HOW ALICE FUZZES BUT MAY NOT EVEN KNOW IT

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The Holographic Way
Nordita, Stockholm, 10 Oct 2012

(with Steve Avery & Andrea Puhm)
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Plan

Information paradox: (Why go beyond extremal BHs, AdS/CFT)

- Black hole complementarity
- Fuzzballs

Firewalls

Unitarity, qubit models & black holes/ fuzzballs

Fuzzball Complementarity

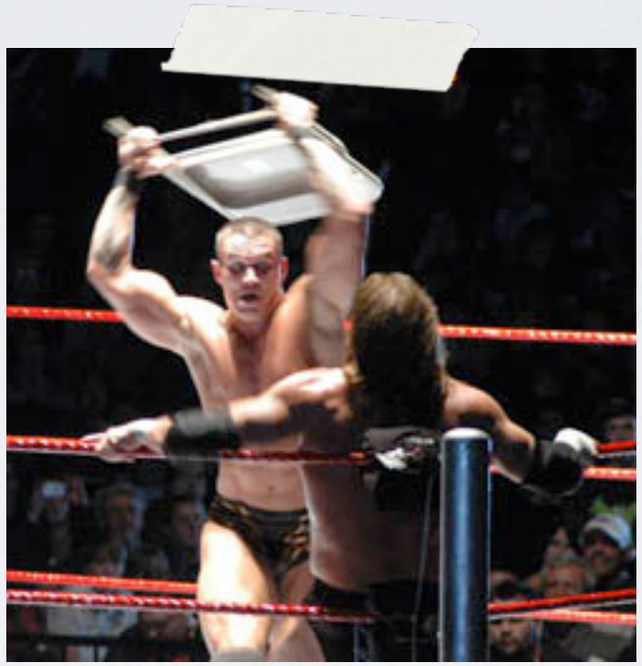
Firewalls: Brings the debate back in focus

Fuzzballs

Mathur et. al., BDC et. al.

Black hole complementarity

Susskind



Remnants

Ori

Please no chairs!

Observer Complementarity

Bousso, Harlow, Nomura et. el.

Holographic Spacetime

Banks et. al.

A history lesson: Information paradox

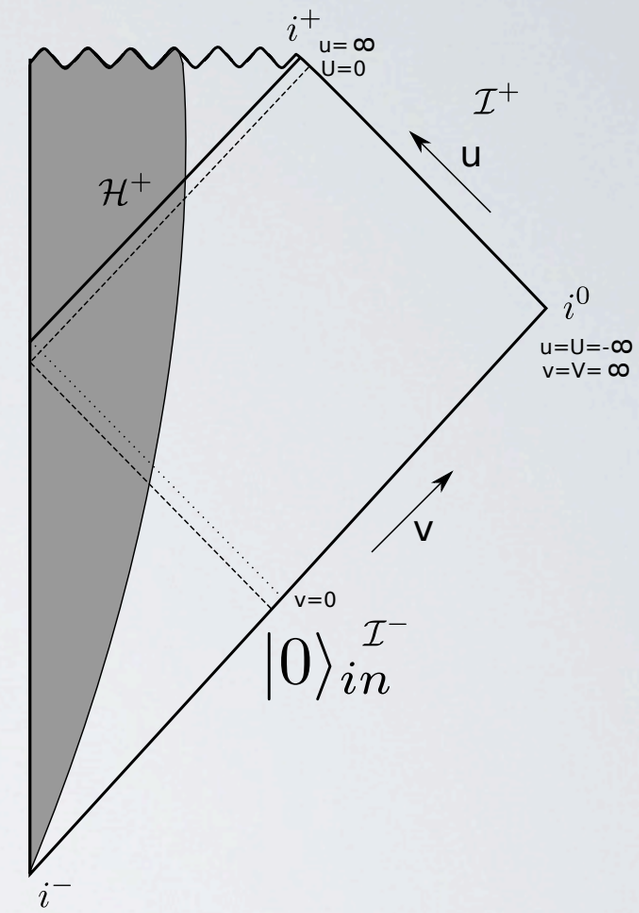
Semiclassical Gravity

Initial state: Shell + Unruh vacuum

Shell falls in making black hole

Tracing inside part of Unruh vacuum gives thermal state

Horizon Area measures



Entropy

Coarse Graining

Bekenstein, Zurek,
Sen, Strominger- Vafa

Entanglement

Remnants

A history lesson: Black Hole Complementarity

Idea

The observations of asymptotic and infalling observer do not commute

Postulates

Black hole S-matrix unitary

Semi-classical physics outside stretched horizon

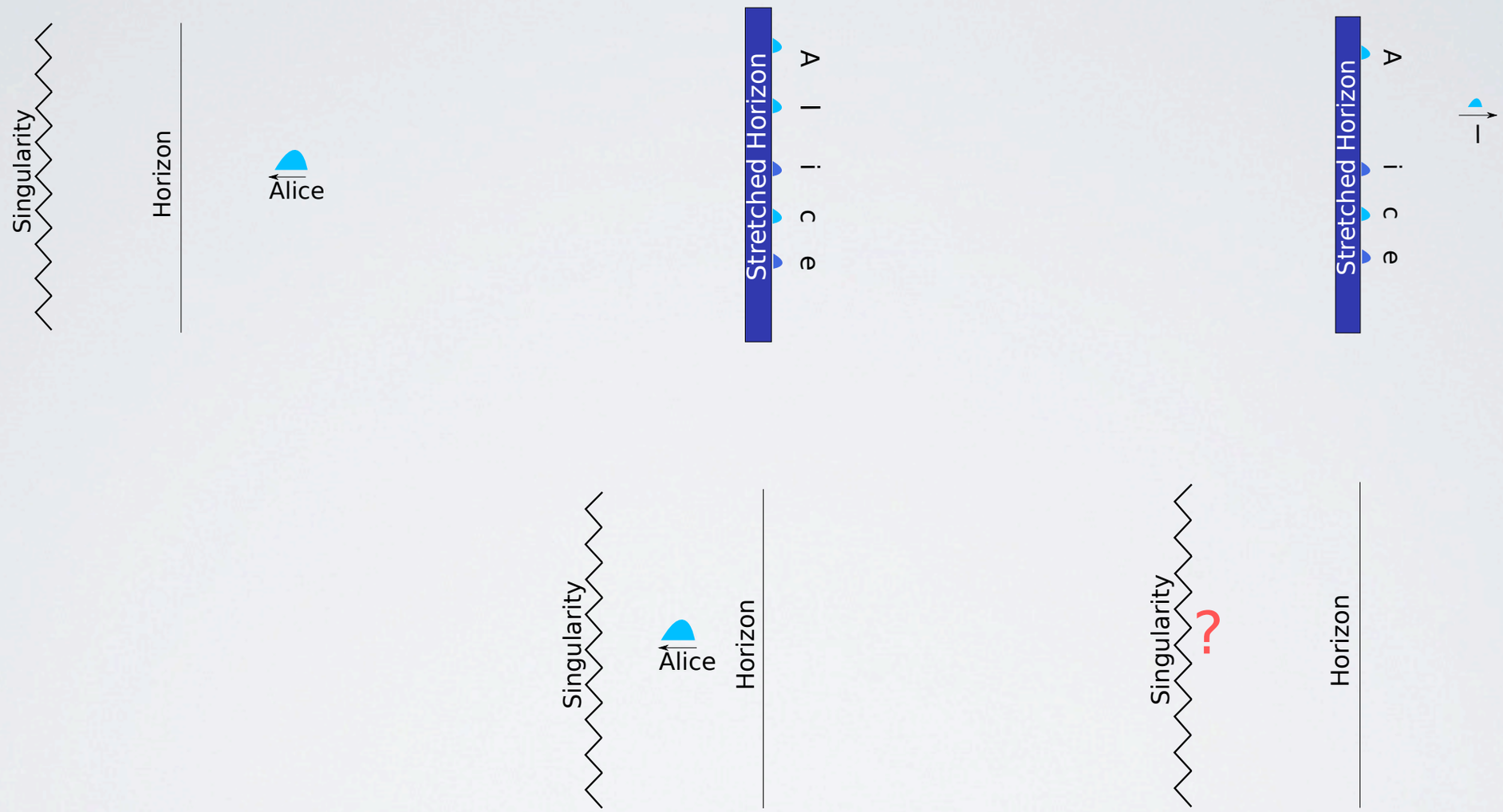
Membrane *for outside observer*

Free fall *for infalling observer*

Note that 1 and 4 are in tension

Its not clear how to see Hawking radiation in the first place

A history lesson: Black Hole Complementarity



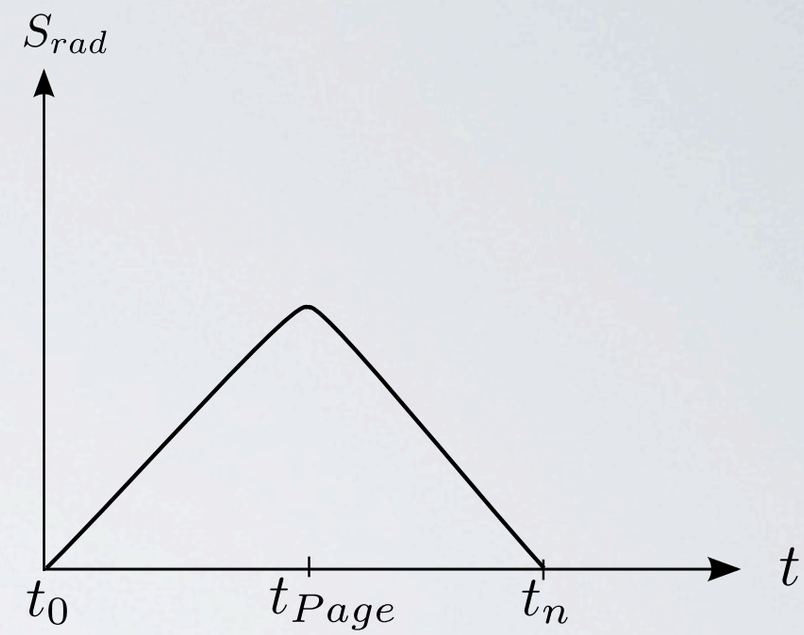
Stop gap procedure to reconcile GR and QM

Entropy in radiation from burning bodies

Page:

For typical state entropy rises and falls

For purity of final state entropy vanishing



Entropy in radiation from burning bodies

Mathur:

Traditional picture $S_{BC}=0$

Strong subadditivity

$$S_{AB} + S_{BC} \geq S_B + S_{ABC}$$

Subadditivity

$$S_{AB} \leq S_B + S_A$$

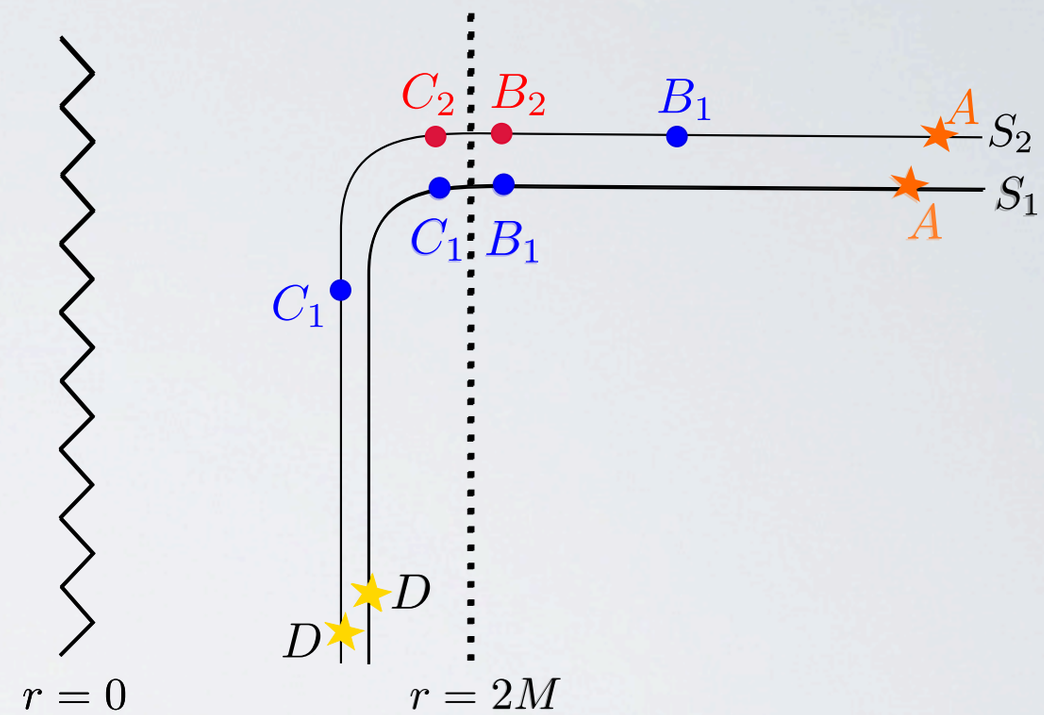
$$\boxed{S_{AB} > S_A}$$

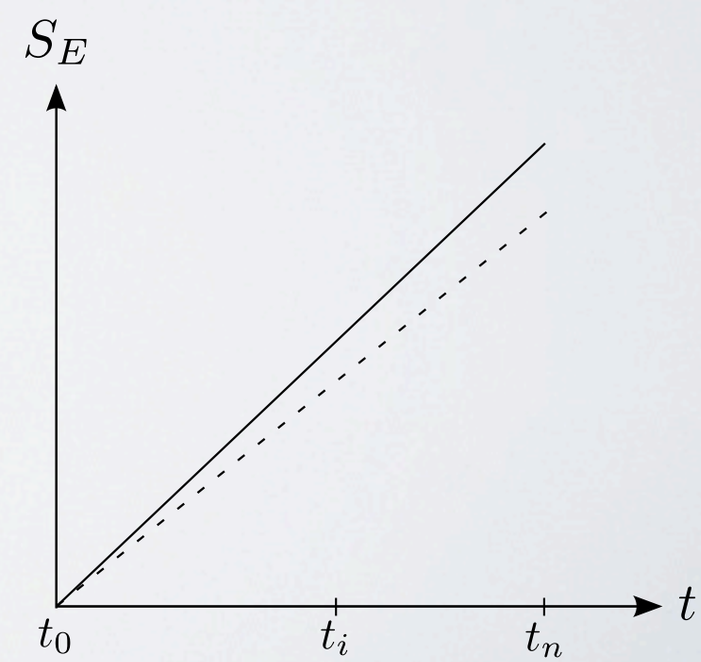
Small corrections do not fix this

(Mathur, Avery)

Horizon cannot be information free

Nice Slices





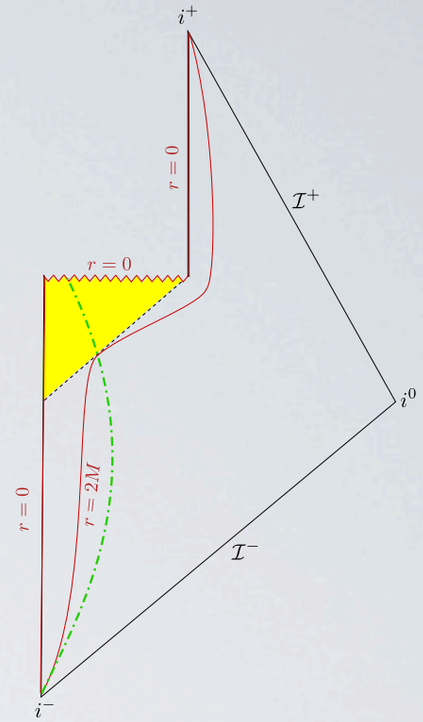
Fuzzballs

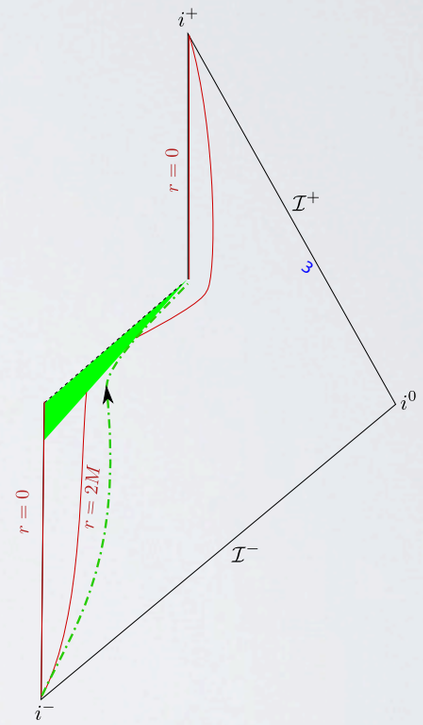
True states of quantum gravity?

Infalling shell tunnels into fuzzball solutions

Fuzzballs have no horizon or singularity

No information paradox; just like a piece of coal





All 2-charge fuzzballs

Lunin+Mathur, Lunin+Maldacena, Skenderis+Taylor

Many 3-charge

Bena, Warner, Gimon, Giusto, Saxena, Levi, JMaRT

Hawking radiation from JMaRT

BDC+Mathur

Possibility of complementarity

Mathur

A large resistance to fuzzballs because *black holes look good*

do they really?

Fuzzballs Before I go further, what is the conjecture?

Radiation from the non-extremal fuzzball; BDC, Mathur; 2008

....the geometries of [13] have an '**ergoregion instability**' ..... these decay modes are **exactly the 'Hawking radiation'** from these special microstates. ....such a result may seem **surprising, because the instability of [14] is a classical instability,** while one normally thinks of Hawking radiation as a weak, quantum process. But we will see that this **difference arises simply because in the microstates under study we have a 'large number of CFT excitations in the same state'.** Consider the radiation emitted by a gas of atoms. Each atom radiates independently, and if there are several different excited levels

Black Holes, Black Rings and their Microstates; Bena, Warner; 2007

In fact, one should be careful and distinguish two variants of this conjecture. The weak variant is that the black hole microstates are horizon-sized stringy configurations that have unitary scattering, **but cannot be described accurately using the supergravity approximation**. These configurations are also sometimes called "fuzzballs." If the weak Mathur conjecture were true then the typical bulk microstates would be configurations where the curvature is Planck scale, and hence cannot be described in supergravity. The strong form of Mathur's conjecture, which is better defined and easier to prove or disprove, is that among the typical black hole microstates there are smooth solutions that can be described using supergravity.

3-charge geometries and their CFT duals; Giusto, Mathur, Saxena; 2005

If we consider extremal holes, and look at states where in the dual CFT we have many component strings in the same state, **then we can have a good description of the geometry in classical supergravity.**

Dual geometries for a set of 3-charge microstates; Giusto, Mathur, Saxena; 2004

Note that in the 3-charge case (unlike the 2-charge case) **we do not expect the generic state to be well-described by a classical geometry; quantum fluctuations can be large**. But there would still be special cases that are in fact well described by a classical metric, and we can gain insight by constructing these explicitly.

Constructing 'hair' for the three charge hole; Mathur, Saxena, Srivastava; 2003

It is possible that the generic state is not well approximated by a classical configuration; what we do **expect** though on the basis of all that was said above is **that the region where the different states depart from each other will be of the order the horizon size and not just a planck sized region near the singularity.**

The last paper is *the first* paper to appear on 3-charge fuzzballs

Fuzzballs Before I go further, what is the conjecture?

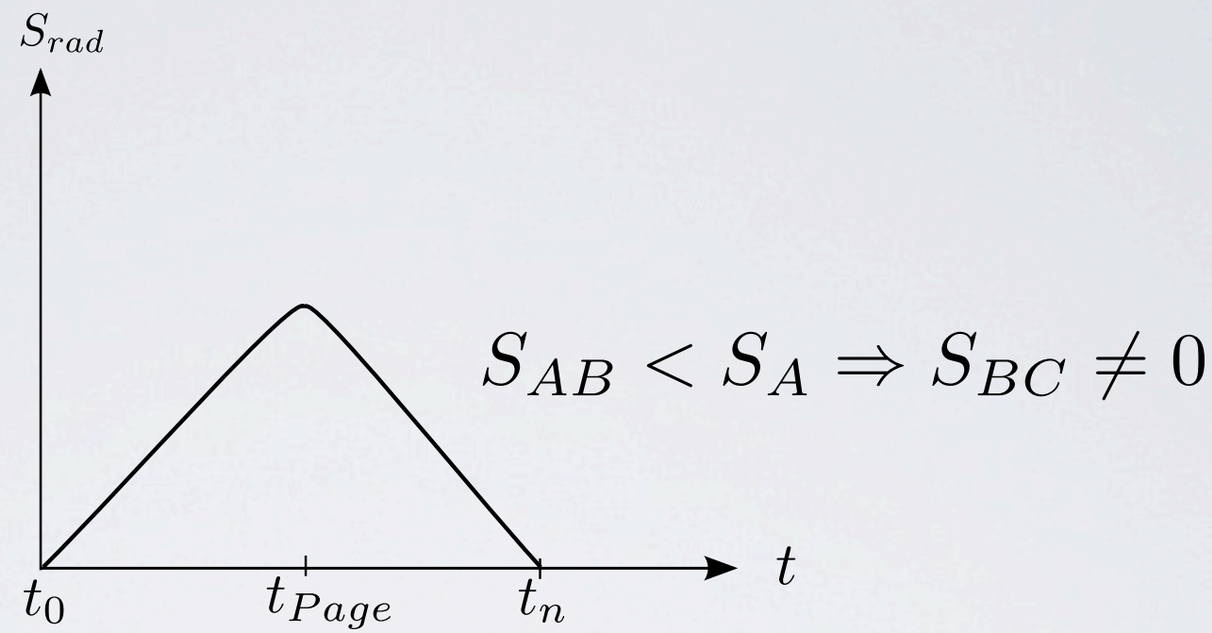
The conjecture says there are O(1) corrections to the horizon.

Does *not* say anything about actual states being describable by SUGRA

SUGRA was used because thats all we knew

Recent results of de Boer et. al. should be seen as critique of some techniques but one must not loose sight of the big picture.

AMPS: Two main arguments



1. Horizon cannot be pure state: not Unruh vacuum

after Page time

2. Blue shifted quanta B $S_{BC} \neq 0$ } Alice burns

Entire argument in infalling frame

Should *fuzzballers* be happy or sad about this?

AMPS: Review of assumptions

Assumptions:

Black hole S-matrix unitary

Semi-classical physics outside stretched horizon

Membrane *for outside observer*

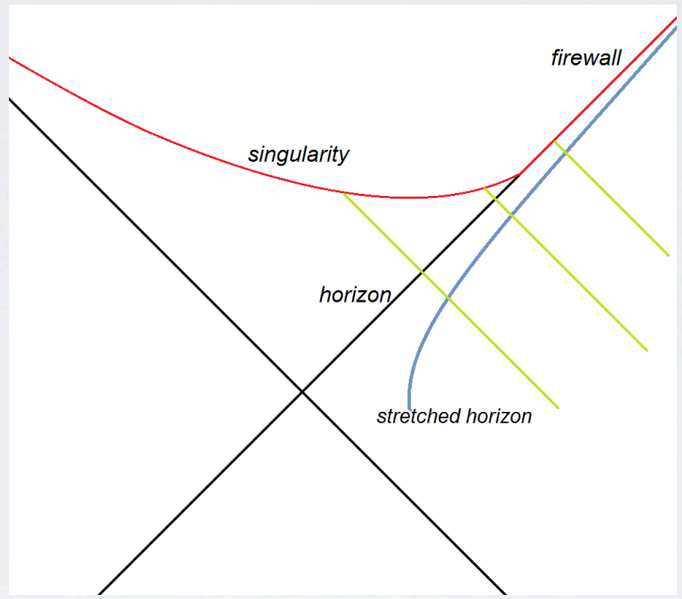
Free fall *for infalling observer*

Further conjecture:

maybe before Page time also

Some responses

Susskind: Firewall behind true horizon, cannot be before Page time, extension of singularity (no mechanism)



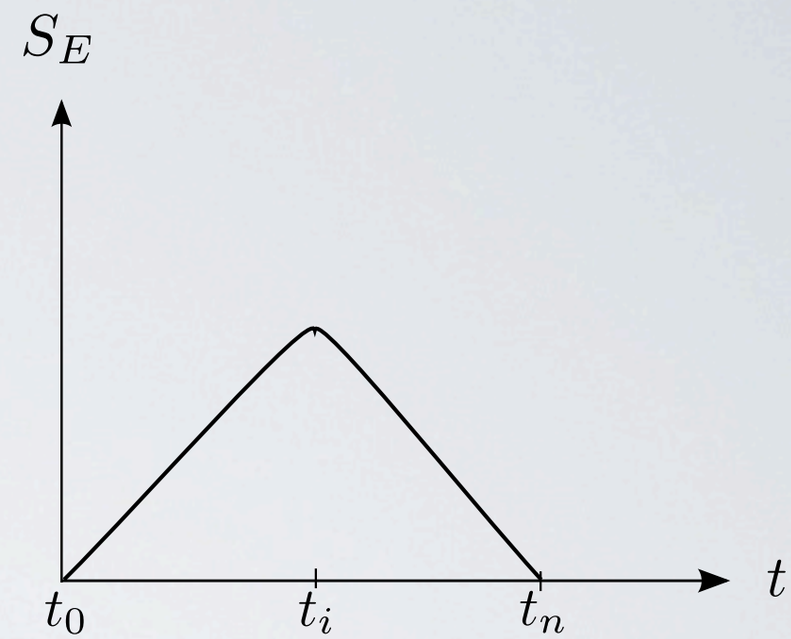
Bousso, Nomura (Harlow): Weaken postulate two - Observer complementarity

Mathur+Turton: Approx. Complementarity from fuzzballs

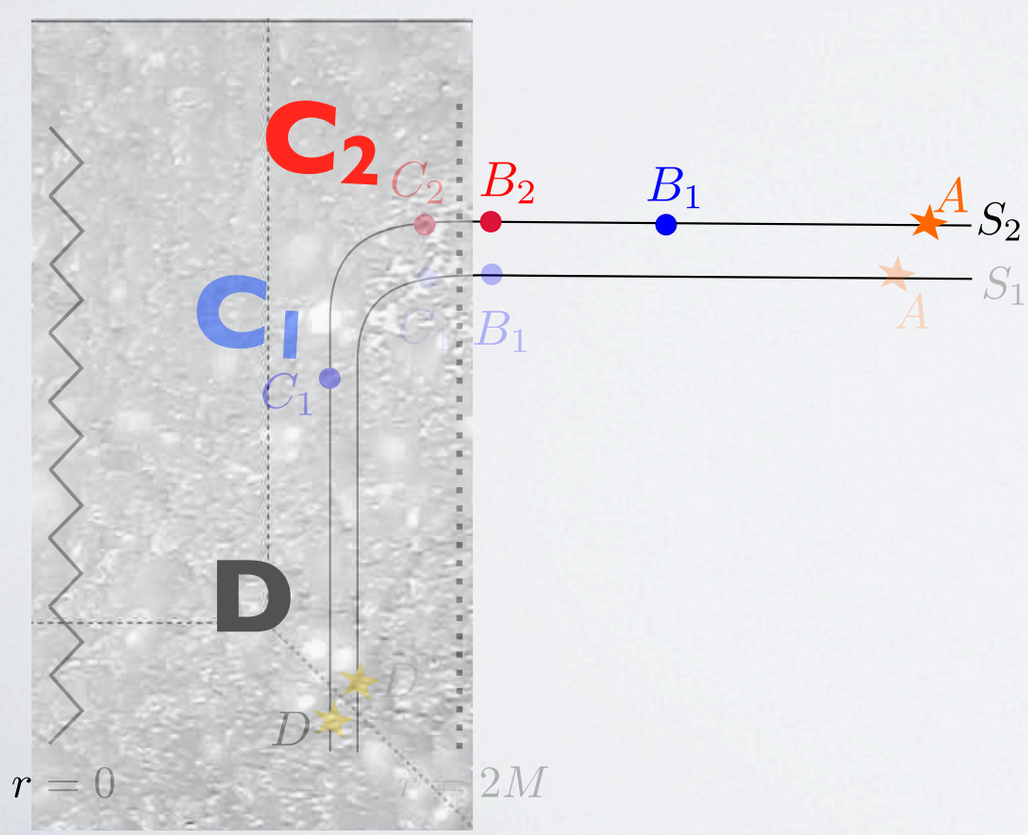
My response: Back to basics

Requirements for Unitarity

1. Purity of final state
2. Invertibility
3. Linearity
4. Preservation of norm



Previous discussion focussed only on point 1.



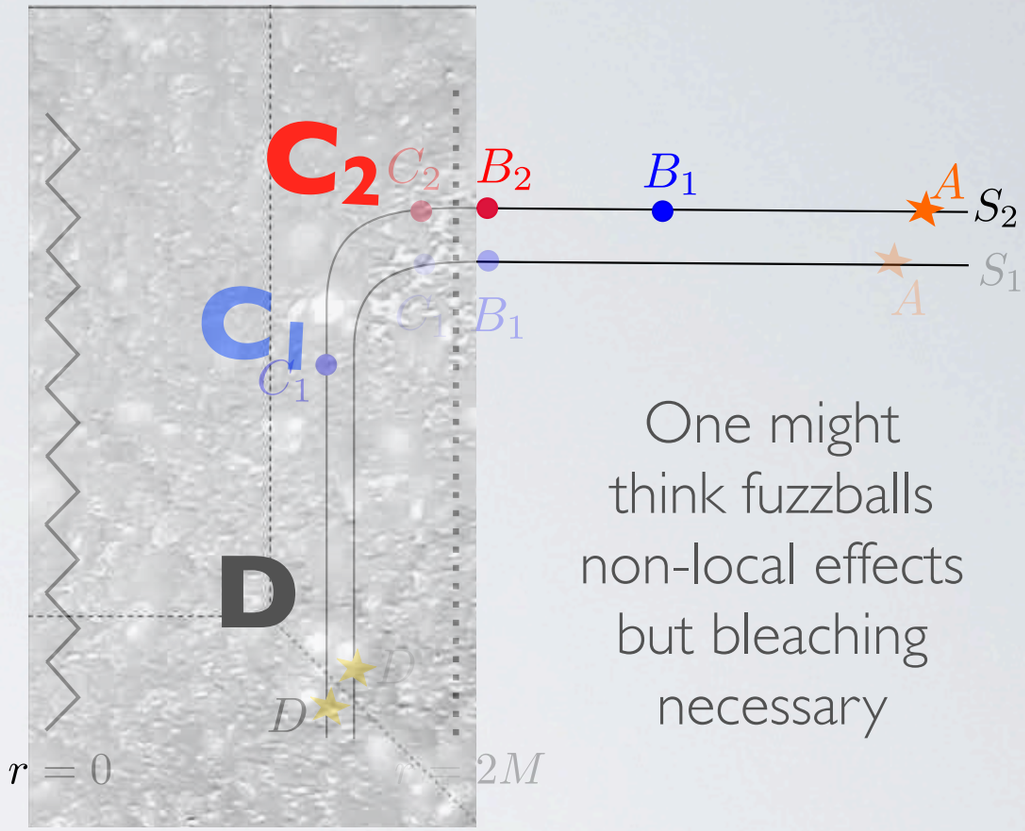
Introduce 'D' for $|\psi_i\rangle$

Do not need any *slices* for this argument

EPR

Invertible $|\psi_i\rangle \to |\psi_f\rangle$

B should *know about* D



One might think fuzzballs non-local effects but bleaching necessary

Hawking pair is like EPR:

$$|\rho_L\rangle\,|\uparrow_L\rangle|\downarrow_R\rangle + |\downarrow_L\rangle|\uparrow_R\rangle\,|\rho_R\rangle$$

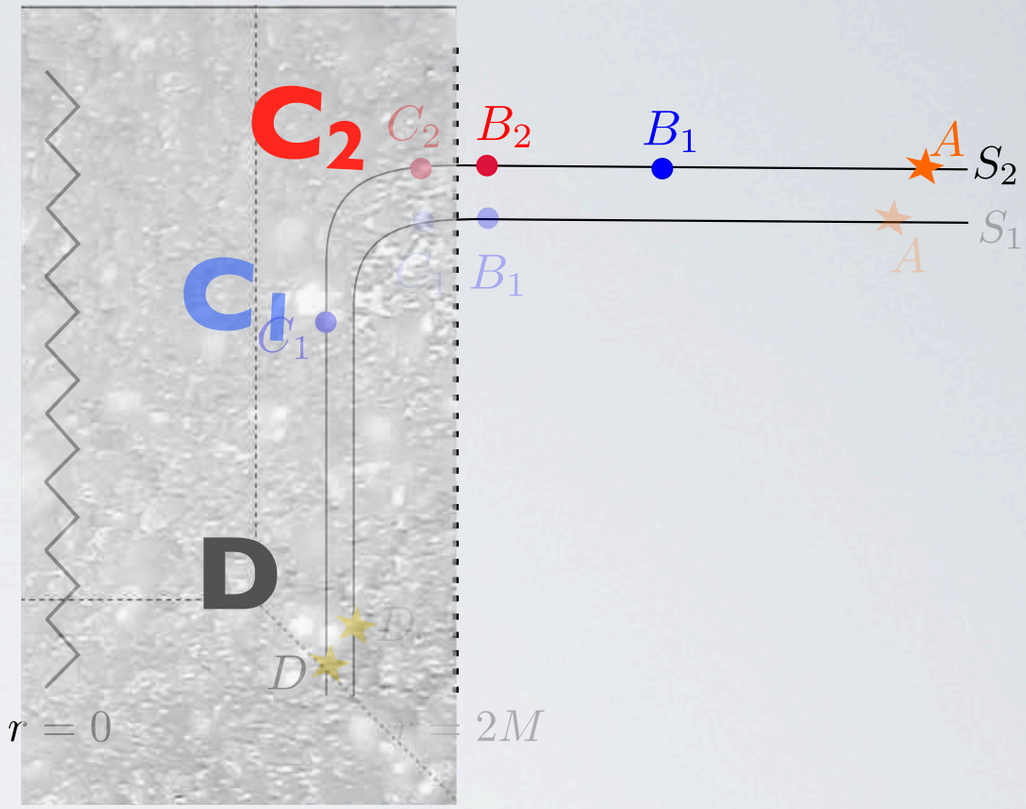
ρ_R does not *know* about Alice

Alice cannot communicate to Bob

No Bleaching, No information

Invertible $|\psi_i\rangle \rightarrow |\psi_f\rangle$

B should *know about* D



More formally

B should be a unitary map of a subsystem of D

Lack of quantum cloning means the said subsystem must be bleached

BC cannot be in a special state in general

Qubit models: "moving bit" model 1

Simplest evaporation model: move qubits from x to y

$$|\psi_0\rangle = |D_n^x\rangle \otimes \cdots \otimes |D_1^x\rangle = \prod_{j=n}^{1} |D_j^x\rangle$$

$$|\psi_i\rangle = \prod_{j=n}^{i-1} |D_j^x\rangle \otimes \prod_{k=i}^{1} |D_k^y\rangle$$

$$|\psi_n\rangle = \prod_{j=n}^{1} |D_j^y\rangle$$

think of typical states: D_j maximally entangled with $D_{!=j}$

Where are B and C?

Turns out it is possible to introduce auxiliary variables at each step

Have to trace over those in the end Avery

Qubit models: "moving bit" model 2

Evaporation with auxiliary states

$$|\psi_0\rangle = |D_n^x\rangle \otimes \cdots \otimes |D_1^x\rangle = \prod_{j=n}^{1} |D_j^x\rangle$$

$$|\psi_1\rangle = \prod_{j=n}^{2} |D_j^x\rangle \otimes |d_1^x\rangle \otimes |c_1^x\rangle \otimes |B_1^y\rangle$$

$$|\psi_i\rangle = \prod_{j=n}^{i+1} |D_j^x\rangle \otimes \prod_{k=1}^{i} \Big(|d_i^x\rangle \otimes |c_i^x\rangle\Big) \otimes \prod_{m=1}^{1} |B_m^y\rangle$$

$$|\psi_n\rangle = \prod_{j=1}^{n} \Big(|d_i^x\rangle \otimes |c_i^x\rangle\Big) \otimes \prod_{m=1}^{n} |B_m^y\rangle$$

To match previous model $|B_i^y\rangle = |D_i^y\rangle$

For unitarity auxiliary states have to be in fiducial form

$$|d_i^x\rangle \otimes |c_i^x\rangle = |\phi\rangle \otimes |\phi\rangle \qquad \forall\ i$$

fiducial form = bleaching = taking information out=no quantum cloning

Information in "moving bit" model

Using this simple "moving bit" model we see

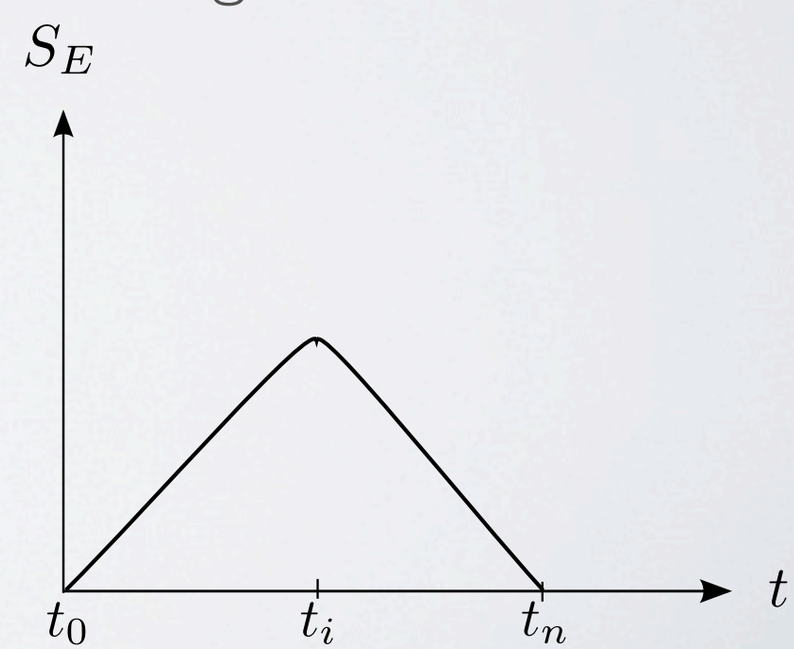
Information leaves at every step, not just after Page time

$$|B_i^y\rangle = |D_i^x\rangle$$

S_{BC} is not zero for any step

$$|c_i^x\rangle = |\phi\rangle$$

For 'typical' D, each *bit* B is maximally entangled with non-auxiliary part of BCD



Final state is pure

$|\psi_i\rangle \to |\psi_f\rangle$ invertible

Qubit models: more general models

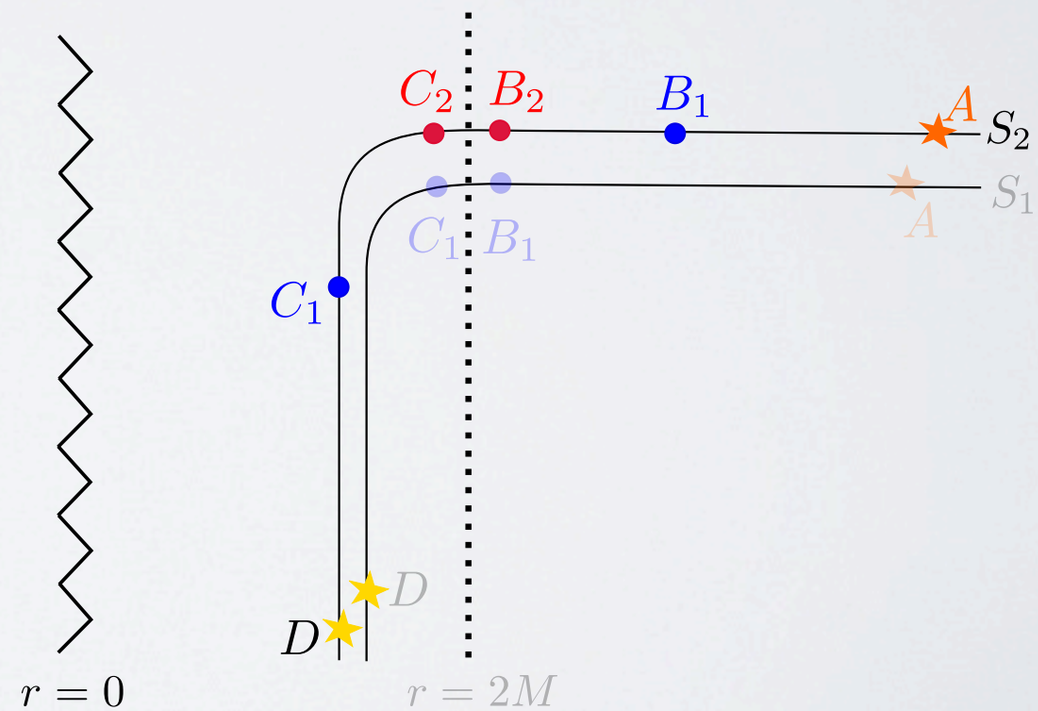
$$\rho_0 = |\psi_0\rangle\langle\psi_0| \qquad |\psi_0\rangle \in \mathrm{span}\{|\hat{q}_1 \cdots \hat{q}_n\rangle\}$$

$$\{|\hat{q}_1\hat{q}_2\cdots\hat{q}_{n+i}\rangle|q_i q_{i-1}\cdots q_1\rangle\} \xrightarrow{C_i} \{|\hat{q}_1\hat{q}_2\cdots\hat{q}_{n+i}\hat{q}_{n+i+1}\rangle|q_{i+1}q_i q_{i-1}\cdots q_1\rangle\}$$
$$\xrightarrow{\hat{U}_i\otimes U_i} \left\{\hat{U}|\hat{q}_1\hat{q}_2\cdots\hat{q}_{n+i}\hat{q}_{n+i+1}\rangle U|q_{i+1}q_i q_{i-1}\cdots q_1\rangle\right\}$$

$$\rho_n = tr_{aux}[U(\rho_{aux}\otimes\rho_0)U^\dagger]$$

Physical motivation

$$|\hat{q}_1\hat{q}_2\hat{q}_3\rangle_{\text{initial}}\,|\hat{1}_4\hat{0}_5\rangle_{\text{infalling}}\,|0_2 1_1\rangle_{\text{outgoing}}$$



Qubit models: more general models

$$\{|\hat{q}_1\hat{q}_2\cdots\hat{q}_{n+i}\rangle|q_iq_{i-1}\cdots q_1\rangle\} \xrightarrow{C_i} \{|\hat{q}_1\hat{q}_2\cdots\hat{q}_{n+i}\hat{q}_{n+i+1}\rangle|q_{i+1}q_iq_{i-1}\cdots q_1\rangle\}$$
$$\xrightarrow{\hat{U}_i\otimes U_i} \left\{\hat{U}|\hat{q}_1\hat{q}_2\cdots\hat{q}_{n+i}\hat{q}_{n+i+1}\rangle U|q_{i+1}q_iq_{i-1}\cdots q_1\rangle\right\}$$

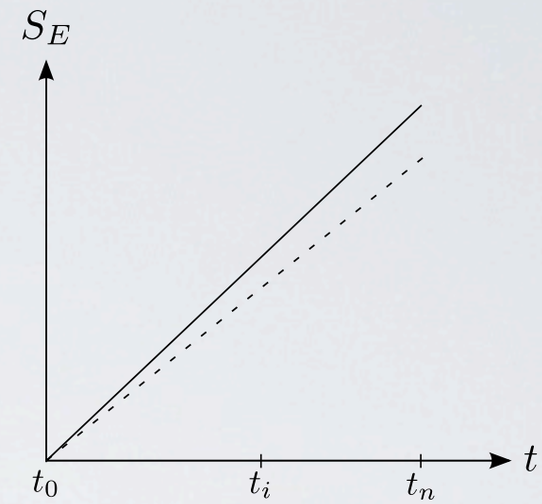
Linearity and norm preservation $(C_i)^\dagger C_i = I$

$$e^{\hat{c}^\dagger b^\dagger}|\hat{0}0\rangle \longrightarrow \begin{aligned}
|\varphi_1^i\rangle &= \frac{1}{\sqrt{2}}\left(|\hat{0}_{n+i+1}\rangle|0_{i+1}\rangle + |\hat{1}_{n+i+1}\rangle|1_{i+1}\rangle\right)\\
|\varphi_2^i\rangle &= \frac{1}{\sqrt{2}}\left(|\hat{0}_{n+i+1}\rangle|0_{i+1}\rangle - |\hat{1}_{n+i+1}\rangle|1_{i+1}\rangle\right)\\
|\varphi_3^i\rangle &= |\hat{0}_{n+i+1}\rangle|1_{i+1}\rangle\\
|\varphi_4^i\rangle &= |\hat{1}_{n+i+1}\rangle|0_{i+1}\rangle\,,
\end{aligned}$$

$$(C_i)^\dagger C_i = \hat{P}_1^\dagger\hat{P}_1 + \hat{P}_2^\dagger\hat{P}_2 + \hat{P}_3^\dagger\hat{P}_3 + \hat{P}_4^\dagger\hat{P}_4 = \hat{I}.$$

Qubit models: more general models

Hawking model: $C_i^H = |\varphi_1\rangle \otimes \hat{I}$



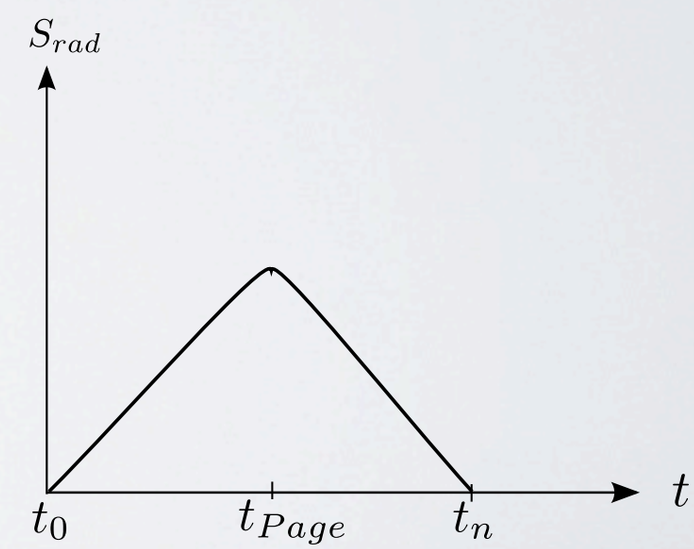
$n \log 2$

Burning Paper:

$$C_i = |\hat{0}_{n+i+1}\rangle\, |1_i\rangle \otimes \left[|\hat{1}\hat{0}\rangle \langle \hat{1}\hat{1}| + \frac{1}{\sqrt{2}} |\hat{0}\hat{0}\rangle \langle \hat{1}\hat{0}| + \frac{1}{\sqrt{2}} |\hat{0}\hat{0}\rangle \langle \hat{0}\hat{1}| \right]_{n+i-1,n+i}$$
$$+ |\hat{0}_{n+i+1}\rangle\, |0_i\rangle \otimes \left[|\hat{0}\hat{0}\rangle \langle \hat{0}\hat{0}| + \frac{1}{\sqrt{2}} |\hat{1}\hat{0}\rangle \langle \hat{1}\hat{0}| - \frac{1}{\sqrt{2}} |\hat{1}\hat{0}\rangle \langle \hat{0}\hat{1}| \right]_{n+i-1,n+i} .$$

Moving bit:

$$C_i = |\hat{0}0\rangle_{\text{pair}} \otimes |\hat{0}\rangle\langle\hat{0}|_{\frac{n}{2}+i} + |\hat{0}1\rangle_{\text{pair}} \otimes |\hat{0}\rangle\langle\hat{1}|_{\frac{n}{2}+i}.$$



Qubit models: more general models

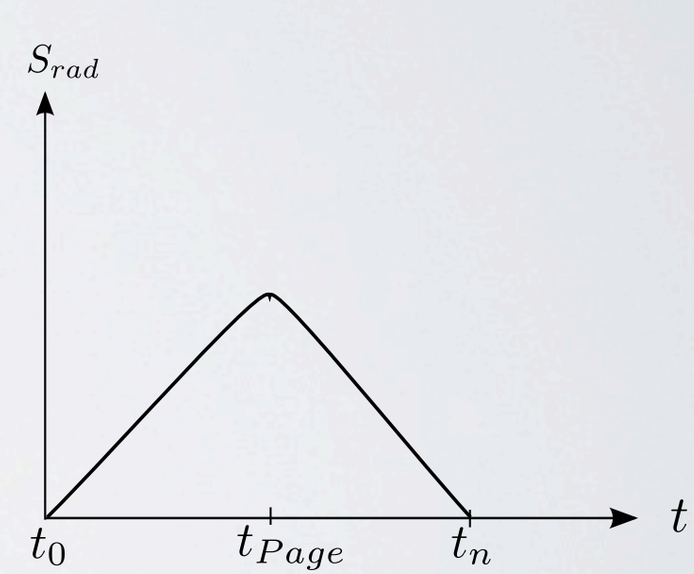
A model *like* AMPS/ Susskind (S_{BC}=0 before Page time):

Hawking before Page time $\quad C_i^H = |\varphi_1\rangle \otimes \hat{I} \qquad i < \frac{n}{2}$

Moving bit *acting on old infalling quanta* after Page time

$$C_i = |\hat{0}0\rangle_{\text{pair}} \otimes |\hat{0}\rangle\langle\hat{0}|_{\frac{n}{2}+i} + |\hat{0}1\rangle_{\text{pair}} \otimes |\hat{0}\rangle\langle\hat{1}|_{\frac{n}{2}+i} \qquad i > \frac{n}{2}$$

$$\begin{aligned}
&|\hat{q}_1 \cdots \hat{q}_4\rangle \\
&\longrightarrow \frac{1}{\sqrt{2}}|\hat{q}_1 \cdots \hat{q}_4\rangle(|\hat{0}0\rangle + |\hat{1}1\rangle) \\
&\longrightarrow \frac{1}{2}|\hat{q}_1 \cdots \hat{q}_4\rangle(|\hat{0}\hat{0}00\rangle + |\hat{0}\hat{1}10\rangle + |\hat{1}\hat{0}01\rangle + |\hat{1}\hat{1}11\rangle) \\
&\longrightarrow \frac{1}{2}|\hat{q}_1 \cdots \hat{q}_4\hat{0}\rangle(|\hat{0}\hat{0}000\rangle + |\hat{1}\hat{0}010\rangle + |\hat{0}\hat{0}101\rangle + |\hat{1}\hat{0}111\rangle) \\
&\longrightarrow \frac{1}{2}|\hat{q}_1 \cdots \hat{q}_4\hat{0}\hat{0}\hat{0}\hat{0}\rangle(|0000\rangle + |1010\rangle + |0101\rangle + |1111\rangle).
\end{aligned}$$



Each quanta after Page time maximally entangled with early system

Information never came out

Non-unitary!!!

General lessons

If Hilbert space is preserved $S_{BC}=0$ for even a single step causes loss of unitarity

Zurek showed that irreversible black hole radiation $S_{rad} = \frac{4}{3} S_{BH}$

reversible black hole radiation $S_{rad} = S_{BH}$

Do not expect black hole properties to depend on how they form or evaporate.

In any case, effects of irreversibility should be spread out

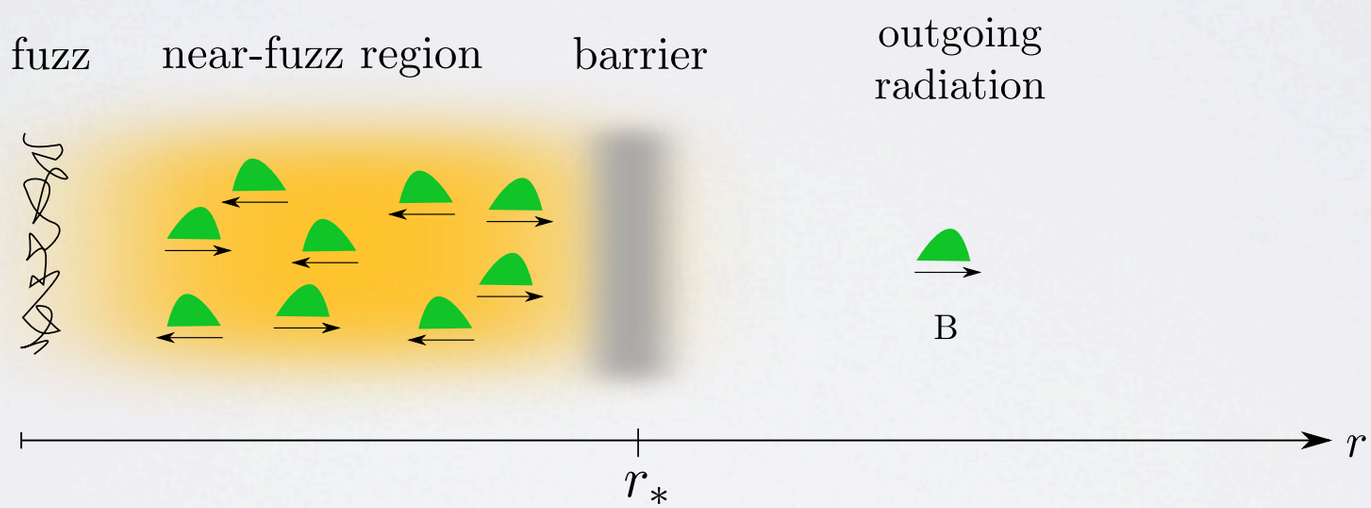
Unitarity requires horizon to *not* be in Unruh vacuum

Fuzzballs: Falling into fuzzballs

Fuzzballs - atypical vs typical

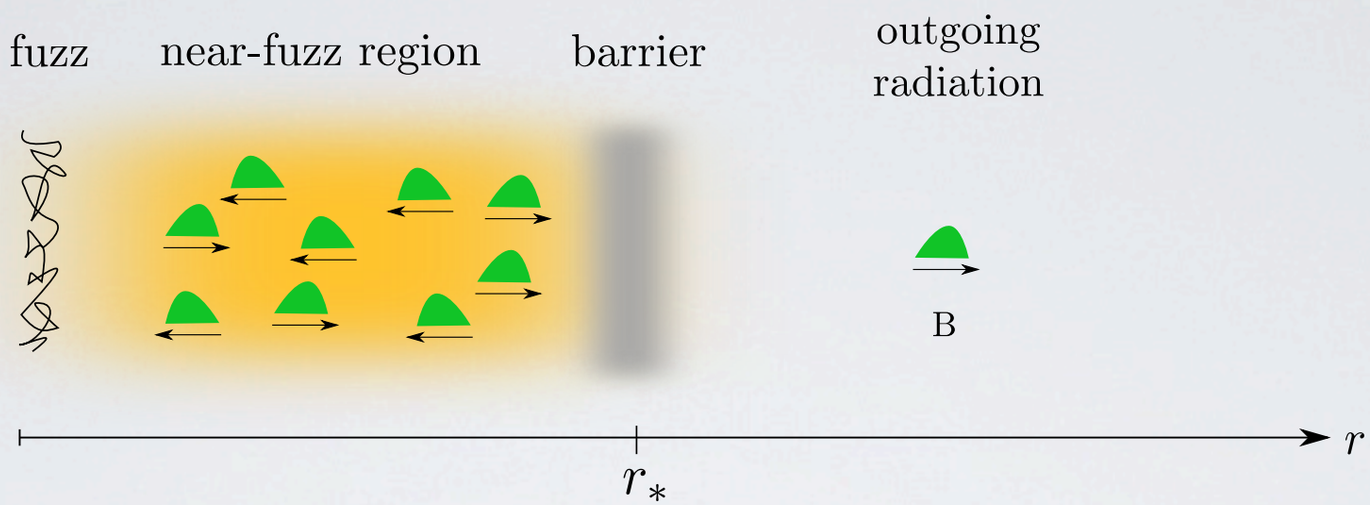
Lots of experience with atypical: Ergoregion instability is Bose enhanced Hawking radiation (BDC,Mathur)

What about typical fuzzballs?

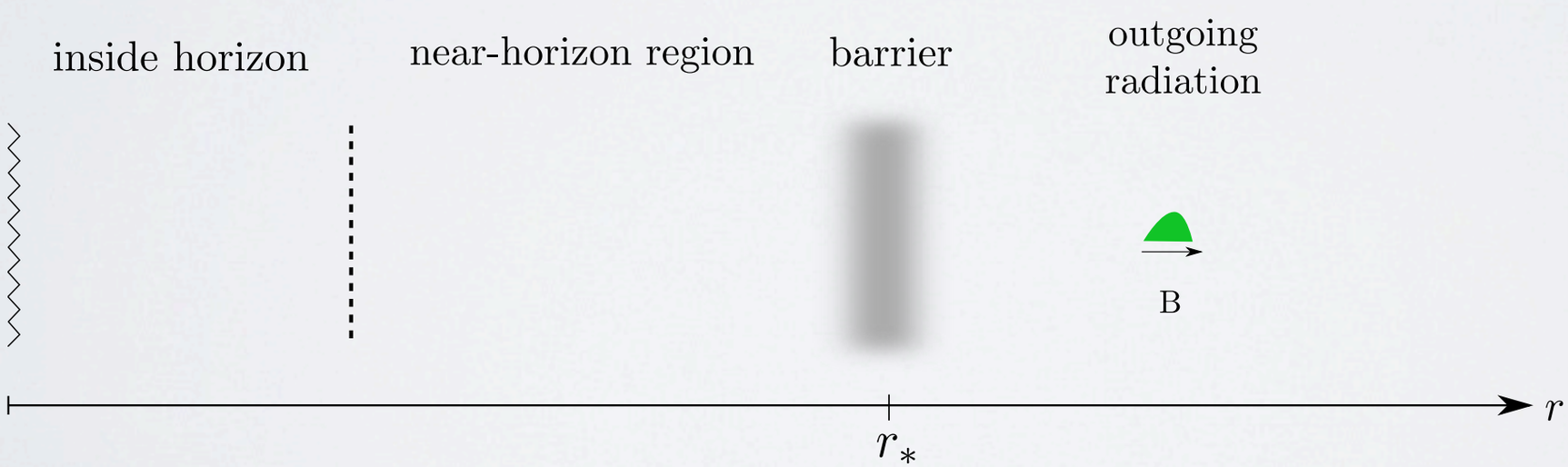


AMPS' argument in the near fuzz region: cannot talk about isolated quantum DAUNTING TASK! But only then can one talk about firewalls!

Fuzzballs: Fuzzball Complimentarity (conjecture)



Can approximate region $r < r_*$ $t < t_{em} \sim GM$



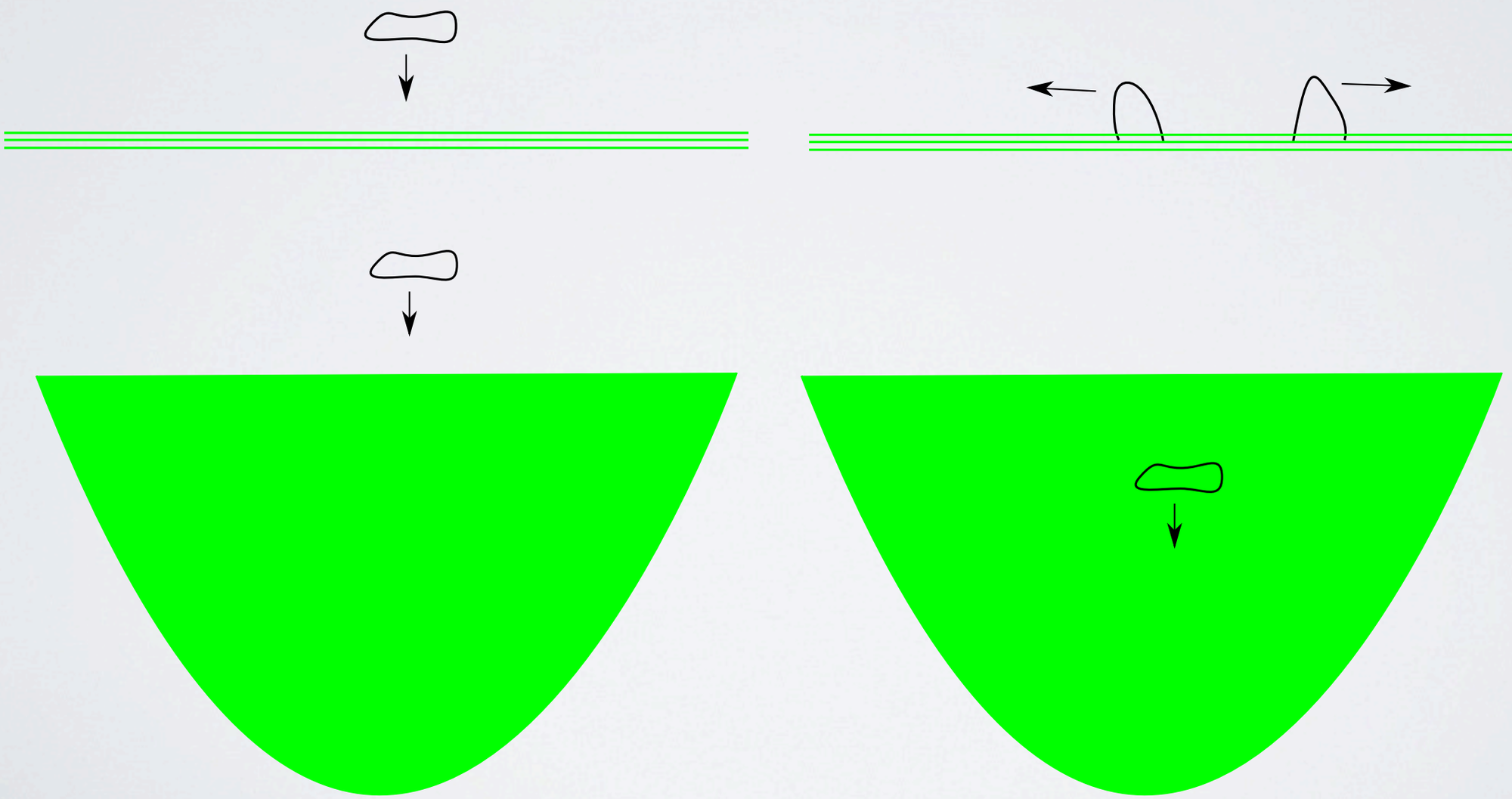
High energy quanta E >> kT (asymptotic) see black hole

Typical quanta E ~ kT (asymptotic) do not see black hole

Fuzzballs: Possibility of complementarity

We already have an example: AdS/CFT

Das+Mathur, Madlacena+Strominger, Lunin-Mathur, BDC+Mathur



Fuzzballs: Possibility of complementarity

For this part we use AdS/CFT but expect lessons more general

Start with atypical state in CFT dual to infalling shell

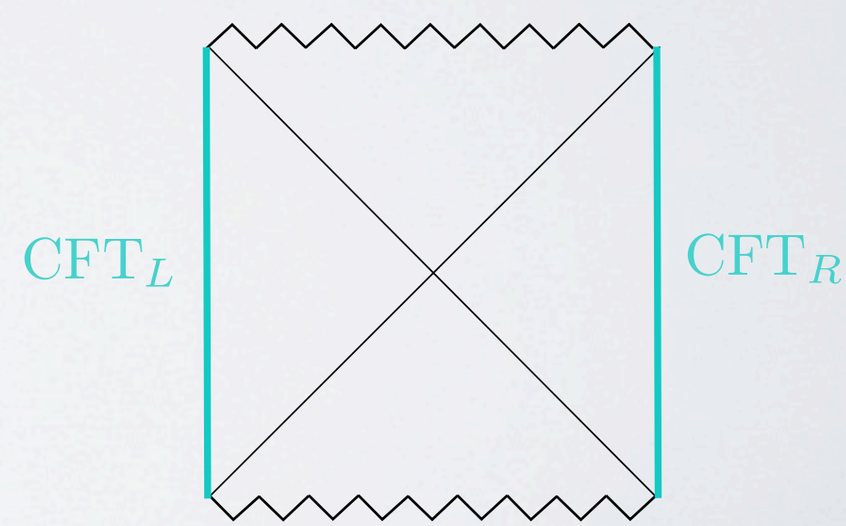
Becomes typical

$$\langle\psi|\hat{O}|\psi\rangle \approx Tr(\rho\hat{O}) = \frac{1}{\sum_i e^{-\frac{E_i}{kT}}} \sum_k e^{-\frac{E_k}{kT}} \ \langle E_k|\hat{O}|E_k\rangle$$

Density matrices can be *purified*

$$|\Psi\rangle = \frac{1}{\sqrt{\sum_i e^{-\frac{E_i}{kT}}}} \sum_k e^{-\frac{E_k}{2kT}} |E_k\rangle_L \otimes |E_k\rangle_R$$

Maldacena: Such entangled CFTs dual to eternal AdS black hole

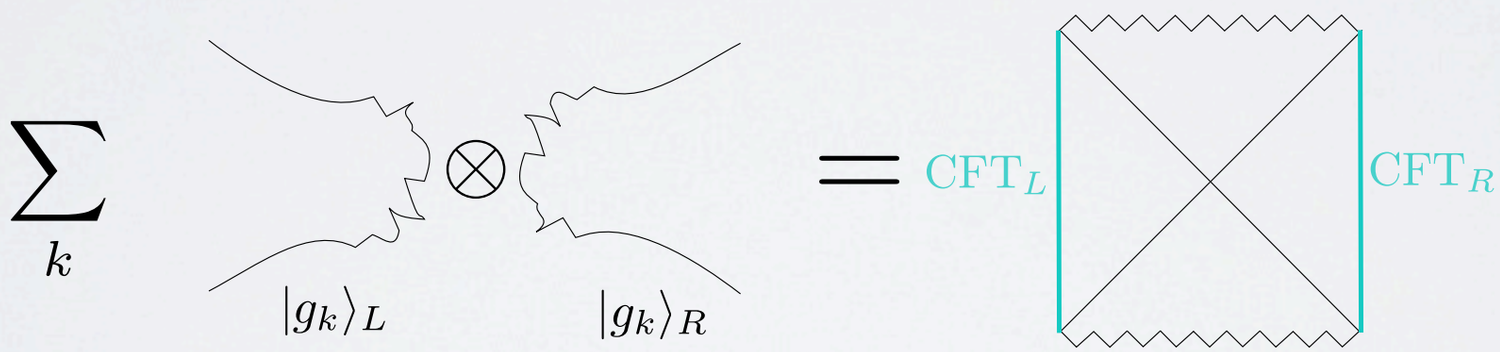


Fuzzballs: Possibility of complementarity

Using AdS/CFT each CFT state dual to (at least asymptotically) gravitational solution

CFT $$|\Psi\rangle = \frac{1}{\sqrt{\sum_i e^{-\frac{E_i}{kT}}}} \sum_k e^{-\frac{E_k}{2kT}} |E_k\rangle_L \otimes |E_k\rangle_R$$

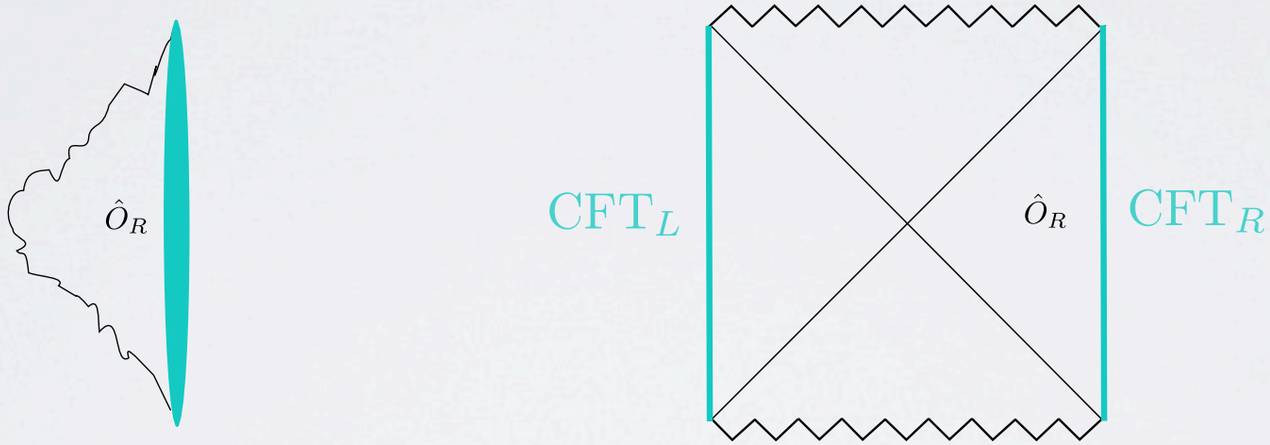
Bulk $$|G\rangle_{eternal} = \frac{1}{\sqrt{\sum_i e^{-\frac{E_i}{kT}}}} \sum_k e^{-\frac{E_k}{2kT}} |g_k\rangle_L \otimes |g_k\rangle_R$$



Fuzzballs: Possibility of complementarity

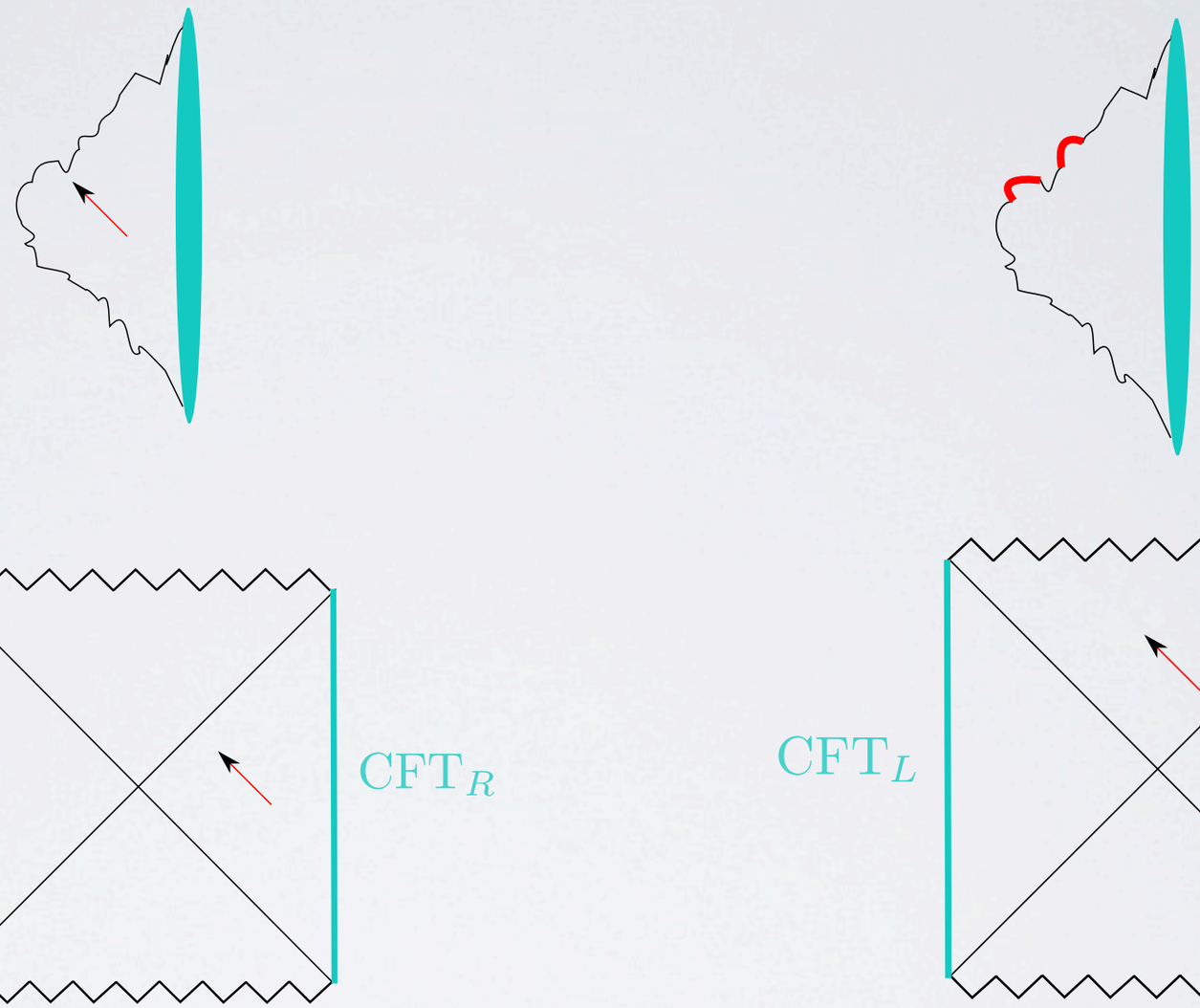
CFT $\quad {}_R\langle\psi|\hat{O}_R|\psi\rangle_R \approx \langle\Psi|\hat{O}_R|\Psi\rangle$

Bulk $\quad {}_R\langle\psi_g|\hat{O}_R|\psi_g\rangle_R \approx \langle G|\hat{O}_R|G\rangle.$



Fuzzballs: Possibility of complementarity

Conjecture: Similar story for observables capturing infall



Fuzzballs: Possibility of complementarity

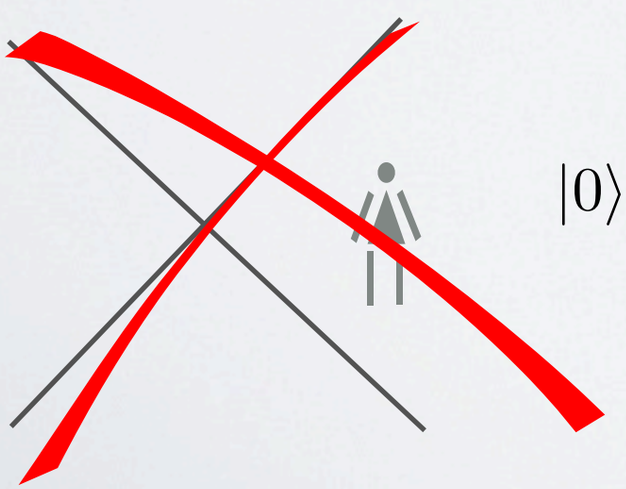
Is Alice burning or fuzzing?

B entangled with D and A *both*

Spacetime *behind* the horizon and the singularity are a short lived t~M approximate description

Alice's encounter with B is strong (AMPS)

inconsistent to look at that in isolation



Unruh radiation

$$|0\rangle = \sum e^{-E/2} |E\rangle_L \otimes |E\rangle_R$$

Fuzzballs: Possibility of complementarity

Is Alice burning or fuzzing?

Alice's encounter with BD is strong

Approximate complementarity arguments show the BD system should be replaced by *temporary picture* with horizon and singularity *not just D*

Conclusions

In the fuzzball conjecture infalling Hawking quanta auxiliary

S_{BC} is *not* zero if unitarity is to be preserved

Approximate complementarity different from Black hole complementarity

Inside of black hole only for $E \gg kT$

temporary description of emergent space from fuzz

Low energy quanta $E \sim kT$ part of fuzzball structure

carry out information, *no free infall*

such infalling quanta will undergo Brownian motion

Is Alice burning or fuzzing?

Alice! Alice! Who the f*** is Alice?