# Constraints on Quantum Gravity

Hirosi Ooguri

Twenty-eighth Arnold Sommerfeld Lectures
Ludwig Maximilian University of Munich
28 – 30 June 2023

# What I would like to tell you today:

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

☆ Why is superstring theory important?

☆ What is the holographic principle?

☆ What are known and not known about quantum gravity ?

# Why has the unification of general reativity and quamtum mechanics been 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 the 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 $F$ [$\sim$ *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/F* ] and [ *momenta/F* ].

Each term in the perturbative expansion can be calculated systematically by renomalizing finite number of parameters.

Kenneth G. Wilson (1936 - 2013)

# Wilsonian View:

The pion theory is a low energy approximation to QCD. It can be derived by performing QCD functional integral while freezing 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

**The Einstein gravity can be used to make reliable predictions including quantum effects, provided energy and momenta are much less than its cutoff scale** (threshold above which a more fundamental theory is required).

For example：☆ **Hawking radiation** from a black hole

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

☆ **Corrections** to the Newton potential

$$V = -\frac{G_N m_1 m_2}{r}\left(1 + 3\,\frac{G_N(m_1+m_2)}{r} + \frac{41}{10\pi^2}\,\frac{G_N \hbar}{r^2} + \cdots\right)$$

relativity effect

one-loop

# Does the Wilsonian approach really work in gravity?

# Gravity is Different

The physical world is hierarchical. Historically, the exploration of **shorter distances = higher energy** has revealed more fundamental features of nature.

This hierarchy of scales will terminates once we complete quantum gravity.

**Black holes turn high energy to long distance.**

# Gravity is Different

This hierarchy of scales will terminates
once we complete quantum gravity.

Black holes turn high energy to long distance.

Separation of scales fails with gravity.

An arbitrary low energy theory with gravity is not guaranteed to have UV completion.

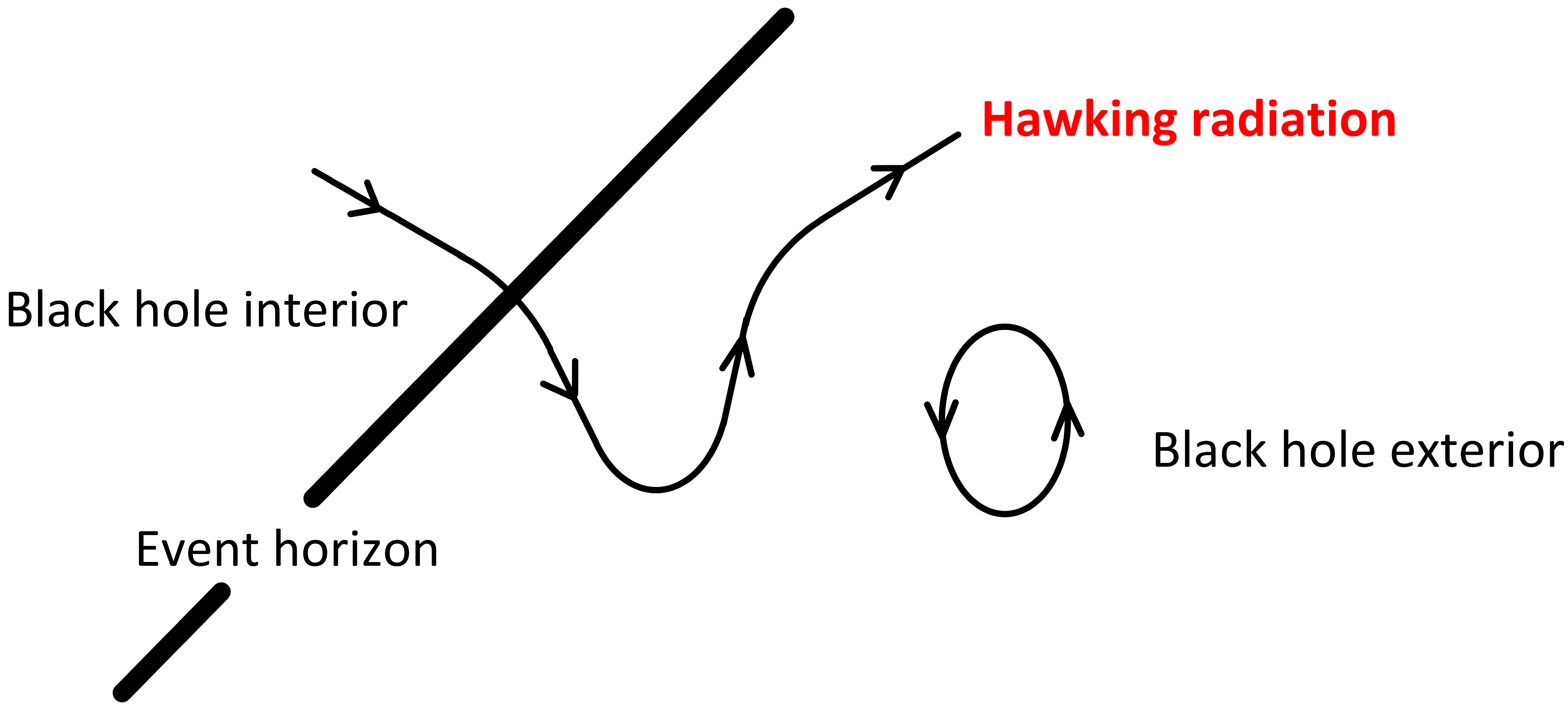
# Gravity is Different

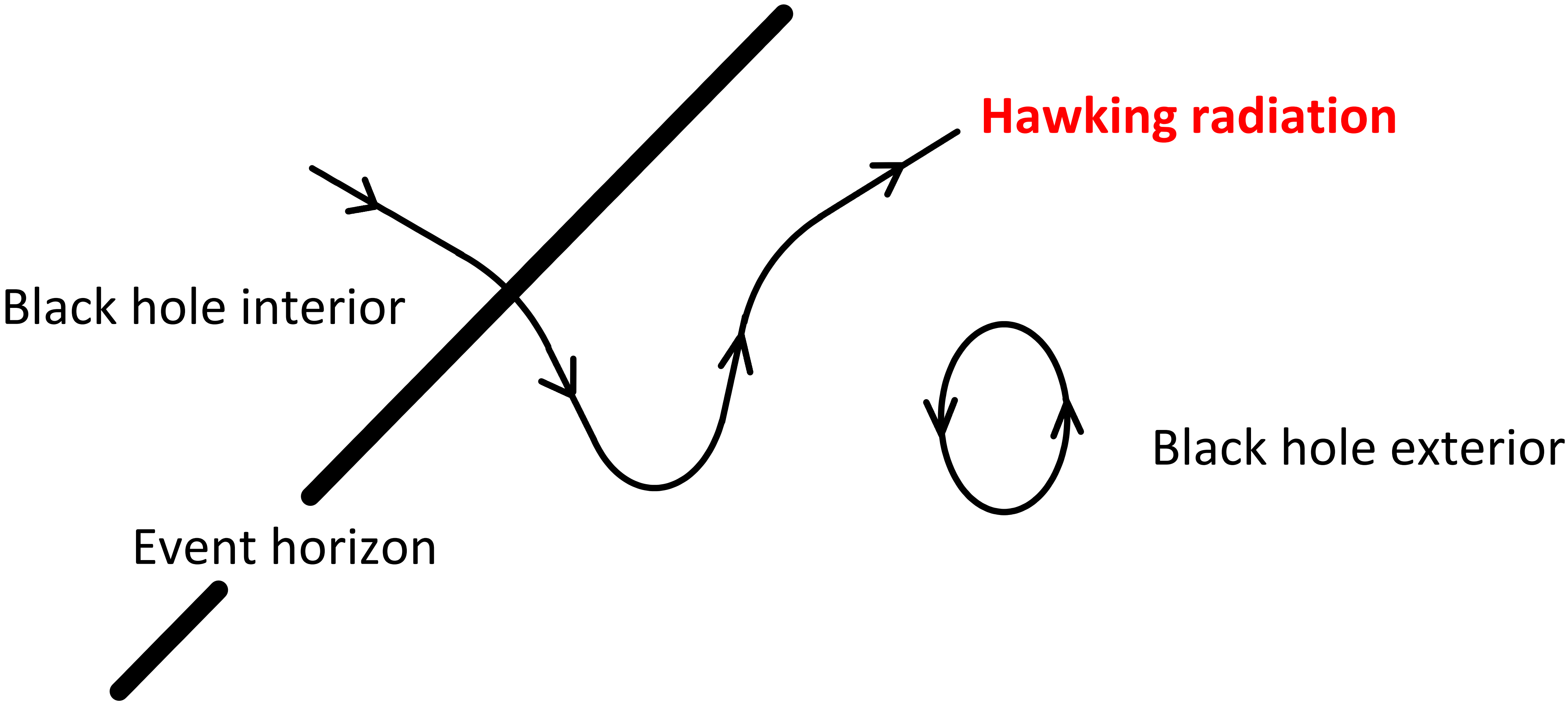
An arbitrary low energy theory with gravity is not guaranteed to have UV completion.

# Swampland

# Black Hole Paradox
# and
# Holographic Principle

Stephen Hawking
(1942 - 2018)


Hawking radiation
Black hole interior
Black hole exterior
Event horizon




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

entropy

energy

temperature

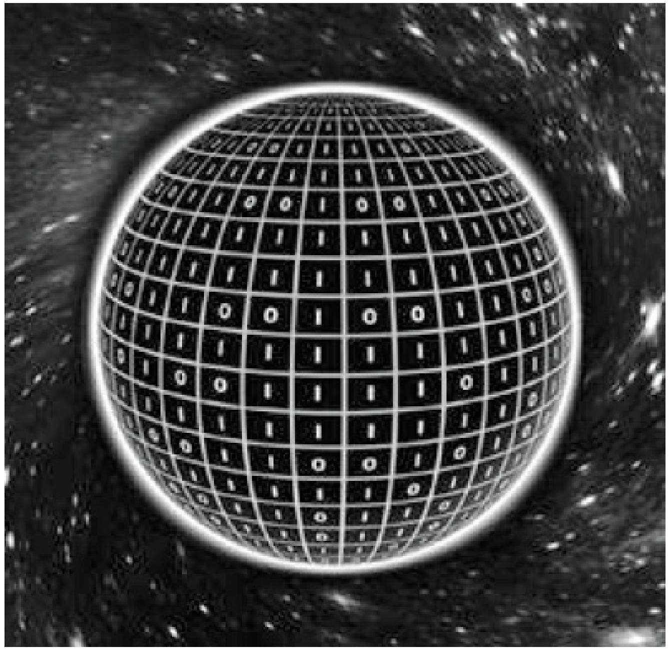
Newton constant

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

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

# Holographic Principle

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



**The holographic principle is realized in string theory.**

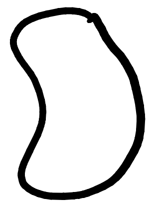
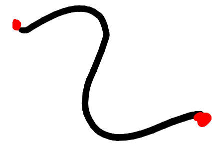
To explain how the holographic principle is realized in string theory, we need some preparation:

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

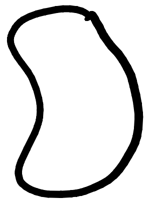
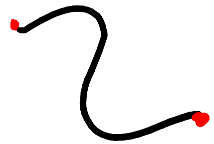
# D-Branes

Joseph Polchinski
(1954 - 2018)

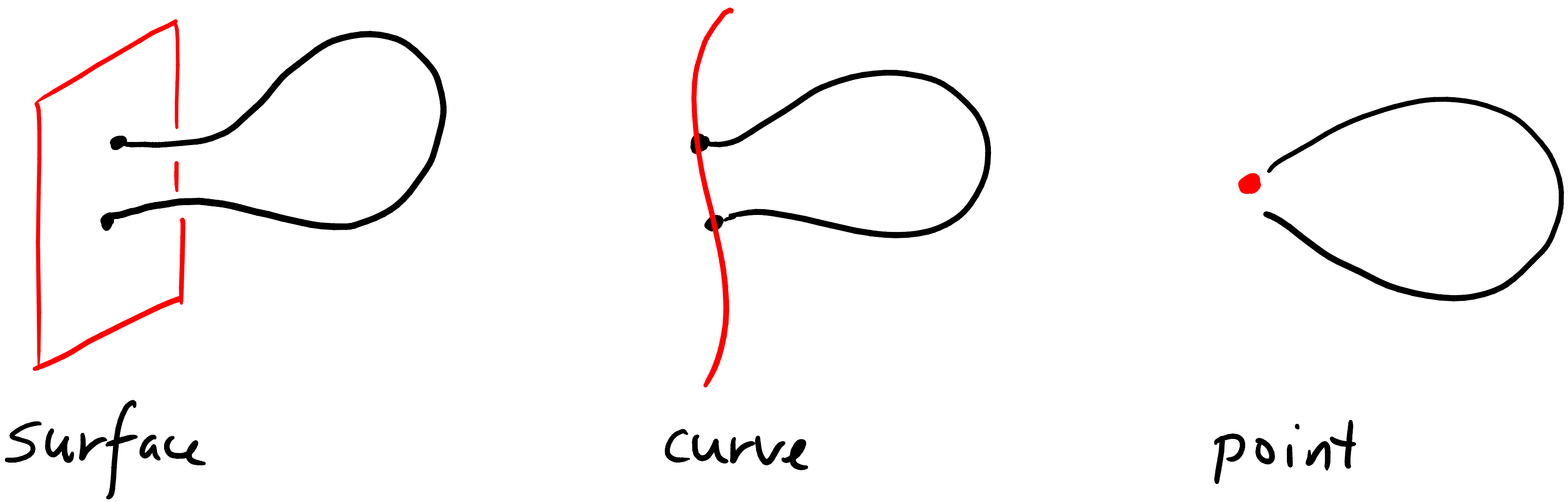
To explain how the holographic principle is realized in string theory, we need some preparation:

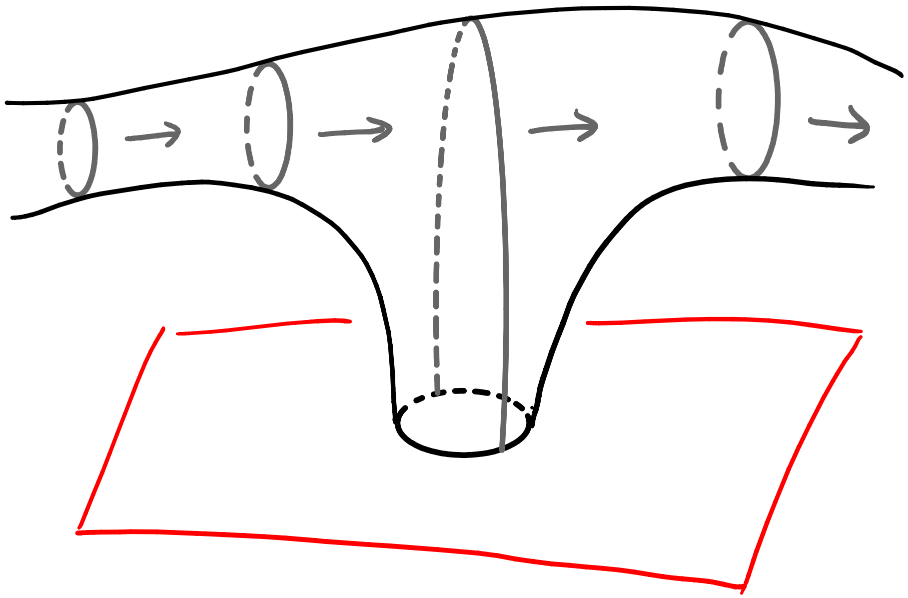
There are closed strings  and open strings 

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

There are closed strings  and open strings 

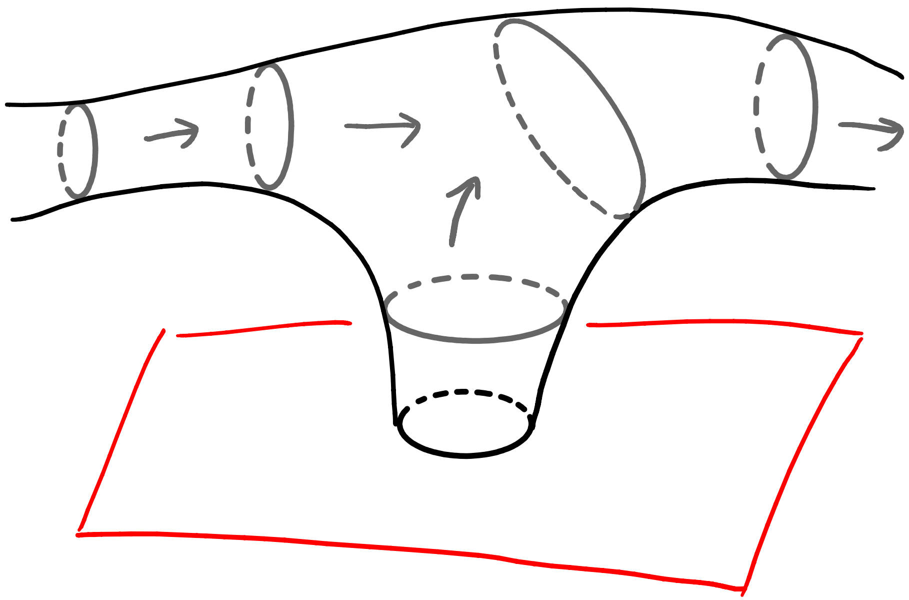
We need to specify a sub-space on which open strings can end.

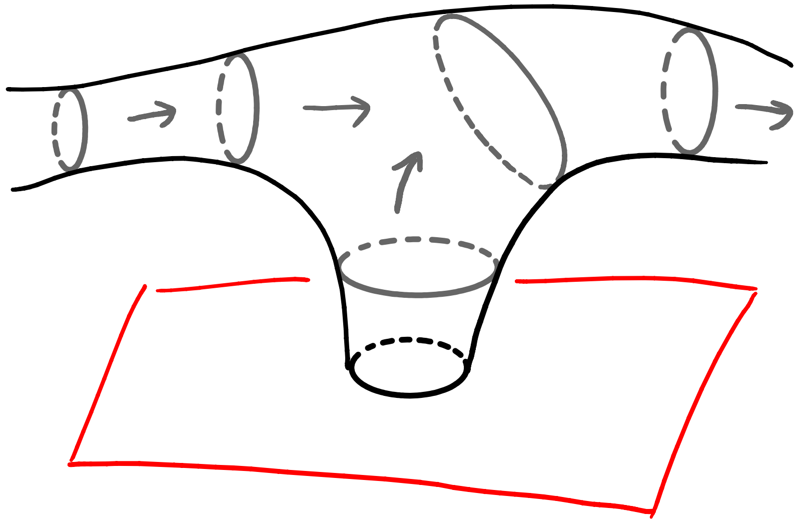


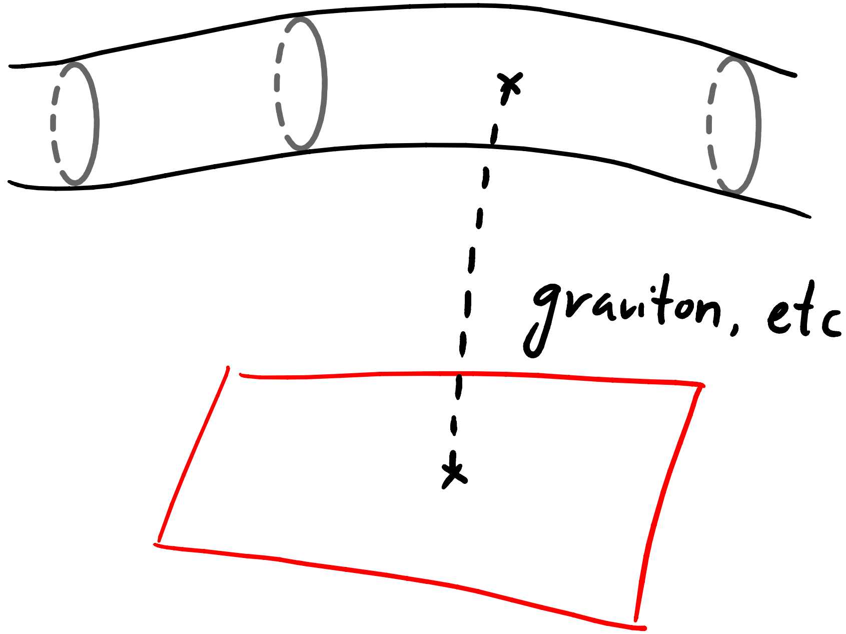


When open string end-points are located in a sub-space,

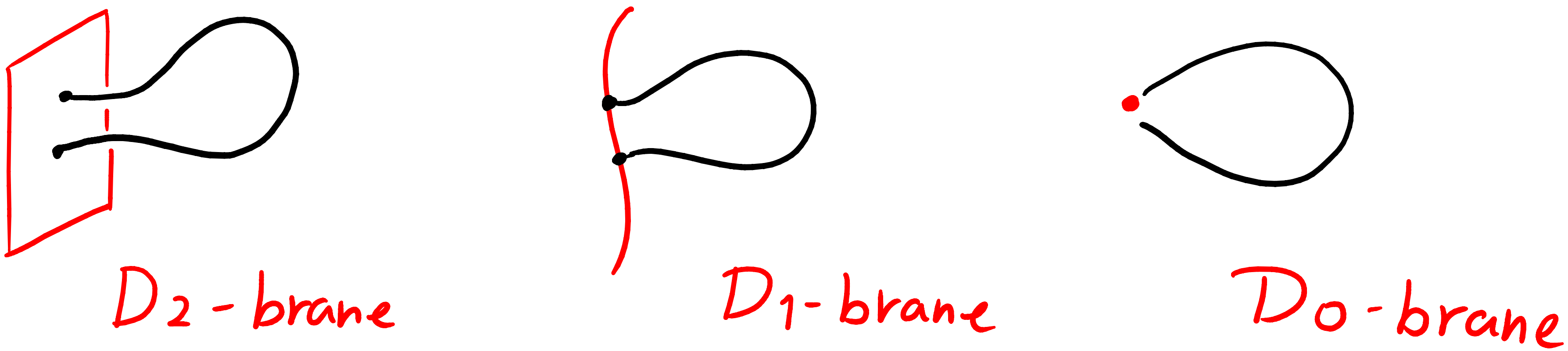
the sub-space can emit and absorb closed strings.








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.

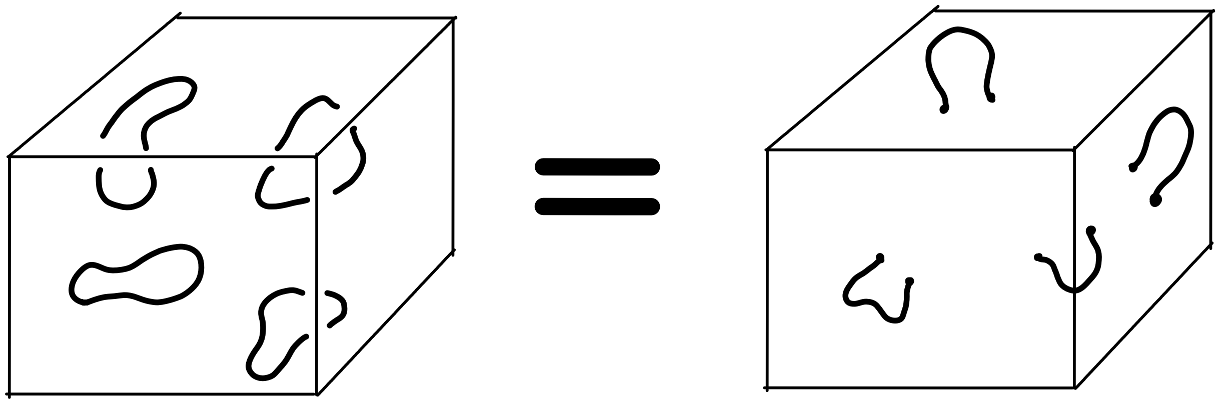


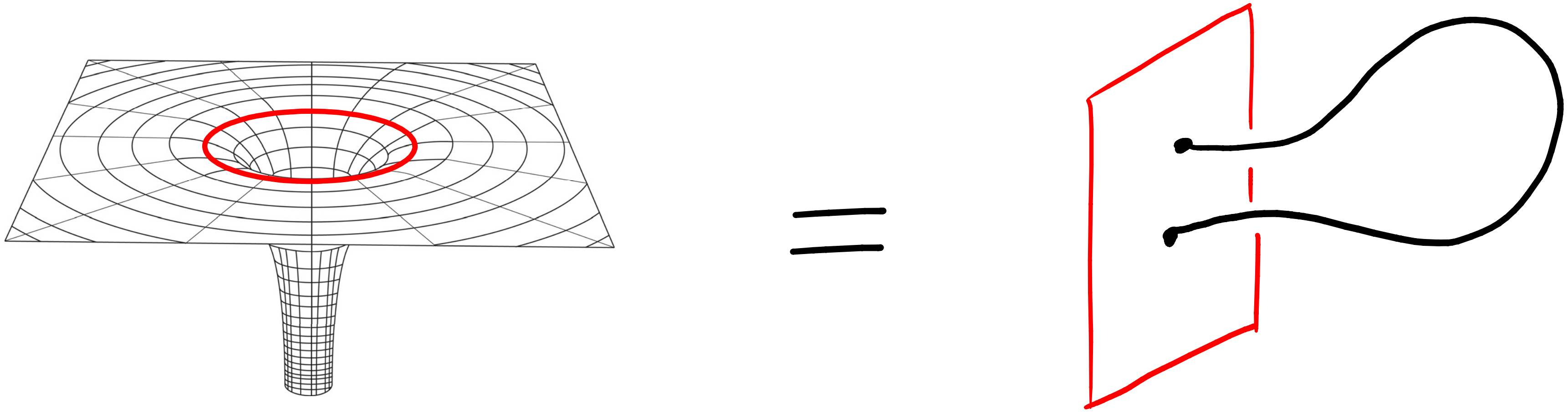
Since mass/energy is localized on the D-brane, it becomes a black hole/brane if the gravity is strong.

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,

$$S = \frac{1}{4G_N}\left(\begin{array}{c}\text{Area of}\\ \text{Event Horizon}\end{array}\right)$$ has been reproduced.





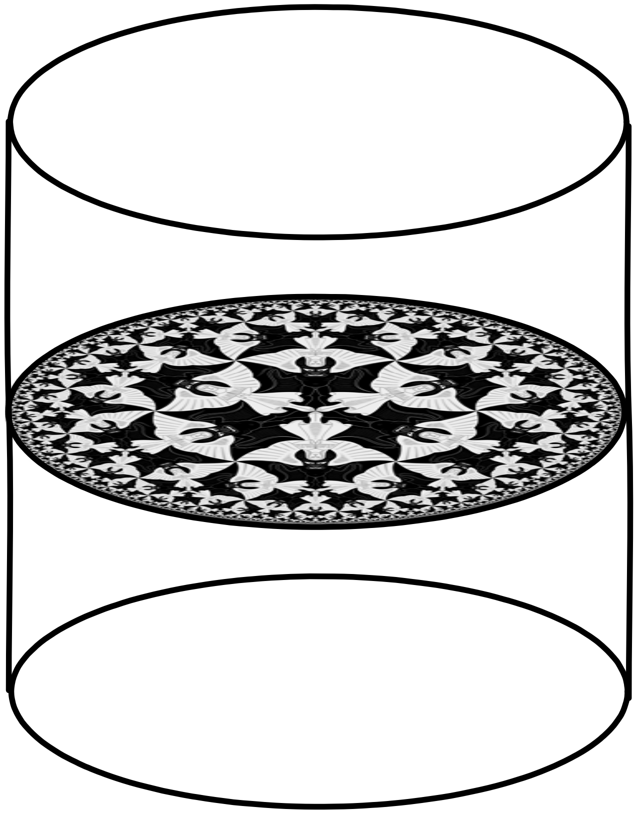
Physical phenomena on the event horizon of a black hole can be described by quantum theory of **open strings** on the corresponding D-brane.

⇒ Quantum theory of open strings does not contain gravity.

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

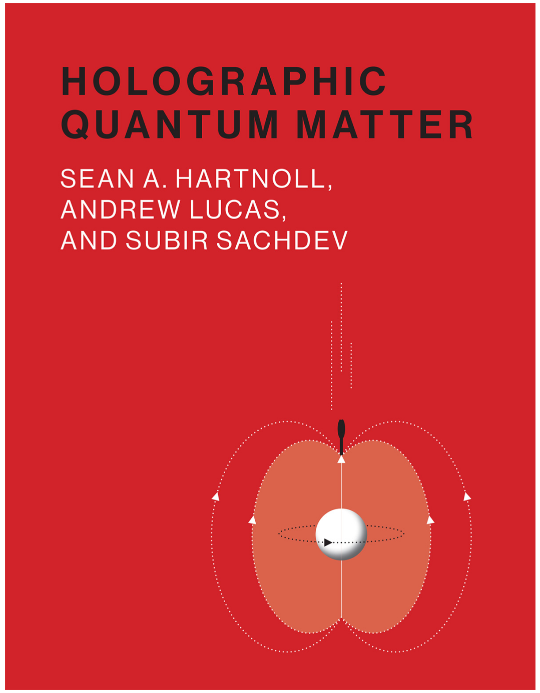
**AdS/CFT correpsondence**:

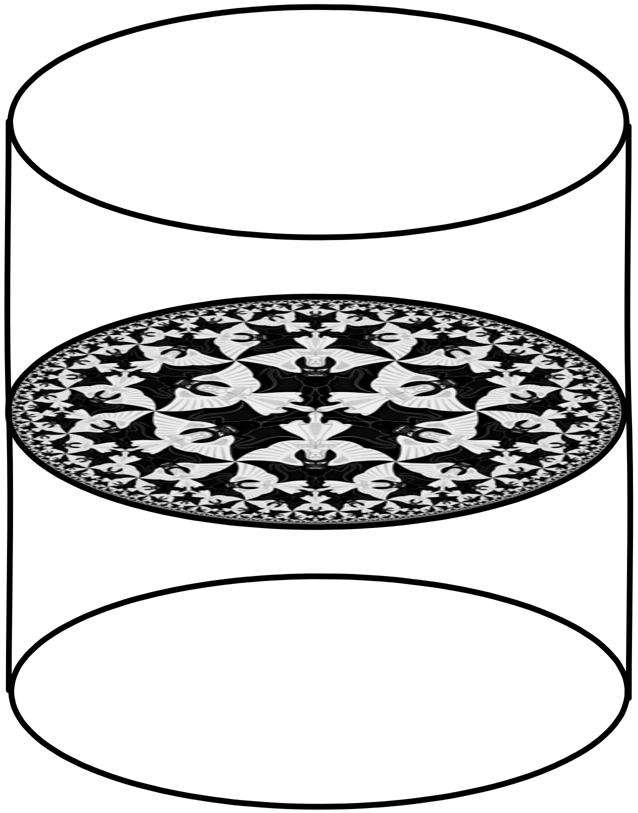
Gravitational theory in anti-de Sitter space (AdS) is equivalent to conformal field theory (CFT) at the boundary.



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 discuss them today.

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

# Quantum Entanglement
# and
# Emergence 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 $\mathcal{H}_A = \{ |0\rangle_A , |1\rangle_A \}$, $\mathcal{H}_B = \{ |0\rangle_B , |1\rangle_B \}$

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

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

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

**Entanglement entropy**: quantifying the entanglement

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

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

Symmetric in A and B.

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

# 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)

**Entanglement entropy**: quantifying the entanglement

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

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

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

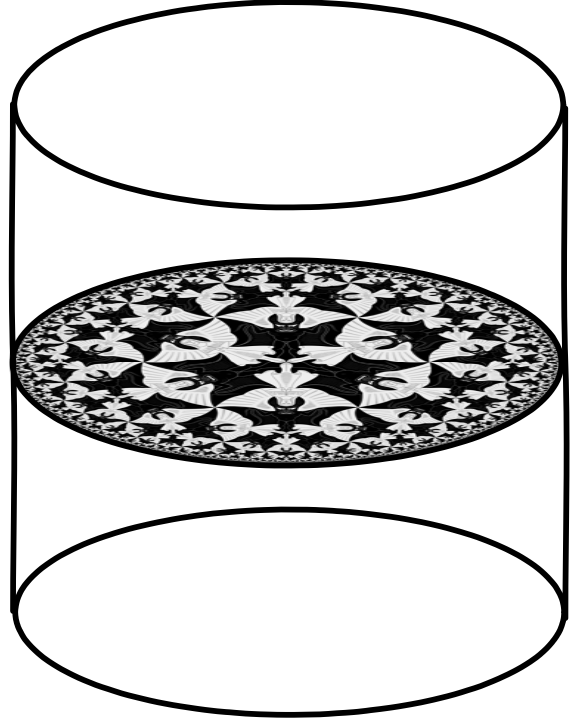
How many EPR pairs can be extracted from $|\psi\rangle$

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

↑ Local Operation and Classical Communication

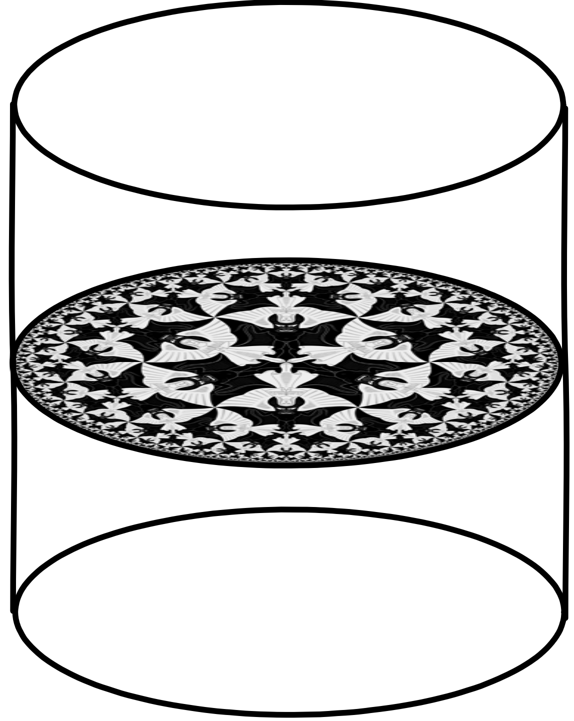
**AdS/CFT correspondence**:

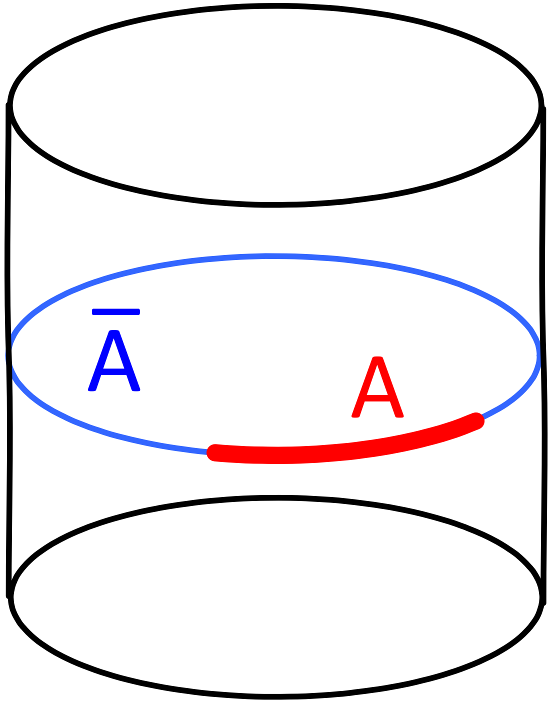
Gravitational theory in AdS
is equivalent to CFT at the boundary.



**AdS/CFT correspondence**:

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

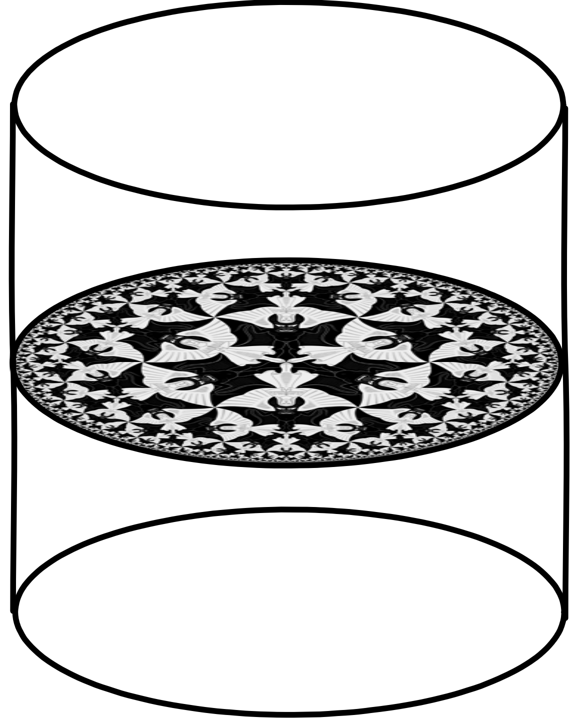


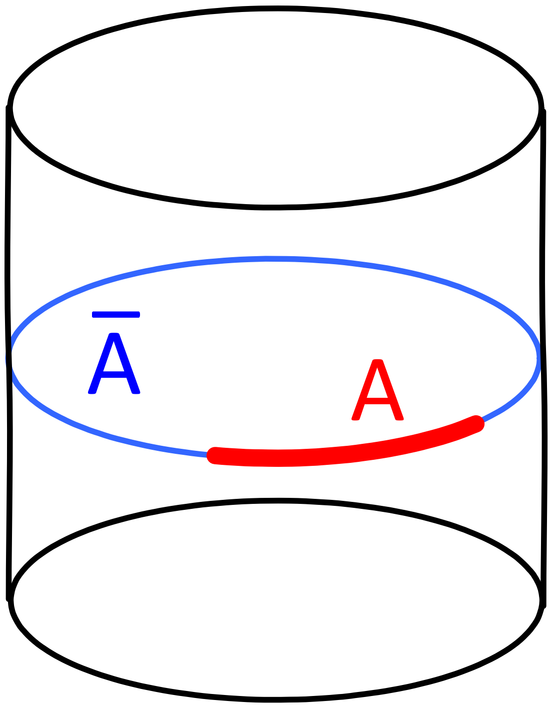



For a given choice of a sub-region **A** and its complement **$\bar{A}$** of the Cauchy surface, we can decompose the total Hilbert space of CFT into a direct product of Hilbert spaces associate to **A** and **$\bar{A}$**.

**AdS/CFT correspondence**:

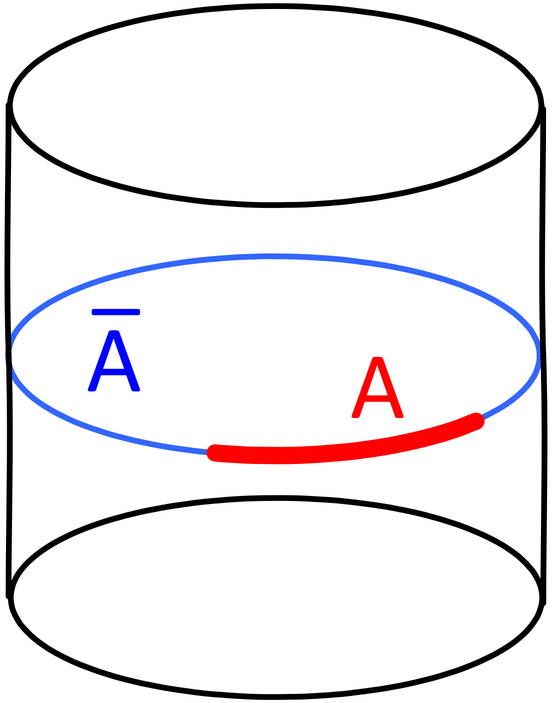
Gravitational theory in AdS
is equivalent to CFT at the boundary.






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 $\bar{\mathbf{A}}$.

*We need to say the right set of words such as Tomita-Takesaki* (富田-竹崎) *.*




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 $\bar{\mathbf{A}}$.

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

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

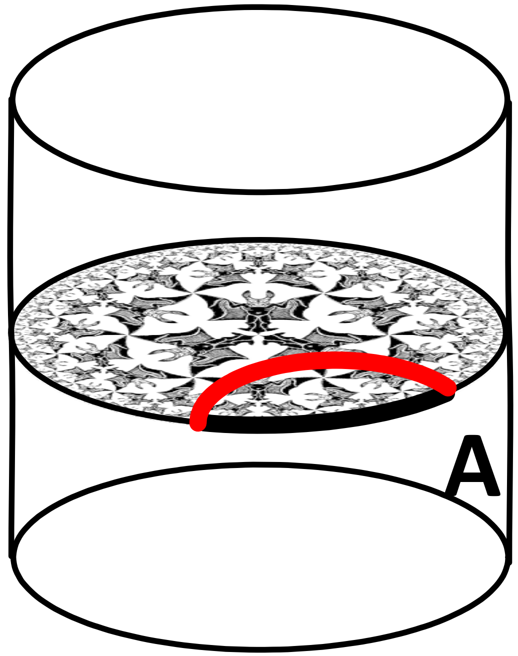
$$S(|\psi\rangle) = -\mathrm{tr}_{\mathcal{H}_A}(\rho \log_e \rho) \quad \text{entanglement entropy}$$

# Ryu-Takayanagi Formula for Entanglement Entropy

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

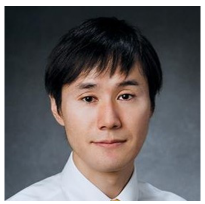
**Holographic Derivation of Entanglement Entropy from the anti–de Sitter Space/Conformal Field Theory Correspondence**

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:

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

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

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

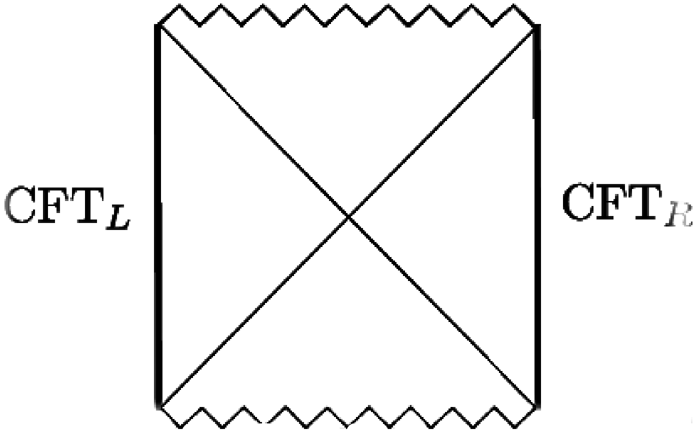
$$T \to 0 \quad : \quad |TFD\rangle \sim |0\rangle_A |0\rangle_B$$

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

# Reconstruction of bulk spacetime by quantum entanglement

Finite temperature state can be regarded as an entangled state.

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




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

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

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)

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

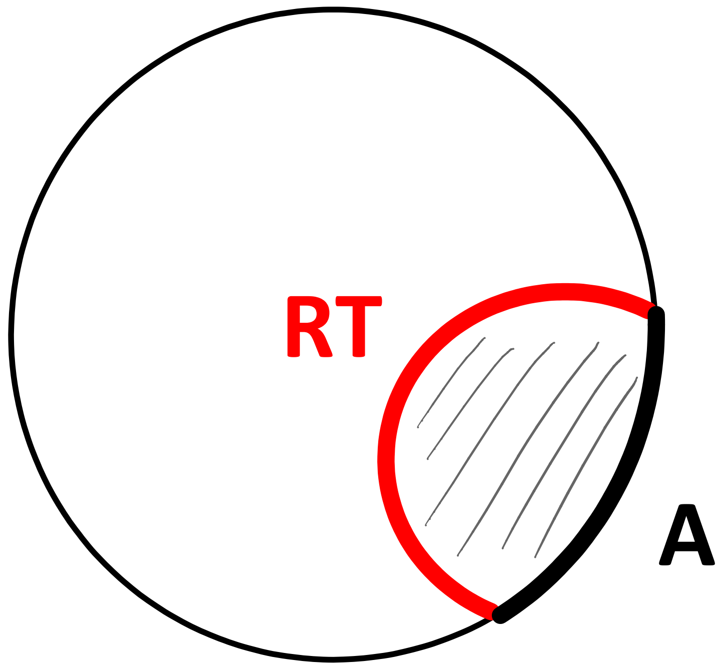
**Cool horizons for entangled black holes**

**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

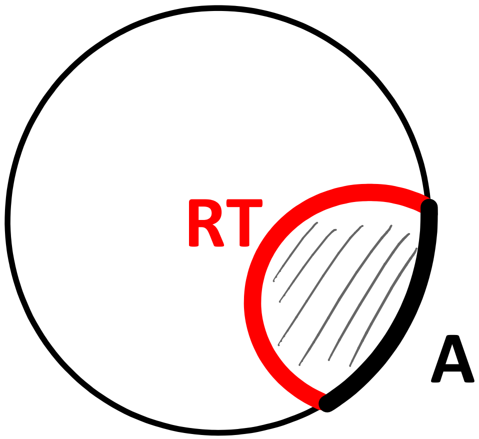
# Reconstruction of bulk spacetime by quantum entanglement

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



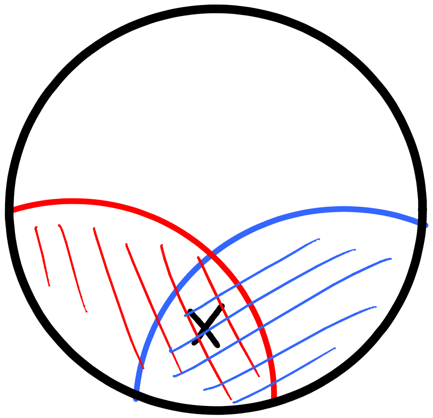

Quantum gravity operator localized in the **shaded region in AdS** can be represented by an operator acting on the sub-region **A of CFT**.

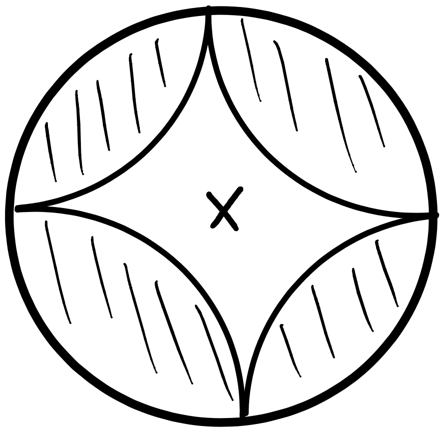
Hamilton, Kabat, Lifschytz, Lowe: hep-th/0606141
Papadodimas, Raju: 1310.6335
Headrick, Hubeny, Lawrence, Rangamani: 1408.6300
Almheiri, Dong, Harlow: 1411.7041, Dong, Harlow, Wall: 1601.05416




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

$\Rightarrow$ **Reconstruction Paradox**

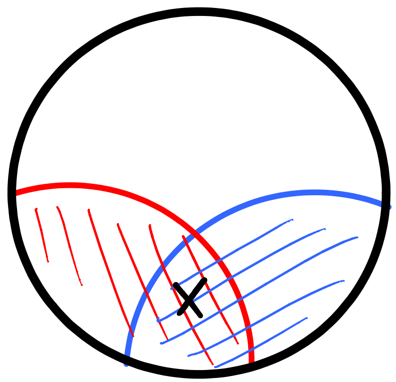


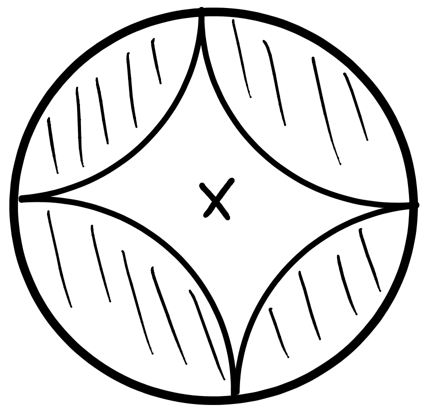


Different operators acting on different sub-spaces of CFT correspond to the same operator in AdS: **uniqueness?**

A local operator in AdS commutes with every local operator in CFT: **contradicting its basic 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 Physics

# 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

# Constraints on Symmetry

Symmetry has played important roles in physics:

in identifying and formulating fundamental laws of nature

and

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 Hilbert spaces
or about their low energy limits
(such as in the Seiberg dualities).

Symmetry can be deceiving:

**Global symmetry** is well-defined and is independent of which Lagrangian description you use.

Symmetry can be deceiving:

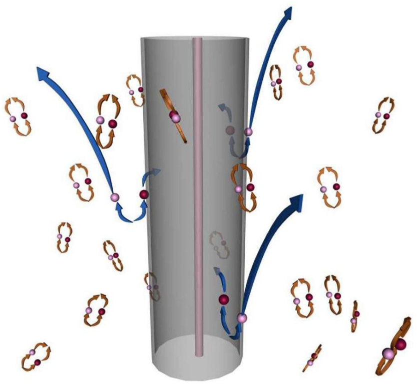
**Global symmetry** is well-defined and is independent of which Lagrangian description you use.

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

Wheeler (1957),
Banks, Dixon (1988); ... ;
Banks, Seiberg: 1011.5120; ...

# Quantum gravity does not have exact global symmetry.

Standard argument:



Suppose there is a global symmetry G.

We can combine a large number of charged matters to make a **black hole in an arbitrary large representation** 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 representation of G with the number of states **exceeding the Bekenstein-Hawking entropy** formula.

This argument has loopholes, and
it does not exclude discrete global symmetry.

# Quantum gravity does not have exact global symmetry.

D. Harlow and I formulated the conjecture precisely and proved it for **both discrete symmetry and continuous symmetry** in the context of the AdS/CFT correspondence using the relation between the **holography and quantum error correcting codes**.

We also proved the **completeness hypothesis** that there must be physical states in every irreducible unitary representation in gauge symmetry.

With some additional assumption, we can also prove that all **internal gauge symmetry groups are compact**.

arXiv:1810.05337 (5 page summary, Phys. Rev. Lett.)
arXiv:1810.05338 (175 page complete proof)

# Generalized Noether Theorem

For a region $\mathcal{R}$ of a Cauchy surface, we can define a unitary operator for every element of the symmetry group G

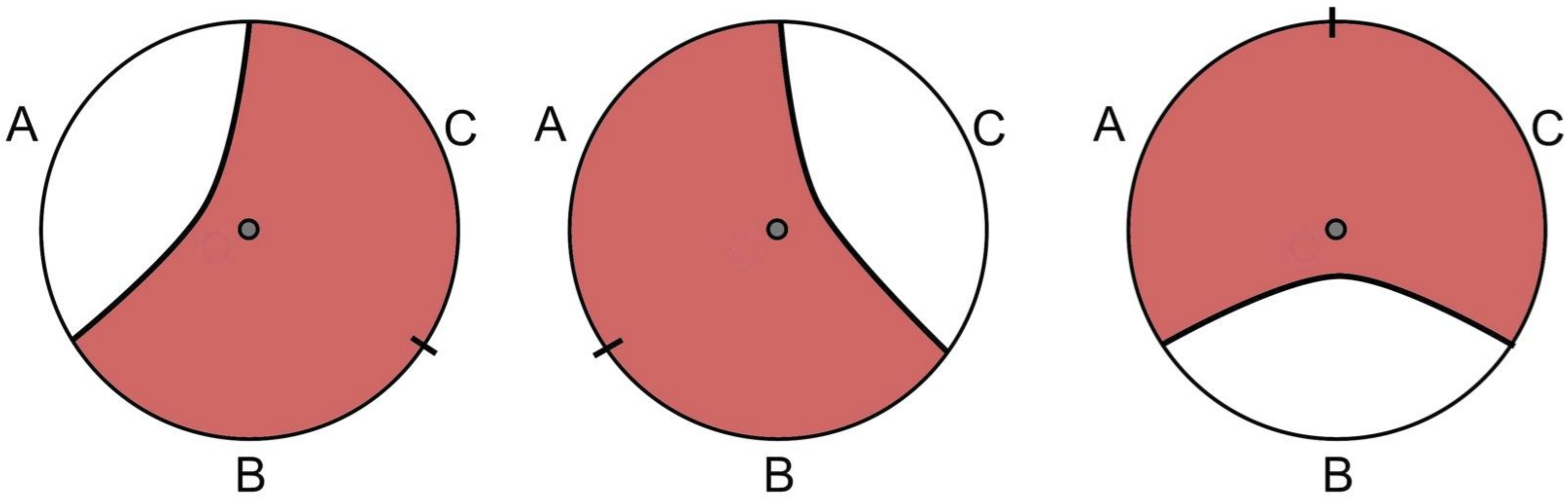
$$U(g, \mathcal{R})$$

If $\mathcal{R}$ is a union of disjoint subregions, this unitary operator can be expressed as a product of unitary operators associated to these subregions.

$$U(g, \bigcup_i \mathcal{R}_i) = \prod_i U(g, \mathcal{R}_i)$$

This is **obvious for continuous symmetry with Noether current,** but it **holds for discrete symmetry also**.

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

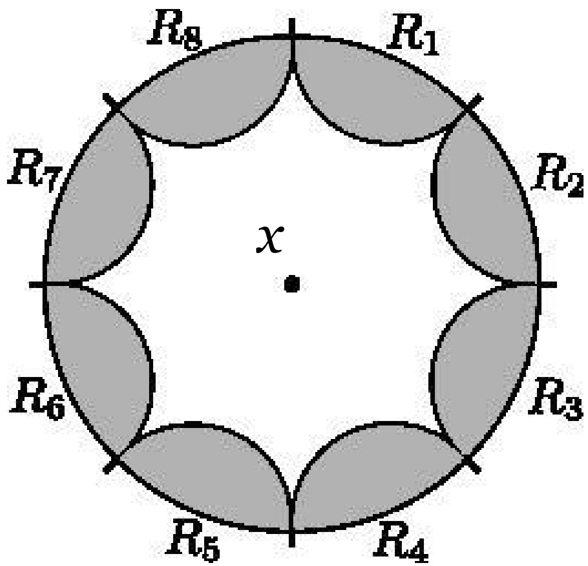


# Global symmetry in AdS is inconsistent with local structure of CFT.

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.

## 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.




Symmetry generator,

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

commute with the local operator at $x$ in the bulk.

# Contradiction

## Comments & Questions:

The **no global symmetry theorem** states that any symmetry in quantum gravity is either broken or gauged.

How is it broken/gauged?
Are symmetry breaking terms power suppressed by the Planck mass?

The **completeness theorem** states that every finite dimensional unitary representation of long range gauge symmetry must be realized.

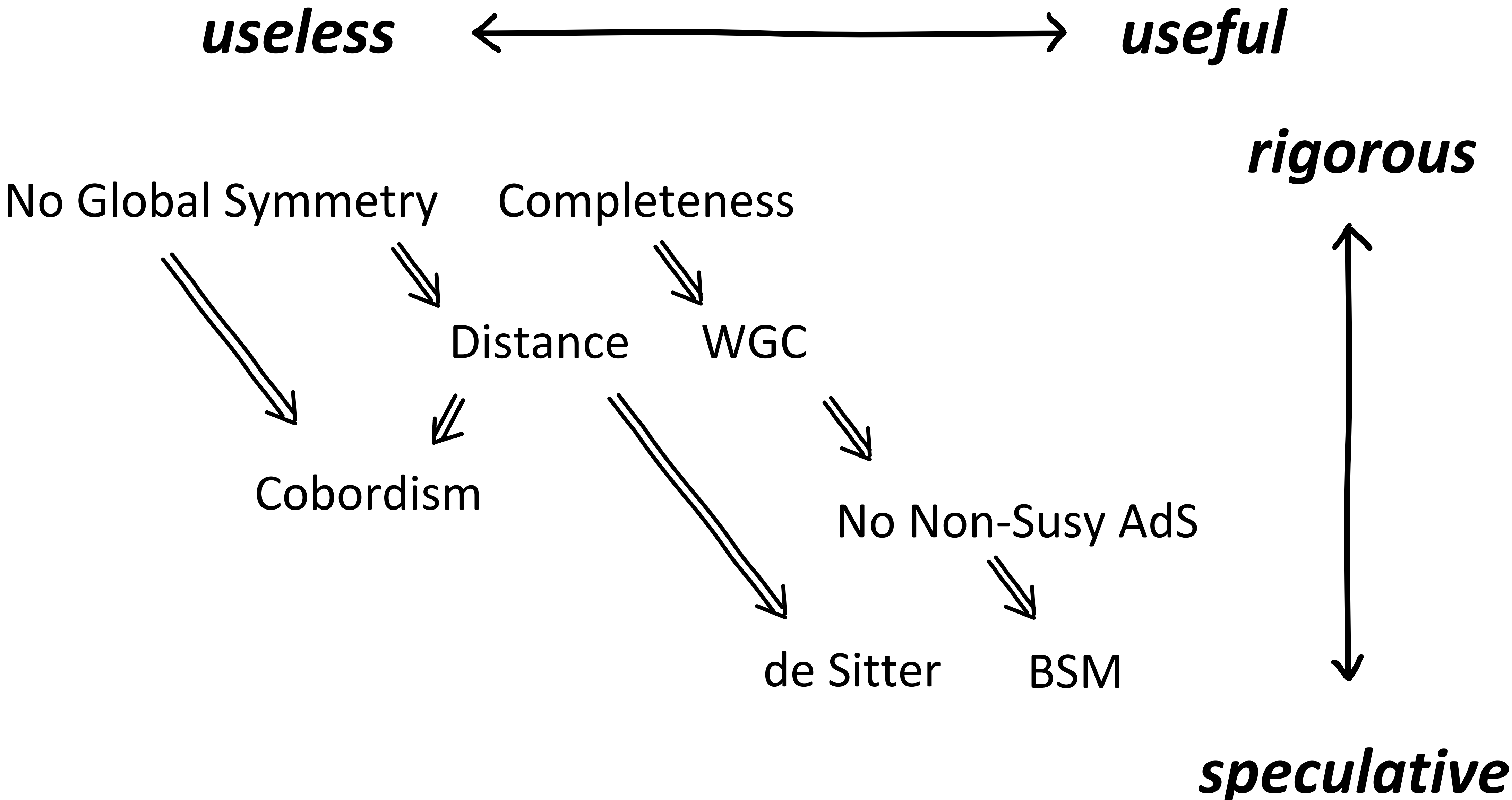
Can we bound the mass of the lightest charged particle?

How can we go beyond the AdS/CFT correspondence and prove quantum gravity theorems for more general spacetime?

So far, I have presented
the theorems I can prove.

Now, we are entering
the territory of conjectures.

# Landscape of Swampland Conditions



# Landscape of Swampland Conditions

***useless*** ⟷ ***useful***

***rigorous***

**No Global Symmetry** **Completeness**

Distance **WGC**

Cobordism

**No Non-Susy AdS**

de Sitter **BSM**

***speculative***

# Weak Gravity Conjecture

Our **no global symmetry theorem** states that any symmetry in quantum gravity is either broken or gauged.

**How is global symmetry broken/gauged?**

Our **completeness theorem** states that every finite dimensional unitary representation of long range gauge symmetry must appear.

**Can we bound the mass of the lightest charged particle?**

**The weak gravity conjecture attempts to quantify these.**

# 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) Intriguing connection to the Cosmic Censorship Hypothesis

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 / $\Gamma$ in IIB:

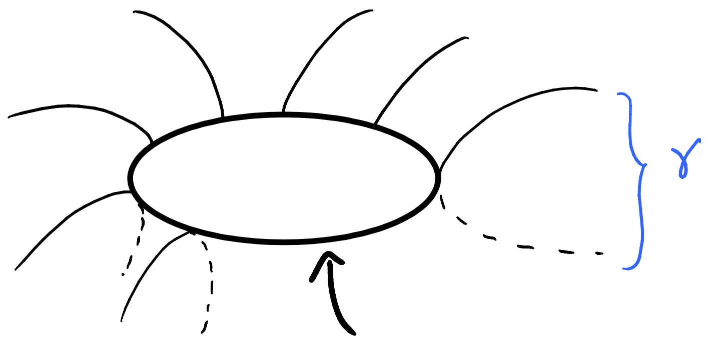
Kachru, Silverstein: hep-th/9802183

Supersymmetry is broken when $\Gamma$ does not fit in SU(3).

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

Dymarsky, Klebanov, Roiban: 0509132

★ If $\Gamma$ 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

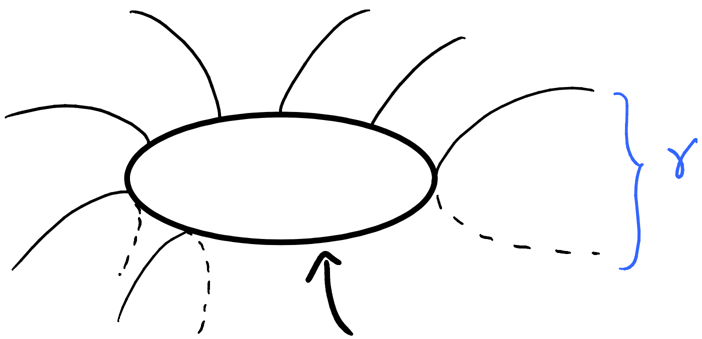
# Example: AdS5 x CP3 in M Theory:

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




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

Wepointed 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

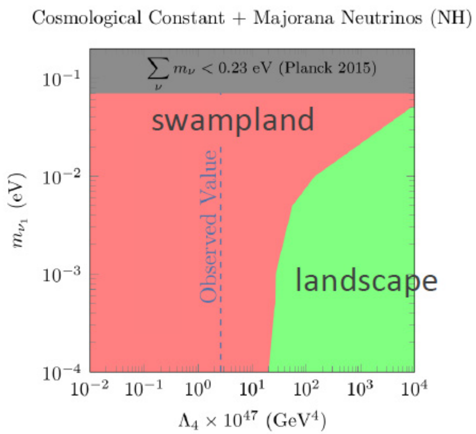
**(neutrino mass)$^4$ < (dark energy density)**

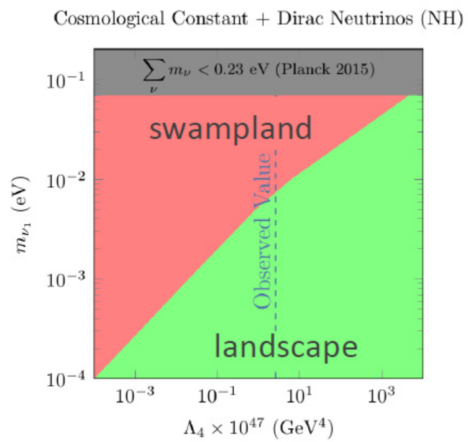
# More precisely:

neutrino masses

$$\Lambda \geq \frac{a(n_f)30(\Sigma m_i^2)^2 - b(n_f, m_i)\Sigma m_i^4}{384\pi^2} \quad \text{with} \quad \begin{aligned} a(n_f) &= 0.184(0.009) \\ b(n_f, m_i) &= 5.72(0.29) \end{aligned} \quad \text{for Majorana (Dirac)}$$

**The lower bound on the dark energy Λ from the first principle!**




Ibáñez, Martín-Lozano, Valenzuela.: 1706.05392

Or, the upper bound on the neutrino masses

$\Rightarrow$ New perspect for naturalness

More precisely:

neutrino masses

$$\Lambda \geq \frac{a(n_f)30(\Sigma m_i^2)^2 - b(n_f, m_i)\Sigma m_i^4}{384\pi^2} \quad \text{with} \quad \begin{array}{r} a(n_f) = 0.184(0.009) \\ b(n_f, m_i) = 5.72(0.29) \end{array} \quad \text{for Majorana (Dirac)}$$

The lower bound on the dark energy Λ from the first principle!

Moreover,

$$\Lambda \lesssim \frac{m_e^4}{8\pi\alpha M_P} \sim 10^{-88}$$

Montero, van Riet, Venken: 1910.01648

The distance conjecture described below can be refined to give the upper bound on Λ **without relying on the Anthropic Principle**.

# Landscape of Swampland Conditions

***useless*** $\longleftrightarrow$ ***useful***

***rigorous***

**No Global Symmetry**

Completeness

**Distance**

WGC

Cobordism

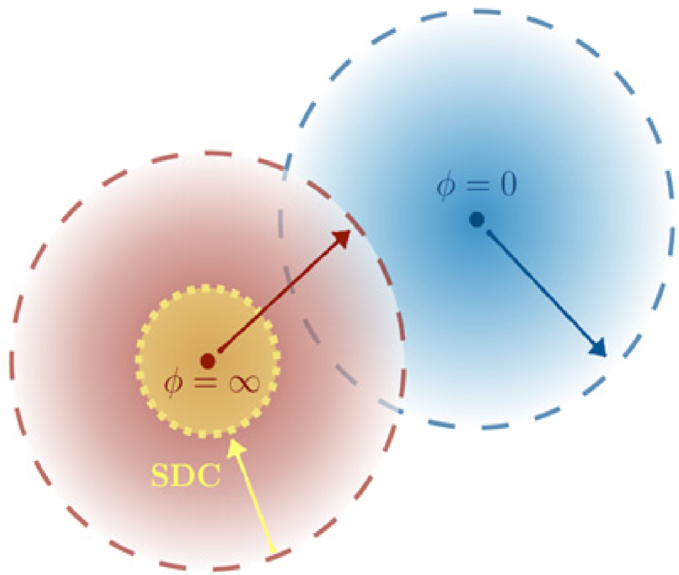
No Non-Susy AdS

**de Sitter**

BSM

***speculative***

# Distance Conjecture



Our proof of the **no global symmetry theorem** works for **spontaneously broken global symmetry**.

In particular, shift symmetry of a scalar field, often invoked in inflation models, must be broken.

**How is the shift symmetry broken?**

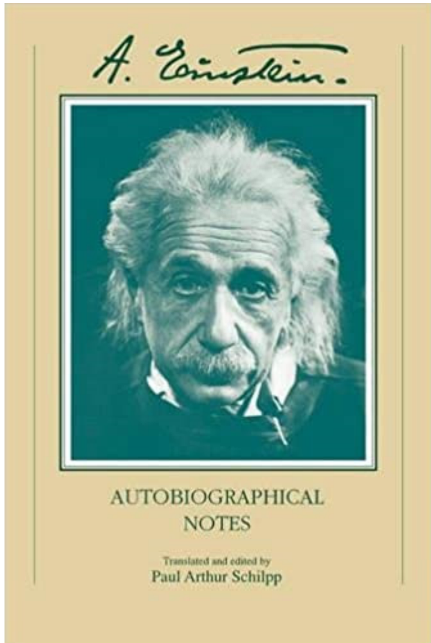
**The distance conjecture attempts to quantify this.**

# Distance Conjecture

String theory has no continuous free parameters. All parameters can vary locally; they are expectation values of scalar fields.

The distance conjecture is about properties of the moduli space M of such scalar fields, with the metric defined by their kinetic terms.

An earlier formulation:




*I would like to state a theorem which at present cannot be based upon anything more than upon a faith in the simplicity of nature: there are no arbitrary constants of this kind, that is to say, nature is so constituted that it is possible logically to lay down such strongly determined laws that within these laws only rationally completely determined constants occur.*

Albert Einstein (Autobiographical Notes)

# Distance Conjecture

1. Moduli space M is non-compact.
   Pick any point X, one can go infinite distance away from it.

2. Compared to the theory at X, the theory at Y with d(X, Y) > T has
   a tower of light particles with mass of the order $M_p \exp(-aT)$.

3. The low energy effective theory defined at X breaks down at Y
   because of the new light degrees of freedom.

4. The closure of M is simply connected.
   There is no-nontrivial 1-cycle with minimum length.

Vafa + HO: hep-th/0605264

# Distance Conjecture

1. True in all known constructions in string theory
   (numerous non-trivial tests with Calabi-Yau compactifications)

2. Connection to Trans-Planckian Censorship.

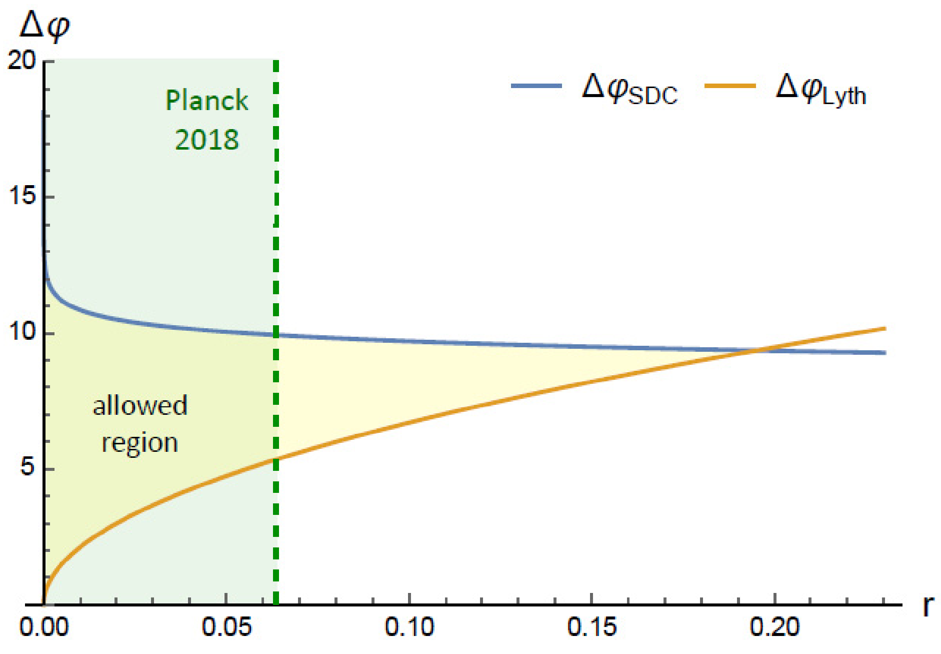
3. Connection to Weak Gravity Conjecture

4. False for non-gravitational systems

5. Gives a universal upper-bound on the inflation excursion.

The distance conjecture imposes constraints on inflation modesl of the early universe.

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




tensor-scalar ratio of CMB B-mode polarization

Upper bound on the inflaton variation.

Complementary to the Lyth bound, which is a lower bound.

Scallisi, Valenzuela: 1812.07558

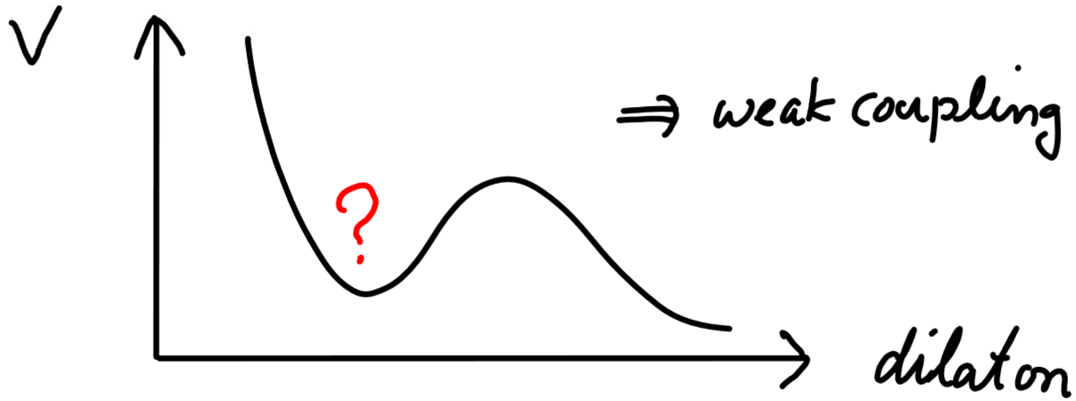
# De Sitter Conjecture

Low energy effective theory of string theory contains several scalar fields.
Can they be all stabilized and produce a **positive cosmological constant**?

**Dine-Seiberg Problem (1985)**

The expectation value of the dilaton determines the string coupling constant.
A perturbatively generated potential cannot stabilize the dilaton.

— it is (almost) impossible to demonstrate existence of meta-stable de Sitter vacua in the perturbative expansion in the string coupling.




The race track mechanism could in principle evade the problem, but it has been difficult to implement this idea in top-down constructions.

# De Sitter Conjecture

Combined with Bousso's entropy bound, the distance conjecture implies that the potential V for scalar fields must satisfy:

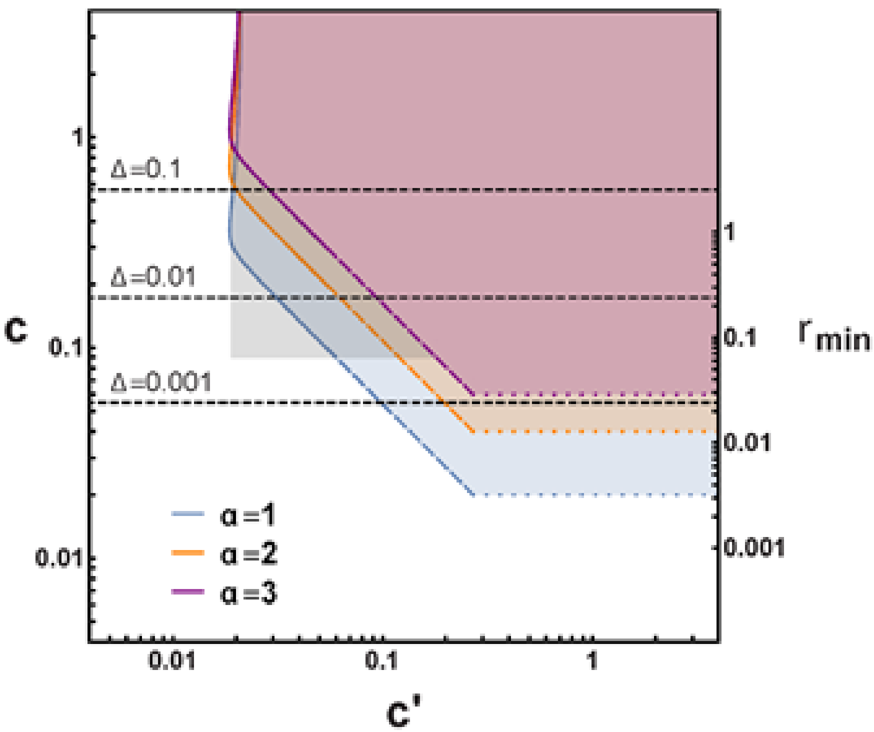
either $$|\nabla V| \geq \frac{c}{M_p} V$$

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

in any asymptotic directions in the scalar field space.

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

The de Sitter conjecture imposes strong constraints on inflation models:

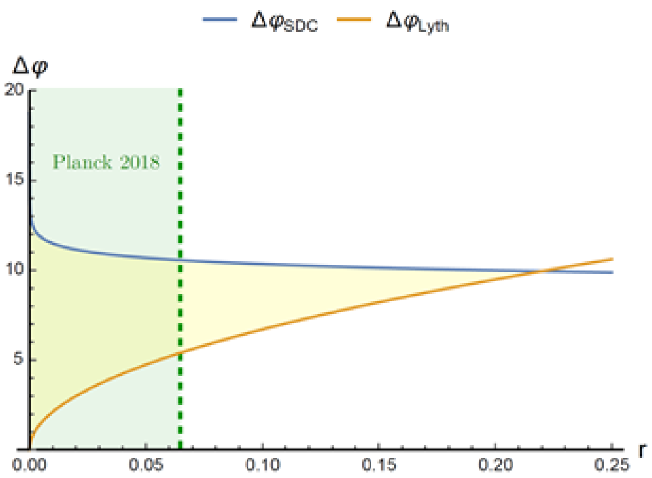



tensor-scalar ratio of CMB B-mode polarization

Chiang, Leedom, Murayama: 1811.01987

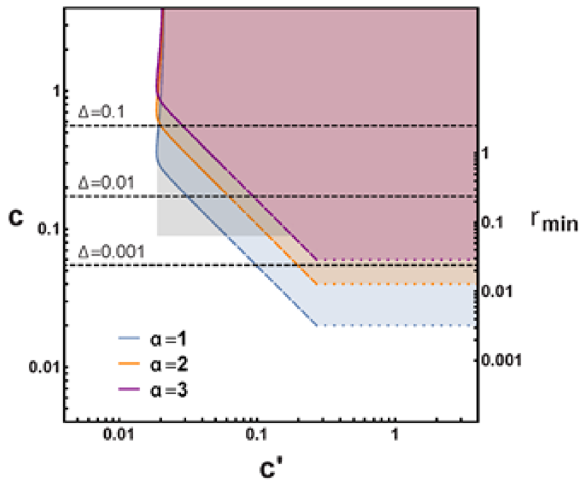
The Distance and de Sitter Conjectures **do not contradict with the inflation scenario** of the early universe but impose **strong contraints on their models**.

Distance Conjecture



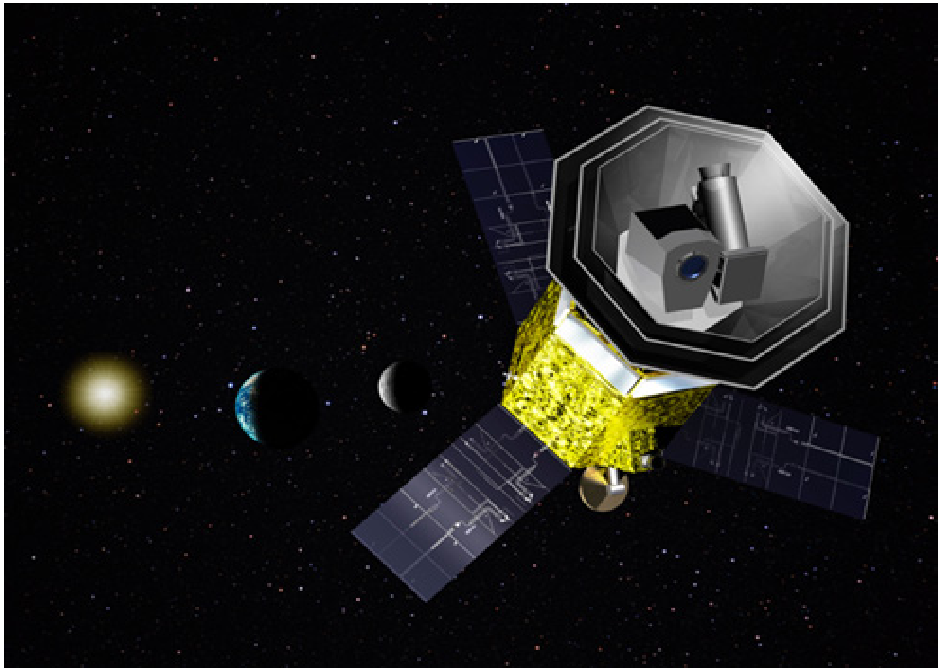

Scalisi, Valenzuela: 1812.07558

de Sitter Conjecture

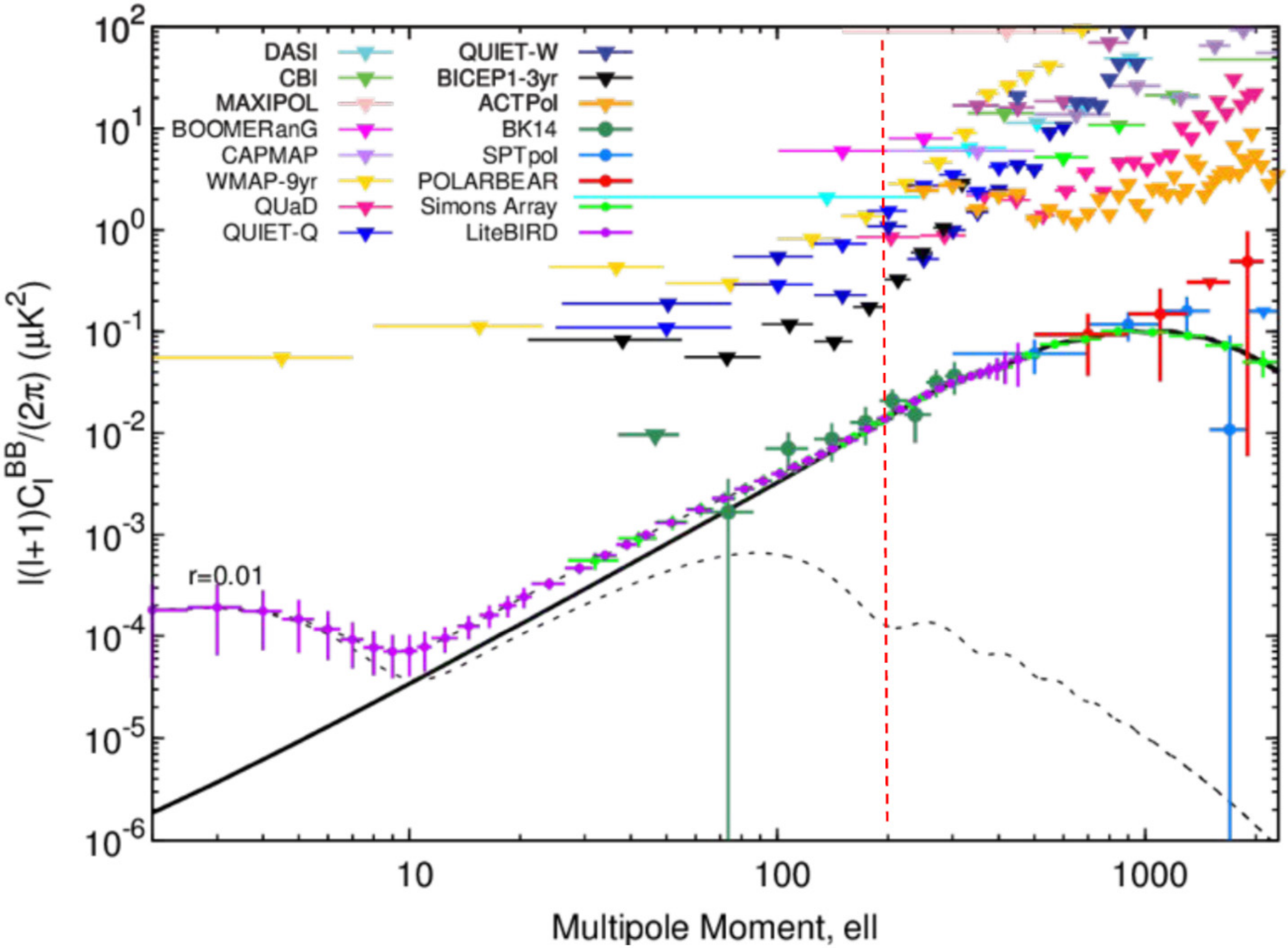



Chiang, Leedom, Murayama: 1811.01987

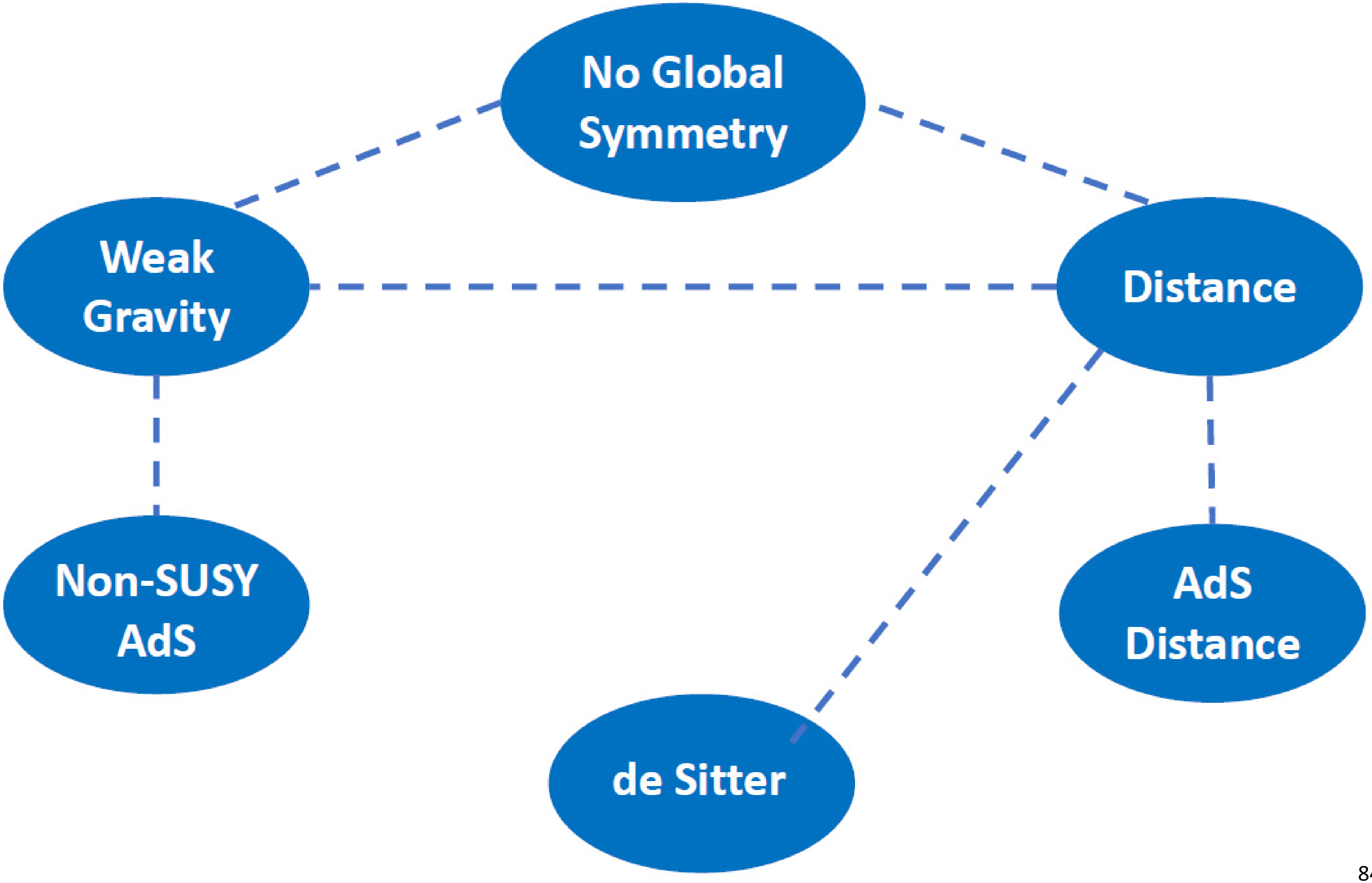
ISAS/JAXA has approved the launch of the LiteBIRD satellite within this decade to measure the CMB B-mode polarization and to test inflation models.



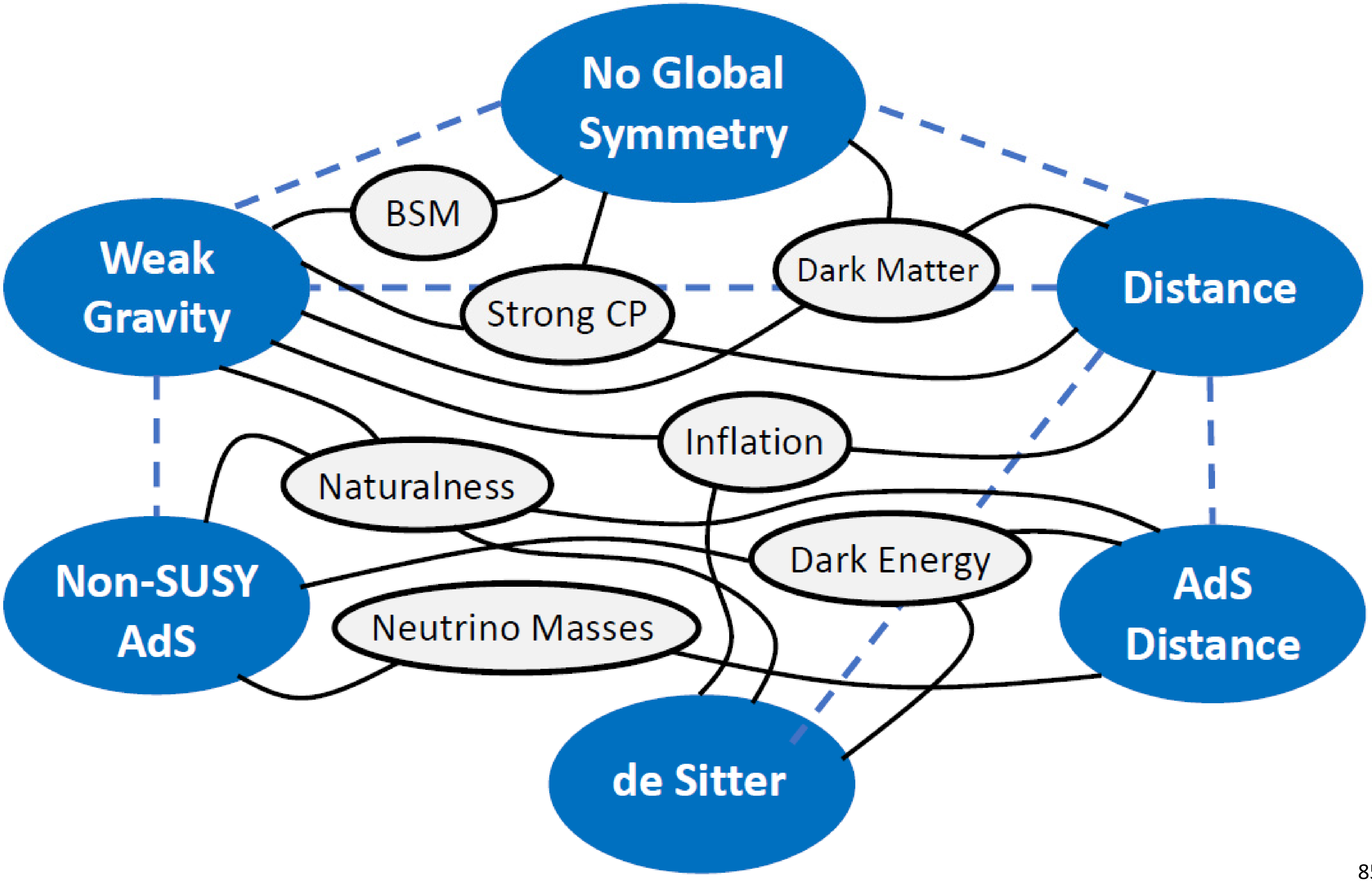
# LiteBIRD provides an unprecedented opportunity for String Theory to be **falsified**.



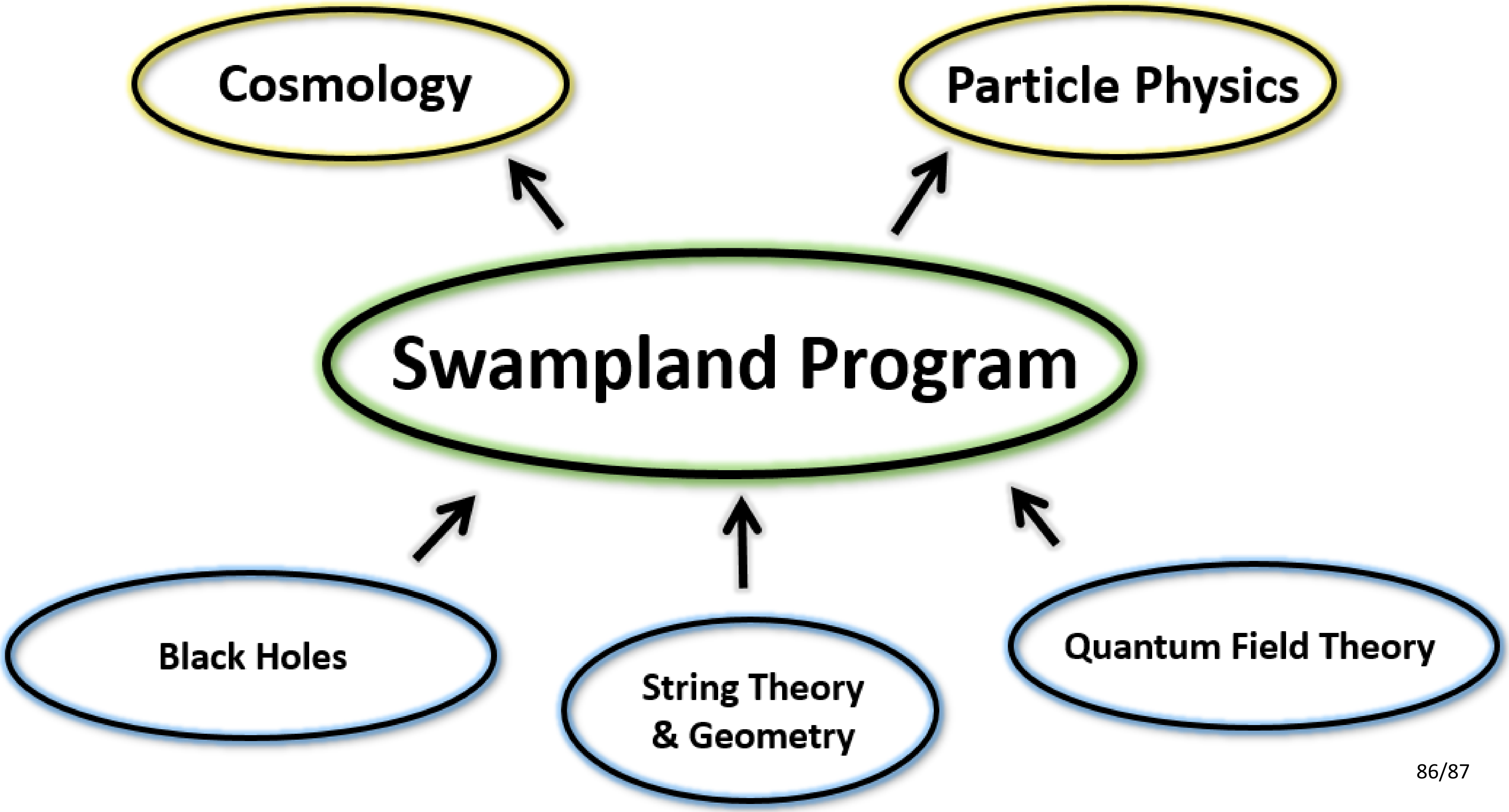
# Web of Swampland Conditions



# Connections to Cosmology and Particle Physics



# Swampland is a conduit to turn formal developments to testable predictions



# Gravity is Different

Mathematical consistency at high energy imposes strong constraints on effective theory.

Although the Planck scale is far away, we may found surprising predictions on low energy.

## Thank you.