Title: Bell's theorem for temporal order

Date: Nov 15, 2017 02:00 PM

URL: http://pirsa.org/17110045

Abstract: In general relativity causal relations between any pair of events is uniquely determined by locally predefined variables - the distribution of matter-energy degrees of freedom in the events' past light-cone. Under the assumption of locally predefined causal order, agents performing freely chosen local operations on an initially local quantum state cannot violate Bell inequalities. However, superposition of massive objects can effectively lead to "entanglement" in the temporal order between groups of local operations, enabling the violation of the inequalities. This shows that temporal orders between events can be "indefinite" in non-classical space-times.

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Bell's theorem for temporal order

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arXiv:1708.00248

Perimeter Institute, November 15th, 2017

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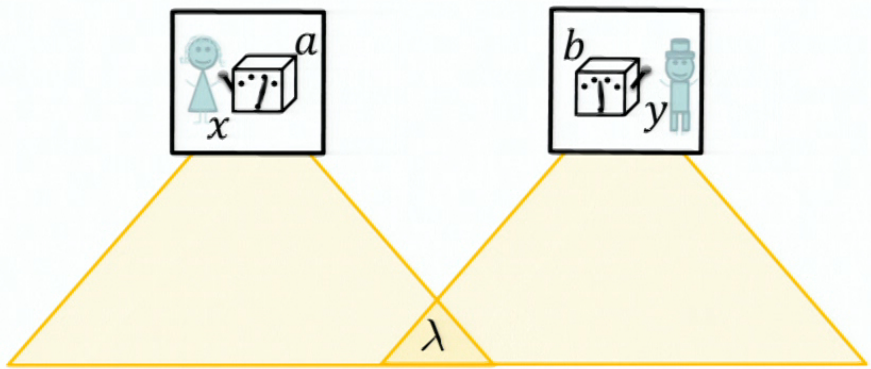
- Assumptions behind Bell‘s theorem for temporal order
  (within the framework of generalized probabilistic theories)
- Quantum violation of Bell‘s inequalities
- Conclusions and Outlook

Bell's theorem



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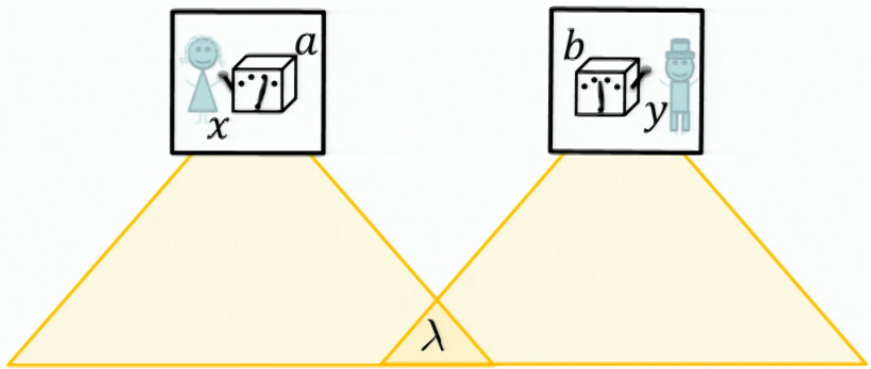
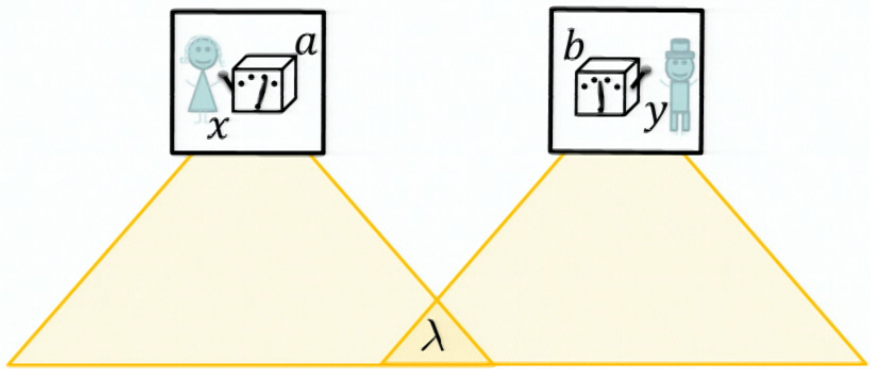


$$p_{LC}(a,b|x,y) := \int d\lambda \rho(\lambda) p(a|x,\lambda) p(b|y,\lambda)$$

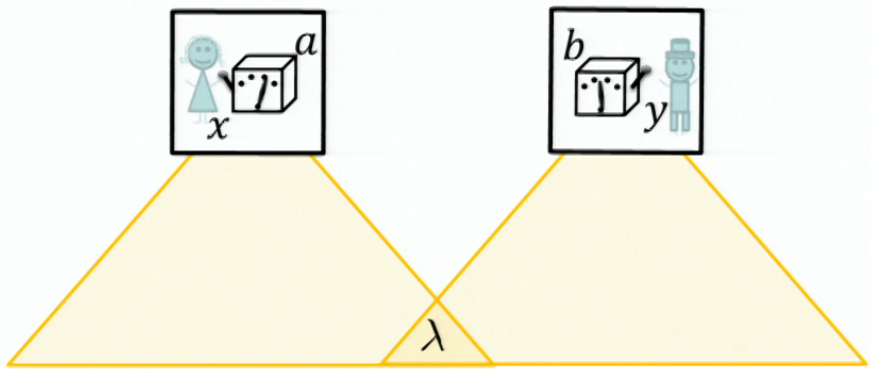
Bell's theorem



$$p_{LC}(a,b|x,y) := \int d\lambda \rho(\lambda) p(a|x,\lambda) p(b|y,\lambda) \neq p_Q(a,b|x,y)$$

Quantum physics violates Bell's "local causality"

Bell's theorem



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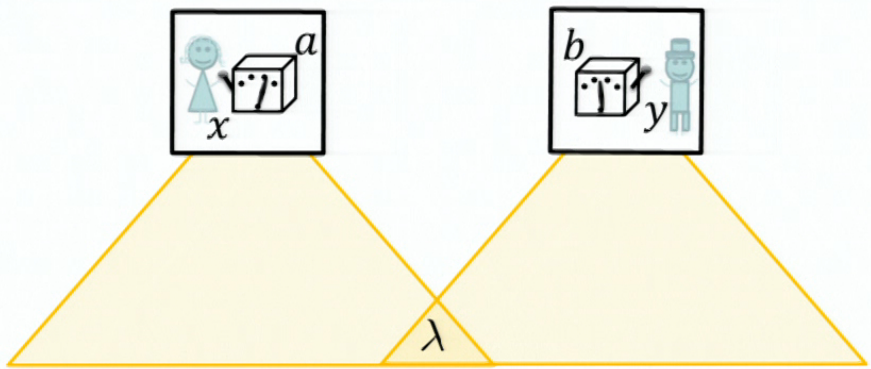

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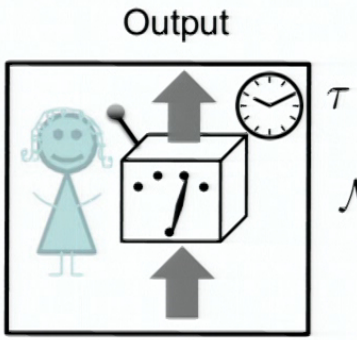
Violation of Bell's inequalities as a **theory-independent** tool for demonstrating „nonclassicality"

Proven for spin, polarization, energy, momenta … temporal order?

Notion of an “event”

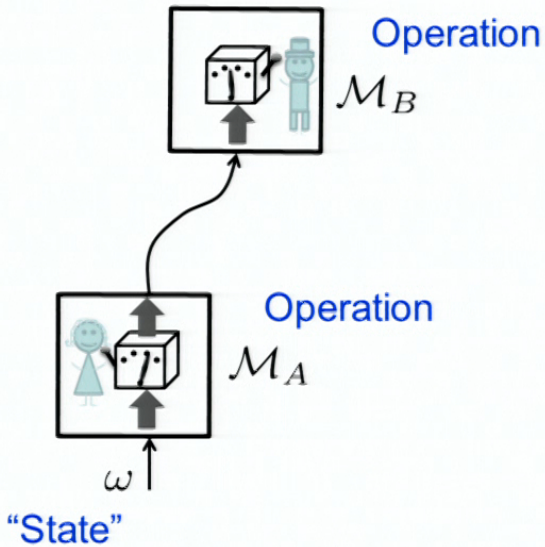


τ

$$\mathcal{M}_a \in \{\mathcal{M}_a\}_{a=1}^{d}$$

- „Event“ = an operation $\mathcal{M}_a$ performed at local time τ
- „Laboratory“ = Label that includes reference frame information
- „Local time“ = An abstraction of the entire internal state of the temporal reference frame

Classical causal order



"$\mathcal{M}_A$ before $\mathcal{M}_B$"

$$\mathcal{M}_B \circ \mathcal{M}_A(\omega) = \mathcal{M}_B(\mathcal{M}_A(\omega))$$

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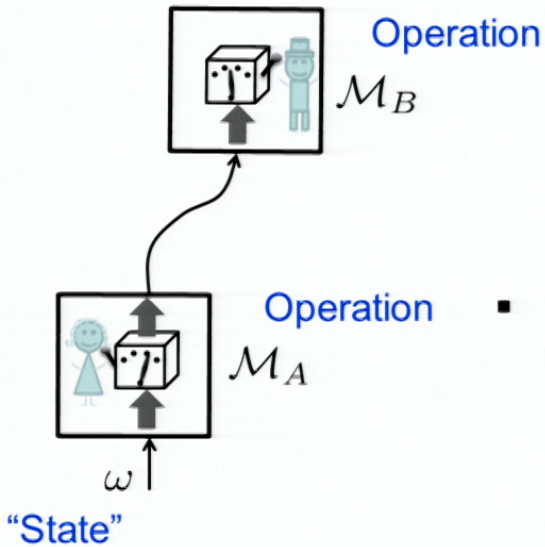

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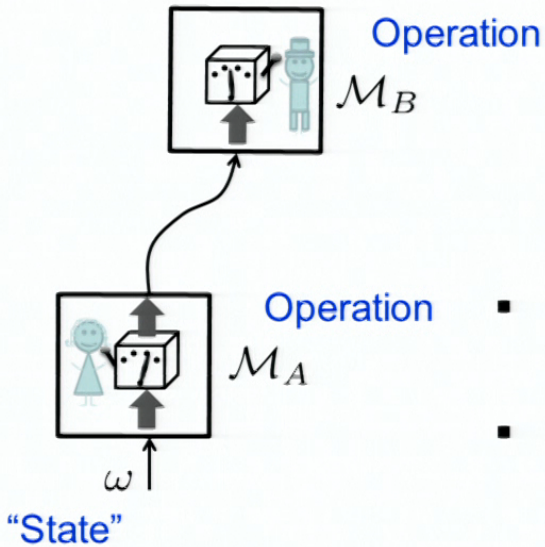

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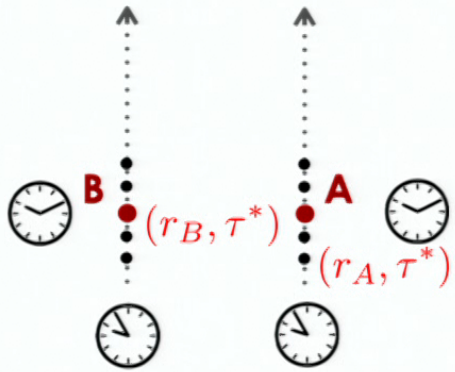
- **Theory-independent** notion of a classical (=definite) causal order
- **Operational definition**: classical causal order implies **one-way signaling** "from the past to the future"

GR: Dynamical causal structure



The events A and B are space-like separated.

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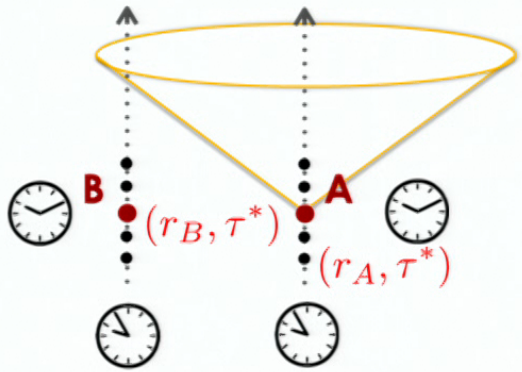

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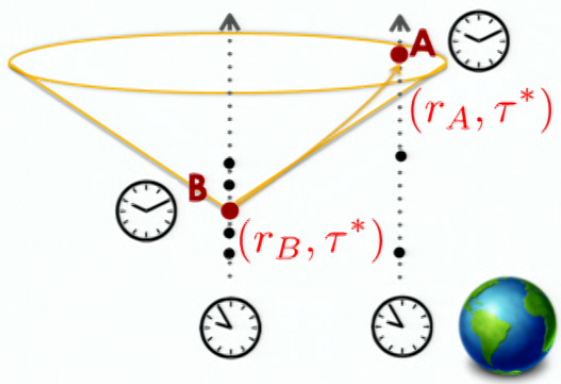

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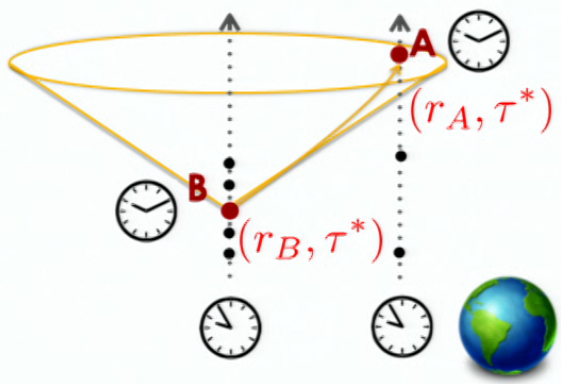

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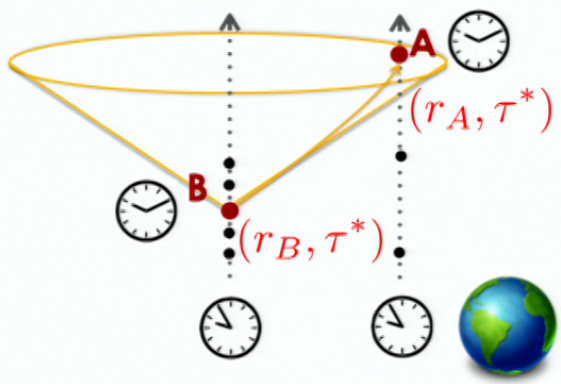

Proper times at A and B

$$\tau_A = \sqrt{\frac{g_{00}(r_A)}{g_{00}(r_B)}}\tau_B$$

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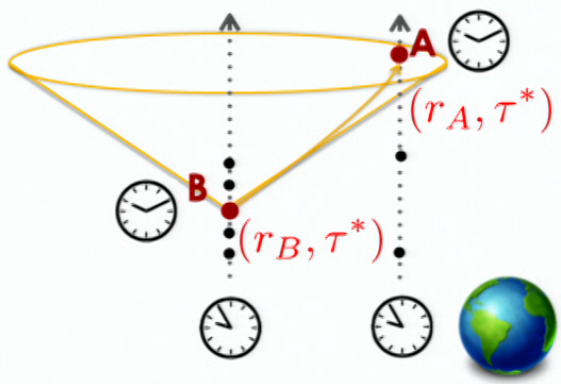

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$$\tau_A = \sqrt{\frac{g_{00}(r_A)}{g_{00}(r_B)}}\tau_B$$

Coordinate time of photon propagation between A and B

$$T_c = \frac{1}{c}\int_{r_B}^{r_A} dr' \sqrt{-\frac{g_{rr}(r')}{g_{00}(r')}}$$

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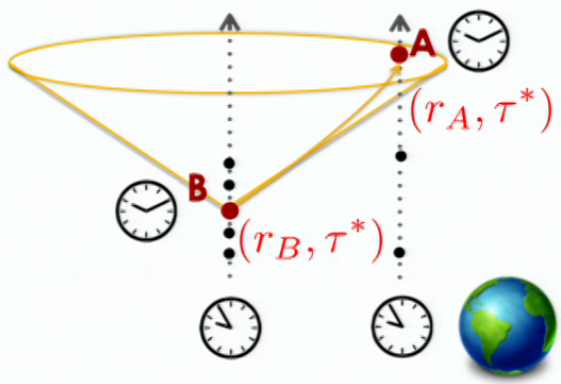

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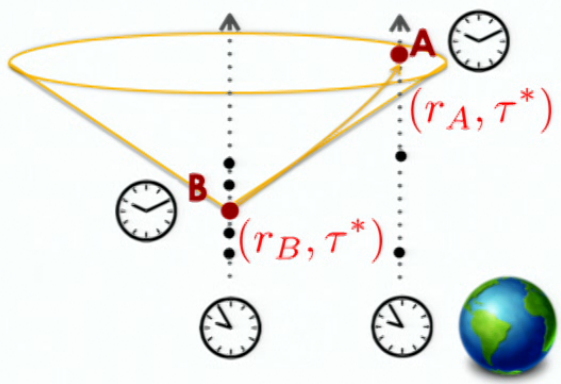

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Event at B measured by B

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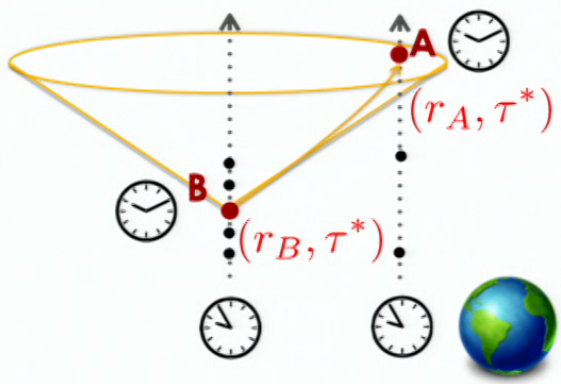

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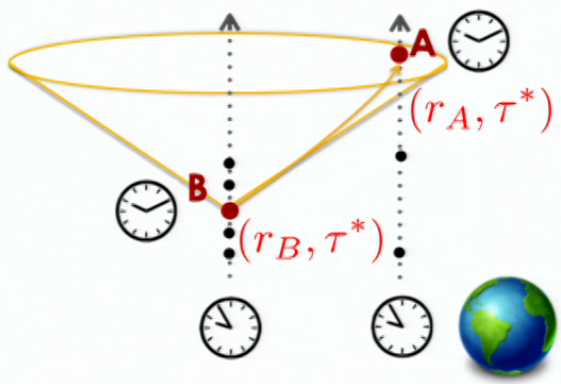

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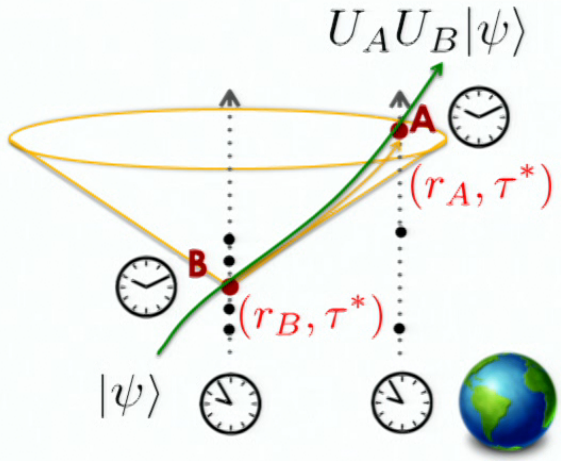
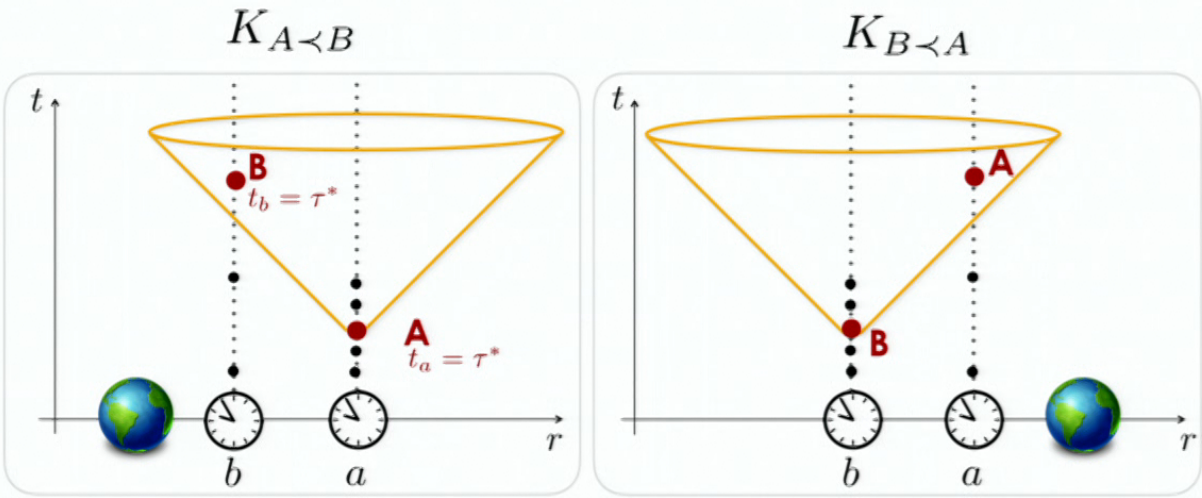


Mass configuration $K_{B \prec A}$

Channel from B to A:

$$U_A U_B |\psi\rangle$$

Dynamical causal structure



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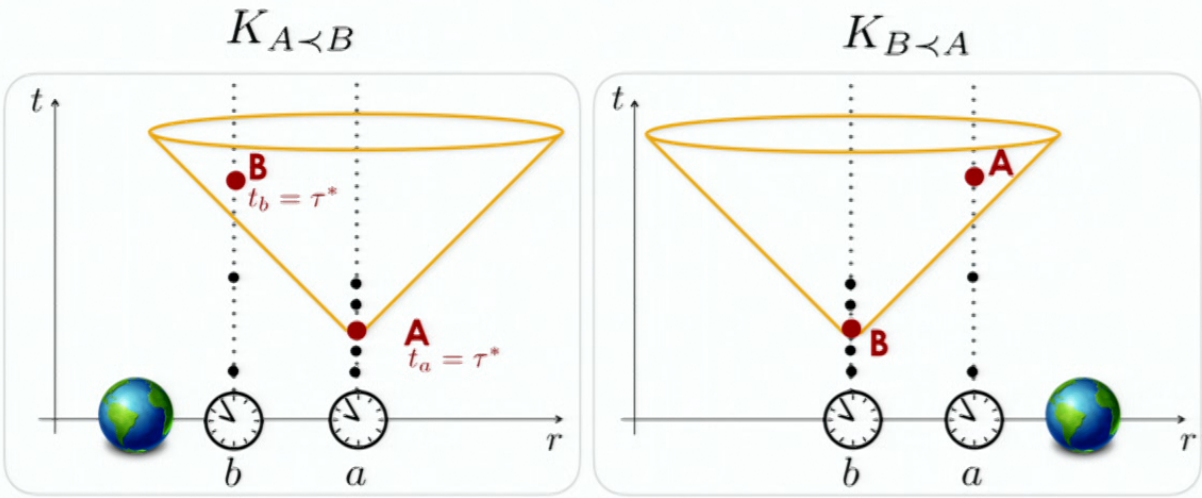
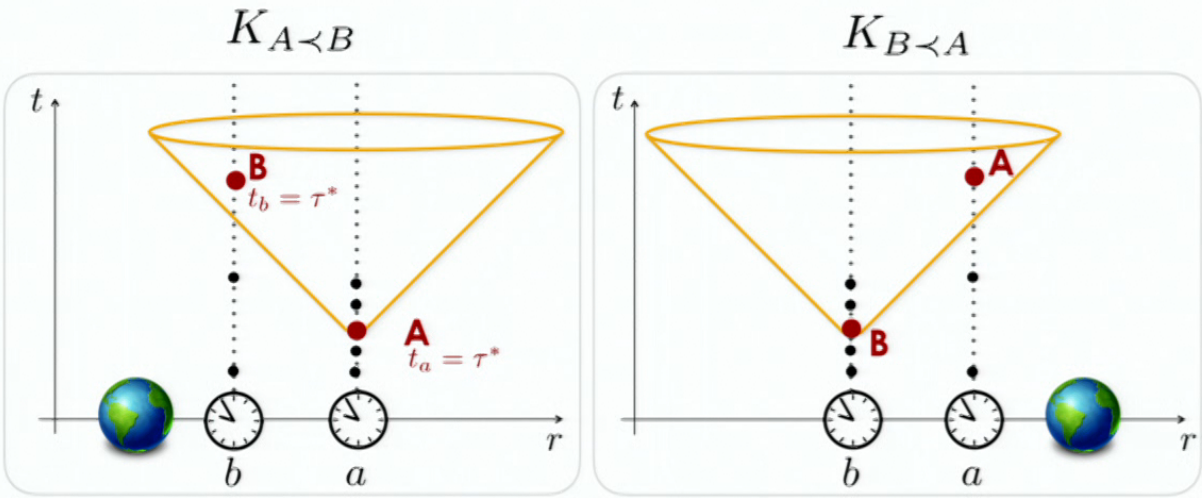


- Causal structure depends on the stress-energy tensor of the matter degrees of freedom in the causal past of the events

Dynamical causal structure



- Causal structure depends on the stress-energy tensor of the matter degrees of freedom in the causal past of the events
- The order between the events is swapped in **all** reference frames

Quantum controlled temporal order

(gravitational quantum switch)

Assumptions:

1) Macroscopically distinguishable states of physical systems can be assigned orthogonal quantum states

2) Gravitational time dilation in a semiclassical limit reduces to that predicted by general relativity

3) The quantum superposition principle holds regardless of the mass of the superposed systems

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Due to 3) the state $\frac{1}{\sqrt{2}}(|K_{A\prec B}\rangle + |K_{B\prec A}\rangle)$ is possible.

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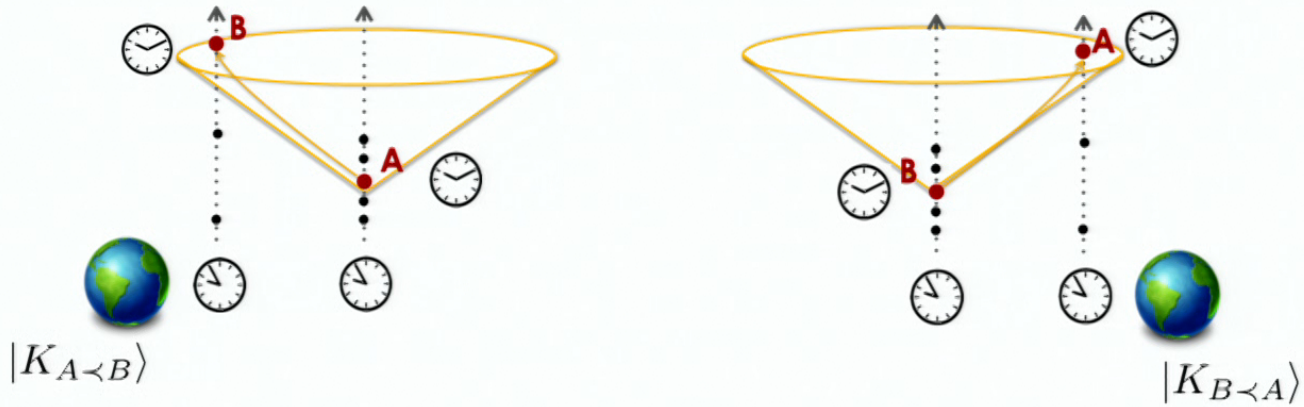

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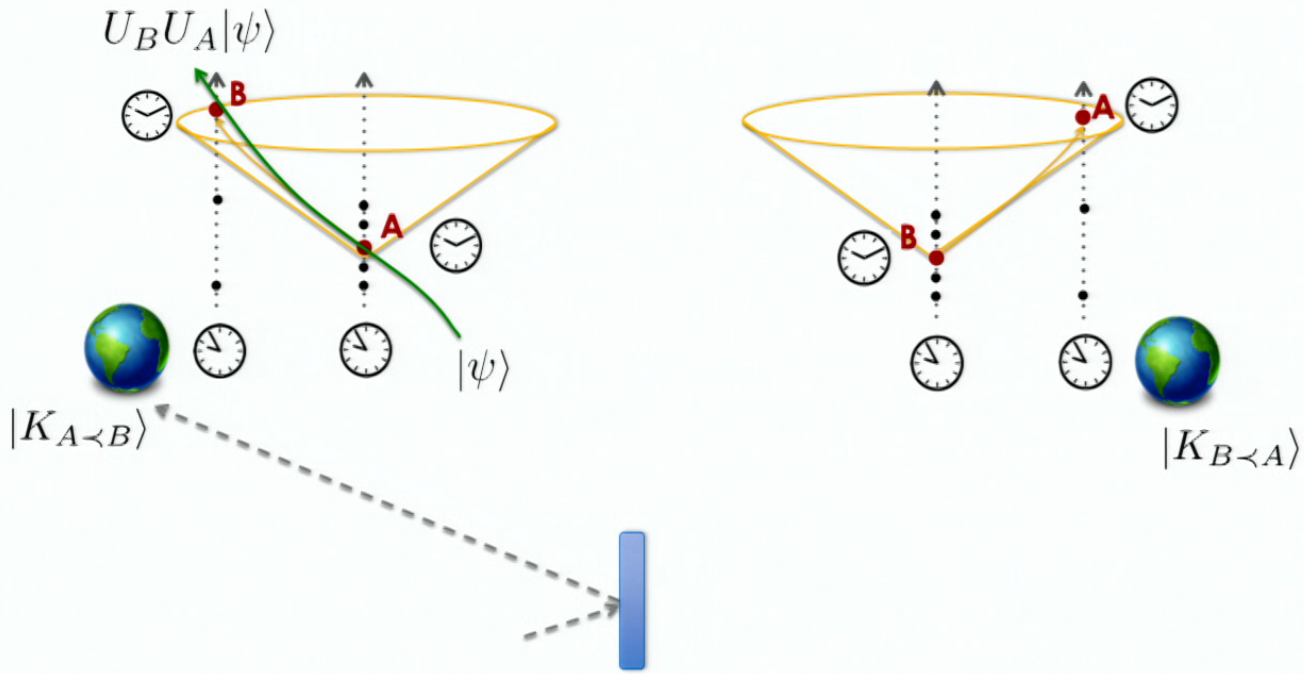

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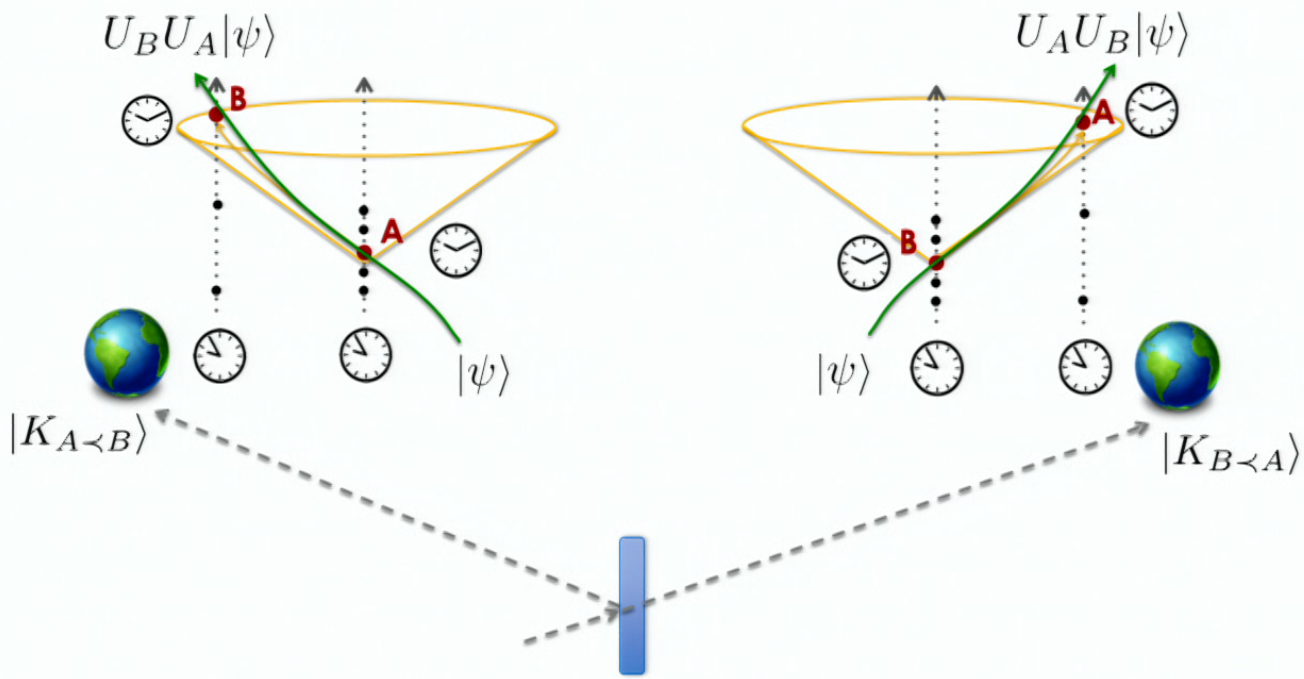

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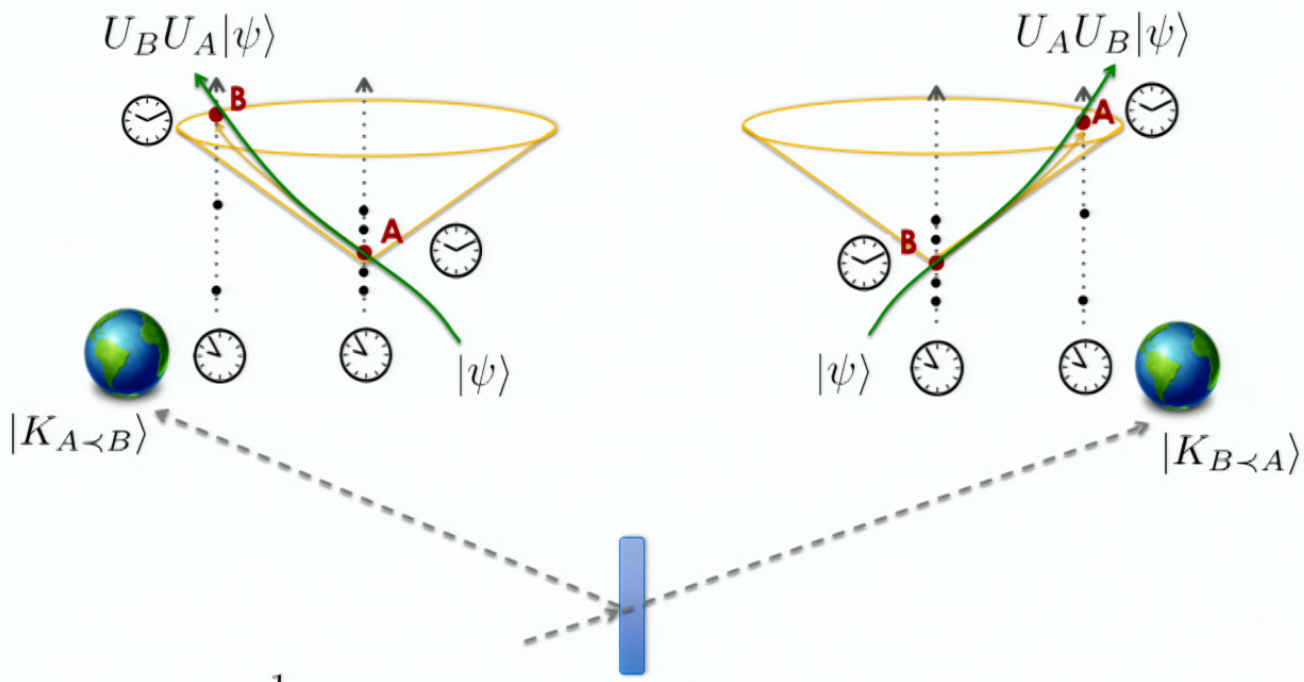

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Generalized probabilistic theories (GPTs)

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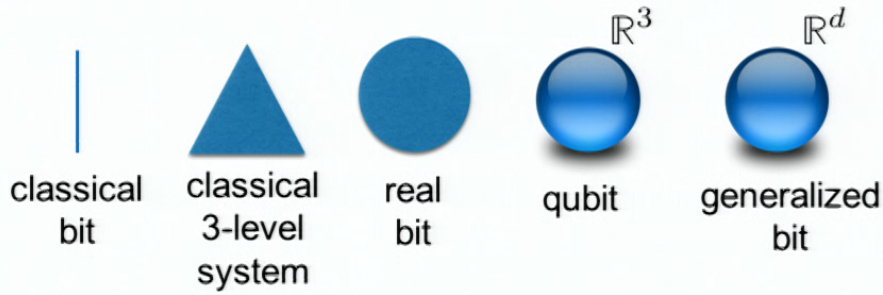
State space: $\omega \in \Omega$



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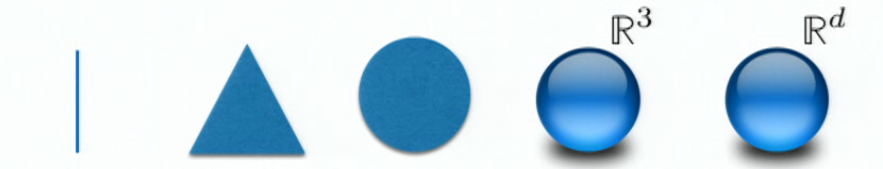

classical bit | classical 3-level system | real bit | qubit | generalized bit

Joint state space: $\omega_{AB} \in \Omega_{AB}$ $\quad \omega_{AB} = (\omega_A, \omega_B, \hat{T}, \lambda)$

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Order of transformations: $\mathcal{M}_n \circ \ \dots \ \circ \mathcal{M}_2 \circ \mathcal{M}_1(\omega)$

"$\mathcal{M}_1$ before $\mathcal{M}_2$ ... before ... $\mathcal{M}_n$"

Local transformations in GPTs

Local transformations (LTs): $(\mathcal{M}_A, \mathcal{M}_B)(\omega_{AB}) = (\mathcal{M}_A(\omega_A), \mathcal{M}_B(\omega_B), \hat{T}', \lambda')$

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Example of qubits (LTs are $SO(3)$ rotations): $\hat{T}' = \hat{M}_A \hat{T} \hat{M}_B^T$

Local transformations in GPTs

Local transformations (LTs): $(\mathcal{M}_A, \mathcal{M}_B)(\omega_{AB}) = (\mathcal{M}_A(\omega_A), \mathcal{M}_B(\omega_B), \hat{T}', \lambda')$

- LTs are reversible and form a group
- LTs obey the no-signalling condition
- $\mathcal{M}_A$ and $\mathcal{M}_B$ commute with each other; there is one corr. tensor $\hat{T}'$
- **The degree of violation of Bell's inequalities cannot increase under LTs** (by definition as it is optimized over local transformations)

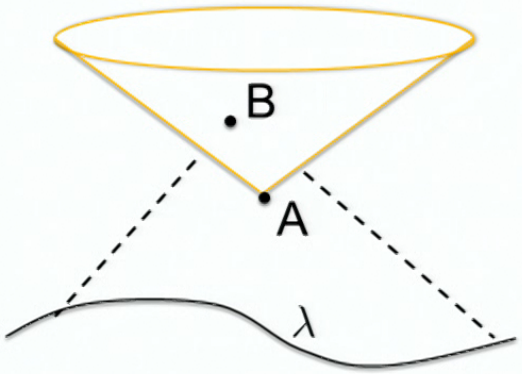
Example of qubits (LTs are $SO(3)$ rotations): $\hat{T}' = \hat{M}_A \hat{T} \hat{M}_B^T$

Horodecki's criterion for violation of the CHSH inequality:

$$\mathrm{diag}(\hat{T}') = \mathrm{diag}(\hat{T}) = (T_{11}, T_{22}, T_{33}),\ T_{11} \geq T_{22} \geq T_{33}$$

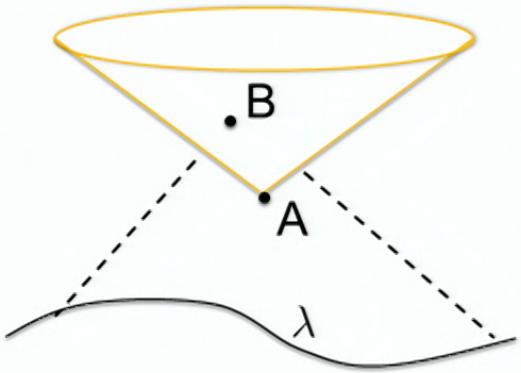
$$\langle \text{CHSH operator} \rangle = 2\sqrt{T_{11}^2 + T_{22}^2}$$

Classical temporal order



Definition: A set of events is classically ordered if, for each pair of events A and B, there exist a space-like surface and a λ variable defined on it that determines the causal relation between A and B: either $A \preceq B$, or $B \preceq A$ or $A \parallel B$.

Classical temporal order



Classical order can be **dynamical** and **stochastic.**

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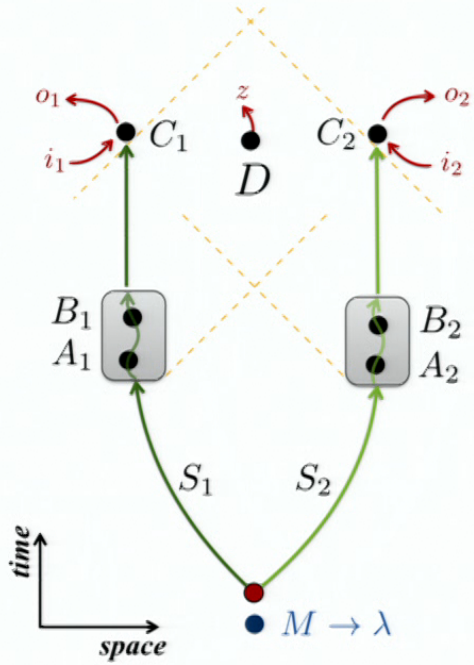
No-go theorem: No states, set of transformations and measurements which obey assumptions 1.-4. can result in violation of Bell's inequalities.

Proof



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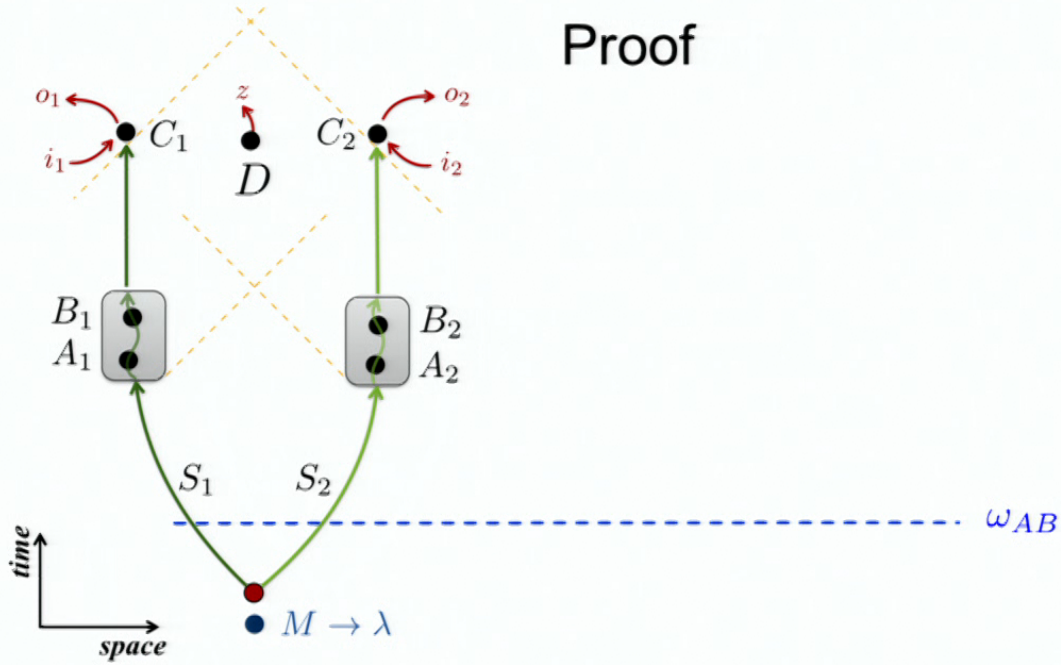
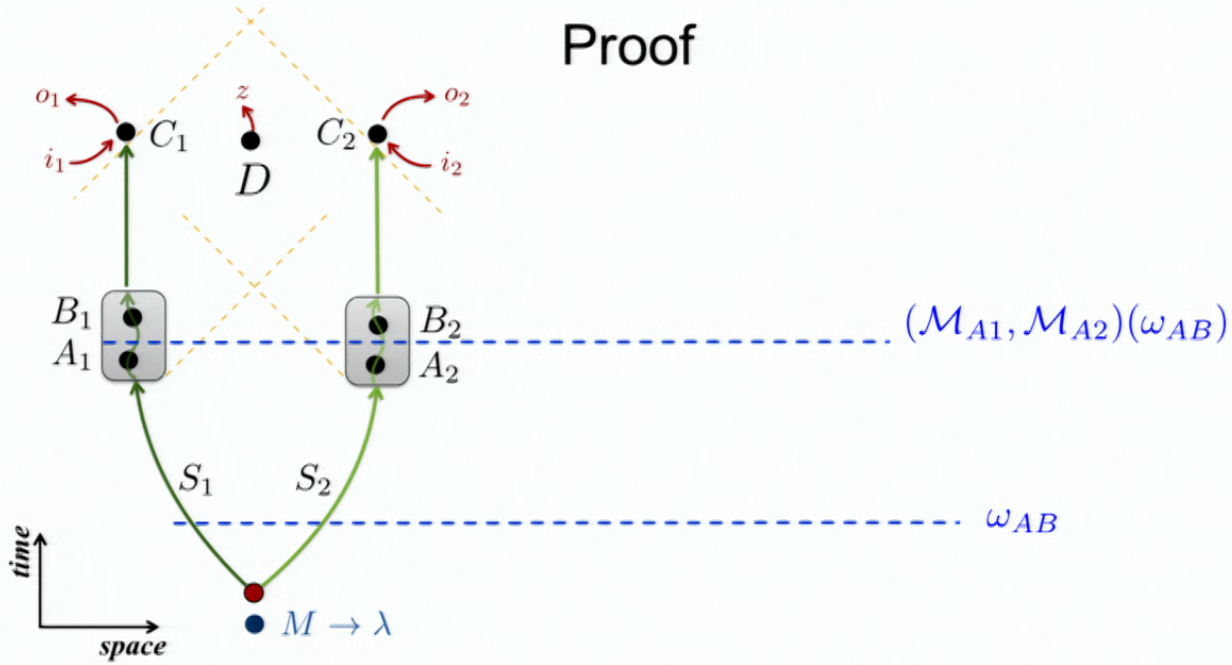


Local state + free choice: $$p(a,b|x,y,\omega_{AB}) = \int d\lambda \rho(\lambda) p(a|x,\lambda,\omega_{AB}) p(b|y,\lambda,\omega_{AB})$$

Proof



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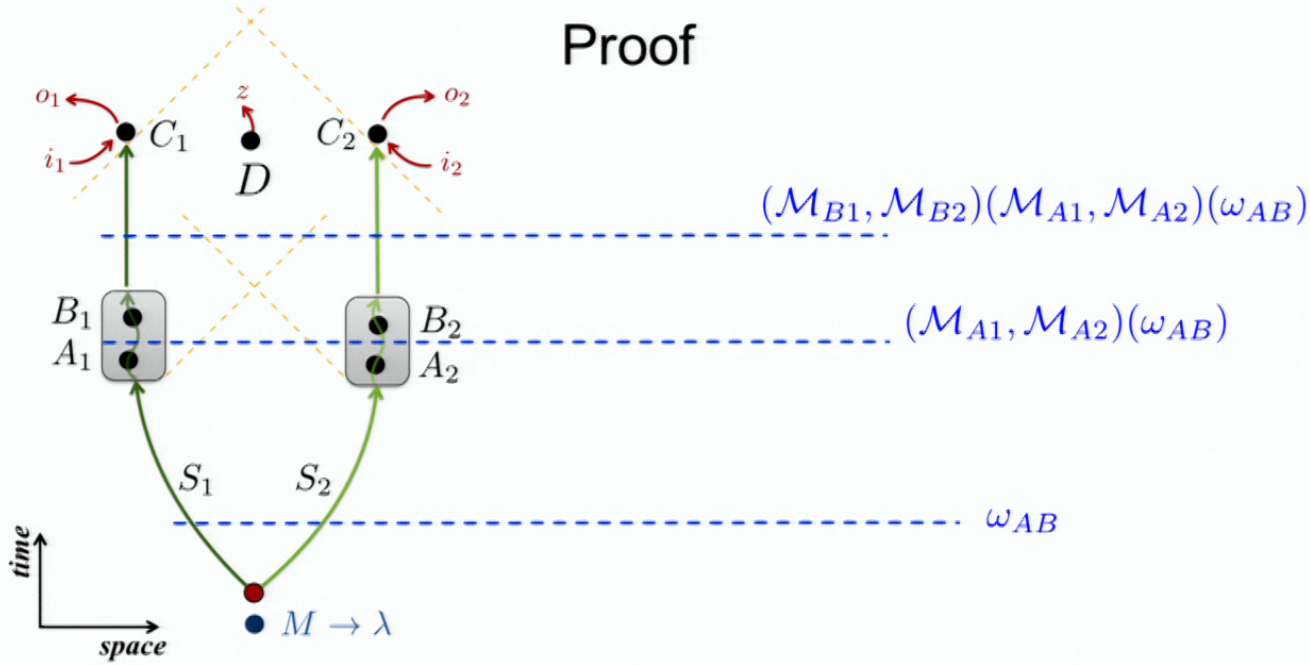

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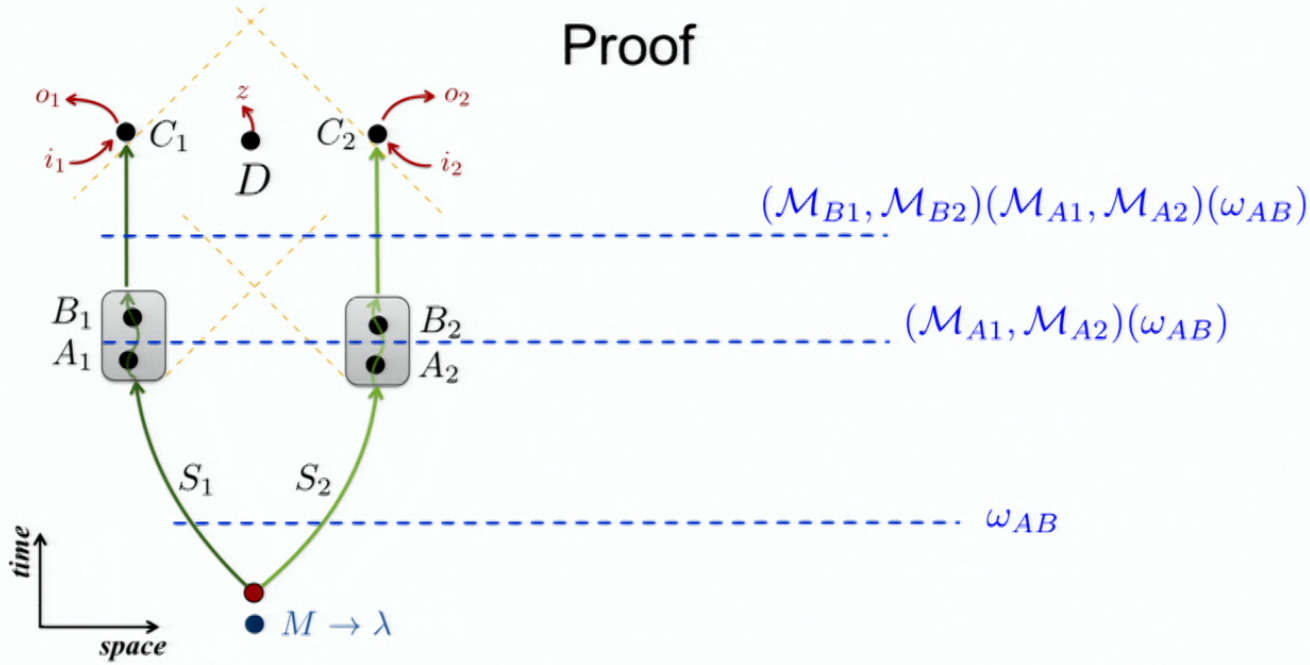

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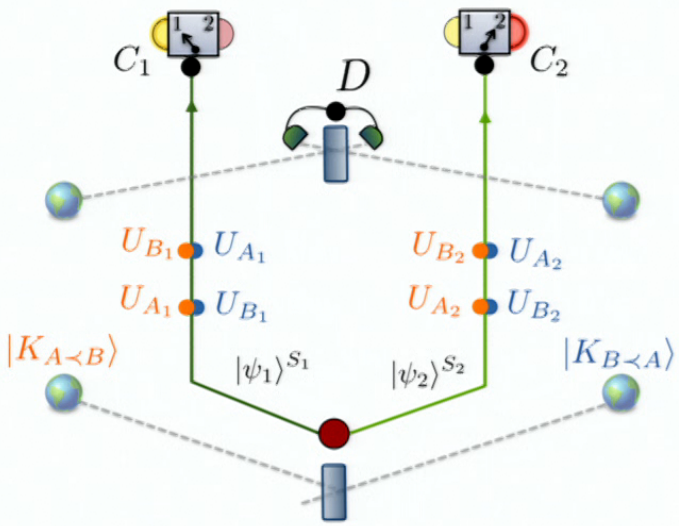
$$\omega'_{AB} = (\mathcal{M}_{B1} \circ \mathcal{M}_{A1}, \mathcal{M}_{B2} \circ \mathcal{M}_{A2})(\omega_{AB})$$
$$= (\mathcal{M}_{B1}, \mathcal{M}_{B2})(\mathcal{M}_{A1}, \mathcal{M}_{A2})(\omega_{AB}))$$

Quantum violation



Mass configuration:

$$\frac{1}{\sqrt{2}}(|K_{A\prec B}\rangle + |K_{B\prec A}\rangle)$$

System:

$$|\psi_1\rangle|\psi_2\rangle$$

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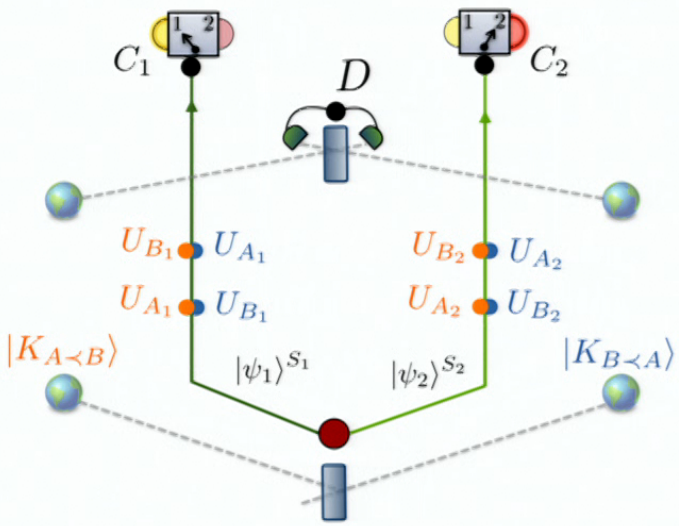

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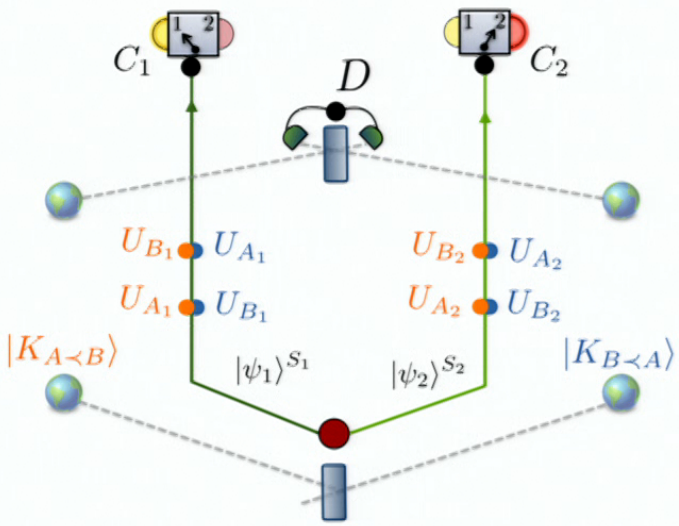

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D measures in basis: $|\pm\rangle = \frac{1}{\sqrt{2}}(|K_{A\prec B}\rangle \pm |K_{B\prec A}\rangle)$

$$\frac{1}{\sqrt{2}}(U_{B_1}U_{A_1}|\psi_1\rangle U_{B_2}U_{A_2}|\psi_2\rangle \pm U_{A_1}U_{B_1}|\psi_1\rangle U_{A_2}U_{B_2}|\psi_2\rangle)$$

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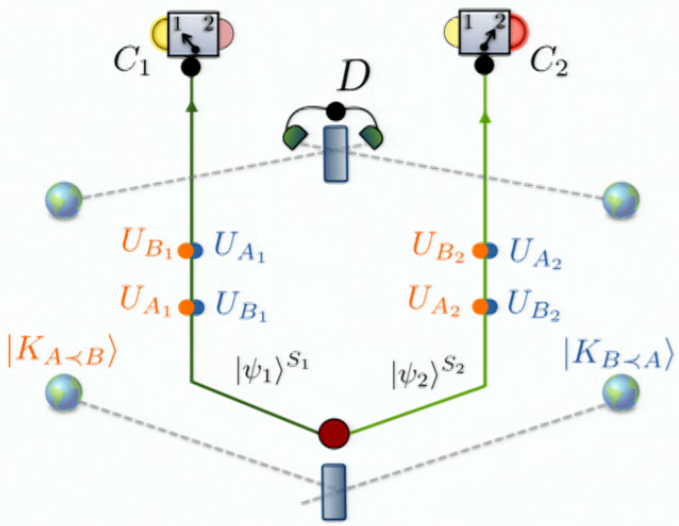


Choice of unitaries:

$$U_{A_1} = U_{A_2} = \frac{\mathbb{1} + i\sigma_x}{\sqrt{2}}$$

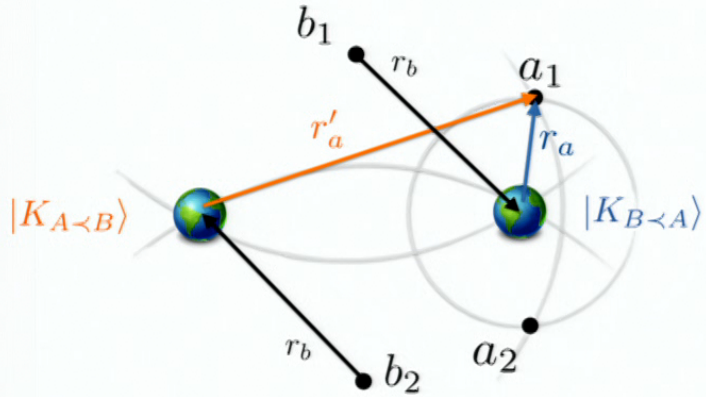
$$U_{B_1} = U_{B_2} = \sigma_z$$

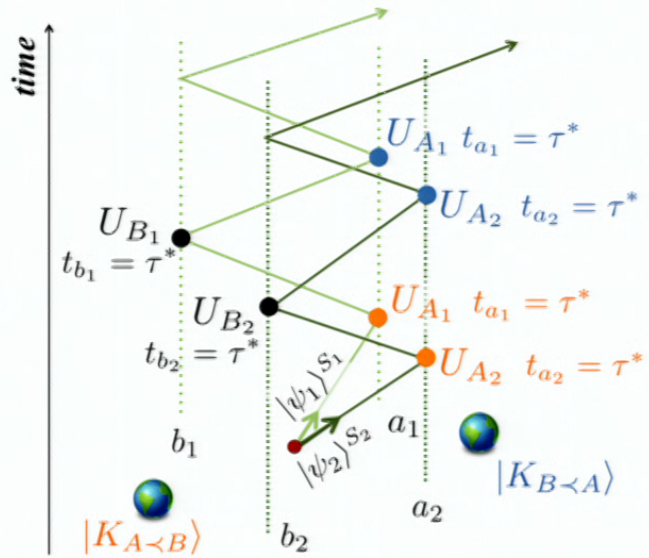
$$\frac{1}{\sqrt{2}}(U_{B_1}U_{A_1}|\psi_1\rangle U_{B_2}U_{A_2}|\psi_2\rangle \pm U_{A_1}U_{B_1}|\psi_1\rangle U_{A_2}U_{B_2}|\psi_2\rangle)$$

$$= \frac{1}{\sqrt{2}}(|x+\rangle|x+\rangle \pm |x-\rangle|x-\rangle)$$

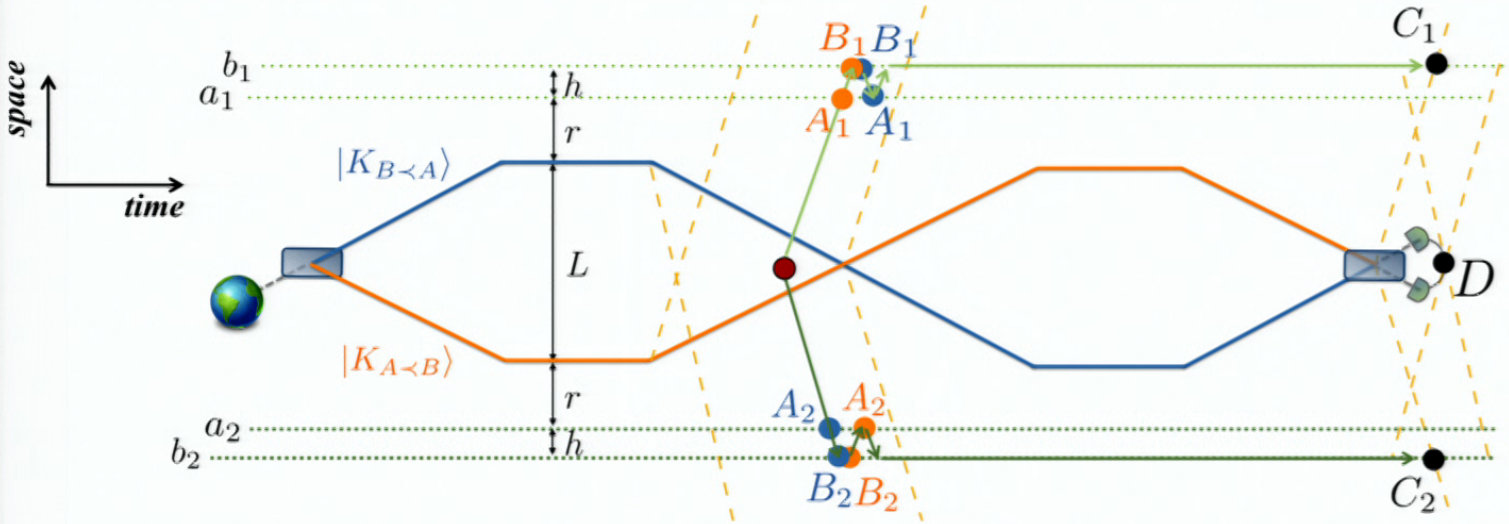
With settings $C_1^0 = \frac{\sigma_y - \sigma_z}{\sqrt{2}}, C_1^1 = \frac{\sigma_y + \sigma_z}{\sqrt{2}}$ and $C_2^0 = \sigma_y, C_1^1 = \sigma_z$ violation $\mp 2\sqrt{2}$

Possible physical realisation





Disentangling clocks from the mass



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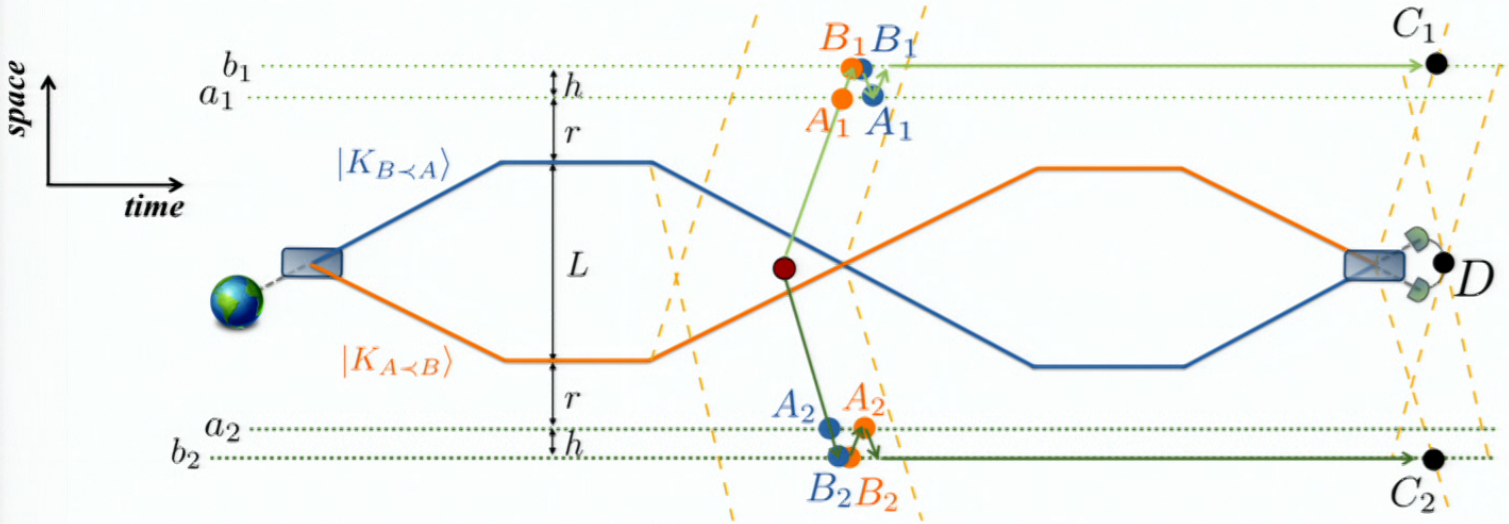

$$M \sim 0.1\mu g,\ L = h \sim 0.1nm,\ l = 1fm,\ T = 10\ hours$$

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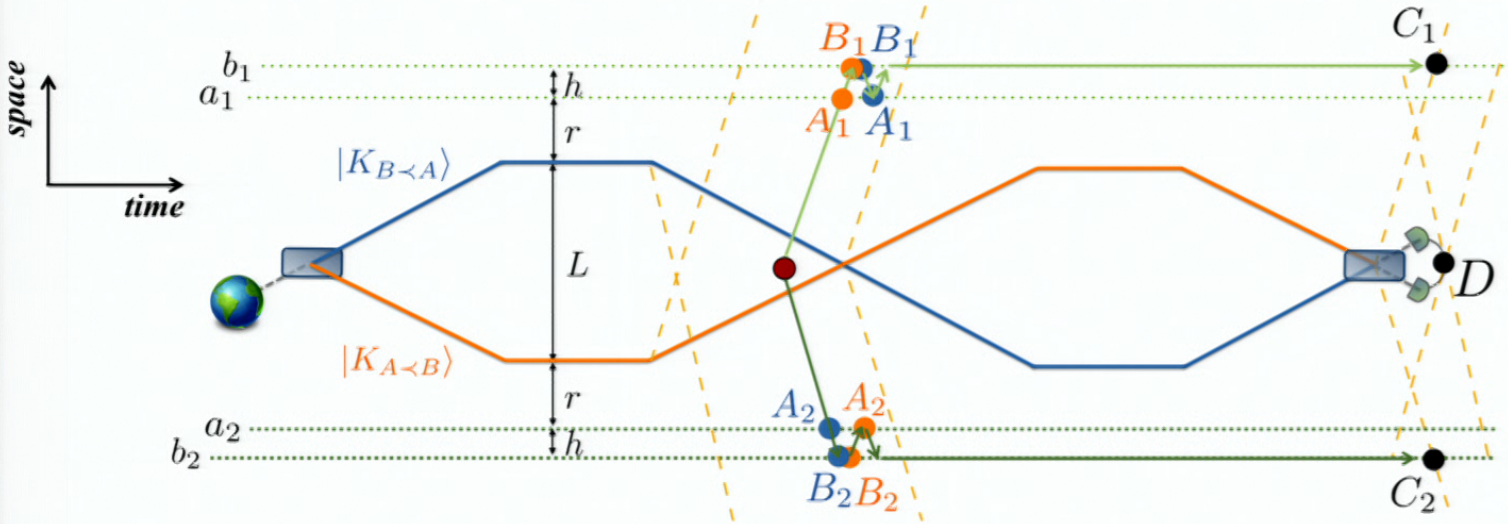

Comparison with the **Diosi-Penrose time**: $T_{DP} = \dfrac{2\delta^3\hbar}{G(ML)^2}$

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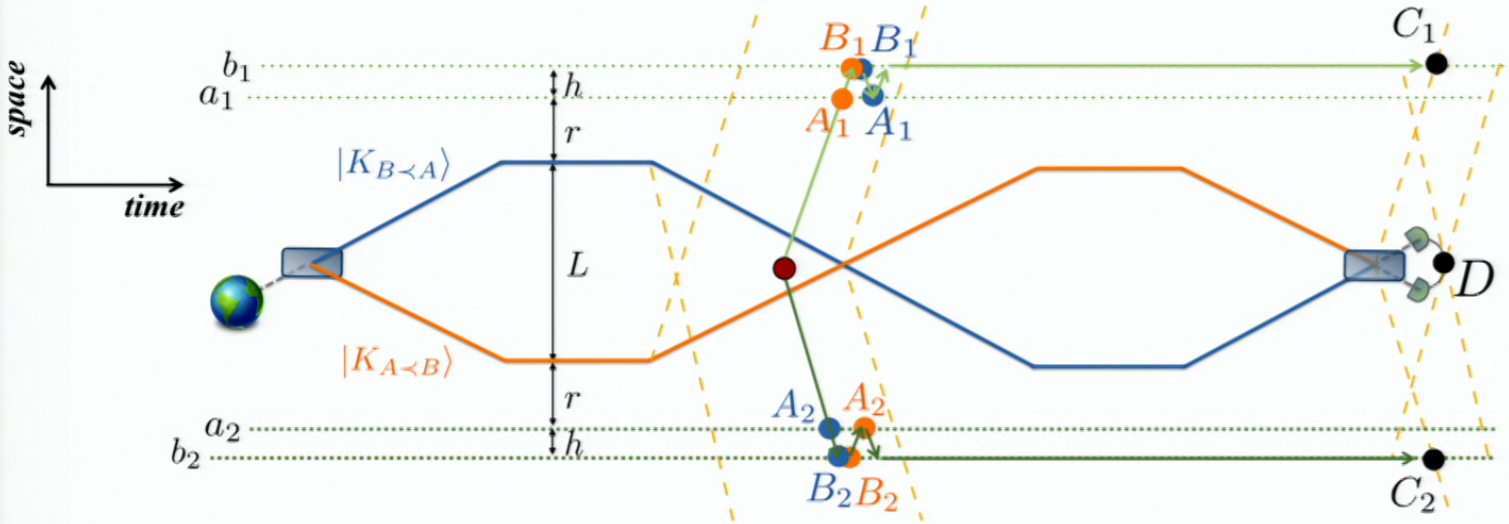

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$\delta = 10^{-7}s$

$$r = 10^{10} R_S,\ L = 5r,\ h = r,\ M = 1g,\ R_S \approx 10^{-30}m,\ T \approx 7\ 10^{-18}s,\ T_{DP} \approx 0.5s$$

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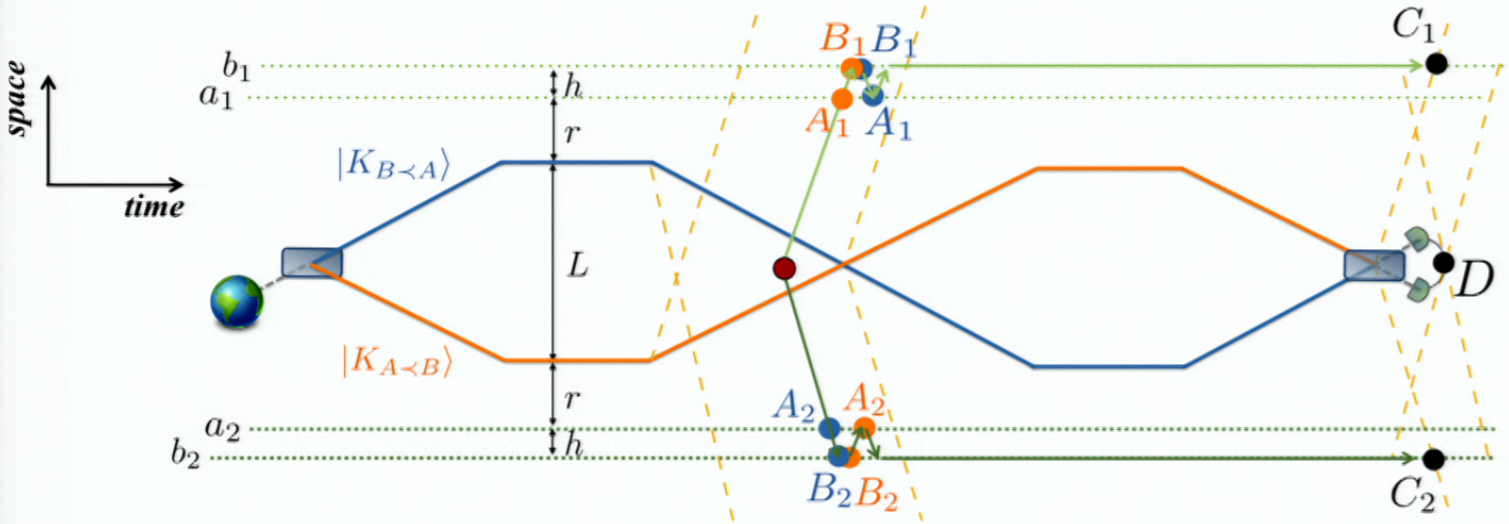

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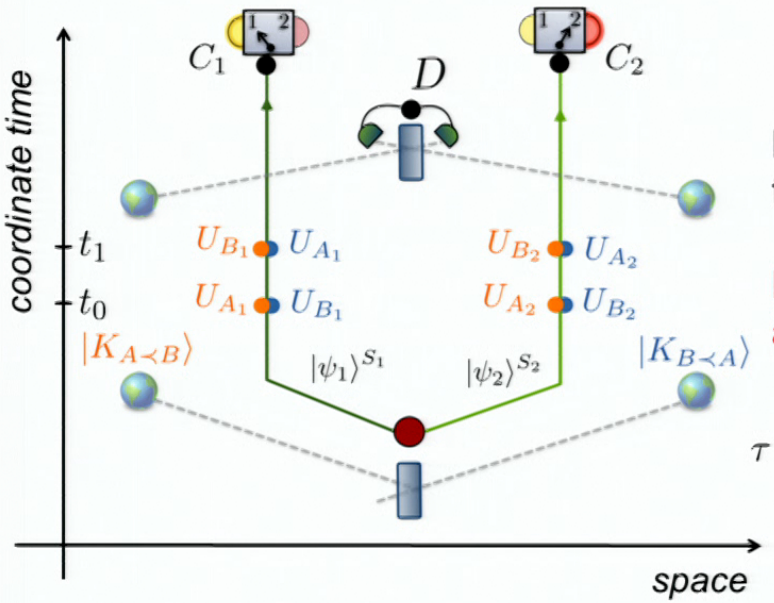
$\delta = 10^{-15}s$

$$r = 10^{7}R_S,\ L = 5\ 10^{5}r,\ h = 10^{5}r,\ M = 10^{-7}kg,\ T \approx 10^{-23}s,\ T_{DP} \approx 10^{-13}s$$

Local vs global temporal order



Time foliation with respect to the coordinate time (local time of a distant observer)

Distant observer sees **two** enterings in the labs at two coordinate times.

Local observers see a **single** entering at the same instant of the proper time.

$$\tau = \sqrt{-g_{00}(K_{A\prec B})}t_0 = \sqrt{-g_{00}(K_{B\prec A})}t_1$$

Summary

- Given all others assumption were fulfilled, the experiment would demonstrate **incompatibility of QM with a local classical temporal order**. The resources for this is a “non-classical space-time”.

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- Notion of the „event“ defined through the local operation, not as a point in the space-time manifold.
- No local classical temporal order, yet there is a global time evolution of the quantum state. *Can one go beyond this?*

Outlook: Causal inequalities

C. Branciard, M. Araújo, F. Costa, A. Feix, and Č. Brukner, New J. Phys. **18**, 013008 (2016)
A. A. Abbott, C. Giarmatzi, F. Costa, C. Branciard, Phys. Rev. A **94**, 032131 (2016)

Outlook: Causal inequalities

Causal correlations: either A signals to B or B signals to A, or no-signalling or a convex combination of these situations

$$p^{caus}(a,b|x,y) = \lambda p^{A\leq B}(a,b|x,y) + (1-\lambda)p^{B\leq A}(a,b|x,y)$$

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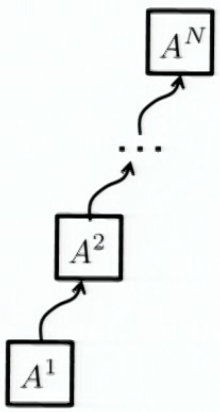

$$p^{caus}(\vec{a}|\vec{x}) = \sum_{\mu\in\{orders\}} q_\mu p_\mu(\vec{a}|\vec{x}), \quad \sum_\mu q_\mu = 1, q_\mu \geq 0$$

Causal correlations satisfy **causal inequalities**.

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Outlook: Non-causal processes

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O. Oreshkov, F. Costa, Č.B., Nature Communication **3**: 1092 (2012)

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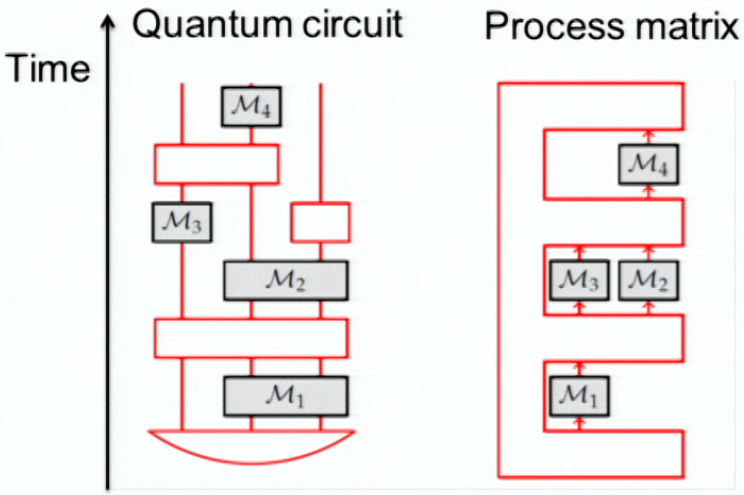

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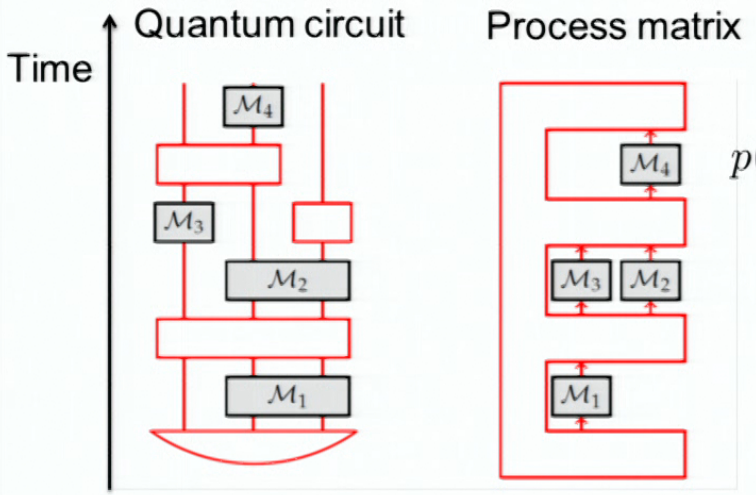

$$p(a_1, a_2, ...|x_1, x_2, ...) =$$
$$= \mathrm{Tr}[W(M_{x_1}^{a_1} \otimes M_{x_2}^{a_2} \otimes ...)]$$

Process matrix

Local quantum transf. (complete-positive maps)

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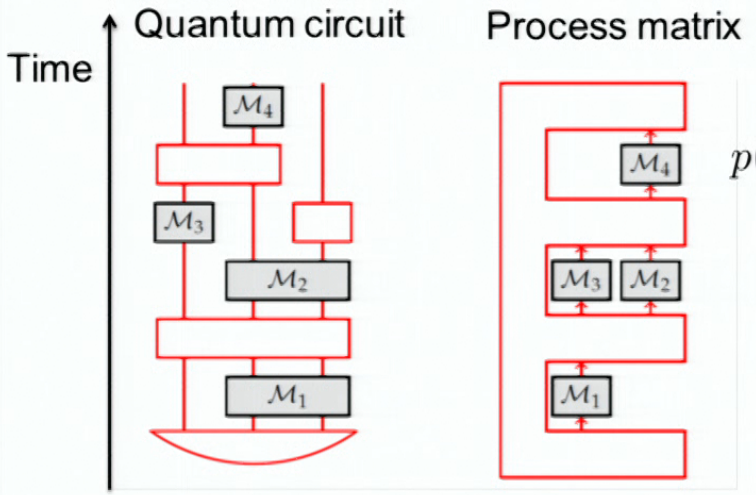

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Process matrix

Local quantum transf. (complete-positive maps)

Can such process matrices be realized in Nature?

O. Oreshkov, F. Costa, Č.B., Nature Communication **3**: 1092 (2012)

Thank you!

CoQuS Complex Quantum Systems

FWF Der Wissenschaftsfonds.

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SUPPORTING SCIENCE - INVESTING IN THE BIG QUESTIONS

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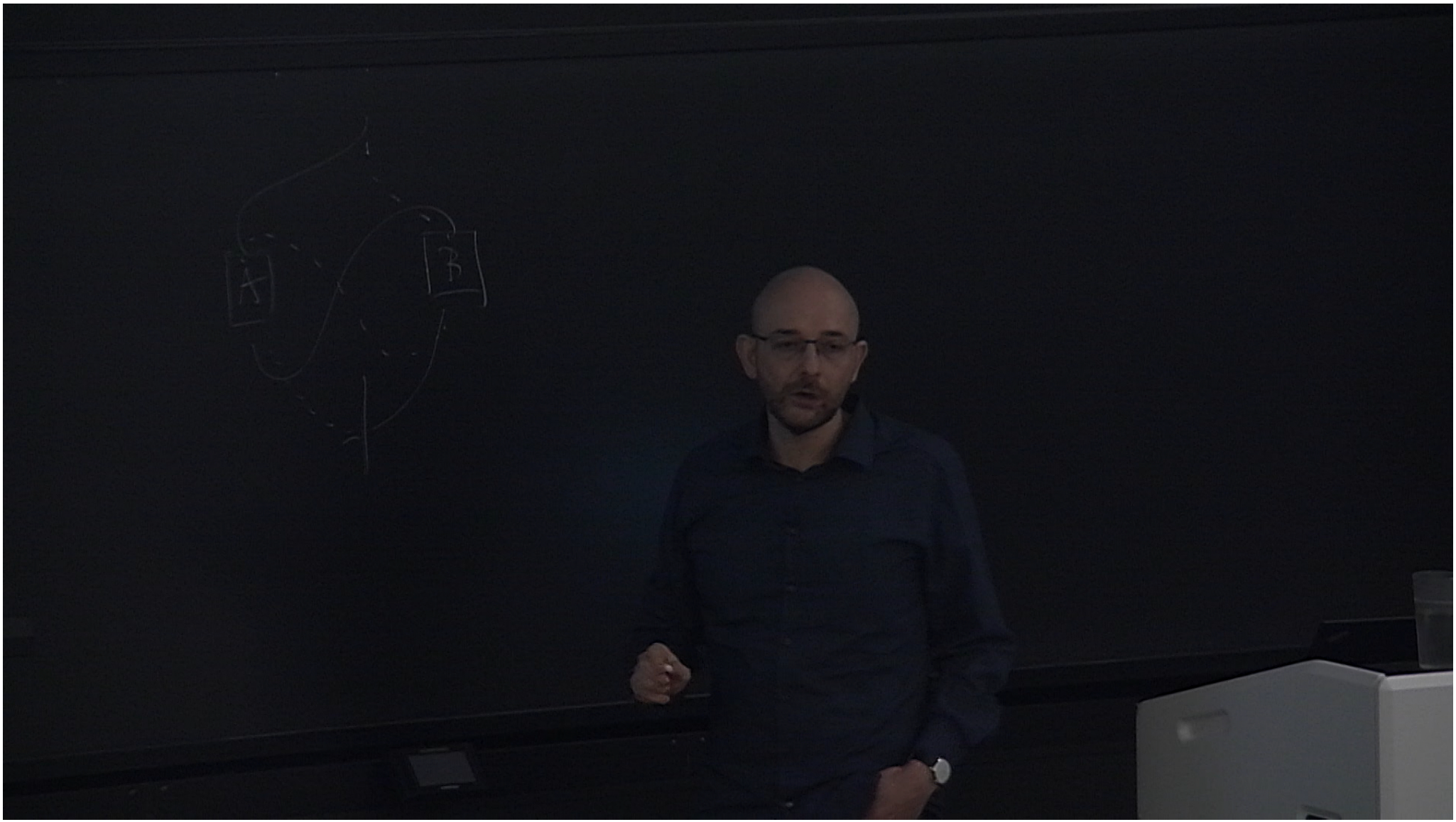
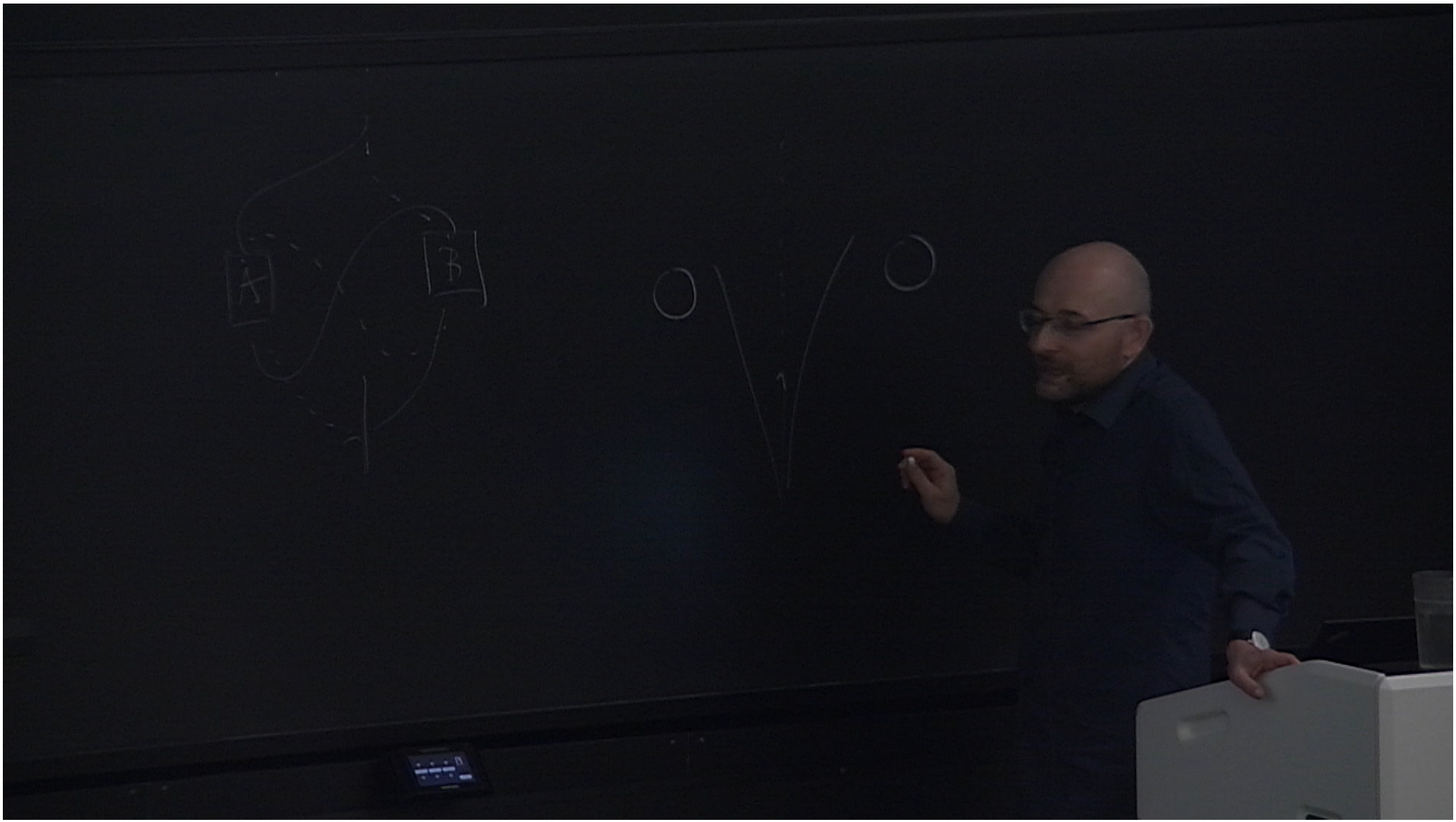
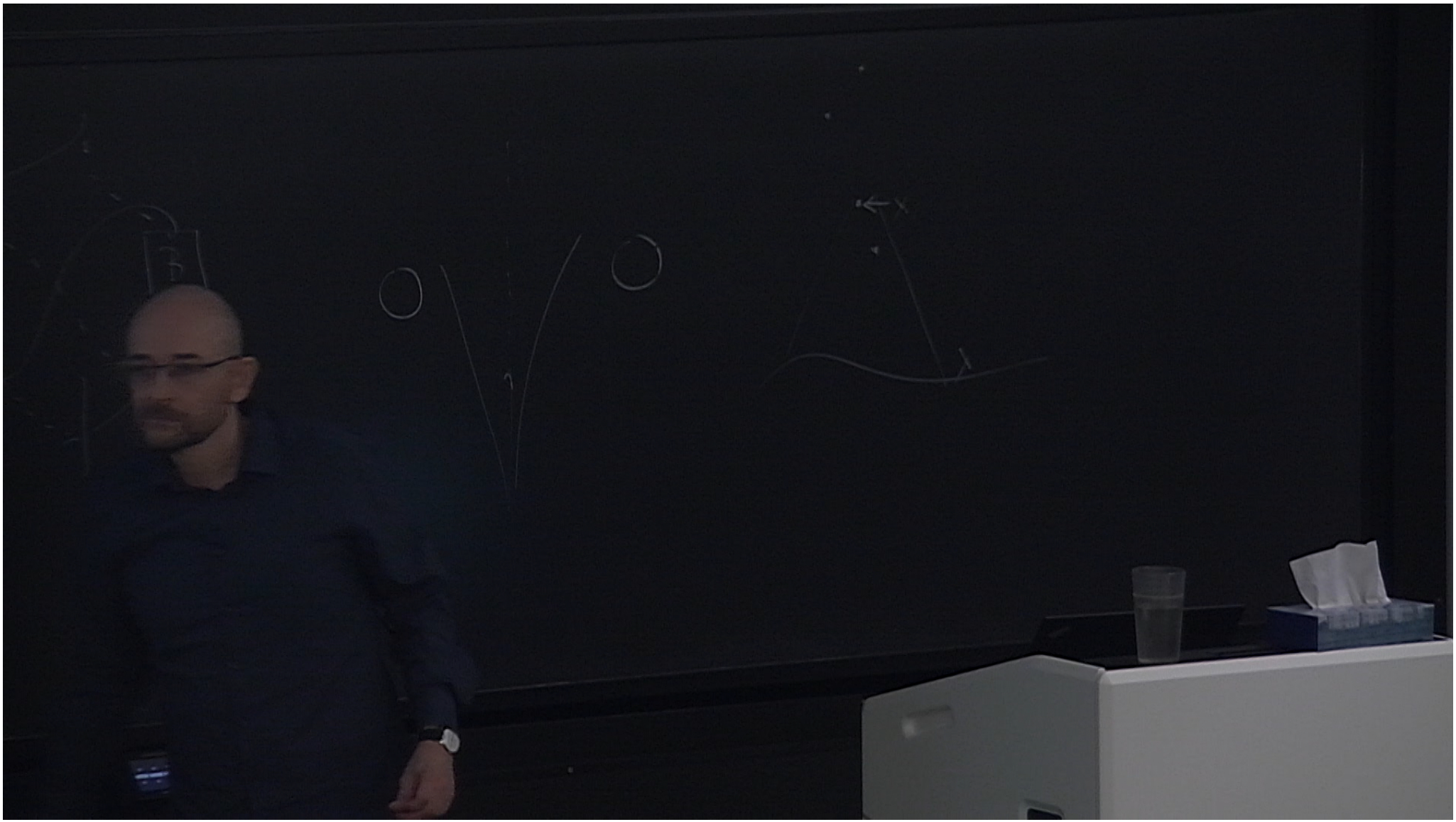

A
B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