“Black Holes are Watching You”

(Killing horizons decohere quantum superpositions)

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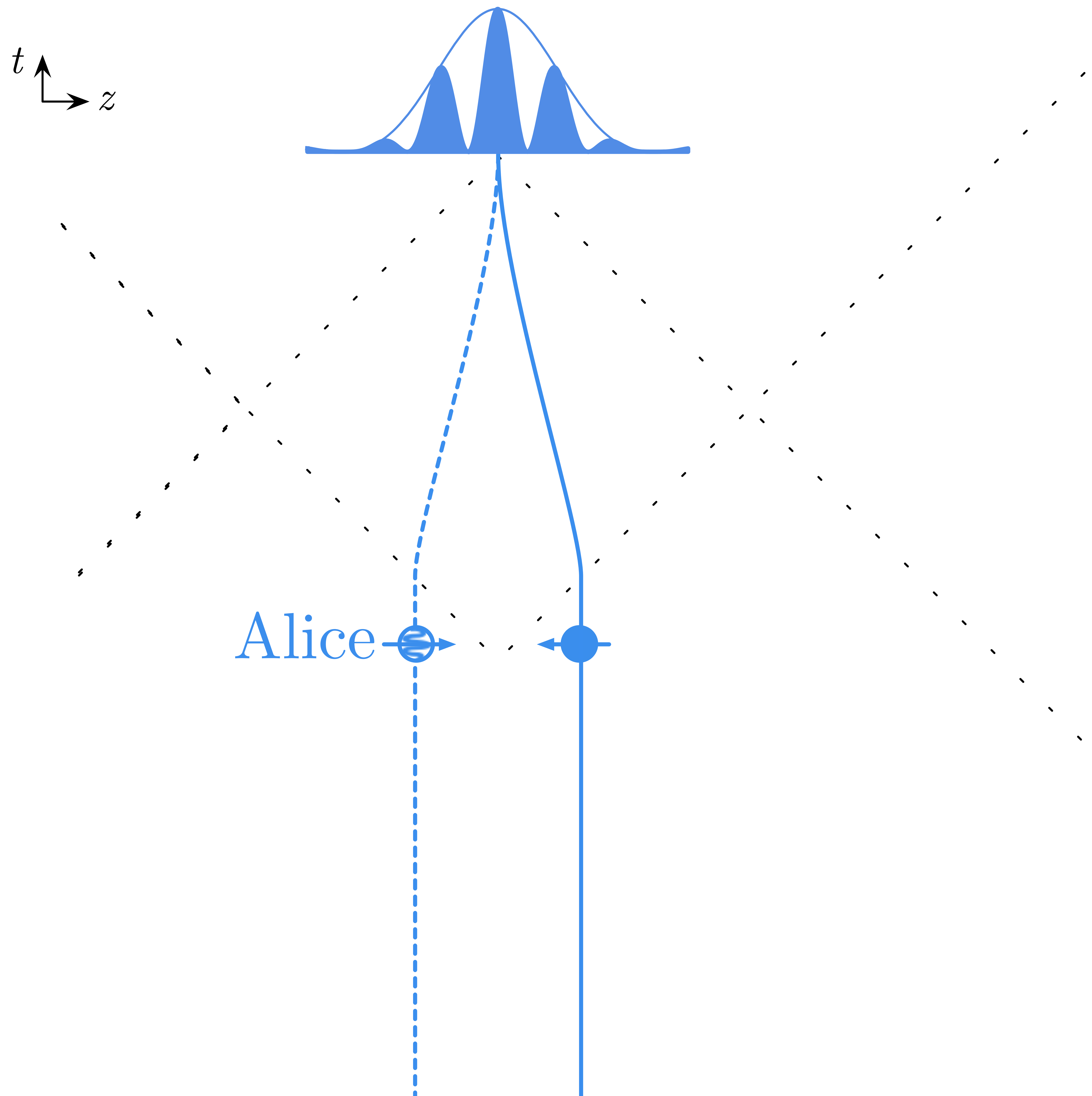
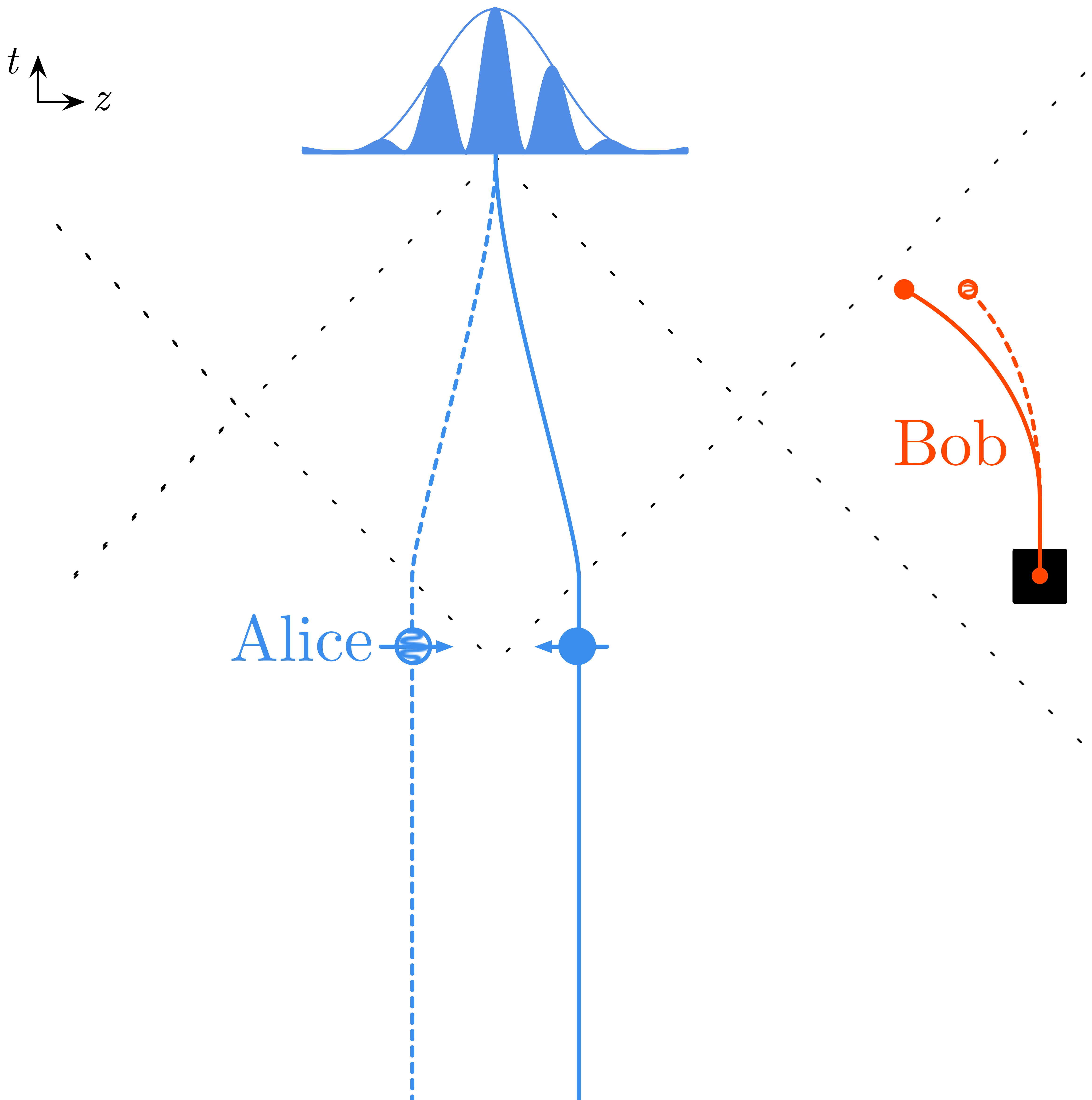
D.L.D., G. Satishchandran R.M. Wald (2023) , *Phys. Rev. D* 108, 025007 (2023), arXiv:2301.00026 [hep-th]
D.L.D., G. Satishchandran, R.M. Wald, *Int. J. Mod. Phys. D* 2241003 (2022), arXiv:2205.06279 [hep-th]
Gravity Research Foundation Essay Competition, Third Award
D.L.D., G. Satishchandran, R.M. Wald, *Phys. Rev. D* 105, 086001 (2022), arXiv:2112.10798 [quant-ph]
D.L.D., J. Kudler-Flam, G. Satishchandran (to appear)

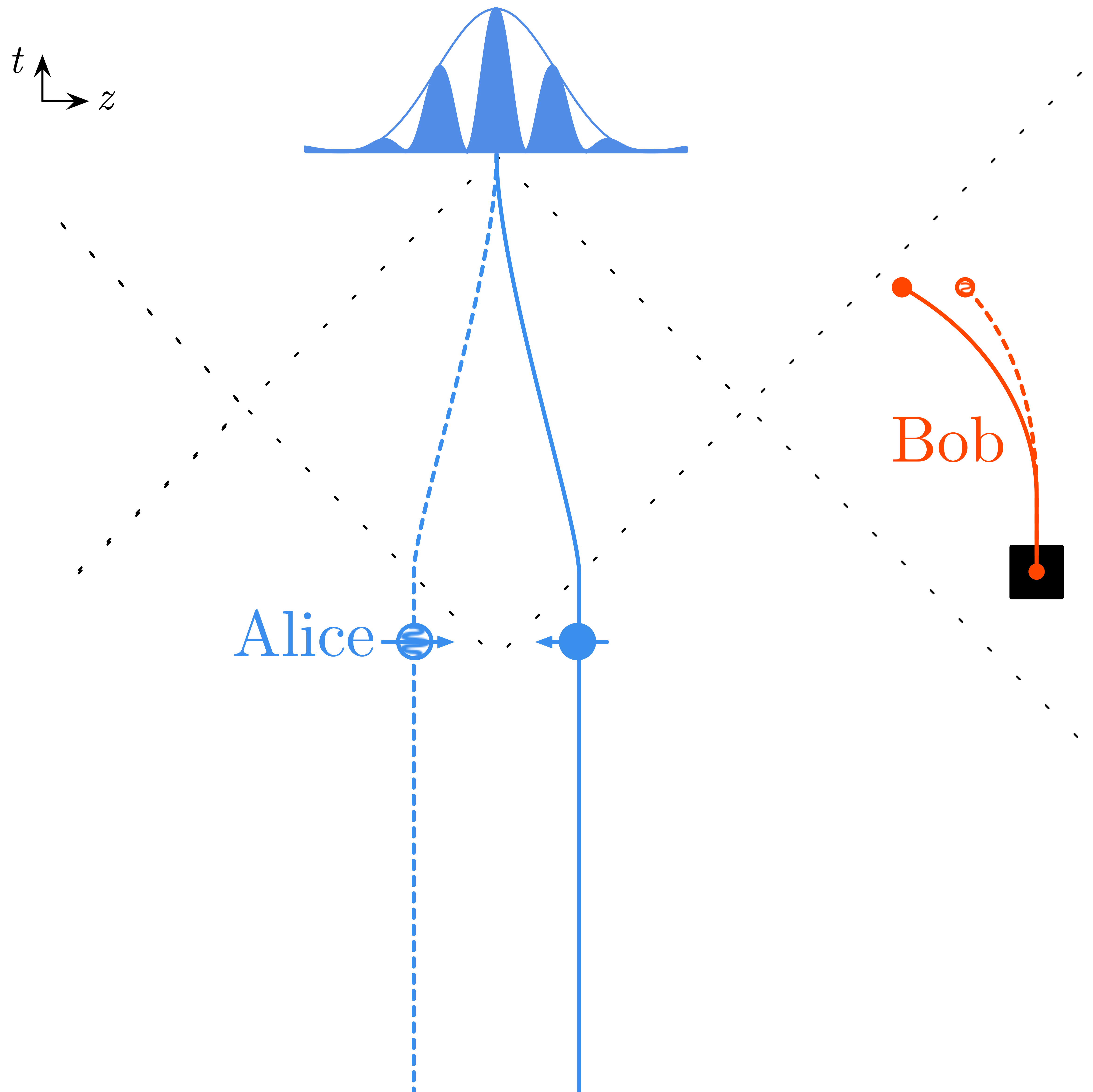


In the past, Alice used a Stern-Gerlach apparatus to produce a **spatial superposition of a massive body.**

Later, she attempts an interference experiment and looks for signs of decoherence.



In a *spacelike-separated region*, Bob may attempt to measure Alice's superposed gravitational field by releasing a particle from a trap.



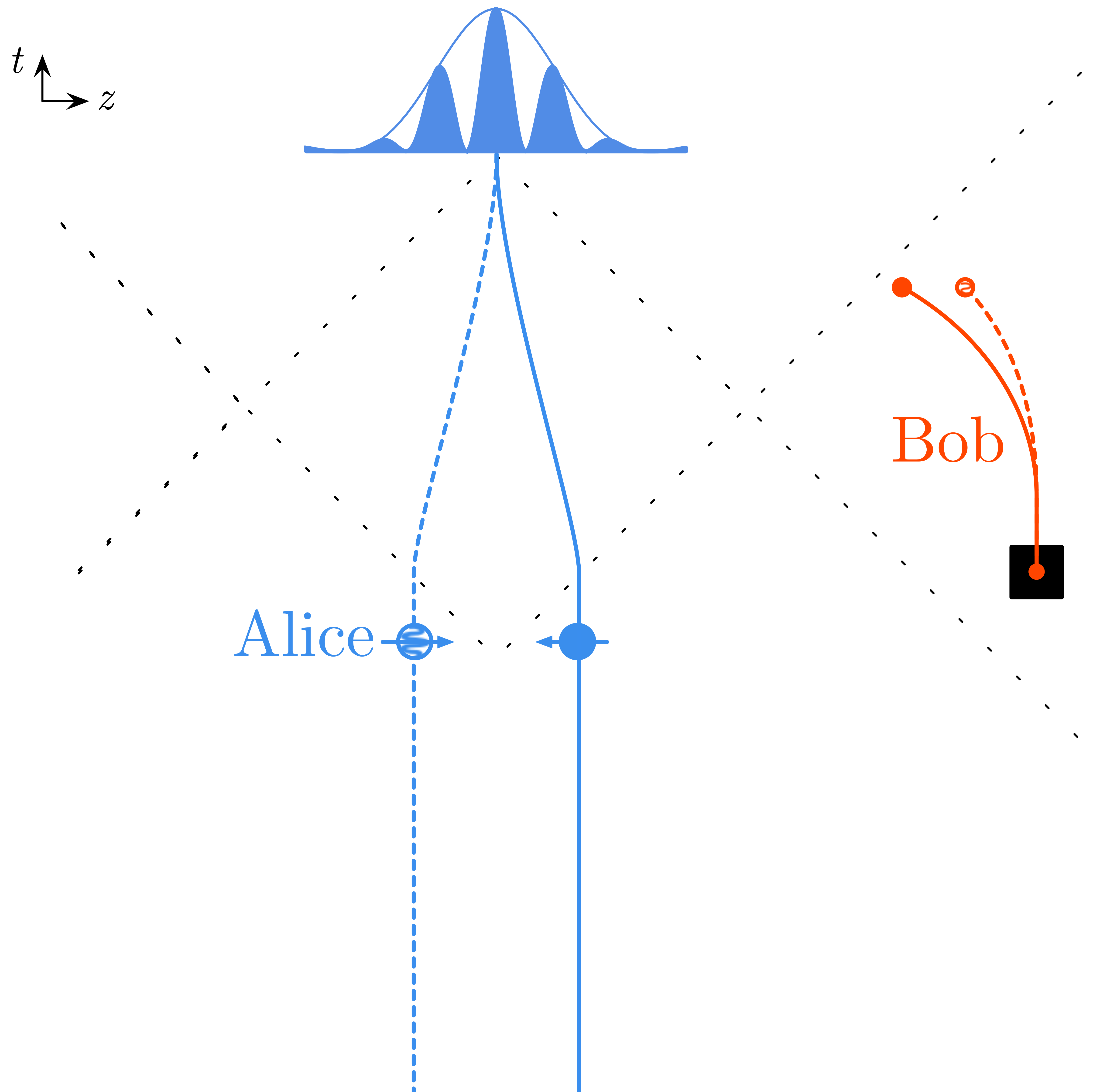
Bob can *choose* to measure, or not to measure, the field.

If Bob successfully measures the field, Alice's particle is decohered.

But Alice can tell whether her particle is decohered!

This seems paradoxical.

Paradox resolved...



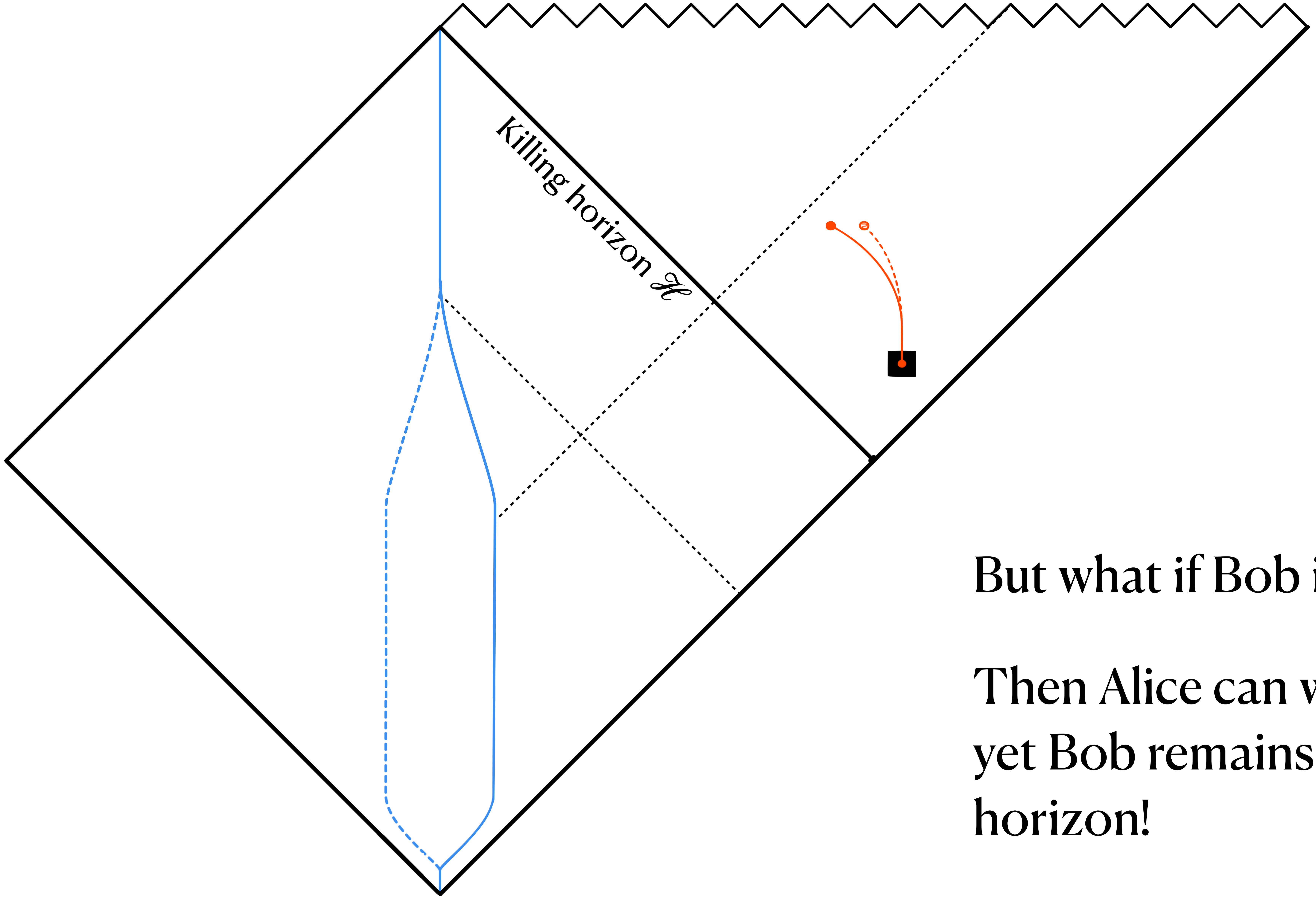
Bob's precision is limited by **vacuum fluctuations** of the metric.

Alice needs to recombine slowly to avoid producing **entangling radiation**.

If Alice goes slower, Bob must measure from farther away to remain spacelike. Thus he measures a weaker field, requiring more time.

[DLD, Satishchandran, Wald (2022). Belenchia *et al.* (2019).]

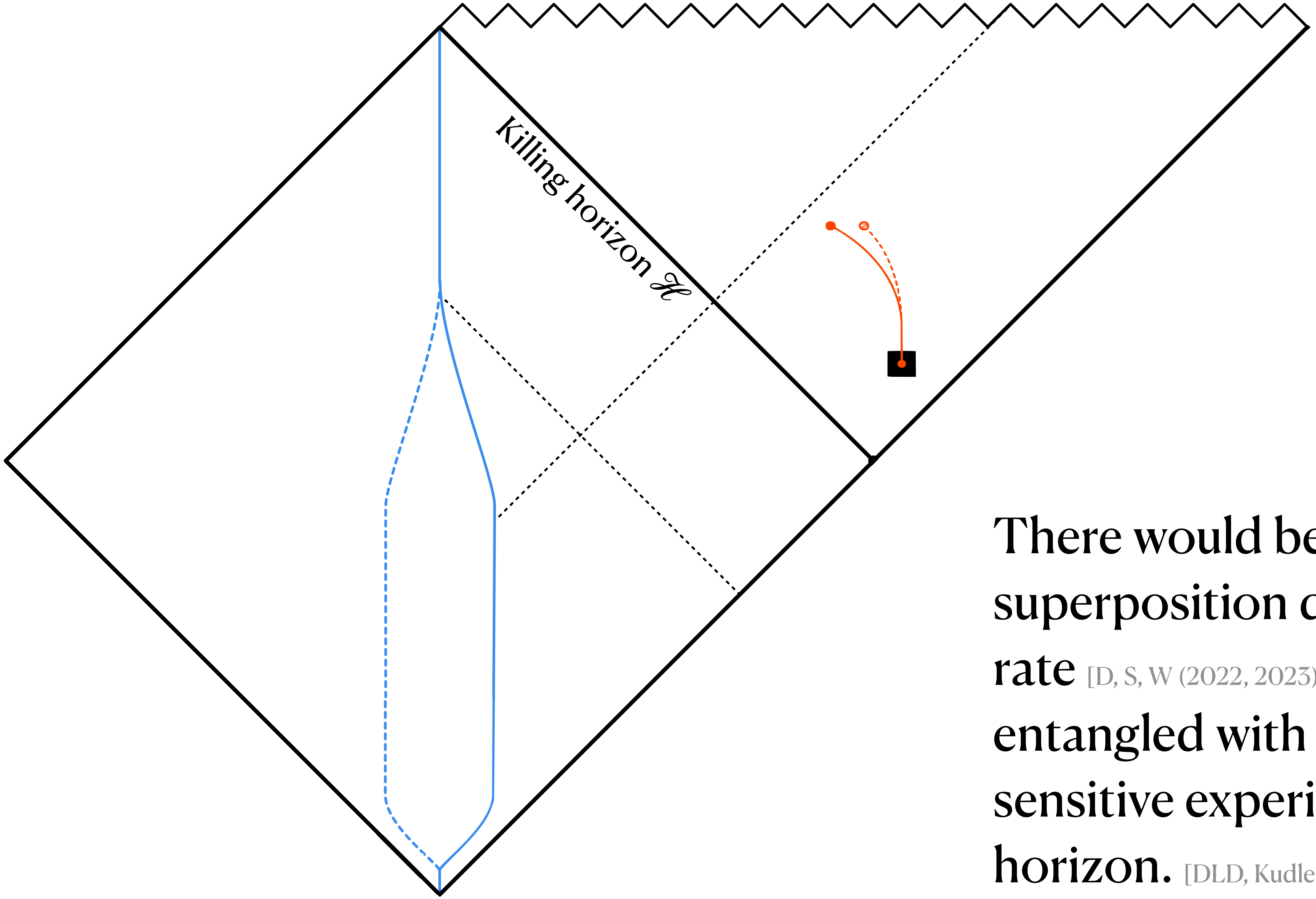
Paradox restored?



But what if Bob is behind a horizon?

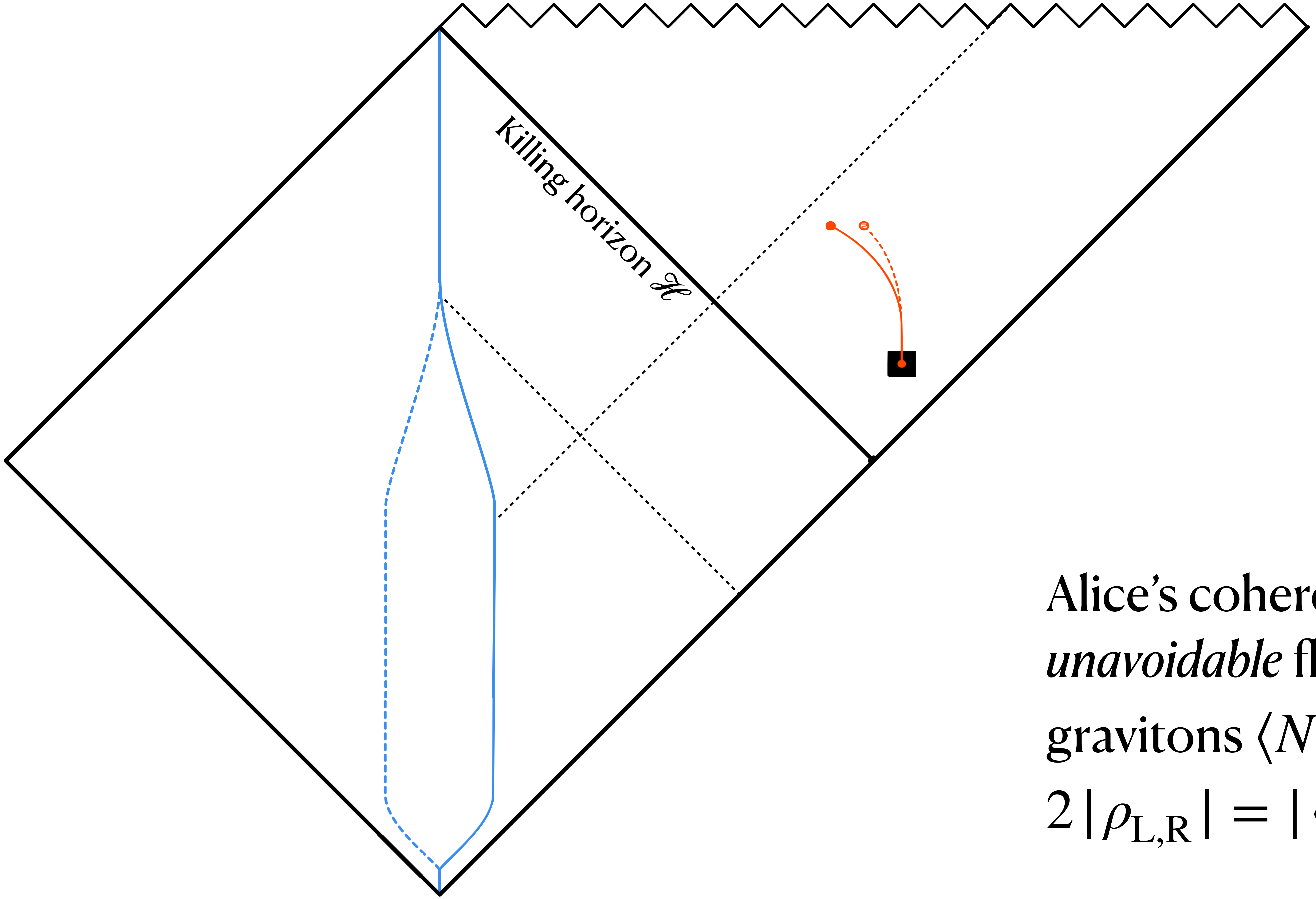
Then Alice can work as slowly as she likes, yet Bob remains spacelike, just beyond the horizon!

Paradox resolved!



There would be no paradox if Alice's superposition decoheres at a constant rate [D, S, W (2022, 2023)] *as if* she were becoming entangled with any number of optimally-sensitive experiments hidden behind the horizon. [DLD, Kudler-Flam, Satishchandran, (to appear)].

Paradox resolved!



Alice's coherence is degraded by an *unavoidable* flux of soft, entangling gravitons $\langle N \rangle$ into the black hole:

$$2\,|\rho_{\mathrm{L,R}}| = |\langle h_{\mathrm{L}} | h_{\mathrm{R}} \rangle_{\mathscr{H}}| = e^{-\frac{1}{2}\langle N \rangle}.$$

Horizon decoherence effect

Due to this *unavoidable* emission of entangling soft gravitons into the horizon, any superposed body outside a black hole will decohere after a time $T_{\mathrm{BH}} \sim \dfrac{\hbar c^{10} D^{10}}{G^6 M^5 m^2 d^4}$.

The effect is weak, but universal.

For a charged particle, an additional effect turns on: $T_{\mathrm{BH}}^{\mathrm{EM}} \sim \dfrac{\hbar c^6 D^6}{G^3 M^3 q^2 d^2}$.

In de Sitter spacetime the analogous decoherence times are

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

[DLD, Satishchandran, Wald (2022, 2023)]

Questions?

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

$$T_{\mathrm{dS}} \sim \frac{\hbar R_{\mathrm{dS}}^5}{G m^2 d^4} \qquad T_{\mathrm{dS}}^{\mathrm{EM}} \sim \frac{\hbar \epsilon_0 R_{\mathrm{dS}}^3}{q^2 d^2}$$

FAQ:

Q: Do horizonless objects do this?
A: No. It is possible for Alice to work adiabatically outside a "star" and thus avoid radiating. [D, S, W (2023)]

Q: What about decoherence due to collisions with Hawking quanta?
A: Our effect is independent and typically much larger. [D, S, W (2023)]

Q: Does this depend on the fate of the black hole?
A: No. The decoherence is typically much, much faster than the evaporation [D, S, W (2023)], and our calculation can be expressed in a manifestly local form. [D, S, W (to appear)]