Firewalls in AdS/CFT

Borun D. Chowdhury (UvA)

Black Hole Horizons and Quantum Information
CERN (26/3/2013)

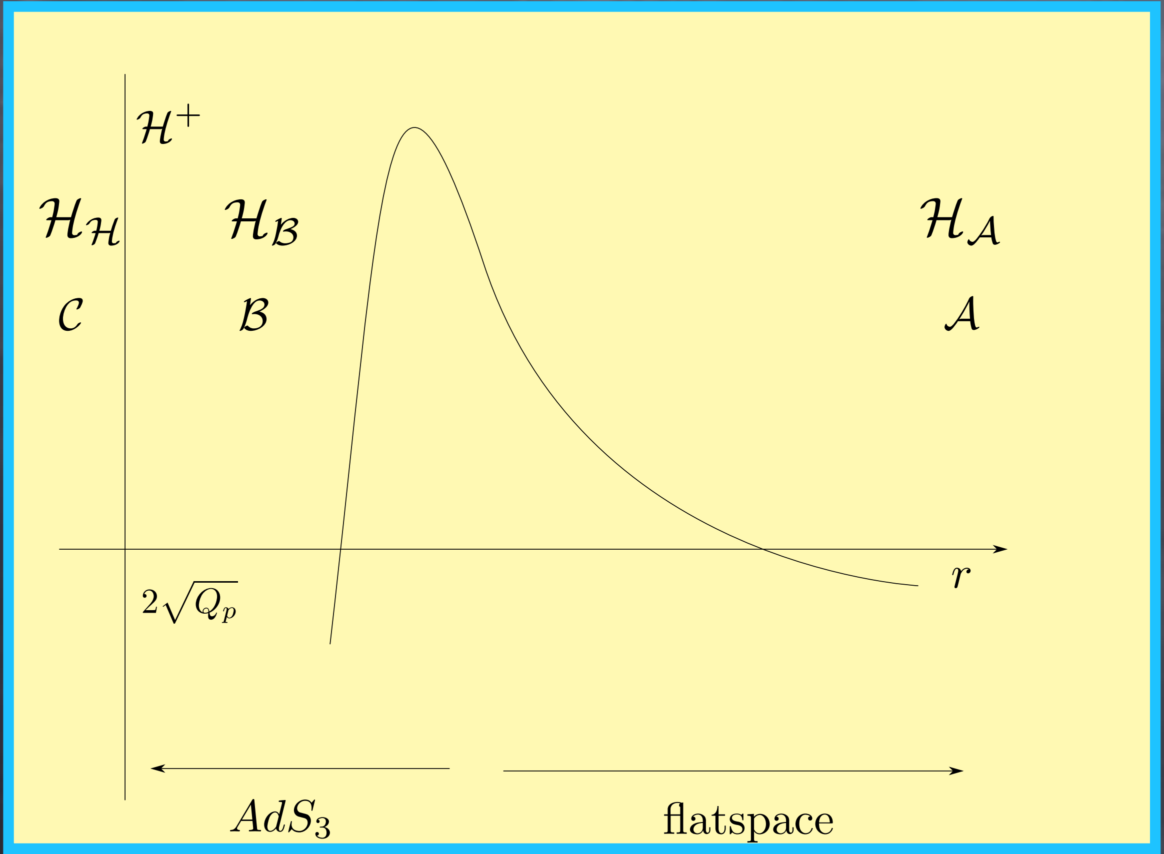
Based on 1302.5428 with Steve Avery and
13xx.xxxx with Jan de Boer, Vijay Balasubramanian, Bartek Czech

Firewalls in AdS/CFT

Take a D1-D5 string in a pure state (Lunin-Mathur geometry) and drop in closed strings in pure state. (hep-th/0202072)

Supposed to be described by D1-D5-P black string. (Fuzzballs?)

Field theory evaporation matched with Hawking radiation. (hep-th/9602043, 9605234,9607149,9606185,9609026)

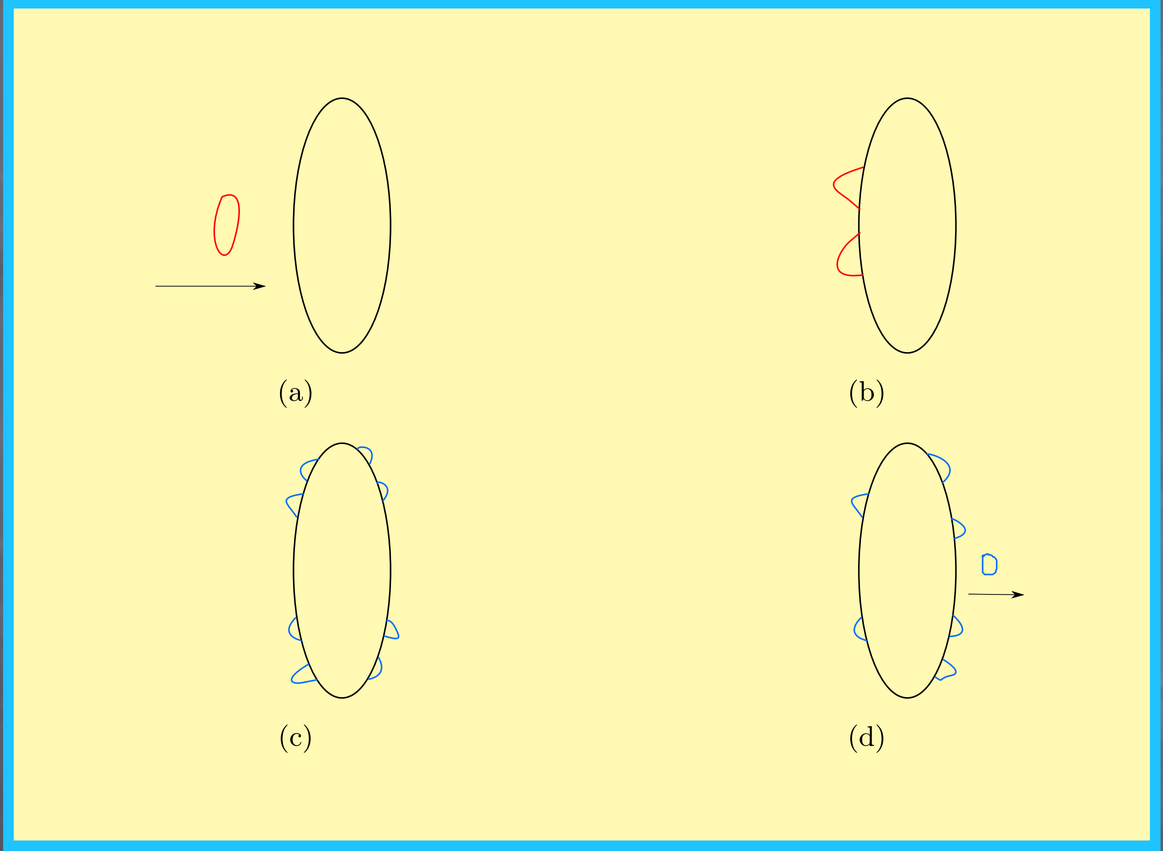


$$t_{Page} \propto \frac{R^5(n_1 n_5)^2}{g_s^2 l_s^4 n_p^2}$$

Can run AMPS on this system.

Firewalls in AdS/CFT

The near horizon region is BTZ, one can look at the field theory
(hep-th/9805097)



Applicable to incarnations of AdS/CFT with brane construction

The firewall question in AdS/CFT is

What is the dual to a thermal state?

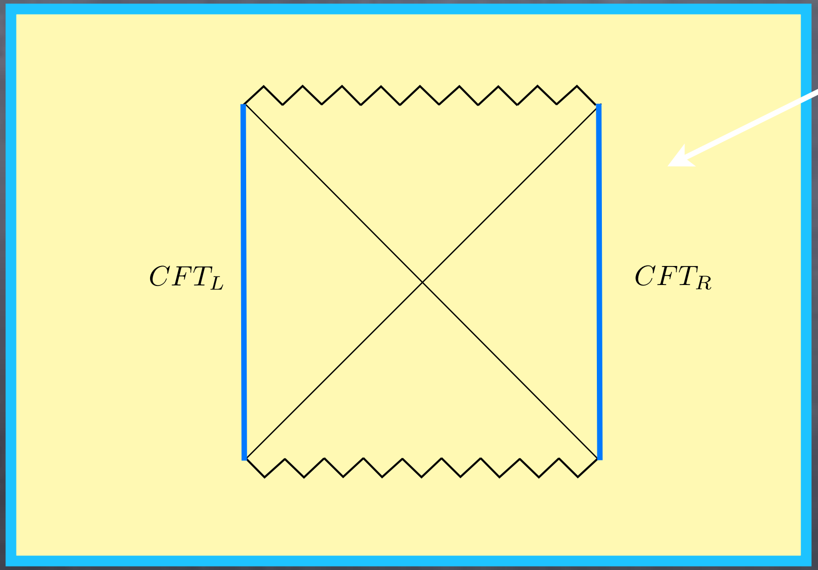
What is the dual to a thermal state?

Thermal CFT described by

$$\rho_{CFT} = \frac{1}{Z} \sum_E e^{-\beta E} |E\rangle\langle E|$$

What is the dual to a thermal CFT?

many reply that its the eternal AdS black hole



CFT_R thermal by itself

(hep-th/0106112)

lets explore this idea

Thermofield double (TFD)

A thermal state described by a thermal density matrix

$$\rho(\beta) = \frac{1}{Z} \sum_E e^{-\beta E} |E\rangle\langle E|$$

It can be *formally* purified by doubling the Hilbert space **(Int.J.Mod.Phys. B10 (1996) 1755-1805)**

$$|\Psi_\beta\rangle = \frac{1}{\sqrt{Z}} \sum_E e^{-\beta E/2} |E\rangle_1 \times |E\rangle_2$$

Maldacena proposed that such a state on two CFTs is dual to eternal AdS black hole (hep-th/0106112)

We are asking for the dual to on thermal CFT but lets first explore TFD more.

Thermofield double: Free bosons (Int.J.Mod.Phys. B10 (1996) 1755-1805)

Hamiltonians

$$H = \omega a^\dagger a$$
$$\tilde{H} = \omega \tilde{a}^\dagger \tilde{a}$$
$$\hat{H} = H - \tilde{H}$$

TFD state

$$|0(\beta)\rangle = (1 - e^{-\beta\omega})^{1/2} exp(e^{-\beta\omega/2} a^\dagger \tilde{a}^\dagger)|0\tilde{0}\rangle$$

TFD annihilation operators

$$a(\beta) = \cosh\eta \; a - \sinh\eta \; \tilde{a}^\dagger$$
$$\tilde{a}(\beta) = \cosh\eta \; \tilde{a} - \sinh\eta \; a^\dagger$$
$$a(\beta)|0(\beta)\rangle = 0$$
$$\tilde{a}(\beta)|0(\beta)\rangle = 0$$
$$\tanh\eta = e^{-\beta\omega/2}$$
$$a^\dagger a - \tilde{a}^\dagger \tilde{a} = a(\beta)^\dagger a(\beta) - \tilde{a}(\beta)^\dagger \tilde{a}(\beta)$$

Action of creation operators

$$a^\dagger(\beta)|0(\beta)\rangle = (e^{\beta\omega} - 1)^{1/2} \; \tilde{a}|0(\beta)\rangle = (1 - e^{-\beta\omega})^{1/2} \; \tilde{a}^\dagger|0(\beta)\rangle$$

$$\tilde{H}|0(\beta)\rangle = 0$$
$$\tilde{H}(a^\dagger)^n(\tilde{a}^\dagger)^n|0(\beta)\rangle = 0$$
$$\tilde{H}(a(\beta)^\dagger)^n(\tilde{a}(\beta)^\dagger)^n|0(\beta)\rangle = 0$$

Thermofield double: Free field of bosons

(Int.J.Mod.Phys. B10 (1996) 1755-1805)

Lagrangians

$$\mathcal{L}(x) = i\phi^\dagger(x)\dot{\phi}(x) - \partial_i\phi^\dagger(x)\partial_i\phi(x)$$
$$\tilde{\mathcal{L}}(x) = -i\tilde{\phi}^\dagger(x)\dot{\tilde{\phi}}(x) - \partial_i\tilde{\phi}^\dagger(x)\partial_i\tilde{\phi}(x)$$

$$\hat{\mathcal{L}}(x) = \mathcal{L}(x) - \tilde{\mathcal{L}}(x)$$

Equal time commutators

$$[\phi(x), \phi^\dagger(x')] = \delta(x)$$
$$[\tilde{\phi}(x), \tilde{\phi}^\dagger(x')] = \delta(x)$$

Second quantization

$$\phi(x) = \sum e^{ikx} e^{-iE_k t} a_k$$
$$\tilde{\phi}(x) = \sum e^{ikx} e^{iE_k t} \tilde{a}_k$$

Hamiltonian

$$H = \sum_k \epsilon_k a_k^\dagger a_k$$
$$\tilde{H} = \sum_k \epsilon_k \tilde{a}_k^\dagger \tilde{a}_k$$

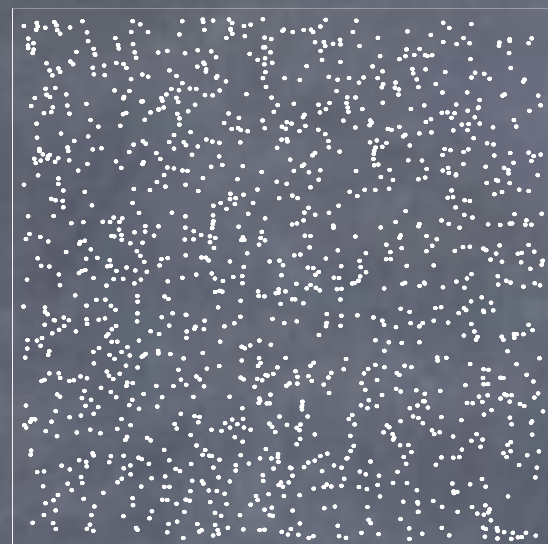
$$\hat{H} = H - \tilde{H}$$

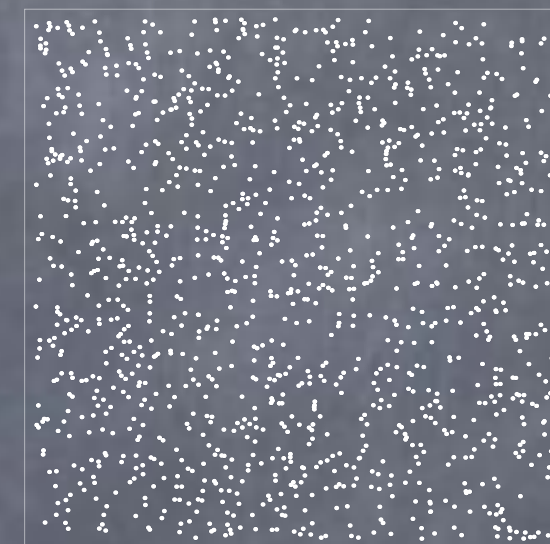
Bogoliubov transformations

$$a_k(\beta) = a_k \cosh\eta_{\beta k} - \tilde{a}_k^\dagger \sinh\eta_{\beta k}$$
$$\tilde{a}_k(\beta) = \tilde{a}_k \cosh\eta_{\beta k} - a_k^\dagger \sinh\eta_{\beta k}$$

Thermofield double: Free field of bosons

$|0\rangle$
$a_k,\ a_k^\dagger$
ρ_β





$|\tilde{0}\rangle$
$\tilde{a}_k,\ \tilde{a}_k^\dagger$
$\tilde{\rho}_\beta$

$$|0(\beta)\rangle = \prod_k \frac{1}{\cosh\eta_{\beta k}} exp(\tanh\eta_{\beta k}\ a_k^\dagger \tilde{a}_k^\dagger)|0\tilde{0}\rangle$$

$$a_k^\dagger(\beta)|0(\beta)\rangle = \frac{1}{\cosh\eta_{\beta k}} a_k^\dagger|0(\beta)\rangle = \frac{1}{\sinh\eta_{\beta k}} \tilde{a}_k|0(\beta)\rangle$$

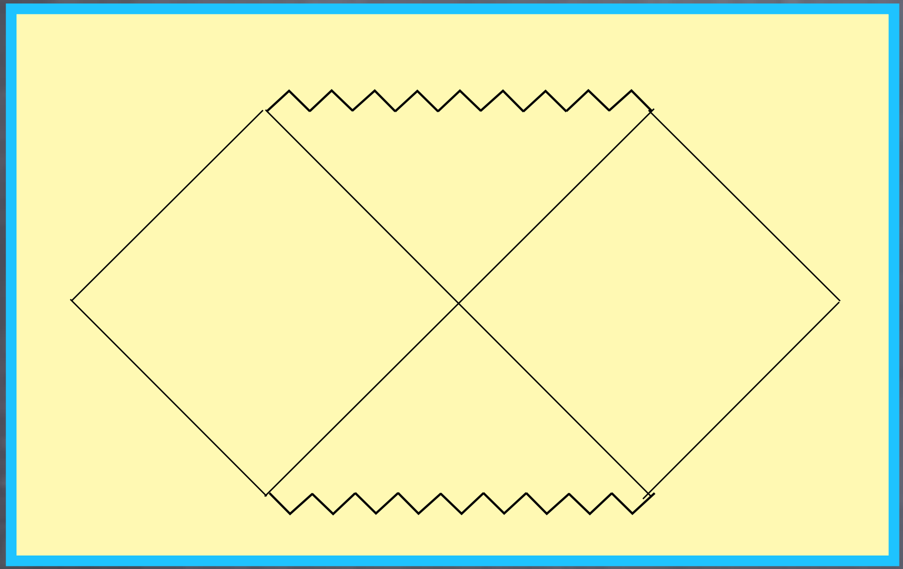
$$\tilde{a}_k^\dagger(\beta)|0(\beta)\rangle = \frac{1}{\cosh\eta_{\beta k}} \tilde{a}_k^\dagger|0(\beta)\rangle = \frac{1}{\sinh\eta_{\beta k}} a_k|0(\beta)\rangle$$

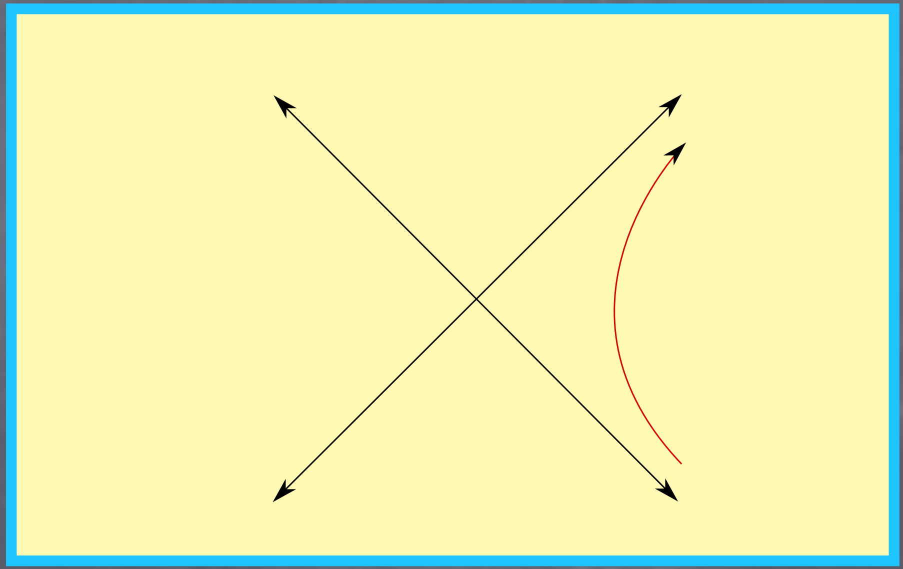
$a_k^\dagger(\beta)$ adds particle to left box OR removes one from right

However, systems are independent and the second one fictitious

Eternal black holes and thermofield double

Israel: For observers on one side of horizon of eternal black hole or Rindlerized Minkowski space, including the other side is thermofield doubling. (Phys.Lett. A57 (1976) 107-110)





$$|HH\rangle = \frac{1}{\sqrt{Z}} \sum e^{-\beta\omega/2} |E\rangle_{SC1} \otimes |E\rangle_{SC2}$$

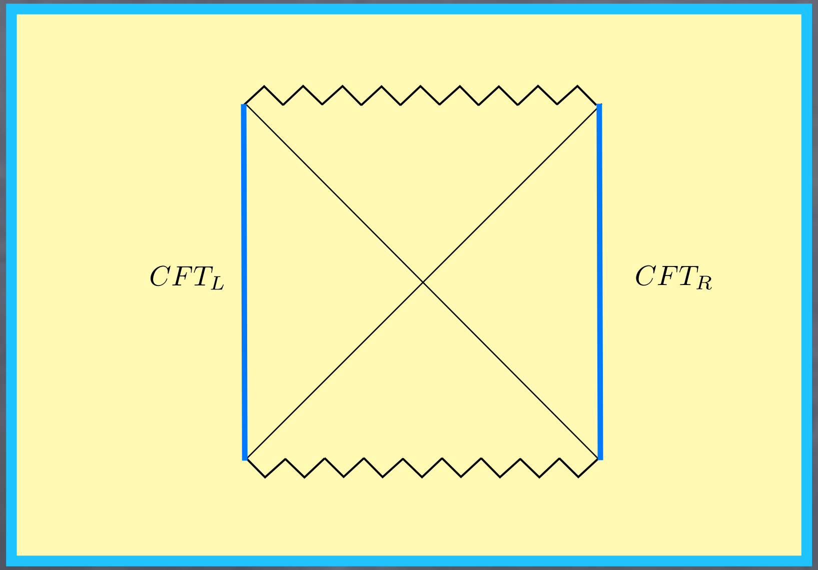
$$|0_M\rangle = \frac{1}{\sqrt{Z}} \sum e^{-\beta\omega/2} |E\rangle_{R1} \otimes |E\rangle_{R2}$$

The “doubled” fields are on the other side of the horizon

In some sense Israel found that the “fictitious” doubled copy of TFD is “real”.

Eternal black holes and thermofield double

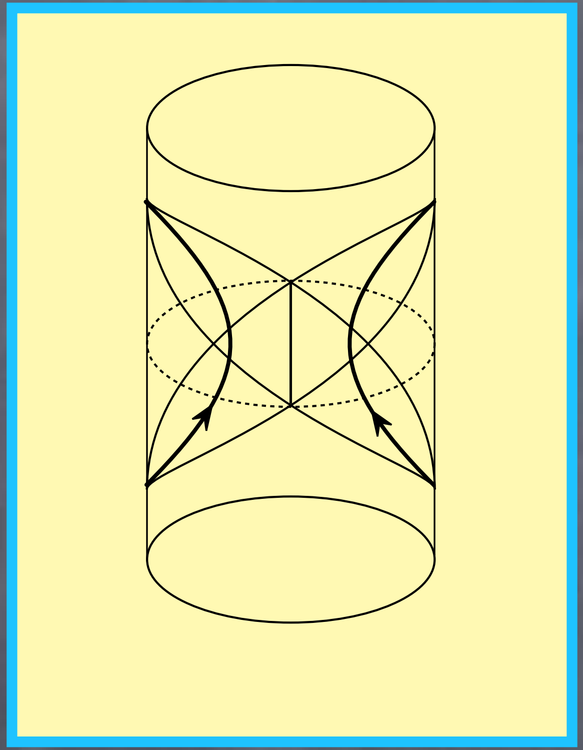
Maldacena put Israel's ideas in AdS/CFT context and proposed the eternal AdS black hole is dual to two copies of CFT entangled in a TFD way (hep-th/0106112)



$$|HHAdS\rangle = \frac{1}{\sqrt{Z}} \sum e^{-\beta\omega/2} |E\rangle_{CFT1} \otimes |E\rangle_{CFT2}$$

Eternal black holes and thermofield double

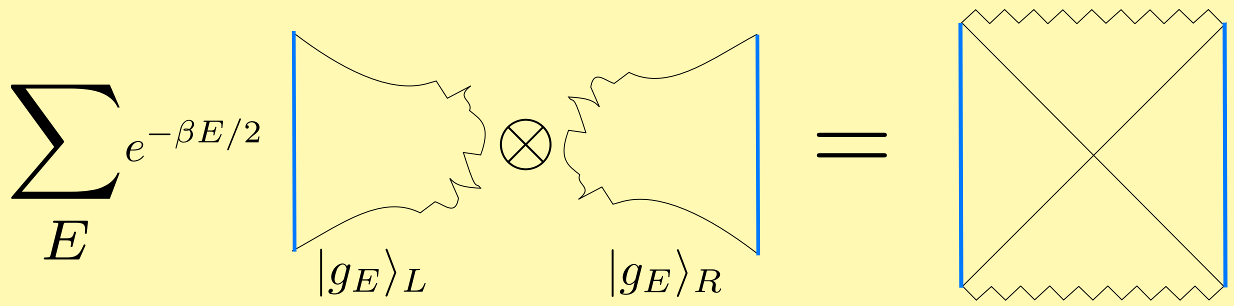
van Raamsdonk et. al. found similar results for global AdS (1206.1323)



$$|GAdS\rangle = \frac{1}{\sqrt{Z}} \sum e^{-\beta E/2} |E\rangle_{HCFT1} \otimes |E\rangle_{HCFT2}$$

Eternal black holes and thermofield double

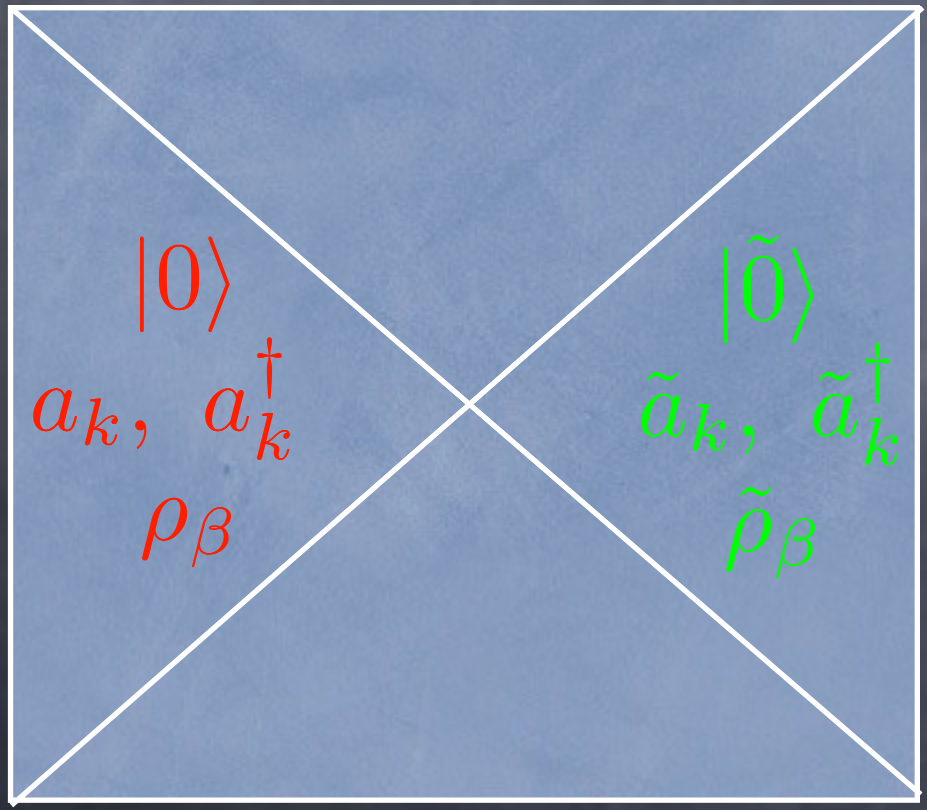
van Raamsdonk took the idea further and said *gravity* states are entangled (1005.3035)



and that entanglement is necessary (sufficient?) for connectedness

Eternal black holes and thermofield double

$a_k^\dagger(\beta)$ adds particle to left box OR removes one from right

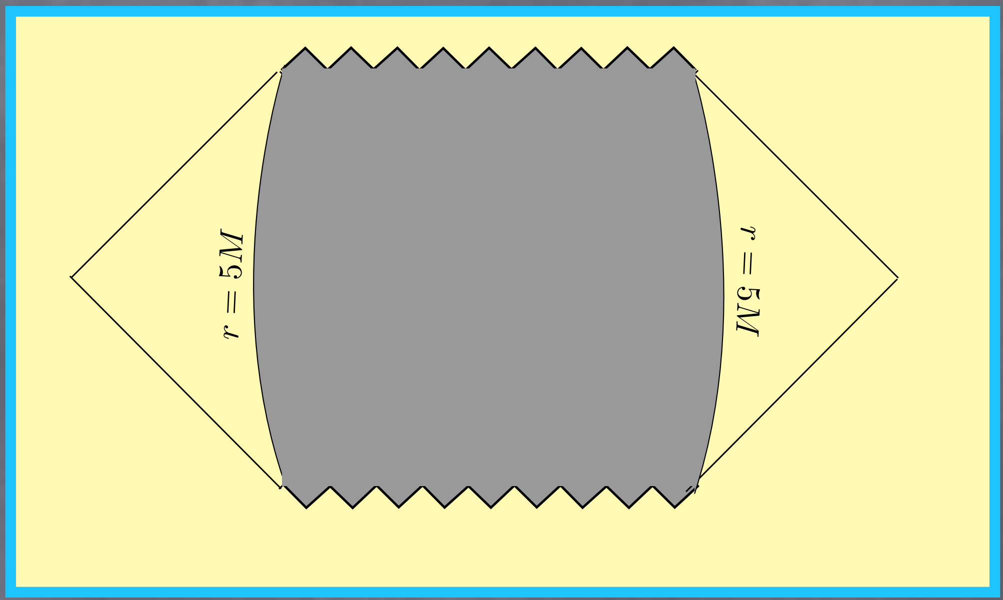


In examples with horizons $a_k^\dagger(\beta)$ correspond to states with span BOTH theories and go beyond them in some sense

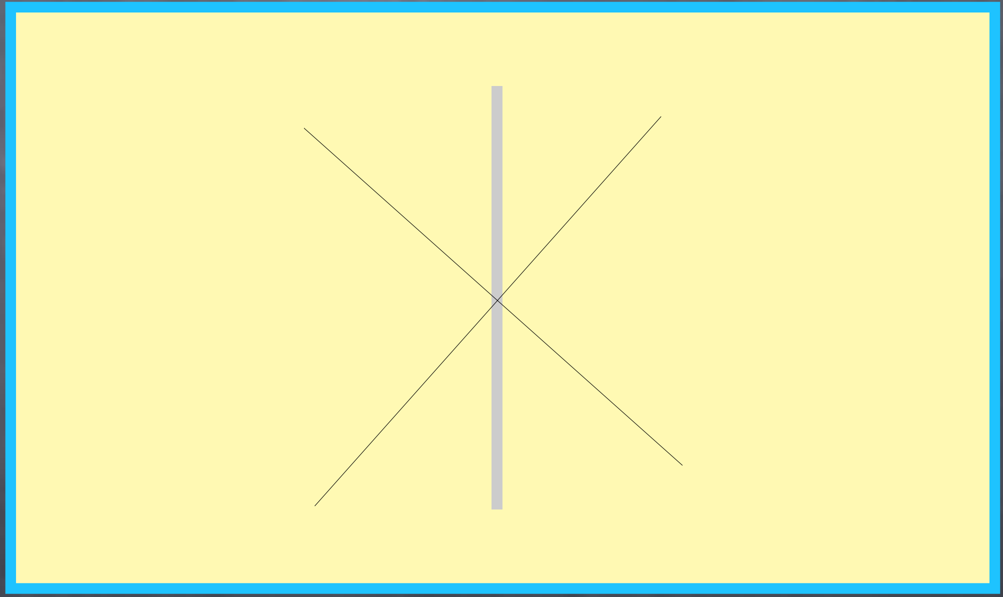
Connectedness more than having a TFD.

TFD without connectivity

TFD of star with Boulware thermal state is two disconnected spacetimes



A double sided mirror placed at x=0 in Minkowski and Rindlerization on top.



We have a_k, $a_k^\dagger$, $\tilde{a}_k$, $\tilde{a}_k^\dagger$ and also $a_k(\beta)$, $a_k^\dagger(\beta)$, $\tilde{a}_k(\beta)$, $\tilde{a}_k^\dagger(\beta)$

But no connectedness.

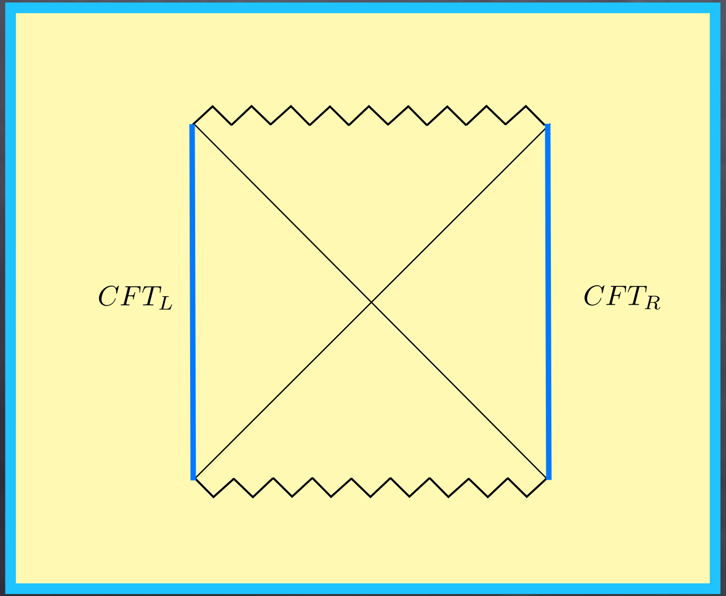
What makes smooth spacetimes?

All identifications of smooth horizons with TFD are basically deconstructions

Given a smooth surface we ask what happens if we trace over part of it

But we secretly know the full solution is smooth

What does it take to go beyond the horizon?

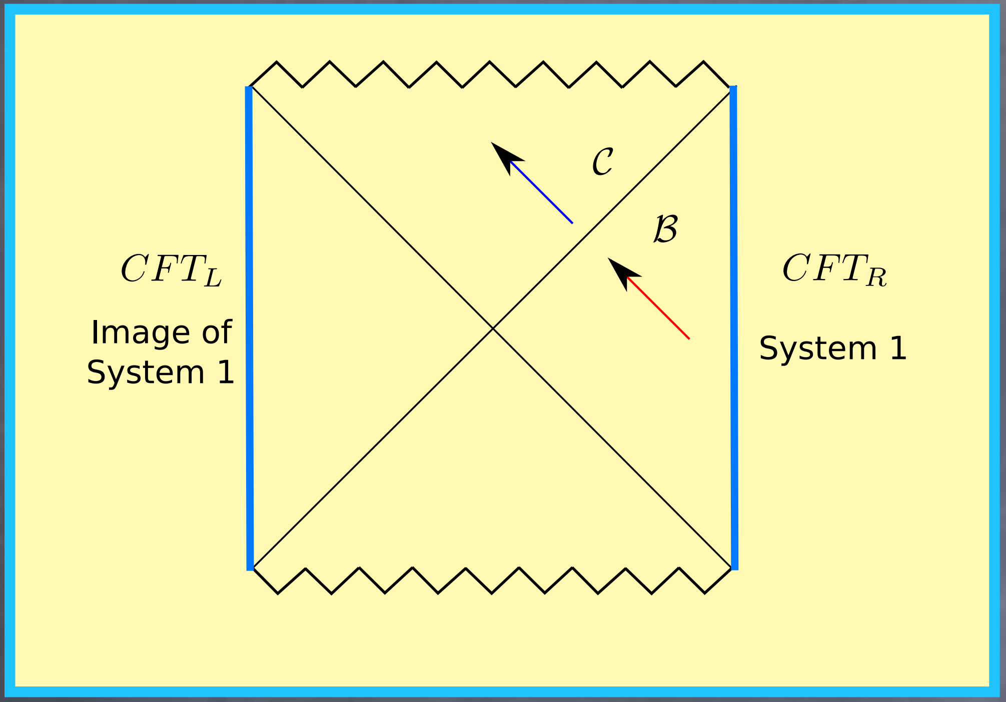


Many evidences for TFD n-point functions being captured by spatial geodesics

Infall is about timelike geodesics

What is the dual to a thermal state?

Suppose we do have an eternal AdS black hole



$$|\Psi\rangle = \frac{1}{\sqrt{Z}} \sum_E e^{-\beta E/2} |E\rangle_{CFT_L} \otimes |E\rangle_{CFT_R}$$

Alice can be dropped in from the right

Alice crosses horizon in infinite CFT time and then requires extra degrees of freedom from left CFT i.e. all dof of TFD are required

What is the dual to a thermal state?

A thermal state will be purified with respect to something

$$\rho_{CFT} = \frac{1}{Z}\sum_E e^{-\beta E}|E\rangle\langle E|$$

generally a heat bath. So the system and image in heat bath
is given by

$$|\Psi\rangle = \frac{1}{\sqrt{Z}}\sum_E e^{-\beta E/2}|E\rangle_{CFT}\otimes|E\rangle_S$$

The heat bath may or may not be a CFT and further the system may or may not have been decoupled from the heat bath after equilibration

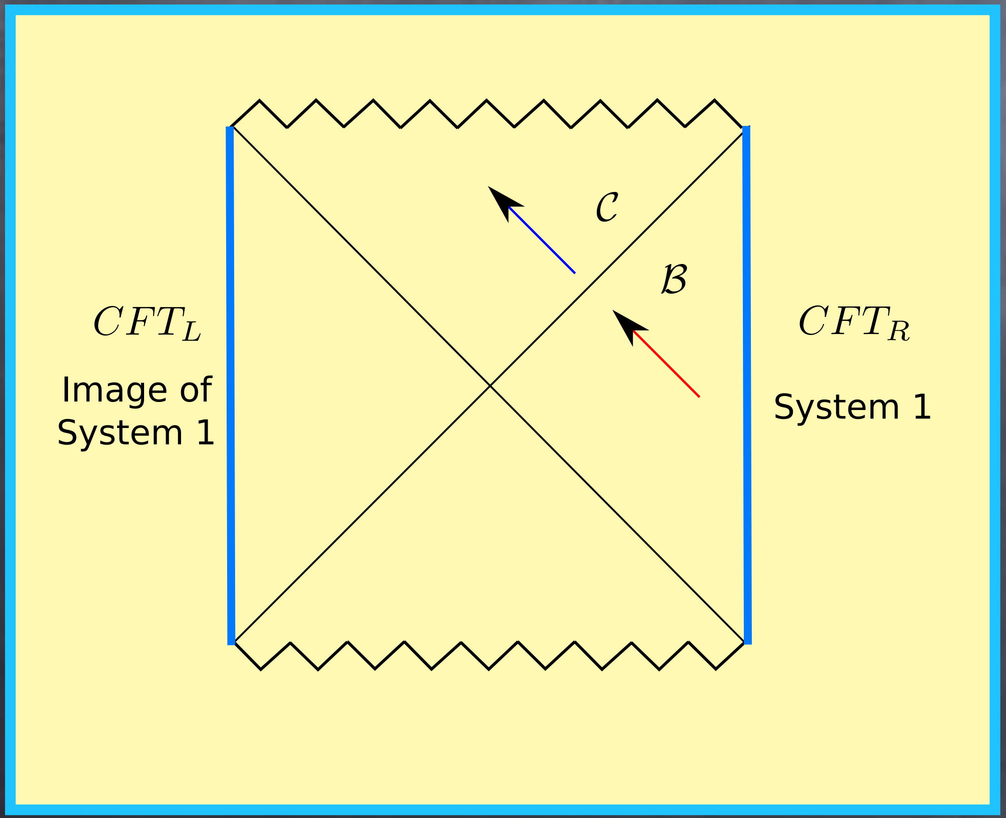
What is the dual to a thermal state?

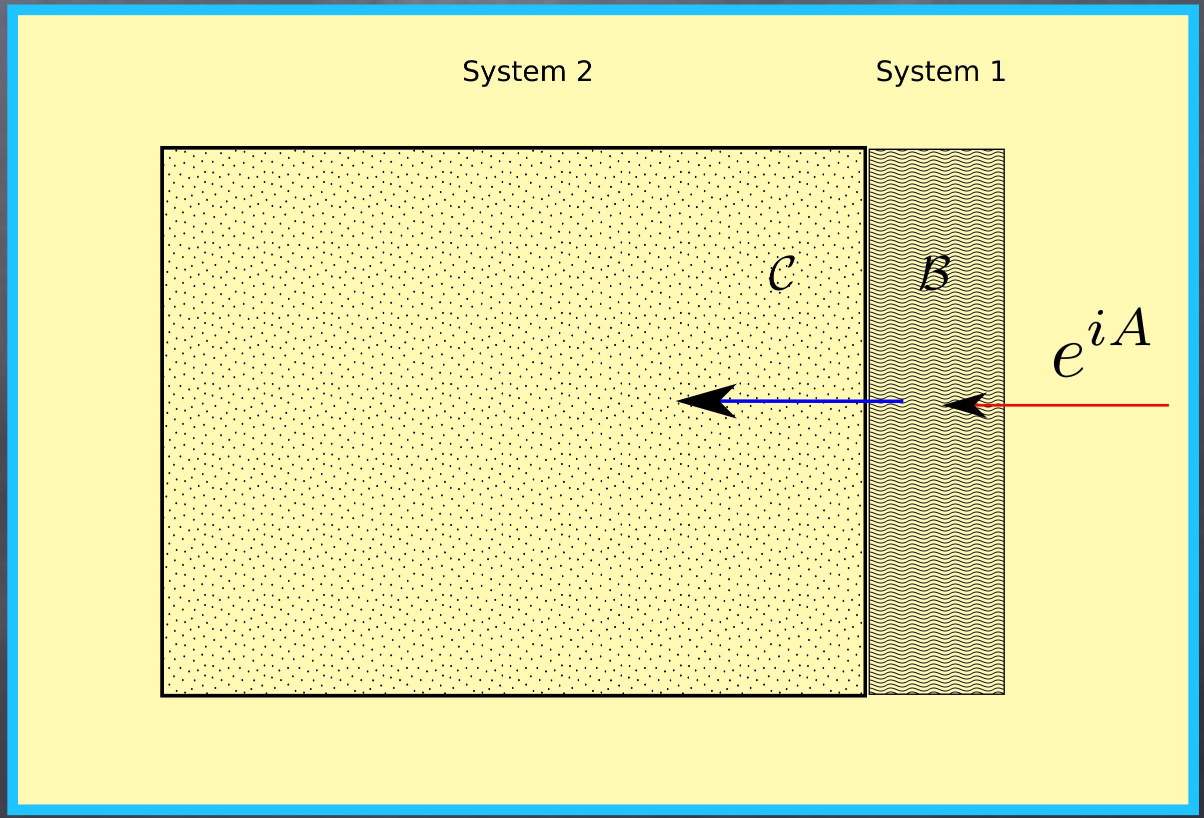
Eternal AdS

$$|\Psi\rangle = \frac{1}{\sqrt{Z}} \sum_E e^{-\beta E/2} |E\rangle_{CFT_L} \otimes |E\rangle_{CFT_R}$$

A perturbation dropped in on CFT_R eventually leaks out.

... at least in some sense ...



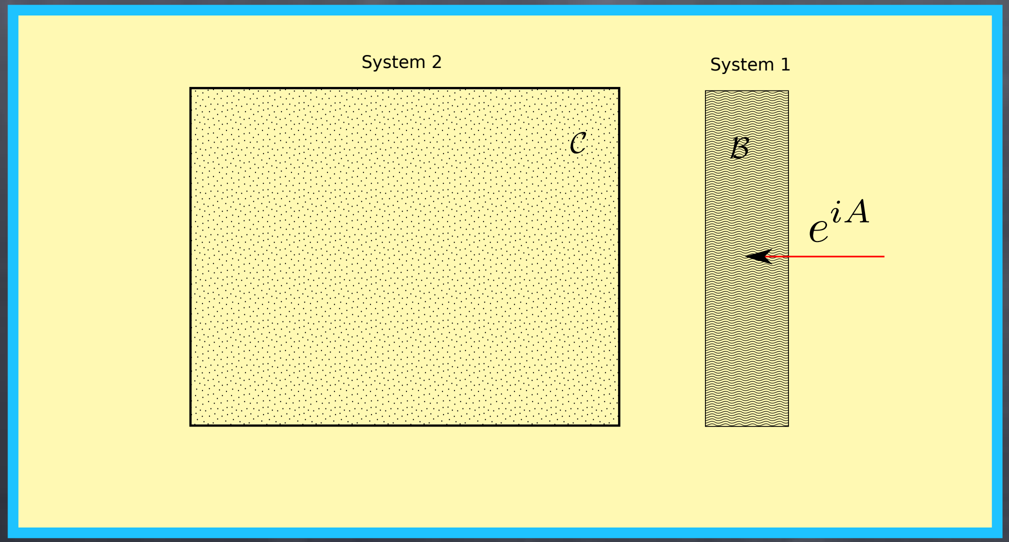


What is the dual to a thermal state?

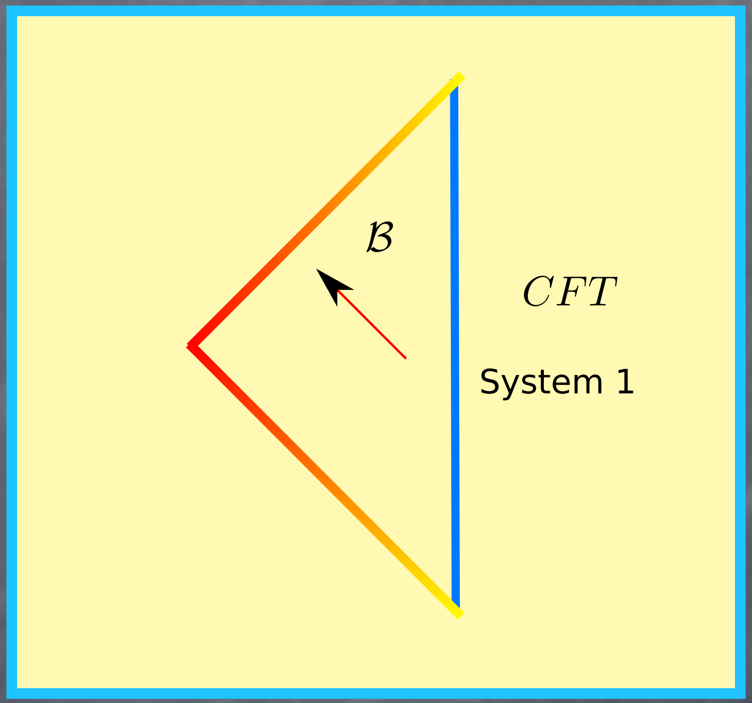
What if the purifier is not a CFT?

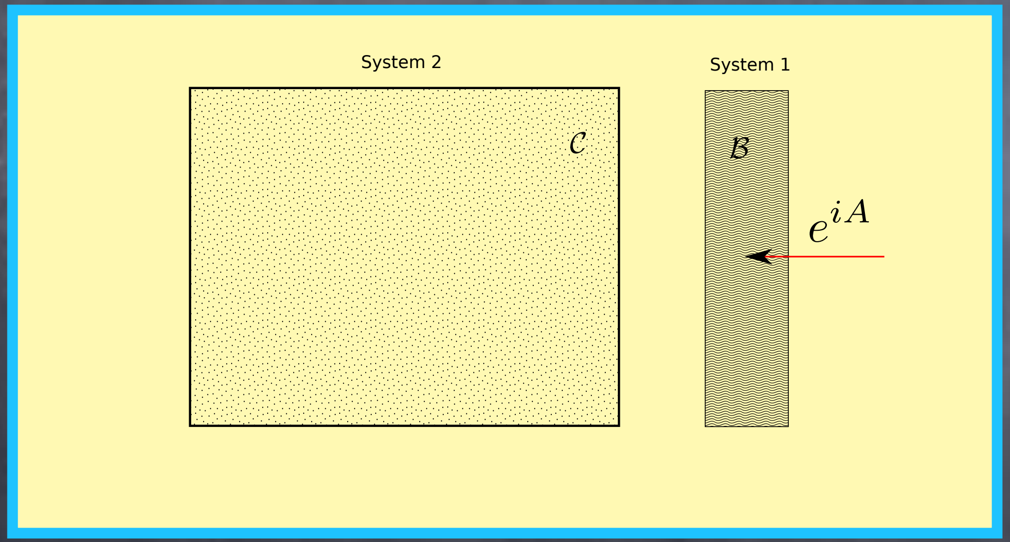
$$|\Psi\rangle = \frac{1}{\sqrt{Z}} \sum_E e^{-\beta E/2} |E\rangle_{CFT} \otimes |E\rangle_S$$

What if the purifier degrees of freedom are not available for some other reason?



What is the dual to a thermal state?

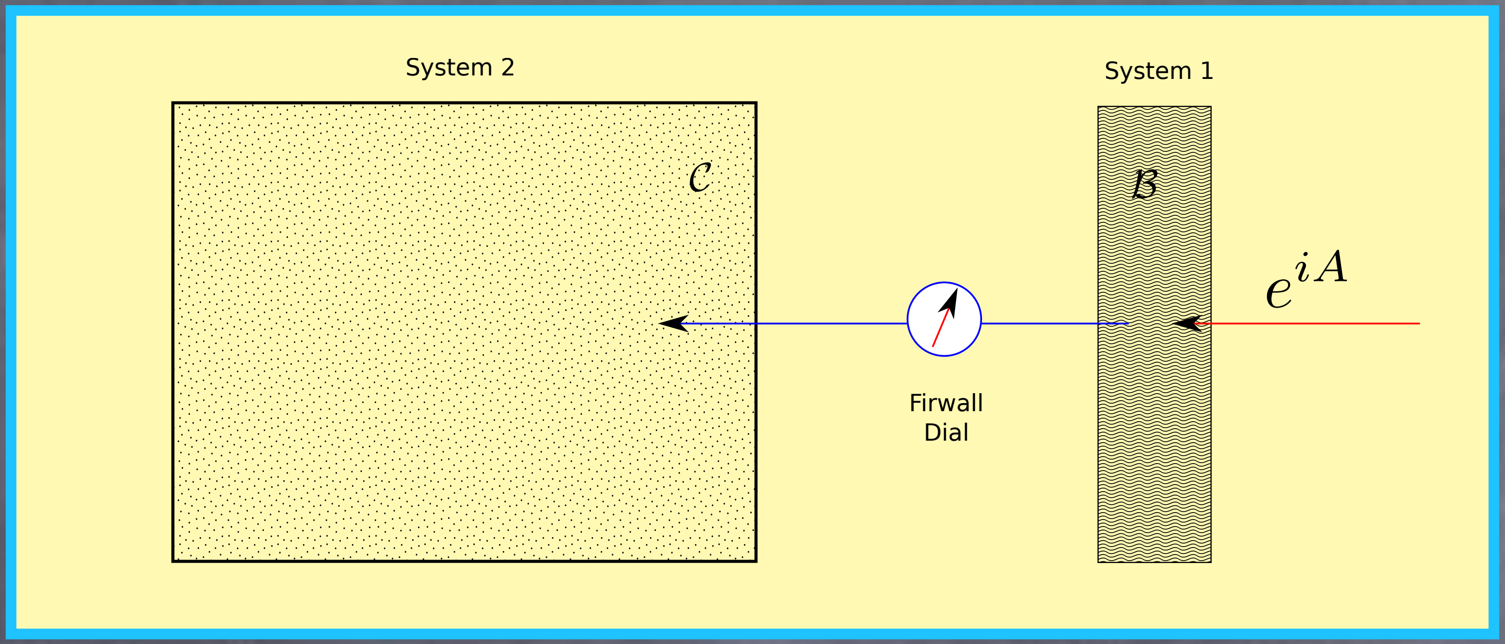




Standard AdS/CFT dictionary would say that outside horizon is the same, but generically behind the horizon would have no spacetime description

What is the dual to a thermal state?

The CFT itself doesn't seem to have information about the purifier degrees of freedom. Seems like superselection sectors.



but in this case generically there *is no other side*

Which superselection sector does QG on flat space live in? QG is complicated enough to speculate it will not be fine tuned to avoid firewalls

What is the dual to a thermal state?

Analytical continuation of outside of BH gives eternal black hole

This is the same as getting the TFD from a thermal state

However, analytical continuation just gives one possible purification of a mixed state

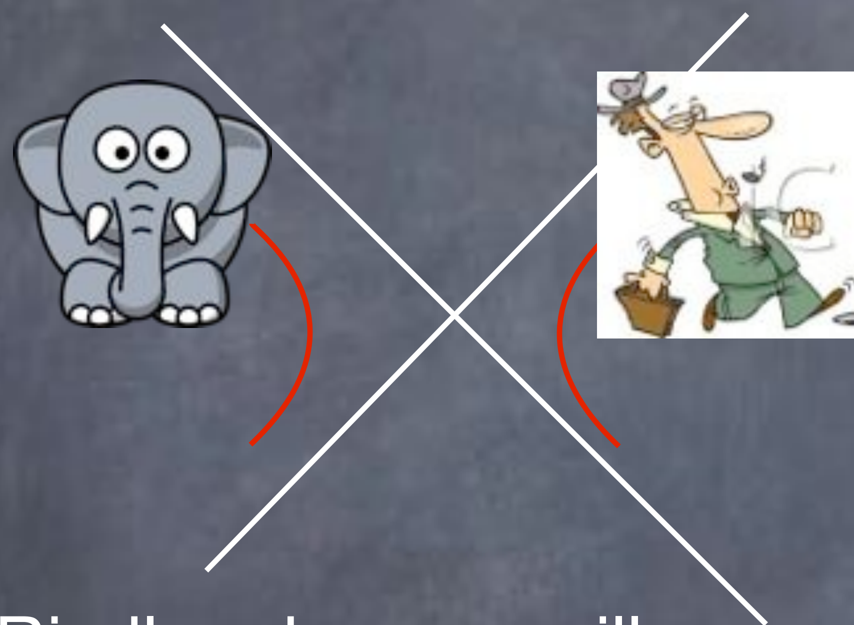
For instance one could simply permute the states in system 2 below to get a different state

$$|\Psi_\beta\rangle = \frac{1}{\sqrt{Z}} \sum_E e^{-\beta E/2} |E\rangle_1 \times |E\rangle_2$$

$$P_2(|\Psi_\beta\rangle) \neq |\Psi_\beta\rangle$$

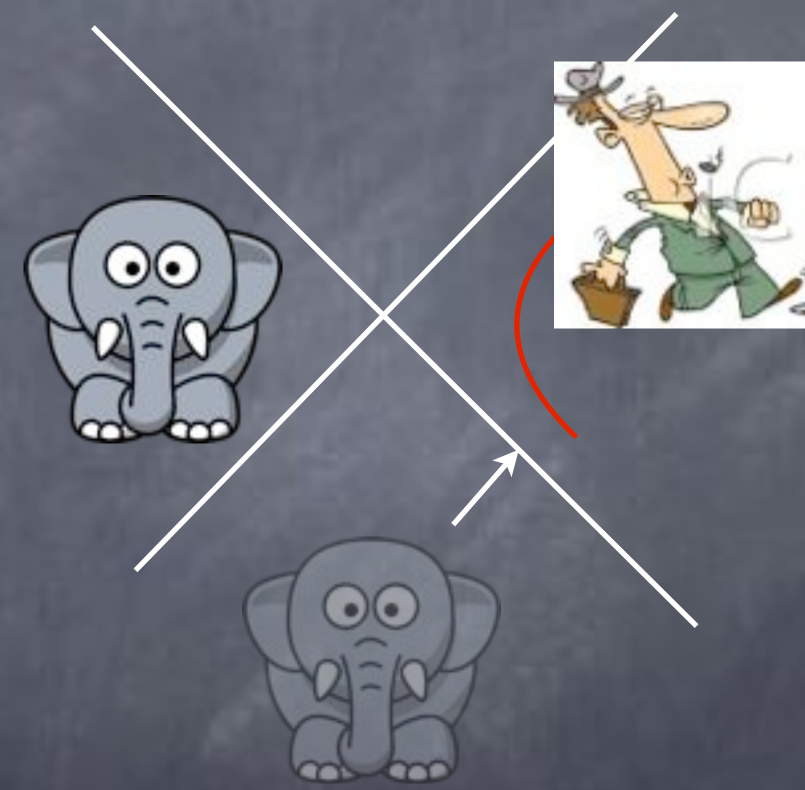
Elephant in the room and analytic continuation

Lets say we have an elephant in the room (global warming, superbacteria, world economy...)



A Rindler observer will miss the Rindler elephant by AC

However, he will not miss a Minkowski elephant by AC



AC of Schwarzschild will miss the elephant in the room - FIREWALL

However, entanglement entropy does not depend on how the state is purified - explains entropy counting of black holes on AC geometries

Summary of post Page time issues discussed

Post page time BH mixed, close to thermal

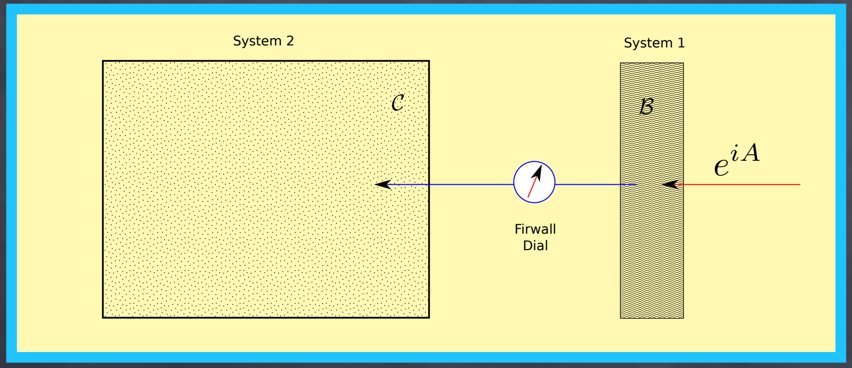
Thermal states can be formally purified - TFD

Deconstruction of smooth spacetimes with horizons involves TFD

All thermal regions do not have smooth connectivity between TFD

Instead of deconstructing spacetime, we want to construct spacetime

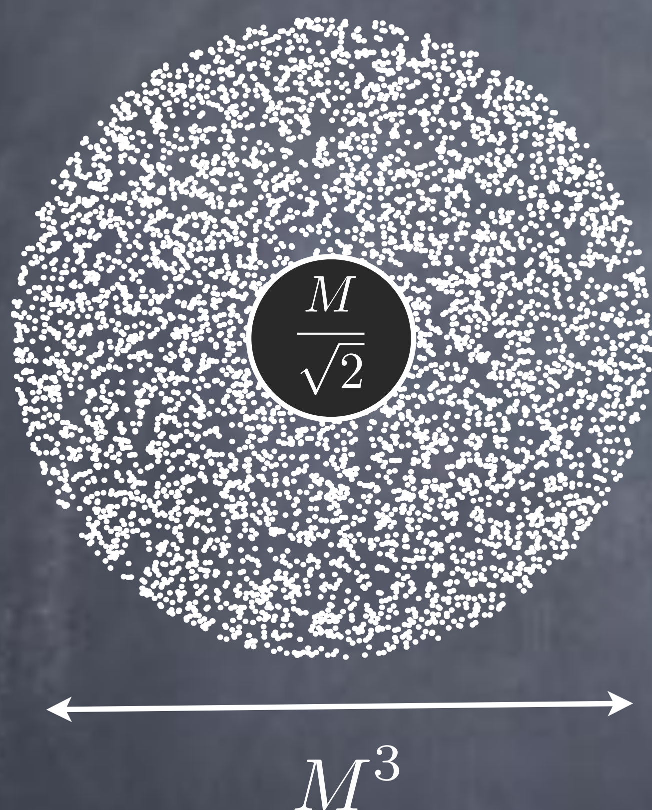
Whether early radiation/ purifier degrees of freedom can play the role of “inside” depends on the global hamiltonian



Pure state is *effectively* a black hole?

GR experience to be reproduced.

To illustrate lets look at C=A scenario



The radiation degrees of freedom construct inside

$$t_{infall} \sim M/\sqrt{2}$$

Would remind one of eternal BH

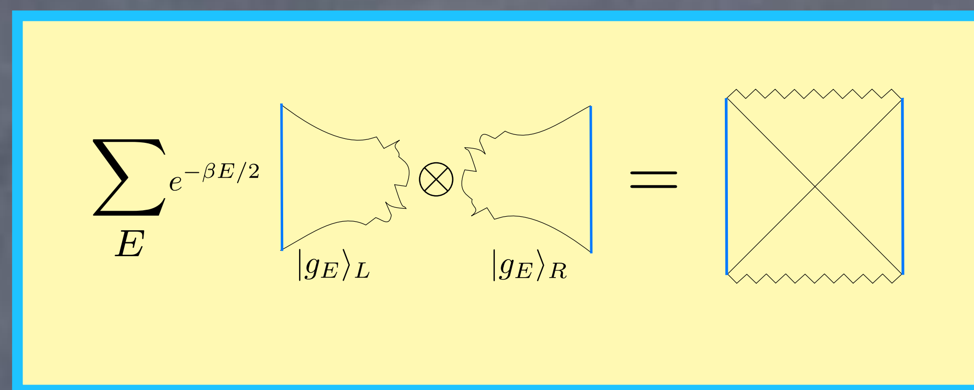
$$\mathcal{D}(CFT_L) = \mathcal{D}(CFT_R)$$

For young black hole, the same degrees of freedom account for free infall

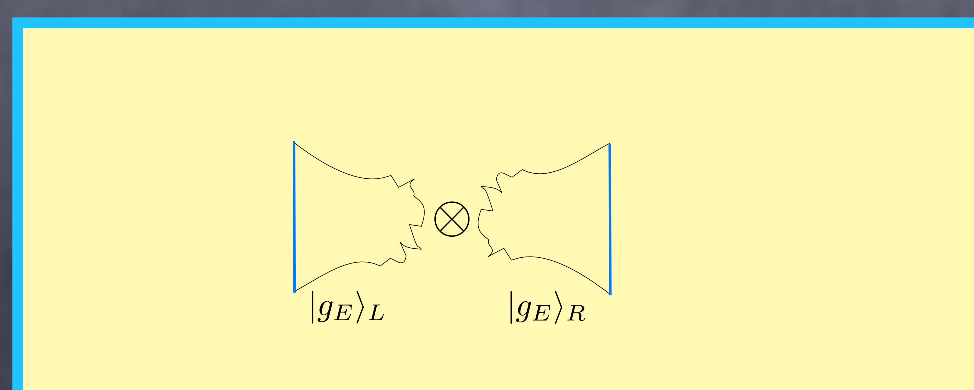
$$t_{infall} \sim M$$

Speculation about pre-Page time physics

van Raamsdonk proposed that connectivity across the horizon involves entanglement across left and right states (in gravity/CFT) (1005.3035)



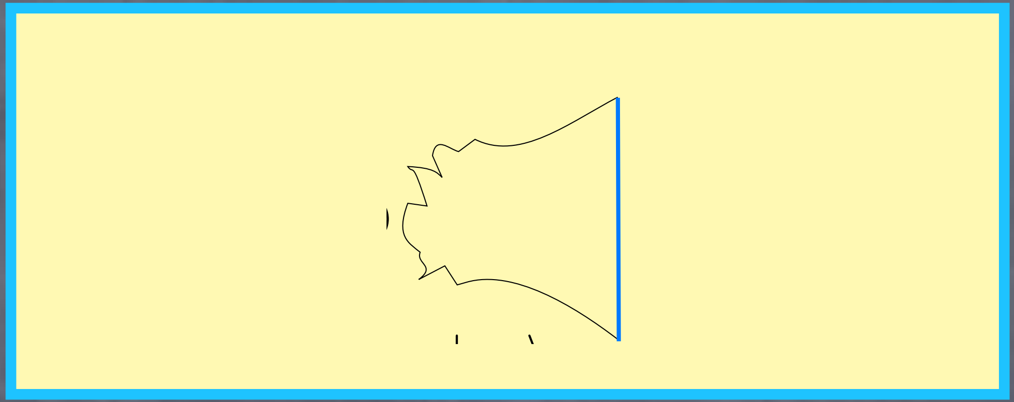
He argued that states of the form



are singular at the horizon

Speculation about pre-Page time physics

Referring to these microstates as fuzzballs* he stopped short of saying that microstates dual to a single CFT (fuzzballs formed from collapse of stars)



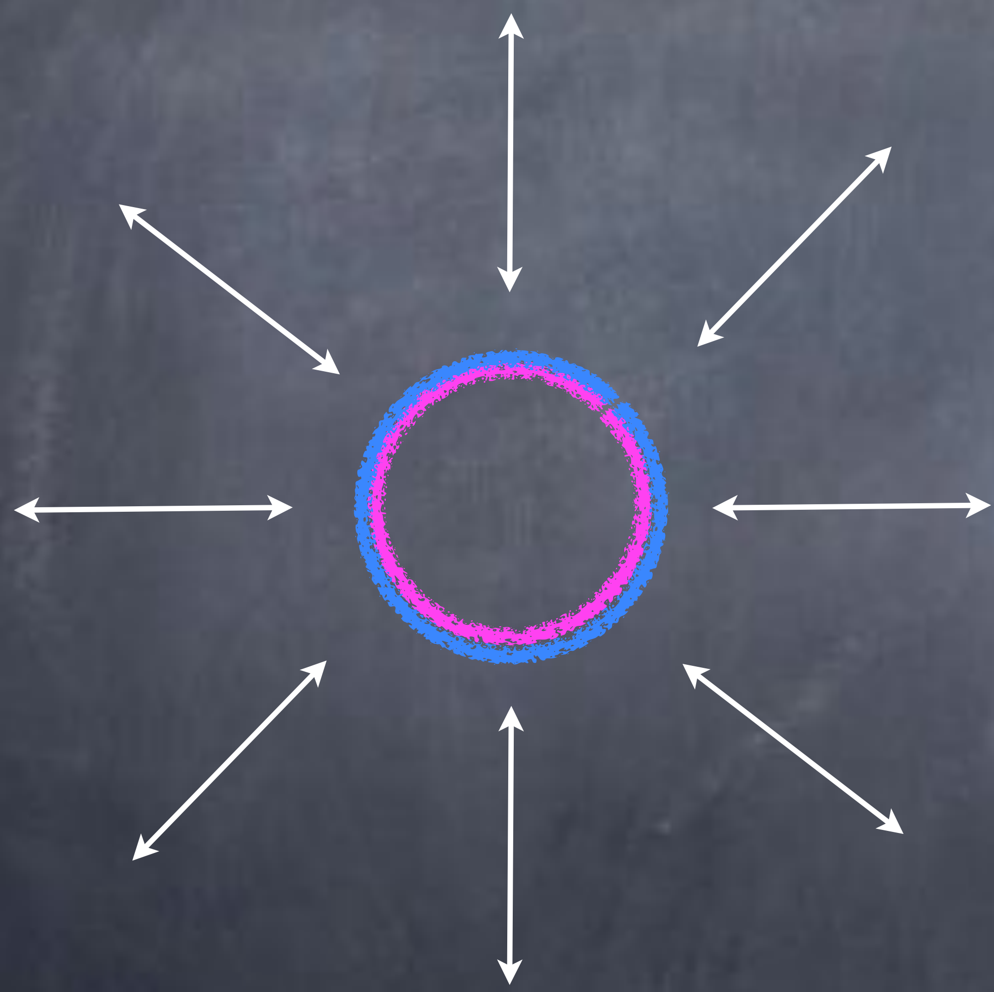
will also be singular just before the horizon. There will be no space behind.

I will pursue this line of thought

* Czech said that if they would have waited two months they would have called these firewalls.

Speculation about pre-Page time physics

Based on the idea that connectivity across horizons requires entanglement, we (Balasubramanian, de Boer, BDC, Czech)* study spherical Rindler.



It <u>seems</u> the entropy of spherical Rindler is given by A/4G*

Entanglement between gravity degrees of freedom - aka fuzzballs - not field theory degrees of freedom

In holographic setting this is dual to UV-IR entanglement of ground state

* See Czech's talk.

Speculation about pre-Page time physics

Do we excite these fuzzballs by putting in matter?

Can one fall through such fuzzballs: fuzzball complementarity - Verlinde^2 construction of inside?

Why would one get fuzzballs? Why would GR break down?

GR is classical theory so based on saddle point approximation.

Path integral has action and also measure $\int [dg] e^{-iS}$

$$[dg] \sim e^{M^2} \qquad S \sim M^2$$

If measure competes with action then cannot trust classical EOM (similar eg. Hagedron behavior, anomalies)

Conclusions...

The firewall story has anything but concluded....

Firewalls after Page time seem pretty generic

Analytic continuation gives the simplest completion in some sense but may not be the physically relevant one

Looking at smooth spacetimes like eternal black holes and searching for signatures of firewalls is probably the wrong path

- Instead of deconstructing spacetime, we want to construct spacetime
- Entanglement is not enough

Future directions...

What is the true quantum nature of fuzzballs?

Do you smash on hitting them or they give way. If so is the complete GR experience reproduced? Even after Page time?

What is the nature of spacetime and what properties other than entanglement are required for it?