Title: Quantum control in foundational experiments

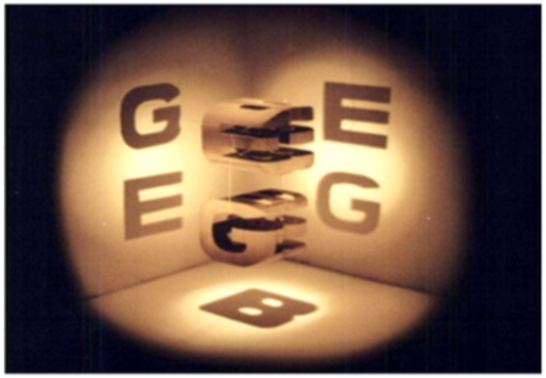
Date: May 05, 2015 03:30 PM

URL: http://pirsa.org/15050016

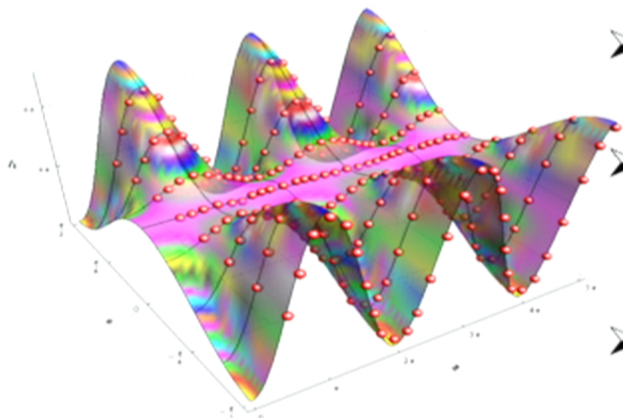
Abstract: <p>Using quantum control in foundational experiments allows new theoretical and experimental possibilities. We show how, e.g., quantum controlling devices reverse a temporal ordering in detection. We consider probing of waveâ€“particle duality in quantum-controlled and the entanglement-assisted delayed-choice experiments. Then we discuss other situations where quantum control may be useful, and finally demonstrate how the techniques we developed are applied to the study of consistency of the classically reasonable requirements. In a version of the delayed-choice experiment which ostensibly combines determinism, independence of hidden variables on the conducted experiments, and wave-particle objectivity we show that these ideas are incompatible with any theory, not only with quantum mechanics.</p>

OUTLINE

- Complementarity & delayed choice
- Hidden variables 101
- Quantum control
- Entangled control
- Contradictions without quantum theory



REFERENCES



- Ionicioiu and Terno, Phys. Rev. Lett. **107**, 230406 (2011).
- Céleri, Gomes,. Ionicioiu, Jennewein, Mann, and. Terno, Found. Phys. **44**, 576 (2014).
- Ionicioiu, Jennewein, Mann, and Terno, Nature Comm. **5**, 3997 (2014)
- Ionicioiu, Mann, and Terno, Phys. Rev. Lett. **114**, 060405 (2015)

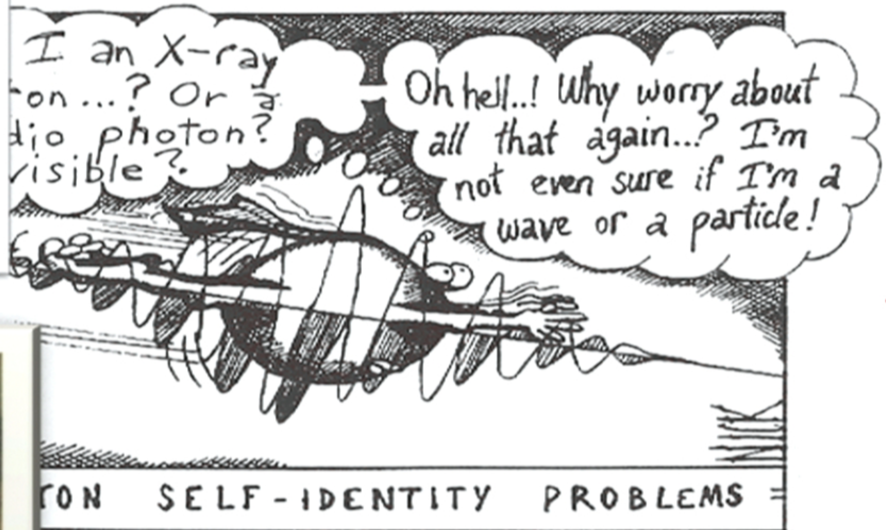
- Ma, Kofler, and Zeilinger, *Delayed-choice gedanken experiments and their realizations*, arXiv:1407.2930v1

PART 1

COMPLEMENTARITY & DELAYED CHOICE

A bit of history
Complementarity
WDC

LIGHT:
WAVES vs PARTICLES



Photons are particles

Photons are waves

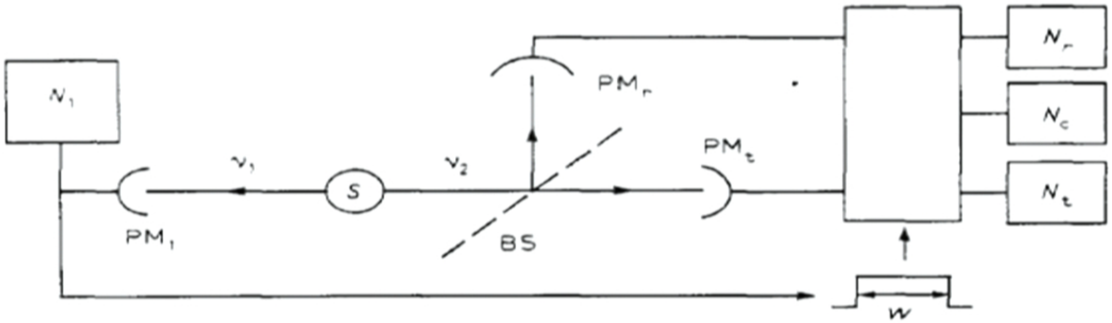
LIGHT:
WAVES vs PARTICLES

Photons are particles

Photons are waves

PHOTONS

at last



Single photons behave as particles

Grangier, Roger and Aspect
Europhys. Lett. **1**, 173 (1986)

PHOTONS

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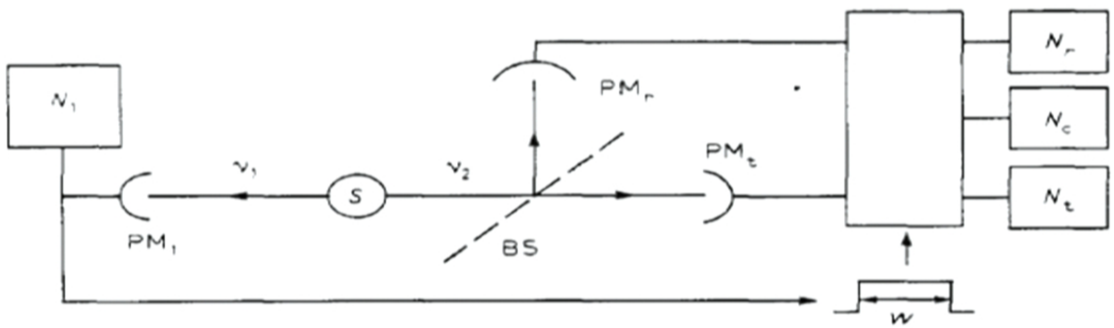

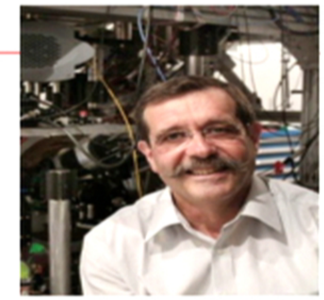

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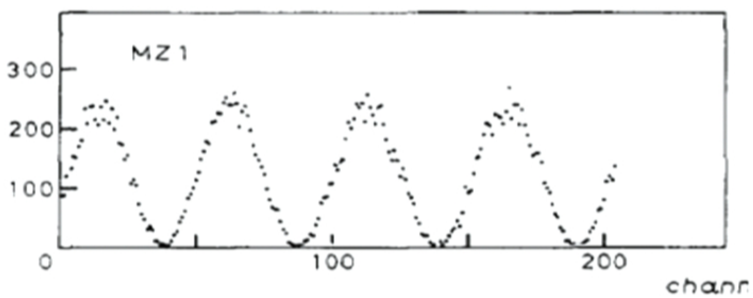

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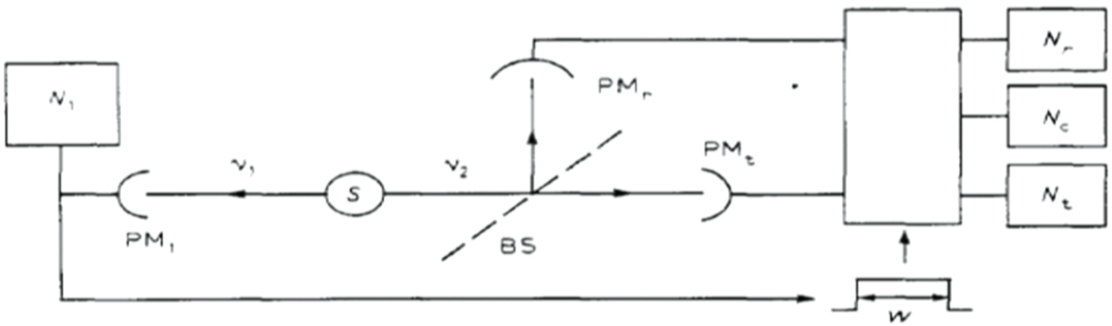

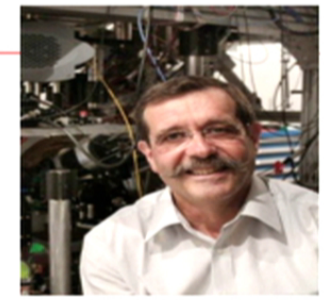

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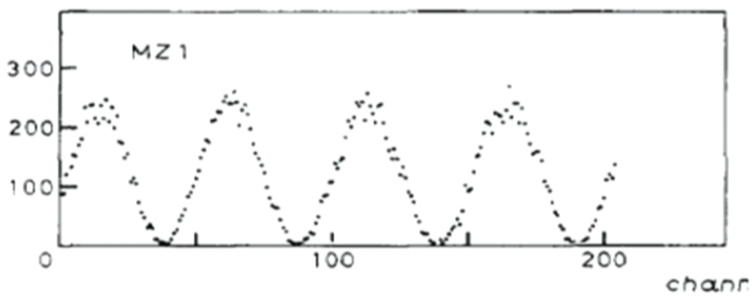

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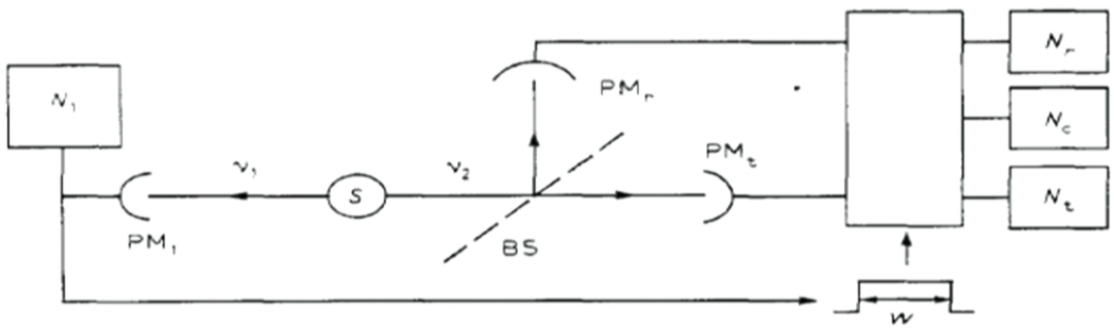

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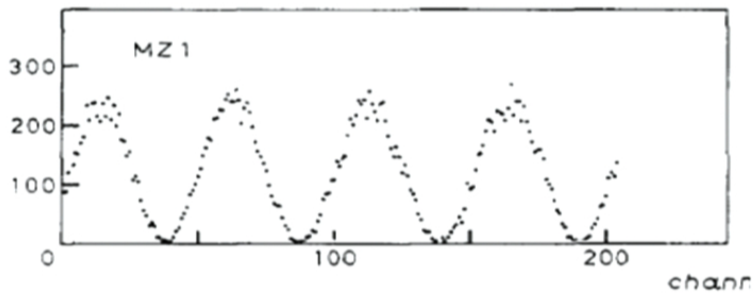


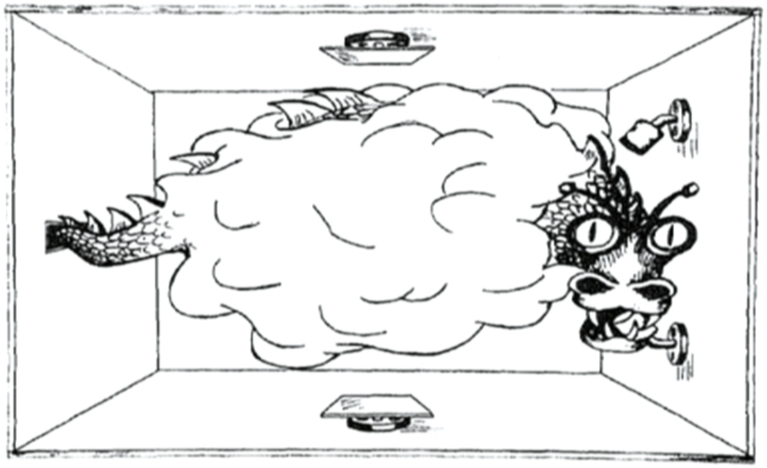
DEFINITIONS

Particles: no interference,
► single path
Waves: interference,
► both paths

COMPLEMENTARITY:

a modern version

... the information provided by different experimental procedures that in principle cannot, because of the physical character of the needed apparatus, be performed simultaneously, cannot be represented by any mathematically allowed quantum state of the system. The elements of information obtainable from incompatible measurements are said to be *complementary*.



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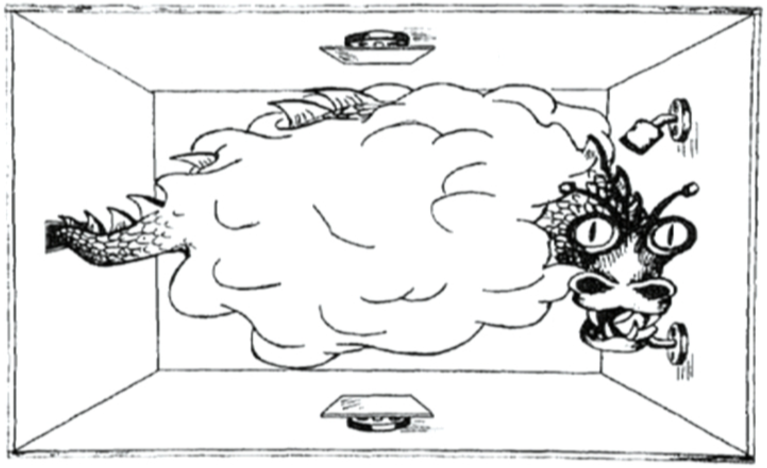
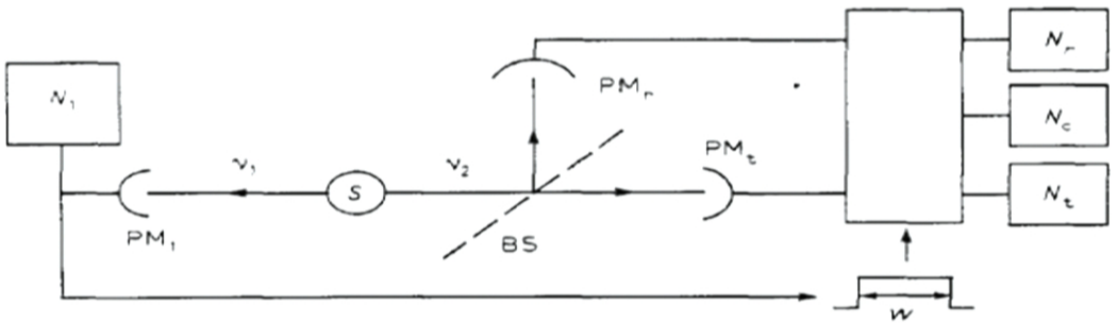
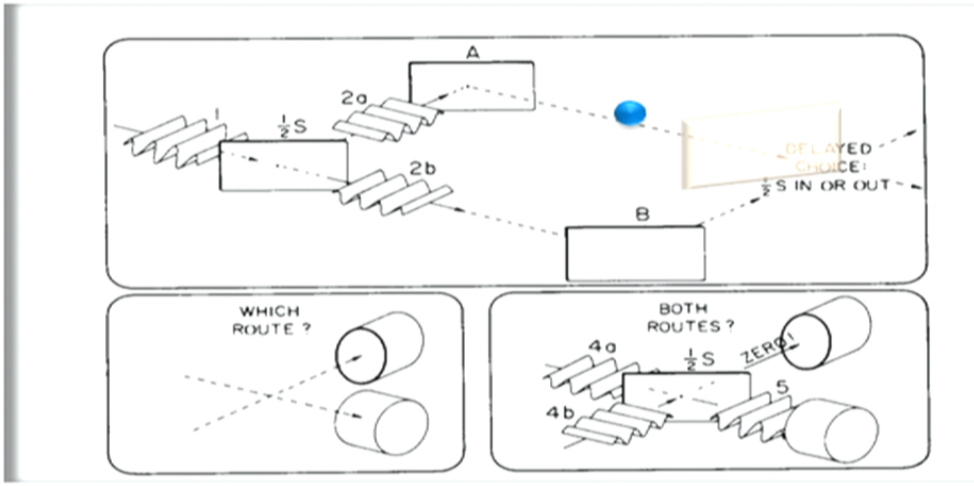


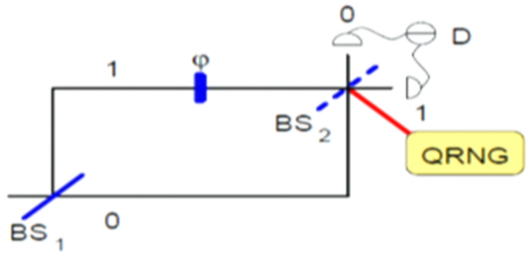
COMPLEMENTARITY: *a conspiracy*

The photon could know in advance of entering the apparatus whether the latter has been set up in the "wave" configuration with BS_2 in place or the "particle" one (BS_2 removed) and adjust accordingly.



DELAYED CHOICE



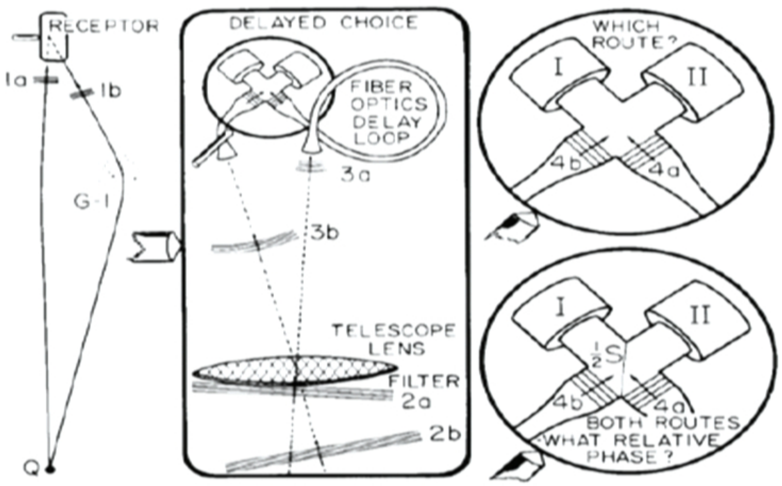


Wheeler, 1978, 1984

By making the choice to close or open the MZI when the photon is already in, it is forced not to change its mind

DELAYED CHOICE

[a tagline v. 1.0]



Hitch guide: to deal with
The ensuing english

...we discover "by which route" it came with one arrangement; or by the other, what the relative phase is of the waves associated with the passage of the photon from source to receptor by both routes"{perhaps 50,000 light years apart as they pass the lensing galaxy G-1. But the photon has already passed that galaxy billions of years before we made our decision

In this sense, we have a strange inversion of the normal order of time. We, now, by moving the mirror in or out have an unavoidable effect on what we have a right to say about the already past history of that photon

HV THEORIES

Purpose: reproduce observed statistics and maintain classical concepts

Viewed as [likely] inadequate, but consistent world view

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Counter-HV action
◇ consider a set-up
◇ make a QM prediction
◇ make a HV prediction
◇ compare
  get a contradiction
◇ make an experiment

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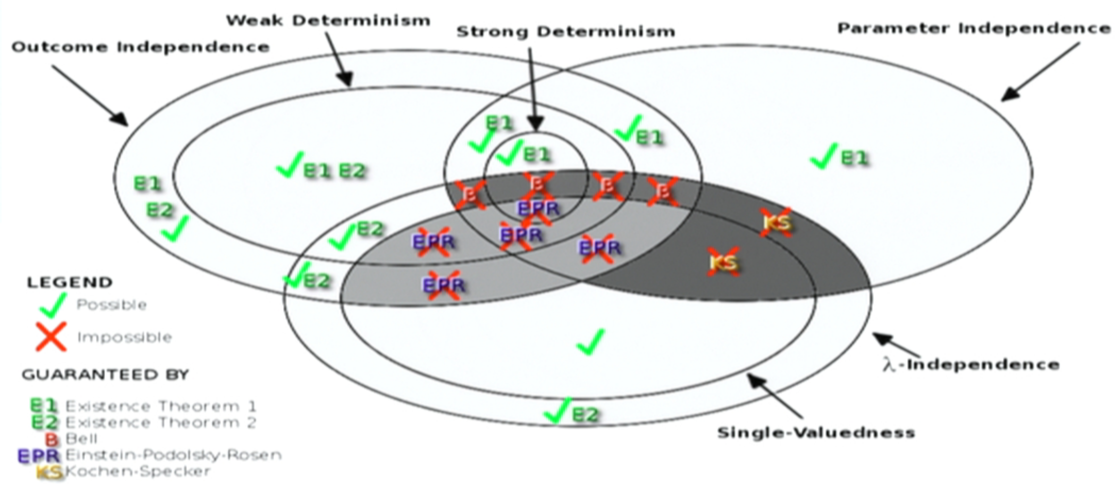
Counter-counter-HV action
- ❑ find a loophole
- ❑ introduce conspiratorial correlations



Brandenburger & Yanofsky
JPA **41** 425302 (2008) ►

HV THEORIES

Measurements and settings:

$A, A'; B, B'$

Outcomes

$a, a'; b, b'$

Brandenburger & Yanofsky, J. Phys. A **315**, 966 (2007)

HV THEORIES

- **Determinism**: once hidden variables are defined, there are no residual randomness [several flavors]

$$\forall A\ \exists a:\ p(a \mid A,\lambda) = 1$$ ◄ strong

- **Parameter independence**: the outcome of any measurement depends only on the HV and the set-up of this measurement

$$p(a \mid A,B,C,\ldots,\lambda) = p(a \mid A,\lambda)$$

- **HV (λ-)independence**: determination of the hidden variable is independent of the choice of measurement

$$p(\lambda \mid A,B\ldots) = p(\lambda \mid A',B'\ldots)$$

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Brandenburger & Yanofsky, J. Phys. A **315**, 966 (2007)

Locality, contextuality, Bell inequalities,... are all derived from these three axioms

HV THEORIES

Extensions & questions

- What is the basis for assertion of wave-particle duality?
- ❑ Can we detect "it" first and decide what was it later?
- ❑ Is space-like separation necessary?
- ❑ What if the controlling devices are quantum?

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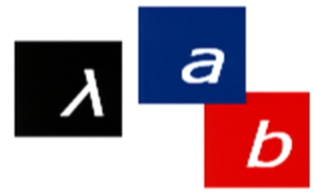
Conspiracy & counter-conspiracy



❑ A hidden variable λ=p,w set at production/before splitting

❑ Reproduction of the observed data for some $p(a,b,\lambda)$

HV THEORIES

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Conspiracy & counter-conspiracy

λ a b

❑ A hidden variable λ=p,w set at production/before splitting

❑ Reproduction of the observed data for some $p(a,b,\lambda)$

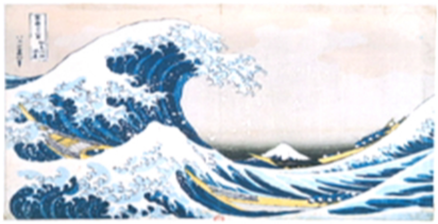
data | HV theory | IC

$$q(a,b) = \sum_{\lambda=p,w} p(a,b,\lambda) = \sum_{\lambda=p,w} p(a,b\mid\lambda) \times p(\lambda)$$

OBJECTIVITY

a.k.a. DEFINITNESS

Photons are either particles $\lambda = p$ or waves $\lambda = w$



$$p(a \mid b = 1, \lambda = w) = (\cos^2 \tfrac{\phi}{2}, \sin^2 \tfrac{\phi}{2})$$

$$p(a \mid b = 0, \lambda = p) = (\tfrac{1}{2}, \tfrac{1}{2})$$

$$p(a \mid b = 0, \lambda = w) = (x, 1 - x)$$
$$p(a \mid b = 1, \lambda = p) = (y, 1 - y)$$

WDC

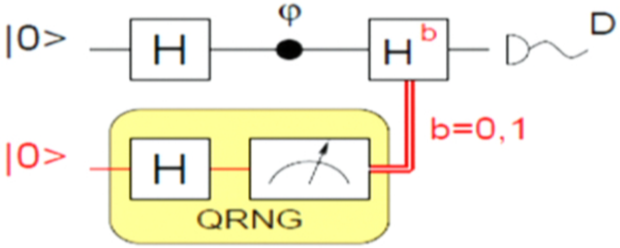
Logic

$$n(a,b)=\sum_{\lambda} p(a\,|\,b,\lambda)\,p(\lambda\,|\,b)\,n(b)$$

Causal:

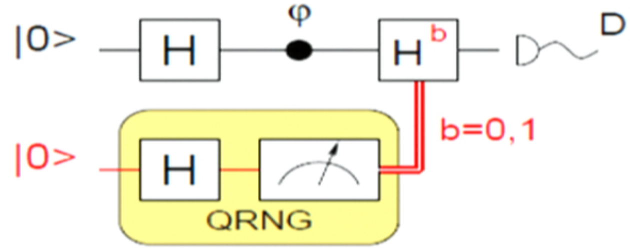
$$p(\lambda\,|\,b)=\delta_{\lambda p}\delta_{b0}+\delta_{\lambda w}\delta_{b1}$$

This is the target of WDC experiments. Dismissed†



WDC *Logic*

$$\underbrace{q(a,b)}_{\text{data}} = \sum_{\lambda} \underbrace{p(a\,|\,b,\lambda)}_{\text{HV theory}} \times \underbrace{p(\lambda\,|\,b) \times n(b)}_{\text{IC}}$$



Causal:

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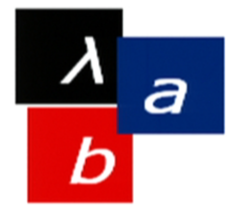

† unless "even more mind boggling" conspiracies are allowed
[e.g.: a correlation between HV of a photon & QRNG]

WDC *Logic*

b λ a

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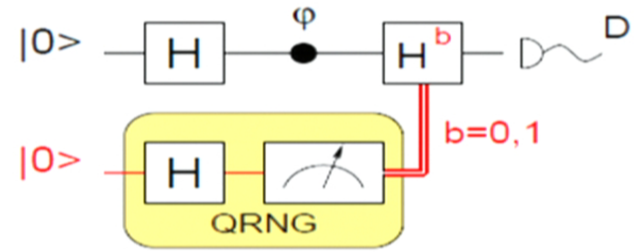

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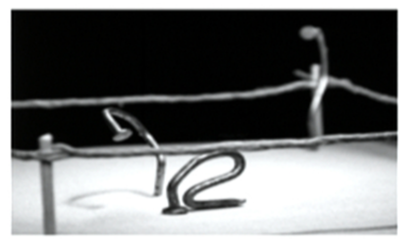
This is the target of WDC experiments. Dismissed†

Stochastic...

$$p(\lambda\,|\,b) = p(\lambda) = (\mathfrak{p}, 1-\mathfrak{p})$$

Consistency requirements resurrect wave-particle duality † :

$$p(a\,|\,b,\lambda) = p(a\,|\,b)$$



λ a b

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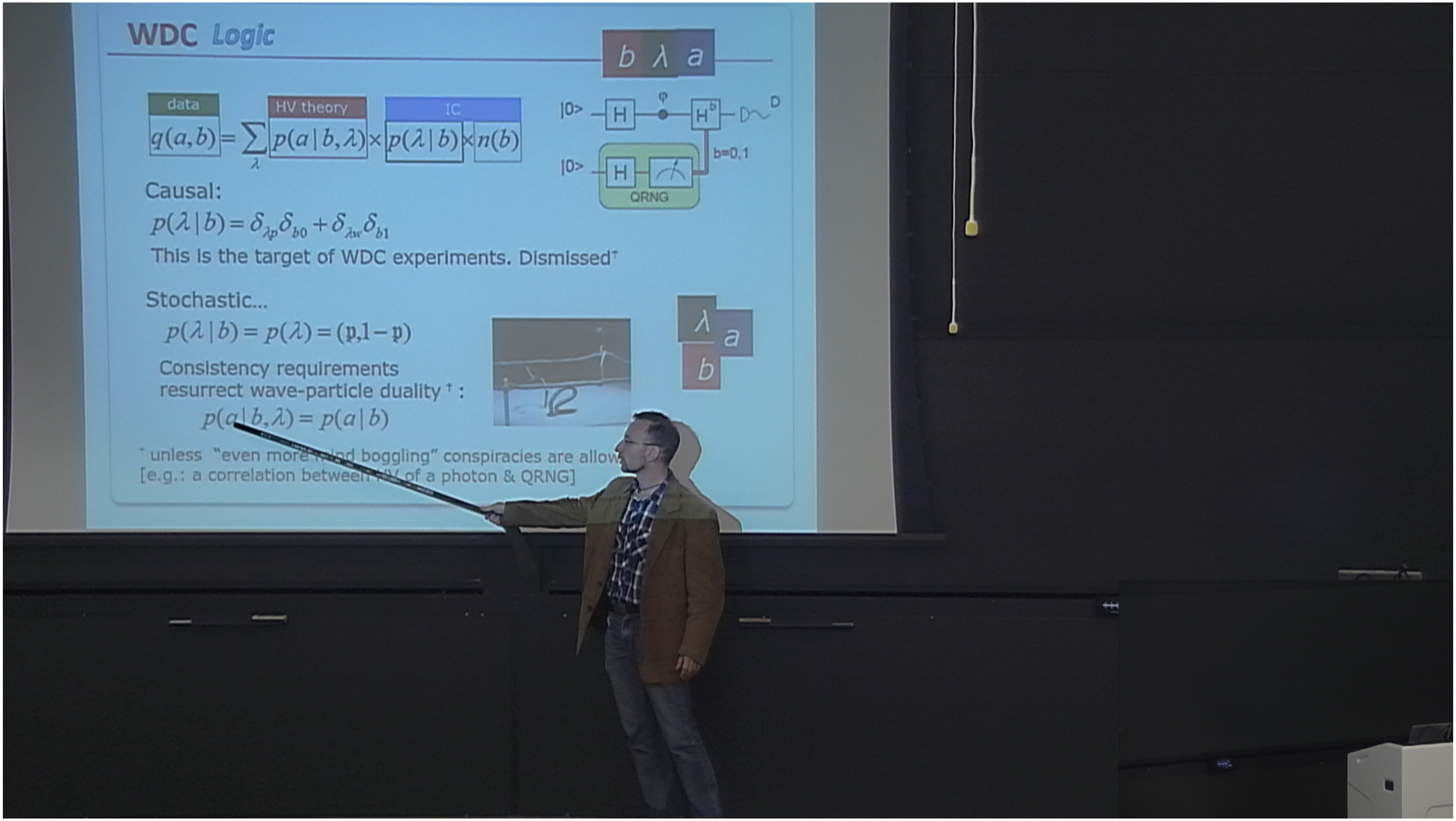
WDC Logic
b λ a
data
HV theory
IC
$q(a,b) = \sum_{\lambda} p(a|b,\lambda) \times p(\lambda|b) \times n(b)$
|0>
H
φ
H^b
D
|0>
H
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λ
a
b
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$p(a|b,\lambda) = p(a|b)$
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[e.g.: a correlation between HV of a photon & QRNG]

DELAYED CHOICE

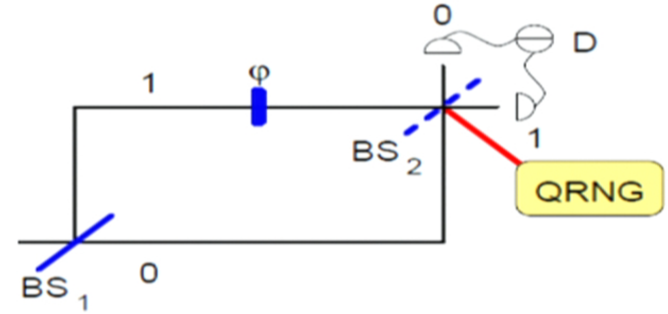
+ QRNG

Open interferometer [particle]

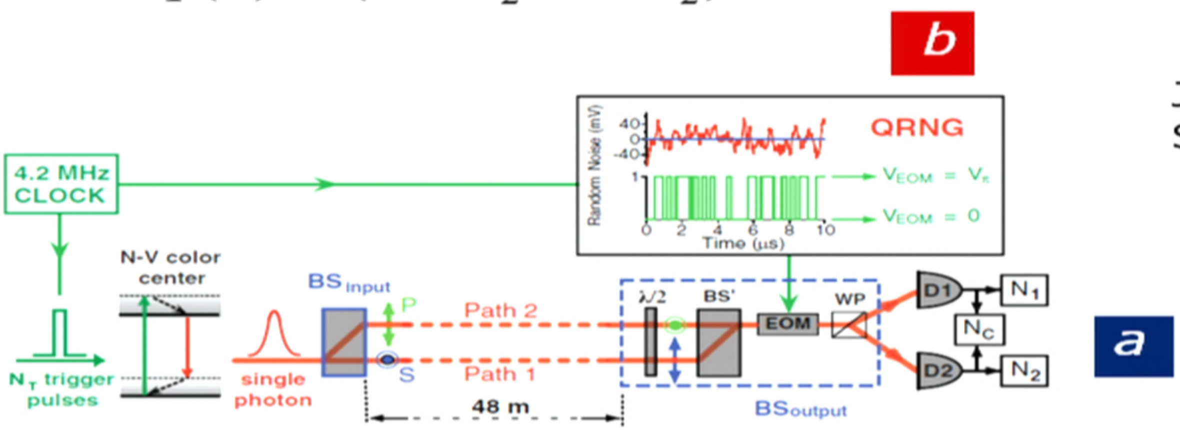
$$q(a) = (\tfrac{1}{2}, \tfrac{1}{2})$$

Closed interferometer [wave]

$$q(a) = (\cos^2 \tfrac{\varphi}{2}, \sin^2 \tfrac{\varphi}{2})$$



Jacques *et al.*,
Science **315**, 966 (2007)



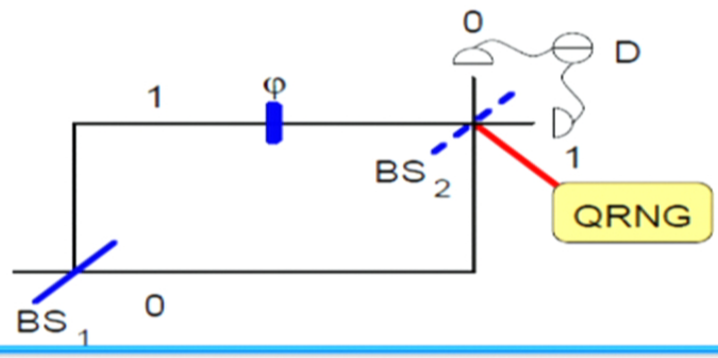
Spacelike separation between the source and the RNG

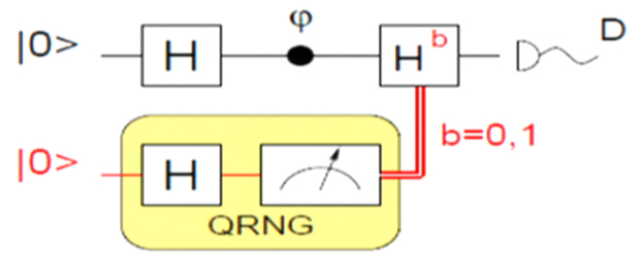
PART 3

QUANTUM CONTROL

Evolution of control
Different set-ups and complementarity
Some experiments

QUANTUM CONTROL





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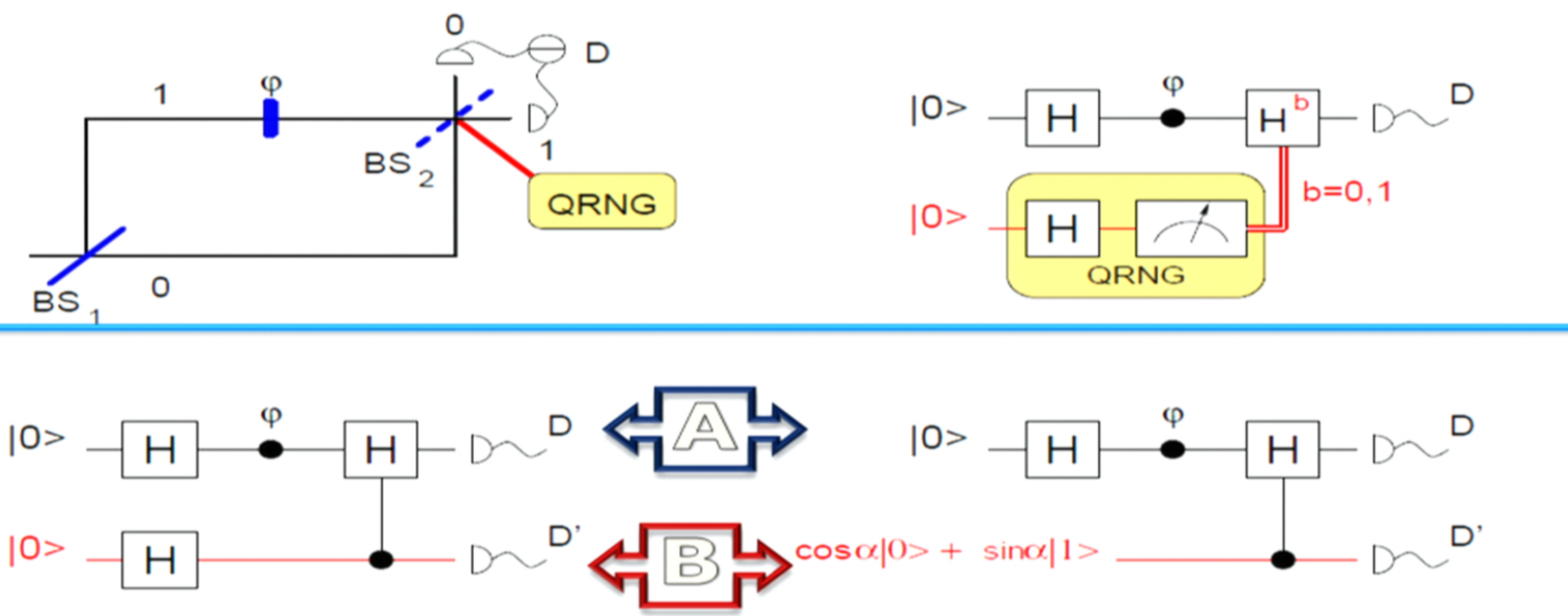
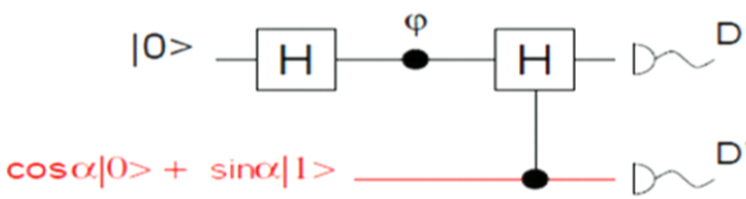


DC

+ Q



- We can detect "it" first and decide what was it later
- No space-like separation
- Duality restored OR HV pushed away (half-step)

Consistency requirements resurrect wave-particle duality:

$$p(a\,|\,b,\lambda) = p(a\,|\,b)$$

$$\mathfrak{p} = 0, x = \tfrac{1}{2}$$

$$\mathfrak{p} = 1, y = \cos^2\tfrac{\phi}{2}$$

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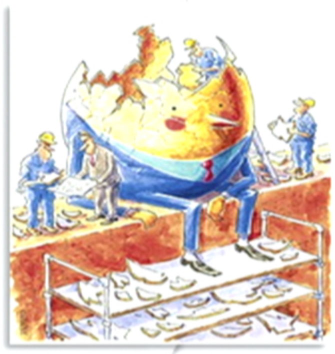
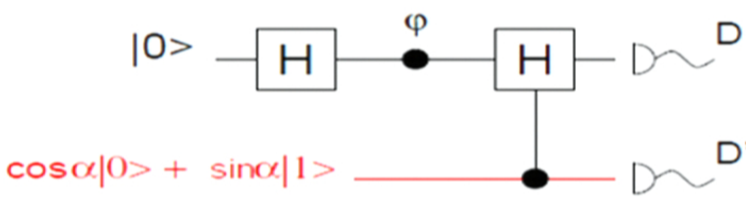


DC

+ Q

λ a b



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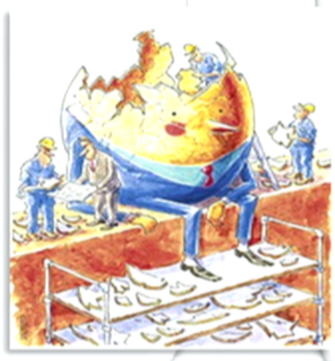

Or imply a higher level conspiracy

$$p(\lambda) = (\cos^2 \alpha, \sin^2 \alpha)$$

Small print:
- If you don't mind this weird causal interaction… but can get rid of it by more delays … but
- HV only on a photon

DELAYED CHOICE | COMPLEMENTARITY

[a tagline v 2.0]

- Complementary phenomena can be observed with a single experimental setup, provided that a component of the apparatus is a quantum device in a superposition state Instead of complementarity of experimental setups (Bohr's view) we have complementarity of the experimental data

- There is no inversion of the normal order of time—in our case we measure the photon before the ancilla deciding the experimental setup (open or closed interferometer). It is only after we interpret the photon data, by correlating them with the results of the ancilla, that either a particlelike or wavelike behaviour emerges: behaviour is in the eye of the observer.

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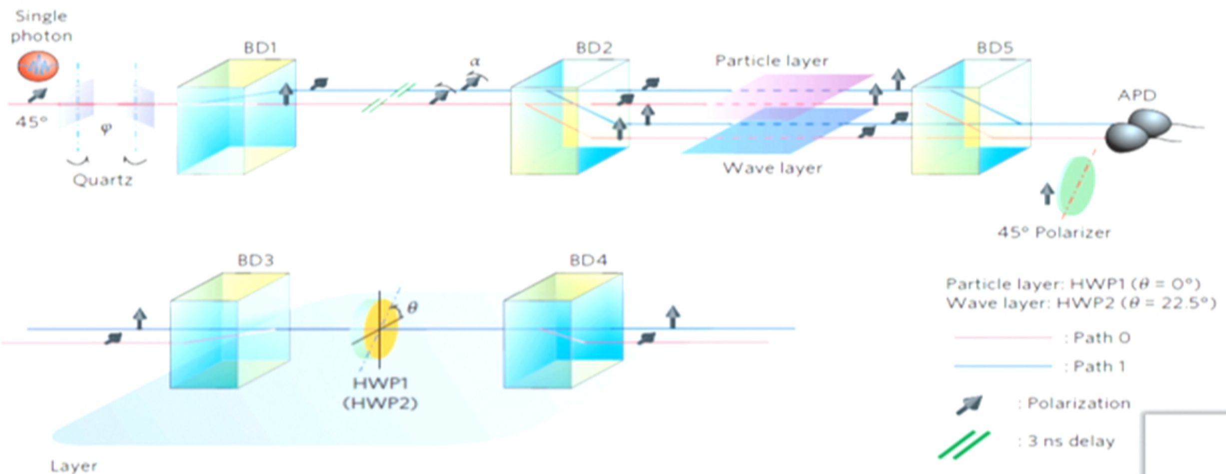
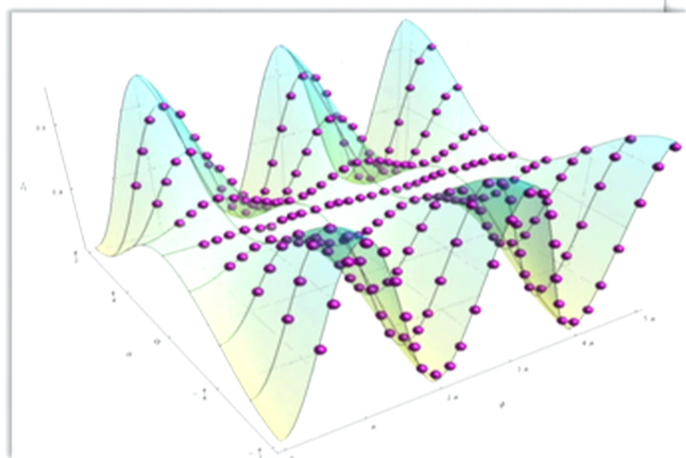
EXPERIMENTS



QOpt implementation

Tang *et al.*, Nature Phot. **6**, 602 (2012)



- ❑ demonstration of standard predictions
- ❑ different counting statistics for

$$|\psi_f\rangle = \cos\alpha|\psi_p\rangle|0\rangle + \sin\alpha|\psi_w\rangle|1\rangle$$

and

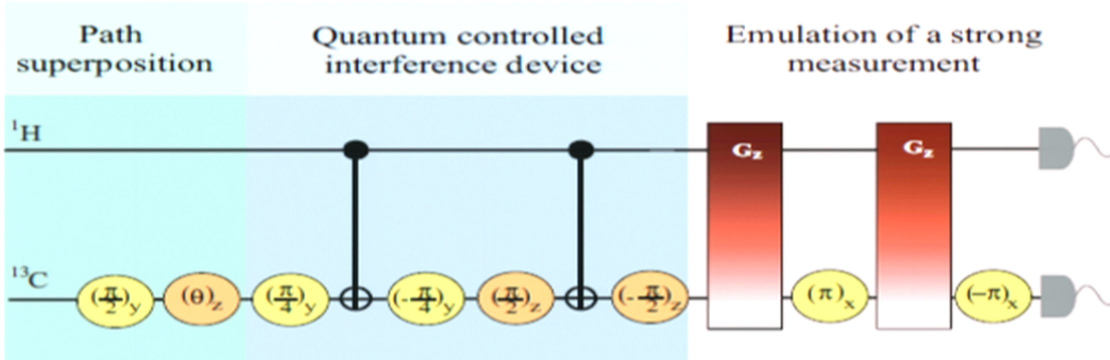
$$\rho = \cos^2\alpha|\psi_p\rangle\langle\psi_p| + \sin^2\alpha|\psi_w\rangle\langle\psi_w|$$

EXPERIMENTS

"exotic" systems

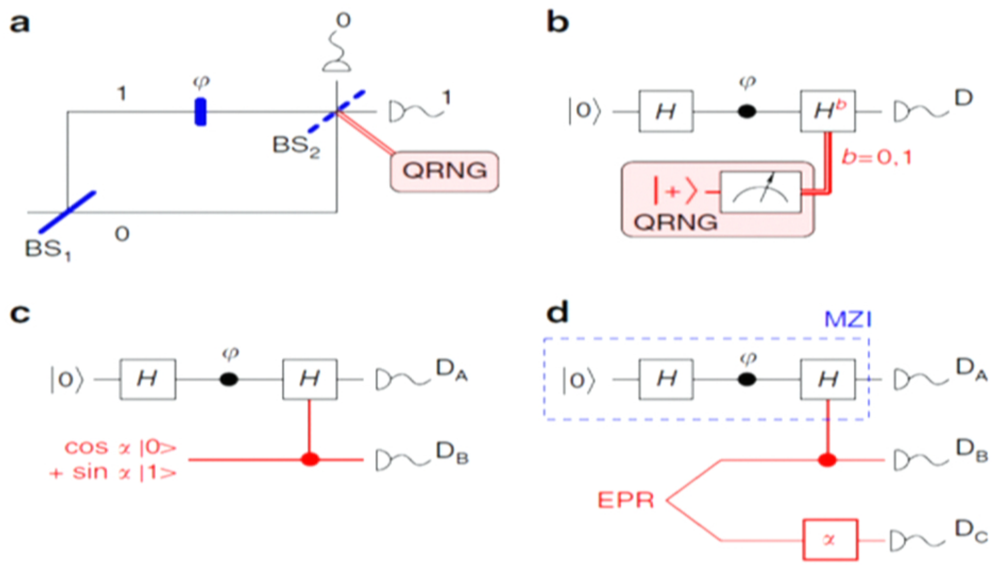
Since there is no space-like separation, it can be done with NMR

Auccaise *et al*, Phys. Rev. A **85**, 032121 (2012)



The first block represents the initial state preparation and employs the two interferometric paths. The second block performs a controlled interference between the two superposition paths encoded in the carbon spin. A controlled-Hadamard gate is decomposed in four single-qubit rotations and two CNOT gates. The third block emulates a strong measurement of the hydrogen spin in the σ_z eigenbasis by means of partial dephasing circuit

DC + *entanglement*



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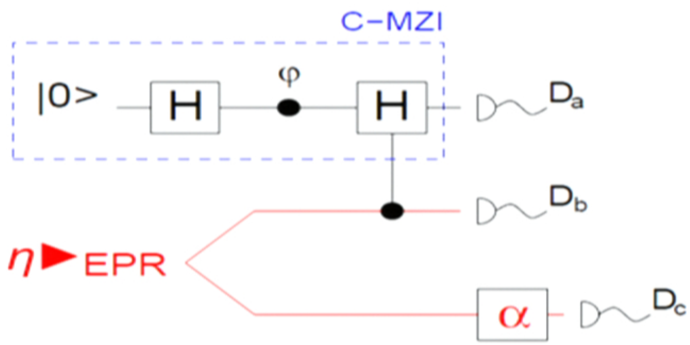

Box 1 | Three classical assumptions.

Wave-particle objectivity. We define particles and waves according to the experimental behaviour in an open, respectively closed, MZI[11]. A particle in an open interferometer ($b=0$) is insensitive to the phase shift in one of the arms and therefore has the statistics

$$p(a \mid b=0,\ \Lambda) = (\tfrac{1}{2}, \tfrac{1}{2}), \quad \forall \Lambda \in \mathcal{L}_p. \tag{3}$$

In contrast, a wave in a closed MZI ($b=1$) shows interference

$$p(a \mid b=1,\ \Lambda) = (\cos^2 \tfrac{\varphi}{2}, \sin^2 \tfrac{\varphi}{2}), \quad \forall \Lambda \in \mathcal{L}_w. \tag{4}$$

The sets $\mathcal{L}_p$ and $\mathcal{L}_w$ must be disjoint; otherwise, there are values of Λ that introduce wave-particle duality. Writing $\mathcal{L}_p \cup \mathcal{L}_w = \mathcal{L}$, the wave/particle property is expressed by a mapping $\lambda: \mathcal{L} \mapsto \{p, w\}$ and the sets $\mathcal{L}_p = \lambda^{-1}(p)$, $\mathcal{L}_w = \lambda^{-1}(w)$ are the pre-images of p, w under the function λ.

Determinism. The HV Λ determines the individual outcomes of the detection[3]. Specifically, for the setup of (Fig. 1d)

$$p(a, b, c \mid \Lambda) = \chi_{abc}(\Lambda), \tag{5}$$

where the indicator function $\chi = 1$, if Λ belongs to some predetermined set, and $\chi = 0$ otherwise.

Local independence. The HV Λ are split into Λ_1 and Λ_2, and the prior probability distribution has a product structure

$$p(\Lambda) = f(\Lambda_1)F(\Lambda_2), \tag{6}$$

for some probability distributions f and F, where the subscripts 1 and 2, respectively, refer to the photon A and the pair BC. Such bilocal variables have been previously considered in ref. 29.

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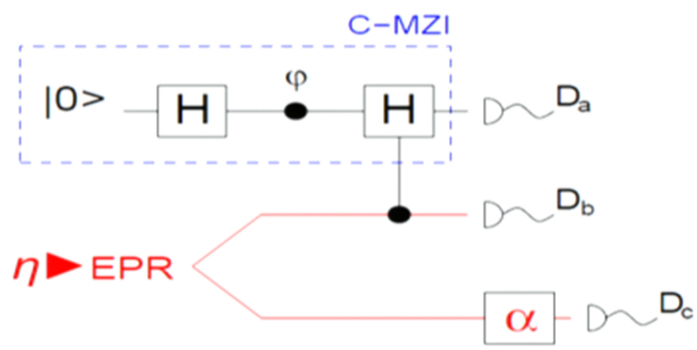

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DC *+ entanglement* logic

1. QM analysis: $q(a,b,c)$

2. Solution to the constraints: finding the HV theory

$$p(a,b,c,\lambda): \sum_{\lambda=p,w} p(a,b,c,\lambda) = p(a,b,c) \equiv q(a,b,c)$$

A non-trivial HV theory requires that λ is determined by the degree of entanglement:

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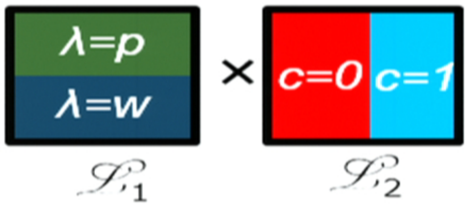
3. Decompose the domain of HV according to the outcomes c=0,1.



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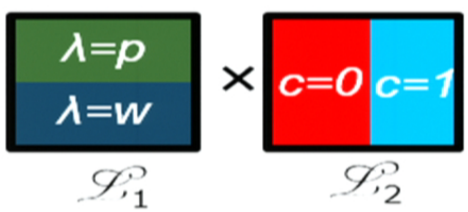

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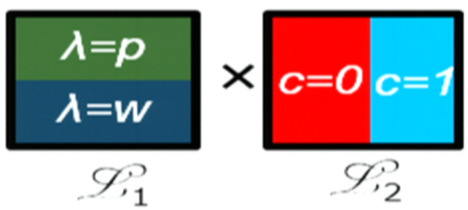
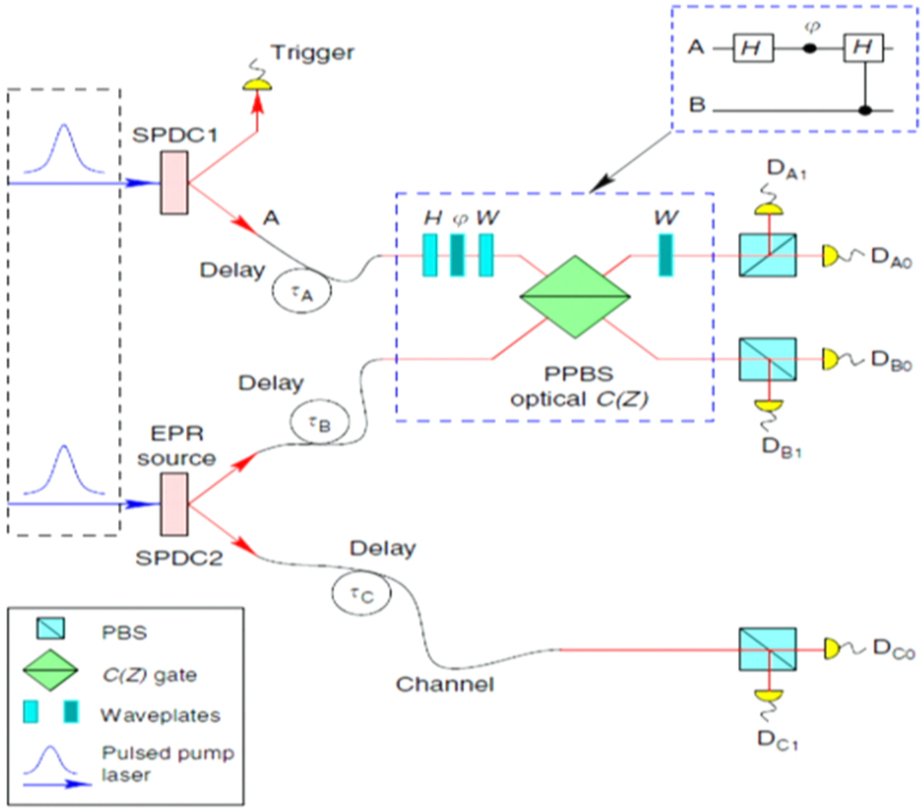


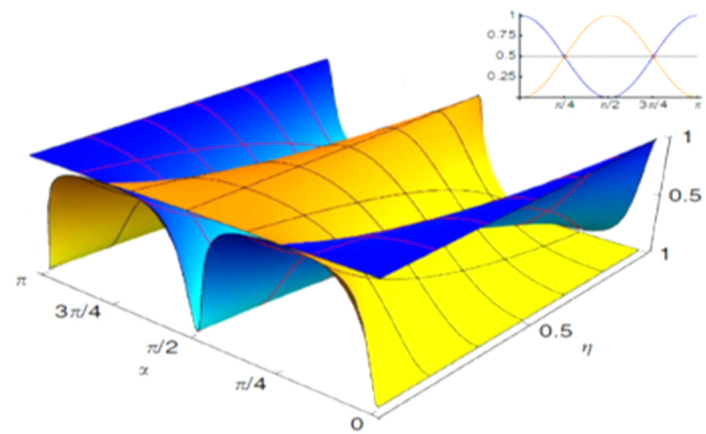
CONTRADICTION

Solution for $p(a,b,c,\lambda)$ exists only if

$$\cos^2 \alpha = 0$$

DC + *entanglement* experimental signature

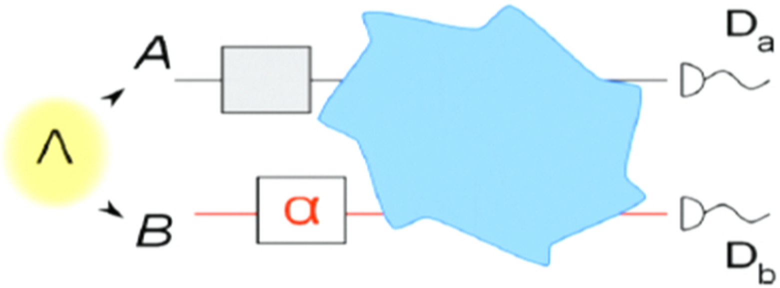




IJMT,

Nature Comm. **5**, 3997 (2014)

THREE INCOMPATIBLE ASSUMPTIONS



Empirical statistics

$$e(a,b) = \big(xe_p, (1-x)e_w, x(1-e_p), (1-x)(1-e_w)\big)$$

$$e(b) = (x, 1-x)$$ ◀ *controller*

two types of stats ▶ $\bar{e}_{\mathrm{p}}(a) = (e_p, 1-e_p), \qquad \bar{e}_{\mathrm{w}}(a) = (e_w, 1-e_w)$

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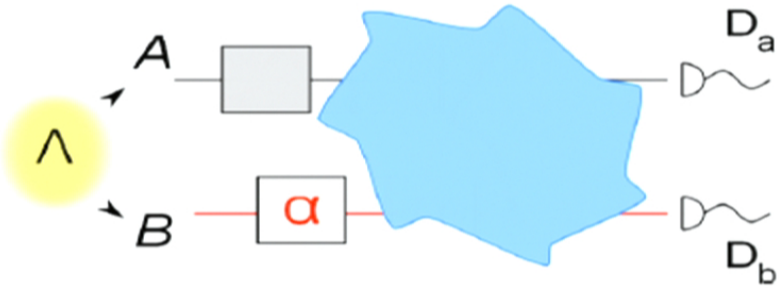

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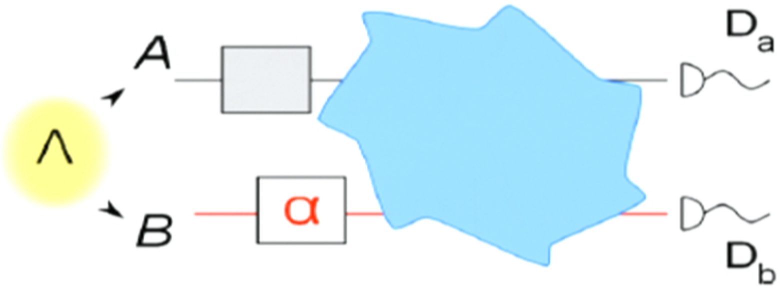

(*) Adequacy

Empirical statistics

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two types of stats ► $\bar{e}_{\mathrm{p}}(a) = (e_p, 1-e_p), \qquad \bar{e}_{\mathrm{w}}(a) = (e_w, 1-e_w)$

$$e(a,b) = p(a,b) = \sum_{\Lambda} p(a,b,\Lambda) = \sum_{\Lambda} p(a,b|\Lambda)\, p(\Lambda)$$

THREE INCOMPATIBLE ASSUMPTIONS

The system is definitely s one or another

$$p(a|b = 1, \lambda = \mathsf{w}) = \bar{e}_{\mathsf{w}}(a)$$

$$p(a|b = 0, \lambda = \mathsf{p}) = \bar{e}_{\mathsf{p}}(a)$$

(i) Objectivity

$$\lambda = \lambda(\Lambda)$$

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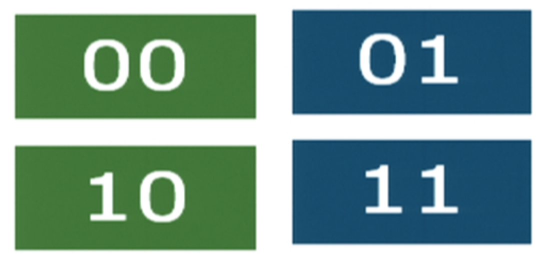
(i) Objectivity

$$\lambda = \lambda(\Lambda)$$

HV theory is (weakly) deterministic

$$p(a,b|\Lambda) = \chi_{ab}(\Lambda)$$

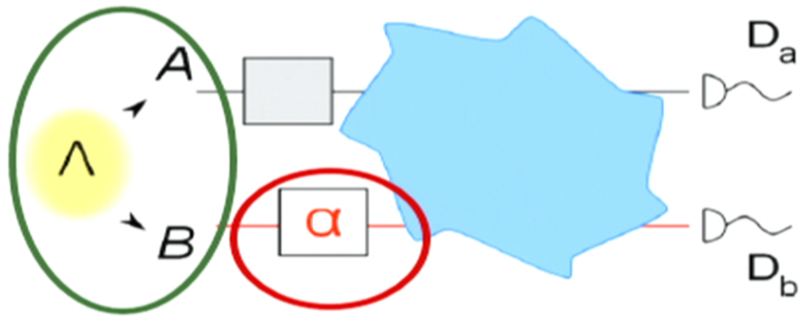
(ii) Determinism



Boundaries of the regions depend on the settings

THREE INCOMPATIBLE ASSUMPTIONS

Is λ-independent



(iii) Independence

$p(\Lambda)$ is independent of the settings

IMT, Phys. Rev. Lett. **114**, 060405 (2015)

THREE INCOMPATIBLE ASSUMPTIONS

LOGIC

Stage 1: find a unique non-trivial solution to (i)-(iii)

Ignoring how it arises from Λ

THREE INCOMPATIBLE ASSUMPTIONS

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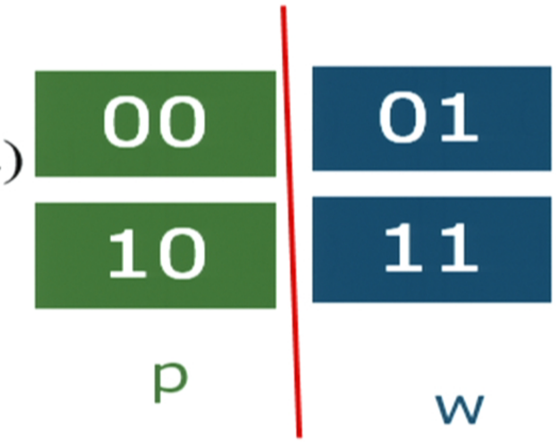
Ignoring how it arises from Λ

Exists, but

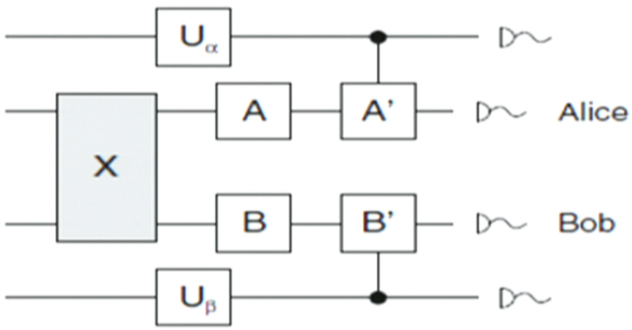
$$p_s(\lambda \mid b) = \delta_{\lambda p}\delta_{b0} + \delta_{\lambda w}\delta_{b1} = p_s(b \mid \lambda)$$

$$p_s(a, b, \lambda) = e(a, b)p_s(b|\lambda)$$



FUTURE

Quantum-controlled CHSH?



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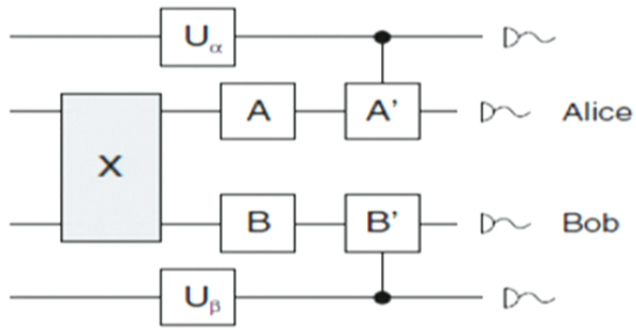
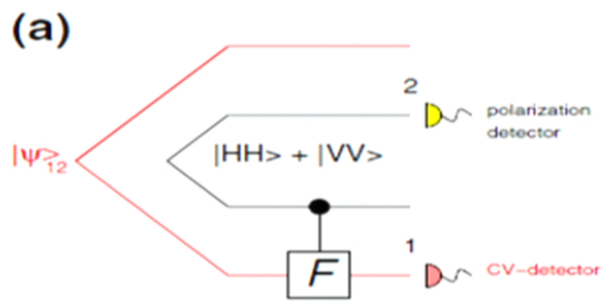
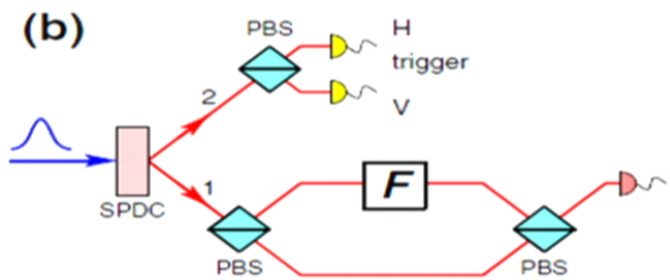


Quantum-controlled
von Weizsäcker?





Céleri, Gomes, IJMT, Found. Phys. **44**, 576 (2014)

SUMMARY

- Hidden variables are useful
- Quantum control: practical & conceptual features
- Entangled control
- Don't (always) blame quantum mechanics
- More?

Thanks to

Roger Colbeck
Bert Englert
Mile Gu
Gerard Milburn
Alberto Peruzzo
Valerio Scarani