Gravitationally Mediated Entanglement: Newtonian Field vs. Gravitons

Gautam Satishchandran

University of Chicago → Princeton

GR23 Beijing

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

D. Danielson, G.S., & R.M. Wald arXiv:2205.06279

D. Danielson, G.S. & R.M. Wald (to appear)

July 4, 2022

Quantum Gravity and Gravitational Entanglement

- While it is generally believed that gravity should be quantized, given the difficulty of formulating such a theory and the lack of experimental evidence, it has been proposed that gravity should be classical or it requires a radical modification of quantum theory [Dyson, 2013],[Penrose,2014],. . .

Quantum Gravity and Gravitational Entanglement

- While it is generally believed that gravity should be quantized, given the difficulty of formulating such a theory and the lack of experimental evidence, it has been proposed that gravity should be classical or it requires a radical modification of quantum theory [Dyson, 2013],[Penrose,2014],...
- Given the recent, rapid developments towards producing coherent spatial superpositions of massive bodies experiments mediating entanglement via a Newtonian gravitational are now in range! [Bose et al.,2017],[Vedral et al.,2017]...

Quantum Gravity and Gravitational Entanglement

- While it is generally believed that gravity should be quantized, given the difficulty of formulating such a theory and the lack of experimental evidence, it has been proposed that gravity should be classical or it requires a radical modification of quantum theory [Dyson, 2013],[Penrose,2014],...
- Given the recent, rapid developments towards producing coherent spatial superpositions of massive bodies experiments mediating entanglement via a Newtonian gravitational are now in range! [Bose et al.,2017],[Vedral et al.,2017]...

What can we learn from such tabletop experiments?

Quantum Gravity and Gravitational Entanglement

- While it is generally believed that gravity should be quantized, given the difficulty of formulating such a theory and the lack of experimental evidence, it has been proposed that gravity should be classical or it requires a radical modification of quantum theory [Dyson, 2013],[Penrose,2014],...
- Given the recent, rapid developments towards producing coherent spatial superpositions of massive bodies experiments mediating entanglement via a Newtonian gravitational are now in range! [Bose et al.,2017],[Vedral et al.,2017]...

What can we learn from such tabletop experiments?

Quantum Gravity and Gravitational Entanglement

- While it is generally believed that gravity should be quantized, given the difficulty of formulating such a theory and the lack of experimental evidence, it has been proposed that gravity should be classical or it requires a radical modification of quantum theory [Dyson, 2013],[Penrose,2014],...
- Given the recent, rapid developments towards producing coherent spatial superpositions of massive bodies experiments mediating entanglement via a Newtonian gravitational are now in range! [Bose et al.,2017],[Vedral et al.,2017]...

What can we learn from such tabletop experiments?

What properties of quantum gravity are necessary in order to consistently describe such a quantum superposition?

Gedankenexperiment of Mari *et al.*

- Two experimenters, Alice and Bob, each control a massive “particle”. There is an electromagnetic version (particle is charged) and a gravitational version (particle is uncharged).

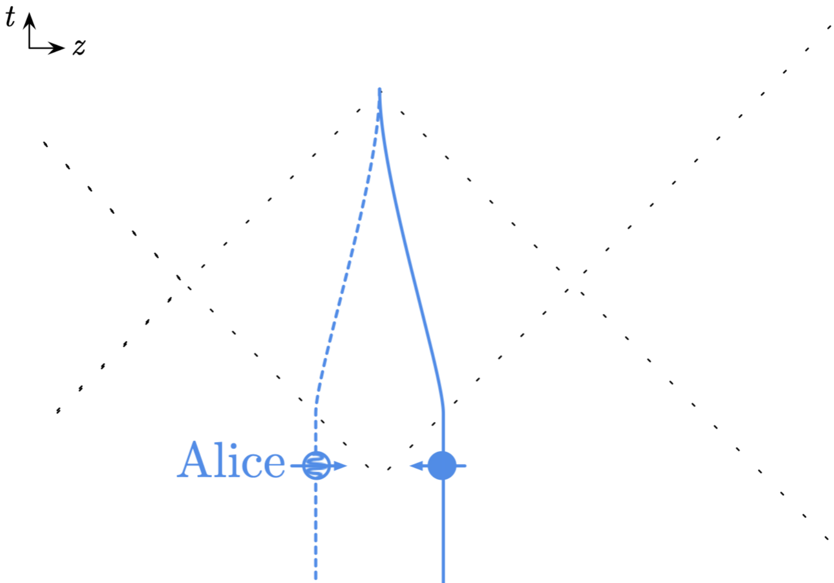
Gedankenexperiment of Mari *et al.*

- Two experimenters, Alice and Bob, each control a massive "particle". There is an electromagnetic version (particle is charged) and a gravitational version (particle is uncharged).
- Alice's particle has spin ($+z$-direction) and, in the far past, she has slowly sent her particle through a Stern-Gerlach apparatus (oriented in the z-direction) so that it is in a 50/50 spatial superposition.

Gedankenexperiment of Mari *et al.*

- Two experimenters, Alice and Bob, each control a massive "particle". There is an electromagnetic version (particle is charged) and a gravitational version (particle is uncharged).
- Alice's particle has spin ($+z$-direction) and, in the far past, she has slowly sent her particle through a Stern-Gerlach apparatus (oriented in the z-direction) so that it is in a 50/50 spatial superposition.
- At some (pre-arranged) time, Alice sends her particle through a "reversing Stern-Gerlach apparatus" and then performs an interference experiment.

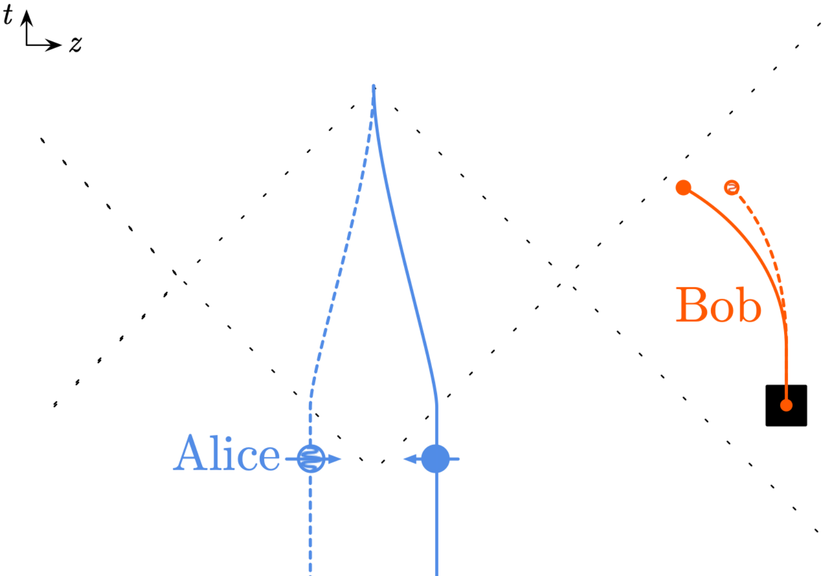
Gedankenexperiment of Mari *et al.*



Gedankenexperiment of Mari *et al.*

- Bob has a particle in a trap which he may choose to release at spacelike separation from Alice. Bob's particle will become entangled with the Coulomb fields of Alice's particle. By measuring the position of his particle he can obtain "which path" information of Alice's superposition.

Gedankenexperiment of Mari *et al.*



Gedankenexperiment of Mari *et al.*

- Bob has a particle in a trap which he may choose to release at spacelike separation from Alice. Bob's particle will become entangled with the Coulomb fields of Alice's particle. By measuring the position of his particle he can obtain "which path" information of Alice's superposition.
- If Bob performs a successful measurement then Alice will be (at least partially) decohered. *Alice can tell if her particle is decohered by performing an interference experiment.* This yields an apparent paradox:

Gedankenexperiment of Mari *et al.*

- Bob has a particle in a trap which he may choose to release at spacelike separation from Alice. Bob's particle will become entangled with the Coulomb fields of Alice's particle. By measuring the position of his particle he can obtain "which path" information of Alice's superposition.

- If Bob performs a successful measurement then Alice will be (at least partially) decohered. *Alice can tell if her particle is decohered by performing an interference experiment.* This yields an apparent paradox:

- Complementarity: If Bob makes a successful measurement then he should be entangled with Alice superposition and she must be decohered

- Causality: Bob cannot influence the state of Alice's particle and/or her interference experiment

Gedankenexperiment of Mari *et al.*

- Bob has a particle in a trap which he may choose to release at spacelike separation from Alice. Bob's particle will become entangled with the Coulomb fields of Alice's particle. By measuring the position of his particle he can obtain "which path" information of Alice's superposition.
- If Bob performs a successful measurement then Alice will be (at least partially) decohered. *Alice can tell if her particle is decohered by performing an interference experiment.* This yields an apparent paradox:
- Complementarity: If Bob makes a successful measurement then he should be entangled with Alice superposition and she must be decohered
- Causality: Bob cannot influence the state of Alice's particle and/or her interference experiment
- The gravitational version of this gedankenexperiment simply corresponds to replacing "Coulomb" $\rightarrow$ "Newtonian" and "test charge" $\rightarrow$ "test mass" ect.

Back-of-the-Envelope Resolution of Belenchia *et al.*

- Alice must recombine her particles within a light-travel time without emitting any quantized entangling radiation. If she accelerates her (charged) superposition too quickly then she will emit an entangling photon/graviton.

Back-of-the-Envelope Resolution of Belenchia *et al.*

- Alice must recombine her particles within a light-travel time without emitting any quantized entangling radiation. If she accelerates her (charged) superposition too quickly then she will emit an entangling photon/graviton.
- Bob's ability to obtain "which-path" information (i.e. resolve the individual Coulomb fields within light-travel time) is bounded by vacuum fluctuations of the EM/gravitational field.

Back-of-the-Envelope Resolution of Belenchia *et al.*

- Alice must recombine her particles within a light-travel time without emitting any quantized entangling radiation. If she accelerates her (charged) superposition too quickly then she will emit an entangling photon/graviton.
- Bob's ability to obtain "which-path" information (i.e. resolve the individual Coulomb fields within light-travel time) is bounded by vacuum fluctuations of the EM/gravitational field.
  - If Bob can successfully obtain which-path information (i.e. Alice's charge or separation is big enough) then she must emit entangling radiation and decohere herself

Back-of-the-Envelope Resolution of Belenchia *et al.*

- Alice must recombine her particles within a light-travel time without emitting any quantized entangling radiation. If she accelerates her (charged) superposition too quickly then she will emit an entangling photon/graviton.
- Bob's ability to obtain "which-path" information (i.e. resolve the individual Coulomb fields within light-travel time) is bounded by vacuum fluctuations of the EM/gravitational field.
  - If Bob can successfully obtain which-path information (i.e. Alice's charge or separation is big enough) then she must emit entangling radiation and decohere herself
  - If Alice's charge is small enough that she can successfully recohere her particle then Bob will not be able to obtain any significant which-path information.

Back-of-the-Envelope Resolution of Belenchia *et al.*

- Alice must recombine her particles within a light-travel time without emitting any quantized entangling radiation. If she accelerates her (charged) superposition too quickly then she will emit an entangling photon/graviton.
- Bob's ability to obtain "which-path" information (i.e. resolve the individual Coulomb fields within light-travel time) is bounded by vacuum fluctuations of the EM/gravitational field.
  - If Bob can successfully obtain which-path information (i.e. Alice's charge or separation is big enough) then she must emit entangling radiation and decohere herself
  - If Alice's charge is small enough that she can successfully recohere her particle then Bob will not be able to obtain any significant which-path information.
- This "order of magnitude" analysis does not prove that no such paradox can occur. For example, one could try to introduce "multiple Bob's" to improve the statistics of the "which path" measurement. Furthermore, this does not yield a precise description of the gravitational entanglement between Alice and Bob.

Back-of-the-Envelope Resolution of Belenchia *et al.*

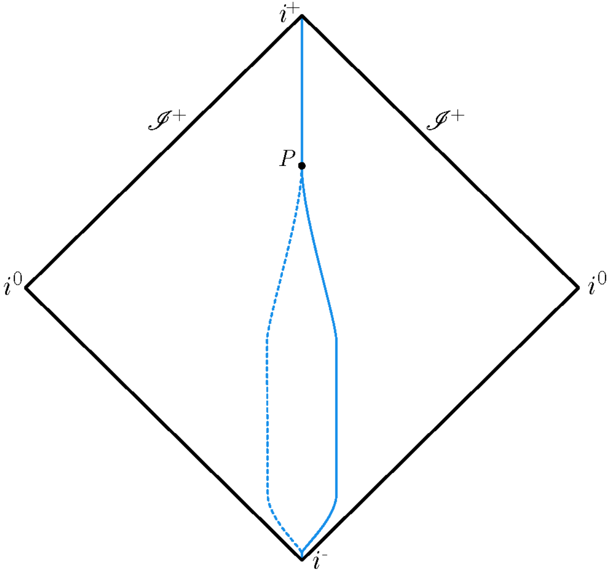
- Alice must recombine her particles within a light-travel time without emitting any quantized entangling radiation. If she accelerates her (charged) superposition too quickly then she will emit an entangling photon/graviton.
- Bob's ability to obtain "which-path" information (i.e. resolve the individual Coulomb fields within light-travel time) is bounded by vacuum fluctuations of the EM/gravitational field.
  - If Bob can successfully obtain which-path information (i.e. Alice's charge or separation is big enough) then she must emit entangling radiation and decohere herself
  - If Alice's charge is small enough that she can successfully recohere her particle then Bob will not be able to obtain any significant which-path information.
- This "order of magnitude" analysis does not prove that no such paradox can occur. For example, one could try to introduce "multiple Bob's" to improve the statistics of the "which path" measurement. Furthermore, this does not yield a precise description of the gravitational entanglement between Alice and Bob.

Back-of-the-Envelope Resolution of Belenchia *et al.*

- Alice must recombine her particles within a light-travel time without emitting any quantized entangling radiation. If she accelerates her (charged) superposition too quickly then she will emit an entangling photon/graviton.
- Bob's ability to obtain "which-path" information (i.e. resolve the individual Coulomb fields within light-travel time) is bounded by vacuum fluctuations of the EM/gravitational field.
- If Bob can successfully obtain which-path information (i.e. Alice's charge or separation is big enough) then she must emit entangling radiation and decohere herself
- If Alice's charge is small enough that she can successfully recohere her particle then Bob will not be able to obtain any significant which-path information.
- This "order of magnitude" analysis does not prove that no such paradox can occur. For example, one could try to introduce "multiple Bob's" to improve the statistics of the "which path" measurement. Furthermore, this does not yield a precise description of the gravitational entanglement between Alice and Bob.

We now give the precise description of the resolution and gravitational entanglement

Decoherence Due to Alice



Decoherence Due to Alice

- Formally, the state of Alice's particle after she makes the spatial superposition is

$$\frac{1}{\sqrt{2}}\left(|\uparrow; A_1\rangle \otimes |\psi_1\rangle + |\downarrow; A_2\rangle \otimes |\psi_2\rangle \right)$$

where $|\psi_1\rangle, |\psi_2\rangle$ are the formal "Coulomb states" of Alice's particle.

Decoherence Due to Alice

- Formally, the state of Alice's particle after she makes the spatial superposition is

$$\frac{1}{\sqrt{2}}\left(|\uparrow; A_1\rangle \otimes |\psi_1\rangle + |\downarrow; A_2\rangle \otimes |\psi_2\rangle \right)$$

  where $|\psi_1\rangle, |\psi_2\rangle$ are the formal "Coulomb states" of Alice's particle.
- These Coulomb states are orthogonal so it appears that Alice is decohered at this earliest time! However this is a false decoherence since, with no external influences, she should be able to recohere her particle.[Unruh,2000]

Decoherence Due to Alice

- Formally, the state of Alice's particle after she makes the spatial superposition is

$$\frac{1}{\sqrt{2}}\left(\left|\uparrow; A_1\right\rangle \otimes \left|\psi_1\right\rangle + \left|\downarrow; A_2\right\rangle \otimes \left|\psi_2\right\rangle \right)$$

where $\left|\psi_1\right\rangle, \left|\psi_2\right\rangle$ are the formal "Coulomb states" of Alice's particle.

- These Coulomb states are orthogonal so it appears that Alice is decohered at this earliest time! However this is a false decoherence since, with no external influences, she should be able to recohere her particle.[Unruh,2000]

- For any time before her recombination, the coherence of Alice's particle is not well-defined. However, at asymptotically late times

$$\frac{1}{\sqrt{2}}\left(\left|\uparrow; A_1\right\rangle_{i^+} \otimes \left|\Psi_1\right\rangle_{\mathscr{I}^+} + \left|\downarrow; A_2\right\rangle_{i^+} \otimes \left|\Psi_2\right\rangle_{\mathscr{I}^+} \right)$$

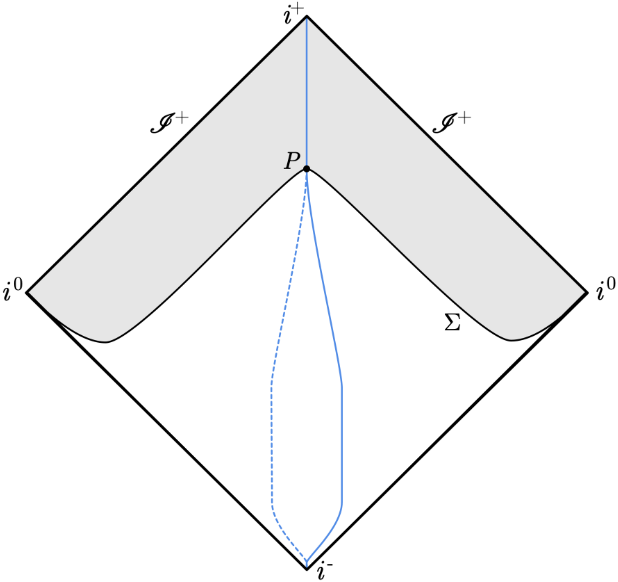
where $\left|\uparrow; A_1\right\rangle_{i^+}, \left|\uparrow; A_2\right\rangle_{i^+}$ are the states of Alice's particle at i^+ and $\left|\Psi_1\right\rangle_{\mathscr{I}^+}, \left|\Psi_2\right\rangle_{\mathscr{I}^+}$ are the free-field, Fock radiation states at $\mathscr{I}^+$ for Alice's particle going to the left or right.

Decoherence Due to Alice

- The decoherence of Alice's particle is then

$$\mathscr{D}_{\text{Alice}} = 1 - \left| \left\langle \Psi_1 \middle| \Psi_2 \right\rangle_{\mathscr{I}^+} \right|$$

Decoherence Due to Alice



Decoherence Due to Alice

- The decoherence of Alice's particle is then

$$\mathscr{D}_{\text{Alice}} = 1 - |\, \langle \Psi_1 | \Psi_2 \rangle_{\mathscr{I}^+} \,|$$

- After recombining her particle, The state of the field on any Cauchy surface Σ is a common Coulomb field (which does not contribute to her decoherence) and radiation (which is responsible for her decoherence). Propagating the asymptotic states $|\Psi_1\rangle_{\mathscr{I}^+}, |\Psi_2\rangle_{\mathscr{I}^+}$ to the "time" Σ yields the (Coulomb-subtracted) free-field Fock states $|\Psi_1\rangle_\Sigma, |\Psi_2\rangle_\Sigma$ which cause Alice's decoherence.

$$\mathscr{D}_{\text{Alice}} = 1 - |\, \langle \Psi_1 | \Psi_2 \rangle_{\Sigma} \,|$$

Decoherence Due to Bob

- Consider the case where Alice would *succeed* in her interference experiment in the absence of external influences (i.e. $|\Psi_1\rangle = |\Psi_2\rangle \approx |0\rangle$). We assume that Bob makes *any* measurement of Alice's field and stops interacting with the field after his measurement.

Decoherence Due to Bob

- Consider the case where Alice would *succeed* in her interference experiment in the absence of external influences (i.e. $|\Psi_1\rangle = |\Psi_2\rangle \approx |0\rangle$). We assume that Bob makes *any* measurement of Alice's field and stops interacting with the field after his measurement.
- Before his measurement, we have that

$$\frac{1}{\sqrt{2}}\left(|{\uparrow}; A_1\rangle \otimes |\psi_1\rangle + |{\downarrow}; A_2\rangle \otimes |\psi_2\rangle \right) \otimes |B_0\rangle$$

Decoherence Due to Bob

- Consider the case where Alice would *succeed* in her interference experiment in the absence of external influences (i.e. $|\Psi_1\rangle = |\Psi_2\rangle \approx |0\rangle$). We assume that Bob makes *any* measurement of Alice's field and stops interacting with the field after his measurement.
- Before his measurement, we have that

$$\frac{1}{\sqrt{2}}\left(|\uparrow; A_1\rangle \otimes |\psi_1\rangle + |\downarrow; A_2\rangle \otimes |\psi_2\rangle \right) \otimes |B_0\rangle$$

- After his measurement, Bob state becomes correlated with the Coulomb field of Alice's particle. The asymptotic state is (ignoring the negligible radiation from Alice)

$$\frac{1}{\sqrt{2}}\left(|\uparrow; A_1\rangle_{i^+} \otimes |B_1\rangle_{i^+} + |\downarrow; A_2\rangle_{i^+} \otimes |B_2\rangle_{i^+} \right) \implies \mathscr{D}_{\text{Bob}} = 1 - |\langle B_1|B_2\rangle|_{i^+}$$

Decoherence Due to Bob

- Consider the case where Alice would *succeed* in her interference experiment in the absence of external influences (i.e. $|\Psi_1\rangle = |\Psi_2\rangle \approx |0\rangle$). We assume that Bob makes *any* measurement of Alice's field and stops interacting with the field after his measurement.
- Before his measurement, we have that

$$\frac{1}{\sqrt{2}}\big(\,|\uparrow; A_1\rangle \otimes |\psi_1\rangle + |\downarrow; A_2\rangle \otimes |\psi_2\rangle\,\big) \otimes |B_0\rangle$$

- After his measurement, Bob state becomes correlated with the Coulomb field of Alice's particle. The asymptotic state is (ignoring the negligible radiation from Alice)

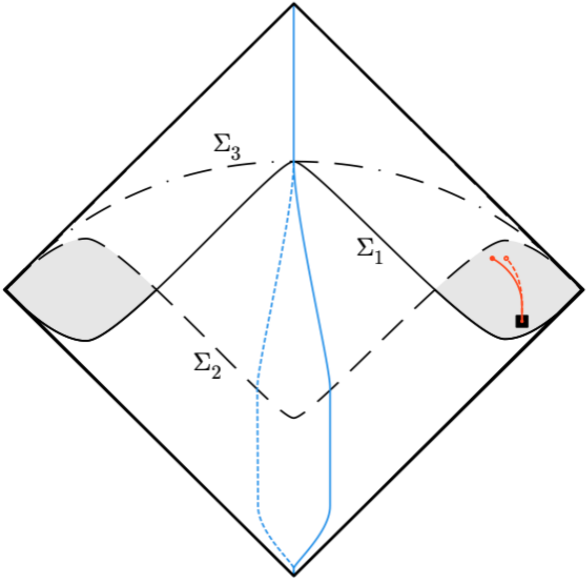
$$\frac{1}{\sqrt{2}}\big(\,|\uparrow; A_1\rangle_{i^+} \otimes |B_1\rangle_{i^+} + |\downarrow; A_2\rangle_{i^+} \otimes |B_2\rangle_{i^+}\,\big) \implies \mathscr{D}_{\text{Bob}} = 1 - |\langle B_1|B_2\rangle|_{i^+}$$

- Since Bob completes his measurement after some time T, it follows that $\mathscr{D}_{\text{Bob}} = 1 - |\langle B_1|B_2\rangle|_T$

Restatement of the Gedankenexperiment

- Consider a Cauchy surface Σ_1 which goes to the future of Alice's experiment but to past of Bob's experiment

Restatement of the Gedankenexperiment



Restatement of the Gedankenexperiment

- Consider a Cauchy surface Σ_1 which goes to the future of Alice's experiment but to past of Bob's experiment
- This decoherence is entirely due to Alice from the (Coulomb-subtracted) radiation states emitted during her experiment

$$\mathscr{D}_{\text{Alice}} = 1 - |\langle \Psi_1 | \Psi_2 \rangle|_{\Sigma_1}$$

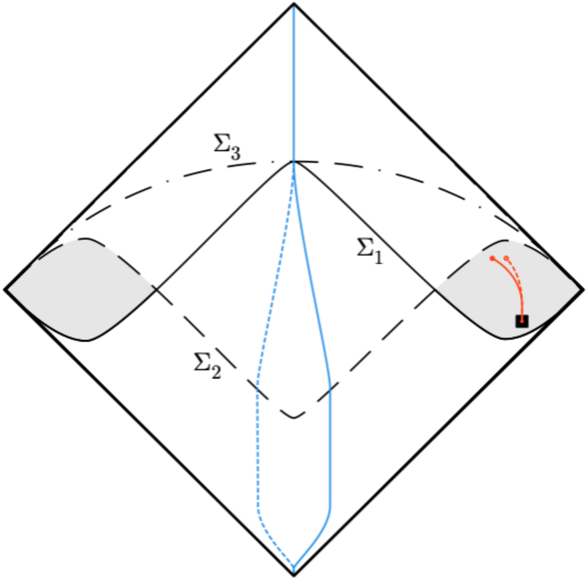
Restatement of the Gedankenexperiment

- Consider a Cauchy surface Σ_1 which goes to the future of Alice's experiment but to past of Bob's experiment
- This decoherence is entirely due to Alice from the (Coulomb-subtracted) radiation states emitted during her experiment

$$\mathscr{D}_{\text{Alice}} = 1 - |\langle \Psi_1 | \Psi_2 \rangle|_{\Sigma_1}$$

- Now consider a surface Σ_2 which goes to the past of Alice's experiment but to the future of Bob's experiment

Restatement of the Gedankenexperiment



Restatement of the Gedankenexperiment

- Consider a Cauchy surface Σ_1 which goes to the future of Alice's experiment but to past of Bob's experiment
- This decoherence is entirely due to Alice from the (Coulomb-subtracted) radiation states emitted during her experiment

$$\mathscr{D}_{\text{Alice}} = 1 - |\langle \Psi_1 | \Psi_2 \rangle|_{\Sigma_1}$$

- Now consider a surface Σ_2 which goes to the past of Alice's experiment but to the future of Bob's experiment
- This decoherence is entirely due to the orthogonality of Bob's states from interacting with the stationary Coulomb field of Alice's particle

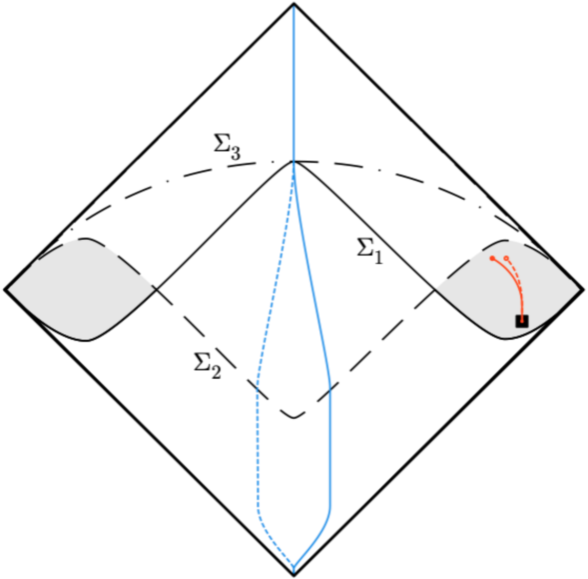
$$\mathscr{D}_{\text{Bob}} = 1 - |\langle B_1 | B_2 \rangle|_{\Sigma_2}$$

There is a paradox if $\mathscr{D}_{\text{Bob}} > \mathscr{D}_{\text{Alice}}$!

Resolution of the Gedankenexperiment

- To see that there is no paradox, consider the evolution of the joint Alice-Bob-field system from Σ_1 to a "time" Σ_3 after both Alice and Bob are done the experiment.

Resolution of the Gedankenexperiment



Resolution of the Gedankenexperiment

- To see that there is no paradox, consider the evolution of the joint Alice-Bob-field system from Σ_1 to a "time" Σ_3 after both Alice and Bob are done the experiment.
- On Σ_1 the state of the joint system is

$$\frac{1}{\sqrt{2}}\left(|\uparrow; A_1\rangle \otimes |\Psi_1\rangle_{\Sigma_1} + |\uparrow; A_2\rangle \otimes |\Psi_2\rangle_{\Sigma_1} \right) \otimes |B_0\rangle$$

Resolution of the Gedankenexperiment

- To see that there is no paradox, consider the evolution of the joint Alice-Bob-field system from Σ_1 to a "time" Σ_3 after both Alice and Bob are done the experiment.
- On Σ_1 the state of the joint system is

$$\frac{1}{\sqrt{2}}\big(|\uparrow; A_1\rangle \otimes |\Psi_1\rangle_{\Sigma_1} + |\uparrow; A_2\rangle \otimes |\Psi_2\rangle_{\Sigma_1} \big) \otimes |B_0\rangle$$

- We now evolve the state from Σ_1 to Σ_3. Alice's state *does not change*. Bob interacts with the radiation states and evolves to $|B\rangle_1, |B\rangle_2$. Due to the interaction, the radiation states evolve to $|\Psi_1'\rangle_{\Sigma_3}, |\Psi_2'\rangle_{\Sigma_3}$

$$\frac{1}{\sqrt{2}}\big(|\uparrow; A_1\rangle \otimes |\Psi_1'\rangle_{\Sigma_3} \otimes |B_1\rangle + |\uparrow; A_2\rangle \otimes |\Psi_2'\rangle_{\Sigma_3} \otimes |B_2\rangle \big)$$

Resolution of the Gedankenexperiment

- To see that there is no paradox, consider the evolution of the joint Alice-Bob-field system from Σ_1 to a "time" Σ_3 after both Alice and Bob are done the experiment.
- On Σ_1 the state of the joint system is

$$\frac{1}{\sqrt{2}}\left(|\uparrow; A_1\rangle \otimes |\Psi_1\rangle_{\Sigma_1} + |\uparrow; A_2\rangle \otimes |\Psi_2\rangle_{\Sigma_1} \right) \otimes |B_0\rangle$$

- We now evolve the state from Σ_1 to Σ_3. Alice's state *does not change*. Bob interacts with the radiation states and evolves to $|B\rangle_1, |B\rangle_2$. Due to the interaction, the radiation states evolve to $|\Psi_1'\rangle_{\Sigma_3}, |\Psi_2'\rangle_{\Sigma_3}$

$$\frac{1}{\sqrt{2}}\left(|\uparrow; A_1\rangle \otimes |\Psi_1'\rangle_{\Sigma_3} \otimes |B_1\rangle + |\uparrow; A_2\rangle \otimes |\Psi_2'\rangle_{\Sigma_3} \otimes |B_2\rangle \right)$$

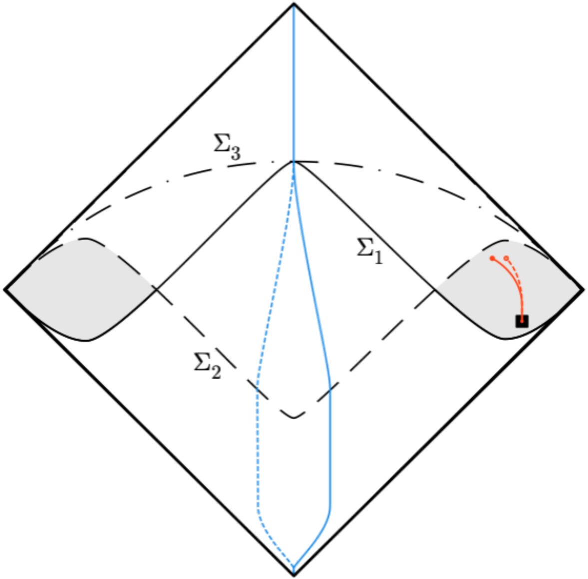
- This evolution is unitary: $\langle\Psi_1'|\Psi_2'\rangle_{\Sigma_3} \langle B_1|B_2\rangle = \langle\Psi_1|\Psi_2\rangle_{\Sigma_1} \langle B_0|B_0\rangle = \langle\Psi_1|\Psi_2\rangle_{\Sigma_1}$

$$|\langle B_1|B_2\rangle| \geq |\langle\Psi_1|\Psi_2\rangle_{\Sigma_1}| \implies \mathscr{D}_{\text{Bob}} \leq \mathscr{D}_{\text{Alice}}$$

Gravitational Entanglement: Newtonian vs. Gravitons

- If we consider the spacetime to the past of Σ_2, Bob is simply measuring the static, superposed Coulomb fields in his region. The entanglement completely via the Newtonian gravitational field.

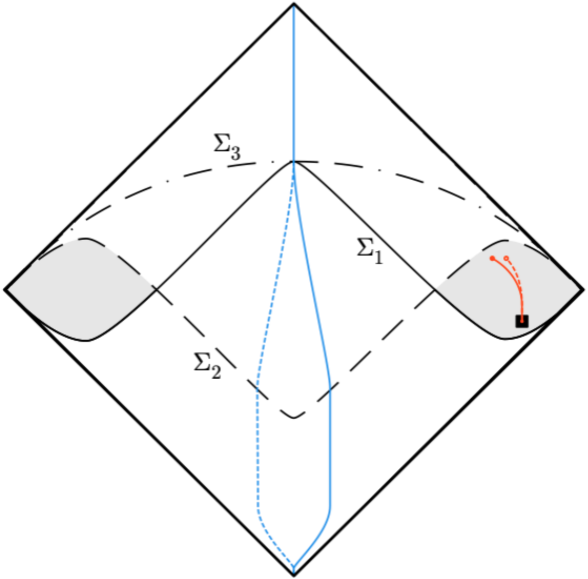
Gravitational Entanglement: Newtonian vs. Gravitons



Gravitational Entanglement: Newtonian vs. Gravitons

- If we consider the spacetime to the past of Σ_2, Bob is simply measuring the static, superposed Coulomb fields in his region. The entanglement completely via the Newtonian gravitational field.
- However, there is an alternative picture if we consider the portion of the spacetime to the future of Σ_1. In that picture, the field that Bob is measuring can be described by propagating free-field initial data off of Σ_1. Bob is becoming entangled with on-shell, propagating degrees of freedom (i.e. gravitons) emitted by Alice during her recombination.

Gravitational Entanglement: Newtonian vs. Gravitons



Gravitational Entanglement: Newtonian vs. Gravitons

- If we consider the spacetime to the past of Σ_2, Bob is simply measuring the static, superposed Coulomb fields in his region. The entanglement completely via the Newtonian gravitational field.
- However, there is an alternative picture if we consider the portion of the spacetime to the future of Σ_1. In that picture, the field that Bob is measuring can be described by propagating free-field initial data off of Σ_1. Bob is becoming entangled with on-shell, propagating degrees of freedom (i.e. gravitons) emitted by Alice during her recombination.
- For spacelike separated measurements, there is no clear distinction between entanglement via the Newtonian field and entanglement via on-shell gravitons. Both viewpoints are equivalent! *Both* viewpoints must be valid descriptions of the process in order to have a consistent description of a quantum superposition.

Gravitational Entanglement: Newtonian vs. Gravitons

- If we consider the spacetime to the past of Σ_2, Bob is simply measuring the static, superposed Coulomb fields in his region. The entanglement completely via the Newtonian gravitational field.
- However, there is an alternative picture if we consider the portion of the spacetime to the future of Σ_1. In that picture, the field that Bob is measuring can be described by propagating free-field initial data off of Σ_1. Bob is becoming entangled with on-shell, propagating degrees of freedom (i.e. gravitons) emitted by Alice during her recombination.
- For spacelike separated measurements, there is no clear distinction between entanglement via the Newtonian field and entanglement via on-shell gravitons. Both viewpoints are equivalent! *Both* viewpoints must be valid descriptions of the process in order to have a consistent description of a quantum superposition.
- This suggests that Newtonian entanglement implies the existence of graviton entanglement and the experimental discovery of Newtonian entanglement can be viewed as implying the existence of the graviton

Summary

- Gedankenexperiments where both quantum theory and gravity play an essential role can give considerable insight into the nature of quantum gravity.
- Many actual experiments have been recently proposed to measure entanglement mediated by the Newtonian field. It has been claimed by a number of authors that such experiments cannot teach us anything about quantum gravity since it doesn't couple to the "true propagating degrees of freedom".
- Our re-analysis of the gedankenexperiment by Mari et al shows that the consistent description a quantum superposition shows that Newtonian entanglement implies the existence of graviton entanglement. Thus, this strongly supports the view that the success of recently posed experiments implies the existence of the graviton as a fundamental particle.