Title: Quantum theory and spacetime: a different perspective

Date: Nov 05, 2014 02:00 PM

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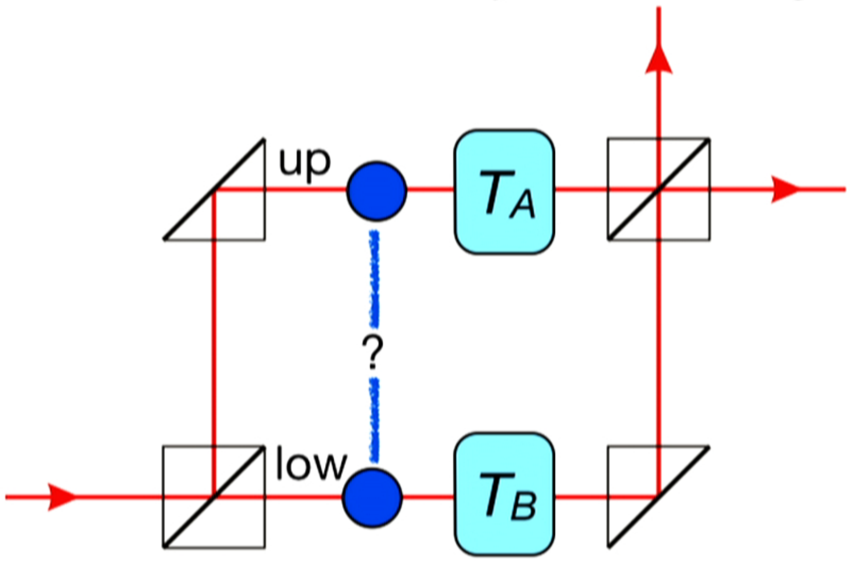
Abstract: <p>Quantum information theory has taught us that quantum theory is just one possible probabilistic theory among many others. In the talk, I will argue that this â€žbirdâ€™s-eyeâ€œ perspective does not only allow us to derive the quantum formalism from simple physical principles, but also reveals surprising connections between the structures of spacetime and probability which can be phrased as mathematical theorems about information-theoretic scenarios.</p>

Quantum theory and spacetime:
a different perspective

Markus P. Müller
Institute for Theoretical Physics, Heidelberg University (Germany)



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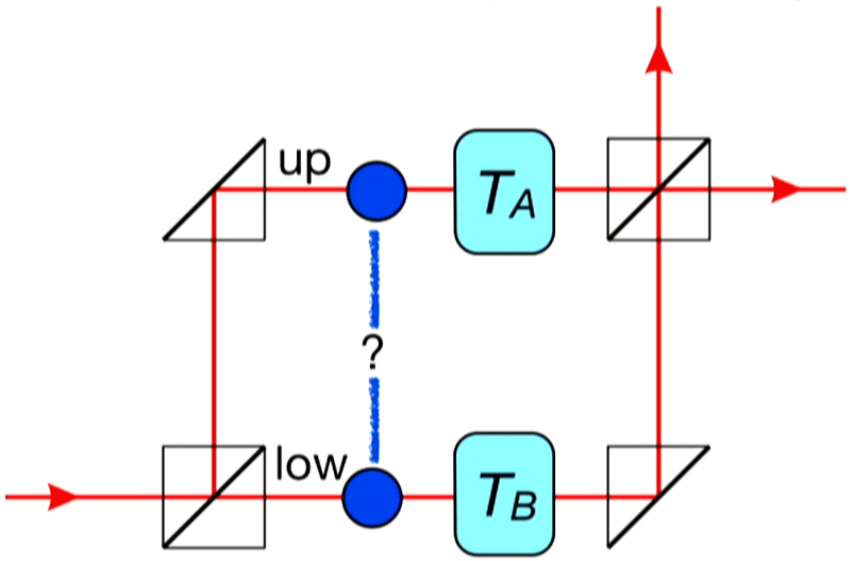

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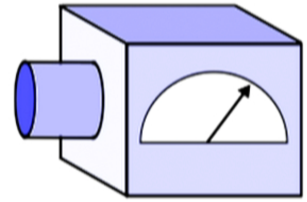
Outline

1. A glance beyond quantum theory



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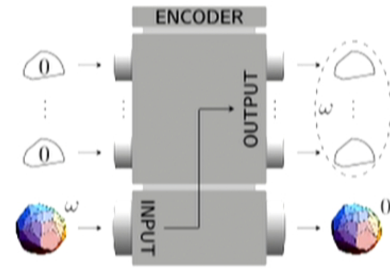
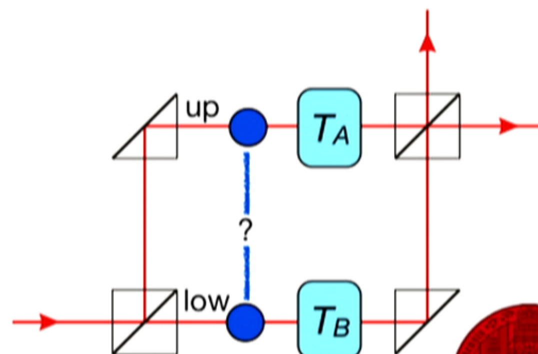
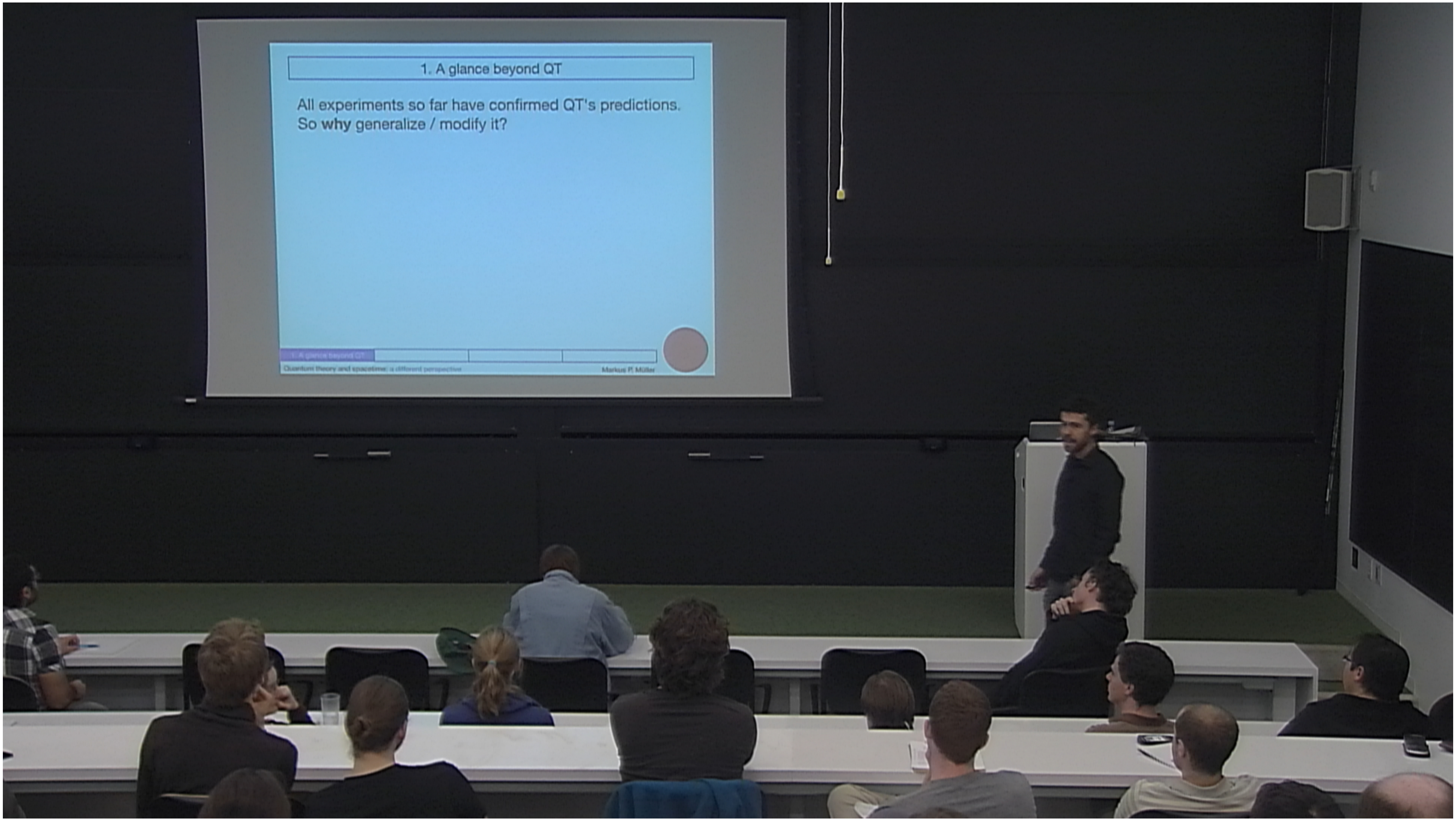


3. QT and spacetime: surprises

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All experiments so far have confirmed QT's predictions.
So **why** generalize / modify it?
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So **why** generalize / modify it?

- In the past, all theories had limits of applicability, were replaced by generalizations. QT maybe too.
- Quantum gravity aims at unifying GR + QT. GR is assumed to be modified. Why not QT?
- Experimental tests of QT
- Better understanding of standard QT

"Bird's eye view" on QT

1. A glance beyond QT

ANNALS OF PHYSICS **194**, 336–386 (1989)

Testing Quantum Mechanics

STEVEN WEINBERG*

Theory Group, Department of Physics,
University of Texas, Austin, Texas 78712

Received March 6, 1989

This paper presents a general framework for introducing nonlinear corrections into ordinary quantum mechanics, that can serve as a guide to experiments that would be sensitive to such corrections. In the class of generalized theories described here, the equations that determine the time-dependence of the wave function are no longer linear, but are of Hamiltonian type. Also, wave functions that differ by a constant factor represent the same physical state and satisfy the same time-dependence equations. As a result, there is no difficulty in combining separated subsystems. Prescriptions are given for determining the states in which observables have definite values and for calculating the expectation values of observables for general states, but the calculation of probabilities requires detailed analysis

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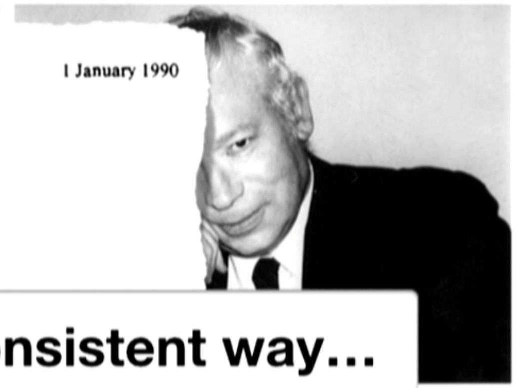

Volume 143, number 1,2 PHYSICS LETTERS A 1 January 1990

WEINBERG'S NON-LINEAR QUANTUM MECHANICS AND SUPRALUMINAL COMMUNICATIONS

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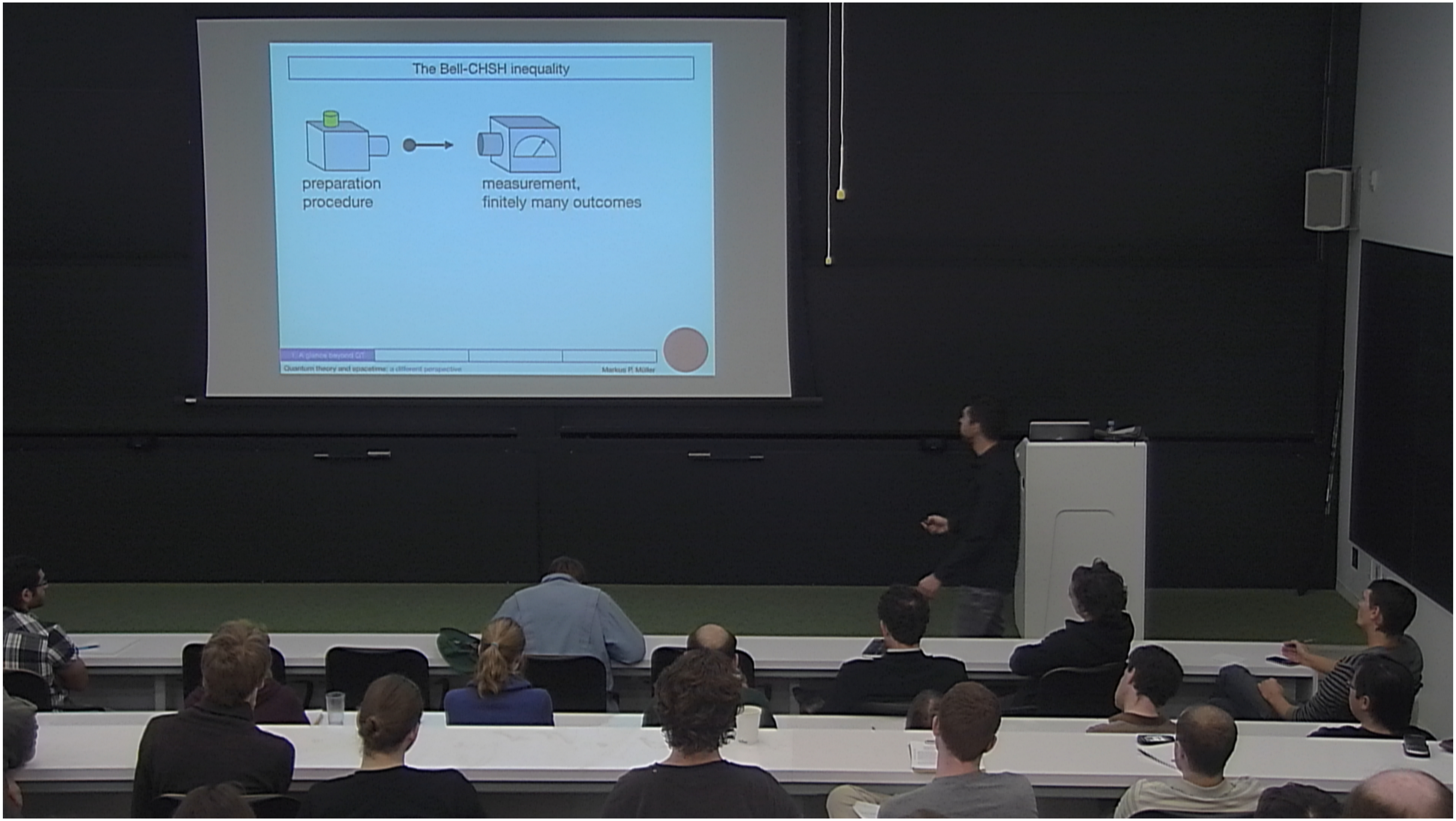
Con

It is hard to modify QT in a consistent way…
… unless one does it very systematically.

We show with an example that Weinberg's general framework for introducing non-linear corrections into quantum mechanics allows for arbitrarily fast communications.

Recently Weinberg has proposed a general framework for introducing non-linear corrections into ordinary quantum mechanics [1,2]. Although we fully support his emphasis on the importance of testing quantum mechanics, we would like in this Letter to draw attention to the difficulty of modifying quantum mechanics without introducing arbitrarily fast actions at a distance. Below we show how to construct, within Weinberg's framework, an arbitrarily fast telephone line. In ordinary quantum mechanics

to know what such an apparatus is... do you know what is inside your phone?) In order to simplify we consider only a single-bit message. The two directions z and u are in the xz-plane orthogonal to the incoming flow of particles, and are 45° from each other. The way the inhomogeneous magnetic field acts on the particles is well-known from experimental evidence. After the apparatus there are two counters. For each particle one of the counters will click. This click will be amplified until all readers of


The Bell-CHSH inequality
preparation
procedure
measurement,
finitely many outcomes
1. A glance beyond QT
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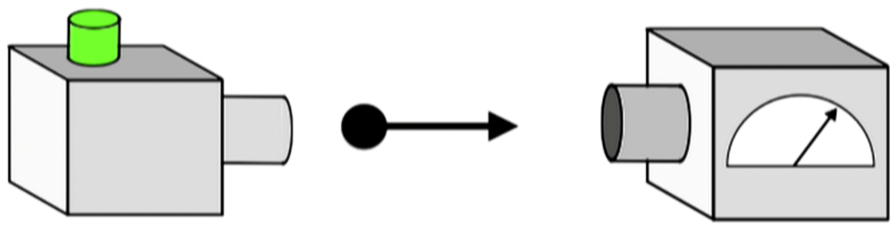
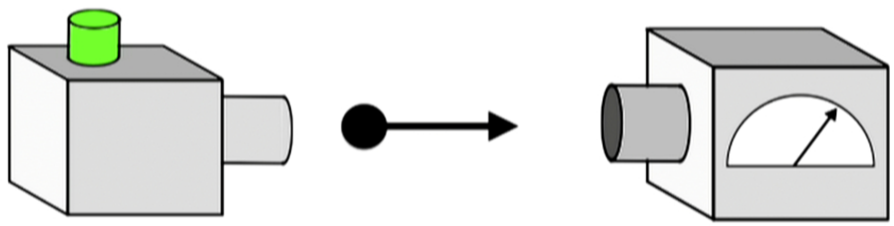
The Bell-CHSH inequality



preparation procedure

measurement, 2 outcomes, $x \in \{-1, +1\}$

The Bell-CHSH inequality



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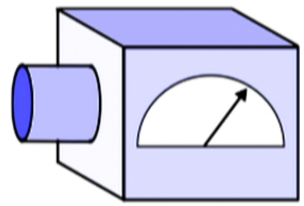
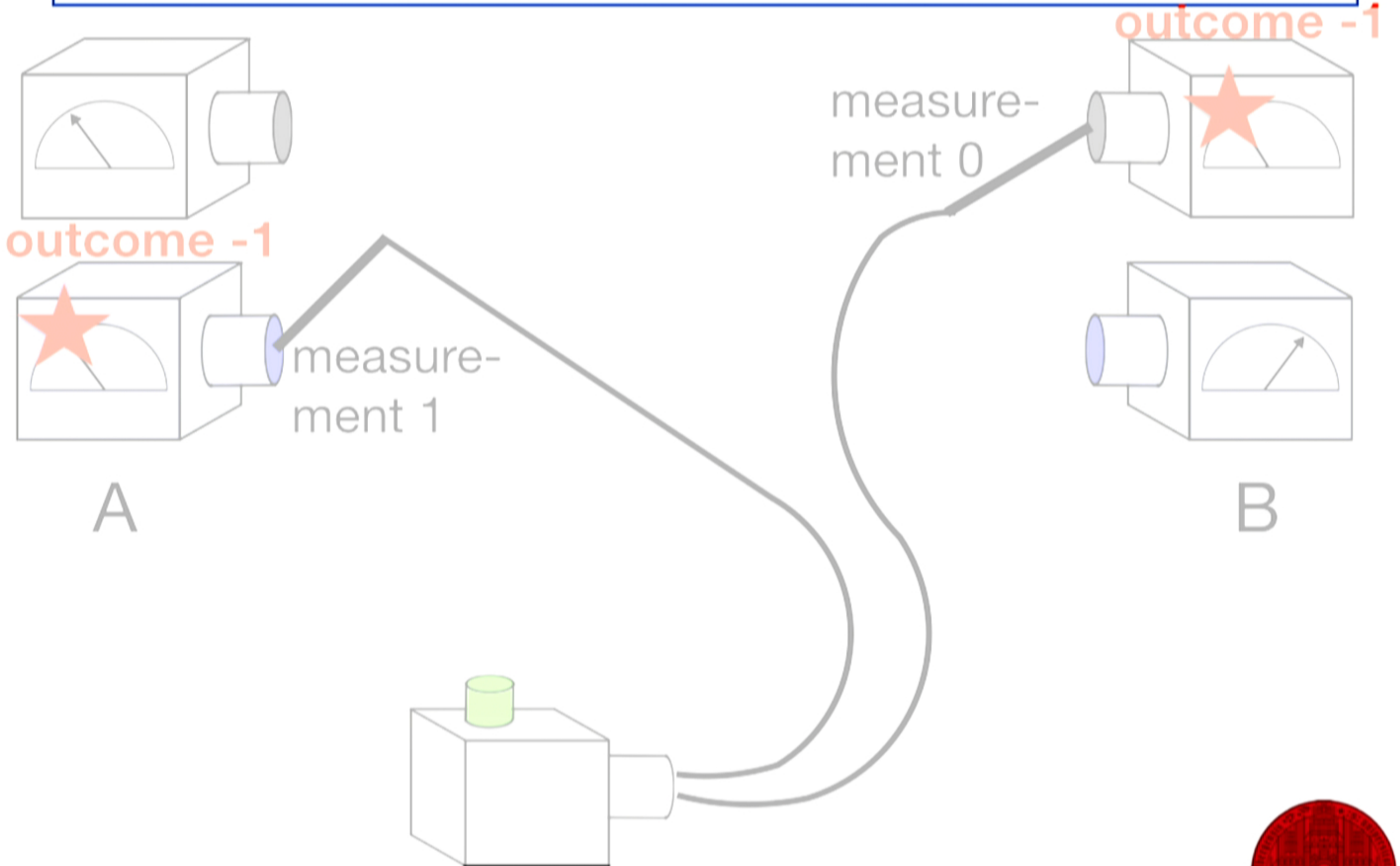


another measurement,
2 outcomes, $x \in \{-1, +1\}$

Slightly more abstract picture...



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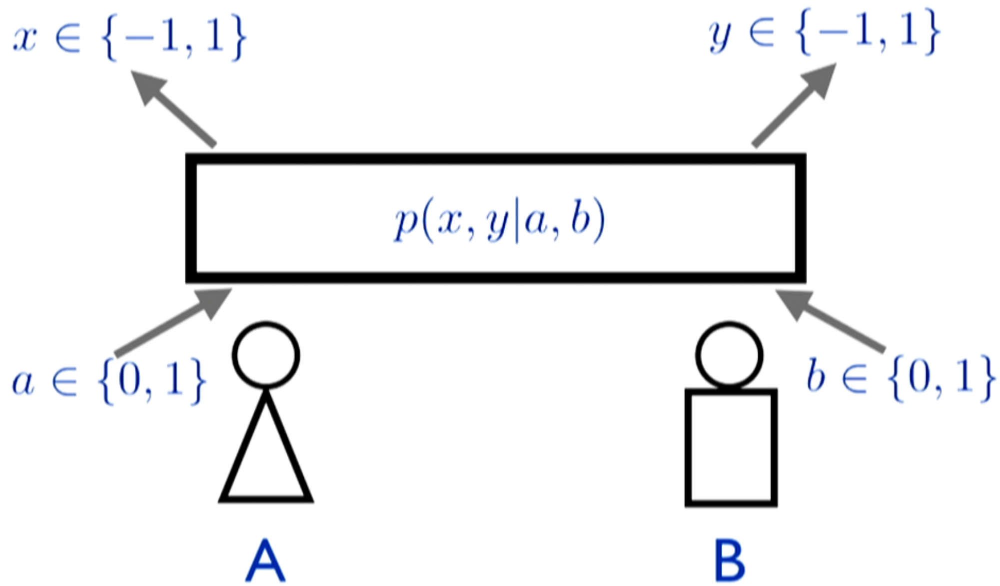

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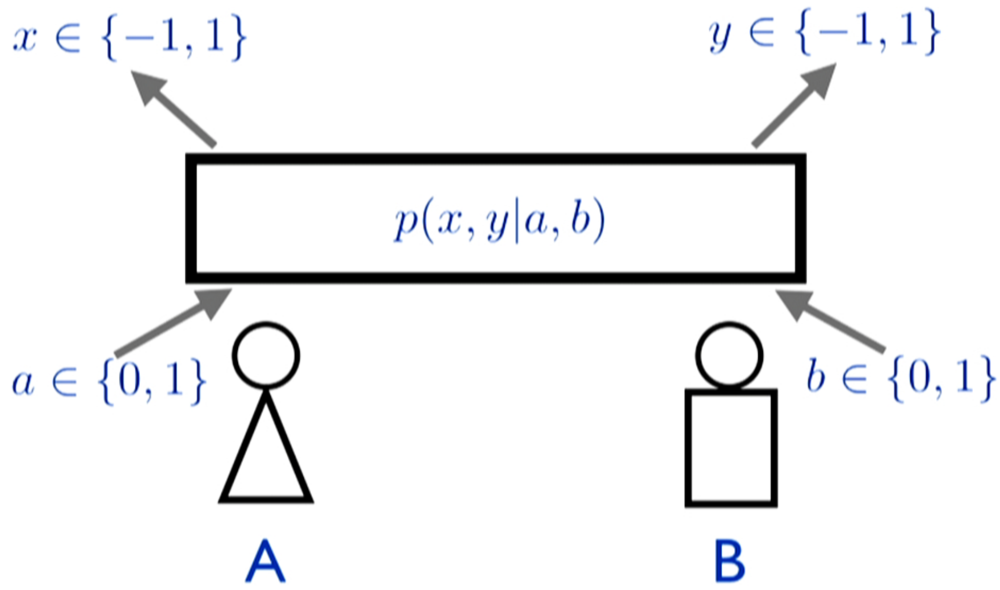
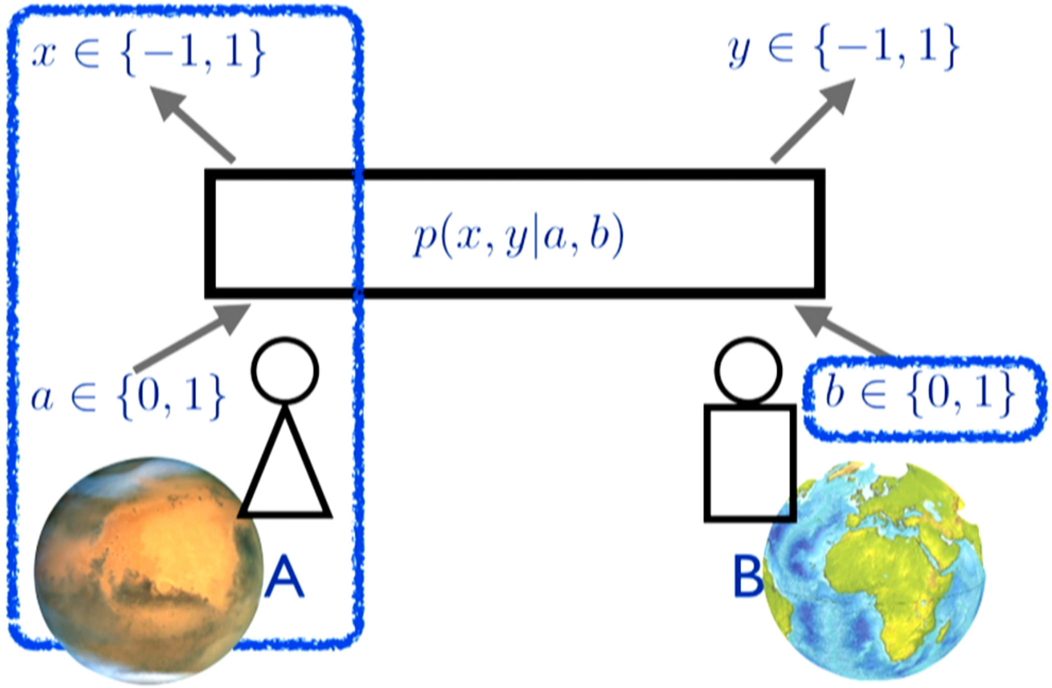


Quantum physics: $p(x, y|a, b) = \langle\psi|\hat{P}_a^x \otimes \hat{P}_b^y|\psi\rangle.$

Classical physics: $p(x, y|a, b)$ conditional prob.

Slightly more abstract picture…



Classical and quantum physics satisfy no-signalling:

$p(x|a)$ does not depend on b (and vice versa).

The Bell-CHSH inequality

Classical probability distributions satisfy Bell inequality:

$$\mathrm{CHSH} := |C_{00} + C_{01} + C_{10} - C_{11}| \leq 2 \quad \text{where} \quad C_{ab} := \mathbb{E}\,(x \cdot y | a, b)\,.$$

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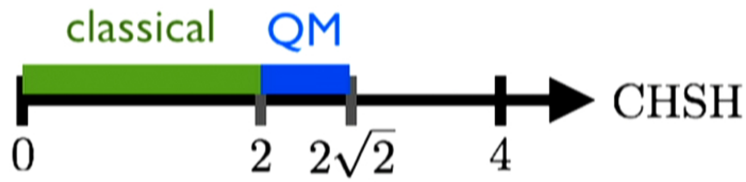

Quantum: Bell inequality violation.

$$\mathrm{CHSH} \leq 2\sqrt{2}.$$

S. Popescu and D. Rohrlich, Found. Phys. **24**, 379 (1994).

In 1994, Popescu and Rohrlich asked:
Are quantum correlations the most general correlations that are non-local, but still fit into relativistic spacetime?

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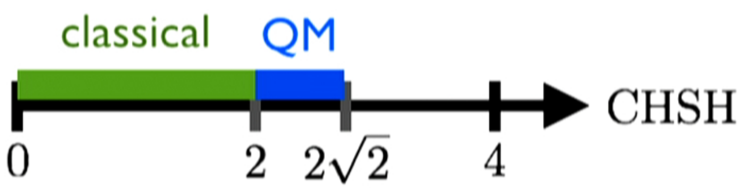

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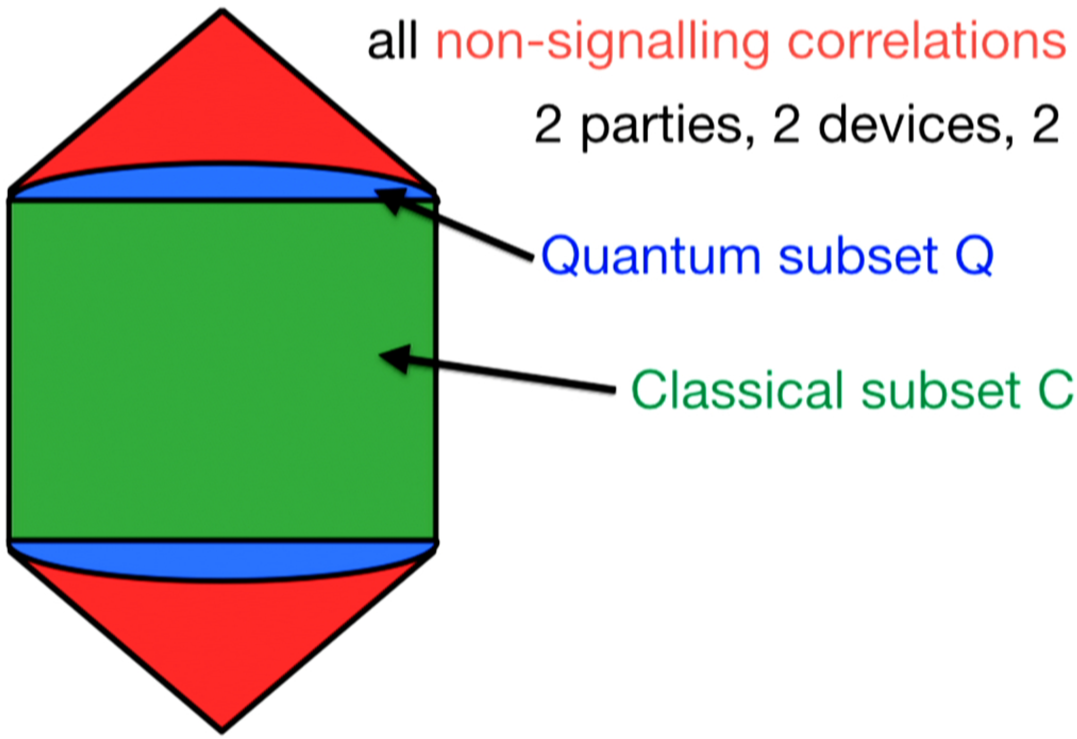
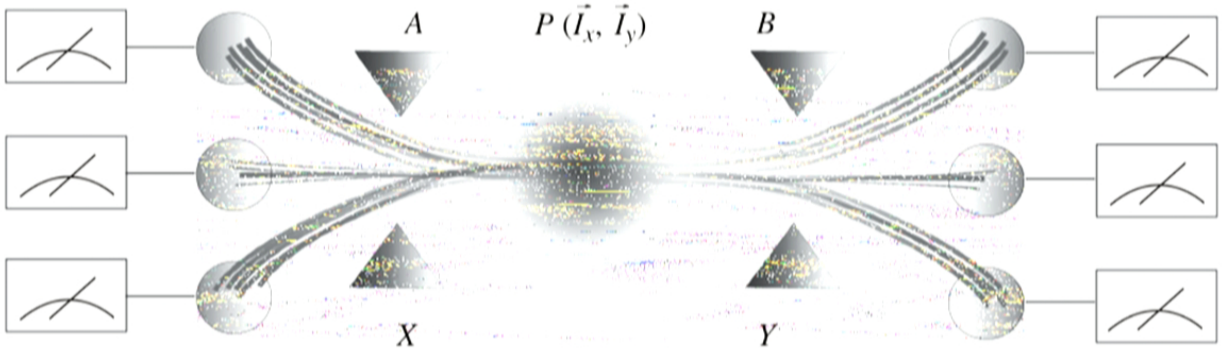
The (8D) no-signalling polytope

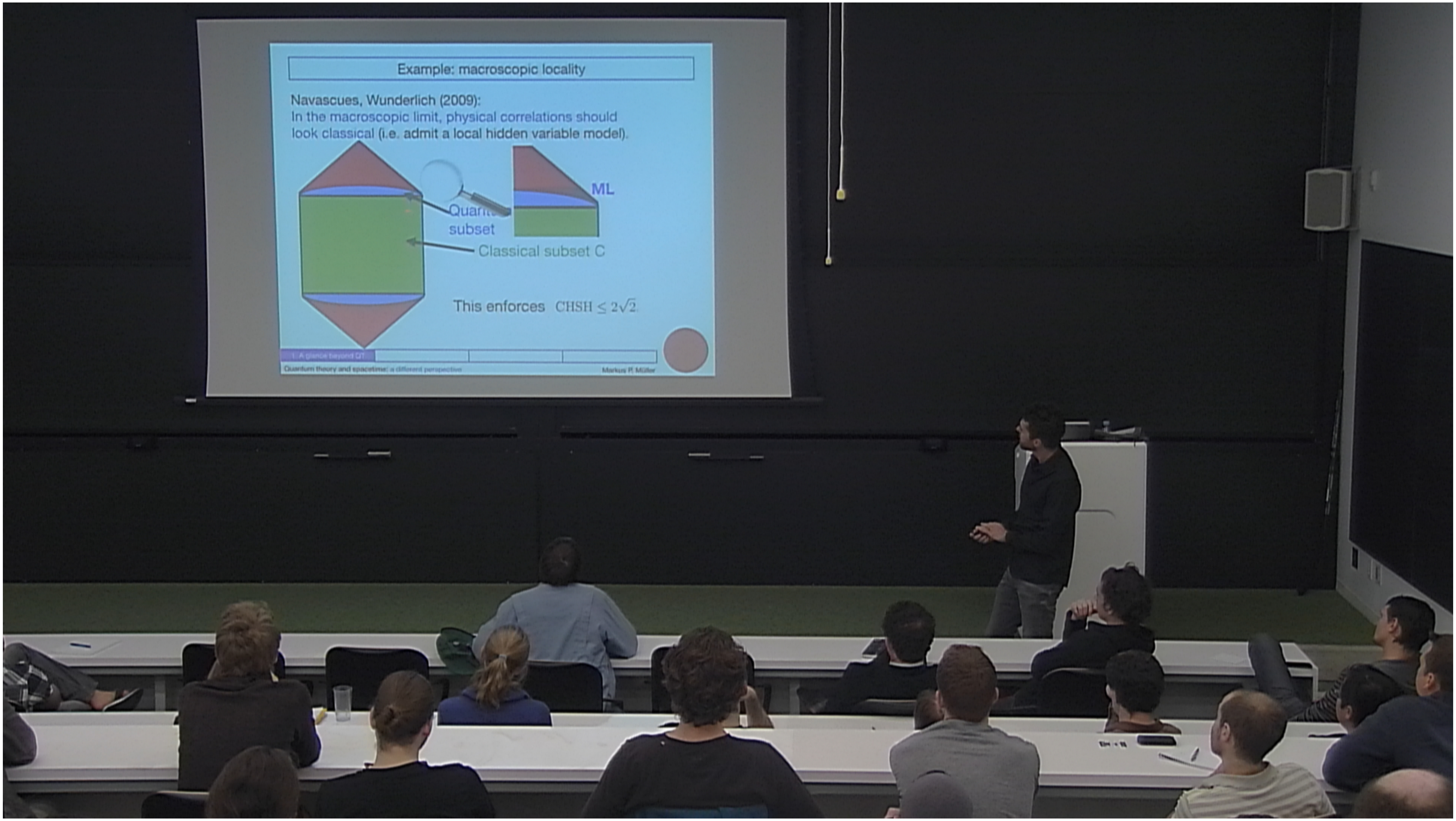


Example: macroscopic locality

Navascues, Wunderlich (2009):
In the macroscopic limit, physical correlations should look classical (i.e. admit a local hidden variable model).



M. Navascues and H. Wunderlich, Proc. R. Soc. A **8**, 881-890 (2009).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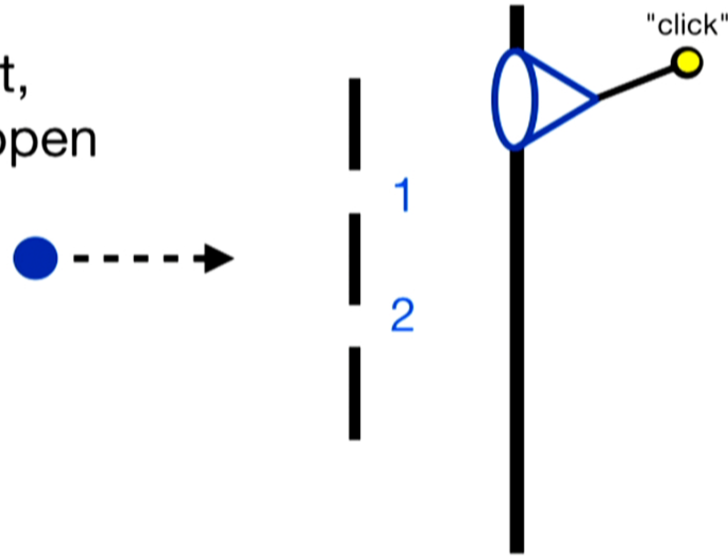
In the macroscopic limit, physical correlations should look classical (i.e. admit a local hidden variable model).
ML
subset
Classical subset C
This enforces CHSH ≤ 2√2.
Markus P. Müller

Higher-order interference

R. D. Sorkin, *Quantum mechanics as quantum measure theory*, Mod. Phys. Lett. A **9**, 3119-3128 (1994).
C. Ududec, H. Barnum, and J. Emerson, *Three slit experiments and the structure of quantum theory*, Found. Phys. **41**, 396-405 (2011).

$p_{i,j,\ldots} :=$ probability of event, if slits $i, j, \ldots$ are open



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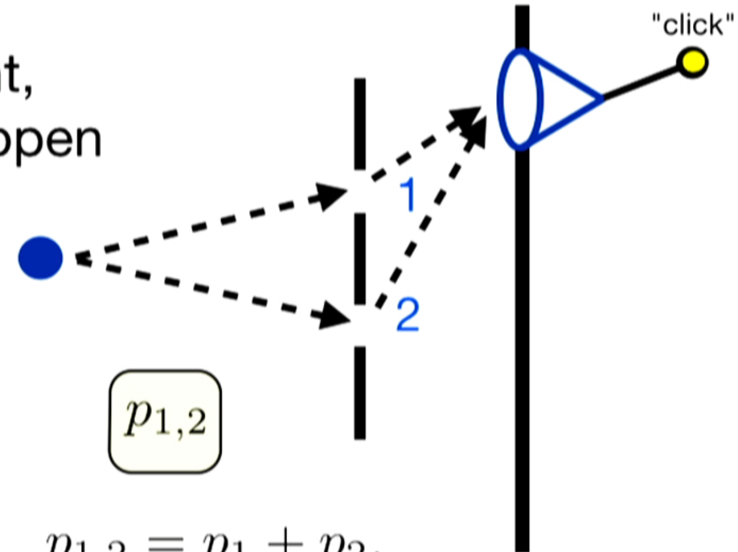

Classical probability theory: $p_{1,2} = p_1 + p_2.$

Quantum theory: $p_{1,2} \neq p_1 + p_2.$ **Interference!**

Higher-order interference

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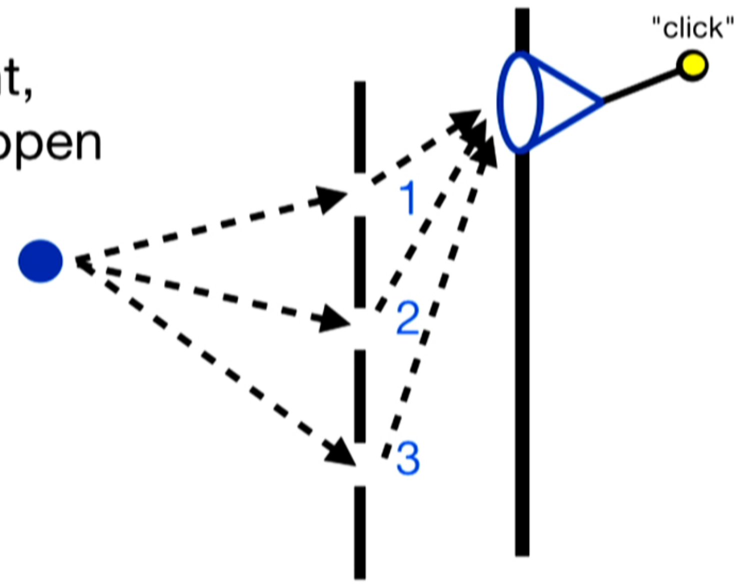
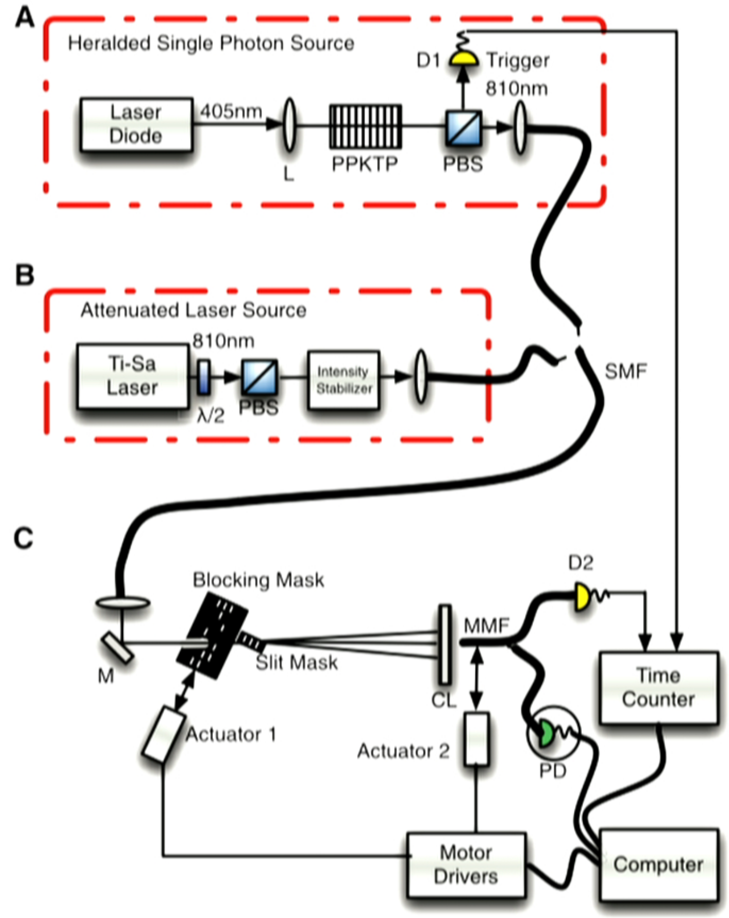


Higher-order interference

Science
AAAS

U. Sinha, C. Couteau, T. Jennewein, R. Laflamme, G. Weihs, *Ruling Out Multi-Order Interference in Quantum Mechanics*, Science **329**, 418 (2010).



Outline

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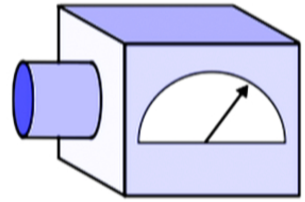
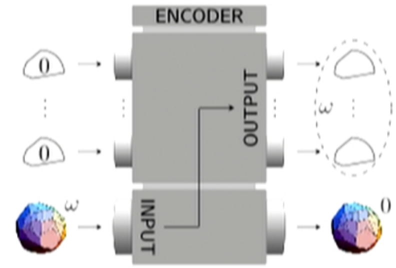
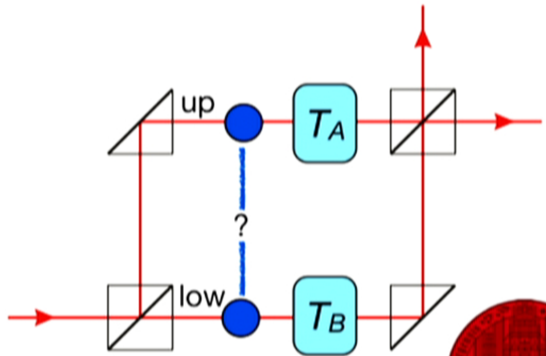


2. QT from simple principles



3. QT and spacetime: surprises

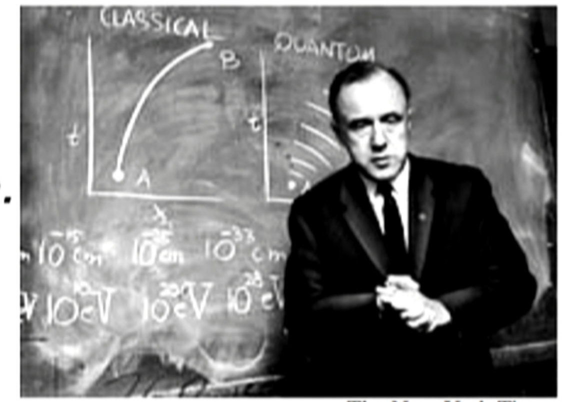


2. Quantum theory from simple principles

John A. Wheeler, New York Times, Dec. 12 2000:

„Quantum physics [...] has explained the structure of atoms and molecules, [...] the behavior of semiconductors [...] and the comings and goings of particles from neutrinos to quarks.

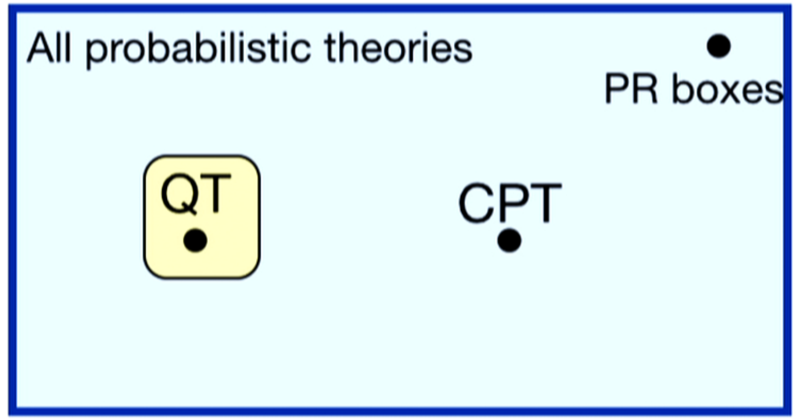
Successful, yes, but mysterious, too.
Why does the quantum exist?"



The New York Times

2. Quantum theory from simple principles

Goal:
Simple principles that yield exactly QT.



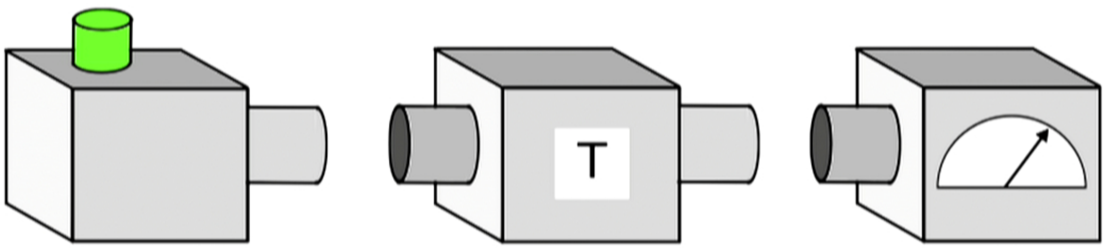
- Many of them are "weirder" than QT;
- many features the same as in QT: no-cloning, entanglement, …


2. Quantum theory from simple principles
Goal:
Simple principles
that yield exactly QT.
All probabilistic theories
PR boxes
QT
CPT
• Many of them are "weirder" than QT;
• many features the same as in QT:
no-cloning, entanglement, ...
2. QT from principles
Quantum theory and spacetime: a different perspective
Markus P. Müller

How to describe a "general probabilistic theory"

Historical background:

- Was independently discovered many times over the decades.
- Contains Jordan algebras *(Jordan, von Neumann, Wigner 1934)* as special cases, as well as quantum logics,
- was studied under the names "base-norm spaces" / "order-unit spaces" and "statistical models" by mathematicians.
- Rediscovered in quantum information theory.



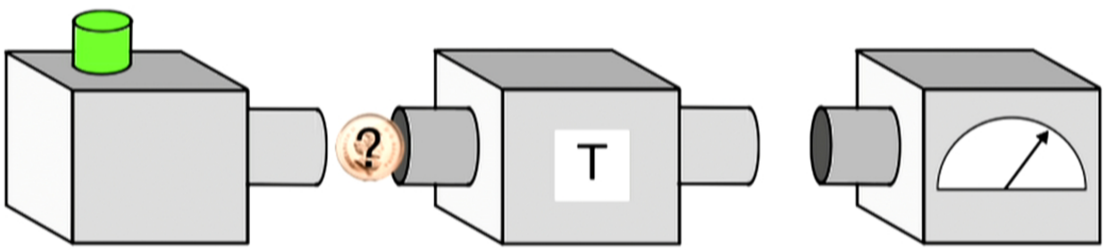
Preparation, transformation, measurement.

How to describe a "general probabilistic theory"

Example: classical coin toss.

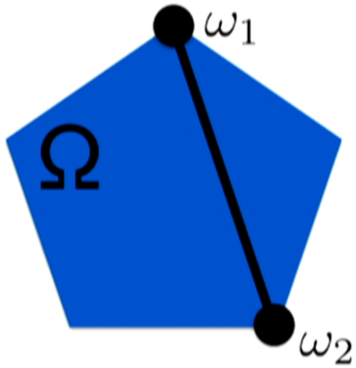
- The preparation device prepares a physical system in a state ω. Here

$$\omega = \begin{pmatrix} \text{Prob(heads)} \\ \text{Prob(tails)} \end{pmatrix} = \begin{pmatrix} p \\ 1-p \end{pmatrix}.$$



How to describe a "general probabilistic theory"

The set of all possible states of a given physical system is called the state space Ω.



For any two states, it also contains their statistical mixtures:

$$\omega = \lambda\omega_1 + (1-\lambda)\omega_2$$
$$(0 \leq \lambda \leq 1)$$

Thus Ω is a (compact) convex set.

QT: Ω_N = set of N×N density matrices

CPT: Ω_N = set of prob. distributions $(p_1, \ldots, p_N)$.

How to describe a "general probabilistic theory"

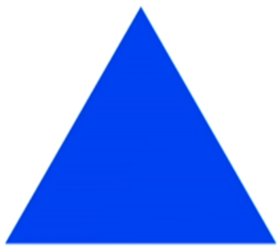
(Almost) everything can be inferred from shape of state space.

classical bit

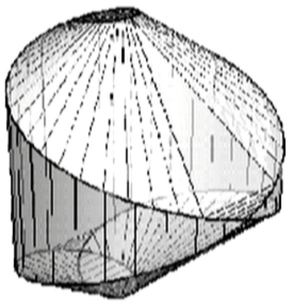
quantum bit

"gbit"

Arbitrary convex state space



Classical "trit" (3-level-system)



Quantum "trit". Complicated, 8D!

History

- Prehistory:

  Lots of early activity: Birkhoff & von Neumann (1936); quantum logic; Ludwig (1954); Alfsen&Shultz (≈1980); .....

- Quantum information revolution:

  L. Hardy 2001: Quantum Theory From Five Reasonable Axioms.
  But needs "simplicity axiom".

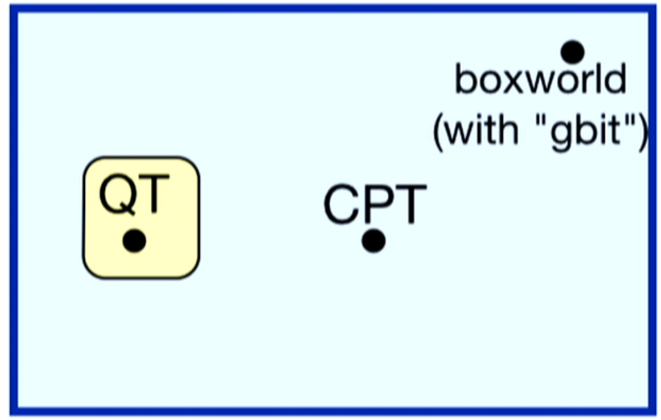
  Dakic+Brukner 2009 (*great ideas, not math. rigorous.*)
  Masanes + **MM** 2010
  Chiribella, d'Ariano, Perinotti 2010; Hardy 2011
  Masanes, **MM**, Augusiak, Pérez-García 2013 …

A reconstruction of quantum theory

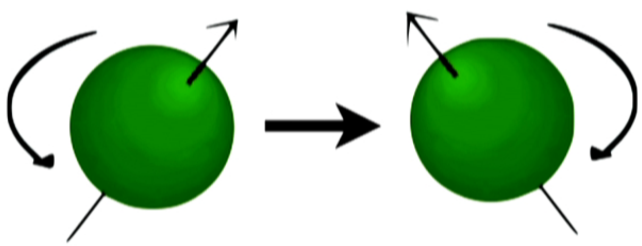
Ll. Masanes, **MM**, R. Augusiak, and D. Pérez-García, PNAS **110**(4), 16373 (2013).

- **Postulate 1**: Continuous reversibility.

In any system, for every pair of pure states, one can in principle engineer time-continuous reversible dynamics that brings one state to the other.



General **probabilistic theories** (GPTs)



A reconstruction of quantum theory

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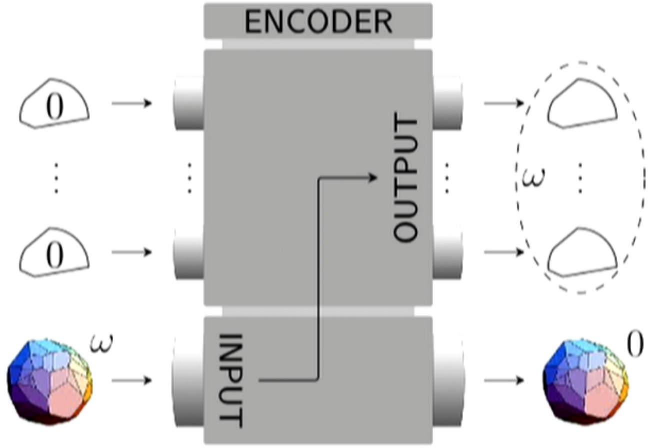
- **Postulate 1**: Continuous reversibility.
- **Postulate 2**: Tomographic locality.
- **Postulate 3**: Existence of an information unit.



There is a type of system (the "ubit") such that the state of any system can be encoded into a sufficiently large number of ubits.

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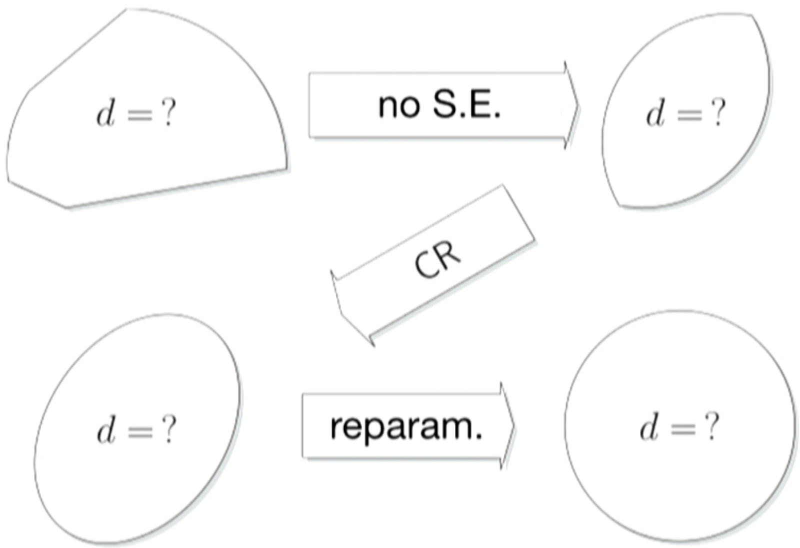

Proof steps:

1. **Show that the ubit state space is a *d*-dim. unit ball.**
2. Show that $d=3$.
3. Show that local QT ⇒ global QT (from these postulates).

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$d = 1$ classical bit

$d = 2$

$d = 3$ quantum bit

Apriori, arbitrary *d* are possible.

Proof steps:

1. **Show that the ubit state space is a *d*-dim. unit ball.**
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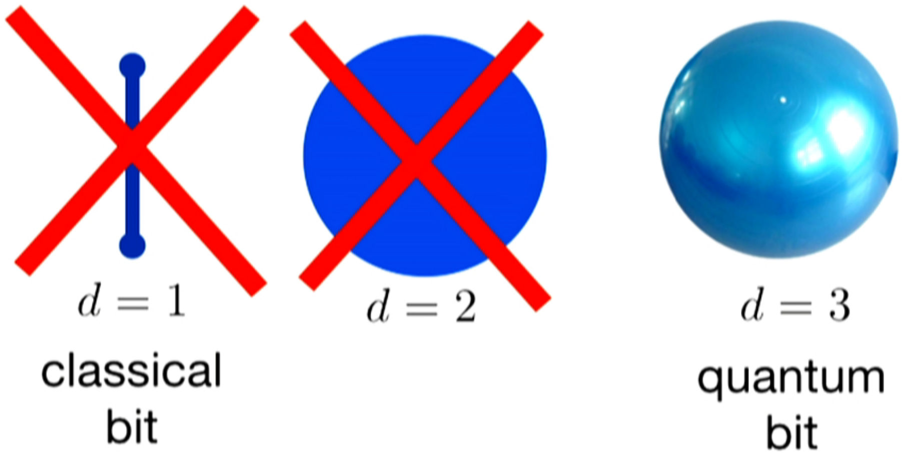


Proof steps:
1. Show that the ubit state space is a *d*-dim. unit ball.
2. **Show that *d*=3.**
3. Show that local QT $\Rightarrow$ global QT (from these postulates).

Some heavy group theory / convex geometry:

Ll. Masanes, **MM**, R. Augusiak, and D. Pérez-García, arXiv:1111.4060.

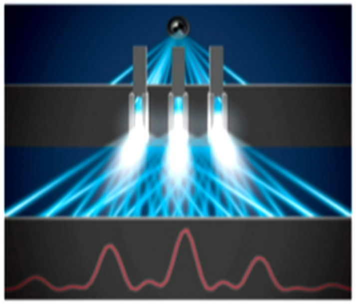
If *d*≠3, then all continuous reversible time evolutions act locally, as $T_A \otimes T_B$.

Interlude: an application

H. Barnum, **MM**, and C. Ududec, *Higher-order interference and single-system postulates characterizing quantum theory*, arXiv:1403.4147 (to appear in NJP)

QT follows also from the following:

1. Lots of transformations;
2. decoherence to classical;
3. ~~**no third-order interference;**~~
4. energy is an observable.



Drop 3. → new solutions in addition to QT?

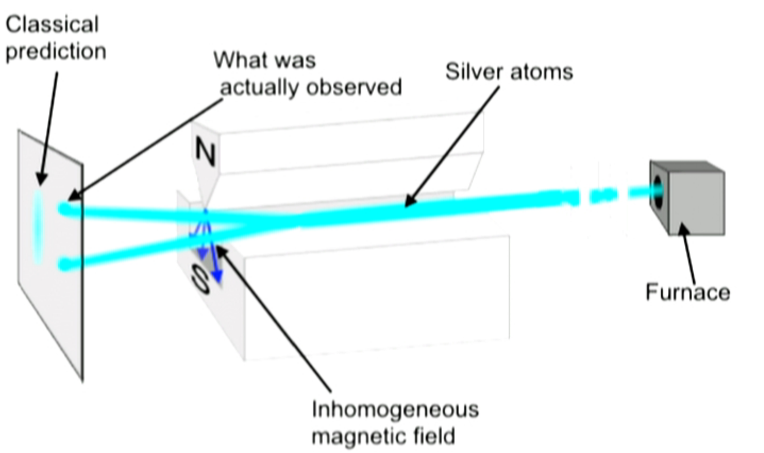
3. QT and spacetime: surprises

quantum 2-level state space

spatial rotations

↕ 1:1

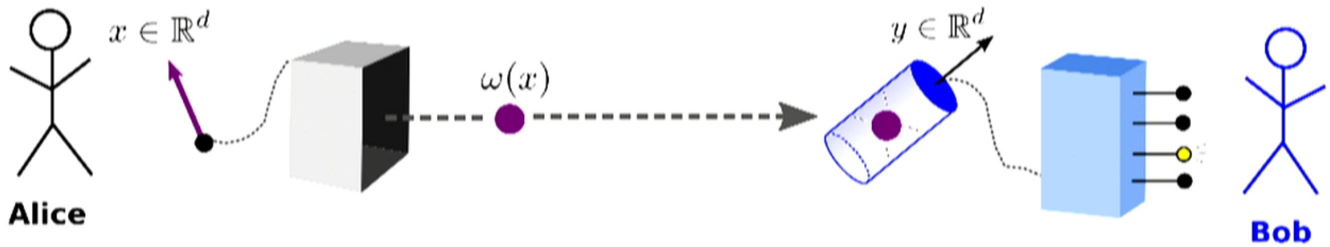
transformations of the probabilistic state



3. QT and spacetime: surprises

MM and Ll. Masanes, *Three-dimensionality of space and the quantum bit: an information-theoretic approach*, New J. Phys. **15**, 053040 (2013), arXiv:1206.0630.

Formulate as information-theoretic task in *d* dimensions:



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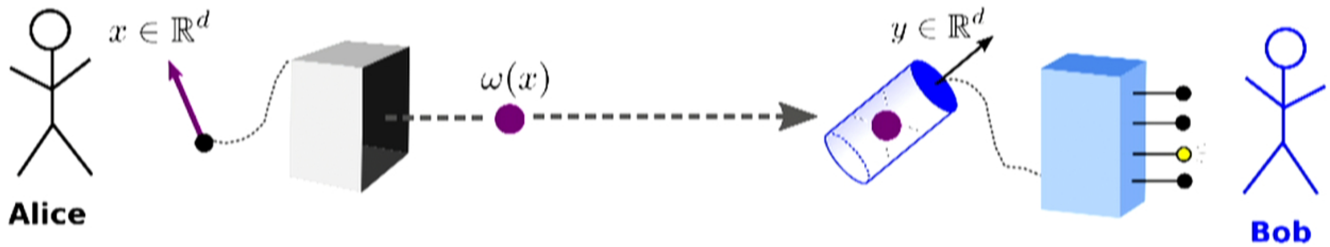

Suppose there is a probabilistic system such that...

1. Alice can encode any spatial direction into the state, but
2. any attempt to encode more results in information loss.
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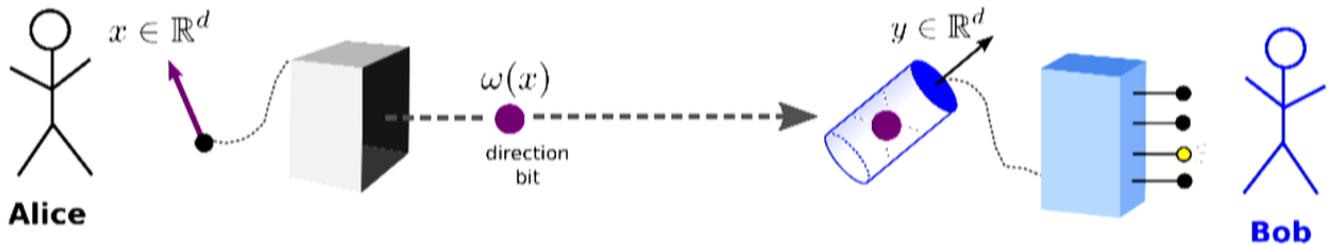

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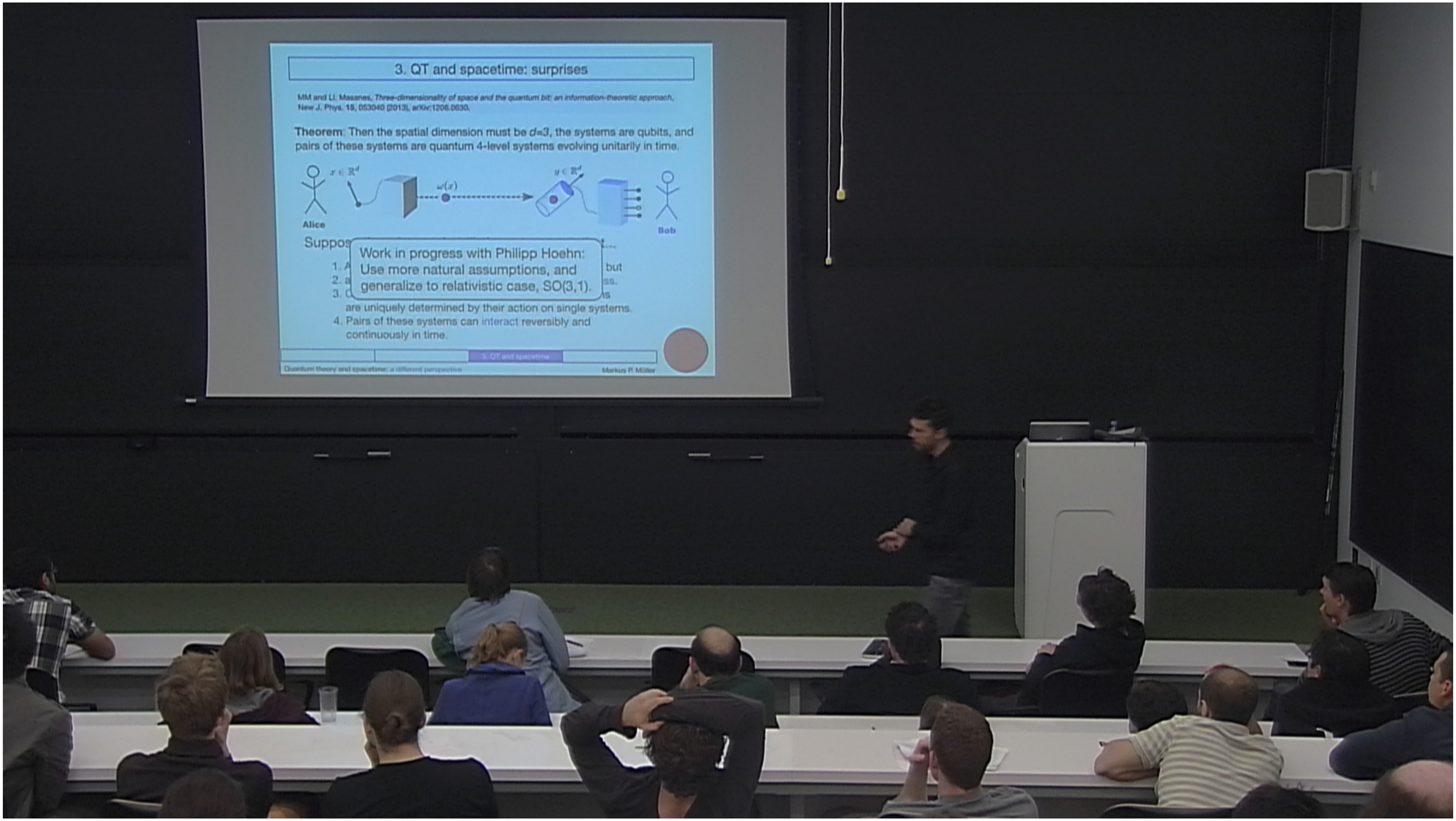
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$x \in \mathbb{R}^d$
$\omega(x)$
$y \in \mathbb{R}^d$
Alice
Bob
Work in progress with Philipp Hoehn:
Use more natural assumptions, and
generalize to relativistic case, SO(3,1).
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Markus P. Müller

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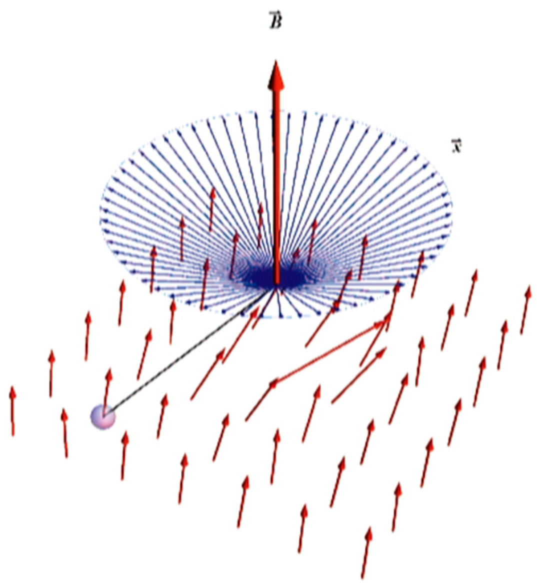
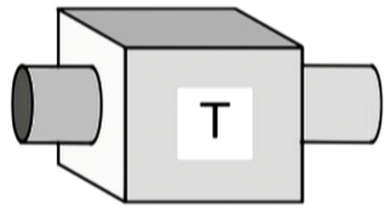
Related work by Dakic and Brukner:

(Transformation) devices are also built from (post-)quantum stuff.





Transformations from pairwise interaction of particle with *d*-dim. spin-coherent state ⇒

d=3 and quantum theory.

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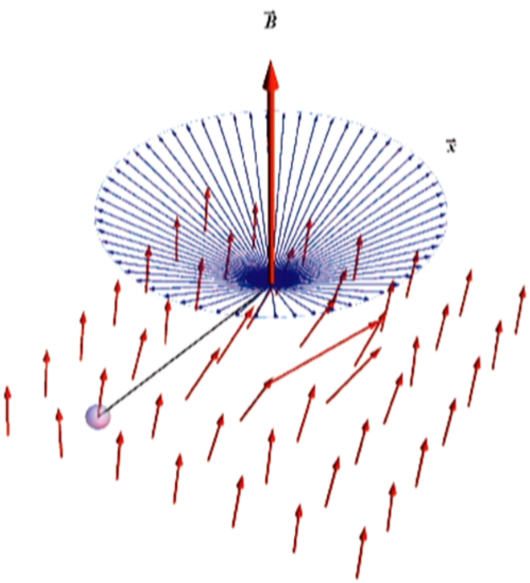

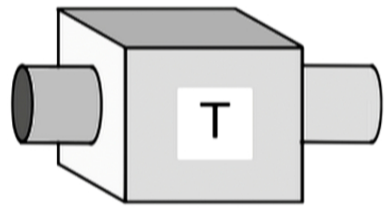

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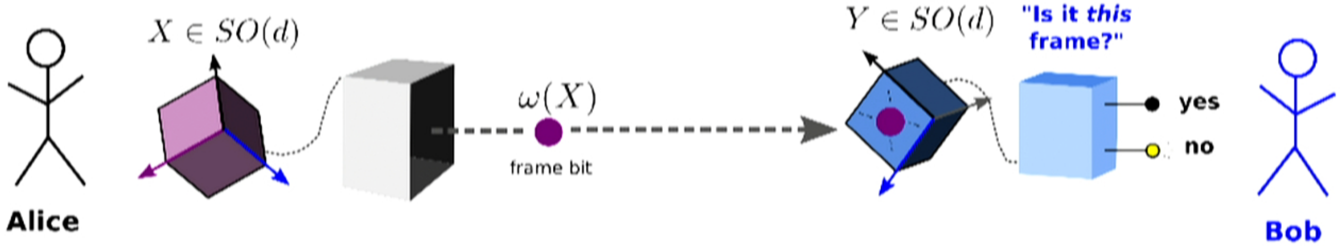
One more Theorem: If "spatial direction" $x \in \mathbb{R}^d, \;\; |x| = 1$, is replaced by "spatial orientation" $X \in SO(d)$, then there is no solution (for topological reasons).



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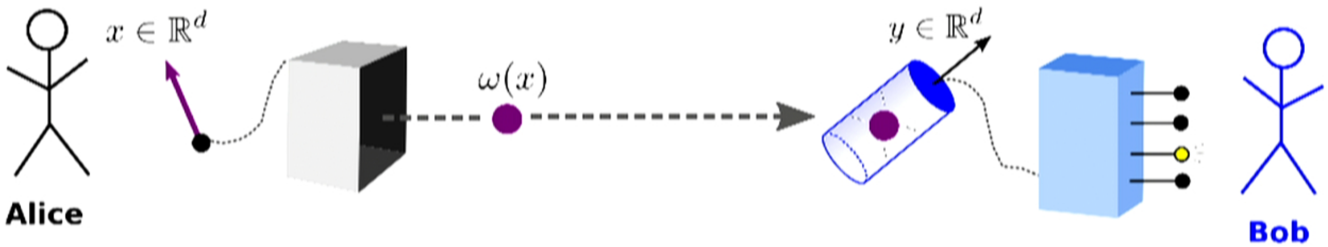


Suppos... t...

1. A... but
2. a... ss.
3. C... ns

are uniquely determined by their action on single systems.

4. Pairs of these systems can interact reversibly and continuously in time.

Work in progress with Philipp Hoehn: Use more natural assumptions, and generalize to relativistic case, SO(3,1).

Relativistic constraints on interference experiments

Two-level state spaces ("bits") are naturally ball state spaces:

$d = 1$

classical bit

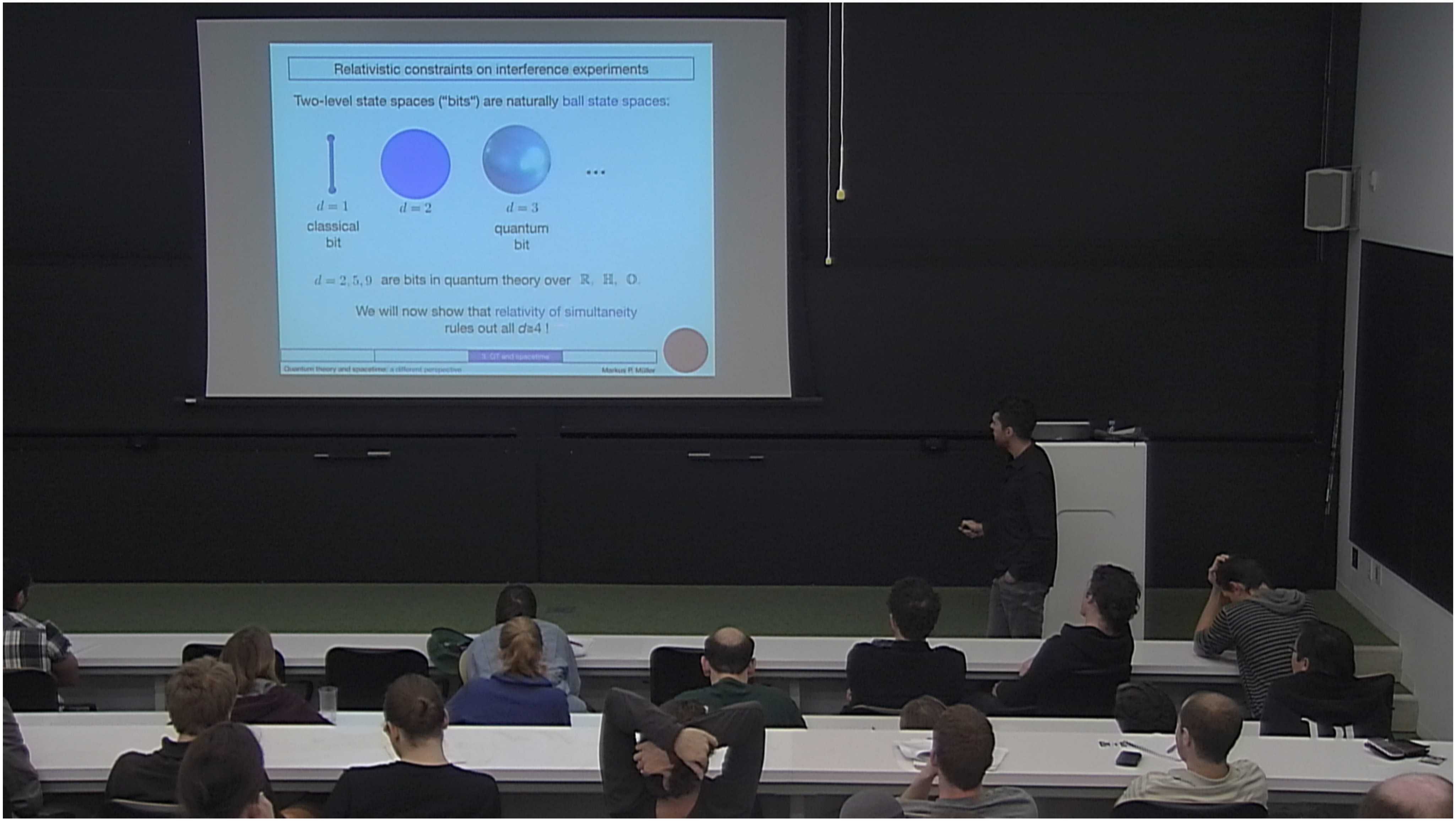
$d = 2$

$d = 3$

quantum bit

...

$d = 2, 5, 9$ are bits in quantum theory over $\mathbb{R}$, $\mathbb{H}$, $\mathbb{O}$.


Relativistic constraints on interference experiments
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$d=1$
classical bit
$d=2$
$d=3$
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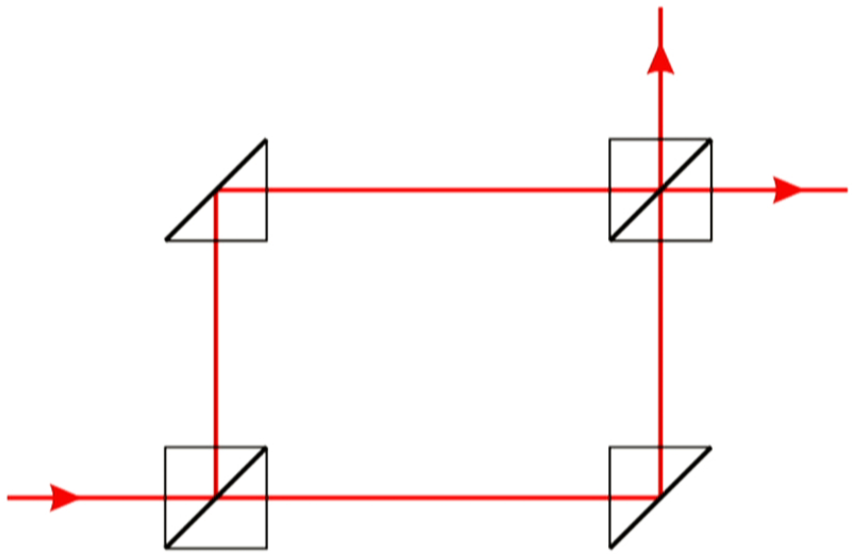
...
$d=2,5,9$ are bits in quantum theory over $\mathbb{R}$, $\mathbb{H}$, $\mathbb{O}$.
We will now show that relativity of simultaneity rules out all $d \geq 4$!

Relativistic constraints on interference experiments

Joint work w/ Andy Garner & Oscar Dahlsten (Oxford):

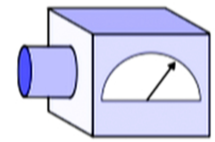


Different perspectives

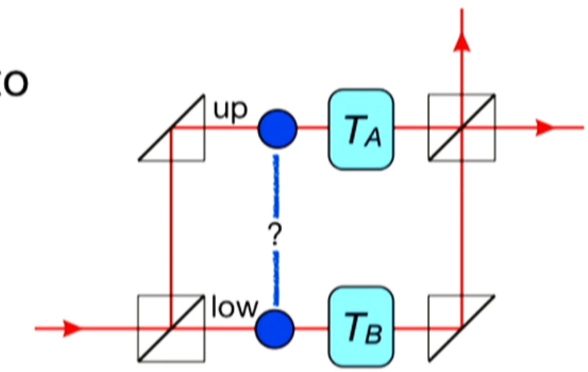
This kind of research allows to ask "why" and "what if" questions:

Why quantum theory?
Why the path integral? Or under which assumptions?
What if A was different, could we still have B?

Conclusion



- QT is just one probabilistic theory among many…
- … and can be derived from simple postulates.
- In this new perspective, relation to spacetime becomes evident.



Thanks to:
Howard Barnum, Oscar Dahlsten, Andy Garner, Lucien Hardy, Philipp Hoehn, Lluís Masanes, Lee Smolin, Rob Spekkens, Cozmin Ududec.

Thank you!