Title: Unitarity, black hole microstates and how Alices fuzzes but may not even know it

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Abstract: The information paradox and the infall problem have been long-standing puzzles in the understanding of black holes. The idea of free infall is in considerable tension with unitarity of the evaporation process and recent developements have made this tension sharp. In the first part of my talk I will address the information question and argue that unitarty requires every quantum of radiation leaving the black hole to carry information about the initial state. Unitary evaporation is thus inconsistent with an information-free horizon at every step of the evaporation process and this extends the recent firewall result. This immediately raises the question of What is the required horizon-scale structure? I will show an explicit construction of near-extremal black hole microstates which put flesh and branes on the fuzzball proposal and may realize firewalls in string theory. In the second part I will address the question of What happens to an observer falling into a fuzzball? I will argue that the answer is dependent on the energy scale of the infalling observer.

Unitarity, black hole microstates and how Alices fuzzes but may not even know it

Andrea Puhm

IPhT, CEA/Saclay

based on

1210.6996	with S. G. Avery, B. D. Chowdhury
1208.2026	with B. D. Chowdhury
1208.3468 and 1109.5180	with I. Bena and B. Vercnocke

Perimeter Institute Seminar 2012

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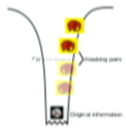
Outline

1. Introduction: What it takes to be pure.
2. Unitarity:



When and how does the *original* information come out?

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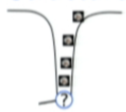

What is the horizon-scale structure?

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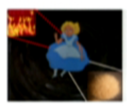

Is Alice burning or fuzzing?

5. Summary and Outlook

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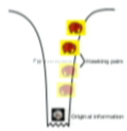

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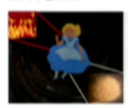

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Black hole complementarity

[Susskind, Thorlacius, Uglum]

Motivation: Reconciliation of unitary evaporation and free infall.

*I*dea: Experience of asymptotic and infalling observer are different.

Postulates:

1. Black hole evolution via unitary S-matrix for *outside* observer.
2. Semi-classical physics valid outside stretched horizon.
3. To distant observer black hole appears as a *membrane*.
4. An *infalling* observer falls freely through horizon of large black hole.

What is the *mechanism* for the membrane?

Pure evaporation [Page]

If **black hole** in a typical pure state and *assume* unitary evaporation:

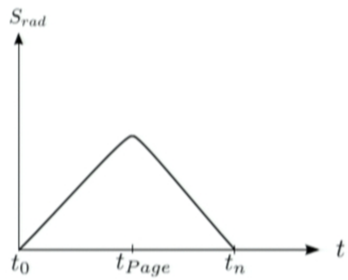


Figure: *Pure evaporation.*

reduced density matrix:

$$\rho_{\rm rad} = {\rm Tr}_{BH}\ \rho_{\rm (BH+rad)}$$

von Neumann entropy:

$$S_{\rm rad} = -{\rm Tr}\ (\rho_{\rm rad}\ \log\ \rho_{\rm rad})$$

As long as radiation smaller part $S_{\rm rad}$ grows.

When black hole is smaller part $S_{\rm rad}$ falls.

For *purity* of final state: $S_{\rm rad}(t_n) = 0$!

Hawking evaporation

[Mathur]

If evaporation via Hawking-pair production:

BC system maximally entangled: $S_{BC} = 0$

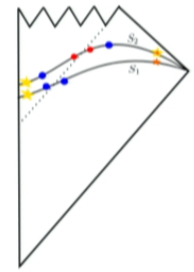
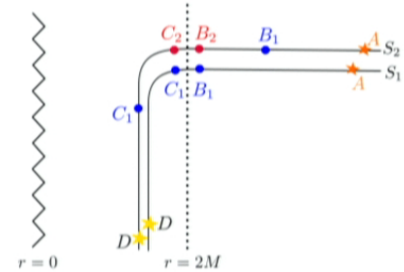


Figure: *Nice spatial slices.*



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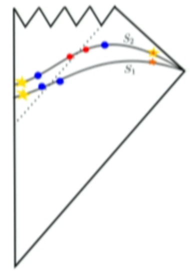

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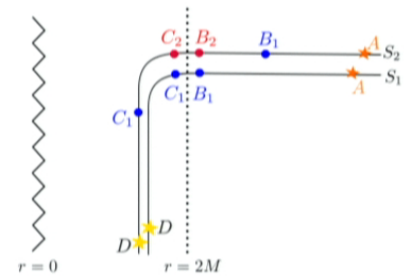

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(s) **Subadditivity**:

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

(ss) **Strong subadditivity** $+ \; S_{BC} = 0$:

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

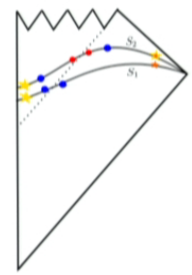
(s) + (ss) :

$$S_{AB} = S_A + S_B$$

A and B are not correlated!

$$S_{AB} \geqslant S_A$$

Entropy of radiation via Hawking pair creation never decreases!



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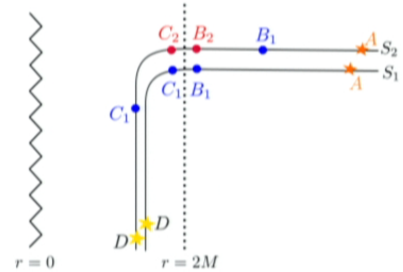

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The large corrections argument

[Mathur; Avery]

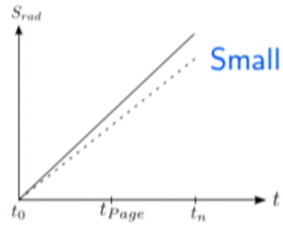


Figure: *Black hole evaporation.*

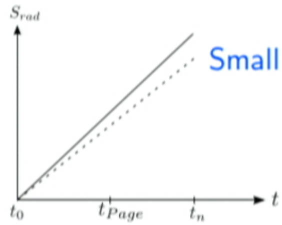
Small corrections cannot bend the entropy curve!

For *purity* of the final radiation state:

Large corrections to Unruh vaccum needed!

There cannot be an information free horizon!

The large corrections argument [Mathur; Avery]



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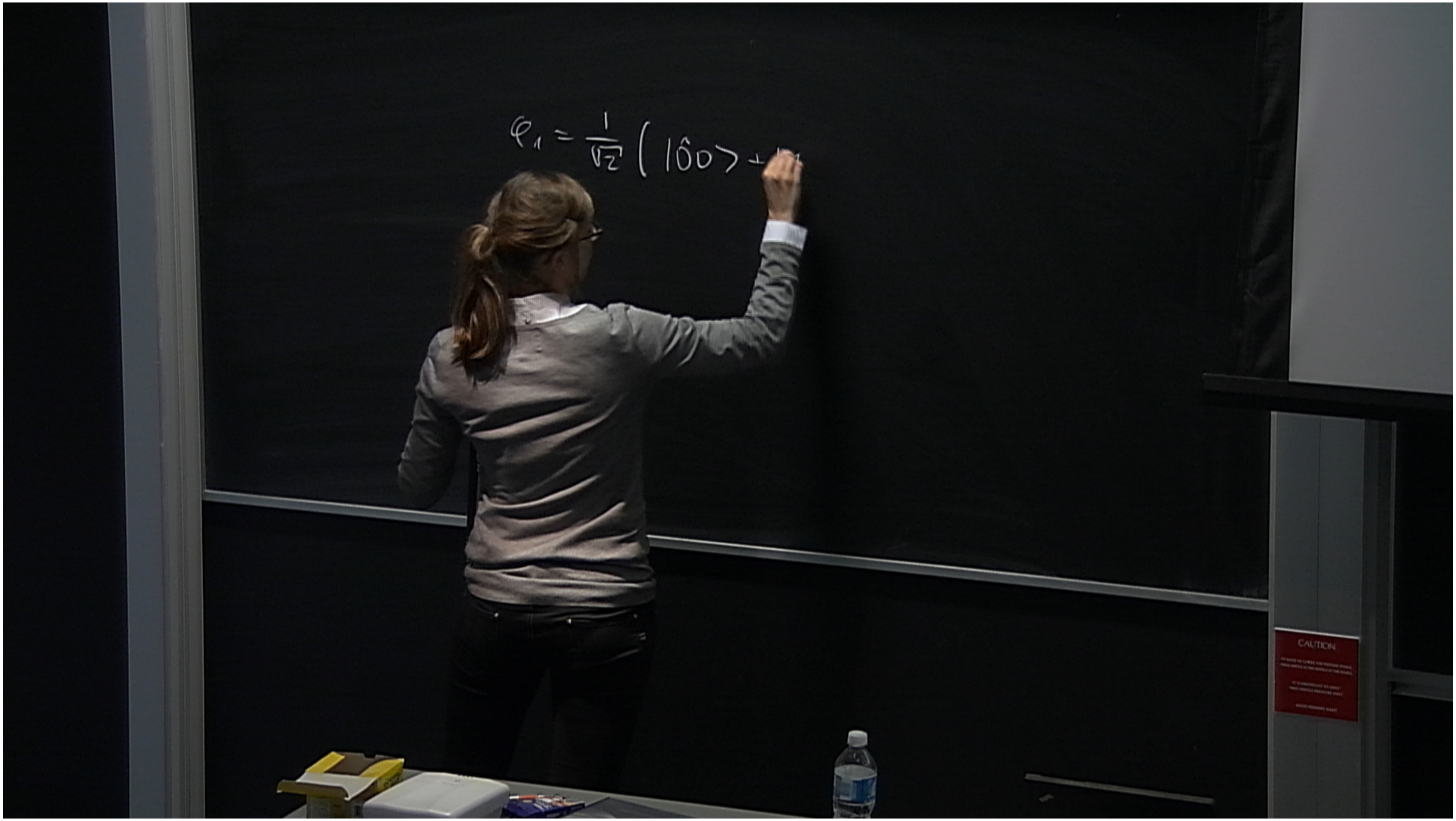
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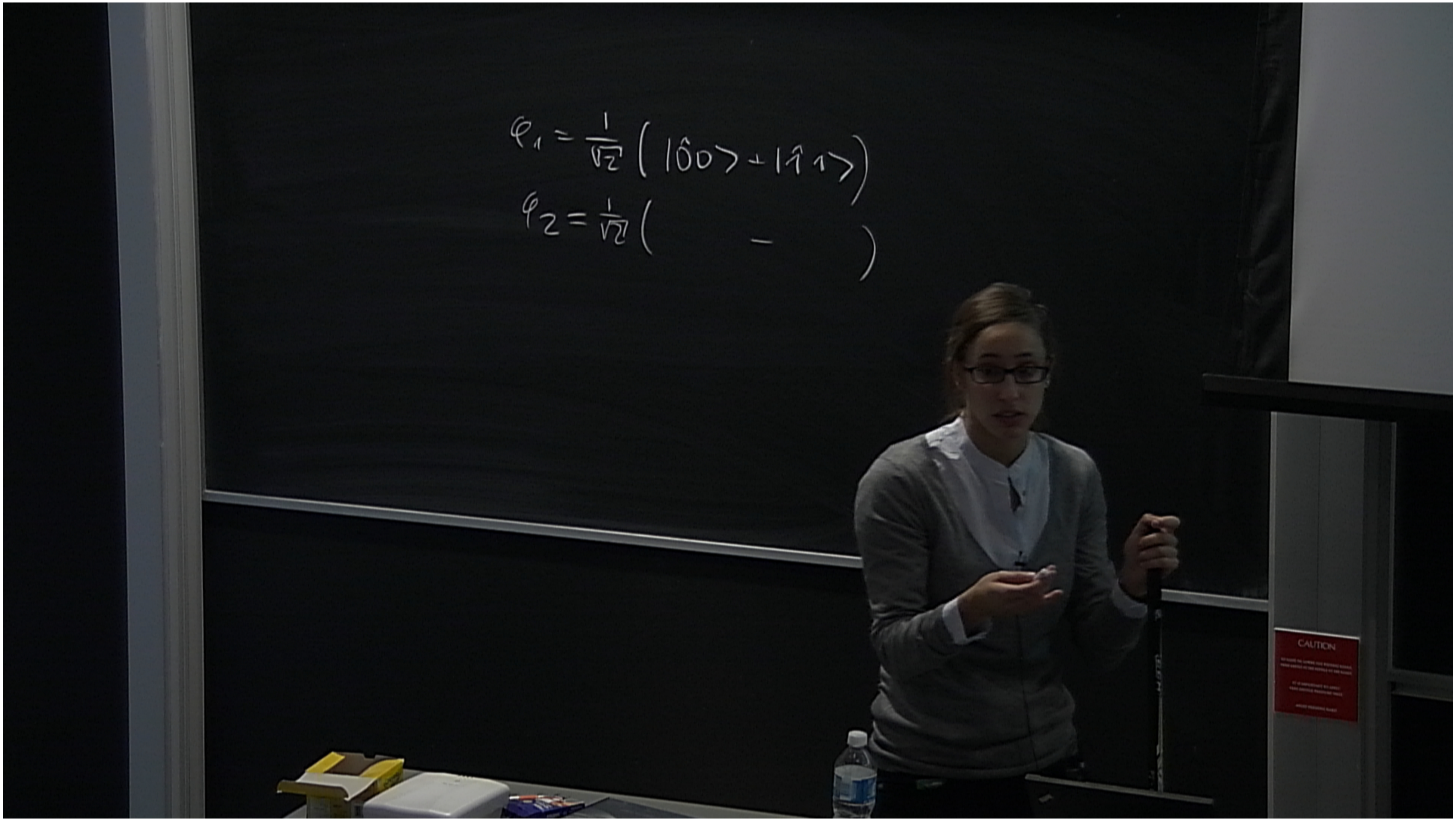
$\varphi_1 = \frac{1}{\sqrt{2}} \left(|00\rangle + |11\rangle \right)$
$\varphi_2 = \frac{1}{\sqrt{2}} \left(\quad - \quad \right)$
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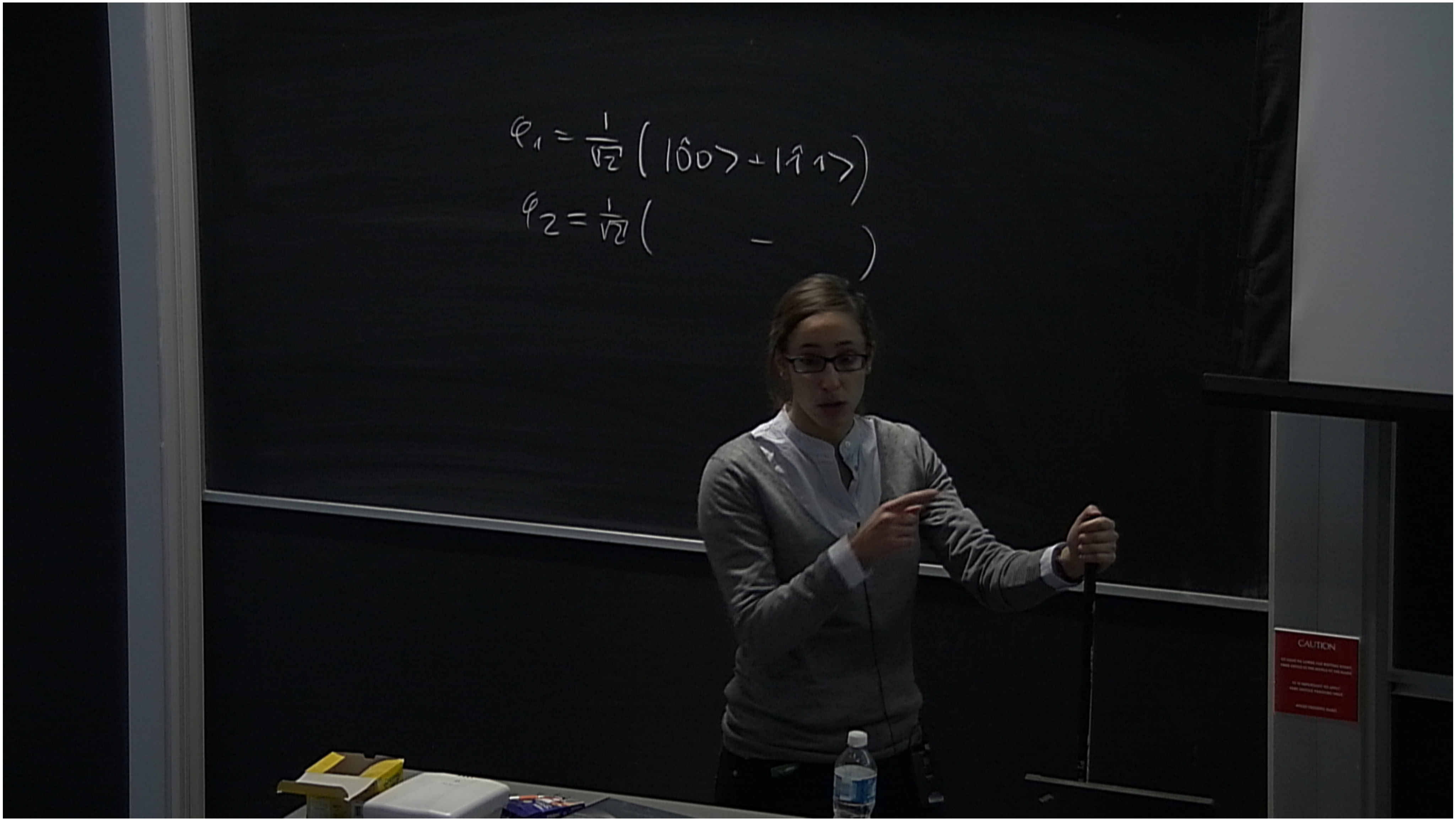
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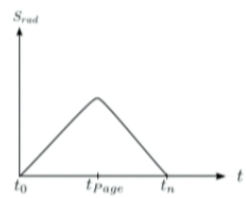
The firewall argument

[Almheiri, Marolf, Polchinski, Sully]

Modified version of Mathur's argument in the infalling observer's frame

→ **challenges black hole complementarity!**



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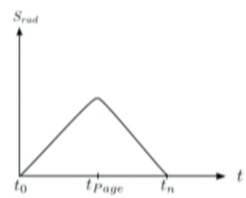

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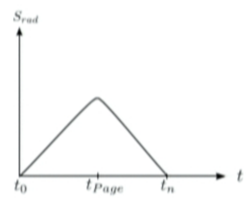

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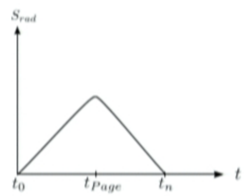

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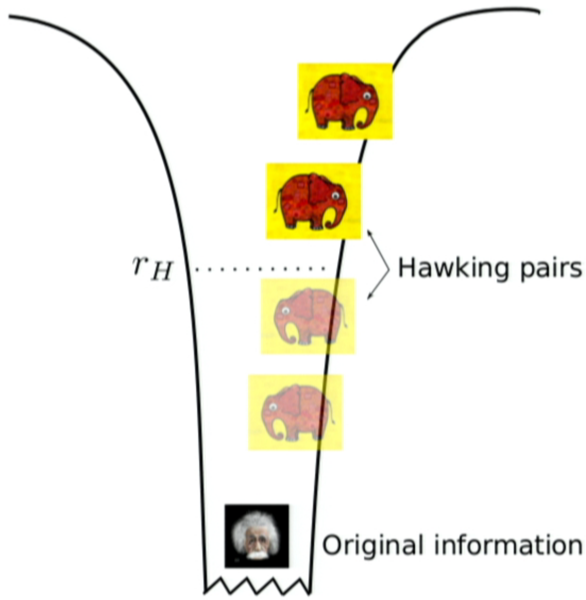

Conditions for unitarity: beyond purity

[Avery, Chowdhury, AP]

Focus so far on *purity* of the final radiation state: $S_{BC} \neq 0$ after t_{Page}.

Unitarity requires much more!

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Unitarity requires much more!

1. Purity: Pure states evolve into pure state.
2. Linearity: The map between initial and final states is linear.
3. Preservation of norm: Evolution of states preserves norm.
4. Invertibility: The map of initial state to the radiation is invertible.

Our claim:

Unitarity requires $S_{BC} \neq 0$ at every step of the evaporation process for typical states!

Work under assumptions a) fixed dimension of physical Hilbert space and b) initial black hole state is not special.

The ‘moving bit’ model I

Simple unitary model of evaporation: moving qubits D from x to y.

Evolution of basis vectors:

$$\begin{aligned}
|\psi_0\rangle &= |D_n^x\rangle \otimes \cdots \otimes |D_1^x\rangle = \bigotimes_{j=n}^{1} |D_j^x\rangle, \\
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Where is the *BC pair*?

The ‘moving bit’ model II

Evaporation via auxiliary qubits:

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The 'moving bit' model: What does it teach us?

Physical lesson:

- Information leaves the system at every step.
- For the above basis vectors: $S_{B_i c_i} = 0$.

  For a **typical state**:
  $$\begin{aligned} S_{B_i c_i} &= S_{B_i} && (c_i \text{ is fiducial}) \\ &= S_{D_i} && (\text{moving bits}) \\ &\neq 0 && \text{at every step!} \end{aligned}$$

  For a non-typical state: even though $S_{B_i c_i} = 0$ possible, the $B_i c_i$ system not in a predetermined state independent of the initial state.

Technical lesson:

- The new quanta B_i leaving the system must carry information of the old quanta D_i and thus **to avoid quantum cloning** the d_i must be bleached.
- **Unitarity** also **requires** the auxiliary quanta c_i to be bleached.

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To match the moving bit model: $B_i^y = D_i^y$.

Unitarity demands the auxiliary states to be in fiducial form:

$$|d_1^x\rangle \otimes |c_1^x\rangle = |\phi\rangle \otimes |\phi\rangle \qquad \forall i .$$

The 'moving bit' model: What does it teach us?

Physical lesson:

- Information leaves the system at every step.
- For the above basis vectors: $S_{B_i c_i} = 0$.

  For a **typical state**:
  $$\begin{aligned} S_{B_i c_i} &= S_{B_i} && (c_i \text{ is fiducial}) \\ &= S_{D_i} && (\text{moving bits}) \\ &\neq 0 && \text{at every step!} \end{aligned}$$

  For a non-typical state: even though $S_{B_i c_i} = 0$ possible, the $B_i c_i$ system not in a predetermined state independent of the initial state.

Technical lesson:

- The new quanta B_i leaving the system must carry information of the old quanta D_i and thus **to avoid quantum cloning** the d_i must be bleached.
- **Unitarity** also **requires** the auxiliary quanta c_i to be bleached.

Hawking evaporation via qubit models

[AMPS]: may have $S_{BC} = 0$ until $t_{\rm Page}$, must have $S_{BC} \neq 0$ after $t_{\rm Page}$.

Initial black hole state: $|\hat{q}_1 \hat{q}_2 \hat{q}_3 \hat{q}_4\rangle$.

Evolution: $$\mathcal{I}_i = \frac{1}{\sqrt{2}}\left(|\hat{0}_{4+i}\rangle|0_i\rangle + |\hat{1}_{4+i}\rangle|1_i\rangle\right) \otimes \hat{I} \quad \text{for} \quad i \leqslant 2\,.$$

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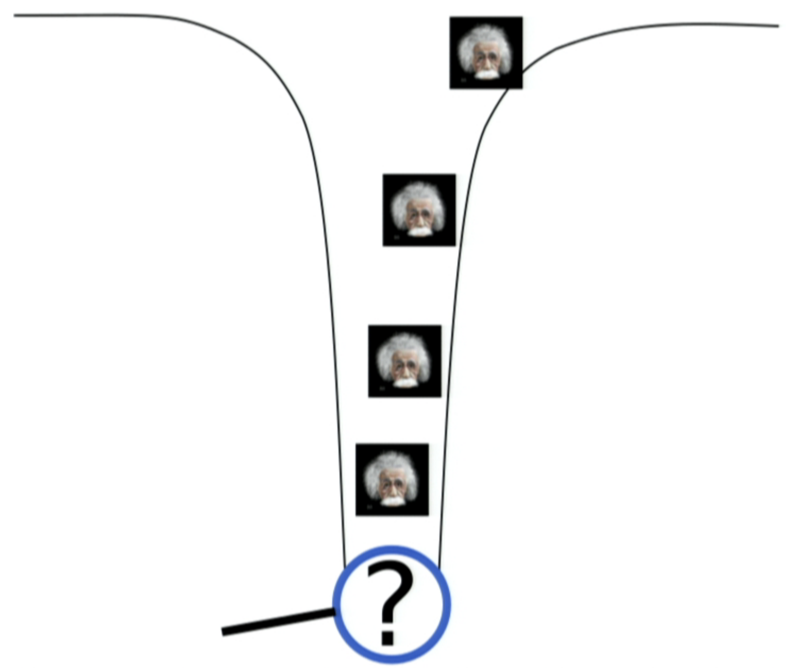
What is the horizon-scale structure?



Fuzzballs: an explicit construction

[Bena, AP, Vercnocke]

The idea:

- negatively charged probe in susy bgd with charge dissolved in flux
- breaking susy and extremality

→ **Near-extremal fuzzballs!**

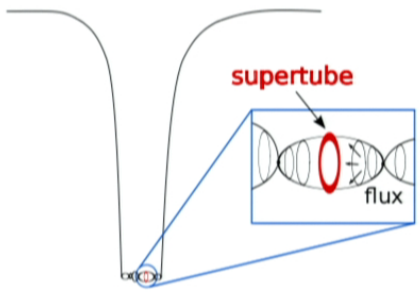


Figure: *Near-extremal fuzzball.*

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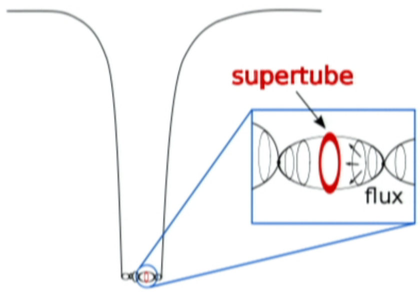


Figure: *Near-extremal fuzzball.*

Background: supersymmetric 'multicenter' solutions

microstates of extremal black holes

4D perspective: Denef multicenter solutions - fluxed D6 branes

Probe: Supertubes

smooth

4D perspective: fluxed D4 branes

Background: extremal black hole microstate

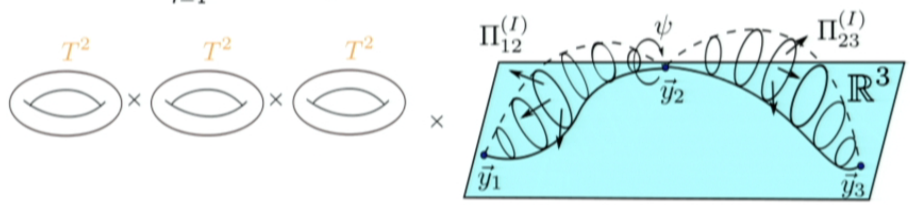
String theory/supergravity: $\mathcal{L}_{5d} \sim \star F \wedge F + A \wedge F \wedge F$

electric fields sourced by electric charge ($d \star F = 0$) and magnetic flux ($d \star F = F \wedge F$)

'Bubbling' geometries:

$$ds_{11}^2 = (Z_1 Z_2 Z_3)^{-2/3}(dt+k)^2 + (Z_1 Z_2 Z_3)^{1/3} ds_4^2 + (Z_1 Z_2 Z_3)^{1/3} \sum_{I=1}^{3} \frac{ds_I^2}{Z_I}$$

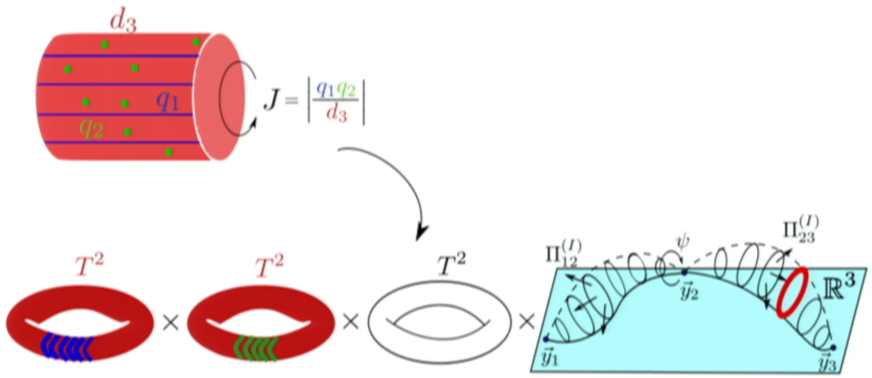
$$F_4 = \sum_{I=1}^{3} \left[d\left(-\frac{dt+k}{Z_I} \right) + \Theta^{(I)} \right] \wedge ds_I^2$$



4d multicener Taub-NUT base

$$ds_4^2 = V^{-1}(d\psi + A)^2 + V ds_3^2$$

Supertubes in backgrounds with charge dissolved in flux



	0	1 2	3 4	5 6	7 8 9	ψ
M5	×	× ×	× ×			×
M2	×	× ×				
M2	×		× ×			

Singularity resolution scale

Length of throat: $L = \int dr \sqrt{g_{rr}}$

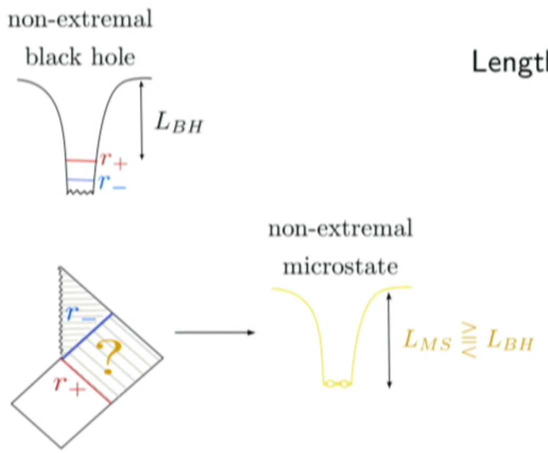
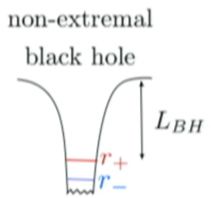


Figure: *Singularity resolution scale.*

Singularity resolution scale



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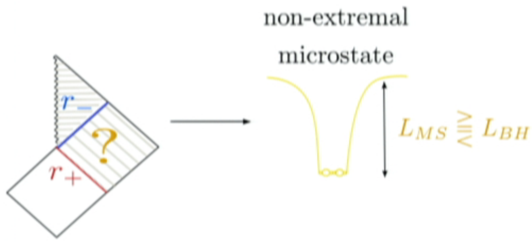

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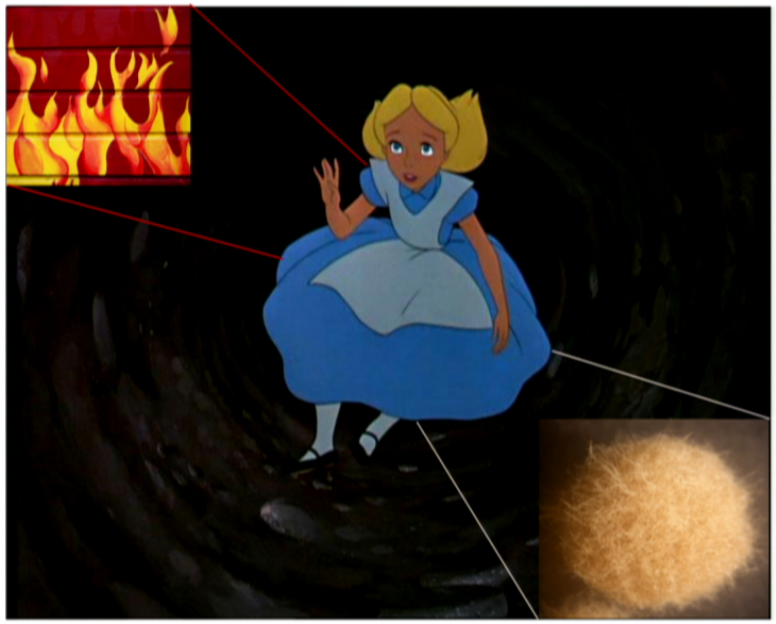
Is Alice burning of fuzzing?



Is Alice burning or fuzzing?

Typical fuzzballs: strong dynamics of infalling observer with fuzzball.

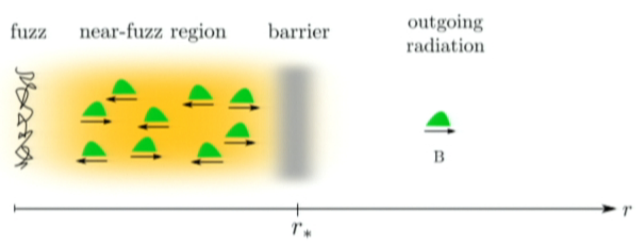


Figure: *Cartoon of a typical fuzzball.*

An infalling observer encounters single radiation quantum outside the barrier, many quanta partially trapped between the 'fuzz' and the barrier and with the 'fuzz' itself!

Falling into typical fuzzballs: an approximation

Use AdS/CFT but expect lesson to hold more generally.

Approximate a typical state by a thermal state:

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

Purify the density matrix:

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

Such entangled CFT states are dual to eternal AdS black hole.
[Maldacena]

Figure: *Penrose diagram of the extended AdS Schwarzschild black hole.*

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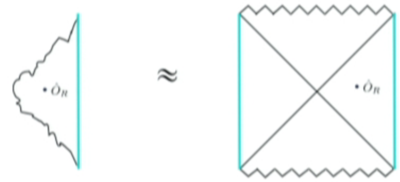
Observables in typical fuzzballs:

CFT	${}_R\langle\psi\vert\hat{O}_R\vert\psi\rangle_R$	$\approx$	$\langle\Psi\vert\hat{O}_R\vert\Psi\rangle\,,$
Bulk	${}_R\langle\psi_g\vert\hat{O}_R\vert\psi_g\rangle_R$	$\approx$	$\langle G\vert\hat{O}_R\vert G\rangle\,.$



What about infalling observers?

- Sufficiently **coarse-grained** operators $\rightarrow$ $E \gg kT_H$ observers
- Sufficiently **fine-grained** operators $\rightarrow$ $E \sim kT_H$ observers

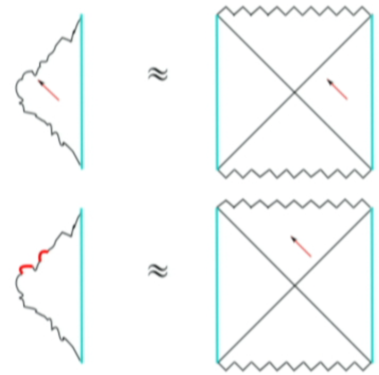
Typical state $\approx$ thermal state approximation is only valid for operators that cannot distinguish the details of different fuzzball microstates $\rightarrow$ only valid for high-energy infalling observers.

Alice fuzzes but may not even know it!

Infalling high-energy quanta will be absorbed by the fuzzball and excite its collective modes.

This process can be approximated by infall into the eternal AdS black hole.

Note: Spacetime behind the horizon and singularity are a short-lived $t \sim M$ approximate description!



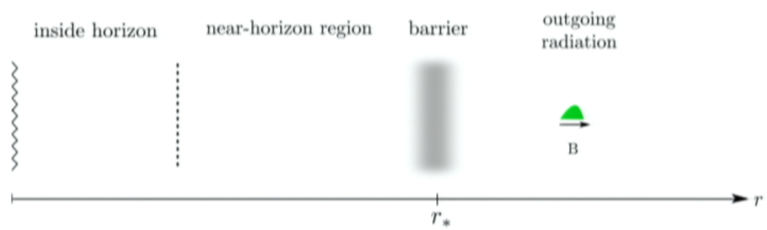


Figure: *Inside of potential barrier of fuzzball ≈ black hole in Hartle-Hawking state.*

Conclusions

When and how does the original information come out?

- Unitary evaporation requires information of the original state to come out in every step of the evolution → traditional black hole horizon is inconsistent with unitarity at every step.

What is the horizon-scale structure?

- No information 'paradox' for fuzzballs! Can explicitly construct near-extremal microstates with structure at the horizon scale. Testing ground for fuzzball and firewall ideas.

Is Alice burning of fuzzing?

- Fuzzball complementarity:
  fine-grained operators experience the details of the fuzzball microstate and coarse-grained operators experience the black hole.
- Energy-scale dependence: Infalling high-energy $E \gg kT_H$ observers experience free fall while low-energy $E \sim kT_H$ observers do not.