# The Black Hole Information Paradox

in the Age of

# Holographic Entanglement Entropy

Netta Engelhardt

Madrid Christmas Conference

# The Information Paradox: 60,000 ft view

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- If the event horizon were a regime where strong quantum gravity effects are always important, it wouldn't be a paradox: we would simply say that semiclassical gravity is not valid there.
- But this isn't the case – spacetime curvature at event horizons of large black holes can be arbitrarily small.

# The Information Paradox: a Caricature

Caricature: Alice and Bob are entangled, and Alice ends up in the black hole while Bob doesn't. If the black hole evaporates, we seem to find that information is lost.

Alice falling down the ~~rabbit~~ black hole

But unitary evolution must preserve entanglement.

# The Information Paradox: the why

- We have never seen violations of unitarity. But then again, we have also never seen violations of GR.
- Information loss would be catastrophic: it would mean that the evolution of the universe is non-unitary: the entire universe is an “open” system.
- Either way, since black holes exist, there is a definitive answer about whether information is lost or conserved.
- Ultimately, the information paradox has a lot to teach us about quantum gravity... provided we can get insight into it without having a direct formulation of quantum gravity.

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- The new results from May 2019 Almheiri, Engelhardt, Marolf, Maxfield; Penington are a purely semiclassical analysis that is a smoking gun signal of information conservation. I think it's safe to say that most of us thought this was impossible.

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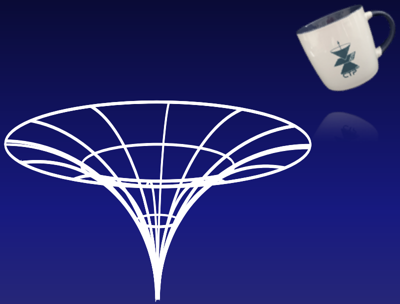
# BH Entropy: Wheeler's Gedankenexperiment



**"Teacup Experiment"**

If a black hole has no microstates, then it has no entropy. If you take a hot teacup (which most certainly has entropy) and throw it into the black hole, then you have decreased the entropy of the universe.

# Black Hole Entropy

*If your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation.*

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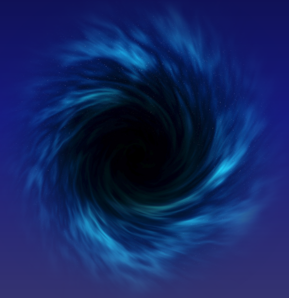
$$S = \frac{\text{Area[ event horizon ]}}{4G\hbar}.$$

For a black hole close to equilibrium, we expect a temperature $T \propto M^{-1}$.

# The Need for Quantum Corrections

This doesn't actually make sense as anything more than analogy in classical gravity, because objects with a temperature have to emit radiation, and black holes in classical GR are perfect absorbers.



In fact, to actually calculate the temperature of a black hole, need to work in perturbative QG, not GR. Hawking

# Evaporating Black Holes

So black hole truly are thermal: they should radiate! If the temperature of the black hole is hotter than its ambient surroundings, then as it radiates, it shrinks in size, losing mass. But

$$T \propto M^{-1}$$

As the black hole evaporates, it gets hotter, so it doesn't stop evaporating – until it is completely gone.

Some numbers:

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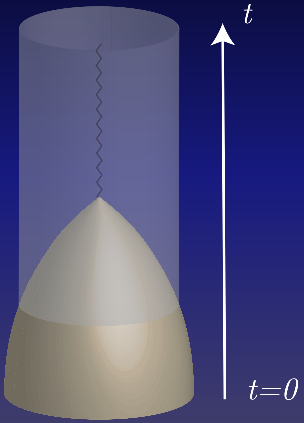
- Coronavirus-sized black hole, $T \sim$ room temperature.

# Collapsing Black Holes



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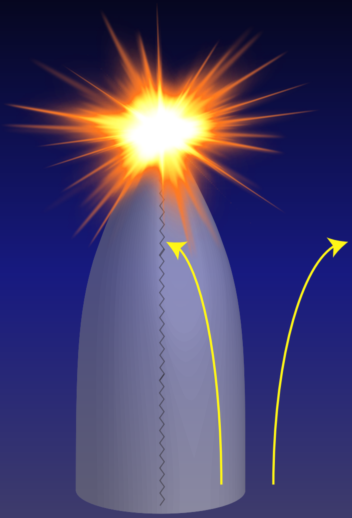
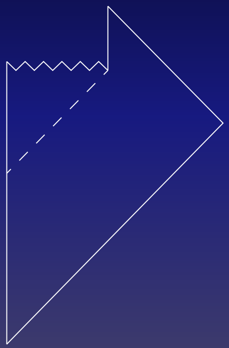


# Evaporating Black Holes

Basic idea: you start out with the vacuum state at $\mathcal{I}^-$, assume the state at the horizon is non-singular, and find that the state at $\mathcal{I}^+$ is thermal with $T = 1/8\pi M$.



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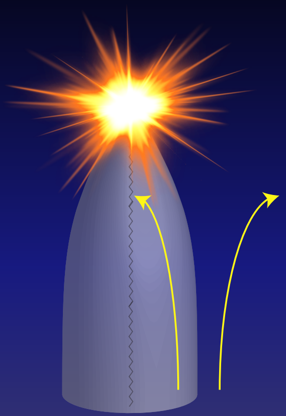

The paradox is what appears to be information loss between the initial state and the post-evaporation state (though you can already derive a paradox a little over halfway through evaporation).

# Entanglement Entropy of a Quantum System

For a density matrix $\rho$, the von Neumann entropy is defined:

$$S_{vN}[\rho] = -\mathrm{tr}\rho\log\rho$$

Properties of $S_{vN}$:

- It is invariant under unitary evolution.
- It vanishes for a pure state (and only for a pure state): $S_{vN}[|\psi\rangle\langle\psi|] = 0$
- It is bounded from above by the thermal entropy

# Information Loss

Some very rough intuition: we can quantify in a rough way the information in a state in terms of the difference

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This happens all the time! An open system will generally interact with its surroundings, settle down to a thermal state, and lose information along the way, because open systems don't evolve unitarily.

But the entire universe is not an open system. And yet Hawking's calculation shows that it evolves from a pure state to a thermal state.

# Information Loss in Hawking Radiation

In the very simplistic toy model of the EPR pair, the initial state of the pair is pure:

$$S_{\text{initial}} = 0.$$

After the black hole has finished evaporating,

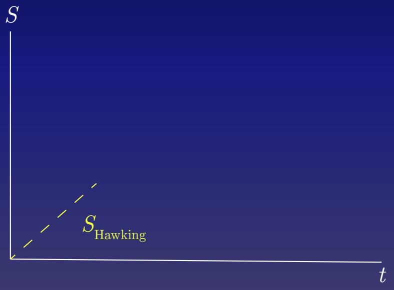
$$S_{\text{final}} = S_{\text{right}} = \log 2 \neq 0$$

The entropy has increased: the system was not evolving unitarily.

# Hawking's Calculation

More accurately, we can imagine forming a black hole from a pure state. Here we consider the entropy of the radiation: that is, the entropy of everything outside of the black hole.

Initially, before the black hole starts evaporating, this is zero. It then increases as the black hole evaporates.



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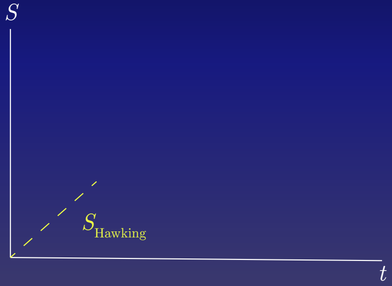
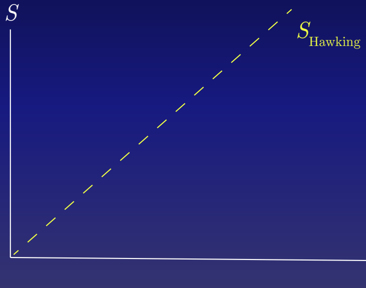



That's ok - there are two interacting systems – the radiation and the black hole – and the entropy of either one is allowed to increase.

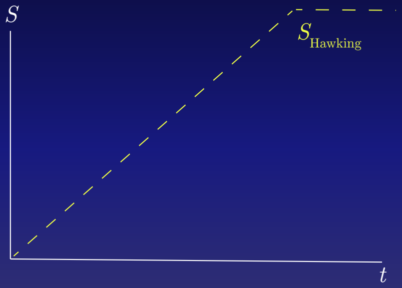
# Hawking's Calculation

The black hole continues to evaporate, and radiation entropy keeps on increasing.



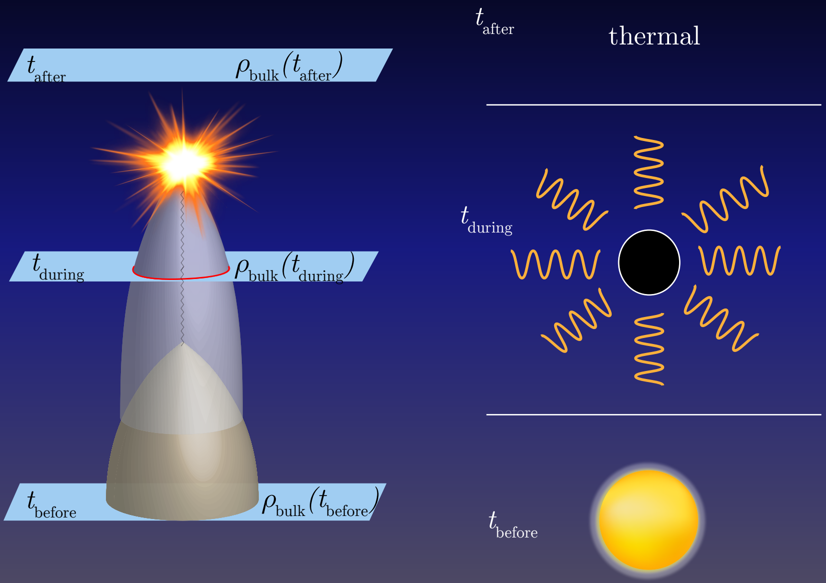
# Hawking's Calculation

But once the black hole finishes evaporating, the entire system is *just* the radiation.




This means that if the radiation doesn't have zero entropy after the black hole finishes evaporating, the end state is not pure: the universe evolves from a pure state to a mixed state, losing information.

# The Idea: Computing Entropy



# The Page Curve

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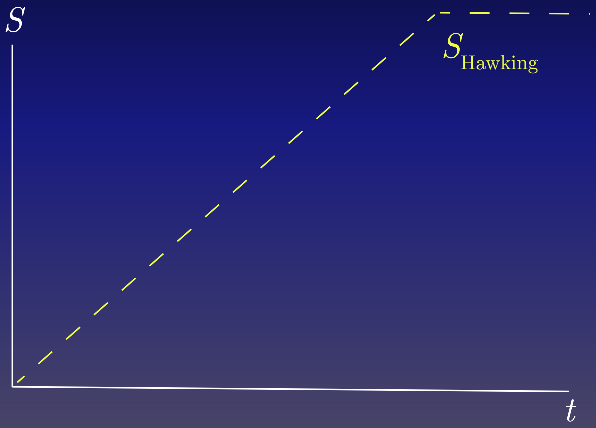
A pure state in a closed system evolves to a mixed state. Information appears to be lost. Is QG non-unitary? Are there corrections that only come in nonperturbatively? (e.g. $e^{G\hbar}$) corrections that somehow fix this? What does a unitary entropy curve look like?



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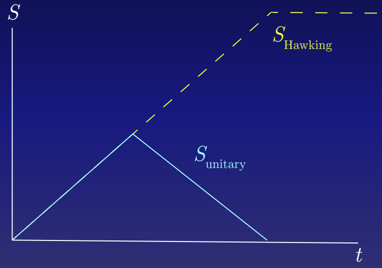
The unitary curve – named after Page for proposing it:



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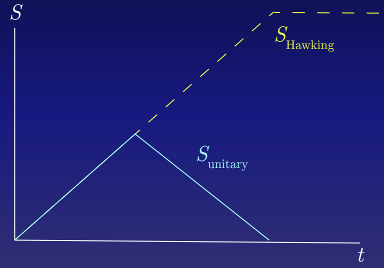


Which is the correct curve for QG? How do we calculate it?

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# Preview: the New Developments

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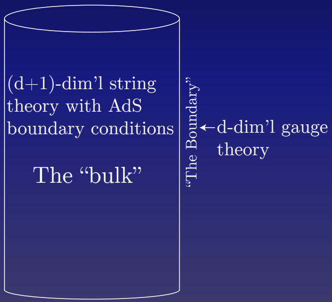
- What we found in the new developments is that a completely semiclassical calculation can give the unitary Page curve – but only if we use an interpretation of the calculation inherited from quantum gravity.

- Specifically, inherited from holography.

# Holography

**AdS/CFT aka Holography**

Quantum gravity with AdS boundary conditions (the "bulk") is dual to a lower-dimensional nongravitational quantum field theory (the "boundary").



# Holography: a Black Hole is just another Quantum System

This means that a black hole in AdS is just an ordinary, nongravitational quantum system.

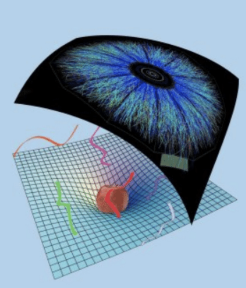


image credit: ESI Programme on AdS Holography and the Quark-Gluon Plasma

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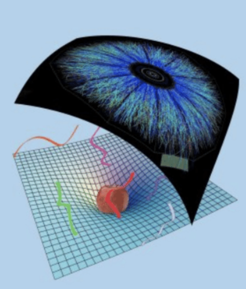

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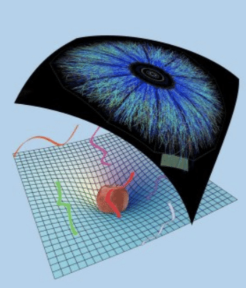

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Are we done?

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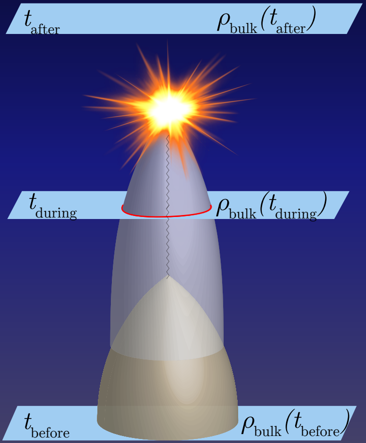


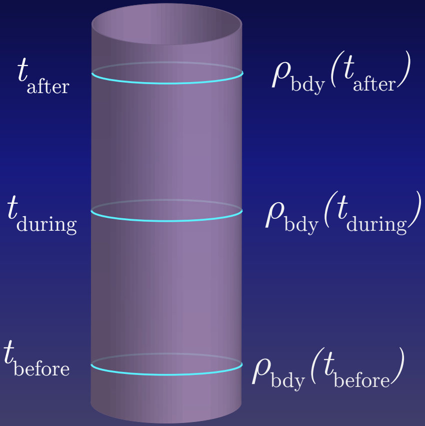

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Since the boundary entropy evolves unitarily, this could give us a way of doing a **perturbative quantum gravity** calculation for a **unitary** entropy!

Remarkably, it does!

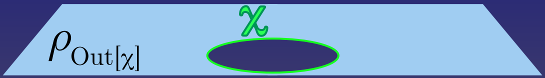
# Holographic Prescription for Computing $S_{\text{vN}}[\rho_{\text{bdy}}]$

The von Neumann entropy of a density matrix $\rho_{\text{bdy}}$ dual to a bulk with perturbative quantum gravity Engelhardt-Wall:

$$S_{\text{vN}}[\rho_{\text{bdy}}] = \frac{\text{Area}[\chi]}{4G\hbar} + S_{\text{vN}}[\rho_{\text{out}[\chi]}] \equiv S_{\text{gen}}[\chi]$$

where $\chi$ is a distinguished type of surface we called "quantum extremal".

the earlier formula without quantum corrections on the geometry was discovered by Ryu-Takayanagi, Hubeny-Rangamani-Takayanagi, and Faulkner-Lewkowycz-Maldacena



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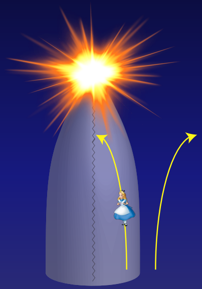
# Evaporating AdS Black Holes

Let's consider now an evaporating AdS black hole. The next few slides are based on Almheiri, Engelhardt, Marolf, Maxfield; Penington.



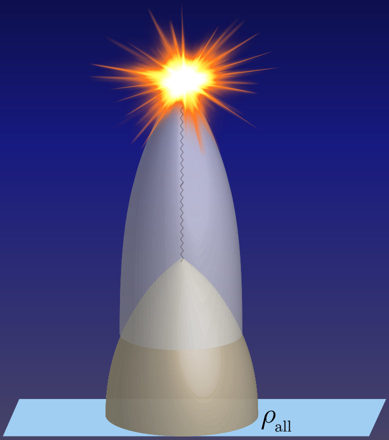
Actually, AdS black holes don't evaporate because AdS is like a box!

We forced the black hole to evaporate by replacing the sides of the box with a cold bath a nasty surprise for the black hole...

# Quantum Extremal Surfaces

Initially, at early times, the QES is the empty set.

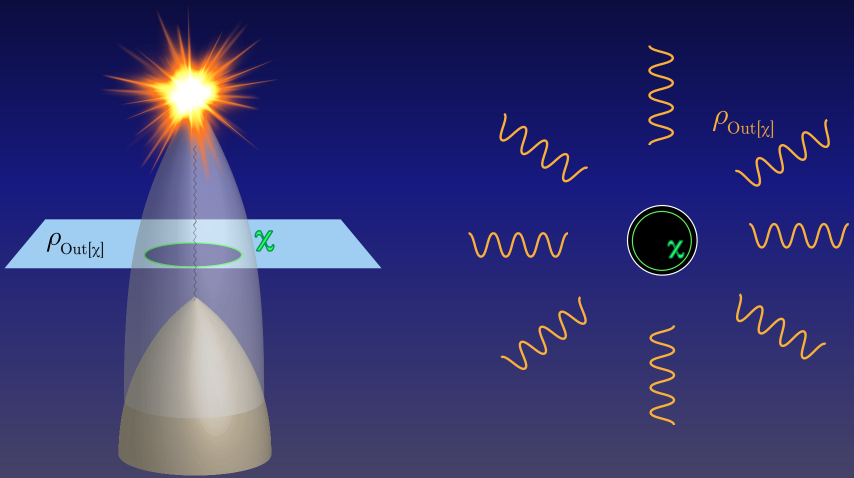
$$S_{vN}[\rho_{bdy}] = \frac{\text{Area}[\varnothing]}{4G\hbar} + S_{\text{vN}}[\rho_{\text{all}}] = S_{\text{vN}}[\rho_{\text{all}}]$$




As the black hole evaporates into the external system, $S_{\text{vN}}[\rho_{\text{all}}]$ grows.

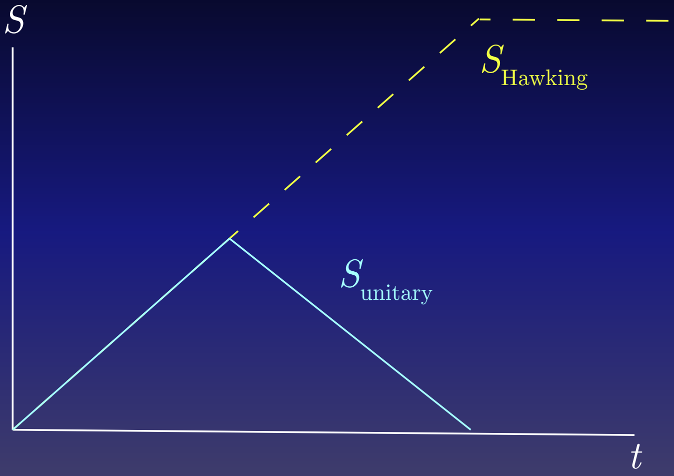
# Quantum Extremal Surfaces

After the black hole has evaporated half its mass, a quantum extremal surface with smaller $S_{\text{gen}}$ than the empty set appears:




As we evolve forward in time, this entropy decreases.

# The Page Curve




The Page curve for unitary evolution is obtained using only semiclassical physics!

# Taking a Step Back

What happened here?

$$S_{vN}[\rho_{\text{bdy}}] = \frac{\text{Area}[\chi]}{4G\hbar} + S_{vN}[\rho_{\text{Out}[\chi]}]$$

where $\rho_{\text{Out}[\chi]}$ is exactly the state that we compute from semiclassical gravity.

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The contribution from $\chi$ – the quantum extremal surface prescription – saves the day.

The only place where nonperturbative quantum gravity appeared is in the **interpretation** of $S_{\text{gen}}[\chi]$ as the entropy of the radiation.

Why does this work?

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Why does quantum gravity repackage entropy in this way?

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Why does quantum gravity repackage entropy in this way?

What microscopic Planckian physics is responsible for the success of the quantum extremal surface prescription?

# Some Progress on this Front

How do we generally compute entropies?

### The Replica Trick

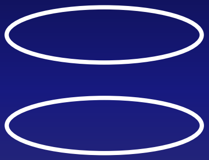
In a nongravitational theory, we can compute the von Neumann entropy using the replica trick

$$S_{\mathrm{vN}}[\rho] = -\mathrm{tr}\rho \ln \rho = -\lim_{n\to 1}\left(\frac{\partial}{\partial n}\log \mathrm{Tr}[\rho^n]\right)$$

where $\rho^n$ is the state $\rho$ on $n$ independent copies ("replicas") of this nongravitational theory.

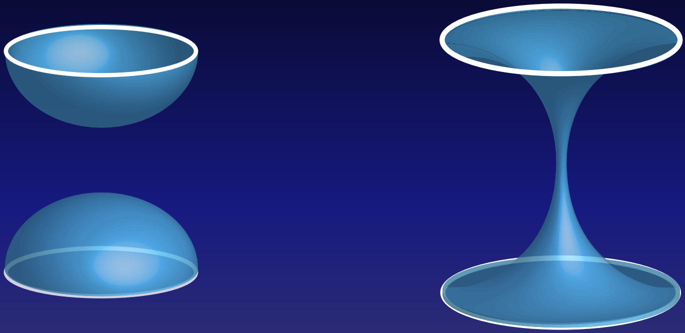
# Many Boundaries

To compute the partition function for $n = 2$, we take two identical copies of the AdS boundary conditions at infinity (and work in Euclidean signature):



In this case, there are two saddle points Penington, Shenker, Stanford, Yang; Almheiri, Hartman, Maldacena, Shaghoulian, Tajdini.

# Two Competing Saddles



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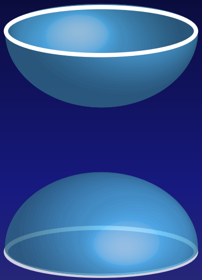

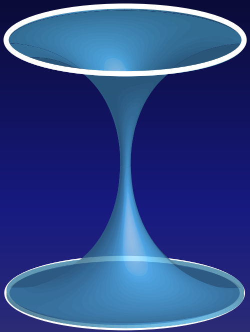

In our case, the quantum extremal surface formula and its generalization to the radiation can be computed directly from the gravitational path integral in this way. The jump in the QES, occurs due to a switchover in the dominating saddles from the disconnected to the connected wormhole.

Penington et al; Almheiri et al

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# Possibilities

One possibility that has been discussed in the literature is that the gravitational path integral computes an ensemble average Giddings, Strominger; Coleman; Maldacena, Maoz.

Another possibility is that nonperturbative corrections restore factorization.

Yet a third possibility is that the path integral is just a really good tool for computing self-averaging quantities in a single theory.

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What I would argue *is* clear is that we have pinned down a key ingredient in the resolution of the information paradox: the gravitational path integral.

We *must* understand why it is dominated by these correlated replicas, why those give rise to unitary evolution and what their contributions mean for the gravitational theory and quantum extremal surface formula.

# Current State of the Information Paradox

Spoiler: **we haven't solved it yet.**

- What entropy is the quantum extremal surface/gravitational path integral calculating? How do we compute it directly from the formula $-\mathrm{tr}\rho\ln\rho$?

- What does an observer outside the black hole actually measure? If we could make arbitrarily accurate measurements and had an arbitrarily good computer, would we, upon feeding those measurements to our computer, find a pure state or a mixed state?

- Is the path integral doing an averaging of some sort? Over what? If not, how do we explain the correlated replicas?

- Where did Hawking go wrong?

Thank you!