Weak gravity conjecture, Multiple point principle and SM landscape

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People used to think

- If (Energy) \ll M_P, effect of gravity is decoupled.

- Model building below Planck scale is independent from gravity (SM, beyond SM).
People used to think

· This might not true.

· Gravity may say something about low energy model building. [Vafa ‘05]
Motivation

- Test conjectures about quantum gravity by SM physics.

- Conjecture 1: Weak Gravity Conjecture
  Gravity is weakest force.
  All non-SUSY AdS vacua are unstable.

- Conjecture 2: Multiple Point criticality Principle
  The parameters of the theory are tuned so that many vacua are degenerate in energy.
Talk Plan

1. Conjectures
2. Standard Model on $M_4$
3. Standard Model on $M_3 \times S^1$
Talk Plan

1. Conjectures
2. Standard Model on $\mathbb{M}_4$
3. Standard Model on $\mathbb{M}_3 \times S^1$
Weak gravity conjecture (WGC)

- Conjecture:
  Gravity is \textit{weakest} force.

- $q$: gauge charge.

WGC requires

(gauge force) \geq (gravity force)

\[ q \geq \frac{m}{M_P} \]
Non-SUSY AdS conjecture

Motivation: It is unnatural that non-BPS state saturates WGC under quantum correction.

- Conjecture 1:
  Except for BPS state, gravity is **strictly** weakest force.

  Implication of conjecture 1.
  All non-SUSY AdS vacua supported by flux are unstable.

- Conjecture 2: All non-SUSY AdS vacua are unstable.

  Motivation: (All known construction from M/string theory, AdS is supported by some flux.) + (Conjecture 1)
Multiple point principle (MPP)

- Conjecture:
  The parameters of the theory are tuned so that many vacua are degenerate in energy.

- Possible principle to extract predictions from vast landscape.
In statical mechanics, micro-canonical ensemble is fundamental. First, \(E\) (extensive variable) is given, and \(T\) (intensive variable) appears as a result.
Motivation of MPP

Statistical mechanics

\[ \Omega(E) = \sum_n \delta(H_n - E) \]

QFT

\[ \int [d\varphi] e^{-S_{\text{extra}}} \delta \left( \int d^4 x \varphi^2 - I_2 \right) \]

Proposal in [Froggatt, Nielsen ’95]

Equivalent in thermodynamic limit

\[ Z(\beta) = \sum_n e^{-\beta H_n} \]

\[ Z(\{\lambda\}) = \int [d\varphi] e^{-S(\{\lambda\})[\varphi]} \]

Canonical

Correspondence:

\[ T \leftrightarrow \text{coupling (intensive variable)}, \]
\[ E \leftrightarrow \int \phi^2 \text{ (extensive variable)}. \]
Coexisting phase

• Add heat to water under constant pressure.

• Point: For wide range of $E$, the temperature $T$ is tuned to be boiling point $T_*$.
QFT version

• Inspired by micro-canonical ensemble, we fix $l_2$.

\[ \int [d\varphi] e^{-S_{\text{extra}}} \delta \left( \int d^4 x \varphi^2 - I_2 \right) \]

• Taking natural value $l_2 = O(V_4 M_P^2)$, the constraint is realized as an average between two vacuum.

• To maintain coexisting phase, vacua should be degenerate.
Talk Plan

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2. Standard Model on $M_4$
3. Standard Model on $M_3 \times S^1$
AdS vacuum in SM

- 4d SM Higgs potential can have AdS$_4$ minimum, depending on $M_t, M_H$ and higher dim. operator

[Degrassi et. al. ’12, …]
SM Higgs potential

Application of WGC
Depending on $M_t$, $M_H$ and higher-dim operators, high scale AdS vacuum appears. WGC can constrain top & Higgs mass. [YH, Shiu ‘17]

Application of MPP
Requiring the degenerate vacua, the predictions on $M_H$, $M_t$ are obtained. The correct $M_H$ was predicted 20 years ago. [Froggatt, Nielsen ‘95]
Talk Plan

1. Conjectures
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S¹ compactification of SM

[Arkani-Hamed, Dubovsky, Nicolis, Villadoro ‘07]

potential for radion L

$$\frac{L_0^2}{(2\pi L)^2} \left\{ \Lambda_4 - \frac{1}{180 L^4(2\pi)^4} - \sum_i 2V_{S^1}^{(1)} \left( L, M_{\nu_i}, \frac{1-z}{2} \right) \right\}$$

One-loop effective potential (Casimir energy)

$$V_{S^1}^{(1)} = (-1)^{2s_p+1} \frac{n_p}{2} \sum_{n=-\infty}^{\infty} \frac{1}{2\pi L} \int \frac{d^3 k}{(2\pi)^3} \log \left( k_0^2 + k_1^2 + k_2^2 + M^2 + \frac{(n+\theta)^2}{L^2} \right)$$
$S^1$ compactification of SM

potential for radion $L$

$$\frac{L_0^2}{(2\pi L)^2} \left\{ \Lambda_4 - \frac{1}{180 L^4 (2\pi)^4} - \sum_i 2V_{S^1}^{(1)} \left( L, M_{\nu_i}, \frac{1-z}{2} \right) \right\}$$

vacuum around neutrino mass scale

[Arkani-Hamed, Dubovsky, Nicolis, Villadoro '07]

[See also Ooguri Vafa '16, Ibanez et. al. '17]

[YH, Shiu '17]

bc & mass of $\nu$
Application of WGC

[YH, Shiu ‘17]

- Neutrino vacuum can be AdS, but it is likely to decay non-perturbatively.
- Consistent with the conjecture.

Runaway behavior for small radius
Application of MPP

- We may consider the degeneracy between 3D and 4D vacua.

Predicted neutrino mass is $m_{\nu,\text{lightest}} = O(1-10)\text{meV}$, and neutrino is Dirac.
Summary

- Conjecture 1: Weak Gravity Conjecture
  Related to Stability of the electroweak vacuum.

- Conjecture 2: Multiple Point criticality Principle
  Prediction:
  Neutrino is Dirac, and $m_{\nu,\text{lightest}} = O(1-10)\text{meV}$.
Backup
Quantum gravity & SM physics

- Motivation: Test of conjectures about quantum gravity by SM physics.

- Conjecture 1: Weak Gravity Conjecture
  Gravity is weakest force. [Arkani-Hamed, Motl, Nicolis, Vafa ‘06]
  Non-SUSY AdS vacua are unstable. (sharpened ver.) [Ooguri, Vafa ‘16]

- Conjecture 2: Multiple Point criticality Principle
  The parameters of the theory are tuned so that many vacua are degenerate in energy. [Froggatt, Nielsen ’95]
Test 1: Higgs potentials

[Degrassi et al. ’12, …]

central value $M_t=173\text{GeV}$ & $c_6=0$, EW vacuum is metastable.

smaller $M_t \lesssim 171\text{GeV}$, EW vacuum is absolutely stable.

$\lambda<0$ for $h > 10^{10}\text{GeV}$.

Requiring the degenerate vacua, the predictions on $M_H$, $M_t$ are obtained. The correct $M_H$ was predicted 20 years ago. [Froggatt, Nielsen ’95]
Test2: $S^1$ compactification of SM

potential for radion $L$

$$\left\{ \begin{array}{c} \Lambda_4 \, - \, \frac{1}{180L^4(2\pi)^4} \, - \, \sum_i 2V_{S^1}^{(1)} \left( L, M_{\nu_i}, \frac{1-z}{2} \right) \end{array} \right\}$$

d.o.f.
$\gamma +$graviton: 4
$\nu$: $2 \times 3 = 6$

balance among
$\Lambda 4 (positive)$
$\gamma +$graviton(negative)
$\nu$ (negative/positive $z = 0$ or $1$)

cc dominates
$
\nu$ dominates
bc & mass of $\nu$

[Arkani-Hamed, Dubovsky, Nicolis, Villadoro '07]
Summary

- SM Higgs potential and SM landscape are good place to test various conjectures.

- Multiple Point criticality Principle predicts Neutrino is Dirac, and $m_{\nu,\text{lightest}} = O(1-10)\text{meV}$. 
AdS vacuum in SM on $S^1$

- potential for radion field.
There is AdS$_3$ minimum.