Gravity is Different

Counterexamples to the Wilsonian Paradigm of Low Effective Theory

Hirosi Ooguri

Wolfgang Paul Centre Theoretical Physics Symposium
“Unsolved Problems in the Theory of Quantum Systems"
14 – 16 May 2025, DESY Hamburg

The physical world is hierarchical.

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Ken Wilson mathematically formulated this idea in the language of **effective theory**.

For each energy scale, there is a set of laws called an effective theory that describes physical phenomena at that scale, and **we can be ignorant of more fundamental laws at higher energies**.

Kenneth G. Wilson
(1961 Caltech PhD)

For example, the pion theory is an effective theory of QCD; we do not need to know details of QCD to discuss pion physics at energies far below the QCD scale.

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The basic assumption is that, **as long as an effective theory satisfies consistency conditions that are evident at the applicable scale, it can be derived from a more fundamental and mathematically consistent theory at higher scales.**

For example, the pion theory is an effective theory of QCD; we do not need to know details of QCD to discuss pion physics at energies far below the QCD scale.

The basic assumption is that, **as long as an effective theory satisfies consistency conditions that are evident at the applicable scale, it can be derived from a more fundamental and mathematically consistent theory at higher scales.**

In this talk, I will show that this assumption is false with gravity.

There are situations where the Einstein gravity,

$$S = \int d^4x\sqrt{g}\ \left(\Lambda + \frac{1}{G_N}R + \text{matter}\right)$$

can be treated as an effective theory and can be used to make reliable predictions including quantum effects, for example:

- **Hawking radiation** from a black hole
- **Fluctuation of cosmic microwave background** caused by quantum effects during the inflation
- **Corrections** to the Newton potential

$$V = -\frac{G_N m_1 m_2}{r}\left(1 + 3\frac{G_N(m_1+m_2)}{c^2 r} + \frac{41}{10\pi^2}\frac{G_N\hbar}{c^3 r^2} + \cdots\right)$$

Classical Relativity Effect **Quantum Effect**

“Presumably no field theory we have ever encountered, and perhaps no field theory of any type, is complete up to arbitrarily high energies. They are all effective theories, valid up to some cutoff.”

Joseph Polchinski (1975 Caltech BS),
Effective Field Theory and the Fermi Surface,
Lectures presented at TASI 1992.

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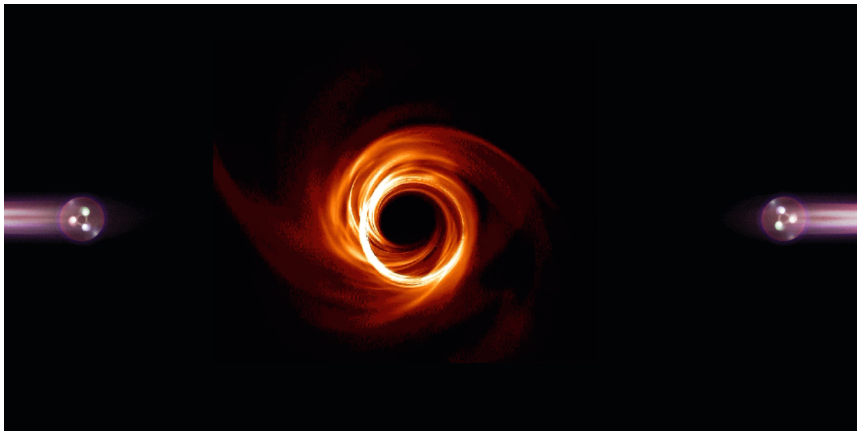
Gravity is different.

There are reasons to believe that any quantum theory of gravity must be complete by itself.

With gravity, the separation of UV and IR degrees of freedom fails. For example, the radius of the black hole horizon grows with energy.



$$\Delta x \sim \max\left(\frac{\hbar c}{E}, \frac{2G_N E}{c^4}\right) \geq \sqrt{\frac{2G_N \hbar}{c^3}}$$

We cannot probe phenomena shorter than

$$\ell_p = \sqrt{\frac{G_N \hbar}{c^3}}$$: Planck length.

This calls into question the validity of the Wilsonian paradigm when gravity is included.

This and known string theory constructions motivated the conjecture that there are conditions that any gravitational effective theory must satisfy, but which are not obvious from low-energy considerations alone.

Vafa: 0509212

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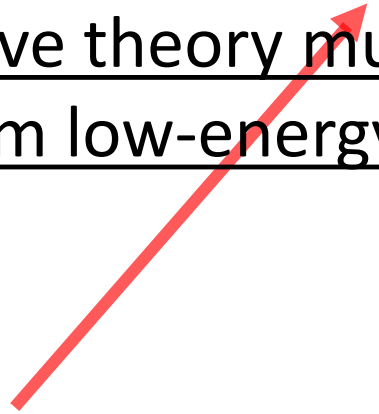

Such conditions would falsify the basic assumptions of the Wilsonian paradigm.

This and known string theory constructions motivated the conjecture that there are conditions that any gravitational effective theory must satisfy, but which are not obvious from low-energy considerations alone.

Vafa: 0509212

We have proven some of such conditions for gravitational theories with a negative cosmological constant, by using the AdS/CFT correspondence as the first principle.

Harlow + **H.O.**: 1810.05337, 1810.05338

Wang + **H.O.**: 2405.00674

This and known string theory constructions motivated the conjecture that there are conditions on gravitational effective theories which are not obvious from low energy considerations alone.

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Proof of Concept

We have proven some of such conditions for gravitational theories **with a negative cosmological constant**, by using the AdS/CFT correspondence as the first principle.

Harlow + **H.O.**: 1810.05337, 1810.05338

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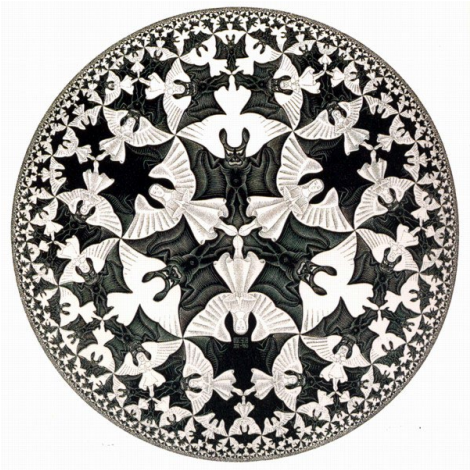
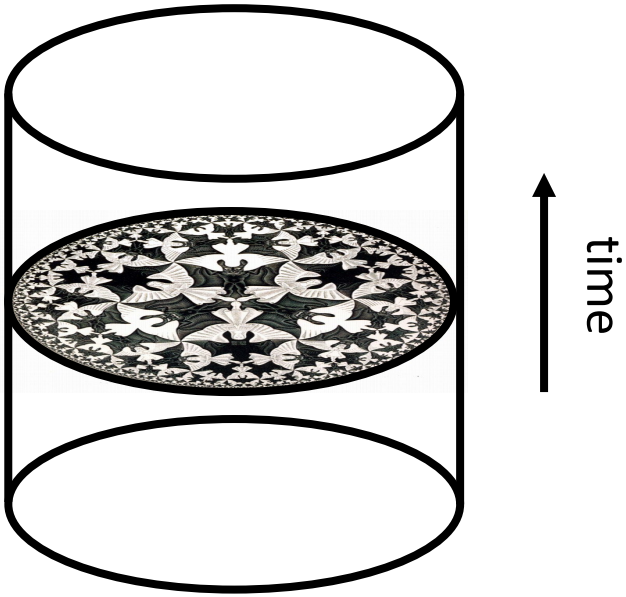
AdS/CFT Correspondence

Maldacena: 9711200

We consider gravitational theories with negative cosmological constant ($\Lambda < 0$).



add time



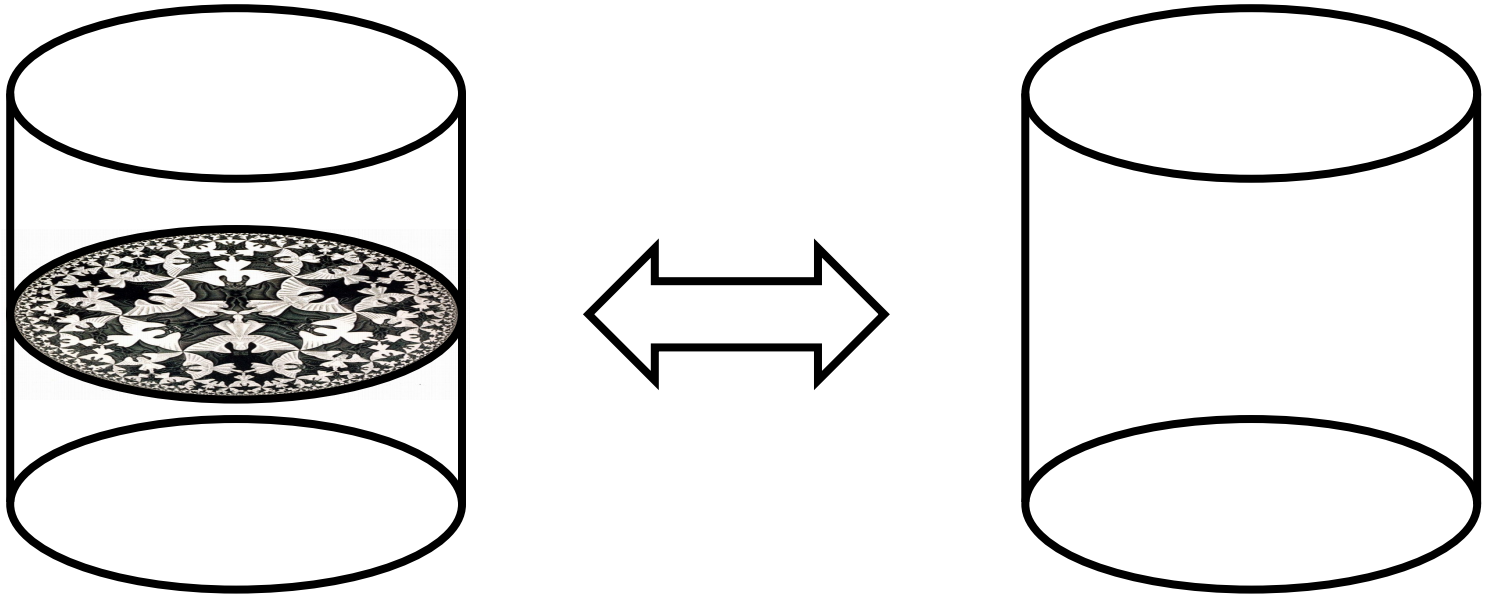
Hyperbolic Ball

Anti–de Sitter (AdS) spacetime

AdS/CFT Correspondence

Maldacena: 9711200

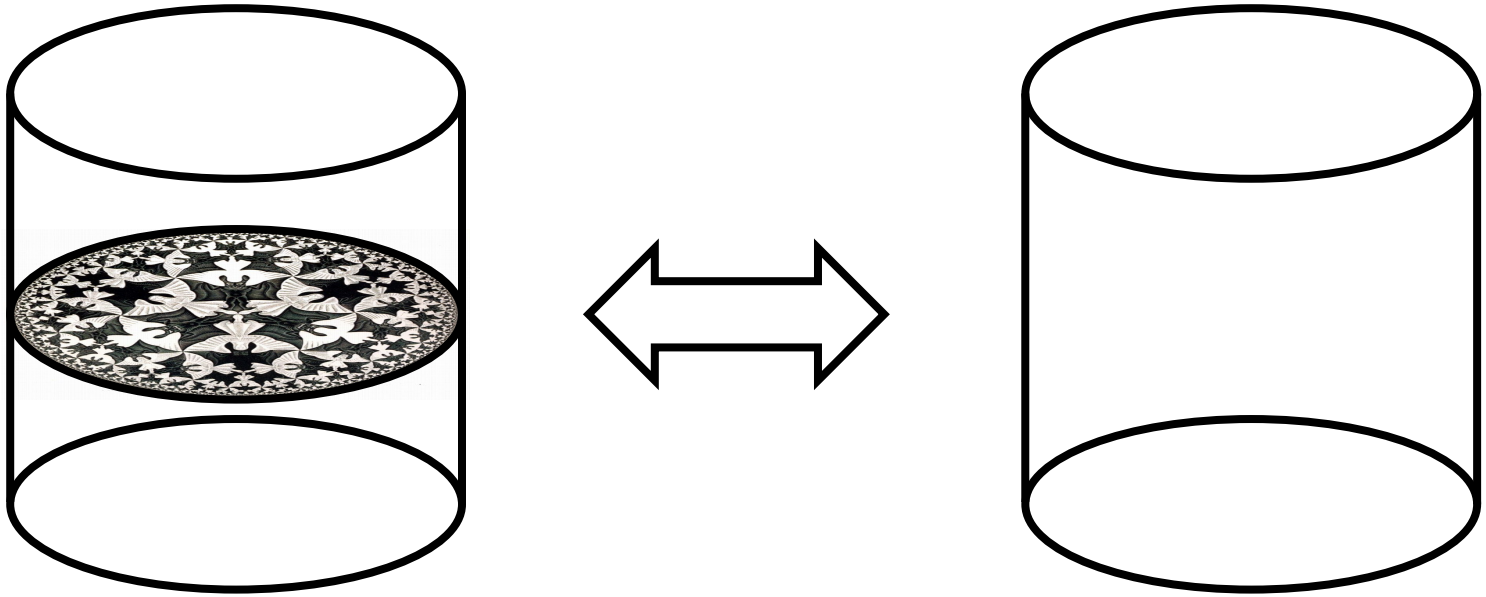
Any quantum gravity theory in $(d+1)$-dimensional **AdS** is equivalent to a scale invariant quantum field theory (**CFT**) without gravity in d dimensions.



AdS$_{d+1}$ gravity **CFT$_d$**

AdS/CFT Correspondence

By using **CFT as a definition of quantum gravity in AdS**, we will **derive several non-Wilsonian conditions**, which are not obvious from low-energy considerations alone.



AdS$_{d+1}$ gravity **CFT$_{d}$**

Two main threads of non-Wilsonian statements on gravitational theories

- No adjustable parameters (1949)

Distance Conjecture (2006)

$$m = \exp(-\alpha\,\phi + O(1))$$

- No global symmetry (1957)

Weak Gravity Conjecture (2006)

$$m^2 \leq \frac{d-2}{8\pi G_{\mathrm{N}}(d-3)}\,Q^2$$

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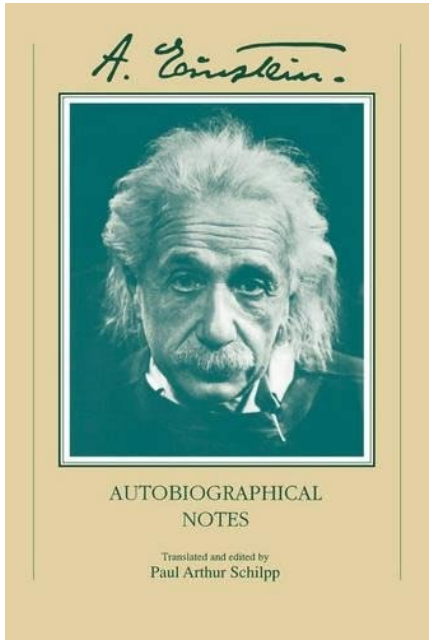
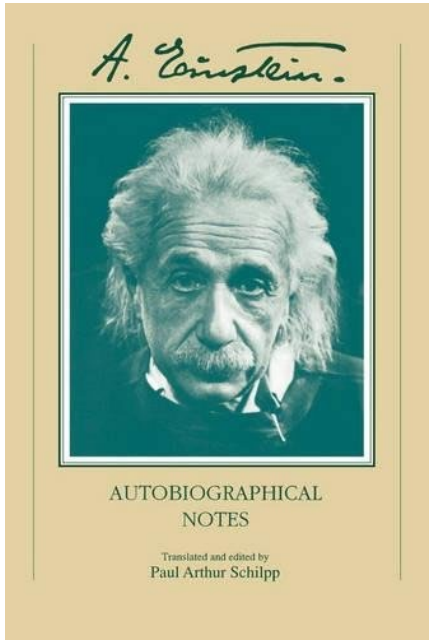
Perhaps, the first non-Wilsonian statement:



Autobiographical Notes
by Albert Einstein, 1949

After explaining the notion of the natural units,

"…, then **only dimensionless constants could occur in the basic equations of physics**. Concerning such I would like to state a theorem which at present cannot be based upon anything more than upon a faith in the simplicity, *i.e.*, intelligibility, of nature: **there are no adjustable constants of this kind** …"



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A modern formulation:

Distance Conjecture

Vafa + **H.O.**: 0605264

Conjecture 0:
Every parameter in quantum gravity is an expectation value of a dynamical field and can be varied by changing its expectation value.

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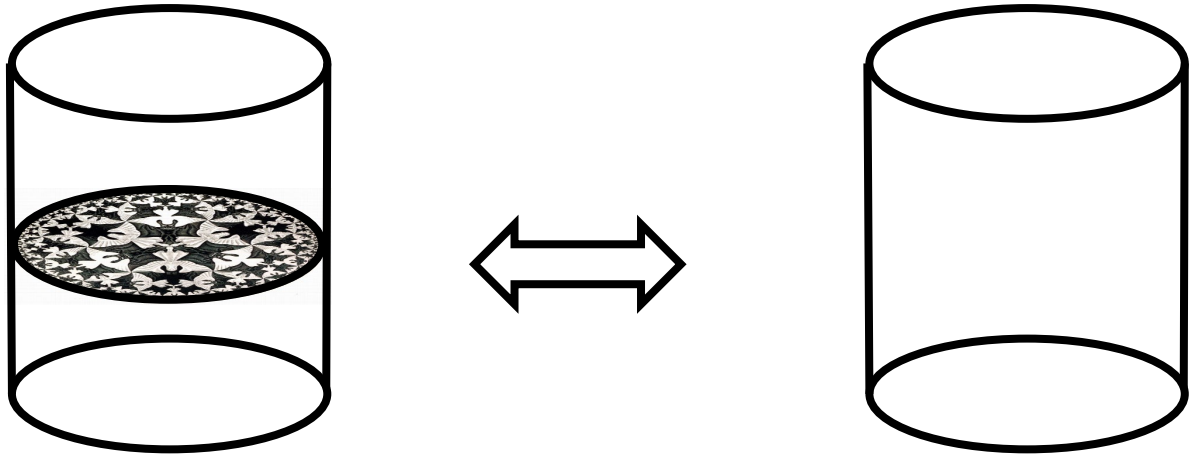
Let's prove it by AdS/CFT.

H.O.: Strings 2022 summary talk

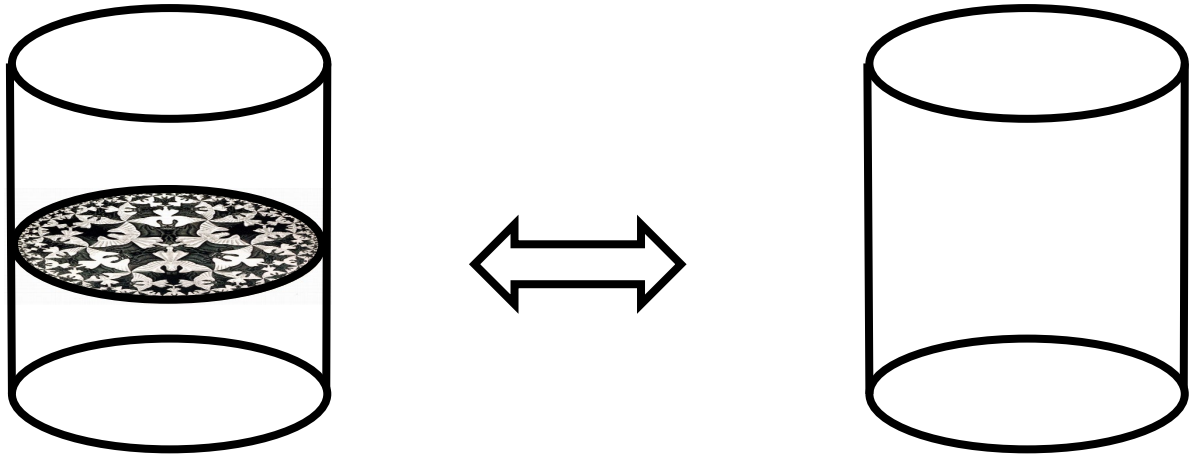


AdS$_{d+1}$ gravity **CFT$_d$**

Conjecture 0: Every parameter in quantum gravity is an expectation value of a dynamical field and can be varied by changing its expectation value.

Suppose there is a gravitational theory with a continuous parameter λ.

$\mathcal{L}_{\mathrm{AdS}}(\lambda)$

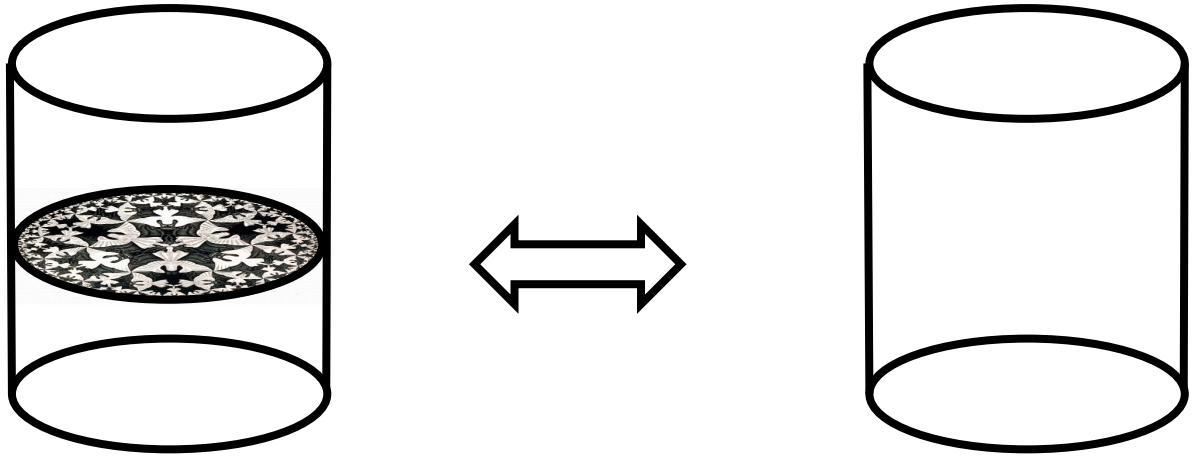


AdS$_{d+1}$ gravity **CFT$_d$**

Conjecture 0: Every parameter in quantum gravity is an expectation value of a dynamical field and can be varied by changing its expectation value.

There is a corresponding parameter in CFT.

$\mathcal{L}_{\mathrm{AdS}}(\lambda)$ $\mathcal{L}_{\mathrm{CFT}}(\lambda)$

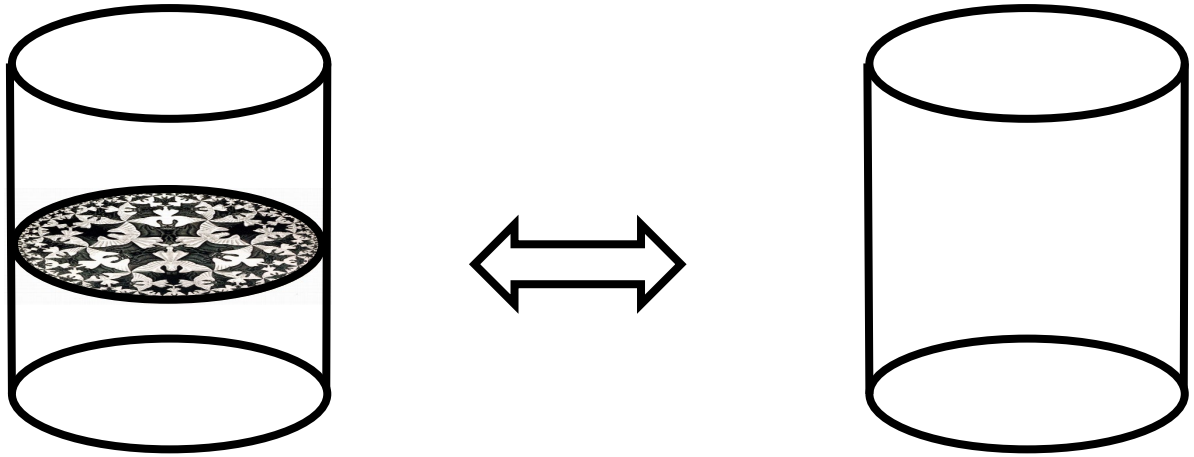


AdS$_{d+1}$ gravity **CFT$_d$**

Conjecture 0: Every parameter in quantum gravity is an expectation value of a dynamical field and can be varied by changing its expectation value.

Each parameter in CFT is associated with an "exactly marginal" operator $\mathcal{O}$.

$$\mathcal{L}_{\mathrm{CFT}}(\lambda + \delta\lambda) = \mathcal{L}_{\mathrm{CFT}}(\lambda) + \delta\lambda\, \mathcal{O}$$



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$$\mathcal{L}_{\mathrm{CFT}}(\lambda + \delta\lambda) = \mathcal{L}_{\mathrm{CFT}}(\lambda) + \delta\lambda\, \mathcal{O}$$

According to the AdS/CFT correspondence, for each $\mathcal{O}$ in CFT, there is a massless scalar ϕ in AdS such that $\delta\lambda = \langle\phi\rangle$.

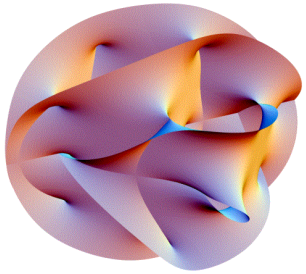
The parameter λ is an expectation value of ϕ in AdS.

Conjecture 0: Every parameter in quantum gravity is an expectation value of a dynamical field and can be varied by changing its expectation value.

This by itself **does not provide a useful constraint** since what appear to be adjustable parameters in a low energy theory may be fixed by potentials in a more fundamental high energy theory.

For example, **the Standard Model of Particle Physics has 19 parameters (plus 7 with massive neutrinos) and the ΛCDM Model of Cosmology has 6 parameters**; They do not contain dynamical fields corresponding to these parameters.

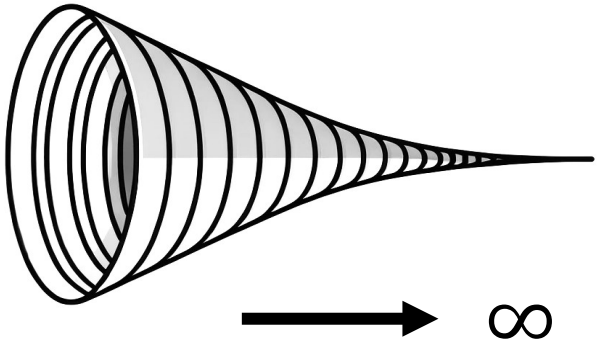
Two more observations based on string theory constructions:



Vafa + **H.O.**: 0605264

1. On the parameter space (called moduli space), there are always **infinite distance directions**.

2. As we go to infinite distance, the low energy effective theory is broken, with **an emergent tower of light particles**.



The distance is measured by the metric defined by the kinetic terms of the fields corresponding to the parameters.

Distance Conjecture

Vafa + **H.O.**: 0605264

Conjecture 0: Every parameter in quantum gravity is an expectation value of a dynamical field and can be varied by changing its expectation value.

Conjecture 1: Choose any point p_0 in the moduli space $\mathcal{M}$. For any positive ϕ, there is another point $p \in \mathcal{M}$ such that $d(p, p_0) > \phi$.

Conjecture 2: Compared to the theory at $p_0 \in \mathcal{M}$, the theory at p with $d(p, p_0) > \phi$ has an infinite tower of light particles starting with mass of the order of $e^{-\alpha\phi}$ for some $\alpha > 0$.

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NUCLEAR PHYSICS B

On the geometry of the string landscape and the swampland

Hirosi Ooguri [a,*], Cumrun Vafa [b]

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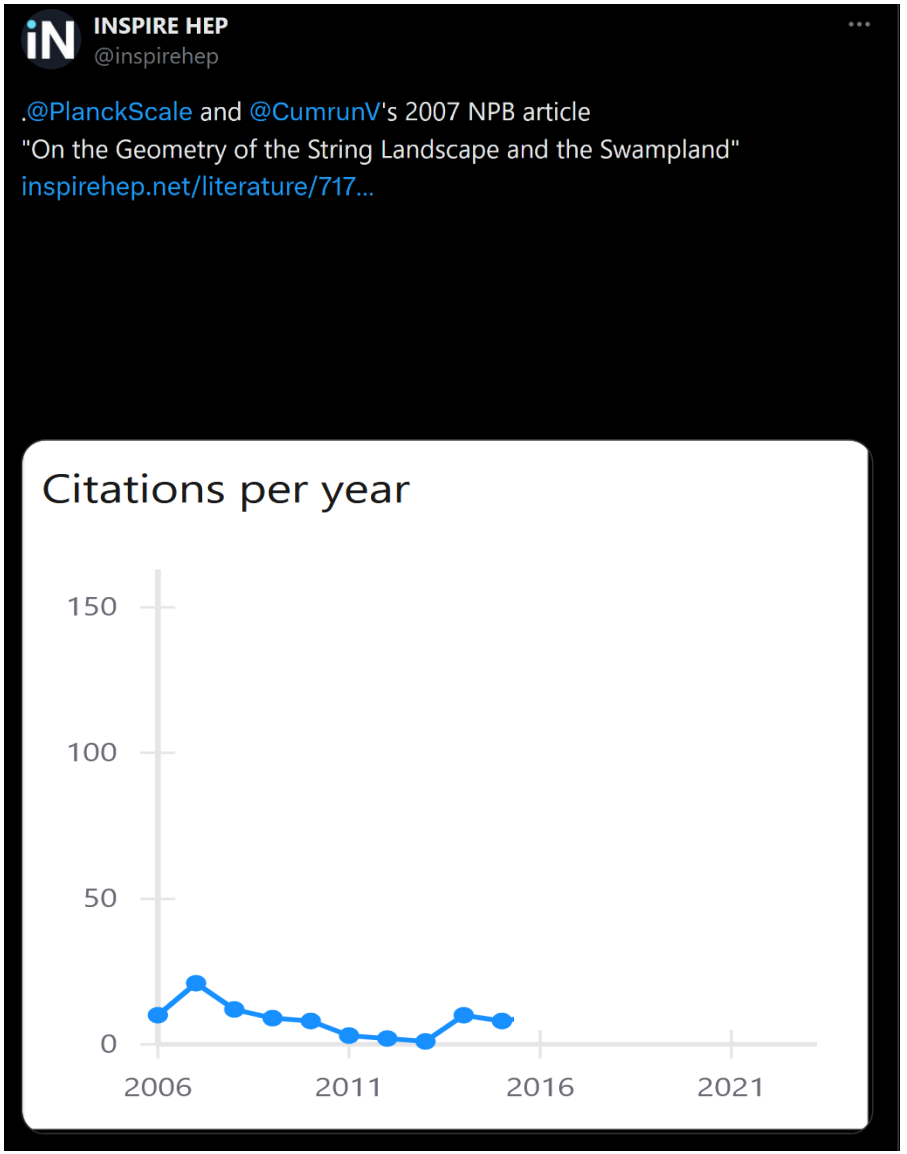
Received 15 September 2006; accepted 18 October 2006
Available online 13 December 2006

Abstract

We make a number of conjectures about the geometry of continuous moduli parameterizing the string landscape. In particular we conjecture that such moduli are always given by expectation value of scalar fields and that moduli spaces with finite non-zero diameter belong to the swampland. We also conjecture that points at infinity in a moduli space correspond to points where an infinite tower of massless states appear, and that near these regions the moduli space is negatively curved. We also propose that there is no non-trivial 1-cycle of minimum length in the moduli space. This leads in particular to the prediction of the existence of a radially massive partner to the axion. These conjectures put strong constraints on inflaton potentials that can appear in a consistent quantum theory of gravity. Our conjectures are supported by a number of highly non-trivial examples from string theory. Moreover it is shown that these conditions can be violated if gravity is decoupled.

1. Introduction

The fact that string theory seems to offer a diverse range of possibilities for vacua has been viewed as a drawback for the theory: we cannot converge on a precise prediction for the theory. However despite this diversity of options for the string landscape, it has been pointed out in [1] that there are also a number of patterns that seem to emerge. Not every effective field theory that appears consistent seems to arise in string theory. It is natural to conjecture that these theories are



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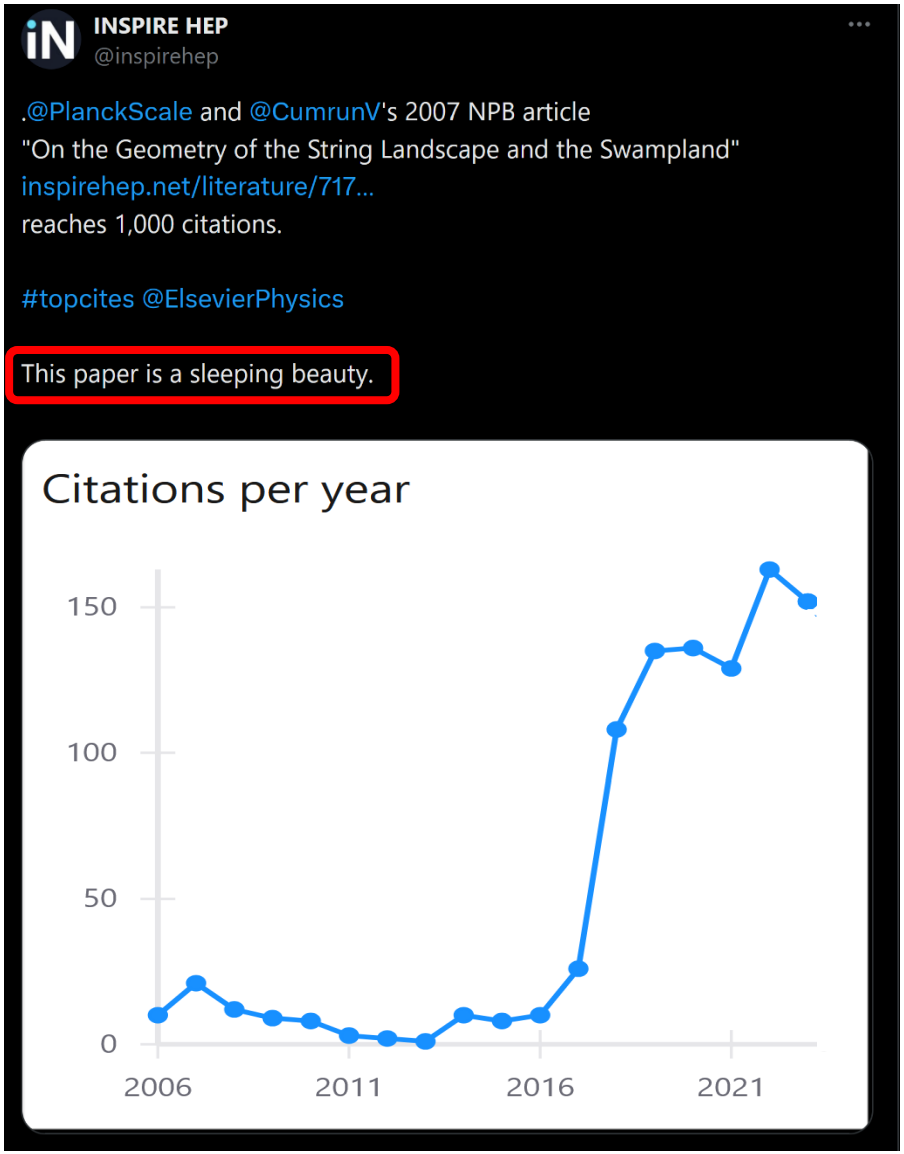
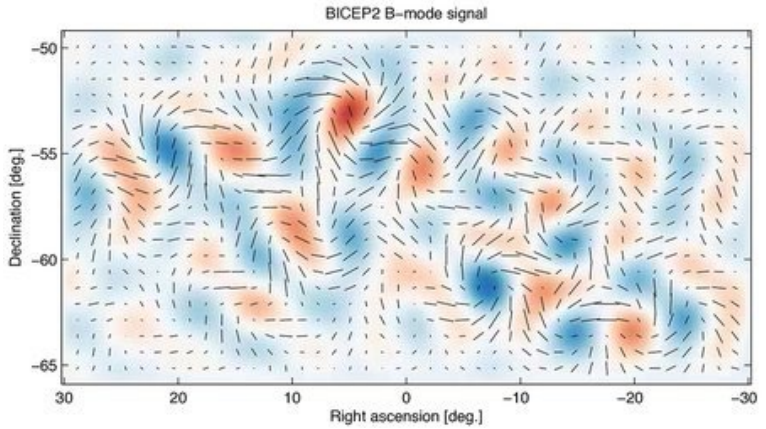
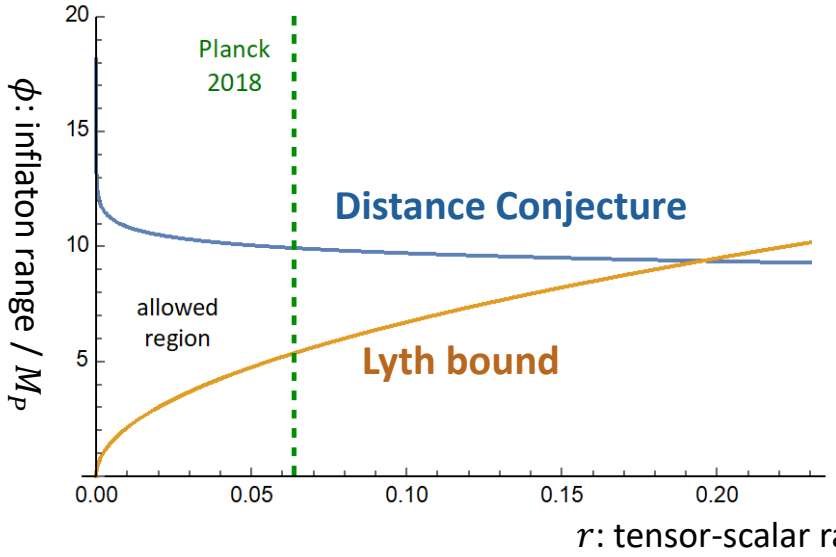




If the 2014 BICEP2 result on the tensor-scalar ratio of the cosmic microwave background radiation had been of a primordial origin, **it would have contradicted our Distance Conjecture.**



Based on a **conservative estimate of α** in $m = e^{-\alpha\phi}$.

We have proven a part of Distance Conjecture in $\mathrm{AdS}_3/\mathrm{CFT}_2$ using the **conformal bootstrap**.

Wang + **H.O.**: 2405.00674

If there is a particle in AdS_3 whose mass vanishes at some point in the moduli space, the distance ϕ to the point is infinite, the mass vanishes exponentially,

$$m^2 = \frac{s-1}{\ell_{\mathrm{AdS}}^2} \exp(-\boldsymbol{\alpha}\,\phi + O(1))$$

and **α is bounded as,**

$$\left(\frac{2}{3}\ell_{\mathrm{P}}\right)^{1/2} \leq \boldsymbol{\alpha} \leq (8\pi\ell_{\mathrm{AdS}})^{1/2}$$

Planck scale

AdS scale

- No adjustable parameters (1949)

Distance Conjecture (2006)

$$m = \exp(-\alpha\,\phi + O(1))$$

- No global symmetry (1957)

Weak Gravity Conjecture (2006)

$$m^2 \leq \frac{d-2}{8\pi G_{\mathrm{N}}(d-3)}\,Q^2$$

Perhaps, the second-earliest non-Wilsonian statement:

Misner, Wheeler, “Classical Physics as Geometry," Annals Phys. 2 (1957) 525.

ANNALS OF PHYSICS: 2, 525–603 (1957)

Classical Physics as Geometry

Gravitation, Electromagnetism, Unquantized Charge, and Mass as Properties of Curved Empty Space*

CHARLES W. MISNER† AND JOHN A. WHEELER‡

Lorentz Institute, University of Leiden, Leiden, Netherlands, and Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

If classical physics be regarded as comprising gravitation, source free electromagnetism, unquantized charge, and unquantized mass of concentrations of electromagnetic field energy (geons), then classical physics can be described in terms of curved empty space, and nothing more. No changes are made in existing theory. The electromagnetic field is given by the "Maxwell square root" of the contracted curvature tensor of Ricci and Einstein. Maxwell's equations then reduce, as shown thirty years ago by Rainich, to a simple statement connecting the Ricci curvature and its rate of change. In contrast to unified field theories, one then secures from the standard theory of Maxwell and Einstein an "*already* unified field theory." This purely geometrical description of electromagnetism is traced out in detail. Charge receives a natural interpretation in terms of source-free electromagnetic fields that (1) are everywhere subject to Maxwell's equations for free space but (2) are trapped in the "worm holes" of a space with a multiply-connected topology. Electromagnetism in such a space receives a detailed description in terms of the existing beautiful and highly developed mathematics of topology and harmonic vector fields. Elementary particles and "real masses" are completely excluded from discussion as belonging to the world of quantum physics.

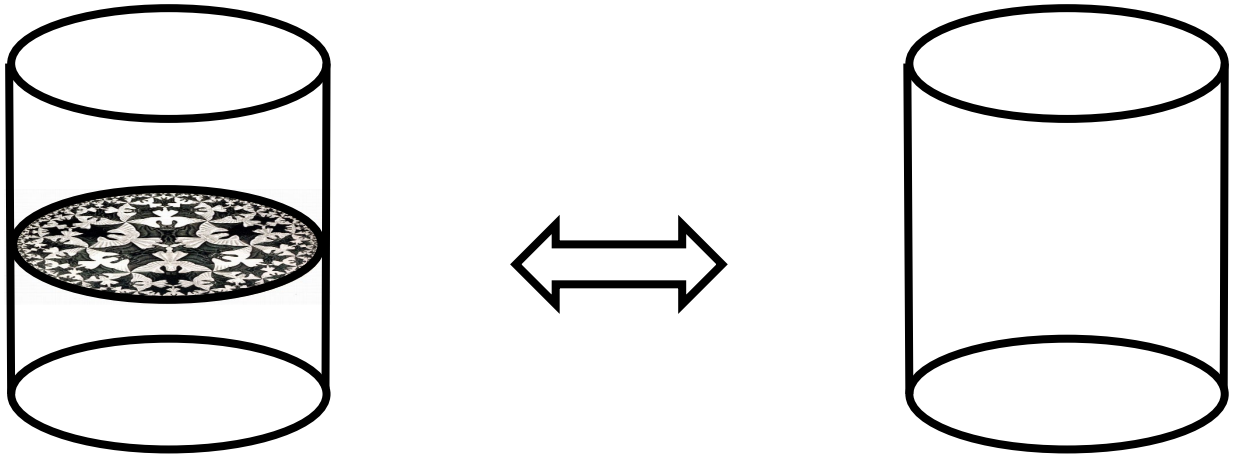
"I transmit but I do not create; I am sincerely fond of the ancient."—Confucius.

A modern formulation:

There is no global symmetry in quantum gravity.

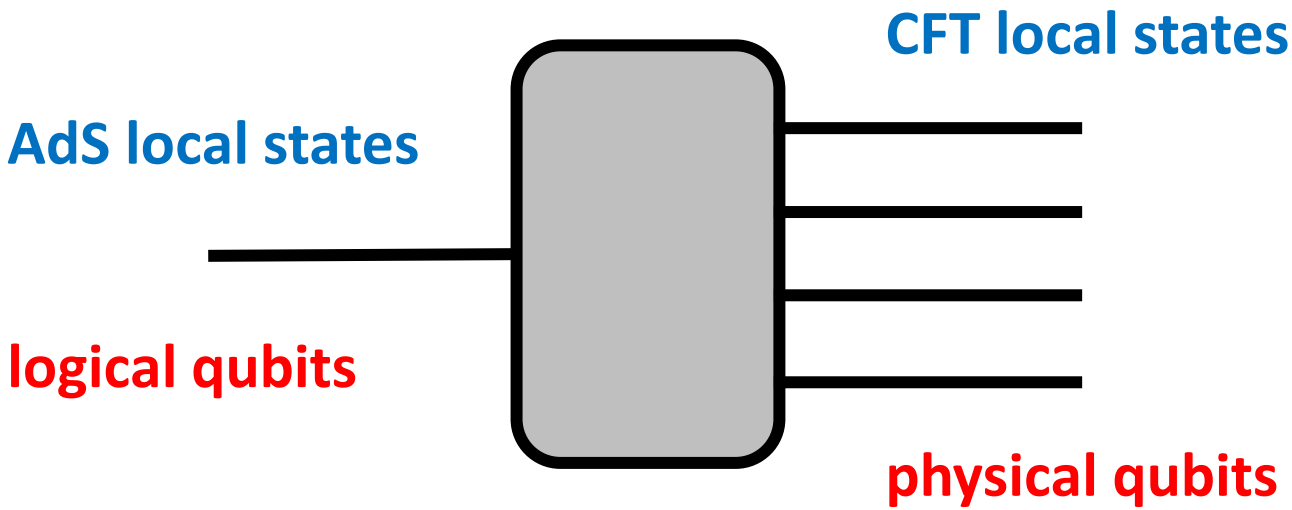
We proved the absence of global symmetry in quantum gravity by using the AdS/CFT correspondence.

Harlow + **H.O.**: 1810.05337
1810.05338



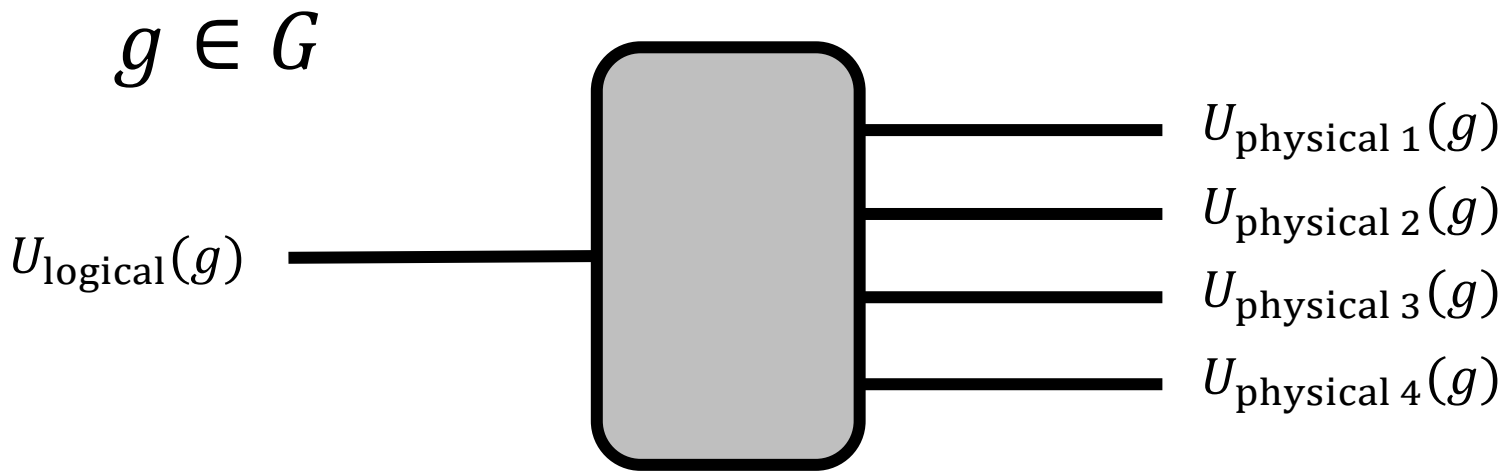
Our proof makes use of the relation between the **holography of quantum gravity** and **quantum error correcting codes** in quantum information theory.

Almheiri, Dong, Harlow: 1411.7041
Harlow: 1607.03901



In quantum information theory, **the Eastin–Knill theorem forbids** quantum error correcting code to have a continuous **symmetry which acts transversely** on physical qubits, *i.e.*, does not couple physical subsystems within the same code block.

Eastin, Knill: 0811.4262

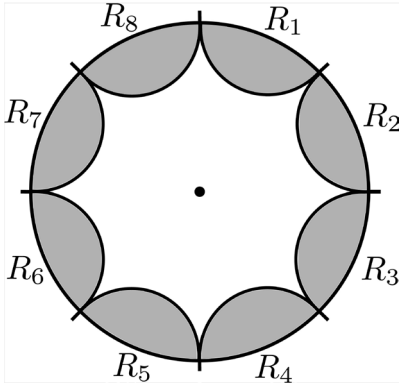


Harlow and I noticed that, in AdS/CFT correspondence, the **transversality** is implied by **the Noether theorem**.

No global symmetry

Harlow + **H.O.**: 1810.05337
1810.05338

If a gravitational theory has global symmetry,
there must be a bulk local operator that transforms faithfully into another local operator.



Symmetry generator,

$$U(g,R) = \otimes_i U(g,R_i)$$

commute with the local operator at x in the bulk.

Contradiction

There is no global symmetry in quantum gravity.

This by itself **does not give a useful constraint** since a low energy theory may have accidental symmetry which is violated in high energy.

For example, the Standard Model of Particle Physics preserves the $(B - L)$ symmetry, but it can be violated or gauged in high energy.

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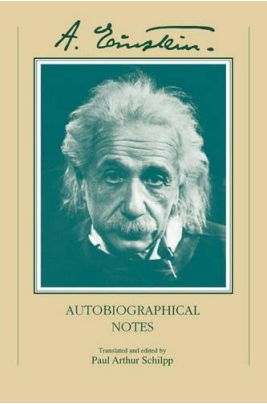


This is analogous to the absence of parameters — what seems like an adjustable parameter may be an expectation value of a dynamical field fixed by a potential.

Weak Gravity Conjecture

Arkani-Hamed, Motl, Nicolis, Vafa: 0601001

In any low energy theory described by the Einstein gravity, a Maxwell field, and a finite number of matter fields,

if it has an UV completion as a consistent quantum theory,

there must be a particle with charge Q and mass $m \ll M_{\text{Planck}}$ such that

$$m^2 \leq \frac{d-2}{8\pi G_{\text{N}}(d-3)} Q^2.$$

A slightly stronger conjecture $m^2 < \frac{d-2}{8\pi G_N (d-3)} Q^2$ implies

implies the **inequality between the dark energy and the neutrino masses**.

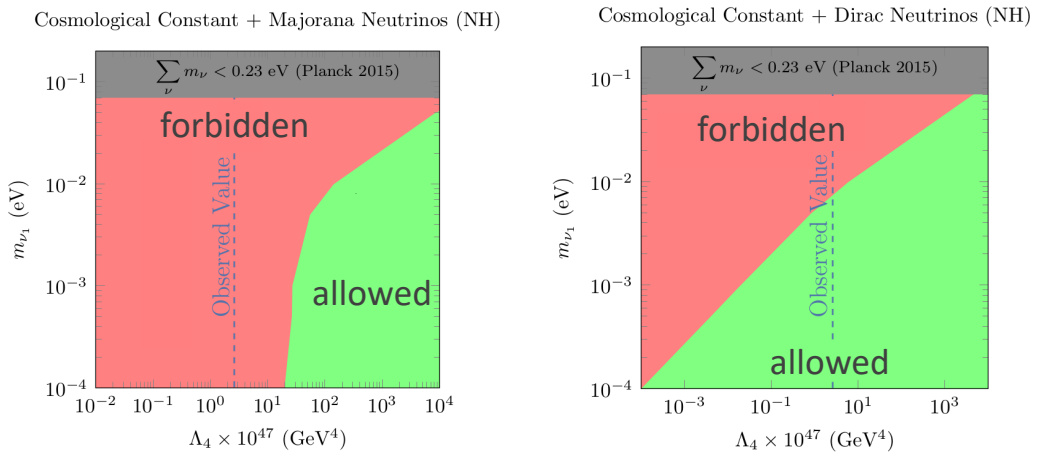
Vafa + **H.O.**: 1610.01533

neutrino masses

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

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

First <u>non-cosmological</u> argument for $\Lambda > 0$.



Ibáñez, Martín-Lozano, Valenzuela: 1706.05392

- No adjustable parameters (1949)

Distance Conjecture (2006)

$$m = \exp(-\alpha\,\phi + O(1))$$

- No global symmetry (1957)

Weak Gravity Conjecture (2006)

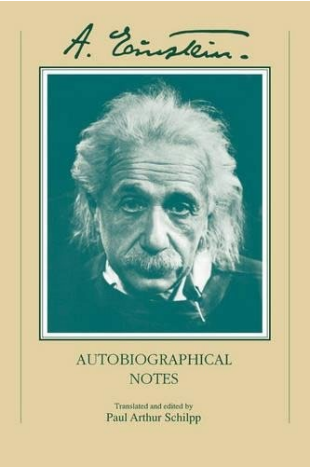
$$m^2 \leq \frac{d-2}{8\pi G_{\mathrm{N}}(d-3)}\,Q^2$$

For the last decade, the notion of global symmetry has been greatly generalized.

Gaiotto, Kapustin, Seiberg, Willett: 1412.5148

- **p-form symmetry**: the Noether charge is co-dimension $(p+1)$.
- **non-invertible symmetry**: makes an algebra, not a group.

Traditional symmetries are 0-form & invertible.



The **absence of adjustable parameters** in quantum gravity can be regarded as the **absence of (-1)-form symmetry**.

- No adjustable parameters (1949)

QUANTIFY

Distance Conjecture (2006)

$$m = \exp(-\alpha\,\phi + O(1))$$

Unified

- No global symmetry (1957)

QUANTIFY

Weak Gravity Conjecture (2006)

$$m^2 \leq \frac{d-2}{8\pi G_{\mathrm{N}}(d-3)}\,Q^2$$

- No adjustable parameters (1949)

QUANTIFY

Distance Conjecture (2006)

$$m = \exp(-\alpha\,\phi + O(1))$$

?

- No global symmetry (1957)

QUANTIFY

Weak Gravity Conjecture (2006)

$$m^2 \leq \frac{d-2}{8\pi G_{\mathrm{N}}(d-3)}\,Q^2$$

Summary

Gravity is different

Unsolved Problems

There are constraints on low-energy effective theories of gravitational systems that cannot be captured by the standard Wilsonian paradigm.

- No arbitrary parameters 

Distance Conjecture
- No global symmetry 

Weak Gravity Conjecture

In AdS, we can quantify and prove parts of these conjectures.

Can we <u>strengthen</u> these results, <u>prove</u> them, and <u>generalize</u> them for spacetimes with <u>zero and positive vacuum energies</u>?