Gauge/Gravity Duality and the Black Hole Interior

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Gauge/gravity duality (BFSS, AdS/CFT, etc.) gives a nonperturbative construction of quantum gravity in spacetimes with special boundary conditions. But how complete is it?

Sharp dictionary for boundary observables, less sharp in the bulk. Is this the best we can do in quantum gravity?

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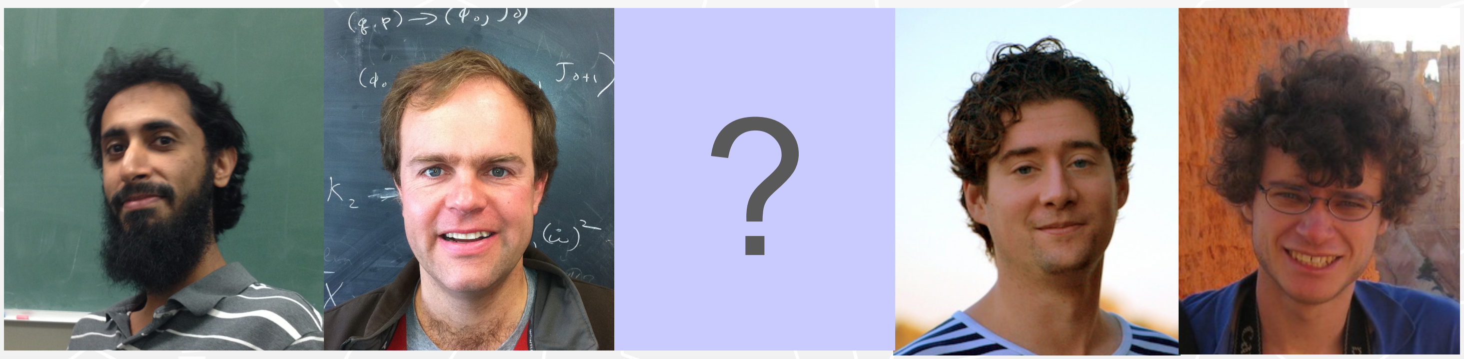


AMPS(S) propose that the black hole interior is in a highly excited state. Can we test this using gauge/gravity duality?

Outline

1. A new version of the AMPS(S) argument, for unentangled AdS black holes.

2. Limits on gauge/gravity duality.

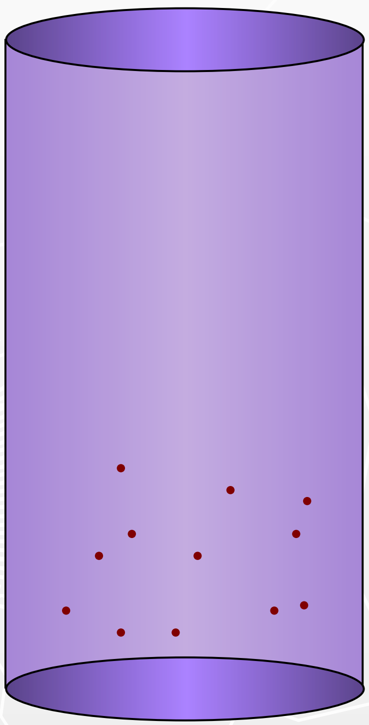
3. EPR = ER for general entanglement?

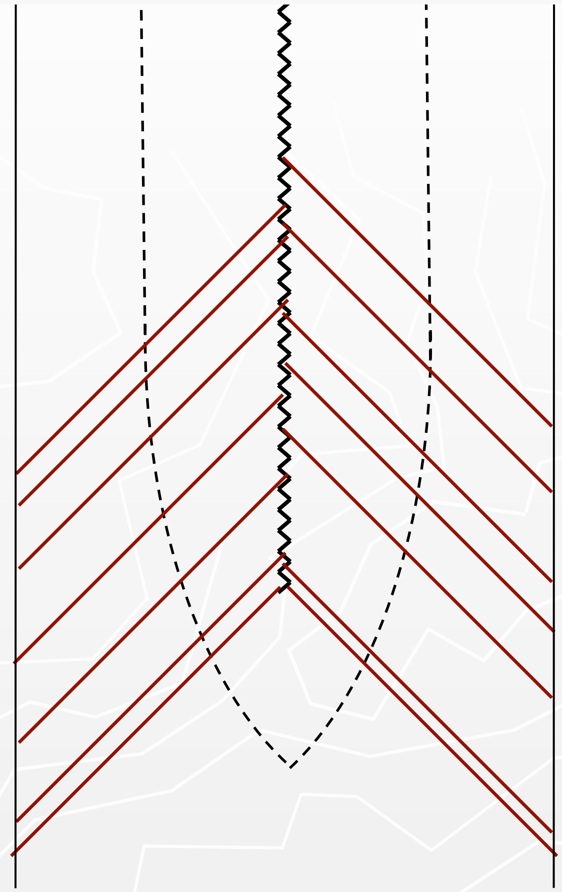
4. Why does the Hawking calculation give the right flux?

1207.3123, 1304.6483 & in preparation.

I. An argument for firewalls in typical black holes

Consider $\mathcal{H}$, all CFT states that can be created by products of local operators:



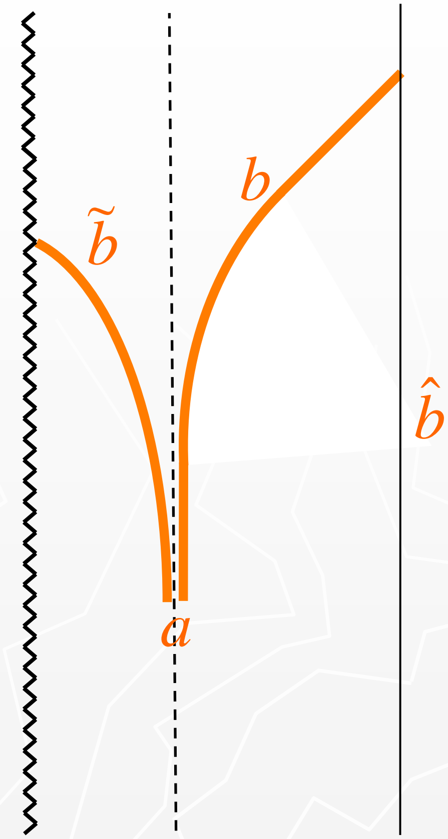


At high enough energy, these are black holes in the bulk.

b: outgoing Hawking mode
$\tilde{b}$: interior partner mode
a: smooth mode across horizon, used by infalling observer

$$b = Ba + Ca^\dagger$$

Adiabatic principle → a is in vacuum → density matrix for b is thermal



b has an image $\hat{b}$ in the CFT, obtained at N^0 by relating mode expansion for bulk field to CFT operator via usual dictionary (Banks, Douglas, Horowitz, Martinec 1998; Balasubramanian, Kraus, Lawrence, Trivedi 1998; Bena 1999). Expandable in $1/N$ (Kabat, Lifschytz, Lowe 2011)

Consider a basis for $\mathcal{H}$ in which $\hat{N}_b = \hat{b}^\dagger \hat{b}$ is diagonal. Since $\hat{N}_b$ is thermal in the a-vacuum,

$$\langle \psi | \hat{N}_a | \psi \rangle \geq O(1)$$

in any $\hat{N}_b$ eigenstate. Taking the average,

$$\mathrm{Tr}(\hat{N}_a)/\ \mathrm{Tr}(1) \geq O(1).$$

Similarly, the projection $\mathrm{P}(\hat{N}_a \neq 0)$ also has $O(1)$ average. Thus, each infalling mode is excited with probability $O(1)$: a firewall. (cf. Bousso)

This argument differs in structure from AMPS, but has similar assumptions. However, it applies to unentangled black holes.

II. Limits on seeing the interior

If gauge/gravity duality were as complete as we might hope, we could test this reasoning by identifying the CFT operator $\hat{T}_{\mu\nu}(x)$ dual to the matter energy-momentum tensor $T_{\mu\nu}(x)$ at some point in the black hole interior, and calculating its expectation in these CFT states.

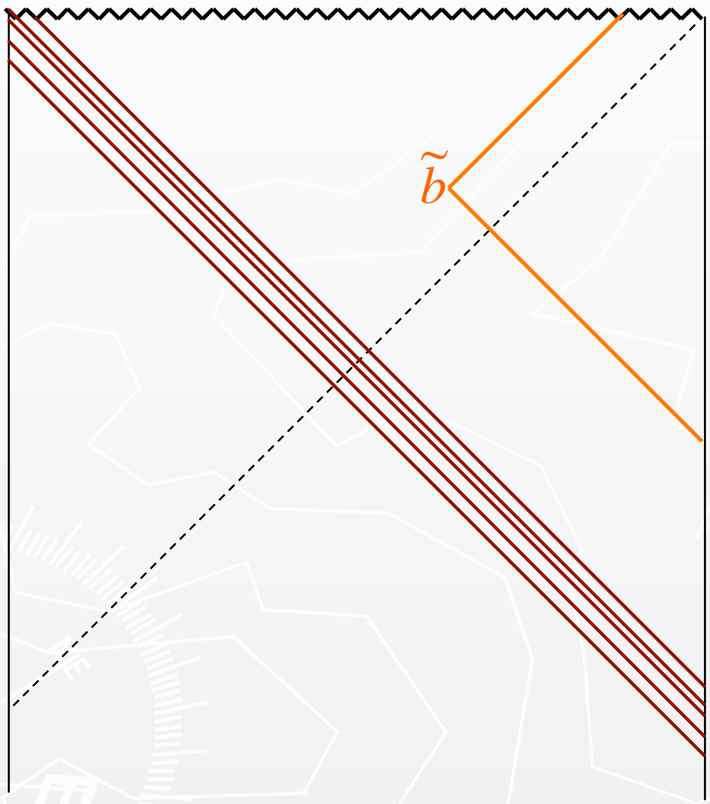
Obvious problem: what is the dictionary?

Less obvious problem: there may be no such dictionary!

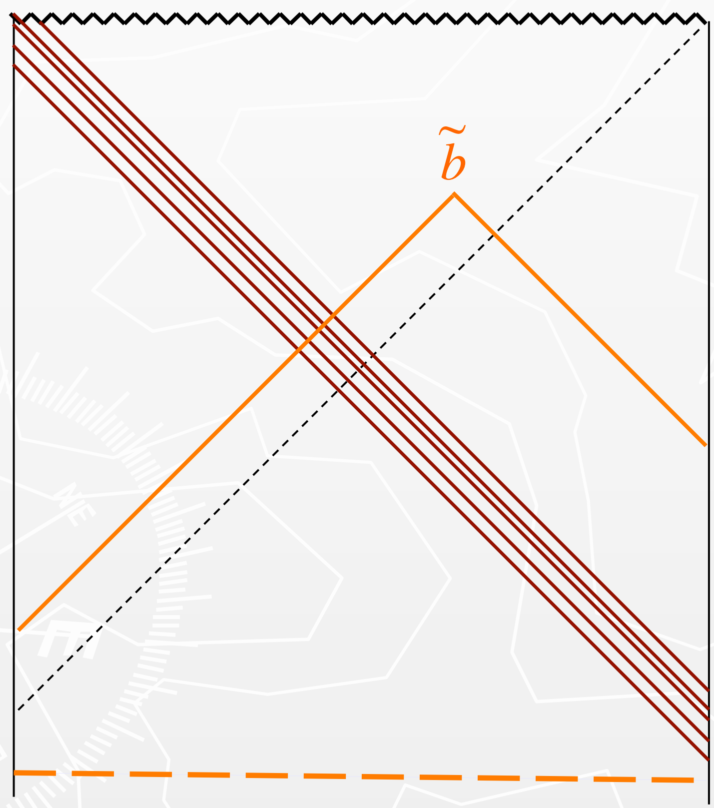
The dictionary $b \rightarrow \hat{b}$ is essentially obtained by integrating in a spacelike direction to the boundary:

This is overdetermined, but OK because boundary data is constrained by AdS/CFT.

For points behind the horizon this runs into the singularity.



Alternately, integrate back in time to before the black hole formed, then outward to the boundary (Freivogel, Susskind 2004; Heemskerk, Marolf, Polchinski, Sully 2012).



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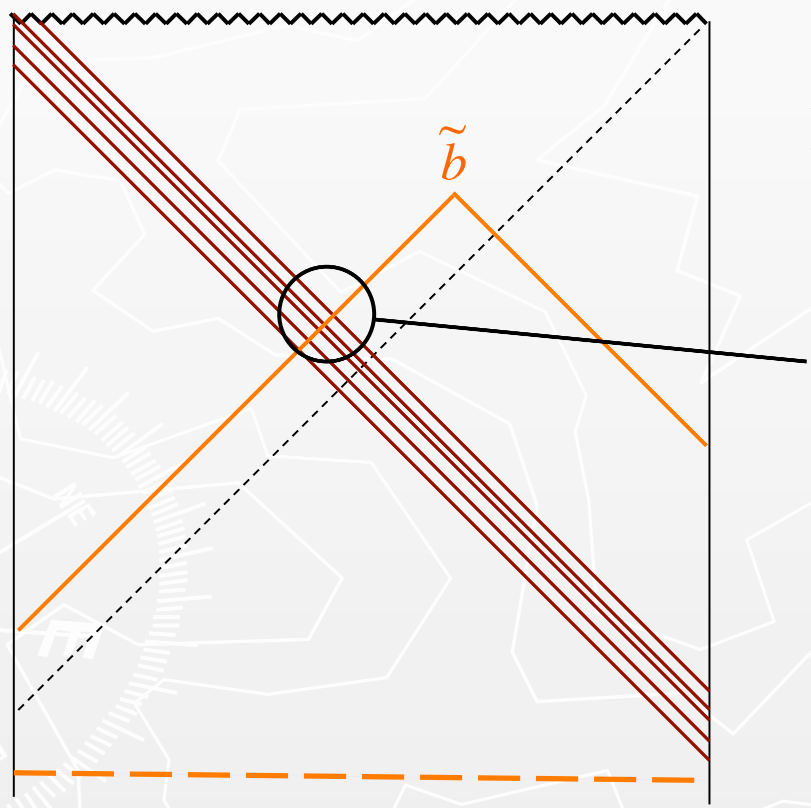


Problem: exponential blue shift leads to trans-Planckian collision, presumable singularity, for b after the scrambling time $R \ln R$.

A more basic problem: there can be *no* operator with the properties (tilde = behind horizon, hat = CFT image)

$$[\hat{\tilde{b}}^\dagger, \hat{\tilde{b}}] = -1, \quad [H, \hat{\tilde{b}}^\dagger] = -\omega\, \hat{\tilde{b}}^\dagger$$

That is, this lowers the energy, where the original Hawking mode is narrowly centered at frequency ω.

Proof: consider all states $|i\rangle$ such that

$$M < E < M+\delta\,.$$

Then for $\hat{\tilde{b}}^\dagger|i\rangle$,

$$M-\omega < E < M-\omega+\delta\,.$$

The number of such states is smaller by a factor $e^{-\beta\omega} = e^{-O(1)}$.

So $\hat{\tilde{b}}^\dagger$ has a kernel. But it cannot, it is a raising operator.

Next: discuss four possible interpretations of this result.

Possible interpretation 1:

There is no $\hat{\tilde{b}}$ because there is no interior.

Possible interpretation 2:

The properties $[\hat{\tilde{b}}^\dagger, \hat{\tilde{b}}] = -1, \quad [H, \hat{\tilde{b}}^\dagger] = -\omega\, \hat{\tilde{b}}^\dagger$ might have large corrections for highly excited states, evading the argument. OK, but it implies that almost all states are highly excited.

Possible interpretation 3: 'Strong Complementarity'

(Banks & Fischler; Bousso; Harlow & Hayden; Page)

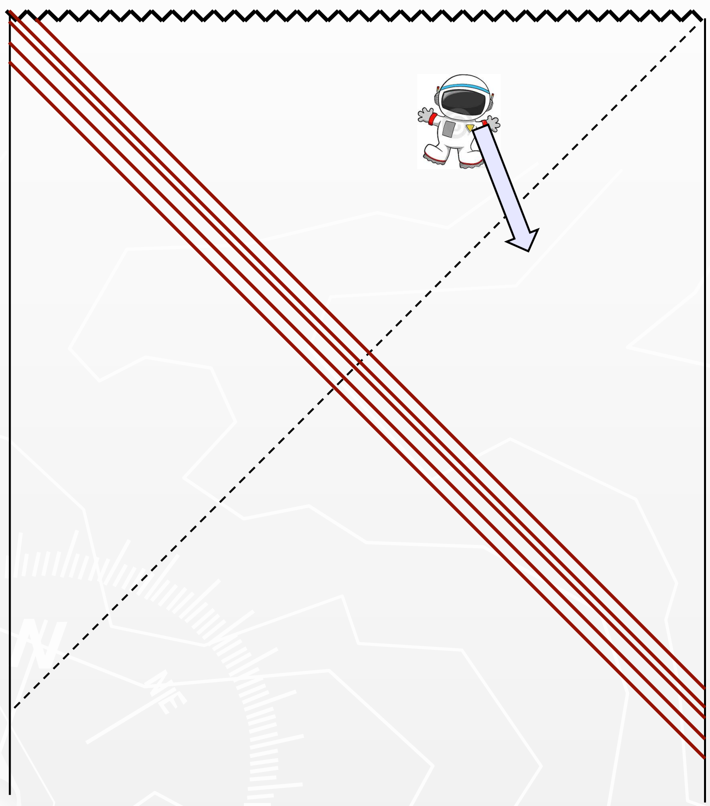
Suppose that the interior exists. In the standard interpretation of Black Hole Complementarity, the Hilbert space of the EFT infalling observer is thought to be embedded in the Hilbert space of the CFT. But this can't be, because the former contains $\tilde{b}$ and the latter does not!

Rather, it must be that $\mathcal{H}_{\rm CFT}$ contains only the subspace of $\mathcal{H}_{\rm EFT}$ that can form in collapse. Each observer has their own Hilbert space, there is no global Hilbert space.

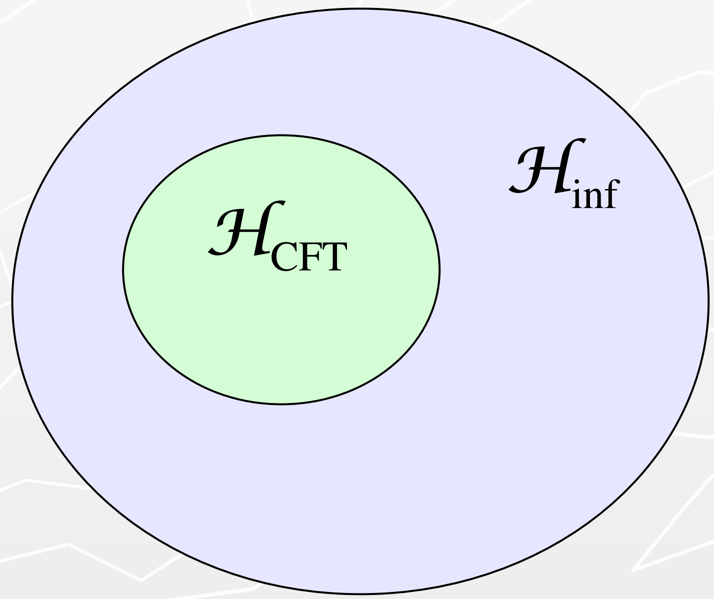
In retrospect this should have been obvious, because in the standard understanding of black holes only the infalling vacuum state forms, by the adiabatic principle.

With the firewall argument, it is a different subspace that forms.

Does the *b* argument from part 1 still apply?



The infalling observer can see the matter that formed the black hole. So the Hilbert space $\mathcal{H}_{\text{inf}}$ that describes all possible observations must contain $\mathcal{H}_{\text{CFT}}$:



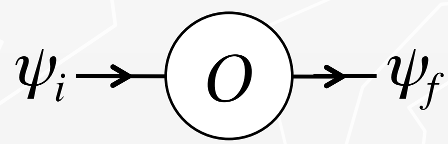
The *b* argument then pushes forward to $\mathcal{H}_{\text{inf}}$.

Possible interpretation 4: Nonlinear state dependence

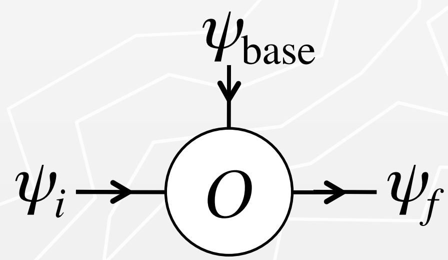
(Papadodimas+Raju 1211.6767, Verlinde^2 1211.6913)

In a typical CFT state, the distribution of N_b is thermal. If we *assume* that some particular such state is infalling vacuum, we can then construct $\hat{b}$ and $\hat{\tilde{b}}$, and the infalling EFT. Observables depend on the choice of this base state:

Normal QM operator:



Here:

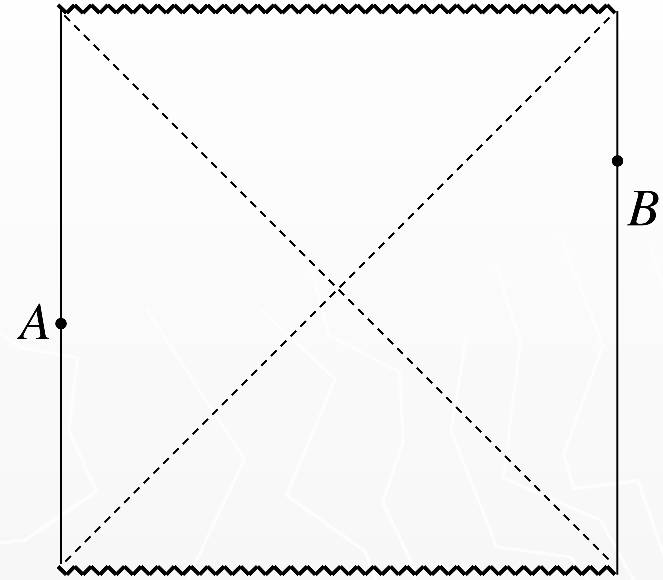


H. Verlinde: choice of base state is "pinning the tail on the quantum donkey."

“God not only plays dice with the world, She also plays pin the tail on the quantum donkey.”

III. A comment on EPR = ER

(Maldacena & Sussind)



Maldacena 2001: two-sided AdS geometry calculates two-CFT correlators in thermofield state

$$\langle\psi|A_L(-t)B_R(t')|\psi\rangle$$

$$= \sum_{\alpha,\beta,\gamma,\delta} e^{-itE_{\delta\gamma}-it'E_{\alpha\beta}} \psi^*_{\delta\beta}\psi_{\gamma\alpha}A_{\gamma\delta}B_{\beta\alpha}$$

$$\psi_{\alpha\gamma} = Z^{-1/2}\delta_{\alpha\gamma}e^{-\beta E_\alpha/2}$$ (Energy eigenbasis)

Does the generic highly entangled state, e.g. one produced thermally, have a geometric interpretation? (cf. Shenker and Stanford, van Raamsdonk)

What do we mean by a geometric interpretation?

For the thermofield state, the time dependence of the correlator is of the form

Exponential falloff given by AdS calculation ≡ geometric
Long-term $O(e^{-S})$ dominated by random phases ≡ non-geometric

$$\langle A_L B_R \rangle = \sum_{\alpha,\beta,\gamma,\delta} e^{-itE_{\delta\gamma} - it' E_{\alpha\beta}} \psi^*_{\delta\beta} \psi_{\gamma\alpha} A_{\gamma\delta} B_{\beta\alpha}$$

Form of matrix element in chaotic system:

$$A_{\alpha\beta} = \mathcal{A}(E)\delta_{\alpha\beta} + e^{-S(E)/2} f(E) R_{\alpha\beta}$$

Eigenvalue Thermalization Hypothesis (Deutsch, Srednicki);
$\mathcal{A}, S, f$ are smooth functions, $R_{\alpha\beta}$ is random and $O(1)$.

With this, the opposite-side correlator is exponentially small and dominated by random phases at all times, so apparently no geometric interpretation.

IV. If there is a firewall, why should the Hawking calculation give the right flux?

• Hawking flux is determined by the density matrix for *b*

• This is the same in every microstate, up to exponentially small corrections, as it is in the thermofield state

• The thermofield state is described by EFT across the horizon, so the Hawking calculation holds

• Unlike the usual derivation of the flux, this does not imply the same fine-grained result

Conclusion

We need a more complete theory of quantum gravity in the bulk.