Swampland

Myth, Fact, and Truth

Hirosi Ooguri

Hitoshi Fest @ Kavli IPMU
16 – 20 December 2024

My Three Encounters with Hitoshi

Institute for the Physics and Mathematics of the Universe

2007 - present

2006

2006

- 28 March: **Cabinet Decision:** Science and Technology Basic Plan

  "The goal is to eventually create around 30 research centers that can be positioned as **world premier research centers**."

- 7 July: **Cabinet Decision:** Basic Policy on Economic and Fiscal Management and Structural Reform

  "**By 2010**, we will develop world premier research centers (approximately 30 centers) and drastically strengthen graduate school education."

- 25 December: **Conference of Experts** on Creating World Premier Research Centers

  "we need to build world premier research centers in Japan … and **create places where the world's best minds can come together**, produce excellent research results, and foster human resources… **this should be put into practice from FY2007**"

The initial response of the University of Tokyo

Tentative name:

Research Center for Neutrinos, Astroparticles and Cosmology

March 2007

IPMU Interview
with Sadanori Okamura
Interviewer: Hiroaki Aihara

IPMU News No. 14

"before the invitation for applications was announced at the university, Professor Katsuhiko Sato had been coordinating submission of at least one proposal in physics. At first, I think **the discussion started to adopt the neutrino as a central topic of the project**, probably influenced by a strong image of Professor Masatoshi Koshiba."

Then, a new leader emerged …

14 April 2007 4:18 AM

Dear Hitoshi,

I understand that Professors Suzuki and Aihara went to see you in Berkeley. I meant to call you earlier, but Yanagida san advised me that it would be useful for me to talk to you after their visit. Would there be a convenient time to call? I am visiting Tokyo until late May, so there is an 8 hour time difference (e.g., 9 am in Tokyo is 5 pm in California).

regards, Hirosi

15 April 2007 3:03 PM

Hi Hirosi,

I'm home after 7pm PDT tonight.
The number here is [redacted]
If you give me your phone number,
I can call, too.

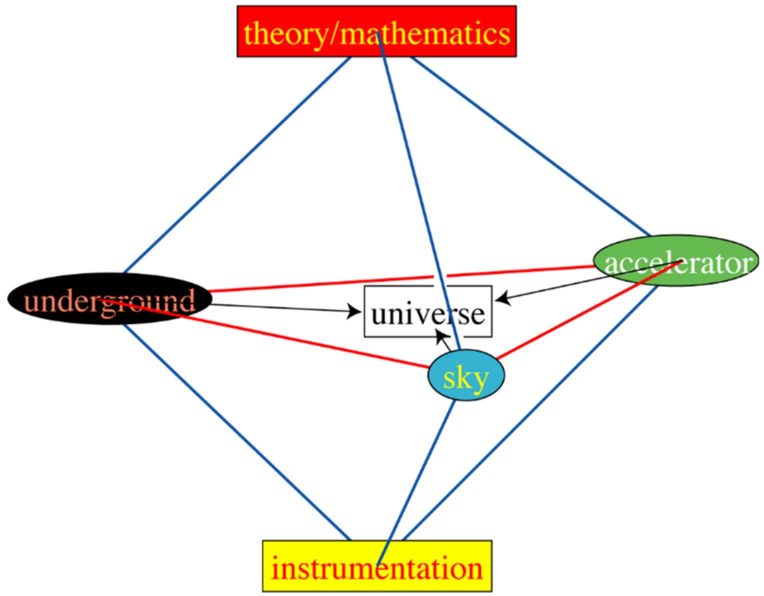
Hitoshi

19 April 2007

Just to make my own thinking clear, I've written a draft vision document that will be needed in the proposal. It is still rough, but I hope it presents a sensible overall vision of the Institute. Nothing is set in stone here; criticisms welcome.

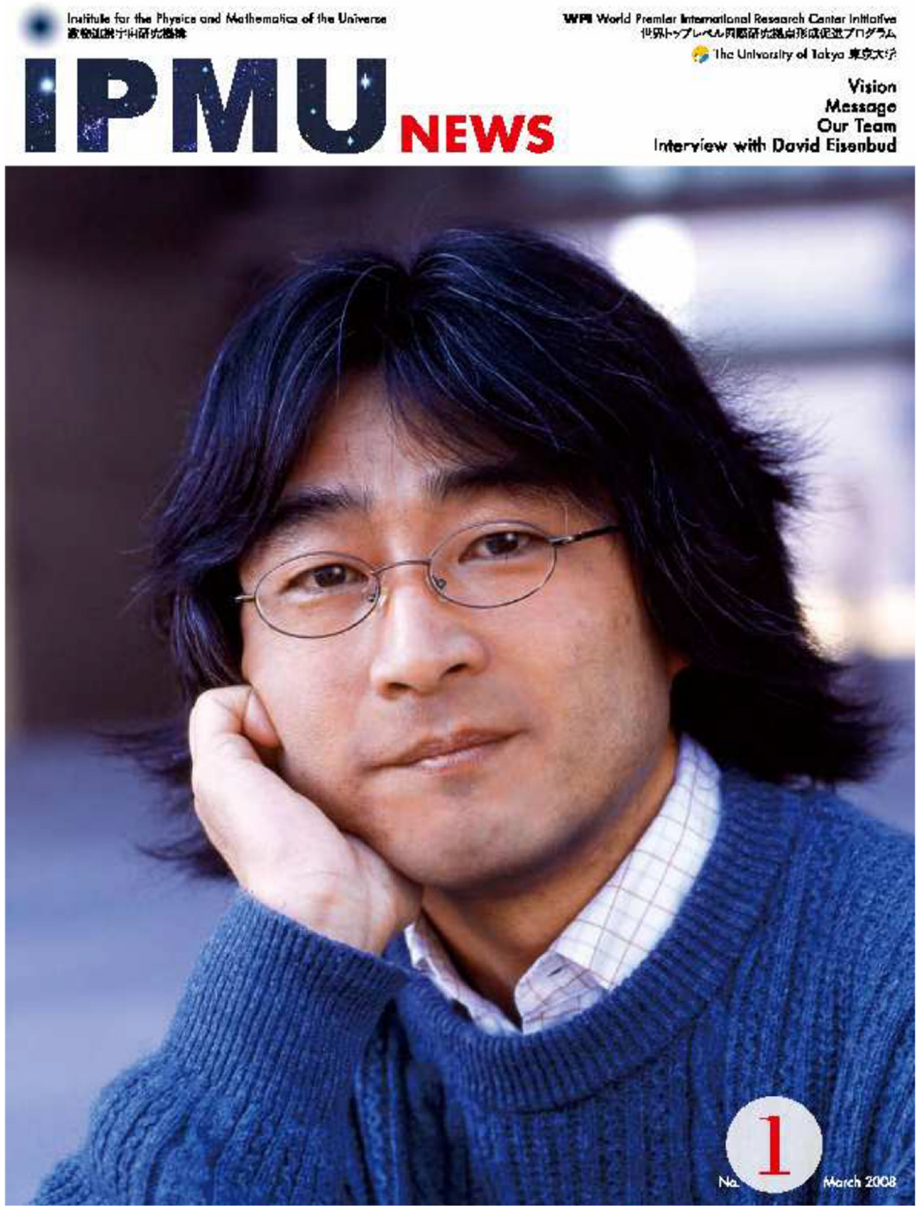
Hitoshi

Attachment "Vison for the Institute for the Unified Description of the Universe"



My vision of the Institute is a multi-prong but coherent attack on these questions. It is based on three broad experimental approaches, tied together with two common threads.

The rest is history …



IPMU News No. 1 (March 2008)

大賞 **宇宙は何でできているのか**
村山 斉 幻冬舎新書 133点

2位	デフレの正体	藻谷浩介	角川oneテーマ21	109点
3位	街場のメディア論	内田 樹	光文社新書	84点
4位	競争と公平感	大竹文雄	中公新書	52点
5位	伊藤博文	瀧井一博	中公新書	35点

2011 New Paperback Grand Prize
9 March 2011

順位	書名	著者	出版	点数
大賞	宇宙は何でできているのか	村山 斉	幻冬舎新書	133点
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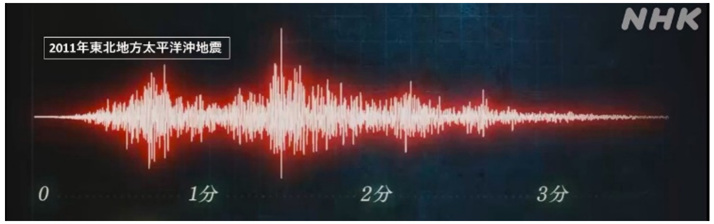
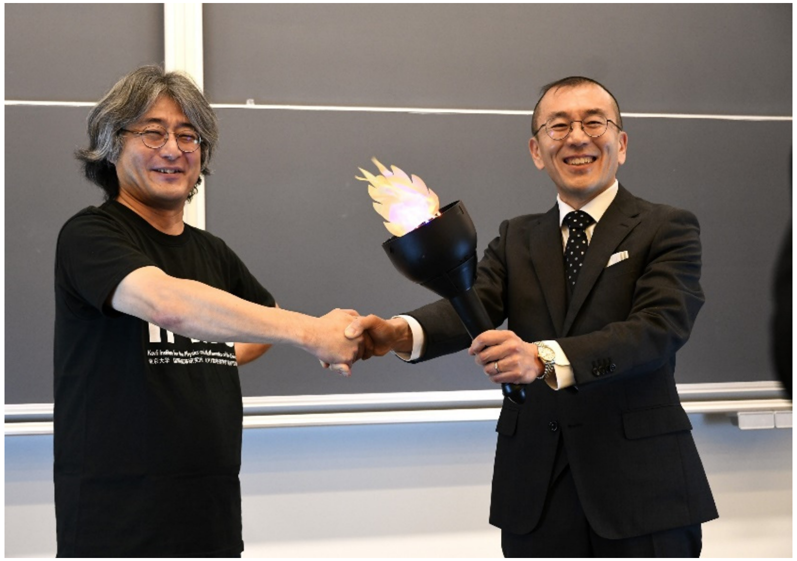


Great East Japan Earthquake
11 March 2011

Kavli IPMU endowment was established in April 2012

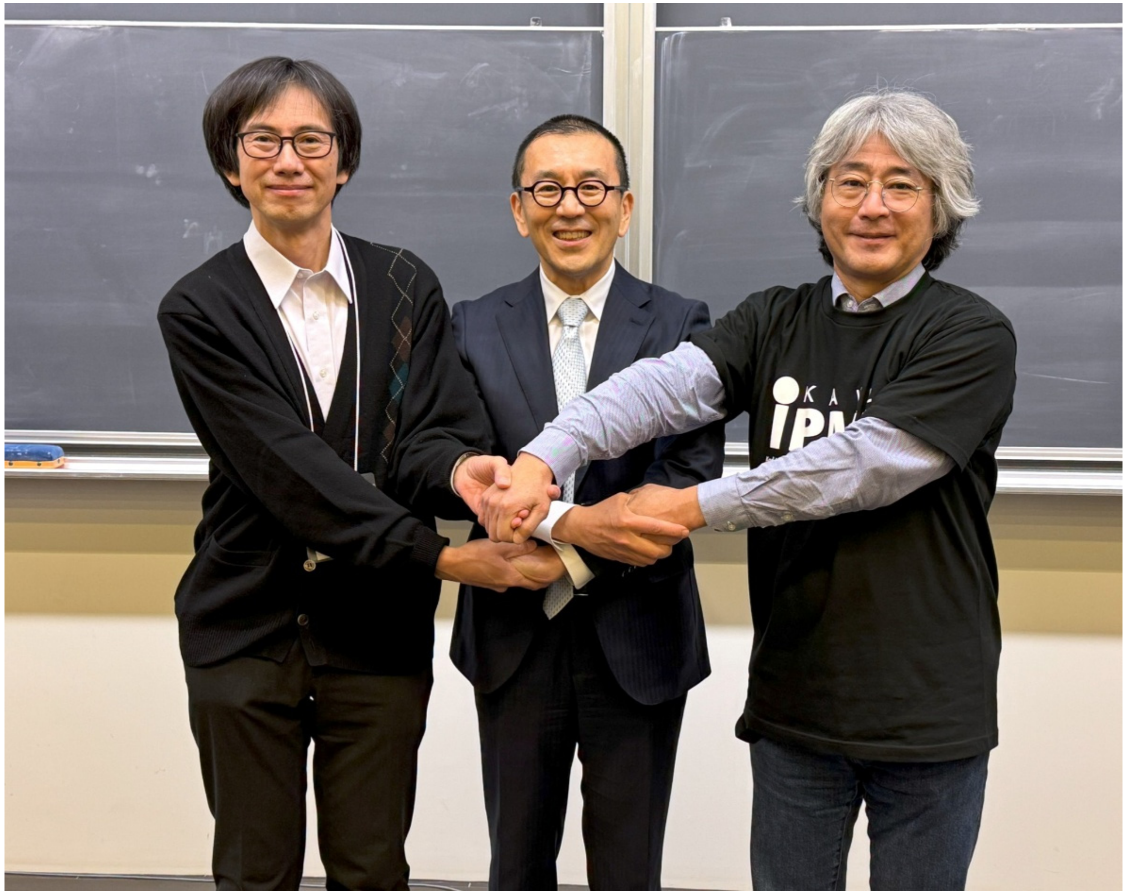
IPMU News No. 7
September 2009

Kavli Prize Ceremony
Oslo, Norway
4 September 2012



Kavli IPMU
15 October 2018

Hongo Campus
12 January 2020



Kavli IPMU
16 December 2024

University of California, Berkeley

1994 – 2000

January 1995

December 1996

JHEP HYPER VERSION RECEIVED: *December 1, 1998*, ACCEPTED: *December 30, 1998*

Gaugino mass without singlets*

Gian F. Giudice and Riccardo Rattazzi
Theory Division, CERN,
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Markus A. Luty
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Hitoshi Murayama
Department of Physics, University of California,
Berkeley, California 94720, USA
E-mail: murayama@lbl.gov

N·H ELSEVIER
28 September 2000
PHYSICS LETTERS B
Physics Letters B 490 (2000) 125–130
www.elsevier.nl/locate/npe

The dark side of the solar neutrino parameter space ☆

André de Gouvêa [a], Alexander Friedland [b,c], Hitoshi Murayama [b,c]

[a] *CERN - Theory Division, CH-1211 Geneva 23, Switzerland*
[b] *Department of Physics, University of California, Berkeley, CA 94720, USA*
[c] *Theory Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

Received 18 August 2000; accepted 23 August 2000

VOLUME 85, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 2000

New Perspective on Cosmic Coincidence Problems

Nima Arkani-Hamed, Lawrence J. Hall, Christopher Kolda, and Hitoshi Murayama
Department of Physics, University of California, Berkeley, California 94720
Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720
(Received 5 June 2000)

University of Tokyo

1986 – 1988

Hitoshi: 1986 – 1991

Physics Tree
The Academic Genealogy of Physics

Takahiko Yamanouchi University of Tokyo	Hironari Miyazawa University of Tokyo	Keiji Igi University of Tokyo
Hironari Miyazawa University of Tokyo	Hirotaka Sugawara University of Tokyo	Hikaru Kawai University of Tokyo

Hitoshi Murayama
UC Berkeley

Hirosi: 1986 – 1988

High Energy Theory Group

The retirement party in honor of
Professor Hironari Miyazawa
29 March 1988

Six months after I went to Princeton, I received this preprint from Tokyo.

UT-542
March, 1989

Explicit Quantization of the Chern-Simons Action

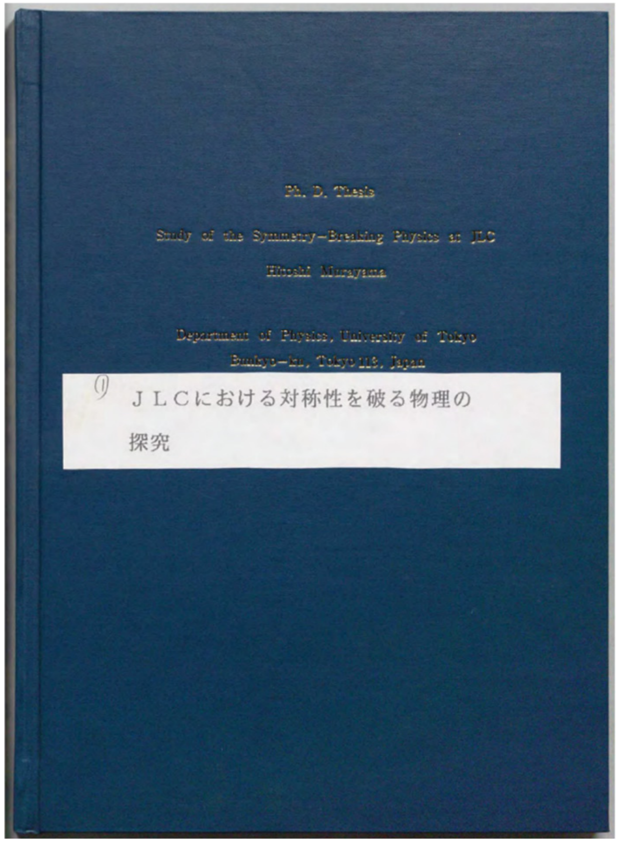
Hitoshi Murayama

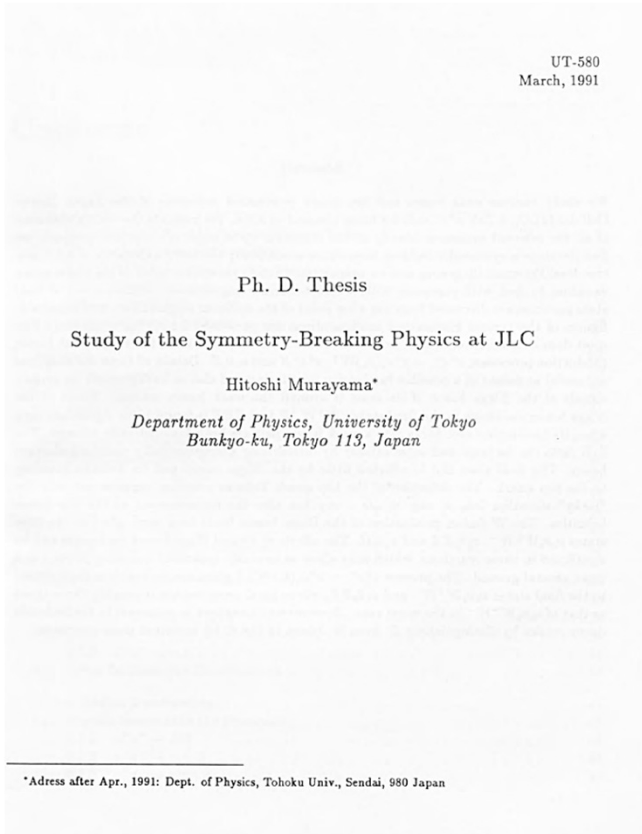
Department of Physics, University of Tokyo
Bunkyo-ku, Tokyo 113, Japan

Abstract

We quantize the three-dimensional Chern-Simons action explicitly. We found that the geometric quantization of the action strongly depends on the topology of the (fixed-time) Riemann surface. On the disk the phase space and the symplectic structure are the same as those of the (chiral) Wess-Zumino-Witten model. On the torus the Hilbert space is the vector space of characters of Kac-Moody algebras. The fusion rules of the primary fields are derived from the *classical* matching condition of the holonomy. In general case, the wave-functional of the theory is the generating function of the current insertion in Wess-Zumino-Witten model.

Although he has moved on to areas more closely connected with experiments and observations and has had a great impact there, …





UT-580
March, 1991

Ph. D. Thesis

Study of the Symmetry-Breaking Physics at JLC

Hitoshi Murayama*

Department of Physics, University of Tokyo
Bunkyo-ku, Tokyo 113, Japan

*Adress after Apr., 1991: Dept. of Physics, Tohoku Univ., Sendai, 980 Japan

… he continues to produce beautiful work on mathematical properties of QFT as well.

PHYSICAL REVIEW D VOLUME 57, NUMBER 11 1 JUNE 1998

Renormalization group invariance of exact results in supersymmetric gauge theories

Nima Arkani-Hamed and Hitoshi Murayama
Theoretical Physics Group, Ernest Orlando Lawrence Berkeley National Laboratory,
University of California, Berkeley, California 94720
and Department of Physics, University of California, Berkeley, California 94720
(Received 10 June 1997; published 12 May 1998)

PRL **108,** 251602 (2012) PHYSICAL REVIEW LETTERS week ending 22 JUNE 2012

Unified Description of Nambu-Goldstone Bosons without Lorentz Invariance

Haruki Watanabe[1,2,*] and Hitoshi Murayama[1,3,4,†]
[1]*Department of Physics, University of California, Berkeley, California 94720, USA*
[2]*Department of Physics, University of Tokyo, Hongo, Tokyo 113-0033, Japan*
[3]*Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[4]*Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, University of Tokyo, Kashiwa 277-8583, Japan*
(Received 3 March 2012; published 21 June 2012)

JHEP HYPER VERSION RECEIVED: *June 15, 2000,* ACCEPTED: *Jun 19, 2000*

Holomorphy, rescaling anomalies and exact β functions in supersymmetric gauge theories

Nima Arkani-Hamed and Hitoshi Murayama
Theoretical Physics Group, E.O. Lawrence Berkeley National Laboratory
University of California, Berkeley, California 94720, and
Department of Physics, University of California, Berkeley, California 94720
E-mail: arkani@thwk1.lbl.gov, murayama@thsrv.lbl.gov

PHYSICAL REVIEW LETTERS **126,** 251601 (2021)

Some Exact Results in QCD-like Theories

Hitoshi Murayama[*]
Department of Physics, University of California, Berkeley, California 94720, USA,
Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa 277-8583, Japan,
and Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
(Received 10 April 2021; revised 13 May 2021; accepted 2 June 2021; published 23 June 2021)

I do not like the classification of high energy theorists into phenomenologists and formal theorists, and **Hitoshi is the reason why**.

Hitoshi Murayama

- Distinguished scientist
- Inspiring teacher
- Visionary leader
- Effective communicator
- Conscientious citizen
- Wonderful friend

Congratulations and thank you!

Swampland

Myth, Fact, and Truth

It is often said that low-energy effective theory is a way to parameterize our ignorance.

It is important to make sure that we are not parameterizing an empty set.

For non-gravitational systems, one can write down any low-energy effective theory and expect that it has a consistent ultraviolet completion.

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This is not the case with the gravity:

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

For non-gravitational systems, one can write down any low-energy effective theory and expect that it has a consistent ultraviolet completion.

This is not the case with the gravity:

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

For gravitational systems, there are **constraints on** their **low-energy effective theories** that cannot be captured by the standard Wilsonian paradigm.

- No arbitrary parameters (1949)

QUANTIFY ⇒ Distance Conjecture (2006)

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

- No global symmetry (1957)

QUANTIFY ⇒ Weak Gravity Conjecture (2006)

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

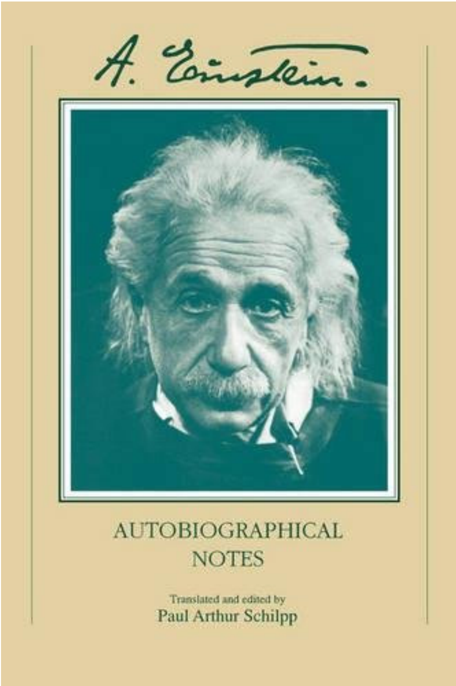
No arbitrary parameters

QUANTIFY →

Distance Conjecture

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

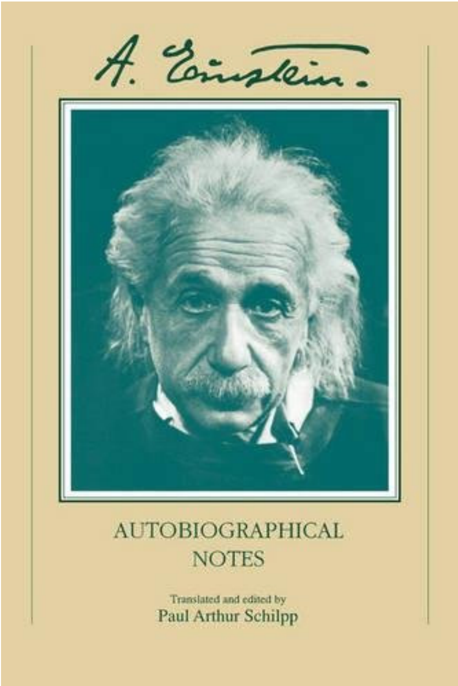
Perhaps, the earliest Swampland condition:



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 arbitrary constants of this kind** …"



Autobiographical Notes
by Albert Einstein, 1949

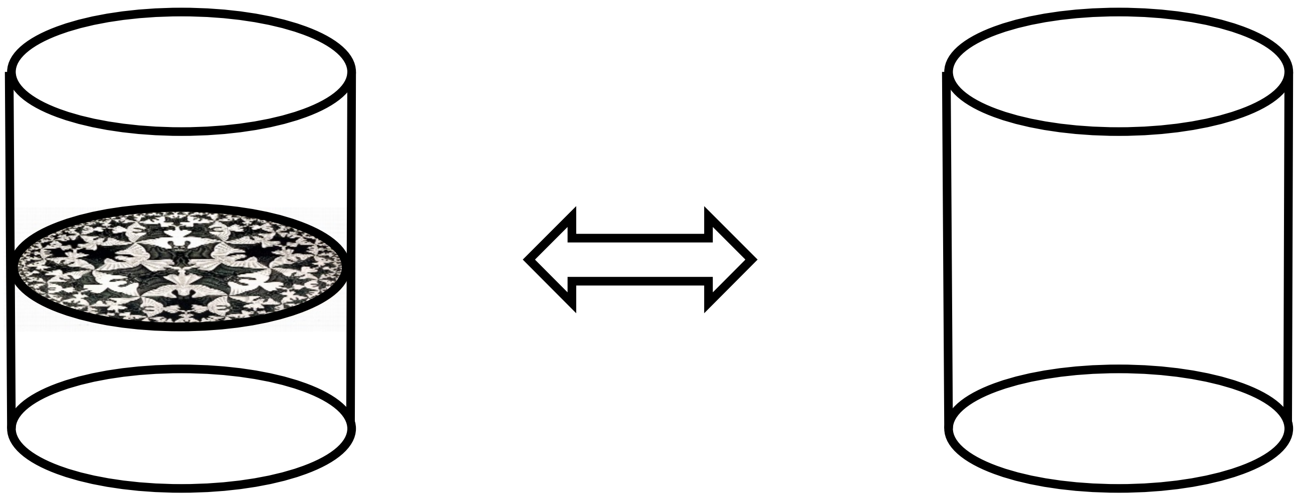
A modern formulation:
Distance Conjecture

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.

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

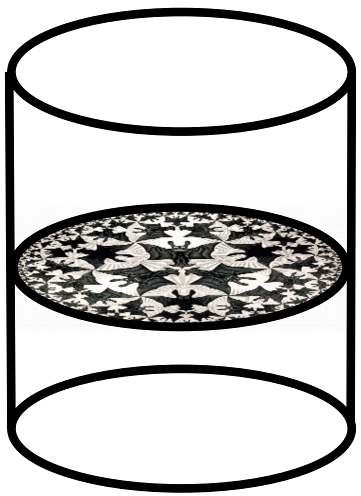
Let's prove it by AdS/CFT.



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.

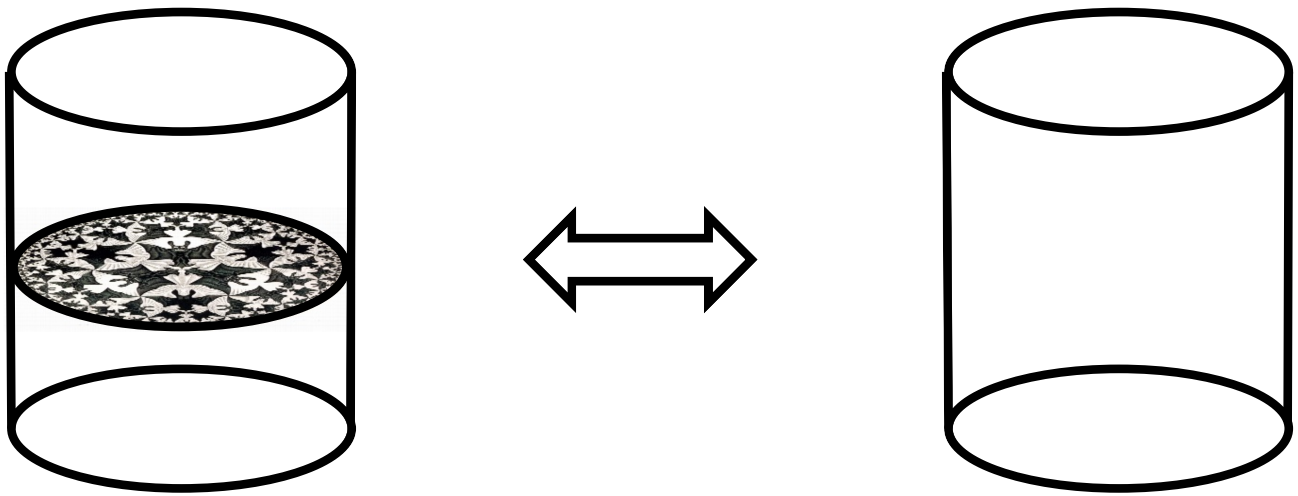
$\mathcal{L}_{\mathrm{AdS}}(\lambda)$



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.

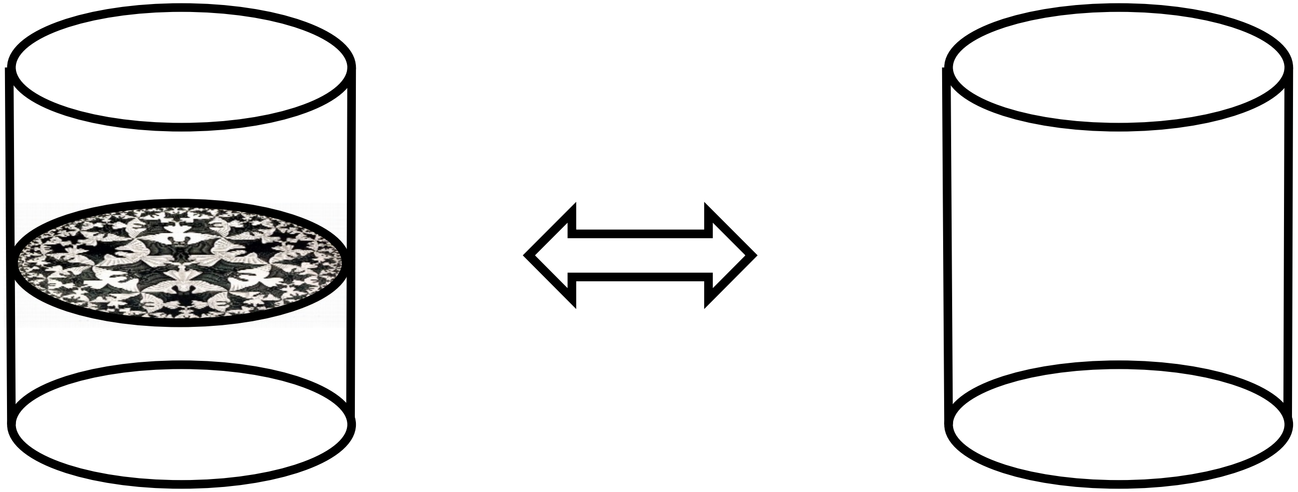
$\mathcal{L}_{\mathrm{AdS}}(\lambda)$ $\qquad\qquad$ $\mathcal{L}_{\mathrm{CFT}}(\lambda)$



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 $\mathcal{O}$.

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



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 $\mathcal{O}$.

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

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.

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

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

To be precise …

This is a conjecture about CFT and requires a proof.

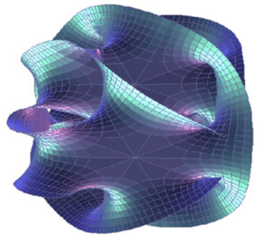
Komatsu, Kusuki, Meineri + H.O., in progress

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 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.**

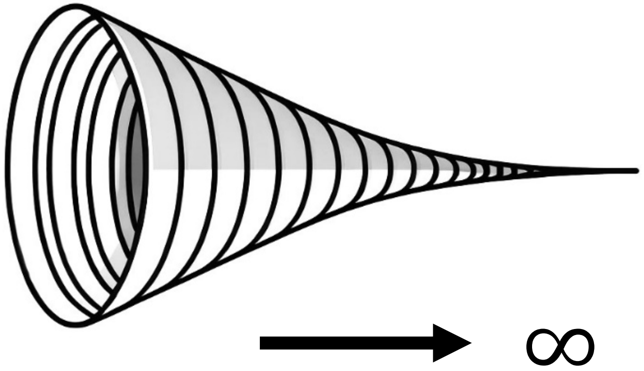
Two more observations based on string theory constructions:



Vafa + H.O.: 0605264

1. On the parameter space (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 $\alpha > 0$.

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics B 766 (2007) 21–33

NUCLEAR PHYSICS B

On the geometry of the string landscape and the swampland

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

[a] *California Institute of Technology, Pasadena, CA 91125, USA*
[b] *Jefferson Physical Laboratory, Harvard University, Cambridge, MA 02138, USA*

Received 15 September 2006; accepted 18 October 2006

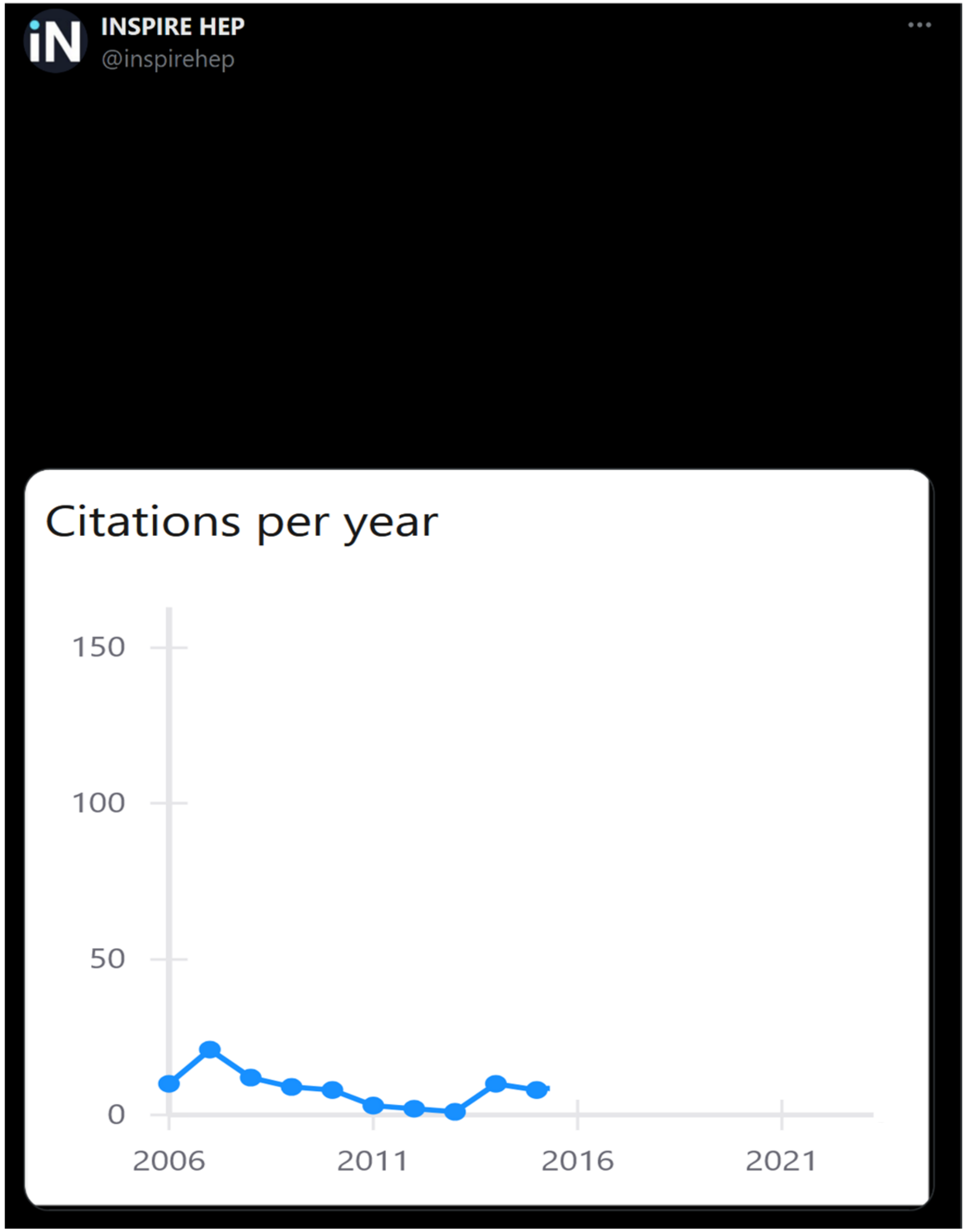
Available online 13 December 2006

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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INSPIRE HEP
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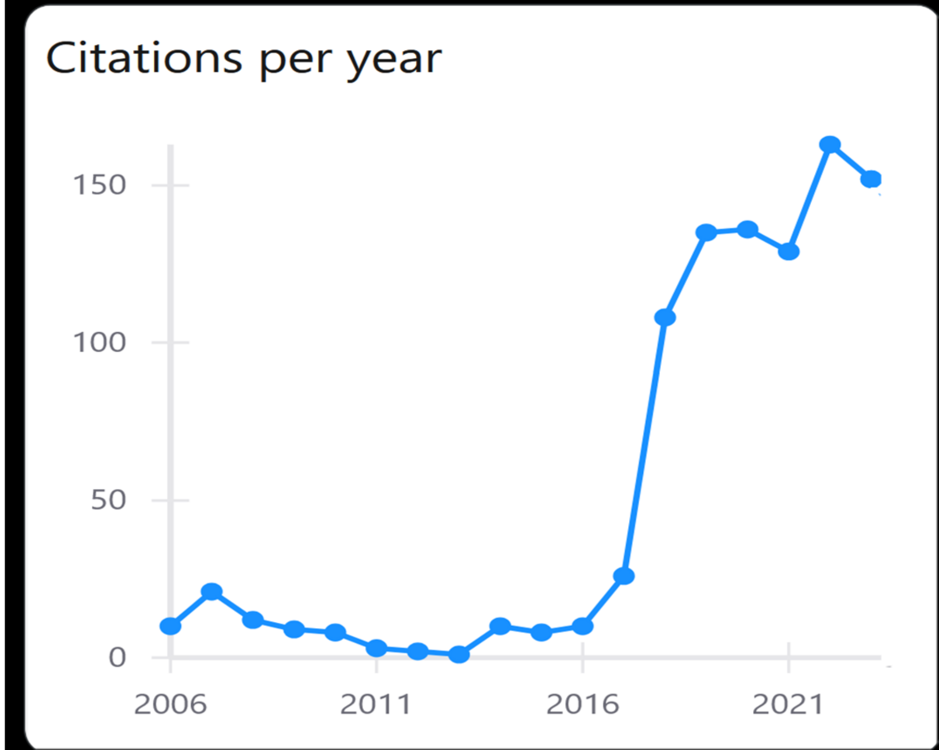
.@PlanckScale and @CumrunV's 2007 NPB article
"On the Geometry of the String Landscape and the Swampland"
inspirehep.net/literature/717...
reaches 1,000 citations.

#topcites @ElsevierPhysics

This paper is a sleeping beauty.



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NUCLEAR PHYSICS B

On the geometry of the string landscape and the swampland

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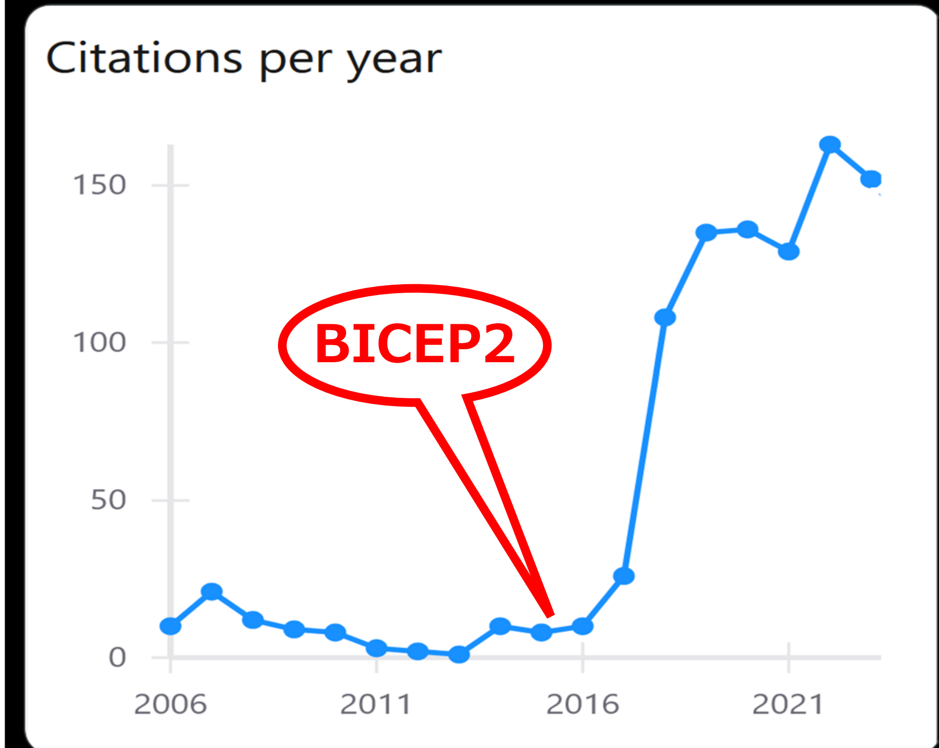
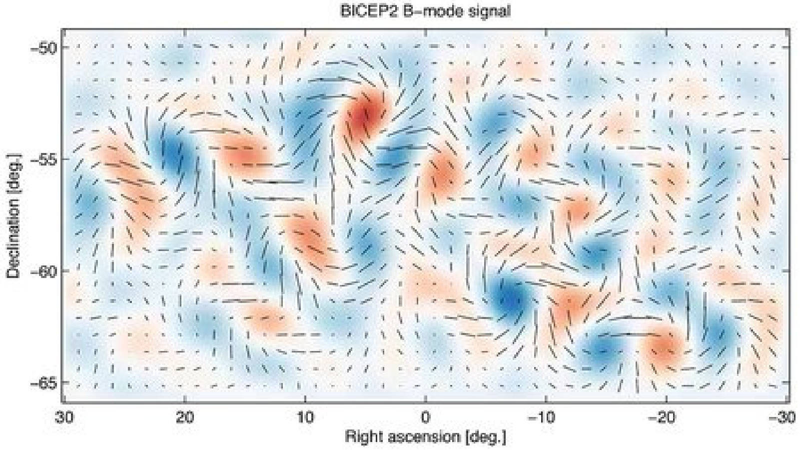
INSPIRE HEP
@inspirehep

.@PlanckScale and @CumrunV's 2007 NPB article
"On the Geometry of the String Landscape and the Swampland"
inspirehep.net/literature/717...
reaches 1,000 citations.

#topcites @ElsevierPhysics

This paper is a sleeping beauty.





Caltech

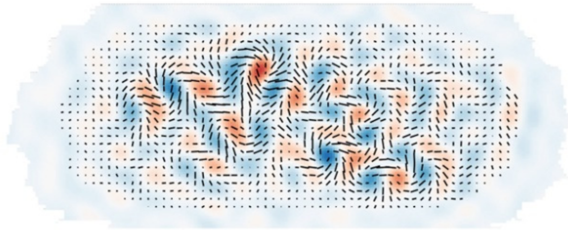
Menu

Home / About / News / BICEP2 Discovers First Direct Evidence of Inflation and Primordial Gravitational Waves

BICEP2 Discovers First Direct Evidence of Inflation and Primordial Gravitational Waves

March 17, 2014

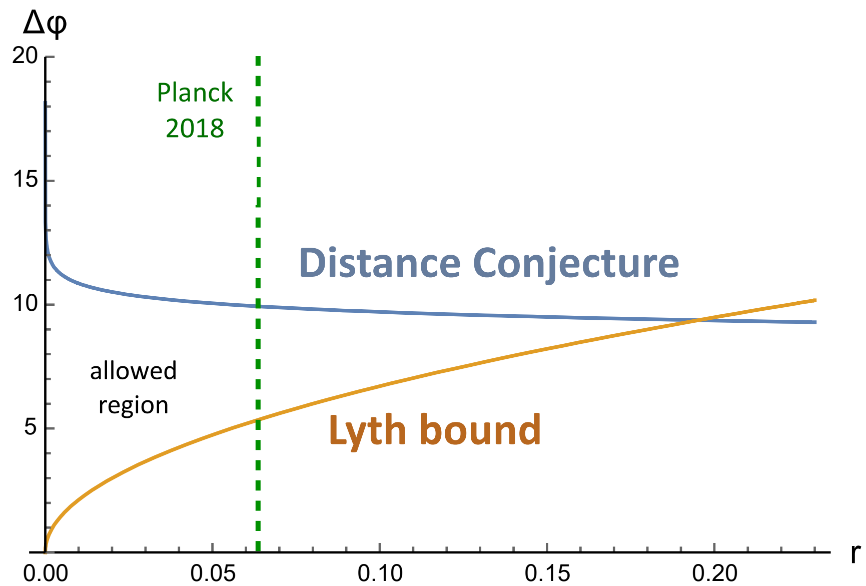
Constraints on Inflation Models



The distance conjecture implies **constraints on the inflaton range $\Delta\phi$ and the tensor-scalar ratio r of the CMB polarization.**

$$|\Delta\phi| \leq \alpha^{-1}\log\left(\frac{M_p}{H}\right) = \alpha^{-1}\log\sqrt{\frac{2}{\pi^2 A_s r}}$$

- It is an **upper bound** on $|\Delta\phi|$
- **Lyth bound is a lower bound** on $|\Delta\phi|$
- Large field inflation is not ruled out but can be strongly constrained.



Scalisi, Valenzuela: 1812.07558

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NUCLEAR PHYSICS B

On the geometry of the string landscape
and the swampland

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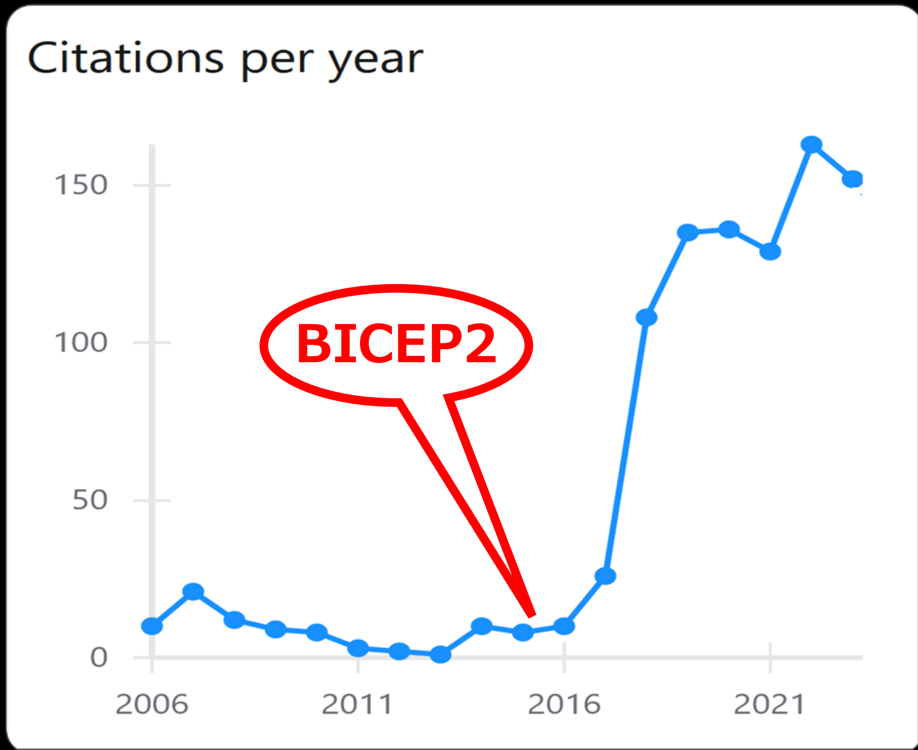
.@PlanckScale and @CumrunV's 2007 NPB article
"On the Geometry of the String Landscape and the Swampland"
inspirehep.net/literature/717...
reaches 1,000 citations.

#topcites @ElsevierPhysics

This paper is a sleeping beauty.



We proved a part of Distance Conjecture in $\mathrm{AdS}_3/\mathrm{CFT}_2$.

Wang + H.O.: 2405.00674

Theorem 1: If there is a geodesic on the conformal manifold along which the conformal dimension Δ vanishes in some limit, the Zamolodchikov distance t to the limit is infinite.

Theorem 2: In the limit, Δ vanishes exponentially $\Delta = \exp(-\alpha\, t + O(1))$, with the universal upper bound $\alpha \leq 1$.

Theorem 3: CFT in the limit contains a subalgebra of local operators described by the sigma-model on $\mathbb{R}^N$ with $N \leq c$.

Theorem 4: There are a geodesic and a primary field with $\Delta \to 0$ along the geodesic such that $\frac{1}{\sqrt{c}} \leq \alpha$.

The upper and lower bounds $\frac{1}{\sqrt{c}} \leq \alpha \leq 1$ are sharp, and we have identified the necessary and sufficient conditions for saturation of the bounds.

Δ can vanish only at infinite distance.

$$\Delta = \exp(-\alpha\, t + O(1))$$

$$\frac{1}{\sqrt{c}} \leq \alpha \leq 1$$

If CFT_2 has a holographic dual in AdS_3

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

and α_{AdS} is bounded as,

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

Planck scale

AdS scale

If CFT_2 has a holographic dual in AdS_3

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

- When $\phi \geq \left(\frac{2}{3}\ell_{\mathrm{P}}\right)^{-\frac{1}{2}}$, the tower of light particles **must emerge**.
- When $\phi \geq (8\pi\ell_{\mathrm{AdS}})^{-\frac{1}{2}}$, the tower of light particles **can emerge**.

Proof of:

$$\Delta = \exp(-\,\alpha\, t + O(1))$$

$$\alpha \;\leq\; 1$$

Start with the simple case when there is only **one marginal operator $\boldsymbol{M}$** and when it is exact.

Suppose there is a primary field $\mathcal{O}$, whose conformal dimension Δ vanishes at some point on the conformal manifold. Choose a geodesic coordinate t so that $\Delta(t)$ monotonically decreases toward the point.

$$\frac{d\Delta(t)}{dt} = -C_{\mathcal{O}\mathcal{O}\boldsymbol{M}}$$

The distance t diverges if $C_{\mathcal{O}\mathcal{O}M}$ vanishes at least linearly in Δ.

We can show the stronger statement $C_{\mathcal{O}\mathcal{O}M} = \Delta\,(1 + O(\Delta))$.
Therefore, $\Delta(t) = \exp\big(-t + O(1)\big)$ with $\alpha = 1$.

In view of time, I will present a **simple but not rigorous proof**.

Since $[L_1, L_{-1}] = 2L_0$, there is an operator J of weights (Δ/2+1, Δ/2) such that $\partial\mathcal{O} = i\sqrt{\Delta}\, J$.

Therefore, $C_{\mathcal{O}\mathcal{O}M} = \Delta\, C_{J\bar{J}M}$. Need to show $C_{J\bar{J}M} = 1 + O(\Delta)$.

From $\langle\mathcal{O}(z)\mathcal{O}(w)\rangle = \frac{1}{|z-w|^{2\Delta}}$,

$$\langle J(z)J(w)\rangle = \frac{1}{(z-w)^2} + O(\Delta),\quad \langle\bar{J}(\bar{z})\bar{J}(\bar{w})\rangle = \frac{1}{(\bar{z}-\bar{w})^2} + O(\Delta),$$

$$\langle J(z)\bar{J}(\bar{w})\rangle = \frac{\Delta}{|z-w|^2} + O(\Delta^2).$$

$$\langle J(z)J(w)\rangle = \frac{1}{(z-w)^2} + O(\Delta), \quad \langle \bar{J}(\bar{z})\bar{J}(\bar{w})\rangle = \frac{1}{(\bar{z}-\bar{w})^2} + O(\Delta),$$

$$\langle J(z)\bar{J}(\bar{w})\rangle = \frac{\Delta}{|z-w|^2} + O(\Delta^2).$$

$$\langle\, \bar{J}(w)\, J(z)\, \bar{J}(u)\, J(v)\, \rangle$$

$$= \frac{\mathbf{1}}{(z-v)^2(\bar{w}-\bar{u})^2} + \cdots + O(\Delta) \text{ in the } t\text{-channel}$$

$$= \frac{\Delta^2}{|z-w|^2|u-v|^2} + \frac{(C_{J\bar{J}M})^2}{(z-v)^2(\bar{w}-\bar{u})^2} + \cdots + O(\Delta) \text{ in the } s\text{-channel}$$

⇧ $\mathbf{1}$ exchange

⇧ $\boldsymbol{M}$ exchange

⇧ exchange of other operators

By the crossing symmetry, $C_{J\bar{J}M} = \mathbf{1} + O(\Delta)$.

Therefore, $\Delta(t) = \exp\big(-t + O(1)\big)$ with $\boldsymbol{\alpha} = \mathbf{1}$.

With several marginal operators M_i, the crossing symmetry gives

$$G^{ij} C_{J\bar{J}M_i} C_{J\bar{J}M_j} = 1 + O(\Delta).$$

For exactly marginal operators M_a, define $\alpha_a = \lim_{t\to\infty} C_{J\bar{J}M_a}$.

- $\Delta(t) = \exp(-\alpha_a t^a + O(1))$.
- $\|\alpha\| = \sqrt{G^{ab}\alpha_a\alpha_b} \leq 1.$
- $\|\alpha\|$ = 1 if and only if $C_{J\bar{J}M_i} = 0$ for all non-exact operators.

Parametrizing $t^a = e^a\, t$ by the geodesic distance t and a unit vector $e^a = \cos\theta\ G^{ab}\alpha_b + \sin\theta\, e_\perp^a$, where $0 \leq \theta \leq \pi/2$ and $e_\perp^a$ is a unit vector satisfying $e_\perp^a c_a = 0$, Δ in the limit is,

$$\Delta(t^a = e^a t) = \exp(-\alpha\, t + O(1)) \text{ with } \alpha = \cos\theta\, \|\alpha\| \leq 1.$$

$$\Delta = \exp(-\,\alpha\, t + O(1))$$

$$\frac{1}{\sqrt{c}} \leq \alpha$$

The lower bound on α can also be proven by consistency of CFT.

Summary, so far:

Δ can vanish only in infinite distant limits on the conformal manifold, where

$$\Delta_{\text{gap}} = \exp(-\alpha\, t + O(1)) \text{ and } \frac{1}{\sqrt{c}} \leq \alpha \leq 1.$$

$$\left(\sqrt{\frac{3}{2c}} \leq \alpha \leq 1 \text{ with superconformal symmetry.} \right)$$

The large volume limit of the quintic Calabi-Yau saturates the lower bound at $\alpha = 1/\sqrt{6}$.

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

If there is a particle in $\mathrm{Ad}S_3$ whose mass vanishes at some point in the moduli space, the distance ϕ to the point is infinite and the mass vanishes exponentially,

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

and $\boldsymbol{\alpha}$ **is bounded as,**

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

Planck scale

AdS scale

- No arbitrary parameters (1949)

QUANTIFY →

Distance Conjecture (2006)

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

- No global symmetry (1957)

QUANTIFY →

Weak Gravity Conjecture (2006)

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

Perhaps, the second-earliest Swampland condition:

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

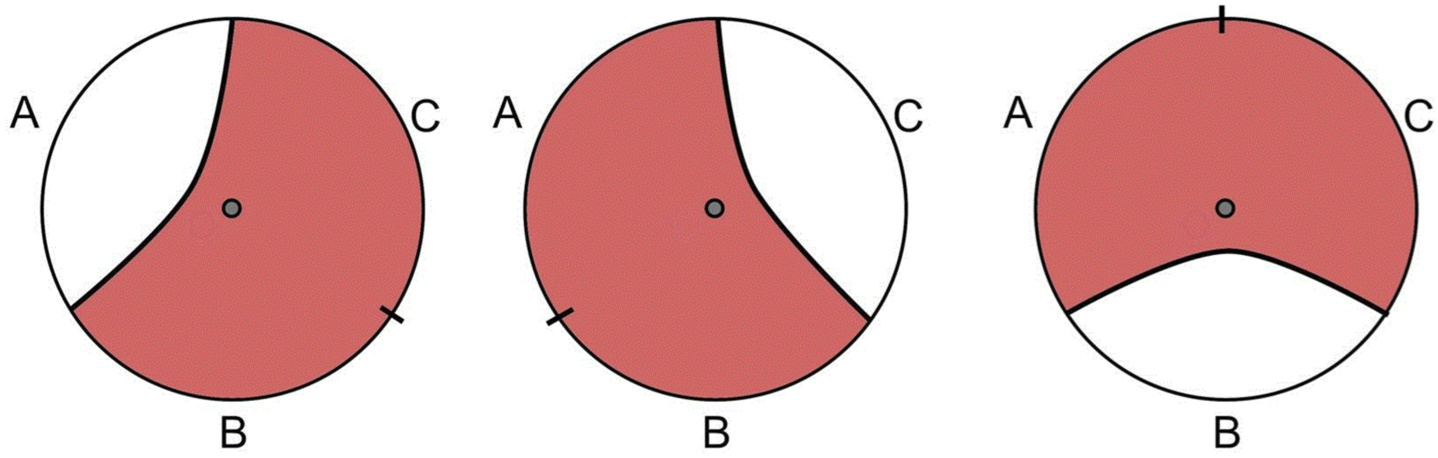
If classical physics be regarded as comprising gravitation, source free electromagnetism, unquantized charge, and unquantized mass of concentrations of electromagnetic field energy (geons), then classical physics can be described in terms of curved empty space, and nothing more. No changes are made in 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.

Entanglement wedge reconstruction

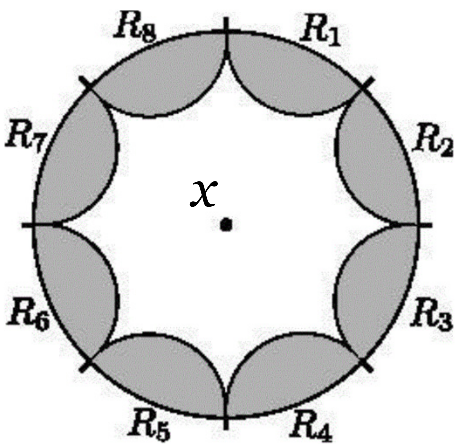


Our proof of the absence global symmetry in quantum gravity makes use of the relation between the holography of quantum gravity and **quantum error correcting codes** in quantum information theory.

Almheiri, Dong, Harlow: 1411.7041
Harlow: 1607.03901

No global symmetry

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.

Harlow + H.O.:1810.05337
1810.05338

Contradiction

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 $\ll M_{\mathrm{Planck}}$ such that

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

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

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

Vafa + HO: 1610.01533

neutrino masses

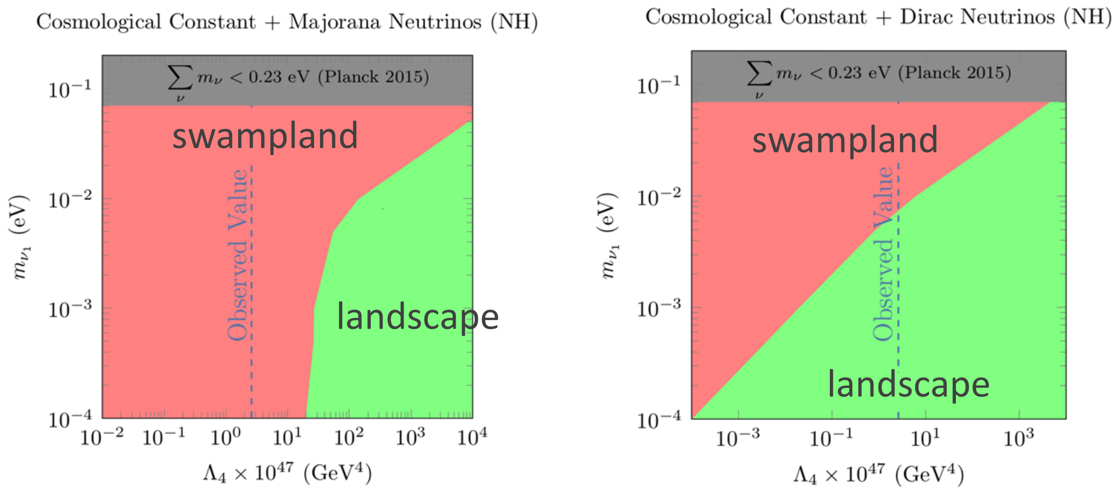
$$\Lambda \geq \frac{a(n_f)30(\Sigma m_i^2)^2 - b(n_f, m_i)\Sigma m_i^4}{384\pi^2}$$

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 $\mathbf{\Lambda > 0}$.



Ibáñez, Martín-Lozano, Valenzuela: 1706.05392

- No arbitrary parameters (1949)

QUANTIFY ⇒ Distance Conjecture (2006)

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

- No global symmetry (1957)

QUANTIFY ⇒ Weak Gravity Conjecture (2006)

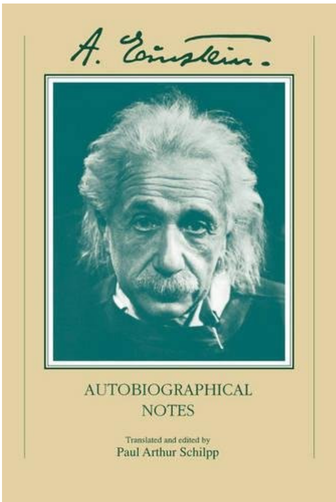
$$m^2 \leq \frac{d-2}{8\pi G_{\mathrm{N}}(d-3)}\,Q^2$$

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

Gaiotto, Kapustin, Seiberg, Willett: 1412.5148

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

Traditional symmetries are $\mathbf{0}$-form & invertible.



The **absence of parameters** in quantum gravity can be regarded as the **absence of $(-\mathbf{1})$-form symmetry**.

- No arbitrary parameters (1949)

QUANTIFY

Distance Conjecture (2006)

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

Unified

- No global symmetry (1957)

QUANTIFY

Weak Gravity Conjecture (2006)

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

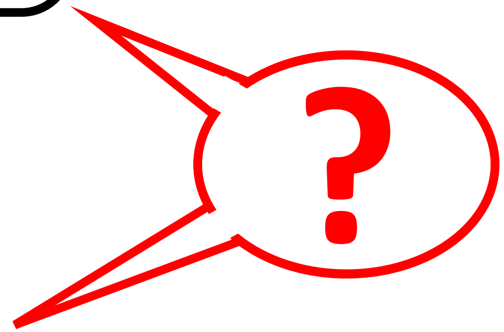
Cobordism Conjecture McNamara, Vafa: 1909.10355

- No arbitrary 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

Summary

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

- No arbitrary parameters → QUANTIFY → Distance Conjecture
- No global symmetry → QUANTIFY → Weak Gravity Conjecture

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

I am working to strengthen these results and generalize them for spacetimes with zero and positive vacuum energies.

Happy 60th Birthday