Title: Talk 61 - Horizons are Watching You

Speakers:

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Abstract: We show that if a massive (or charged) body is put in a quantum superposition of spatially separated states in the vicinity of any (Killing) horizon, the mere presence of the horizon will eventually destroy the coherence of the superposition in a finite time. This occurs because, in effect, the long-range fields sourced by the superposition register on the black hole horizon which forces the emission of entangling "soft gravitons/photons" through the horizon. This enables the horizon to harvest "which path" information about the superposition. We provide estimates of the decoherence time for such quantum superpositions in the presence of a black hole and cosmological horizon. Finally, we further sharpen and generalize this mechanism by recasting the gedankenexperiment in the language of (approximate) quantum error correction. This yields a complementary picture where the decoherence is due to an "eavesdropper" (Eve) in the black hole attempting to obtain "which path" information by measuring the long-range fields of the superposed body. We explicitly compute the quantum fidelity to determine the amount of information such an Eve can obtain and show, by the information-disturbance tradeoff, a direct relationship between the information gained by Eve and the decoherence of the superposition in the exterior. In particular, we show that the decoherence of the superposition corresponds to the "optimal" measurement made by Eve in the black hole interior.

Horizons are Watching You

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It From Qubit 2023

D. Danielson, G.S., & R.M. Wald Phys. Rev. D 105, 086001 (2022) [arXiv:2112.10798]

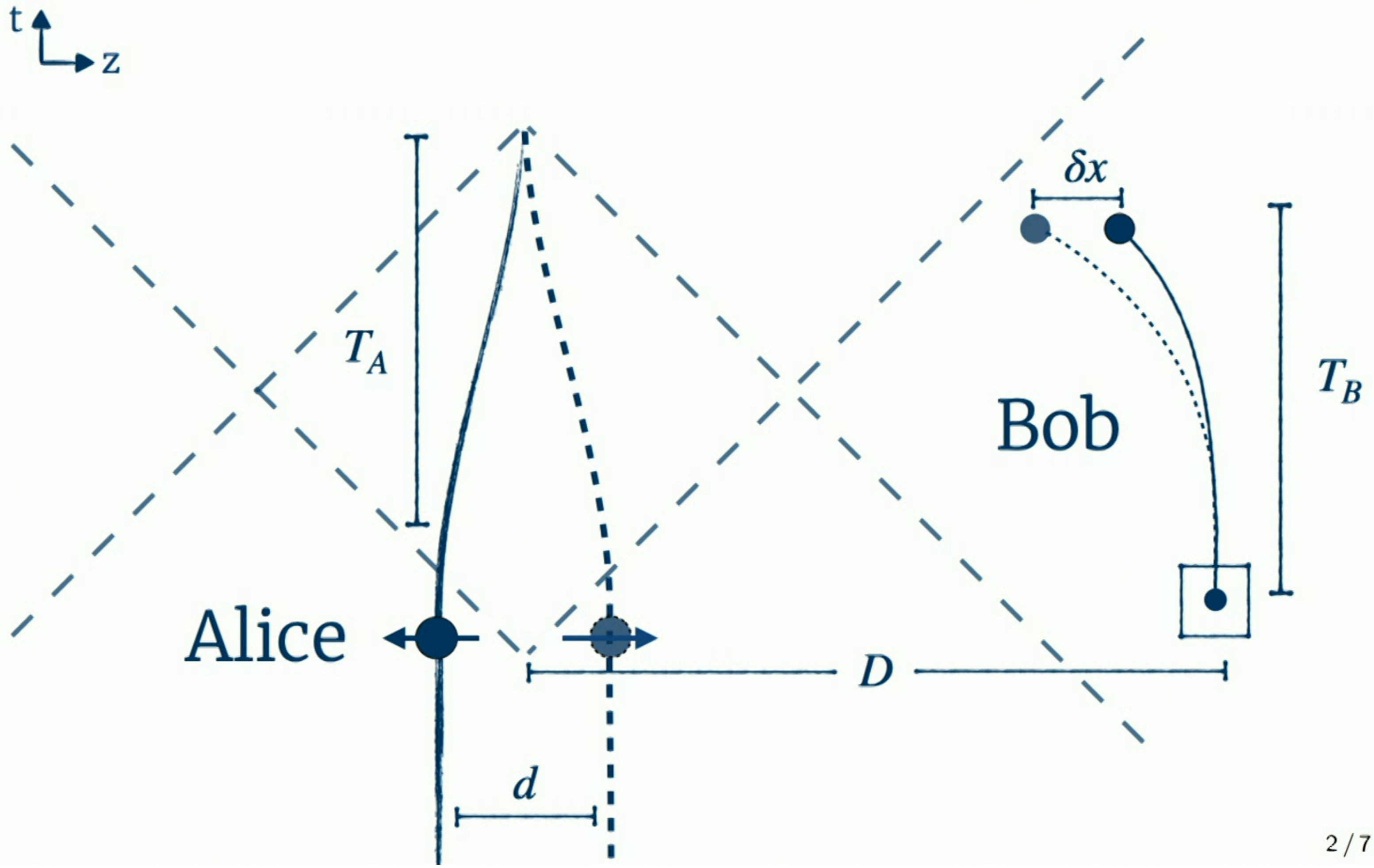
D. Danielson, G.S., & R.M. Wald Int. J. Mod. Phys. D 2241003 (2022) [arXiv:2205.06279]
Gravity Research Foundation Essay: 3rd Prize

D. Danielson, G.S. & R.M. Wald (2023) [arXiv:2301.00026]

D. Danielson, J. Kudler-Flam, G.S. (to appear)

July 31, 2023

A Gedankenexperiment in Flat Spacetime



A Gedankenexperiment in Flat Spacetime

- Consider an experimenter Alice who creates a 50/50 spatial superposition of a particle with EM charge q_A. At a predetermined time, she recombines her particle and checks its coherence

- Another experimenter Bob, has a particle in the trap which he releases at spacelike separation from Alice's recombination.
  - Complementarity: If Bob can obtain "which path" info then his particle is entangled with Alice's. Thus, Alice's particle must be decohered to some degree!
  - Causality: Bob should not be able to influence the coherence of Alice's particle at all!

- Alice's experiment is limited by the emission of entangling radiation. Bob's particle displacement measurement is limited by vacuum fluctuations of the field.

A Gedankenexperiment in Flat Spacetime

- If $|\Psi_1\rangle$ and $|\Psi_2\rangle$ correspond to the electromagnetic radiation states along each path then amount of decoherence due to radiation is

$$\mathscr{D} = 1 - |\langle\Psi_1|\Psi_2\rangle| = 1 - e^{-\frac{1}{2}\langle N\rangle_{\Psi_1-\Psi_2}} \quad \text{where } \langle N\rangle \sim (q_A d/T_A)^2$$

  So, even in the absence of Bob, to maintain coherence Alice must recombine sufficiently slowly ($T_A > q_A d$) to avoid decohering herself.

- Meanwhile Bob's particle is "buffeted around" by vacuum fluctuations of the EM field which yields a fundamental noise $\Delta x_{\text{vac}} \sim q_B/m$. Bob must integrate the displacement of his particle ($\delta x > q_B/m$) within a light travel time from Alice.
  - Both Alice and Bob cannot be succeed for $T_A, T_B < D$ [Belenchia et al., 2019]. For a completely general and rigorous resolution see [Danielson, **G.S.**, Wald, 2022].

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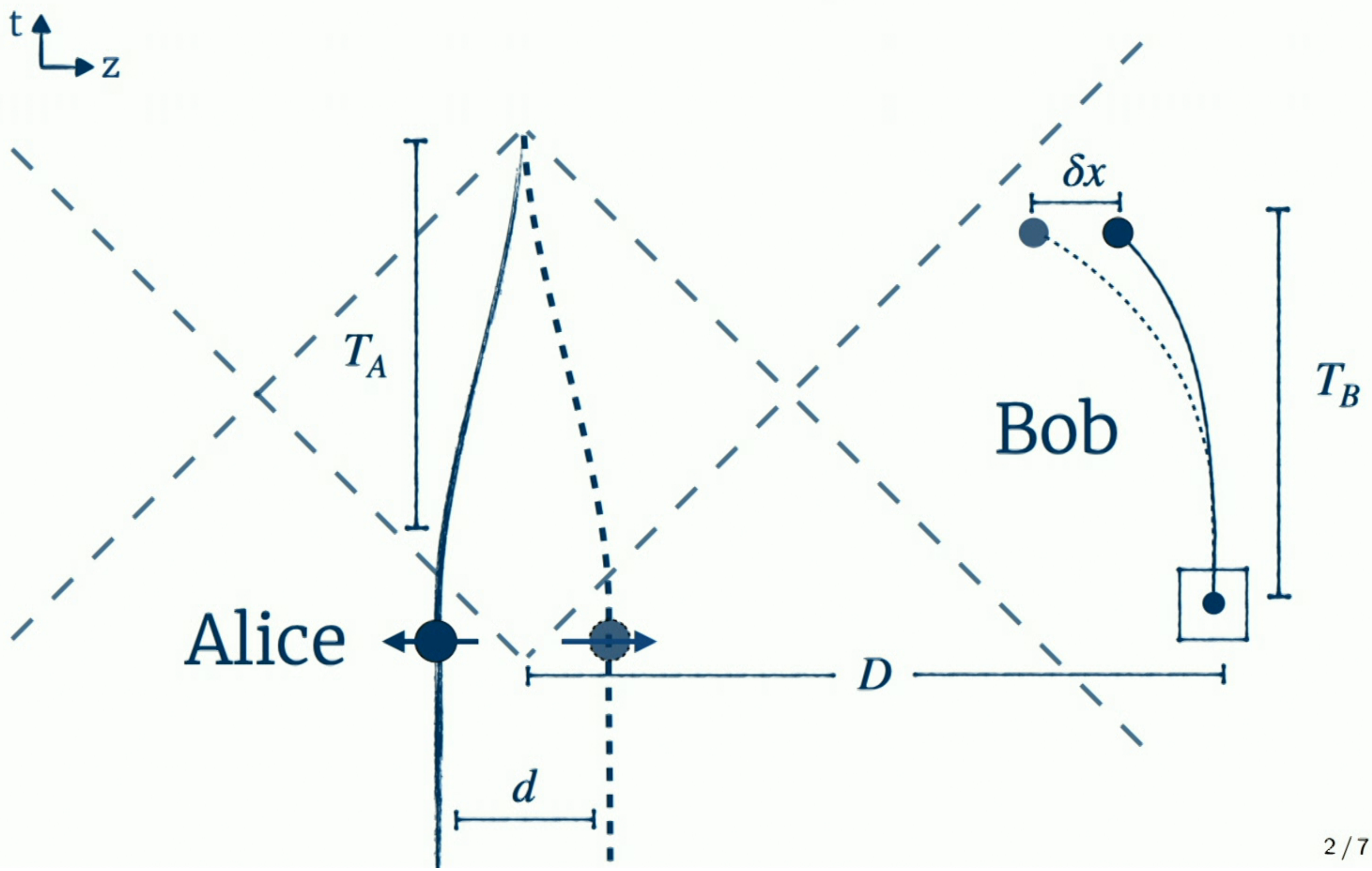

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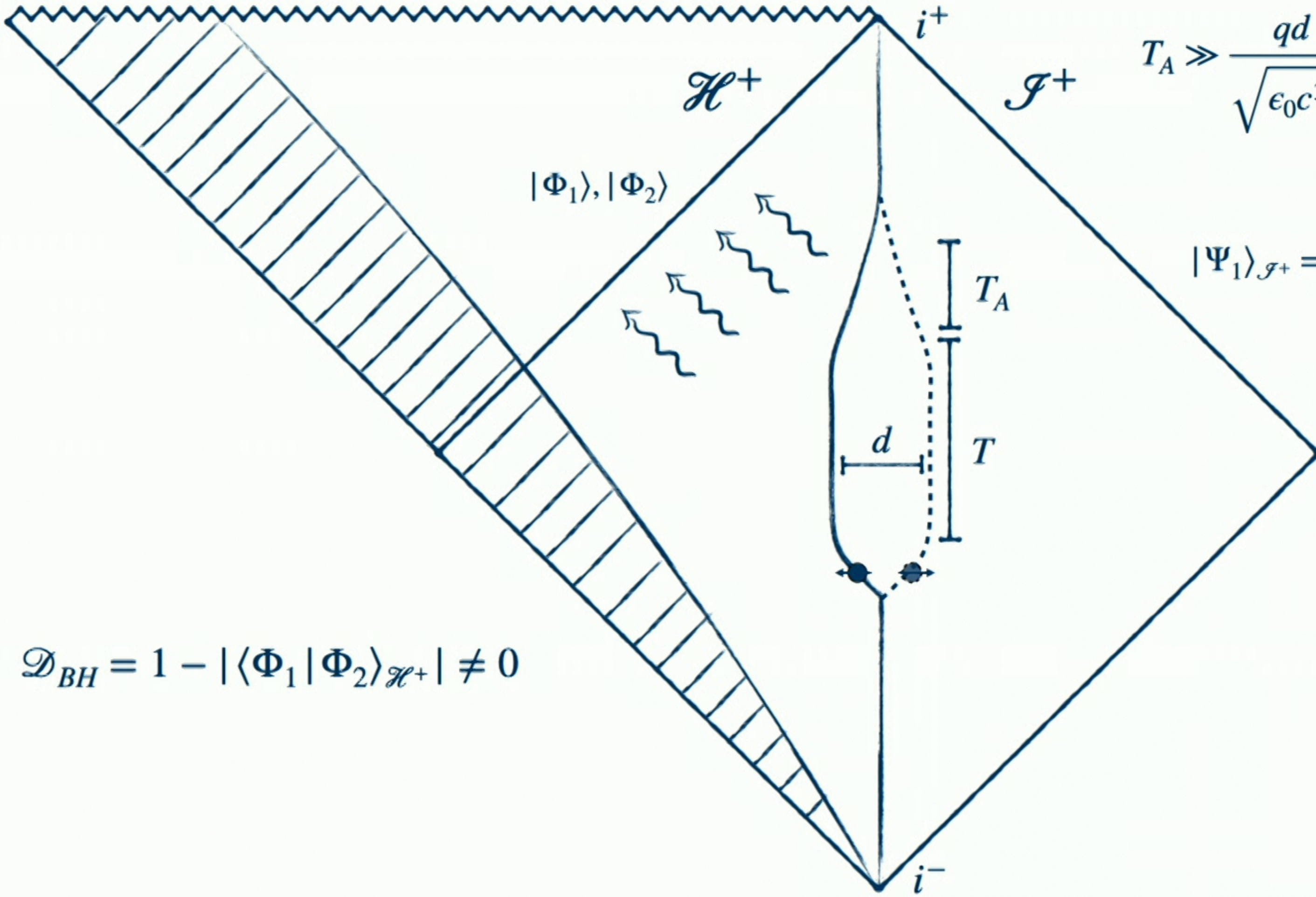
- Lesson: *Alice must decohere herself (by emitting entangling radiation) at least as much as any Bob(s) could decohere her.* If Alice recombines sufficiently adiabatically, in flat spacetime, (i.e. $T_A \gg q_A d$) then she can maintain coherence and, similarly, any Bobs cannot obtain "which path" information

A Gedankenexperiment Outside of a Black Hole



$$T_A \gg \frac{qd}{\sqrt{\epsilon_0 c^3 \hbar}} \text{ and } \frac{GM}{c^3}$$

$$|\Psi_1\rangle_{\mathscr{I}^+} = |\Psi_2\rangle_{\mathscr{I}^+} \approx |0\rangle_{\mathscr{I}^+}$$

$$\mathscr{D}_{BH} = 1 - |\langle \Phi_1 | \Phi_2 \rangle_{\mathscr{H}^+}| \neq 0$$

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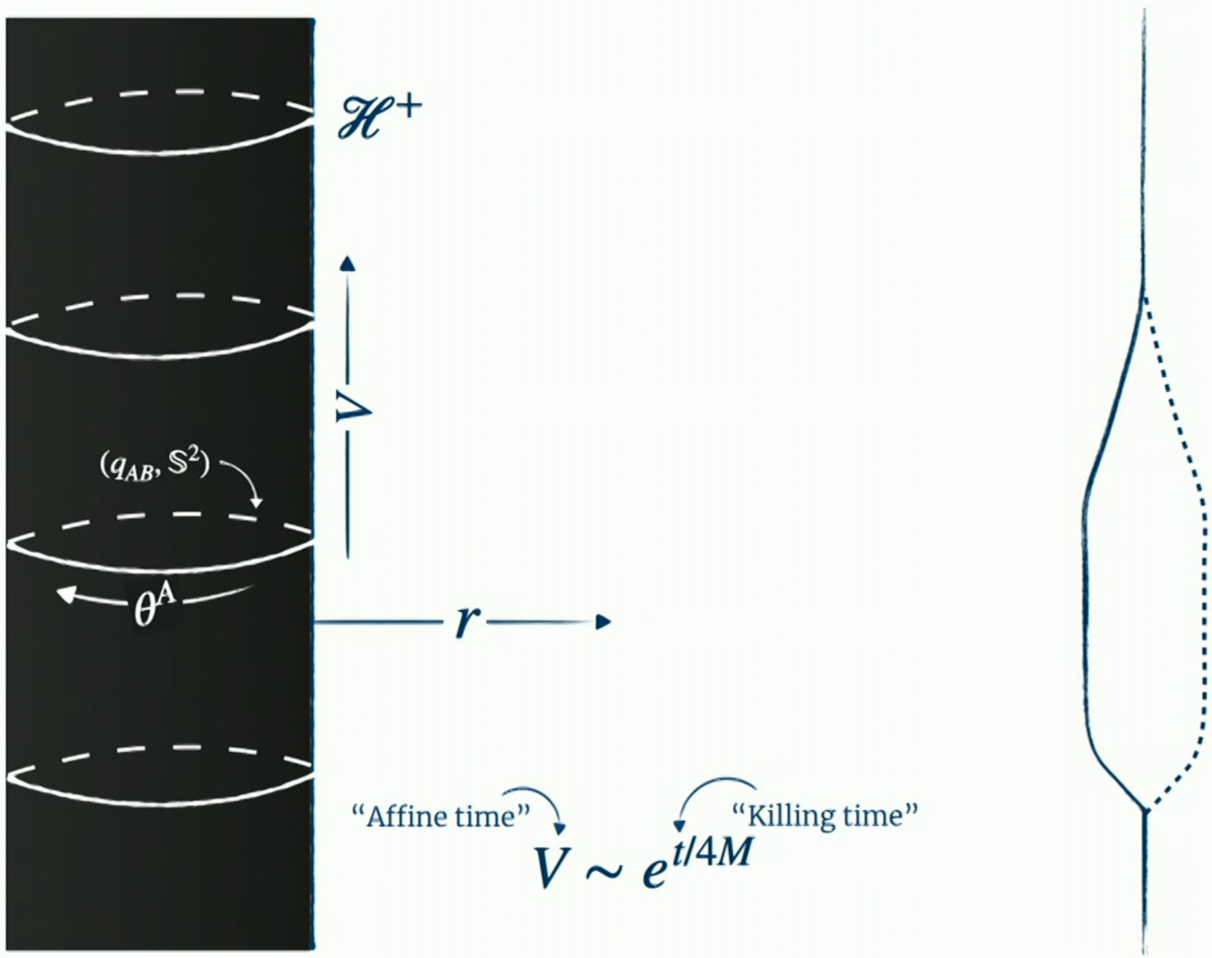


Warm-Up: Displacing a Classical Charge Outside a Black Hole

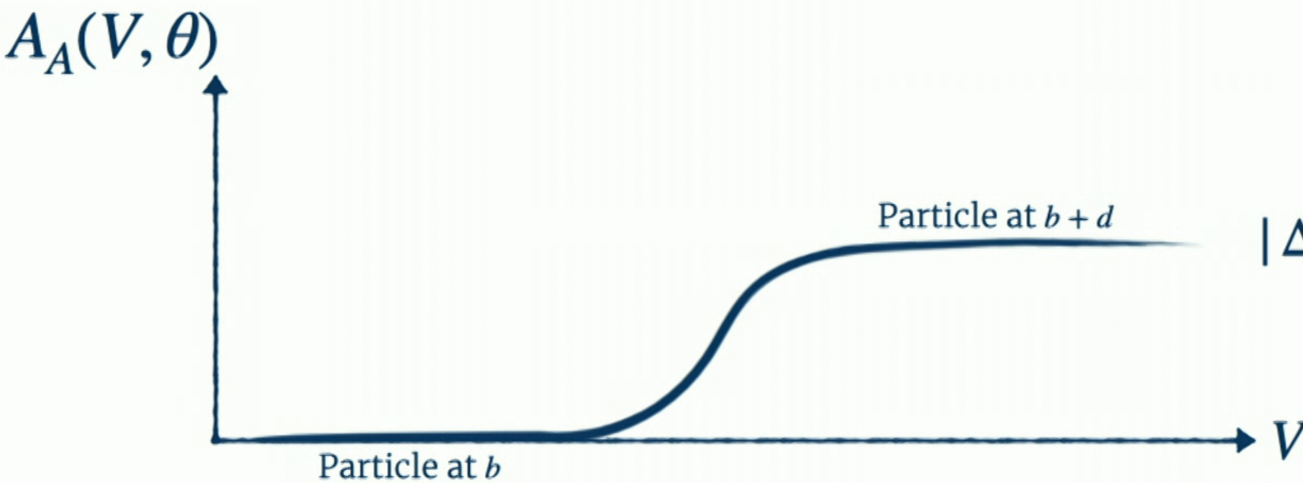
- Let's consider the simpler warm-up problem of the radiation produced by a charged body initially at a position $r = D$ and then is displaced to a position $r = D + d$ where $d \ll D$.
- To analyze the radiation on the horizon we need Maxwell's equation on $\mathscr{H}^+$. Maxwell's equation relates changes in the "Coulombic field" E_r on the horizon to "horizon radiation" E_A which propagates into the horizon.

$$\mathcal{D}^A E_A = -\partial_V E_r$$

- For a static test charge at $r = D$, E_A *vanishes* and $|E_r| \sim q/D^2$. Throughout this process, E_A is very small however, due to the displacement,

$$|\Delta E_r| \sim \frac{qd}{D^3} \implies \int dV \ E_A \neq 0$$

Number of Horizon Photons



$$|\Delta A_A| \propto \frac{qd}{D^3}$$

$$\Delta A_A \neq 0 \implies \tilde{A}_A(\omega,\theta) \sim \frac{1}{\omega}$$

$$\implies \langle N \rangle = ||A||^2 \sim \int_0^\infty \frac{d\omega}{\omega}$$

Number of Horizon Photons

- The quantum state of a classical solution A_a is a coherent state $|\Phi\rangle$. The expected number of horizon photons is

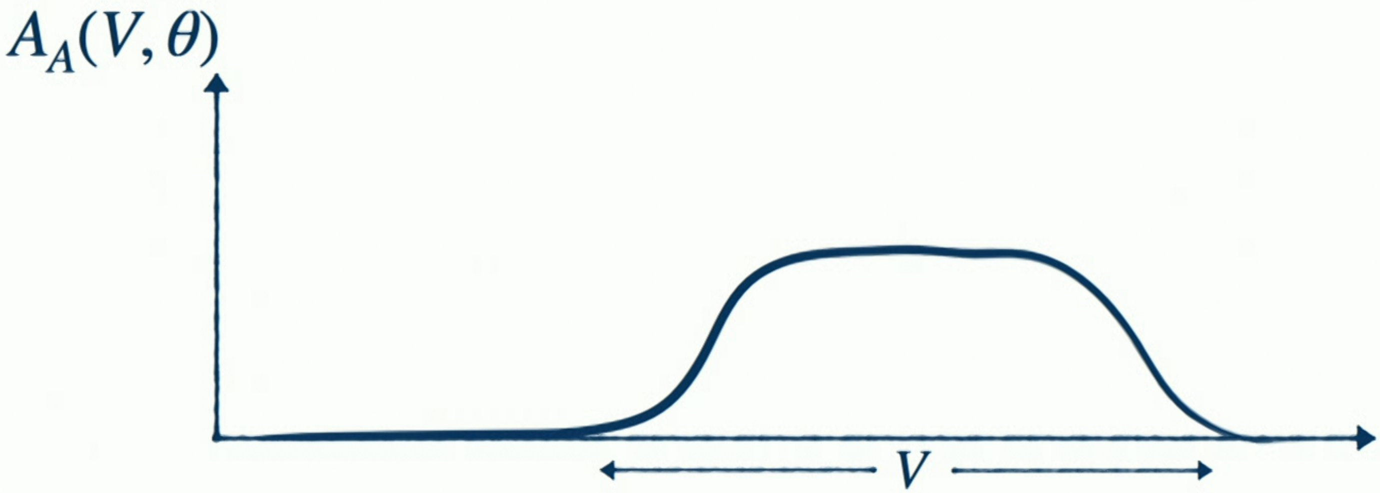
$$\langle N\rangle_\Phi = ||A||^2 = \int_{\mathbb{S}^2} d\Omega \int_0^\infty \omega d\omega \, |\tilde{A}_A(\omega, \theta^A)|^2$$

which is the norm in the one-particle Hilbert space associated to the Hartle-Hawking vacuum (which is equivalent to the Unruh vacuum at low frequencies).

- Displacing a charged body outside of a black hole and keeping there *forever* results in the emission of an infinite number of soft horizon photons.

- If it is displaced back after a time T then $\langle N\rangle_\Phi$ is *finite* but large for large T

Number of Horizon Photons



$$V = e^{T/4M}$$

$$\langle N \rangle = ||A||^2 \sim \frac{G^4 M^4 q^2 d^2}{\hbar c^9 D^6} \ln V = \frac{G^3 M^3 q^2 d^2}{\hbar c^5 D^6} T$$

Black Holes Decohere Quantum Superpositions

- Both branches of Alice's superposition will be forced to radiate soft photons through the horizon over a proper time T such that number of entangling soft photons is given by

$$\langle N \rangle_{\Phi_1 - \Phi_2} \propto T$$

- The decoherence entirely due to the presence of the black hole is given by

$$\mathscr{D}_{\mathrm{BH}} = 1 - |\langle \Phi_1 | \Phi_2 \rangle_{\mathscr{H}^+}| = 1 - e^{-\langle N \rangle_{\Phi_1 - \Phi_2}}$$

and so after the emission of an $O(1)$ number of entangling soft photons the superposition completely decohered.

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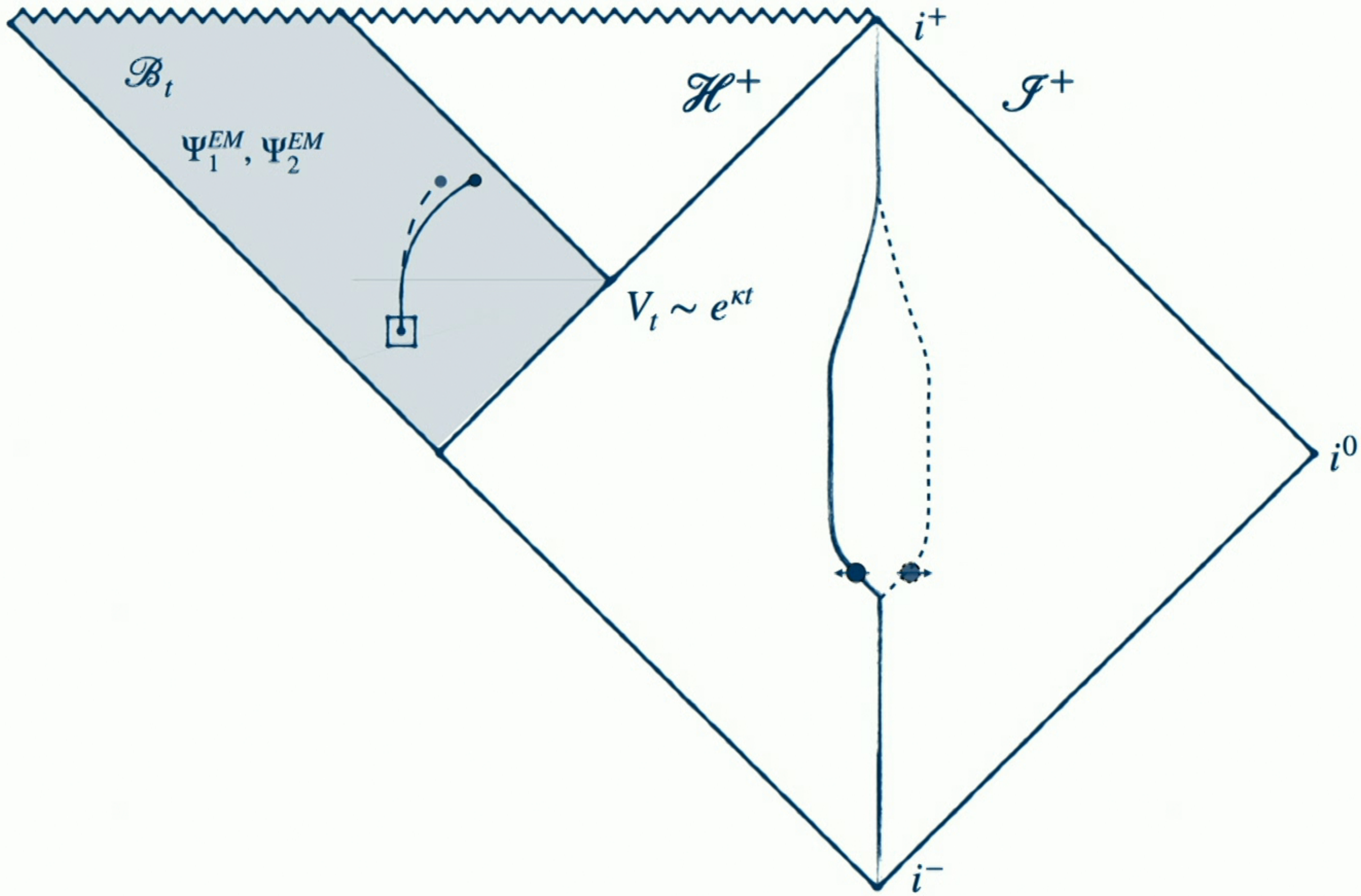
- A charged/massive spatial superposition held outside of a black hole is totally decohered in a time

$$T_{\mathrm{D}}^{\mathrm{EM}} \sim \frac{D^6}{M^3 q^2 d^2} \qquad T_{\mathrm{D}}^{\mathrm{GR}} \sim \frac{D^{10}}{M^5 m^2 d^4}$$

- If performed sufficiently adiabatically, the gravitational field of an ordinary massive body ($r_{\mathrm{body}} \gg r_{\mathrm{S}}$) will not decohere Alice's particle [G.S., S. Carot-Huot, (in prep.)].

Quantum Information Inside the Black Hole

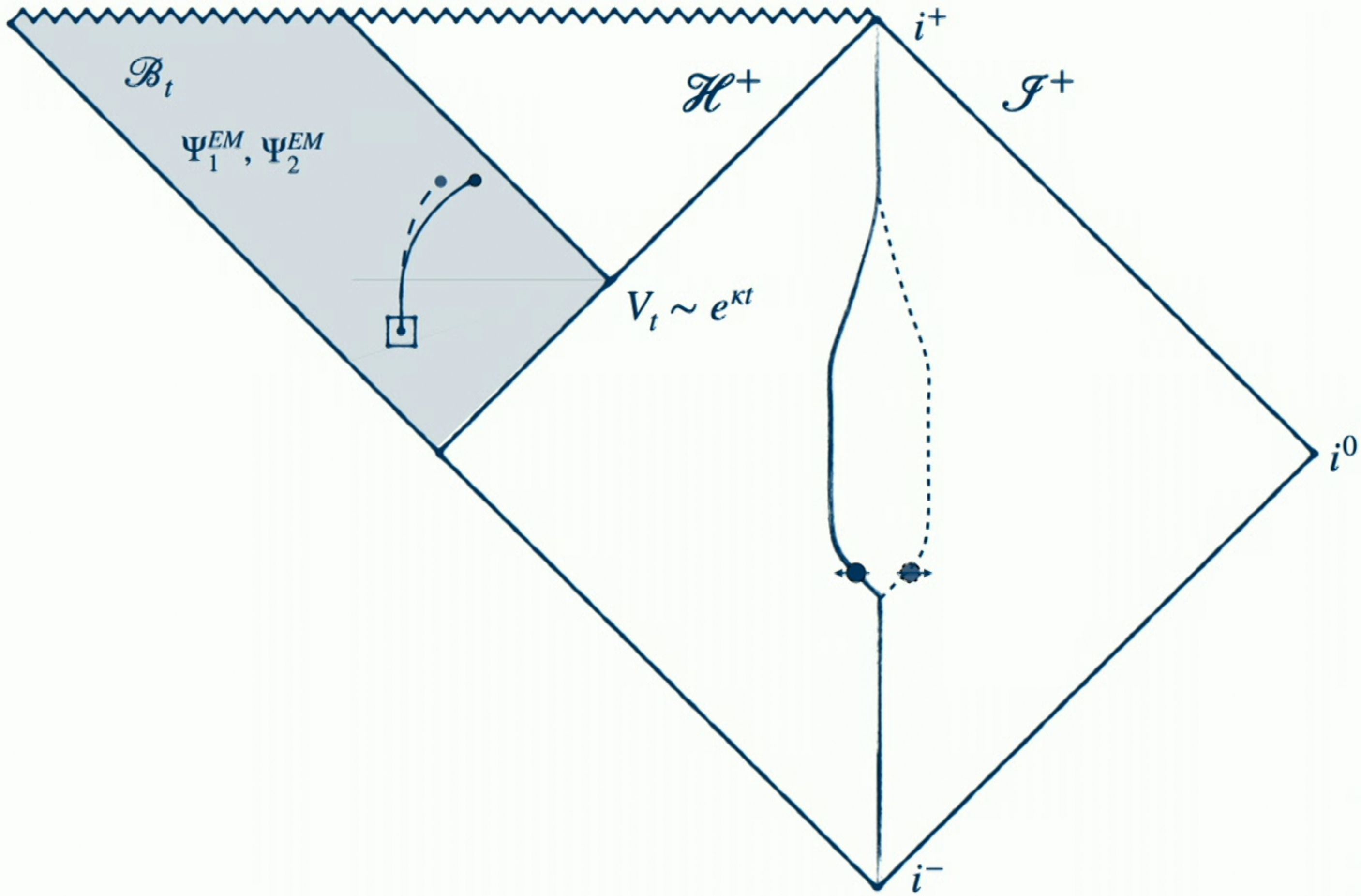


Quantum Information Inside the Black Hole

- What about the decoherence due to Bob(s) inside the black hole? Let $\mathscr{B}_t$ be a bounded region inside the black hole, and let Ψ_1^{EM} and Ψ_2^{EM} be the two possible (mixed) states of the EM field restricted to $\mathscr{B}_t$.
- Decoherence due to Bob(s) "optimal" measurement is determined by "fidelity"
  - Fidelity - The error in Bob's "optimal" measurement in distinguishing states Ψ_1 and Ψ_2 in $\mathscr{B}_t$ and is denoted by $0 \leq F_t(\Psi_1^{\mathrm{EM}}, \Psi_2^{\mathrm{EM}}) \leq 1$

  In quantum mechanics, the fidelity of two density matrices is $F_t^2 = \mathrm{Tr}[\sqrt{\rho_1}\sqrt{\rho_2}]$. In QFT F_t is defined using modular theory [Danielson, Kudler-Flam, **G.S.** (to appear)].
- The fidelity is monotonic as the region $\mathscr{B}_t$ increases. However we prove that
  - $F_t(\Psi_1^{\mathrm{EM}}, \Psi_2^{\mathrm{EM}})$ is a strictly decreasing function of t
  - $F_t(\Psi_1^{\mathrm{EM}}, \Psi_2^{\mathrm{EM}}) > \exp(-\frac{1}{2}\langle N\rangle_t)$ where $\langle N\rangle_t \sim (q^2 d^2 M^3/D^6)\cdot t$
  - $\lim_{t\to\infty} F_t(\Psi_1^{\mathrm{EM}}, \Psi_2^{\mathrm{EM}}) = \exp(-\frac{1}{2}\langle N\rangle_T)$

Quantum Information Inside the Black Hole



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  - $\lim_{t\to\infty} F_t(\Psi_1^{\mathrm{EM}}, \Psi_2^{\mathrm{EM}}) = \exp(-\frac{1}{2}\langle N\rangle_T)$

The decoherence due to the black hole — or any horizon — is equivalent to the decoherence due to the optimal "which path" measurement made in its interior

Quantum Information Inside the Black Hole

- The growth of quantum information in the interior of the black hole suggests a relationship between F_t and the accrued decoherence of Alice's particle at time t from simply holding the superposition outside the black hole. [Danielson, Kudler-Flam, **G.S.** (to appear)]
- Alice's experiment can be more precisley thought of as a quantum channel $\mathcal{N}_t$ which maps her (initially pure) state to a (possibly mixed) state at time t.
- To characterize the decoherence of the channel we applying a "decoding channel" $\mathcal{D}$ which attempts to "reverse" Alice's quantum channel. The decoherence is then given by

$$\mathscr{D}_t(\mathcal{N}) = \inf_{\mathcal{D}} ||\mathcal{D} \circ \mathcal{N}_t - 1||_\diamond$$

Recombining the particle at $t = T$ yields $\mathscr{D}_T(\mathcal{N}) = \mathscr{D}_{\text{B.H.}}$.

- The information disturbance tradeoff relates F_t to $\mathscr{D}_t(\mathcal{N})$ for all t [Kretschmann et al., 2006]

$$1 - \sqrt{1 - \frac{1}{64}\mathscr{D}_t(\mathcal{N})} \leq 1 - F_t^2(\Psi_1, \Psi_2) \leq \sqrt{\mathscr{D}_t(\mathcal{N})}$$

Summary and Conclusions

- If one creates a quantum spatial superposition in the presence of a Killing horizon, the long range fields of the quantum superposition register on the horizon. This results in a constant rate of production of "entangling radiation" into the horizon.
- In this manner, horizons harvest "which path" information about quantum superpositions in their vicinity. Eventually, the horizon will decohere any quantum superposition.
- This effect is *not* due to thermal radiation or the local acceleration of Alice's lab.
- We give a more general and precise description of Alice's protocol in terms of quantum channels and (failure of) quantum error correction and relate the decoherence of the channel due to "optimal" measurements made in the black hole interior. [Danielson, Kudler-Flam, **G.S.** (to appear)]

We believe the fact that black holes and cosmological horizons will eventually decohere any quantum superposition in their vicinity may be of fundamental significance to our understanding of the nature of black holes and horizons in a quantum theory of gravity