

Title: TBA

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Collection: Indefinite Causal Structure

Date: December 13, 2019 - 9:50 AM

URL: <http://pirsa.org/19120034>

Indefinite causal order from quantum spacetime to the lab

F. Costa

Indefinite causal Structures

Perimeter Institute
13 December 2019

Indefinite causal structures: Why?

Foundations

Quantum properties observed for

Position

Energy

mass

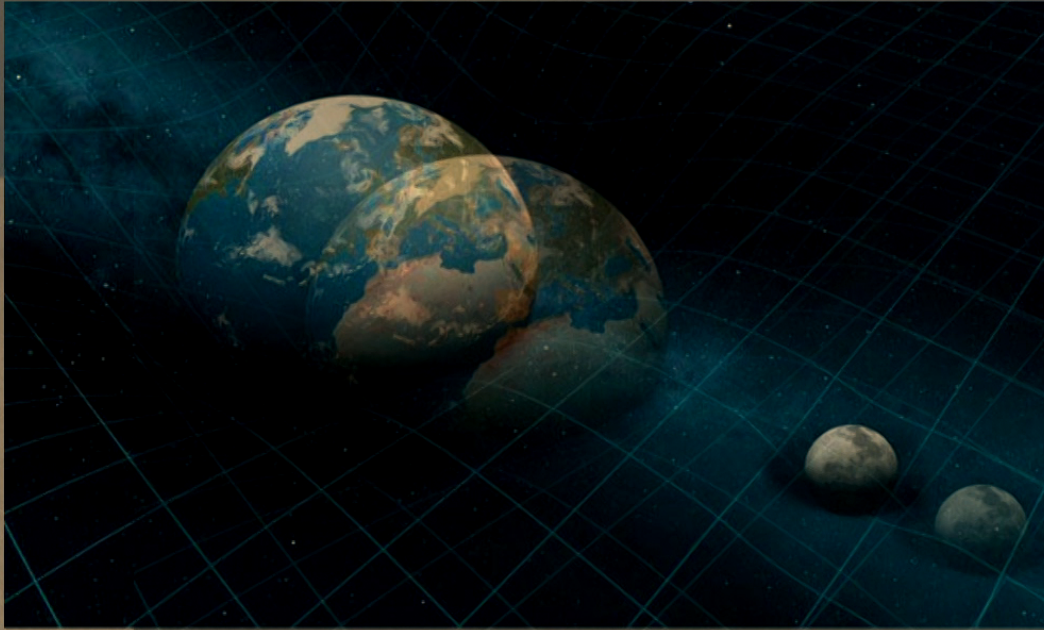
Angular momentum

...

What about *causal structure*?

Indefinite causal structures: Why?

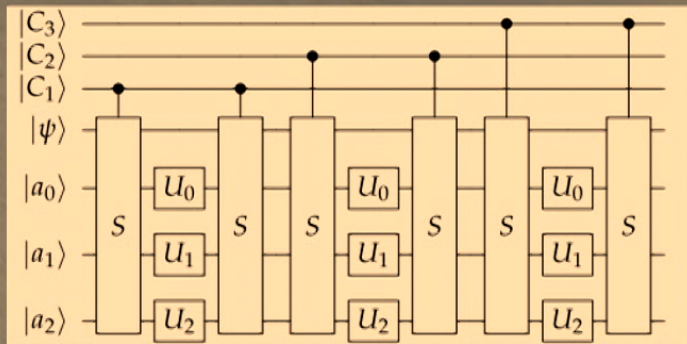
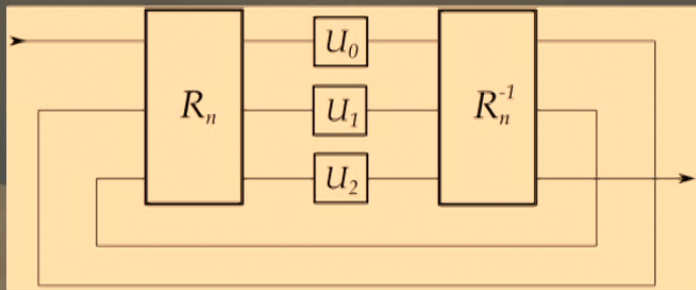
Quantum + gravity



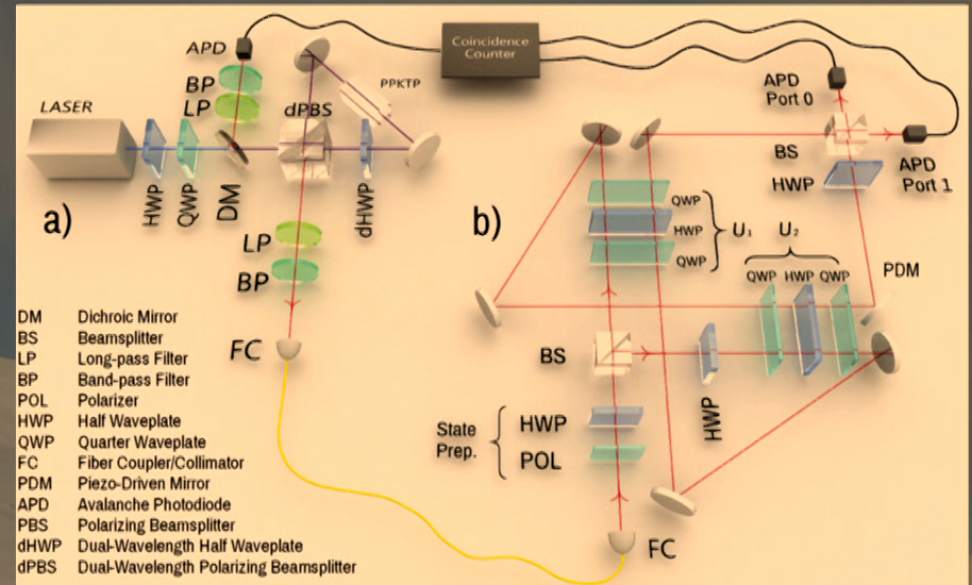
L. Hardy,
arXiv:gr-qc/0509120

Indefinite causal structures: Why?

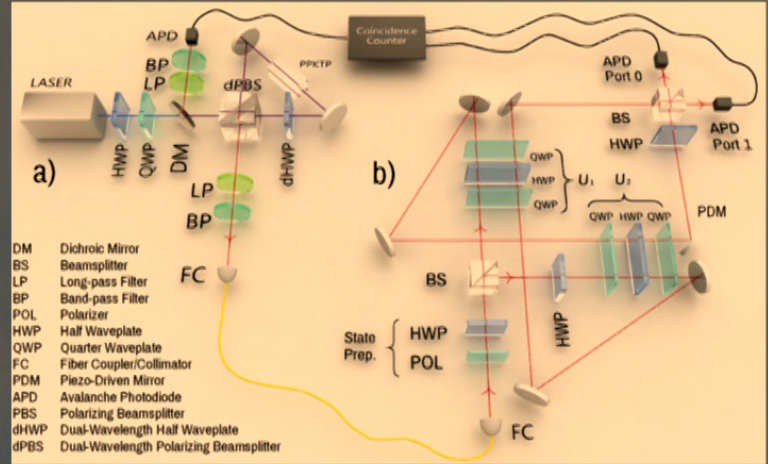
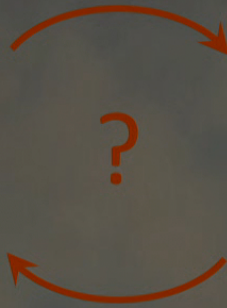
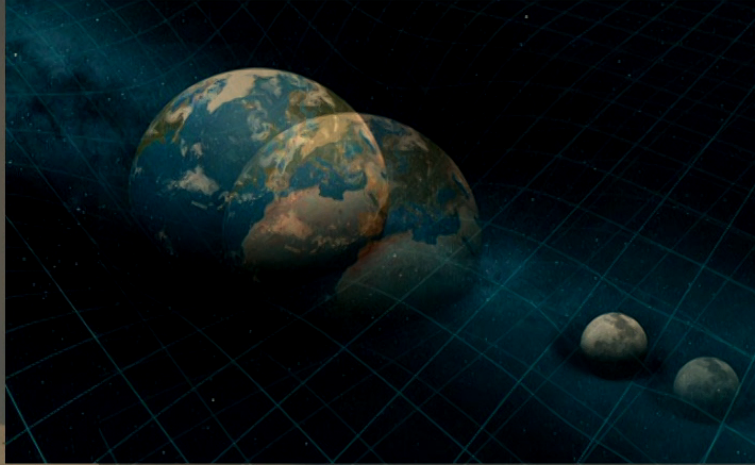
Practical resource



- M. Araújo, F.C., Č. Brukner, Phys. Rev. Lett. **113**, 250402
- ...



- Procopio et al., *Nat. Comm.* **6**, 7913 (2015).
- ...



- Simulation?
- Real resource?

Outlook

- Causal structure – manipulation and geometry
- Quantum spacetime
 - “Gravitational switch”
- Indefinite causal structure in the lab

What is causal structure?

Set of relations between events

What kind of relations?

What are events?

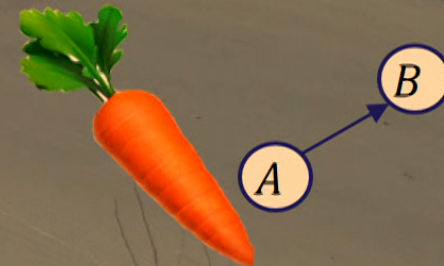
Causal structure—interventions

Events:

any quantity that can be observed and intervened on

Causal relations:

correlations between “free” intervention and “passive” observation



Causal structure—geometry

Events:

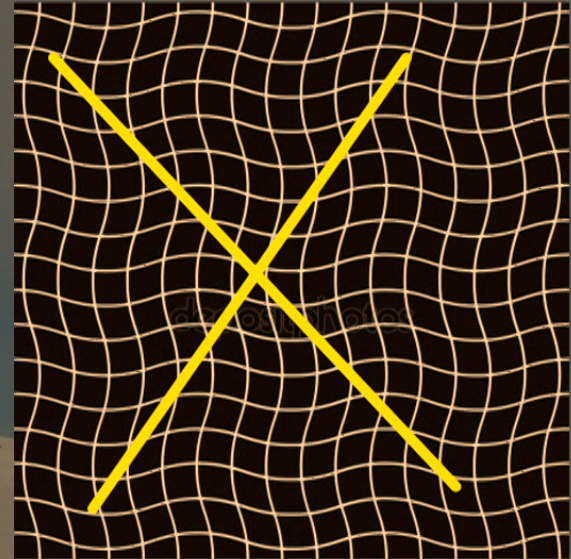
Points in a space-time manifold

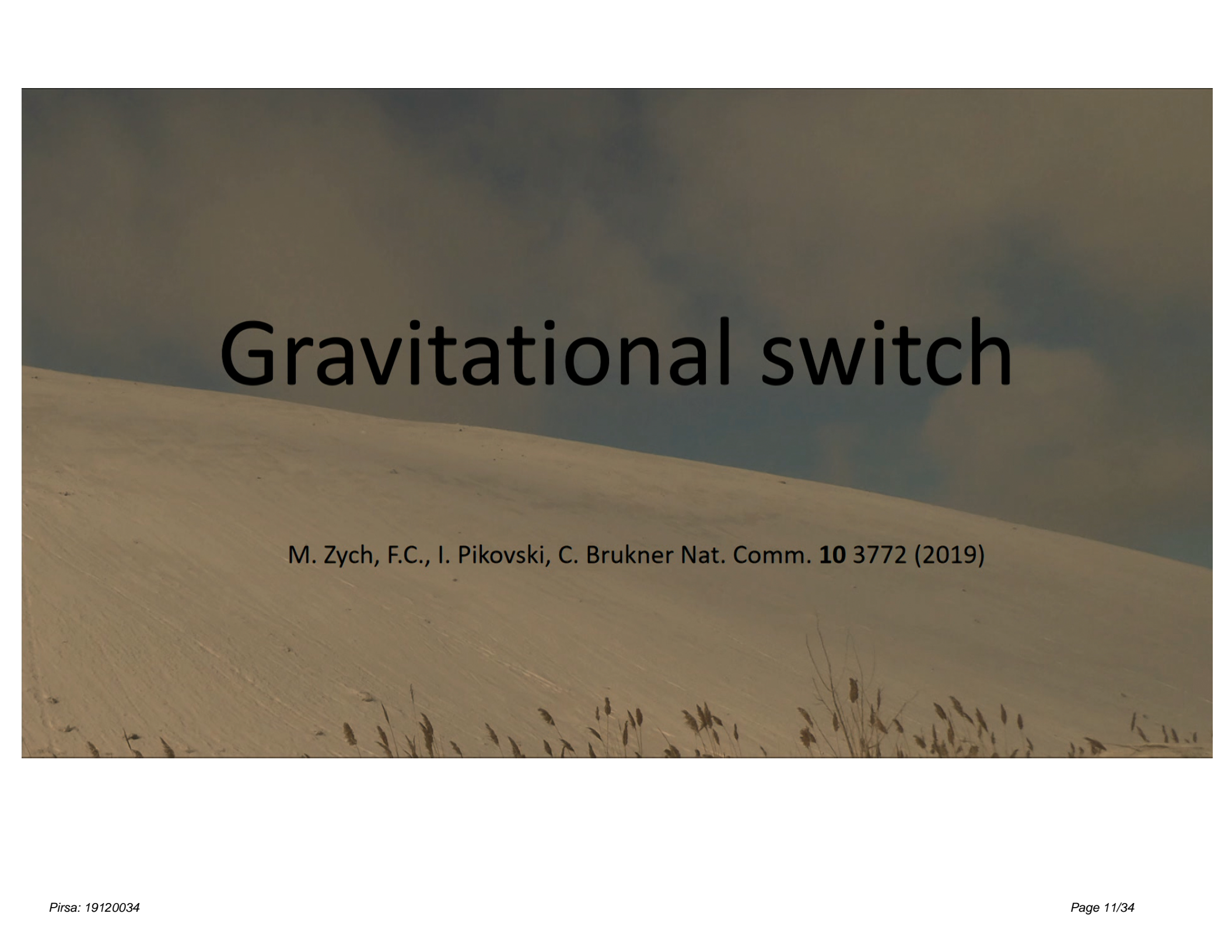
Causal relations:

partial order given by light-cone structure

Imposes constraints on dynamics

Constrains causal relations between localised interventions



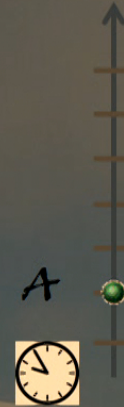


Gravitational switch

M. Zych, F.C., I. Pikovski, C. Brukner Nat. Comm. **10** 3772 (2019)

Spacetime events

Defined relative to physical systems



Dynamical causal structure

Define events A, B relative to local clocks



Dynamical causal structure

Define events A, B relative to local clocks

Initialise such that, in flat space time,
events are space-like



Dynamical causal structure

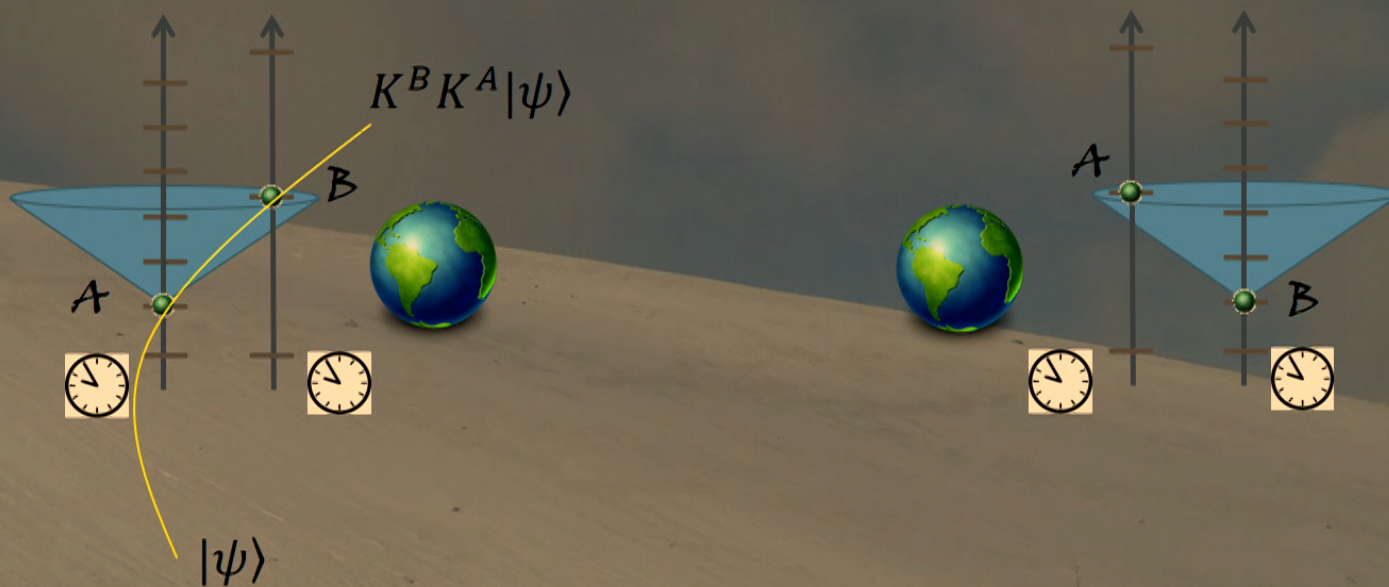
Introduce mass, compare two scenarios:



Causal order depends on position of mass

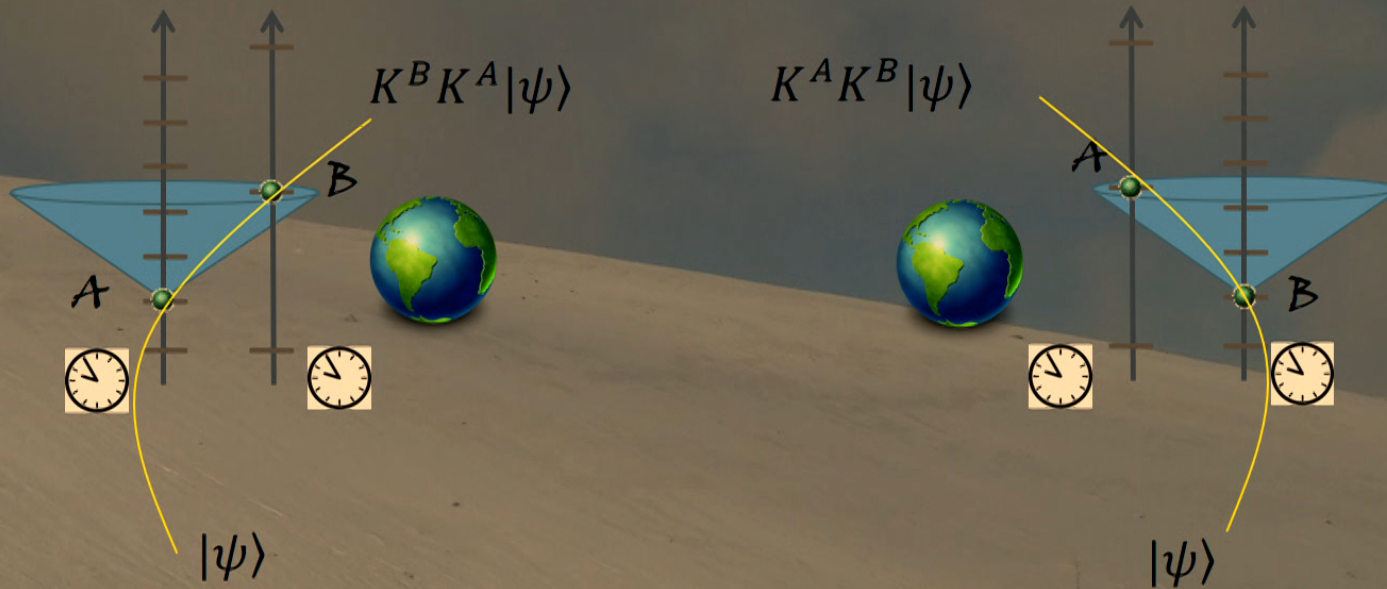
Gravitational switch

Intervention on target at A, B .
(K^A, K^B Kraus operators)



Gravitational switch

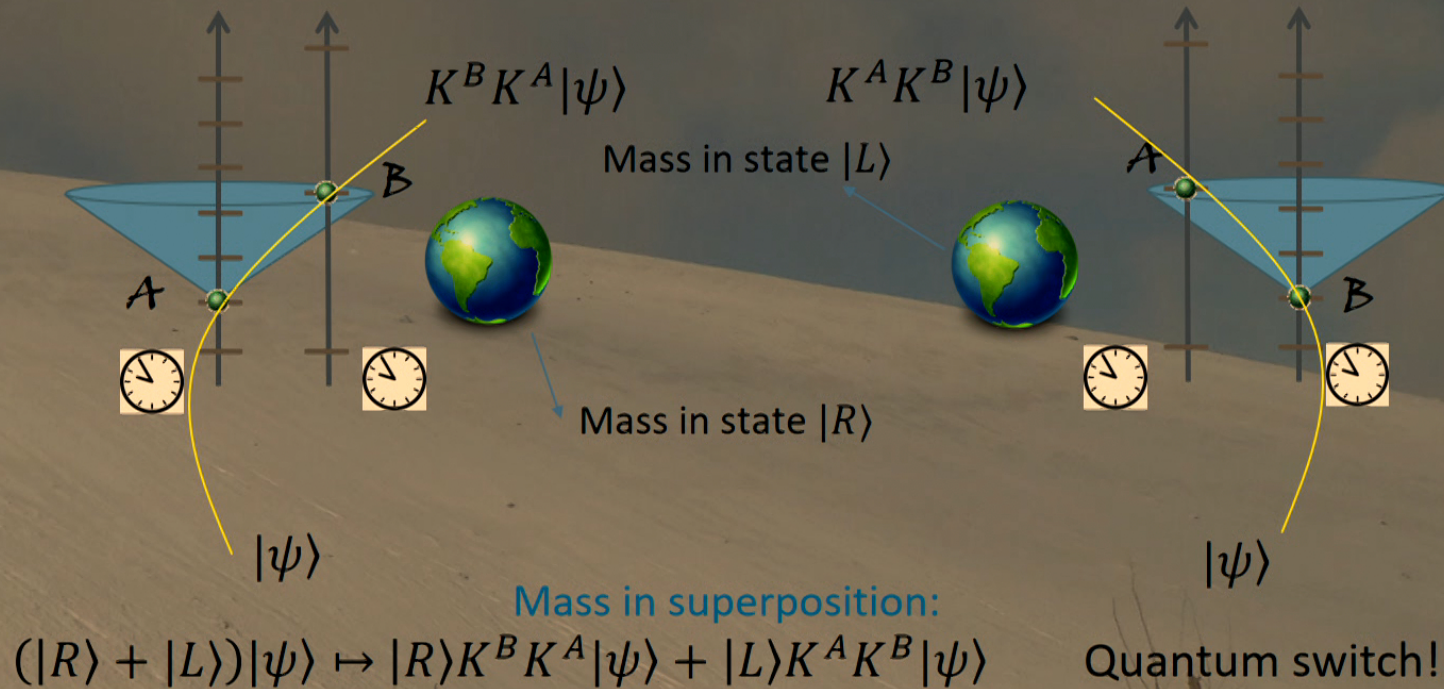
Intervention on target at A, B .
(K^A, K^B Kraus operators)



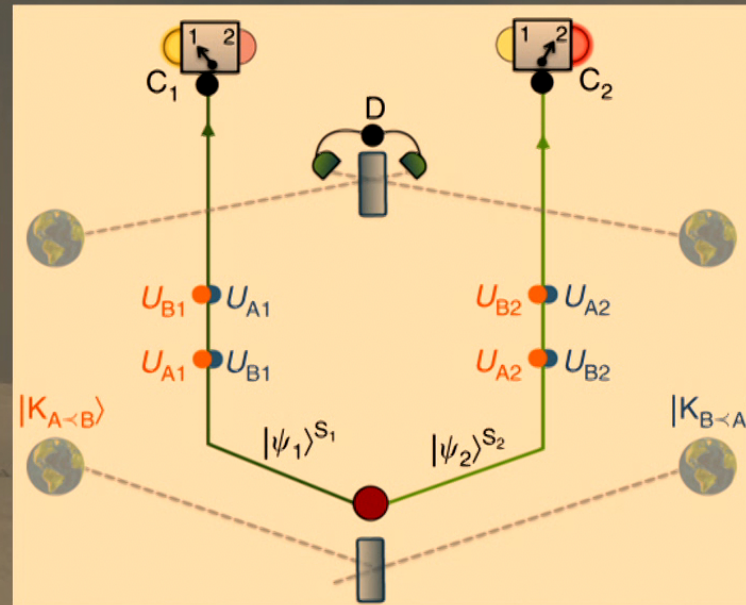
Can be arranged so that trajectories
do not correlate with mass position

Gravitational switch

If quantum theory universal, mass positions \sim orthogonal states



Bell test for causal order

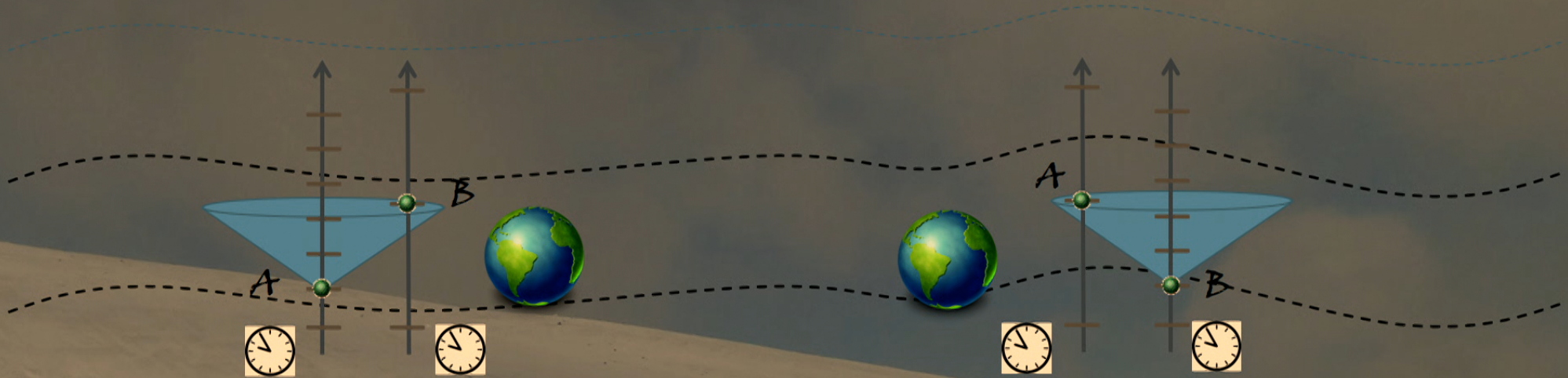


No local, classical description of causal structure possible.

Just two events?

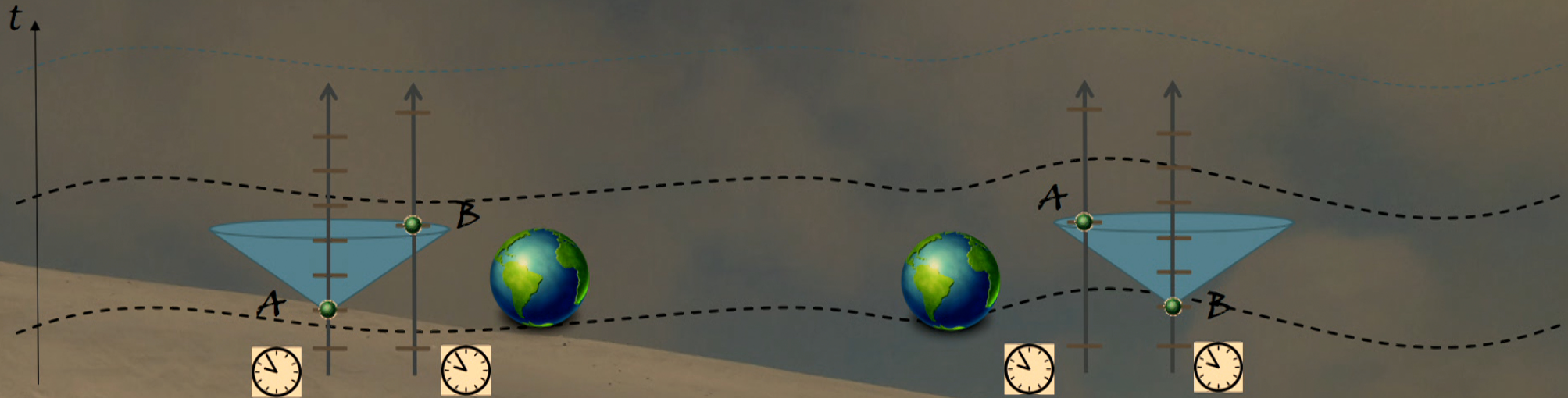


Just two events?



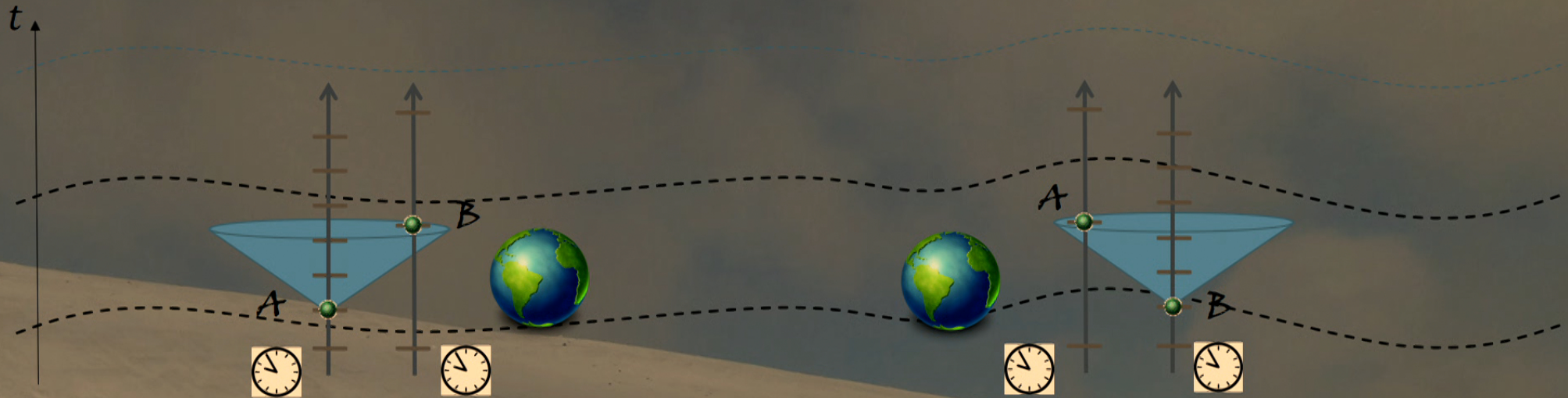
There is common foliation for the two geometries

Just two events?



There is common foliation for the two geometries
Defines mass-independent coordinate time t (time of distant observer)

Just two events?



There is common foliation for the two geometries

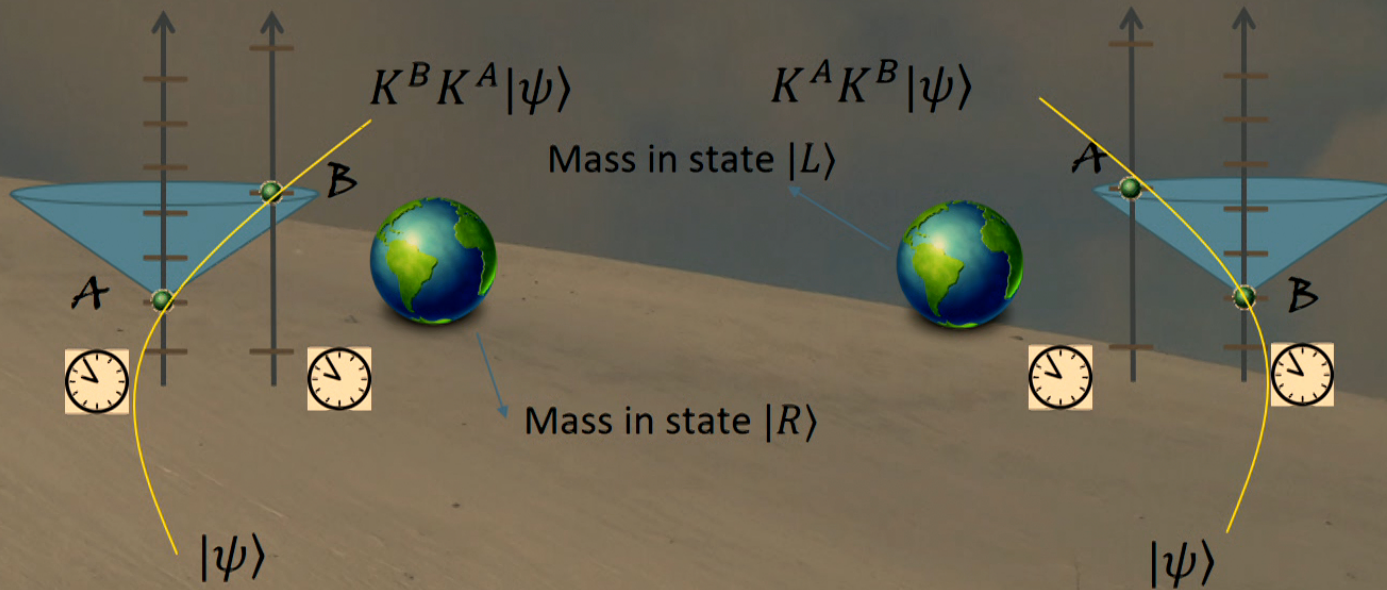
Defines mass-independent coordinate time t (time of distant observer)

Global evolution generated by Hamiltonian (including clocks)

Four “events” (manifold points) in these coordinates. Still, **two** physical events.

Gravitational switch

If quantum theory universal, mass positions \sim orthogonal states



Operational characterisation

Causal relations are **geometrical** if events are labelled relative to *black box* reference systems (clocks)

Results of any protocol independent of particular choice of physical reference system

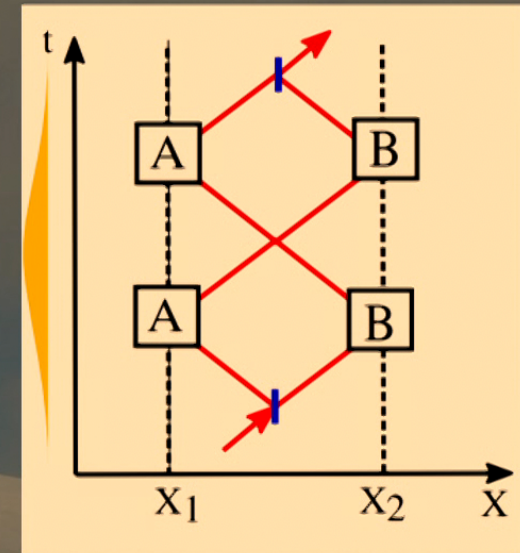
Geometrical indefinite causal order impossible in classical, causal space-time

Indefinite causal structure in the lab

Classical spacetime, events delocalised in time

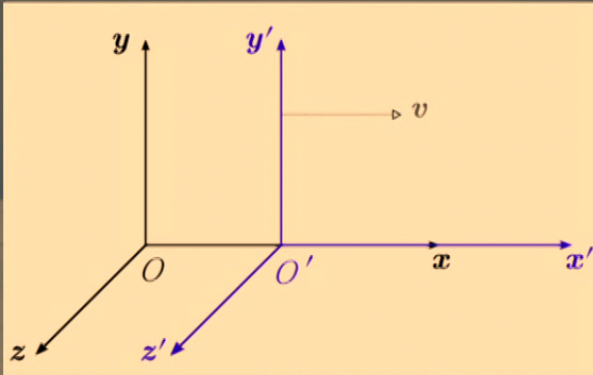
Formally: time-delocalised subsystems

O. Oreshkov, Quantum **3**, 206 (2019)

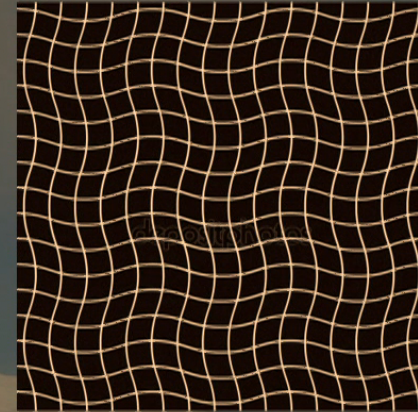


Analogy

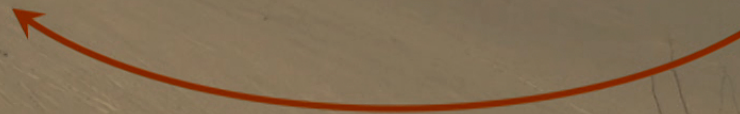
Special relativity:
global inertial reference frames



General relativity:
non-inertial frames



Non-inertial frames meaningful
in special relativity too



Useful resource?

Experiments:	Control	Target
<ul style="list-style-type: none">• Procopio et al., <i>Nat. Comm.</i> 6, 7913 (2015).• Rubino et al., “Experimental verification of an indefinite causal order”, <i>Science Advances</i> 3, e1602589 (2017).• Rubino, et al., “Experimental Entanglement of Temporal Orders.”, arXiv:1712.06884 (2017).• Guo et al., “Experimental Investigating Communication ...”, arXiv:1811.07526 (2018).	Position	Polarisation
<ul style="list-style-type: none">• Goswami et al., “Indefinite Causal Order in a Quantum Switch”, <i>Phys. Rev. Lett.</i> 121, 090503 (2018).• Goswami et al., “Communicating via ignorance”, arXiv:1807.07383 (2018).	Polarisation	Orbital angular momentum
<ul style="list-style-type: none">• Wei et al., “Experimental Quantum Switching ...”, <i>Phys. Rev. Lett.</i> 122, 120504 (2019).	Position	Time bins*

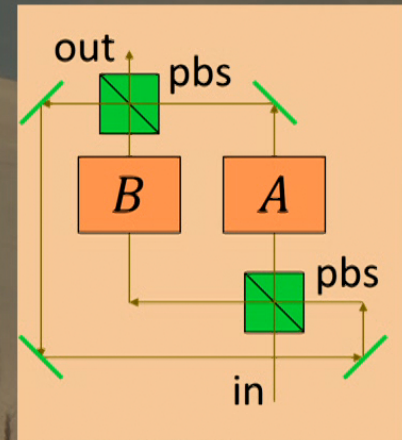
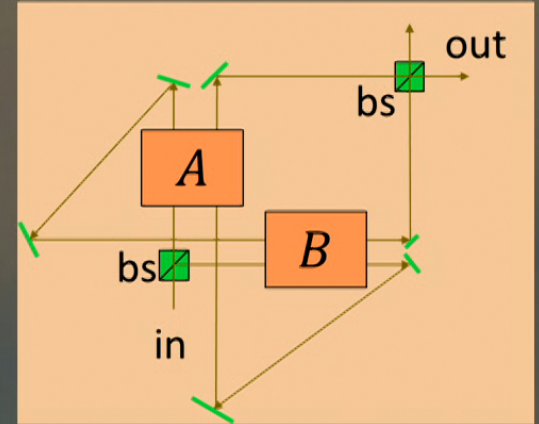
*Phase modulation has to be timed only to affect the “second passage” of the pulse train.

	Vienna	UQ
Control	position	polarisation
Target	polarisation	Orbital angular momentum
Setup		

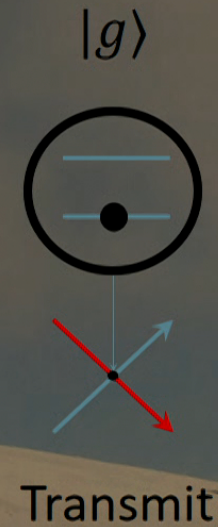
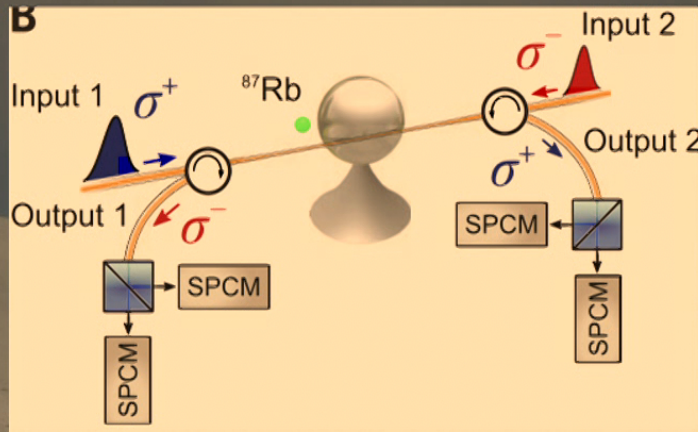
Limitations of current implementations

“Single use”?

- Control dof accessible to local operations
 - Operation can reveal which order information
 - Compensation needed to avoid action on control



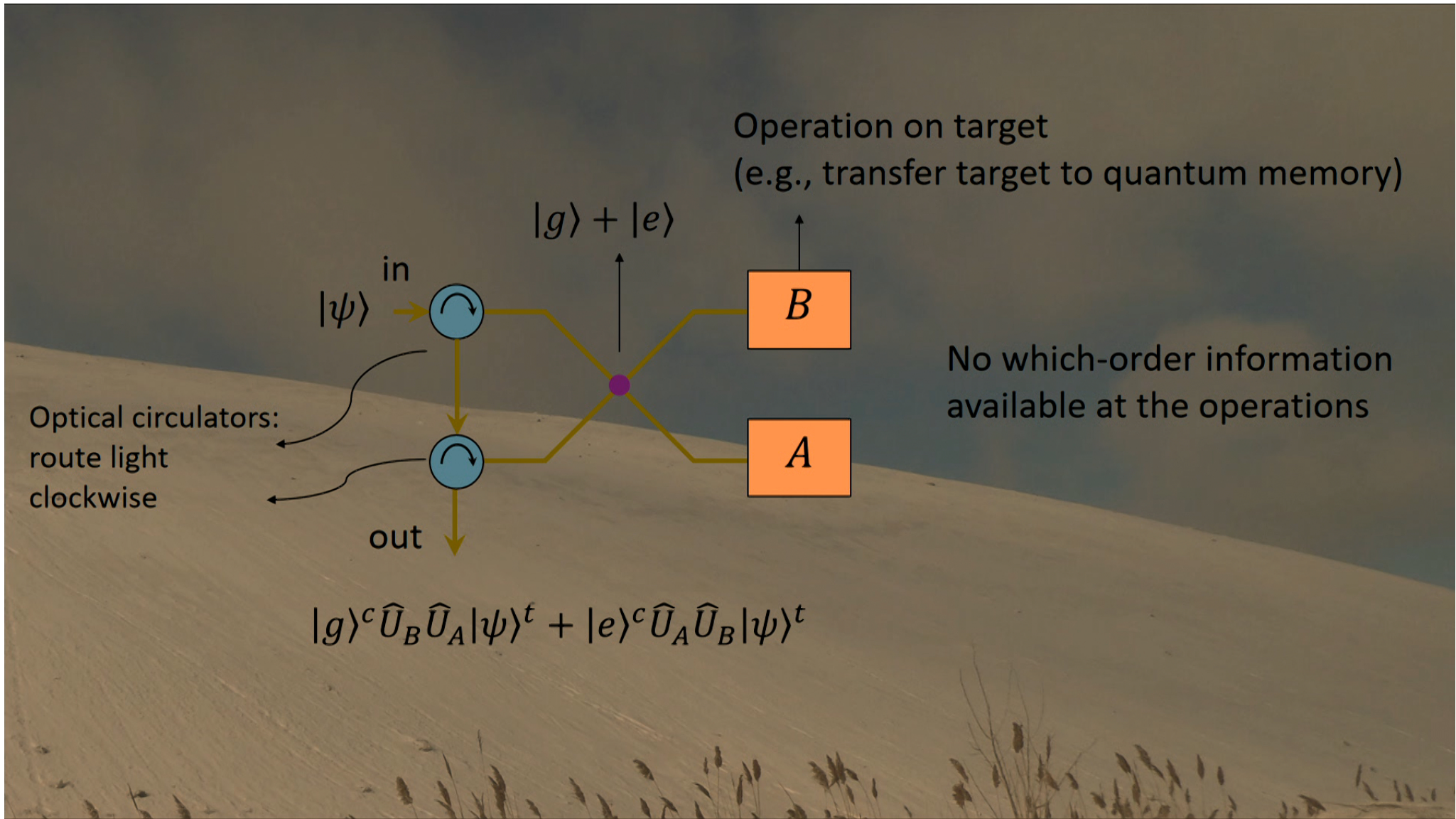
Single-atom optical router



I. Shomroni et al

“All-optical routing of single photons by a one-atom switch controlled by a single photon”

Science **345**, 903 (2014).



Scalable: control $n!$ Permutations with $\frac{1}{2}n(n-1)$ atoms.



$O(n \log n)$ scaling possible?

Summary

- Meaning of “Causal structure”
 - Space-time: localised events relative to black-box reference frames
 - Practical: events need not be localised
- Gravitational switch: demonstrates quantum + gravity leads to indefinite causal structure of space-time
 - No absolute localisation of events
- Quantum switch in the lab
 - Formally: indefinite causal order for time-delocalised events
 - Current experiments: not useful resources
 - Scalable “single use” realisation possible