Title: Time reference frames and gravitating quantum clocks

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Collection: Indefinite Causal Structure

Date: December 12, 2019 - 9:50 AM

URL: http://pirsa.org/19120043

Abstract: The standard formulation of quantum theory relies on a fixed space-time metric determining the localisation and causal order of events. In general relativity, the metric is influenced by matter, and it is expected to become indefinite when matter behaves quantum mechanically. Here we explore the problem of operationally defining events and their localisation in the presence of gravitating quantum systems. We develop a framework for "time reference frames," in which events are defined in terms of quantum operations with respect to a quantum clock. We find that, when clocks and quantum systems interact gravitationally, the temporal localisability of events becomes relative, depending on the time reference frame. We argue that the impossibility to find a reference frame in which all events are localised is a signature of an indefinite metric, which might yield an indefinite causal order of events. Even if the metric is indefinite, for any event we can find a time reference frame with respect to which the event is localised in time, while other events may remain delocalised. In this frame, time evolution takes its standard (SchrÃ¶dinger) form, including the unitary dilation of the quantum operation defining the event. In addition, this form is preserved when moving from the frame localising one event to the frame localising another one, thereby implementing a form of covariance with respect to quantum reference frame transformations.

Time reference frames and gravitating quantum clocks

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Indefinite causal structures
Perimeter Institute, December 2019

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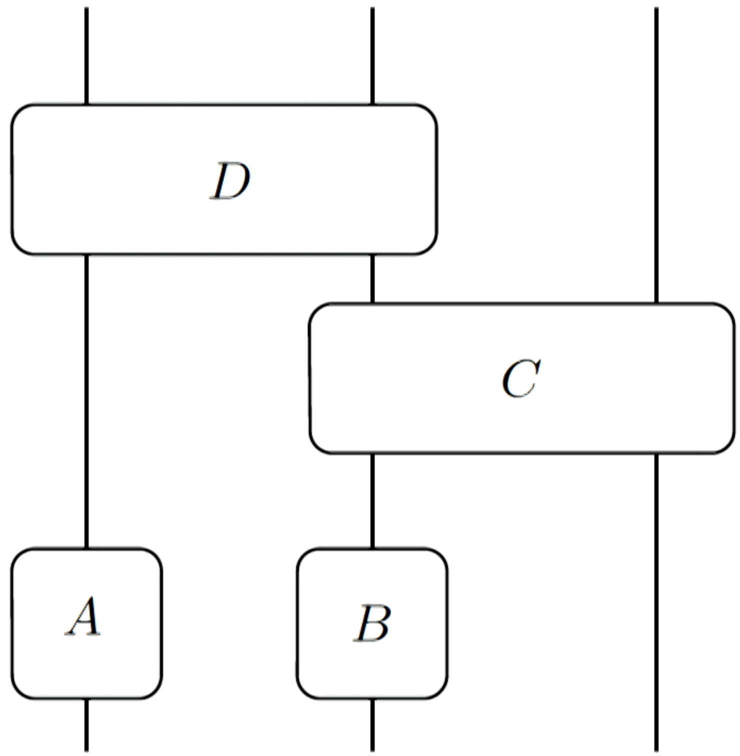
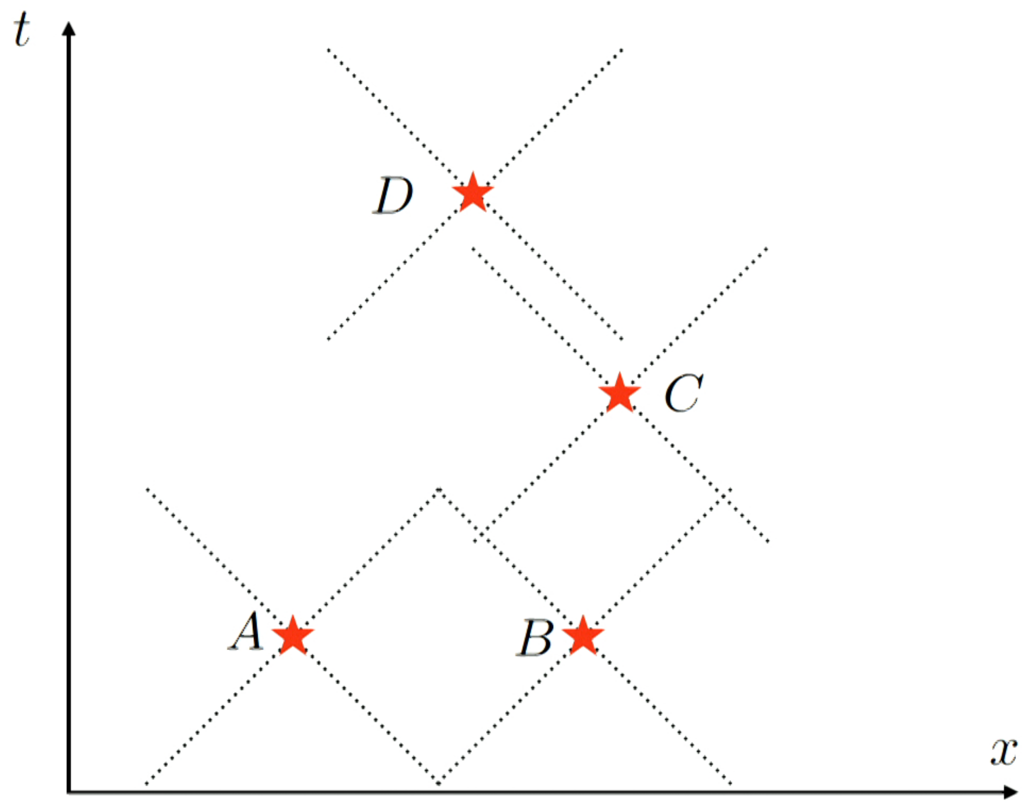
Outline

1. Events (introduction)
2. Gravitating quantum clocks (motivation)
3. Quantum clocks as temporal reference frames
4. Outlook

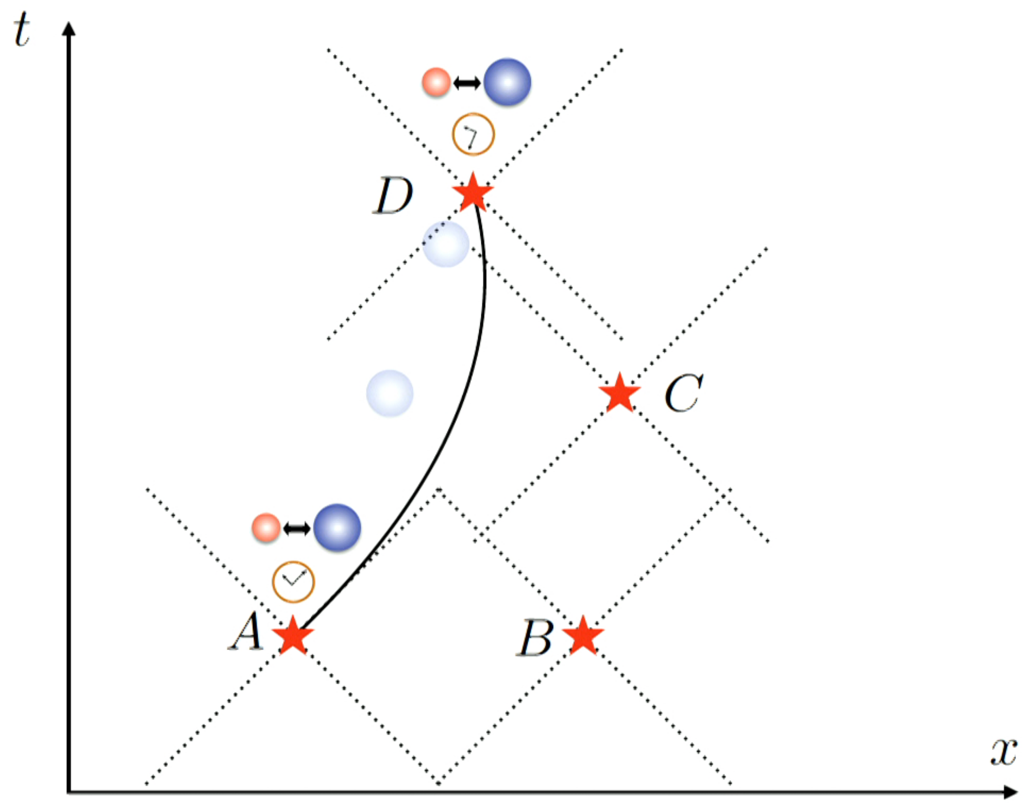
1.1 Relative localisation and causal order of events



1.1 Localisation and causal order of events



1.3 Clocks track time evolution and events



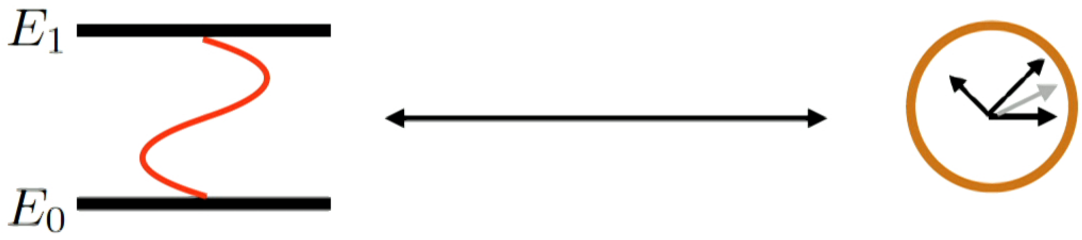
2. Gravitating quantum clocks
(motivation)

2.1 A simple clock model

$$|\psi_0\rangle = \frac{|E_0\rangle + |E_1\rangle}{\sqrt{2}}$$

$$t_\perp = \frac{\hbar\pi}{E_1 - E_0}$$

2.2 Gravitating clocks lead to a non-fixed metric background



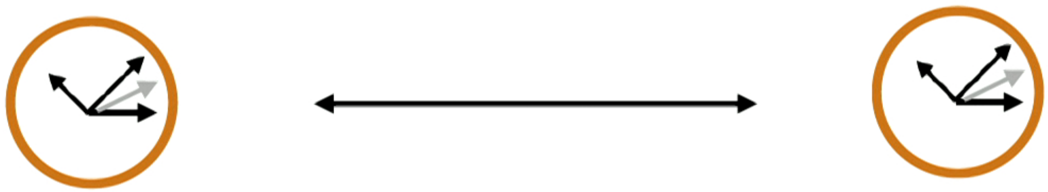
$$\Delta\Phi(x) = \frac{G(E_1 - E_0)}{c^4 x}$$

$$t_\perp \Delta t = \frac{\pi \hbar G t}{c^4 x}$$

ECR, F Giacomini, C Brukner, *PNAS* (2017)

2.3 Entanglement of Quantum clocks through gravity

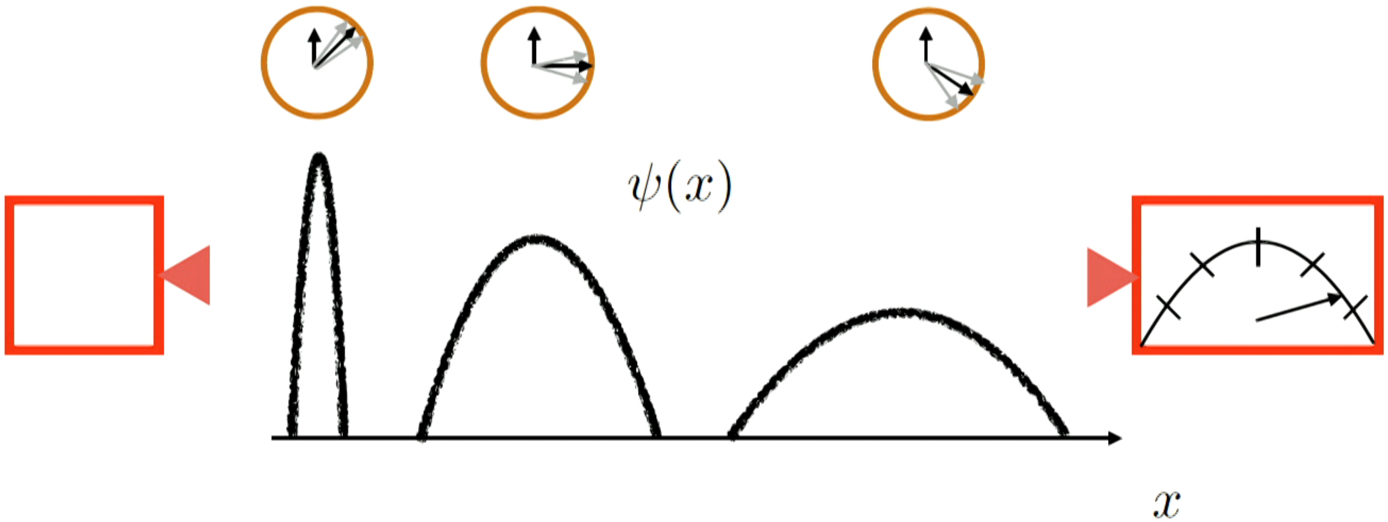
$$H = H_A + H_B - \frac{G}{c^4 x} H_A H_B$$



$$|\psi\rangle = \frac{1}{\sqrt{2}}|0\rangle \left[\frac{1}{\sqrt{2}}\left(|0\rangle + e^{-\frac{it}{\hbar}\Delta E}|1\rangle\right)\right]$$
$$+\frac{1}{\sqrt{2}}|1\rangle \left[\frac{1}{\sqrt{2}}\left(|0\rangle + e^{-\frac{it}{\hbar}\Delta E\left(1-\frac{G\Delta E}{c^4 x}\right)}|1\rangle\right)\right]$$

ECR, F Giacomini, C Brukner, *PNAS* (2017)

2.4 The general problem: gravitating quantum systems make the metric "fuzzy"



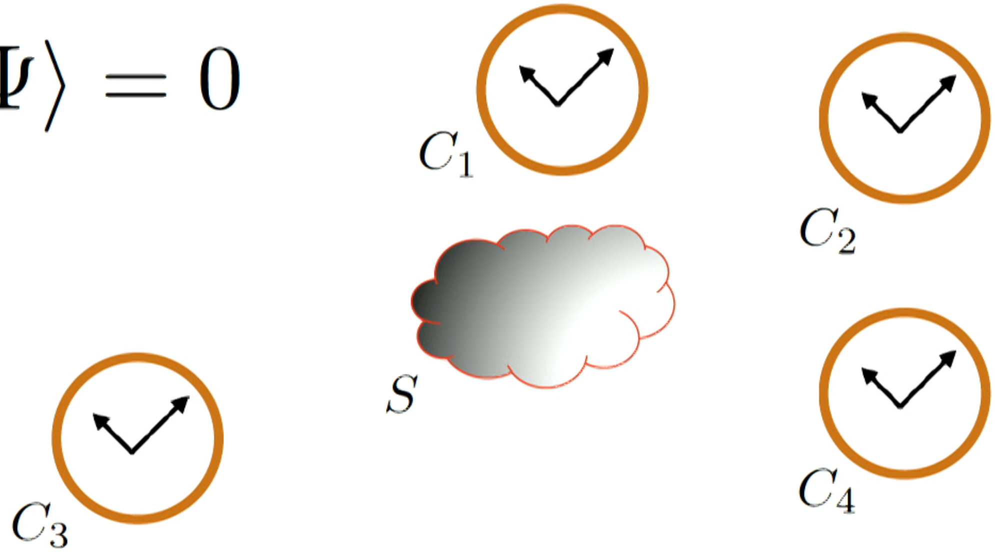
$$i\hbar \frac{\mathrm{d}|\psi\rangle}{\mathrm{d}t} = H|\psi\rangle$$

What is $\frac{\mathrm{d}}{\mathrm{d}t}$ **?**

3. Quantum clocks as temporal reference frames

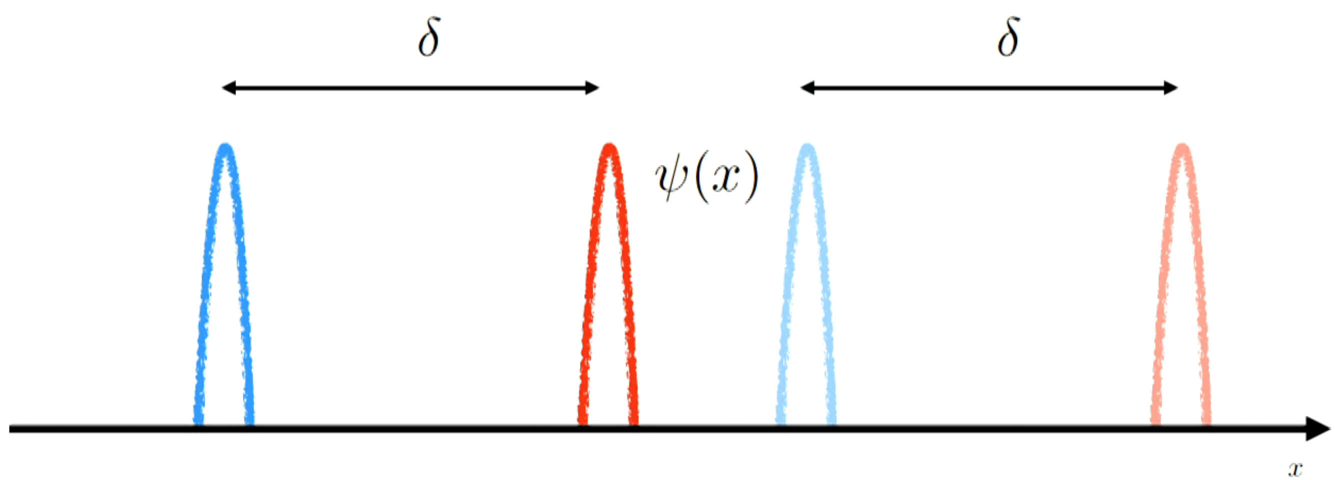
3.1 "Jumping" onto a (quantum) clock's reference frame?

$$\hat{\mathrm{C}}|\Psi\rangle = 0$$



$$|\Psi\rangle = \int \mathrm{d}\alpha\, \mathrm{e}^{-\mathrm{i}\alpha\hat{\mathrm{C}}}|\varphi\rangle$$

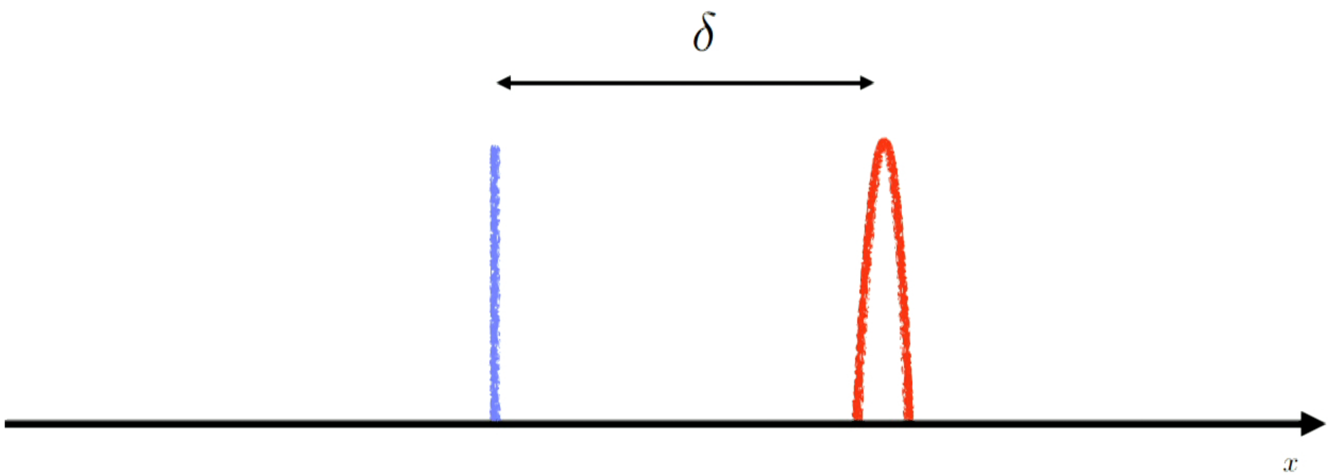
3.2 Analogy: quantum reference frames for space



$$|\Psi\rangle = \frac{1}{\sqrt{2}}|0\rangle|\delta\rangle + \frac{1}{\sqrt{2}}|1-\delta\rangle|1\rangle$$

F Giacomini, ECR, C Brukner, *Nat. Commun.* (2019)

3.2 Analogy: quantum reference frames for space

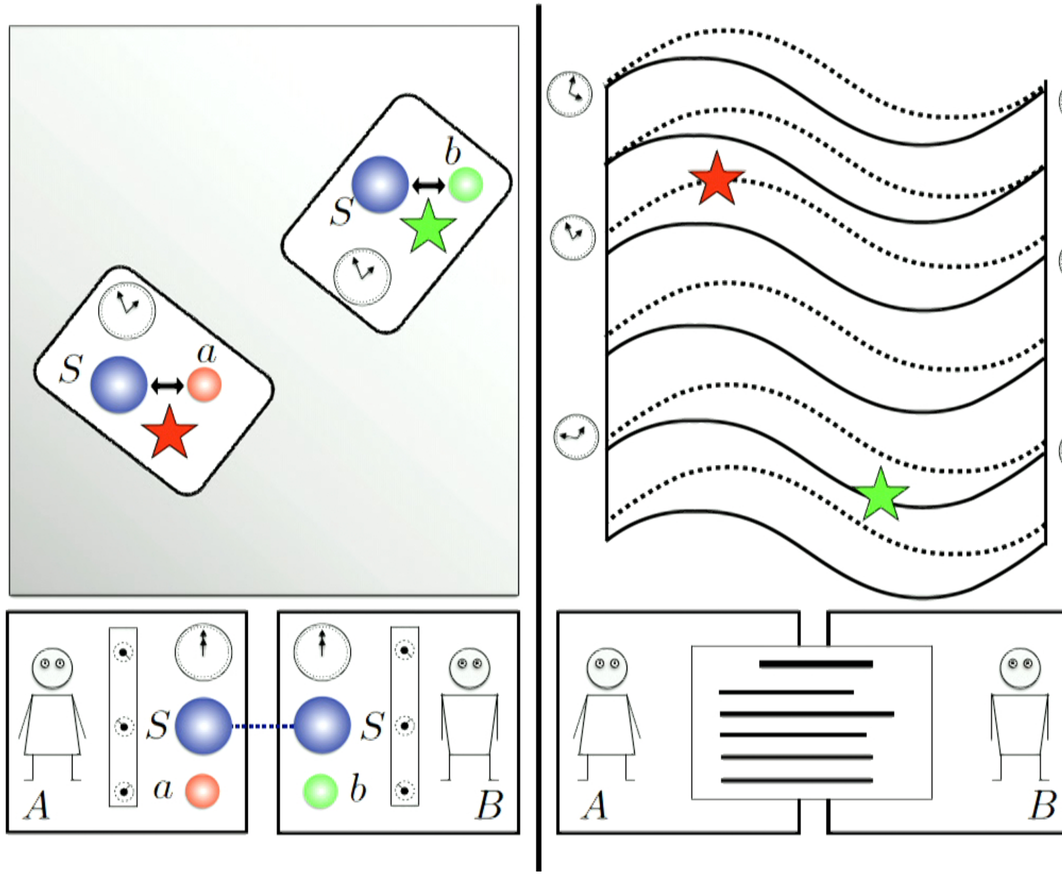


$$|\Psi\rangle = |\delta\rangle$$

F Giacomini, ECR, C Brukner, *Nat. Commun.* (2019)

3.3 Operational definition of events

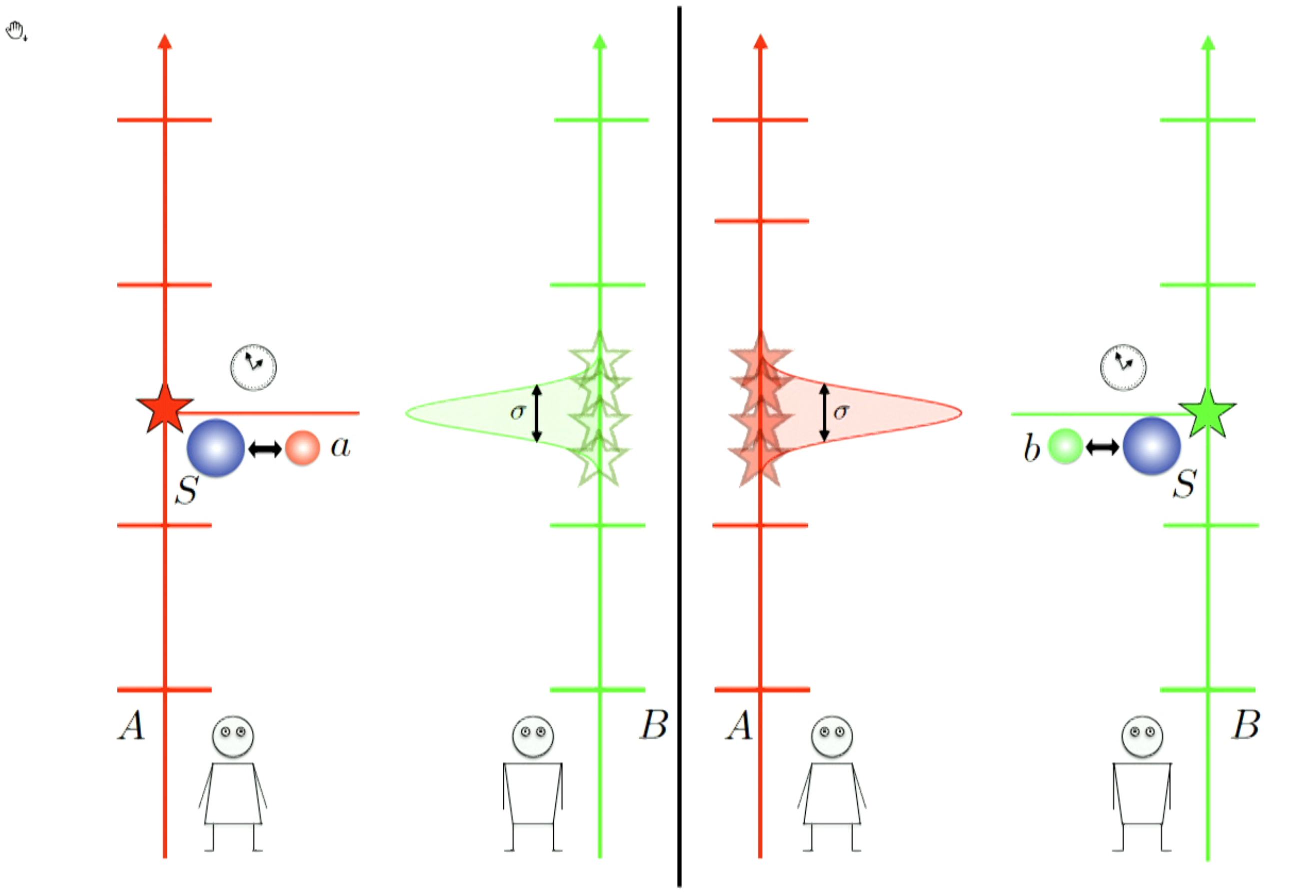
$$(\hat{H}_A + \hat{H}_B + \hat{f}_A(\hat{T}_A) + \hat{f}_B(\hat{T}_B))|\Psi\rangle = 0$$



3.4 The simplest case: non-interacting clocks

$$(\hat{H}_A + \hat{H}_B + \delta(\hat{T}_A - t^*_A)\hat{K}^{(A)} + \delta(\hat{T}_B - t^*_B)\hat{K}^{(B)}|\Psi\rangle = 0$$

3.4 The simplest case: non-interacting clocks

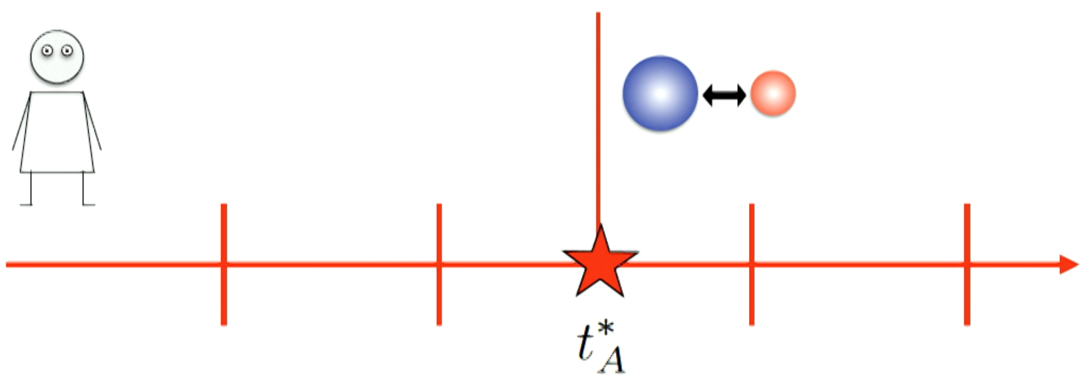


3.5 Entanglement of quantum clocks through gravity (once more)

$$\hat{U}_{\bar{C}} = \mathrm{e}^{-\mathrm{i}\tau_C(\hat{H}_A+\hat{H}_B+\lambda\hat{H}_A\hat{H}_B)}\,\mathrm{T}\,\mathrm{e}^{-\mathrm{i}\int_0^{\tau_C}\mathrm{d}s(1+\lambda\hat{H}_B)\,\hat{f}(s(1+\lambda\hat{H}_B)+\hat{T}_A)}$$

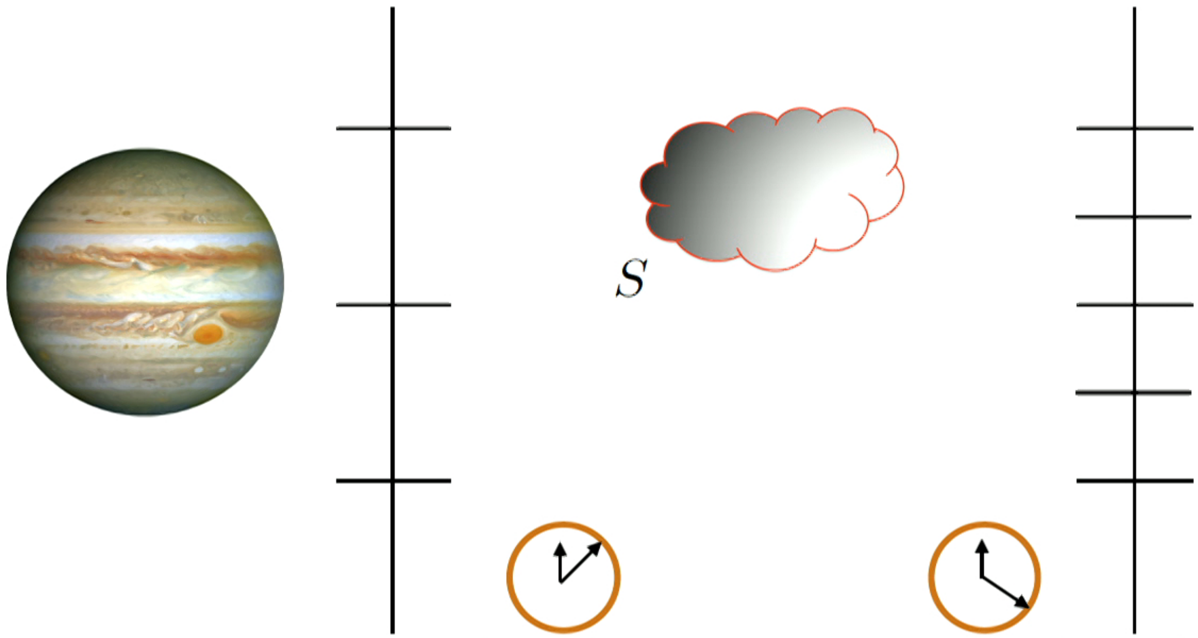
3.5 Entanglement of quantum clocks through gravity (once more)

$$\hat{U}_{\bar{A}} = \mathrm{T}\,\mathrm{e}^{-\mathrm{i}\int_0^{\tau_A} \mathrm{d}s\,\left(\frac{\hat{H}_B+\hat{H}_C}{1+\lambda\hat{H}_B}+\hat{f}(s)\right)}$$



3.6 Gravitational quantum switch

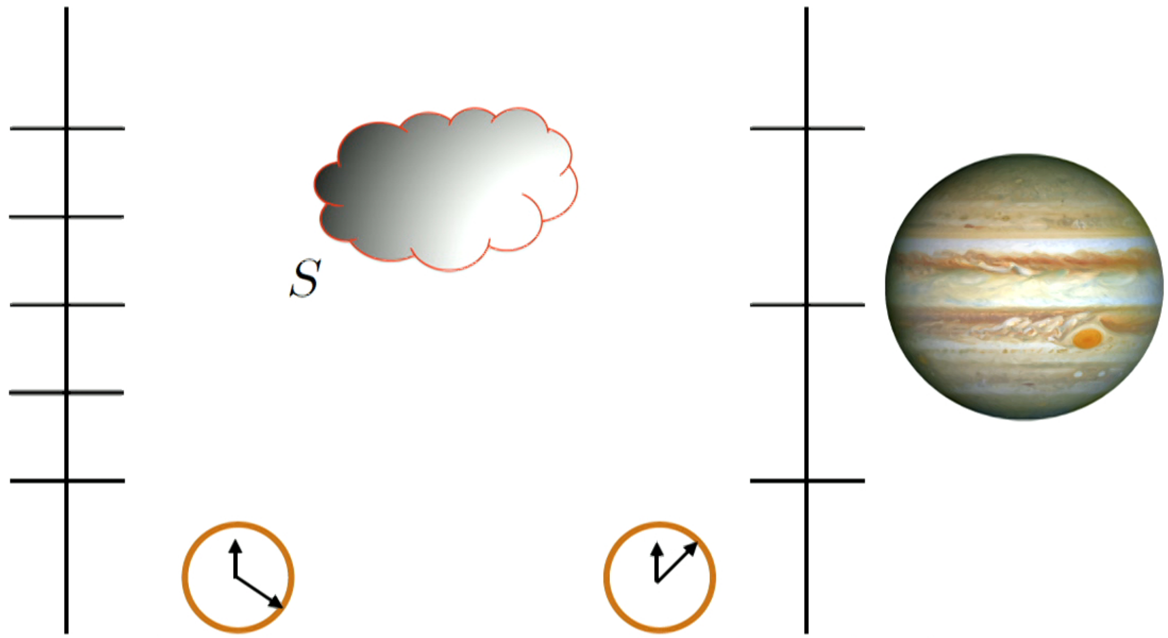
$$\left(\sum_I \hat{H}_I(1+\hat{\Phi}_I) + \sum_I \hat{f}_I(\hat{T}_I)(1+\hat{\Phi}_I)\right)|\Psi\rangle = 0$$



M.Zych, F. Costa, I. Pikovski, C. Brukner https://arxiv.org/abs/1708.00248v2

3.6 Gravitational quantum switch

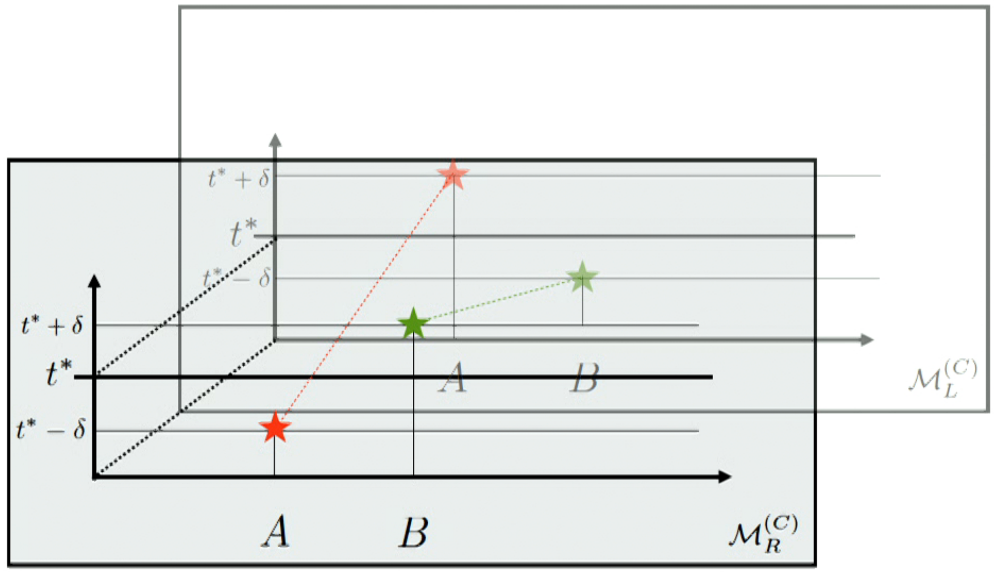
$$\left(\sum_I \hat{H}_I (1 + \hat{\Phi}_I) + \sum_I \hat{f}_I(\hat{T}_I)(1 + \hat{\Phi}_I) \right) |\Psi\rangle = 0$$



M.Zych, F. Costa, I. Pikovski, C. Brukner https://arxiv.org/abs/1708.00248v2

3.6 Gravitational quantum switch

$$|\Psi\rangle = \int \mathrm{d}t\, |t\rangle_C \otimes \left(U_A^{aS} U_B^{bS} |\phi\rangle |L\rangle_M + U_B^{bS} U_A^{aS} |\psi\rangle |R\rangle_M\right)$$



G Chiribella, GM D'Ariano, P Perinotti, B Valiron (2009)

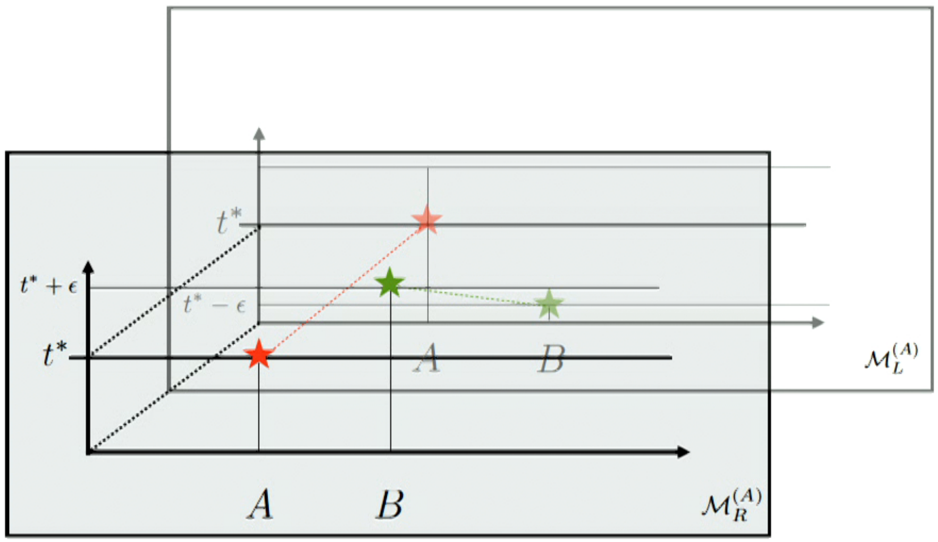
4. Outlook

- **Beyond superpositions of semiclassical states?**
- **Inclusion of spatial quantum reference frames?**
- **Connection with indefinite causal structures via causal reference frames?**

F Giacomini, ECR, C Brukner, *Nat. Commun.* (2019)
O Oreshkov, *arXiv:1801.07594* (2018)
P Allard Guérin, C Brukner *NJP* (2018)

3.6 Gravitational quantum switch

$$|\Psi\rangle = \int \mathrm{d}t\, |t\rangle_A \otimes \left(U_A^{aS}(t-t^*)U_B^{bS}|\phi\rangle|L\rangle_M + U_B^{bS}U^{aS}(t-t^*)_A|\psi\rangle|R\rangle_M\right)$$



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