Symmetry in Quantum Gravity

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ICTS Distinguished Lecture, Bengaluru, India (15 January 2018)

What I would like to tell you today:

☆ Why is the unification of general relativity and quantum mechanics difficult?

☆ Why is superstring theory important?

☆ What is the holographic principle?

☆ What are known and not known about quantum gravity ?

Why is the unification of general reativity and quamtum mechanics difficult?

It is often said that, since the Einstein theory:

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

is *not renormalizable*, we cannot use it to compute quantum gravity effects reliably.

This is not a whole story.

For example, the pion theory in nuclear physics,

$$S = \int d^4x \, \frac{(\partial \vec{\pi}(x))^2}{1 + \vec{\pi}(x)^2 / F^2}$$

is also *not renormalizable*.

Neverthelss, we can used it to study phenomena whose energy scale is less than F [∼*184 MeV*] , and compute their quantum effects reliably.

In the pion theory,

$$S = \int d^4x \frac{(\partial \vec{\pi}(x))^2}{1 + \vec{\pi}(x)^2/F^2}$$

we can expand observable quantities in powers of energy and momenta, and each term in the perturbative expansion can be calculated systematically by renomalizing finite number of parameters.

Wilsonian View:

The pion theory is a low energy approximation to QCD, and it can be derived by performing QCD functional integral, except for the low energy pion degrees of freedom.

$\Rightarrow$ Effective Theory

Despite being non-renormalizable, low energy predictions including quantum effects can be made; they have been verified experimentally.

Einstein gravity is also an effective theory

As in the pion theory, provided energy and momenta are less than the cutoff scale (threshold above which a more fundamental theory is required), the Einstein gravity can be used to make reliable predictions including quantum effects

For example：☆ Hawking radiation from a black hole

☆ Cosmic microwave background fluctions caused by quantum effects during the inflation

☆ Corrections to the newton potential

$$V = -\frac{G_N m_1 m_2}{r}\left(1 - \frac{G_N(m_1+m_2)}{r} - \frac{135}{30\pi^2}\frac{G_N \hbar}{r^2} + \cdots\right)$$

relativity effect

one-loop

Problems:

[1] In relativity, energy cutoff depents on observers.
Does the Wilsonian approach work gravity?

$\Leftarrow$ Black hole firewall paradox.

[2] The pion theory can be UV-completed by QCD,
which is a consistent quantum theory.

Is the Einstein gravity guaranteed to have a UV completion?

[3] The asymptotic freedom of strong interaction was
not expected in the pion theory.

Many interesting phenomena specific to quantum gravity,
such as a fate of an evaporating black hole, top-down
derivation of inflation models, and the initial singularity
of the Universe, cannot be addressed by the Einstein gravity.

[2] The pion theory can be UV-completed by QCD, which is a consistent quantum theory.

Is the Einstein gravity guaranteed to have a UV completion?

【**Existence Theorem** of Consistent Quantum Gravity】

☆ In superstring theory, one can compute quantum effects without UV cuttoff to all order in the perturbative expansion.

☆ Its low energy effective theory contains the Einstein gravity.

☆ By compactifying the spacetime dimensions to 4:

- several generations of quarks and leptons
- gauge interactions including SU(3) x SU(2) x U(1)
- Higgs mechanism

can be derived.

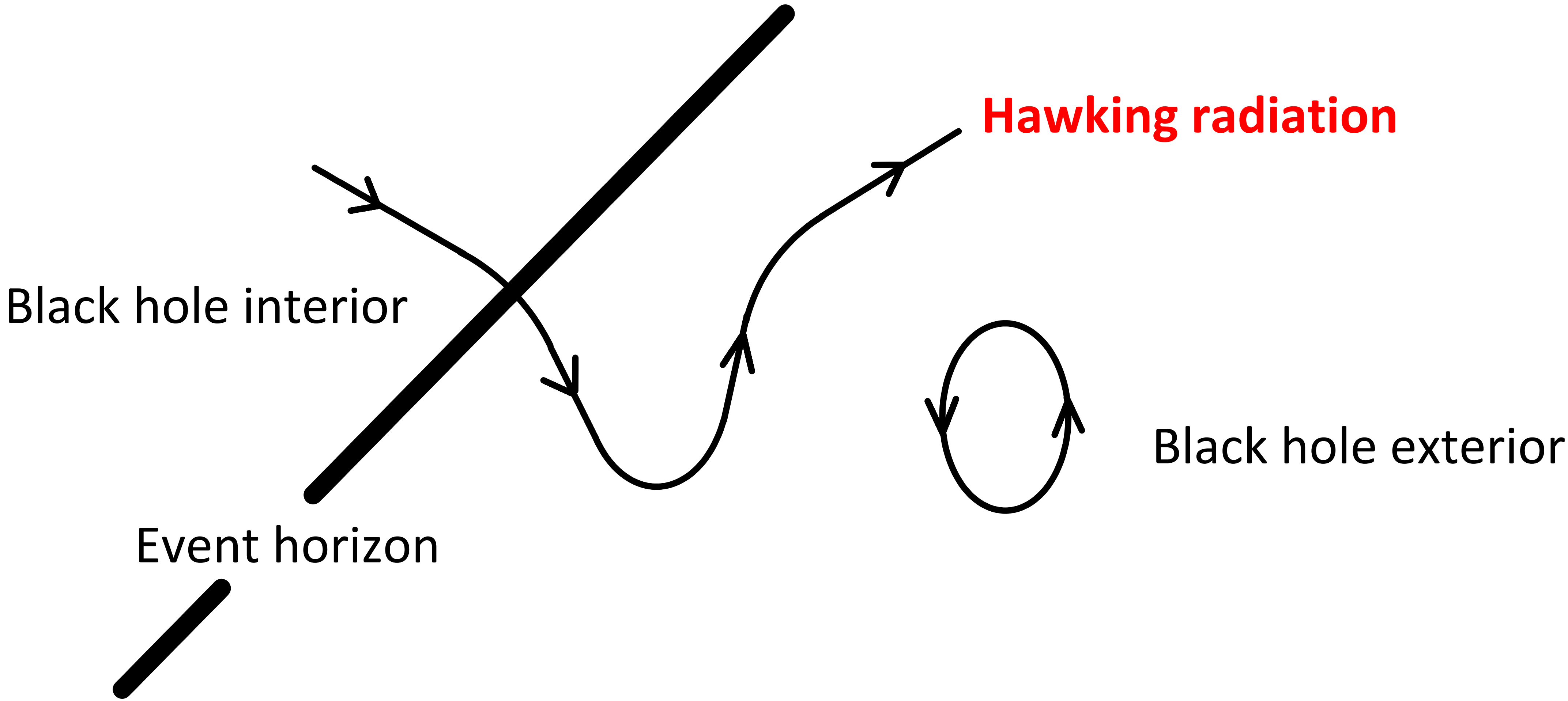
Moreover:

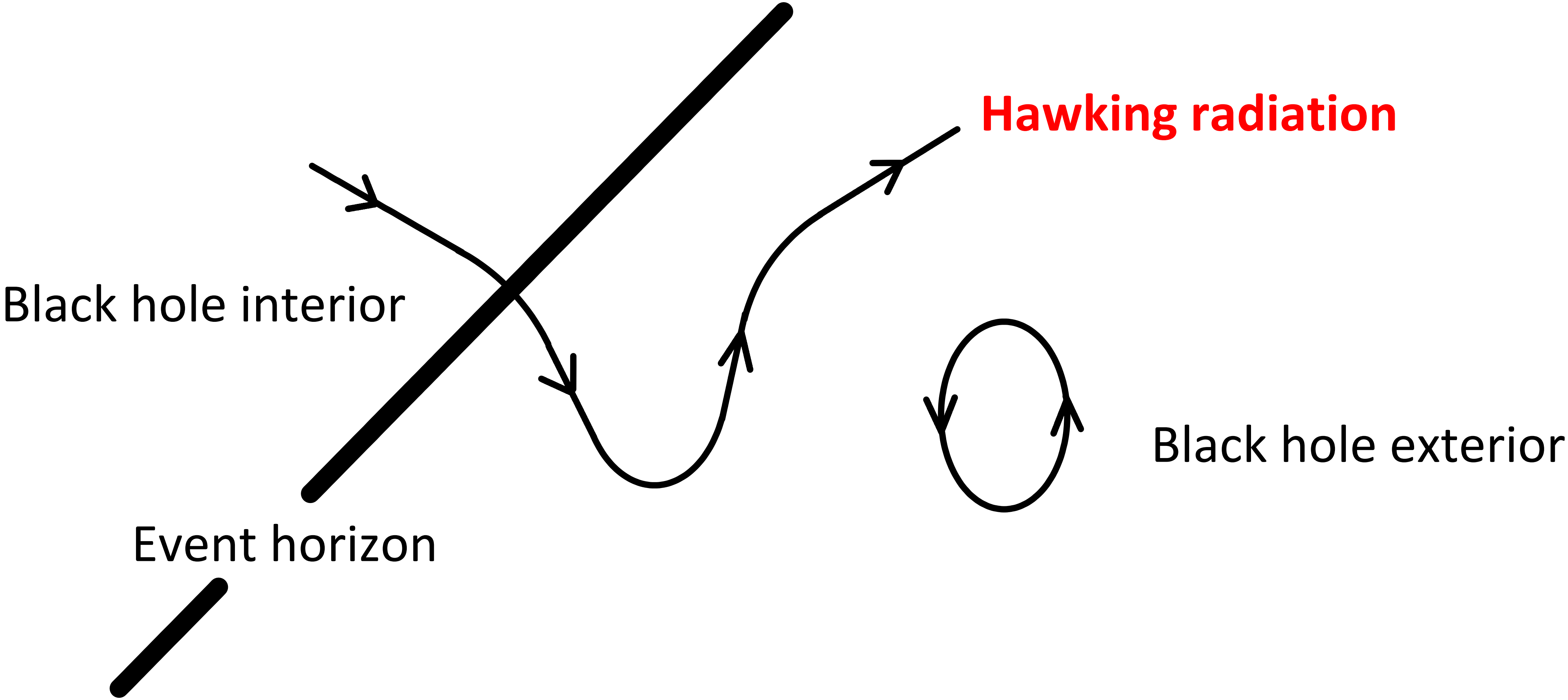
The hierarchy of the physical world, where more fundamental laws are discovered by exploring shorter distance scales, will terminates once we complete quantum gravity.

Quantum gravity will lead us to the ultimate unification of elementary particles and forces.

(If physicists in the early 20th century had been satisfied with the Bohr-Sommerfeld semi-classical quantization, they would not have completed quantum mechanics.)

Black Hole Paradox and Holographic Principle


Hawking radiation
Black hole interior
Black hole exterior
Event horizon



$$\frac{1}{T} = \frac{\partial S}{\partial E} \implies S = \frac{1}{4G_N}\left(\text{Area of Event Horizon}\right)$$

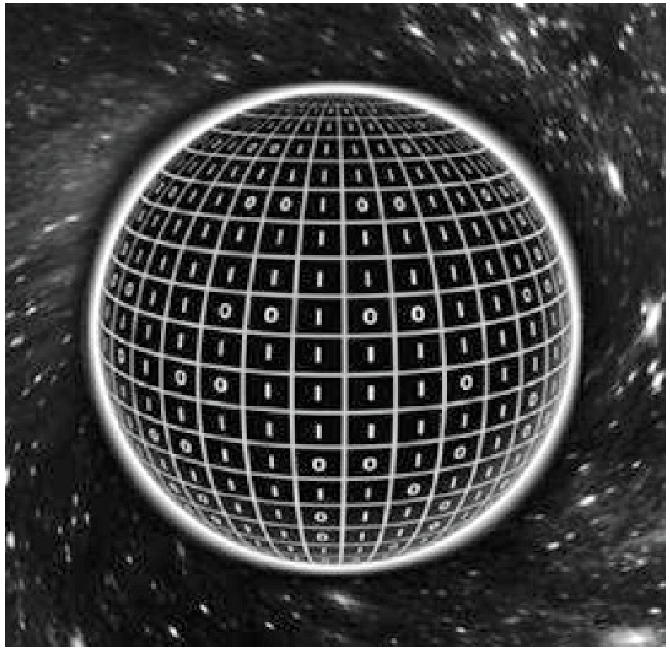
temperature: T; entropy: S; energy: E; Newton constant: G_N

$$S = \frac{1}{4G_N}\left(\text{Area of Event Horizon}\right)$$

Entropy is extensive.
Why is it proportional to the **area**?

Holographic Principle

Fundamental degrees of freedom for a given region of spacetime are defined on the surface surrounding it.



The holographic principle is realized in string theory.

To explain how the holographic principle is realized in string theory, we need some preparation:

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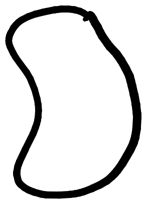
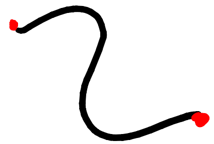
There are closed strings  and open strings 

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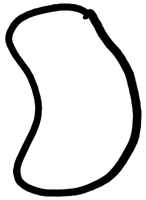
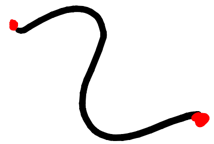
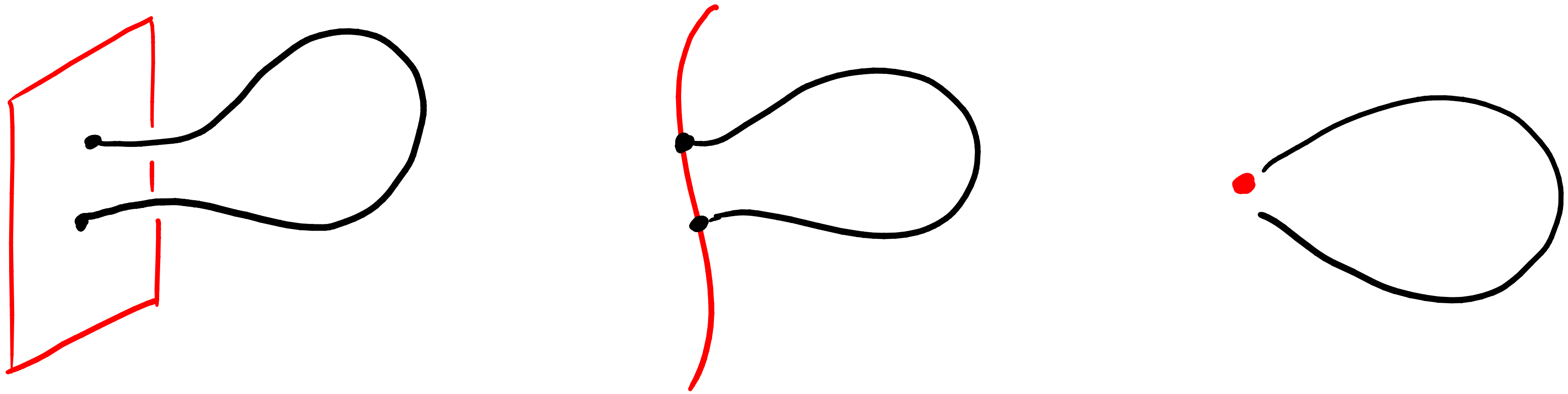
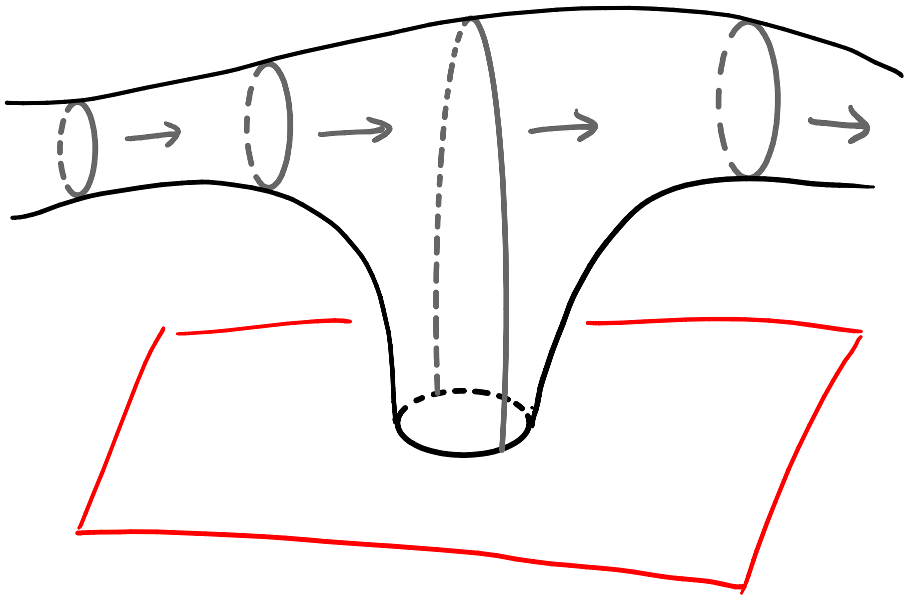
There are closed strings  and open strings 

End-points of open strings may be restricted on a sub-space



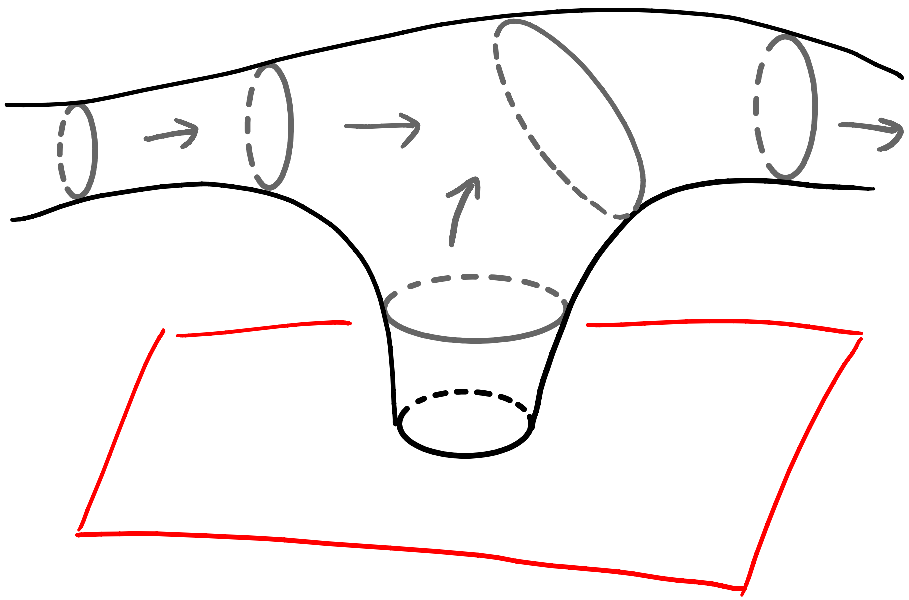
surface curve point

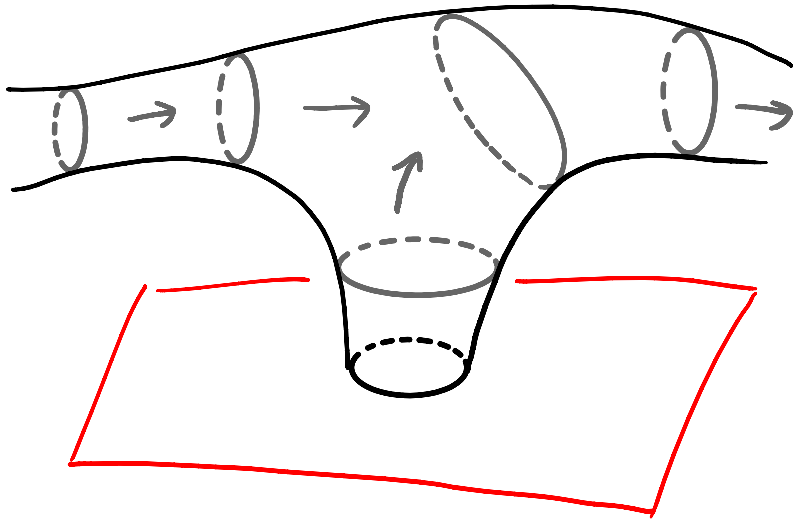
These sub-spaces carry mass/energy and emit gravitons

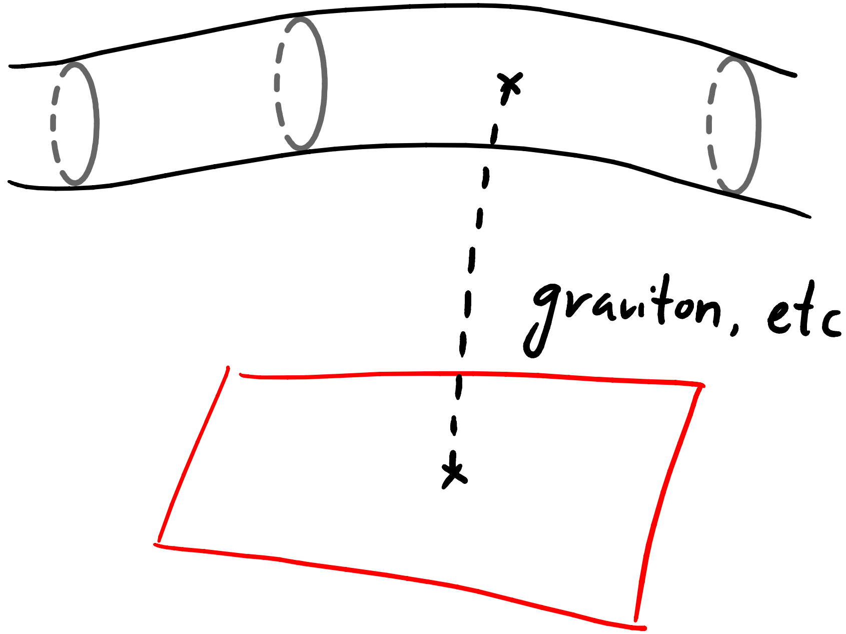


When open string end-points
are located in a sub-space,

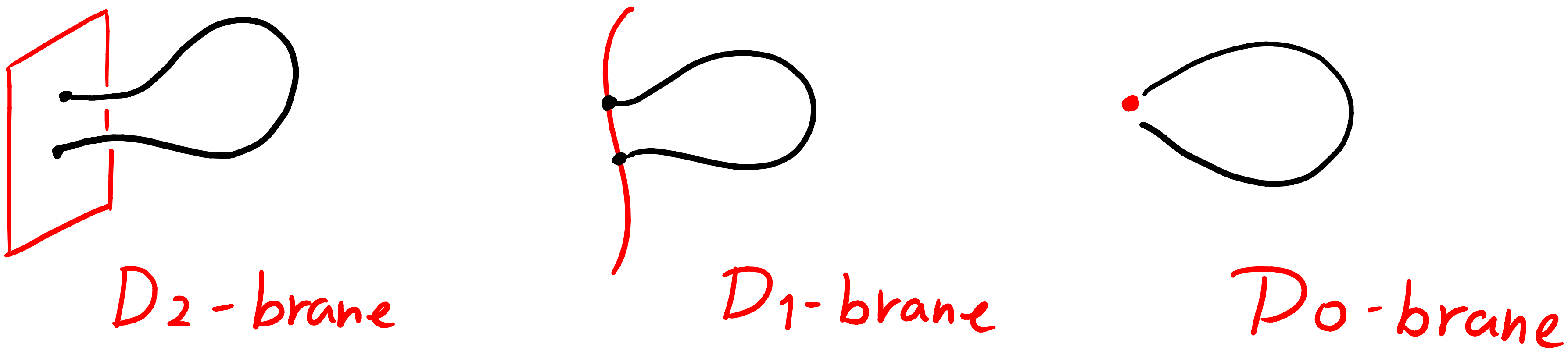
the sub-space can emit
and absorb closed strings.

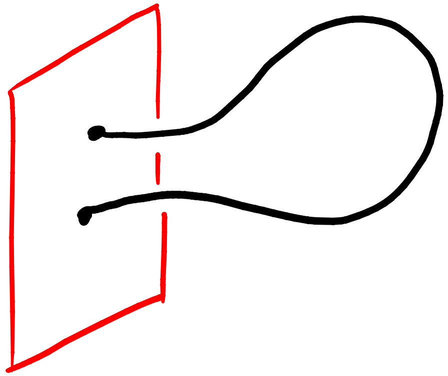






The graviton is also a closed string state. The fact that a sub-space can emit and absorb closed strings means that mass/energy is localized on the sub-space.





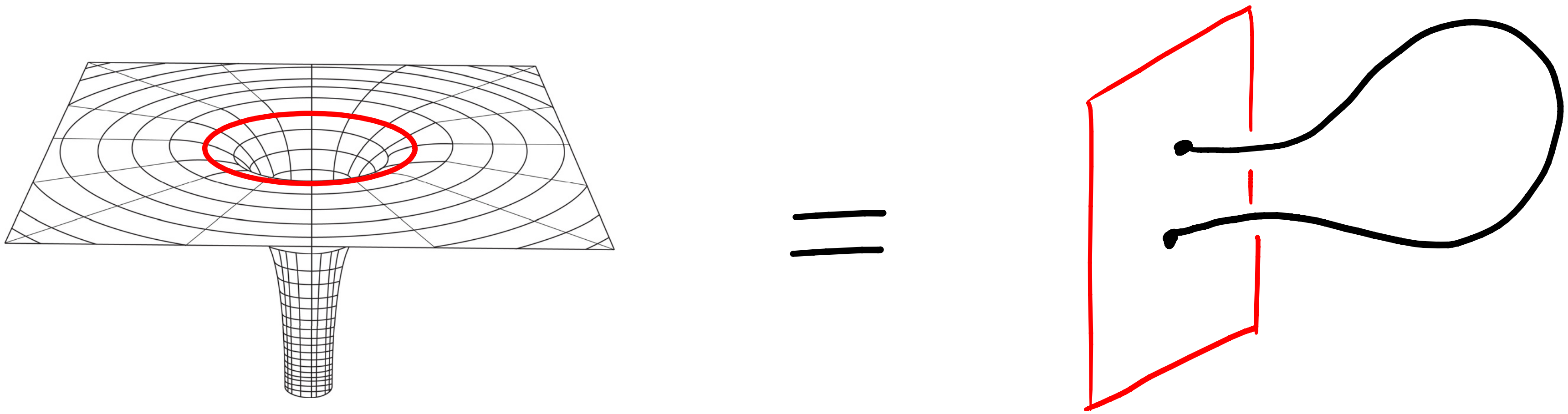
Since mass/energy is localized on the D-brane, it becomes a black hole/brane if the gravity is strong.

By quantizing open strings on the D-brane and by analyzing its Hilbert space, one can count black hole microstates.

In cases when this calculation can be done exactly,

$$S = \frac{1}{4G_N}\left(\text{Area of Event Horizon}\right)$$

has been reproduced.



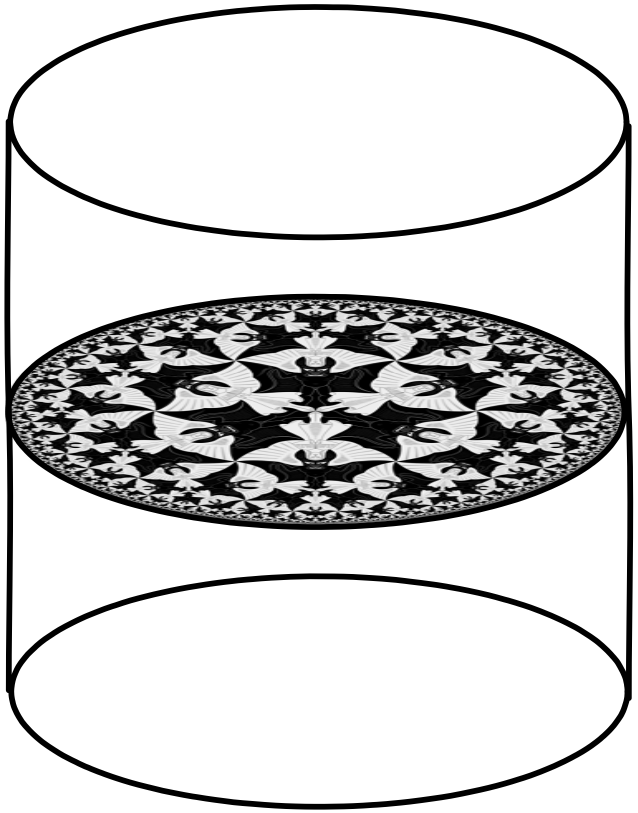
Physical phenomena on the event horizon of a black hole can be described by quantum theory of **open strings** on the corresponding D-brane.

⇒ Quantum theory of open strings does not contain gravity.

⇒ Gravitational phenomena can be described by the non-gravitational theory, localized on the horizon.

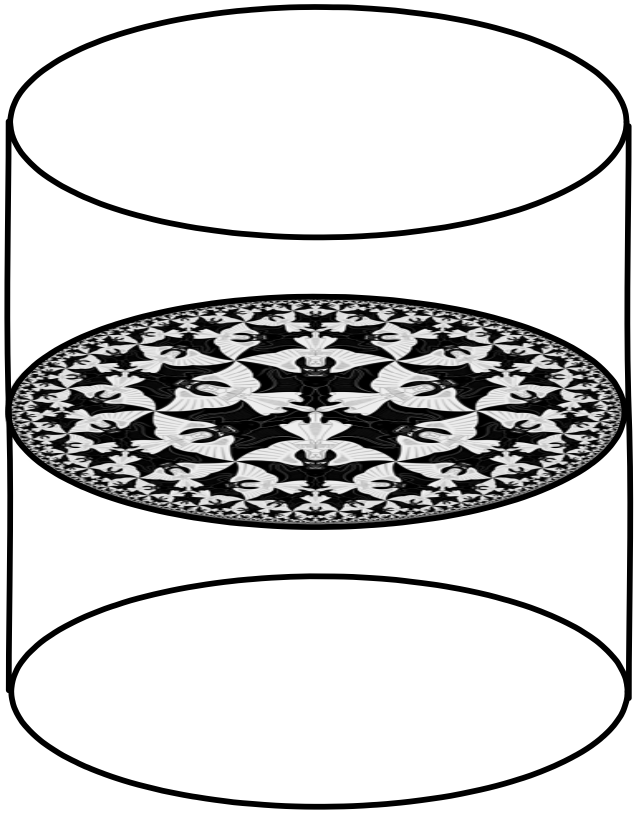
AdS/CFT correpsondence:

Gravitational theory in anti-de Sitter space (AdS)
is equivalent to conformal field theory (CFT)
at the boundary.



The evaporation of a black hole by the Hawking radiation can be described by a unitary time evolution in CFT.
(*In principle*, it provides a solution to the information paradox.)

The AdS/CFT correspondence defines a consistent quantum theory of gravity including non-perturbative effects.



There are important applications to condensed matter physics and hadron physics, but we will not cover them today.

Instead, let me discuss new insights into quantum gravity provided by the holographic principle.

Quantum Entanglement
and
Geometry of Spacetime

Quantum Entanglement

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

$\mathcal{H}_A \otimes \mathcal{H}_B$ with $\mathcal{H}_A = \{ |0\rangle_A, |1\rangle_A \}$, $\mathcal{H}_B = \{ |0\rangle_B, |1\rangle_B \}$

$$\begin{cases} |0\rangle_A |0\rangle_B & : \text{no entanglement} \\ |EPR\rangle = \frac{1}{\sqrt{2}} \left(|0\rangle_A |0\rangle_B + |1\rangle_A |1\rangle_B \right) & : \text{maximally entangled} \end{cases}$$

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Entanglement entropy: quantifying the entanglement

$$|\psi\rangle \in \mathcal{H}_A \otimes \mathcal{H}_B, \quad \text{partial trace } \rho_A = \mathrm{tr}_{\mathcal{H}_B} \left(|\psi\rangle\langle\psi| \right)$$

$$S(|\psi\rangle) = - \mathrm{tr}_{\mathcal{H}_A} \left(\rho_A \log_2 \rho_A \right)$$

↑ Symmetric in A and B.

$$= \begin{cases} 0 & (|\psi\rangle = |0\rangle_A |0\rangle_B) \\ 1 & (|\psi\rangle = |EPR\rangle) \end{cases}$$

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$$= \begin{cases} 0 & (|\psi\rangle = |0\rangle_A |0\rangle_B) \\ 1 & (|\psi\rangle = |EPR\rangle) \end{cases}$$

How many EPR pairs can be extracted from $|\psi\rangle$

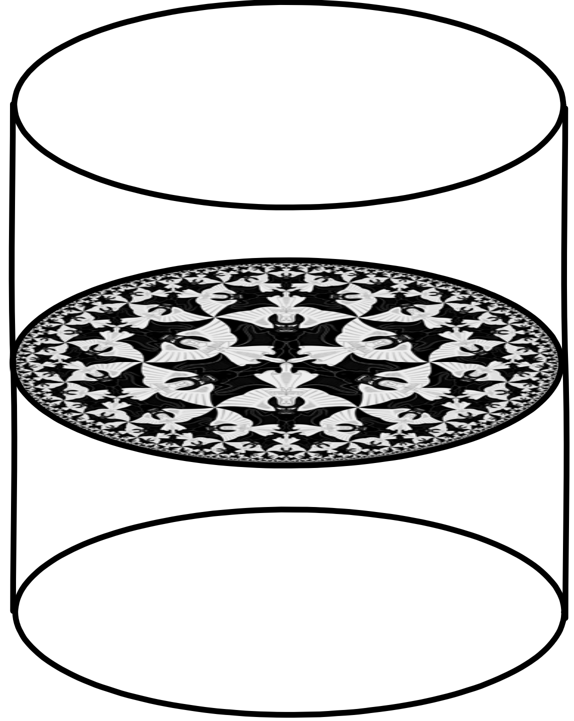
$$|\psi\rangle^{\otimes n} \Longleftrightarrow |EPR\rangle^{\otimes \lfloor n \times S(|\psi\rangle) \rfloor}$$

← integer part

↑ Local Operation and Classical Communication

AdS/CFT correspondence:

Gravitational theory in AdS
is equivalent to CFT at the boundary.



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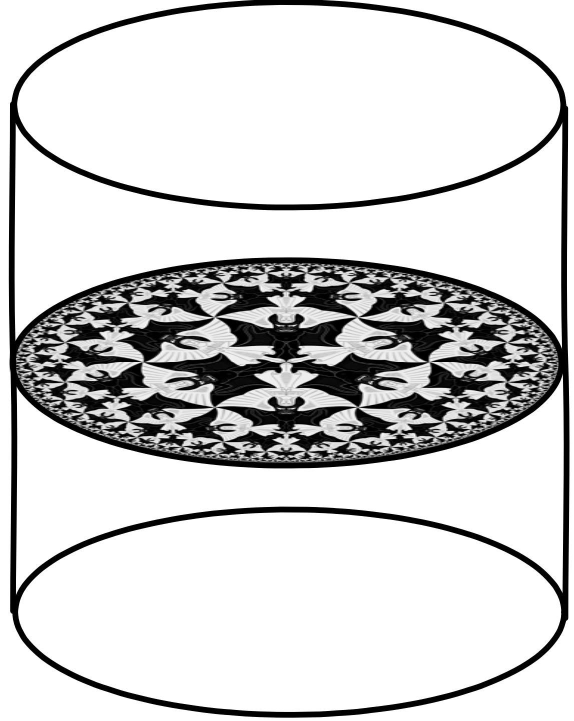

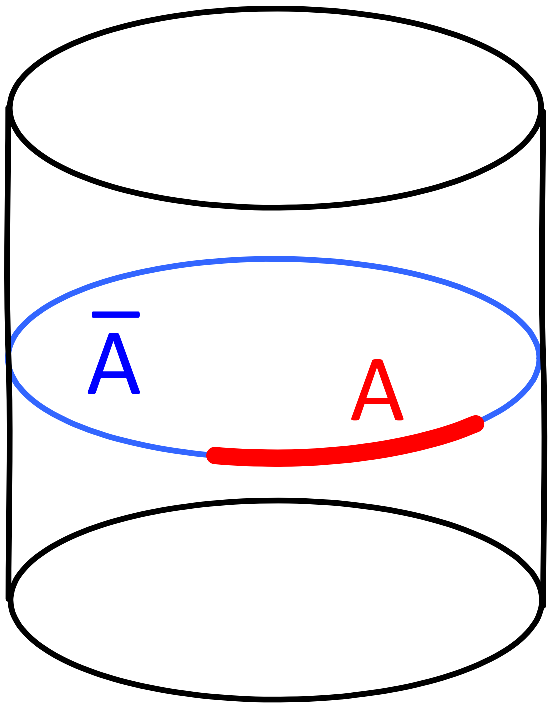

For a given choice of a sub-region **A** and its complement $\bar{\mathbf{A}}$ of the Cauchy surface, we can decompose the total Hilbert space of CFT into a direct product of Hilbert spaces associate to **A** and $\bar{\mathbf{A}}$.

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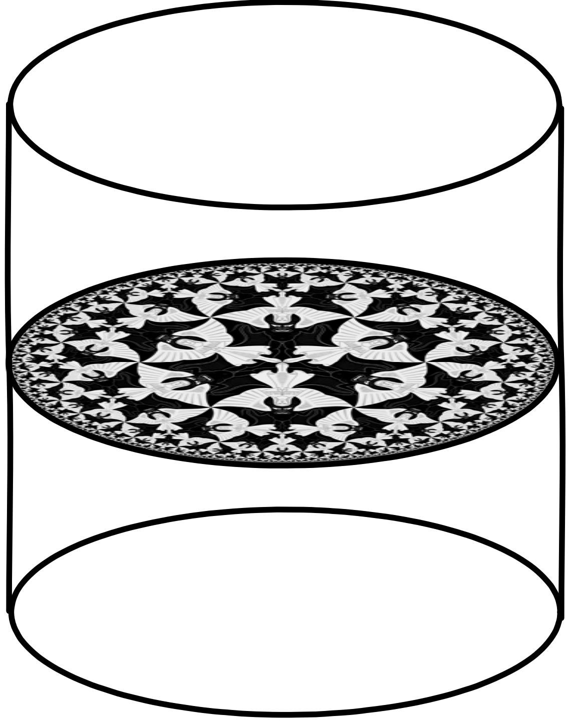
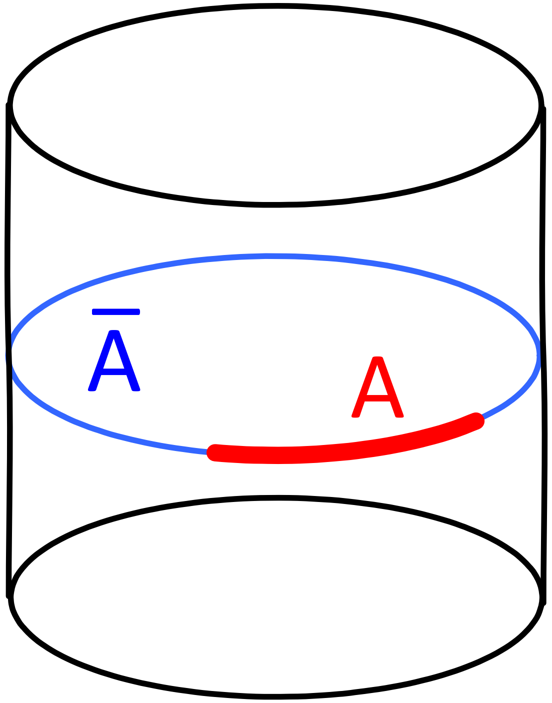
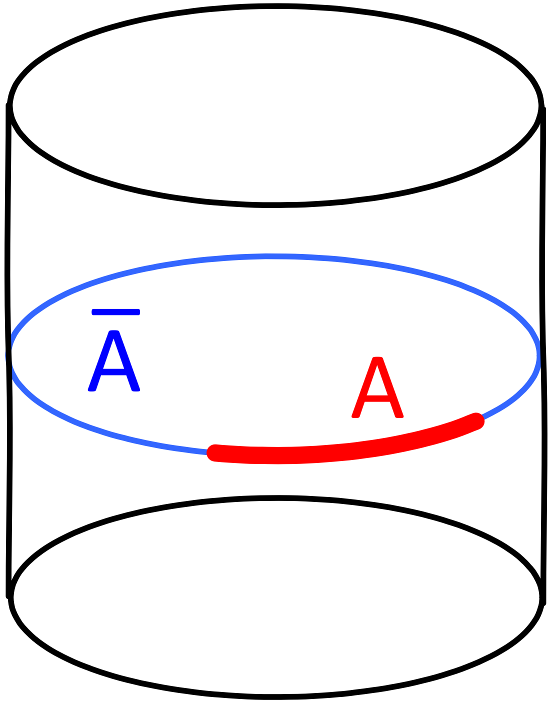




For a given choice of a sub-region **A** and its complement $\bar{A}$ of the Cauchy surface, we can decompose the total Hilbert space of CFT into a direct product of Hilbert spaces associate to **A** and $\bar{A}$.



For a given choice of a sub-region **A** and its complement **Ā** of the Cauchy surface, we can decompose the total Hilbert space of CFT into a direct product of Hilbert spaces associate to **A** and **Ā**.

To measure entanglement between A and $\bar{A}$ for $|\psi\rangle$,

$$\rho(|\psi\rangle) = \mathrm{tr}_{\mathcal{H}_{\bar{A}}}(|\psi\rangle\langle\psi|) \quad \text{partial trace}$$

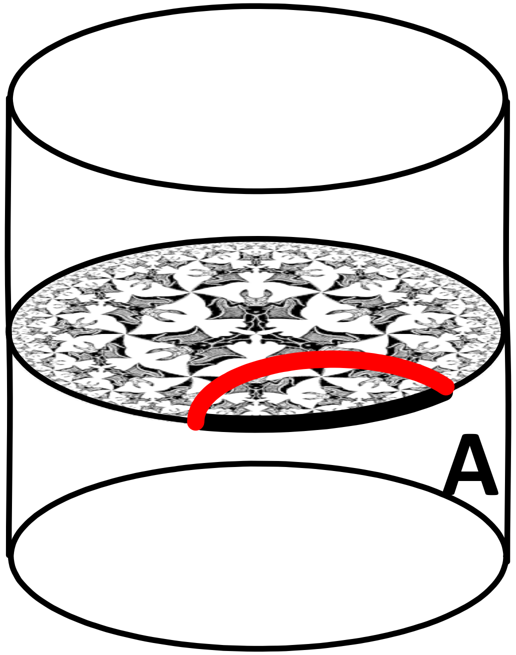
$$S(|\psi\rangle) = -\mathrm{tr}_{\mathcal{H}_{A}}(\rho \log_e \rho) \quad \text{entanglement entropy}$$

Ryu-Takayanagi Formula for Entanglement Entropy

PRL **96,** 181602 (2006) PHYSICAL REVIEW LETTERS week ending 12 MAY 2006

Holographic Derivation of Entanglement Entropy from the anti–de Sitter Space/Conformal Field Theory Correspondence

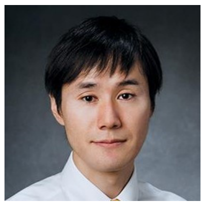
Shinsei Ryu and Tadashi Takayanagi
Kavli Institute for Theoretical Physics, University of California, Santa Barbara, California 93106, USA
(Received 8 March 2006; published 9 May 2006)



$$\rho(|\psi\rangle) = \mathrm{tr}_{\mathcal{H}_{\bar{A}}}(|\psi\rangle\langle\psi|)$$

$$S(|\psi\rangle) = -\mathrm{tr}_{\mathcal{H}_A}(\rho \log_e \rho)$$

$$= \frac{1}{4G_N}\left(\text{Area of minimum surface subtending } A\right)$$



Reconstruction of bulk spacetime by quantum entanglement

Finite temparature state can be regarded as an entangled state:

Thermo **F**ield **D**ouble :
$$|TFD\rangle \sim \sum_i e^{-\frac{E_i}{2kT}} |i\rangle_A |i\rangle_B$$

$$tr_{\mathcal{H}_B} |TFD\rangle\langle TFD| \sim \sum_i e^{-\frac{E_i}{kT}} |i\rangle_A \langle i|_A$$

The higher the temperature *T*, the more entanglement:

$$T \to 0 \ : \ |TFD\rangle \sim |0\rangle_A |0\rangle_B$$

$$T \to \infty \ : \ |TFD\rangle \sim \sum_{E_i \ll kT} |i\rangle_A |i\rangle_B + \cdots$$

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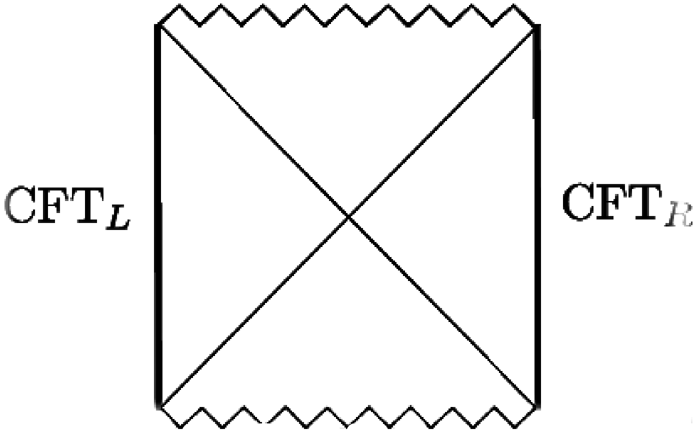
$$\sum_i e^{-\frac{E_i}{2kT}} |i\rangle_A |i\rangle_B$$



In AdS gravity, a finite temperature state can be interpreted as an eternal black hole (with two asymptotic AdS regions).

The strength of the entanglement (i.e., the **number of EPR pairs**) is proportional to the **size of the Einstein-Rosen bridge**.

Reconstruction of bulk spacetime by quantum entanglement

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JULY 1, 1935 PHYSICAL REVIEW VOLUME 48

The Particle Problem in the General Theory of Relativity

A. EINSTEIN AND N. ROSEN, *Institute for Advanced Study, Princeton*
(Received May 8, 1935)

ER = EPR ?

Fortschr. Phys. **61**, No. 9, 781 – 811 (2013) / **DOI** 10.1002/prop.201300020

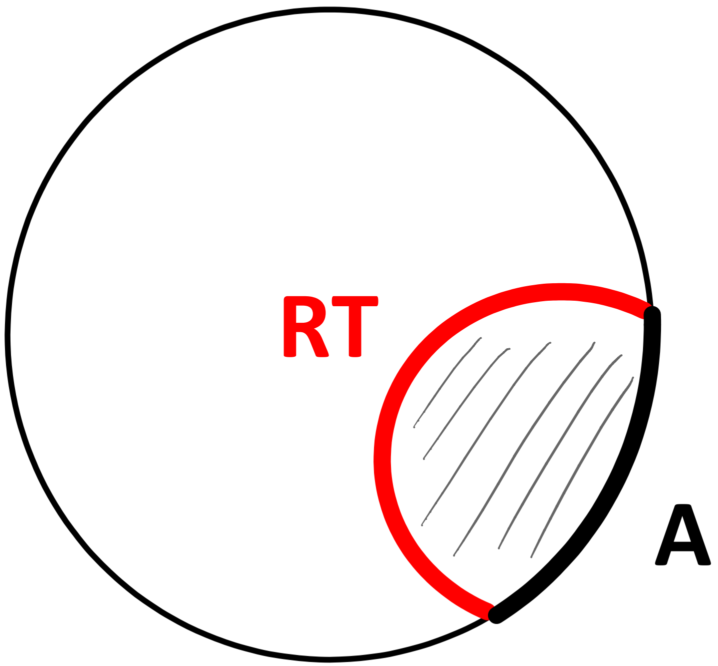
Cool horizons for entangled black holes

Juan Maldacena[1,*] and **Leonard Susskind**[2]

[1] Institute for Advanced Study, Princeton, NJ 08540, USA
[2] Stanford Institute for Theoretical Physics and Department of Physics, Stanford University, Stanford, CA 94305-4060, USA

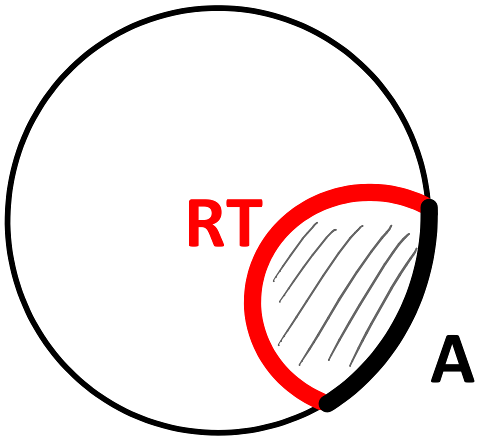
Reconstruction of bulk spacetime by quantum entanglement

Consider the shaded sub-region bounded by **A** on the boundary and the Ryu-Takayanagi surface **RT** subtending it.



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



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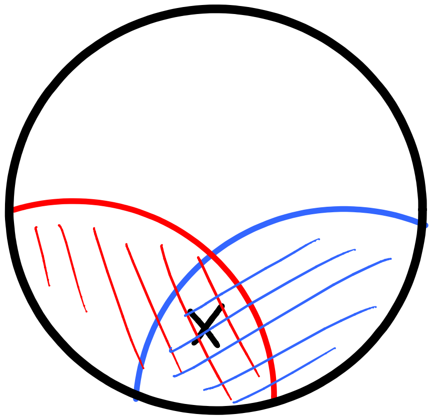
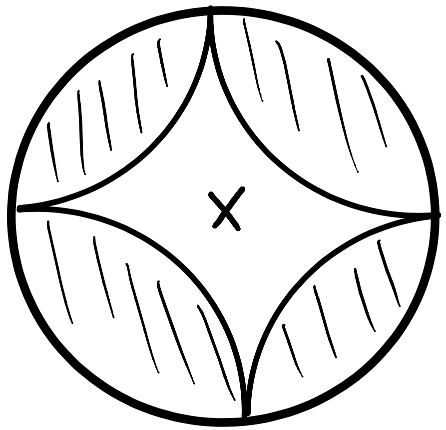
⇒ **Reconstruction Paradox**

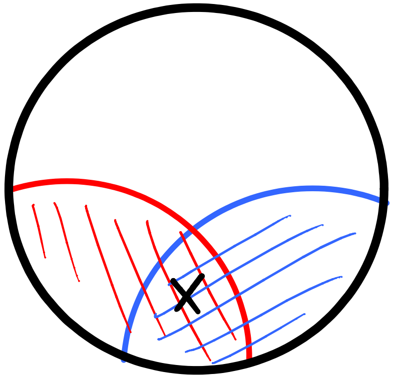


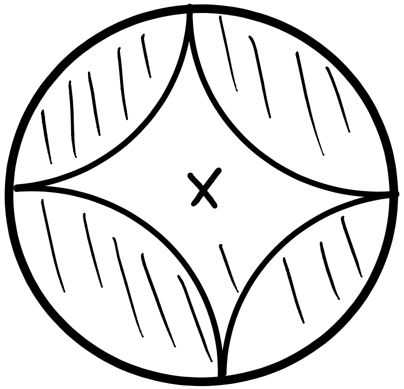


Different operators acting on different sub-spaces of CFT correspond to the same operator in AdS: **uniqueness?**

A local operator in AdS commutes with every local operator in CFT: **contradicting the Wightman axioms?**

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**.

Applications of Quantum Information to Gravitational Theory

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?

Constraints on Symmetry

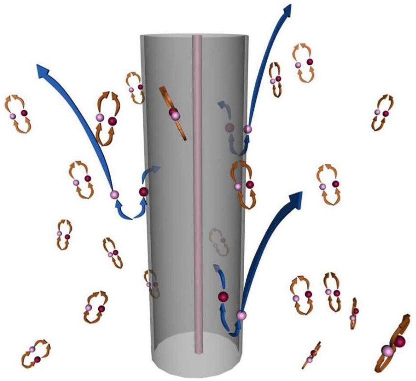
Two well-known conjectures:

(1) **No global symmetry** in quantum gravity.

(2) If a low energy effective theory of quantum gravity contains a compact gauge group G, there are **physical states in every finite-dimensional unitary representations** of G. If G = U(1), charges are quantized consistently with the Dirac condition. [Completeness Hypothesis]

Standard argument for

No global symmetry in quantum gravity:



If there is 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.

Since the Hawking radiation is G-blind, the black hole still contains the large reprentation of G with the number of states **exceeding the Bekenstein-Hawking entropy** formula.

Standard argument for

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If there is 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.

Since the Hawking radiation is G-blind, the black hole still contains the large reprentation of G with the number of states exceeding the Bekenstein-Hawking entropy formula.

How about discrete groups?
e.g., G = Z_2, where only the only faithful representation is 1 dim.

How about higher brane charges?

It is desirable to have an argument that applies to any symmetry.

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

《 work in progress with D. 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.

We need to define what we mean by symmetry.

Global Symmetry

Standard definition:

For every element g of group G, there is a unitary operator $U(g)$ on the Hilbert space such that,

$$U(g_1)\, U(g_2) = U(g_1 \cdot g_2),$$

$$[\, U(g),\ \text{Hamiltonian} \,] = 0.$$

How about the projection operator onto the 42th eigenstates? 

We would like to make additional **locality** assumptions.

Global Symmetry

We sharpen our requirements:

(1) Symmetry should map a local operator to a local operator.

(2) Symmetry action should be faithful on the set of local operators.

(3) Symmetry should commute with the energy-momentum tensor.

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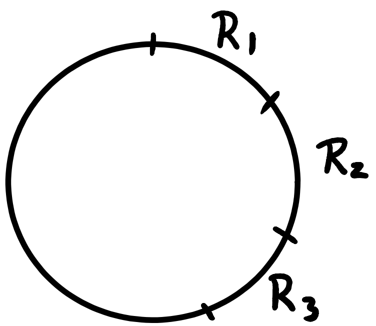
(4) For a set of open disjoint subspaces of the Cauchy surface:



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

$$U^\dagger(g,R)\,\mathcal{O}(x)\,U(g,R) = \begin{cases} U^\dagger(g)\,\mathcal{O}(x)\,U(g), & x \in R \\ \mathcal{O}(x), & x \in \text{interior of } \bar{R} \end{cases}$$

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

For continuous symmetry, (1) + (2) + (3) ⇒ (4) by the Noether theorem.

More generally, (4) hold unders the split property assumption.

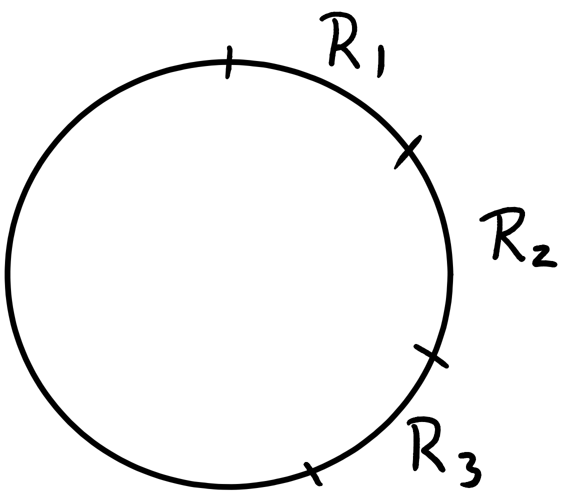
[Buchholz-Duplicher-Lungo: Ann. Phys. 170 (1989) 1]

Basic idea : If U : unitary on $\mathcal{H} = \otimes_i \mathcal{H}_i$

s.t. for $^\forall \mathcal{O}$ acting non-trivially only on $\mathcal{H}_i$,

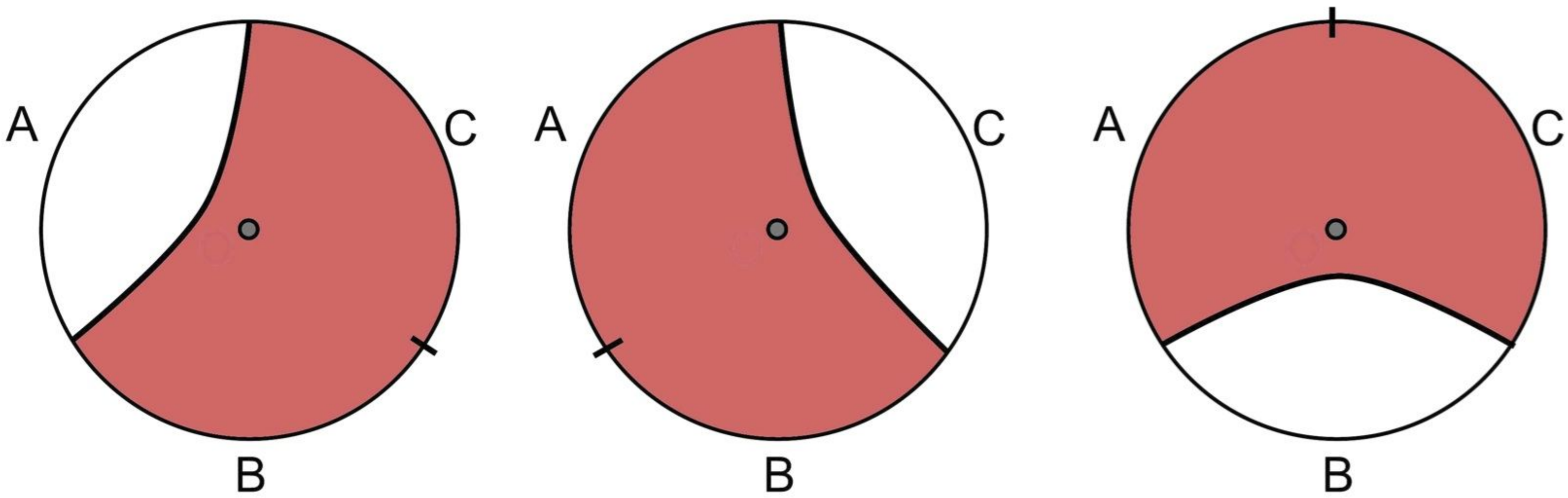
$U^\dagger \mathcal{O} U$ also acts non-trivially only on $\mathcal{H}_i$,

$\Rightarrow$ $U = \otimes_i U_i$, $^\exists U_i$: unitary on $\mathcal{H}_i$.



Gauge theory can also have the split property by adding degrees of freedom in UV.

In the following, we will apply the entangement wedge reconstruction.



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

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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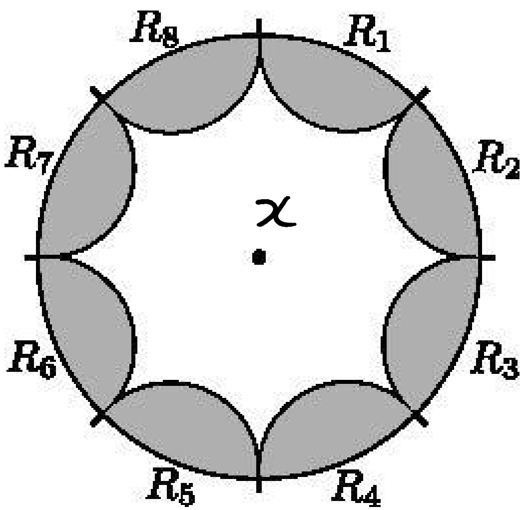


Symmetry generator,

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

commute with the local operator at x in the bulk.

Contradiction

We have also proven:

(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.

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:

$$m \leqq \frac{|Q|}{\sqrt{G}}, \qquad G: \text{Newton constant}$$

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.

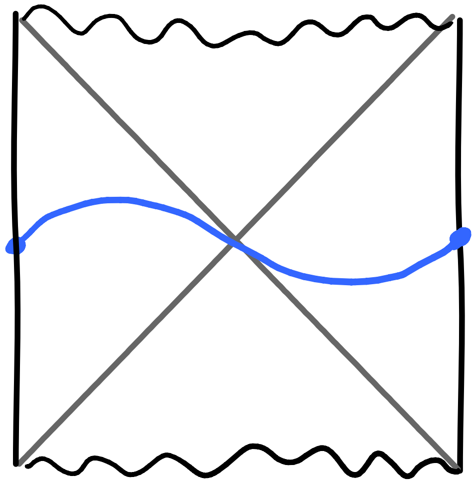
Otherwise, charged black holes can decay to Planck-size remnants with entropies, exceeding the Bekenstein-Hawking bound.

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

(3) Holography (described below)

Holographic Motivation

Harlow: 1510.07911



AdS Schwarzschild

The Wilson line should be a sum of products of operators acting on the left and right Hilbert spaces.

⇒ Bulk gauge field must be emergent at $\Lambda < M_{Planck}$.

Example : $\mathbb{C}P^{N-1}$ model

For $N \gg 1$, $\exists$ phase with $U(1)$ + scalar (m, Q).

$$Q^2 = \frac{1}{N}\Lambda^{4-d}, \quad G_{eff} = \frac{1}{N}\Lambda^{2-d}$$

$m < \Lambda$ implies $m < \frac{|Q|}{\sqrt{G_{eff}}}$

This seems to be a general phenomenon for emergent gauge fields.

Multiple U(1)'s and the convex hull condition of Cheung, Remmen: 1402.2287.

$$\prod_{i=1}^{k} \mathbb{C}P^{N_i-1} \text{ model} \Rightarrow \bigoplus_{i=1}^{k} \left[U(1)_i + \text{scalar}(m_i, Q_i) \right]$$

$$Q_i^2 = \frac{1}{N_i} \Lambda^{4-d}, \quad G_{eff} = \frac{1}{\sum_{i=1}^{k} N_i} \Lambda^{2-d}$$

If $m_i < \Lambda$,

$$\sum_{i=1}^{k} \left(\lambda_i \frac{Q_i}{\sqrt{G}\, m_i} \right)^2 > 1 \quad \text{for} \quad \sum_{i=1}^{k} \lambda_i = 1, \quad \lambda_i \geqq 0$$

convex hull condition

Harlow + H.O., to appear

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:

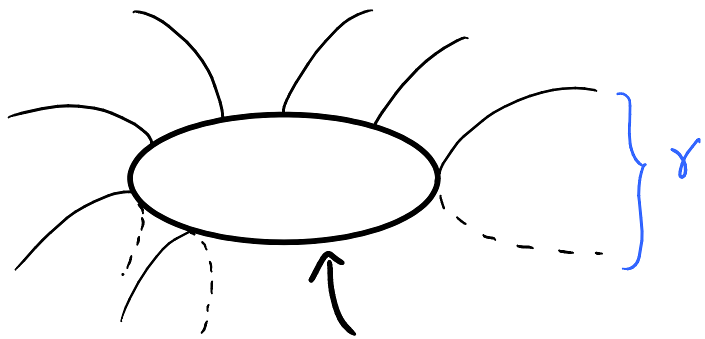
[Kachru, Silverstein: hep-th/9802183]

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.



The bulk geometry terminates with S1 collapsing.

Witten (1982)
Horowitz, Orgera, Polchinski: 0709.4262

Example: AdS5 x CP3 in M Theory:

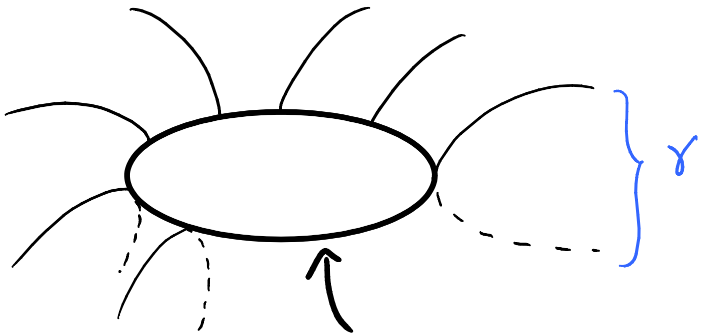
[Martin, Reall: 0810.2707]

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]

SUGGESTION



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.

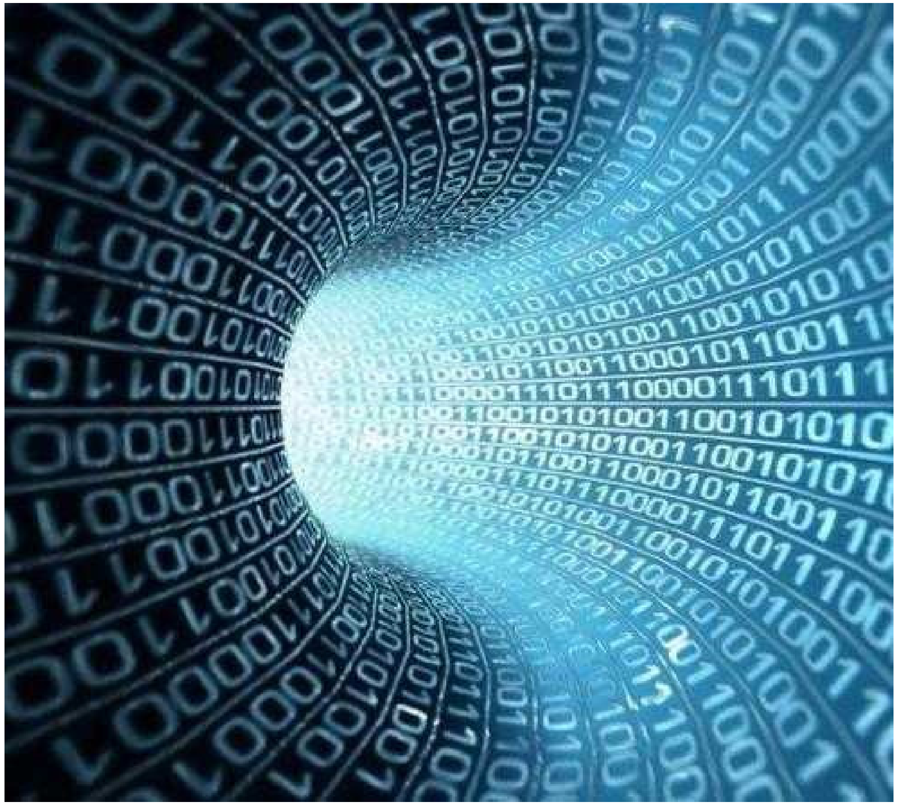
[Arkani-Hamed Dubovsky, Nicolis, Villadoro: hep-th/0703067]

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.

Recently, a more thorough study on this issue has appeared, where the sharpened conjecture is shown to imply a lower bound on the cosmological constant by (neutrino mass)^4.

[Ibanez, Martin-Lozano, Valenzuela: 1706.05392]

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



Collaborations with quantum information
may provide a key to quantum gravity.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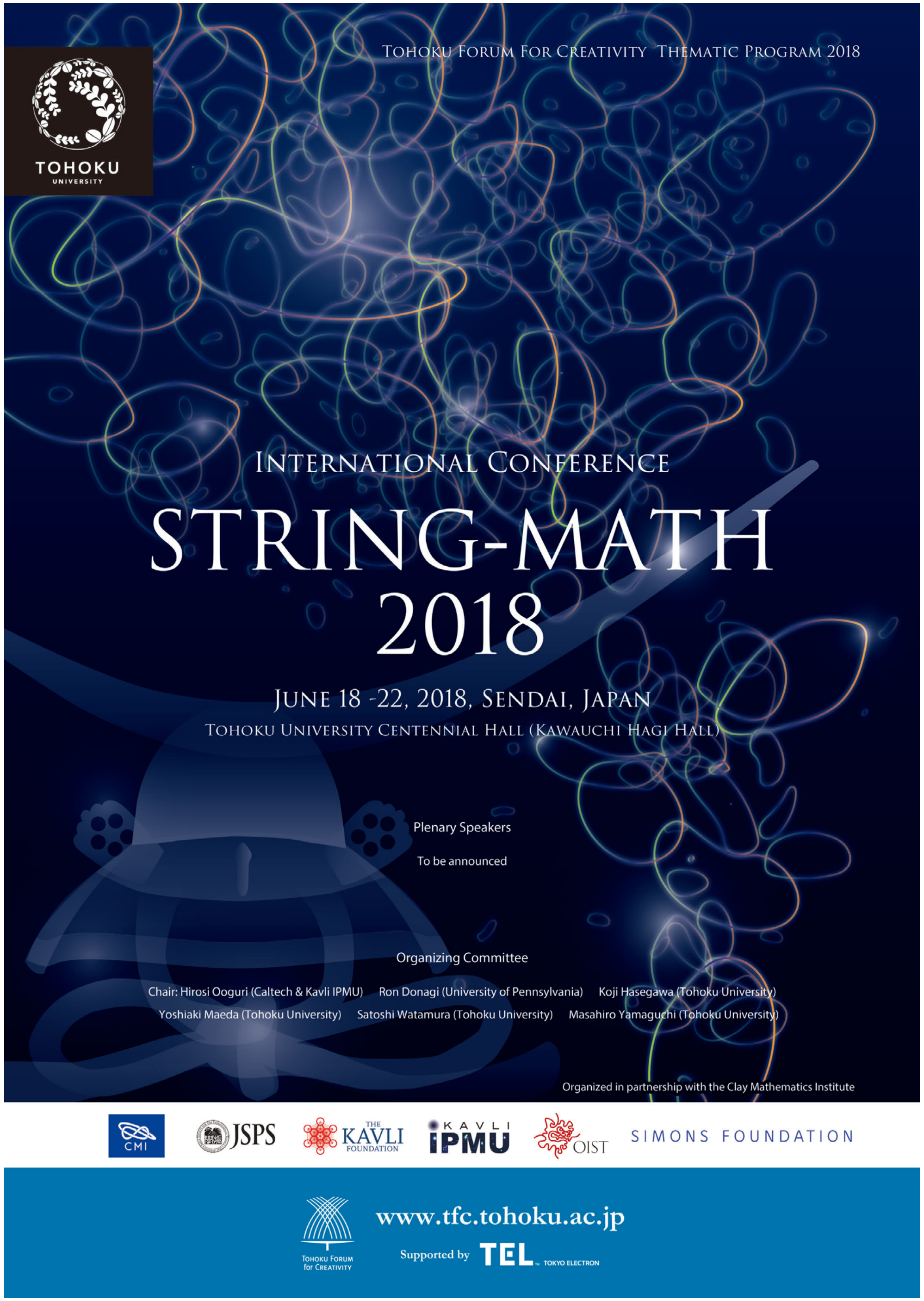

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