Swampland Conjectures

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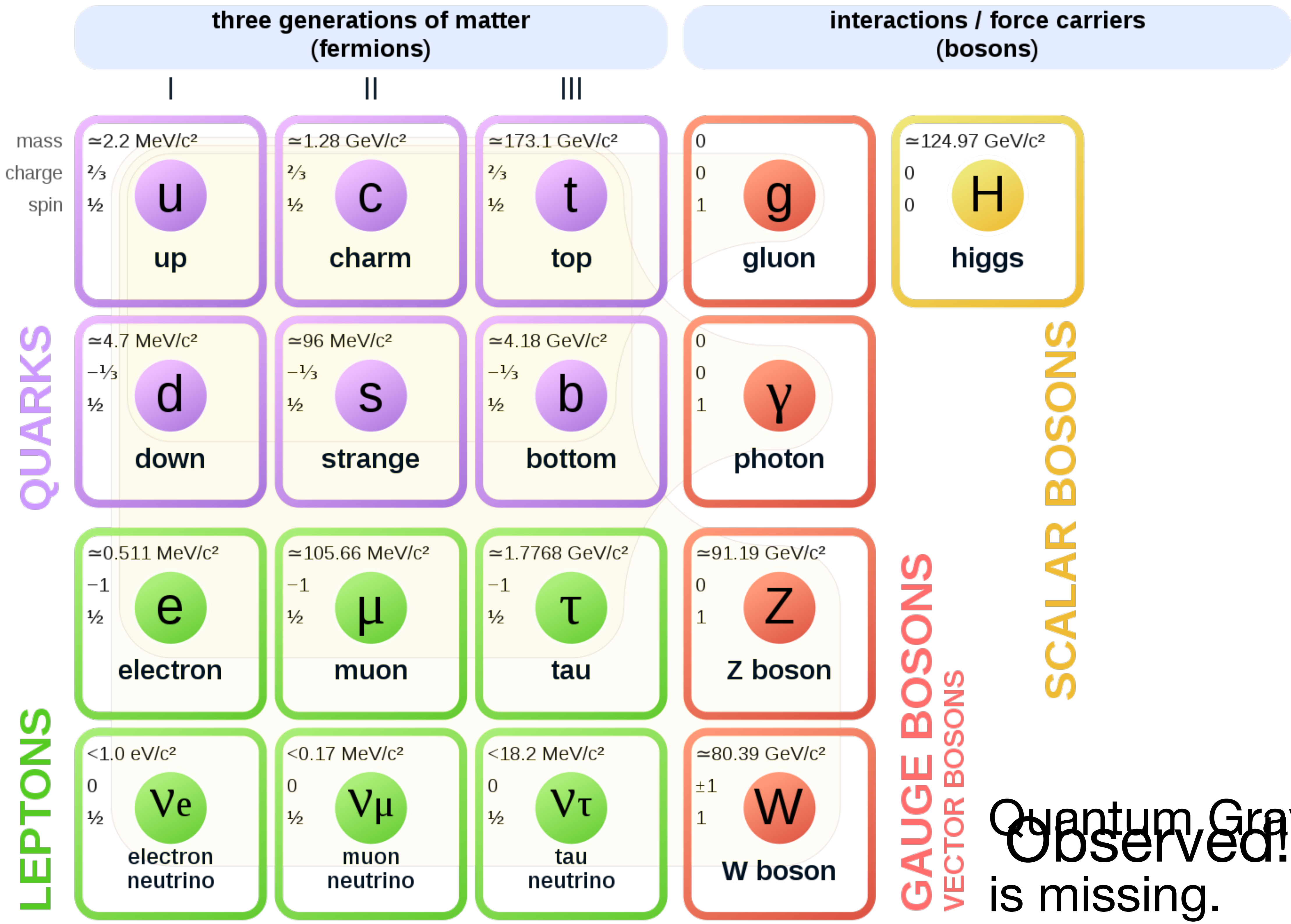
Kitahara-san's request:

Talk for master students
interested in particle phenomenology.

Standard Model of Elementary Particles



Quantum Gravity (QG) is missing.

Observed!

Two Question

1: Do we have a framework of QG?

String Theory

2: Is QG relevant at low-energy?

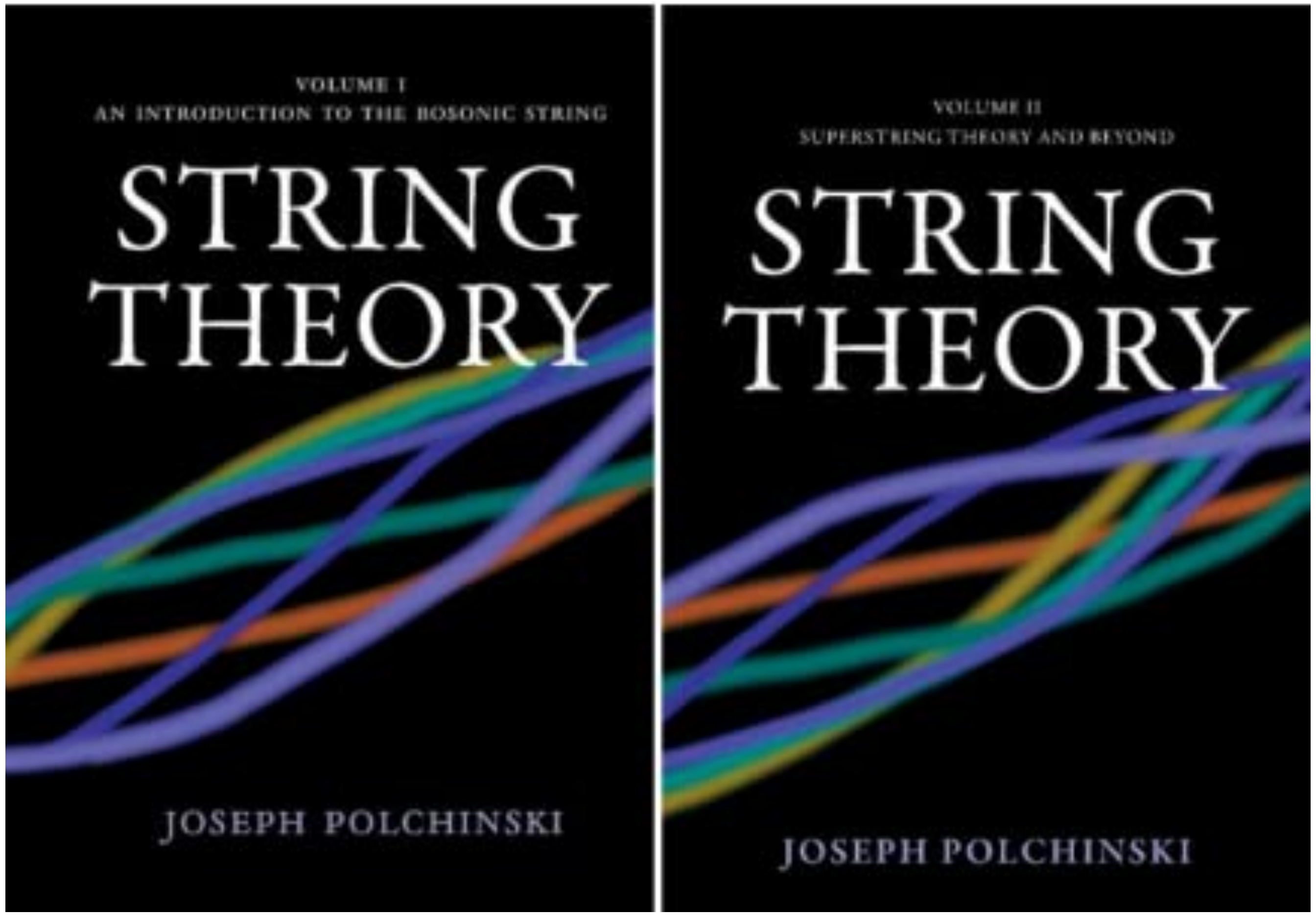
If not, QG is not useful for particle pheno at $(\text{low energy}) \ll M_P$

even though it is useful to study the scattering at M_P.

String Theory: A candidate of Quantum Gravity.

Advantage:

Around the flat background, the one-loop diagram of graviton is finitely computed!



String Theory: A candidate of Quantum Gravity.

Advantage:

The entropy of BPS black hole (stable black hole by supersymmetry) is reproduced!

N·H
ELSEVIER

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PHYSICS LETTERS B

Microscopic origin of the Bekenstein-Hawking entropy

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Abstract

The Bekenstein-Hawking area-entropy relation $S_{BH} = A/4$ is derived for a class of five-dimensional extremal black holes in string theory by counting the degeneracy of BPS soliton bound states.

Two Question

1: Do we have a framework of QG?

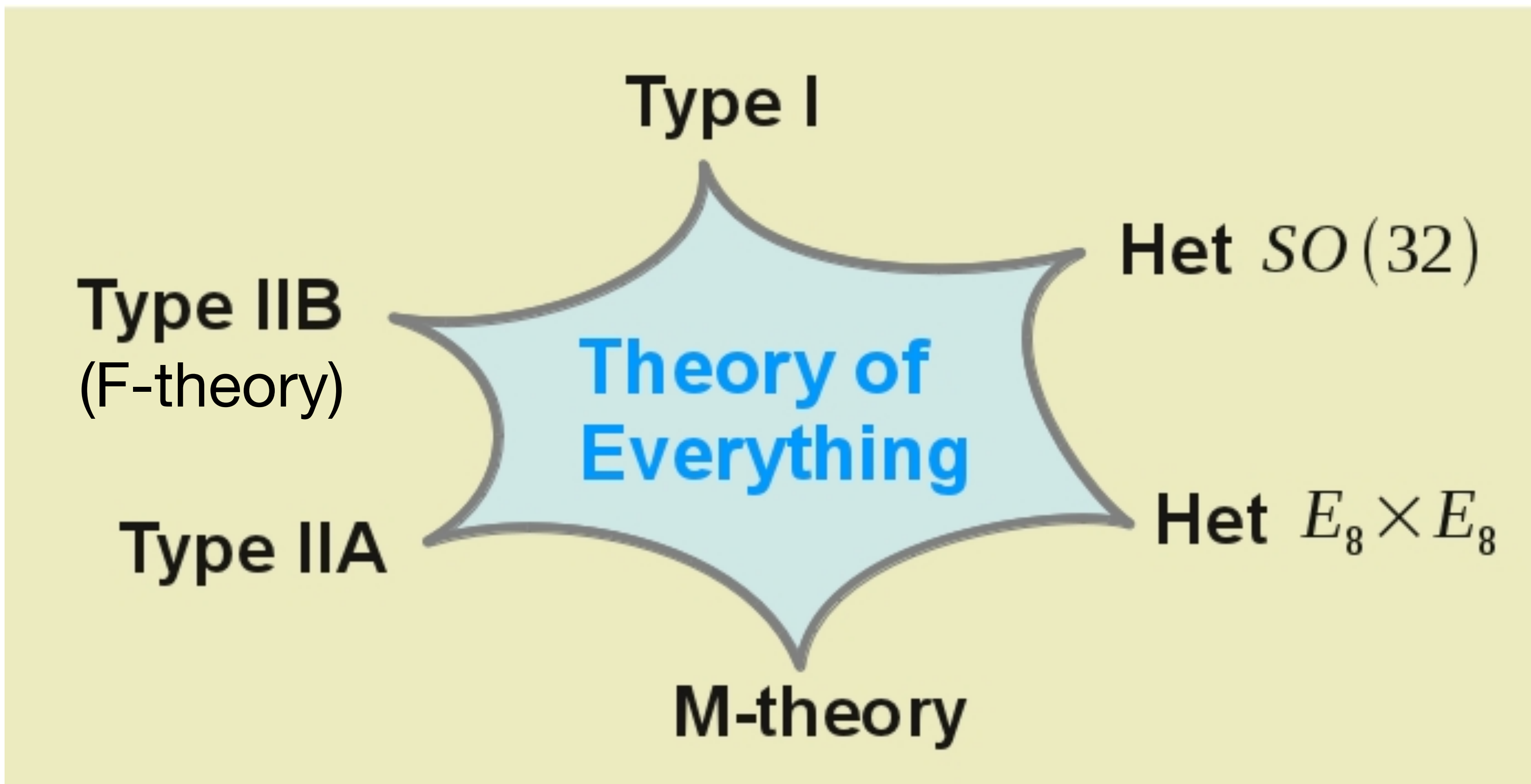
String Theory

2: Is QG relevant at low-energy?

If not, QG is not useful for particle pheno at $(\mathrm{low\,energy}) \ll M_P$

even though it is useful to study the scattering at M_P.

String Theory predicts 10 or 11 dimensions.



String Theory predicts 10 or 11 dimensions.

Of course, our universe is 4 dimensional.

$$10 = 4 + 6$$

our universe

extra dimension (compact dimension)

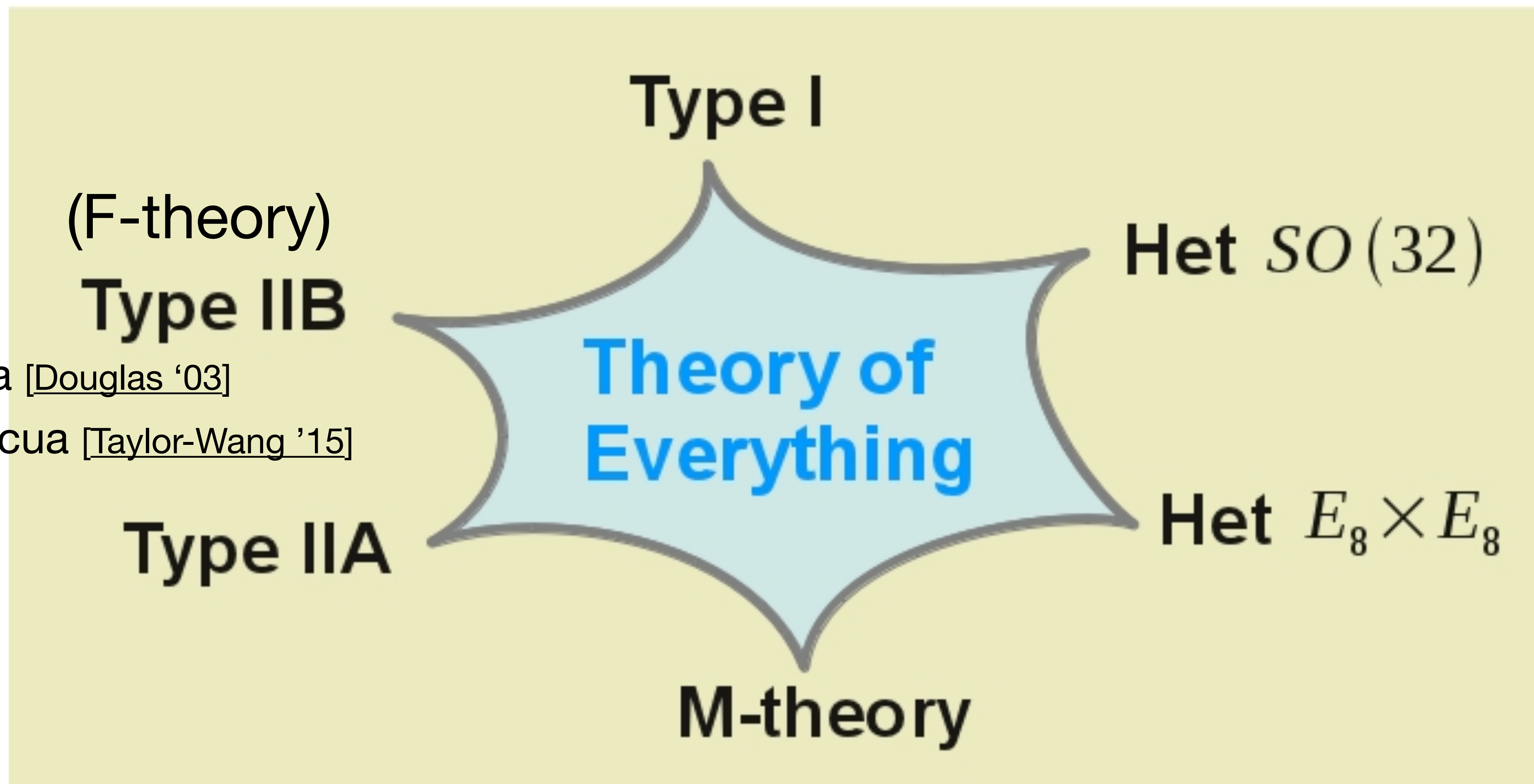
String theory predicts extra dimensions.

Choice of extra dimensions = Choice of EFT.

$\forall\ \mathrm{EFT}_A\ \exists\ \mathrm{extra\,dim}_X$, s.t. (string theory on $\mathrm{extra\,dim}_X$) = EFT_A

If this is the case, string theory may not be useful for low-energy.

Number of vacua



10^{500} vacua [Douglas '03]

10^{272000} vacua [Taylor-Wang '15]

Even though the number of vacua is huge,
it is still finite!

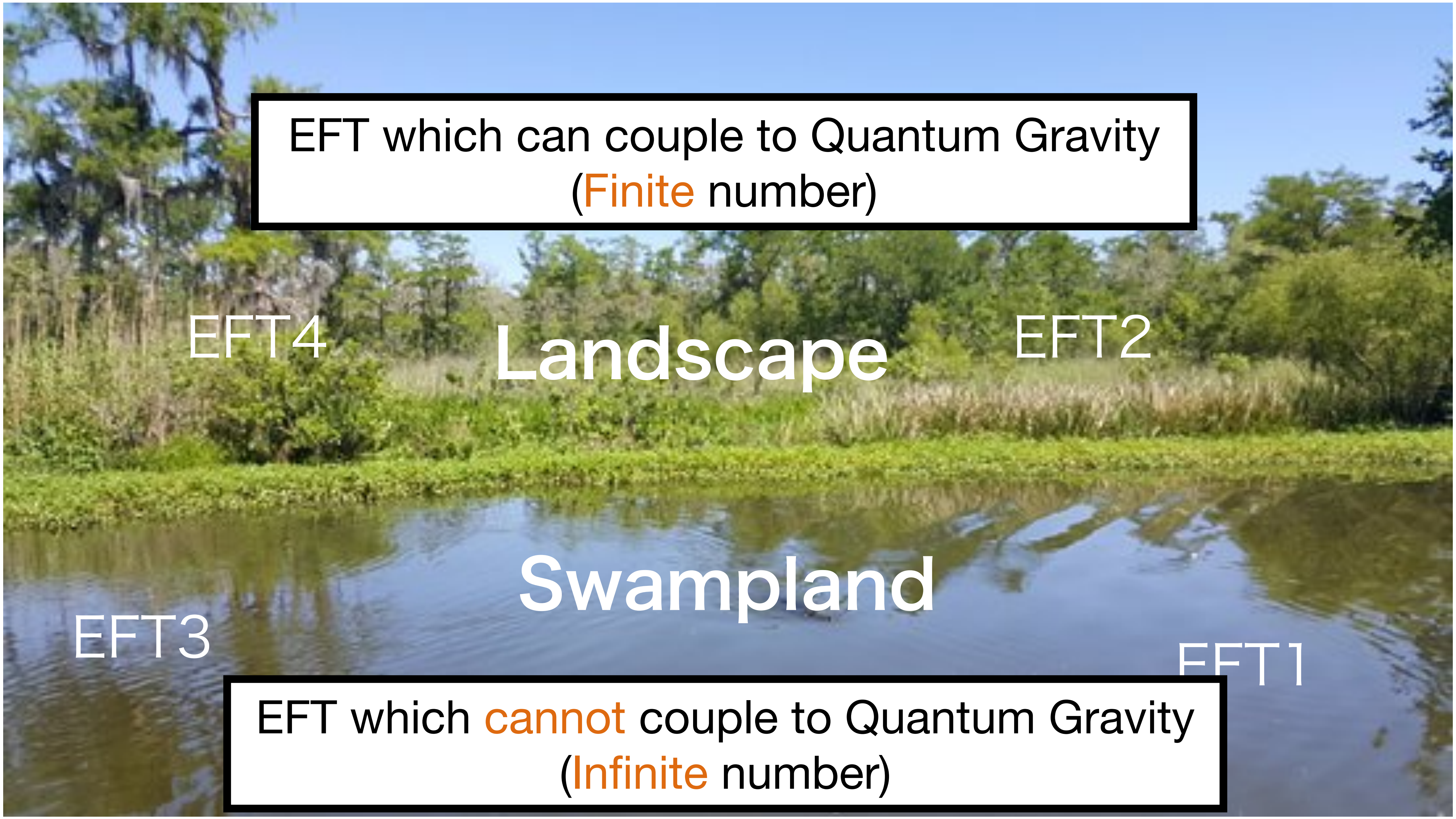
This is remarkable since the number of EFT is infinite.

For example, There are infinite number of $SU(N)$ gauge theory parametrized by $N = 2,3,4,\cdots$.

This leads to the notion of
the Landscape and the Swampland.

[Vafa '05, Ooguri-Vafa '06]

Landscape vs Swampland

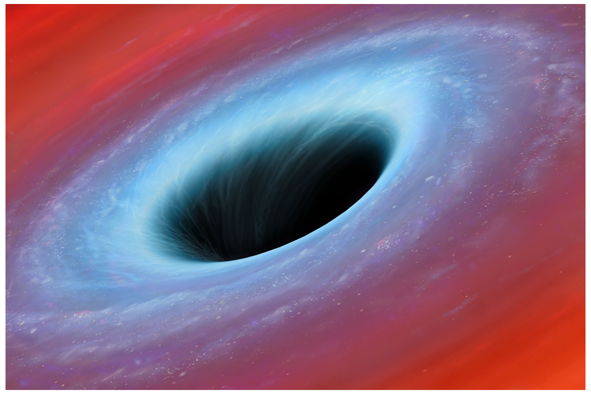


Q: What is the boundary between the Landscape and the Swampland?

Swampland Conjectures

There are hidden conditions for healthy EFT.

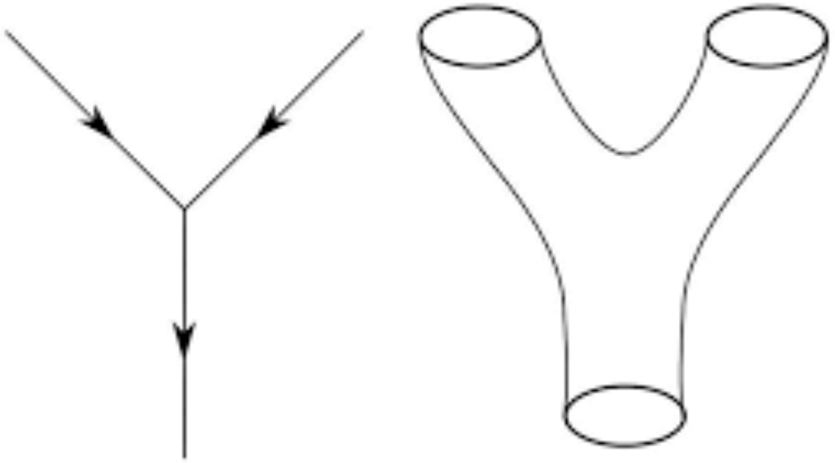
Talk Plan



Motivated from Black Hole (BH)

$S_{BH} = A/4$, A: BH area.

No Global Symmetry Conjecture —Generalization→ Weak Gravity Conjecture

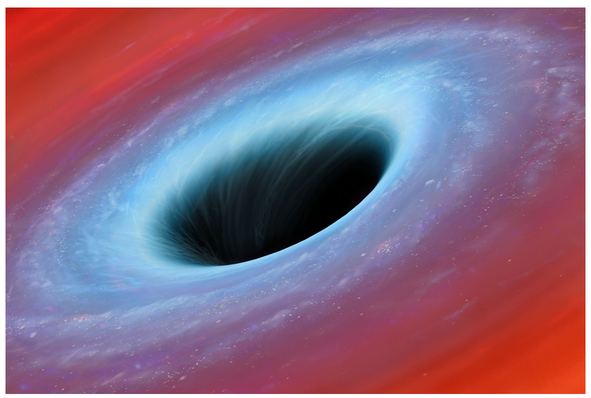


Motivated from String Theory

Distance Conjecture

de Sitter Conjecture

Talk Plan



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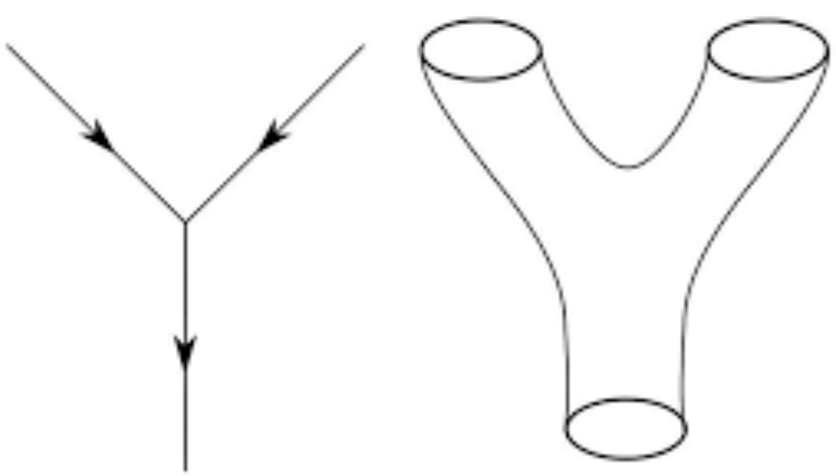

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No Global Symmetry

Statement: No Global Symmetry in QG.

[…, Banks-Dixon ’88, …, Banks-Seiberg ’10, …, Harlow-Ooguri ’18, …]

Perturbative string BH Holography

There are no discrete and continuous global symmetries.

For example, there are no $\mathbb{Z}_N$ and $SU(2)$ global symmetries.

The Conjecture also applies to new notion of symmetry such as higher form symmetry and non-invertible symmetry.

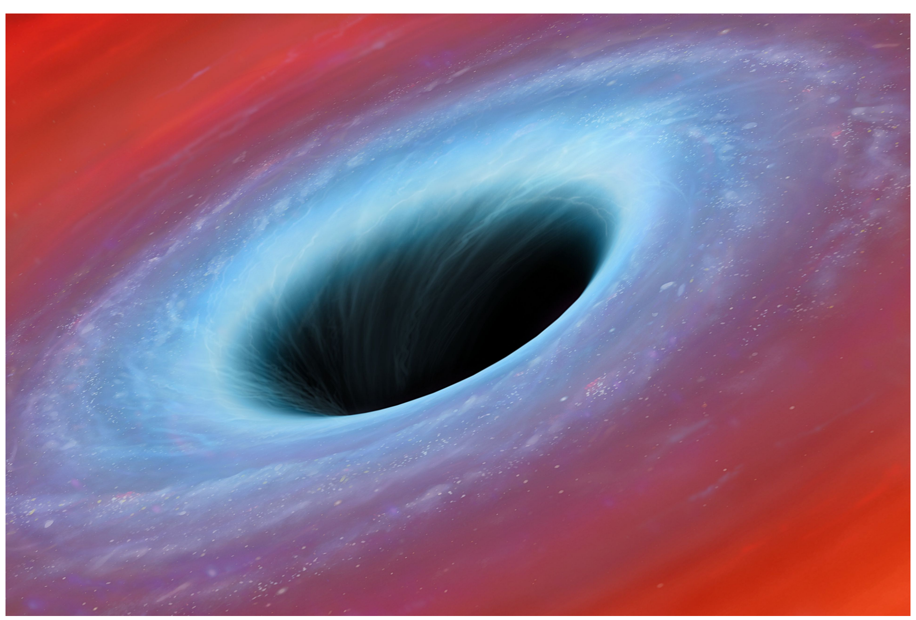
The global symmetry at the boundary of the spacetime is OK. (e.g. AdS/CFT)

Relation to Black Hole

Suppose there is $SU(2)$ global symmetry.

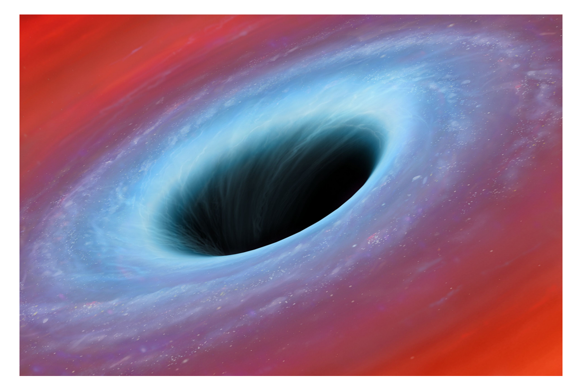
By throwing Spin J matter into BH,

the BH with an arbitrarily $SU(2)$ charge is constructed.



Hawking radiation

Distant observer cannot distinguish $SU(2)$ charge. The number of indistinguishable state contributes to entropy, but $e^{S_{BH}}$ is finite.



$S_{BH} = A/4.$

A: BH area.

Solutions

Solution(1) Explicit braking.

There are no global symmetries.

Solution(2) Gauging

The distance observer can see the black hole charge through the electric field.

$B - L$

The Standard Model possesses global $B - L$ symmetry.

(1) Explicitly broken

The left-handed neutrino Majorana mass term (after turning on)

$$\mathscr{L} = \frac{1}{\Lambda} LHLH + \dots$$

This breaks from $U(1)_{B-L}$ to $\mathbb{Z}_2$.

(2) Gauging

The SM is extended in such a way that $U(1)^3_{B-L}$ anomaly is canceled.

Typically, we add 3 right-handed neutrinos.

Strong CP problem

QCD action is

$$S \sim \int d^4x \left(-F_{\mu\nu}F^{\mu\nu} + \theta\, F_{\mu\nu}\tilde{F}^{\mu\nu} \right)$$

Experimental constraint is $\theta \lesssim 10^{-10}$.

An explanation is given by QCD axion a.

Lagrangian is

$$S \sim \int d^4x \left((\partial_\mu a)^2 - F_{\mu\nu}F^{\mu\nu} + \frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} \right)$$

EOM for axion requires

$$\frac{\delta}{\delta a} Z \sim \langle F_{\mu\nu}\tilde{F}^{\mu\nu} \rangle = 0 \quad \longrightarrow \quad \theta = 0.$$

Axion quality problem

Axion is Nambu-Goldstone boson of chiral symmetry $U(1)_{PQ}$ associated with symmetry breaking by $\langle\Phi\rangle$. Φ: $U(1)_{PQ}$ charged scalar

$U(1)_{PQ}$ symmetry is broken only through $U(1)_{PQ}SU(3)_C^2$ anomaly.

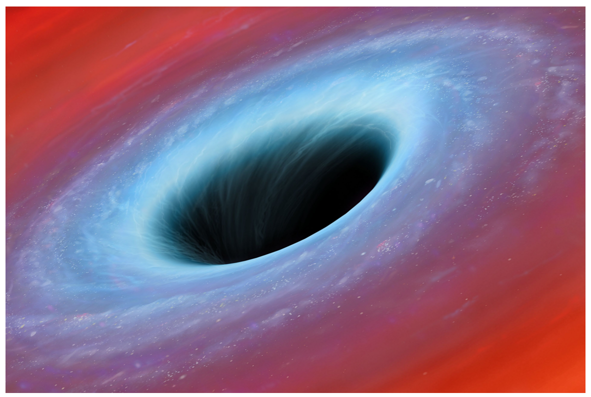
However, according to no global symmetry conjecture, one may expect $U(1)_{PQ}$ breaking term.

$$\mathscr{L} \sim \frac{\Phi^5}{M_P}$$

This spoils axion solution with $\langle\Phi\rangle \sim 10^{10}$ GeV (value preferred from cosmology).

$U(1)_{PQ}$ must be ``good" symmetry even in the presence of the gravity.

Talk Plan



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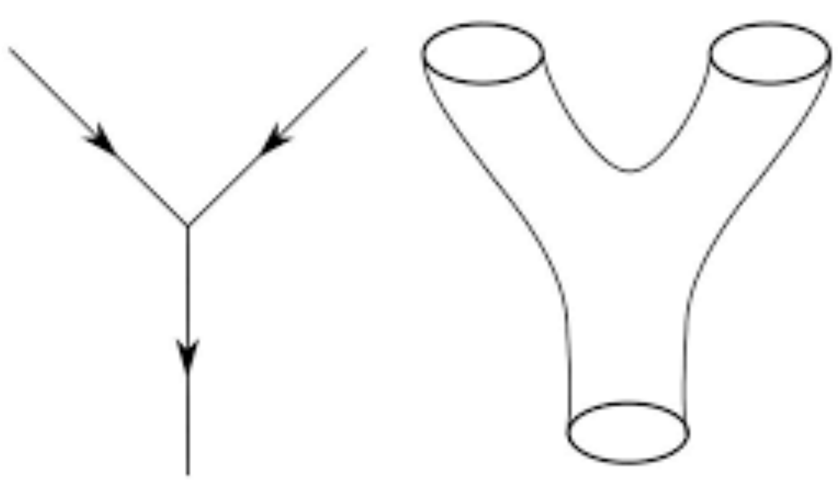
Generalization

No Global Symmetry Conjecture → **Weak Gravity Conjecture**



Motivated from String Theory

Distance Conjecture

de Sitter Conjecture

[ArkaniHamed-Motl-Nicolis-Vafa ‘06]

Weak Gravity Conjecture (WGC)

Statement:

For $U(1)$ gauge group, there exists at least one charged state which satisfies (in $2M_P^2=1$ unit)

$$|Q| \geq M$$

(M, Q): mass and $U(1)$ charge of the state.

The magnetic version is $|Q_M| \geq m_M$.
(m_M, Q_M): monopole mass and $U(1)$ magnetic charge.

Why WGC is true?

Original motivation: Decay of Extremal BH. [ArkaniHamed-Motl-Nicolis-Vafa ‘06]
No counterexample in string theory.

Explanation from unitarity and causality in photon-photon scattering amplitude.
Extremal BH is a state satisfying WGC.
[Hamada-Noumi-Shiu ‘18]

Argument from Holography [Montero ‘18]

[Ooguri, Vafa '16]

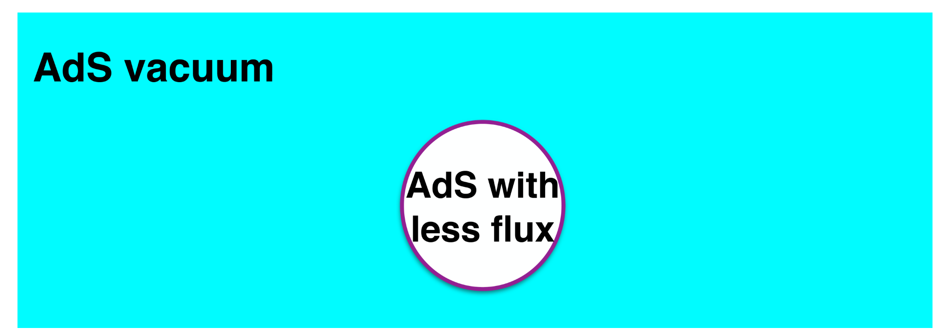
Non-SUSY AdS conjecture

- Conjecture1:

  Except for BPS state, gravity is strictly weakest force. $|Q|>M$.

  ↓ [Maldacena, Michelson, Strominger '98]

  All non-SUSY AdS vacua supported by flux are unstable.



- Conjecture2: All non-SUSY AdS vacua are unstable.

  (as long as low energy action is Einstein gravity with finite number of fields)

  Motivation: All known construction from M/string theory,

  AdS is supported by some flux.

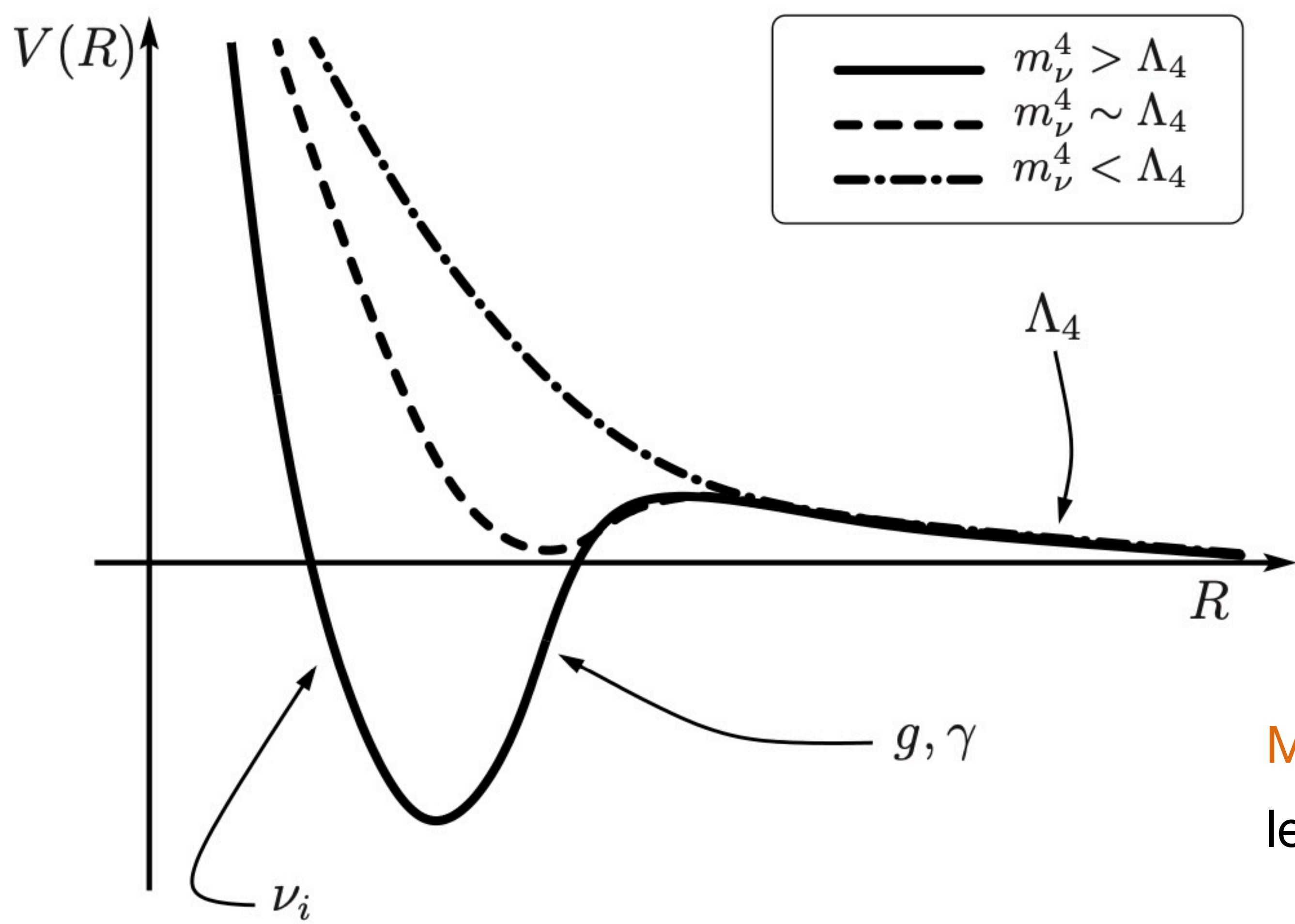
[Arkani-Hamed, Dubovsky, Nicolis, Villadoro '07]

AdS vacuum in SM

Idea: The conjecture applies all theories in Landscape.

Assumption: SM is in Landscape.

Then, it is likely that S^1 compactification of SM is in Landscape.



Dirac neutrino

S^1: raidus R

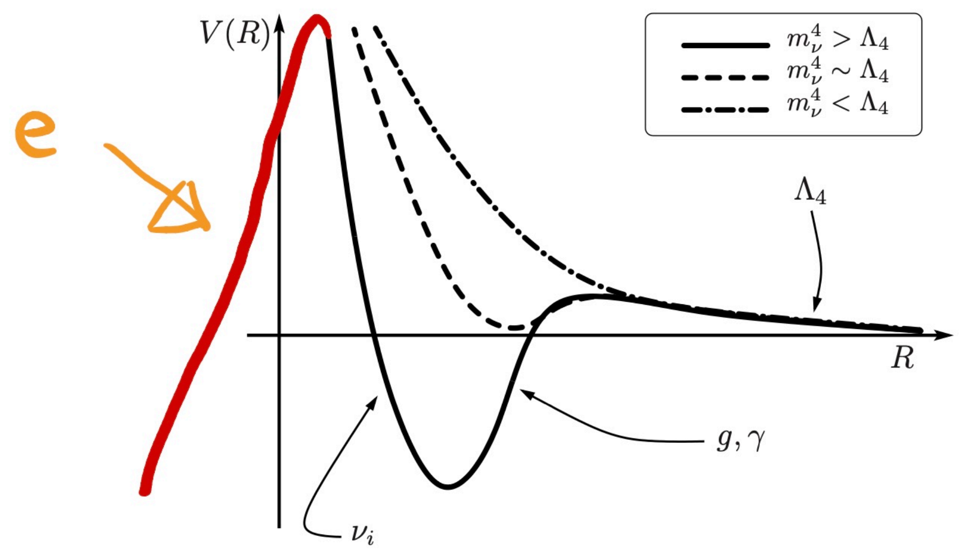
Majorana neutrino always leads to AdS_3.

Depending on neutrino mass and type (Dirac/Majorana), $AdS_3 \times S^1$ appears.

Neutrino Mass

If this vacuum is stable, this is in the Swampland [Ooguri, Vafa '16, Ibanez, Martin-Lozano, Valenzuela '17]

$AdS_3 \times S^1$ vacuum is non-perturbatively unstable [Hamada-Shiu '17]



Attempts to constraint neutrino mass and type by using more complicated compactification and different conjectures. [Gonzalo-Herraez-Ibanez '18, Gonzalo-Ibanez-Valenzuela '21]

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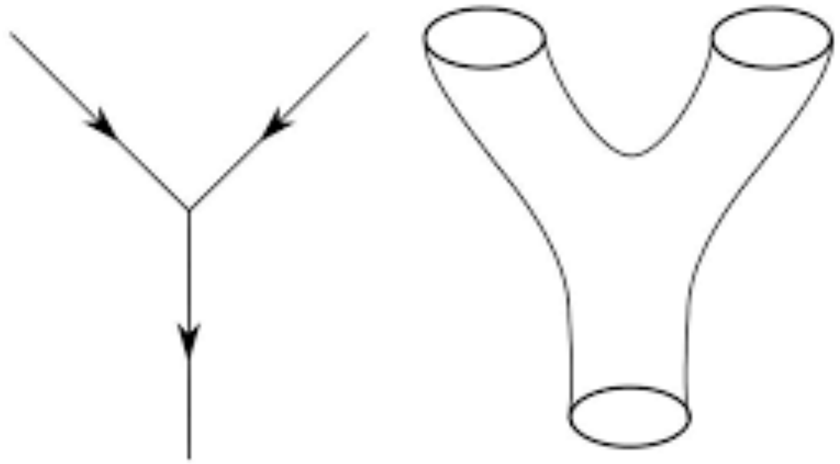

Motivated from String Theory

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Distance Conjecture

The Lagrangian of the massless scalar field is

$$\mathscr{L} = \frac{1}{2}\eta^{\mu\nu} g_{IJ}(\partial_\mu \phi^I)(\partial_\nu \phi^J)$$

g_{IJ} is called field space metric. The field space distance is defined from g_{IJ}.

$$(\text{distance from } \phi_0 \text{ to } \phi_1 \text{ with path A}) = \int_{\phi_0}^{\phi_1} ds, \qquad ds^2 = g_{IJ} d\phi^I d\phi^J$$

Statement: At large geodesic distance $\Delta\phi \to \infty$, the exponentially light tower of state appears.

$$M_{\text{tower}} \sim M_P\, e^{-n\alpha\Delta\phi}, \qquad \text{for} \quad \Delta\phi \to \infty, \quad n = 1,2,\cdots$$

where α is $\mathcal{O}(1)$ positive number.

Two Towers

Limit 1: KK tower

$D = d + 1$ dimensional spacetime compactified on S^1.

The radius R corresponds to the radion field ϕ.

$$2\pi R = e^{\sqrt{\frac{d-2}{2(d-1)}}\phi}, \qquad M_{KK}^2 \sim e^{-\sqrt{\frac{2(d-1)}{d-2}}\phi}.$$

For $\phi \to \infty$, d-dimenaional EFT breaks down.

Limit 2: String tower

The relation between dilaton field ϕ (string coupling e^{ϕ})and string scale M_{st} is

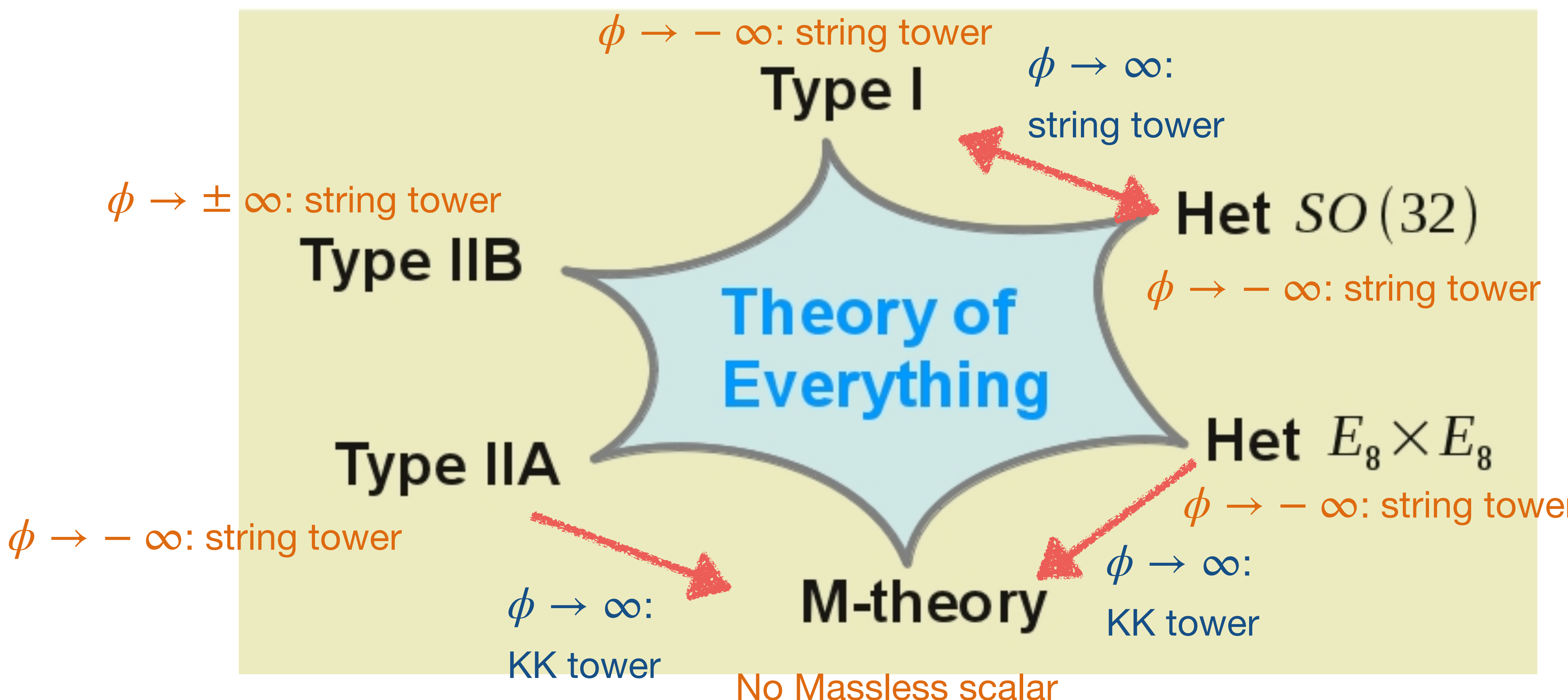
$M_P^8 = M_{st}^8 e^{-2\phi}$ in 10d.

In $\phi \to \infty$ limit with fixed M_P, the string excited states become light.

Emergent String Conjecture: These two are only possibilities. [Lee-Lerche-Weigand '19]

Examples in String Theory

Dilaton ϕ (String coupling e^{ϕ})



[From web]

[Scalisi-Valenzuela ‘18]

Inflation

The dynamics of inflaton may be modified if (cutoff scale) < (Hubble scale).

$$H \lesssim M_P\, e^{-\alpha \Delta\phi / M_P}, \qquad \frac{\Delta\phi}{M_P} \lesssim \frac{1}{\alpha} \log\left(\frac{M_P}{H}\right)$$

$\Delta\phi$ is bounded from above for fixed H.

One the other hand, Lyth bound [Lyth ‘96] is lower bound on $\Delta\phi$ for fixed H.

$$10^5 \frac{H}{M_P} \lesssim \frac{\Delta\phi}{M_P}$$

Therefore, $$\frac{H}{M_P} \lesssim \frac{10^{-5}}{\alpha}.$$

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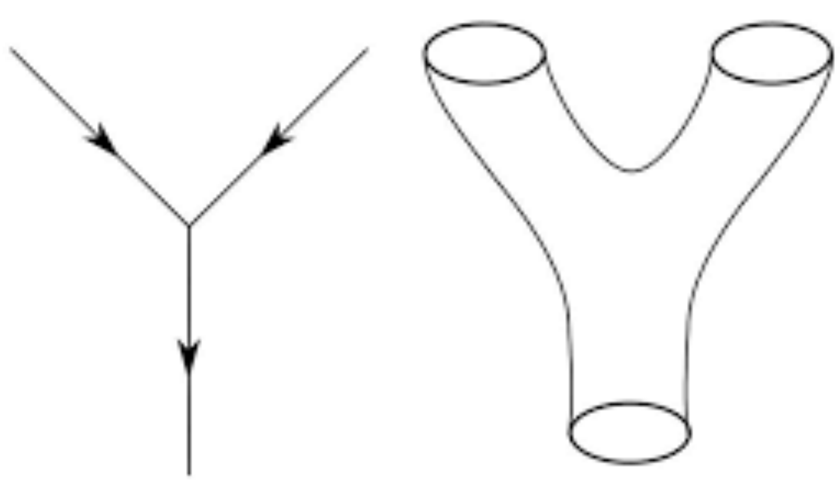

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Distance Conjecture

de Sitter Conjecture

[Obied-Ooguri-Spodyneiko-Vafa '18, Ooguri-Palti-Shiu-Vafa '18]

de Sitter Conjecture

Statement: Potential $V(\phi)$ must satisfy either

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

where c and c' are $\mathcal{O}(1)$ positive numbers.

The conjecture excludes de Sitter vacua because $|\nabla V| = 0$ and $\min(\nabla_i \nabla_j V) > 0$ are impossible.

[Alvarez-Gaume, Ginsparg, Moore, Vafa '86
Dixon Harvey '86]

$SO(16) \times SO(16)$ Heterotic String

$SO(16) \times SO(16)$ heterotic string: 10d theory without supersymmetry nor tachyon.

Tree level cosmological constant is zero. The one-loop cosmological constant is computed as

$\Lambda_{10} \simeq 4 \times 10^{-6} (\alpha')^{-5}$ $(\alpha')^{-1}$: string tension.

Positive cosmological constant (fermion/boson gives rise positive/negative contribution).
de Sitter solution in string theory?

Runaway Potential

This is NOT de Sitter solution.

String frame action is

$$S = (\alpha')^{-4} \int d^{10}x \sqrt{g} e^{-2\phi} \left(\frac{1}{2} R + 2(\nabla \phi)^2 - (\alpha')^4 \Lambda_{10} + \cdots \right)$$

ϕ is dilaton ($g_s = e^{\phi}$ is string coupling). Einstein frame action is

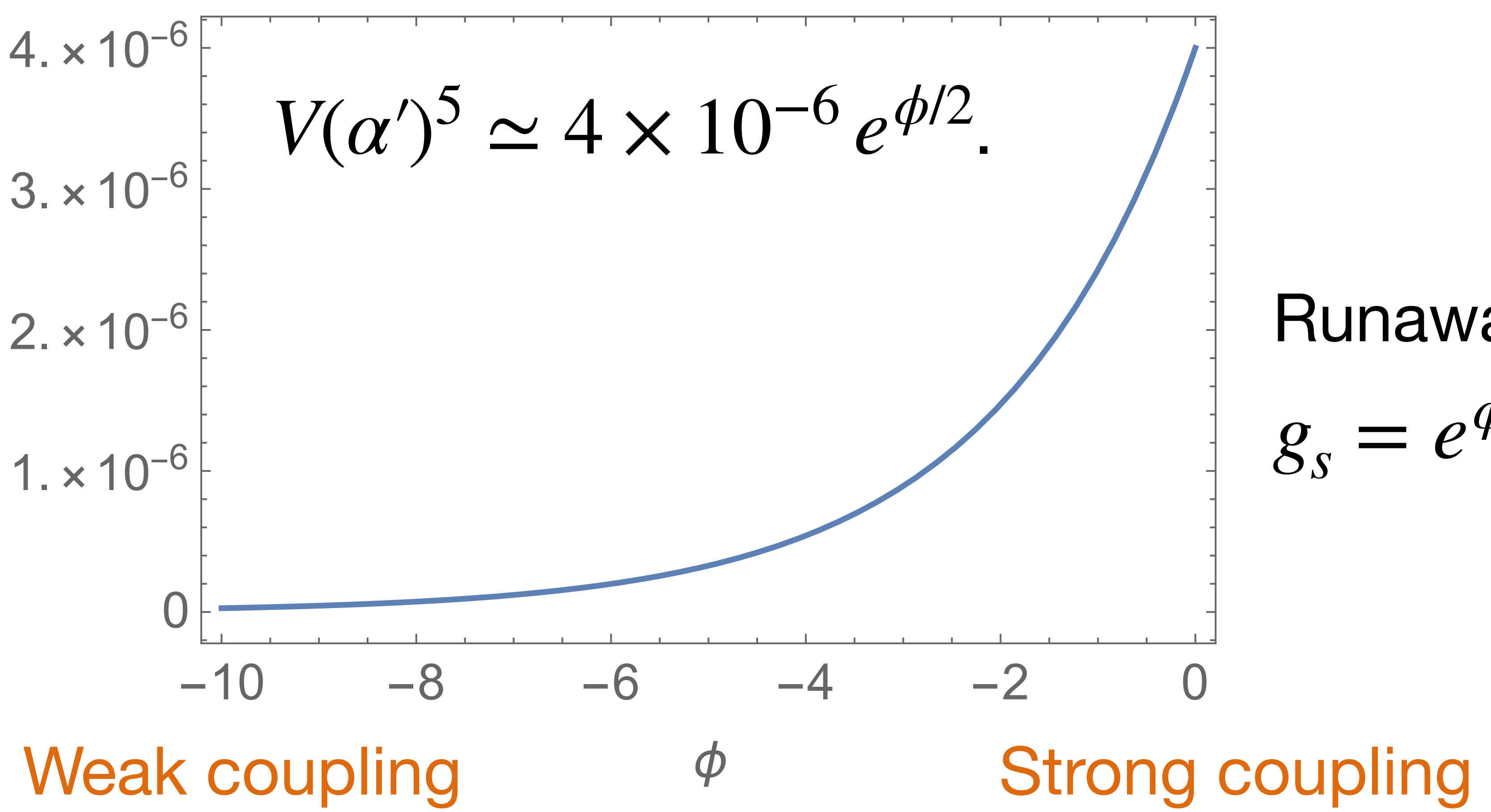
$$S = \int d^{10}x \sqrt{g} \left(R + \frac{1}{2} (\nabla \phi)^2 - \Lambda_{10} e^{\phi/2} + \cdots \right)$$

The potential is $V = \Lambda_{10} e^{\phi/2}$.

$$V = \Lambda_{10}\, e^{\phi/2}$$

Einstein frameでのdilaton potential:

$$V = \Lambda_{10} e^{\phi/2} \simeq 4 \times 10^{-6} (\alpha')^{-5} e^{\phi/2}.$$



Runaway potential to $g_s = e^{\phi} \to 0.$

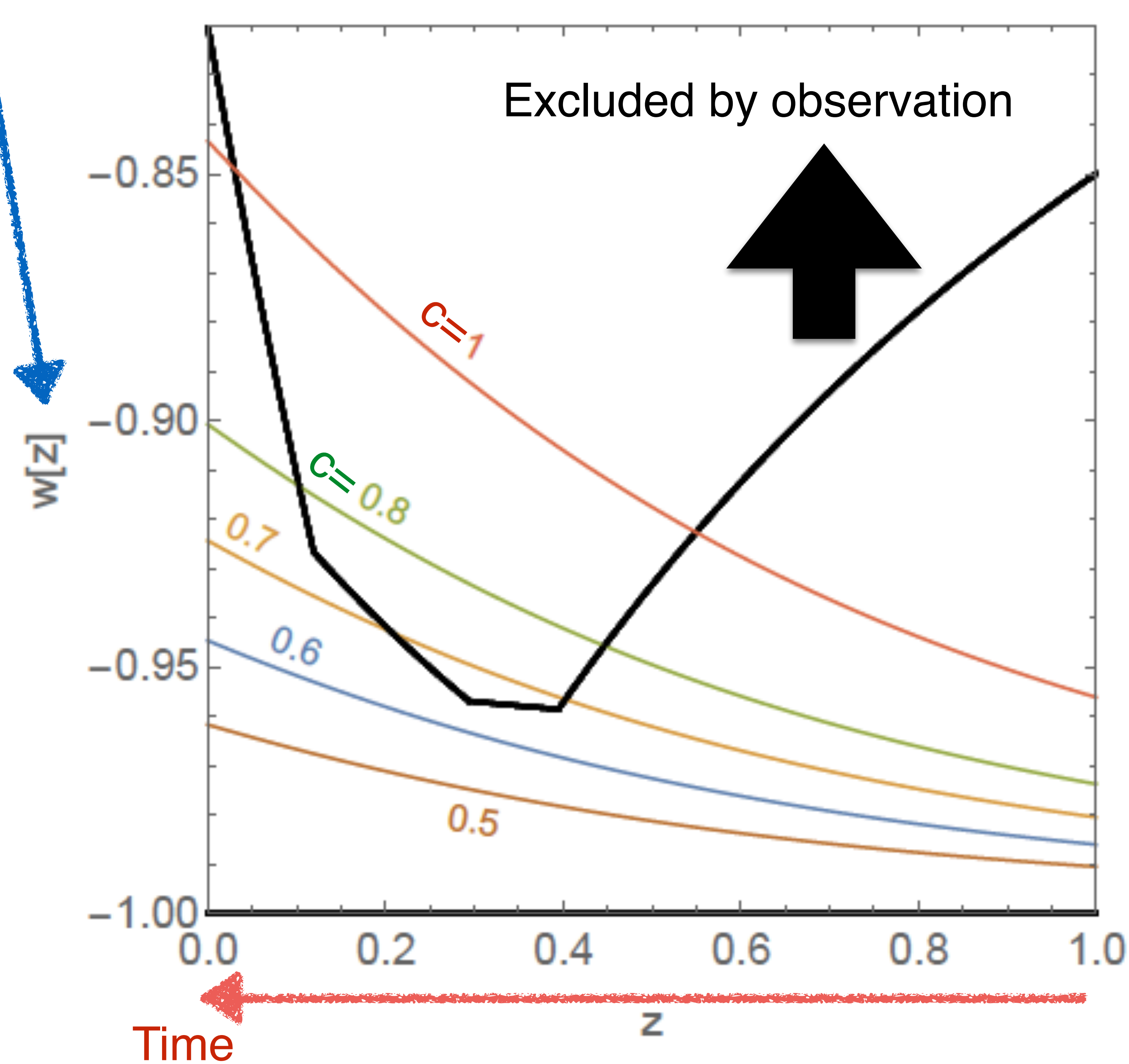
Constraint

$$|\nabla V| \geq \frac{c}{M_P} V.$$

制限は $c < 0.6$.

Equation of state, p=wρ

[Agrawal-Obied-Steinhardt-Vafa ’18]



Summary

The study of BH and string theory implies the number of Swampland Conjectures.

- No Global Symmetry Conjecture
- Weak Gravity Conjecture
- Distance Conjecture
- de Sitter Conjecture