Title: On the Road to Cosmic Censorship: a Holographic Argument for the Penrose Inequality in AdS

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Series: Quantum Fields and Strings

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Abstract: I will give a holographic argument in favor of the AdS Penrose inequality, which conjectures a lower bound on the total mass in terms of the area of apparent horizons. This inequality is often viewed as a test of cosmic censorship. Time permitting, Iâ€™ll also discuss a generalization to charged black holes and connections with a quasi-local energy and the second law for apparent horizons.


Netta Engelhardt
THE ROAD TO COSMIC CENSORSHIP:
OLOGRAPHIC ARGUMENT FOR THE
ADS PENROSE INEQUALITY
Netta Engelhardt
Princeton Gravity Initiative
Based on
w/ G Horowitz
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Cosmic Censorship

un fact #1: Generic solutions to Einstein's equations have ngularities.

Fun fact #2: We have never observed a singularity ever.

Fun fact #3: Einstein's equations describe the universe pretty well.

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Cosmic Censorship

Cosmic Censor: Nature Abhors a Naked Singularity

Penrose: in nature, singularities are always cloaked behind event horizons (except initial singularity).

Sadly, would mean that we can never directly observe strong quantum gravity physics from a naked singularity.

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Cosmic Censorship: is it true?

- CC comes in two different flavors: strong and weak, with neither implying the other.
- Neither one has been proven, and there are now counterexamples for both.
- But just because cosmic censorship is violated for certain solutions of the Einstein equation doesn't mean that those solutions admit a UV completion within quantum gravity.
- If quantum gravity indeed prefers to hide singularities behind horizons, CC (or some relaxed version of it) would be a deep fact about nature. How can we figure this out?
- Use AdS/CFT: a formulation of nonperturbative quantum gravity.

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Cosmic Censorship

Cosmic Censorship [Penrose '69]

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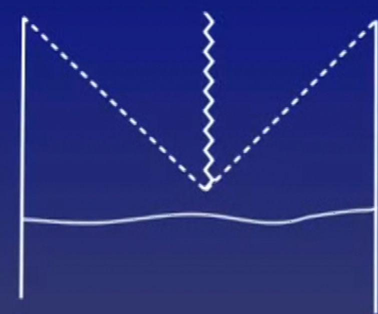

The maximal Cauchy development of a set of generic asymptotically flat (or AdS) initial data is asymptotically flat (AdS), strongly asymptotically predictable. (complete $\mathscr{I}^+$, or complete conformal boundary)

Violations of CC

- In 5 or more dims, Gregory-Laflamme type instability results in a pinch-off singularity [Lehner, Pretorius '10; Figueras, Kunesch, Tunyasuvunakool '16; Figueras, Kunesch, Lehner, and Tunyasuvunakool '17]

Image credit: P. Figueras

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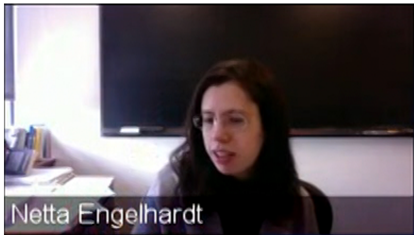
Image credit: P. Figueras

- More recently, counterexamples for asymptotically AdS_4 initial data by Horowitz, Santos '16, '19; Crisford, Horowitz, Santos '17, '18

Violations of CC

- Initial known violations were "mild": the pinch-off singularity or critical collapse are small violations (localized to Planck-sized regions and most likely resolved in QG w/o any effects visible to asymptotic observers)



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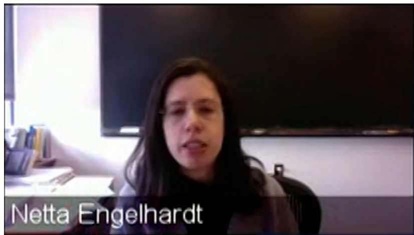

Violations of CC

- Initial known violations were "mild": the pinch-off singularity or critical collapse are small violations (localized to Planck-sized regions and most likely resolved in QG w/o any effects visible to asymptotic observers)
- Might suggest that a relaxed version of CC is still valid
- But the examples of Crisford, Horowitz, and Santos are different: the curvature grows without bound in an extended region. Perhaps CC is altogether false?

QG to the Rescue?

The Crisford-Horowitz-Santos counterexamples are for Einstein-Maxwell in AdS_4.

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QG to the Rescue?

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They found: if you add a charged scalar, and if the charge to mass ratio satisfies a conjecture about quantum gravity – the so-called weak gravity conjecture [Arkani-Hamed, Motl, Nicolis, Vafa] – then CC is no longer violated.

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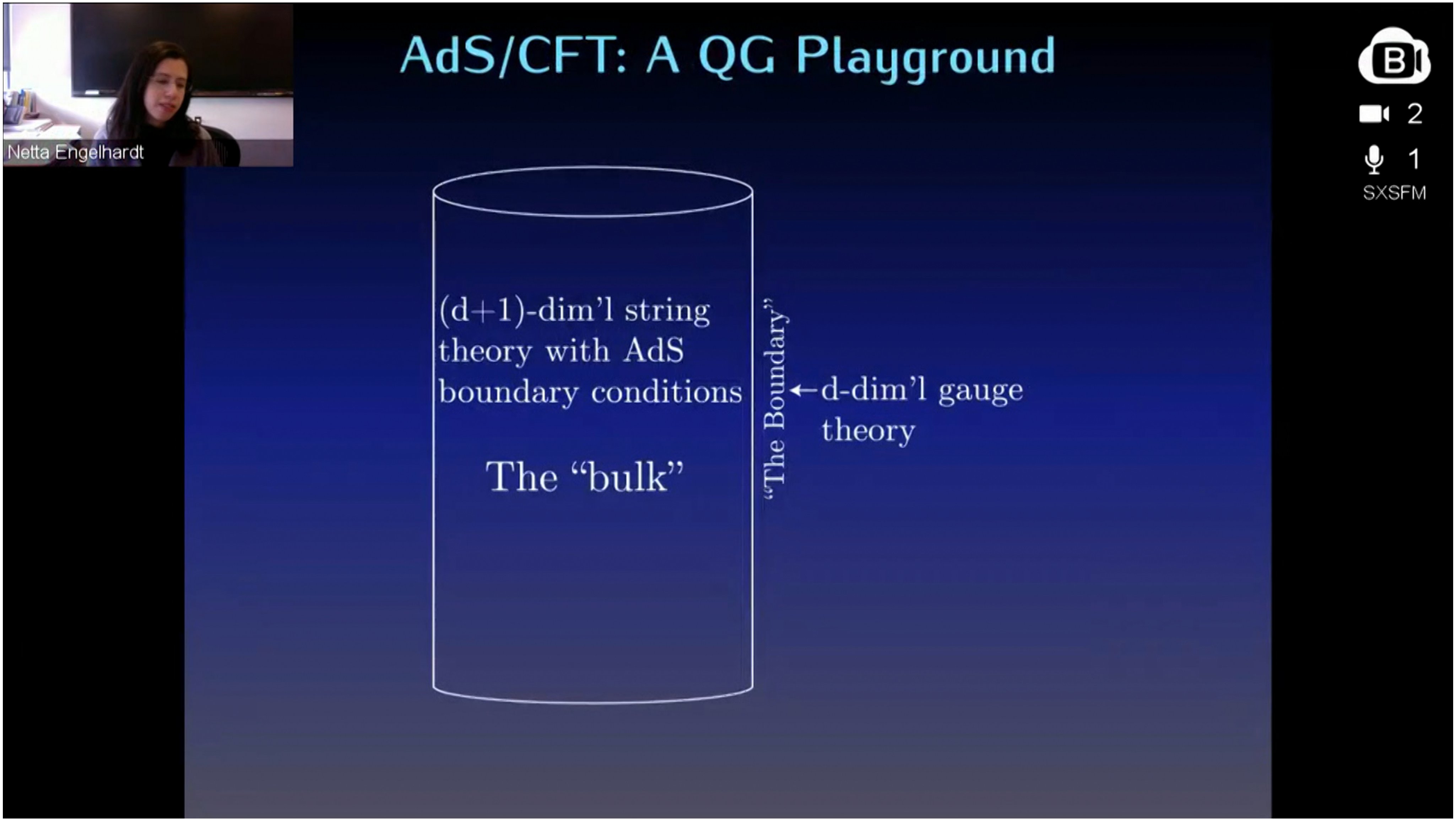
Possible hypothesis?

Might suggest that even though CC **can** be badly violated in solutions to General Relativity, it **won't** be violated (except very mildly) in solutions to General Relativity that admit a UV completion.


AdS/CFT: A QG Playground
(d+1)-dim'l string theory with AdS boundary conditions
The "bulk"
"The Boundary"
d-dim'l gauge theory
Netta Engelhardt
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The Apparent Horizon

he Penrose Inequality is a conjecture about the area of *apparent horizons.*

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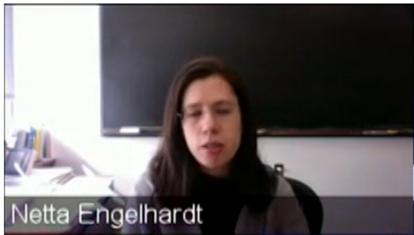

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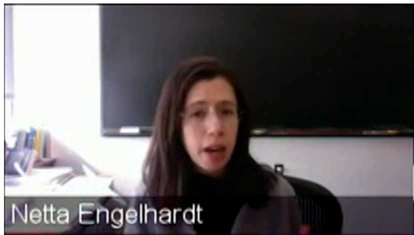

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To define the apparent horizon, recall some facts about light rays.

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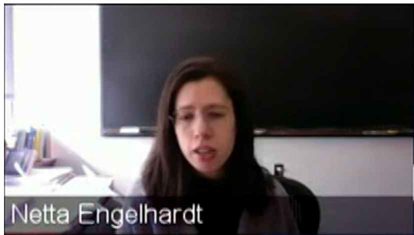

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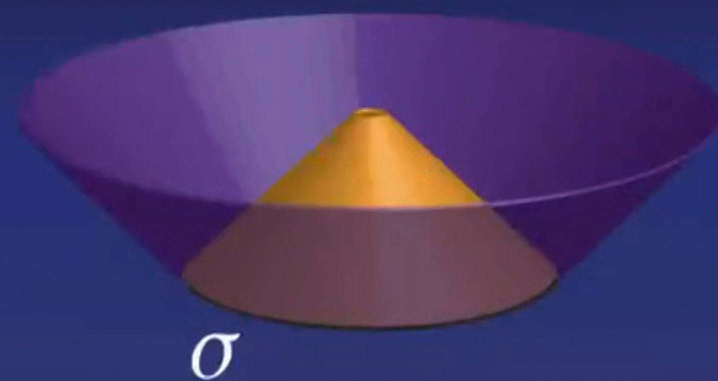
To define the apparent horizon, recall some facts about light rays. 2 ways to fire light from a spacelike surface to the future, given by 2 vectors:

Causal Structure

Generate two null surfaces:



Causal Structure

- Our (approximately) flat space intuition says the future-outwards congruence should expand in cross-sectional area while the future-inwards ones should shrink.
- In curved space, outgoing light rays can contract and ingoing light rays can expand.

Apparent Horizon

- Near a black hole singularity (or close to a big crunch), spacetime volume contracts: both ingoing and outgoing null rays contract: trapped surfaces.

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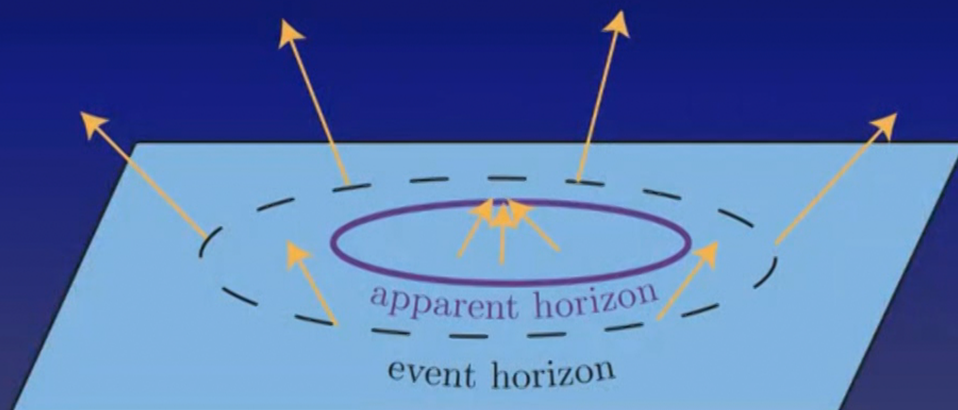
- If we think of the black hole as being populated by trapped surfaces and the black hole exterior as being populated by normal surfaces, then between the two regions we have surfaces with contracting ingoing null rays and outgoing null rays that neither contract nor expand.
- We can think of the outermost surface whose outgoing light rays are not expanding as the black hole boundary.

Definition: apparent horizon

pparent Horizon

An apparent horizon is the outermost surface on a Cauchy slice whose outgoing null light rays are non-contracting.



For stationary BHs, event and apparent horizons coincide.

Penrose Inequality from CC + other assumptions

- Suppose we have a 4D asympt. flat spacetime with total mass M and apparent horizon σ.

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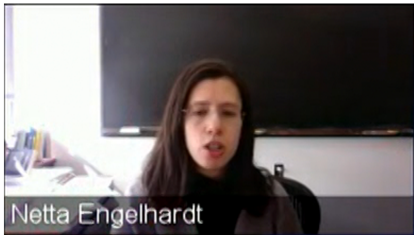

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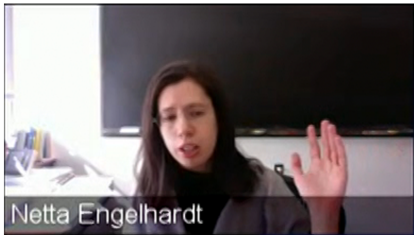

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- Assume that the area of an apparent horizon is smaller than the area of EH on some Cauchy slice. This is known to be false in certain cases for the above defn of apparent horizon e.g. [Ben-Dov '04]. More on this later.
- Area of the EH only increases with time [Hawking], so:

$$\text{Area}[\sigma] \leq \text{Area}[EH_{finite}] \leq \text{Area}[EH_{\text{final}}]$$

Penrose Inequality from CC + other assumptions

ssume any black hole settles down to Kerr. Then:

$$
\begin{aligned}
\text{Area}[EH_{\text{final}}] &= \text{Area}[\text{Kerr w/ mass } M] \\
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- So CC implies:

$$\boxed{M \geq \left(\frac{\text{Area}[\sigma]}{16\pi}\right)^{1/2}}$$

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Penrose Inequality

An analogous equation can be derived from CC in AdS under similar assumptions (and also assuming reflecting bdy conds at infinity).

In general, it is the statement that:

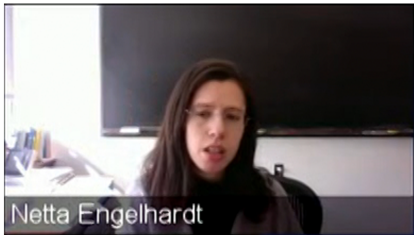
General AdS Penrose Inequality

Let σ be an apparent horizon in D dims, and let M be the spacetime mass. Then:

$$\text{Area}[\sigma] \leq \text{Area}[\text{Static AdS BH w/ mass } M].$$

Motivation: Penrose Inequality

Previous argument has issues, but suggests that Penrose inequality derives from CC.



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In reverse, if Penrose Inequality is true, it is good evidence in favor of some version of CC.

Proving CC is hard; proving Penrose Inequality (w/o assuming CC) might be easier.

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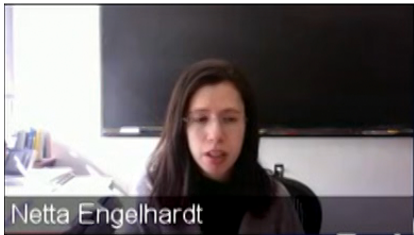
Current Status of Penrose Inequality

- Without assuming CC, proofs exist in the asymptotically flat Riemannian case e.g. [Huisken, Ilmanen '01; Bray '01] .



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- Even less is known about the asymptotically AdS case see [de Lima; Girao; Husain, Singh; Bakas, Skenderis] for the little that is known

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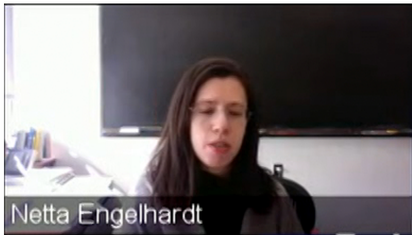

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- Thanks to [Horowitz, Santos; Crisford, Horowitz, Santos], we now know that CC **can** be violated for asymptotically AdS initial data. So we **don't** expect that we can prove Penrose's Inequality for general asympt. AdS spacetimes.

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- But maybe for asympt. AdS spacetimes with UV completion?

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Penrose Inequality in AdS/CFT

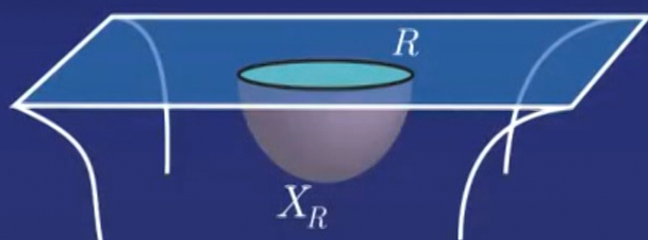
Holography Implies an AdS Penrose Inequality

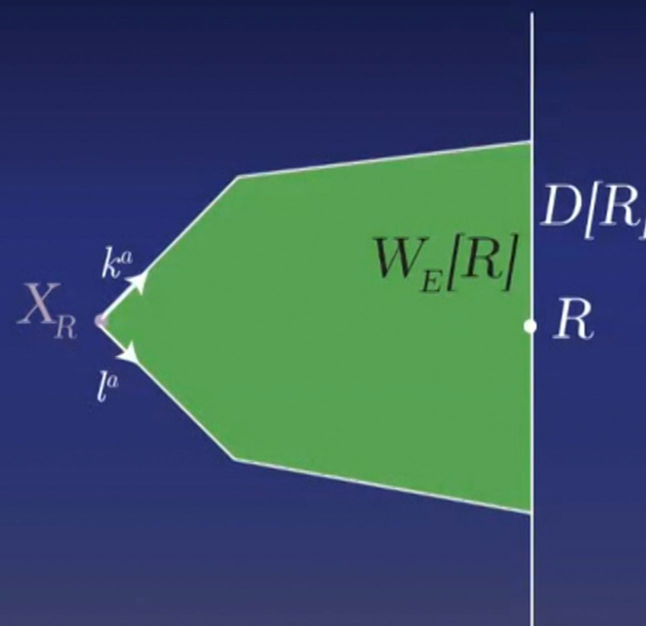
Let σ be an apparent horizon in an asympt. AdS spacetime with mass M + other assumptions which will be stated later. Assuming the holographic entanglement entropy proposal (see next slide) and AdS/CFT:

$$\text{Area}[\sigma] \leq \text{Area}[\text{Static BH with mass } M].$$

Argument: Step 1

$$S_{vN}[\rho_R] = \frac{\text{Area}[X_R]}{4G\hbar} + \cdots$$ [Hubeny-Rangamani-Takayanagi, Ryu-Takayanagi]

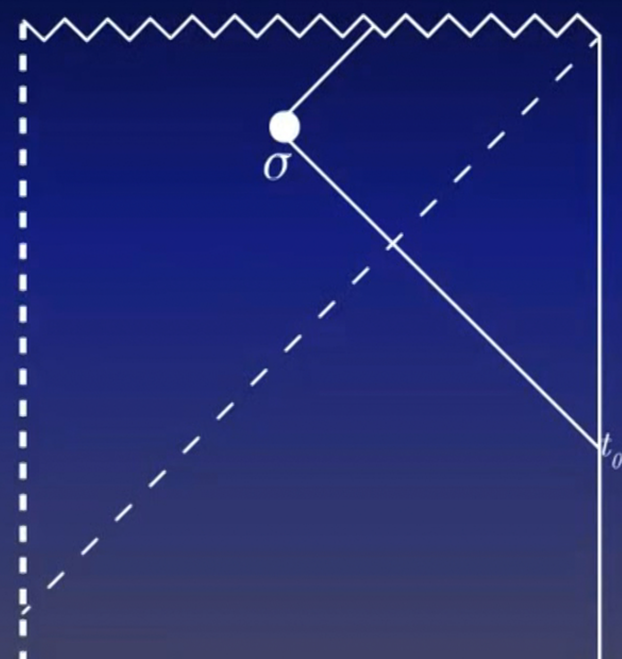




where X_R is the minimal area surface which is (1) homologous to R and (2) is a stationary point of the area functional.

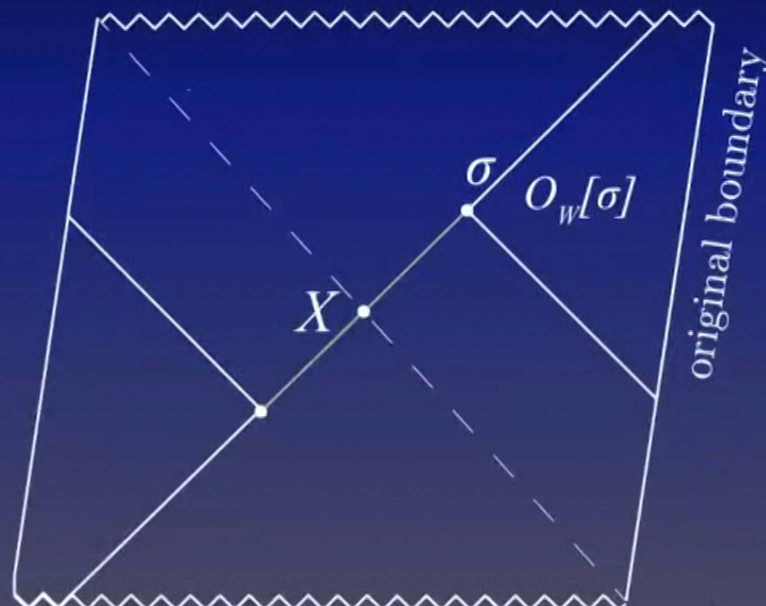
Argument: Step 1

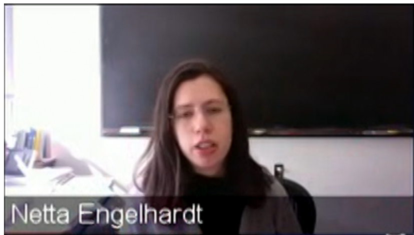
o suppose we have some spacetime with an apparent horizon:



Argument: Step 1

orrowing from the construction of [NE, Wall '17; NE, Wall '18], we can prepare a spacetime in which σ is still an apparent horizon, and the region outside of σ, $O_W[\sigma]$ is unaffected, but on the other side of σ there is an extremal surface with the same area as σ:





Aside: Minimar Surfaces

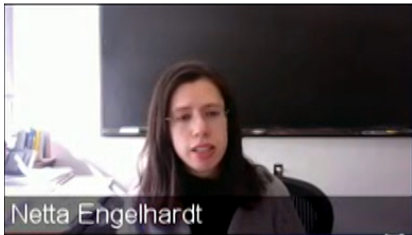
Actually, need to refine the notion of an apparent horizon into a *minimar surface* [NE, Wall '18]:

Minimar Surface

Let σ be a compact, marginally trapped surface homologous to a connected component of the asymptotic boundary. We say that σ is minimar if

1. σ is strictly stably outermost (roughly, there is a small outwards deformation of σ which results in a normal surface)

2. σ is the minimal area surface (homologous to the boundary) on a Cauchy slice of its exterior.



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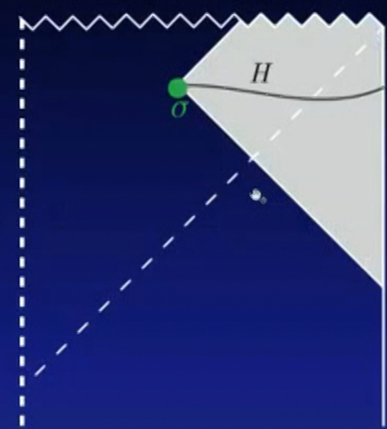
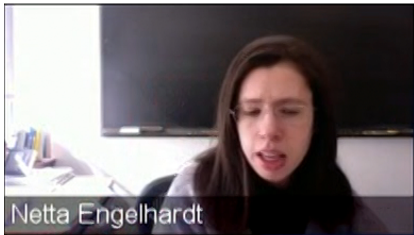


It is possible to prove Penrose inequality from CC and black holes settling down for minimar surfaces. No issues regarding area of σ vs area of EH.



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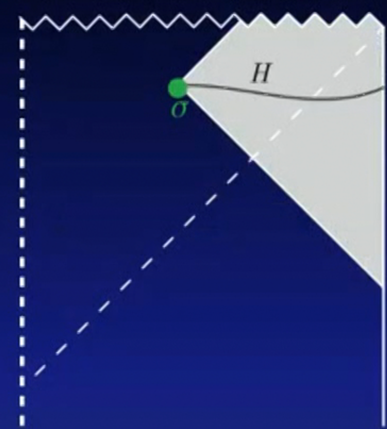

It is possible to prove Penrose inequality from CC and black holes settling down for minimar surfaces. No issues regarding area of σ vs area of EH.

Under certain generic conditions (and assuming smoothness, etc.) apparent horizons are minimar.

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Argument: Step 1

ssuming the NEC, X has the minimal area of all stationary surfaces in $D[\Sigma]$ (homologous to one bdy).

Coarse-Grained Spacetime

There exists a spacetime (M', g') in which

$$\text{Area}[X] = \text{Area}[\sigma]$$

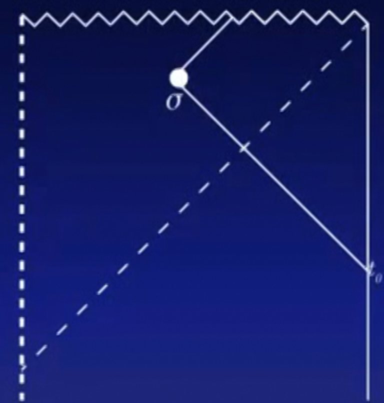
where X is the HRT surface of one boundary of M'.

So there exists a state ρ in the CFT dual to (M', g'), and

$$S_{vN}[\rho] = \frac{\text{Area}[\sigma]}{4G\hbar}$$

Or the HRT prescription is wrong/incomplete.

Argument: Step 2

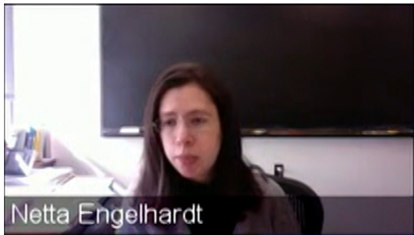


The asymptotic charges in the region outside σ are identical in (M, g) and (M', g'). In particular, the mass is the same, which means the CFT energy E (integrated stress tensor) is the same.

Argument: Step 2

This immediately implies that the von Neumann entropy of the microcanonical ensemble with energy E is larger:

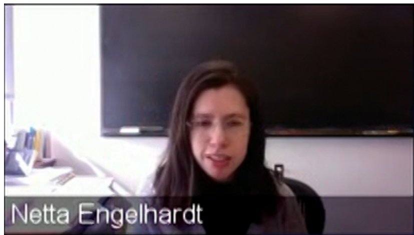
$$\frac{\mathrm{Area}[\sigma]}{4G\hbar} = S_{vN}[\rho] \leq \max_{E} S_{vN} = S_{vN}[\rho_{\mathrm{micro}}]$$



Argument: Step 3

It was recently argued [Marolf '18] that in the large-N limit, the microcanonical ensemble is dominated by static black holes (even if they are small).

$$S_{vN}[\rho_{\text{micro}}] = \frac{\text{Area[Static BH w/ mass } m]}{4G\hbar}$$



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Altogether:

$$\mathrm{Area}[\sigma] = S_{vN}[\rho]G\hbar \leq S_{vN}[\rho_{micro}]G\hbar$$
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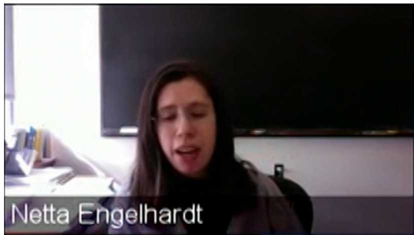

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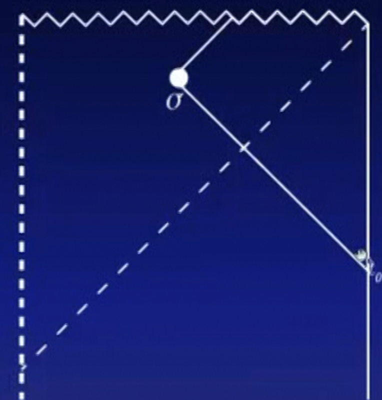
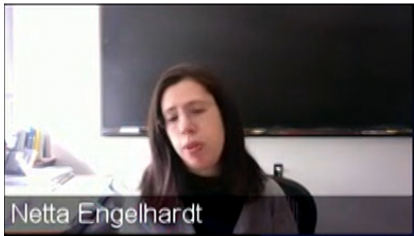
$$\boxed{\text{Area}[\sigma] \leq \text{Area}[\text{static BH w/ mass } m]}$$

In fact, same argument can be made for black holes with charge for a charged Penrose inequality.

Argument: Step 2



The asymptotic charges in the region outside σ are identical in (M, g) and (M', g'). In particular, the mass is the same, which means the CFT energy E (integrated stress tensor) is the same.

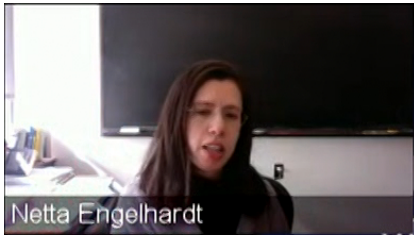


Altogether:

$$\text{Area}[\sigma] = S_{vN}[\rho]G\hbar \leq S_{vN}[\rho_{micro}]G\hbar$$
$$= \text{Area}[\text{static BH w/ mass } m]$$

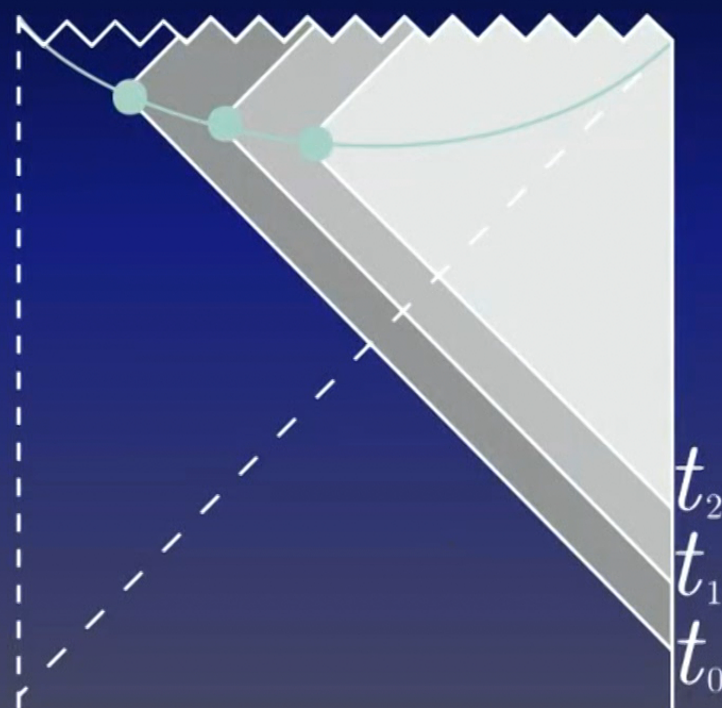
$$\boxed{\text{Area}[\sigma] \leq \text{Area}[\text{static BH w/ mass } m]}$$

In fact, same argument can be made for black holes with charge for a charged Penrose inequality.



Apparent Horizon Area Law

pparent horizons (under a particular construction), satisfy
n area increase theorem [Hayward '93; Ashtekar-Krishnan '02; Bousso-NE '15]:



Aside: Thermodynamics for Apparent Horizons NE, Wall

The entropy of the state (M', g') actually maximizes the von Neumann entropy for the fixed outer wedge:

$$\frac{\text{Area}[\sigma]}{4G\hbar} = \max_{\rho\in\mathcal{H}} S_{vN}[\rho] \equiv S^{\text{outer}}[\sigma]$$

where $\mathcal{H}$ is the set of all ρ with a semiclassical dual containing $O_W[\sigma]$.

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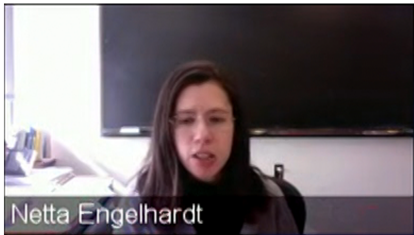
SXSFM



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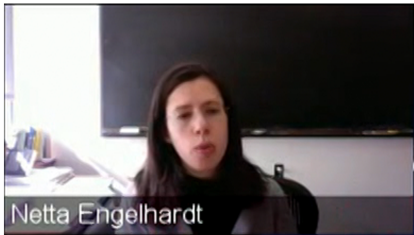
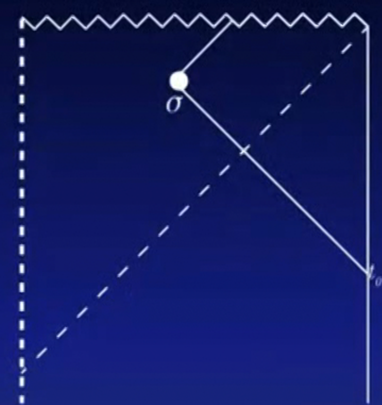
The outer entropy of σ is a coarse-grained entropy: area law for apparent horizons corresponds to increase in the outer entropy: second law of thermodynamics..



Area Law and Sources

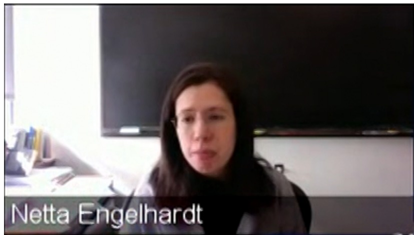
/e obtain our mass at time t_0:



With reflecting boundary conditions, the energy at t_0 gives the lowest bound: inserting sources to the future of t_0 will only cause an energy increase.

Means that we expect the bound to go up for apparent horizons corresponding to boundary slices to the future of t_0.

Penrose inequality is related to grav thermodynamics?



Quasi-Local Mass

is possible to define the outer entropy of a general surface.

- For a "normal" surface n, the outer entropy is bounded by the area NE, Wall:

$$\frac{\text{Area}[n]}{4G\hbar} > S^{\text{outer}}$$

- It has been proposed that S^{outer} is a good candidate for a quasi-local gravitational mass, and that it satisfies monotonicity under inclusion Bousso et al

- Using the exact same argument as above, it is simple to show that the outer entropy of a normal surface is bounded from above by the total mass. This is an important consistency check.

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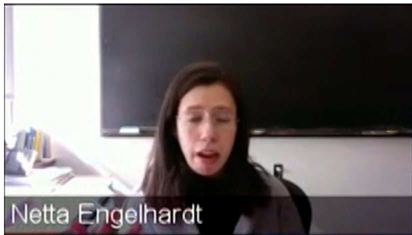
SXSFM



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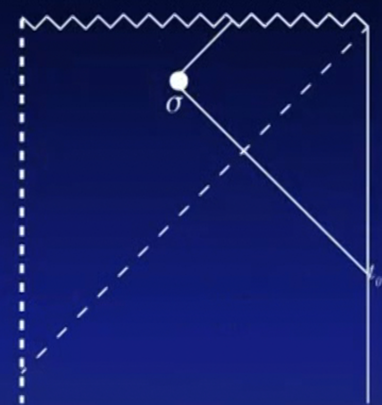

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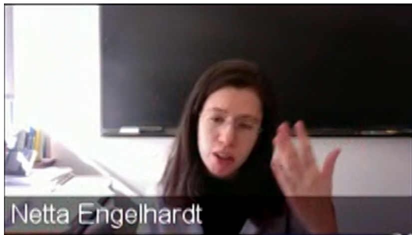

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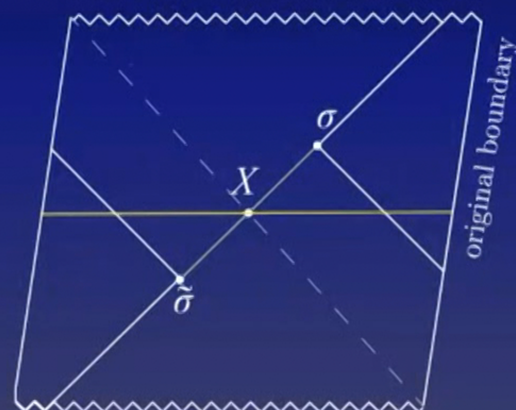
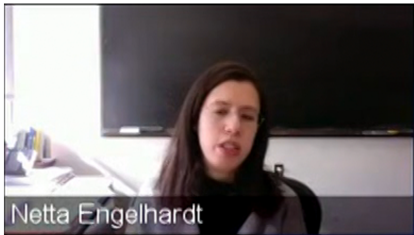
onnection with Weak Gravity Conjecture

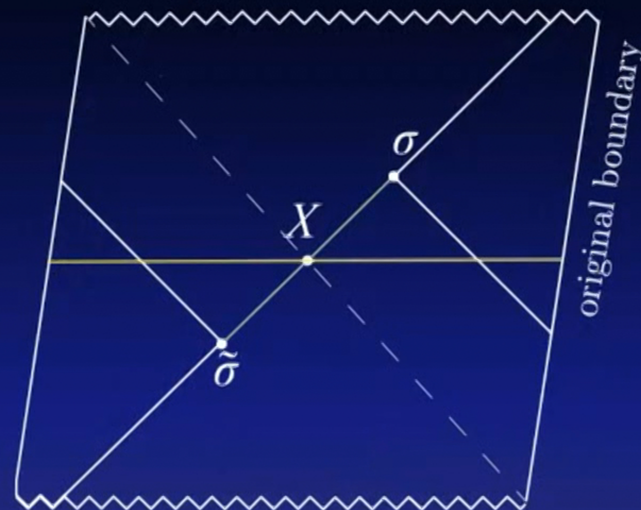
risford, Horowitz, and Santos found that WCC is satisfied hen the Weak Gravity Conjecture (WGC) is satisfied, but that it can be violatd when WGC is violated. One could argue that Harlow's arguments suggest AdS/CFT in general satisfies WGC. But is there a more direct connection between PE and WGC?



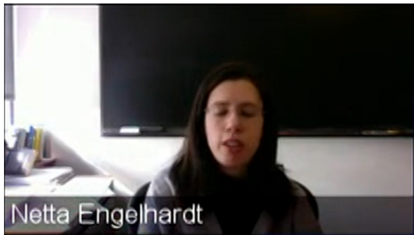
In this spacetime, we can use the procedure of [Harlow] to thread the wormhole with a boundary-to-boundary Wilson line, adding some small electric charge.



Connection to WGC



Argument of [Harlow]: the Wilson line factorizes, so it must end on charges on either side of X. Because effective field theory must reproduce the connected Wilson line at all scales below some UV cutoff, this requires bulk electric field to have fundamental charge. But these charges have to be sufficiently light to not form black holes: $m \leq qG^{-1/2}$.



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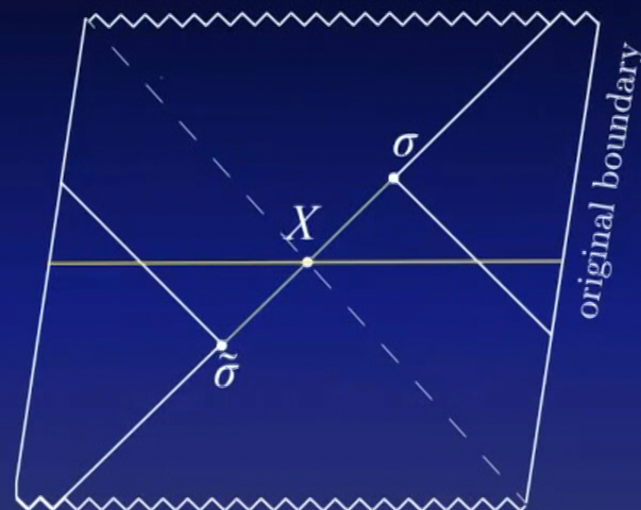

Our construction, by virtue of relying on a wormhole, is related to WGC.

Summary

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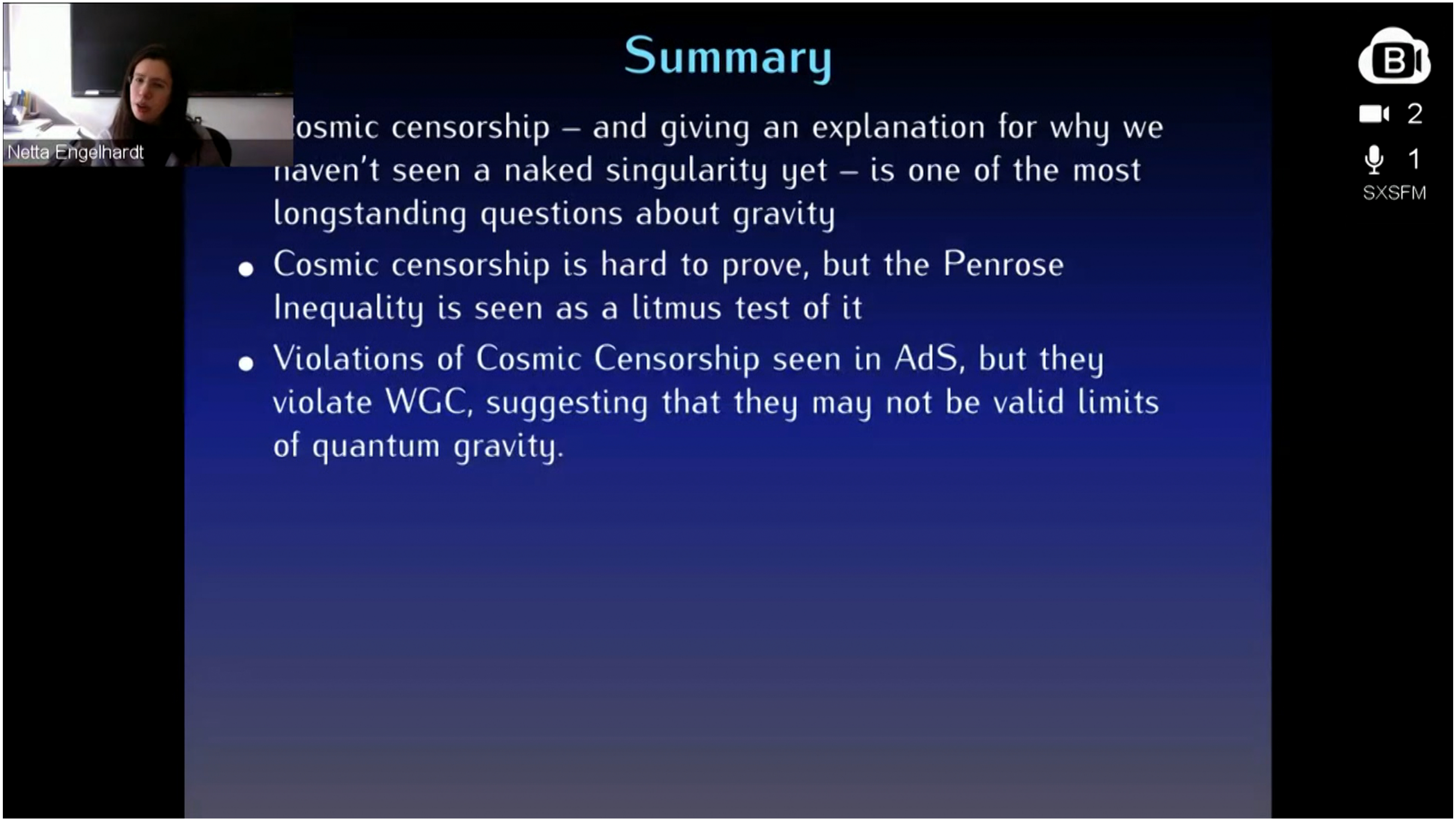
Netta Engelhardt
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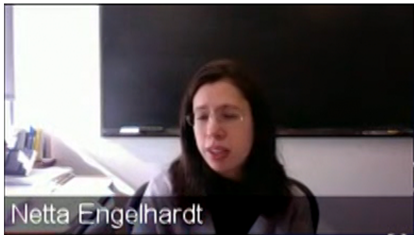

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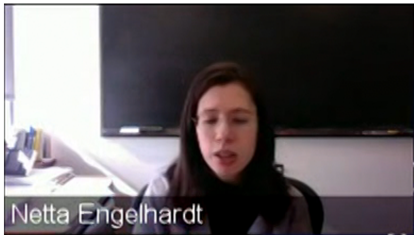

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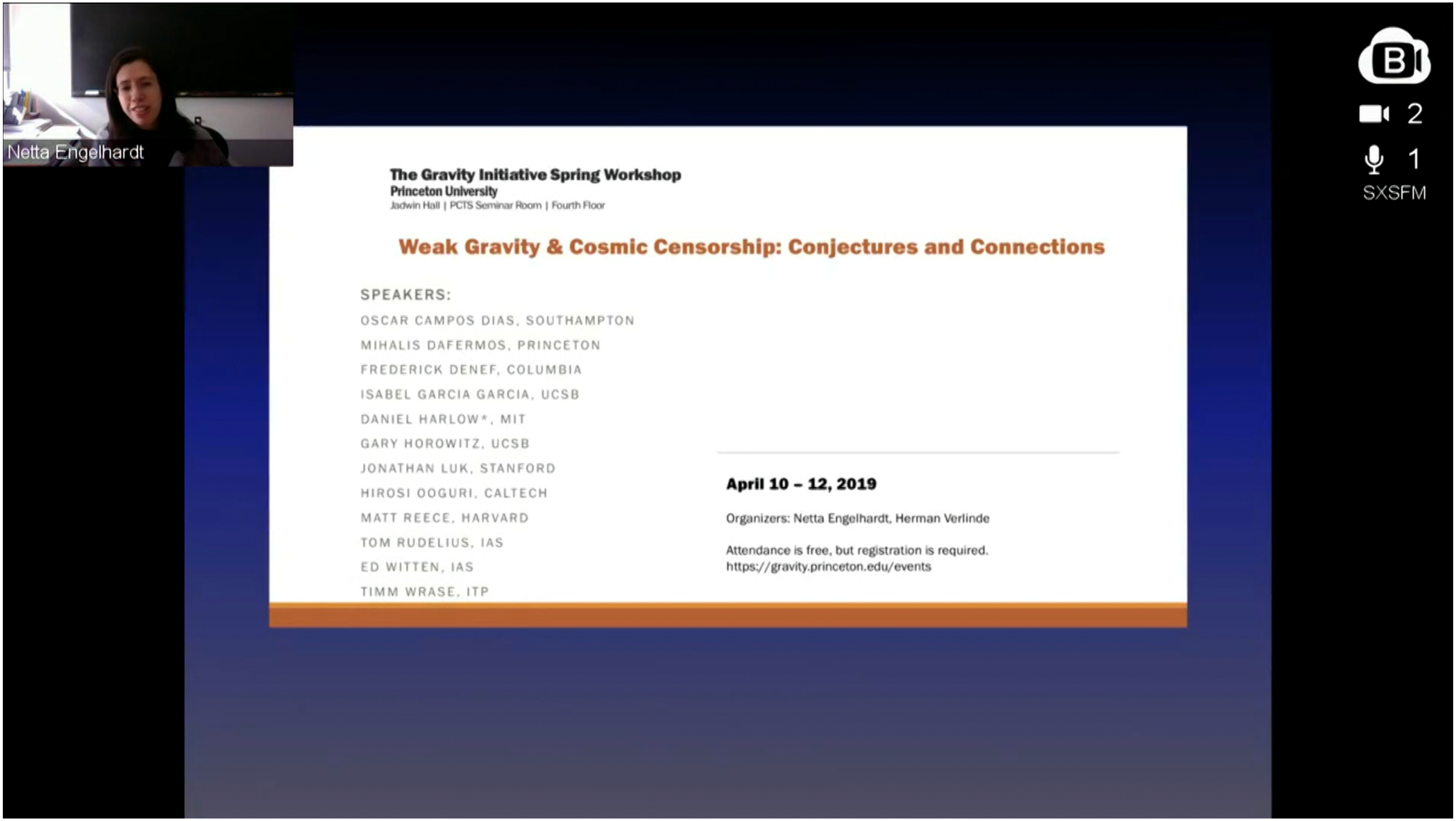
- This also bodes well for using AdS/CFT to test (or even eventually prove) cosmic censorship.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Princeton University
Jadwin Hall | PCTS Seminar Room | Fourth Floor
Weak Gravity & Cosmic Censorship: Conjectures and Connections
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MIHALIS DAFERMOS, PRINCETON
FREDERICK DENEF, COLUMBIA
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