Title: Evaporating Black Holes in AdS

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Evaporating Black Holes in AdS

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Emmy Noether Conference, PI

Based on: A. Almheiri, NE, D. Marolf, H. Maxfield '19

C. Akers, NE, D. Harlow '19

The Structure of Quantum Spacetime

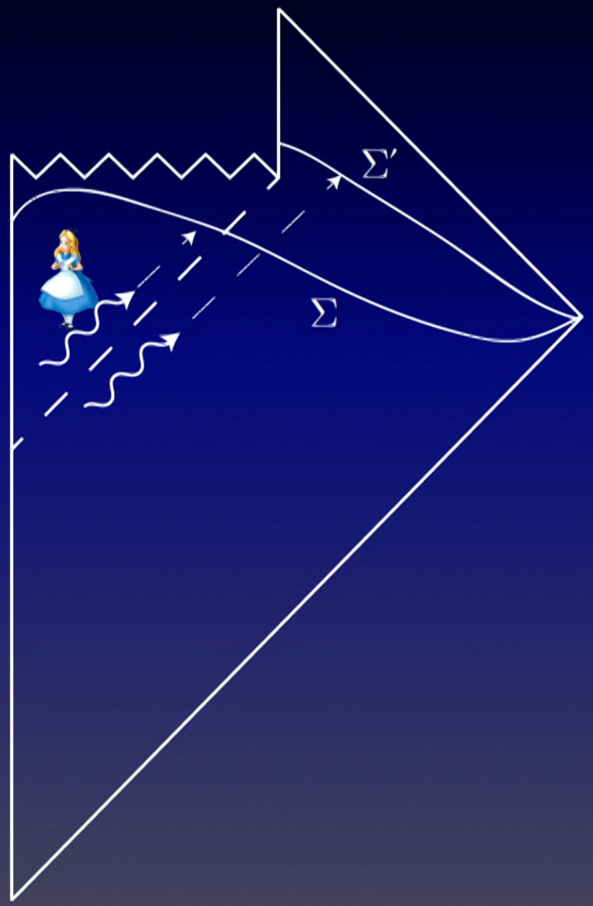
- One of the biggest hurdles to understanding the behavior of gravity on quantum scales is the information paradox
- Recall: Alice and Bob are entangled, and Alice ends up in the black hole while Bob survives to the asymptotic future.

- If the black hole then evaporates, the evolution of the entiire universe (a closed system!) is from a pure state to a mixed state. This contradicts unitary time evolution.

Quantum Spacetime and Information

- If we expect that QG is unitary (which I at least do), then information must be conserved.
- In this sense, AdS/CFT (if you subscribe to it) gives an answer to the question: information is conserved.
- But this is of course an unsatsifactory answer: in order to make progress towards understanding the quantum structure of spacetime, we really need to understand *how* QG manages to conserve the information.

Background: the BH Information Paradox

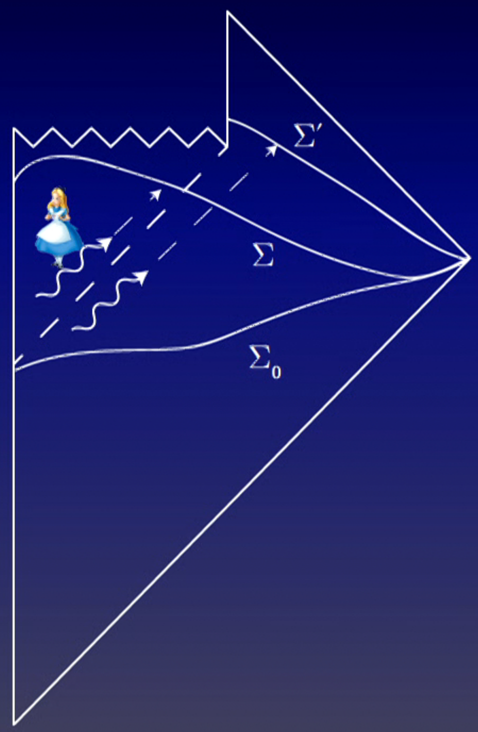


A black hole with $T > T_{ambient}$ radiates, growing progressively hotter and evaporating until it disappears (explodes?).

If the black hole forms from the collapse of a pure state, the state $|\psi\rangle$ on Σ is pure. But the state ρ on Cauchy slices of the spacetime post evaporation (e.g. Σ') is mixed.

A Diagnostic: Entropy of the Radiation

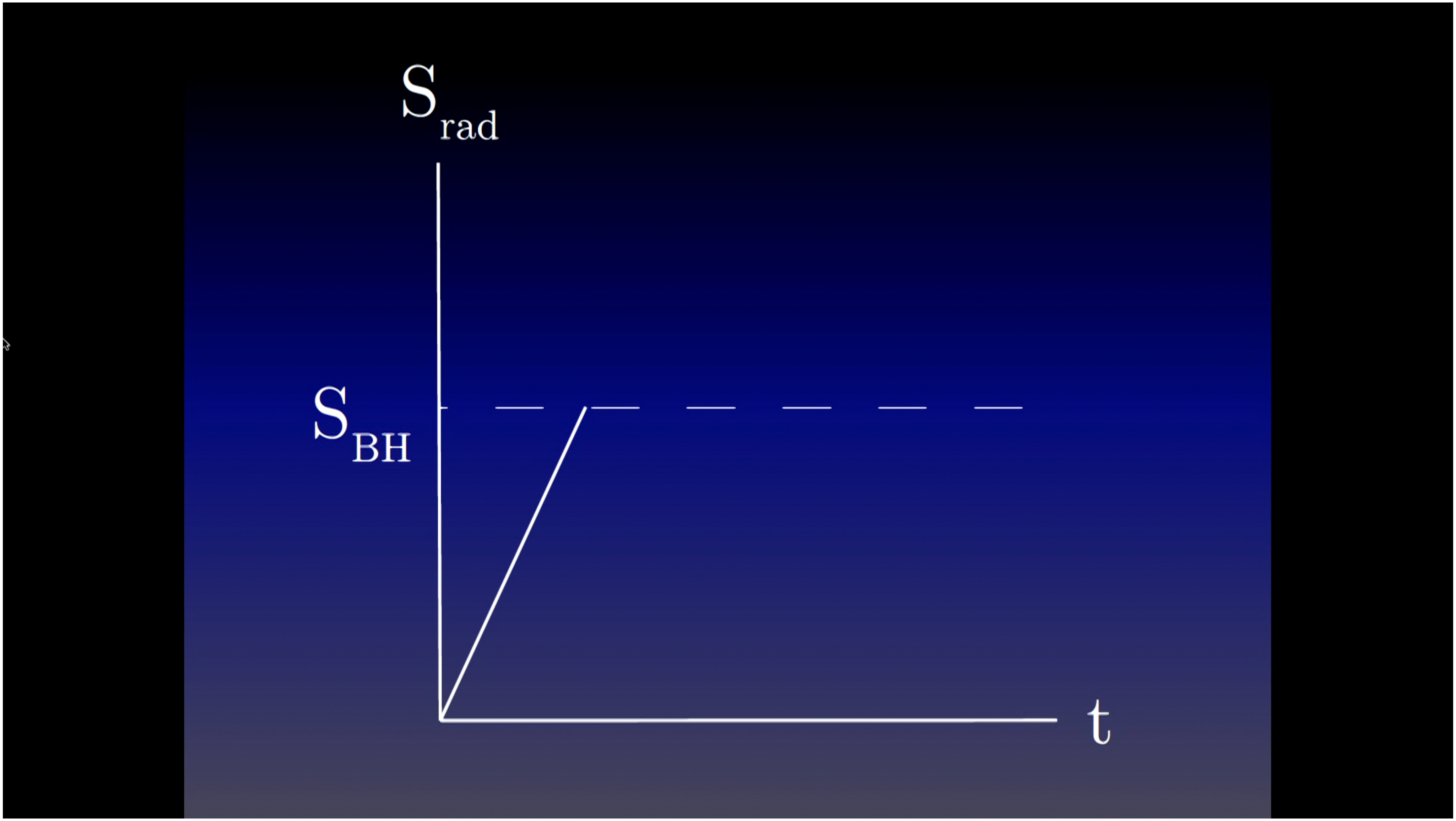
$$S_{\rm rad} = -{\rm tr}\rho_{\rm rad} \ln \rho_{\rm rad}$$



Let us assume that at Σ_0, the state of any quantum fields in our spacetime is pure.

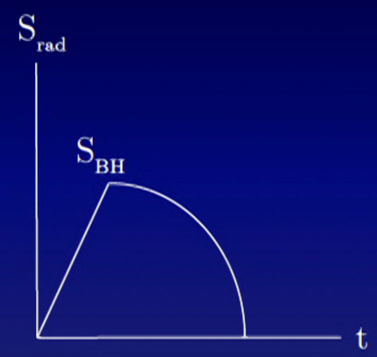
The state on Σ' is either pure if QG is unitary and info gets out, or it is mixed and info is lost.

On Σ, half of the black hole has evaporated: the entropy outside the BH is exactly the Bekenstein-Hawking entropy of the BH.


S_{rad}
S_{BH}
t

After the Page time

If the evolution is unitary, then as the black hole continues to radiate, the radiation purifies.



If evolution is non-unitary, the entropy S_{out} continues to grow until the black hole finishes evaporating, reaching a mixed final state.

AdS/CFT as a tool

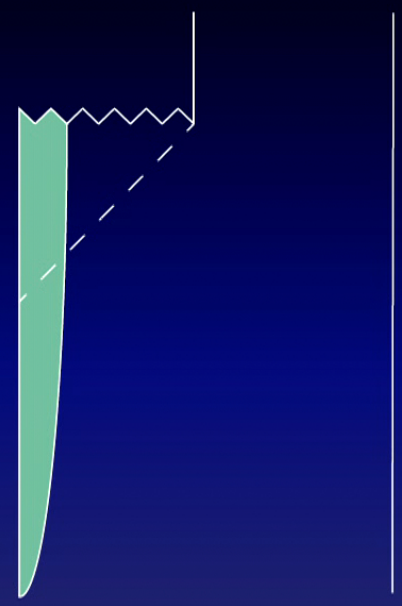
AdS equals CFT

Duality between quantum gravity with AdS boundary conditions and conformal field theory in one lower dimension. Means that CFT gives a formulation of nonperturbative quantum gravity.

There's a lot of evidence in favor of AdS/CFT, including from Noether's 2nd theorem: the Hamiltonian in GR is a boundary term, which is the Hamiltonian of the CFT.

Idea: pose BH information problem in a context where we can get some handle on the quantum gravity dynamics.

The Information Paradox in AdS/CFT



Same problem as before, except now we know the answer: the evaporation process *must* be unitary, because the CFT evolution is unitary.

… Wait, do AdS BHs Evaporate?

It is often said that black holes in AdS don't evaporate because the radiation is simply reflected off of asymptotic infinity.

This is true for large black holes (large compared with the AdS radius); small black holes *do* evaporate.

But we don't understand small black holes well though see Marolf '18; so it seems that we are at an impasse.

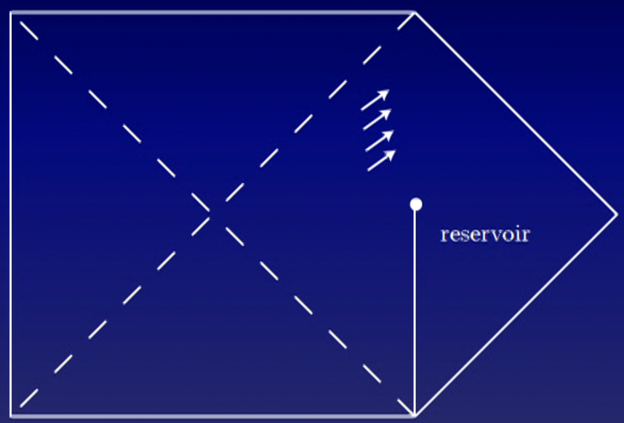
There *does* exist a version of the information paradox for large black holes (in terms of correlation functions at late times) Maldacena; Saad, but it is more complicated and less viscerally disturbing!

So how can we model BH evaporation in AdS?

Modeling BH Evaporation in AdS

Almheiri, NE, Marofl, Maxfield; Penington

If the issue preventing the black hole from evaporating is the reflecting BC at infinity, let's change the asymptotic BCs.



We want to now compute the Page curve of the black hole entropy. To simplify calculations, we work in AdS_2/CFT_1 (SYK Sachdev, Ye; Kitaev). Similar results hold in higher dimensions Penington.

Computing Entropy in AdS/CFT

We would like to compute the entropy holographically.
In the $G\hbar \to 0$ (and $\ell_{string} \to 0$) limit, we have the (H)RT proposal Ryu, Takayanagi; Hubeny, Rangamani, Takayangi

$$S_{vN}[\rho(t)] = \frac{\text{Area}[X_t]}{4G\hbar}$$

where $\rho(t)$ is the density matrix of the CFT_1 at boundary time t, and X_t is the minimal area (dilaton) surface which extremizes the area (dilaton). So long as the boundary system is evolving unitarily, the t-dependence is irrelevant.

When $G\hbar \neq 0$...

We clearly cannot use the strict classical regime to describe black hole evaporation. Need a generalization of HRT that includes backreaction due to quantum fields.

Quantum Extremal Surfaces NE, Wall '14

The entropy of $\rho(t)$ in perturbative quantum gravity is holographically dual to

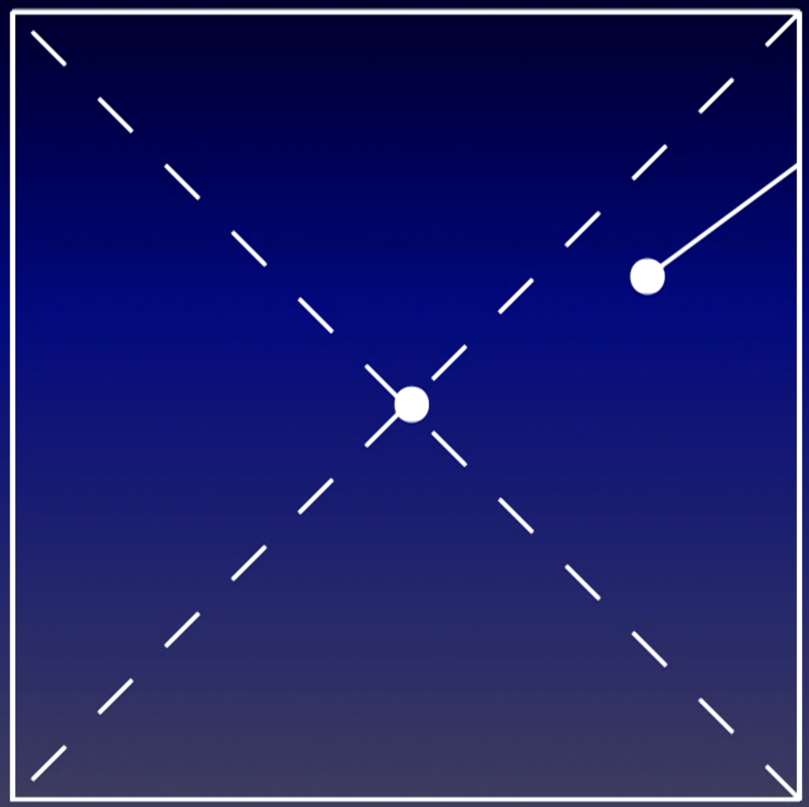
$$\frac{\text{Area}(\mathcal{X}(t))}{4\ell_P} + S_{\text{out}}[\mathcal{X}(t)] + \text{c.t.} + \text{ higher deriv.},$$

where $\mathcal{X}(t)$ is a *quantum extremal surface*: a surface which extremizes S_{gen}.

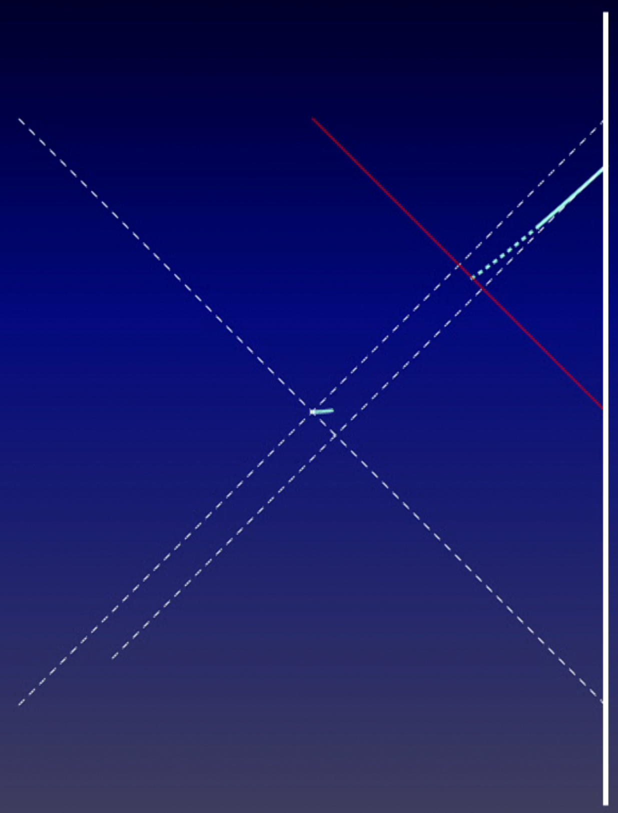
Quantum Extremal Surfaces

- Naively, we might expect that classical and quantum extremal surfaces would lie next to one another in the perturbative regime: after all, in such a regime $1/G$ is much larger than S_{out}.
- However, for quantum extremality is not the balance between $A/4G$ and S_{out} that matters but the the balance between their *gradients* that matters.
- In the evaporating black hole, we Almheiri, NE, Marolf, Maxfield; Penington find that after the Page time the entropy is changing fast enough that its gradient balances out the change in $A/4G$ even while the entropy remains subleading.
- $\Rightarrow$ there is a new quantum extremal surface nucleating where no classical extremal surface exists. And it dominates the holographic calculation.

The Quantum Extremal Surface and the Evaporating BH



The Quantum Extremal Surface and the Evaporating BH



A Puzzle: two Page Curves

- The QES gives a unitary Page curve: entropy goes up until the transition, then decreases afterwards.
- A direct computation of the entropy gives a Hawking curve: entropy goes up and eventually saturates.

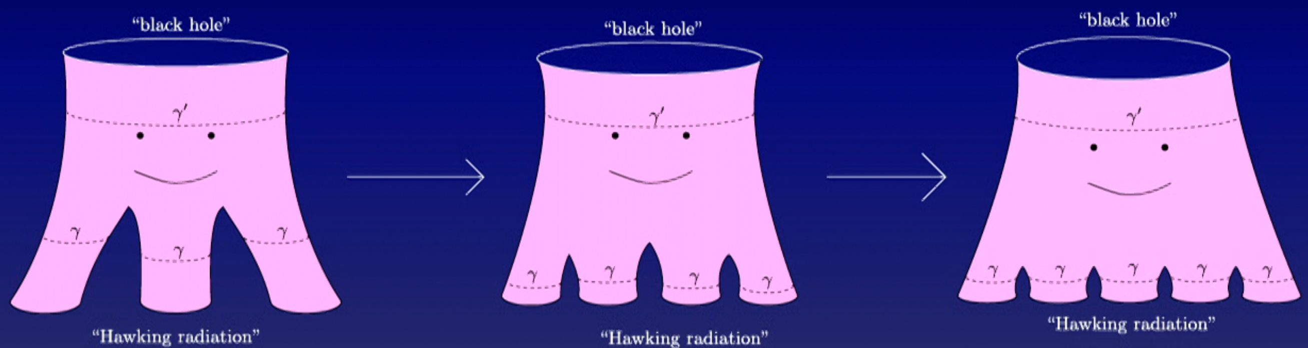
Towards a Resolution: Quantum Gravity dynamics

- The Hawking curve is expected: we are doing a semiclassical calculation, the same one that Hawking did. We get the same answer: a mixed state.
- The unitary Page curve is also expected: we are working a unitary quantum gravity theory.
- ... are we?
- The dynamics of this theory are not unitary, because semiclassical gravity is non-unitary. Whatever quantum gravity magic happens to conserve the information can't happen in this model because we are evolving the system via semiclassical gravity.
- The unitary Page curve from the QES is what the system would do if it were genuinely holographic; but it's just an approximation to some holographic system, which is why the exact calculation of the entropy yields a non-unitary

A Toy Model of BH Evaporation

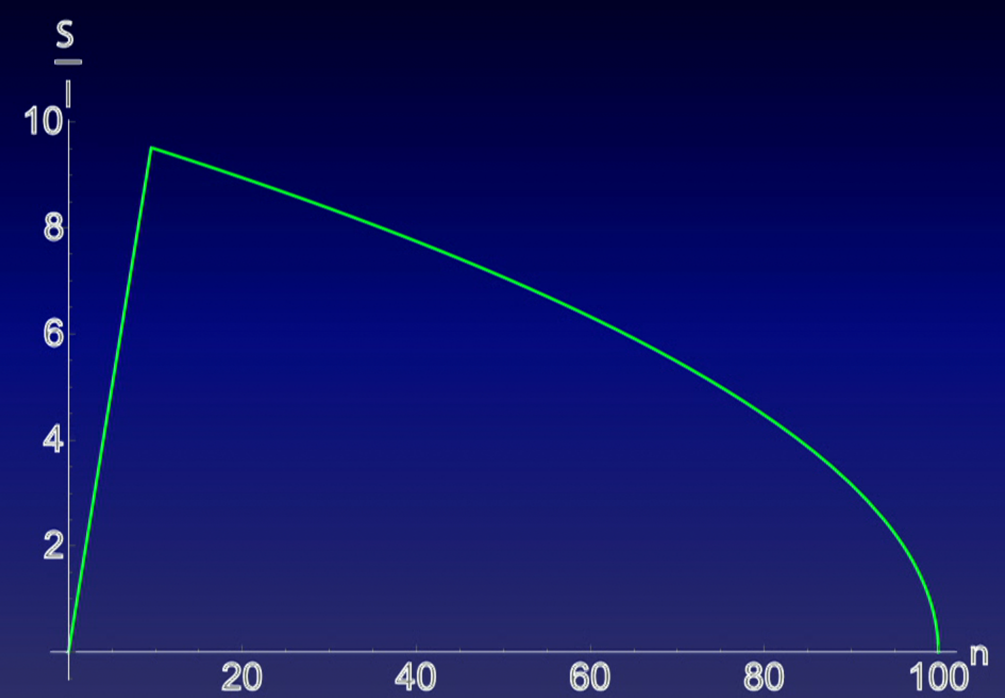
Akers, NE, Harlow

Let's work with a toy model: the black hole evaporates via emission of smaller black holes, which are our stand-ins for the Hawking quanta.



This is a realization of ER=EPR Van Raamsdonk; Maldacena, Susskind, the "quantum octopus" realized classically.

The Page Curve for the Toy Model



The Road Forward

- Understanding the information paradox is of paramount importance for understanding spacetime and spacetime emergence in quantum gravity.
- AdS/CFT provides a tractable way of modeling BH evaporation within quantum gravity.
- Modeling it assuming semiclassical gravity in the bulk gets us into a bit of trouble, but gives inspiration for how QG may actually solve the problem
- We need to understanding better how/whether the toy model is actually describing quantum gravity dynamics (classical wormhole is really a quantum wormhole).
- Many exciting developments yet to come!