Probing the interior of typical black hole microstates

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AdS/CFT at 20, ICTS
Bengaluru, 24 May 2018

Main Question:

What is the bulk dual geometry of a typical black hole microstate in AdS/CFT?

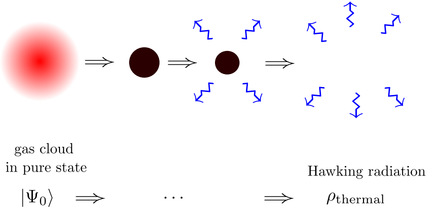
- Black hole information paradox and smoothness of black hole horizon
  $\Rightarrow$ Typical state paradox in AdS/CFT
- Typical states represent majority of states counted by $S = \frac{A}{4G}$

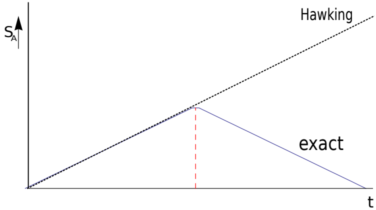
Outline:

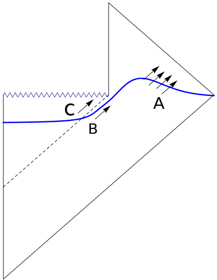
1. Conjecture: extended AdS/Schwarzchild geometry, including part of left region
2. Hilbert space of CFT contains states corresponding to excitations of this region
3. Proposal for 1-sided analogue of Gao-Jafferis-Wall "traversable wormhole protocol" — allows us to probe this region
4. Analogue of Hayden-Preskill protocol for information recovery from black holes

based on earlier work with S. Raju and more recent work [KP 1708.06328], [J. de Boer, R. van Breukelen, S. Lokhande, E. Verlinde, arXiv: 1804.10580] + in progress

The information paradox







Violation of strong subadditivity of entanglement entropy

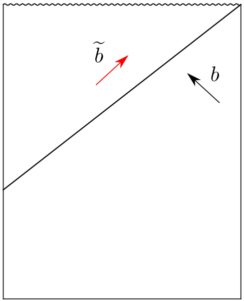
$$S_{AB} + S_{BC} \geq S_A + S_C$$

[Mathur], [Almheiri, Marolf, Polchinski, Sully]

Paradox for large AdS black holes

- These black holes are in equilibrium with their Hawking radiation and do not evaporate
- Nevertheless a firewall-like paradox has been formulated even for these stable black holes [Almheiri, Marolf, Polchinski, Stanford, Sully], [Marolf, Polchinski]
- It suggests that big AdS black holes have a singular horizon.
- Precise formulation of the paradox.

Paradox for large AdS black holes



$$[b, b^\dagger] = 1$$
$$[H, b^\dagger] = \omega b^\dagger$$

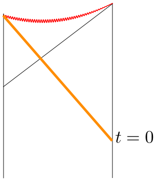
$$[\widetilde{b}, \widetilde{b}^\dagger] = 1$$
$$[H, \widetilde{b}^\dagger] = -\omega \widetilde{b}^\dagger$$

- [AMPSS, MP] paradox: if typical CFT states have smooth horizon, using $[H, \widetilde{b}^\dagger] = -\omega \widetilde{b}^\dagger$ we find

  $$\mathrm{Tr}[e^{-\beta H} \widetilde{b}^\dagger \widetilde{b}] < 0$$

  which is inconsistent
  This naively suggestes that $\widetilde{b}$ does not exist in CFT, horizon is singular and black hole has no interior.

Collapsing vs typical black holes



Black holes formed by (simple) gravitational collapse are *a-typical*

Typical black hole microstates are defined by "microcanonical measure"

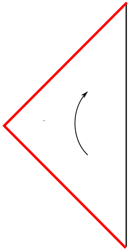
$$|\Psi\rangle = \sum_i c_i |E_i\rangle$$

where $E_i \in E_0 \pm \delta E$ and c_i selected randomly by Haar measure
Notice that typical states are almost time-independent

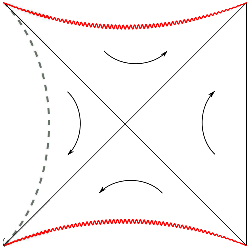
$$\langle\Psi|\frac{dA}{dt}|\Psi\rangle = \sum_{ij} c_i^* c_j A_{ij} \frac{d}{dt} e^{iE_{ij}t} = O(e^{-S/2})$$

Typical states are *equilibrium states*.

Geometry of typical state



vs



Typicality, Eigenstate-Thermalization-Hypothesis (ETH) $\Rightarrow$
Exterior region $=$ AdS-Schwarzchild

If future horizon is smooth, we expect interior region to be consistent with (approximate) Killing isometry.

Notice effective "cutoff" in left region

Proposal for black hole interior reconstruction

[KP, S. Raju]

- We identified a set of CFT operators $\widetilde{\mathcal{O}}$ which can play the role of modes $\widetilde{b}$ inside the horizon.
- These operators are selected by their entanglement with the fields outside the horizon — they are *state-dependent*.
- Using these we proposed that we can reconstruct local bulk fields behind the future horizon.
- This proposal predicts that typical black holes have a smooth future horizon

Tomita-Takesaki modular theory

Introduce a "small algebra" $\mathcal{A}$ of simple operators (single trace + small products).

We define the small Hilbert space (also called "code-subspace")

$$\mathcal{H}_\Psi = \mathcal{A}|\Psi\rangle$$

The algebra $\mathcal{A}$ probes the typical pure state $|\Psi\rangle$ as a thermal state

$$\langle\Psi|\mathcal{O}(x_1)...\mathcal{O}(x_n)|\Psi\rangle = Z^{-1}\mathrm{Tr}[e^{-\beta H}\mathcal{O}(x_1)...\mathcal{O}(x_n)] + O(1/N)$$

No annihiliation operators in $\mathcal{A}$ $\Rightarrow |\Psi\rangle$ is a *cyclic* and *separating* vector.

Tomita-Takesaki theorem: *The representation of the algebra $\mathcal{A}$ on $\mathcal{H}_\Psi$ is reducible, and the algebra has a non-trivial commutant $\mathcal{A}'$ also acting on $\mathcal{H}_\Psi$.* Moreover $\mathcal{A}'$ is isomorphic to $\mathcal{A}$.

The mirror operators

Following the Tomita-Takesaki construction we define the "mirror operators"

$$\widetilde{\mathcal{O}}_\omega|\Psi\rangle = e^{-\frac{\beta H}{2}}\mathcal{O}_\omega^\dagger e^{\frac{\beta H}{2}}|\Psi\rangle$$

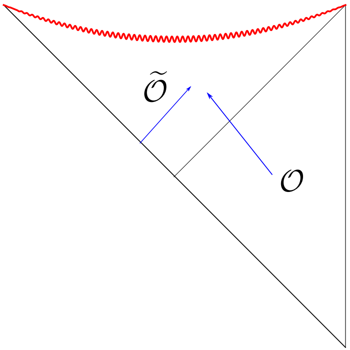
$$\widetilde{\mathcal{O}}_\omega\mathcal{O}....\mathcal{O}|\Psi\rangle = \mathcal{O}...\mathcal{O}\widetilde{\mathcal{O}}_\omega|\Psi\rangle$$

$$[H,\widetilde{\mathcal{O}}_\omega]\mathcal{O}....\mathcal{O}|\Psi\rangle = \omega\widetilde{\mathcal{O}}_\omega\mathcal{O}....\mathcal{O}|\Psi\rangle$$

These equations define the operators $\widetilde{\mathcal{O}}$ on the code-subspace $\mathcal{H}_\Psi \subset \mathcal{H}_{\rm CFT}$, which is relevant for EFT experiments around BH microstate $|\Psi\rangle$

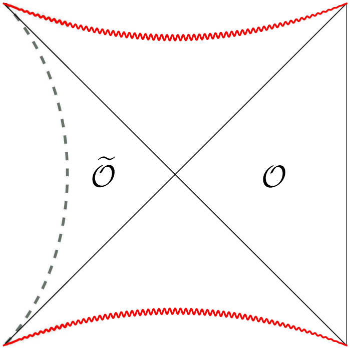
- Operators defined only on $\mathcal{H}_\Psi$, not on full CFT Hilbert space - they are *state-dependent* operators.
- $[\mathcal{O},\widetilde{\mathcal{O}}]=0$ only inside $\mathcal{H}_\Psi$, not as operator equation
- We define these operators for $\omega<\omega_*$, where ω_* does not grow too fast with N

Infalling observer



$$\phi(t, r, \Omega) = \int_0^\infty d\omega \Big[\mathcal{O}_\omega\, f_\omega(t, \Omega, r) + \widetilde{\mathcal{O}}_\omega g_\omega(t, \Omega, r) + \text{h.c.}\Big]$$

Extended geometry

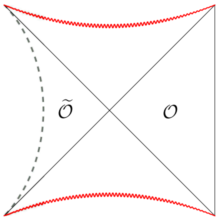


The cutoff on the left is determined by ω_*.

Since $\widetilde{\mathcal{O}}$ do not fundamentally commute with $\mathcal{O}$, left region should not be though as a fundamentally independent part of the Hilbert space (BH complementarity)

Summary and comments

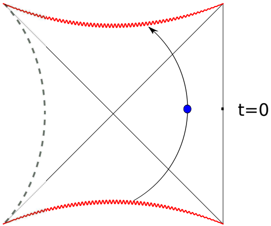
Conjecture: typical state should be associated to the following geometry:



In general we can characterize the geometry of a state by classifying possible ways to excite it.

We will identify perturbations of the CFT state corresponding to excitations of left region

Standard non-equilibrium states



$U(\mathcal{O})|\Psi\rangle$

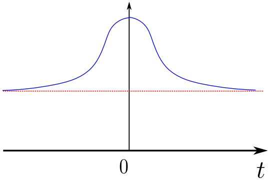
Excited (somewhat a-typical) state

$$|\Psi\rangle = U(\mathcal{O})|\Psi_0\rangle = e^{i\theta\mathcal{O}(0)}|\Psi_0\rangle$$

Correlators

$$\langle\Psi|\mathcal{O}(t)|\Psi\rangle$$

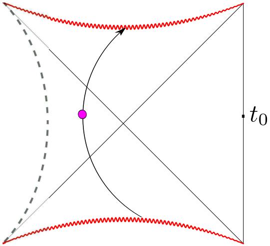
are t-dependent



State prepared to undergo a spontaneous fluctuation out of equilibrium at $t \approx 0$.

Exciting the left region

[KP 1708.06328]



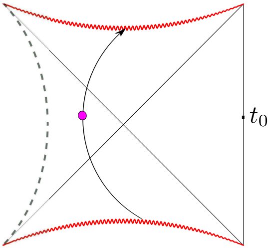
$$U(\widetilde{\mathcal{O}})|\Psi\rangle$$

But we can also write this as

$$U(\widetilde{\mathcal{O}})|\Psi\rangle = e^{-\frac{\beta H}{2}} U(\mathcal{O})^\dagger e^{\frac{\beta H}{2}} |\Psi\rangle$$

Exciting the left region

[KP 1708.06328]



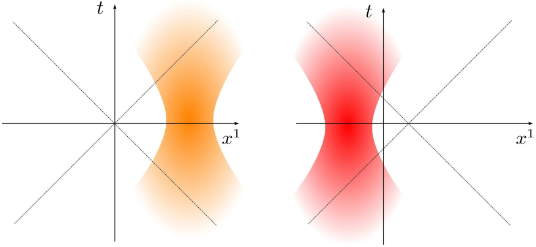
$$e^{-\frac{\beta H}{2}} U(\mathcal{O})^\dagger e^{\frac{\beta H}{2}} |\Psi\rangle$$

$\boxed{\text{Existence and properties of these states } \textbf{independent} \text{ of } \widetilde{O}\text{-operator construction}}$

Unusual type of non-equilibrium state, excitation not visible in single-trace correlators

Acting with $e^{-\frac{\beta H}{2}} U(\mathcal{O})^\dagger e^{\frac{\beta H}{2}}$ *lowers* CFT energy

Localized states in Rindler space



For Rindler space, modular Hamiltonian is Lorentz boost generator M in t, x^1 plane.
Unruh inverse temperature $\beta = 2\pi$

$$e^{-\pi M} U_R e^{\pi M} |0\rangle = U'_L |0\rangle$$

See for example Bisognano-Wichmann theorem

Notice: state vs operators

Properties of the states

At large N state

$$|\Psi\rangle = e^{-\frac{\beta H}{2}} U(\mathcal{O}) e^{\frac{\beta H}{2}} |\Psi_0\rangle$$

seems to be in equilibrium wrt algebra $\mathcal{A}$

$$\langle\Psi|A|\Psi\rangle = \langle\Psi_0|e^{\frac{\beta H}{2}} U(O)^\dagger e^{-\frac{\beta H}{2}} A e^{-\frac{\beta H}{2}} U(O) e^{\frac{\beta H}{2}} |\Psi_0\rangle$$

$$= \frac{1}{Z}\mathrm{Tr}[e^{-\beta H} e^{\frac{\beta H}{2}} U(O)^\dagger e^{-\frac{\beta H}{2}} A e^{-\frac{\beta H}{2}} U(O) e^{\frac{\beta H}{2}}] + O(1/S)$$

$$= \frac{1}{Z}\mathrm{Tr}[e^{-\beta H} A] + O(1/S)$$

Including H in correlators. We define $\hat{H} = H - E_0$ and to be concrete consider the state

$$|\Psi\rangle = e^{-\frac{\beta H}{2}} e^{i\theta\mathcal{O}(t_0)} e^{\frac{\beta H}{2}} |\Psi_0\rangle \tag{1}$$

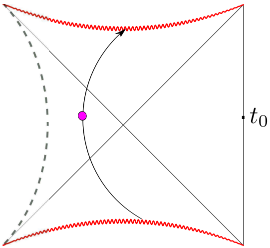
and compute

$$\langle\Psi|\mathcal{O}(t)\hat{H}|\Psi\rangle = i\theta\left[\langle\Psi_0|\mathcal{O}(t)\hat{H}\mathcal{O}(t_0 + i\frac{\beta}{2})|\Psi_0\rangle - \langle\Psi_0|\mathcal{O}(t_0 - i\frac{\beta}{2})\mathcal{O}(t)\hat{H}|\Psi_0\rangle\right] + O(\theta^2)$$

$$\langle\Psi|\mathcal{O}(t)\hat{H}|\Psi\rangle \approx \theta\langle\Psi_0|\mathcal{O}(t)\frac{d\mathcal{O}}{dt}(t_0 + i\frac{\beta}{2})|\Psi_0\rangle \tag{2}$$

This correlator decays exponentially as $|t - t_0|$ becomes very large, but it is nonzero and $O(1)$ around the time $t = t_0$.

Properties of the states



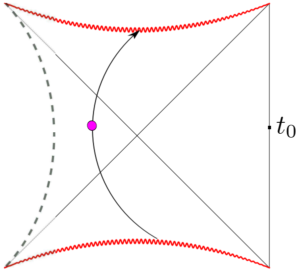
- They seem to be in equilibrium in terms of single-trace correlators

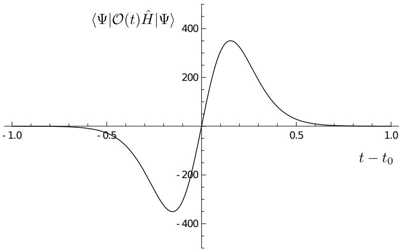
$$\frac{d}{dt}\langle\Psi|\mathcal{O}(t)|\Psi\rangle = 0$$

- It can be seen that they are out of equilibrium by incuding H in the correlator

$$\frac{d}{dt}\langle\Psi|\mathcal{O}(t)H|\Psi\rangle \neq 0$$

Example





Consider a 2d CFT on $\mathbb{S}^1 \times R$ on a state $|\Psi\rangle = e^{-\frac{\beta H}{2}} U(\mathcal{O}) e^{\frac{\beta H}{2}} |\Psi_0\rangle$, with $U = e^{i\theta\mathcal{O}(t_0)}$. Then at large c we find

$$\langle\Psi|\mathcal{O}(t)\hat{H}|\Psi\rangle = \theta\, 2\Delta \left(\frac{2\pi}{\beta}\right)^{2\Delta+1} \sum_{m=-\infty}^{+\infty} \frac{\sinh\left(\frac{2\pi(t-t_0)}{\beta}\right)}{\left[2\cosh\left(\frac{4\pi^2 m}{\beta}\right) + 2\cosh\left(\frac{2\pi(t-t_0)}{\beta}\right)\right]^{\Delta+1}}$$

Notice that

$$e^{-\frac{\beta H}{2}} U(\mathcal{O}) e^{\frac{\beta H}{2}}$$

is not a unitary, however the state $e^{-\frac{\beta H}{2}} U(\mathcal{O}) e^{\frac{\beta H}{2}} |\Psi_0\rangle$ has norm 1 up to $1/S$ corrections.

Also notice that

$$e^{-\frac{\beta H}{2}} U(\mathcal{O}) e^{\frac{\beta H}{2}}$$

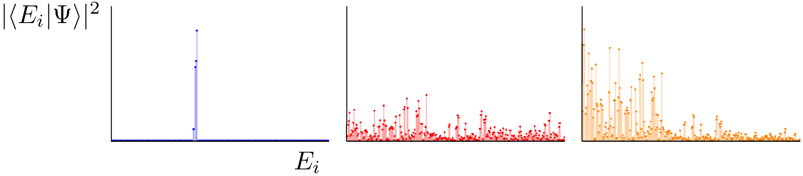
lowers the energy for *typical states*. Is this possible given that this is an invertible operator and that there are fewer states at lower energies?

Yes. This operator only lowers the **expectation value** of the energy. The states

$$e^{-\frac{\beta H}{2}} U(\mathcal{O}) e^{\frac{\beta H}{2}} |\Psi_0\rangle$$

have spread in energy, and are borrowing "phase space" from higher energies. However their low energy components are enhanced, thus decreasing the expectation value of the energy.

Non-equilibrium states in SYK



Distribution of $|\langle E_i|\Psi\rangle|^2$ in SYK for

a) left: typical state $|\Psi_0\rangle$

b) middle: usual non-equilibrium state $U(\mathcal{O})|\Psi_0\rangle$

c) right: non-equilibrium state of form $e^{-\frac{\beta H}{2}}U(\mathcal{O})^\dagger e^{\frac{\beta H}{2}}|\Psi_0\rangle$

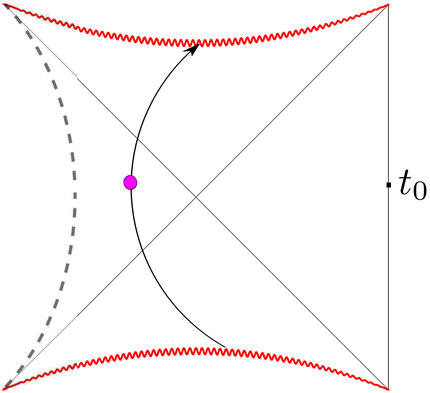
- We identified a class of non-equilibrium states present in any statistical system. In holographic CFTs these states may correspond to excitations behind the black hole horizon.

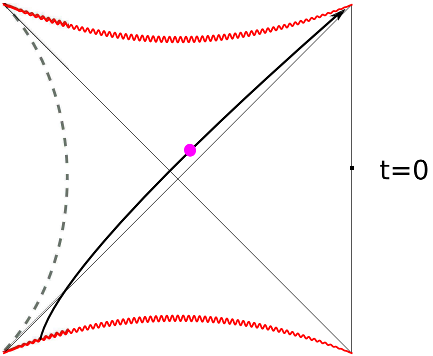
- The number of such states is in correspondence with possible ways to excite the region behind the horizon in EFT assuming the conjectured geometry for a typical state

- The existence of these states is motivated by, but logically independent from state-dependent operators $\widetilde{\mathcal{O}}$.

- This shows that the CFT contains in its Hilbert space a class of states which can be naturally identified with excitations of the left region

Can we find more evidence for the interpretation of these states?

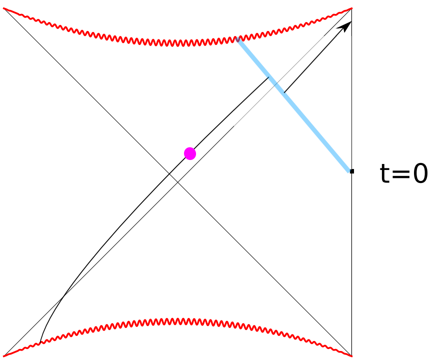

t_0


t=0

Extracting the particle

Following Gao-Jafferis-Wall we will try to create a negative energy shockwave by perturbing the CFT with

$$H = H_0 + g\mathcal{O}\widetilde{\mathcal{O}}$$



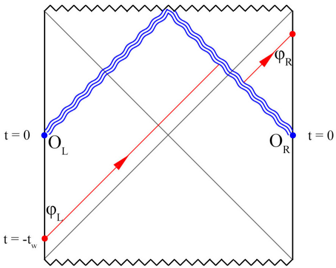
see also [Kourkoulou, Maldacena],[Almheiri, Mousatov, Shyani] for somewhat related constructions

Comments on using state-dependent operators on the boundary

1. The use of state-dependent operators on the boundary fits within the standard framework of quantum mechanics
2. We can imagine many identically prepared systems all in state $|\Psi\rangle$.
3. The boundary observer can use these systems to perform many measurements and identify the state $|\Psi\rangle$
4. Then the observer can prepare a device acting with $\widetilde{\mathcal{O}}$ on one of the remaining (un-measured) systems which is still in the state $|\Psi\rangle$.

It remains a non-trivial question whether the infalling bulk observer can use state-dependent operators to perform quantum measurements.

Gao-Jafferis-Wall



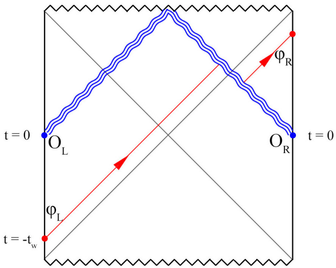
at $t = 0$ we briefly couple the CTFs by a double-trace interaction

$$H = H_L + H_R + gf(t)\mathcal{O}_L\mathcal{O}_R$$

For given sign of g this creates negative energy shockwaves in the bulk. Probe undergoes time advance when crossing shockwaves

Wormhole becomes traversable!

Gao-Jafferis-Wall



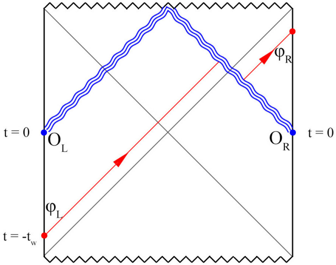
Change of CFT energy

$$\delta\langle H_R\rangle \propto g\langle \mathcal{O}_L\mathcal{O}_R\rangle + O(g^2)$$

Black hole horizon shrinks somewhat, probe can cross the wormhole
CFTs briefly interacted via $O_L O_R$ at $t = 0$, so information can be exchanged

Gao-Jafferis-Wall

[Maldacena-Stanford-Yang]



We create the probe on the left by

$$e^{i\epsilon\phi_L(-t)}|\mathrm{TFD}\rangle$$

At $t = 0$ we apply double-trace perturbation coupling the two CFTs

$$e^{igO_L O_R(0)}e^{i\epsilon\phi_L(-t)}|\mathrm{TFD}\rangle$$

We measure the operator $\phi_R(t)$ on this state. To leading order in ϵ we need

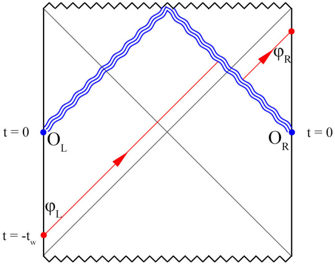
$$\langle\mathrm{TFD}|[\phi_L(-t), e^{-igO_L O_R(0)}\phi_R(t)e^{igO_L O_R(0)}]|\mathrm{TFD}\rangle$$

Expanding in g

$$\langle\mathrm{TFD}|[\phi_L(-t), O_L(0)][\phi_R(t), O_R(0)]|\mathrm{TFD}\rangle$$

Gao-Jafferis-Wall

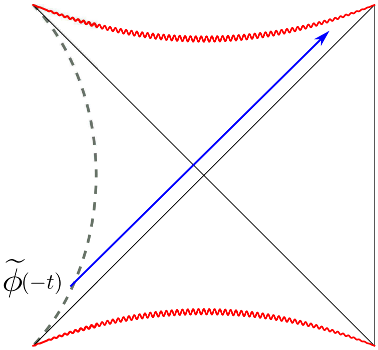
analysis by [Maldacena-Stanford-Yang]



Growth of out-of-time-order-correlators (OTOC) due to quantum chaos

$$\langle \mathrm{TFD}|[\phi_L(-t), O_L(0)][\phi_R(t), O_R(0)]|\mathrm{TFD}\rangle \sim e^{\frac{2\pi}{\beta}t}$$

Exciting the left region



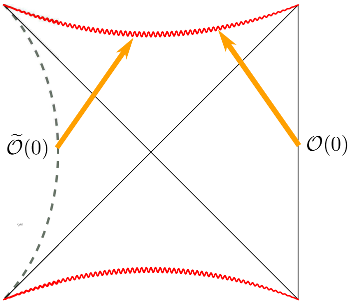
We prepare the CFT in state $e^{i\epsilon\widetilde{\phi}(-t)}|\Psi_0\rangle$

(this operator is smeared in time due to cutoff $\omega < \omega_*$)

Excitation is invisible by simple CFT operators

Creating negative energy shockwaves for 1-sided black hole

[J. de Boer, R. van Breukelen, S. Lokhande, KP, E. Verlinde]

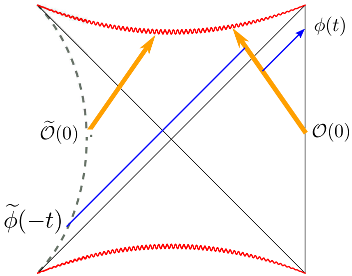


At $t = 0$ we perturb CFT Hamiltonian by

$$g\mathcal{O}\widetilde{\mathcal{O}}(0)$$

Compute effect on bulk correlators $\Rightarrow$ generates negative energy shockwaves for appropriate choice of g. Computation of $\langle T_{\mu\nu}\rangle_{\text{bulk}}$ similar to that of Gao-Jafferis-Wall

The experiment



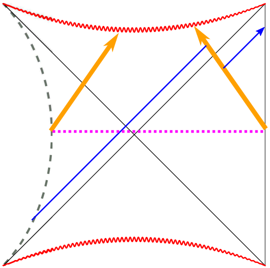
We create a probe in the left region of the black hole by acting with $\widetilde{\phi}(-t)$.

Then at $t = 0$ we perturb the CFT by $g\mathcal{O}(0)\widetilde{\mathcal{O}}(0)$. Finally we detect the probe by measuring $\phi(t)$.

The conjectured Penrose diagram makes a prediction about CFT correlators (signal around $t = \beta \log S$)

$$\langle\Psi_0|[\widetilde{\phi}(-t), e^{-ig\widetilde{\mathcal{O}}\mathcal{O}(0)}\phi(t)e^{ig\widetilde{\mathcal{O}}\mathcal{O}(0)}]|\Psi_0\rangle$$

Some subtleties

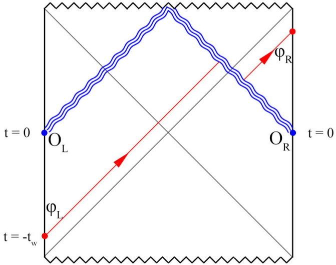


Operators $\widetilde{\mathcal{O}}$ are gravitationally dressed wrt the right $\Rightarrow$ Wilson lines extending across geometry

Backreaction and Einstein equations at subleading order?

Comparing correlators in 2-sided and 1-sided case

Eternal black hole



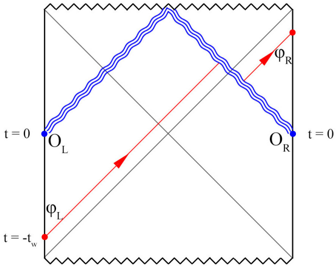
$$C \equiv \langle \mathrm{TFD} | [\phi_L(-t), e^{-igO_L O_R(0)} \phi_R(t) e^{igO_L O_R(0)}] | \mathrm{TFD} \rangle$$

Using

$$\begin{aligned} \mathcal{O}_{L,\omega} |\mathrm{TFD}\rangle &= e^{-\frac{\beta \hat{H}}{2}} \mathcal{O}^{\dagger}_{R,\omega} e^{\frac{\beta \hat{H}}{2}} |\mathrm{TFD}\rangle, \\ \mathcal{O}_{L,\omega} \mathcal{O}_{R,\omega_1} \ldots \mathcal{O}_{R,\omega_n} |\mathrm{TFD}\rangle &= \mathcal{O}_{R,\omega_1} \ldots \mathcal{O}_{R,\omega_n} \mathcal{O}_{L,\omega} |\mathrm{TFD}\rangle, \\ [\hat{H}, \mathcal{O}_{L,\omega}] \mathcal{O}_{R,\omega_1} \ldots \mathcal{O}_{R,\omega_n} |\mathrm{TFD}\rangle &= \omega \mathcal{O}_{L_\omega} \mathcal{O}_{R,\omega_1} \ldots \mathcal{O}_{R,\omega_n} |\mathrm{TFD}\rangle. \end{aligned} \quad (3)$$

where $\hat{H} \equiv H_R - H_L$.

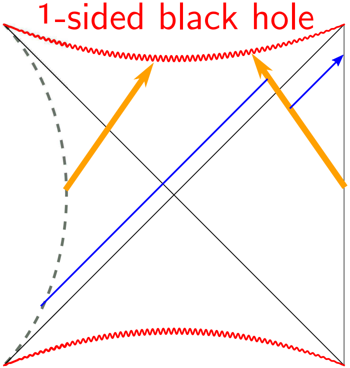
Eternal black hole



$$C \equiv \langle \mathrm{TFD} | [\phi_L(-t), e^{-igO_LO_R(0)}\phi_R(t)e^{igO_LO_R(0)}] | \mathrm{TFD} \rangle$$

$$C = \langle \mathrm{TFD} | \mathcal{X}(\phi_R, O_R) | \mathrm{TFD} \rangle$$

$$\boxed{C = \frac{1}{Z}\mathrm{Tr}[e^{-\beta H}\mathcal{X}(\phi, O)]}$$



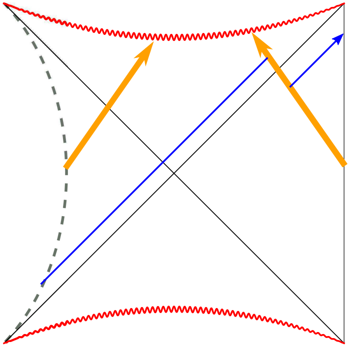
1-sided black hole

$$C' \equiv \langle \Psi_0 | [\widetilde{\phi}(-t), e^{-ig\widetilde{\mathcal{O}}\mathcal{O}(0)} \phi(t) e^{ig\widetilde{\mathcal{O}}\mathcal{O}(0)}] | \Psi_0 \rangle$$

Using

$$\begin{aligned} \widetilde{\mathcal{O}}_\omega |\Psi_0\rangle &= e^{-\frac{\beta H}{2}} \mathcal{O}^\dagger_\omega e^{\frac{\beta H}{2}} |\Psi_0\rangle, \\ \widetilde{\mathcal{O}}_\omega \mathcal{O}_{\omega_1} ... \mathcal{O}_{\omega_n} |\Psi_0\rangle &= \mathcal{O}_{\omega_1} ... \mathcal{O}_{\omega_n} \widetilde{\mathcal{O}}_\omega |\Psi_0\rangle, \\ [H, \widetilde{\mathcal{O}}_\omega] \mathcal{O}_{\omega_1} ... \mathcal{O}_{\omega_n} |\Psi_0\rangle &= \omega\, \widetilde{\mathcal{O}}_\omega \mathcal{O}_{\omega_1} ... \mathcal{O}_{\omega_n} |\Psi_0\rangle. \end{aligned} \tag{4}$$

1-sided black hole



$$C' \equiv \langle \Psi_0 | [\widetilde{\phi}(-t), e^{-ig\widetilde{\mathcal{O}}\mathcal{O}(0)} \phi(t) e^{ig\widetilde{\mathcal{O}}\mathcal{O}(0)}] | \Psi_0 \rangle$$

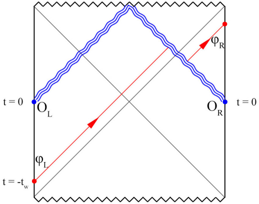
takes the form

$$\boxed{C' = \langle \Psi_0 | \mathcal{X}(\phi, O) | \Psi_0 \rangle}$$

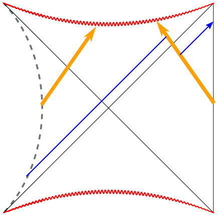
where $\mathcal{X}$ is **exactly the same expression as before**

Comparison

2-sided BH



1-sided BH



$$C = \frac{1}{Z}\mathrm{Tr}[e^{-\beta H}\mathcal{X}(\phi, O)]$$

$$C' = \langle\Psi_0|\mathcal{X}(\phi, O)|\Psi_0\rangle$$

Moreover, in stat-mech we have

$$C' = \mathrm{Tr}[\rho_m \mathcal{X}(\phi, \mathcal{O})] + O(e^{-S})$$

where $\rho_m =$ microcanonical density matrix

Condition for CFT correlators

$$C = \frac{1}{Z}\mathrm{Tr}[e^{-\beta H}\mathcal{X}(\phi, O)] \qquad C' = \mathrm{Tr}[\rho_m \mathcal{X}(\phi, O)]$$

We need that:

$$\boxed{\lim_{N\to\infty} C = \lim_{N\to\infty} C'}$$

- No general proof, trace-distance $||\rho_\beta - \rho_m||$ between ensembles is almost maximal.
- It is a question about how "reasonable" the observable $\mathcal{X}$ is.
- $\mathcal{X}(\phi, O)$ is a complicated observable, product of operators at time separation $\Delta t \sim \beta \log S$
- Conjecture is related to whether $\mathcal{X}(\phi, O)$ obeys Eigenstate Thermalization Hypothesis (ETH)

$$\langle E_i|\mathcal{X}|E_j\rangle = f(E_i)\delta_{ij} + R_{ij}. \tag{5}$$

with $\frac{df}{dE} \sim O(1/S)$. (notice that usually f dependends on E via T)

Condition for CFT correlators

- Interesting effect comes from subleading corrections of the form

$$\frac{1}{N^2} e^{\frac{2\pi t}{\beta}}$$

  At scrambling time they become O(1).

  Are these "chaos-enhanced" $1/N^2$ corrections the same in microcanonical and thermal ensemble?

- Our condition requires that correlators agree *even after analytic continuation* by $t \to t - i\frac{\beta}{2}$.

  In general this analytic continuation may enhance small difference between correlators, but we only need analytic continuation of low-pass-frequency-filtered correlators (related to cutoff ω_*)

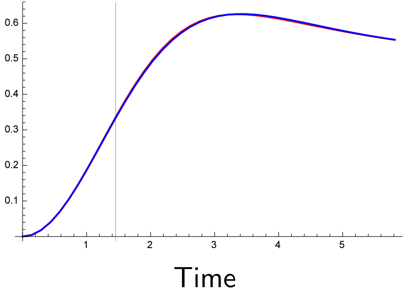
Comments

1. ETH expected to hold for products of operators at small time separation. We can show that it also holds for very large time separations (when chaos saturates). It is perhaps natural to expect that it holds for intermediate times of order $\beta \log S$

2. In 2d CFTs with large c and sparse spectrum where correlators are dominated by Virasoro identity block [Turiaci, H.Verlinde]

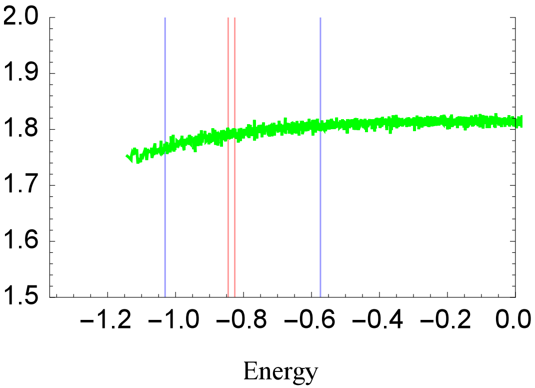
3. Preliminary numerical evidence in SYK model (apologies for our small N...)

Pure vs thermal state OTOC in SYK



$$\langle\{\psi^i(t),\psi^j(0)\}^2\rangle$$

ETH for chaotic observables in SYK

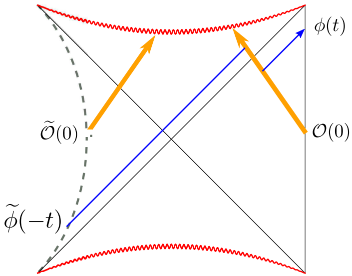


Matrix elements in SYK

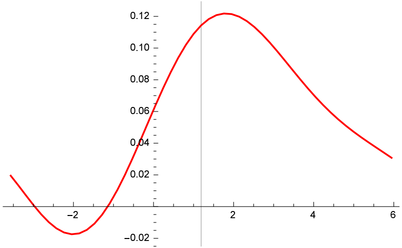
$$\langle E_i | \{\psi^i(t), \psi^j(0)\}^2 | E_i \rangle$$

for $t \approx \beta \log S$

Extracting particle from behind the horizon



Warning about numerics: very preliminary, small N, must be improved



Recovering information from a black hole

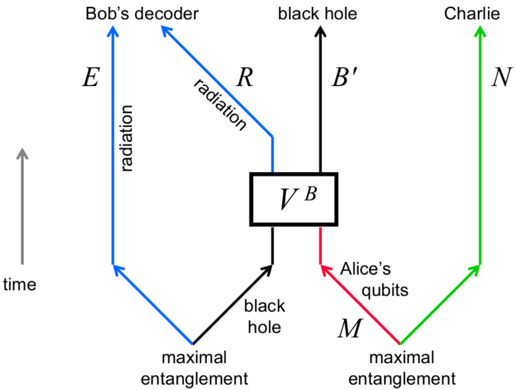
We throw a qubit into black hole. How long do we need to wait to recover the information from Hawking radiation?

$$t_{evap} \sim G^2 M^3$$

Hayden Preskill (2007): if we have access to more than half of Hawking radiation we only need to wait scrambling time

$$t_S \sim GM \log S$$

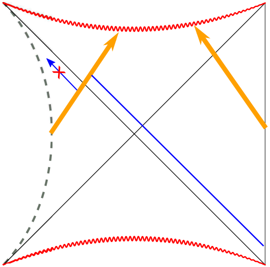
Hayden-Preskill protocol



Reformulation by Maldacena-Stanford-Yang in terms of traversable wormholes

- Collect half of Hawking radiation and collapse it into a second BH
- Apply complicated unitary to bring two BHs into TFD-like state
- Alice throws qubit into original BH
- Apply double trace coupling (corresponds to extracting a few Hawking particles in HP)
- Alice's qubit emerges in geometric form from the second BH

An analogue using mirror operators



We throw qubit $\phi(-t_s)$ into black hole. At $t = 0$ we act with $\mathcal{O}\widetilde{\mathcal{O}}$

After scrambling time we can *extract* the quantum information of the qubit my measuring operator $\widetilde{\phi}(t_s)$.

$$\langle\Psi_0|[\phi(-t), e^{-ig\widetilde{\mathcal{O}}\mathcal{O}(0)}\widetilde{\phi}(t)e^{ig\widetilde{\mathcal{O}}\mathcal{O}(0)}]|\Psi_0\rangle$$

As in HP: we need to know the quantum state to act with the state-dependent $\widetilde{\mathcal{O}}$.

Summary

- We considered the possibility that typical BH microstates in AdS extend partly into left region.
- We identified non-equilibrium states in CFT which can naturally be identified with excitations in that region
- We proposed a 1-sided analogue of the Gao-Jafferis-Wall protocol to extract excitations from that region
- We derived some necessary conditions for CFT correlators at scrambling time, in order for the conjectured geometry to be correct

Thank you