Title: Indefinite temporal order on a superposition of spherical shells - VIRTUAL

Speakers: NatÃ¡lia SalomÃ© MÃ³ller

Series: Quantum Foundations

Date: January 11, 2024 - 11:00 AM

URL: https://pirsa.org/24010078

Abstract: The field of indefinite order in quantum theory was born from an attempt to construct a theory of quantum gravity, where the first step is to construct a generalized quantum theory in which events could have an indefinite order [1]. It is expected that such a theory would lead us more naturally to the construction of a quantum gravity theory. One way to explore this topic operationally is to consider that two agents Alice and Bob apply operations A and B on a given target system and that quantum mechanics holds locally for each agent [2]. The quantum switch is the simplest example of a task with indefinite order, where the order of operations applied by two agents on a target system is entangled with the state of a quantum control system. In particular, in the gravitational quantum switch, the order of these operations is entangled with the state of a quantum spacetime [3].

In this talk, I will present a recent result, where we propose a distinct protocol for performing a gravitational quantum switch [4]. One of the agents crosses the interior region of massive spherical shells in a superposition of different radii and becomes entangled with their geometry. This entanglement is used as a resource to control the order of operation in the implementation of the quantum switch. Novel features of the protocol include: i) the superposition of nonisometric geometries; ii) the existence of a region with a definite geometry; iii) the fact that the agent that experiences the superposition of geometries is in free fall, preventing information on the global geometry to be obtained by this agent.

[1] Hardy, J. Phys. A: Math. Theor. 40, 3081 (2007);
[2] Chiribella, D'Ariano, Perinotti, Valiron, PRA 88, 022318 (2013); Oreshkov, Costa, Brukner, Nat. Commun. 3, 1092 (2012).
[3] Zych, Costa, Pikovski, Brukner, Nat. Commun. 10, 3772 (2019).
[4] Móller, Sahdo, Yokomizo, arXiv:2306.10984 (2023).

Zoom link https://pitp.zoom.us/j/96568644174?pwd=ak9qM0Y1R29WdXRXREIxdTFtcDhYUT09

Indefinite temporal order on a superposition of spherical shells

Natália S. Móller
Research Center for Quantum Information
Slovak Academy of Sciences
11th January 2024

Perimeter Institute
Quantum Foundations group

arXiv:2306.10984

In collaboration with
B. Sahdo and N. Yokomizo

VEGA

APVV

Indefinite temporal order

Indefinite temporal order

Indefinite causal order

Indefinite order of operations

Indefinite order

Quantum switch

Gravitational quantum switch

Conservative and radical features of GR and QT

	General Relativity	Quantum Theory
Conservative feature:	deterministic	causal structure fixed in advance
Radical feature:	non-fixed causal structure +	irreducibly probabilistic

➢ Formulate probabilistic theories with no pre-defined causal order.

Hardy, arXiv:0509120 (2005);
JPA **40**, 3081 (2007).

Closed laboratories as delocalized Einstein's elevators

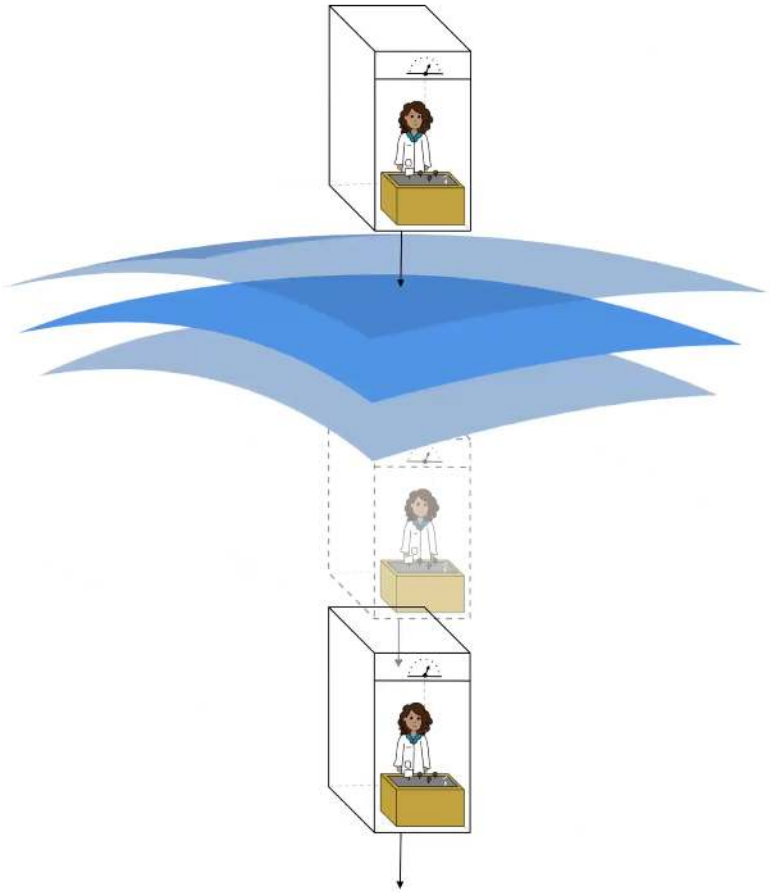
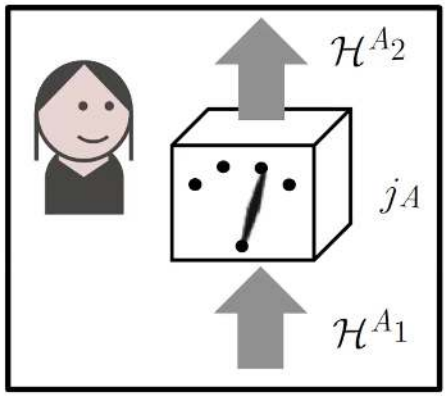
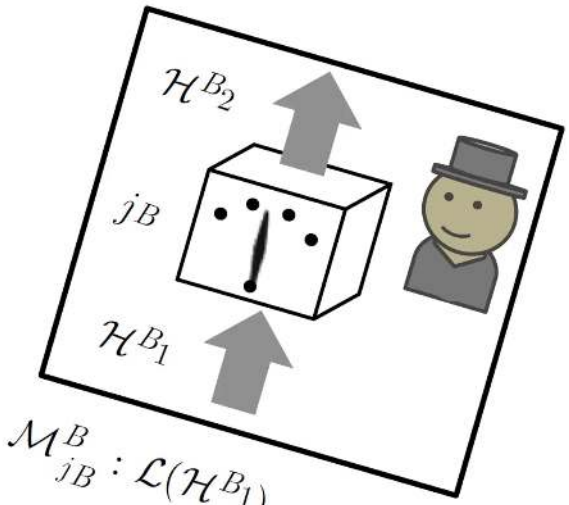


Figure from Bruna Sahdo's presentations.

Closed laboratories in the process matrix framework



$\mathcal{M}^A_{j_A} : \mathcal{L}(\mathcal{H}^{A_1}) \to \mathcal{L}(\mathcal{H}^{A_2})$



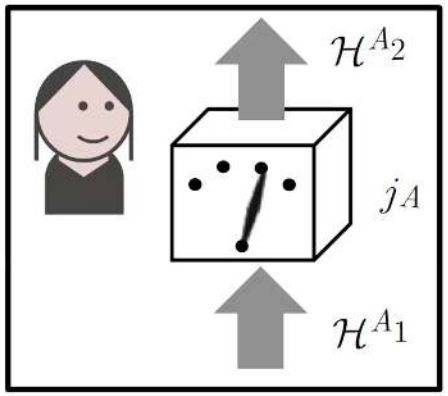
$\mathcal{M}^B_{j_B} : \mathcal{L}(\mathcal{H}^{B_1}) \to \mathcal{L}(\mathcal{H}^{B_2})$

Quantum theory is assumed to hold locally, that is, inside each laboratory.

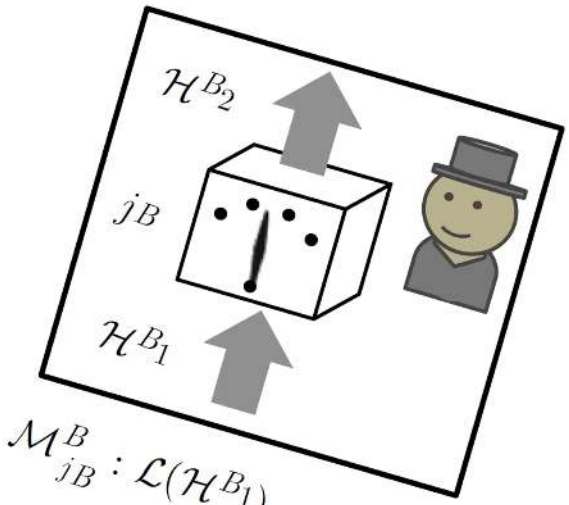
Events are defined through operations that closed laboratories can apply on a target qubit.

Oreshkov, Costa, Brukner,
Nat. Commun. **3**, 1092 (2012).

Closed laboratories in the process matrix framework



$\mathcal{M}^A_{j_A} : \mathcal{L}(\mathcal{H}^{A_1}) \to \mathcal{L}(\mathcal{H}^{A_2})$



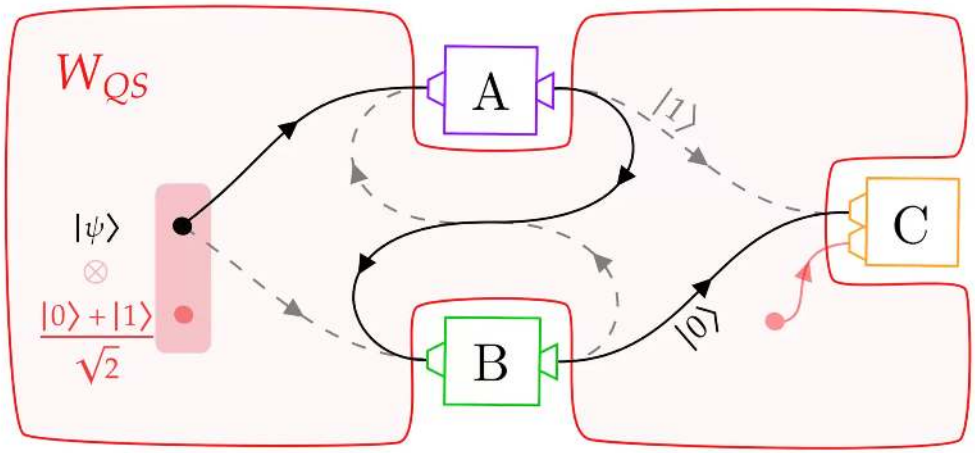
$\mathcal{M}^B_{j_B} : \mathcal{L}(\mathcal{H}^{B_1}) \to \mathcal{L}(\mathcal{H}^{B_2})$

A large set of tasks with indefinite order that do not lead to paradoxes is characterized.

The best known example of a task of such kind is the quantum switch.

Oreshkov, Costa, Brukner,
Nat. Commun. **3**, 1092 (2012).

Quantum switch

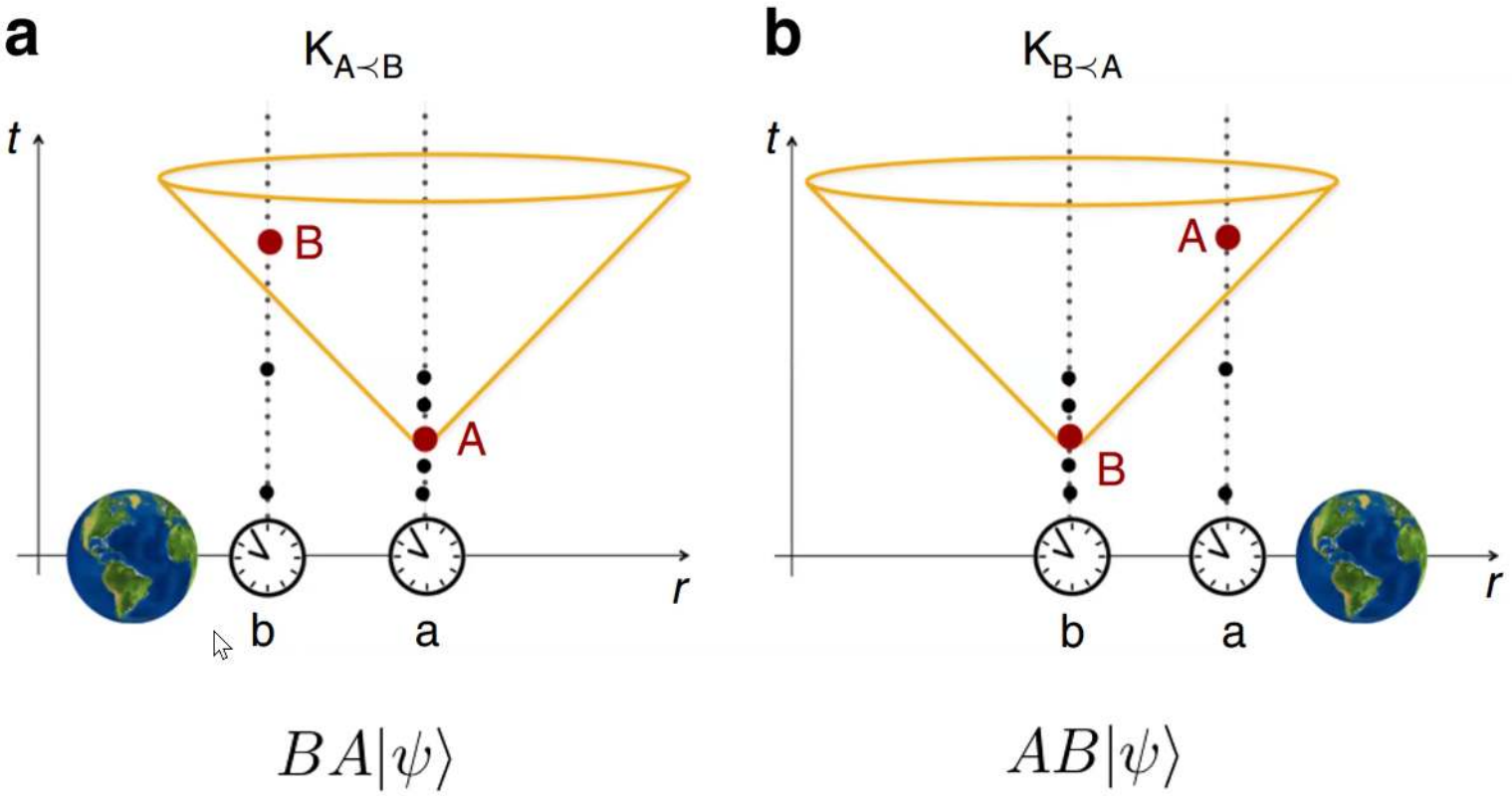


$$\frac{AB|\psi\rangle \otimes |0\rangle + BA|\psi\rangle \otimes |1\rangle}{\sqrt{2}}$$

Process introduced in Chiribella, D'Ariano, Perinotti, Valiron, PRA **88**, 022318 (2013); ArXiv 0912.0195 (2009).

Figure from Bruna Sahdo's Masters thesis (2023).

Gravitational quantum switch



$BA|\psi\rangle$ $AB|\psi\rangle$

Events are defined considering the proper time of each laboratory.

Zych, Costa, Pikovski, Brukner, Nat. Commun. **10**, 3772 (2019).

Questions

Zych, Costa, Pikovski, Brukner,
Nat. Commun. **10**, 3772 (2019).

Móller, Sahdo, Yokomizo,
PRA **104**, 042414 (2021).

Superposition of masses X entangled clocks

Zych, Costa, Pikovski, Brukner,
Nat. Commun. **10**, 3772 (2019).

Móller, Sahdo, Yokomizo,
PRA **104**, 042414 (2021).

We developed strategies to perform the quantum switch on the gravity of Earth with current technology.

Questions: 1)

Zych, Costa, Pikovski, Brukner,
Nat. Commun. **10**, 3772 (2019).

Móller, Sahdo, Yokomizo,
PRA **104**, 042414 (2021).

- Quantum spacetime can be re-expressed as a classical spacetime, given some symmetries.

  J. Foo, R. B. Mann, M. Zych, arXiv:2302.03259.

1) Is it possible to construct non-isometric spacetimes to perform a gravitational quantum switch?

Questions: 2)

Zych, Costa, Pikovski, Brukner,
Nat. Commun. **10**, 3772 (2019).

Móller, Sahdo, Yokomizo,
PRA **104**, 042414 (2021).

1) Is it possible to construct non-isometric spacetimes to perform a gravitational quantum switch?

- Events defined according the proper time inside the laboratories:
  -what about other inner observables?
  -what about the weight?

- A possible measurement of weight would not lead the protocol to decohere?

Questions: 3)

Zych, Costa, Pikovski, Brukner,
Nat. Commun. **10**, 3772 (2019).

Móller, Sahdo, Yokomizo,
PRA **104**, 042414 (2021).

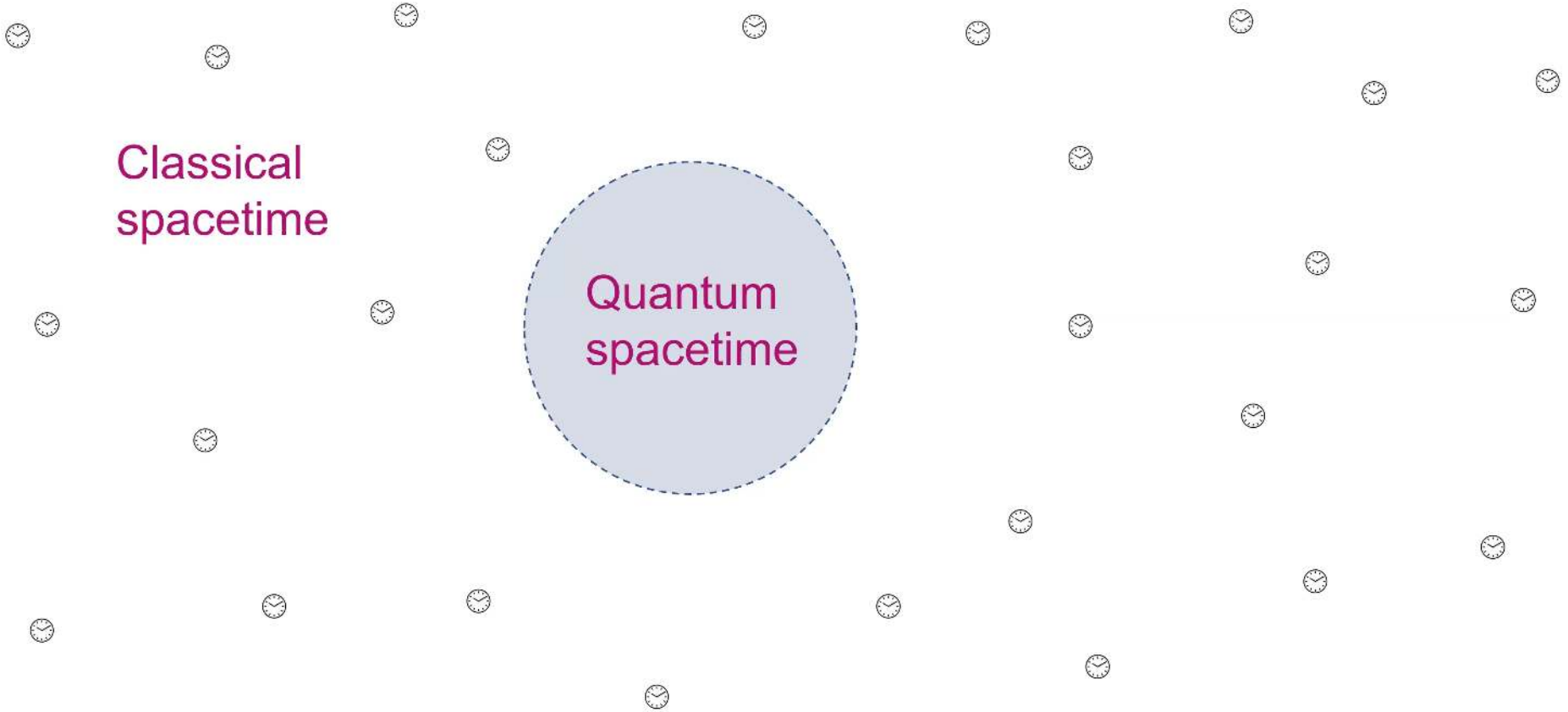
1) Is it possible to construct non-isometric spacetimes to perform a gravitational quantum switch?

2) Is it possible to avoid possible measurements of weight?

- In general, an external observer should be located in the infinite.

3) Is it possible to bring an external observer closer?

Bounded quantum spacetime



Móller, Sahdo, Yokomizo, arXiv:2306.10984 (2023).

Basic assumptions

1. The gravitational field can exist in a superposition of semiclassical states:

$$\frac{|g^1_{\mu\nu}\rangle + |g^2_{\mu\nu}\rangle}{\sqrt{2}}$$

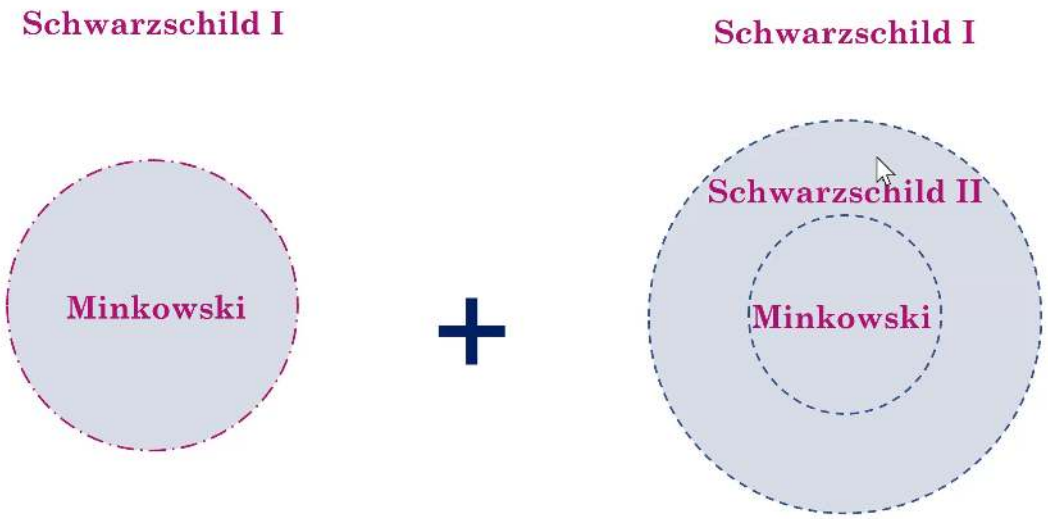
2. Events are defined operationally using inner observables.

   For each event in $\mathcal{M}_1$ there is a correspondent event in $\mathcal{M}_2$.

3. The dynamics can be computed semi-classically.

Móller, Sahdo, Yokomizo,
arXiv:2306.10984 (2023).

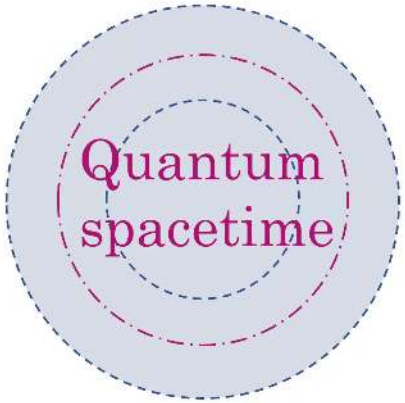
Quantum switch in a quantum spacetime



Móller, Sahdo, Yokomizo,
arXiv:2306.10984 (2023).

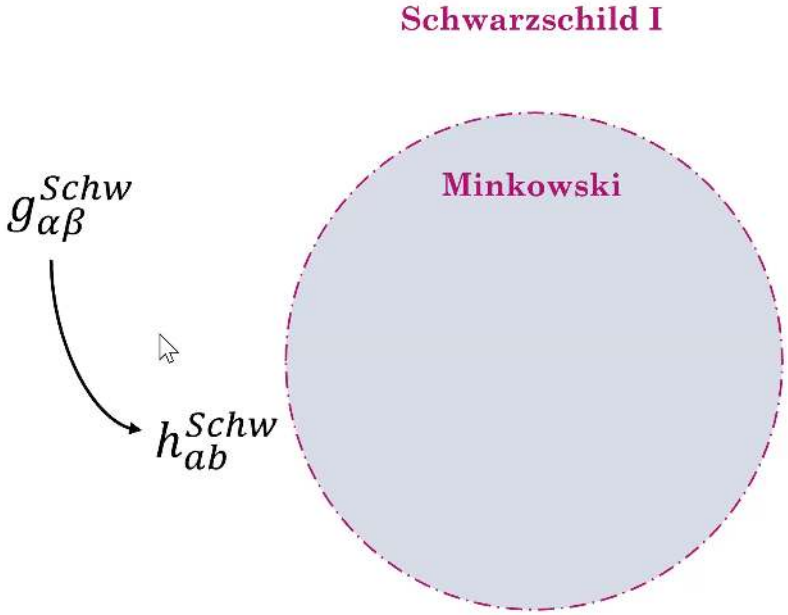
Quantum switch in a quantum spacetime

Classical spacetime = Schwarzschild I



Móller, Sahdo, Yokomizo,
arXiv:2306.10984 (2023).

Junction conditions on the semiclassical spacetimes



$$d\tau_{Mink} \overset{?}{\sim} d\tau_{Schw}$$

$$dt_{Mink} \overset{?}{\sim} dt_{Schw}$$

E. Poisson, A relativist's toolkit (Cambridge University Press, 2004).

Móller, Sahdo, Yokomizo, arXiv:2306.10984 (2023).

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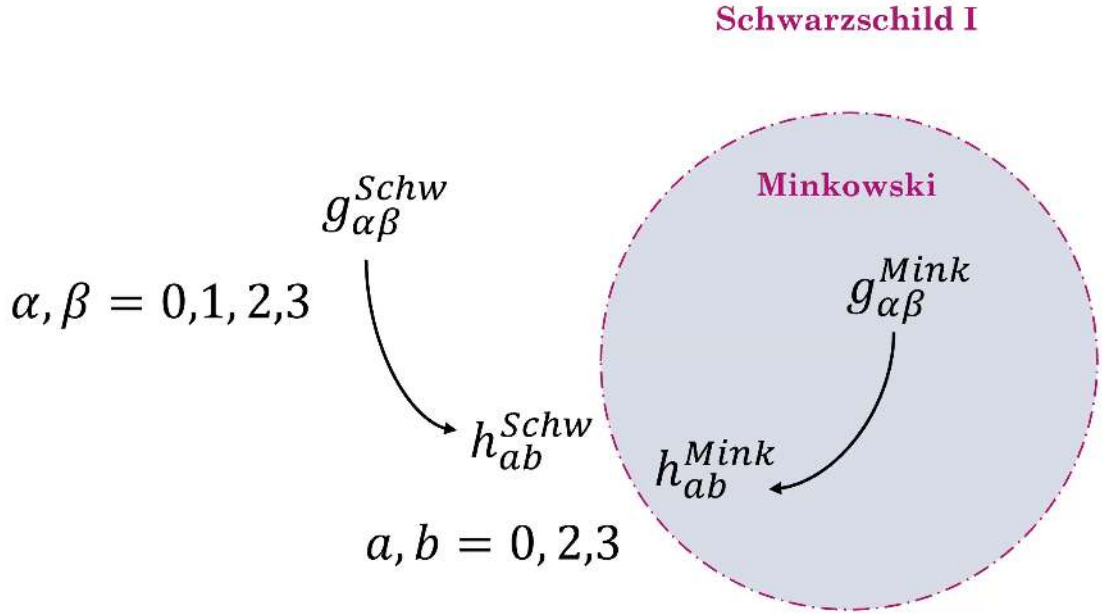

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Móller, Sahdo, Yokomizo, arXiv:2306.10984 (2023).

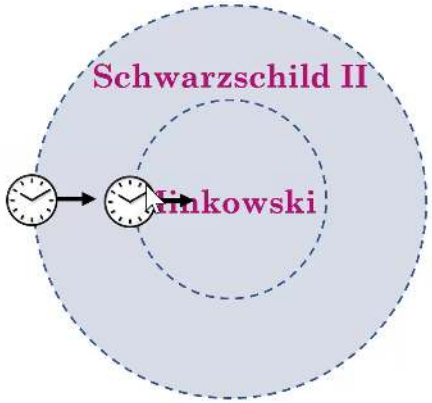
Gravitational quantum switch

We define similar conditions for this spacetime

Schwarzschild

$$h_{ab}^{Schw} = h_{ab}^{Mink}$$

Schwarzschild I



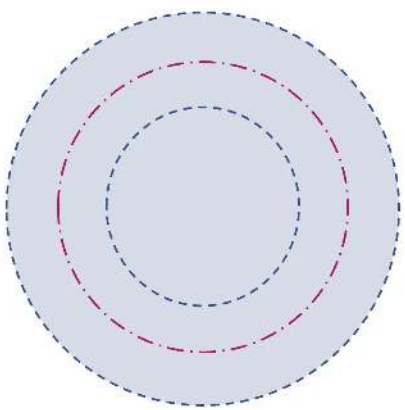
$$h_{ab}^{SchwI} = h_{ab}^{SchwII}$$

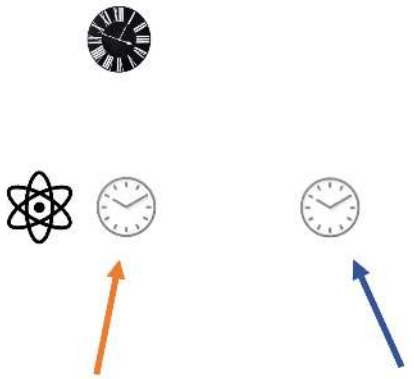
$$h_{ab}^{SchwII} = h_{ab}^{Mink}$$

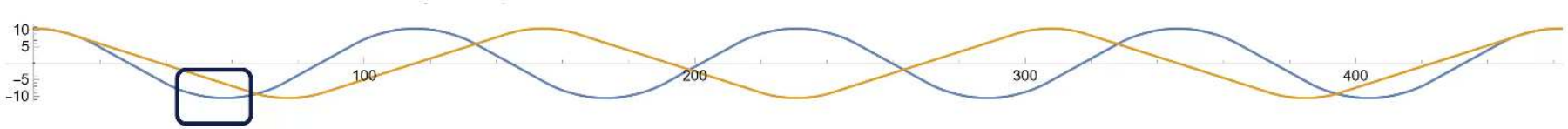
Móller, Sahdo, Yokomizo,
arXiv:2306.10984 (2023).

Gravitational quantum switch

After the protocol, the two wave packets fall back into the spherical shells and recombine in one single trajectory.







Móller, Sahdo, Yokomizo,
arXiv:2306.10984 (2023).

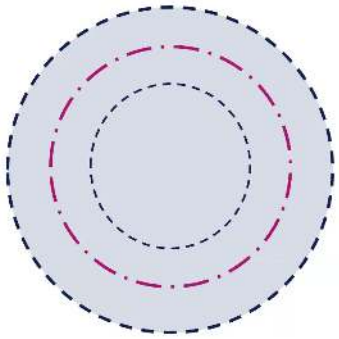
Gravitational quantum switch

After the protocol, the two wave packets fall back into the spherical shells and recombine in one single trajectory.

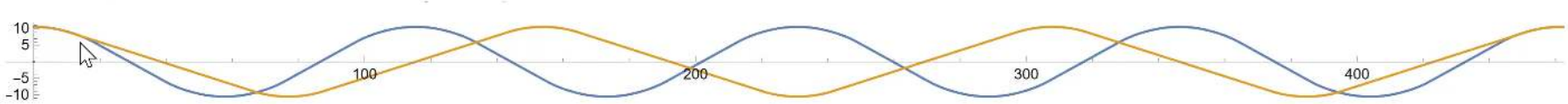
How to find this solution:

1. Free parameters: radii of the outer spheres.

2. Set the conditions:



$$\frac{\Delta\tau^{(1)}}{\Delta t^{(1)}} = \frac{\Delta\tau^{(2)}}{\Delta t^{(2)}}$$



Móller, Sahdo, Yokomizo, arXiv:2306.10984 (2023).

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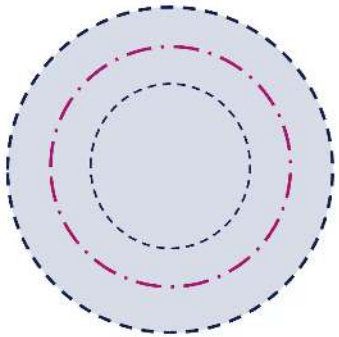
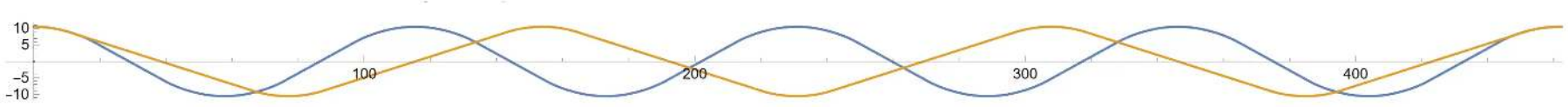


$$\frac{\Delta\tau^{(1)}}{\Delta t^{(1)}} = \frac{\Delta\tau^{(2)}}{\Delta t^{(2)}} \qquad \frac{\Delta t^{(1)}}{\Delta t^{(2)}} = \frac{p}{q}, \qquad p, q \in \mathbb{N},$$



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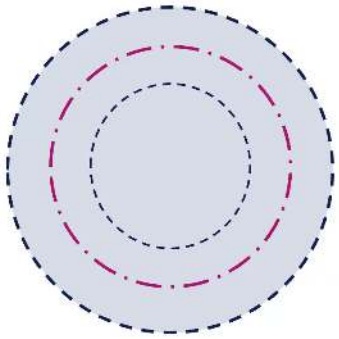

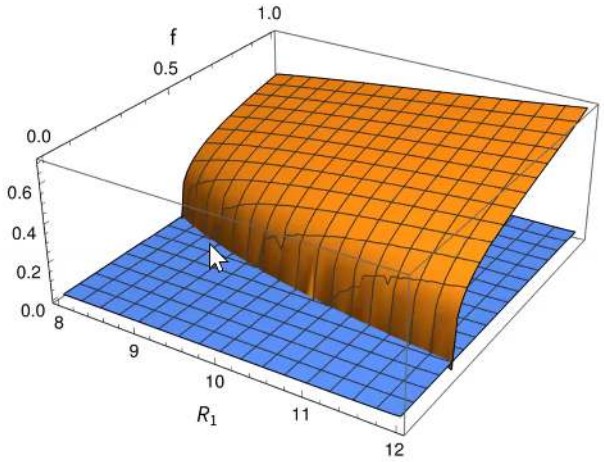

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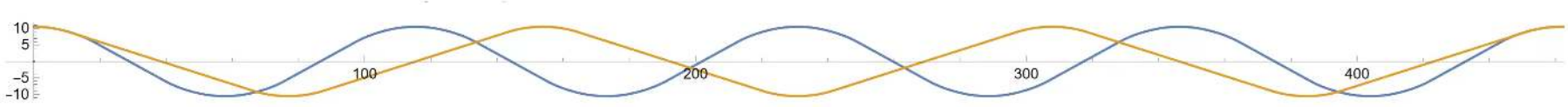
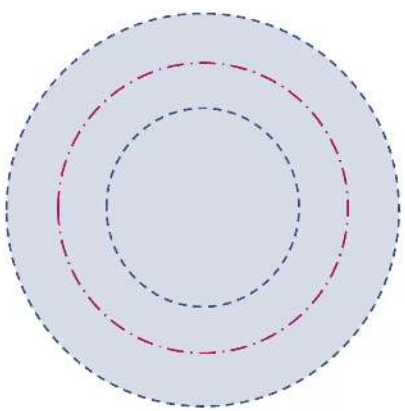
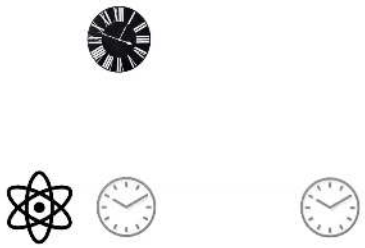


Móller, Sahdo, Yokomizo, arXiv:2306.10984 (2023).

Gravitational quantum switch





$$\frac{AB|\psi\rangle \otimes |0\rangle + BA|\psi\rangle \otimes |1\rangle}{\sqrt{2}}$$

Móller, Sahdo, Yokomizo,
arXiv:2306.10984 (2023).

Interventions of the agents

Let us consider that Alice applies its operations conditioned on some inner observable λ:

$$\mathcal{A}(\lambda)$$

Such that $\mathcal{A}(\lambda_1) \neq \mathcal{A}(\lambda_2)$ for $\lambda_1 \neq \lambda_2$.

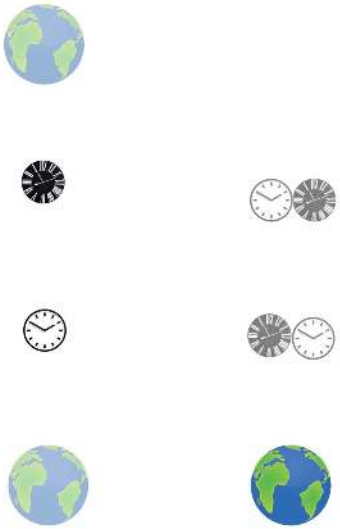
Suppose $\mathcal{A}(a) = A$.

Protocol when $\lambda_1 = \lambda_2 = a$:

$$\frac{\mathcal{A}(\lambda_1 = a)B|\psi\rangle \otimes |0\rangle + B\mathcal{A}(\lambda_2 = a)|\psi\rangle \otimes |1\rangle}{\sqrt{2}} = \frac{AB|\psi\rangle \otimes |0\rangle + BA|\psi\rangle \otimes |1\rangle}{\sqrt{2}}$$

Móller, Sahdo, Yokomizo, arXiv:2306.10984 (2023).

Interventions of the agents



Let λ and η be the weight of Alice and Bob.

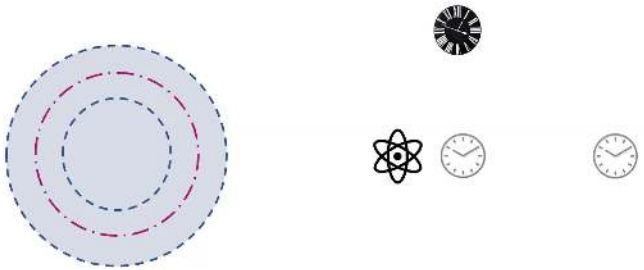
It might happen that:

$$\frac{\mathcal{A}(\lambda_1)\mathcal{B}(\eta_1)|\psi\rangle \otimes |0\rangle + \mathcal{B}(\eta_2)\mathcal{A}(\lambda_2)|\psi\rangle \otimes |1\rangle}{\sqrt{2}} = \frac{CD|\psi\rangle \otimes |0\rangle + EF|\psi\rangle \otimes |1\rangle}{\sqrt{2}}$$

Alice and Bob must be systems that are insensitive to weight.

Móller, Sahdo, Yokomizo, arXiv:2306.10984 (2023).

Interventions of the agents



Let λ and η be the any inner observable of Alice and Bob.

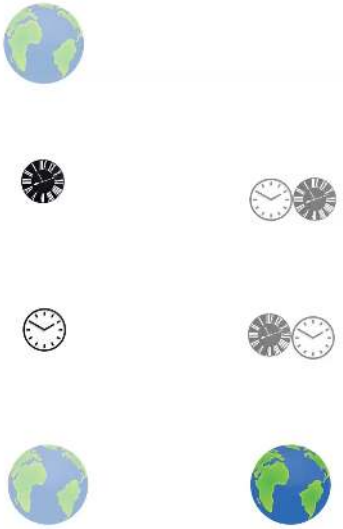
It always happen that:

$$\frac{\mathcal{A}(\lambda_1)\mathcal{B}(\eta_1)|\psi\rangle \otimes |0\rangle + \mathcal{B}(\eta_2)\mathcal{A}(\lambda_2)|\psi\rangle \otimes |1\rangle}{\sqrt{2}} = \frac{AB|\psi\rangle \otimes |0\rangle + BA|\psi\rangle \otimes |1\rangle}{\sqrt{2}}$$

Because, by construction, we always have that $\lambda_1 = \lambda_2$ and $\eta_1 = \eta_2$.

Móller, Sahdo, Yokomizo,
arXiv:2306.10984 (2023).

Interventions of the agents



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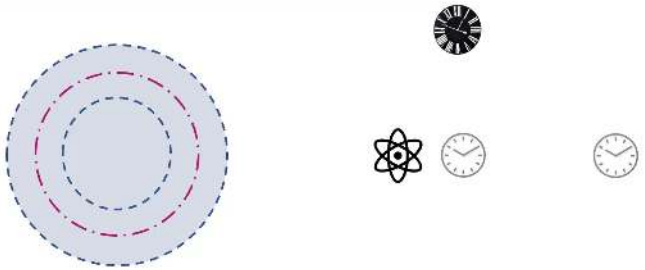
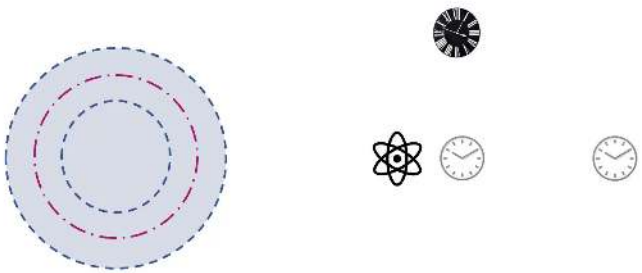


Alice and Bob could be any kind of system.

Quantum switch depend only on the external environment.

Móller, Sahdo, Yokomizo, arXiv:2306.10984 (2023).

Prospects



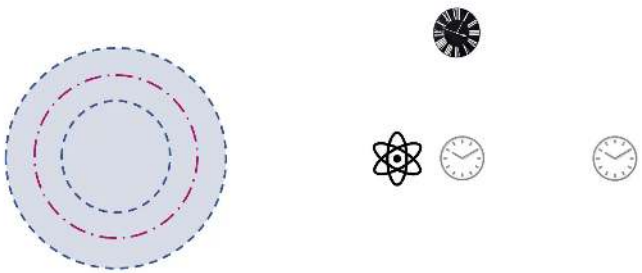
Explore more realistic clocks in the vicinity of the shells.

Explore the formalisms of quantum reference frames within this model.

They have the potential to impact topics such as:

- equivalence principle
- measurement problem
- quantum to classical transition

Prospects



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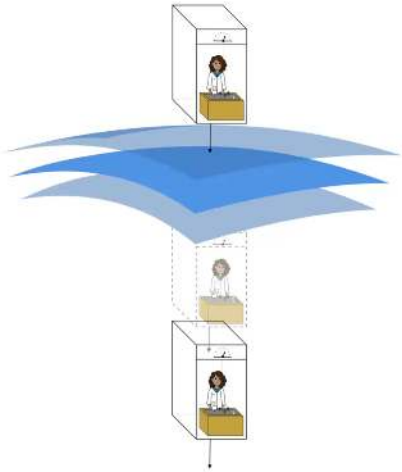
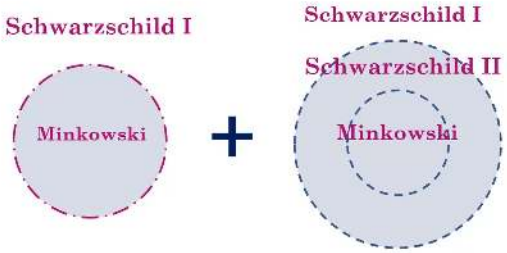
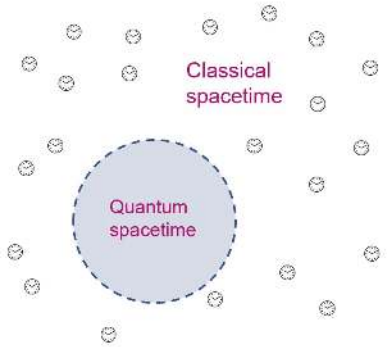


Summary

Superposition of non-isometric spacetimes



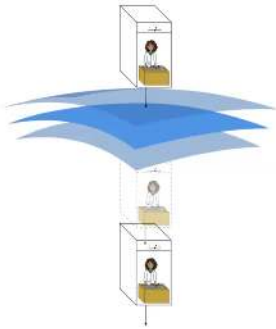
External observers are well-defined in a classical region.



Proposal for a gravitational quantum switch;

Solutions for geodesic trajectories of Alice's wave packets;

Alice can perform any operation on the target system, even those that measure her weight;



Móller, Sahdo, Yokomizo, arXiv:2306.10984 (2023).

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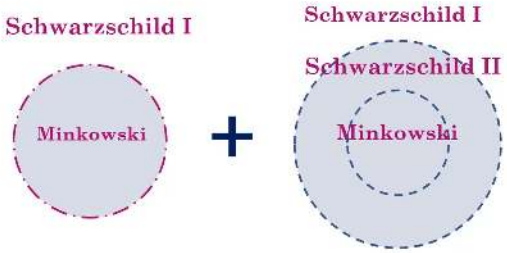

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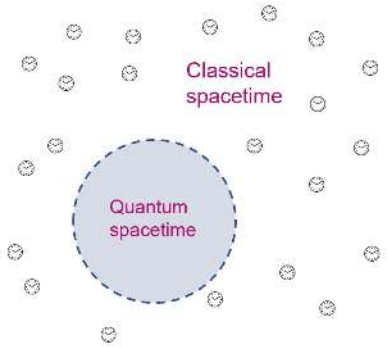

Proposal for a gravitational quantum switch;

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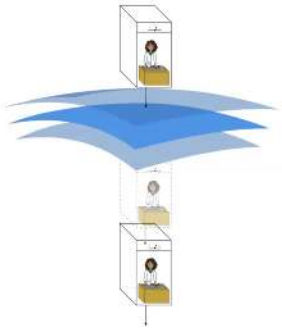
Alice can perform any operation on the target system, even those that measure her weight;

This is the most accurate example of a closed laboratory in a protocol with indefinite causal order.



Móller, Sahdo, Yokomizo, arXiv:2306.10984 (2023).

Thank you for your attention!

VEGA

APVV

Basic assumptions

1. The gravitational field can exist in a superposition of semiclassical states:

$$\frac{|g^1_{\mu\nu}\rangle + |g^2_{\mu\nu}\rangle}{\sqrt{2}}$$

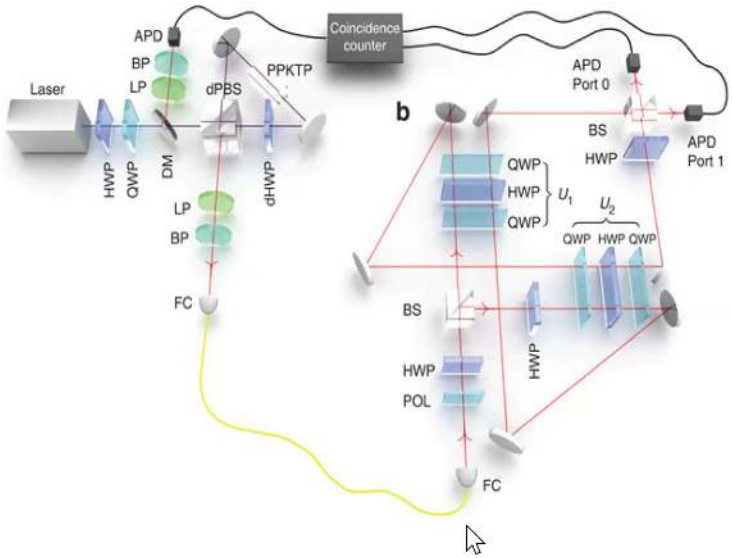
2. Events are defined operationally using inner observables.

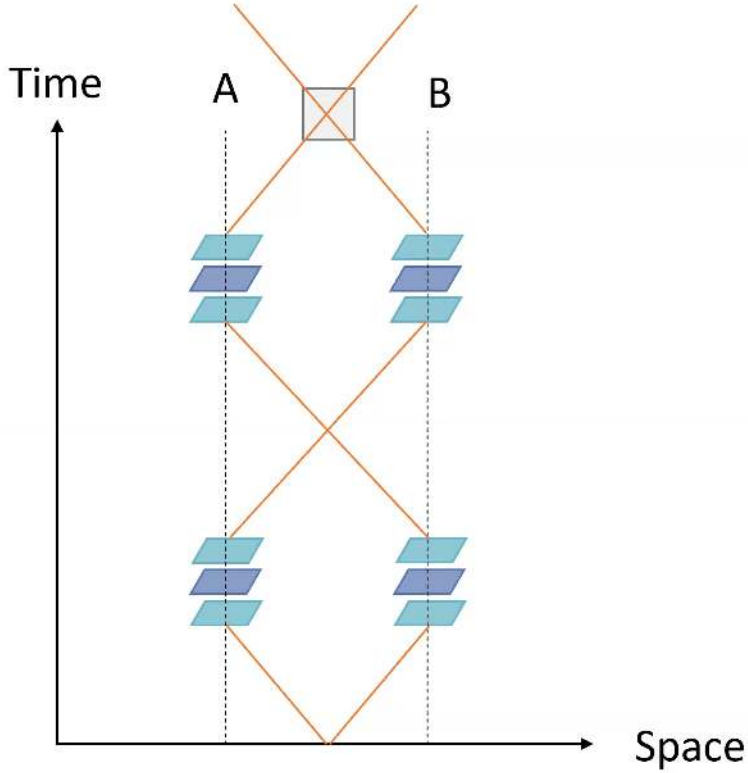
   For each event in $\mathcal{M}_1$ there is a correspondent event in $\mathcal{M}_2$.

3. The dynamics can be computed semi-classically.

Móller, Sahdo, Yokomizo,
arXiv:2306.10984 (2023).

Quantum switch in an optical experiment



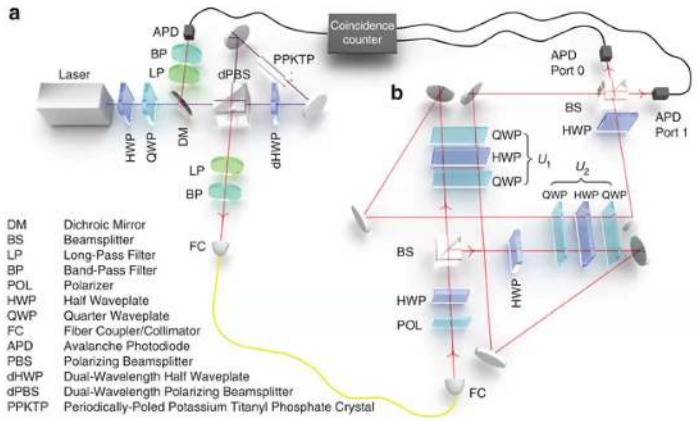


Target qubit: polarization

Control qubit: path

Procopio, Moqanaki, Araújo, Costa, Calafell, Dowd, Hamel, Rozema, Brukner, Walther, Nat. Commun. **6**, 7913 (2015)

Interventions of the agents – optical experiments



Let λ and η be the proper time of Alice and Bob.

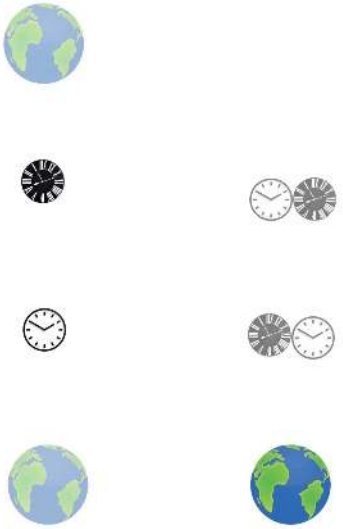
It might happen that:

$$\frac{A(\lambda_1)B(\eta_1)|\psi\rangle \otimes |0\rangle + B(\eta_2)A(\lambda_2)|\psi\rangle \otimes |1\rangle}{\sqrt{2}} = \frac{CD|\psi\rangle \otimes |0\rangle + EF|\psi\rangle \otimes |1\rangle}{\sqrt{2}}$$

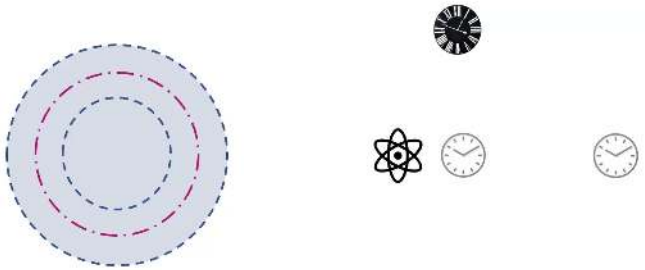
Procopio, Moqanaki, Araújo, Costa, Calafell, Dowd, Hamel, Rozema, Brukner, Walther, Nat. Commun. **6**, 7913 (2015)

Móller, Sahdo, Yokomizo, arXiv:2306.10984 (2023).

Interventions of the agents



Alice and Bob must be systems that are insensitive to weight.



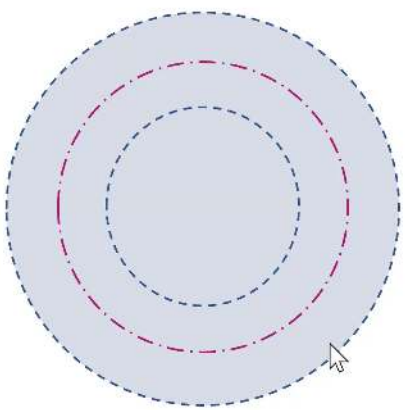
Alice and Bob could be any kind of system.

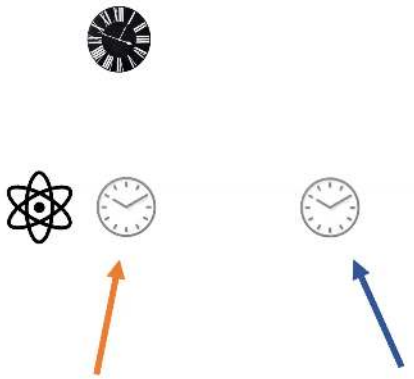
Quantum switch depend only on the external environment.

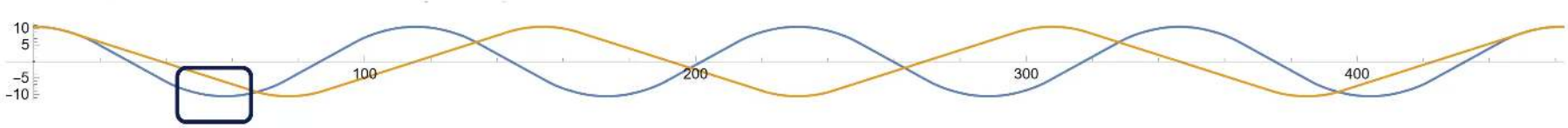
Móller, Sahdo, Yokomizo, arXiv:2306.10984 (2023).

Gravitational quantum switch

After the protocol, the two wave packets fall back into the spherical shells and recombine in one single trajectory.







Móller, Sahdo, Yokomizo, arXiv:2306.10984 (2023).

Questions: 1)

Zych, Costa, Pikovski, Brukner,
Nat. Commun. **10**, 3772 (2019).

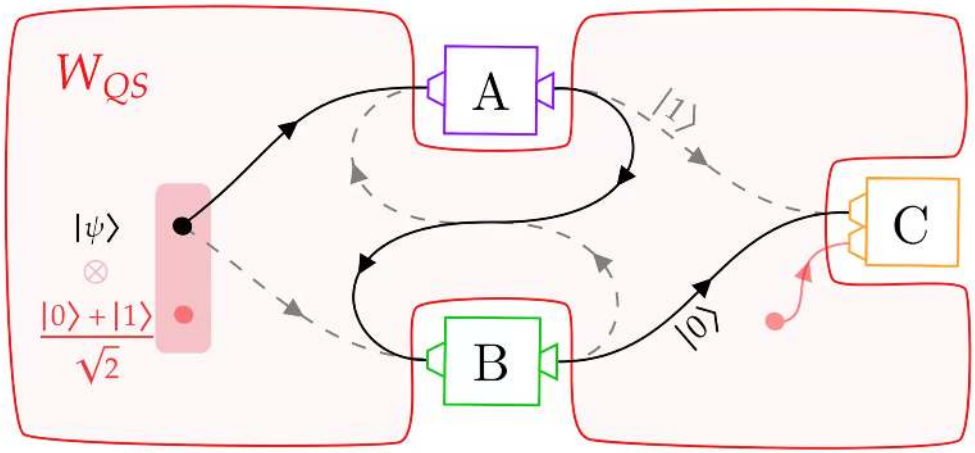
Móller, Sahdo, Yokomizo,
PRA **104**, 042414 (2021).

- Quantum spacetime can be re-expressed as a classical spacetime, given some symmetries.

  J. Foo, R. B. Mann, M. Zych, arXiv:2302.03259.

1) Is it possible to construct non-isometric spacetimes to perform a gravitational quantum switch?

Quantum switch



$$\frac{AB|\psi\rangle \otimes |0\rangle + BA|\psi\rangle \otimes |1\rangle}{\sqrt{2}}$$

Process introduced in Chiribella, D'Ariano, Perinotti, Valiron, PRA **88**, 022318 (2013); ArXiv 0912.0195 (2009).

Figure from Bruna Sahdo's Masters thesis (2023).