Quantum Teleportation & Nonlocality

Nicolas Gisin, Hugo Zbinden

Mikael Afzelius, Hugues de Riedmatten, Christoph Simon,
Rob Thew, Alexios Beveratos, Sebastien Tanzilli
S. Fasel, J.A.W. van Houwelingen, O. Landry, M. Halder,
D. Stucki, D. Salart, S. Hasting, M. Staudt

Group of Applied Physics
Geneva university
Switzerland

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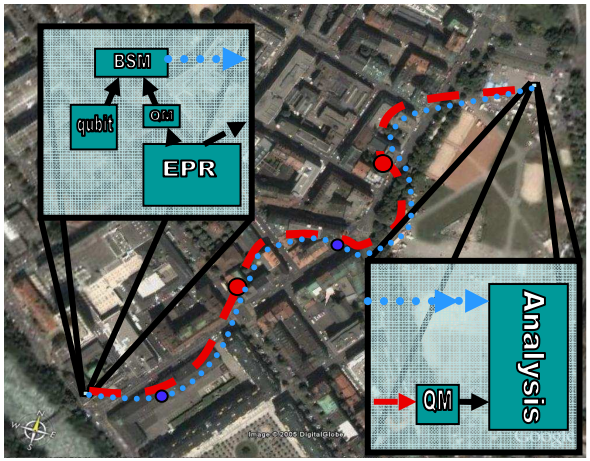

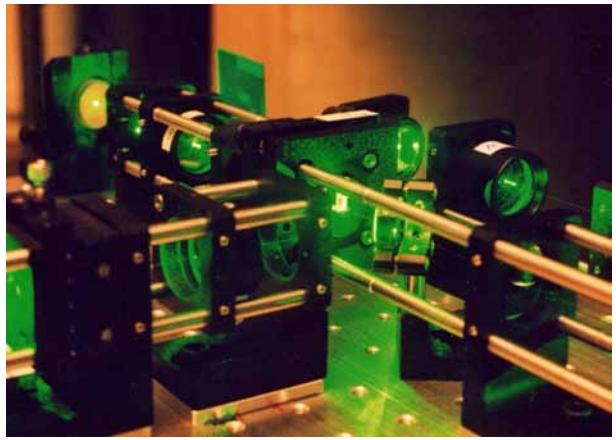

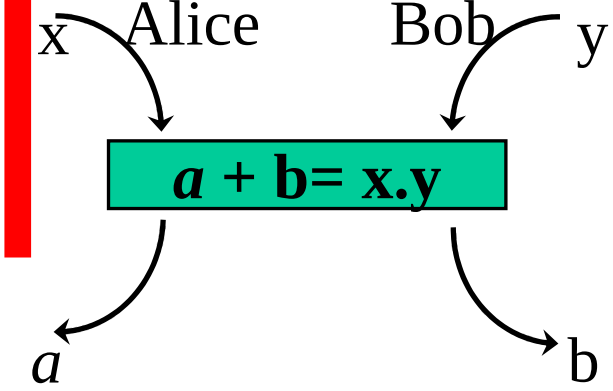

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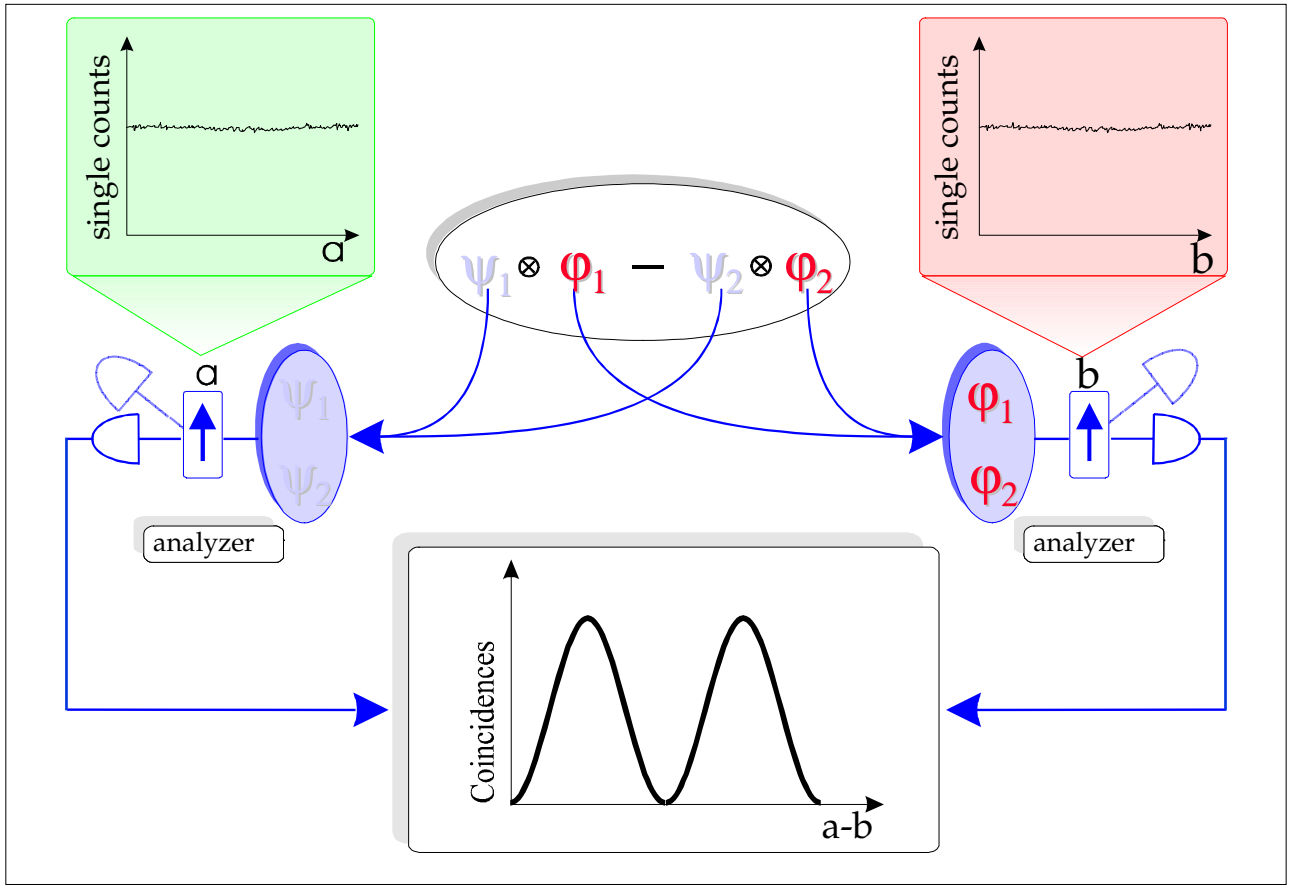
Quantum non locality



- **the statistics of the correlations can‘t be described by local variables ➥ Quantum non locality**

The Geneva Teleportation experiment over the Swisscom network

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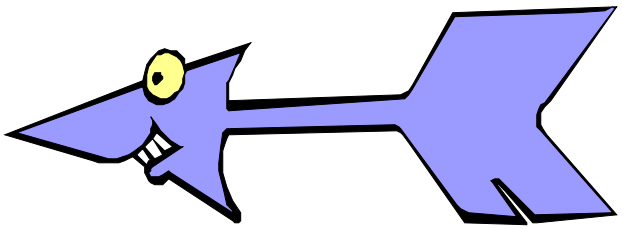
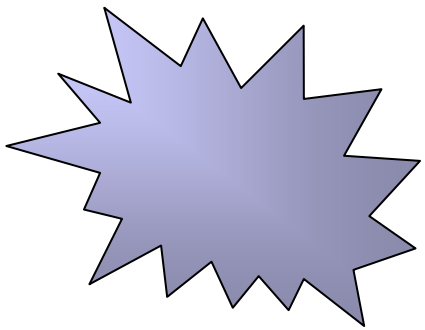
Photon = particle (atom) of light

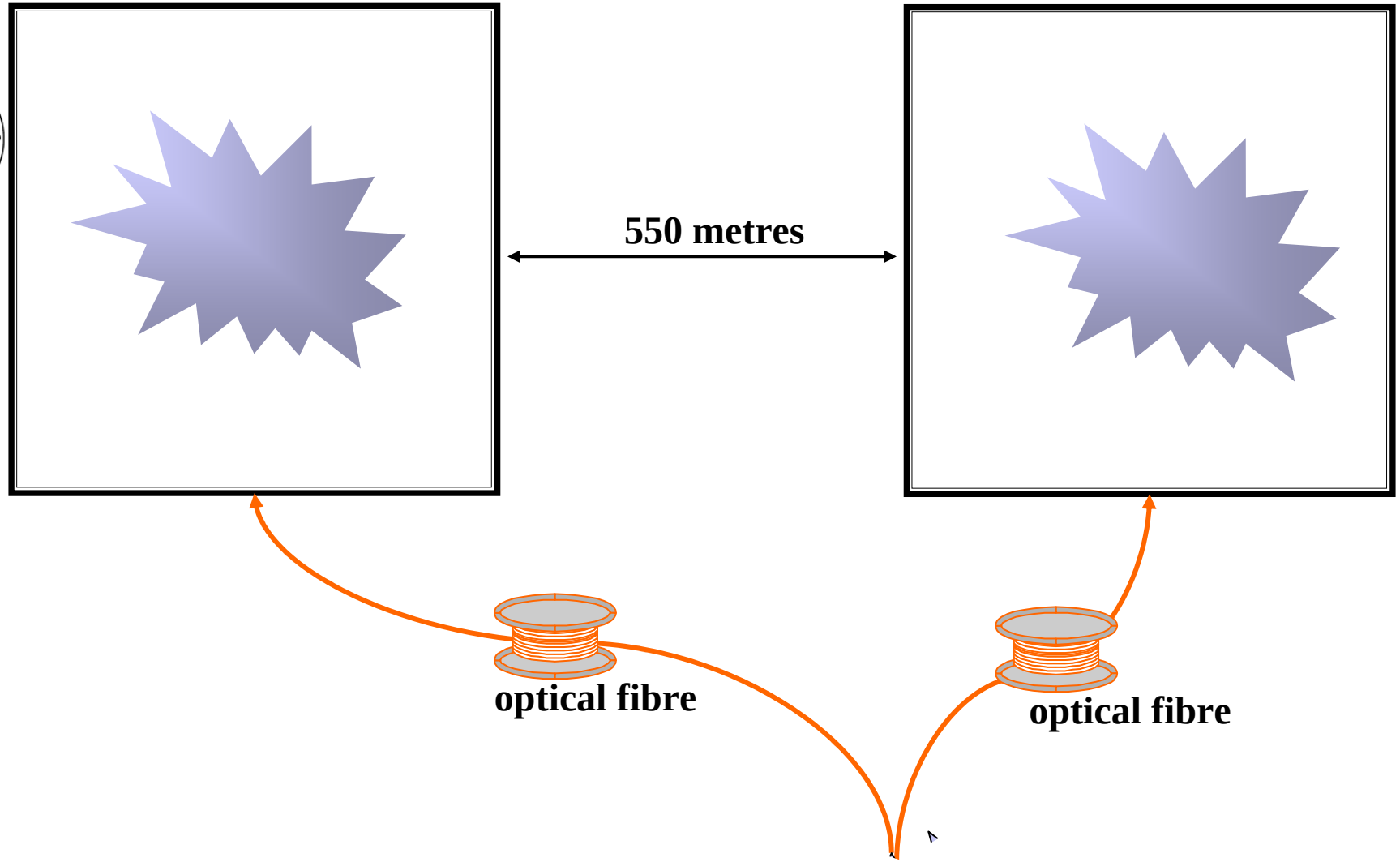
Polarized photon
(≈ structured photon)



Unpolarized photon
(≈ unstructured ≈ dust)



C.H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres and W. Wootters, *PRL* 70, 1895 (1993)
D. Boschi *et al.*, *Phys. Rev. Lett.* 80, 1121 (1998)
Y-K. Kim *et al.*, *Phys. Rev. Lett.* 86, 1370 (2001)
D. Bouwmeester *et al.*, *Nature* 390, 575 (1997)
I. Marcikic *et al.*, *Nature* 421, 509 (2003)



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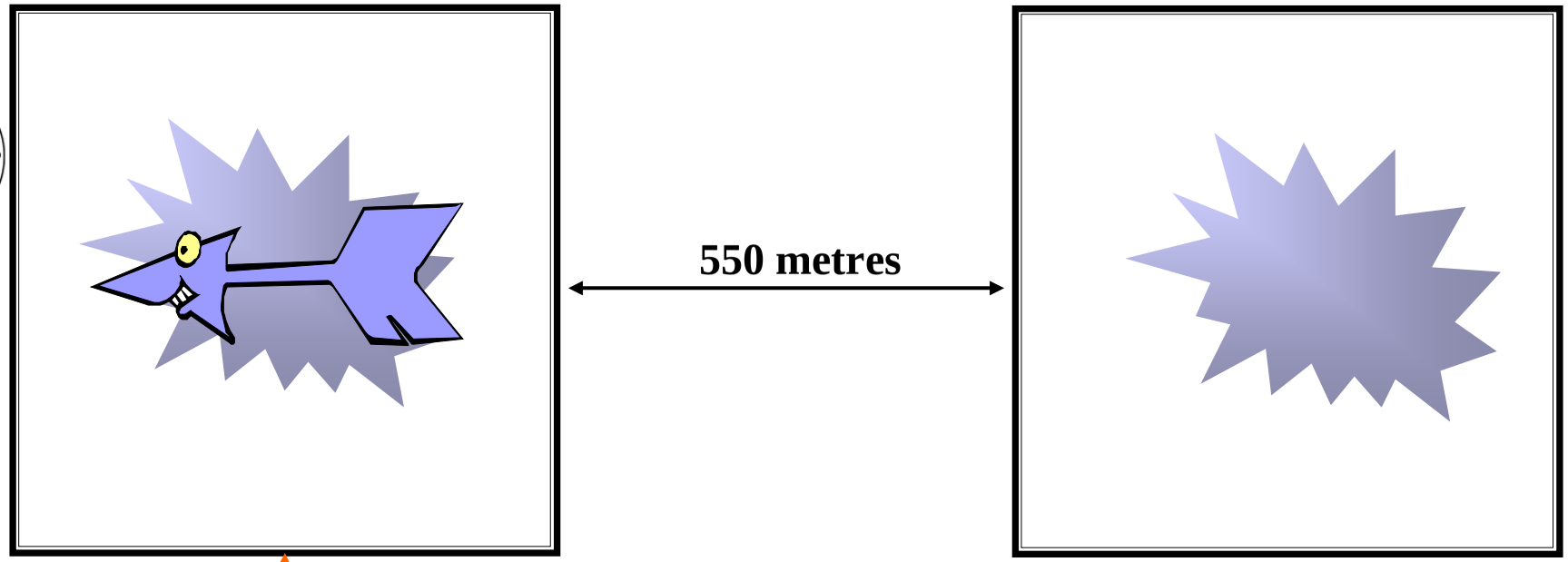

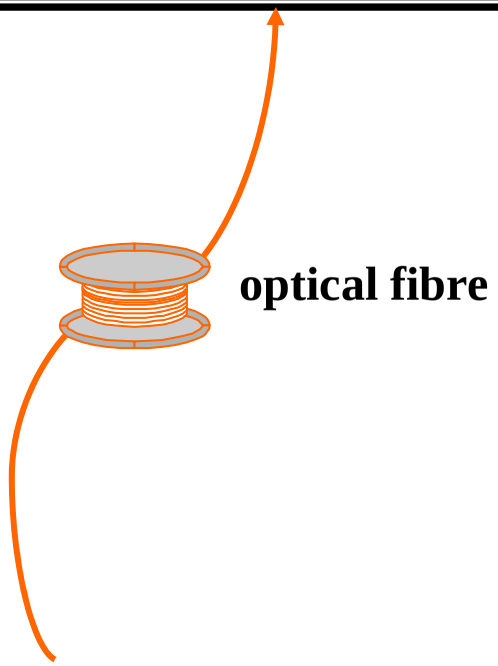

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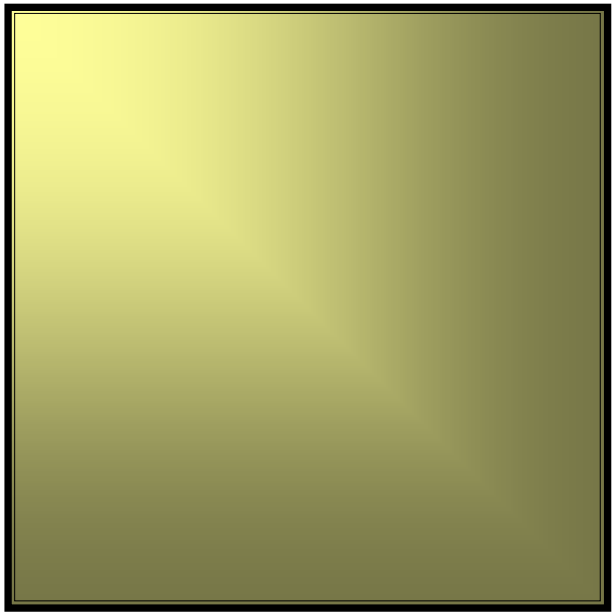
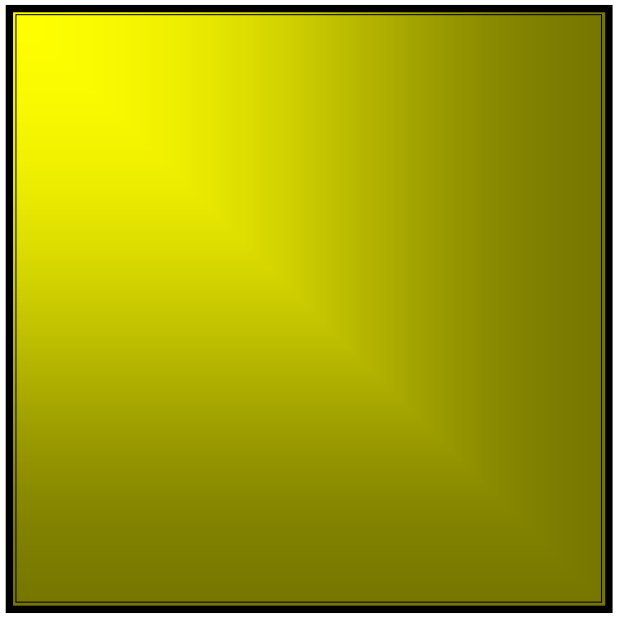


550 metres



Bell measurement (partial) } **Are you similar ?**

the 2 photons interact

The "question" is about the relative state of the 2 photons, i.e. about their relation.

4 possible results:
0, 90, 180, 270 degrees

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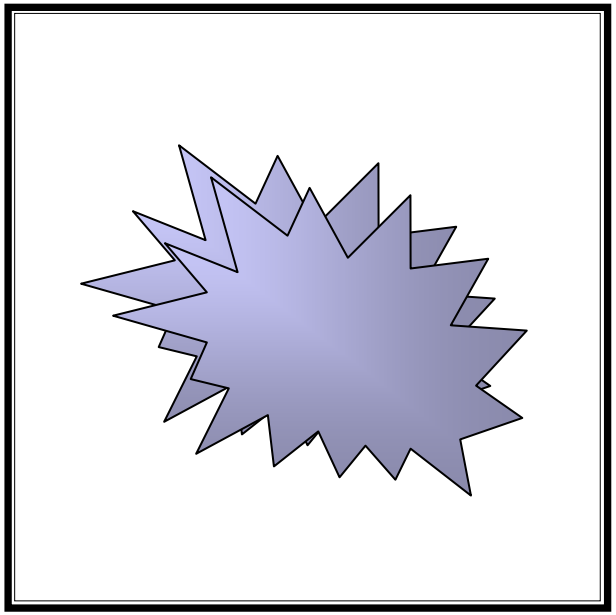

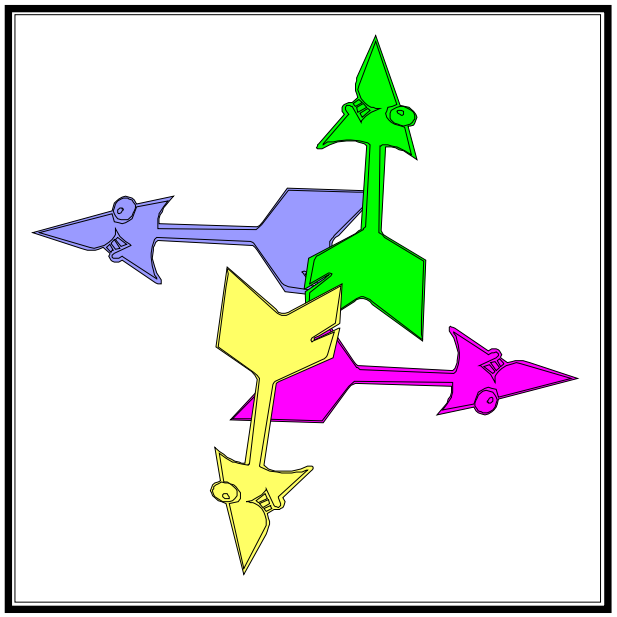

550 metres

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Bell measurement
(partial)

the 2 photons interact

4 possible results:
0, 90, 180, 270 degrees

Perfect Correlation

The correlation is independent of the quantum state which may be unknown or even entangled with a fourth photon

What is teleported ?

- **According to Aristotle, objects are constituted by *matter* and *form, ie* by *elementary particles* and *quantum states*.**

- **Matter and energy can not be teleported from one place to another: they can not be transferred from one place to another without passing through intermediate locations.**

- **However, quantum states, the ultimate structure of objects, can be teleported. Accordingly, objects can be transferred from one place to another without ever existing anywhere in between! But only the structure is teleported, the matter stays at the source and has to be already present at the final location.**

C.H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres and W. Wootters, *PRL* 70, 1895 (1993)
D. Boschi *et al.*, *Phys. Rev. Lett.* 80, 1121 (1998)
Y-K. Kim *et al.*, *Phys. Rev. Lett.* 86, 1370 (2001)
D. Bouwmeester *et al.*, *Nature* 390, 575 (1997)
I. Marcikic *et al.*, *Nature* 421, 509 (2003)

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How can one realize
Quantum Teleportation ?

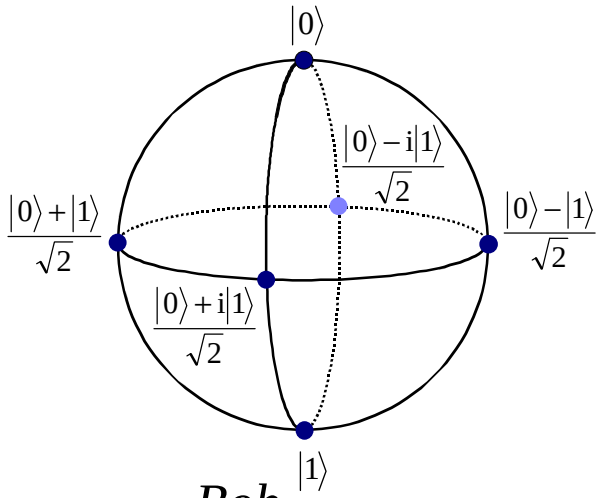
How can one understand
Quantum nonlocality ?

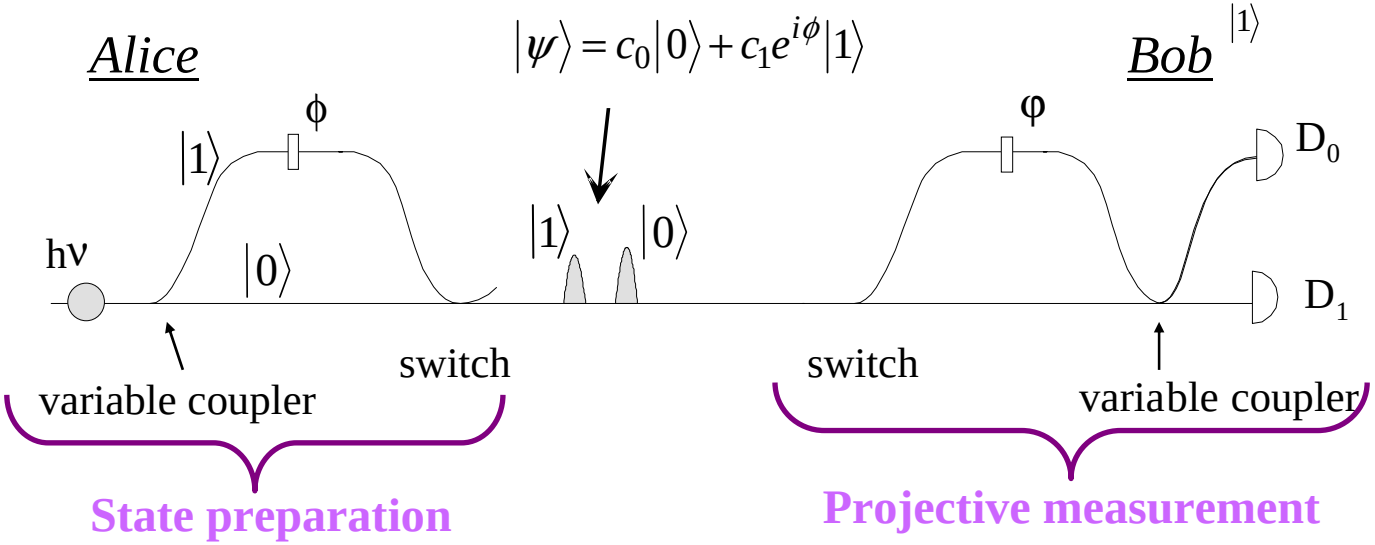
For what could
teleportation-nonlocality-entanglement
be good for ?

Time-bin qubits

- **qubit :** $|\psi\rangle = c_0|0\rangle + c_1 e^{i\phi}|1\rangle$

- **any qubit state can be created and measured in any basis**





W. Tittel & G. Weihs, *Quant. Inf. Comput.* 1, Number 2, 3 (2001)

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Stabilisation of the interferometers

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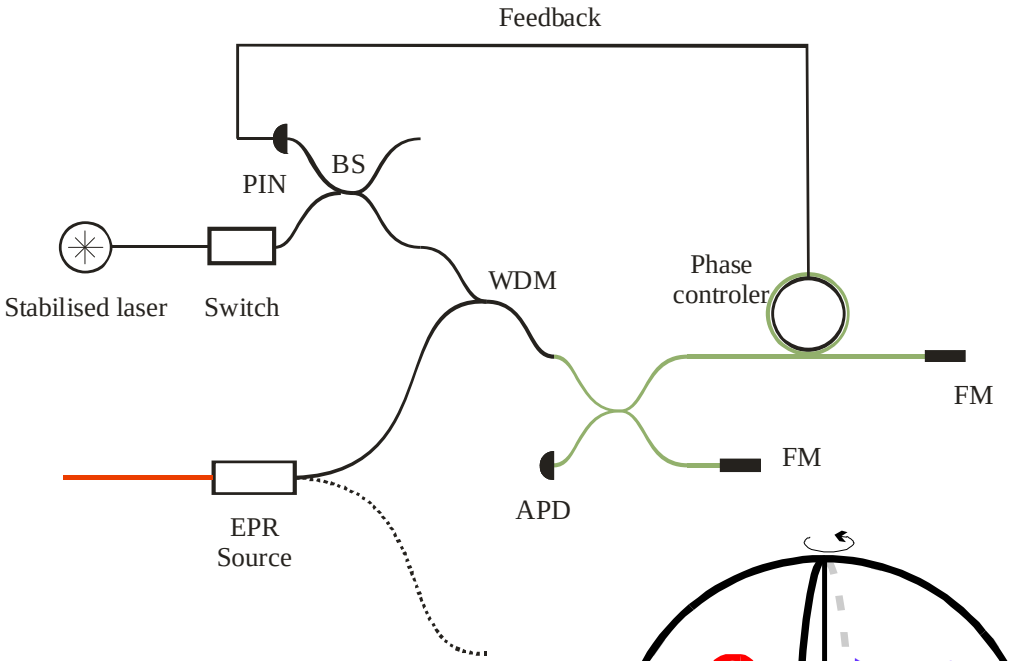
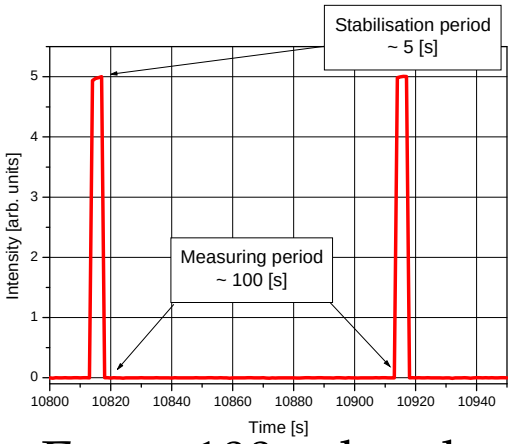
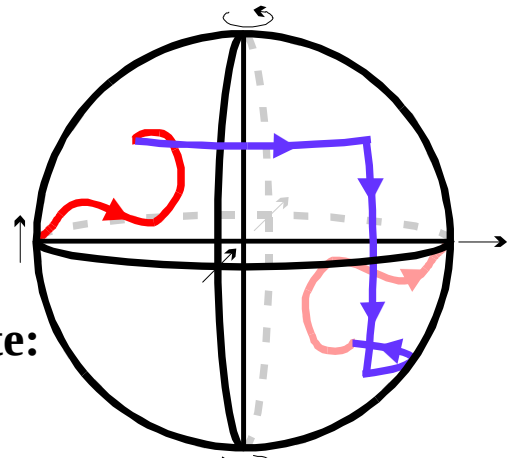
- Idea: verify from time to time the phase





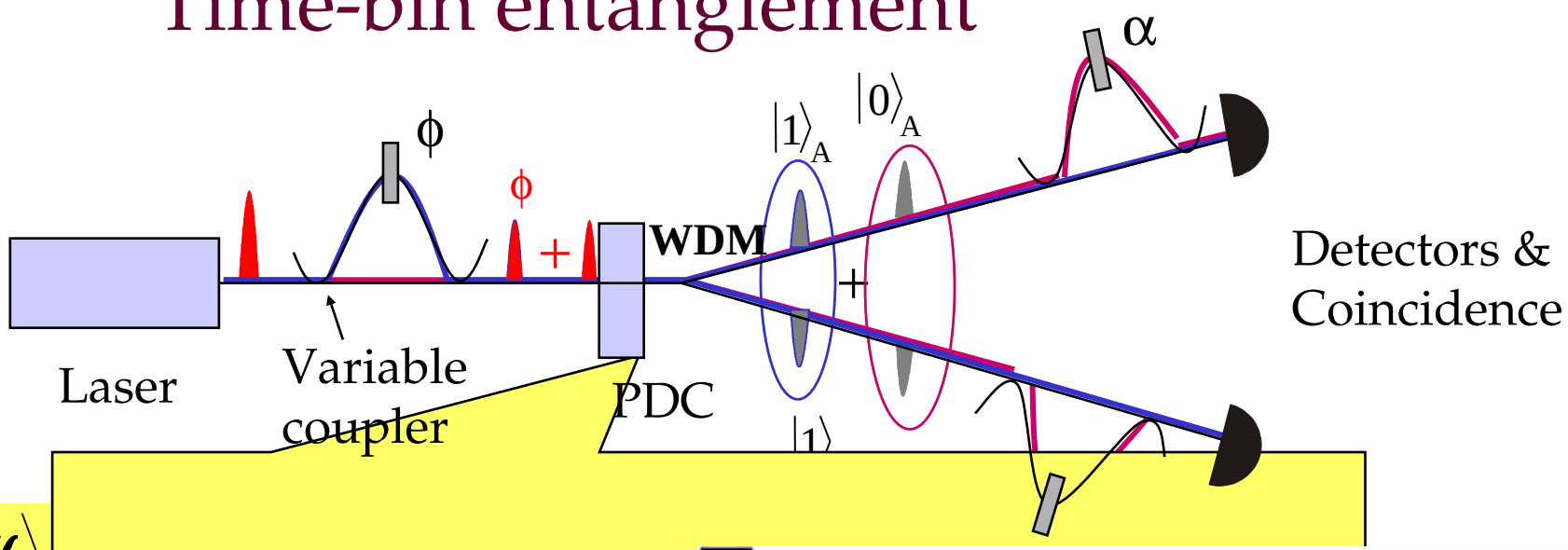
Every 100 s the phase is brought back to a given value



FM=Faraday mirror transforms polar.state:

$$\vec{m} \mapsto -\vec{m}$$

Time-bin entanglement



$|\psi\rangle$

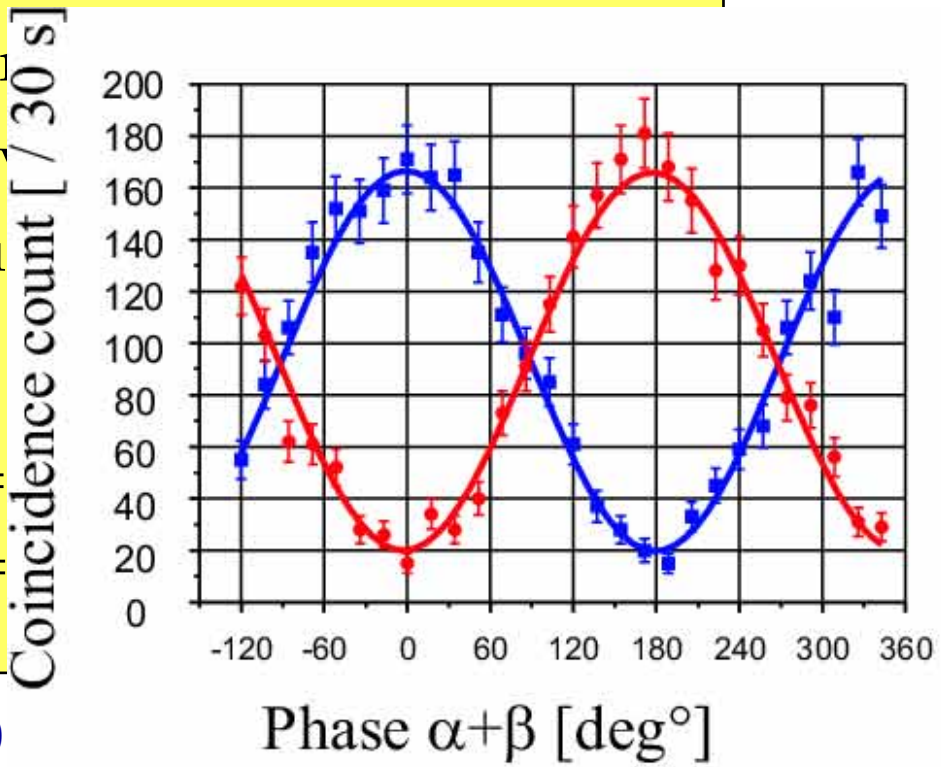
- Photon pair creation i
- Parametric down-con
- Energy and momentu

$\omega_p = \omega_s + \omega_i$

25 + 25 km

Robust against decoherence in optical fibers

- λ_p = 710 nm
- λ_s =
- λ_i =



I. Marcikic *et al.*, *PRL* 93, 180502 (2004)

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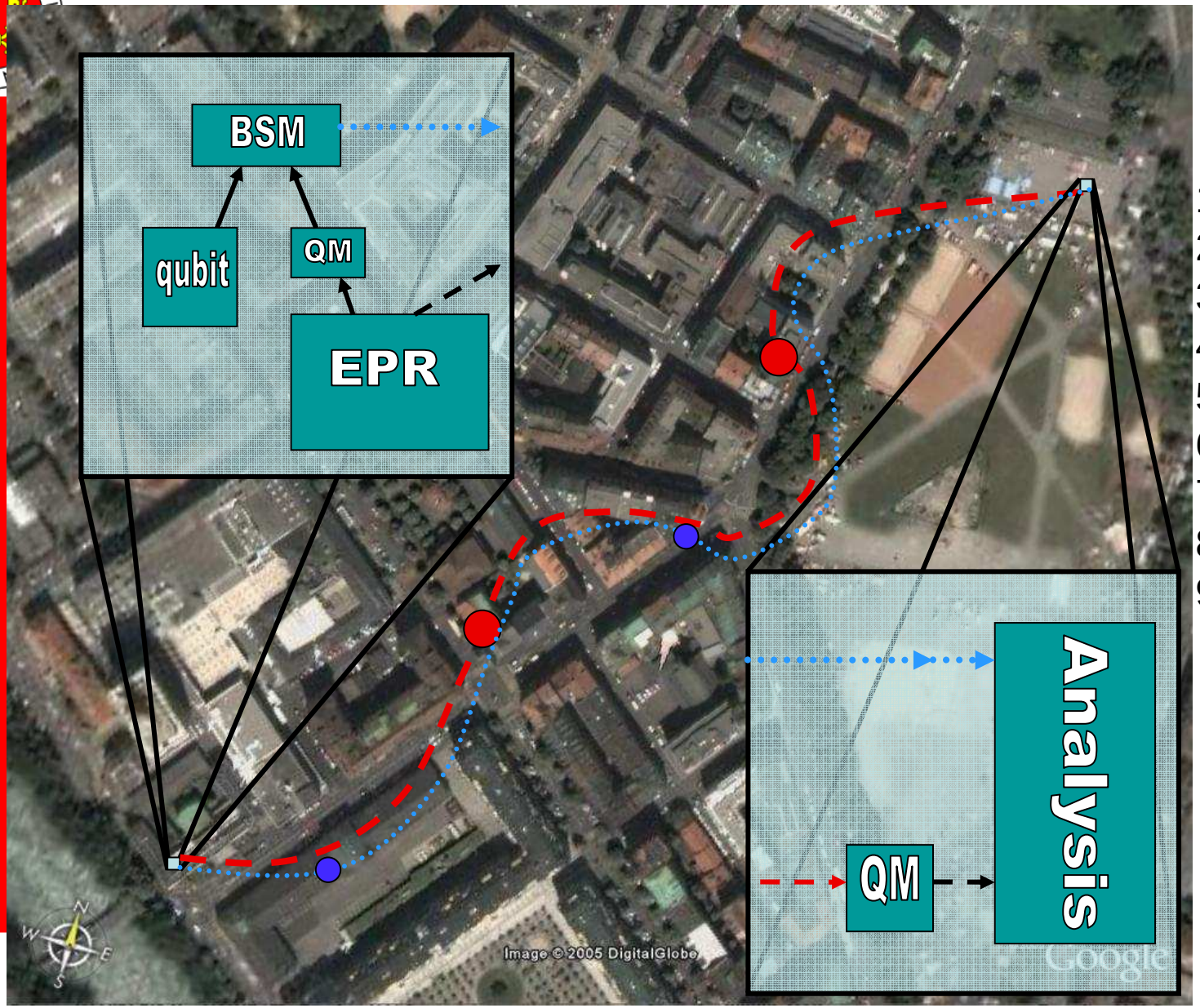
1. Q teleportation



1: EPR
2: Distribute
3: Create Qubit
4: Prepare BSM
5: BSM
6: Send result
7: Store photon
8: Wait for BSM
9: Analysis

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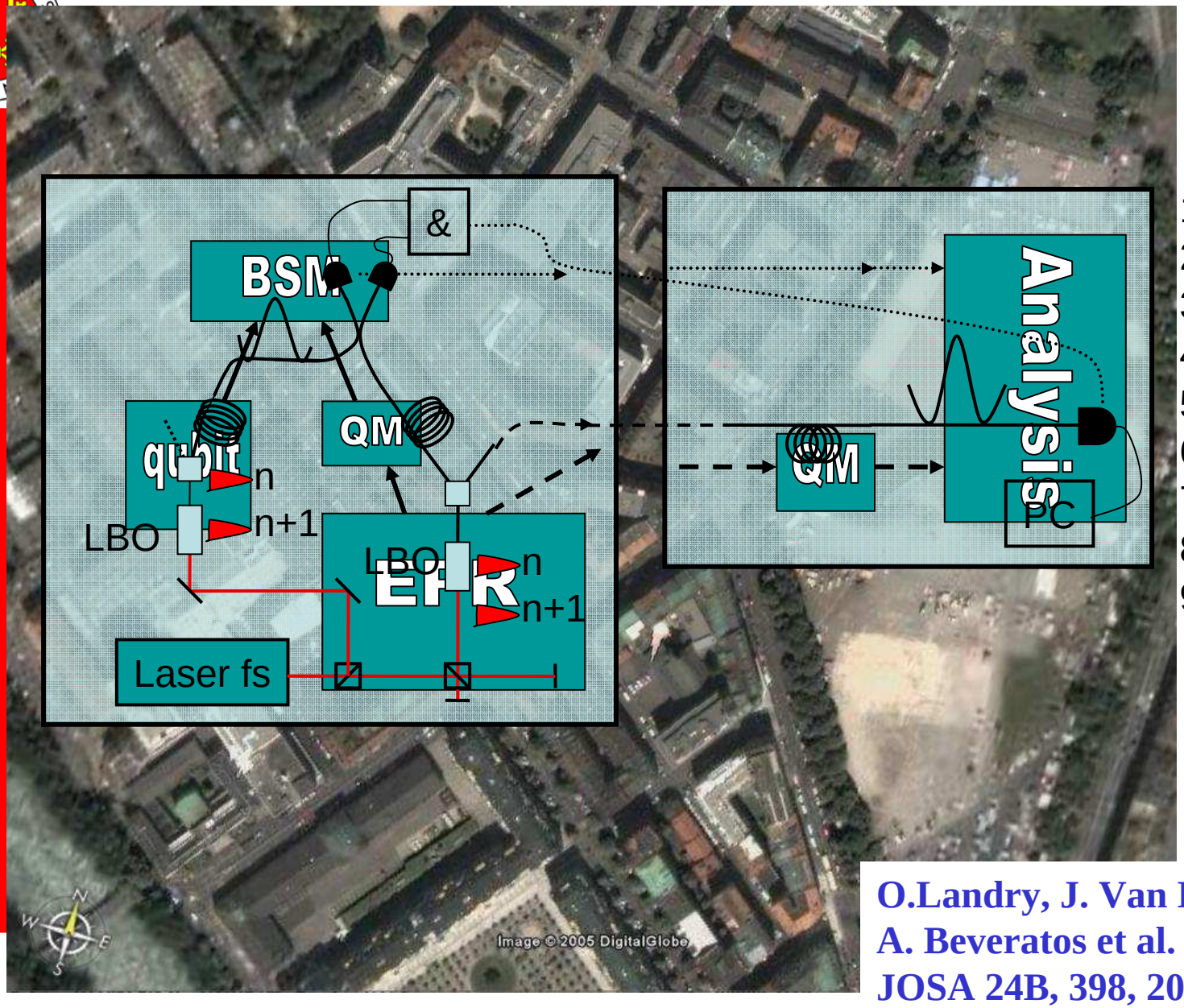

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O.Landry, J. Van Houwelingen, A. Beveratos et al.
JOSA 24B, 398, 2007
quant-ph/0605010

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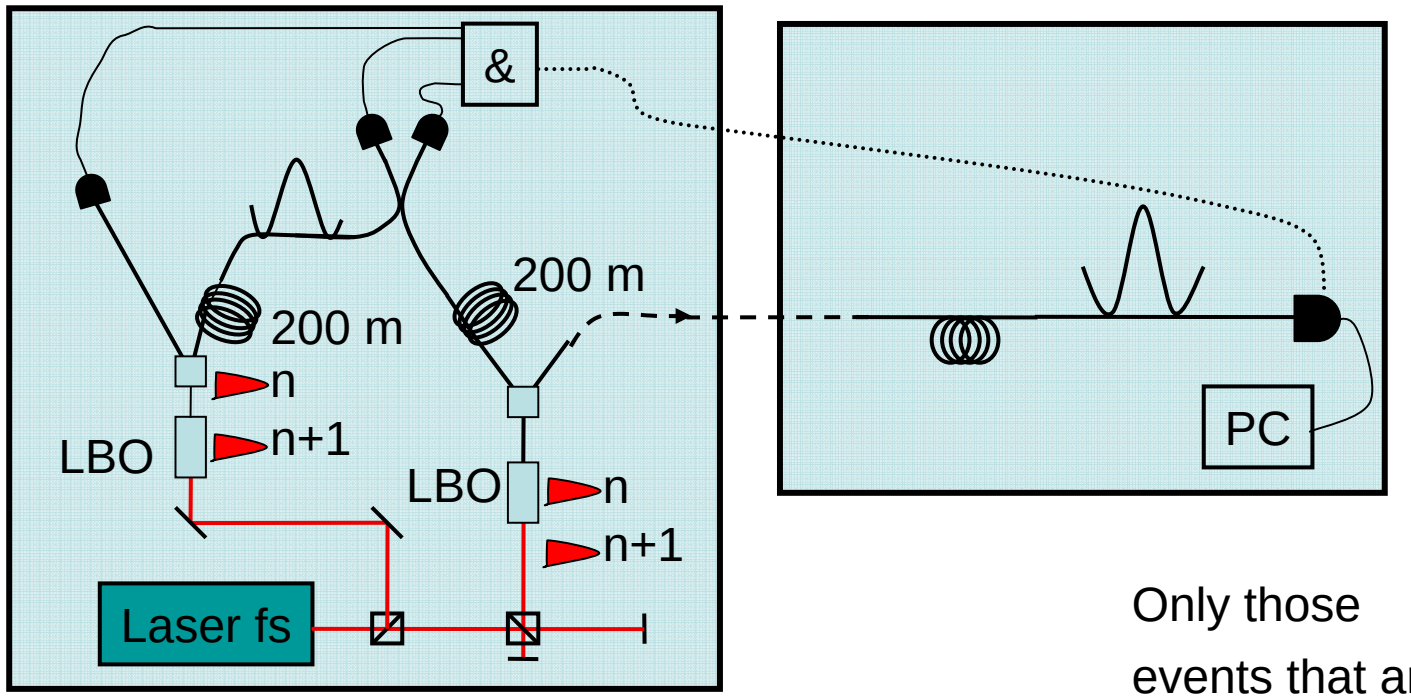
Teleportation of a heralded single photon



Only those events that are coincident with the 4th produced photon are considered

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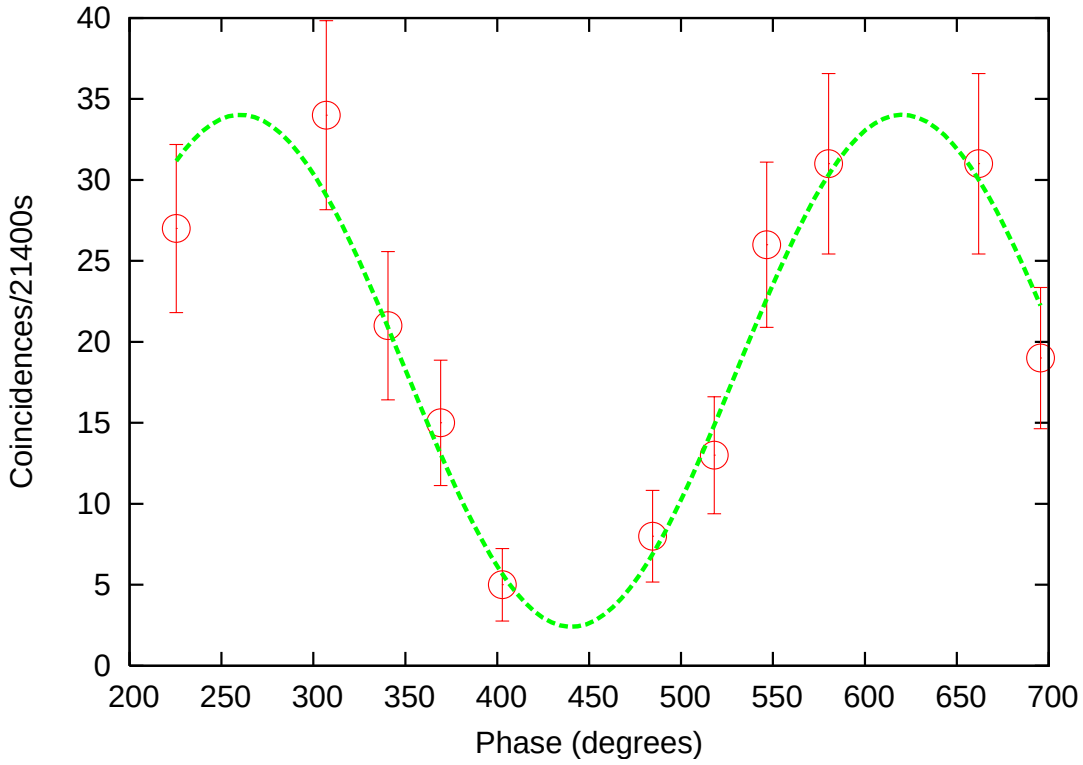
Teleportation results

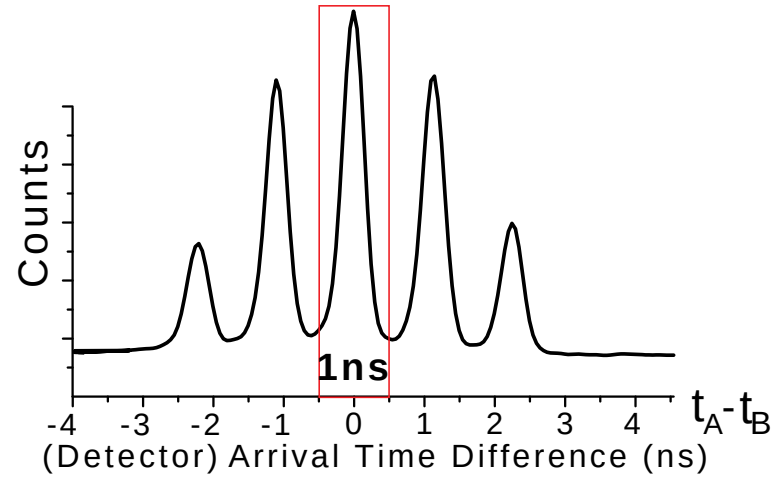


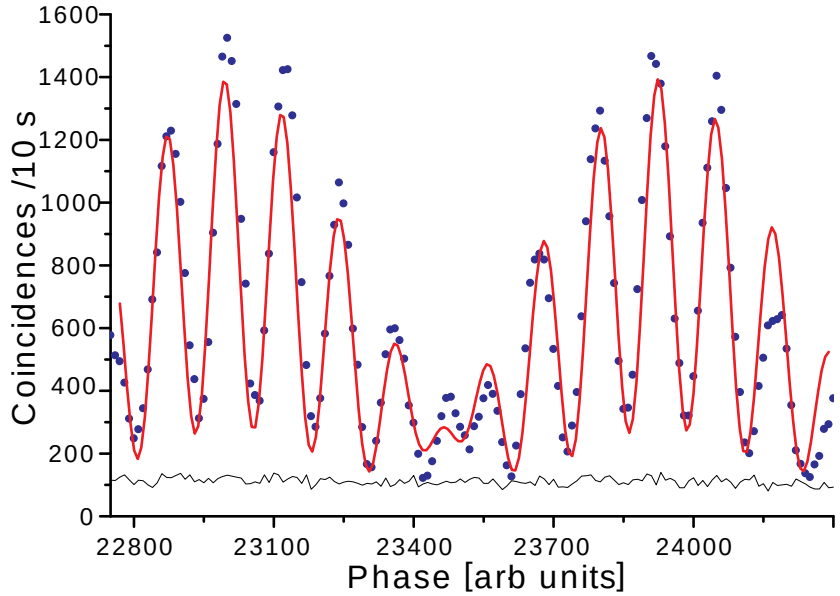
V_{raw}=0.87+/-0.07

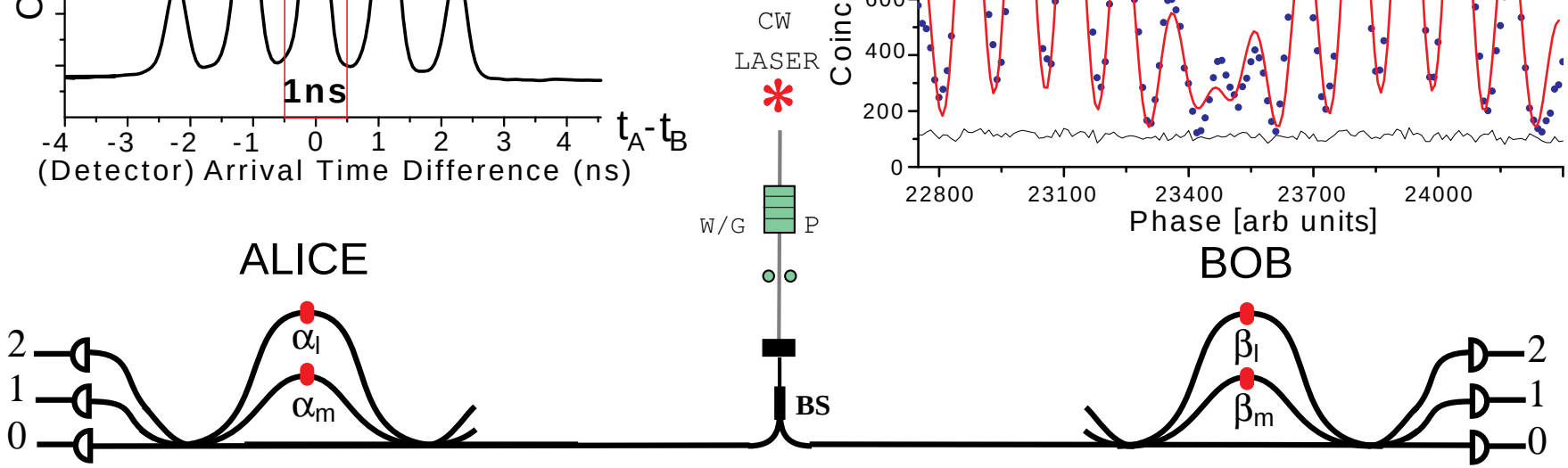
F_{raw}=0.93+/-0.04

O.Landry, J. Van Houwelingen, A. Beveratos et al.
JOSA 24B, 398, 2007
quant-ph/0605010

Qutrit Entanglement







$$|\psi\rangle = c_0|ss\rangle + c_1 e^{i(\alpha_m+\beta_m)}|mm\rangle + c_2 e^{i(\alpha_l+\beta_l)}|ll\rangle$$

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PRL 93, 010503, 2004

Bell Violation

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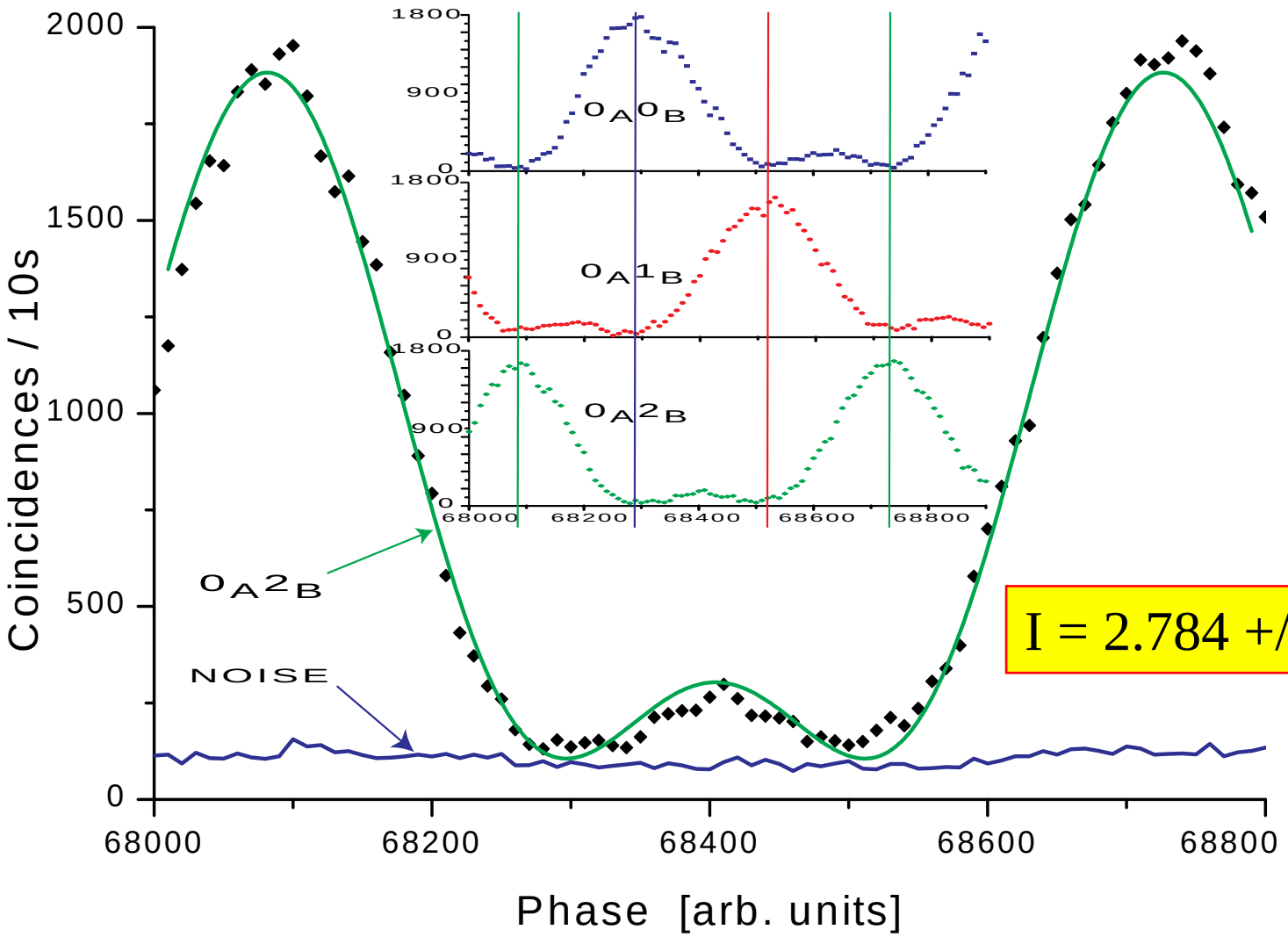
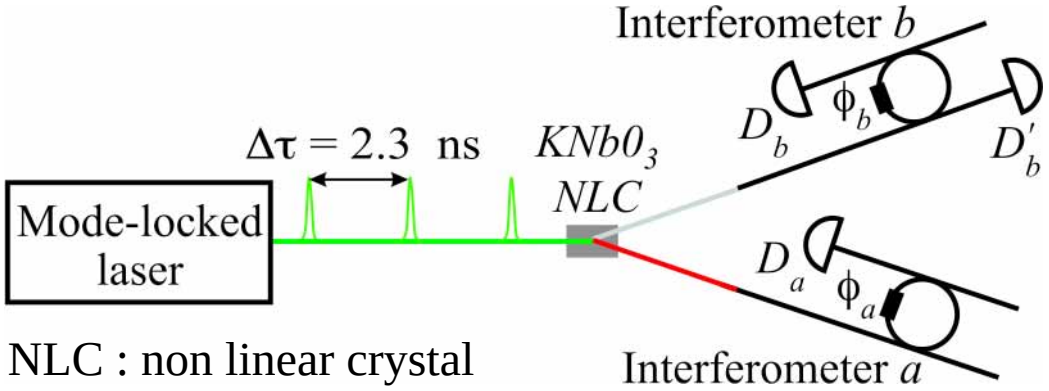
$$I(lhv) = 2 \quad < \quad I(2) = 2.829 \quad < \quad I(3) = 2.872$$



$$I = 2.784 +/- 0.023$$

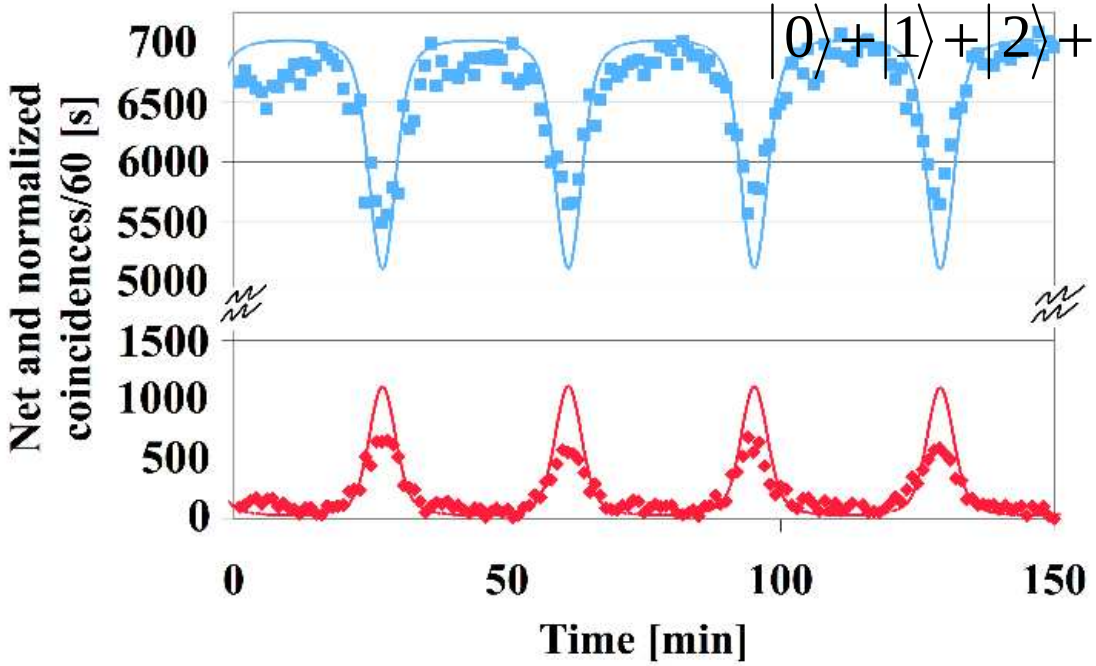
Two-photon Fabry-Perot interferometer

Aim :
direct detection of high dimensional entanglement



NLC : non linear crystal

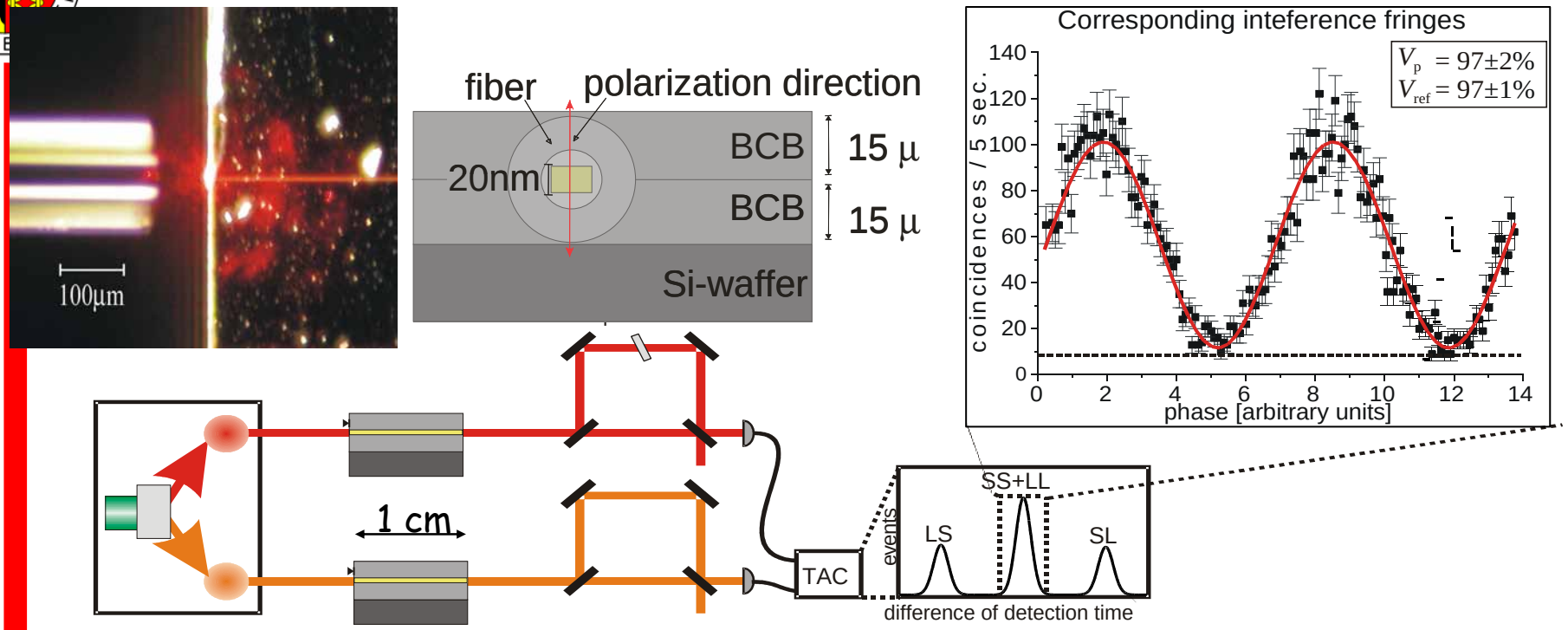
$$|0\rangle + |1\rangle + |2\rangle + \cdots \rightarrow |0,0\rangle + |1,1\rangle + |2,2\rangle + \cdots$$



Coincidences D_a-D_b (red) and D_a-D_b' (blue) as function of time while varying the phase ϕ_a

Ref. : D. Stucki et al., quant-ph/0502169

Plasmon assisted entanglement transfer



⇒ a short lived phenomenon like a plasmon can be coherently excited at two times that differ by much more than its lifetime. At a macroscopic level this would lead to a "Schrödinger cat" in superposition of living at two epochs that differ by much more than a cat's lifetime.

PRL 94, 110501-1/4, 2005, quant-ph/0410064
New Journal of Physics 8, 13, 2006, quant-ph/0512022

Quantum Interface: Quantum Information transfert

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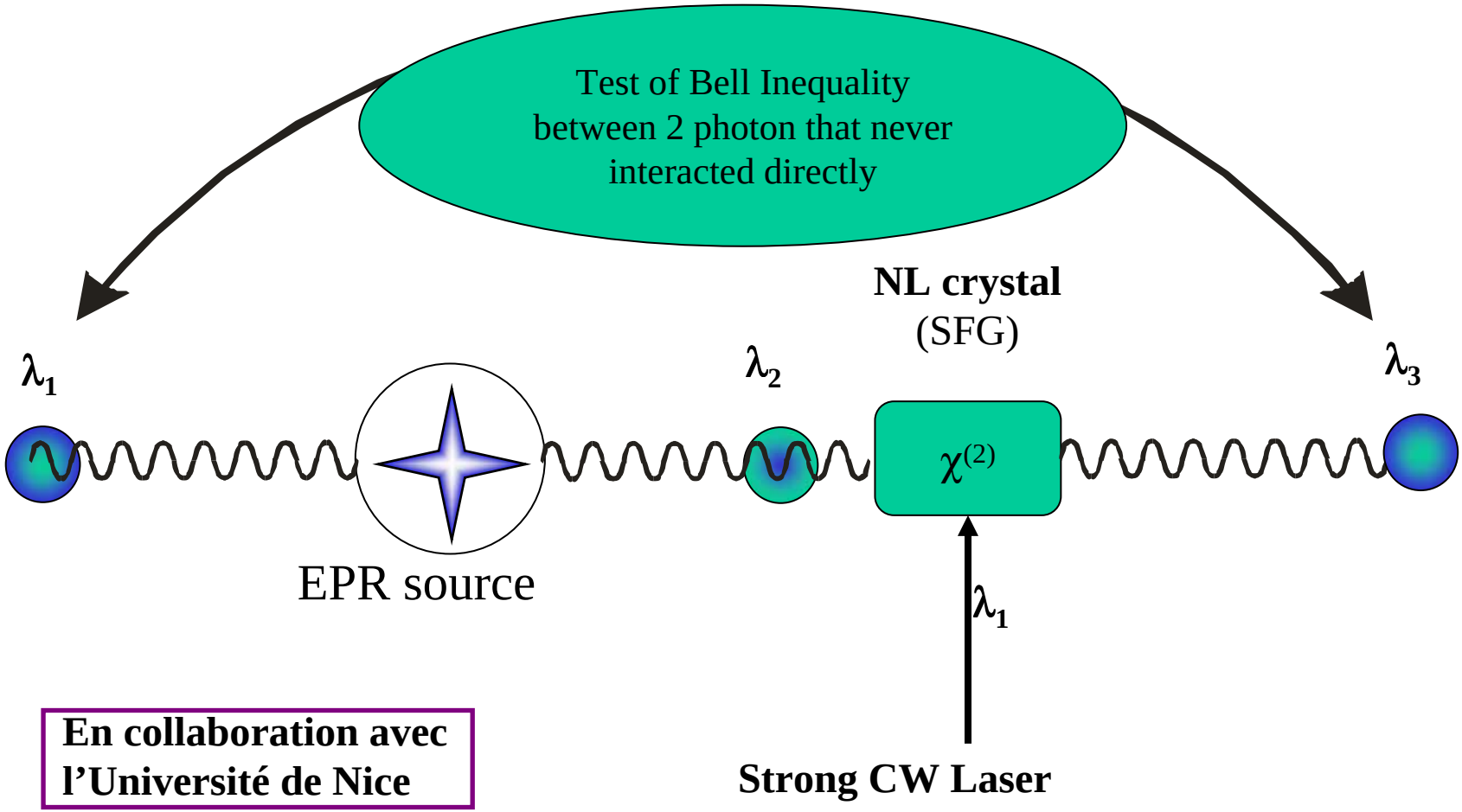

En collaboration avec l'Université de Nice

Nature, 437, 116-120, 2005

Long distances: Entanglement Swapping

PRA 71, 05302, 2005

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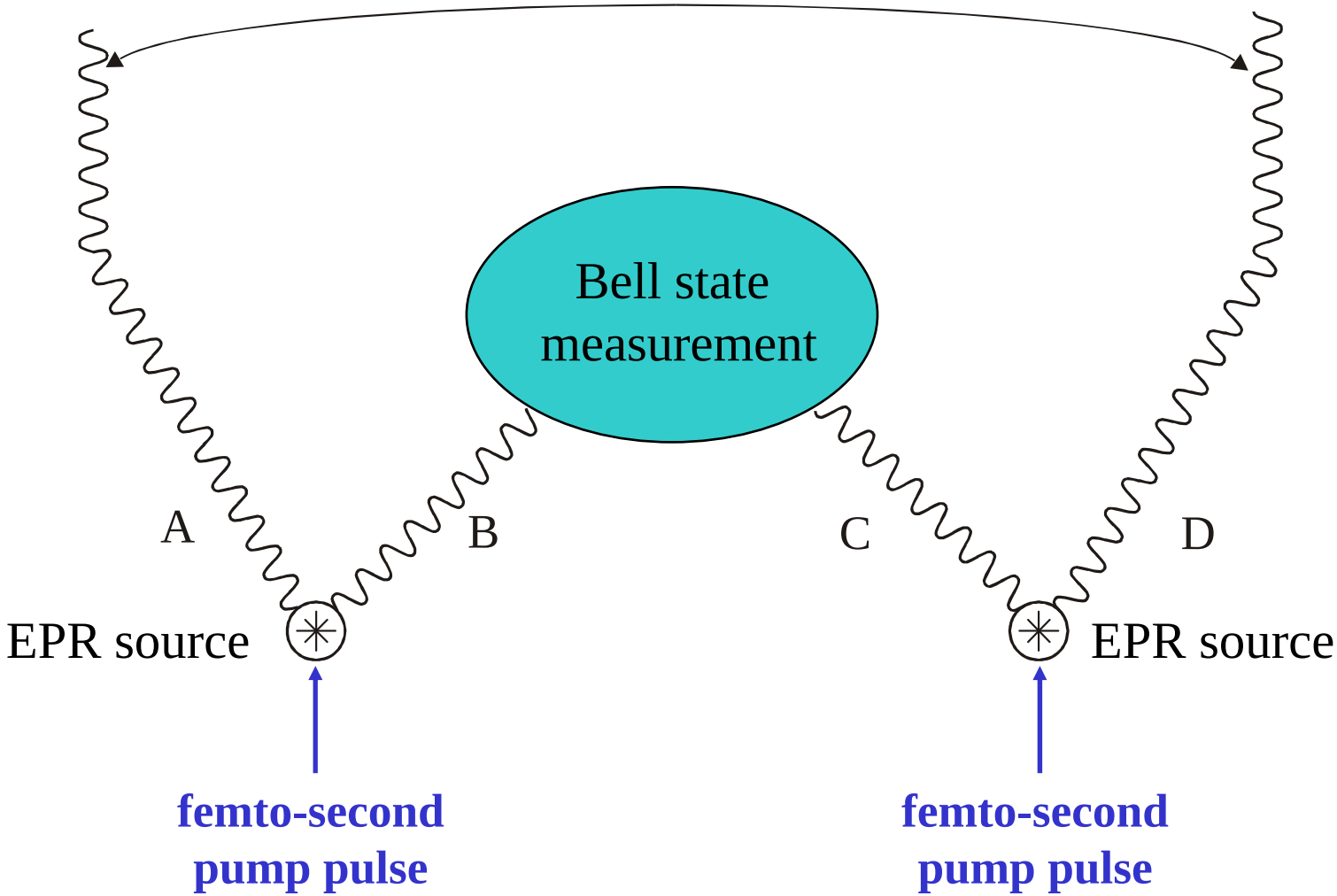
Entangled photons that never interacted



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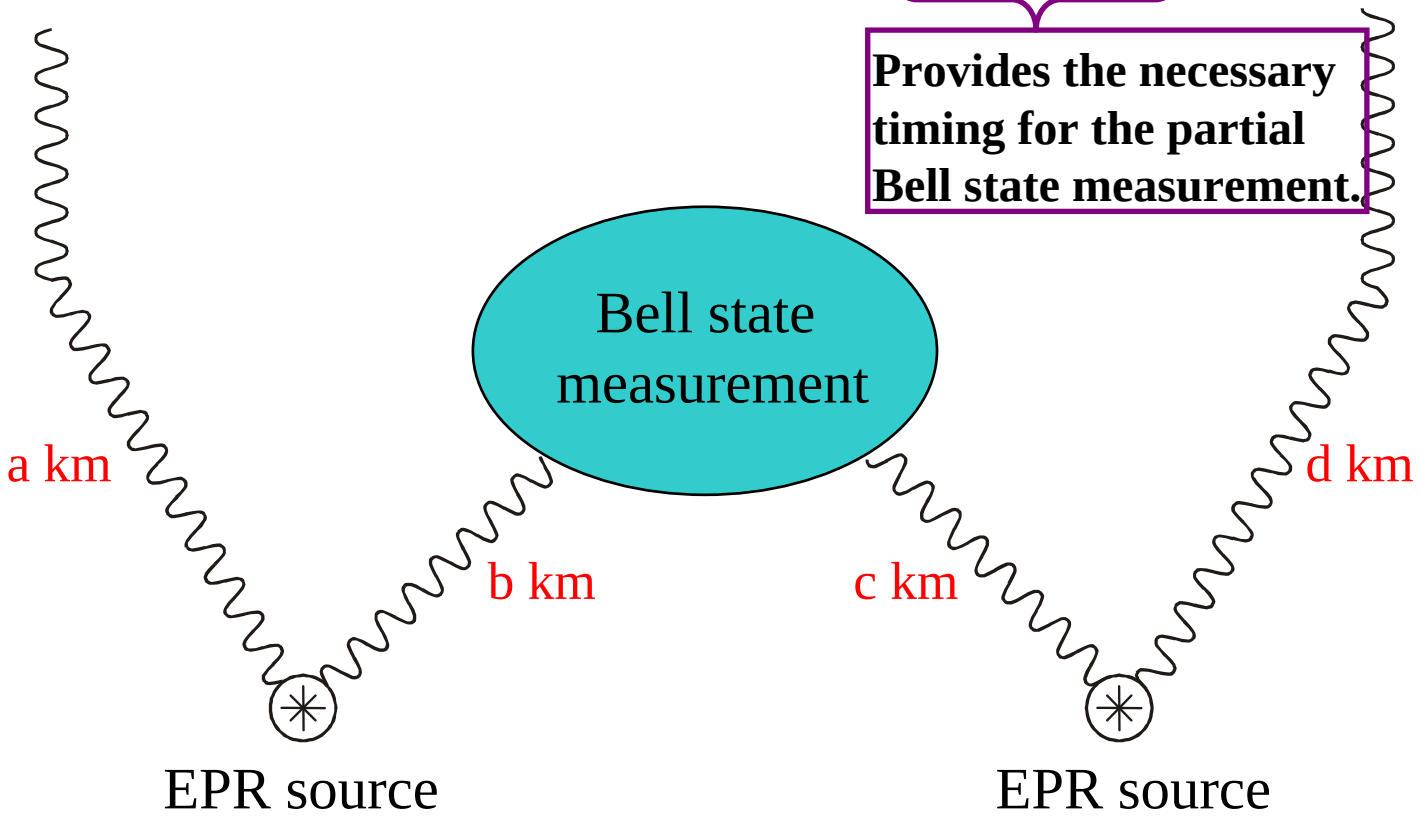
Optical length stability problem

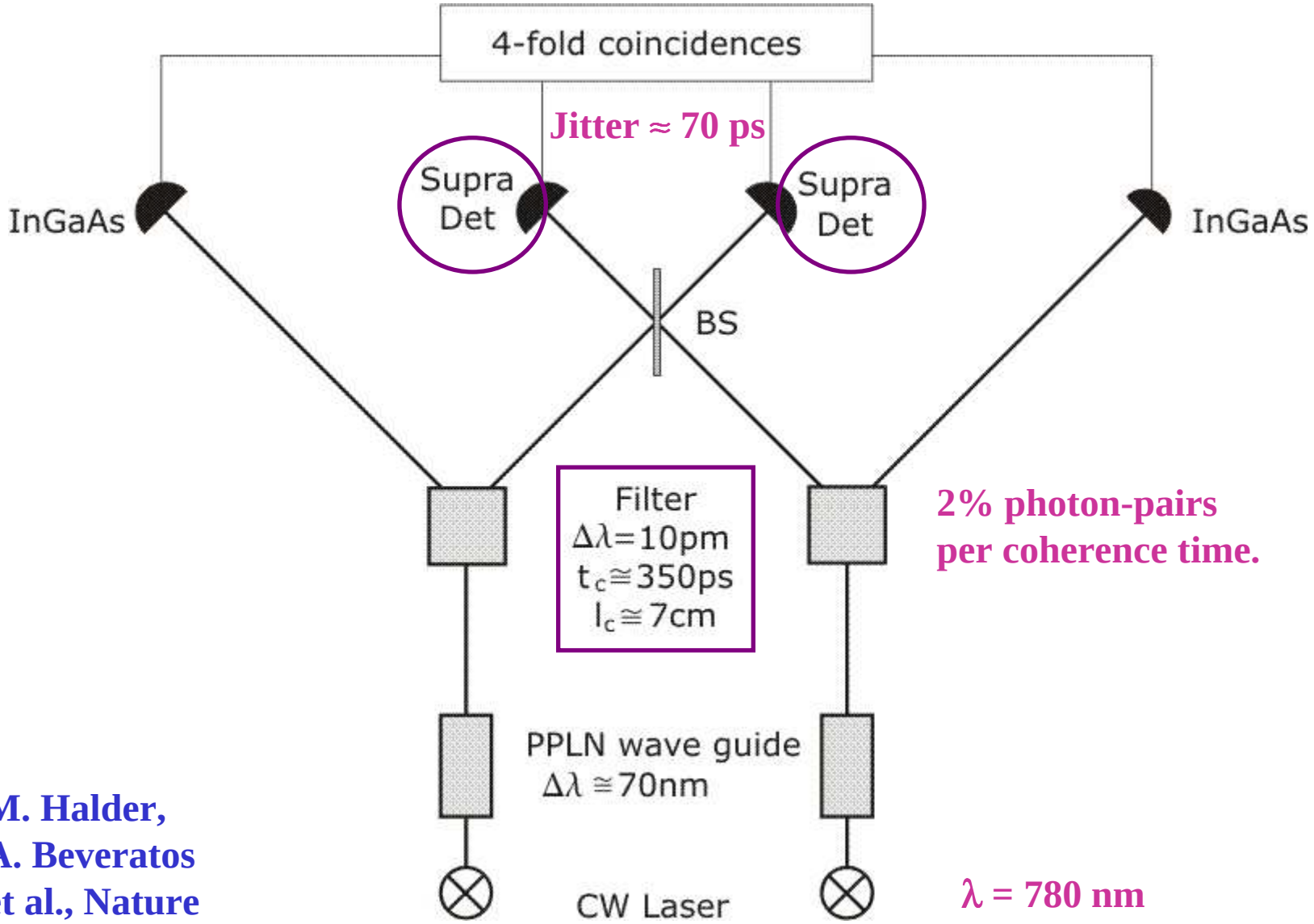
Thermal effects: 10^{-5} /dg $\Rightarrow$ on tens of km one has ± cm per degree
$\Rightarrow$ femto-second laser pulses are useless.

Solutions: 1. go for synchronized picosecond lasers
2. use cw lasers … and fast detectors

Provides the necessary timing for the partial Bell state measurement.



Scheme of a Mandel-dip experiment with cw laser diodes



2% photon-pairs per coherence time.

λ = 780 nm

M. Halder, A. Beveratos et al., Nature Physics 3, 692, 2007

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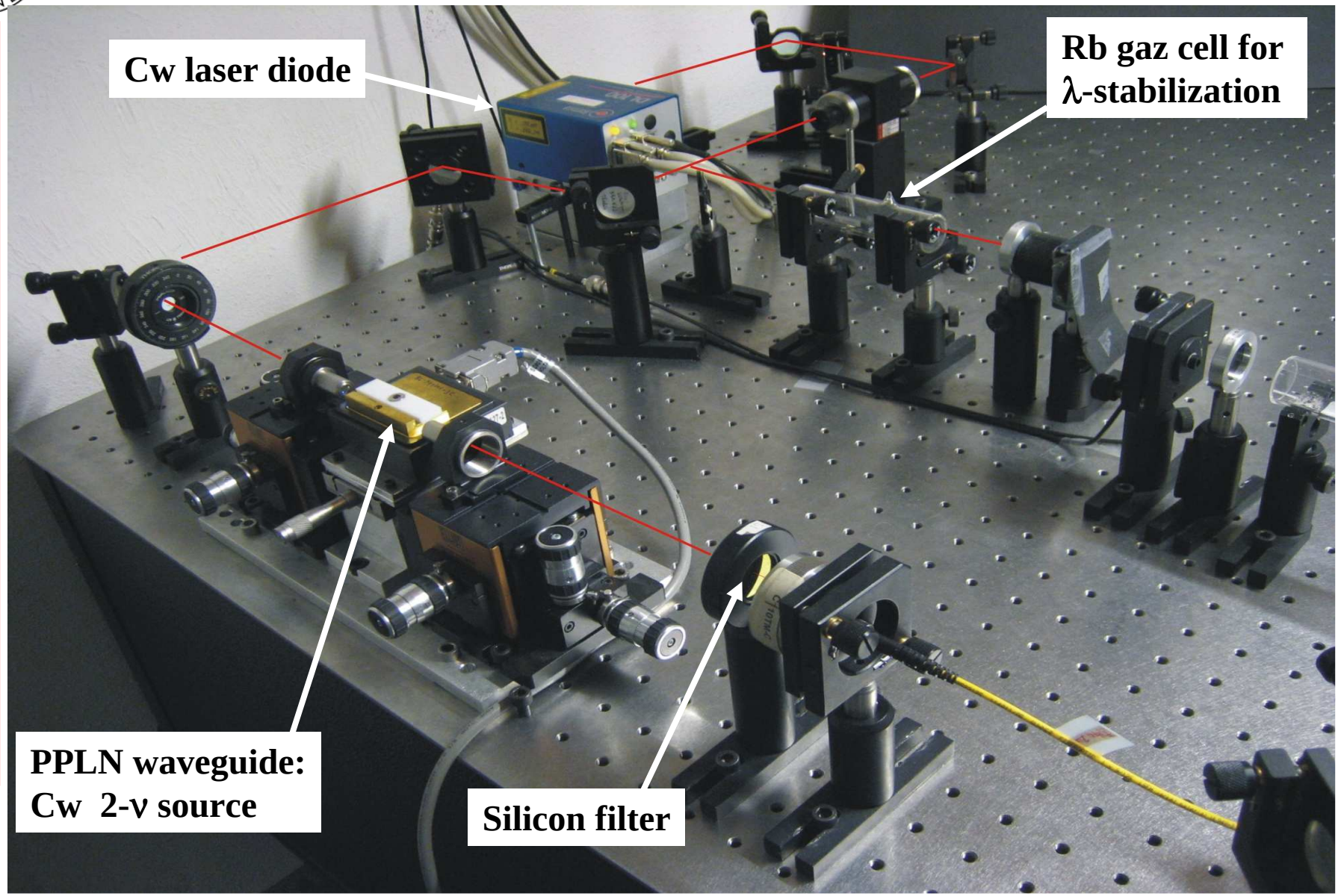
cw source



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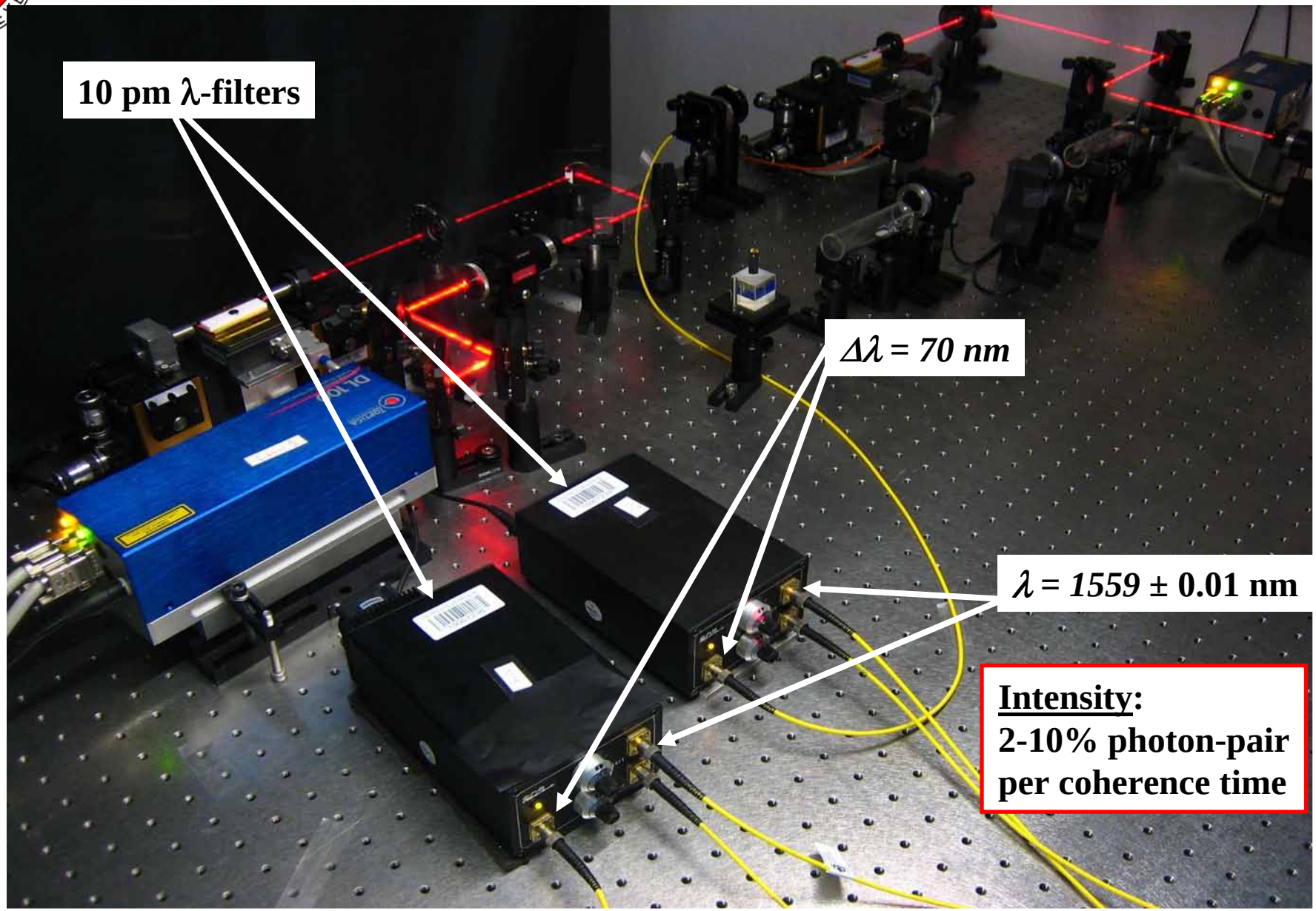
2 cw sources



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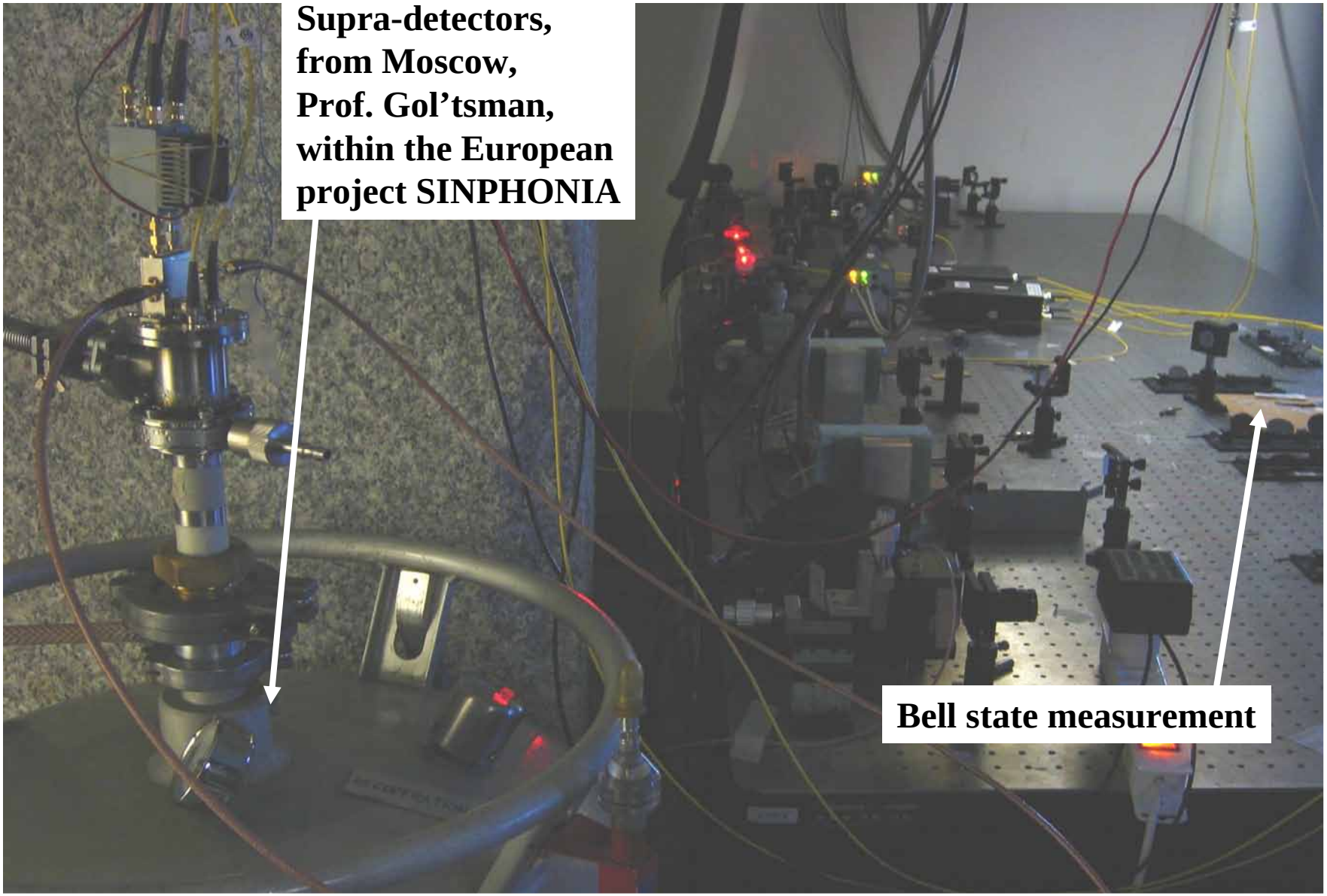
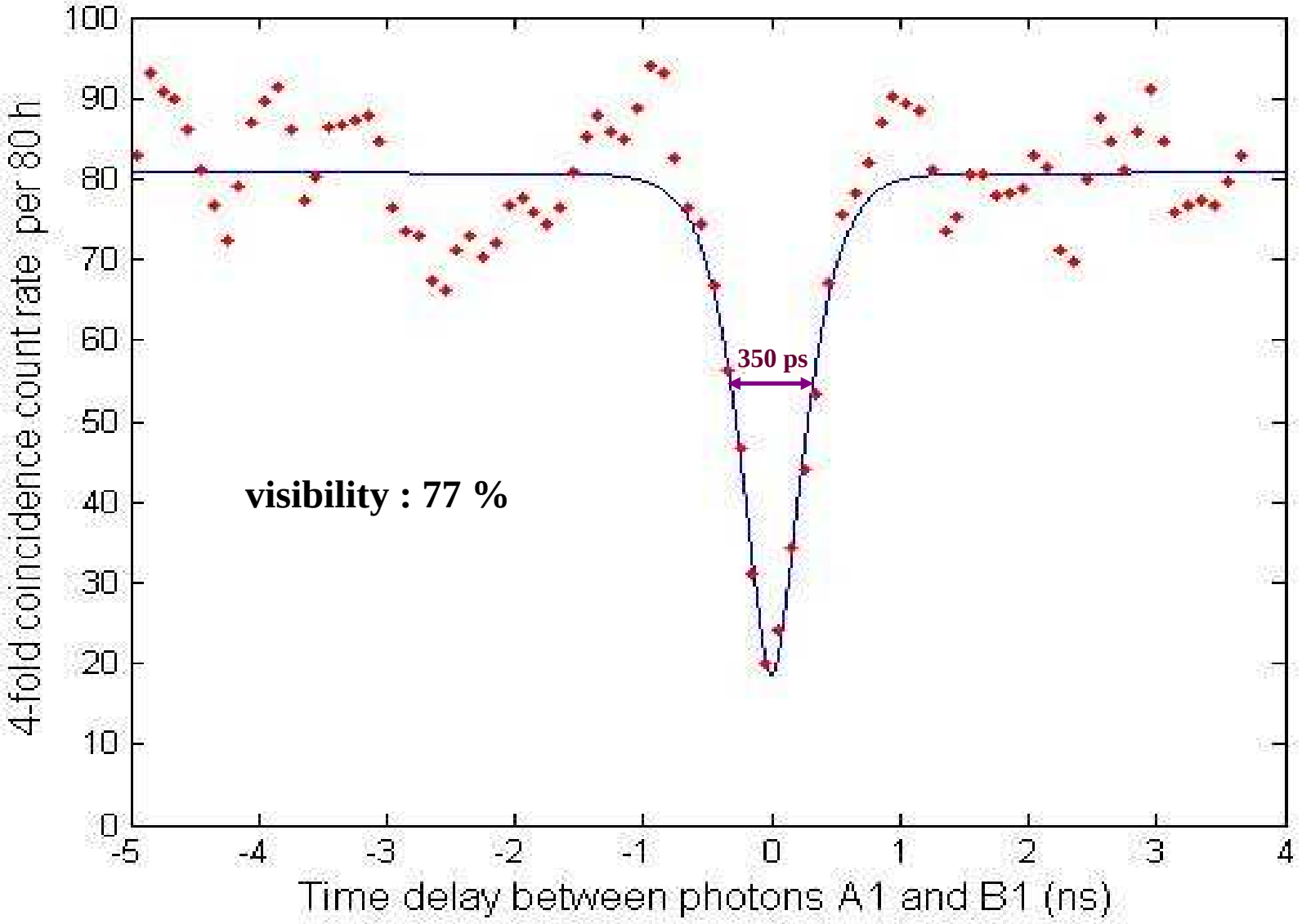
The entire experiment

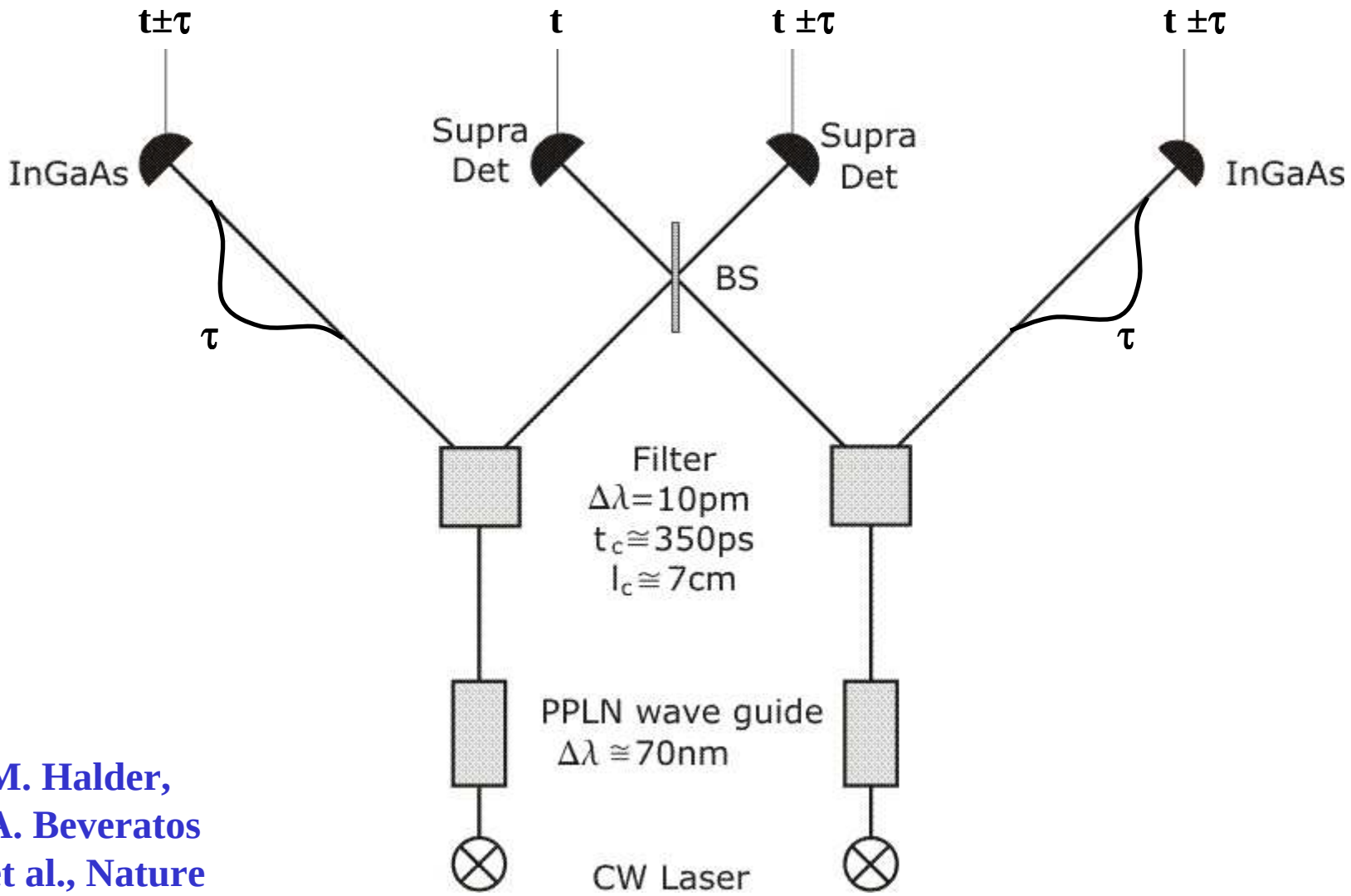


Observed Mandel-dip between two cw autonomous sources

M. Halder, A. Beveratos et al., Nature Physics 3, 692, 2007



Entanglement Swapping bw 2 autonomous cw sources



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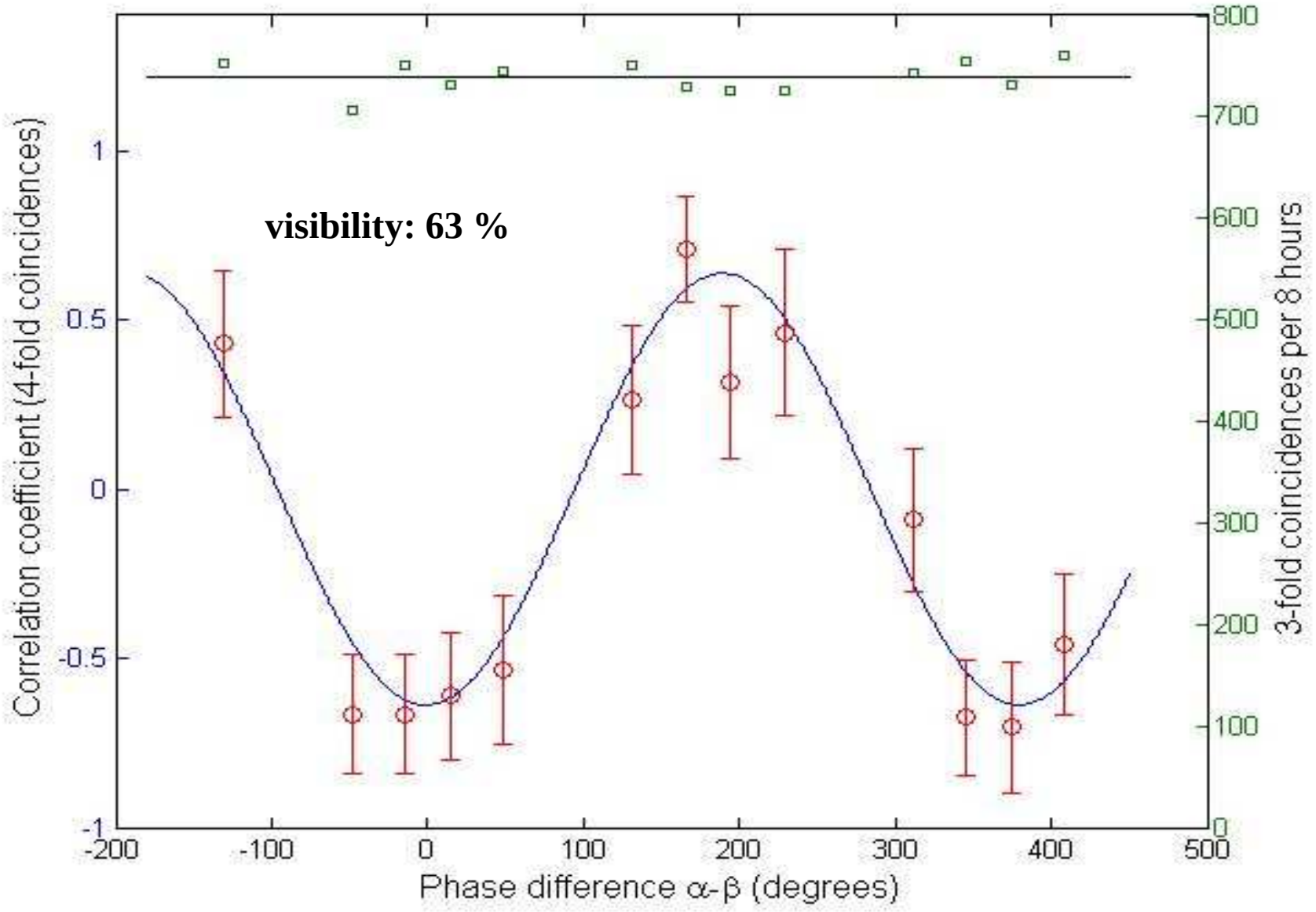
M. Halder,
A. Beveratos
et al., Nature
Physics 3, 692, 2007

Entanglement Swapping with two totally autonomous cw sources

M. Halder, A. Beveratos et al., Nature Physics 3, 692, 2007



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Conclusion

Entanglement is incredibly robust

Understanding Quantum Correlations

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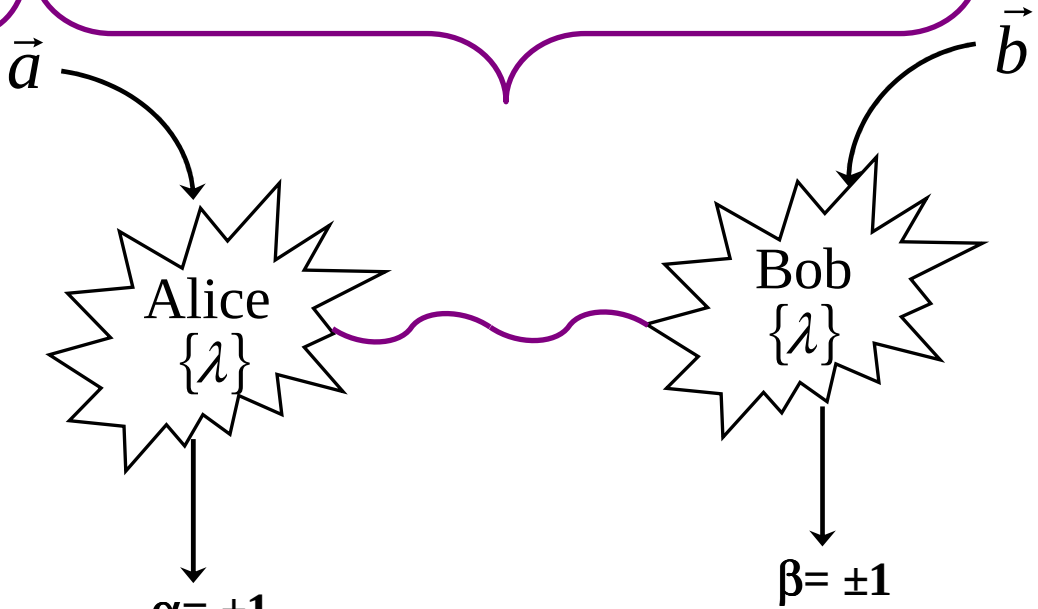
- **Intuition**
- **decomposition into "simpler" correlations**
- **simulation with "simpler" correlations**



$$P_{QM}(\alpha,\beta\,|\,\vec{a},\vec{b}) = \frac{1}{4}\left(1-\alpha\beta\cdot\vec{a}\cdot\vec{b}\right)$$

$$= \int d\lambda\, P_\lambda(\alpha,\beta\,|\,\vec{a},\vec{b})$$

$$= \int d\lambda \frac{1}{4}\left(1+\alpha\cdot M_A^\lambda(\vec{a})+\beta\cdot M_B^\lambda(\vec{b})+\alpha\beta\cdot C_\lambda(\vec{a},\vec{b})\right)$$

local marginals

nonlocal correlation coefficient

Bell locality

$$\Leftrightarrow \quad P_\lambda(\alpha,\beta\,|\,\vec{a},\vec{b}) = \frac{1}{4}\left(1+\alpha\cdot M_A^\lambda(\vec{a})\right)\cdot\left(1+\beta\cdot M_B^\lambda(\vec{b})\right)$$

i.e. $$C_\lambda(\vec{a},\vec{b}) = M_A^\lambda(\vec{a})\cdot M_B^\lambda(\vec{b})$$

By far the most natural assumption !
… refuted beyond (almost) any reasonable doubts.

Hence, quantum correlations happen, but the probabilities of their occurrence are not defined by local variables.

How come the correlation ?

- How can these two locations out there in space-time know about each other ?

- via entanglement? (in Hilbert space) or
- via communication ? (in space-time)

⇒ **There is no spooky action at a distance:**
there is not a first event that influences a second event.

⇒ **Quantum correlation just happen, somehow from outside space-time ! (there is no story in space-time that tell us how it happens)**

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Leggett's "locality"

Found.Phys. 10,1469,2003

Assume that locally everything is "normal",
i.e. that individual particles are always in pure states:

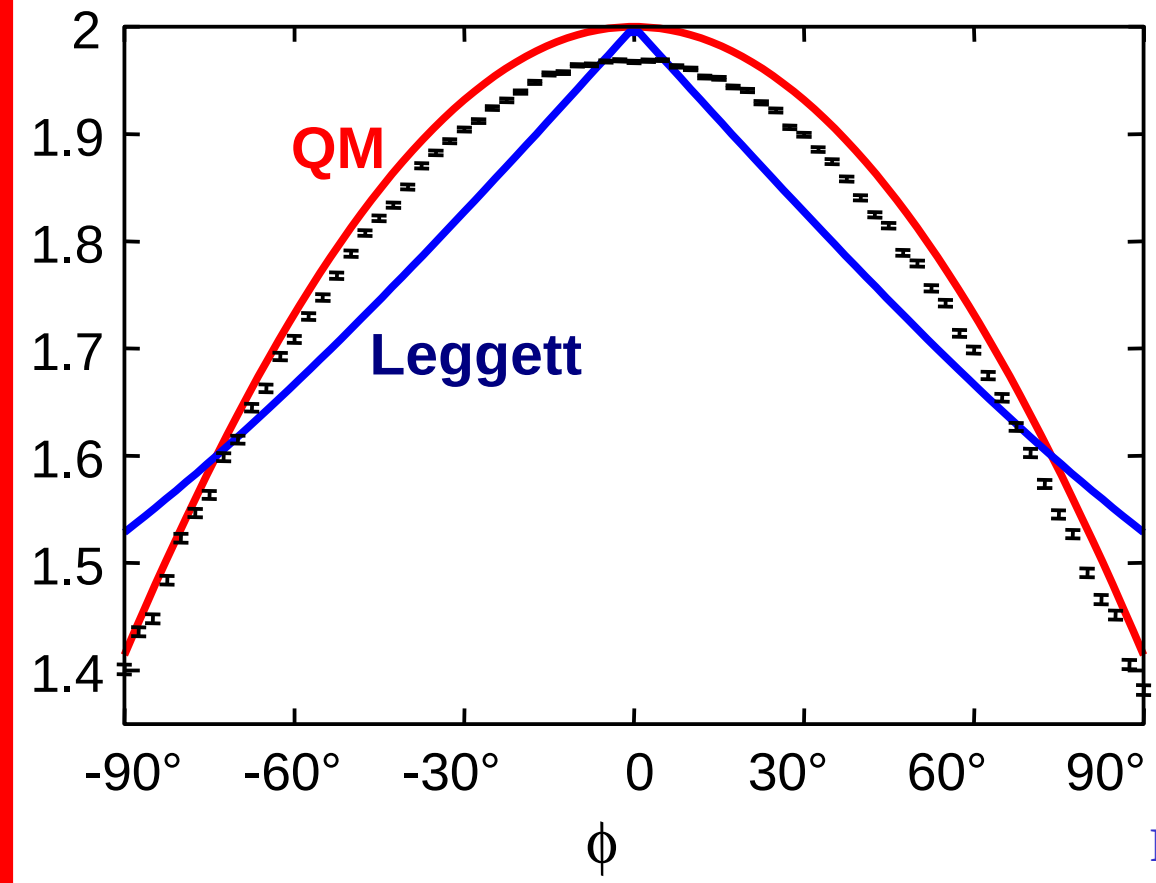
$$P_\theta^{QM}(\alpha,\beta\,|\,\vec{a},\vec{b}) = \int d\lambda\; P_\lambda(\alpha,\beta\,|\,\vec{a},\vec{b})$$

where $\lambda = |\mu\rangle \otimes |\nu\rangle$

and $$P_{\mu\nu} = \frac{1}{4}\left(1 + \alpha\cdot\langle\vec{a}\vec{\sigma}\rangle_\mu + \beta\cdot\langle\vec{b}\vec{\sigma}\rangle_\nu + \alpha\beta\cdot C_{\mu\nu}(\vec{a},\vec{b})\right)$$

"Only" the correlations $C_{\mu\nu}$ are nonlocal.
They just happen, without any classical explanation.
They are only constraint by $P_{\mu\nu} \geq 0$

Experimental refutation of Leggett's model



- integration time: 4 x 15 sec / setting
- maximal violation: L=1.925 ± 0.0017 (40.6 σ) at φ = -25°

  L=1.922 ± 0.0017 (38.1 σ) at φ = +25°

for 60 sec/setting:

$L_3(-30°)=5.7204\pm0.0028$ (83.7 σ)

PRL 99,210406,2007
PRL 99,210407,2007
Branciard et al. in preparation

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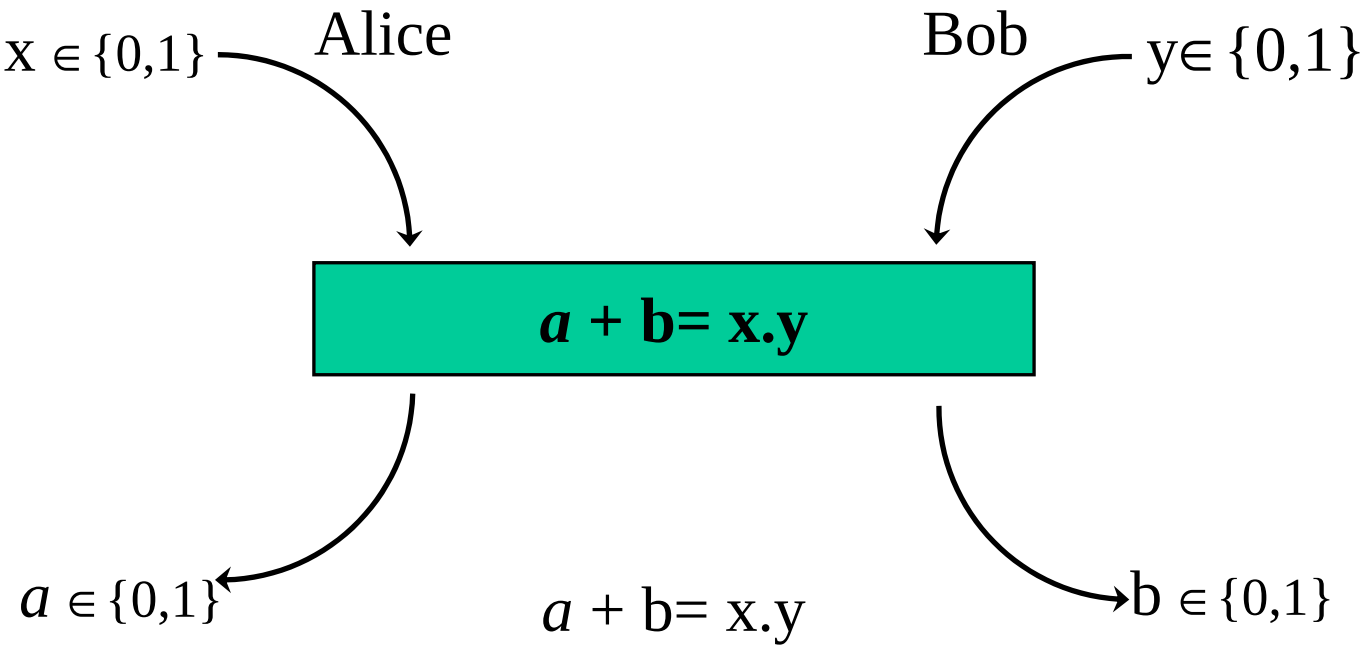
Simulation with a nonlocal-box

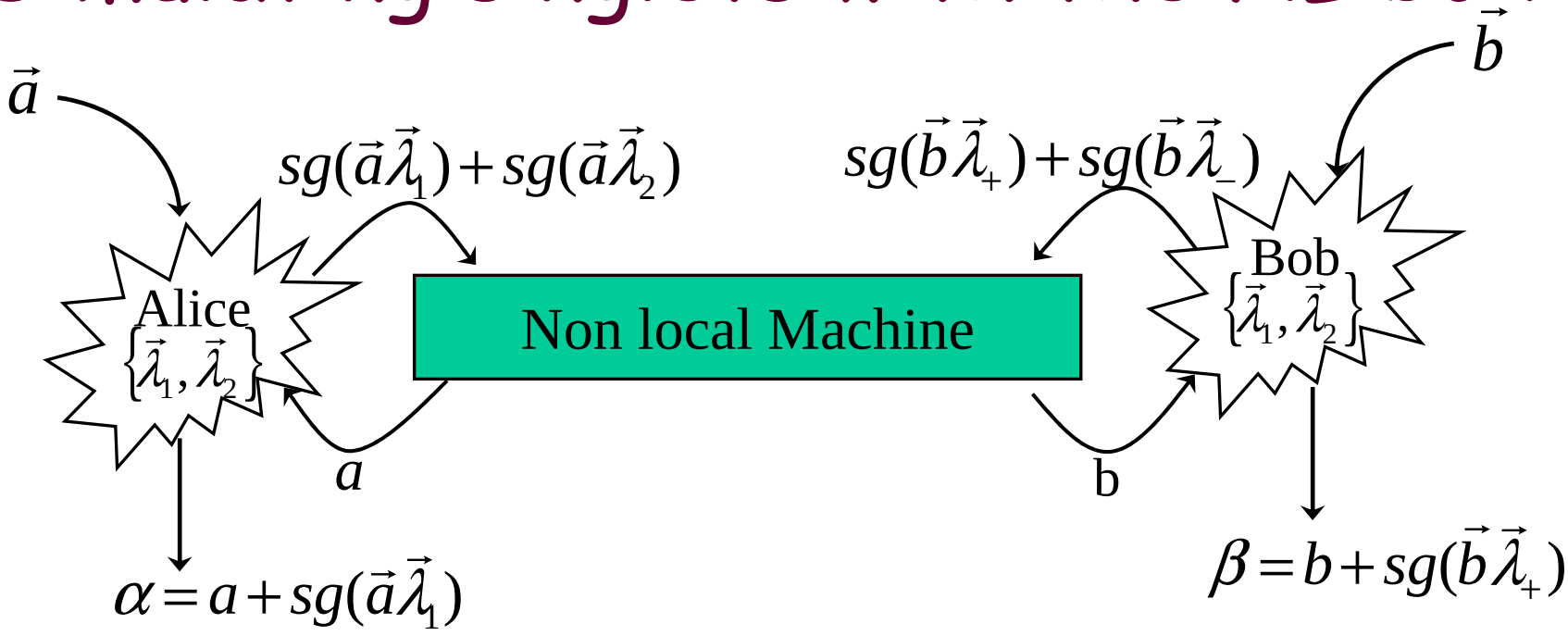


A single bit of communication suffice to simulate the PR-box (assuming shared randomness).
But the PR-box does not allow any communication.

Hence, the PR-box is a strickly weaker ressource than communication.

Found.Phys. 24, 379, 1994

Simulating singlets with the NL box



where $\vec{\lambda}_1$ *and* $\vec{\lambda}_2$ *are distributed uniformly on* $S^{(2)}$,

$$sg(x)=\begin{cases}1 & if\ x\geq 0\\ 0 & if\ x<0\end{cases} \quad and\ \vec{\lambda}_{\pm}=\vec{\lambda}_1\pm\vec{\lambda}_2$$

Given $\vec{a}$ & $\vec{b}$, the statistics of α & β is that of the singlet state:

$$P(\alpha,\beta\,|\,\vec{a},\vec{b})=\frac{1}{4}\left(1-\alpha\beta\cdot\vec{a}\vec{b}\right)$$

PRL 94,220403,2005

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Does this help our understanding ?

- After all, in a PR-box the correlation merely happen, without any explanation.
- Yes, but this **has** to be the case!
- Yes, but this is also the case in quantum physics (and in models à la Leggett)!

- Moreover, a+b=x.y is really simply !

- At least it helps me …

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How can one realize Quantum Teleportation ?

How can one understand Quantum nonlocality ?

For what could teleportation-nonlocality-entanglement be good for ?

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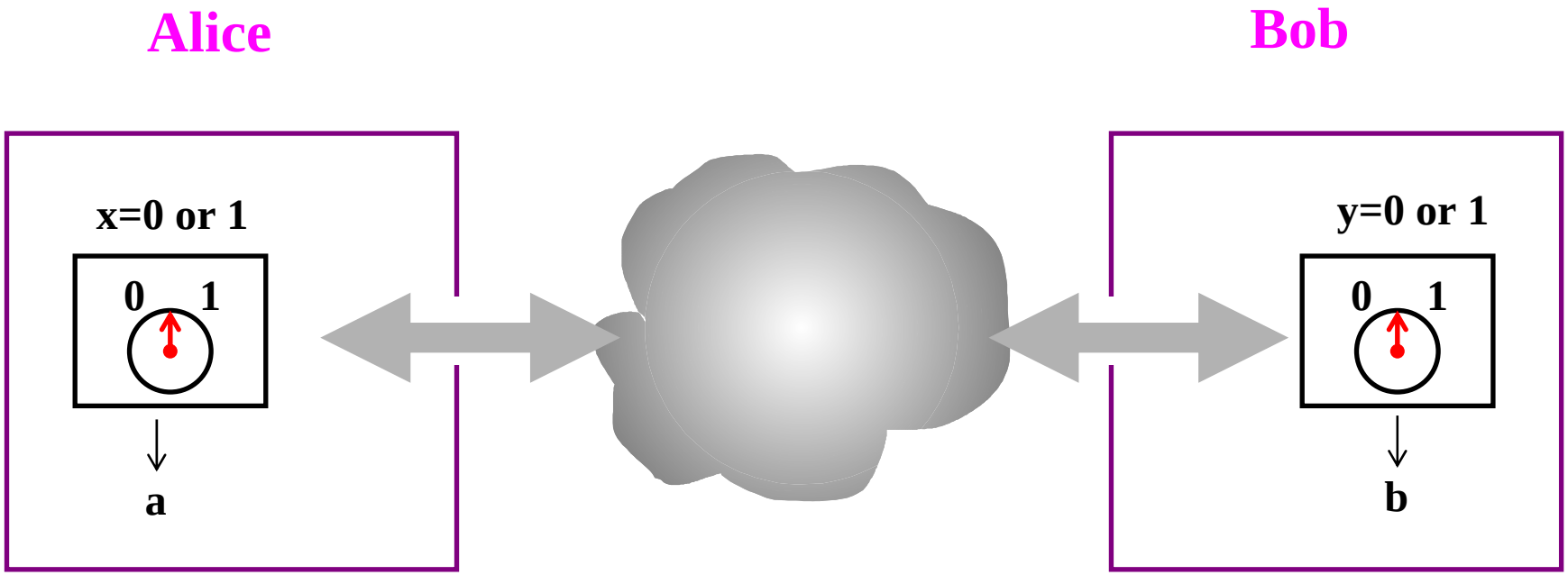
Basics of QKD



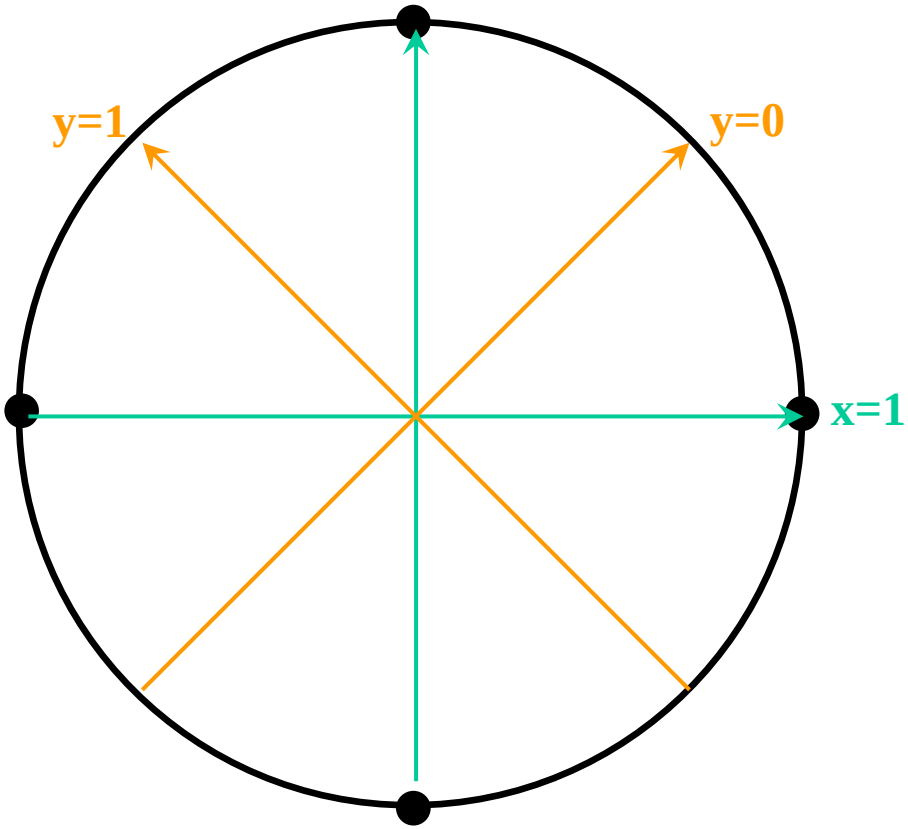
After publicly announcing a fair sample of their data, Alice and Bob's information is entirely contained in the conditional probability

$$p(a,b|x,y)$$

CHSH Quantum Cryptography protocol

A.Acin, L.Masanes, NG
PRL 97, 120405 (2006)

$$\Phi = \frac{1}{\sqrt{2}}\left(|0,0\rangle + |1,1\rangle\right)$$



pseudo-sifting:

1. Alice announces her x
2. Bob : b ⟶ b+xy

Note:

- all bits are kept
- noisy even without Eve
- 1-way
- I(E,A) > I(E,B)

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From no-signaling to Bell

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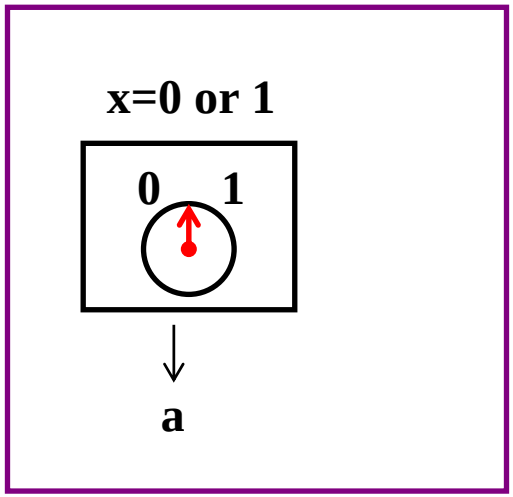
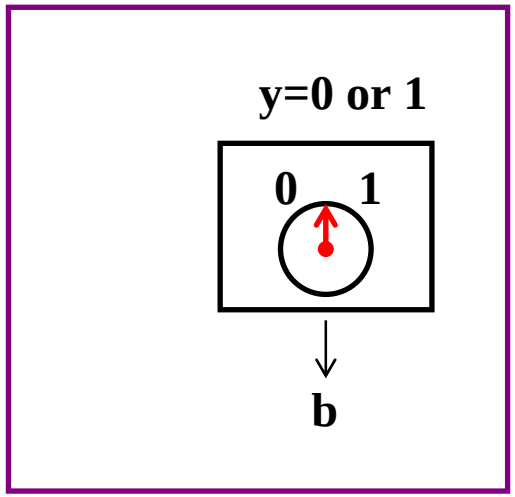
Alice **Bob**

a,b,x,y ∈ {0,1}





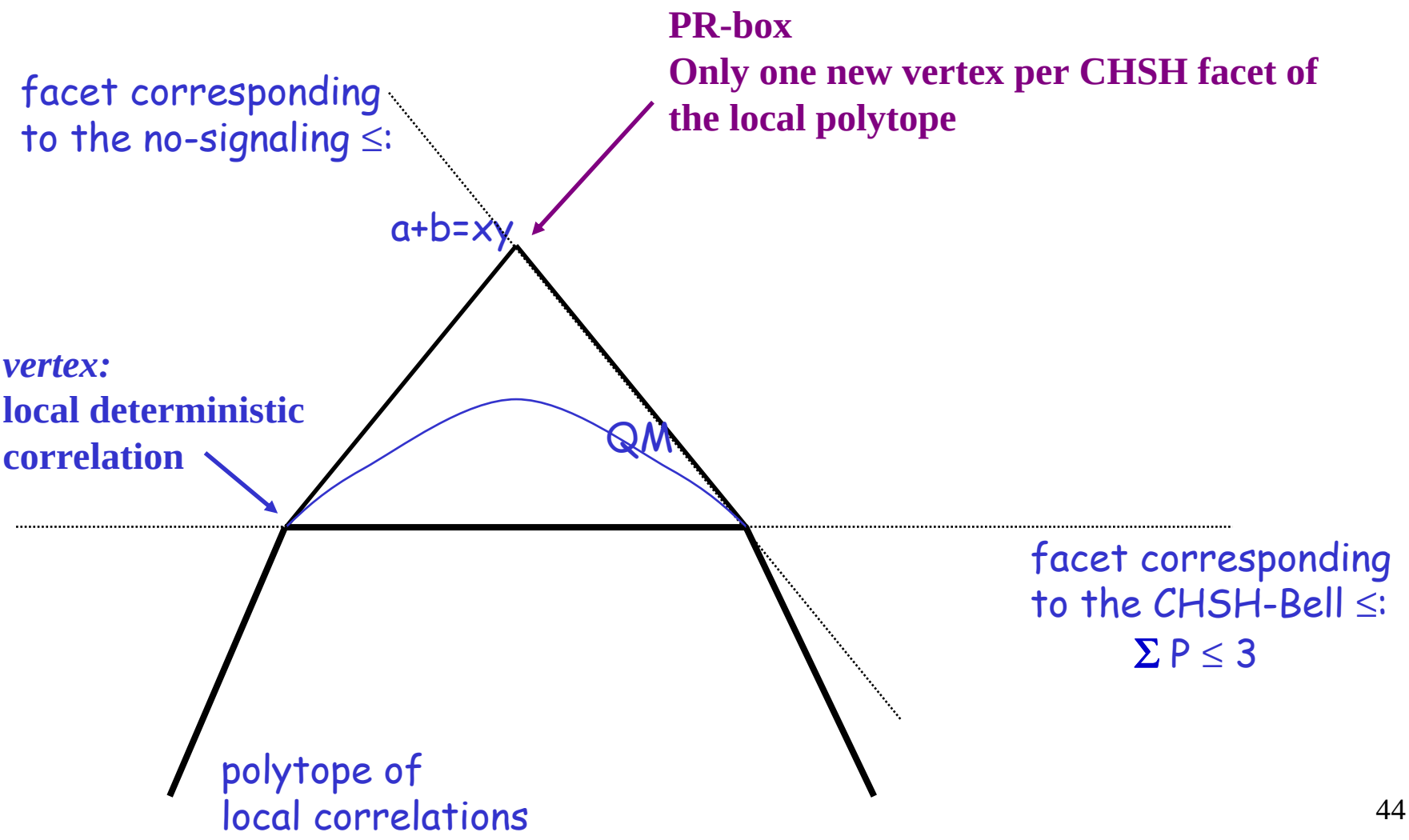
p(a,b|x,y) admits a lhv model iff

$$\Sigma_{x,y=0,1}\, p(a+b=xy|x,y) \leq 3$$

In this framework, the independence assumption is not justified by relativistic space-like separation considerations, but by natural assumptions about the privacy of Alice and Bob's offices.

The no-signaling polytope

J.Barrett et al, PRL'05



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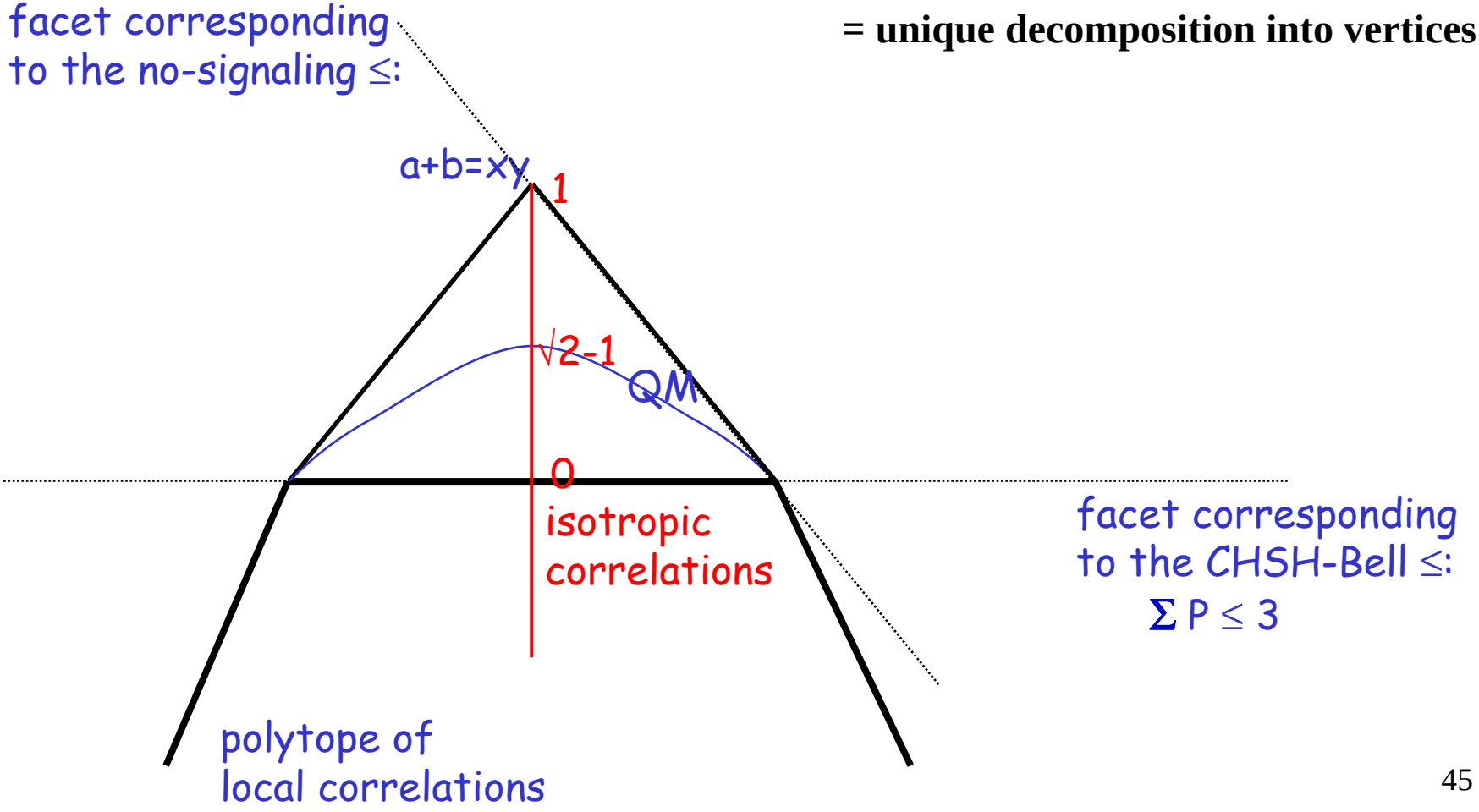
Security against individual attacks from no-signaling

A.Acin, L.Masanes, NG
PRL 97, 120405 (2006)

$$P(a,b,e|x,y,z) = \Sigma_e\, p(e|z)\, p(a,b|x,y,e,z)$$

= unique decomposition into vertices



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Security against individual attacks from no-signaling

A.Acin, L.Masanes, NG
PRL 97, 120405 (2006)

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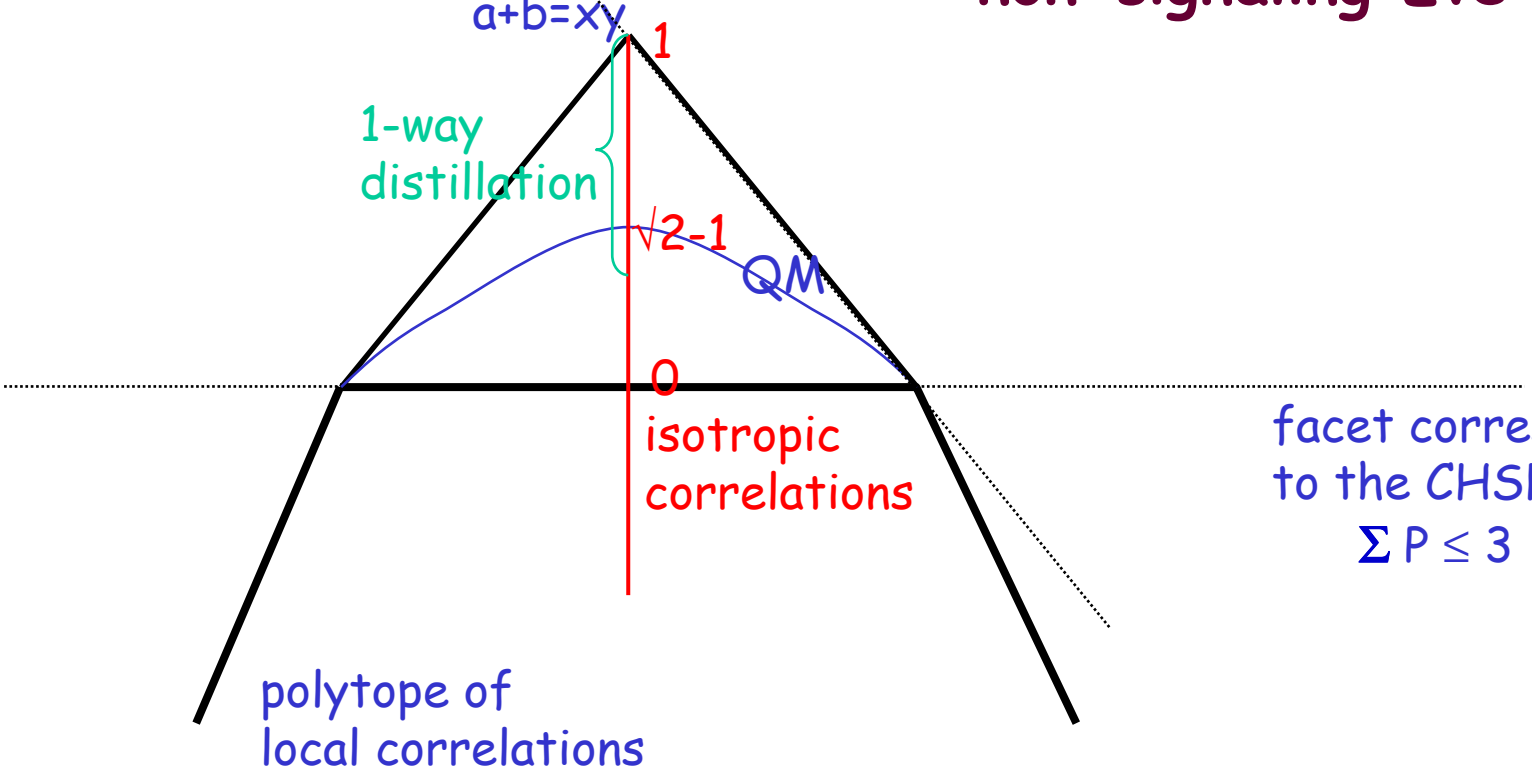
facet corresponding to the no-signaling ≤:

$\Rightarrow$ **secure QKD against individual attacks by any post-quantum non-signaling Eve !**

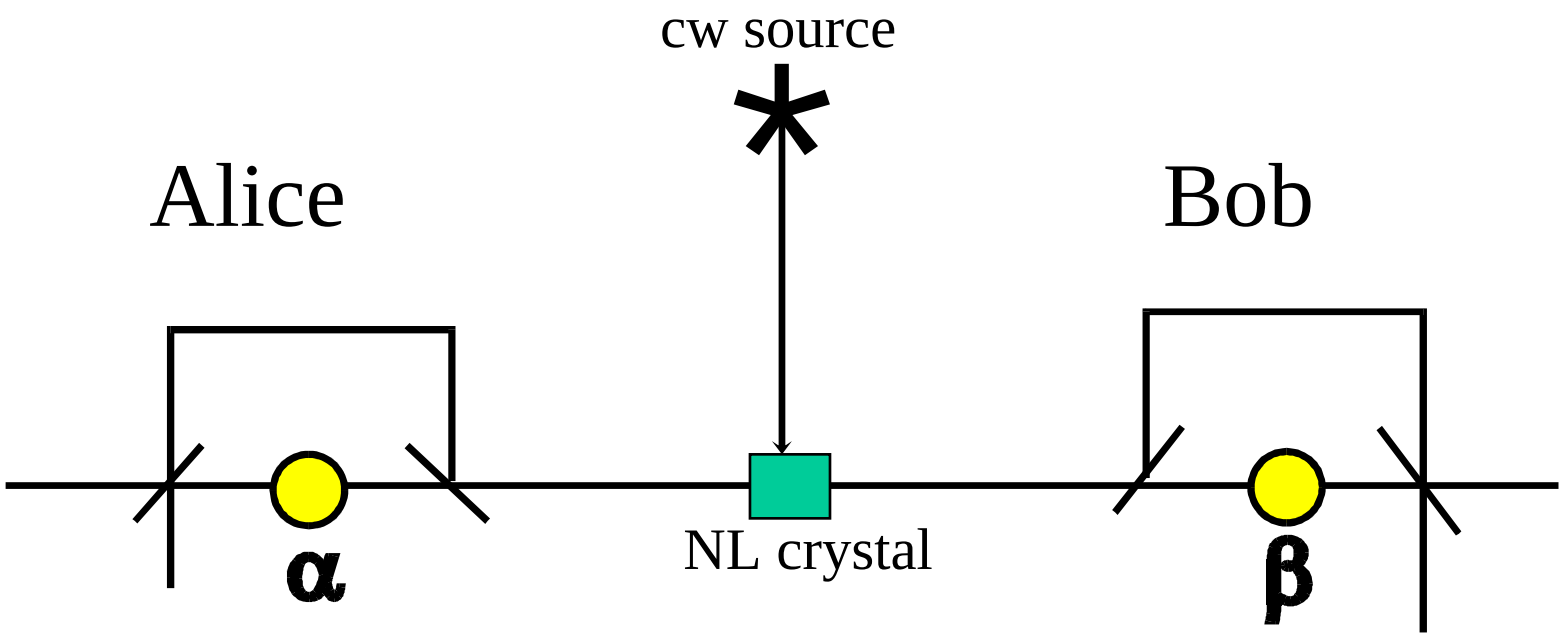


facet corresponding to the CHSH-Bell ≤:

$\Sigma P \leq 3$

Experimental QKD with entanglement

let's simplify QKD as much as possible without comprising security



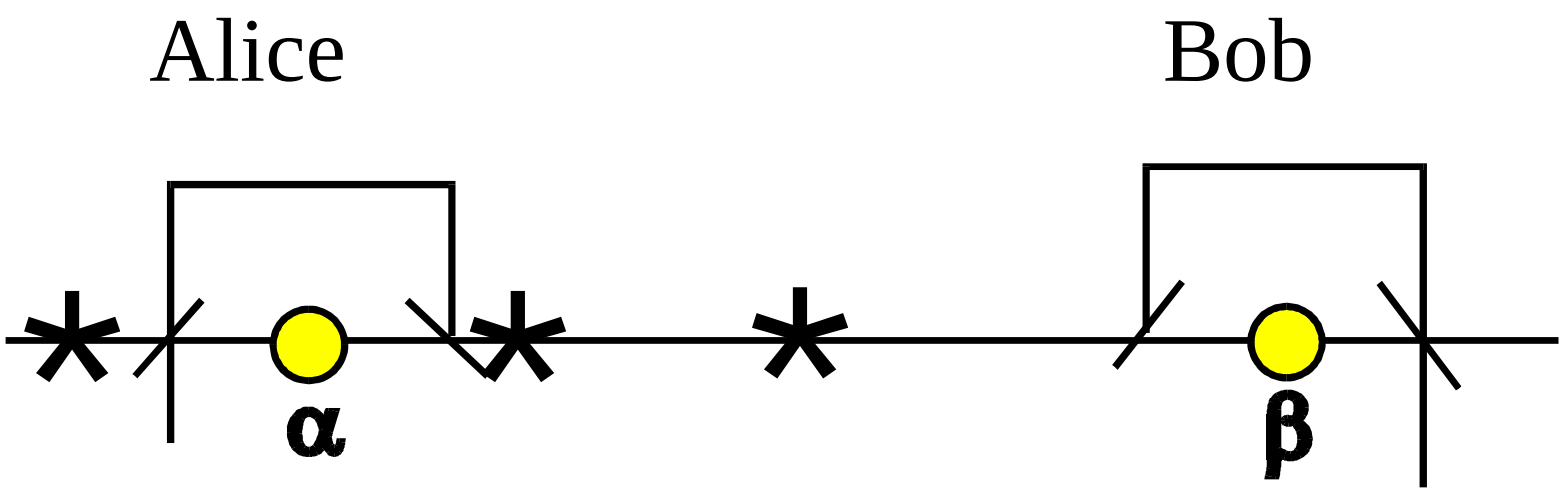
J. Franson, PRL 62, 2205, 1989

W. Tittel et al., PRL 81, 3563-3566, 1998

N. Gisin & N. Brunner, quant-ph//0312011

QKD

weak laser pulse QKD guarantees the same level of security as single photons !



$$U \otimes 1 \left| 00+11 \right\rangle = 1 \otimes U^{*} \left| 00+11 \right\rangle$$

G. Ribordy et al., Phys. Rev. A 63, 012309, 2001

S. Fasel et al., European Physical Journal D, 30, 143-148, 2004

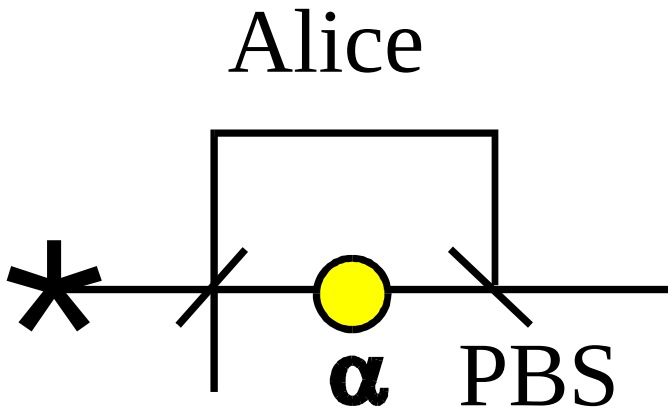
P.D. Townsend et al., Electr. Lett. 30, 809, 1994

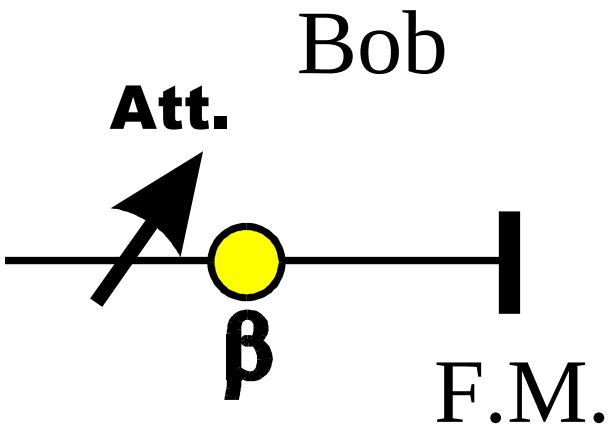
R. Hughes et al., J. Modern Opt. 47, 533-547 , 2000

A. Shields et al., Optics Express 13, 660, 2005

N. Gisin & N. Brunner, quant-ph//0312011

Quantum cryptography below lake Geneva





Applied Phys. Lett. 70, 793-795, 1997.
Electron. Letters 33, 586-588, 1997; 34, 2116-2117, 1998.
J. Modern optics 48, 2009-2021, 2001.

N. Gisin & N. Brunner, quant-ph//0312011

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QKD over 67 km, QBER ≈ 5%

RMP 74, 145-195, 2002,
Quant-ph/0101098

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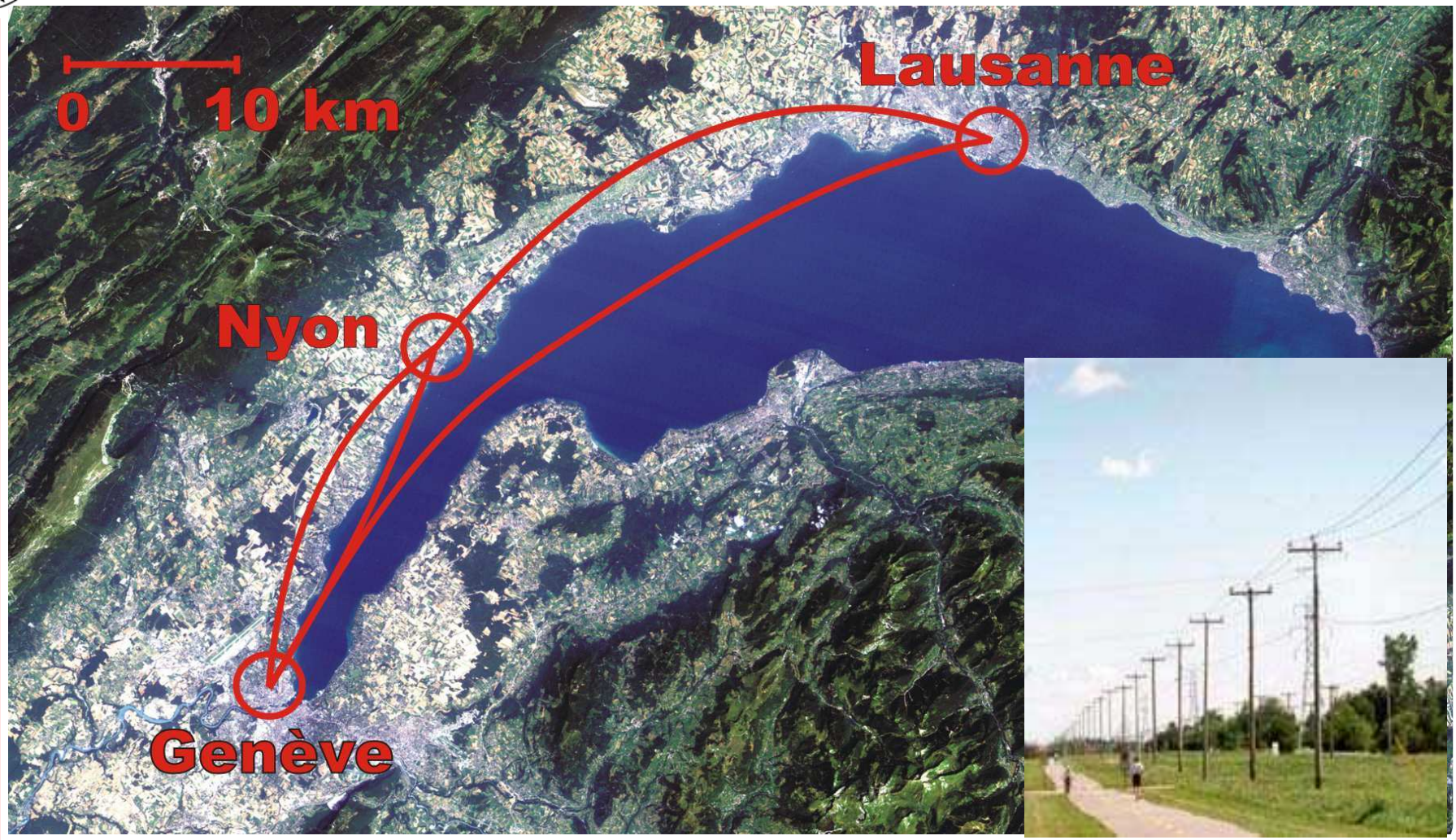

D. Stucki et al., New Journal of Physics 4, 41.1-41.8, 2002. Quant-ph/0203118

+ aerial cable (in Ste Croix, Jura) !

Vectis Link Encryptor

QKD: 5 MHz
encryption: 1 GHz

- Main features
  - Layer 2, Ethernet Encryption (IEEE802.3)
  - Networking protocole independe
  - Low latency
  - Remote monitoring (SNMP)
  - Automated key management
  - Dedicated pair of optical fibers (« dark fiber »)
  - Distance < 100 km

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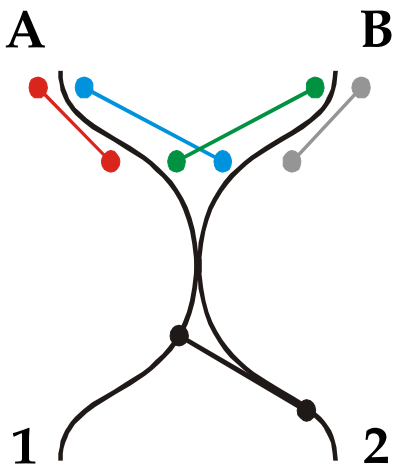
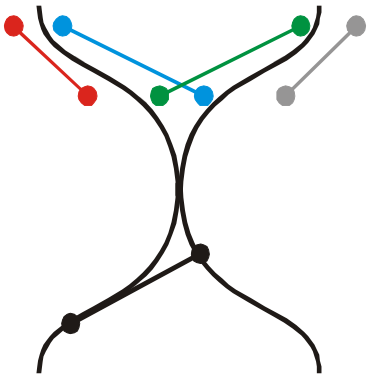
Conclusions

- Q communication is a mature topic. Lots of progress have been achieved, but many important and fascinating questions are still open.
- Quantum correlations are very peculiar. They combine nonlocal correlations with non-trivial marginals in a way that is difficult to reproduce.
- Quantum cryptography offers absolute security (even against the quantum computer that would beat today's public key crypto-systems).
- Quantum cryptography exists: you may buy it !
- Quantum communication in general (including cryptography and teleportation) is an ideal tool for the education of physicists and telecom engineers: it combines Q physics, information theory and fiber optic technologies.

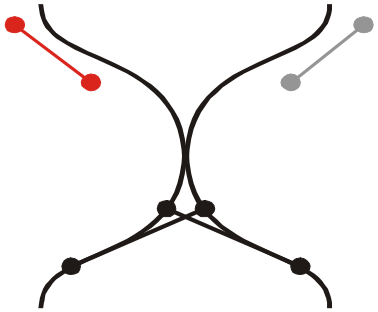
Bell state measurement

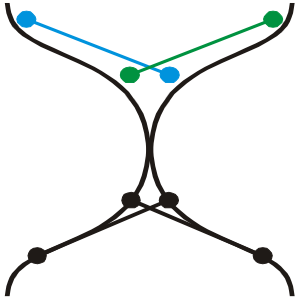




$$|0\rangle_1|1\rangle_2 \mapsto i|0\rangle_A|1\rangle_A + i|0\rangle_B|1\rangle_B + |0\rangle_A|1\rangle_B - |1\rangle_A|0\rangle_B$$

$$|1\rangle_1|0\rangle_2 \mapsto i|0\rangle_A|1\rangle_A + i|0\rangle_B|1\rangle_B - |0\rangle_A|1\rangle_B + |1\rangle_A|0\rangle_B$$





$$|0\rangle_1|1\rangle_2 + |1\rangle_1|0\rangle_2 \mapsto i(|0\rangle_A|1\rangle_A + |0\rangle_B|1\rangle_B)$$

$$|0\rangle_1|1\rangle_2 - |1\rangle_1|0\rangle_2 \mapsto |0\rangle_A|1\rangle_B - |1\rangle_A|0\rangle_B$$

H. Weinfurter, Europhysics Letters 25, 559-564 (1994)
H. de Riedmatten *et al.*, *Phys. Rev. A* 67, 022301 (2003)

Experimental Setup

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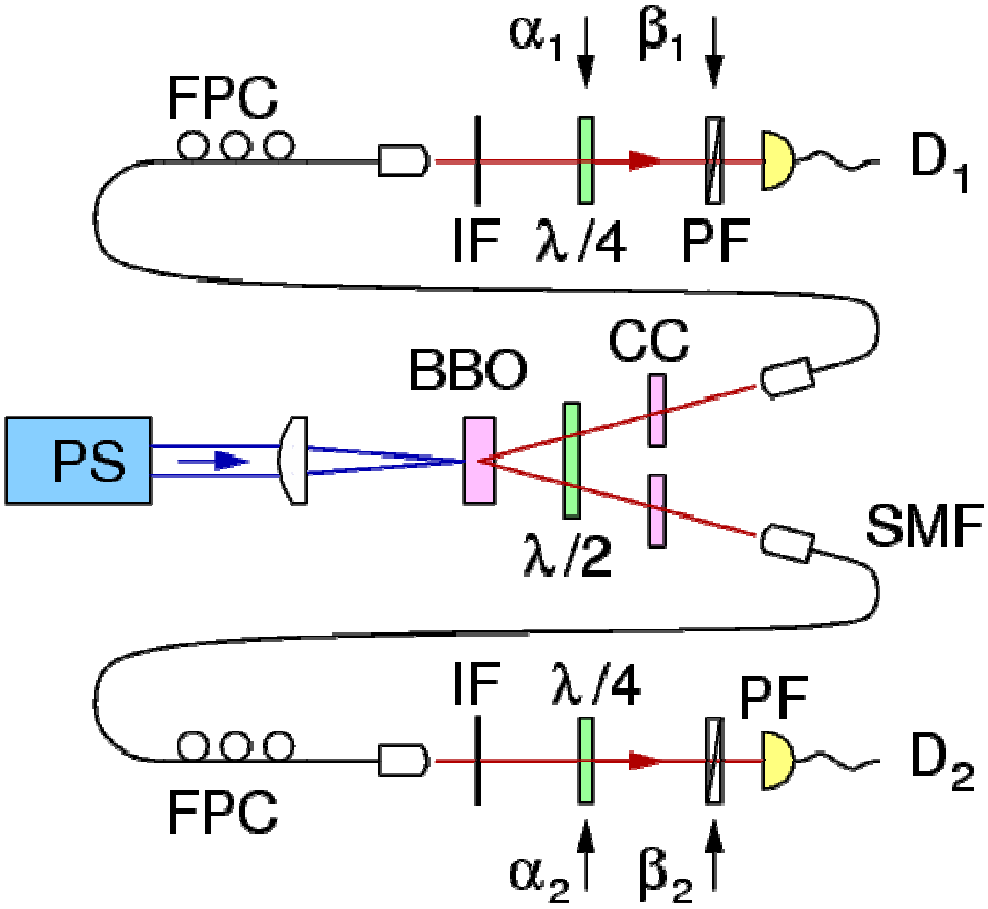
Traditional Type-II parametric down conversion source:



- photon pairs @702nm
- HV: vis= 98.9±0.8%
- ±45°: vis=97.8±0.8%
- max. coincidence rate: 630 s^{-1}, accidentals: 0.3 s^{-1}

Leggett's inequalities

PRL 99,210406,2007
PRL 99,210407,2007
Branciard et al. in preparation

$$P_\lambda(\alpha,\beta|\vec{a},\vec{b}) = \frac{1}{4}\left(1+\alpha\cdot M_\lambda^A(\vec{a})+\beta\cdot M_\lambda^B(\vec{b})+\alpha\beta\cdot C_\lambda(\vec{a},\vec{b})\right)\geq 0$$

$$\Leftrightarrow \quad -1+\left|M_\lambda^A+M_\lambda^B\right| \leq C_\lambda \leq 1-\left|M_\lambda^A-M_\lambda^B\right|$$

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Leggett's inequalities

PRL 99,210406,2007
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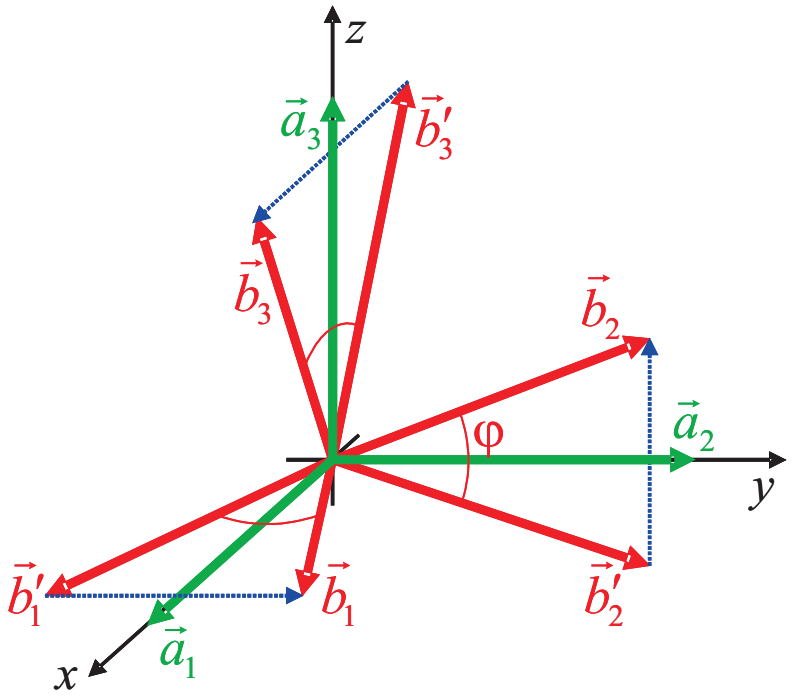

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Leggett's inequalities

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$$P_\lambda(\alpha,\beta|\vec{a},\vec{b}) = \frac{1}{4}\left(1+\alpha\cdot M_\lambda^A(\vec{a})+\beta\cdot M_\lambda^B(\vec{b})+\alpha\beta\cdot C_\lambda(\vec{a},\vec{b})\right)\geq 0$$

$$\Leftrightarrow \quad -1+\left|M_\lambda^A+M_\lambda^B\right| \leq C_\lambda \leq 1-\left|M_\lambda^A-M_\lambda^B\right|$$

$$\Rightarrow \quad \frac{1}{3}\sum_{j=1..3}\left|C(\vec{a}_j,\vec{b}_j)+C(\vec{a}_j,\vec{b}_j')\right| \leq 2-\int d\lambda\,\frac{1}{3}\sum_{j=1..3}\left|\vec{v}(\vec{b}_j-\vec{b}_j')\right|$$

$$= \sum_{j=1..3}|v_j| \geq 1$$

$$\Rightarrow \quad \frac{1}{3}\sum_{j=1..3}\left|C(\vec{a}_j,\vec{b}_j)+C(\vec{a}_j,\vec{b}_j')\right| \leq 2-\frac{2}{3}\left|\sin\frac{\varphi}{2}\right| \approx 2-\frac{\varphi}{3}$$

$$\overset{QM}{=} 2\left|\cos\frac{\varphi}{2}\right| \approx 2-\frac{\varphi^2}{4}$$