Icezones vs. Firewalls

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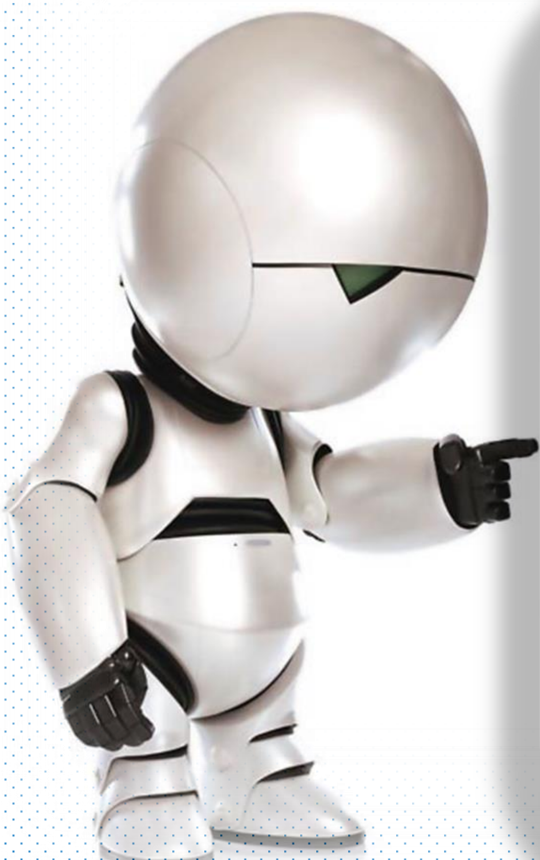
Motivation

Black Holes

- Most interesting and intriguing objects in our Universe
- Hawking (1974): black holes radiate
- Treatment only semi-classical
- Many questions left unanswered (information loss paradox)
- Recent developments:

Firewall Paradox!

Outline



- **Black holes – basics**
- **The setup of the Firewall Paradox**
- **Assumptions made in FP**
- **No need for firewalls**
- ***Unitary evolution perhaps implies "icezones"***
- ***Interactions can purify thermal density matrix***

Firewall Paradox

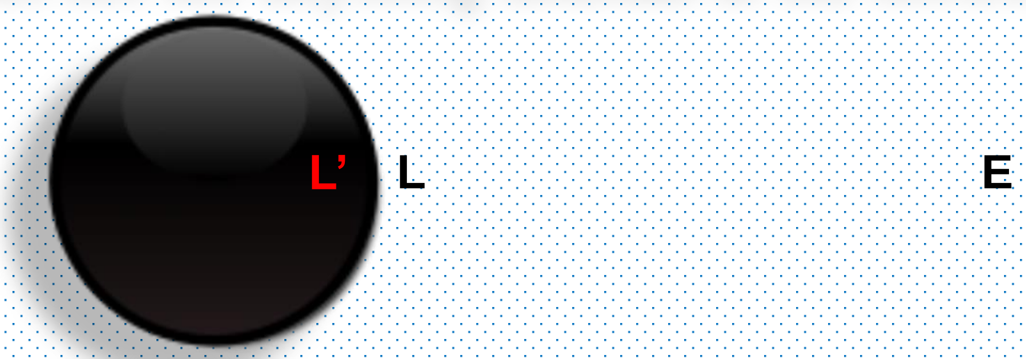
The Setup

We Believe that

(1) Hawking evaporation is information preserving

(2) Low energy effective field theory should be valid
beyond some microscopic distance from the horizon

(3) Infalling observer does not see anything unusual at the horizon



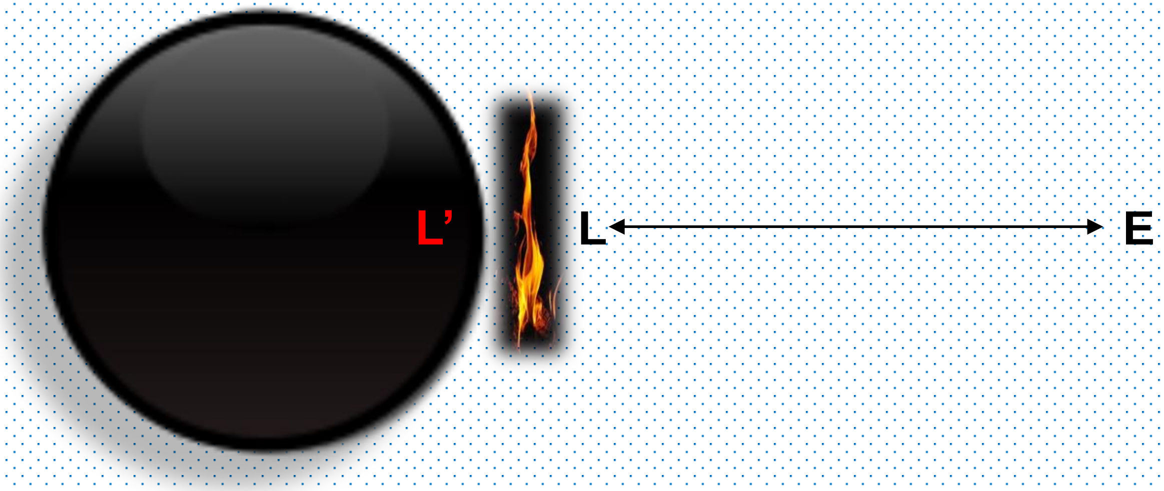
L - mode of late Hawking radiation

Unitarity: L is entangled with earlier radiation E

Smooth horizon: L is also entangled with mode L' inside the horizon

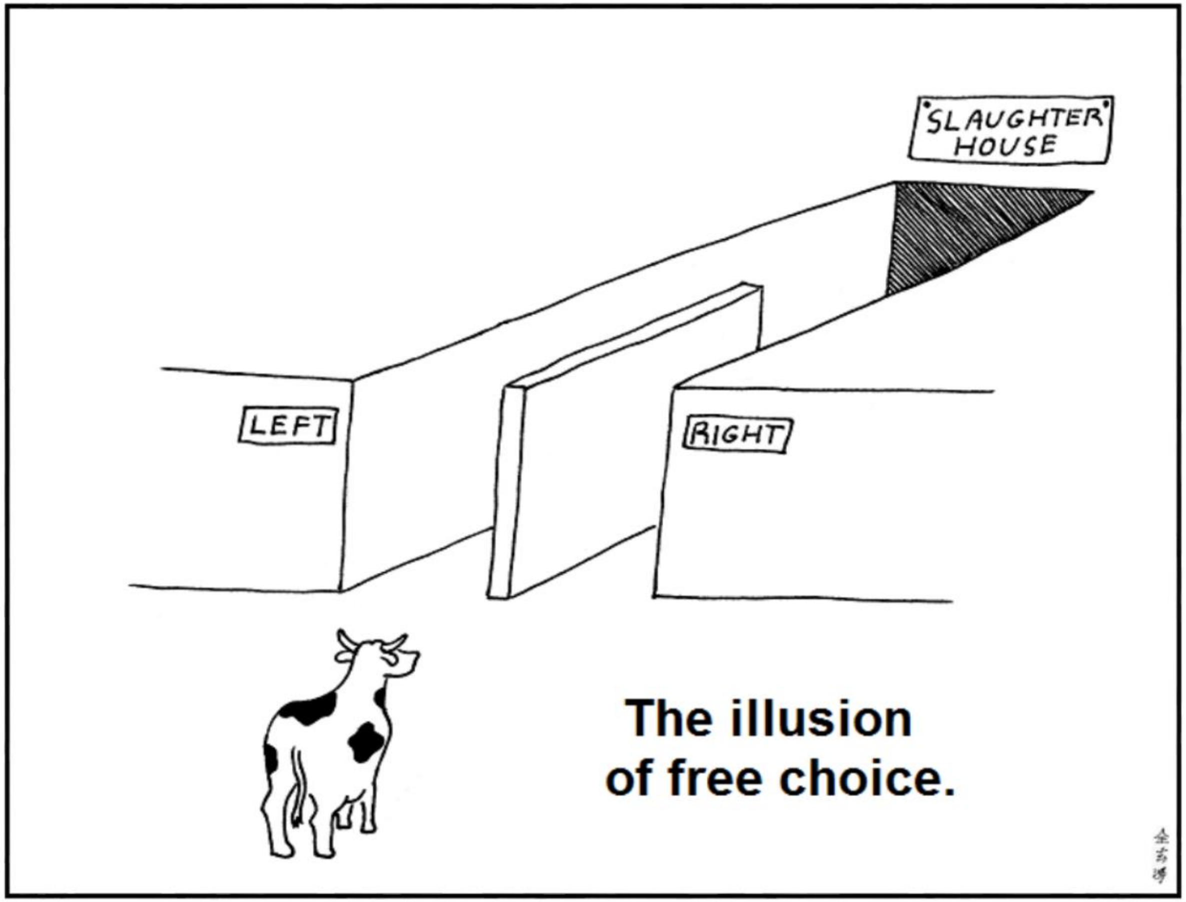
$L \leftrightarrow E$ and simultaneously $L \leftrightarrow L'$ which is impossible!

AMPS: The least painful option - FIREWALL



A. Almheiri, D. Marolf, J. Polchinski and J. Sully, ***JHEP 1302, 062 (2013)***

AMPS gave us a free choice:
abandon unitarity and/or QFT, or accept the firewalls

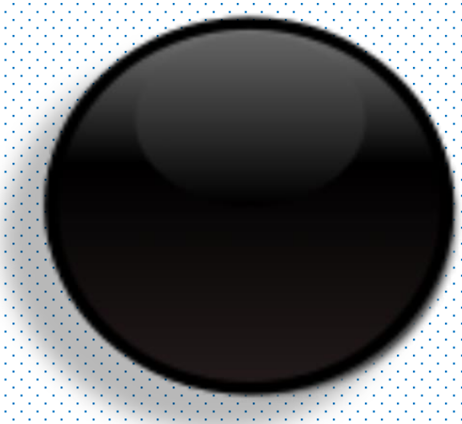


Option 1:

Dismiss firewalls altogether!

Old School (Bill Unruh, Bob Wald…)

Large BH can have arbitrarily small curvature at the horizon



- We tested GR in the low curvature region very well
- Quantum corrections to classical GR solutions negligible

Not a good argument!

The same argument implies:
superconductivity or superfluidity can't exist

We tested Maxwell's equations at the scale of cm many times

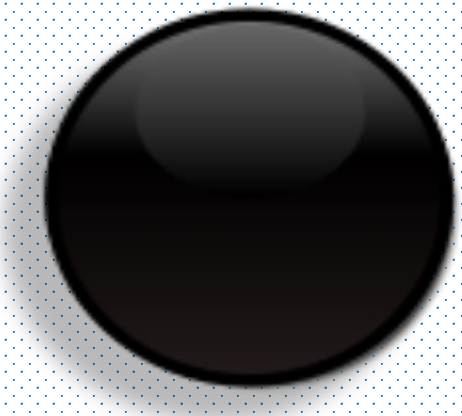
We know that electrons interact with EM force with ions in the crystal lattice – finite resistance

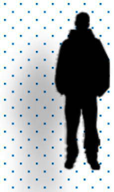
HOWEVER

Macroscopic quantum phenomena like SC and SF still possible

Option 2:

Dissect the firewalls paradox!



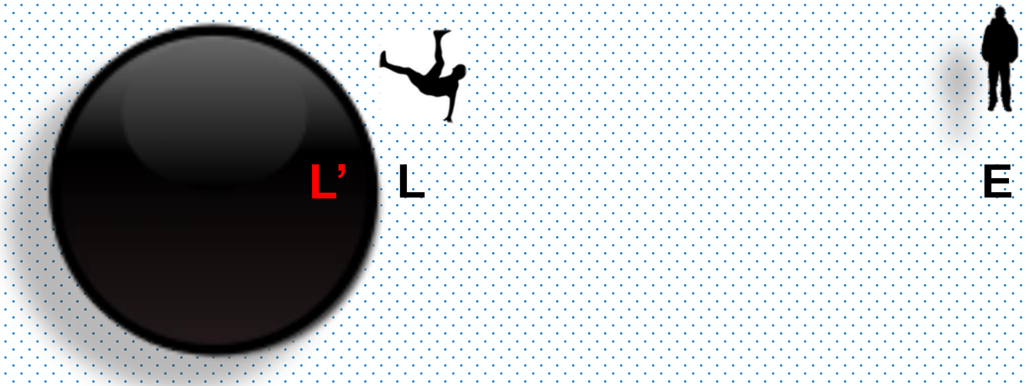


Observers

To have a paradox, someone has to observe it

Asymptotic observer can't see all three modes

Infalling can, but he can never compare his findings with asymptotic



Bousso: Infalling guy comes close to the horizon, uses his theory to infer entanglement between L and L' and then comes back to infinity

Entanglement is observer dependent

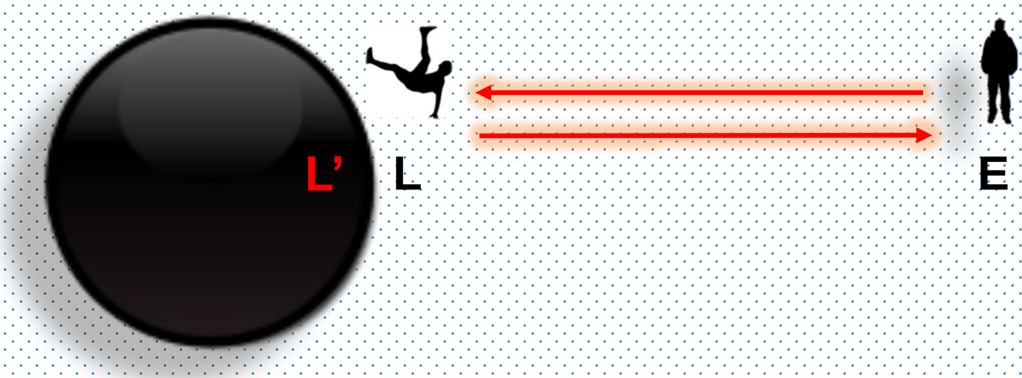
In QM two modes are either entangled or not $\psi = \alpha|\uparrow\downarrow\rangle + \beta|\downarrow\uparrow\rangle$

In GR, accelerated observer sees **entanglement degradation**

Reason: flux of Hawking radiation (interactions destroy entanglement)

I. Fuentes-Schuller and R. B. Mann, Phys. Rev. Lett. 95, 120404 (2005)

E. Martin-Martinez, L. J. Garay and J. Leon, Phys. Rev. D 82, 064006 (2010)

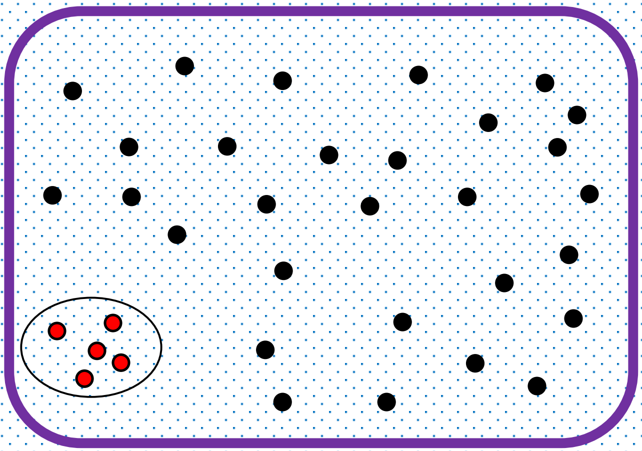


Infalling guy becomes accelerated when he turns back!
He will witness entanglement degradation

Large and small subsystems

- Formulation of the paradox heavily relies on the statement about the strong correlations between the large and small subsystems

- If we divide a system into small and large subsystems



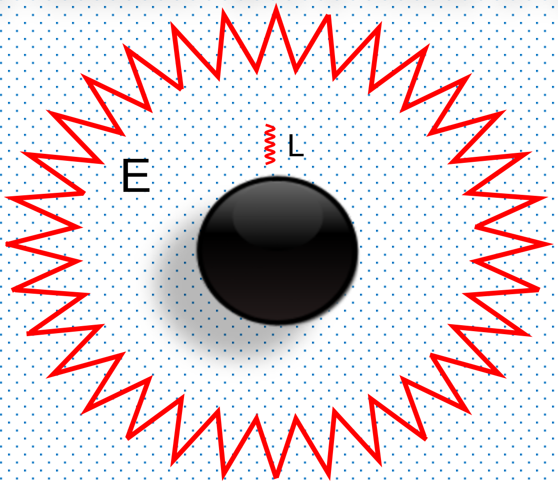
- All the information is in the correlations between the systems
- Large and small systems are maximally entangled

AMPS: Unitarity implies L $\leftrightarrow$ E

- All the information is in the correlations between the small and large systems
- Large and small systems are maximally entangled

- Large subsystem is early Hawking radiation E
- Small subsystem is late Hawking radiation L

- AMPS interpretation: early radiation and a mode of the late radiation must be maximally entangled.



D. N. Page, *Phys. Rev. Lett. 71, 1291 (1993)*

- Divide a system into two subsystems of sizes *m* and *n*, *m<n*
- After long enough time there is almost no information left in the small subsystem

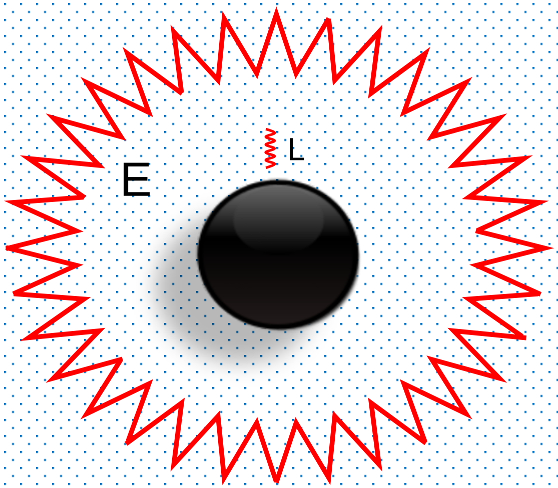
$$I_m = S_{\max} - \langle S \rangle \approx \frac{m}{2n}, \qquad for\ 1 << m < n$$

- All the information is in the correlations between the systems

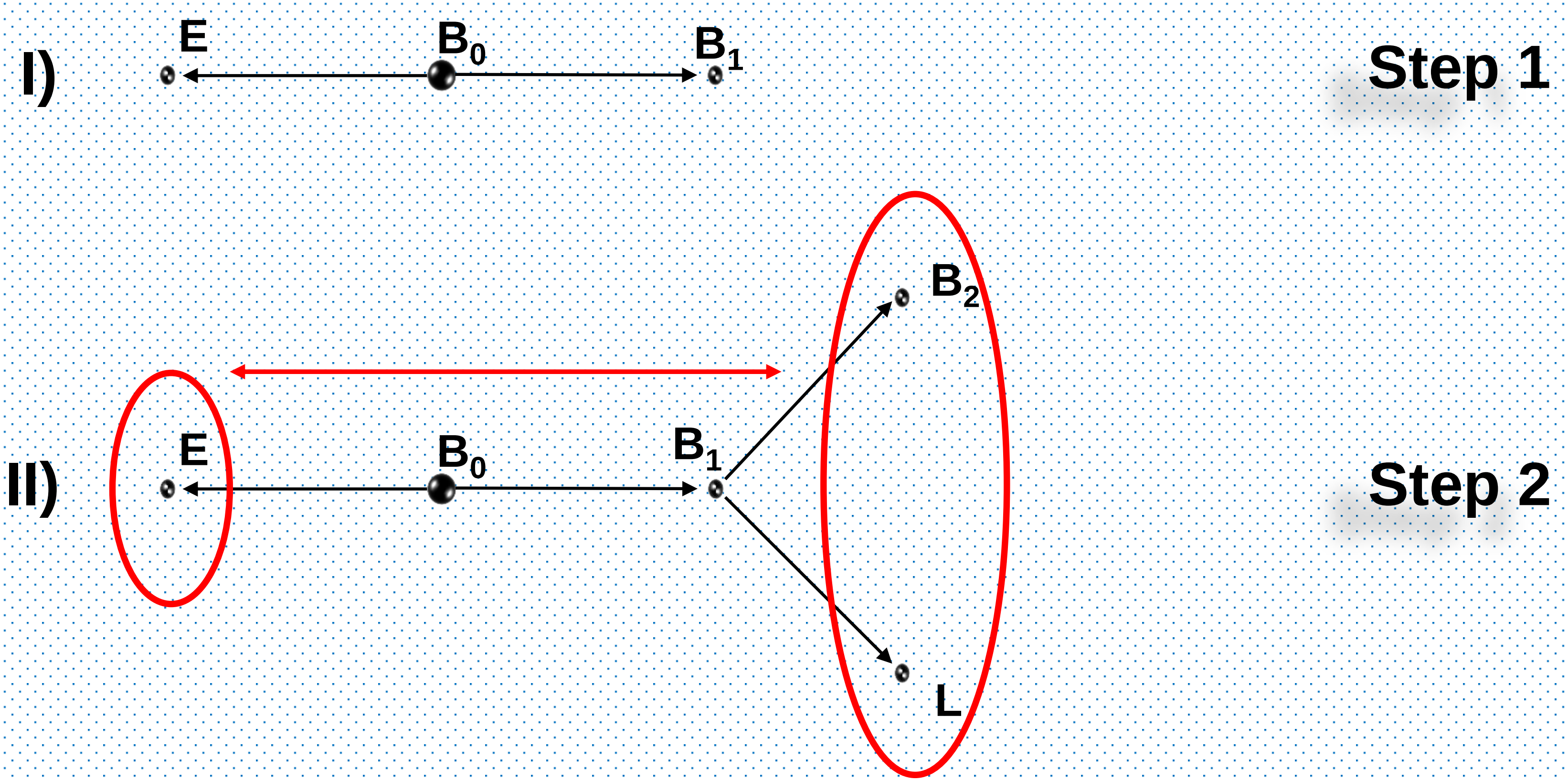
Problem with AMPS interpretation:

1. Note that 1<< m, so the "small system" can't be L
2. Not clear why BH is taken out of the picture

(you can do it only at the end of evaporation, not before)

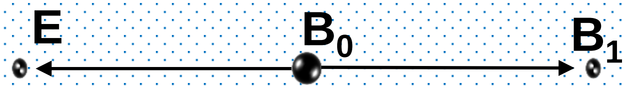


Unitary process of particle decay



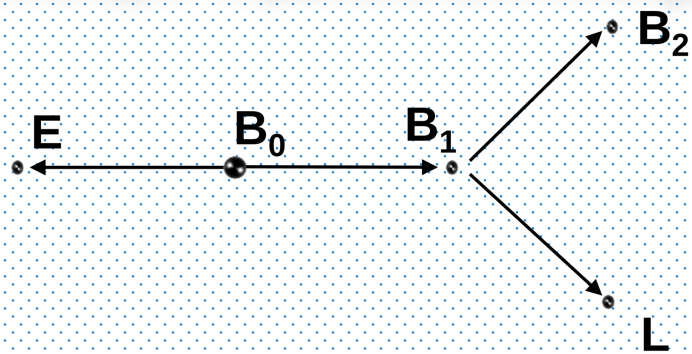
- It is incorrect to say that E is strongly entangled with L
- E is strongly entangled with the system B + L

Step 1: black hole B_0 emits spin ½ particle and changes its state into B_1



$$\psi_{B_1E} = \alpha\left|\uparrow_{B_1}\downarrow_E\right\rangle + \beta\left|\downarrow_{B_1}\uparrow_E\right\rangle$$

Step 2: black hole B_1 emits spin ½ particle and changes its state into B_2



$$\psi_{B_2EL} = \alpha\left(\gamma\left|\Uparrow_{B_2}\downarrow_E\downarrow_L\right\rangle + \delta\left|0_{B_2}\downarrow_E\uparrow_L\right\rangle\right) + \beta\left(\lambda\left|\Downarrow_{B_2}\uparrow_E\uparrow_L\right\rangle + \sigma\left|0_{B_2}\uparrow_E\downarrow_L\right\rangle\right)$$

If we know the state of E (say E=↑) ➡

then we know the state of the system (B+L)

$$\psi_{B_2 L} = \lambda\left|\Downarrow_{B_2} \uparrow_L\right\rangle + \delta\left|0_{B_2} \downarrow_L\right\rangle$$

If we know the state of L (say L=↓) ➡

then we know the state of the system (B+E)

$$\psi_{B_2 E} = \alpha\left|\Uparrow_{B_2} \downarrow_E\right\rangle + \beta\left|0_{B_2} \uparrow_E\right\rangle$$

But we never know separate states of all three members!

- **All we can say is that**

- **E is strongly correlated with (L+B)**

  or

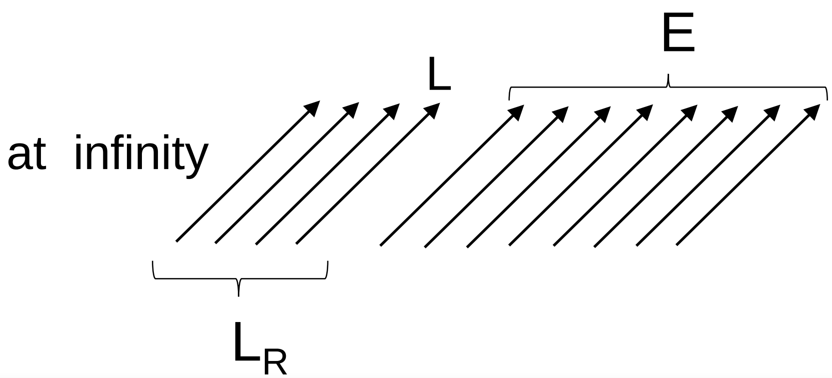
- **L is strongly correlated with (E+B)**

  or

- **B is strongly correlated with (L+E)**

But we can’t say that L is correlated with E and B(L’) separately!

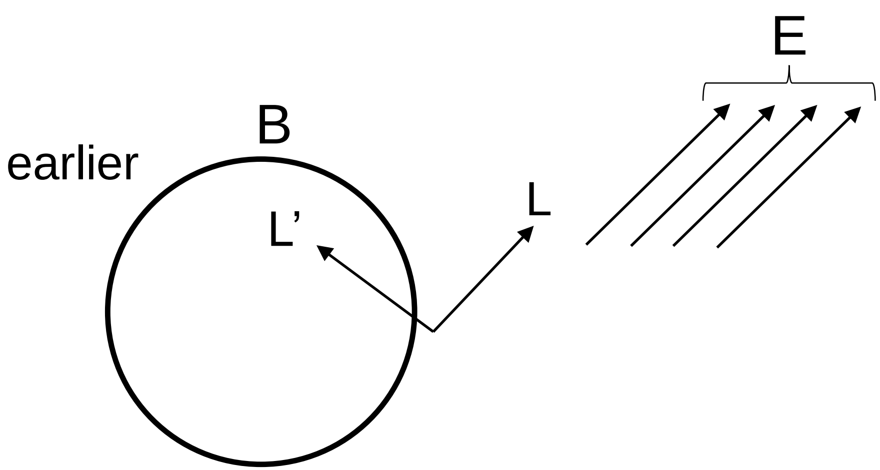
Correct interpretation of Don Page's result



No black hole

$$L_R \leftrightarrow E$$
$$L \leftrightarrow E + L_R - L$$

$$\cancel{\mathbf{L \leftrightarrow E}}$$



Black hole still exists

$$L_R \equiv L + B$$

$$\underbrace{L \leftrightarrow E + B}_{\text{unitarity}}$$
$$\overbrace{E \leftrightarrow L + B}$$

$$\cancel{\mathbf{L \leftrightarrow L'}}$$

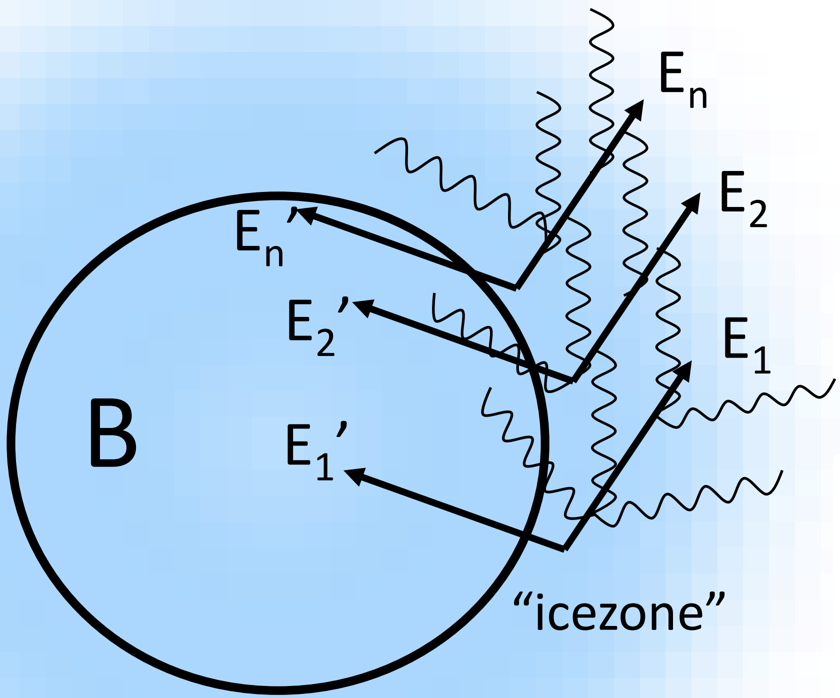
We never have L↔E and L↔L'

- **Interesting case**

L is strongly correlated with (E+B)
~~L↔L’~~ Rindler approximation fails

Extended entanglement needed!

The Icezone



$E_1, E_2, \ldots, E_n \equiv E$

$E_1 \leftrightarrow B$

$E_2 \leftrightarrow E_1 + B$

……….

$E_n \leftrightarrow E_1 + E_2 + \ldots + B$

All the outgoing modes will eventually be entangled

"Icezone" consists of a sea of quanta that mediate interactions (either perturbative or non-perturbative) between the thermal Hawking quanta

Density Matrix

$$\rho = \sum_i p_i \left|\psi_i\right\rangle\left\langle\psi_i\right|$$

Pure state

$$\rho_{pure} = \begin{pmatrix} p_1 & & & \\ & 0 & & \\ & & 0 & \\ & & & \ddots \end{pmatrix}$$

Mixed state

$$\rho_{mixed} = \begin{pmatrix} p_1 & & & \\ & p_2 & & \\ & & p_3 & \\ & & & \ddots \end{pmatrix}$$

You can't convert mixed thermal state of Hawking radiation into a pure state

Small corrections do not help

$$\rho = \begin{pmatrix} p_1+\varepsilon & 0 & 0 & 0 \\ 0 & p_2+\varepsilon & 0 & 0 \\ 0 & 0 & p_3+\varepsilon & 0 \\ 0 & 0 & 0 & p_4+\varepsilon \end{pmatrix}$$

If we include interactions?

$$\rho = \begin{pmatrix} p_{11} & \varepsilon p_{12} & \varepsilon p_{13} & \varepsilon p_{14} \\ \varepsilon p_{21} & p_{22} & \varepsilon p_{23} & \varepsilon p_{24} \\ \varepsilon p_{31} & \varepsilon p_{32} & p_{33} & \varepsilon p_{34} \\ \varepsilon p_{41} & \varepsilon p_{42} & \varepsilon p_{43} & p_{44} \end{pmatrix}$$

Not so clear!

Interactions can purify thermal density matrix!

Including interactions

Hawking: after black hole emits K quanta its density matrix is thermal

$$\rho_0 = \frac{1}{2^K}\mathbf{1}_K$$

spin ½ particles
# of states is 2^K

Superoperator G gives corrections to ρ_0 due to interactions

$$\rho(t) = G(t)\rho_0 = (\mathbf{1} + A)\rho_0$$

Interactions:

$$A = a\mathbb{1} = a\begin{pmatrix} 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{pmatrix}$$

Magnitude of the effect

Coefficient a gives the magnitude of the interactions

Non-perturbative:

$$a = e^{-S} \approx \frac{1}{2^{N-K}}$$

$N = \left(M_{bh} / M_{Pl}\right)^2$ Total number of quanta that a BH can emit

K - Number of quanta emitted at a given moment

$$\rho_K = (\mathbf{1} + A)\rho_0 = \left(\mathbf{1}_K + \frac{1}{2^{N-K}}\mathbf{1}_K\right)\frac{1}{2^K}\mathbf{1}_K$$

$$= \rho_{\max} + \frac{1}{2^N}\mathbf{1}_K$$

At the end of evaporation, K=N

$$\rho_N = \frac{1}{2^N}\left(\mathbf{1}_N + \mathbf{1}_N\right) = \frac{1}{2^N}\begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{pmatrix} = \rho_{pure}$$

$$\rho_{pure} = \frac{1}{2^N}\sum_{i,j}|i\rangle\langle j|$$

is the density matrix of the pure state

$$\psi = \frac{1}{2^{N/2}}\sum_i |i\rangle$$

Non-perturbative interactions can unitarize Hawking radiation

Perturbative interactions

$$a = \frac{1}{\frac{N!}{(N-K)!K!}}$$

Normalized by the number of ways to choose K quanta out of N total quanta

$$\rho_K = \left(\mathbf{1}_K + \frac{1}{\frac{N!}{(N-K)!K!}} \mathbf{1}_K \right) \frac{1}{2^K} \mathbf{1}_K = \rho_{\max} + \frac{1}{2^K \frac{N!}{(N-K)!K!}} \mathbf{1}_K$$

At the end, K=N

$$\rho_N = \left(\mathbf{1}_N + \mathbf{1}_N \right) \frac{1}{2^N} = \rho_{pure}$$

Perturbative interactions can unitarize Hawking radiation

Interesting trend

$$a = \frac{1}{\dfrac{N!}{(N-K)!K!}}$$

If K=1, then a =1/N → suppression is large

a stays small until K=N/2

When K=N, then a=1

Agrees well with

Page's result:
black hole only starts to emit information at significant rate after half of the black hole has been radiated away

No need for firewalls whatsoever

Conclusions

1. Useful to keep questioning well established truths

2. Firewall paradox made us carefully re-examine some old statements

3. Firewall paradox not formulated consistently

4. Icezones are more likely than firewalls
(small corrections due to standard physics)

THANK YOU