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RESEARCH

Constraints on Quantum Gravity

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Abstract
Recently, it has become increasingly clear that there are constraints on the low-energy effective theories of quantum gravity that cannot be captured by the standard Wilsonian paradigm. For gravitational theories in asymptotically anti-de Sitter spacetimes, we can formulate such constraints and aim to prove or falsify them using the AdS/CFT correspondence. I will review the work I did with Daniel Harlow on constraints on symmetries of quantum gravity. I will also discuss more recent progress in this holographic approach, and present the proof that Yifan Wang and I completed this year, which proves and strengthens a part of the Distance Conjecture that I proposed with Cumrun Vafa in 2006.

Contents

1 Introduction

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 it to have a mathematically consistent ultraviolet completion, provided it satisfies a simple set of consistency conditions visible in low energy such as being anomaly-free. Since the unification of general relativity and quantum mechanics is expected to occur at the extremely high Planck energy, if this paradigm of low energy effective theory were also applicable to quantum gravity, signatures of the unification would be dif-

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ficult to observe at low energy because they would be suppressed by inverse powers of the Planck energy. However, there is evidence that the mathematical consistency of quantum gravity imposes non-trivial constraints on low energy physics. The term Swampland was christened by Cumrun Vafa as the set of effective theories that appear to be consistent at low energy, but are not low energy descriptions of any consistent quantum gravity [1]. It is a complement to the Landscape, which is the set of effective theories of consistent quantum gravity. The fundamental question in this area of research is to identify useful criteria for distinguishing the Landscape from the Swampland.

For gravitational theories in asymptotically anti-de Sitter (AdS) spacetimes, we can formulate such constraints and aim to prove or falsify them using the AdS/CFT correspondence. For example, there was a conjecture for mote than 60 years that quantum gravity does not allow global symmetries [2]. It was also conjectured that quantum gravity requires that there must be dynamical objects transforming in all irreducible representations of any internal gauge symmetry and that quantum gravity requires that any internal gauge symmetry group is compact [3, 4]. These conjectures were proven for gravitational theories in AdS in my work with Daniel Harlow [5, 6]. In particular, we showed proved that any global symmetry in a quantum gravity theory in AdS would lead to an inconsistency in its dual conformal field theory (CFT).

One of the earliest conjectures about the Swampland is by Albert Einstein, who wrote in his autobiographical note published 1949 that "there are no arbitrary constants in Nature," implying that all such constants should be determined dynamically [7]. In a modern language, it is believed that every parameter in quantum gravity is an expectation value of a dynamical field and can be varied by changing its expectation value. For gravitational theories in AdS, this conjecture can be proven as follows. If there is a continuous parameter in AdS, there is a corresponding parameter in the dual CFT. Such a parameter is believed to be associated with an exactly marginal operator in the CFT, which then corresponds to either a massless scalar field in the bulk or (when the marginal operator is double-trace) a continuous deformation of the boundary condition at the infinity of AdS. In particular, continuous parameters in the bulk Lagrangian must be expectation values of massless scalar fields.

However, this conjecture alone does not lead to a sharp constraint on a low-energy effective Lagrangian, since the parameters of the Lagrangian may have been fixed at high energy, *e.g.*, by potentials for the corresponding scalar fields. For example, the Standard Model of particle physics has 19 parameter (and 7 more if we take into account the neutrino masses) and the ΛCDM Model of Cosmology has 6 parameters, but they do not contain dynamical fields corresponding to those parameters. This is analogous to the absence of global symmetry proven in [5, 6], which also does not produce a sharp constraint on a low-energy effective Lagrangian since the low-energy theory may have an accidental symmetry, which is broken or gauged at high energy. The analogy can be made more precise by interpreting the conjecture as the absence of (-1)-form global symmetry.

To formulate more useful Swampland conjecture, Cumrun Vafa and I proposed the Distance Conjecture [8] in 2006. The conjecture claims the following set of properties about continuous moduli of quantum gravity theories,

(0) The moduli space $\mathcal{M}$ is parametrized by expectation values of massless scalar fields. If this conjecture holds, the moduli space is endowed with a natural metric given by the kinetic term of the moduli fields, which defines a notion of distance $d(p, p')$ between any two points $p, p' \in \mathcal{M}$.

(1) Choose any point $p_0 \in \mathcal{M}$. For any positive t, there is another point $p \in \mathcal{M}$ such that the distance $d(p, p_0)$ between p and p_0 is greater than t.

(2) Compared to the theory at $p_0 \in \mathcal{M}$, for sufficiently large t, the theory at p with $d(p, p_0) > t$ has an infinite tower of light particles starting with mass of the order of $\exp(-\alpha t)$ for some $\alpha > 0$. In the $t \to \infty$ limit, the number of extra light particles of mass less than a fixed mass scale becomes infinite.

If the coefficient α can be bounded, this conjecture will give a sharp constraint on low-energy effective theories.

Recently, Yifan Wang and I proved part of the Distance Conjecture about gravitational theories in three-dimensional AdS and gave both upper and lower bounds on the AdS version of the coefficient α in the above [9]. Specifically, for any unitary conformal field theory in two dimensions with the central charge c, we prove that, if there is a nontrivial primary operator whose conformal dimension Δ vanishes in some limit on the conformal manifold, the Zamolodchikov distance t to the limit is infinite, the approach to this limit is exponential $\Delta = \exp(-\alpha t + O(1))$, and the decay rate obeys the universal bounds $c^{-1/2} \le \alpha \le 1$. In the limit, we also find that an infinite tower of primary operators emerges without a gap above the vacuum and that the conformal field theory becomes locally a tensor product of a sigma-model in the large radius limit and a compact theory. As a corollary, we establish a part of the Distance Conjecture about gravitational theories in $3d$ AdS. In particular, our bounds on α indicate that the emergence of exponentially light states is inevitable as the moduli field corresponding to t rolls beyond the Planck scale along the steepest path and that this phenomenon can begin already at the curvature scale of the bulk geometry.

In this contribution to the proceedings of the Lemaître Conference 2024, I will summarize the papers [5, 6] on the absence of global symmetry in quantum gravity in AdS and the paper [9] about the Distance Conjecture in AdS_3.

2 Absence of Global Symmetry

We show that any global symmetry in a gravitational theory AdS would lead to a contradiction in its dual CFT on the boundary. The argument uses the entanglement wedge reconstruction [10, 11].

Suppose to the contrary that there were a bulk global symmetry G. In this case, each element $g \in G$, there is a unitary operator $U(g)$ acting on the Hilbert space of the theory. Since boundary local operators in CFT are limits of bulk local operators in AdS, $U(g)$ also generates a global symmetry of the boundary CFT. By the generalized Noether theorem proven in [12], we may then split up each $U(g)$ into a product of $U(g, R_i)$, each which is localized in a region R_i of the boundary spatial slice so that

$\{R_i\}_i$ make a disjoint cover of the boundary spatial slice,

$$U(g) = \prod_i U(g, R_i) \times U_{\mathrm{edge}}, \tag{2.1}$$

where U_{edge} is an operator with support only at the boundaries of the R_i, to fix up the arbitrariness at those boundaries.

The contradiction arises because we can choose all the R_i to be small enough that their associated Ryu-Takayanagi surfaces do not reach far enough in the bulk for the $U(g; R_i)$ to not commute with an operator in the center of the bulk which is charged under the global symmetry: therefore there can be no localized operators charged under the global symmetry, which is a contradiction.

This contradiction holds even if the operator creating the charged object has large but finite size, such as an operator which creates a black hole of finite energy, since we can always shrink the R_i to pull their entanglement wedges as close to the boundary as we like. An important subtlety here is that there are no truly localized operators in a gravitational theory, so we need to define heir locations relationally to the boundary using "gravitational Wilson lines". Our argument here can be refined to take this into account, see [6] for details. Another important subtlety is that the semiclassical picture of the bulk used here is valid only in a "code subspace" of the boundary CFT [13], this is dealt with also in [6] and the contradiction persists. An interesting connection to a famous theorem in quantum information theory [14] is also discussed there.

It is instructive to see how this contradiction is avoided for a long-range gauge symmetry in the bulk. In that case, any operator of net charge needs to be attached to the asymptotic boundary by a Wilson line. This Wilson line will always intersect the entanglement wedge of some one of the R_i, so then $U(g; R_i)$ is allowed to detect it.

One important issue which this argument does not touch is approximate global symmetries: our argument for the absence of global symmetry required assuming an exact global symmetry in the bulk. In string theory there are many examples of approximate global symmetries, which are violated by Planck-suppressed terms in the low-energy effective action. It would be very interesting to establish some sort of lower bound on the coefficients of these terms.

3 Distance Conjecture

The AdS versions of the Distance Conjecture have been proposed in [15] for bulk spacetime dimensions ≥ 4. The main claim is that all theories at infinite distance in the bulk moduli space have an emergent higher spin symmetry, generated by an infinite tower of conserved currents. Since the bulk moduli space is identified as a conformal submanifold of the dual CFT, which we will also denote as $\mathcal{M}$, these conjectures can be stated precisely in CFT terms and therefore are called the CFT Distance Conjectures. They include:

(I) All points with emergent higher spin symmetries are at infinite distance on $\mathcal{M}$.
(II) All CFTs at infinite distance on $\mathcal{M}$ are higher spin points.

For supersymmetric theories, the conjecture (I) was proven in [15] by using the fact that higher spin symmetries imply the existence of free decoupled sectors in their dual superconformal theories. More recently, it was proven for any unitary CFT with an energy-momentum tensor in [16]. The conjecture (II) remains open.

For CFT in two dimensions, these conjectures need to be modified since there are always higher spin currents constructed from composites of the holomorphic stress tensor [15, 17–19]. In [9], we prove dthe following four theorems about two-dimensional CFTs.

(A) If there is a geodesic on the conformal manifold $\mathcal{M}$ along which the conformal dimension Δ of a primary operator vanishes in some limit, then the geodesic distance t to the limit measured by the Zamolodchikov metric is infinite.

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

(C) The compact CFT of central charge c in the limit of vanishing Δ contains a subalgebra of local operators which are described by the sigma-model on R^N for some positive integer $N \leq c$. This theorem shows that the limit can always be understood as the decompactification limit of an emergent target space of CFT and confirms the conjecture of Kontsevich and Soibelman in [17].

In general, the parameter α defined in Theorem (B) depends on the geodesic to reach the limit as well as on the primary operator we follow along the geodesic. For the optimal choice of geodesic (which we assume to be in the direction of a parity-even exactly marginal operator) and primary operator, we can derive the following lower bound on α,

(D) There exists a geodesic and a primary operator with a vanishing conformal dimension along the geodesic such that the exponential decay rate obeys $N^{-1/2} \leq \alpha$.

Since $N \leq c$, this theorem also implies the lower bound $c^{-1/2} \leq \alpha$. Combining these results, we obtain the upper and lower bounds on α,

$$\frac{1}{\sqrt{c}} \leq \alpha \leq 1\,. \tag{3.1}$$

These bounds are sharp, and we will find necessary and sufficient conditions to saturate each bound at $\alpha = c^{-1/2}$ and $\alpha = 1$. For superconformal CFTs, the lower bound is strengthened to $\sqrt{3/2}\, c^{-1/2} \leq \alpha$.

To prove these four theorems, we do not need to assume that the CFTs have holographic duals in AdS or that the central charge c is large. We only assume that the CFTs are unitary and each have a normalizable conformally invariant vacuum (away from the limit), there is an exactly marginal operator for each tangent vector on their conformal manifolds, and the genus-zero four-point functions of the light primary operators are well-defined in the limit of vanishing gap $\Delta_{\text{gap}} \to 0$. To prove Theorems (A) and (B), we do not even assume the existence of a local stress tensor. Therefore, these theorems also apply to the conformal manifolds of surface defects in $d \geq 3$ CFTs (such as the Gukov-Witten surface defects in the $\mathcal{N} = 4$ super-Yang-Mills theory [20]).

Furthermore, Theorem (C) does not assume that the family of CFTs is related by deformation with an exactly marginal operator. Therefore, it also holds for a discrete sequence of CFTs under the assumptions stated in the above. For example, the large k limit of the level k Wess-Zumino-Witten model for a compact Lie group G is locally equivalent to the theory of free non-compact bosons with $c = \dim G$, and the large k limit of the A_k-type Virasoro minimal model CFTs is locally described in terms of a non-compact boson at $c = 1$ with a pair of walls in the target space infinitely distant from each other [21, 22]. If we can also generalize Theorems (A), (B), and (D) to include discrete families of CFTs, it would open the possibility to study the flat space limits of AdS gravities and test the conjecture in [23].

For the purpose of understanding the implications of our CFT results for quantum gravity, it is useful to translate the bound (3.1) on α in the units appropriate for a gravitational theory in AdS_3. If we normalize the kinetic term of the massless scalar field ϕ in AdS_3 dual to the geodesic coordinate t on the conformal manifold of CFT_2 as

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + \cdots , \tag{3.2}$$

without the inverse of the Newton constant in front, by the AdS/CFT dictionary we can identify the asymptotic value of ϕ with the geodesic distance t on the conformal manifold as $\phi = t \cdot (8\pi L_{\text{AdS}})^{-1/2}$, where L_{AdS} is the curvature radius of AdS. Correspondingly, $\alpha_{\text{AdS}} = \alpha \cdot (8\pi L_{\text{AdS}})^{1/2}$ controls the exponential decay $e^{-\alpha_{\text{AdS}}\phi}$ of the energy gap in the bulk. Using the relation

$$c = \frac{3L_{\text{AdS}}}{2G_N} = 8\pi L_{\text{AdS}} \cdot \frac{3}{2L_{\text{Planck}}} , \tag{3.3}$$

where G_N is the Newton constant and $L_{\text{Planck}} = 8\pi G_N$ is the reduced Planck length in three dimensions. The inequality (3.1) can then be expressed in terms of the bulk variables as,

$$\left(\frac{2}{3}L_{\text{Planck}}\right)^{1/2} \leq \alpha_{\text{AdS}} \leq (8\pi L_{\text{AdS}})^{1/2} . \tag{3.4}$$

The lower bound means that the emergence of exponentially light states with energy Δ is inevitable when ϕ rolls beyond the Planck scale at $\phi = (2L_{\text{Planck}}/3)^{-1/2}$ along the path of the steepest descent, while the upper bound implies that this phenomenon can begin already at the AdS curvature scale $\phi = (8\pi L_{\text{AdS}})^{-1/2}$.

If the theory is supersymmetric, the lower bound is strengthened and can be translated in the AdS units as

$$(L_{\text{Planck}})^{1/2} \leq \alpha_{\text{AdS}} \leq (8\pi L_{\text{AdS}})^{1/2} . \tag{3.5}$$

These bounds on the decay rate of the AdS energy can be translated to that of the mass for the corresponding particles using the standard AdS/CFT dictionary [27]. The energy Δ and the mass m for scalar fields in AdS_3 are related by

$$\Delta = 1 \pm \sqrt{1 + m^2 L_{\text{AdS}}^2} , \tag{3.6}$$

where the plus sign corresponds to the standard quantization and the minus sign corresponds to the alternative quantization, which is valid for $m^2 < 0$. Furthermore, unitarity requires the Breitenlohner-Freedman (BF) bound, $m^2 L_{\rm AdS}^2 \geq -1$ [28]. The light scalar particle states arise from the alternative quantization of the scalar field dual to the light scalar operators in the CFT. Therefore, while the energy of these scalar particle states approach zero from above, their masses-squared approach zero from below as in

$$m^2 \sim -\frac{2}{L_{\rm AdS}^2}\Delta = -\frac{2}{L_{\rm AdS}^2}\exp(-\alpha_{\rm AdS}\phi + O(1))\,, \tag{3.7}$$

which is a phenomena specific to gravity in AdS_3 at infinite distance on the moduli space (since unitarity bounds in higher dimensions are stronger). Note that, in addition to the exactly marginal operator corresponds to t, other marginal operators may emerge at infinite distance. They correspond to scalar fields in AdS_3 with the standard quantization and their masses-squared approaching zero from above.

Furthermore, there are also infinite towers of massive spinning particles whose masses-squared approach zero from above in the limit, in a way similar to what happens in higher dimensional AdS gravity as described in [15]. Indeed they are associated with massive (higher) spin fields which correspond to (higher) spin (quasi-primary) operators in the CFT that only become conserved in the limit (*i.e.* vanishing twist). In this case, the dictionary between the energy (scaling dimension) and the mass is

$$\Delta = 1 + \sqrt{(s-1)^2 + m^2 L_{\rm AdS}^2} \tag{3.8}$$

for $s \geq 1$ (and the alternative quantization is only possible for $s = 1$ at $m = 0$). Therefore, for the massive particles with spin $s \geq 2$ whose energy approaches the unitarity bound $\Delta = s$ in the limit, their masses-squared approach zero from above as for the twist in

$$m^2 \sim \frac{2(s-1)}{L_{\rm AdS}^2}(\Delta - s) = \frac{2(s-1)}{L_{\rm AdS}^2}\exp(-\alpha_{\rm AdS}\phi + O(1))\,. \tag{3.9}$$

For the special case of massive vector (*i.e.* $s = 1$), this becomes

$$|m| = \frac{1}{L_{\rm AdS}}(\Delta - 1) = \frac{1}{L_{\rm AdS}}\exp(-\alpha_{\rm AdS}\phi + O(1))\,. \tag{3.10}$$

In the dual CFT, such higher spin particles correspond to spinning operators constructed from products of the emergent currents in the infinite distance limit[1] and this is how the last equalities in (3.9) and (3.10) are deduced.

Let us now comment on the implications of our bounds in AdS on the decay rates of the masses of light particles for the similar question of quantum gravity in asymptotically flat space (*i.e.* Conjecture (2) in the original Distance Conjecture in flat space). To this end, we note that a lower bound on the mass decay rate in the effective field theory in D-dimensional flat space was proposed in [24] under the name of the Sharpened Distance Conjecture. It claims the existence of an infinite tower of light particles

[1] They are Virasoro primary operators (and their quasi-primary descendants) that are descendants with respect to the emergent current algebra in the limit.

with exponentially descreasing mass of the order $\exp(-\alpha_{\text{flat},D}\tilde{\phi})$ with the coefficient $\alpha_{\text{flat},D}$ bounded below as,

$$\alpha_{\text{flat},D} \geq \frac{L_{\text{Planck},D}^{(D-2)/2}}{(D-2)^{1/2}}\,, \tag{3.11}$$

where $L_{\text{Planck},D}$ is the reduced Planck length in D dimensions and the modulus field $\tilde{\phi}$ is canonically normalized as in (3.2). As explained in [25], this bound follows from the Emergent String Conjecture [26], which states that an infinite distance limit of its moduli space either decompactifies, or reduces to an asymptotically tensionless, weakly coupled string theory. This bound was further supported by evidence from supergravity [24].

By taking an appropriate flat space limit $L_{\text{AdS}} \to \infty$, our bounds for the AdS_3 gravity should produce bounds for quantum gravity in asymptotically flat spacetime of dimension $D = 3+n \geq 3$ where n counts the internal dimensions that decompactify in this limit.[2] Our lower bound (3.4), after taking into account the canonical normalization in D dimensions,[3] implies that

$$\alpha_{\text{flat},D} \geq \frac{1}{\sqrt{6}} L_{\text{Planck},D}^{(D-2)/2}\,, \tag{3.12}$$

and for the supersymmetric case a stronger lower bound follows from (3.5),

$$\alpha_{\text{flat},D} \geq \frac{1}{2} L_{\text{Planck},D}^{(D-2)/2}\,. \tag{3.13}$$

Naively, these bounds can be further strengthened by a factor of 2, due to the faster decay of the mass of spin $s = 1$ particles in (3.10). However, from known top-down examples, we expect these vector fields to be governed by a one-derivative action to leading order in AdS_3 and their mass-squared in the flat space limit obey the same exponential decay rate as the other light particles. We emphasize that taking the flat space limit generally involves a discrete sequence of AdS/CFT dual pairs (*e.g.* with increasing central charge c), and when deducing the bounds above we have assumed that the direction parametrized by ϕ (or t) on the AdS moduli space (CFT conformal manifold) is common to all instances in the sequence.

In higher dimensions, Conjecture (I),which is analogous to our Theorem (A), has been proven for supersymmetric theories in [15] and more recently for general CFTs in [16]. However except for special classes of supersymmetric theories [15], no universal bounds on the exponential rate (analogous to α in two dimensions) are known. Here our universal upper bound on α follows from the bootstrap equation for the four-point

[2] It was conjectured in [23] that such a decompactifying internal space always exists in any AdS gravity. Though the KK modes on the decompactifying internal space also become massless in the flat space limit, we are interested in the contribution to the mass that do not vanish in this limit.

[3] Since both $\tilde{\phi}$ and ϕ are canonically normalized in D and 3 dimensions, respectively, they are related as $\phi = V_{D-3}^{1/2}\,\tilde{\phi}$, where V_{D-3} is the volume of the internal dimensions that decompactify in the limit. Therefore $\alpha_{\text{AdS}} = V_{D-3}^{-1/2}\,\alpha_{\text{flat},D}$ in the flat space limit. On the other hand, $L_{\text{Planck},3} = L_{\text{Planck},D}^{D-2}/V_{D-3}$. Combining these, (3.4) gives (3.12) in the flat space limit.

function, and it is natural to ask whether this idea is useful in higher dimensions. As a more direct application of the bootstrap philosophy to gravity, it may also be interesting to apply the S-matrix bootstrap to find constraints on the effective theory of massless scalar fields coupled to gravity in asymptotically flat spacetime. Furthermore, it remains an open question to prove or falsify the converse, as for the $d = 2$ CFT/$d = 3$ gravity

4 Discussion

There are many other intriguing features of conformal manifolds that appear to be universal and worth further investigating. For example, in $d = 2$, the singularities on the conformal manifolds seem to be one of the following four types with distinct features: orbifold point (enhanced symmetries), conifold point (continuous spectrum with a non-zero gap above the vacuum), branching point (accidental exactly marginal operators), and infinite distance limit (vanishing gap). It would be interesting to understand if they are all the possibilities for $d = 2$ conformal manifold and what are the global constraints on their existence. Among the four possibilities, the conifold points and the infinite distance limits share the property that the CFT becomes singular there ($i.e$ develops a continuous spectrum). One could ask the same questions for higher dimensional CFTs. In particular, the sum rules derived in the recent paper [29] relating Zamolodchikov curvature to OPE data in the CFT could be useful to address these questions.

Another potentially interesting direction is to study topological constraints on the conformal manifolds. In [8], the following conjecture was proposed in addition to Conjectures (0), (1), and (2).

(3) There is no non-trivial 1-cycle with minimum length within a given homotopy class in $\mathcal{M}$.

This conjecture has been proven for gravitational theories in flat space with more than eight supercharges [30]. Since it was motivated by the absence of global symmetries in quantum gravity, which has been proven in AdS by the consistency of CFT [5, 6], it may be possible to prove Conjecture (3) for general AdS gravities similarly

Finally, it would be interesting to further develop and generalize the bootstrap analysis to probe more refined CFT data over the conformal manifold, such as general constraints on the perturbative expansion around the infinite distance limit (cusp point) in terms of the anomalous dimensions of protected operators.

It is often said that low-energy effective theory is a way to parameterize our ignorance. Since there are constraints on low-energy effective theories of gravitational systems that cannot be captured by the standard Wilsonian paradigm, it is important to make sure that we are not parameterizing an empty set. In AdS, we can quantify and prove parts of the Swampland conjectures by translating them into statements about CFT. I hope to strengthen these results and generalize them for spacetimes with zero and positive vacuum energies.

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Declarations

Competing interests The authors declare no competing interests.

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