Symmetry in Quantum Gravity

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Caltech & Kavli IPMU

50 Years of the Veneziano Model
Galileo Galilei Institute, 11 - 15 May 2018

Swampland Question

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

Vafa: hep-th/0509212;
Vafa + HO: hep-th/0605264

Constraints on Symmetry

Symmetry has played important roles in physics

(1) In identifying and formulating fundamental laws of nature

(2) In using these laws to understand and predict dynamics and phases of matters.

Symmetry can be deceiving:

Two seemingly different microscopic Lagrangians with **different gauge symmetries** and different matter contents **can describe the same quantum system.**

"Duality"

Equivalencen can be between full quantum theories,
such as in the S-duality of N=4 super Yang-Mills theory,
or about their low energy limits, such as in the Seiberg dualities.

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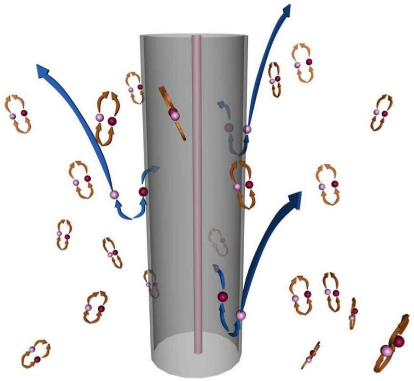
However, it has been argued that a **consistent quantum theory of gravity does not have global symmetry**.

Standard argument for

No global symmetry in quantum gravity:



If there is a continuous global symmetry G, we can combine a large number of G-charge matters to make a **black hole in an arbitrary large representations of G**.

Let it Hawking-radiate, keeping its mass > the Planck mass.

The Hawking radiation is G-blind (If G were a gauge symmetry, the radiation would have charge inbalance). The dimension of the G representation exceeds **the number of states allowed by the Bekenstein-Hawking entropy** formula.

We have refined and proven these conjectures in AdS/CFT,
by generalizing and extending the earlier work, Harlow:1510.07911.

《 work in progress with Daniel Harlow 》

(1) Any **global symmetry** in AdS is **inconsistent** with locality of CFT.

(2) A compact (discrete or continuous) symmetry G in CFT corresponds to a **gauge symmetry** with the same G in AdS.

(3) In a gravitational theory with gauge group G, there must be physical states in **every finite dimensional irreducible unitary representation** in G.

+ with some additional assumption:
(4) Internal global symmetry of CFT is compact.

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Global Symmetry

We need to sharpen our requirements:

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If a Noether current exists, (1) - (3) imply (4).

However, the **Noether theorem is not always true in QFT** even for continuous symmetry.

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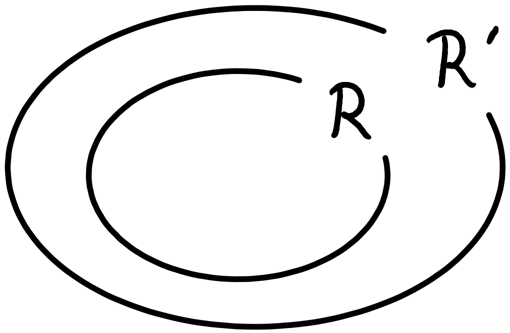
If QFT satisfies the split property, (1) - (3) impy (4).

Buchholz-Duplicher-Lungo: Ann. Phys. 170 (1989) 1

QFT has the split property on Σ if there is a type I factor $\mathcal{N}$ (von Neumann algebra with trivial center) for every nested open subregions $\mathcal{R}$ and $\mathcal{R}'$ such that: $\mathcal{A}[\mathcal{R}] \subset \mathcal{N} \subset \mathcal{A}[\mathcal{R}']$

↑ with a trivial center



A type I factor can always be realized as the set of all operators on some Hilbert space.

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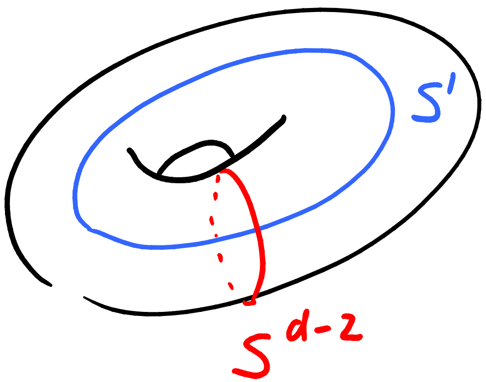
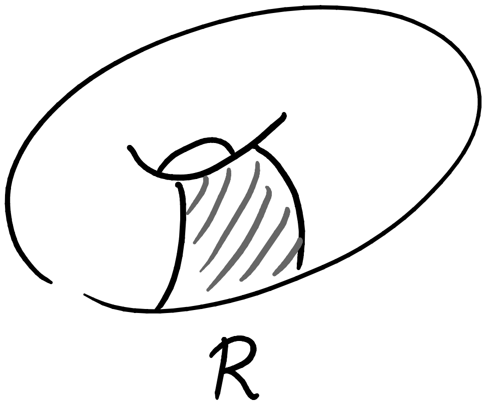
The split property does not hold in the pure Maxwell theory.





$$\phi = \int_{S^{d-2}} {}^*F \in \mathcal{A}[\mathcal{R}]$$

The flux across the S^{d-2} generates a non-trivial center since it does not commute with a Wilson line around the S'.

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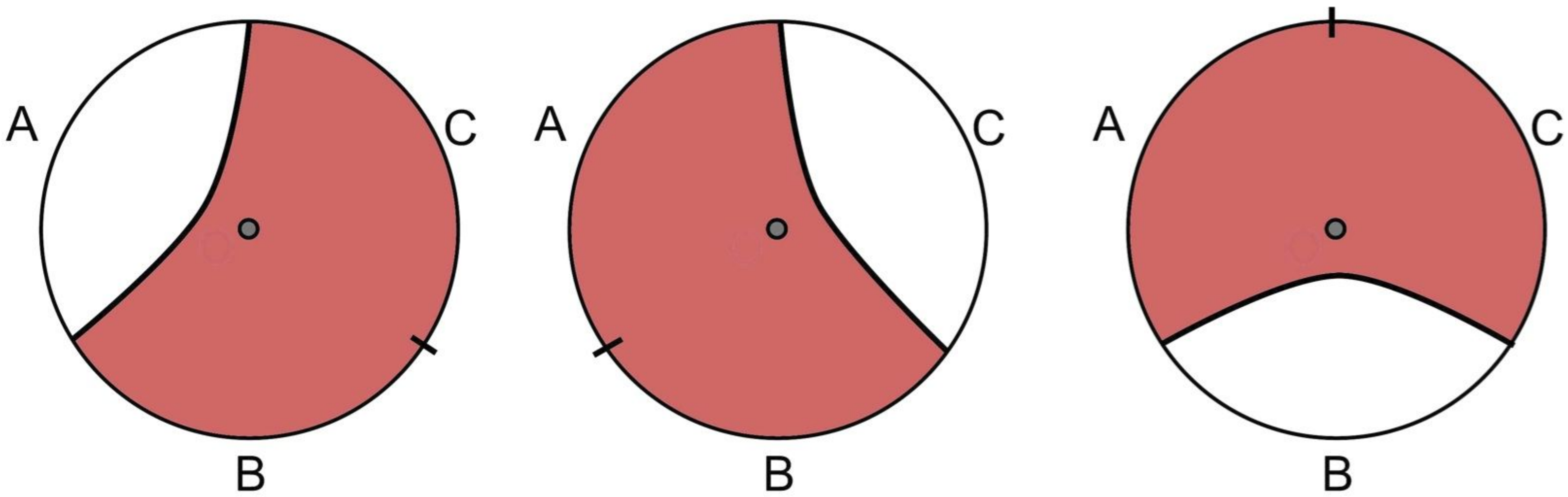
We think it is plausible that:

Symmetries that are not splittable can be made so by adding heavy degress of freedom.

We do not need these conjectures to prove our results, but they will simply my presentations today.

In the following, we will apply the entangement wedge reconstruction in AdS/CFT.

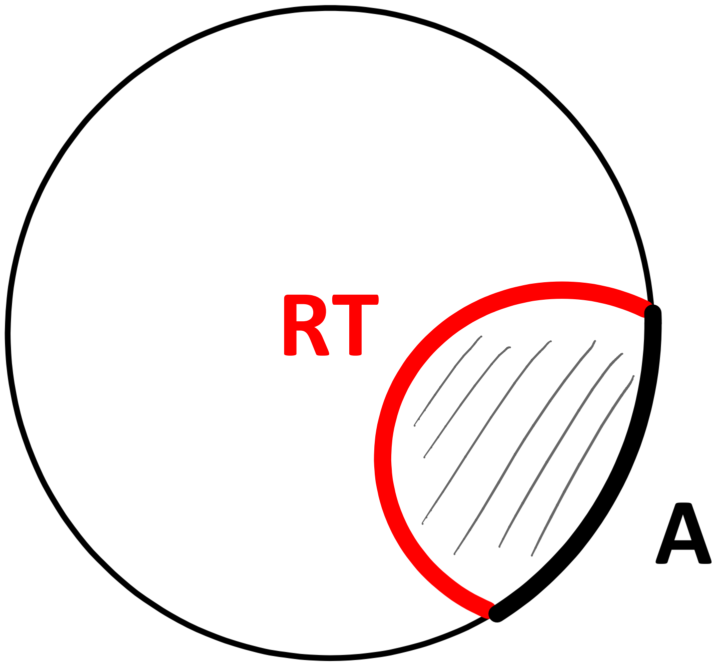


Hamilton, Kabat, Lifschytz, Lowe: hep-th/0606141
Papadodimas, Raju: 1310.6335
Headrick, Hubeny, Lawrence, Rangamani: 1408.6300
Almheiri, Dong, Harlow: 1411.7041, Dong, Harlow, Wall: 1601.05416

Entangement Wedge Reconstruction

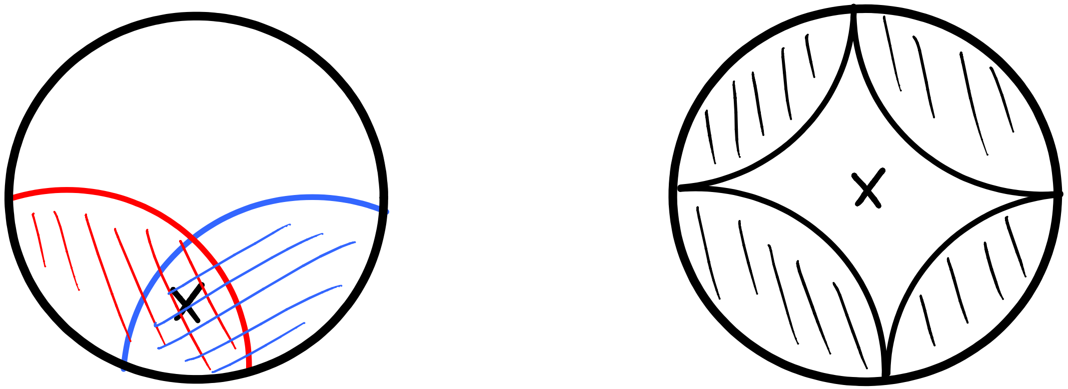
Reconstruction of bulk spacetime by quantum entanglement

Consider the shaded sub-region bounded by **A** on the boundary and the Ryu-Takayanagi surface **RT** (= minimum surface subtending **A**).



Quantum gravity operator localized in the **shaded region in AdS** can be represented by an operator acting on the sub-region **A of CFT**.

Relation to Quantum Error Correcting Codes



Almheiri, Dong, Harlow: 1411.7041
Harlow: 1607.03901

Local excitations of the gravitational theory in AdS correspond to states with a special type of entanglement in CFT similar to the one used for **quantum error correcting codes**, where different sub-spaces of CFT share **quantum secret keys**.

Global symmetry in AdS is inconsistent with local structure of CFT.

If a gravitational theory in AdS has global symmetry G, there must be a bulk local operator that transforms faithfully into another local operator at the same point.

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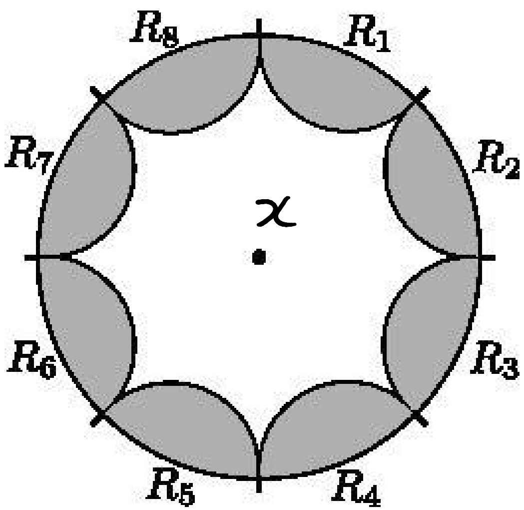


Symmetry generator,

$$U(g) = \prod_i U(g, R_i)$$

commute with the local operator at x in the bulk.

Contradiction

With the precise definition of quantum gravity by AdS/CFT, we are able to talk about what are possible and not possible in quantum gravity.

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 theory, there must be a particle with charge *Q* and mass *m* << *M*_Planck, such that:

$$m \leq \frac{|Q|}{\sqrt{G}}$$

Arkani-Hamed, Motl, Nicolis, Vafa: hep-th/0601001

$$\exists\ (m, Q) \quad \text{s.t.} \quad m \leq \frac{|Q|}{\sqrt{G}}$$

Motivated by:

(1) Black Hole Physics: Extremal black holes should decay unless protected by supersymmetry.

Otherwise, charged black holes can decay to Planck-size remnants with entropies, exceeding the Bekenstein-Hawking bound.

(2) True in all known constructions from string theory.

(3) Holography

In all cases,

$$m < \frac{Q}{\sqrt{G}} \quad (\text{no } "=") \text{ unless BPS.}$$

If this sharpened weak gravity conjecture is true,
non-SUSY AdS supported by fluxed **must be unstable**.

Vafa + H.O.: 1610.1533

All known non-SUSY AdS's are marginally stable at best, and some of them are unstable in interesting ways.

Example: AdS5 x S5 / Γ in IIB:

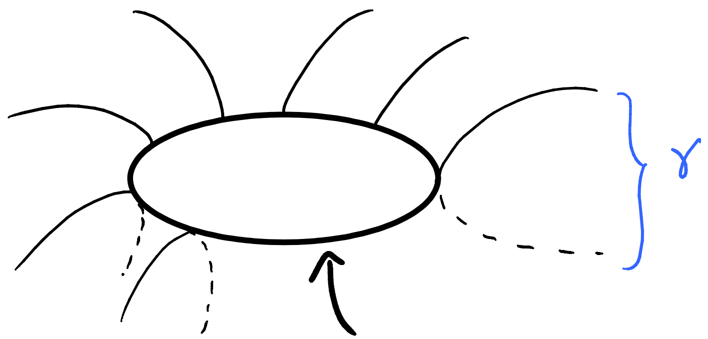
Kachru, Silverstein: hep-th/9802183

Supersymmetry is broken when Γ does not fit in SU(3).

★ If Γ has a fixed point or S5 is small,
there is a tachyon violating the BF bound.

Dymarsky, Klebanov, Roiban: 0509132

★ If Γ has no fixed point and S5 is large,
there is Witten's instanton, creating a bubble of nothing.



Witten (1982)
Horowitz, Orgera, Polchinski: 0709.4262

The bulk geometry terminates with S1 collapsing.

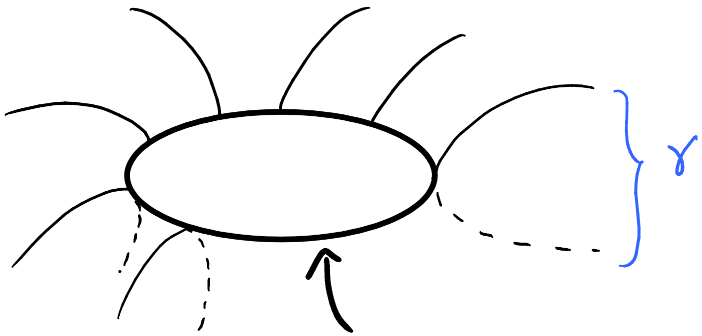
Example: AdS5 x CP3 in M Theory:

Martin, Reall: 0810.2707

Supersymmetry is broken.

Though the fundamental group of CP3 is trivial
(and thus, there is no Witten's instanton),
the geometry allows a generalization of Witten's instanton
where a 2-sphere collapses.

Spodyneiko + H.O.: 1703.03105



The bulk geometry terminates with S2 collapsing.

Standard Model of Particle Physics gives rise to a rich landscape of stable dS and AdS vacua in 2 and 3 dimensions upon compactification, depending on types (Majorana or Dirac) of neutrinos and their masses.

Arkani-Hamed Dubovsky, Nicolis, Villadoro: hep-th/0703067

We pointed out that the sharpened weak gravity conjecture would **rule out certain types and masses of neutrinos** if they give rise to stable non-supersymmetric AdS_3.

Vafa + H.O.: 1610.1533

Our idea has been explored further in recent papers, leading to **constraints on particle physics models beyond the Standard Model**.

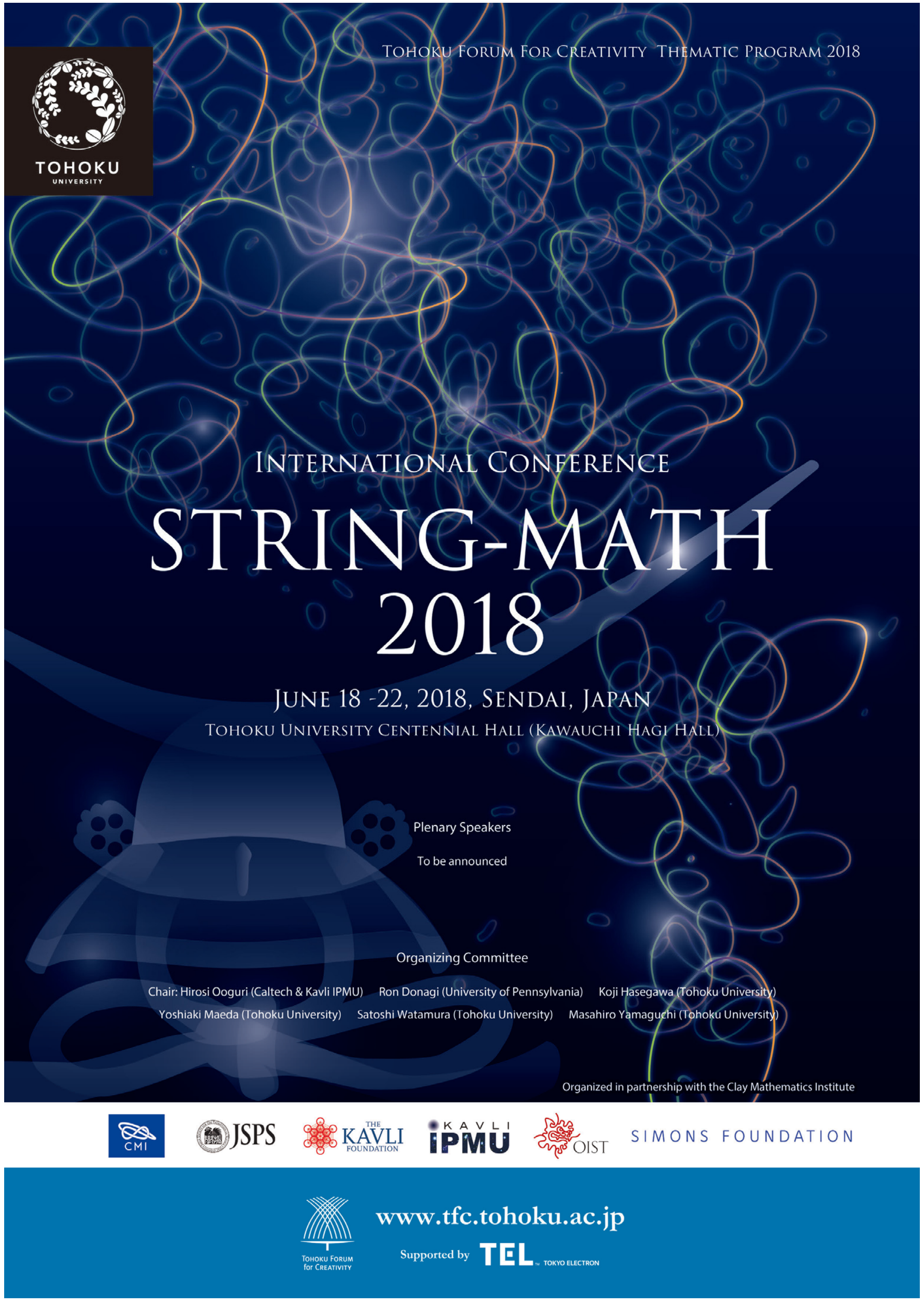
Ibanez, Martin-Lozano, Valenzuela: 1706.05392,1707.05811;
Hamada, Shiu: 1707.06326;
Gonzalo, Herraez, Ibanez: 1803.08455

The UV/IR connection may imply surprising IR predictions on observable phenomena from UV completion of quantum gravity.

"And so I 'm stuck to have to continue this investigation, and of course you all appreciate that this is the secret reason for doing any work, no matter how absurd and irrational and academic it looks; we all realize that no matter how small a thing is, if it has physical interest and is thought about carefully enough, you're bound to think of somethig that is good for something else."

based on a tape-recording of Feynman's lecture
"Quantum Theory of Gravitation" in Poland in July 1962.


Strings 2018
25 - 29 June in Okinawa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Over 530 have registered.

- IAS + Princeton: 18
- Harvard: 15
- Caltech: 13
- Tata Institute: 11

142 applied to the Gong Show.

18 + 11 have been selected for travel fellowships.

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Golden Jubilee Celebration

David Gross, Chair

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