Can tabletop experiments discover the graviton?

Daine L. Danielson, Gautam Satishchandran, Robert M. Wald

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

The University of Chicago – Enrico Fermi Institute & Kadanoff Center for Theoretical Physics

Background and Objectives

- A robust low-energy prediction in quantum gravity is that gravity should mediate entanglement.
- Entanglement mediation by gravitational interactions has not yet been experimentally confirmed.
- Currently contemplated experiments hope to measure gravitational entanglement (e.g., Snowmass LOI arXiv:2203.11846).

***Objective**: what will tabletop experiments teach us about the existence of the graviton?*

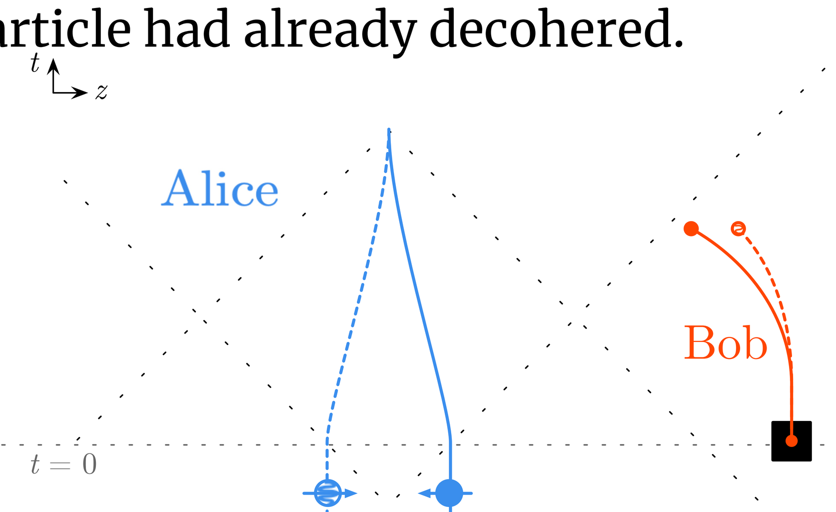
***Significance**: Confirmation of gravitational entanglement in these experiments may be viewed as evidence for the existence of the graviton, whose existence is, today, unconfirmed experimentally.*

A thought experiment by Mari *et al.*

***Design and Execution**: We will consider a simple thought-experiment, and give a rigorous analysis.*

***Relevance:** Our rigorous analysis of this puzzle has implications for future experiments.*

- In the far past, Alice used a Stern-Gerlach apparatus to prepare a massive body in a spatial superposition $\frac{1}{\sqrt{2}}(|\uparrow; A_1\rangle + |\downarrow; A_2\rangle)$ where spins point along z.
- At t=0, Alice begins to recombine her superposition. After recombining, she measures spin along the x-axis. A single "down" result would tell Alice that her particle had already decohered.



- In a spacelike-separated region, Bob may attempt to determine the position of Alice's particle by measuring the superposed Newtonian field.
- If Bob's measurement succeeds, then by complementarity, Alice is decohered. This is different from a Bell pair: Alice can tell if her particle is decohered. But this seems to allow Bob to signal to Alice!

Back-of-Envelope Resolution

The resolution of this paradox involves generic aspects of quantum gravity:

- Quantized Gravitational Radiation: Alice must recombine slowly to avoid decohering herself by radiation. (Phys. Rev. D 98, 126009 (2018))
- Vacuum fluctuations of the gravitational field: Bob must measure for a sufficient duration to distinguish his result from vacuum fluctuations.
- But, could Bob and n-1 assistants combine independent measurements to reduce their uncertainty by $1/\sqrt{n}$? *Remarkably, the entanglement structure of the vacuum fluctuations of spacetime will prevent this...*

Decoherence due to Alice

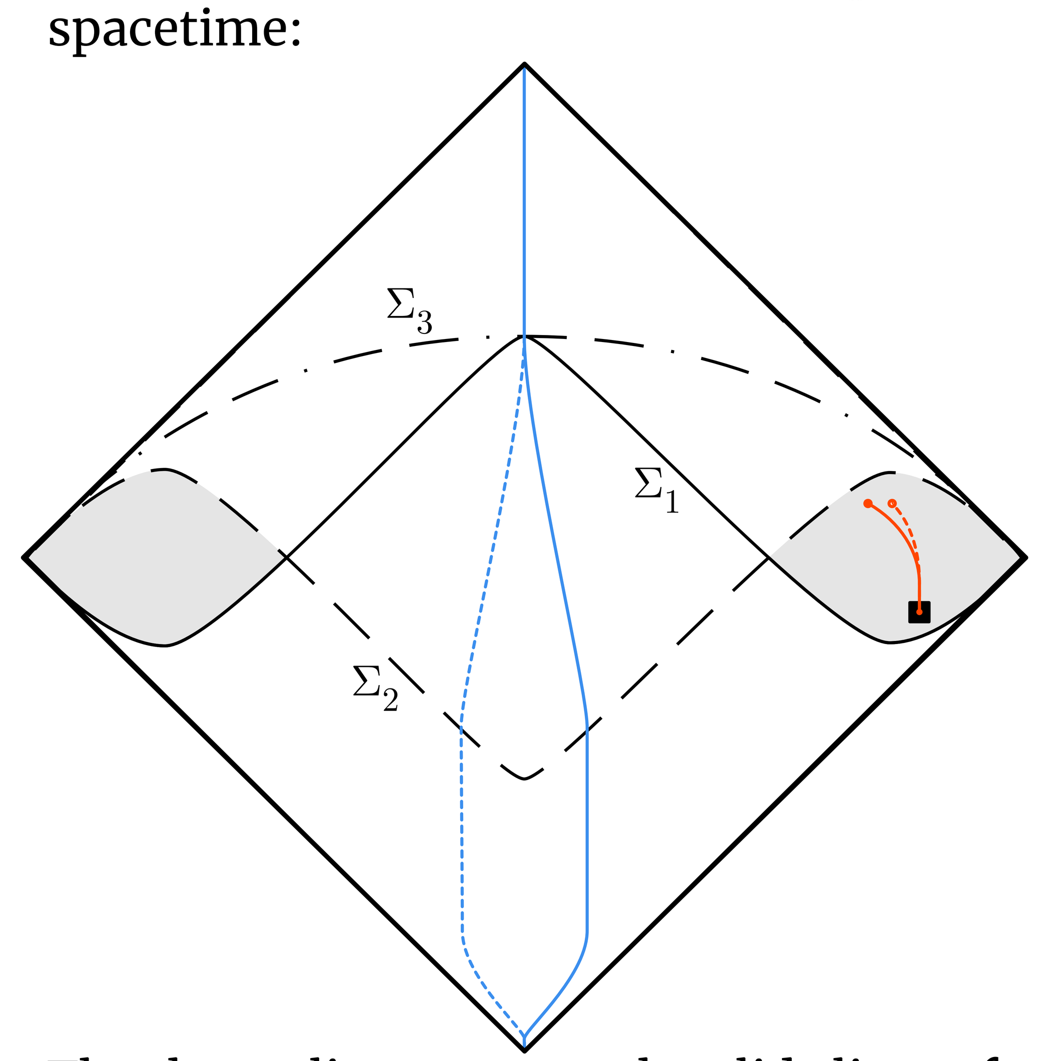
- Suppose Bob performs no measurement. The final state of Alice's particle and field will be of the form:
$$\frac{1}{\sqrt{2}}(|\uparrow; A_1\rangle \otimes |\Psi_1\rangle + |\downarrow; A_2\rangle \otimes |\Psi_2\rangle)$$
- Alice's degree of decoherence will be determined by the orthogonality of the entangled field states:
$$\mathscr{D}_{\text{Alice}} = 1 - |\langle\Psi_1|\Psi_2\rangle|$$

Decoherence due to Bob

- Suppose Alice violates the protocol, recombining arbitrarily slowly to avoid radiating—and placing Bob in the causal *past* of her recombination event.
- In this case Bob has sufficient time to decohere Alice by measuring her Newtonian field with arbitrary precision.
- The final state of the Alice-Bob system becomes,
$$\frac{1}{\sqrt{2}}(|\uparrow; A_1\rangle \otimes |B_1\rangle + |\downarrow; A_2\rangle \otimes |B_2\rangle)$$
- In this case Alice's decoherence is entirely due to the orthogonality of states of Bob's apparatus, and is given by,
$$\mathscr{D}_{\text{Bob}} = 1 - |\langle B_1|B_2\rangle|$$

Resolution of the Paradox

- We return to the original thought experiment, permitting Bob *any* measurement, or ensemble of n measurements, in the (shaded) region of spacetime:



- The three slices Σ_i are each valid slices of time, differing only by a coordinate choice.
- The "time" Σ_1 lies entirely to the future of Alice and to the past of Bob, so any decoherence on Σ_1 is entirely attributable to Alice: $\mathscr{D}_{\text{Alice}} = 1 - |\langle\Psi_1|\Psi_2\rangle_{\Sigma_1}|$
- The "time" Σ_2 lies entirely to the past of Alice and to the future of Bob, so any decoherence on Σ_2 is entirely attributable to Bob:
$$\mathscr{D}_{\text{Bob}} = 1 - |\langle B_1|B_2\rangle|$$
- There would be a paradox if Bob could decohere Alice more than she decoheres herself.
That is, a paradox if $|\langle B_1|B_2\rangle| < |\langle\Psi_1|\Psi_2\rangle_{\Sigma_1}|$
- But this inequality cannot possibly hold. The states on Σ_1 and Σ_3 are related by unitary time evolution, giving
$$\langle\Psi_1'|\Psi_2'\rangle_{\Sigma_3}\langle B_1|B_2\rangle = \langle\Psi_1|\Psi_2\rangle_{\Sigma_1}\langle B_0|B_0\rangle = \langle\Psi_1|\Psi_2\rangle_{\Sigma_1}$$
which implies Bob cannot affect Alice's decoherence whatsoever, and in particular,
$$|\langle B_1|B_2\rangle| \geq |\langle\Psi_1|\Psi_2\rangle_{\Sigma_1}|$$
for *all potential* measurements performable in the causal complement. **Thus no paradox can ever arise.**

Implications for Experiment

- Under time evolution from Σ_1 to Σ_3, Bob's apparatus is becoming entangled with Alice's particle due to freely-propagating (on-shell) graviton radiation.
- However, under time evolution from Σ_2 to Σ_3, Bob's apparatus is becoming entangled with Alice's particle due to the superposed "Newtonian field" (constraints of GR) of Alice's superposition.
- The difference between these two explanations is a coordinate choice. So under the protocol of the gedankenexperiment, there is no clear distinction between "Newtonian entanglement" and "on-shell graviton entanglement."

If either description holds, then both descriptions must hold simultaneously:

- Suppose gravitons decohere Alice, while the Newtonian field cannot mediate entanglement. The Newtonian field differs from the *graviton field* only by a choice of coordinates in Bob's region, so the graviton field must not mediate entanglement, either. But this is not consistent: gravitons should be able to interact in any theory where they can be produced.
- Suppose instead that Newtonian entanglement decoheres Alice, but gravitons cannot. Then, Alice would not decohere unless Bob is present, in violation of causality.
- These considerations show that there is a direct relationship between Newtonian entanglement and the existence of gravitons. Our argument for such a relationship is strictly valid when the measurement of the Newtonian field/gravitons is carried out within a one light travel time to the source. However, this causal regime is continuously connected by a deformation of "Alice's" protocol to the regime of actual proposed experiments.

***Interpretation**: This yields strong support for the view that any observation of entanglement mediated by a gravitational field provides evidence for the existence of the graviton.*

Email: daine@danielson.pro | Slack: @Daine Danielson | Contribution ID: 330