Thematic school

From the first to the second quantum revolution

Applications of non-locality

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20 sept 2021, Peyresq

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UNIVERSITÉ CÔTE D'AZUR

QET Labs

University of BRISTOL

Photonics is all around us

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Photonics is about light:

Photonics is all around us

Laser sources

Light Peak

Photonics is about light:

- Generation

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Distribution
Fiber optics & comp.

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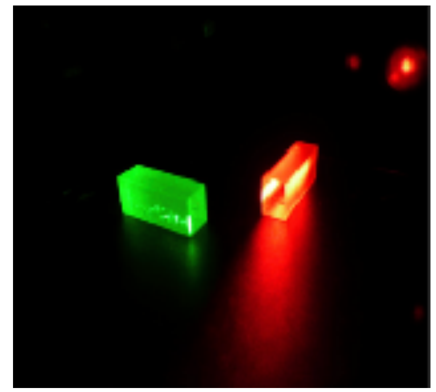

DWDM
Demultiplexer

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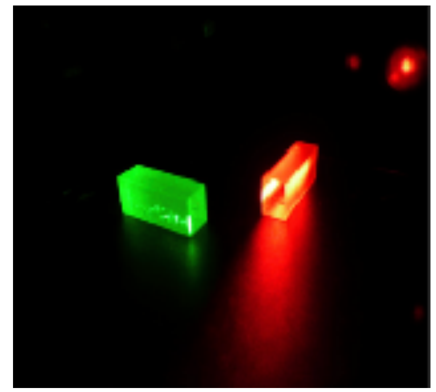

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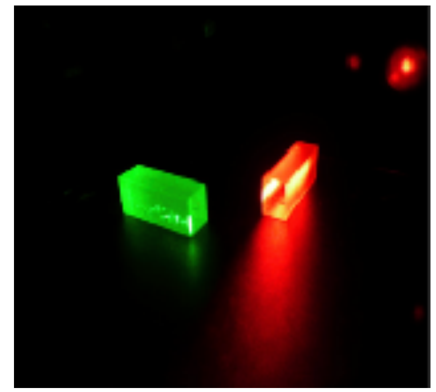

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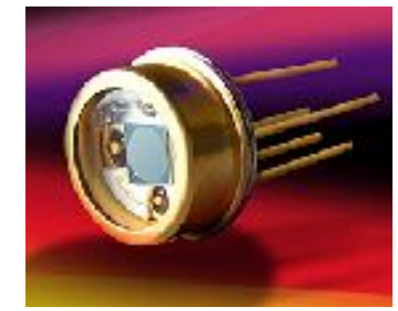
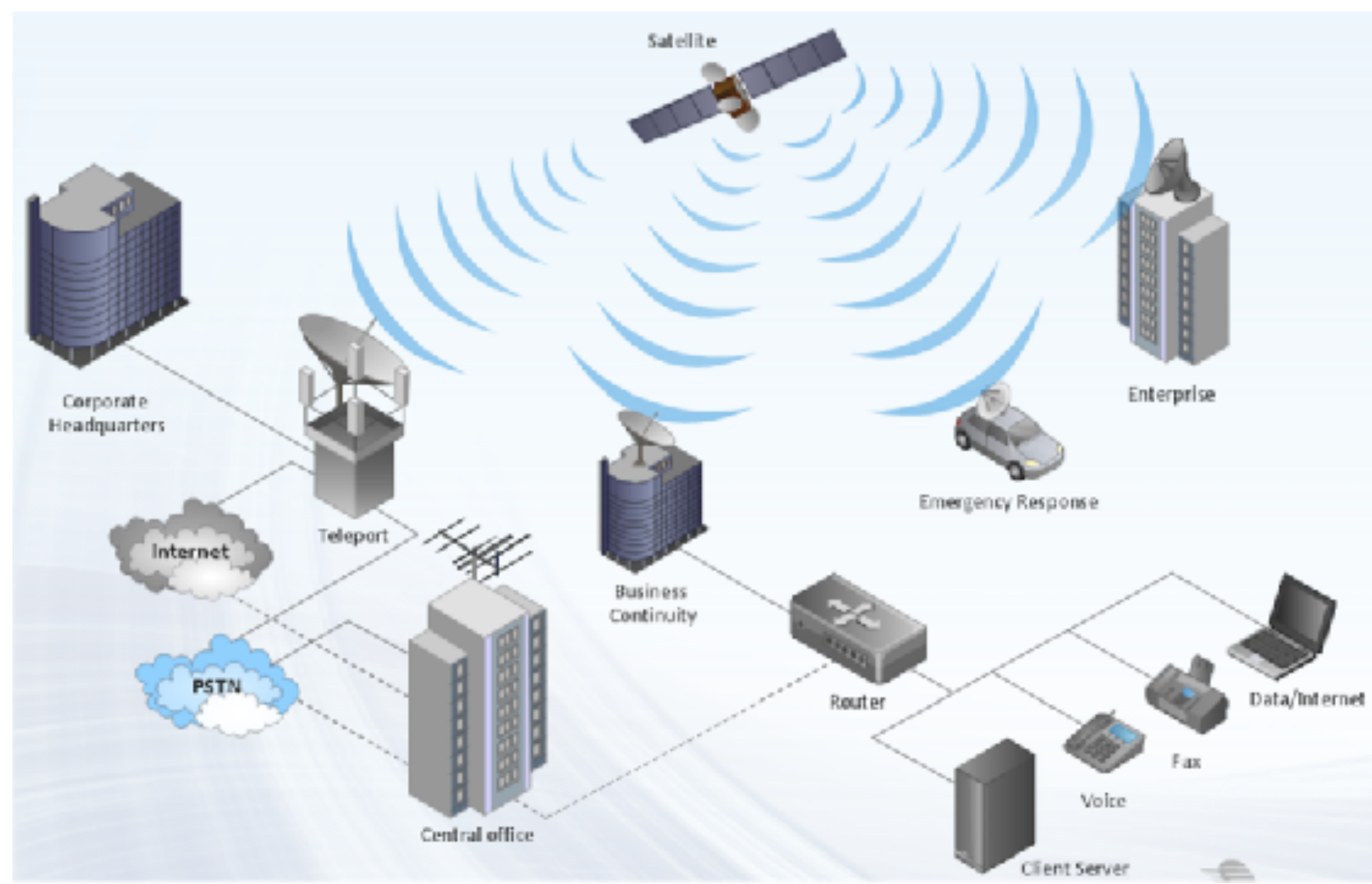


Telecommunication networks



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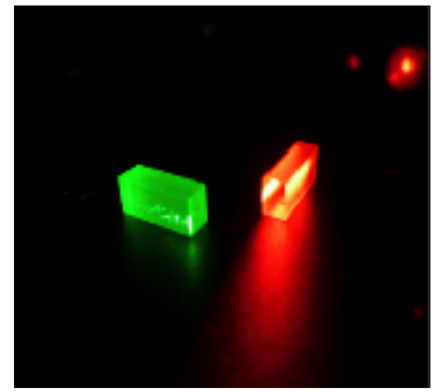

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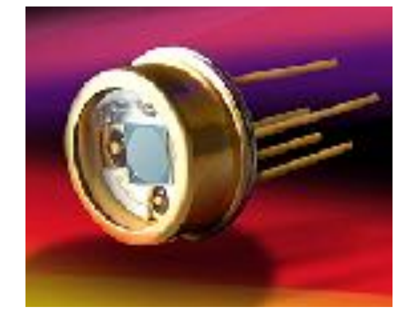

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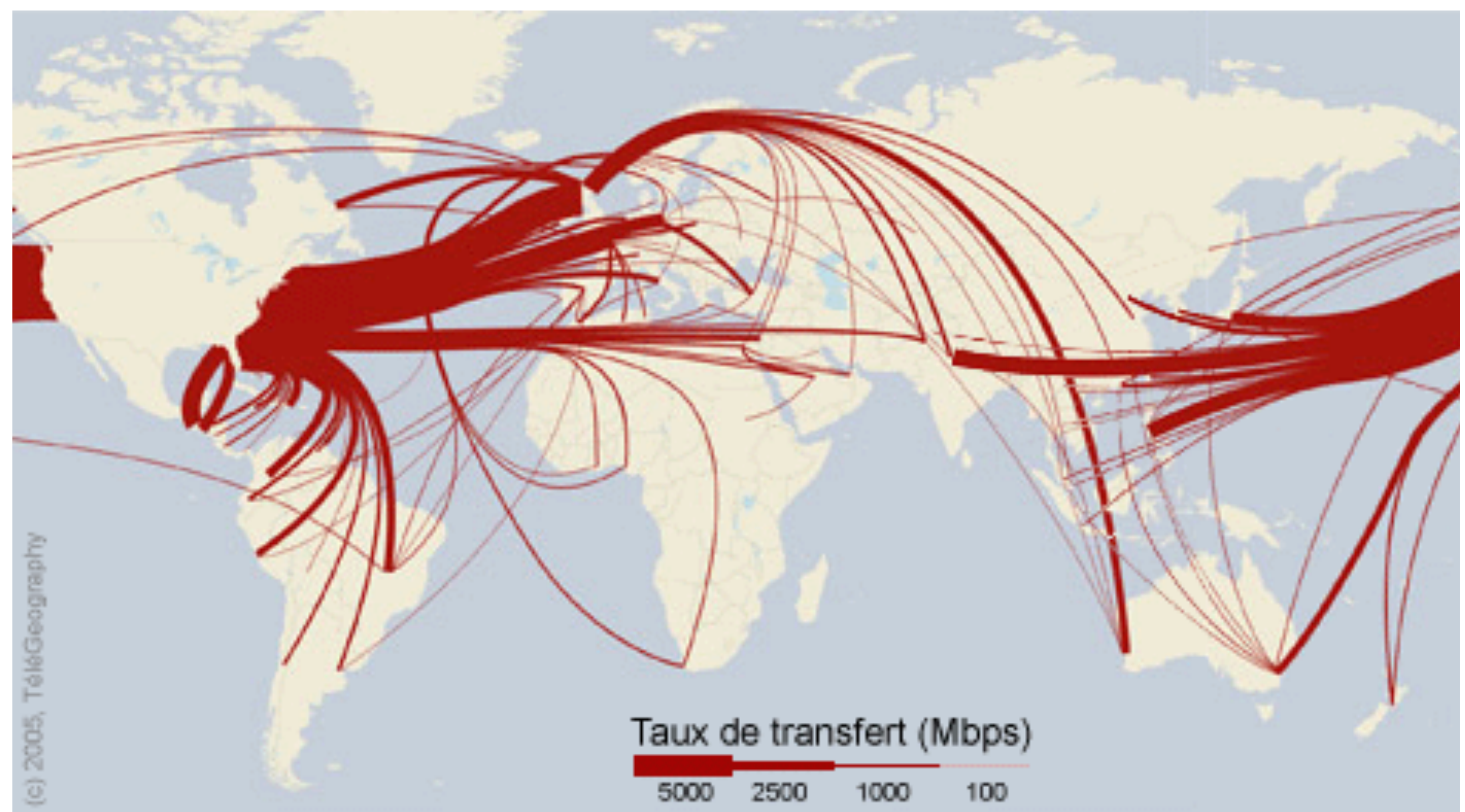

<u>Photonics is about light:</u>

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- Distribution
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What about quantum photonics ?

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Quantum photonics is also about:

Generation, distribution, manipulation and detection of light.

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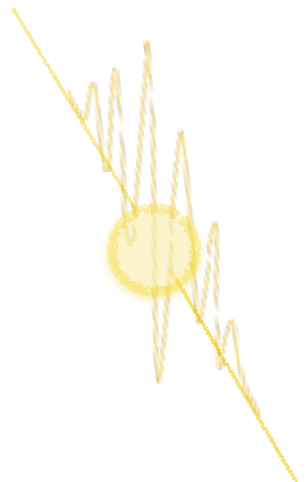
Single photon



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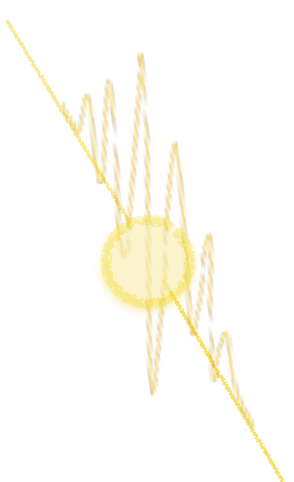
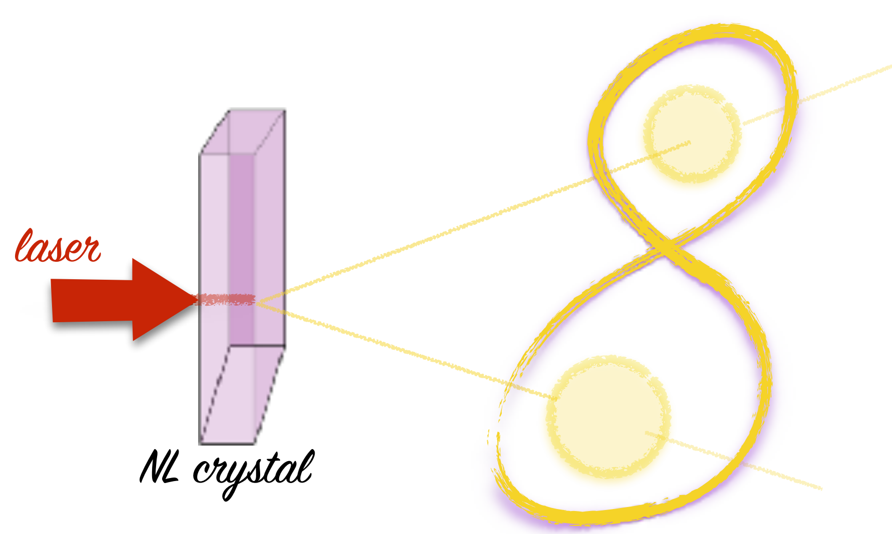


Twin photons



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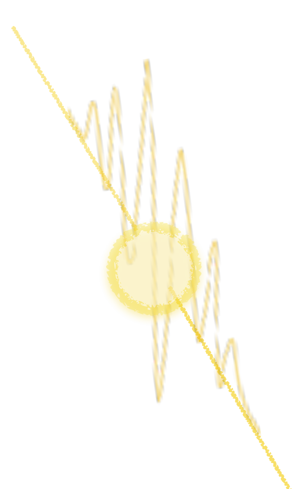

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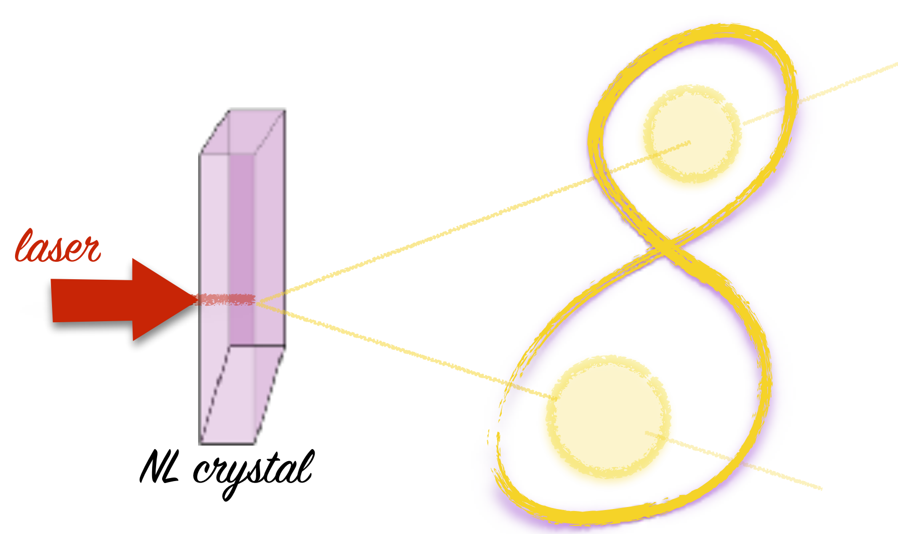


and more …

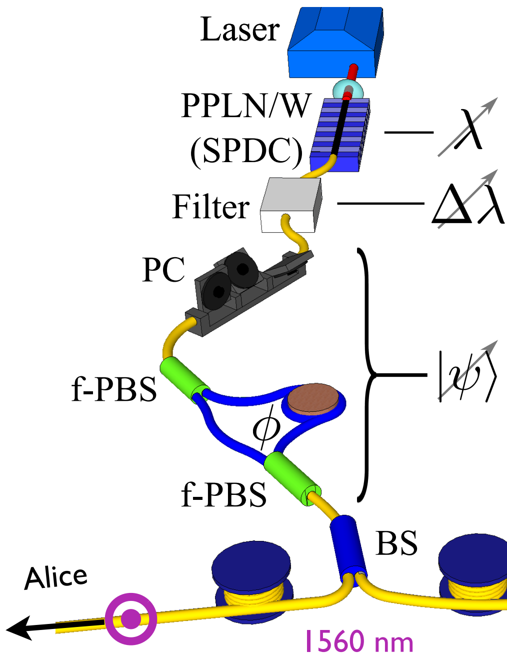
Entanglement & quantum applications

Entanglement

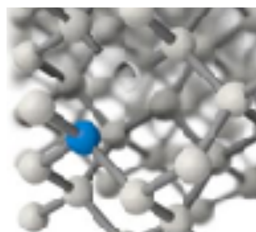
Entanglement & quantum applications

Terminal stations

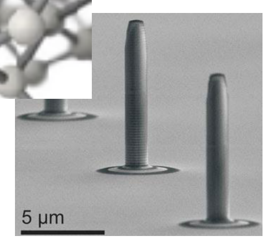
Parametric sources



NV centers

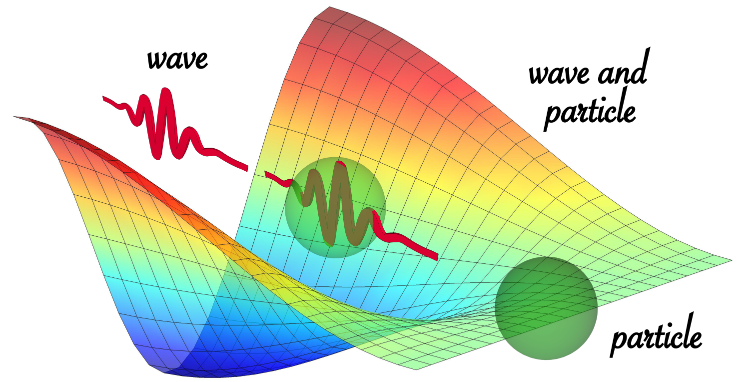


Q-dots



Fundamental studies

Non locality



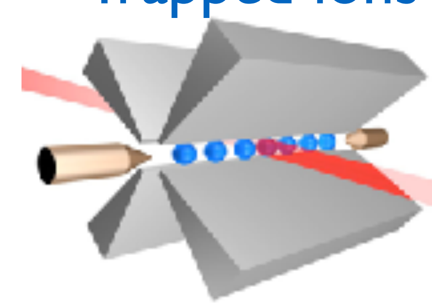
Secured channels

Q-key distribution

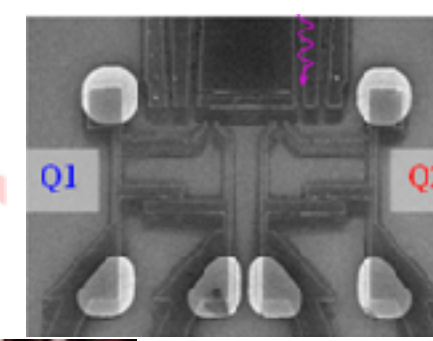
Entanglement

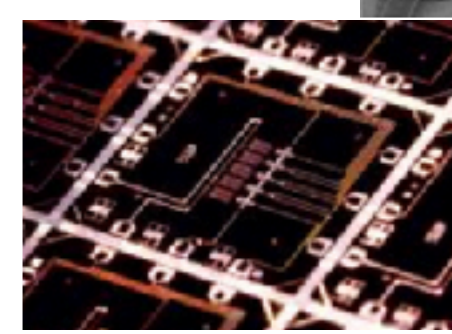
Processing

Trapped ions



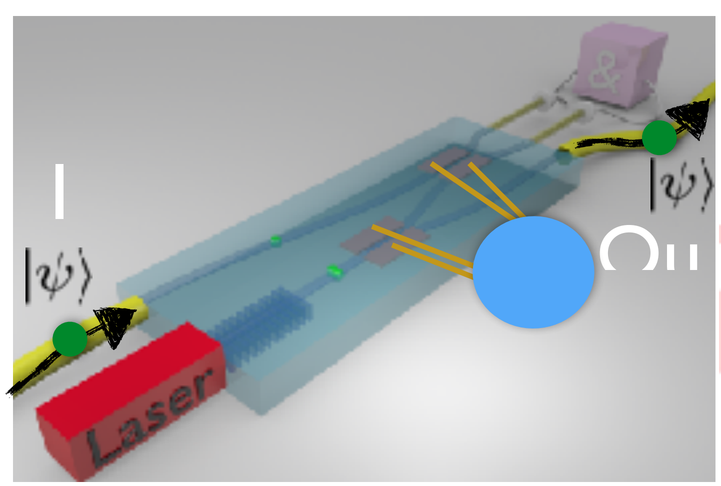
Supercond. circuits



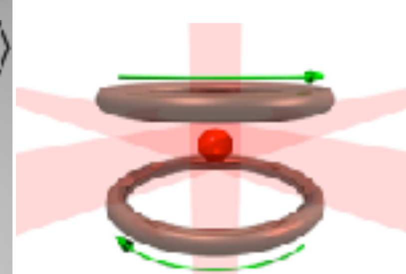


Spin qubits
Silicon

Relays, storage, & repeaters

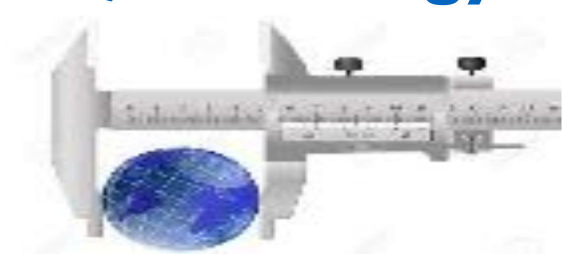


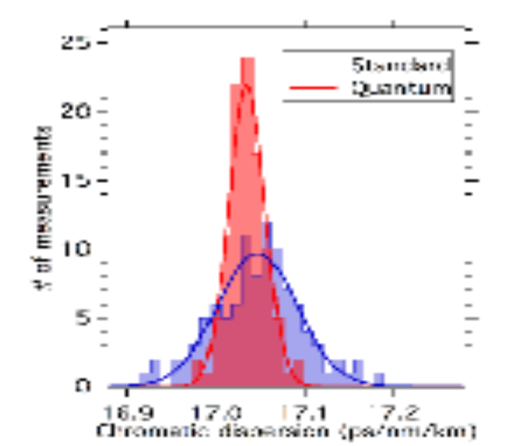
Cold atoms



Rare-earth doped crystals or fibers

Q-Metrology





OUTLINE

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Entanglement in short

$$|\psi_{ab}\rangle = |\psi_a\rangle \otimes |\psi_b\rangle = \alpha_a\alpha_b|0_a\rangle|0_b\rangle + \alpha_a\beta_b|0_a\rangle|1_b\rangle + \beta_a\alpha_b|1_a\rangle|0_b\rangle + \beta_a\beta_b|1_a\rangle|1_b\rangle$$

2 qubits Bell state basis

$$\begin{cases} |\Psi^+\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle) \\ |\Psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle) \\ |\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \\ |\Phi^-\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle). \end{cases}$$

Entanglement in short

- The tensor product of 2 qubits:

$$|\psi_{ab}\rangle = |\psi_a\rangle \otimes |\psi_b\rangle = \alpha_a\alpha_b|0_a\rangle|0_b\rangle + \alpha_a\beta_b|0_a\rangle|1_b\rangle + \beta_a\alpha_b|1_a\rangle|0_b\rangle + \beta_a\beta_b|1_a\rangle|1_b\rangle$$

- But there are 2 qubits states that cannot be written as such called entangled state:

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Bell violation with photon pair sources

VOLUME 49, NUMBER 2 PHYSICAL REVIEW LETTERS 12 JULY 1982

Experimental Realization of Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*: A New Violation of Bell's Inequalities

Alain Aspect, Philippe Grangier, and Gérard Roger
Institut d'Optique Théorique et Appliquée, Laboratoire associé au Centre National de la Recherche Scientifique, Université Paris-Sud, F-91406 Orsay, France
(Received 30 December 1981)

The linear-polarization correlation of pairs of photons emitted in a radiative cascade of calcium has been measured. The new experimental scheme, using two-channel polarizers (i.e., optical analogs of Stern-Gerlach filters), is a straightforward transposition of Einstein-Podolsky-Rosen-Bohm *gedankenexperiment*. The present results, in excellent agreement with the quantum mechanical predictions, lead to the greatest violation of generalized Bell's inequalities ever achieved.

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First experimental realisation:

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Entanglement Photon Pair Sources (EPPS)

In a dielectric material, a pump field oscillating at a given angular frequency creates a deformation of the charge distribution in a crystal called polarisation density.

Polarization density:

$$\vec{P} = \epsilon_0 \chi_e \vec{E}.$$

Linear function of the electric field.

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<u>Polarization density:</u>

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But under strong pump fields and specific crystal symmetries:

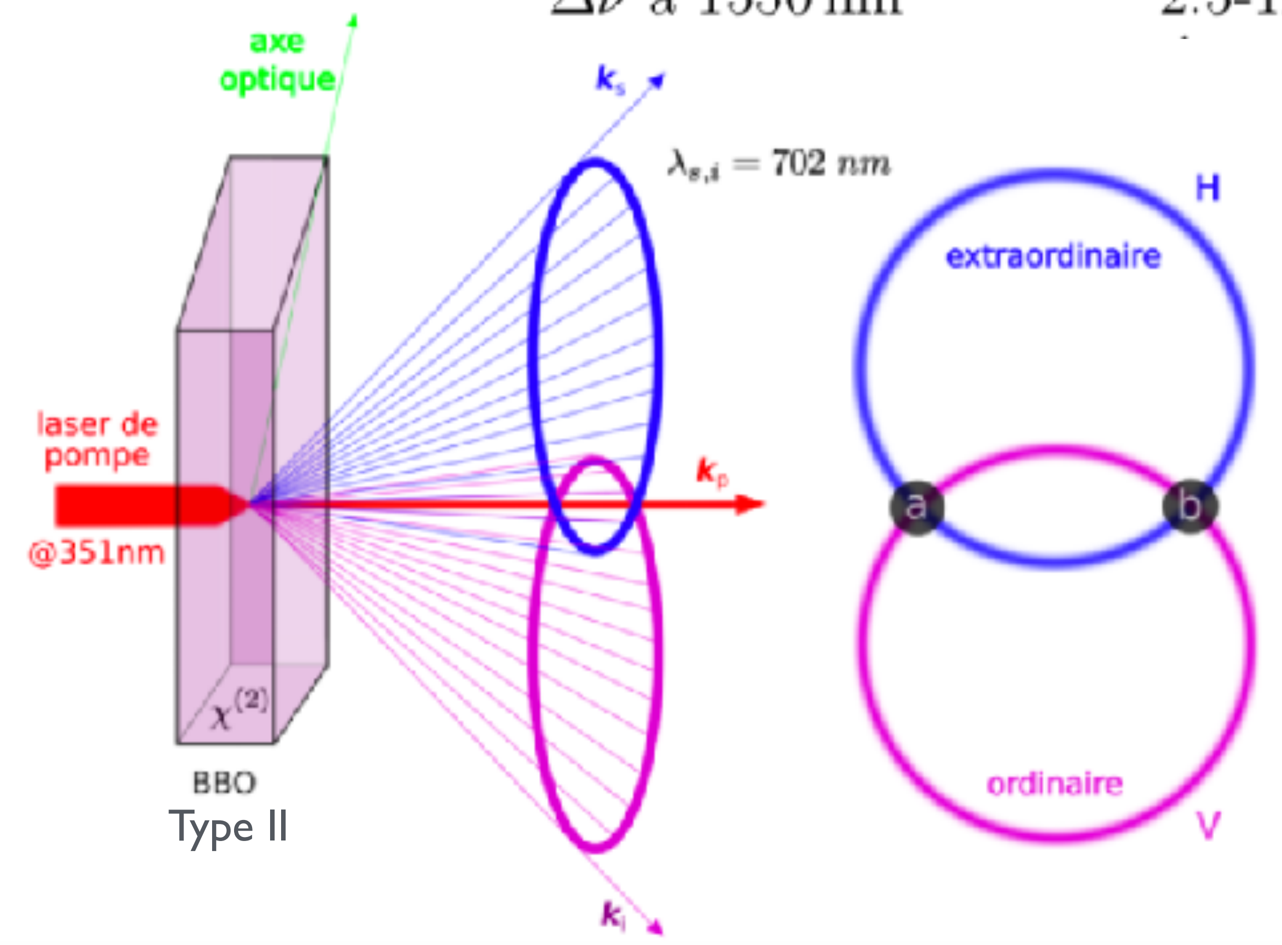
$$\vec{P}(\vec{E}) = \epsilon_0 \overleftrightarrow{\chi}^{(1)} \vec{E} + \epsilon_0 \overleftrightarrow{\chi}^{(2)} \vec{E}\vec{E} + \epsilon_0 \overleftrightarrow{\chi}^{(3)} \vec{E}\vec{E}\vec{E} + \ldots = \epsilon_0 \overleftrightarrow{\chi}^{(1)} \vec{E} + \vec{P}^{NL}(\vec{E})$$

The polarisation density also depends on higher orders of $\vec{E}$

This non linear form allows the distribution to oscillate not only the frequency of the pump but also at linear combination of this frequency.

Entanglement Photon Pair Sources (EPPS)

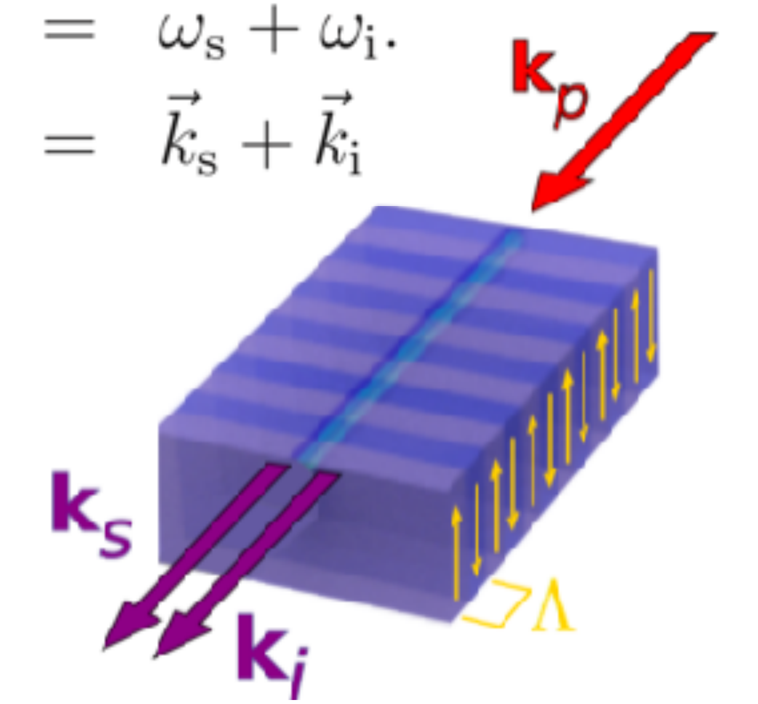
Type d'interaction	type-0	type-I	type-II
Polarisation	$\lvert V\rangle_p \to \lvert V\rangle_s \lvert V\rangle_i$	$\lvert V\rangle_p \to \lvert H\rangle_s \lvert H\rangle_i$	$\lvert H\rangle_p \to \lvert H\rangle_s \lvert V\rangle_i$
$\chi^{(2)}$ coeff. du LiNbO3	$d_{33} \approx 30\,\text{pm/V}$	$d_{31} \approx -5\,\text{pm/V}$	$d_{24} \approx 10\,\text{pm/V}$
η_{SPDC} dans	$10^{-6} - 10^{-5}$	10^{-7}	10^{-9}
$\Delta\lambda$ à 1550 nm	20-100 nm	20-100 nm	0.8-3 nm
$\Delta\nu$ à 1550 nm	2.5-12.5 THz	2.5-12.5 THz	0.1-0.375 THz



Kwiatt *et al.*, (1995)

<u>Conservation laws:</u>

$$\omega_p = \omega_s + \omega_i.$$
$$\vec{k}_p = \vec{k}_s + \vec{k}_i$$



$$\vec{k}_p = \vec{k}_s + \vec{k}_i + \frac{2\pi}{\Lambda} \cdot \vec{u}.$$

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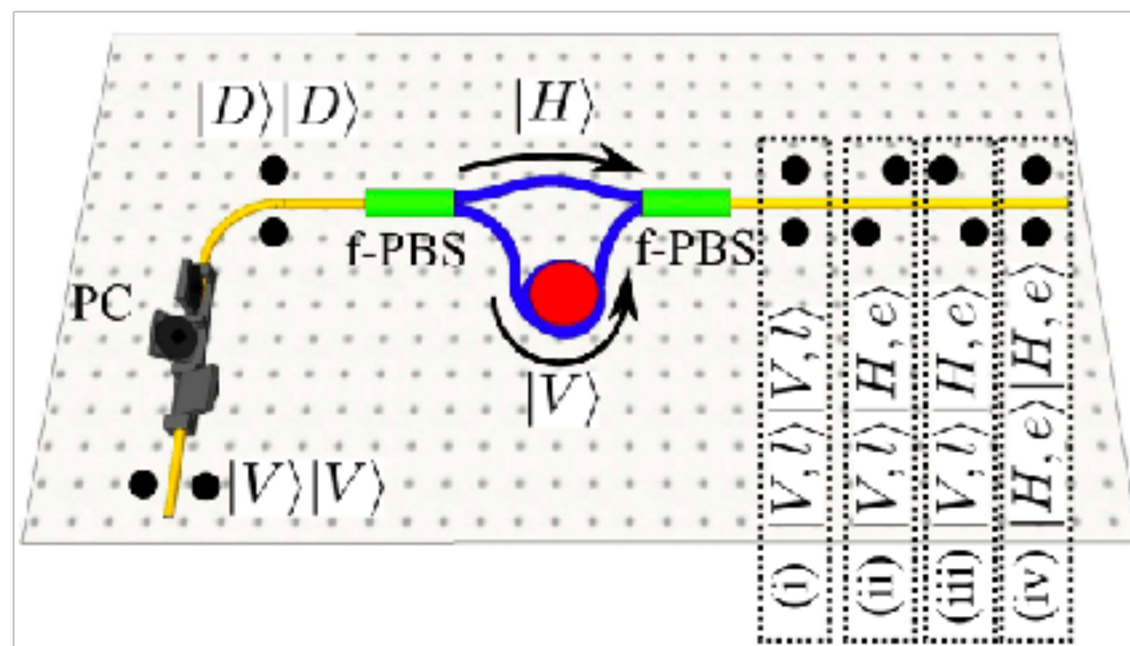

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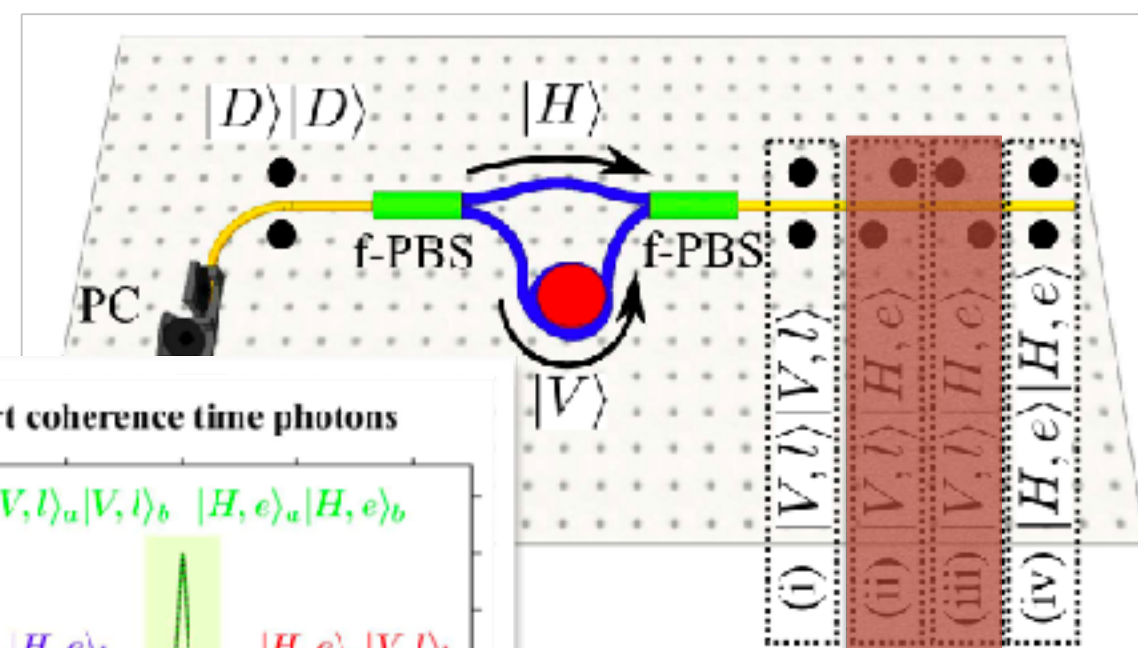

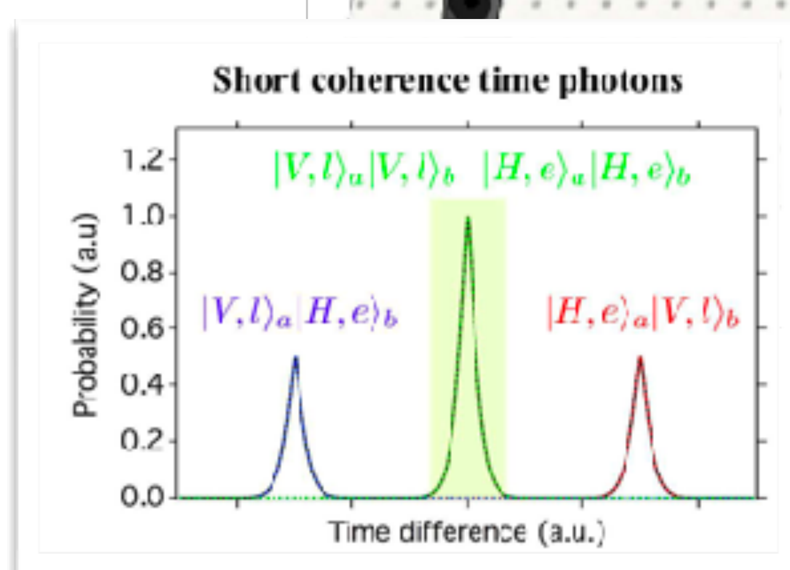

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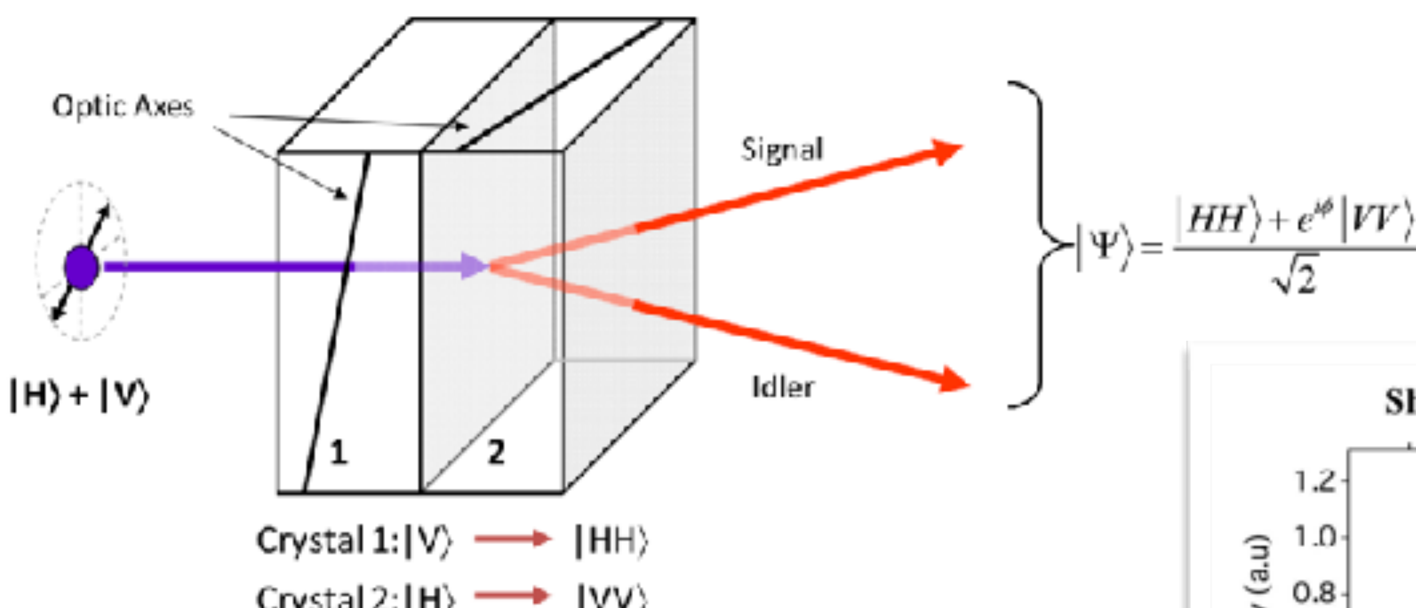
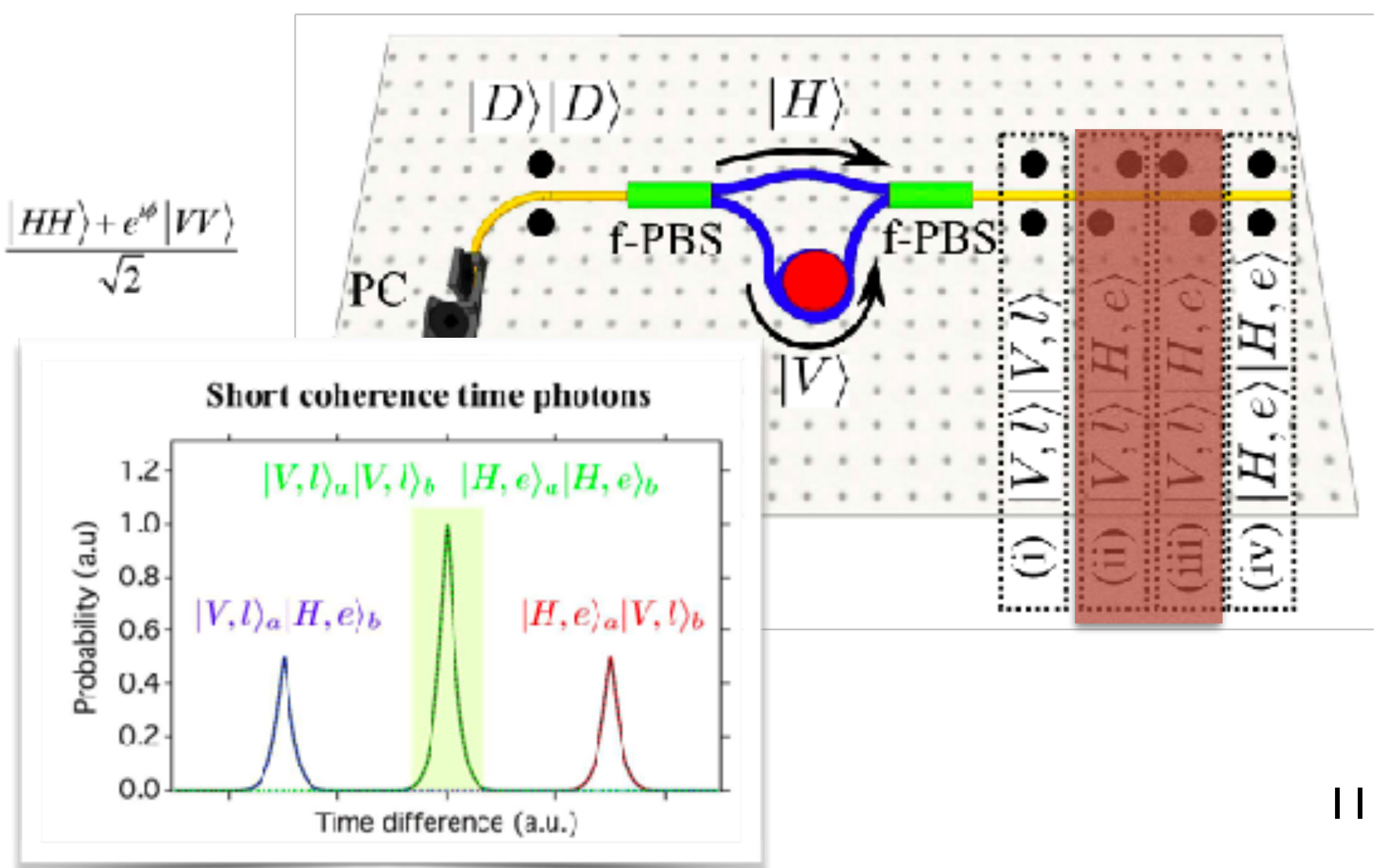


BBO
Type I



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OUTLINE

1. Introduction

2. Fundamental tests on nonlocality

- Correlations nature & origine
- Bell non-locality
- Eberhardt inequality

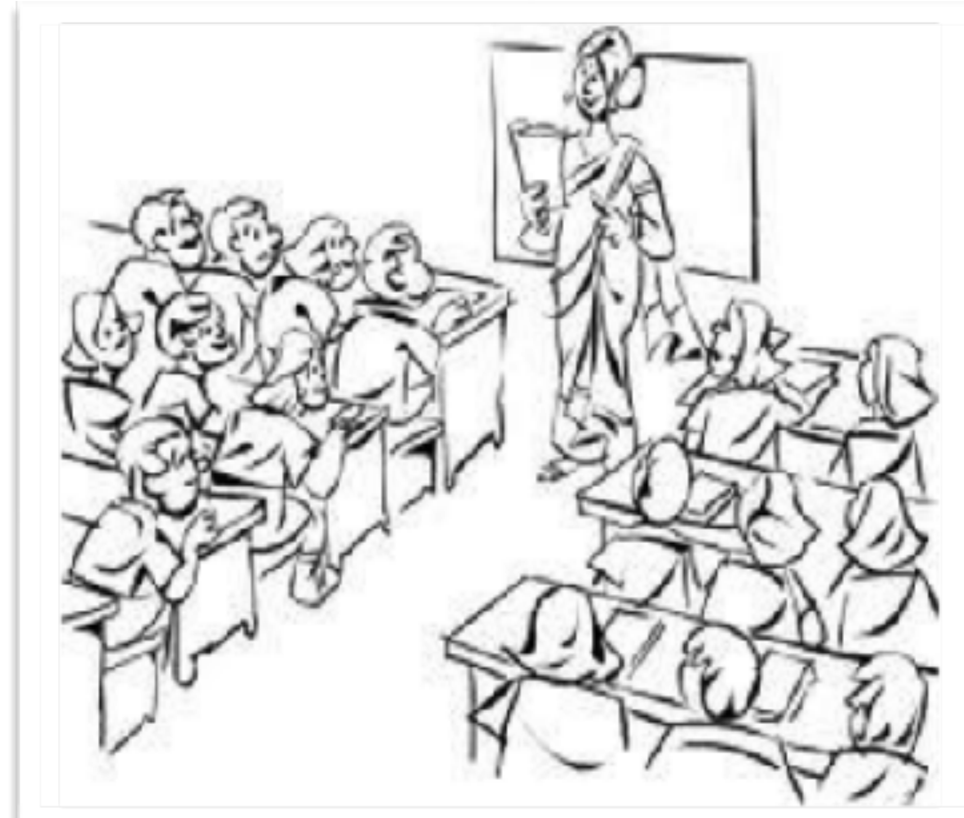
3.

4. Conclusion & outlook

Correlations in the classical world

systems:

professor
+
student



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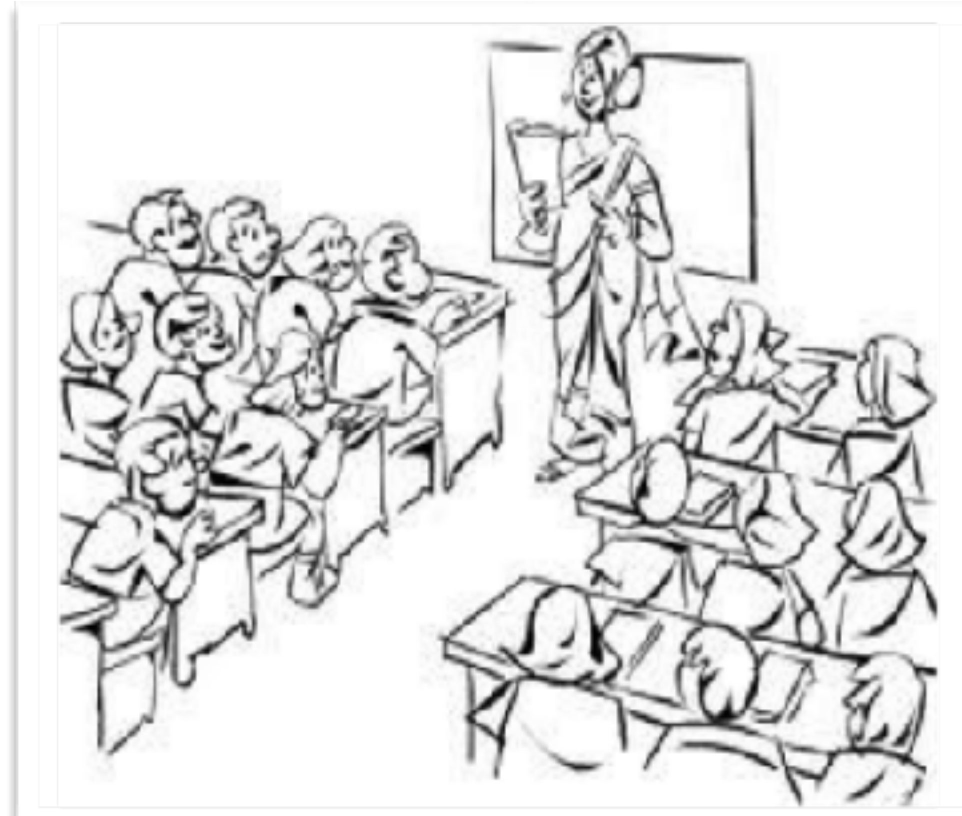

Two possible origins for classical correlations

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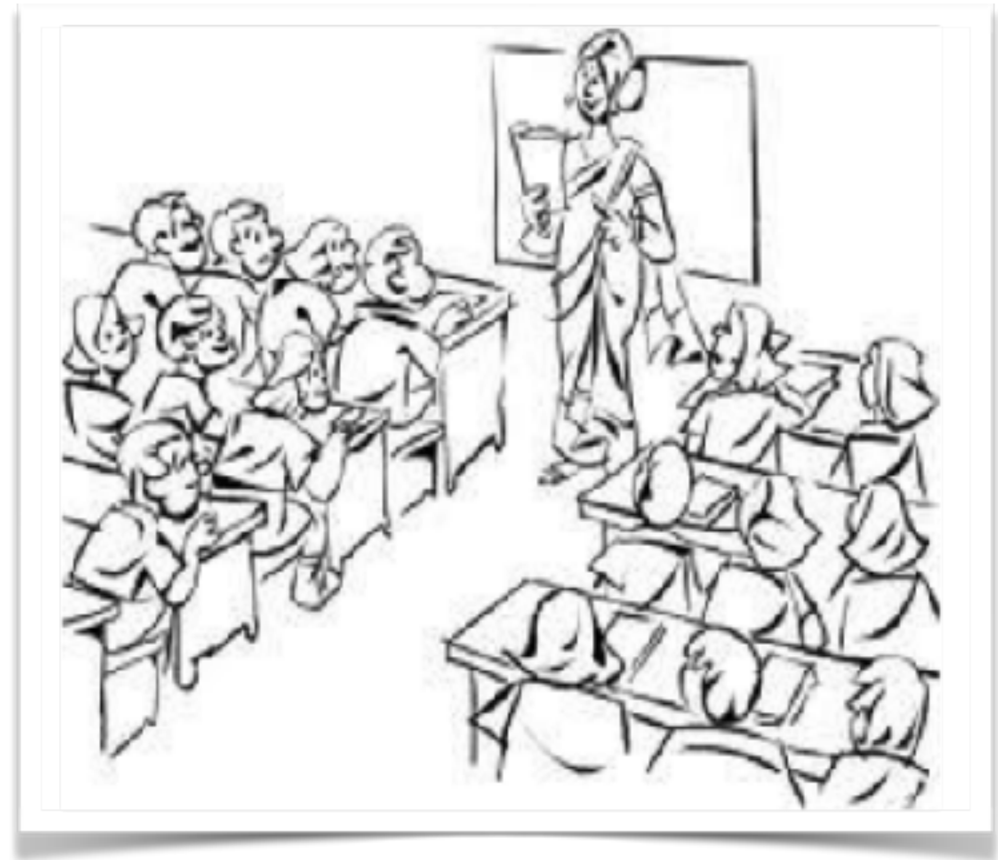

Through a signal between two subsystems:

- The professor yell and the students calm down.

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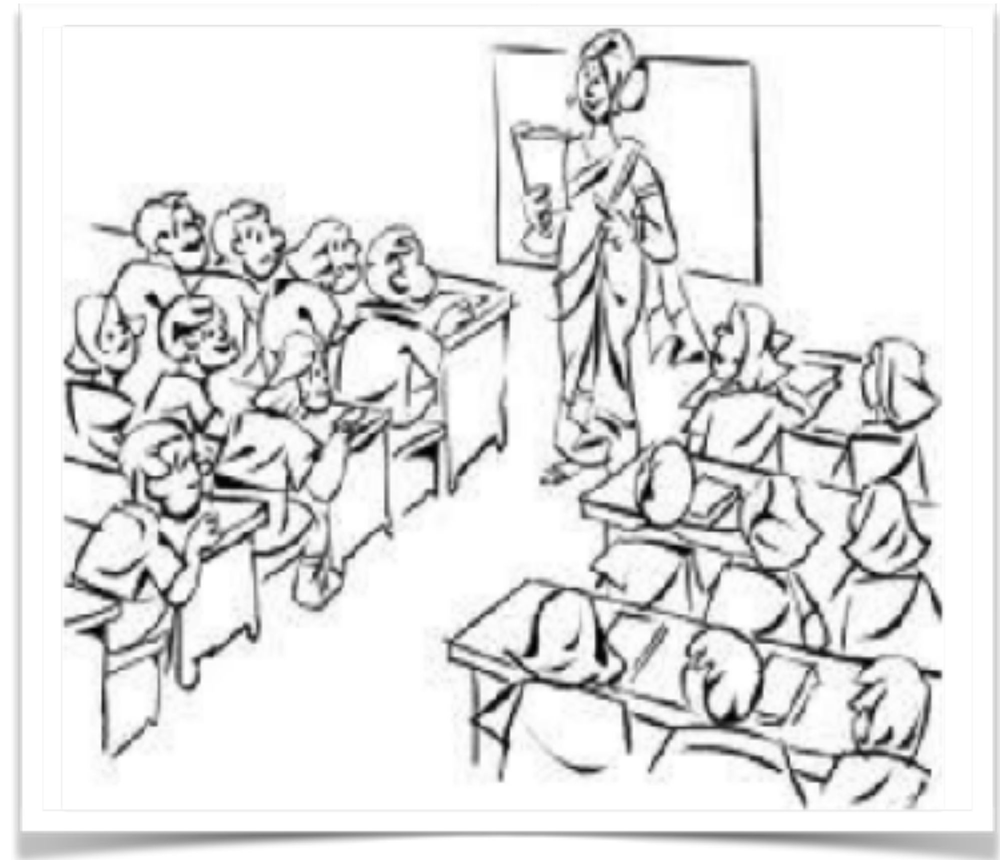

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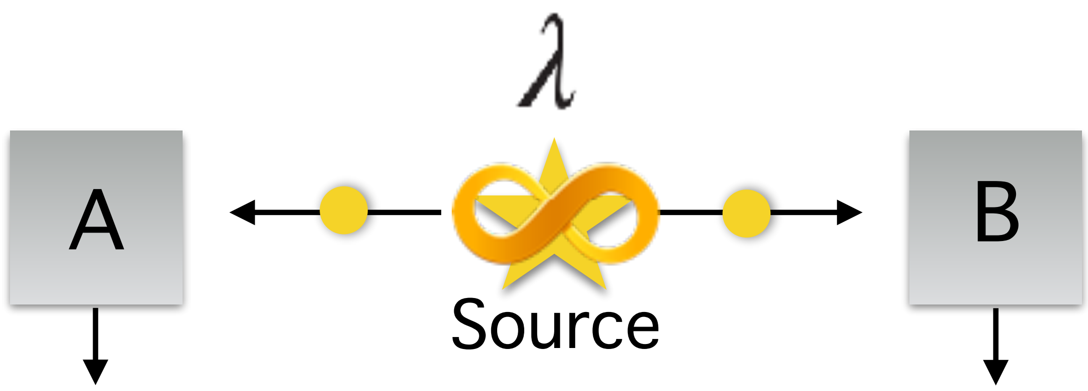
Two possible origins for classical correlations

With a pre-established strategy:

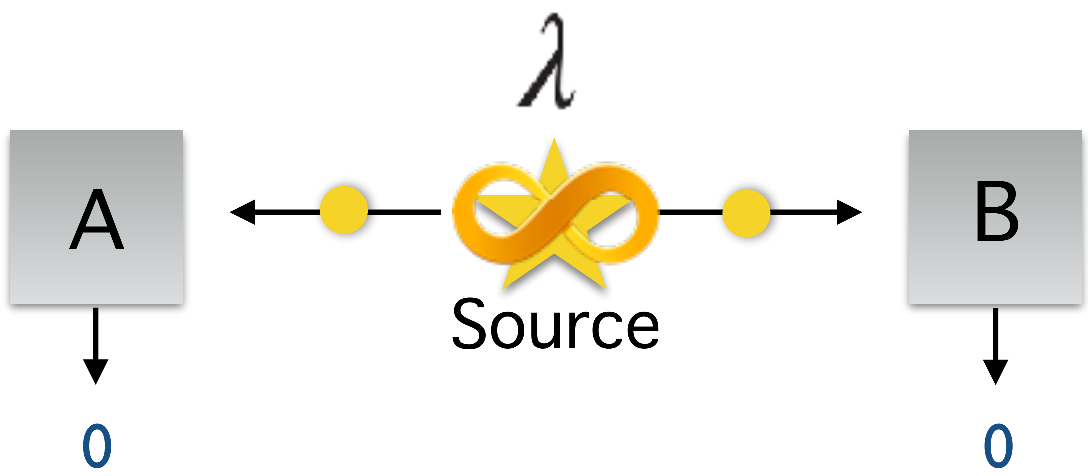
- The professor establish rules at the beginning of the year.

  # No chit-chat.
  # No changing seat.
  # Listening quietly.

Quantum correlations



Quantum correlations



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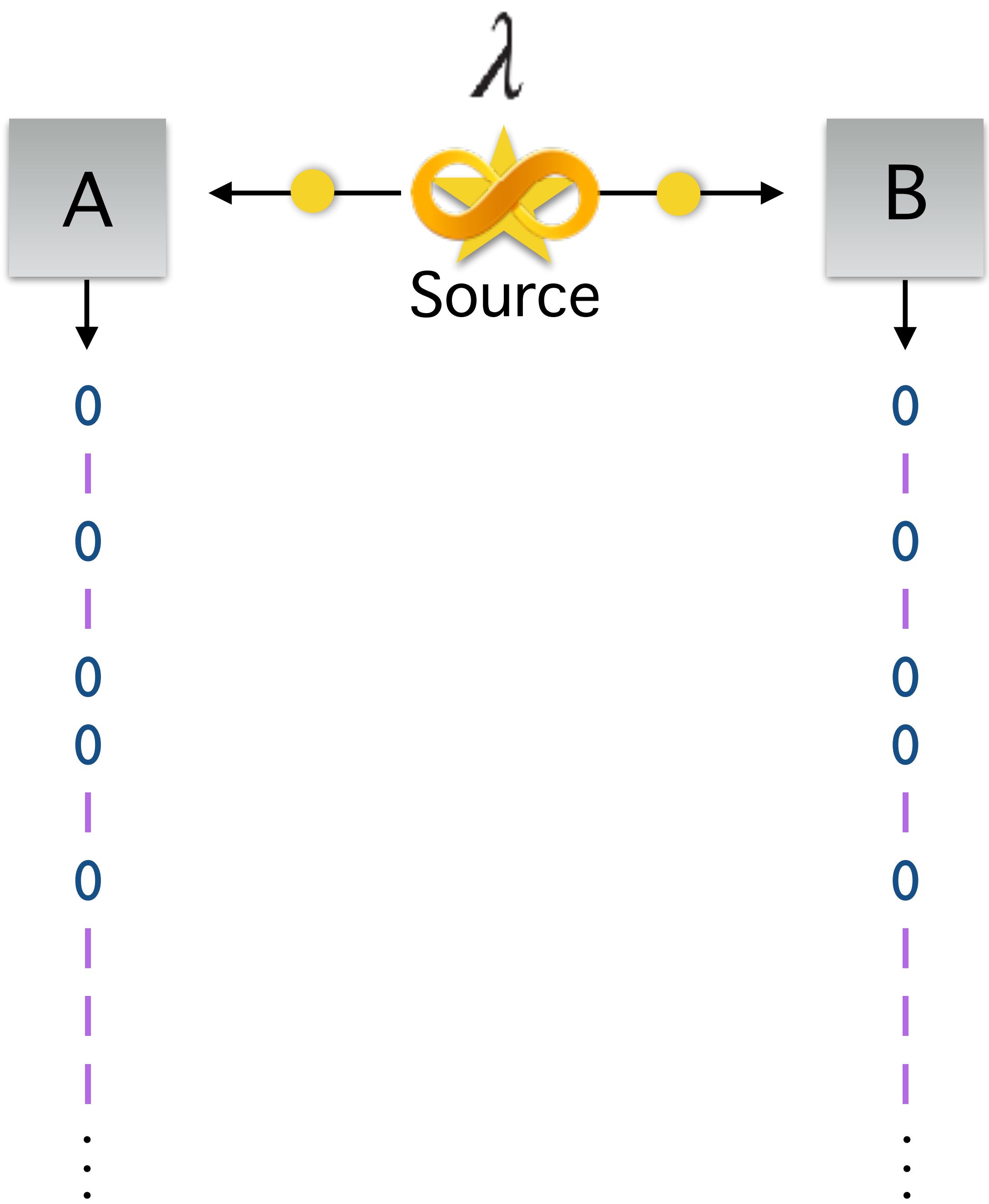

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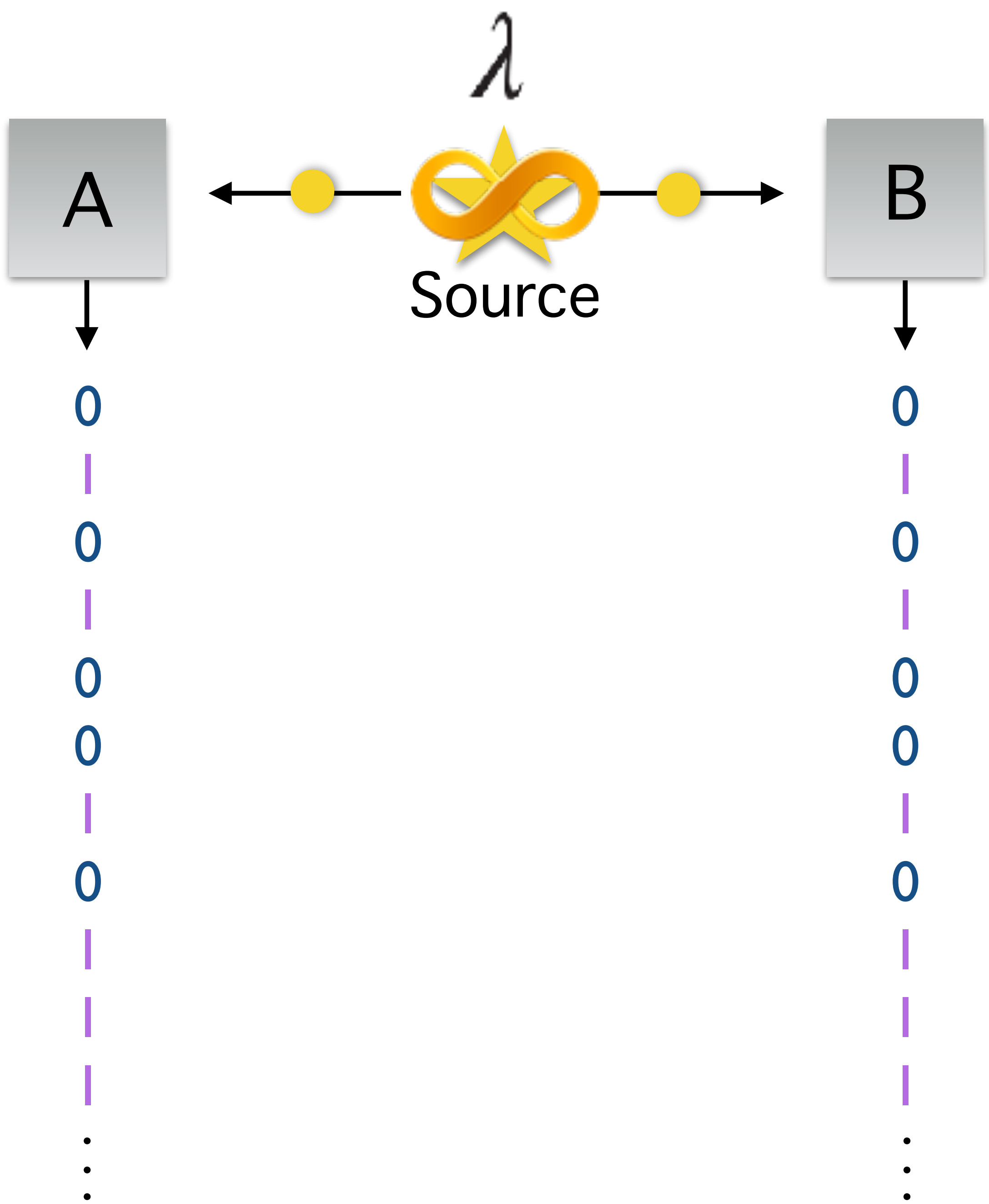


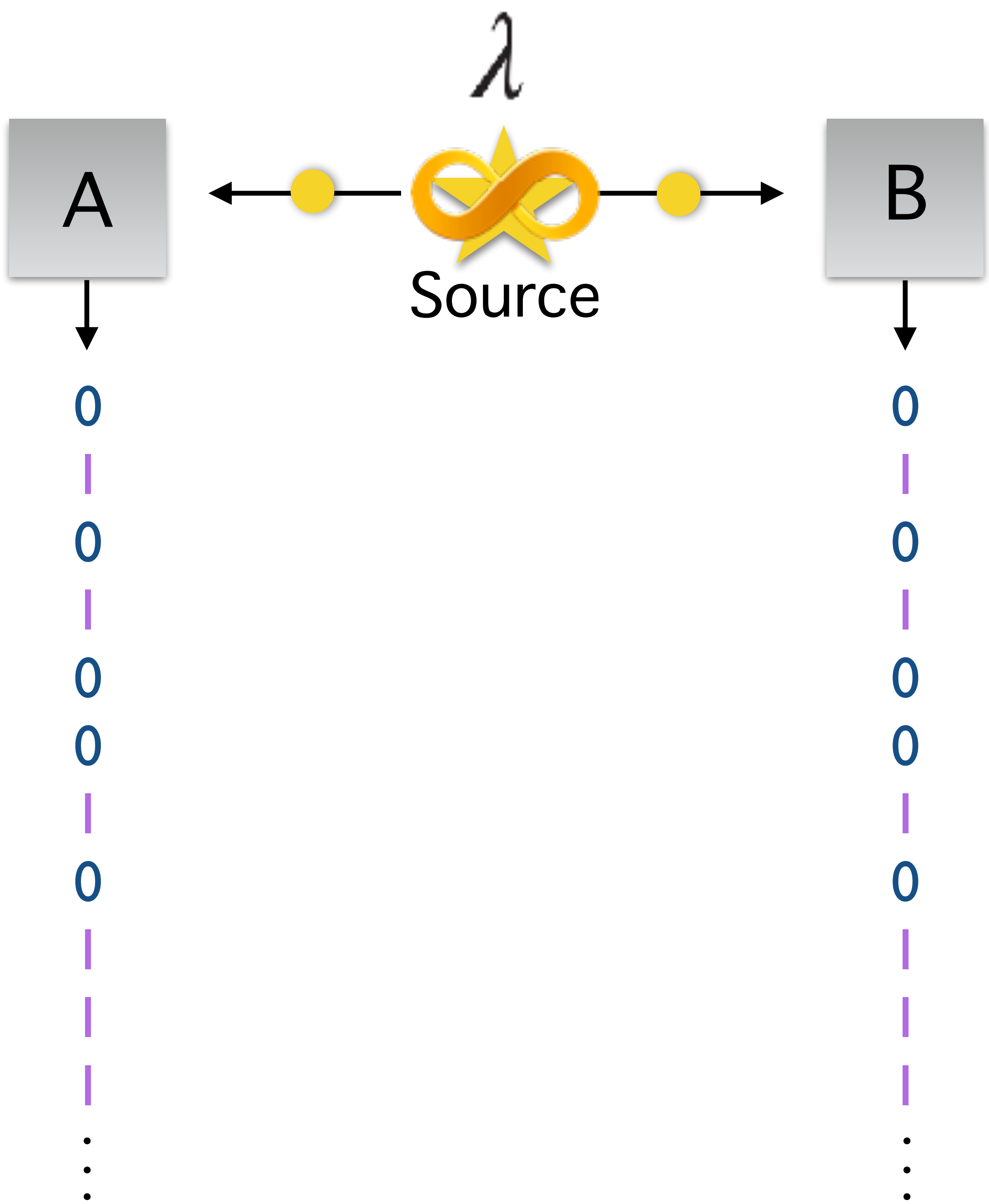
A and B gets the same answer,

Whatever the question!
(exclude strategy)

Whatever the distance!
(exclude signaling)

« *Spooky* » action
at a distance

Quantum correlations



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« *Spooky* » action
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Strong Q-correlations
provided by entangled states

Entanglement & original Bell test (1964)

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$$|\Psi\rangle = 1/\sqrt{2}\,(|H_a H_b\rangle + |V_a V_b\rangle)$$

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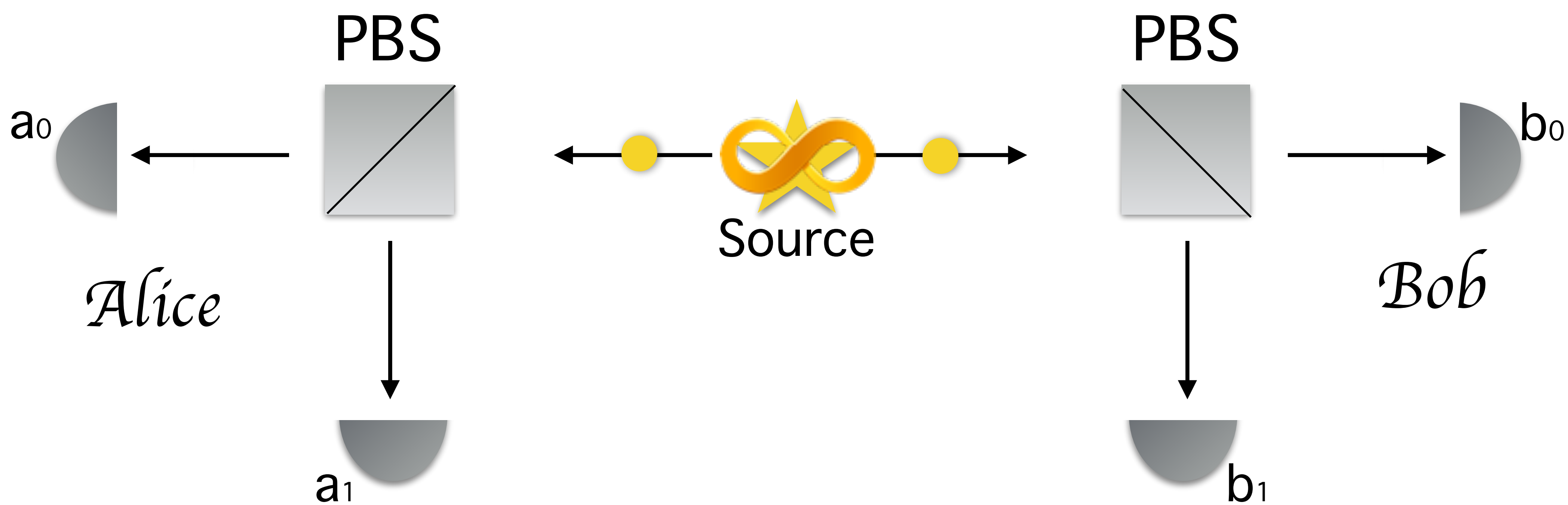

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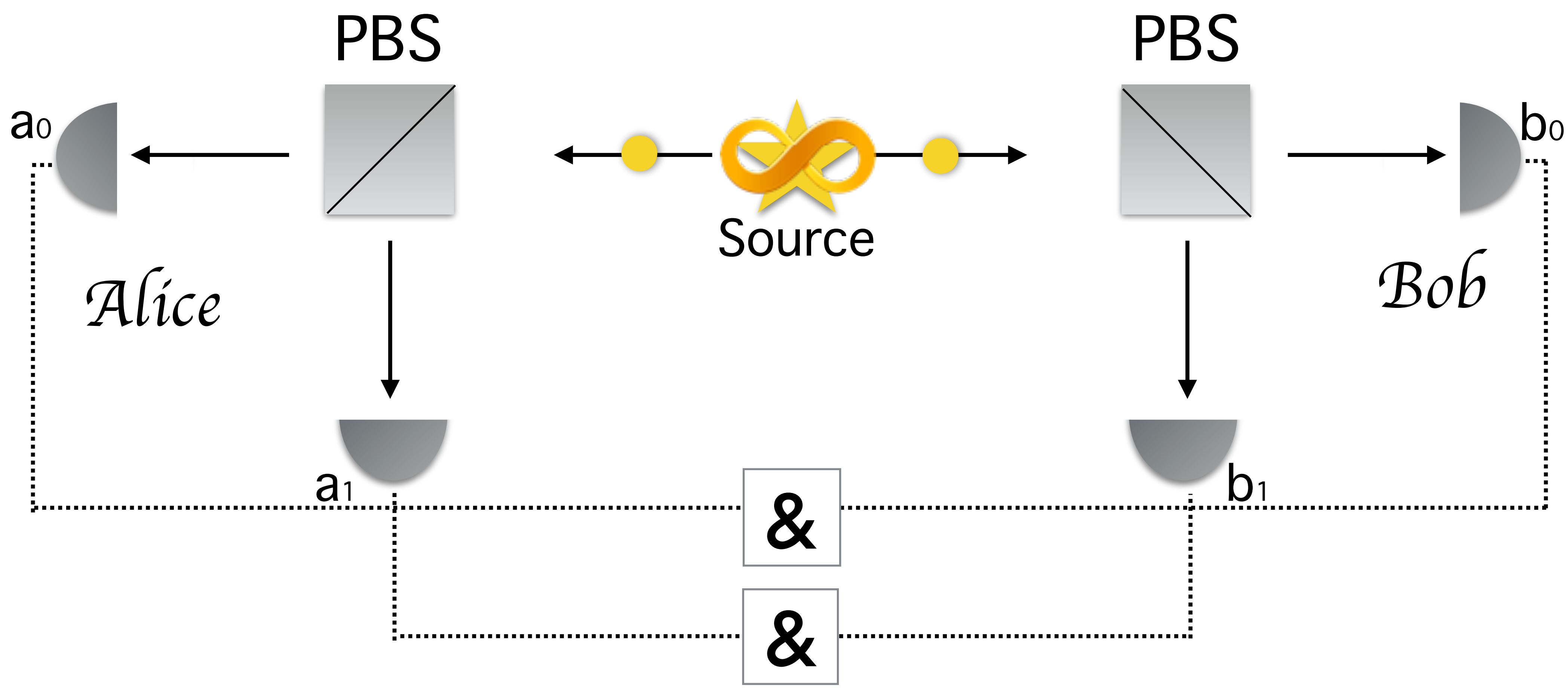

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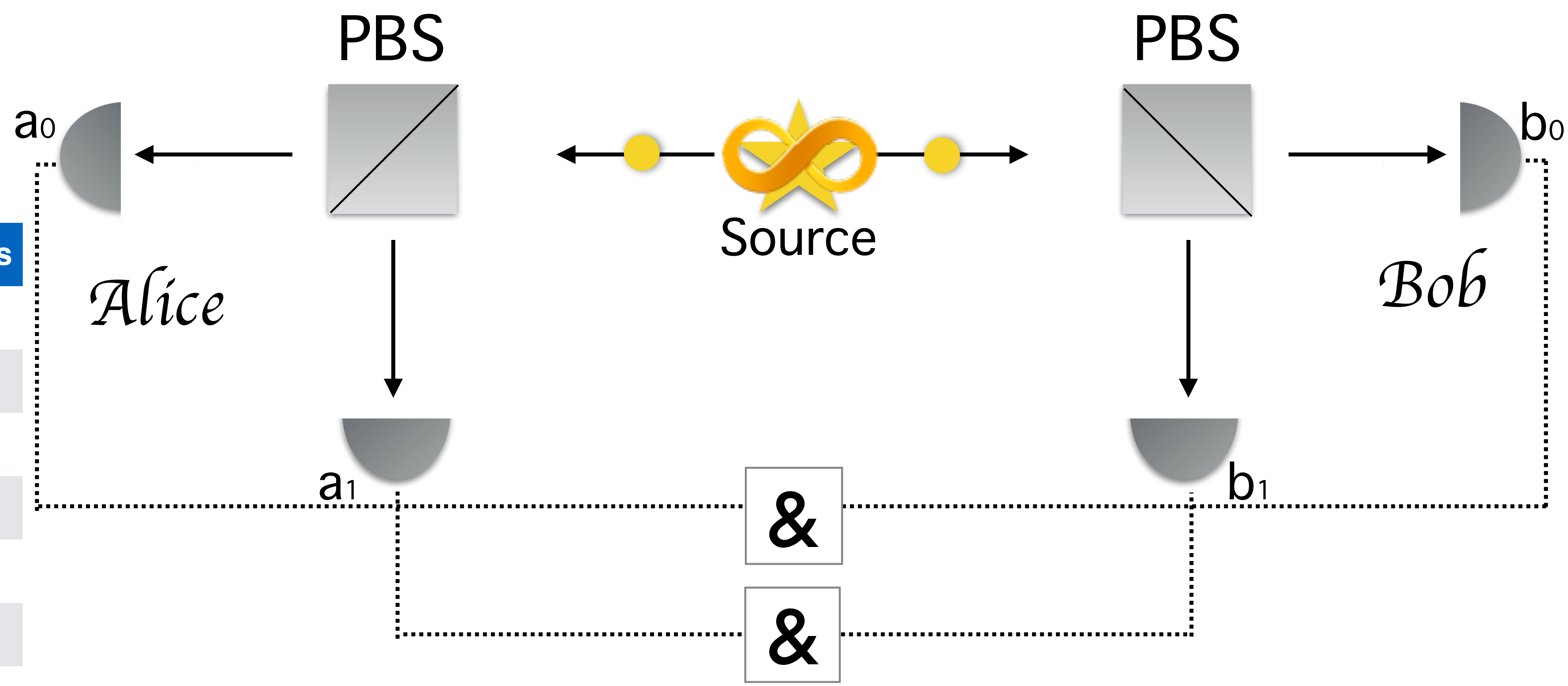

#	Measures
1	1
2	0
3	0
4	1
5	1
6	0
7	1
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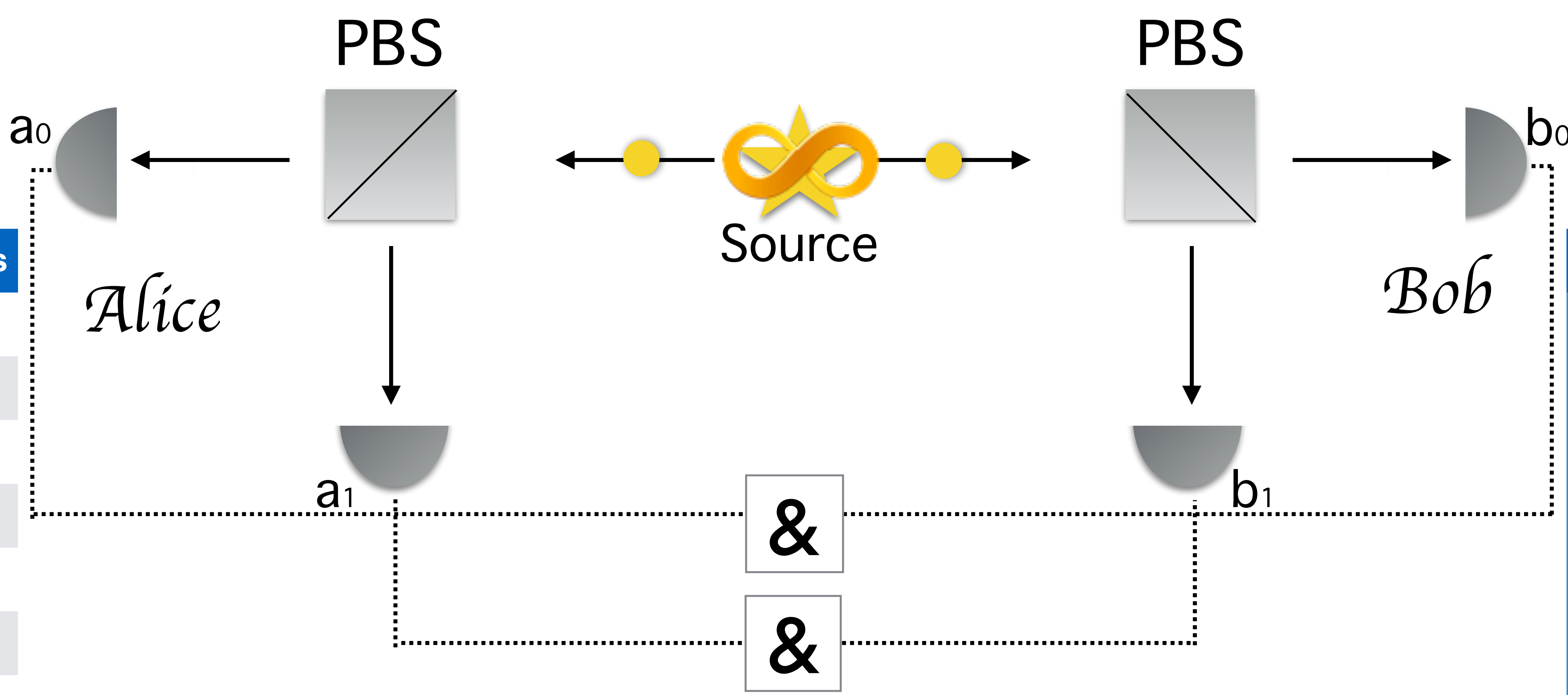

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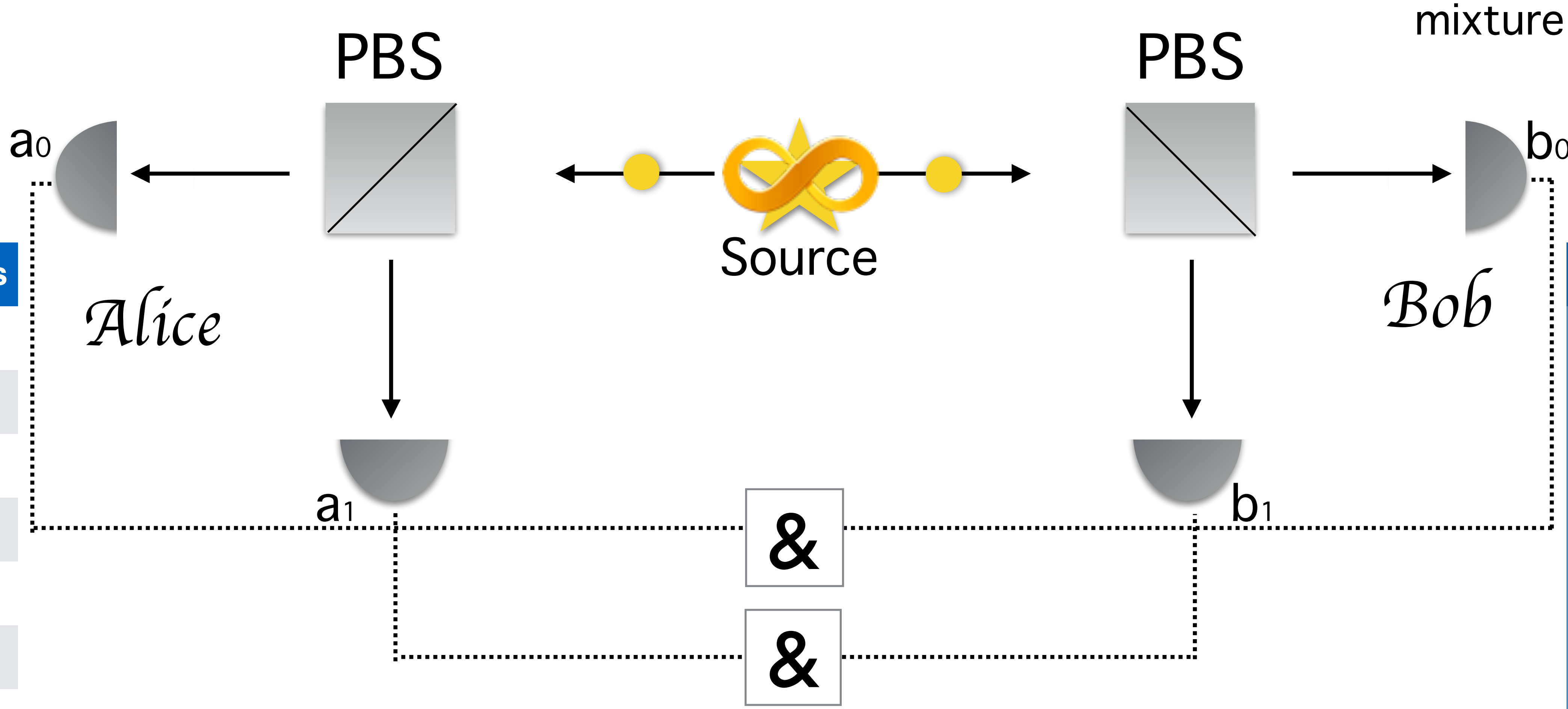
$$\Psi = \begin{cases} P = \frac{1}{2} \to |HH\rangle \\ P = \frac{1}{2} \to |VV\rangle \end{cases}$$

mixture



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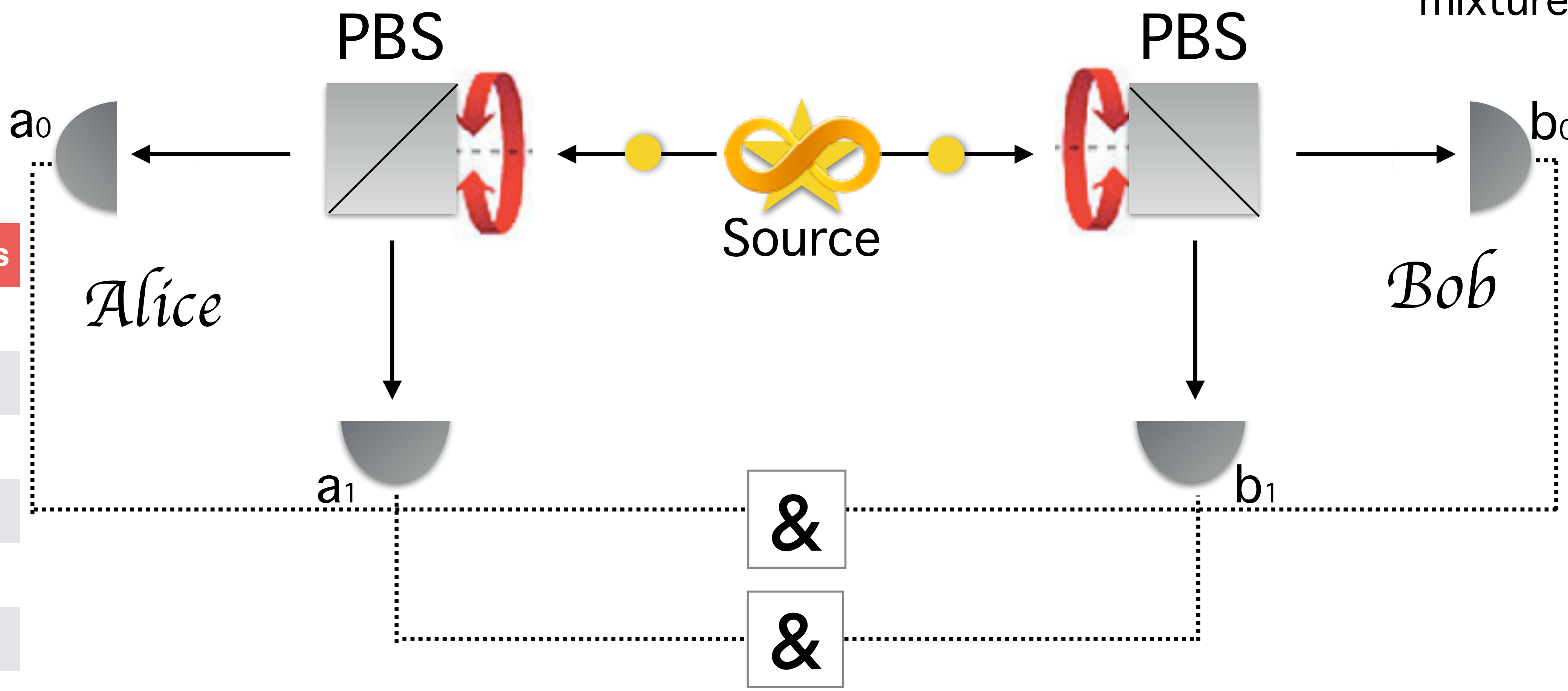

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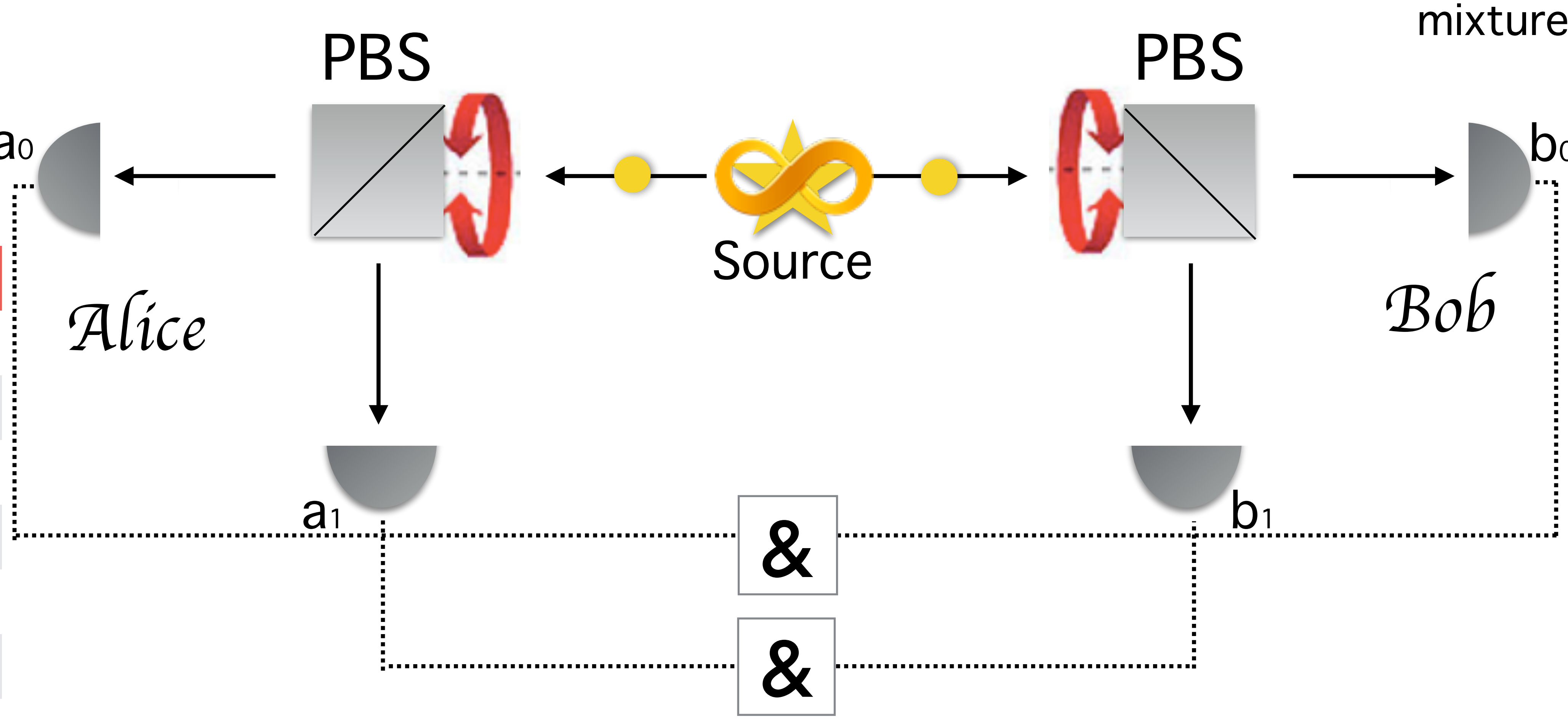

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correlations
invariant through rotation

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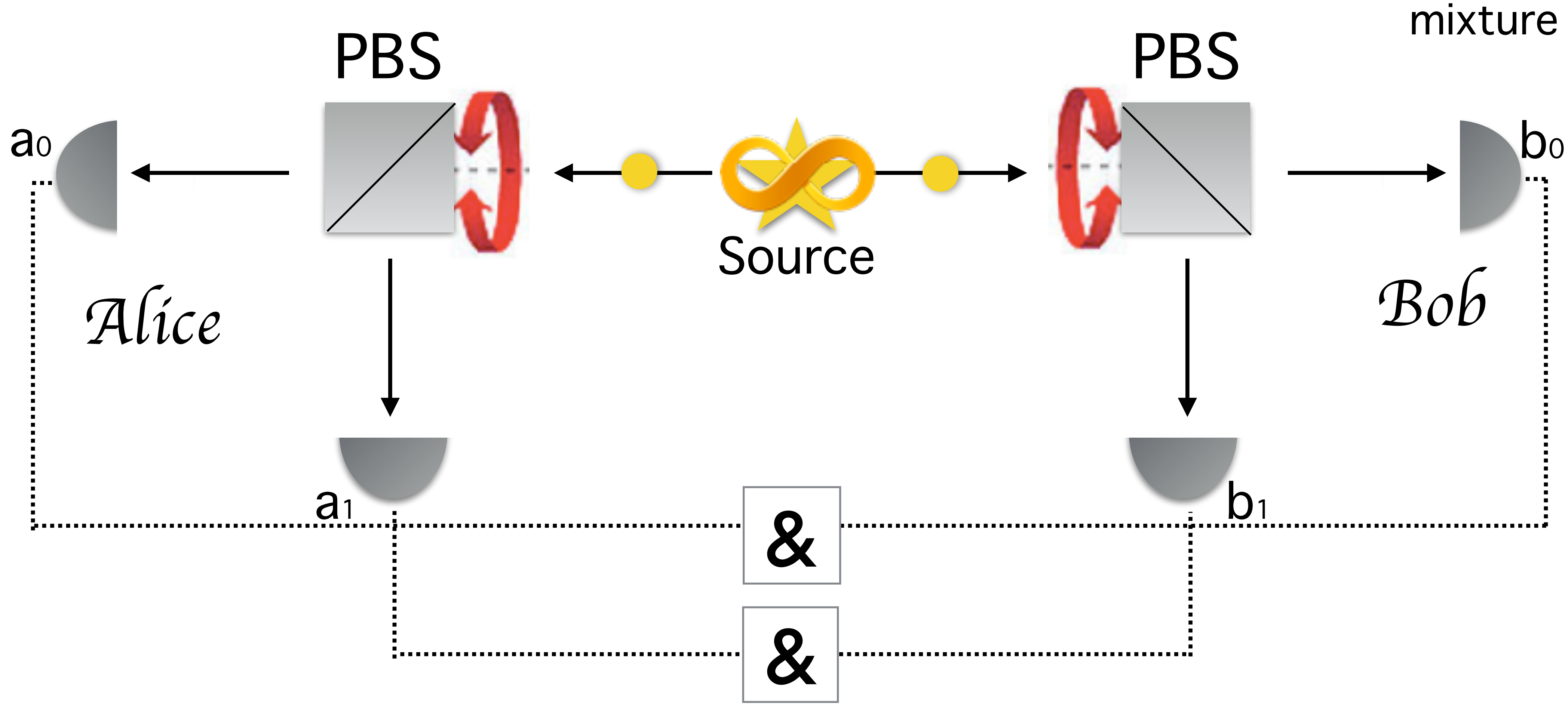

correlations
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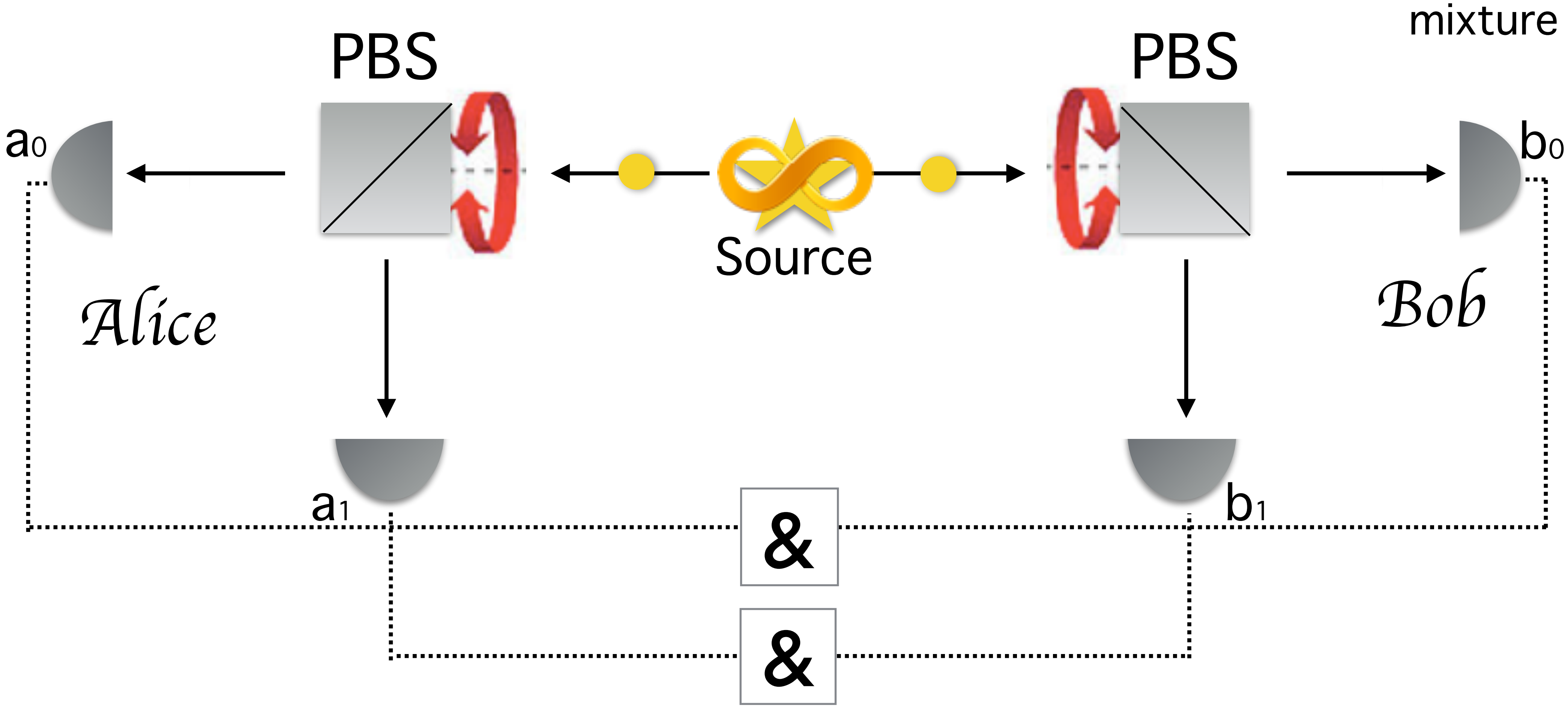
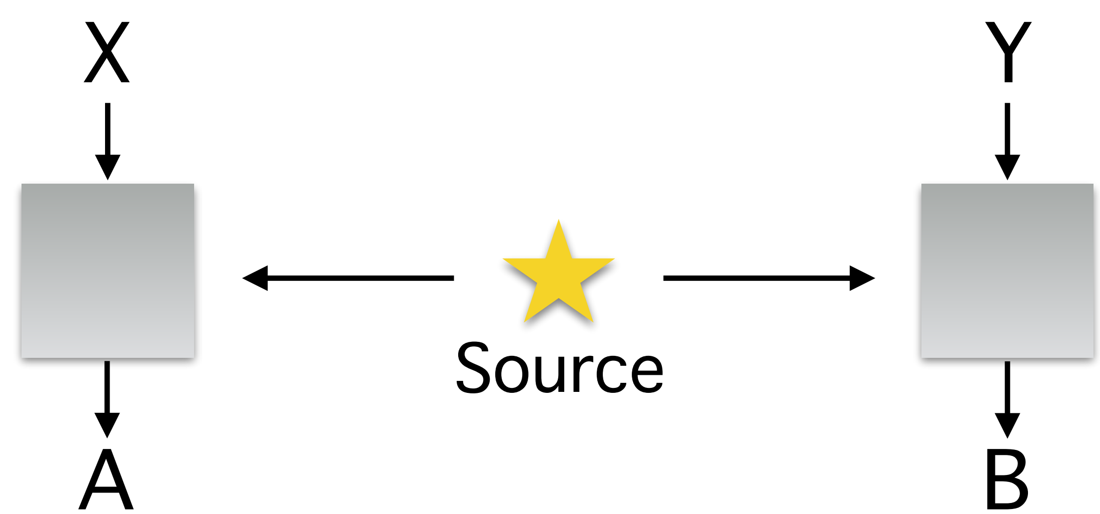


correlations invariant through rotation → most unintuitive

Bell *(non)locality* (1964)



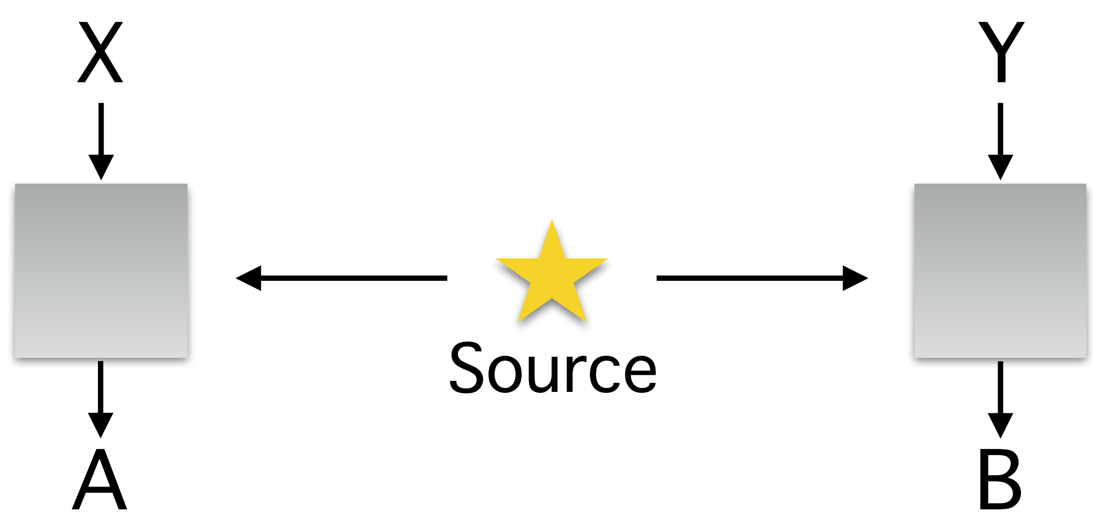
(X,Y) : settings

(A,B) : outcomes

$$p(ab|xy) \neq p(a|x)p(b|y)$$

Brunner *et al*, Rev. Mod. Phys., 86, No. 2 (2014)

Bell *(non)locality* (1964)



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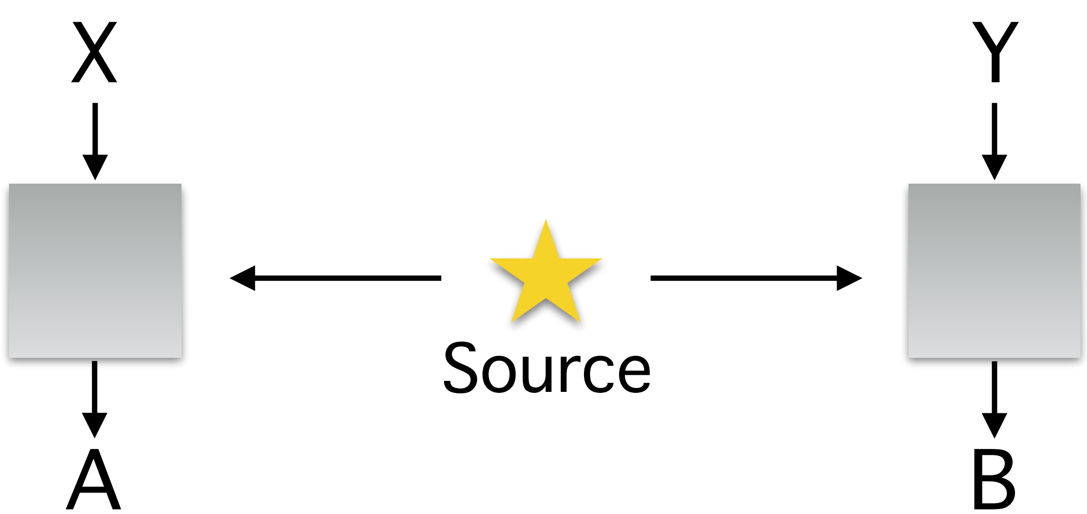

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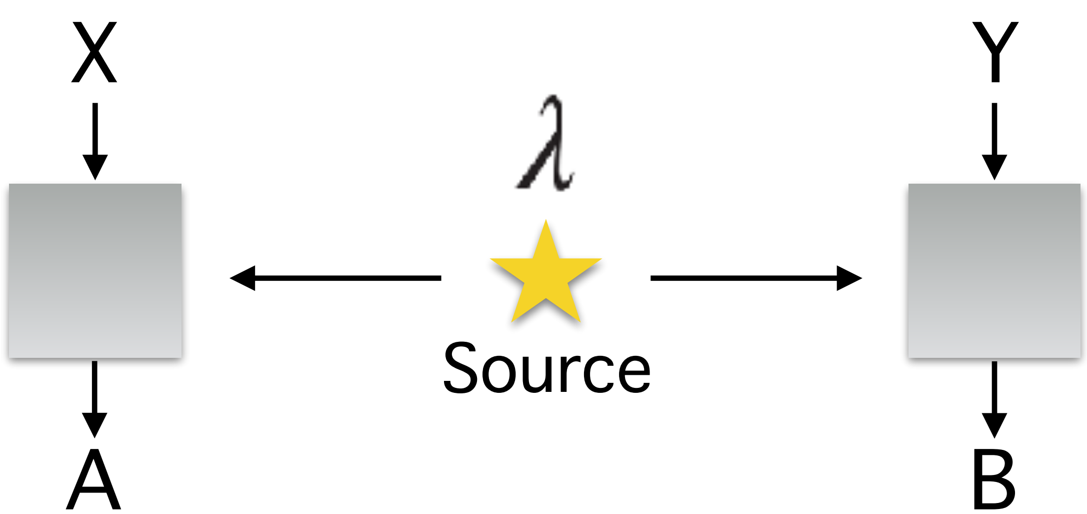

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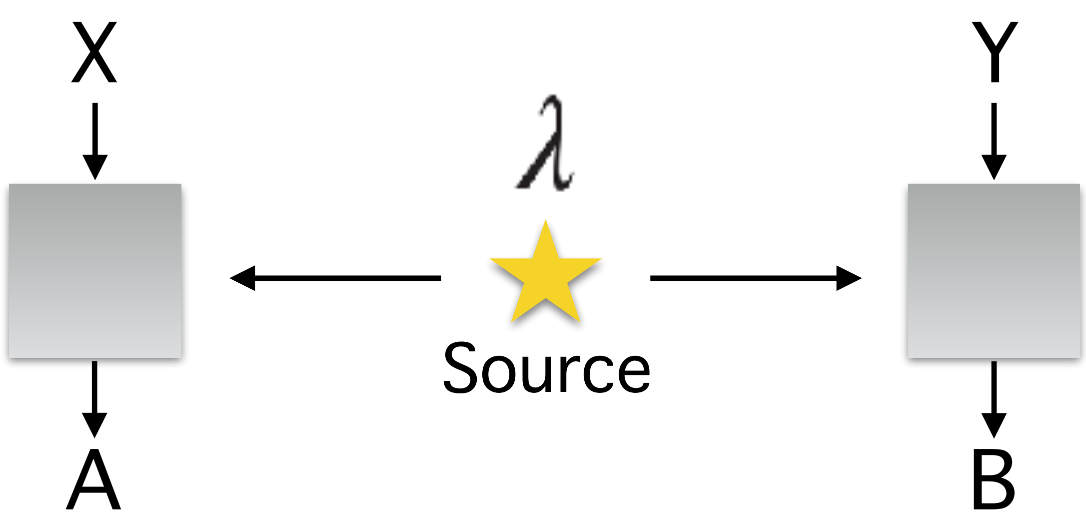

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Outcome independence:

$$p(ab|xy\lambda) = p(a|xy\lambda)p(b|xy\lambda)$$

parameter independence:

$$p(a|xy\lambda) = p(a|x\lambda)$$
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Brunner *et al*, Rev. Mod. Phys., 86, No. 2 (2014)

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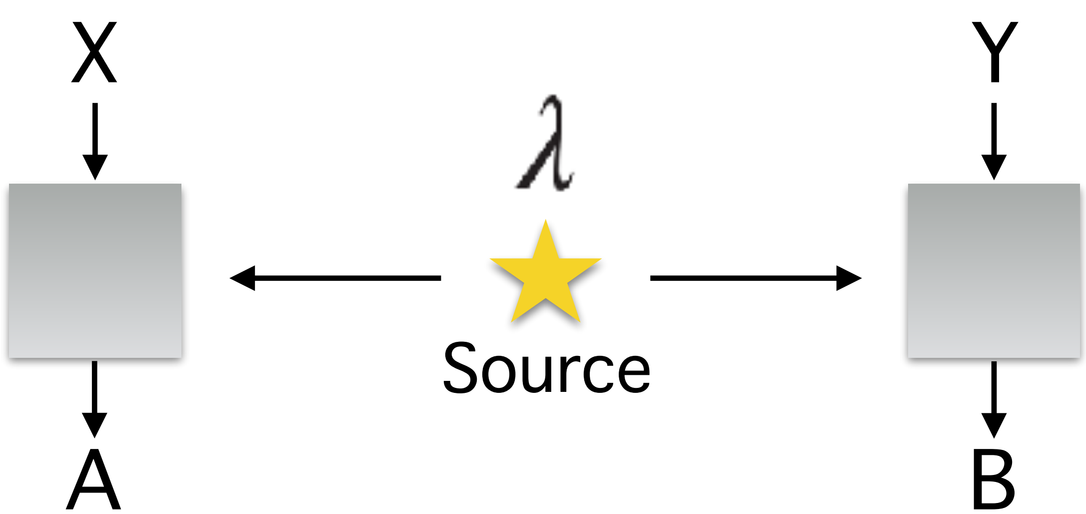

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Locality formalized:

$$p(ab|xy,\lambda) = p(a|x,\lambda)p(b|y,\lambda)$$

$$p(ab|xy) = \int_\Lambda d\lambda q(\lambda)p(a|x,\lambda)p(b|y,\lambda)$$

Brunner *et al*, Rev. Mod. Phys., 86, No. 2 (2014)

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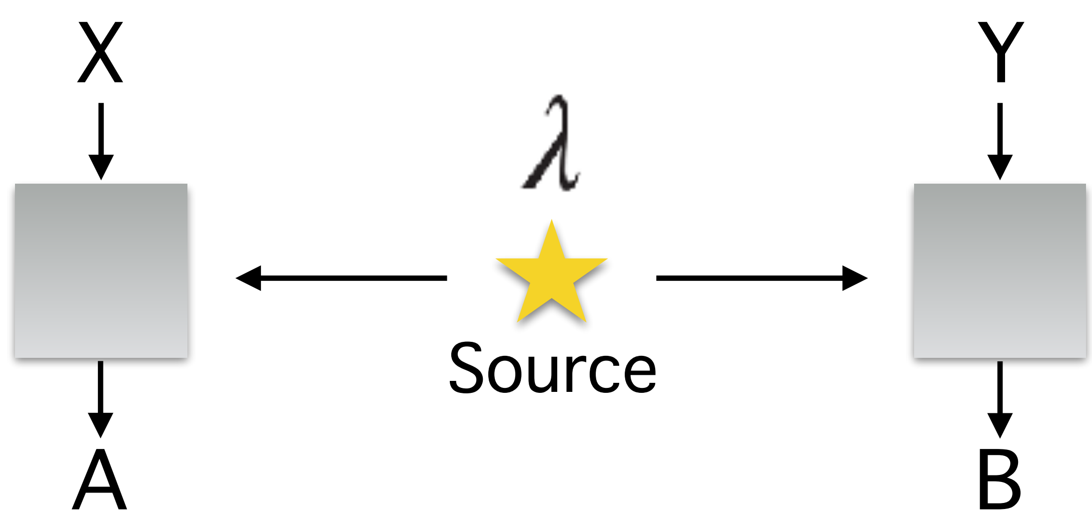

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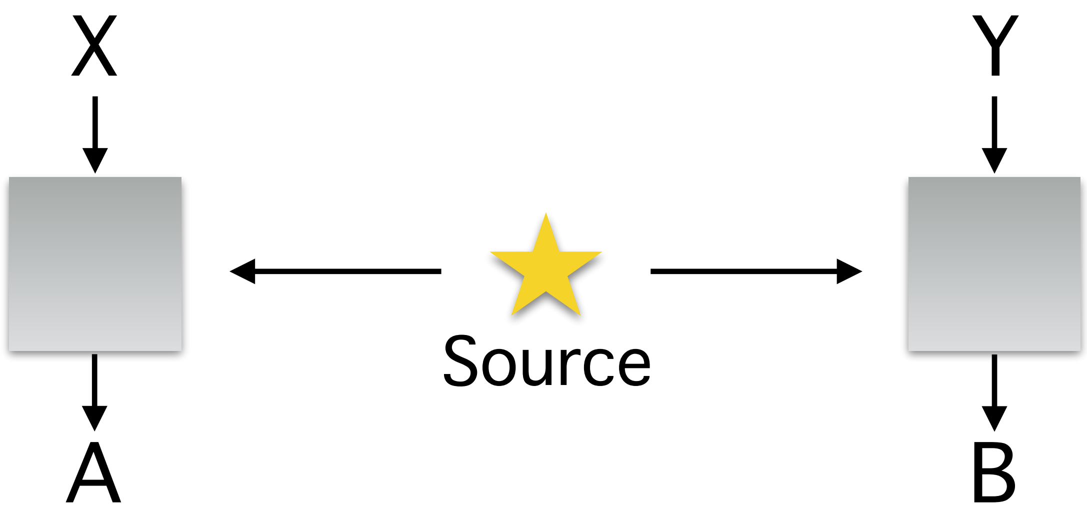
measurement independence:

$$p(xy|\lambda) = p(xy)$$

Brunner *et al*, Rev. Mod. Phys., 86, No. 2 (2014)

Bell-CHSH inequality (1969)



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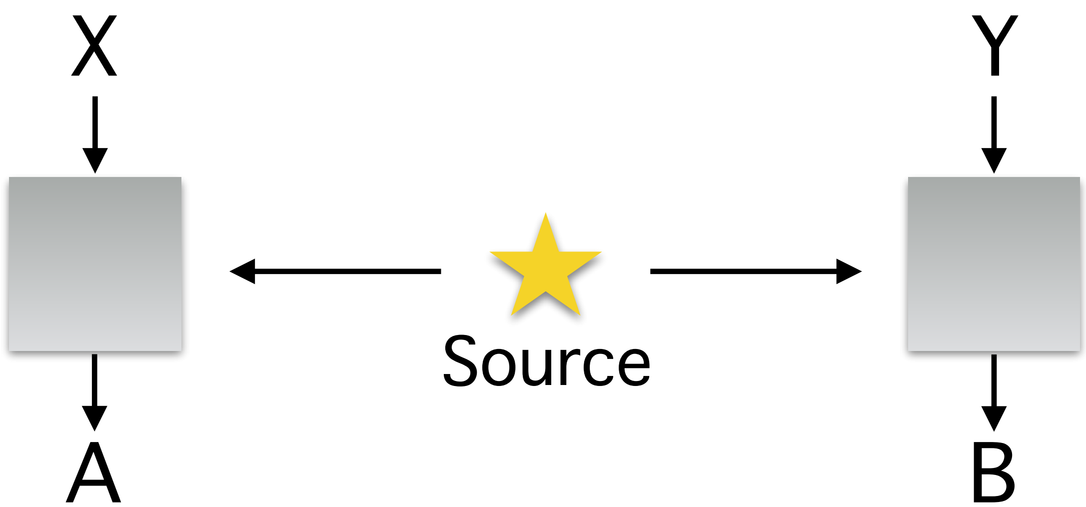
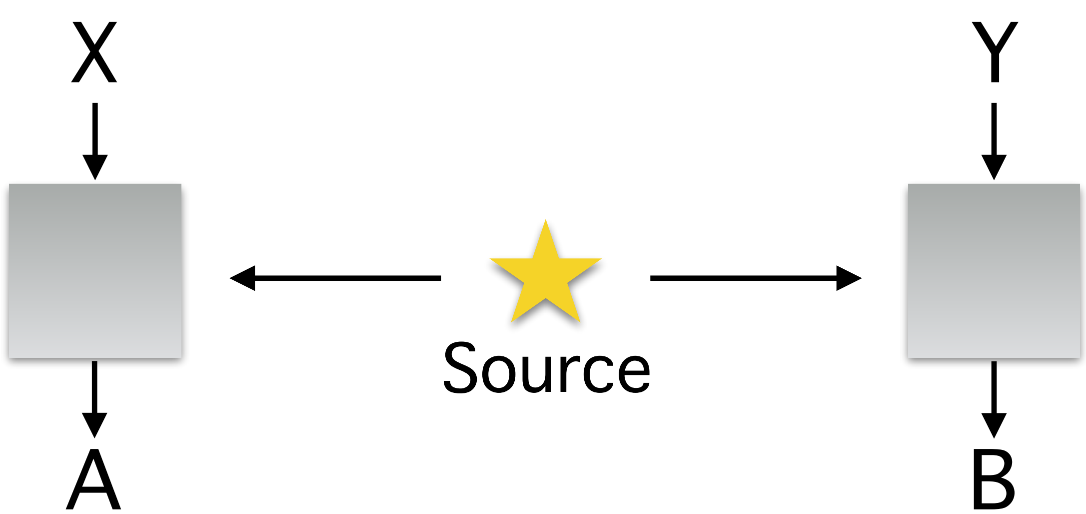


Simple case (binary):

$$x, y \in \{0, 1\}$$

$$a, b \in \{-1, +1\}$$

Bell-CHSH inequality (1969)



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$$S = \left|\langle a_0 b_0 \rangle + \langle a_0 b_1 \rangle + \langle a_1 b_0 \rangle - \langle a_1 b_1 \rangle\right| \leq 2$$

Bell-CHSH inequality

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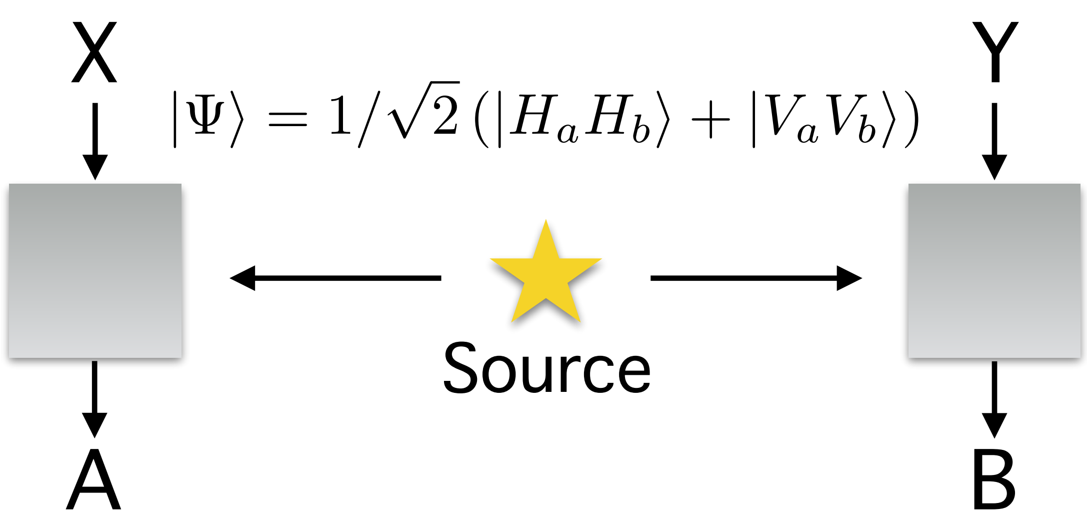

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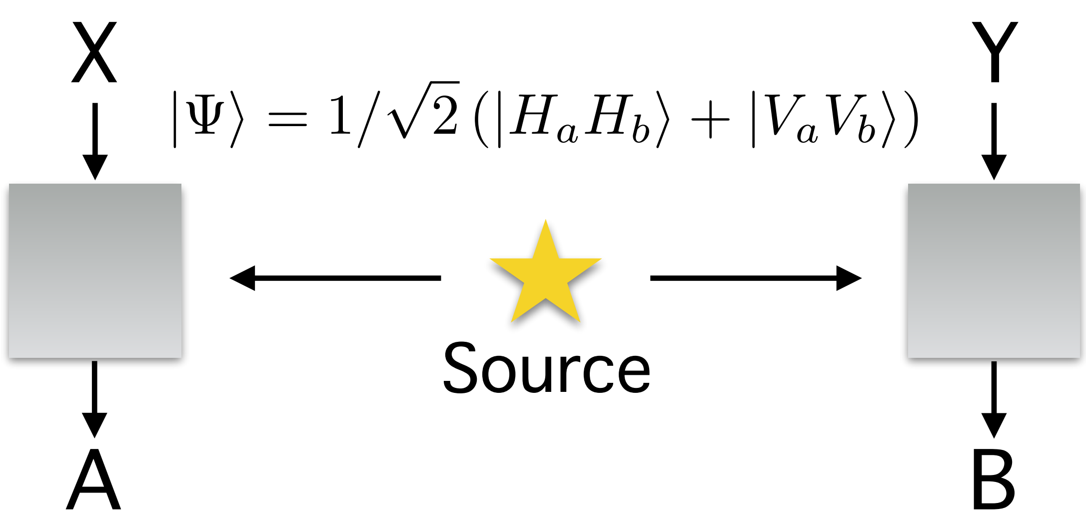
$1/\sqrt{2}$ $1/\sqrt{2}$ $1/\sqrt{2}$ $-1/\sqrt{2}$

Bell-CHSH inequality

quantum correlations with proper settings:

$$S = 2\sqrt{2} > 2$$

Bell-CHSH inequality (1969)



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Bell-CHSH inequality

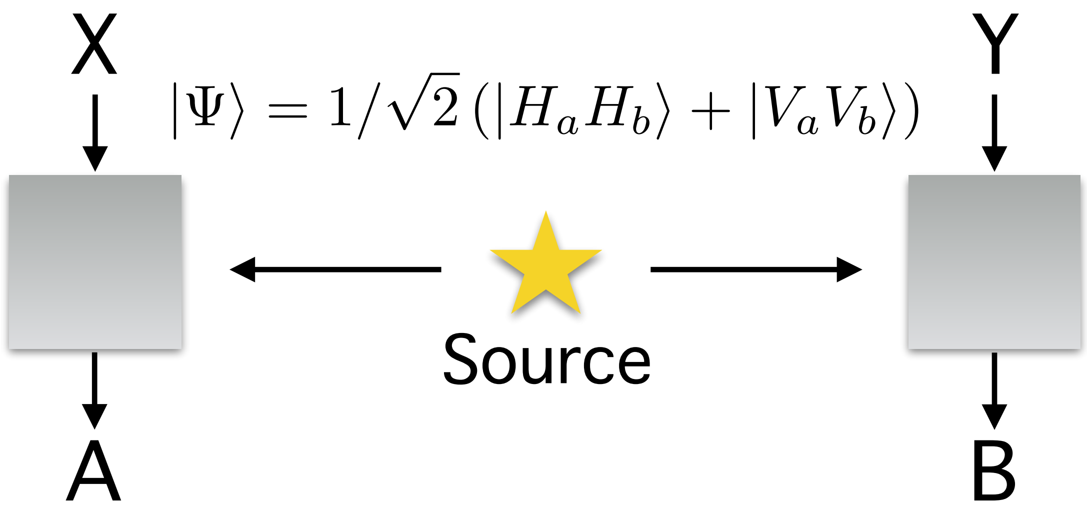
quantum correlations with proper settings:

$$S = 2\sqrt{2} > 2$$

Detection Loophole !

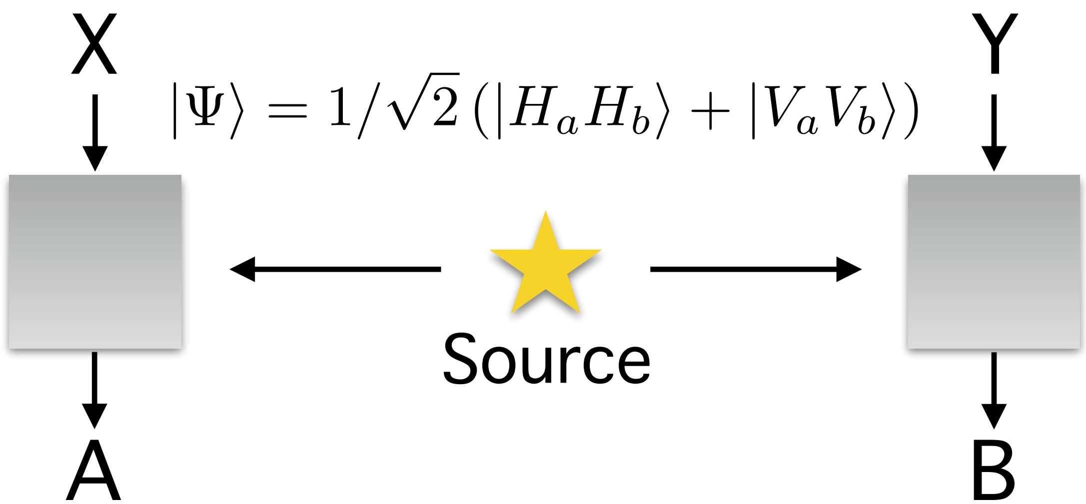
$\eta_{thr} = 2(\sqrt{2}-1) \approx 0.83$

Bell-CHSH inequality (1969)



Quantum predictions contradict Bell's locality

Bell-CHSH inequality (1969)



Quantum predictions contradict Bell's locality

Power of entanglement

- Pair of particles ⟶ well defined properties
- Individual particles ⟶ NO well defined properties

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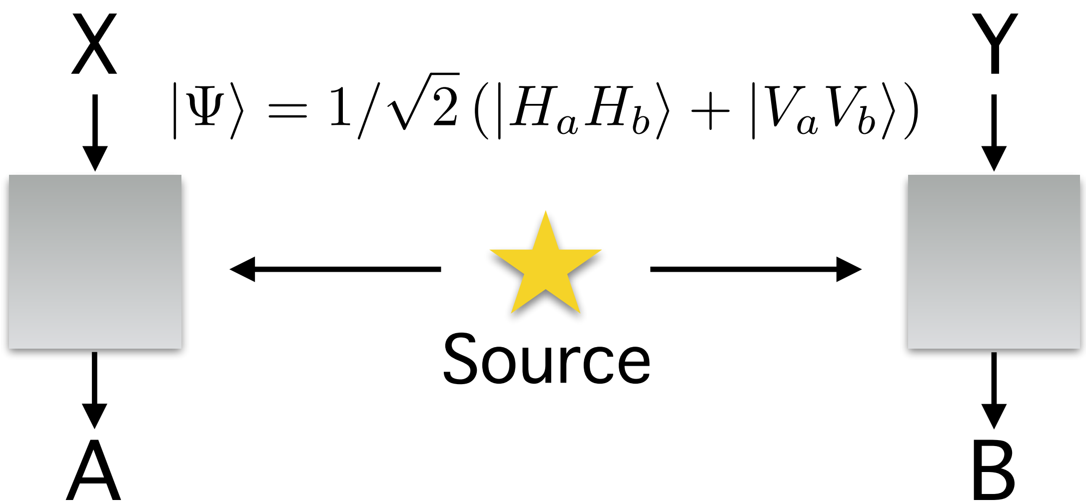

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Device Independent Applications
(Device Independent Quantum Information Processing)

Eberhardt inequality & Fair sampling

$$N^{++}(a,b) - N^{+0}(a,b') - N^{0+}(a',b) - N^{++}(a',b') \leq 0$$

Eberhardt inequality & Fair sampling

Not coincidences clics

$$N^{++}(a,b) - N^{+0}(a,b') - N^{0+}(a',b) - N^{++}(a',b') \leq 0$$

Coincidences clics

Coincidences clics

Eberhardt inequality & Fair sampling

Not coincidences clics

$$\boxed{N^{++}(a,b)} - \boxed{N^{+0}(a,b') - N^{0+}(a',b)} - \boxed{N^{++}(a',b')} \leq 0$$

Coincidences clics

Coincidences clics

Which is actually the CH-inequality:

$$N^{++}(a,b) + N^{++}(a,b') + N^{++}(a',b) - N^{++}(a',b') - S(a) - S(b) \leq 0$$

With:

$$S(a,j) = N^{+0}(a,j) + N^{++}(a,j)$$

Eberhardt inequality & Fair sampling

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$S(a,j) = N^{+0}(a,j) + N^{++}(a,j)$

$$\eta^2 \times [P^{++}(a,b) + P^{++}(a,b') + P^{++}(a',b) - P^{++}(a',b')] - \eta \times [P^{+}(a) + P^{+}(b)] \equiv J \leq 0$$

Eberhardt inequality & Fair sampling

Not coincidences clics

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Single >> Coincidences

Eberhardt inequality & Fair sampling

$$|\psi_E\rangle = (1+r^2)^{-1/2}\{|x_A, y_B\rangle + r|y_A, x_B\rangle\}$$

Coincidence: $$P^{++}(a,b) = (1+r^2)^{-1}[\cos(a)\sin(b) + r\sin(a)\cos(b)]^2$$

Singles:

$$P^{+}(a) = (1+r^2)^{-1}[\cos^2(a) + r^2\sin^2(a)]$$

$$P^{+}(b) = (1+r^2)^{-1}[r^2\cos^2(b) + \sin^2(b)]$$

Eberhardt inequality & Fair sampling

- Use non maximally entangled state:

$$|\psi_E\rangle = (1+r^2)^{-1/2}\{|x_A, y_B\rangle + r|y_A, x_B\rangle\}$$

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$$P^{++}(a,b) = (1+r^2)^{-1}[\cos(a)\sin(b) + r\sin(a)\cos(b)]^2 \quad \sim r^2$$

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With:

$\cos(a) \approx 0$

$\sin(b) \approx 0,$

Eberhardt inequality & Fair sampling

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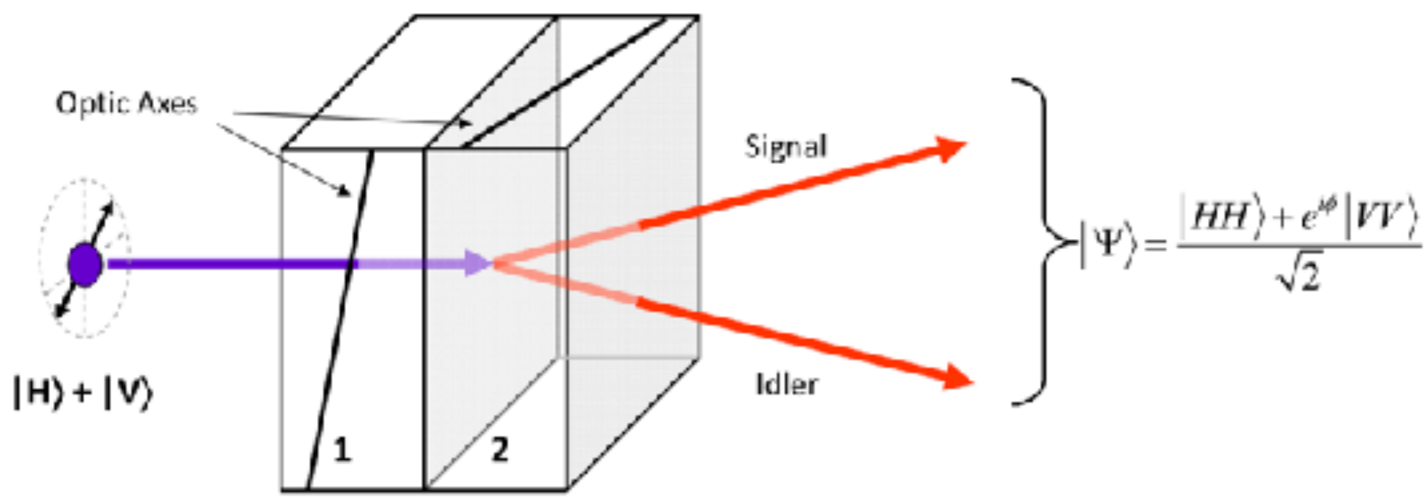
$$J \approx 3\eta r^2 - 2r^2 \leq 0$$

Detection Loophole !

$\eta_{thr} = 2/3$

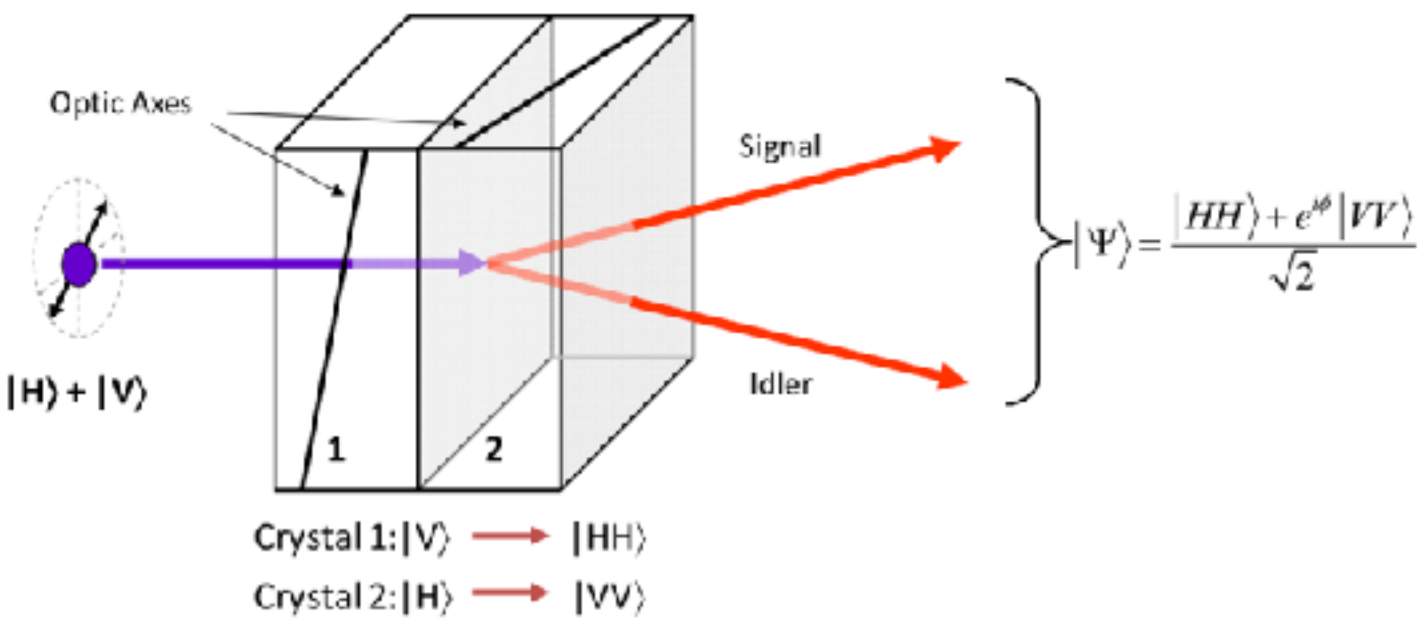
Non-maximally entangled states



BBO
Type I

Source: Kwiat *et al*, PRA, **60** R773 (1999)

Non-maximally entangled states



BBO
Type I

$$P^{++}(a,b) = (1+r^2)^{-1}[\cos(a)\cos(b) + r\sin(a)\sin(b)]^2$$

$$P^{+}(a) = (1+r^2)^{-1}[\cos^2(a) + r^2\sin^2(a)]$$

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OUTLINE

1. Introduction
2. Fundamental tests on nonlocality
3. Generalised Bell inequality
4. Conclusion & outlook

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1. Introduction

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3. Generalised Bell inequalities

- Measurement Dependent Locality (MDL)
  - Theoretical framework
  - Experimental demonstration
- Limited Detection Locality (LDL)
  - Theoretical framework
  - Experimental demonstration

4. C

MDL inequality

Arbitrarily small amount of measurement independence is sufficient to manifest quantum nonlocality

Gilles Pütz,[1,*] Denis Rosset,[1] Tomer Jack Barnea,[1] Yeong-Cherng Liang,[2] and Nicolas Gisin[1]

[1] *Group of Applied Physics, University of Geneva, CH-1211 Geneva 4, Switzerland.*
[2] *Institute for Theoretical Physics, ETH Zurich, 8093 Zurich, Switzerland.*

(Dated: October 6, 2018)

The use of Bell's theorem in any application or experiment relies on the assumption of free choice or, more precisely, measurement independence, meaning that the measurements can be chosen freely. Here, we prove that even in the simplest Bell test — one involving 2 parties each performing 2 binary-outcome measurements — an *arbitrarily small amount* of measurement independence is *sufficient* to manifest quantum nonlocality. To this end, we introduce the notion of measurement dependent locality and show that the corresponding correlations form a convex polytope. These correlations can thus be characterized efficiently, e.g., using a finite set of Bell-like inequalities — an observation that enables the systematic study of quantum nonlocality and related applications under limited measurement independence.

$$\ell P(0000) - h\big(P(0101) + P(1010) + P(0011)\big) \overset{MDL}{\leq} 0$$

MDL inequality

1	$P_{A\|X}(0\|0)$	$P_{A\|X}(0\|1)$	$P_{B\|Y}(0\|0)$	$P(00\|00)$	$P(00\|10)$	$P_{B\|Y}(0\|1)$	$P(00\|01)$	$P(00\|11)$
$12h^2-11h+2$	$2h-1$	$4h-1$	$2h-1$	$2h$	$2-6h$	$4h-1$	$2-6h$	$-2h$
$12h^2-11h+2$	$4h-1$	$3h-1$	$4h-1$	$-h$	$1-3h$	$3h-1$	$1-3h$	$1-3h$
$11h^2-8h+1$	$-4h^2+5h-1$	$5h^2-4h+1$	$-4h^2+5h-1$	$-3h^2-2h+1$	$3h^2-2h$	$5h^2-4h+1$	$3h^2-2h$	$-9h^2+9h-2$
$8h^2-7h+1$	$4h^2$	0	$-4h^2+5h-1$	$-h$	$1-3h$	$-4h^2+2h$	$-h$	$3h-1$
$13h^2-8h+1$	$-8h^2+6h-1$	$-5h^2+2h$	$-h^2+h$	$5h^2-2h$	h^2-h	0	$3h^2-4h+1$	$-3h^2+4h-1$
$20h^2-13h+2$	$-8h^2+6h-1$	$-7h^2+5h-1$	$-8h^2+6h-1$	$5h^2-2h$	$3h^2-4h+1$	$-7h^2+5h-1$	$3h^2-4h+1$	$-h^2+h$
$1-4h$	$3h-1$	0	$3h-1$	$1-3h$	h	0	h	$-h$

TABLE I. Conjectured families of MDL inequalities for $h \in]\frac{1}{4}, \frac{1}{3}[$. The Table contains the coefficients belonging to each term (given in the first row). We denote by $P_{A|X}(a|x)$ the marginal distribution over Alice's ouput A conditioned on her input X and similarly for Bob. The expression being ≤ 0 is a representative MDL inequality from each family.

MDL inequality

1	$P_{A\|X}(0\|0)$	$P_{A\|X}(0\|1)$	$P_{B\|Y}(0\|0)$	$P(00\|00)$	$P(00\|10)$	$P_{B\|Y}(0\|1)$	$P(00\|01)$	$P(00\|11)$
$12h^2-11h+2$	$2h-1$	$4h-1$	$2h-1$	$2h$	$2-6h$	$4h-1$	$2-6h$	$-2h$
$12h^2-11h+2$	$4h-1$	$3h-1$	$4h-1$	$-h$	$1-3h$	$3h-1$	$1-3h$	$1-3h$
$11h^2-8h+1$	$-4h^2+5h-1$	$5h^2-4h+1$	$-4h^2+5h-1$	$-3h^2-2h+1$	$3h^2-2h$	$5h^2-4h+1$	$3h^2-2h$	$-9h^2+9h-2$
$8h^2-7h+1$	$4h^2$	0	$-4h^2+5h-1$	$-h$	$1-3h$	$-4h^2+2h$	$-h$	$3h-1$
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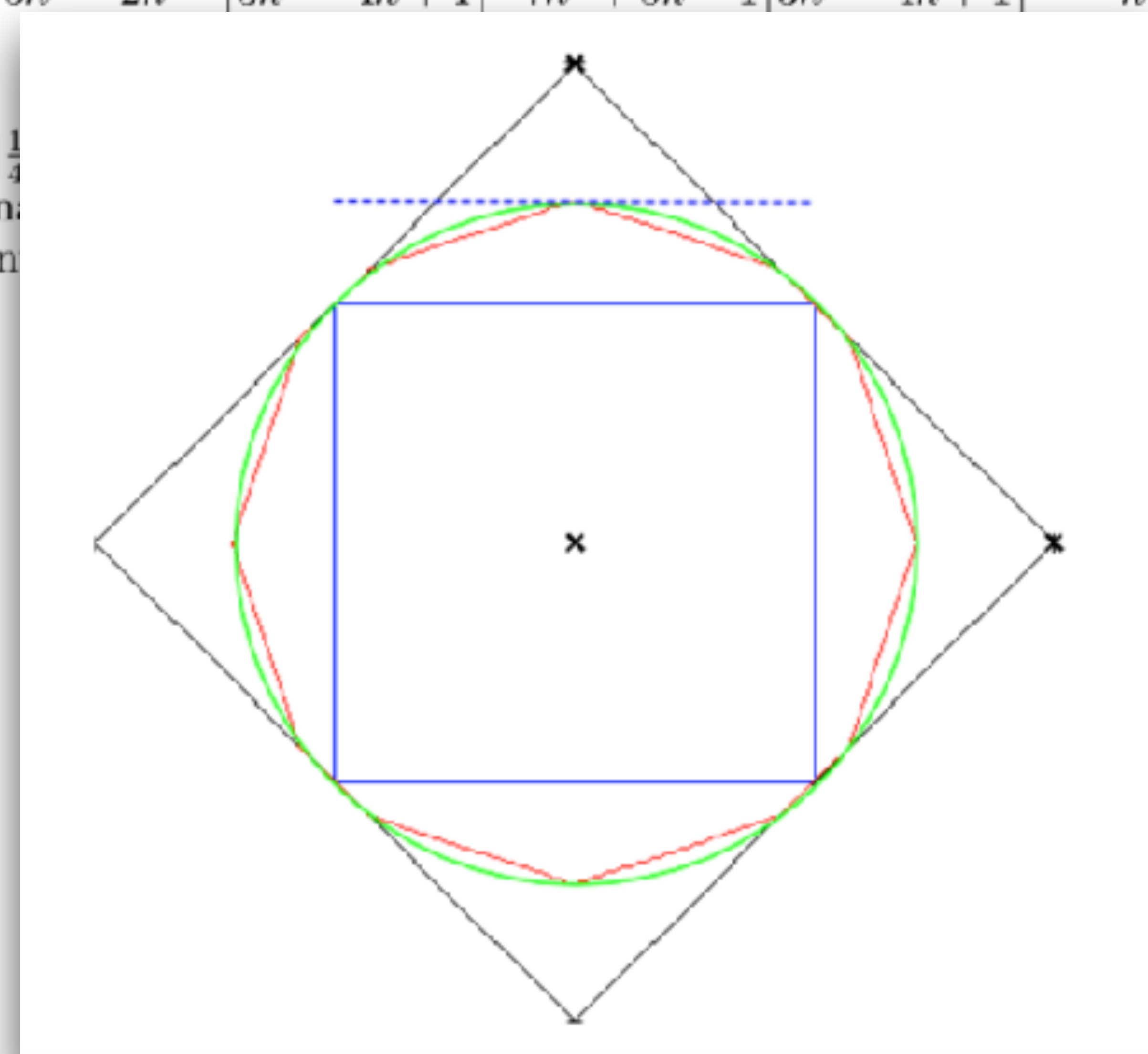

Measurement Dependent Locality

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Assume an adversary can influence the choices of measurement (but only to a certain extent).

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Then locality is now rewritten:

$$P(abxy) = \int d\lambda P(\lambda) P(xy|\lambda) P(a|x\lambda) P(b|y\lambda)$$

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Any pure non maximally entangled state* & every $\ell > 0$

Experimental realization

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$$\ell P(0000) - (1-3\ell)(P(0101) + P(1010) + P(0011)) \overset{\text{MDL}}{\leq} 0$$

$$|\Psi\rangle = \frac{1}{\sqrt{3}}\left(|01\rangle + |10\rangle - |11\rangle\right)$$

input 0: $\{\frac{|0\rangle+|1\rangle}{\sqrt{2}}, \frac{|0\rangle-|1\rangle}{\sqrt{2}}\}$ & input 1: $\{|0\rangle, |1\rangle\}$

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$\approx 0,083$

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$$|\Psi\rangle = \frac{1}{\sqrt{3}}(|01\rangle + |10\rangle - |11\rangle) \underset{\text{golden state}}{=} \frac{1}{\sqrt{3}}\left(\frac{\sqrt{5}-1}{2}|H_{\mathcal{A}}, H_{\mathcal{B}}\rangle + \frac{\sqrt{5}+1}{2}|V_{\mathcal{A}}, V_{\mathcal{B}}\rangle\right)$$

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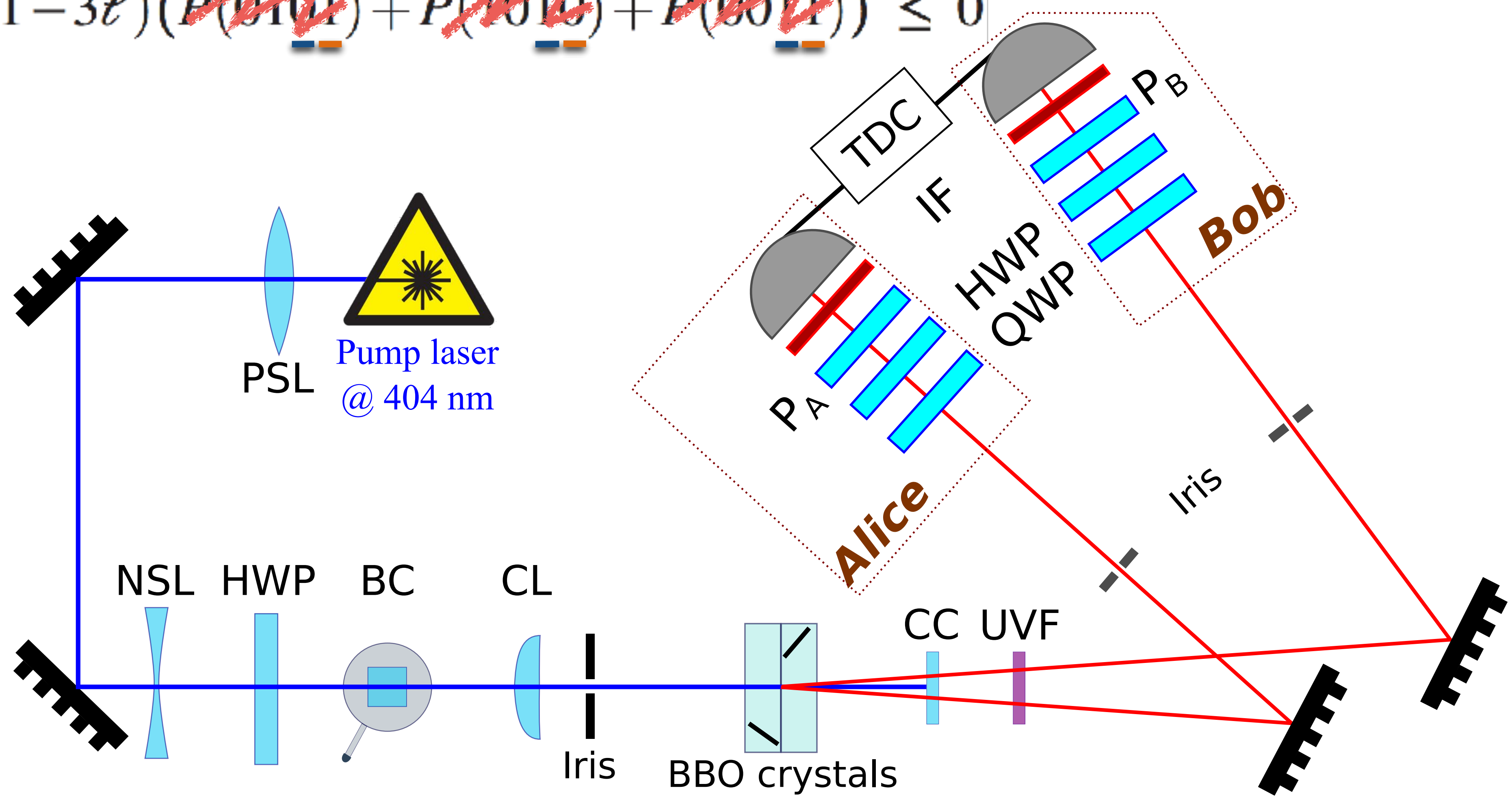

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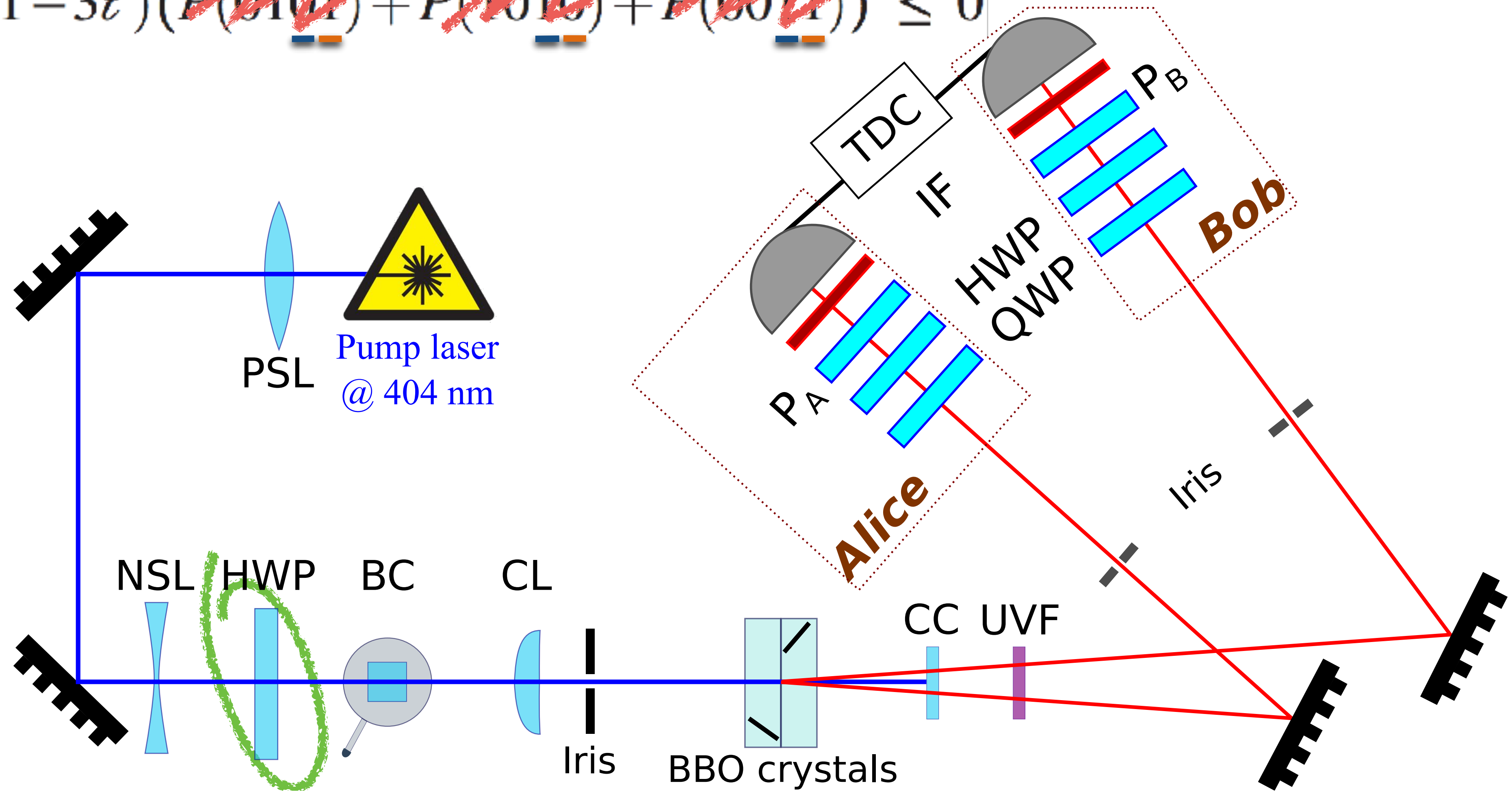

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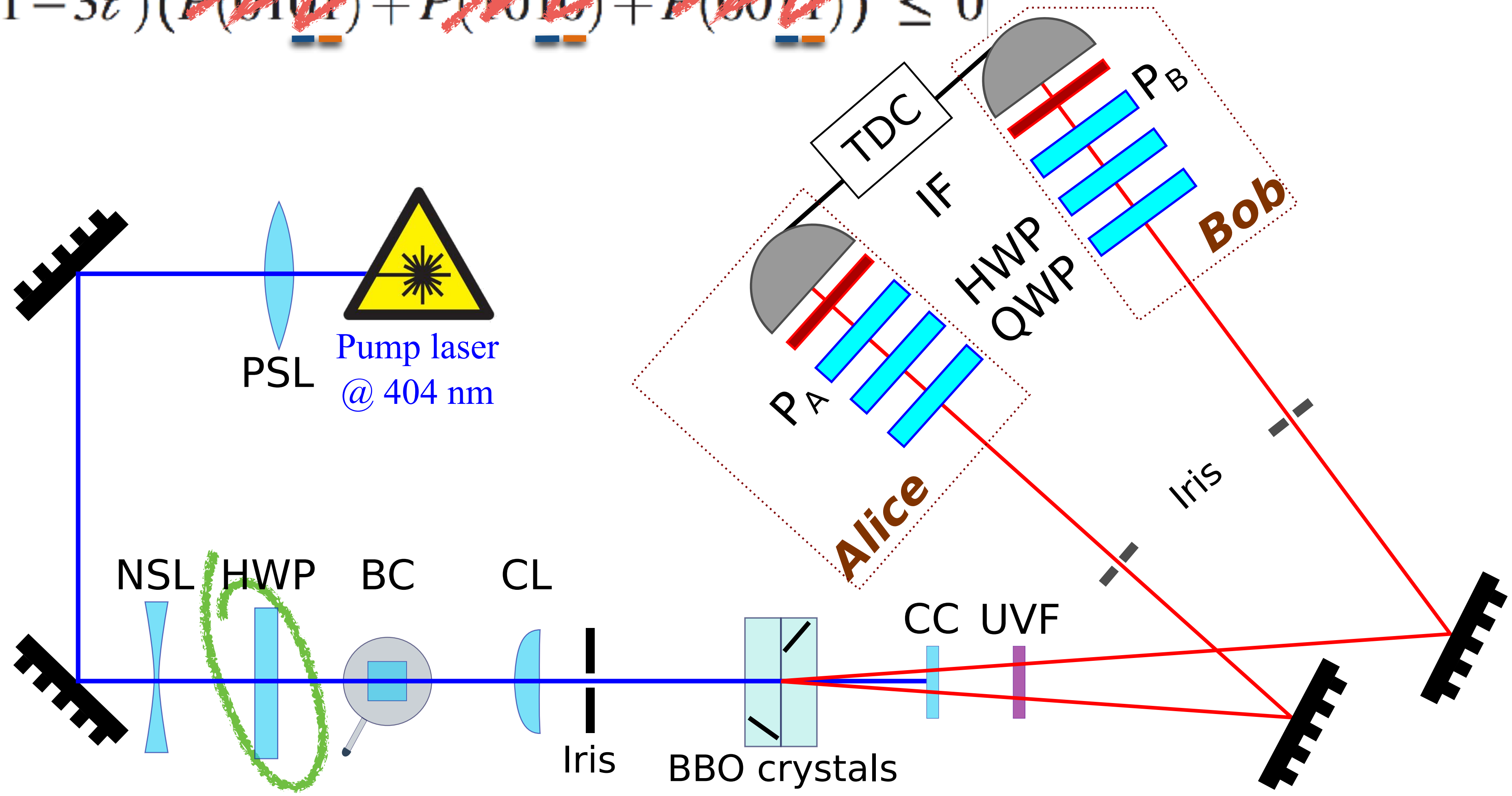

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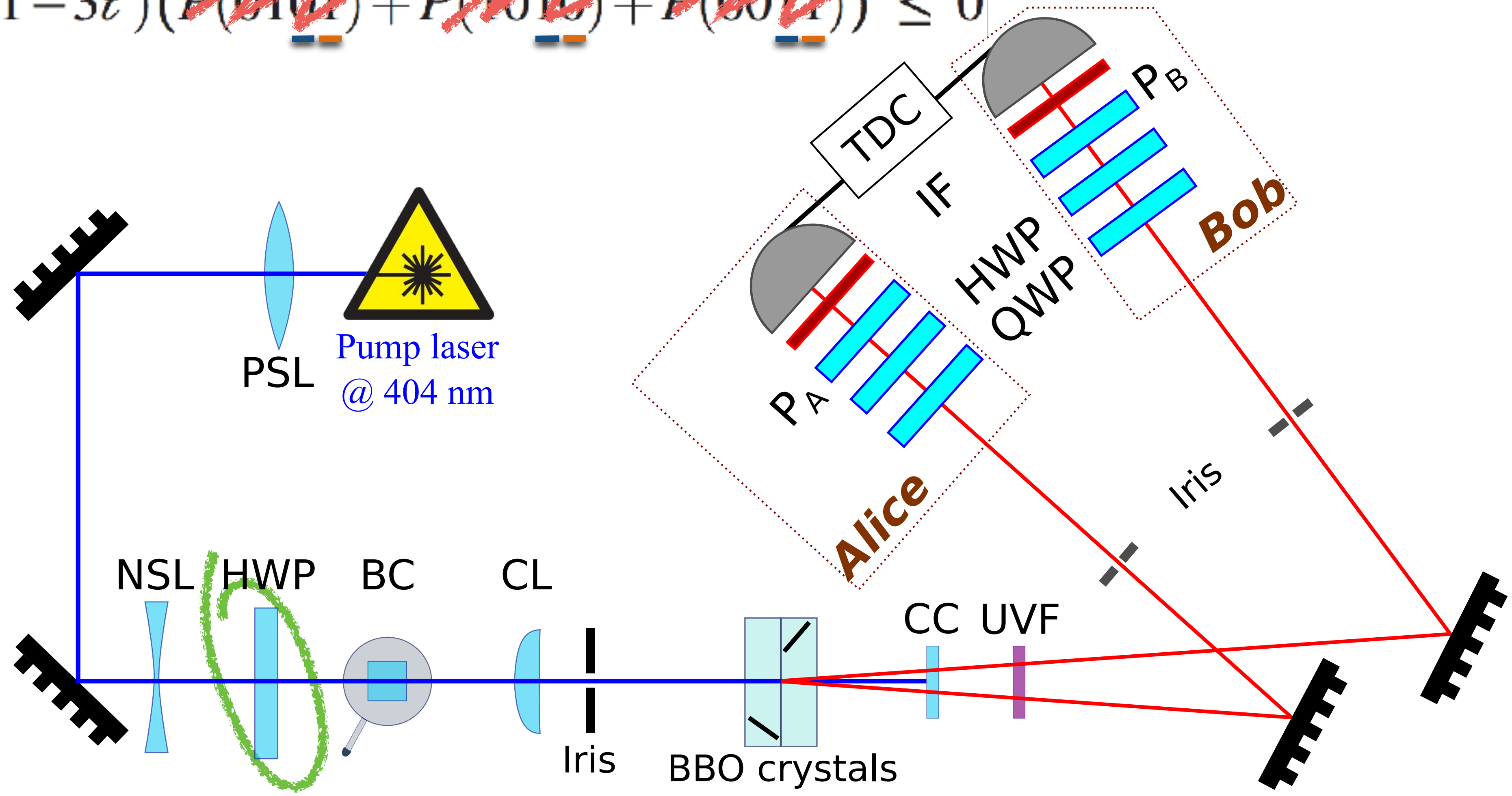

$$\theta = \operatorname{arcos}\sqrt{1/2 + 1/\sqrt{5}}$$

Projectors:

$$\mathcal{A}\begin{cases} |A_0(\theta)\rangle = \cos(\theta)|0\rangle + \sin(\theta)|1\rangle \\ |A_1(\theta)\rangle = |A_0(\theta + \pi/4)\rangle \end{cases}$$

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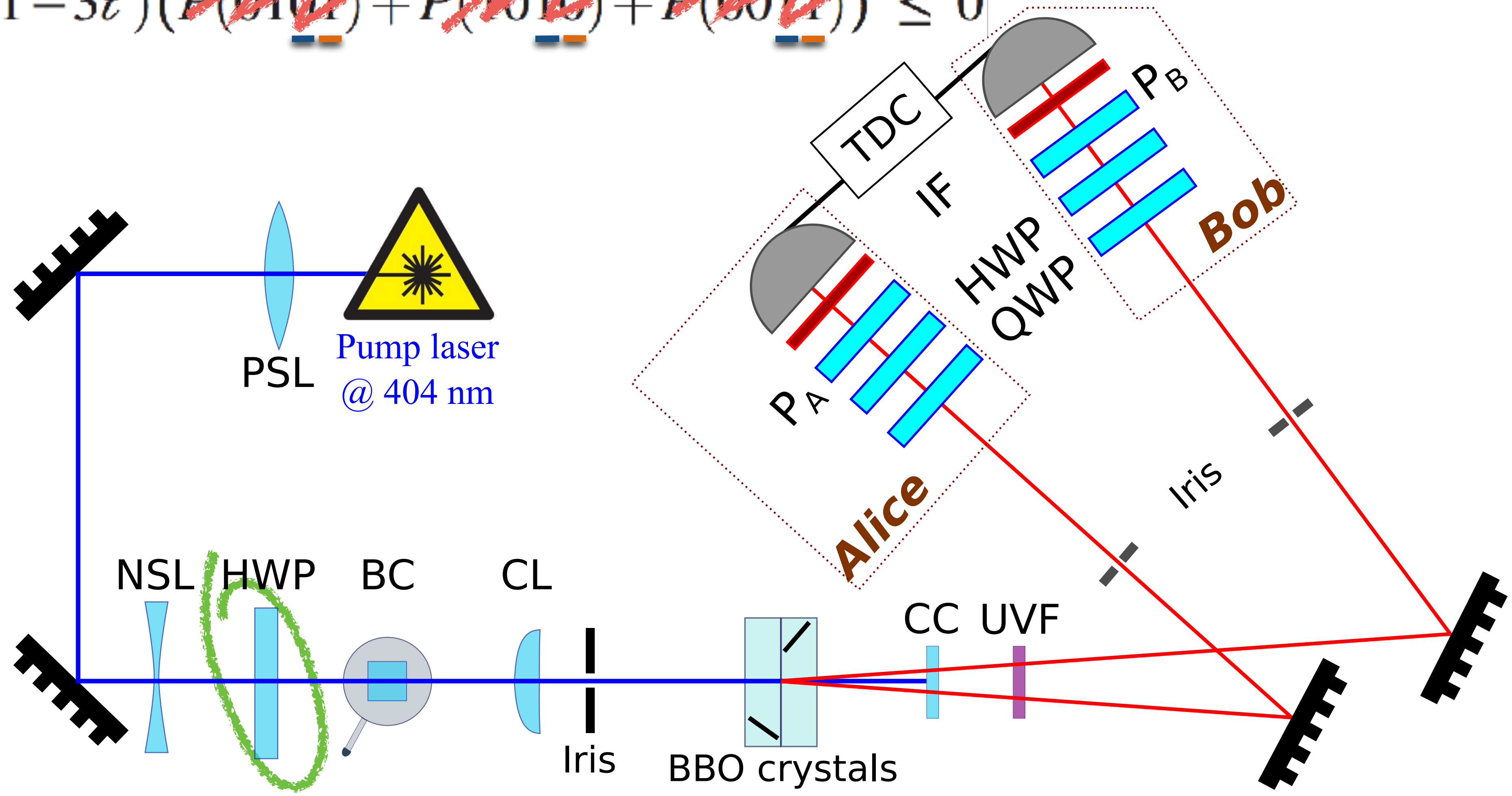

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Results

Analyseurs dans la base $\{A_0, B_0\}$

Alice α (°)	Bob β (°)	Coïncidences (/30 s)	Bruit (/30 s)
13,3	-13,3	2939	14
13,3	76,7	2926	27
103,3	-13,3	3040	48
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Analyseurs dans la base $\{A_0, B_1\}$

Alice α (°)	Bob β (°)	Coïncidences (/30 s)	Bruit (/30 s)
13,3	301,7	129	26
13,3	31,7	5394	9
103,3	301,7	25240	163
103,3	31,7	5895	72

Analyseurs dans la base$\{A_1, B_0\}$

Alice α (°)	Bob β (°)	Coïncidences (/30 s)	Bruit (/30 s)
58,3	-13,3	114	32
58,3	76,7	21780	155
328,3	-13,3	6247	15
328,3	76,7	6552	78

Analyseurs dans la base $\{A_1, B_1\}$

Alice α (°)	Bob β (°)	Coïncidences (/30 s)	Bruit (/30 s)
328,3	31,7	130	23
328,3	301,7	13405	72
58,3	31,7	10529	69
58,3	301,7	12898	112

$$\mathcal{A}\begin{cases} |A_0(\theta)\rangle = \cos(\theta)|0\rangle + \sin(\theta)|1\rangle \\ |A_1(\theta)\rangle = |A_0(\theta+\pi/4)\rangle \end{cases}$$
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Theory: Puetz *et al*, PRL, **113** 190402 (2014)
Experiment: Aktas *et al*, PRL, **114** 220404 (2015)

Results

Results

Alice (x)	Bob (y)	Coïncidences	Bruit	$P^{\text{raw}}(ab\|xy)$	$P^{\text{net}}(ab\|xy)$
0	0	2939 / 35183	14 / 269	$P(00\|00) = 0,0835(10)$	$P(00\|00) = 0,0838(15)$
0	1	129 / 36658	26 / 270	$P(01\|01) = 0,0035(3)$	$P(01\|01) = 0,0028(3)$
1	0	114 / 34693	32 / 280	$P(10\|10) = 0,0033(3)$	$P(10\|10) = 0,0024(3)$
1	1	130 / 36962	23 / 276	$P(00\|11) = 0,0035(3)$	$P(00\|11) = 0,0027(3)$

➔ MDL inequality violated for $\ell_{\text{raw}} > 0.090(4)$
$\ell_{\text{net}} > 0.074(6)$

Theory: Puetz *et al*, PRL, **113** 190402 (2014)
Experiment: Aktas *et al*, PRL, **114** 220404 (2015)

Results

Alice (x)	Bob (y)	Coïncidences	Bruit	$P^{raw}(ab\|xy)$	$P^{net}(ab\|xy)$
0	0	2939 / 35183	14 / 269	$P(00\|00) = 0,0835(10)$	$P(00\|00) = 0,0838(15)$
0	1	129 / 36658	26 / 270	$P(01\|01) = 0,0035(3)$	$P(01\|01) = 0,0028(3)$
1	0	114 / 34693	32 / 280	$P(10\|10) = 0,0033(3)$	$P(10\|10) = 0,0024(3)$
1	1	130 / 36962	23 / 276	$P(00\|11) = 0,0035(3)$	$P(00\|11) = 0,0027(3)$

→ MDL inequality violated for $\ell_{raw} > 0.090(4)$
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An adversary would need to be able to prevent a given settings to appear with a probability less than 9% to mimic nonlocal correlations

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An adversary would need to be able to prevent a given settings to appear with a probability less than 9% to mimic nonlocal correlations

1) Standard Bell test cannot do better than $\ell > 0.149$
2) Detector's noise is not the main limitation.

Theory: Puetz *et al*, PRL, **113** 190402 (2014)
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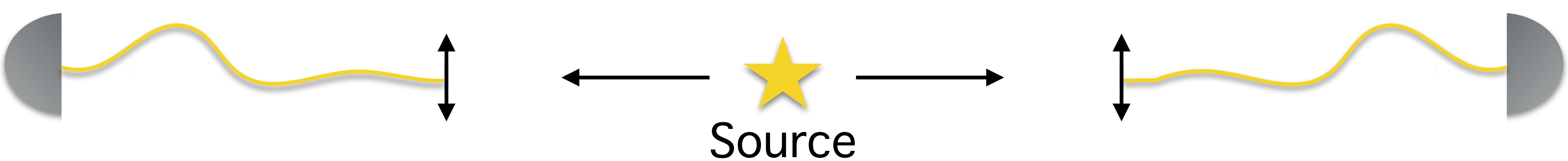
Limited Detection Locality

Detection loophole:

Granting nonlocality with Bell's Inequality → overall detection efficiency $\geq 2/3$



Hensen *et al*, Nature **526**, 682 (2015)
Shalm *et al*, Phys. Rev. Lett. **115**, 250402 (2015)
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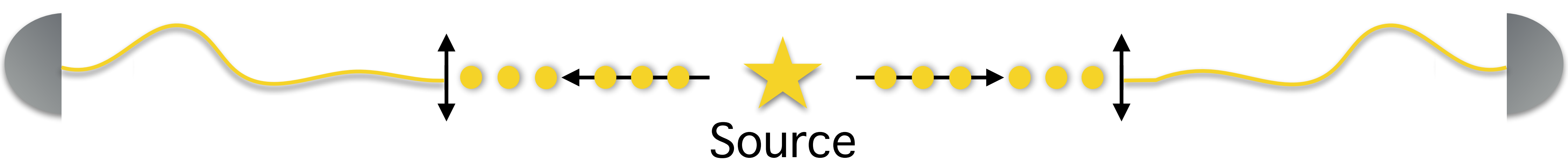

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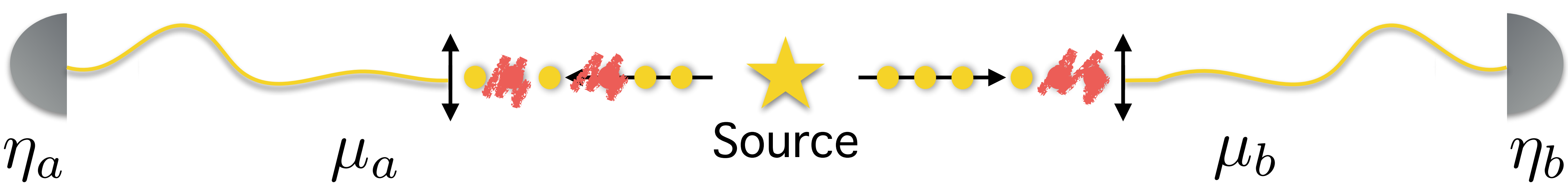

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Limited Detection Locality

Computing LDL inequality:

Suppose that there exist fixed η_{min} and η_{max} with $[\eta_{min}, \eta_{max}] \subsetneq [0,1]$ such that $\eta_{min} \leq P(a \neq \varnothing | x\lambda) \leq \eta_{max}$

(and same for Bob)

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We can now focus on the postselected limited detection local distributions:

$$P(ab|xy, a \neq \varnothing, b \neq \varnothing) = \frac{P(ab|xy)}{\eta_{xy}}$$

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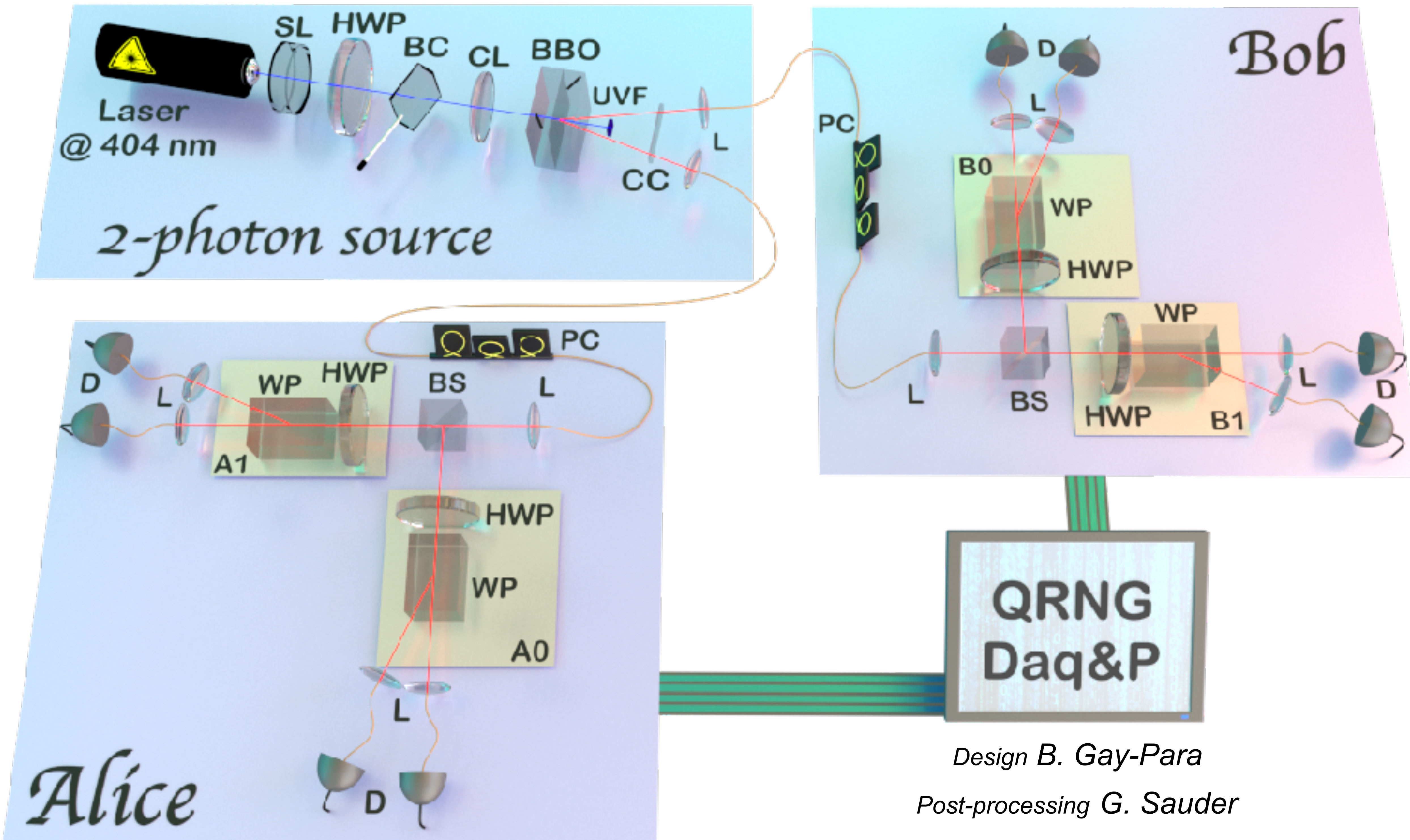
Bell-like inequality:

$$\eta_{min}^2 P(00|00) - \eta_{min}\eta_{max} P(01|01) - \eta_{min}\eta_{max} P(10|10) - \eta_{max}^2 P(00|11) \overset{LDL}{\leq} 0$$

for every η_{max} & $\eta_{min} > 0$

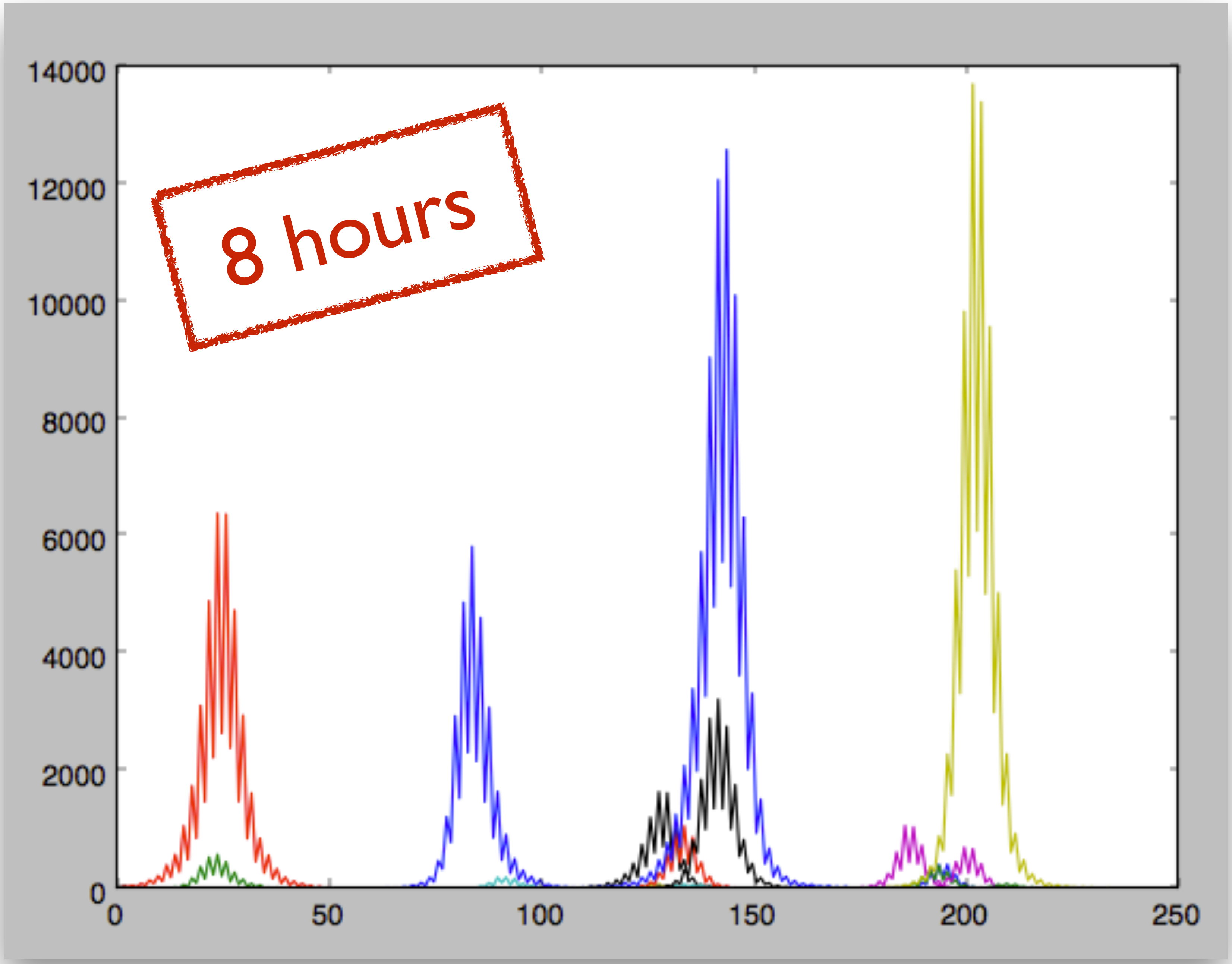
LDL experiment and results



Design *B. Gay-Para*

Post-processing *G. Sauder*

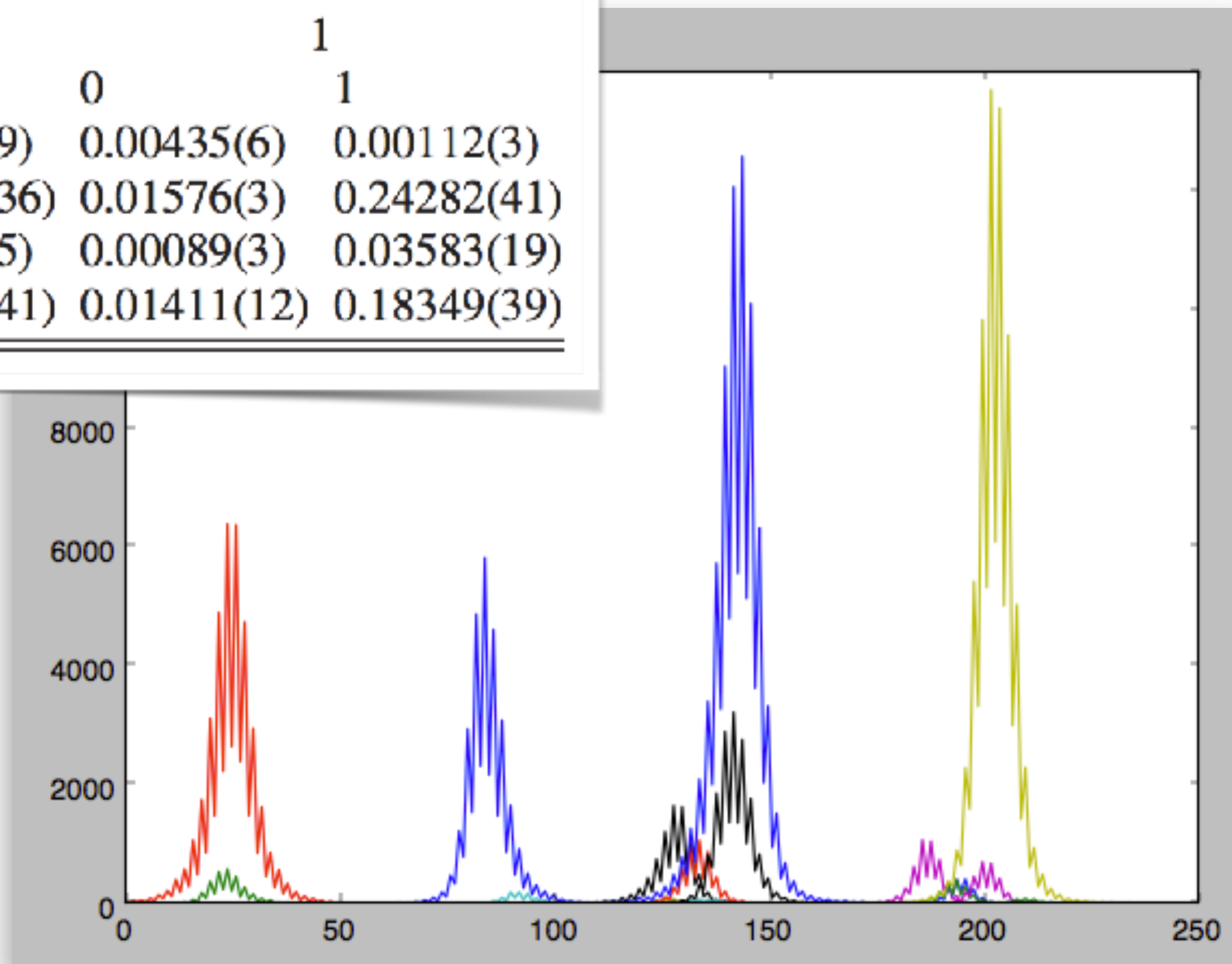
Results



8 hours
14000
12000
10000
8000
6000
4000
2000
0
0
50
100
150
200
250

Results

Alice		Bob			
		$y=0$		1	
x	a	$b=0$	1	0	1
0	0	0.01977(12)	0.01003(9)	0.00435(6)	0.00112(3)
	1	0.00830(8)	0.19763(36)	0.01576(3)	0.24282(41)
1	0	0.02536(15)	0.00325(5)	0.00089(3)	0.03583(19)
	1	0.00106(3)	0.23631(41)	0.01411(12)	0.18349(39)



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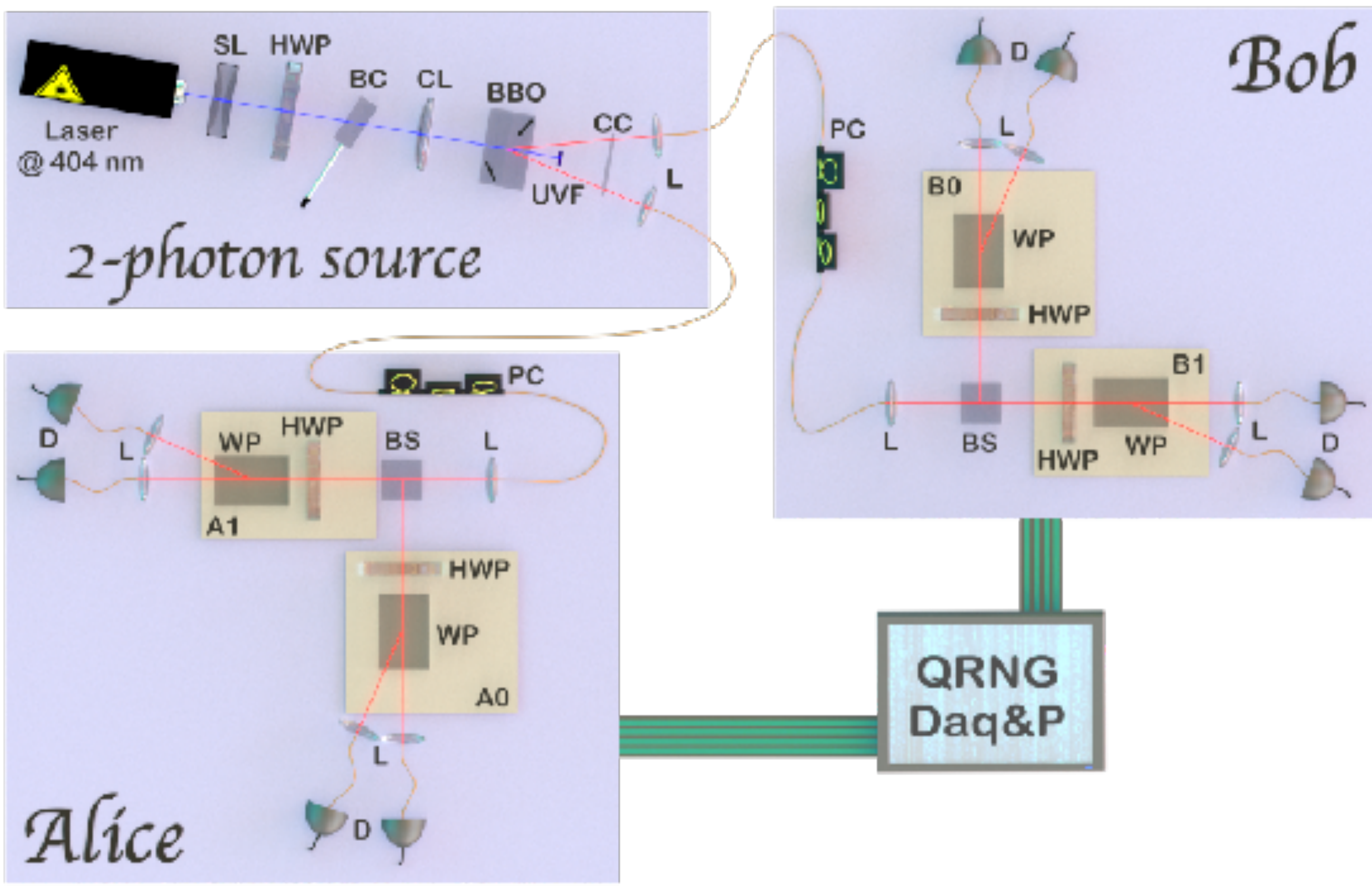
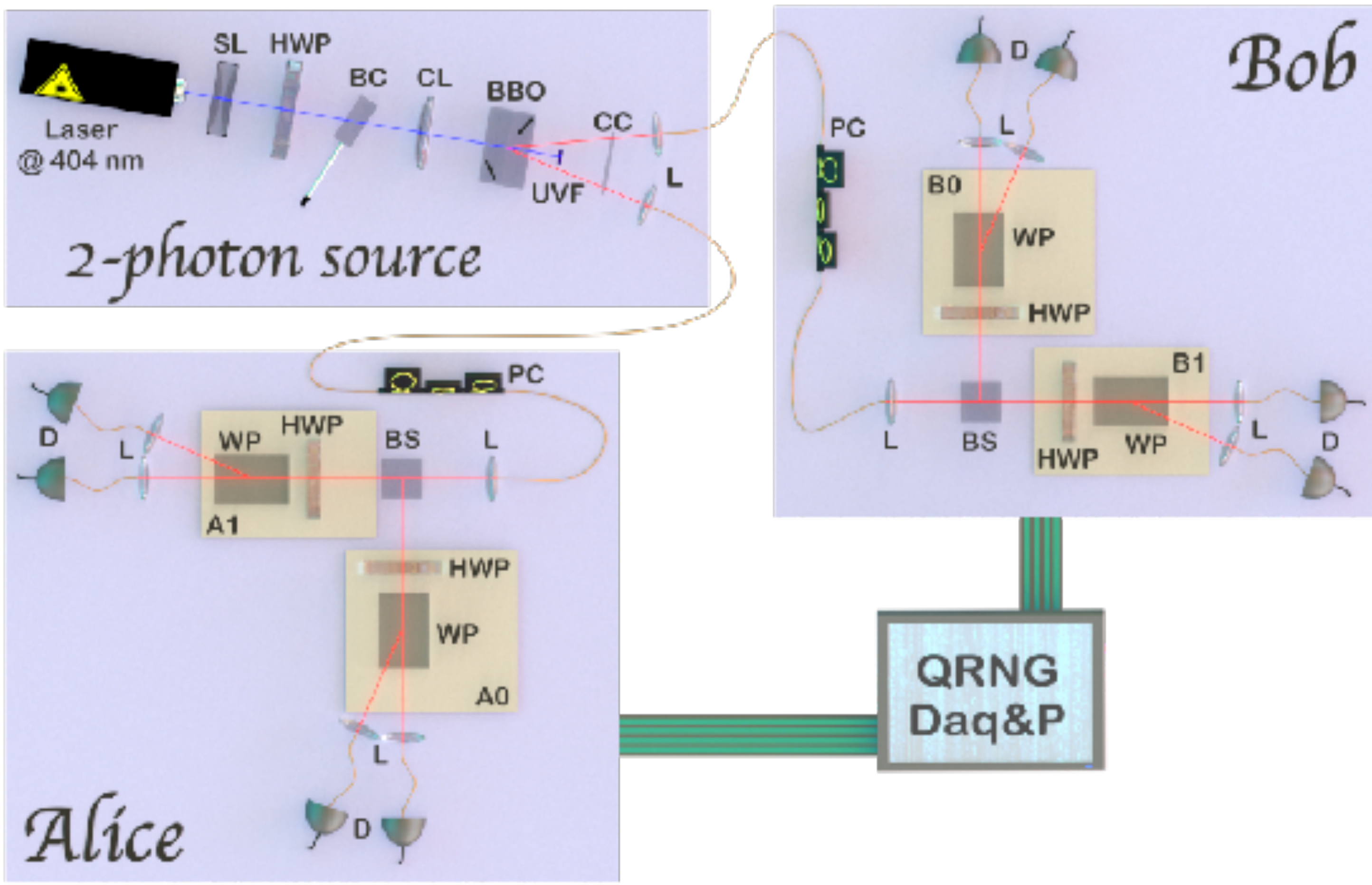


We conclude that we can reveal non locality for :

$$\frac{\eta_{min}}{\eta_{max}} > 0.267$$

Theory & experiment: Puetz *et al*, PRL **116**, 10401 (2016)

LDL experiment and results



We conclude that we can reveal non locality for :

$$\frac{\eta_{min}}{\eta_{max}} > 0.267$$

An adversary would need to lower the overall detection efficiency below 26.7% to mimic non-local correlations

Theory & experiment: Puetz *et al*, PRL **116**, 10401 (2016)

OUTLINE

1. Introduction
2. Fundamental tests on nonlocality
3. Generalised Bell inequality
4. Conclusion & outlook

Conclusion

Beyond standard Bell tests:

1. How to compute new Bell like inequality.
2. (MDL) How to relax a strong original assumption of **measurement independence**.
3. (LDL) Still attest for non-locality in **lossy experiments**.

Which may be useful for (semi-)DIQIP applications

Laboratoire Physique de la Matière Condensée

Thanks for your attention !

The QILM team @ CNRS LPMC Nice (& GAP Geneva)

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cnrs

IDQ FROM VISION TO TECHNOLOGY

Draka A brand of the Prysmian Group

IXCORE FONDATION POUR LA RECHERCHE

institut non linéaire de Nice SOPHIA ANTIPOLIS

PADERBORN UNIVERSITY

UNIVERSITÉ DE GENÈVE

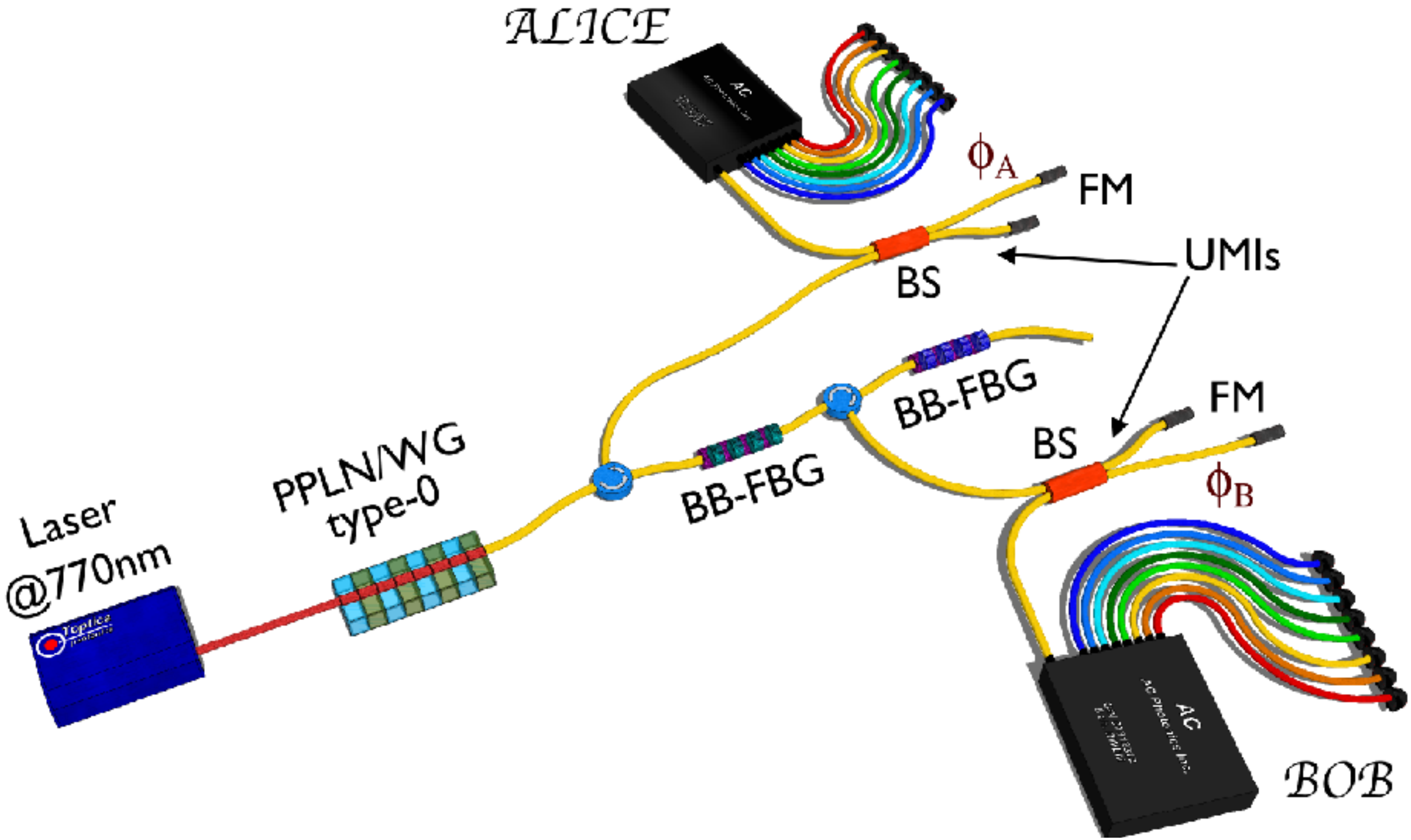
ANR PROJET FINANCÉ PAR L'ANR PROJECT FUNDED BY THE ANR

Région PACA

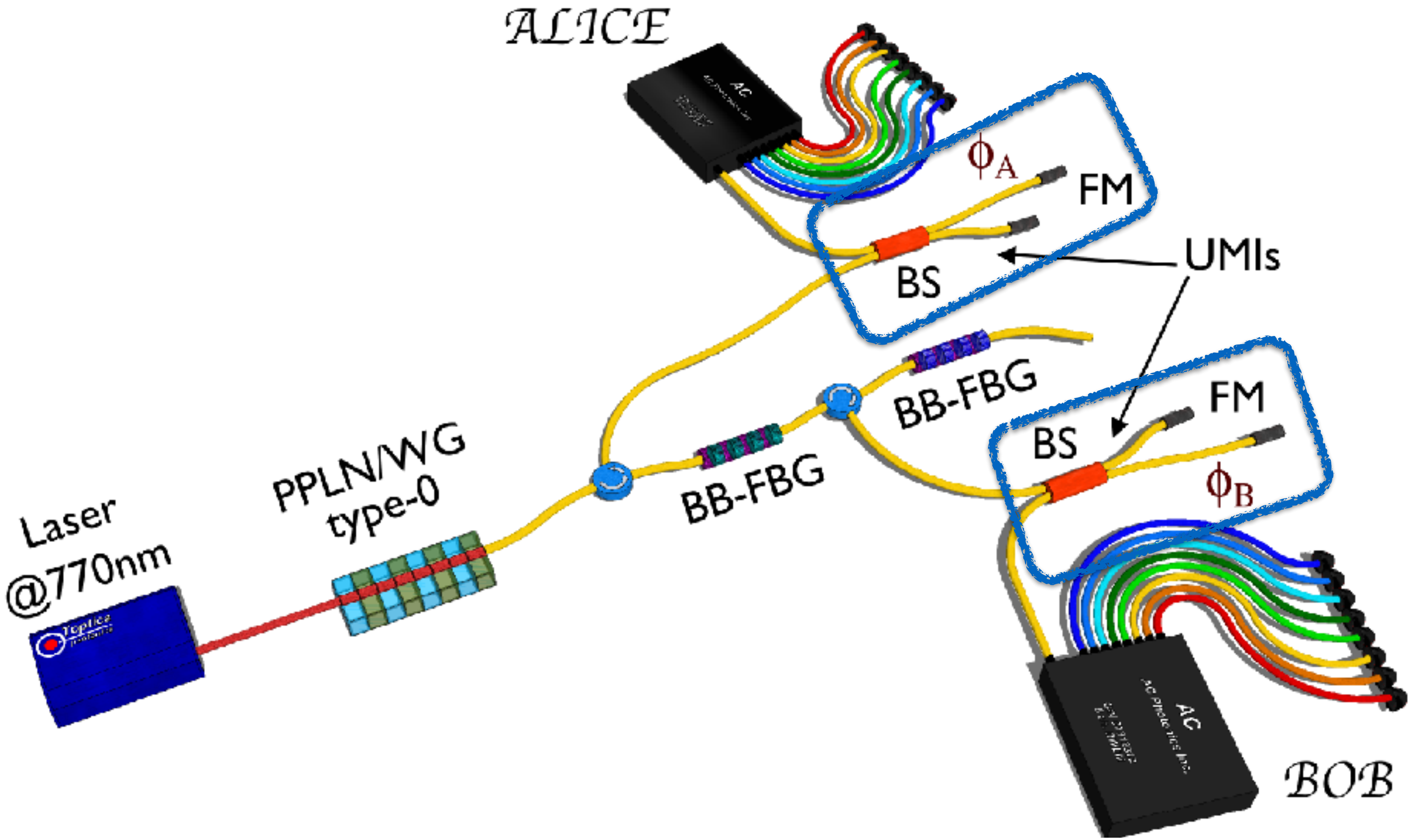
Liberté • Égalité • Fraternité RÉPUBLIQUE FRANÇAISE MINISTÈRE DE L'ENSEIGNEMENT SUPÉRIEUR ET DE LA RECHERCHE

C2N

Distributing ET-entanglement



Distributing ET-entanglement



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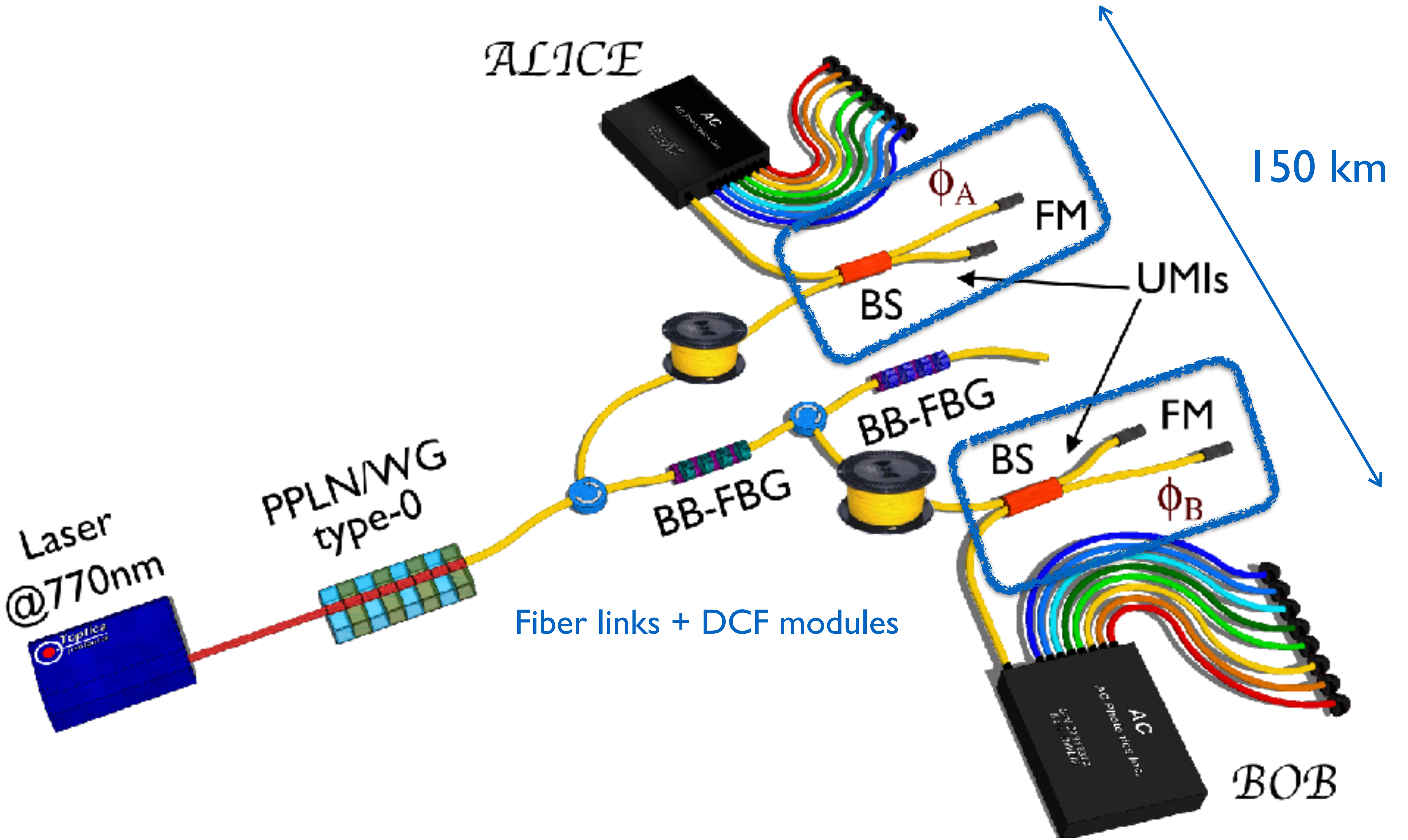
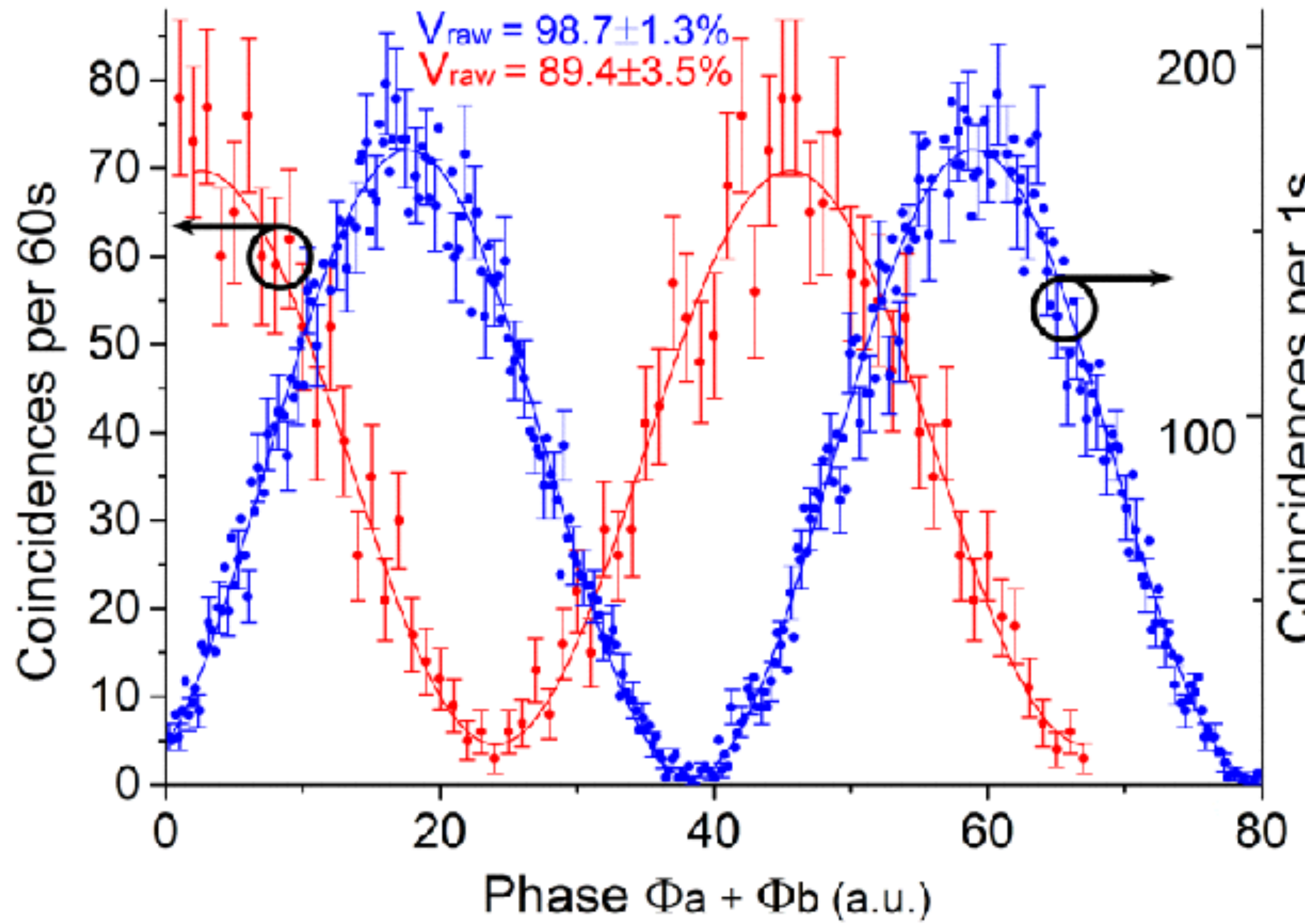


Results - using DWDMs

Aktas *et al*, LPR **10**, p451 (2016)

0 km & 150 km



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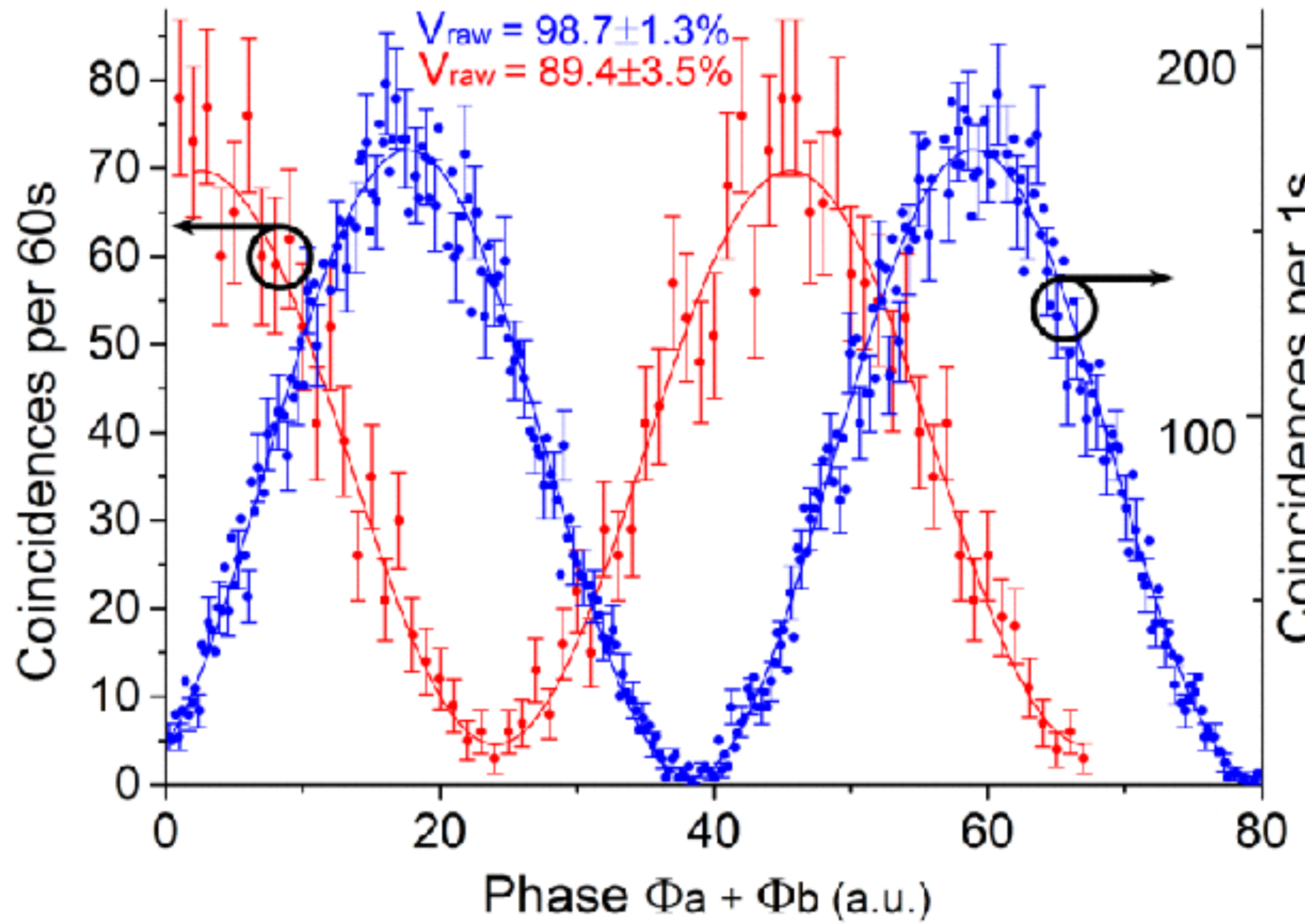
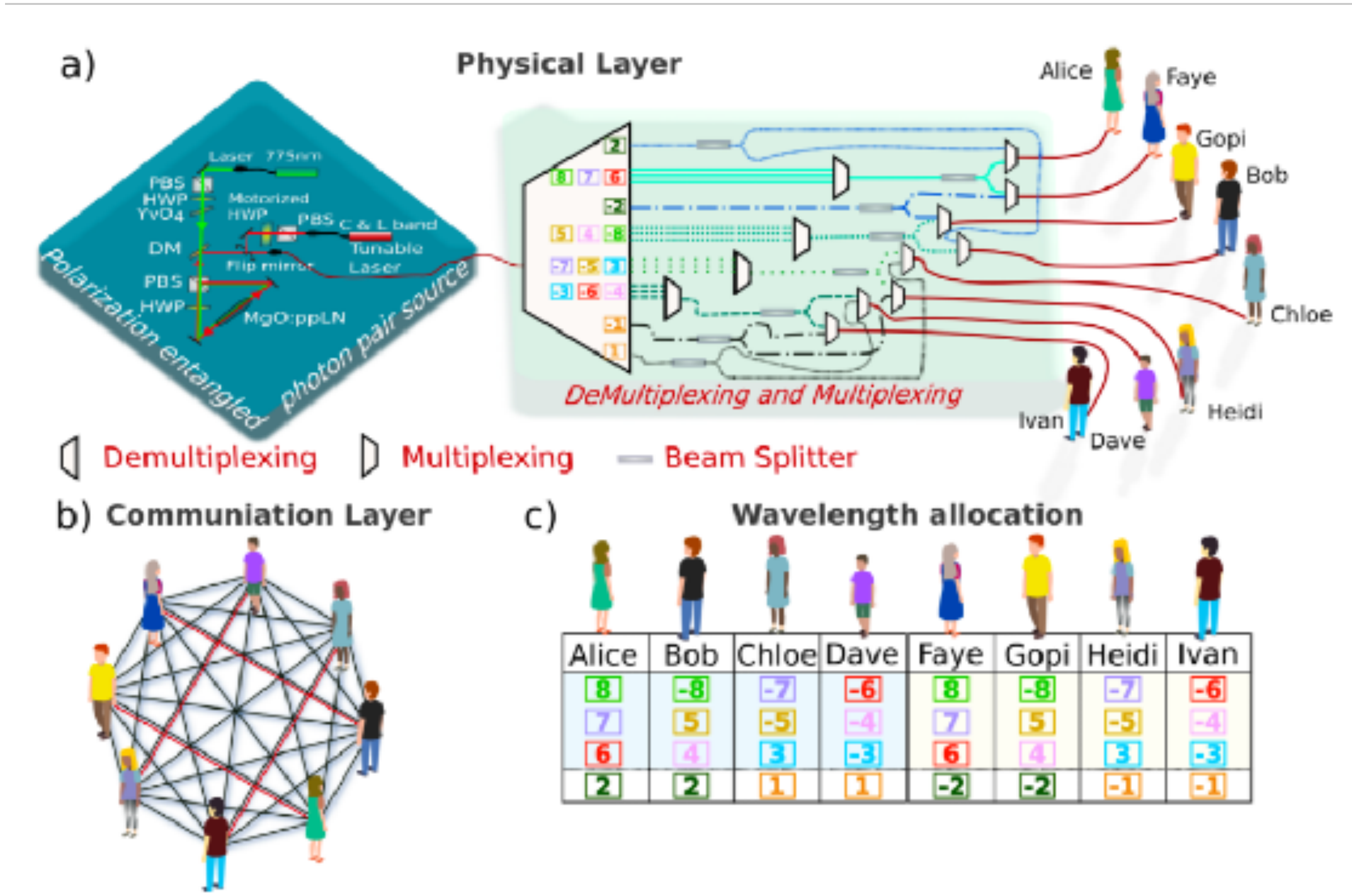


Similar patterns and V's are obtained for all pairs of channels @ 150 km

Key rate scales with the number of exploited paired channels…

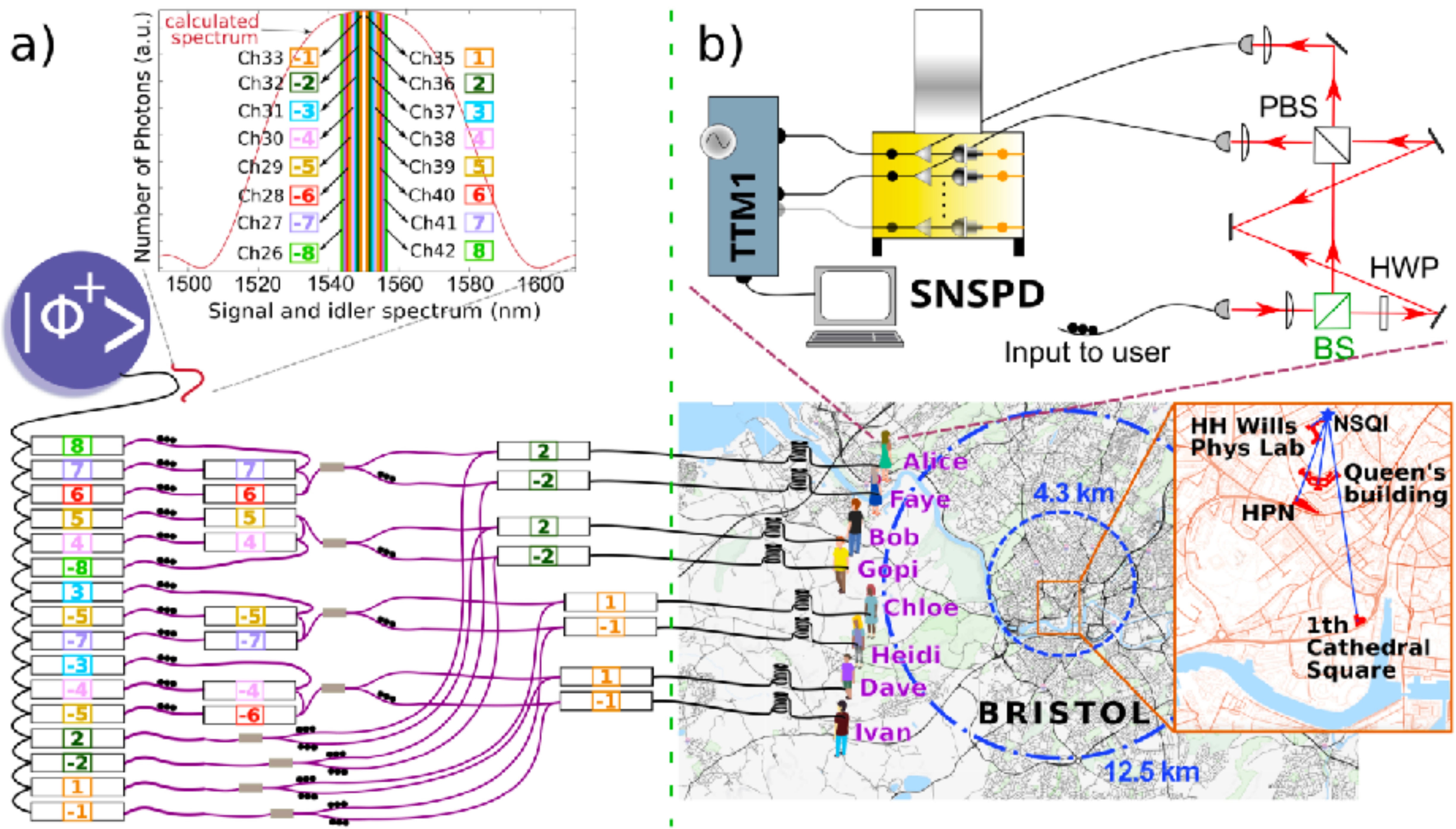
Consequences



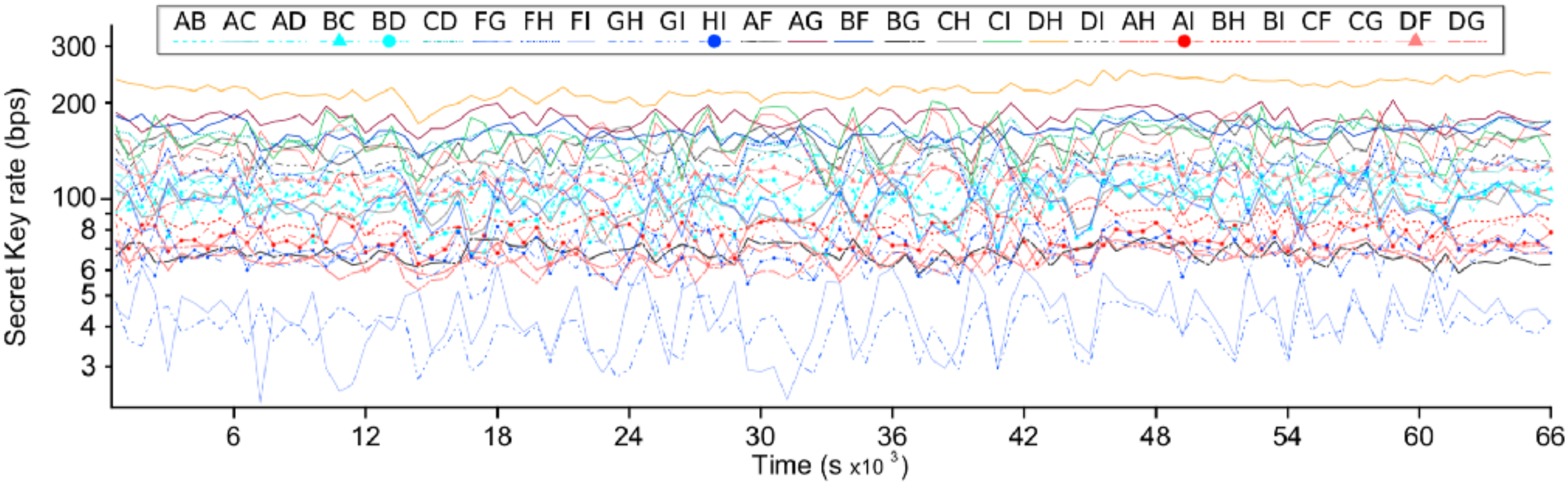
Extended Data Table II. **Total secure key (Mega bits) for the laboratory demonstration** as measured continuously over 18.45 hours after accounting for all finite key size effects.

	Alice	Bob	Chloe	Dave	Faye	Gopi	Heidi	Ivan
Alice		8.67	9.54	8.48	11.22	14.08	8.14	6.15
Bob			8.04	7.33	13.28	5.26	6.62	5.21
Chloe				12.27	11.10	6.14	7.12	12.10
Dave					9.17	5.25	17.01	9.95
Faye						7.27	9.59	3.65
Gopi							5.25	3.26
Heidi								5.49

Consequences



Consequences



- Fully connected Network (28 links)
- All positive SKR for ~18h (SNSPDs cycle time)