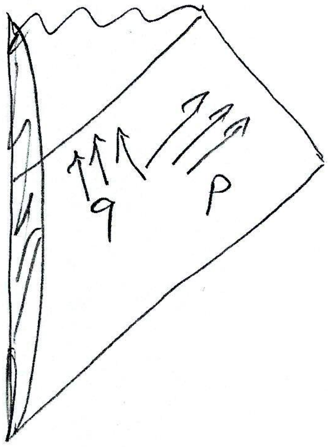
The firewall problem : Itzhaki '96, Braunstein et al. '09 Mathur '09, AMPS '12, MP '13

Assume unitary evolution, as in the Page model.

Add dynamics: combine the Page model with Hawking's model.

Use the pair production picture.

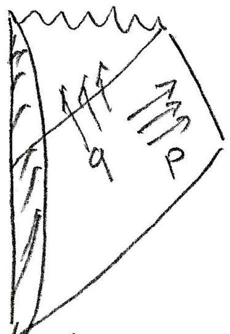
⇒ Need to learn about the ingoing modes q's.



In going modes, pair production and all that

More ambiguous: positive and negative frequencies cannot be defined precisly

Hawking: " A stationary observer outside the BH could regard the outgoing particles as a rusult of gravitational pair production similar to pair production of e^+e^- pair in a electric field. One member falls into the BH, the other emitted."



The Schwinger effect

$\mathcal{E}_E = eEL$, $\mathcal{E}_{pair} = 2m \Rightarrow L = \frac{2m}{eE}$

$P_{pair} \sim e^{-L/\lambda}$, $\lambda = \hbar/m$

$P \sim e^{-\frac{2m^2}{eE}}$, $R_{pp} \sim (eE)^2 e^{\frac{-\pi m^2}{eE}}$

Gravitational pair production

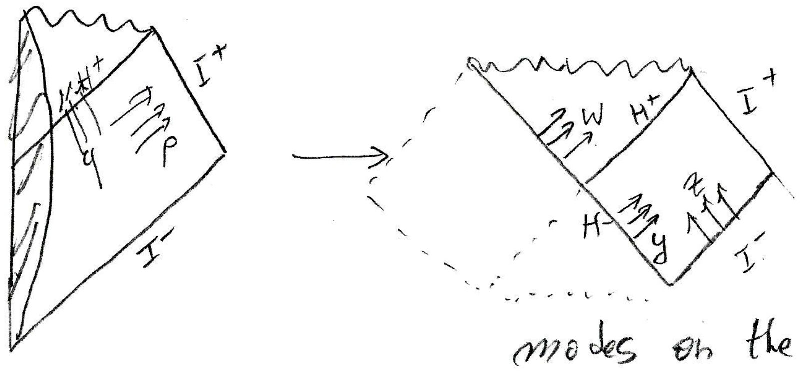
$$eE \longleftrightarrow \frac{GM_{BH}}{r^2} \cdot \mathcal{E}_{particle} \sim \frac{\mathcal{E}}{R_S}$$

$$R_{pp} \sim \frac{\mathcal{E}^2}{R_S^2} e^{-\pi \frac{\mathcal{E}^2}{\mathcal{E}/R_S}} = \frac{\mathcal{E}^2}{R_S^2} e^{-\pi R_S \mathcal{E}}$$

$\frac{\partial R_{pp}}{\partial \mathcal{E}} = 0$ $(R_{pp})_{max} \Rightarrow \mathcal{E} \sim \frac{1}{R_S} \sim T_H$, $R_{pp} \sim \frac{1}{R_S^4} \sim T_H^4$

Hawking: " The horizon states <u>will be chosen</u> so that some of them describe those negative energy particles that the stationary observer considers to exist inside the BH" ! !

Integrate shell and replace it by an eternal BH geometry with BC : PRD '76



$$\phi = \sum_i \left(f^{(1)} a_i^{(1)} + \overbrace{f^{(3)} a_i^{(3)} + f^{(4)} a_i^{(4)}}^{\text{modes on the full } H^-} + \text{H.c} \right)$$

$$\{ f^{(1)}, f^{(3)}, f^{(4)} \} \to \{ z, w, y \} , \qquad z = f_1$$

$$y = \sqrt{1-x}\, f_3 \qquad x = e^{-\frac{\omega}{T_H}}$$

$$w = \sqrt{1-x}\, f_4$$

$$\begin{pmatrix} w \\ y \end{pmatrix} : \quad (g_\omega - e^{-\frac{1}{2}\frac{\omega}{T_H}} h_\omega^\dagger)|0_-\rangle = 0$$

$$(h_\omega - e^{-\frac{1}{2}\frac{\omega}{T_H}} g_\omega^\dagger)|0_-\rangle = 0$$

$$z : \quad j_\omega |0_-\rangle = 0$$

$\Downarrow$

particles are created in pairs of outgoing and ingoing particles

Particles are created in a TFD state

$$|\psi\rangle \sim \sum_i e^{-\frac{\beta E_i}{2}} |E_i^{(+)}\rangle |E_i^{(-)}\rangle \sim |0_-\rangle$$

vaccuum almost perfect.

$$\hat{\rho} = |\psi\rangle\langle\psi| \Rightarrow \hat{\rho}_{out} = \mathrm{Tr}_{in} \hat{\rho} = \sum e^{-\beta E_i} |E_i^{(+)}\rangle\langle E_i^{(+)}|$$

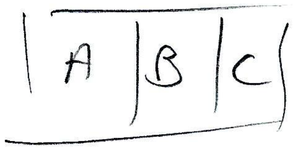
thermal state. ([illegible] discuss in more detail later)

Pair picture only heuristic!

The firewall problem: When the outgoing radiation starts to purify, the state of the pairs near the horizon cannot be a thermofield double state ⇒ the state cannot be close to $|0_-\rangle$

⇒ Higly excited state near horizon ⇒ "Firewall" breakdown of the Equivalence Princ.

New technical tool: Strong subadditivity in 3-partite Hilbert spaces

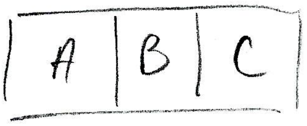


AMPS:
A - early radiation (emitted before the Page time)
B - late radiation (emitted after Page time)
C - ingoing partners of B

Mathur:
A - early radiation $\{b_1, \dots, b_n\}$
B - next positive energy mode b_{n+1}
C - next negative energy mod c_{n+1}

Strong subaditivity (SSA) Araki+Lieb '70

Assume A, B, C parts of ABC



then $S^{ABC} + S^B \leq S^{AB} + S^{BC}$ (1)

or $S^A + S^C \leq S^{AB} + S^{BC}$ (2)

(1) → (2) by assuming a purifier D such that $S^{ABCD} = 0$

So $S^{AB} = S^{CD}$, $S^{ABC} = S^D$ etc.

Strong subadditivity vs. subadditivity

$$S^{AB} \leq S^A + S^B$$

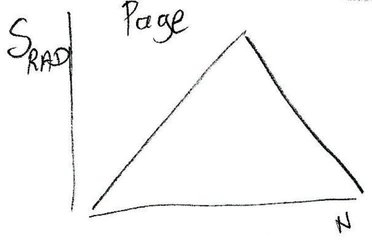
In QM this is not true! $S^{AB} = 0$ pure state

while $S^A, S^B \neq 0$

as we have seen previously

Problem 3: from paper 1203.5116

Show SSA for Renyi entropy (for $\underset{\text{quadratic Hamiltonians}}{\text{free fields}}$ $\equiv$ Gaussian states) $\hat{\rho}$ = Gaussian



$$S^A + S^C \leq S^{AB} + S^{BC}$$

Entropy of outgoing radiation is decreasing

$$S^{AB} < S^A$$

$S^{BC} \simeq 0$ partners in ~TFD state near vacuum $|0_-\rangle$

<u>Contradiction</u>

$$\underset{\overset{\vee}{0}}{S^A - S^{AB}} + \underset{\overset{\vee}{0}}{S^C} \lesssim 0$$

~thermal

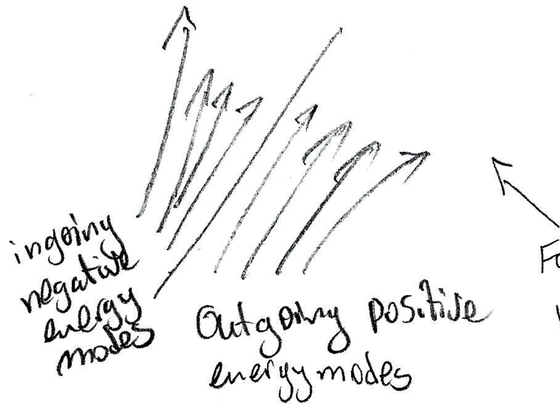
Conclusion:

Near horizon state has to deviate substantially from TFD to allow Hawking radiation to begin to purify

"Fire wall" : Deviation from TFD

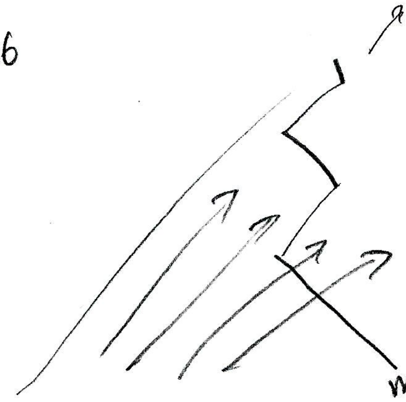
⇒ A state with excitations at arbitrary high energies limited only by QFT cutoff. "Planckian Wall of fire"

Equivalence priciple is violated: Horizon can be detected (burn)



Falling object will see a highly excited state - will burn

Itzhak. '96



will never reach horizon before BH evaporates completly

massless particle

"bombarded by high energy hawking modes"

Equivalence principle is violated: postion of the horizon can be detected by an infalling observer.