Inflation Panel, Cosmic Controversies Conference

"Tour of the Swampland"

November 6, 2019

Hirosi Ooguri (Caltech & Kavli IPMU)

PowerPoint file accompanying the remarks is attached at the end of this text.

Swampland Conditions

In quantum field theory without gravitational degrees of freedom, it is generally believed that we can write down any low energy effective theory and expect that it has a consistent ultraviolet completion. The only requirement is consistency that one can check in low energy. For example, all gauge anomalies must be cancelled. This is what the Wilsonian view of the renormalization group tells us. However, the situation may be different in theories with gravitational degrees of freedom. Indeed, there are non-trivial constraints that are not obvious in low energy.

One of such constraints says that quantum gravity does not have global symmetry. We can easily write down a low energy effective theory with global symmetry, but it cannot be exact symmetry in full quantum gravity. Any accidental global symmetry in low energy has to be either broken or a gauge symmetry in disguise. Daniel Harlow and I have recently completed a proof of this statement in the context of the AdS/CFT correspondence. We have also proven the completeness hypothesis, which states that all possible charges with respect to long range gauge symmetry must be realized.The logic we used to prove these theorems does not rely on string theory. We only assumed the AdS/CFT correspondence, which we believe should be applicable to any consistent quantum theory of gravity.

In 2005, Cumrun Vafa proposed the swampland as a set of effective theories that seem consistent in low energy, but cannot be derived as low energy

approximation to consistent quantum gravity. Swampland conditions delineate the border between the swampland and the landscape. Over the last 14 years, several swampland conditions have been proposed with various degrees of rigor.

No Global Symmetry, Weak Gravity Conjecture, and Distance Conjecture

As I mentioned, the absence of global symmetry and the completeness of gauge representations have become theorems by my work with Harlow. The weak gravity conjecture and the distance conjecture strengthen and quantify these theorems as I am going to discuss now.

The weak gravity conjecture states that, in any effective theory described by the Einstein gravity coupled to Maxwell field, if it has a consistent ultra-violet completion, there must be a particle with charge Q and mass m such that m measured in the Planck units is less than or equal to the absolute value of Q.

String theory has no continuous free parameters. All parameters can vary locally. They are expectation values of scalar fields. The distance conjecture Cumrun Vafa and I proposed in 2006 is about properties of the moduli space of such scalar fields, with the metric defined by their kinetic terms. The distance conjecture states that:

- ✧ The moduli space is non-compact. Pick any point X, one can go infinite distance away from it.
- ✧ It also states that compared to the theory at X, the theory at Y in distance much greater than the Planck scale has a tower of light particles with exponentially small masses, namely masses suppressed by the exponential of the distance between X and Y measured in the Planck units.
- ✧ The low energy effective theory defined at X breaks down at Y because of these new light degrees of freedom.

Though the weak gravity conjecture and the distance conjecture have not been proven rigorously, over the last decade, these conjectures have successfully passed highly non-trivial tests with a large variety of Calabi-Yau compactifications. Logical connections between these conjectures and other conjectures such as the cosmic censorship hypothesis have been found. We believe that these conjectures are applicable to any consistent quantum gravity, not restricted to

string theory. So far, tests have only been done in string theory since it is the only theory in which reliable calculations can be done.

These swampland conditions have stronger implications on low energy effective theories. As I mentioned, the no global symmetry theorem does not tell us how symmetry should be broken or gauged. The completeness theorem predicts magnetic monopoles, but it does not tell us how heavy these monopoles are. The weak gravity conjecture and the distance conjecture strengthen and quantify these statements.

Let me give you one example. Daniel Harlow and I have shown that the no global symmetry theorem applies to spontaneously broken symmetry also. For example, if there is a low energy effective theory with a massless scalar field with a flat potential, the theory has a symmetry which shifts the value of the scalar field by a constant. This symmetry is spontaneously broken in three or more spacetime dimensions, and the scalar field is a Goldson field. The no global symmetry theorem prohibits such symmetry even if it is spontaneously broken. Therefore, the shift symmetry must be violated. My distance conjecture with Cumrun quantifies how it is violated. If the value of the scalar field shits much more than the Planck scale, the low energy effective theory must break down by a tower of exponentially light particles.

Axion Monodromy

The only potential counter-example to the distance conjecture I am aware of is the axion monodromy model proposed in 2008 by Liam McAllister, Eva Silverstein and Alexander Westphal. Therefore, I would like to take this opportunity to explain why it does not make a counter-example.

To make sure that what I am going to tell you is fair to those who worked on the axion monodromy, I discussed it with Westphal, who is a co-inventor of the model. He and I worked on this part of my presentation together, and he approved of the remarks that I am going to read now

Over the past decade, several papers have appeared, pointing out that trans-Planckian excursions in the axion monodromy may become difficult once one takes into account moduli stabilization. In fact, recent studies based on some

semi-explicit examples have demonstrated that back-reaction there is already important at sub-Planckian distances.

Typically, the models contain both axion modes and radial modes. As we go around the axion directions, back-reaction to the potential starts to move the radial modes and eventually destabilize them. The radial modes then start running away toward the large volume limit, shutting off the monodromy excursion of the axion modes. At the same time, the runaway of the radial modes generates a tower of light Kaluza-Klein modes. This behavior is consistent with the distance conjecture.

To circumvent this problem, the F-term axion monodromy inflation was proposed by several groups in 2014. However, papers by Irene Valenzuela and her collaborators in 2016 and 17, following upon an earlier paper by Baume and Palti in 2016, showed that the F-term monodromy also suffers from control issues, if a hierarchy of mass scales cannot be engineered. A similar problem for models with D7 branes was pointed out last year by Liam McAllister, who is a co-inventor of the axion monodromy. In the paper posted last December, McAllister and his student reported that moving D7 branes induce the D3 brane charge and that the resulting back-reaction may preclude large field inflation due to what they call a dramatic effect on the superpotential even in one period of the axion field

The distance conjecture is an asymptotic statement and is applicable for a field range parametrically larger than the Planck scale. So far, some models of axion monodromy seem to avoid the instability within a field range of a few times the Planck scale. If that can be confirmed in fully explicit constructions, it would remain useful as an ingredient of certain inflation scenarios. Such a model would not be a counter-example to the distance conjecture since there is an order one factor leeway in the field range as for when the exponential behavior begins to set in.

Neutrino Mass and Dark Energy

Let me turn to other low energy implications of swampland conditions. 3 years ago, Cumrun Vafa and I pointed out that the weak gravity conjecture will have further implications on low energy physics, if we strengthen it slightly by stating

that the equality holds only for BPS particles in theories with unbroken supersymmetry.

We found that this strengthened version of the weak gravity conjecture would put restrictions the neutrinos in the Standard Model. Our observation has been examined more carefully by Ibanez, Martin-Lozano, and Valezuela, and by Hamada and Shiu, leading to the relation between neutrino masses and the density of the dark energy of the universe. The fourth power of neutrino masses must be bounded above by the dark energy density, under some assumption on physics beyond the Standard Model of Particle Physics.

De Sitter Space

Given that a variety of constraints on low energy effective theories of consistent quantum gravity have been proposed and some have been proven, it seems reasonable to ask if there are constraints on the accelerated expansion of the universe. In the spirit of the title of this panel, let me pose the following question:

"Can one derive a low energy effective theory from a known consistent quantum theory of gravity that accommodates a stable or quasi-stable de Sitter space as its solution that explains either the observed accelerated expansion of the current universe or the proposed inflationary period of the early universe?"

Cumrun Vafa and I, together with our students Georges Obied and Lev Spodyneiko, asked such a question and came up with a conjecture stating that, if a low energy effective theory contains scalar fields, either the gradient of their potential is bounded below or the minimum of its Hessian eigenvalues is bounded above. This conjecture as well as the distance conjecture does not exclude the inflation scenario, but they can put non-trivial constraints on inflation models.

Since there have been proposals on top-down constructions of quasi-stable de Sitter spaces from string theory, it would be appropriate to discuss them at this point.

KKLT scenario proposed by Kachru, Kallosh, Linde, and Trivedi 16 years ago is one of the best efforts to derive quasi-stable de Sitter solutions top-down from string theory. It has also been the most scrutinized proposal. KKLT starts with an anti-de Sitter solution, and then turns on supersymmetry breaking to lift the

potential, aiming at creating a local minimum in the potential with a small positive vacuum energy. Several steps in this scenario have been questioned and their validities are currently being debated at various fronts.

Dine-Seiberg Problem and Compactness of Internal Space

Rather than going into technical details of these on-going debates about KKLT, let me point out two fundamental difficulties one encounters in any attempt at top-down construction of this type from string theory. One is the Dine-Seiberg problem and another is compactness of the internal Calabi-Yau manifold. Let me discuss each of them.

String theory has no free parameter, and any parameters of a low energy effective theory is an expectation values of some scalar field in high energy. KKLT requires that all scalar fields be stabilized and their expectation values be fixed. This means that, if they succeed in what they want to do, there is no adjustable parameter in their model. Already in 1988, Dine and Seiberg pointed out that it is difficult, if not impossible, to find a quasi-stable state in the domain that allows a weak coupling expansion with respect the string coupling constant

When flux compactifications were found to be abundant in the early 2000, it was hoped that, since there are so many of them, it may be possible to find a series of flux compactification, guaranteeing smallness of the coupling constant by using fluxes as control parameters. Indeed, there are a large number of parametrically controlled flux compactifications which give rise to the landscape of anti-de Sitter spaces. Unfortunately, this idea has not been successfully implemented in constructing de Sitter spaces. Since a controlled approximation has not been possible, it has been difficult to check claims made about such constructions in reliable manners.

Let me turn to issues with compactness of Calabi-Yau manifolds. In mathematics, problems dealing with compact geometric objects are often more difficult than those with non-compact counterparts. For example, no one has been able to construct a Ricci-flat Kaehler metric explicitly on any smooth compact Calabi-Yau manifold, even though its existence is guaranteed by Yau's proof of the Calabi conjecture. In contrast, it is very easy construct a Ricc-flat

Kaehler metric explicitly on a non-compact Calabi-Yau manifold. One of the reasons is that, in compact cases, we cannot hide problems by pushing them away toward the infinity; rather we have to confront global constraints

These global constraints in mathematics mirror the swampland conditions in physics. The connection is that the Newton coupling in a low energy theory vanishes in the limit when the volume of the Calabi-Yau manifold become infinite. In the infinite volume limit, the gravity decouples and the constraints disappear, taking us back to the traditional Wilsonian view of the renormalization group and effective field theories, where we can write down any low energy effective theory and expect that it has a consistent ultraviolet completion. For a compact internal space giving rise to a non-zero Newton coupling, we have to confront global issues over the compact manifold, and swampland conditions emerge.

At the Strings 2019 conference in Brussels in June, Liam McAllister gave an excellent review talk in support of KKLT, responding to a variety of issues raised about the scenario. Leaving aside the question on whether his assessments are overly optimistic or not, he agreed at the end of his talk that there has been no explicit compactification that unifies all necessary components of KKLT. Given that KKLT is a proposal for a top down construction from string theory, it is desirable to have at least one concrete model to show how everything works out.

Closing

Over the next decade, a variety of astrophysical experiments are planned for precision tests of the inflation. They include the Japanese satellite project LiteBIRD to measure the primordial B-mode polarization. As the Director of the Kavli IPMU, I proposed this project to the Master Plan 2020 of the Japanese Science Council. Just a few months ago, we heard a wonderful news that JAXA, the Japanese Aerospace Exploration Agency, approved the launch of LiteBIRD in 8 years. We should improve our theoretical tools and strive to make more precise and sharper statements about low energy effective theories of string theory and their implications on the current and early universes before the next astrophysical experiment verifies or falsifies the inflation in the early universe or nails the equations of state of the dark energy in the current universe.

Cosmic Controversies Panel Discussion

Can Inflation be transformed into
a fundamental theory of the early Universe?

Hirosi Ooguri

Caltech & KAVLI IPMU

No Global Symmetry

Any symmetry in quantum gravity is either broken or gauged.

Completeness

Every finite dimensional unitary representation of long range gauge symmetry must appear.

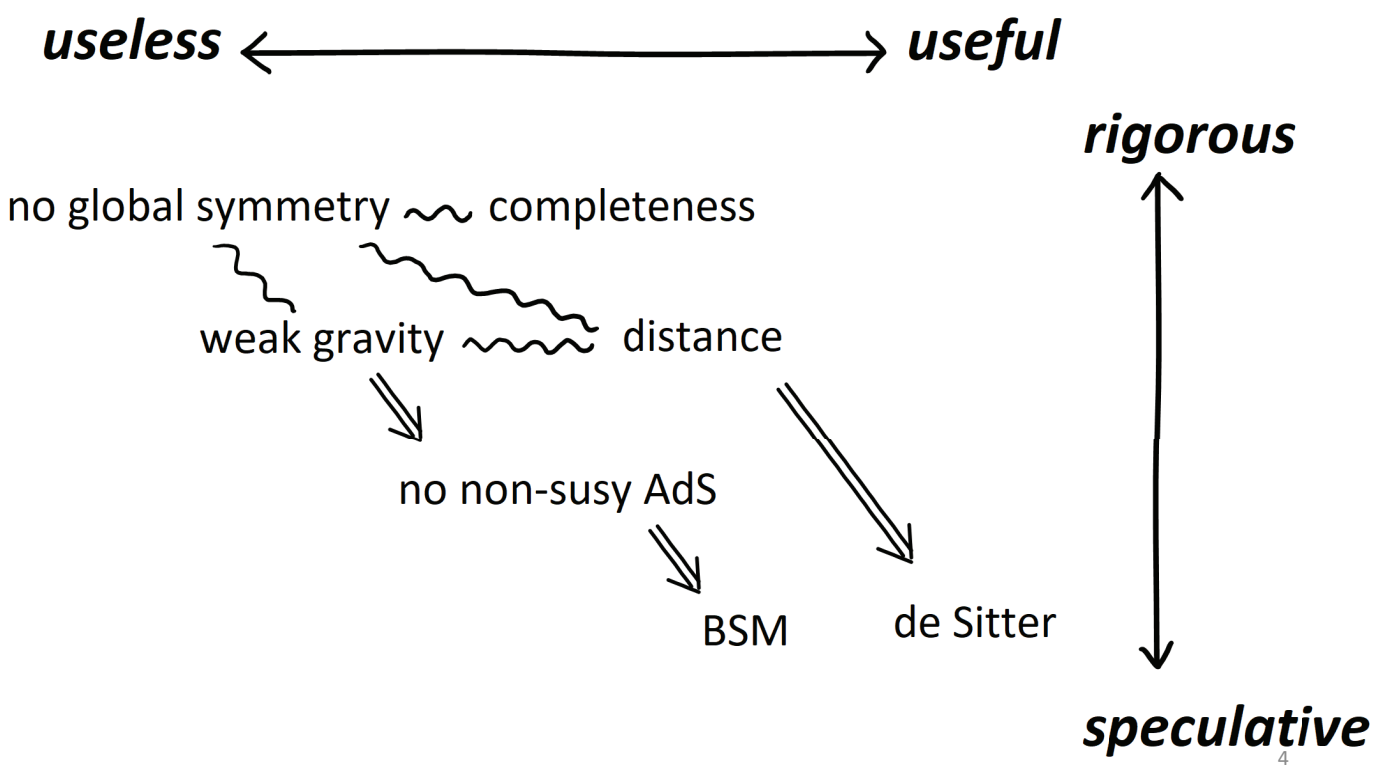
Harlow + H.O.: 1810.05337 (5 pages announcement)
1810.05338 (175 page complete proof)

Swampland Question

Given an effective theory of gravity, how one can judge whether it is realized as a low energy approximation to a consistent quantum theory **with ultraviolet completion**, such as string theory?

Vafa: 0509212

Landscape of Swampland Conditions



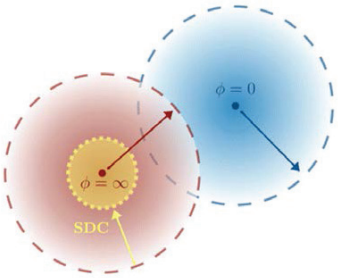
Weak Gravity Conjecture

In any low energy theory described by the Einstein gravity + Maxwell field + finite number of matters, if it has an UV completion as a consistent quantum gravity, **there must be a particle with charge Q and mass m, such that**:

$$m \leq M_p |Q|$$

Arkani-Hamed, Motl, Nicolis, Vafa: 0601001

Distance Conjecture



- Moduli space is non-compact. Pick any point X, one can go infinite distance away from it.
- Compared to the theory at X, the **theory at Y at distance $\gg M_p$ has a tower of light particles** with exponentially small masses.
- The **low energy effective theory** defined at X **breaks down at Y** because of the new light degrees of freedom.
- The closure of the moduli space is simply connected. There are no nontrivial one-cycles with minimum length.

Vafa + H.O.: 0605264

No Global Symmetry Theorem

Any symmetry in quantum gravity is either broken or gauged.

How is global symmetry broken/gauged?

Completeness Theorem

Every finite dimensional unitary representation of long range gauge symmetry must appear.

What is the mass of the lightest charged particle?

The weak gravity conjecture and the distance conjecture address these questions.

Our proof of the **no global symmetry theorem** also works for **spontaneously broken global symmetry**. The shift symmetry of a scalar field must be broken.

How is the shift symmetry broken?

The distance conjecture quantify this.

Axion Monodromy

Silverstein, Westphal: 0803.3085
McAllister, Silverstein, Westphal:0808.0706

Weak Gravity Conjecture 2.0

Vafa + H.O.: 1610.1533

$m < M_p|Q|$, rather than $\leq$,
except in supersymmetric cases

➡ The neutrino mass is bounded as*

$$(\textbf{neutrino mass})^4 < (\textbf{dark energy})$$

*: with some assumption on physics beyond the Standard Model.

Ibanez, Martin-Lozano, Valenzuela: 1706.05392, 1707.05811;
Hamada, Shiu: 1707.06326; Gonzalo, Herraez, Ibanez: 1803.08455

Question

Can one derive a low energy effective theory **from a known consistent quantum theory of gravity** that accommodates a stable or quasi-stable **de Sitter space** as its solution that explains either the observed **accelerated expansion of the current universe** or the proposed **inflationary period of the early universe**?

De Sitter Conjecture*

*: There are other formulations also.

$$|\nabla V| \geq \frac{c}{M_p} V$$

or

$$\min\left(\nabla_i \nabla_j V\right) \leq -\frac{c'}{M_p^2} V$$

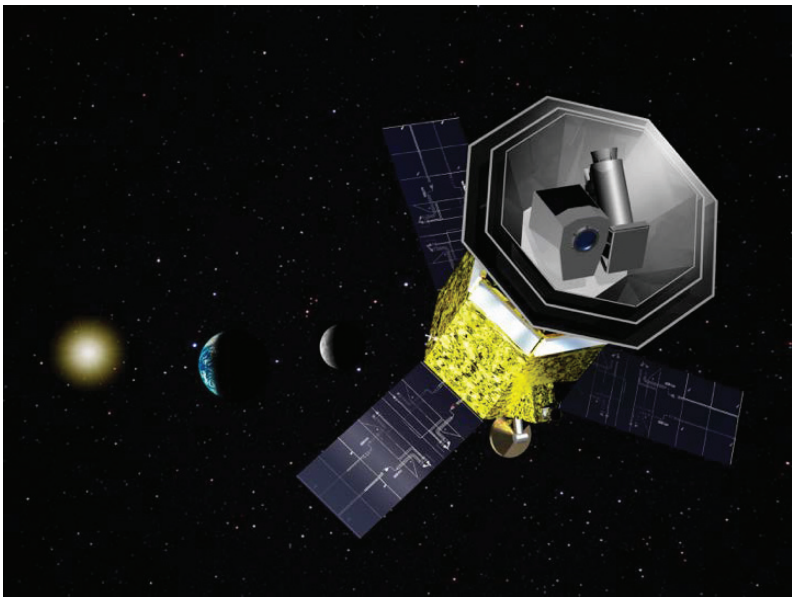
Obied, Spodyneiko, Vafa + H.O.:1806.08362
Palti, Shiu, Vafa + H.O.: 1810.05506

KKLT

Kachru, Kallosh, Linde, Trivedi: 0301240

- **Dine-Seiberg Problem**
- **Compactness of Internal Space**

JAXA has approved the launch of the LiteBIRD satellite in 8 years to perform all-sky CMB polarization survey and to test the cosmic inflation.



We should improve our theoretical tools and make more precise and sharper statements about low energy effective theories of string theory and their implications on the early universe.