \psi_p(x+2\pi R) = e^{2\pi i\theta_p}\psi_p(x)$
- Radion potential can be computed by Coleman-Weinberg formula (e.g. in Hamada-Shiu)

$$V(R) = \frac{2\pi\Lambda_{\rm cc}}{R^2} - \sum_p (-1)^{2s_p} n_p \frac{m_p^2}{4\pi^3 R^4} \sum_{n=1}^{\infty} \frac{K_2(2\pi n m_p R)}{n^2} \cos(2\pi n\theta_p) \ ,$$

- 1+2 d can be de-Sitter, Minkowski or AdS

Circle compactification of SM model

- We focus on R > QCD scale
- Consider only light (composite) fields

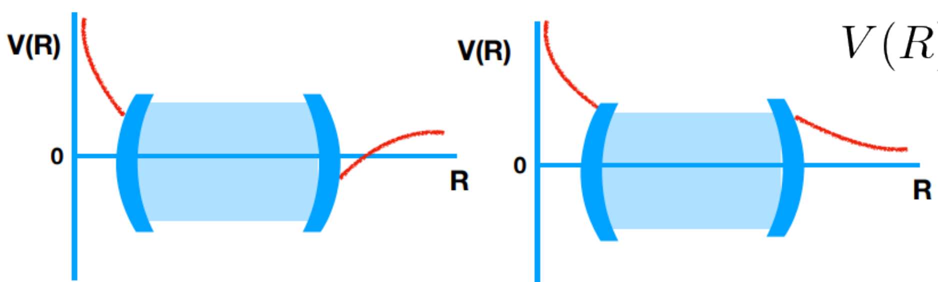
Particle	Mass	DOF
Photon	0	2
Graviton	0	2
ν	< 0.1 eV	6 (Majorana) or 12 (Dirac)
e	0.511 MeV	4
μ	100 MeV	4
π	140 MeV	3
K	500 MeV	4
η	550 MeV	1

- Lepton number (B-L in SM) can be twisted

Compactification of SM + gravity

- Assume Non-SUSY AdS conjecture
- Study radion potential at $\theta_p = 0$ (Gonzalo, Ibanez Valenzuela,``AdS swampland conjectures and light fermions)

$$V(R) = \frac{2\pi\Lambda_{cc}}{R^2} - \sum_p (-1)^{2s_p} n_p \frac{m_p^2}{4\pi^3 R^4} \sum_{n=1}^{\infty} \frac{K_2(2\pi n m_p R)}{n^2} \cos(2\pi n \theta_p) \ ,$$



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

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

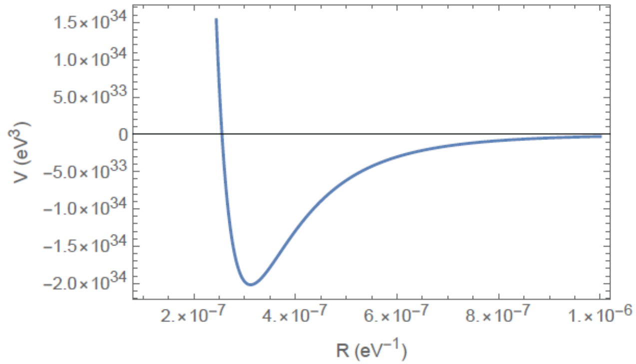
$$V(R) \sim \frac{2\pi\Lambda_{cc}}{R^2} - \sum_{\text{massless}} (-1)^{2s_p} n_p c \frac{1}{R^6}$$

- To avoid non-SUSY AdS, we need cosmologically light fermions: DOF must be larger than 4! (→ Dirac!)

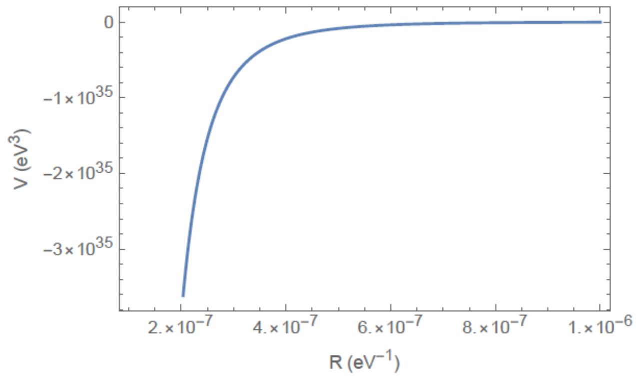
$$m_\nu < 8.3 \text{ meV(NH)}$$

Compactification of SM + gravity

- Now assume Dirac neutrino. Is it consistent at non-zero theta?
- Not really!!



$$\theta = 0.196$$



$$\theta = 0.197$$

- Larger theta → "More bosonic" and AdS appears (BAD)
- Much larger theta → "AdS vacuum" disappears (OK)

$$V(R) = \frac{2\pi\Lambda_{cc}}{R^2} - \sum_p (-1)^{2s_p} n_p \frac{m_p^2}{4\pi^3 R^4} \sum_{n=1}^{\infty} \frac{K_2(2\pi n m_p R)}{n^2} \cos(2\pi n \theta_p) \ ,$$

Compactification of SM + gravity

- Larger theta → "More bosonic" and AdS appears (BAD)
- Much larger theta → "AdS vacuum" disappears (OK)

- It is only consistent if $\theta < 0.13$ or $\theta > 0.197$

- Recall philosophy of swampland criteria: all the solutions must be consistent

To rescue AdS conjecture

- To be consistent with AdS conjecture, we have to remove theta

$$0.13 < \theta < 0.197$$

- This can be done if the theory breaks U(1) down to a subgroup

$$\mathbb{Z}_4 : 0, 0.25, 0.5, 0.75, 1.0$$

$$\mathbb{Z}_8 : 0, 0.125, 0.25, 0.375, 0.5 \cdots$$

$$\mathbb{Z}_{10} : 0, 0.1, 0.2, 0.3, 0.4, 0.5 \cdots$$

- This may be anticipated from no global symmetry swampland conjecture!
- Neutrino Mass must be further constrained

$$m_\nu < 4.5 \text{ meV } \ (\mathbb{Z}_8, \text{NH})$$

Summary and Conclusion

- Swampland conjecture may relate neutrino mass to CC
- We cannot explain cc by itself, but if we explain neutrino mass, it may explain cc
- One may get similar results from AdS distance conjecture
- Of course, you always have a right to be against AdS conjecture
- But, it is VERY tantalizing that the scale of CC and neutrino is so close

AdS distance conjecture

Some proposed swampland criteria

- AdS distance conjecture
- In consistent theory of quantum gravity, if we can (effectively) vary parameters, then Minkowski limit (from AdS side) must accompany infinite tower of light states
  - This conjecture allows dS/ AdS solution
  - Typically, it is accompanied by KK modes (→ Minkowski limit corresponds to decompactification)

AdS distance conjecture

- Suppose we have series of compactification with one-parameter (with fixed CC)

$$m_1(\lambda) = \lambda m_1^{\exp}$$
$$m_2(\lambda) = \lambda\sqrt{(m_1^{\exp})^2 + \Delta m_{21}^2}$$
$$m_3(\lambda) = \lambda\sqrt{(m_1^{\exp})^2 + \Delta m_{21}^2 + \Delta m_{32}^2}$$
$$10^{-4} < \lambda < 1$$

- It violates AdS distance conjecture when m is larger

To rescue AdS distance conjecture

- Neutrino must be Dirac and the mass must be cosmologically small
- The same applies with twisted condition