Title: Horizons are Watching You

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Series: Quantum Gravity

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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) the mere presence of the horizon will eventually destroy the coherence of the superposition. This occurs because, in effect, the long-range fields sourced by the superposition registers on the horizon which forces the radiation of entangling soft gravitons/photons through the horizon. This allows the horizon to harvest "which path" information about the superposition. The electromagnetic decoherence arises only when the superposed particle carries electric charge. However, since all matter sources gravity, the quantum gravitational decoherence applies to all superpositions. We provide estimates of the decoherence time for such quantum superpositions. Additionally, we show that this decoherence is distinct from--and larger than--the decoherence resulting from the presence of thermal radiation from the horizon (i.e. Hawking/Bunch-Davies/Unruh radiation). We believe that the fact that Killing horizons will eventually decohere any quantum superposition may be of fundamental significance for our understanding of the nature of black holes and horizons in quantum gravity. (Based on arXiv:2205.06279 and arXiv: 2301.00026).

Zoom link: https://pitp.zoom.us/j/95263116767?pwd=amZ6SkROV1lxckVpdzhNbFhYc1ZiQT09

Horizons are Watching You

Gautam Satishchandran

Princeton University

Perimeter Institute Quantum Gravity Seminar

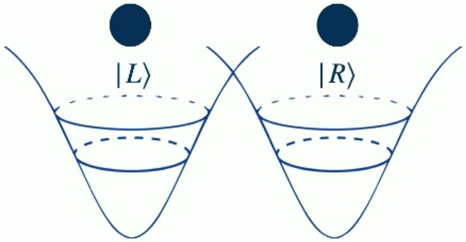
D. Danielson, G.S. & R.M. Wald (2023) [arXiv:2301.00026]

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 Phys. Rev. D 105, 086001 (2022) [arXiv:2112.10798]

February 2, 2023

Gedankenexperiments and Quantum Gravity



[Bose et al. 2017], [Marletto et al. 2017],[Aspelmeyer et al., 2011-now], ...

> *"One should think about designing a gedankenexperiment which uses a gravitational link and at the same time shows quantum interference."*

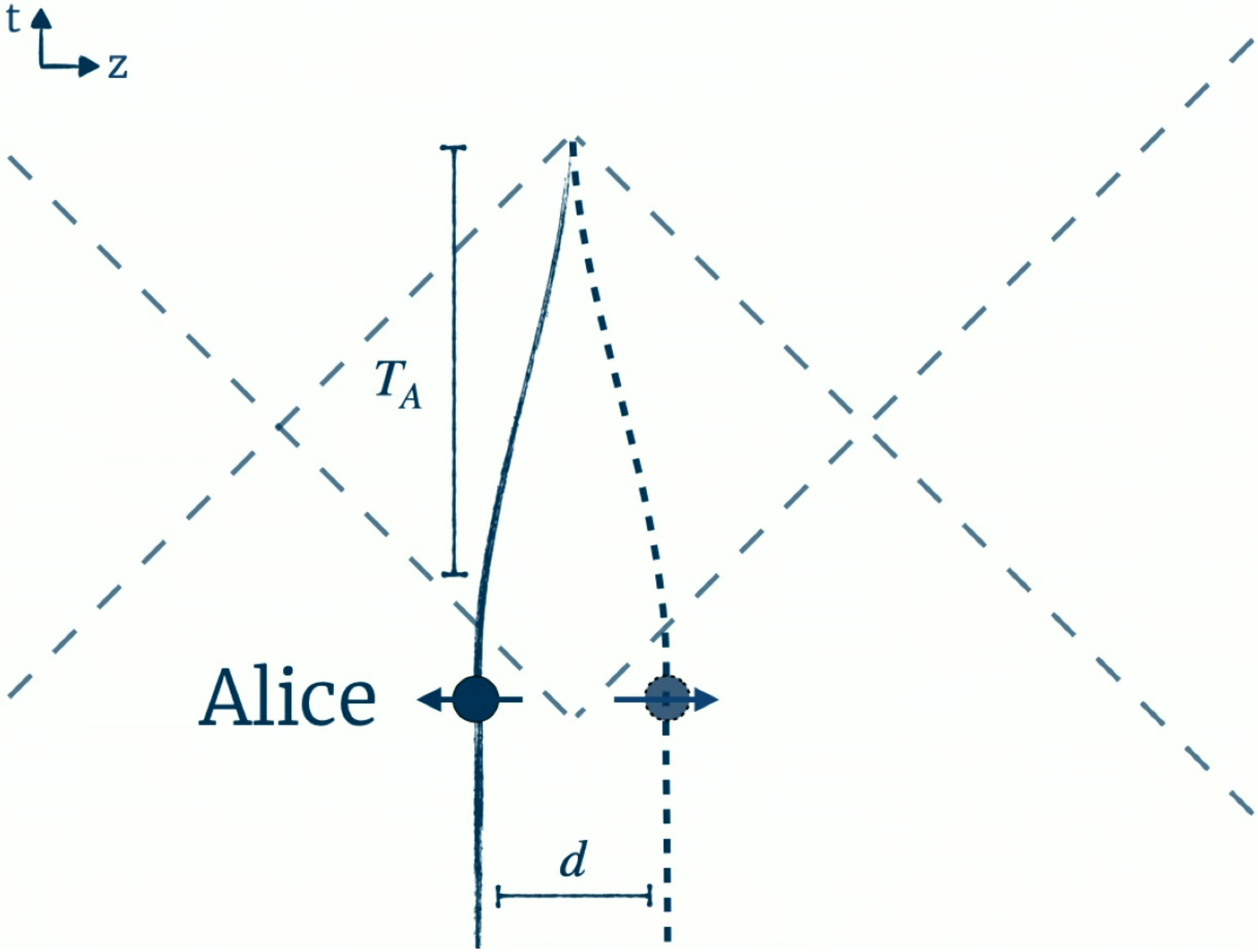
[Feynman, 1957 Chapel Hill Conference]

- To probe properties of quantum gravity, it's useful to consider situations where both quantum theory and gravity play an essential role.
- In the spirit of Feynman, we shall show that such gedankenexperiments provide insights into the relationship between horizons and decoherence of quantum superpositions in a quantum theory of gravity.

A Gedankenexperiment in Flat Spacetime

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

A Gedankenexperiment in Flat Spacetime



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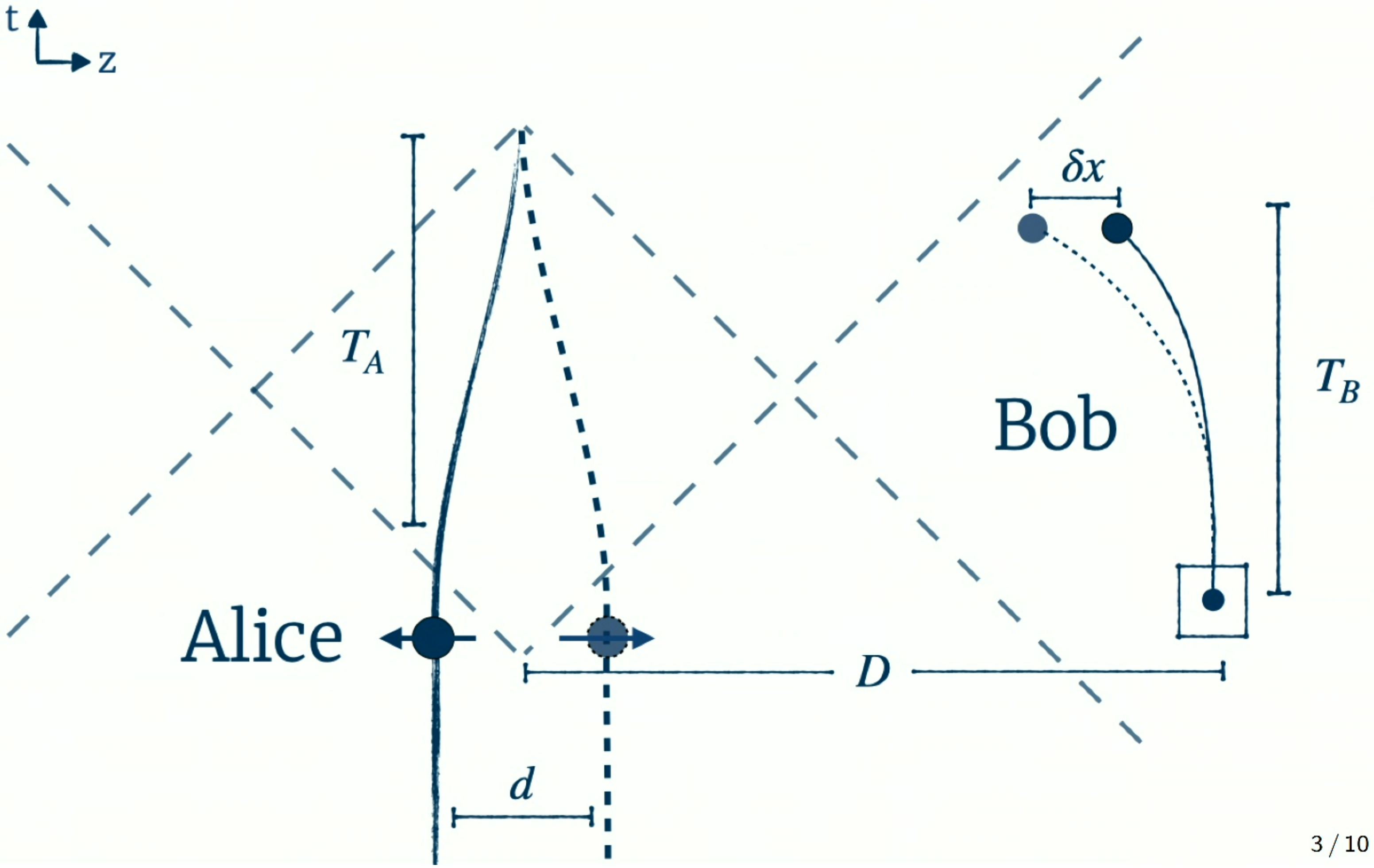

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- Another experimenter Bob, has a particle in the trap which he releases at spacelike separation from Alice's recombination. Due to the superposition of Coulomb fields his particle will become deflected differently (and therefore entangled) according to "which path" Alice's particle went on.
    - 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.

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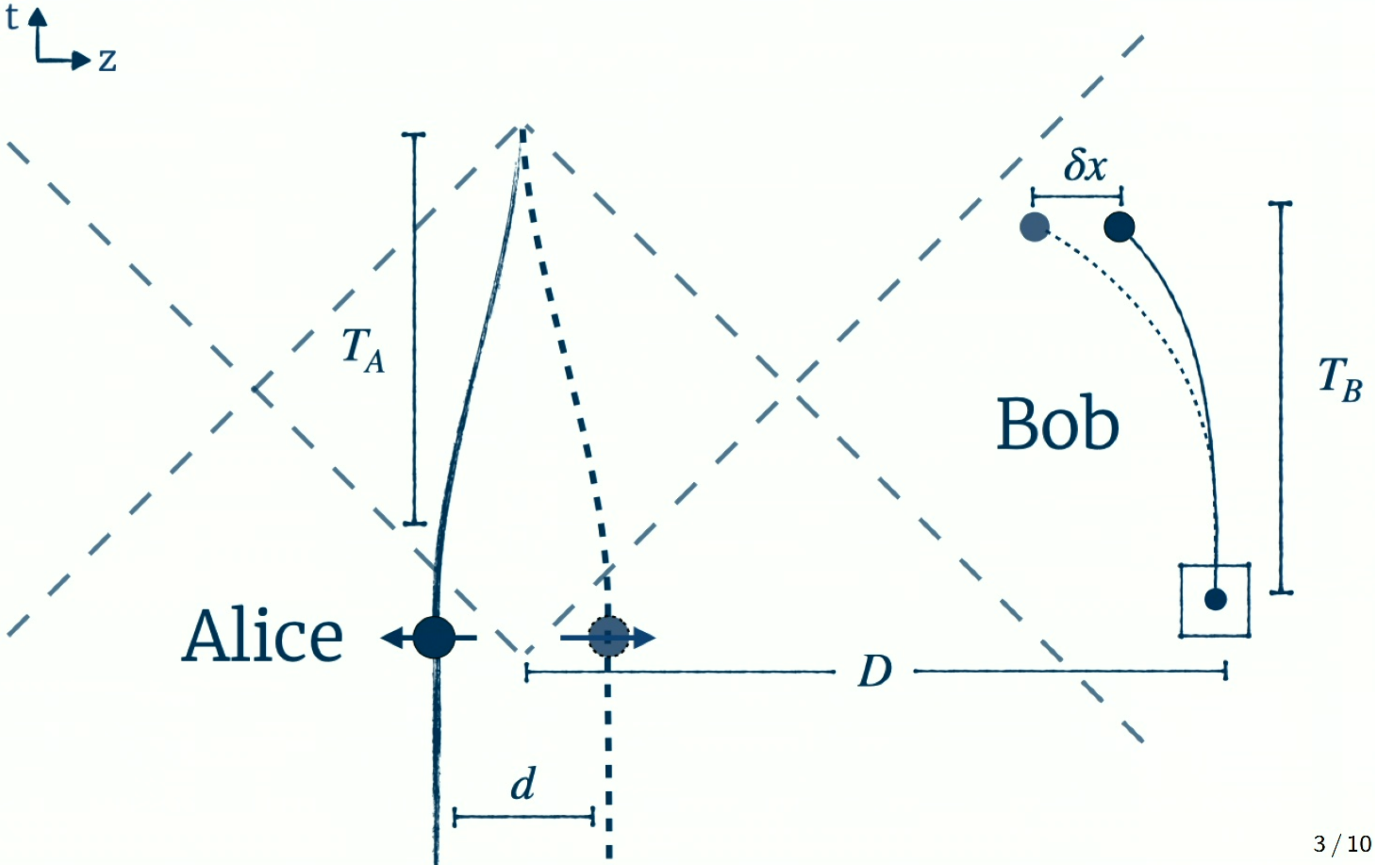

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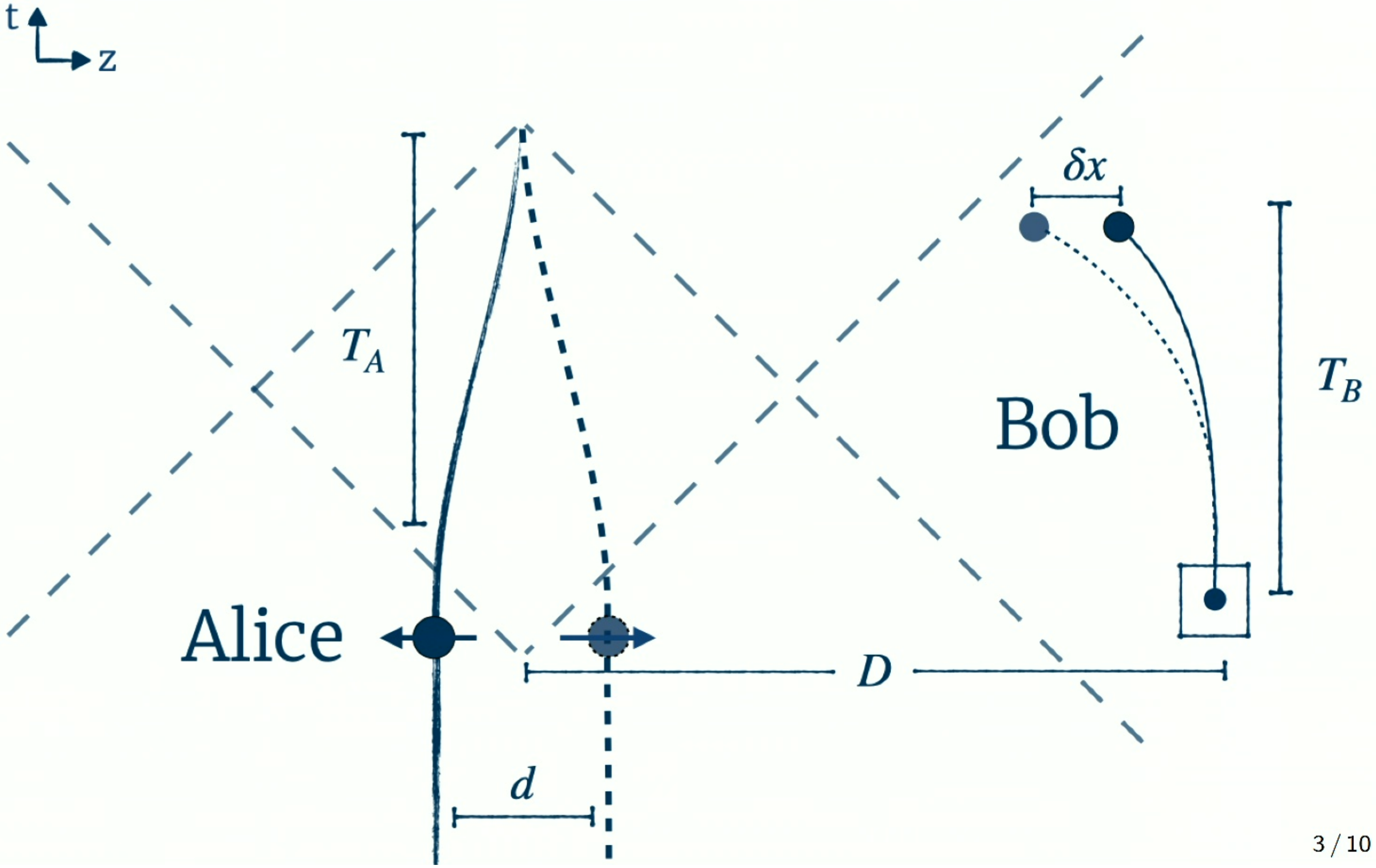

A Gedankenexperiment in Flat Spacetime

- 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

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

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- Meanwhile Bob's particle is "buffeted around" by vacuum fluctuations of the EM field. So to make a measurement $\delta x > \Delta x_{\text{vac}} \sim q/m$ which is the case iff $qd > D$.
  - Both of these conditions cannot be achieved 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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- 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. $T_A \gg qd$) then she can maintain coherence and, similarly, any Bobs cannot obtain "which path" information

A Gedankenexperiment Outside of a Black Hole

- Now suppose a black hole is present and suppose Bob (or a sequence of Bobs) are *inside* the black hole. Alice is outside of the black hole and can now maintain her superposition for as long as she likes.
- The Bobs cannot causally influence Alice but, if the superposition is maintained for a long time, they should be able to accumulate arbitrarily good which path information.

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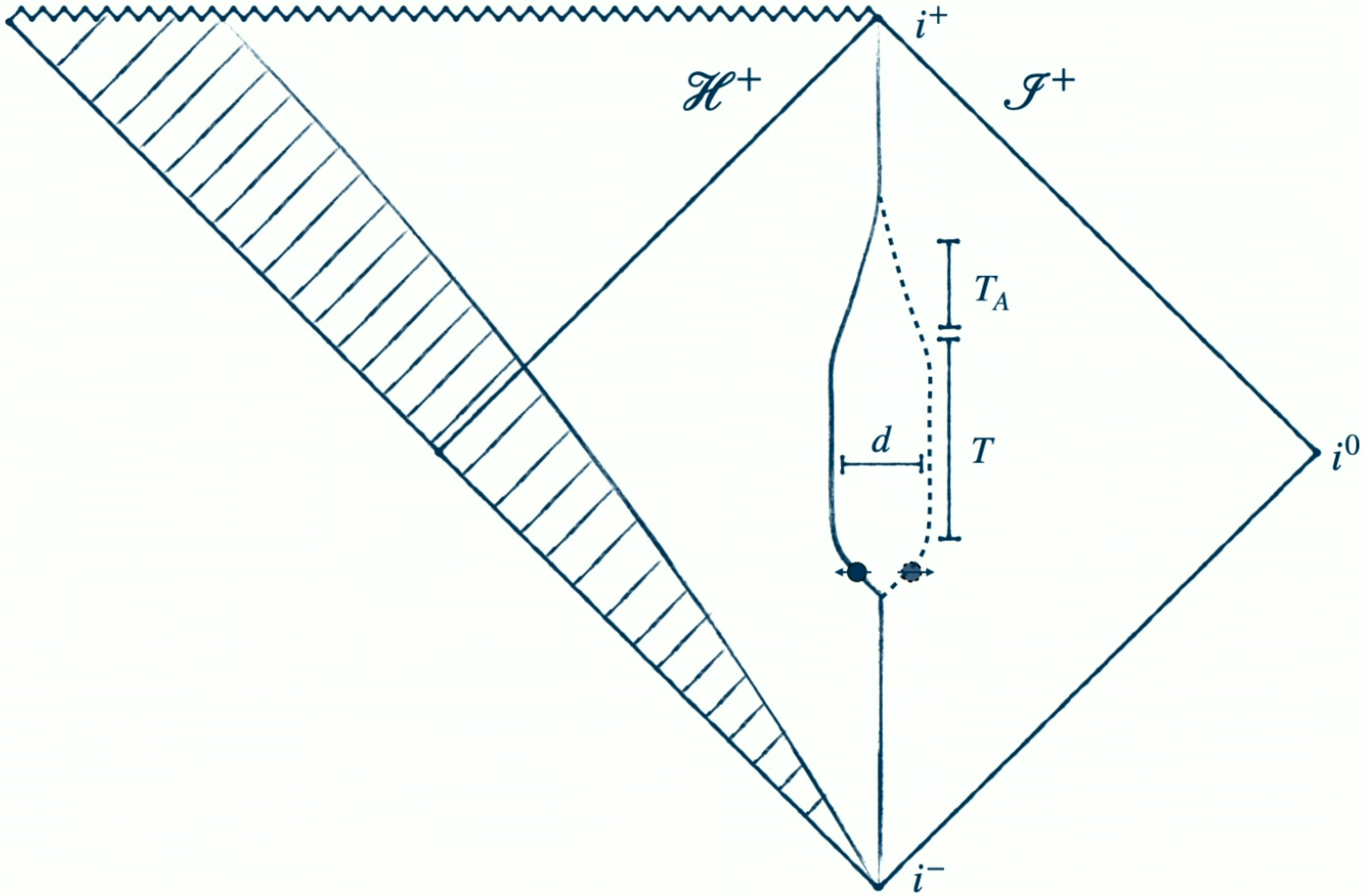

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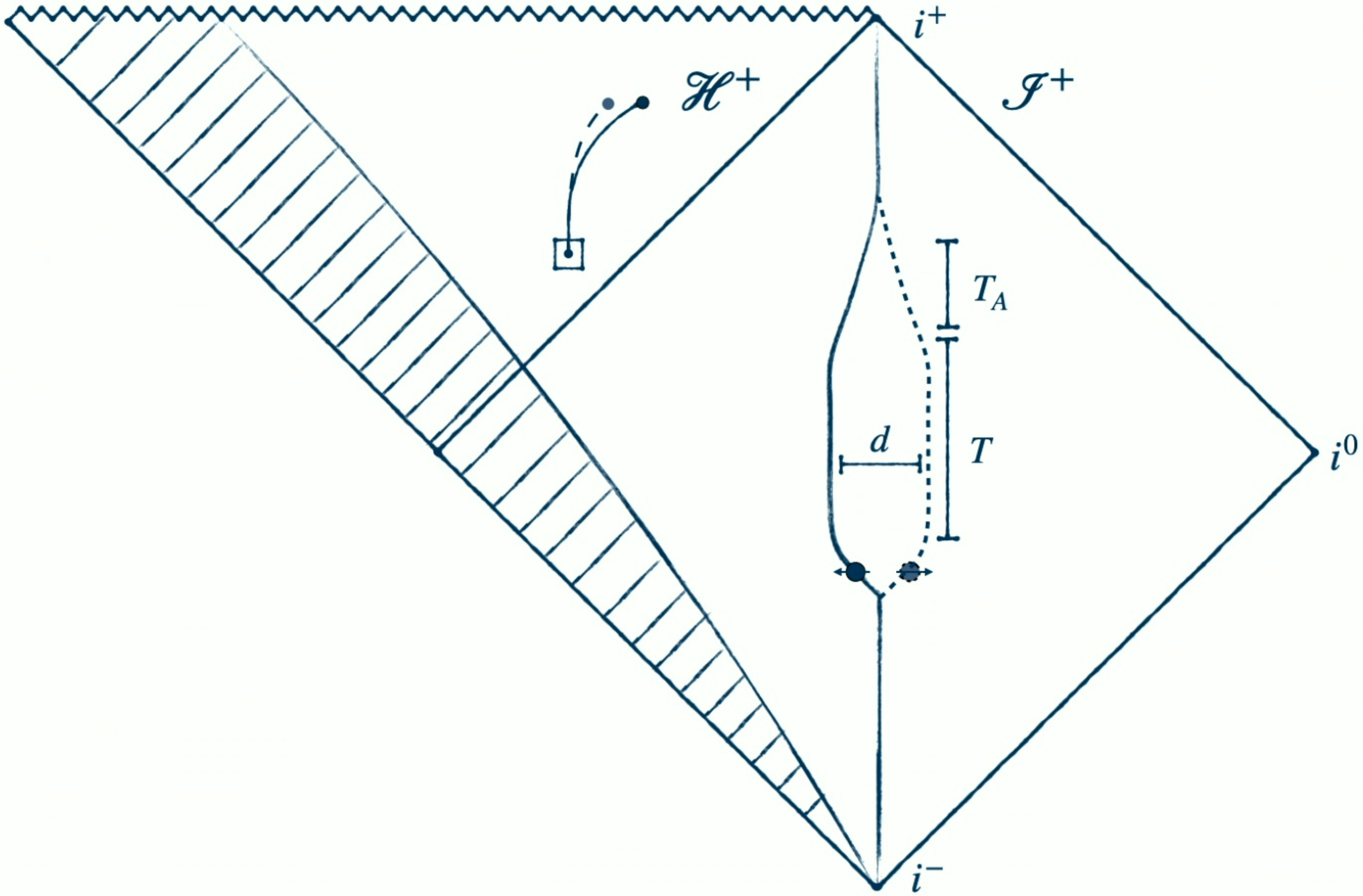

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- The Bobs cannot causally influence Alice but, if the superposition is maintained for a long time, they should be able to accumulate arbitrarily good which path information.
- We will now show that black holes, indeed, harvest which path information of quantum superpositions held in their exterior. In particular, the presence of a black hole forces Alice's particle to emit entangling "soft" photons/gravitons into the black hole resulting in a constant rate of decoherence

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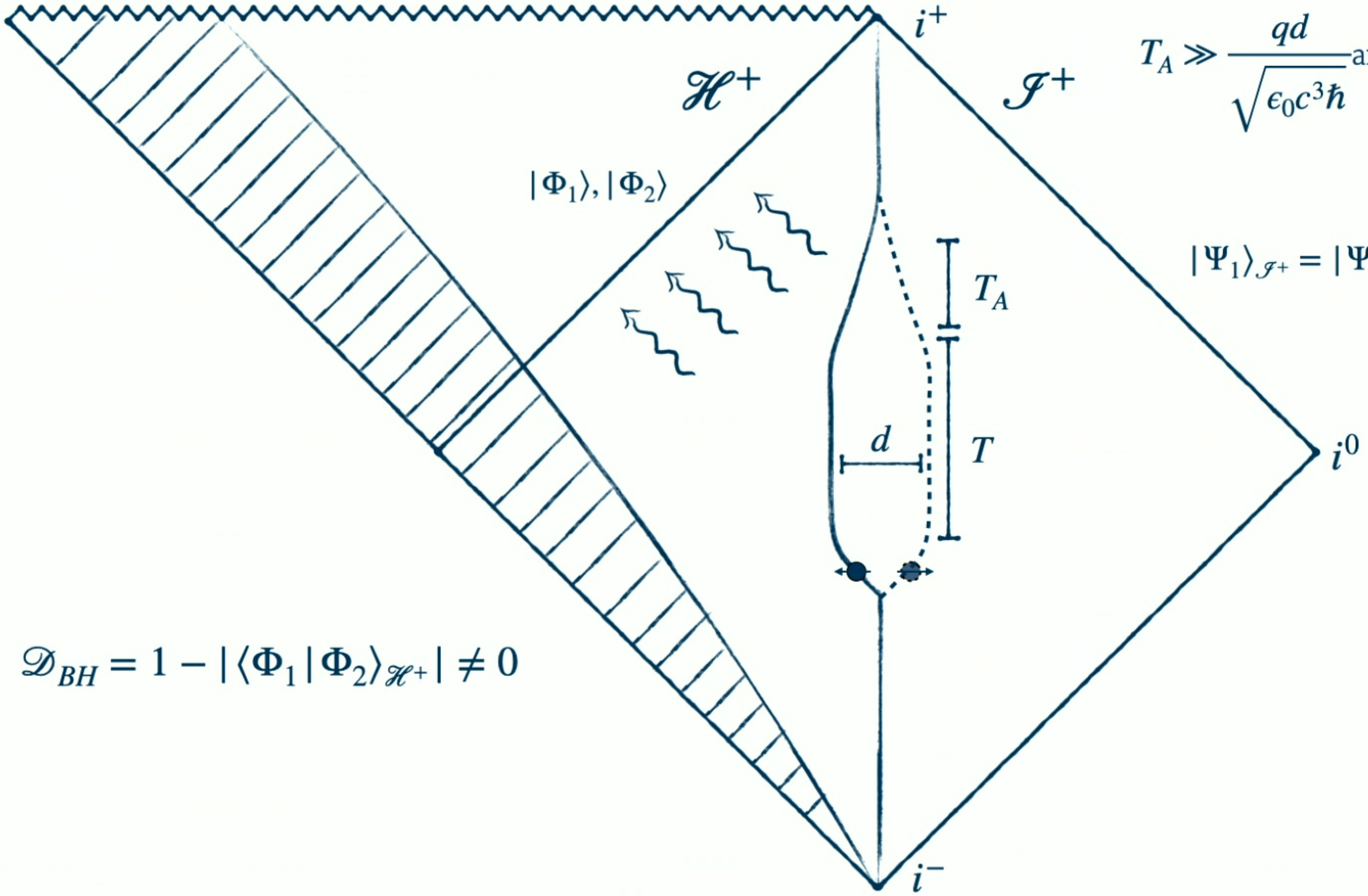

$$T_A \gg \frac{qd}{\sqrt{\epsilon_0 c^3 \hbar}} \text{ and } \frac{GM}{c^3}$$

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

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

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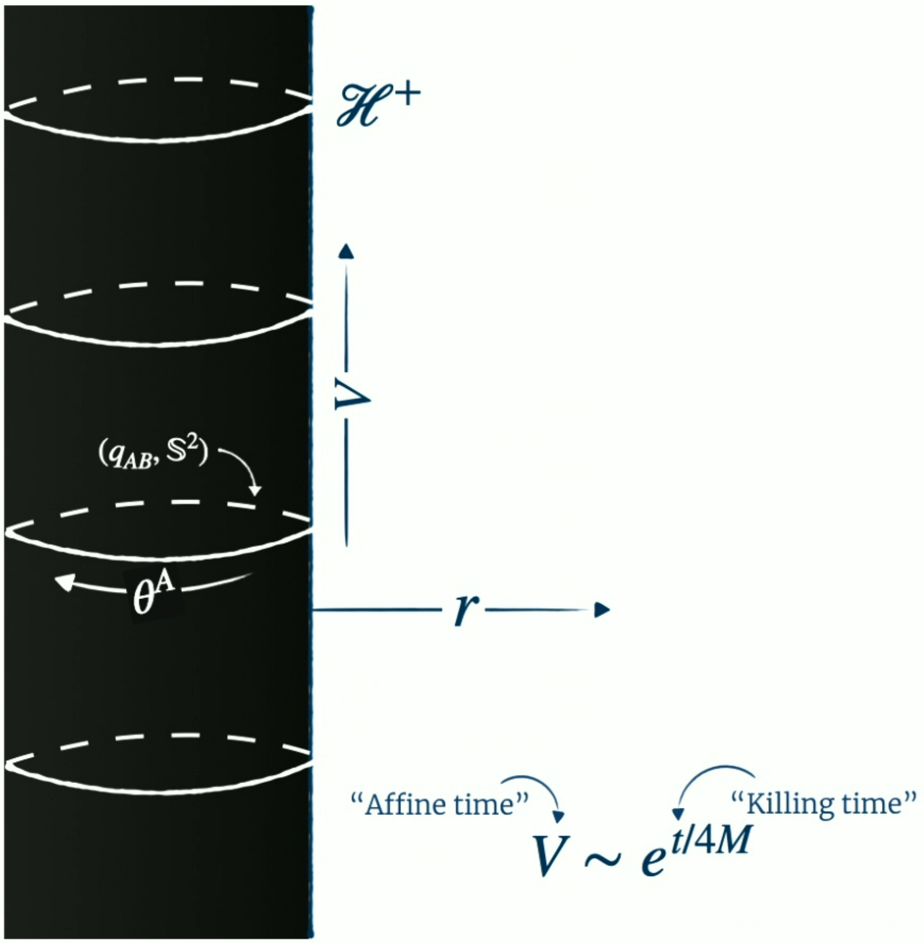
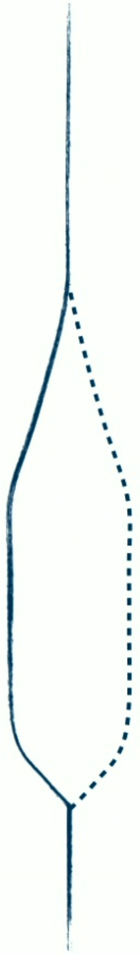


$$V \sim e^{t/4M}$$



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 $d \ll D$.

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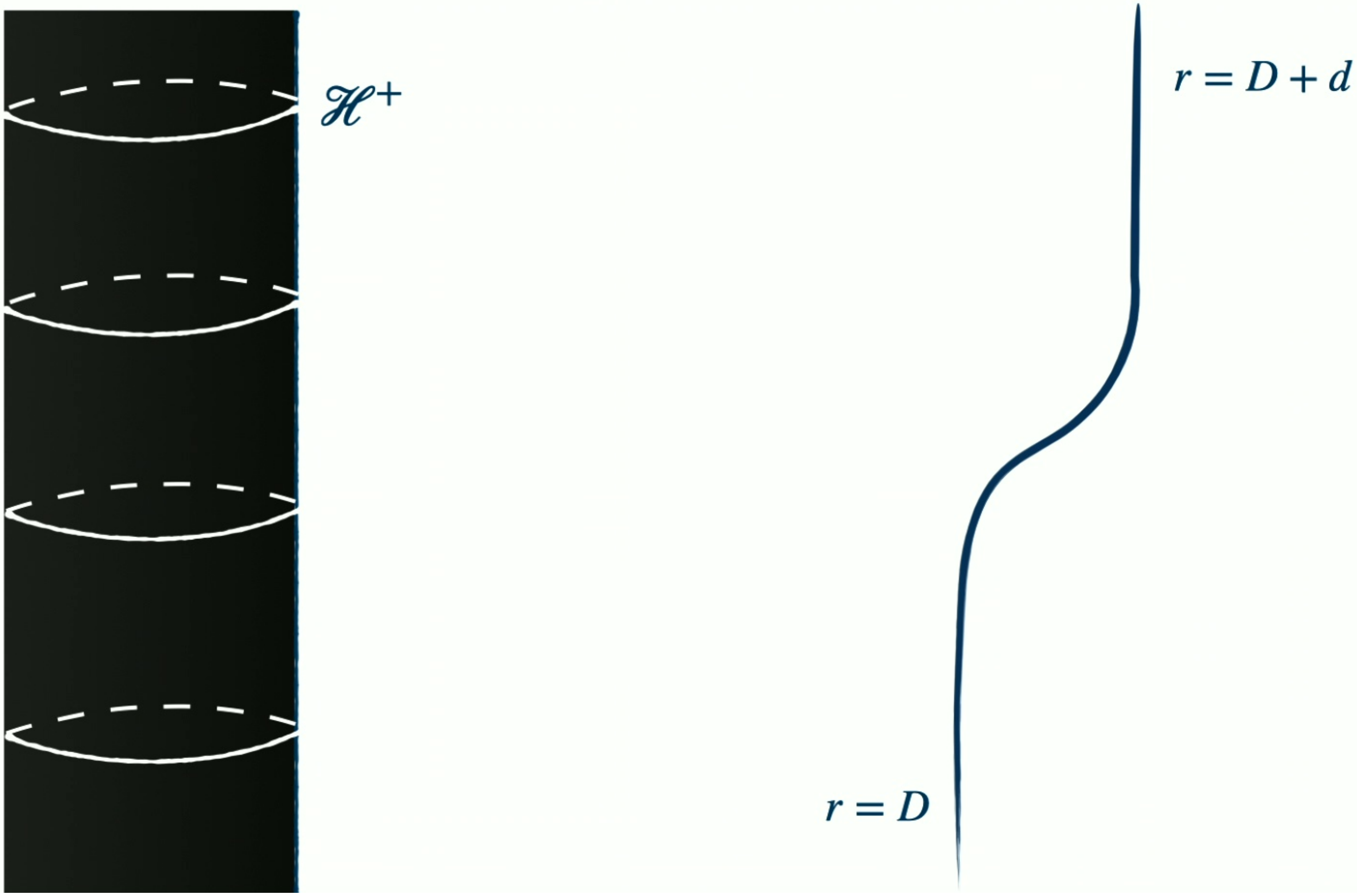

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- To analyze the radiation on the horizon we need Maxwell's equation on $\mathscr{H}^+$. Maxwell's equation relates changes in the "Coulombic field" E_r on the horizon to "horizon radiation" E_A which propagates into the horizon.

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- 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,

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- In terms of the vector potential on the horizon $E_A = \partial_V A_A$, this implies that A_A must suffer a permanent change between early and late times.

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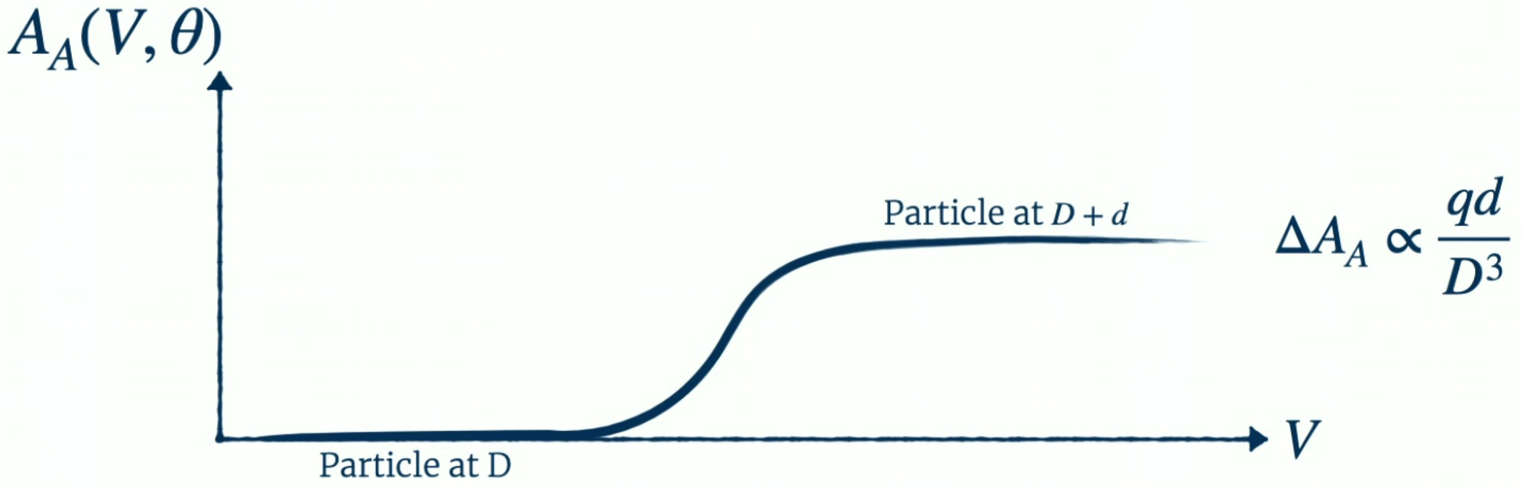

$$D^A E_A = -\,\partial_V E_r \qquad E_A = \partial_V A_A$$

$$\Delta E_r \neq 0 \implies \Delta A_A \neq 0$$

Number of Horizon Photons

- The quantum state of a classical solution A_a is a coherent state $|\Phi\rangle$. The expected number of photons in a coherent state above a chosen vacuum state is given by the norm of the classical solution in the corresponding one-particle Hilbert space.

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- The "vacuum state" for a black hole formed from gravitational collapse is the "Unruh vacuum" '[Hawking, '75] which, at low frequencies is equivalent to the "Hartle-Hawking vacuum" [Hawking, '75]. The corresponding Hilbert space has the following norm on the horizon

$$||A||^2_{\mathscr{H}^+} = \frac{2c}{\hbar}\int_{\mathbb{S}^2} d\Omega \int_0^\infty \omega d\omega \, |\tilde{A}_A(\omega, \theta^A)|^2$$

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- Displacing a charge outside of black hole and keeping it there *forever* results in an infinite number of "soft" horizon photons.

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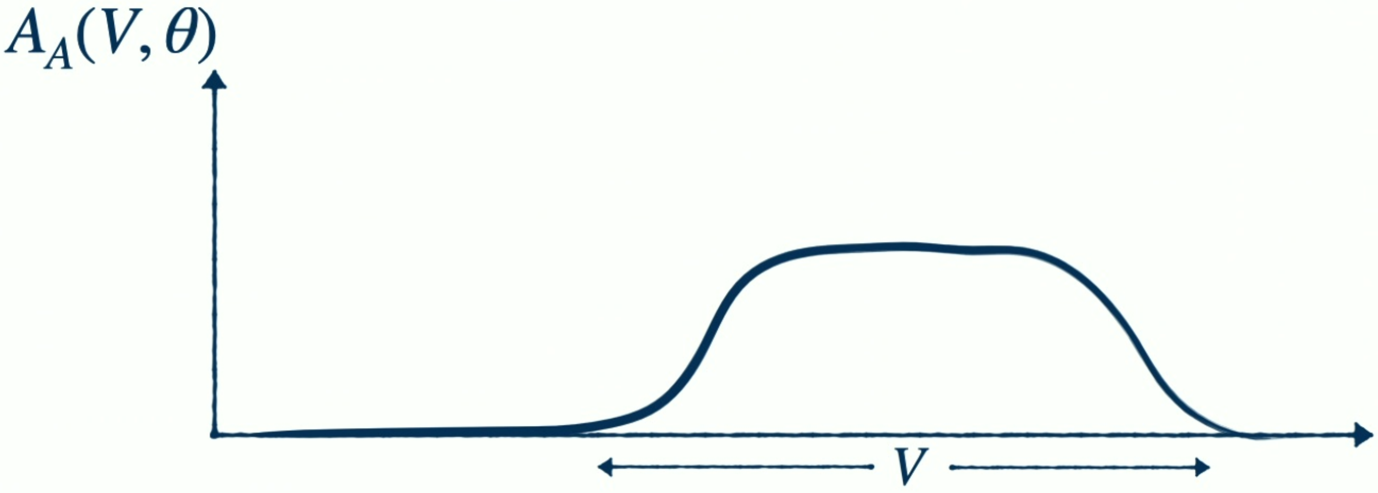

$$V = e^{T/4M}$$

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

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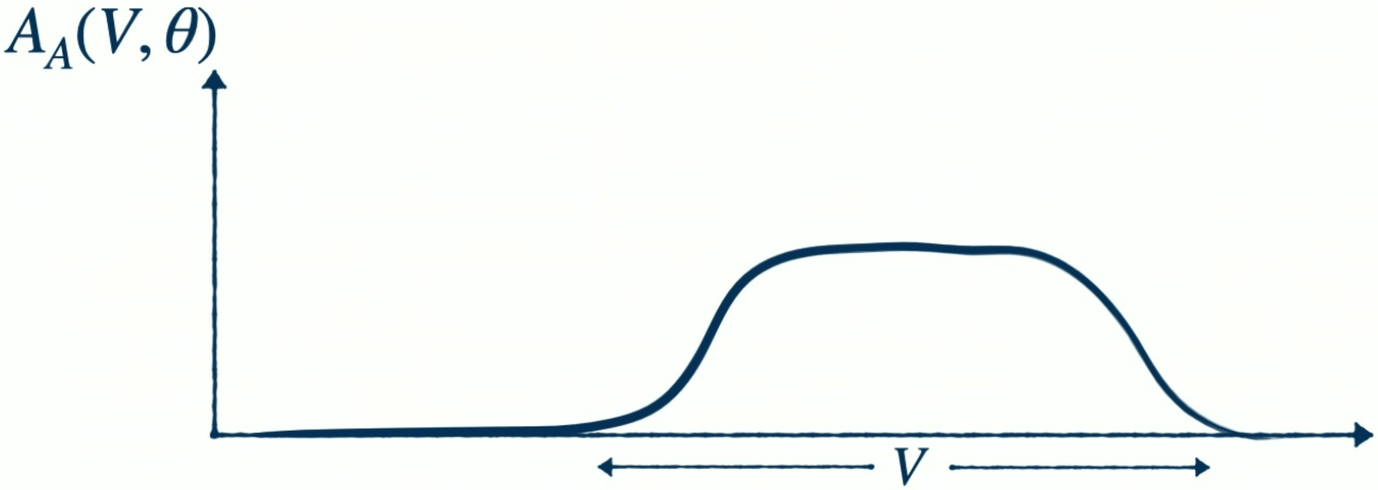

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Black Holes Decohere Quantum Superpositions

- If $|\Phi_1\rangle_{\mathscr{H}^+}$ and $|\Phi_2\rangle_{\mathscr{H}^+}$ correspond to the radiation states of Alice's particle on the horizon then both branches of Alice's 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

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

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

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Black Holes Decohere Quantum Superpositions

- A charged spatial superposition held outside of a black hole will be totally decohered in a time

$$T_{\rm D}^{\rm EM} \sim \frac{\epsilon_0 \hbar c^6 D^6}{G^3 M^3 q^2 d^2} \sim 10^{43}\ \text{years} \left(\frac{D}{\rm a.u.}\right)^6 \cdot \left(\frac{\rm M_\odot}{M}\right)^3 \cdot \left(\frac{\rm e}{q}\right)^2 \cdot \left(\frac{\rm m}{d}\right)^2$$

However, if the experiment is done at the ISCO, $D \sim 6GM/c^2$ then $T_{\rm D}^{\rm EM} \sim 5$ minutes.

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  However, if the experiment is done at the ISCO, $D \sim 6GM/c^2$ then $T_{\mathrm{D}}^{\mathrm{EM}} \sim 5$ minutes.

- A similar analysis of the linearized Einstein equation yields that a massive superposition held outside of a black hole will be totally decohered in a time

$$T_{\mathrm{D}}^{\mathrm{GR}} \sim \frac{\hbar c^{10} D^{10}}{G^6 M^5 m^2 d^4} \sim 10\ \mu\mathrm{s} \left(\frac{D}{\mathrm{a.u.}}\right)^{10} \cdot \left(\frac{\mathrm{M}_\odot}{M}\right)^5 \cdot \left(\frac{\mathrm{M}_{\mathrm{Earth}}}{m}\right)^2 \cdot \left(\frac{\mathrm{R}_{\mathrm{Earth}}}{d}\right)^4$$

  It would not be easy to put the Earth in such a superposition!

Killing Horizons Decohere Quantum Superposition

- A similar analysis holds for any stationary superposition in the presence of a Killing horizon (i.e. Rindler horizon in flat spacetime, cosmological horizon in de Sitter...).
- A stationary body sources a Coulomb/Newtonian field which registers on the horizon. A quantum superposition sources a superposition of Coulomb/Newtonian fields on the horizon. This results in the emission of soft entangling radiation across the horizon leading to complete decoherence of the superposition.
- In the cosmological case, however, this decoherence occurs even for inertial superpositions.
- In de Sitter spacetime with horizon radius R_{H} an inertial superposition will be completely decohered due to the emission of soft photons/gravitons in a time

$$T_{\mathrm{D}}^{\mathrm{EM}} \sim \frac{\hbar \epsilon_0 R_{\mathrm{H}}^3}{q^2 d^2} \quad \text{and} \quad T_{\mathrm{D}}^{\mathrm{GR}} \sim \frac{\hbar R_{\mathrm{H}}^5}{G m^2 d^4}.$$

Since $d \ll R_{\mathrm{H}}$ the decoherence time will be much larger than the Hubble time R_{H}/c unless $q \gg q_P \sim 10\mathrm{e}$ or $m \gg m_P \sim 10\mu\mathrm{g}$.

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 due to the presence of a horizon. It is not due to thermal radiation or the acceleration of Alice’s lab. If her lab was outside of a star, then she can perform the experiment sufficiently adiabatically to ensure she emits negligible radiation.

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 (Killing) horizons in quantum gravity