Recherche sur la transition du monde quantique au monde classique à travers un processus d'amplification

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Outlines

- **Introduction**

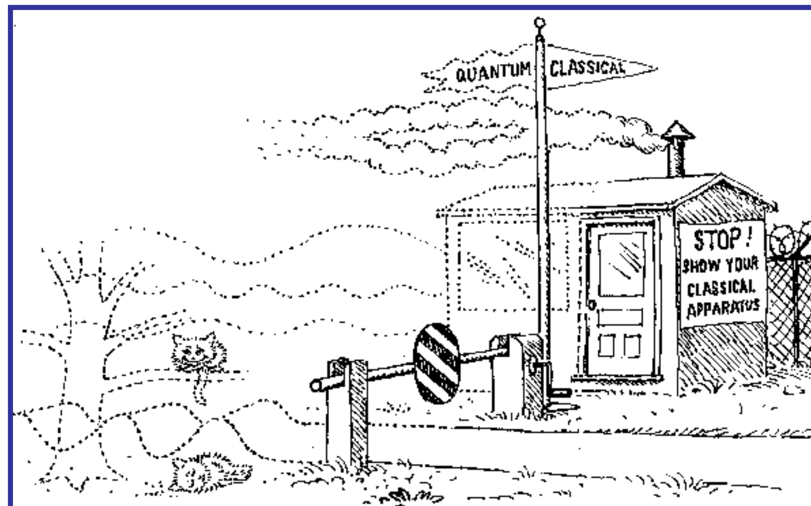
  Investigation of quantum phenomena with systems generated in the microscopic world and then transferred in the macro one through an amplification process.

I) Generation of photonic entangled states: observation of large number entanglement via spontaneous parametric down-conversion

II) Increasing the "size" of quantum state:
-a) Optimal quantum cloning via optical parametric amplification

-b) Amplification of entangled states: Micro-macro light entanglement

-c) Reflection from mirror BEC: Toward light-matter entangled state



Zurek, Physics Today 1995

Quantum Information

Theory of Information

+

Quantum Mechanics → **Quantum Information**

Quantum bit (qubit): quantum state in H_2 $|\varphi\rangle = \alpha|0\rangle + \beta|1\rangle$

Challenges: from basic sciences to emerging quantum technologies

(1) Fundamental physics:

Shed light on the boundary between classical and quantum world

Exploiting quantum parallelism to simulate quantum random many-body systems

(1) New cryptographic protocols, quantum imaging, quantum sensing

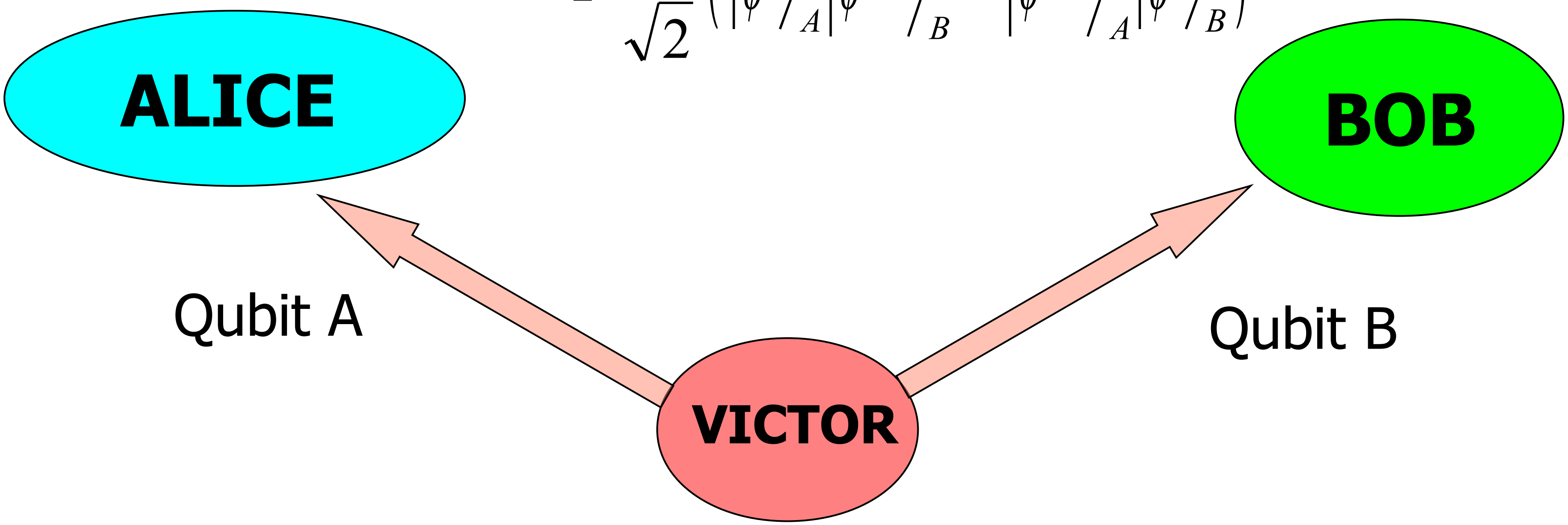
(2) Large-scale Quantum Computing ?

superposition principle
many systems → **Entanglement:**
"the" characteristic trait
of Quantum Mechanics
E. Schrödinger

Entanglement and non locality

$$\left|\Psi^{-}\right\rangle_{AB} = \frac{1}{\sqrt{2}}\left(\left|0\right\rangle_{A}\left|1\right\rangle_{B} - \left|1\right\rangle_{A}\left|0\right\rangle_{B}\right)$$

$$= \frac{1}{\sqrt{2}}\left(\left|\phi\right\rangle_{A}\left|\phi^{\perp}\right\rangle_{B} - \left|\phi^{\perp}\right\rangle_{A}\left|\phi\right\rangle_{B}\right)$$



Einstein: "spooky action at distance"

Local realism → Bell's inequalities
Entanglement violates such inequalities

Quantum optics for quantum information processing

- Qubit state $\alpha|0\rangle + \beta|1\rangle \Longrightarrow \alpha|H\rangle + \beta|V\rangle$

  Polarization of a single photon

  $|0\rangle \Leftrightarrow |H\rangle$ horizontal

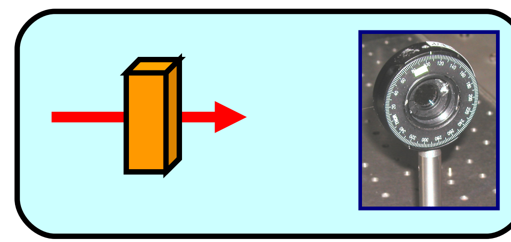
  $|1\rangle \Leftrightarrow |V\rangle$ vertical

  $\lambda = 800nm$

  Mode of the electromagnetic field (k,λ)

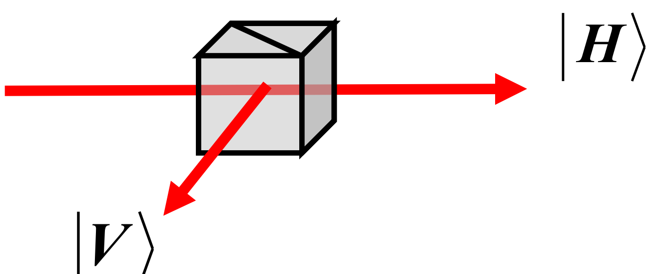
- Trasformation on the qubit

  rotation of the polarization: quartz waveplate

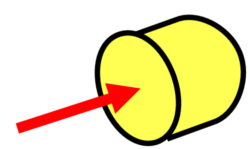


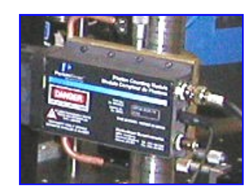
- Projective measurement

  polarizing beam splitter



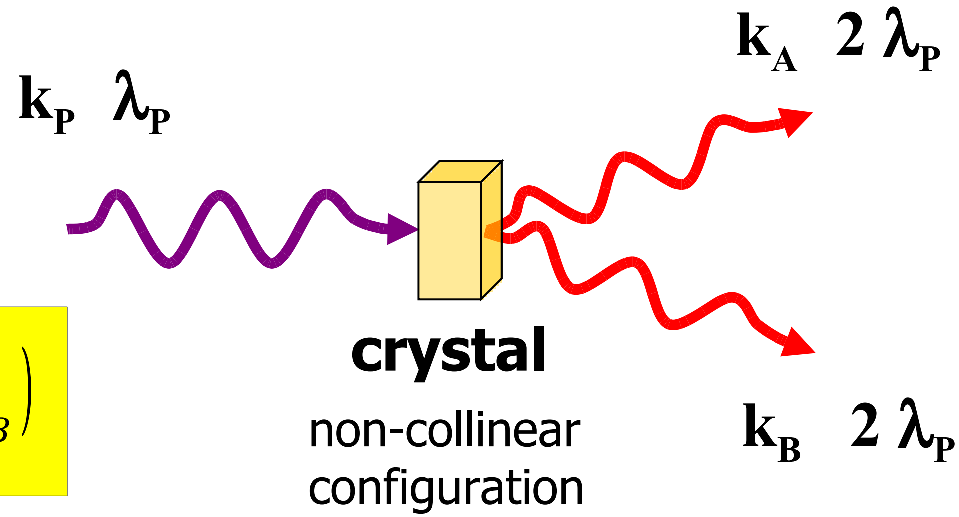
Single photon detectors





Parametric interaction: generation of entangled states

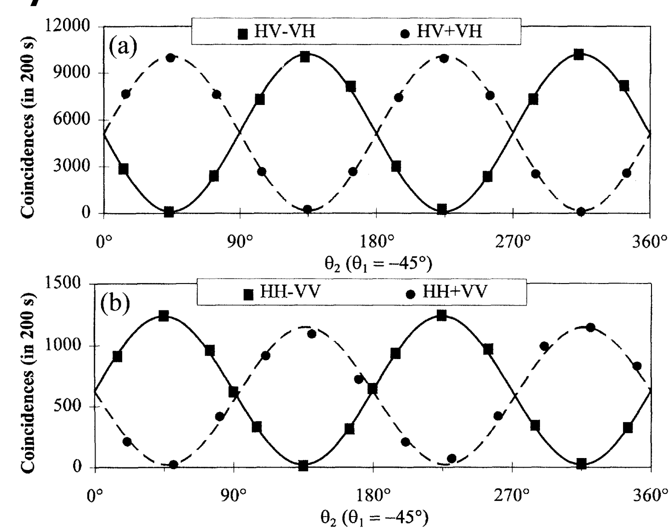
spontaneous parametric
down-conversion
for generation
of entangled states



$$\frac{1}{\sqrt{2}}\left(|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B\right)$$

Parametric interaction:
Non-linear crystal and LASER with frequency

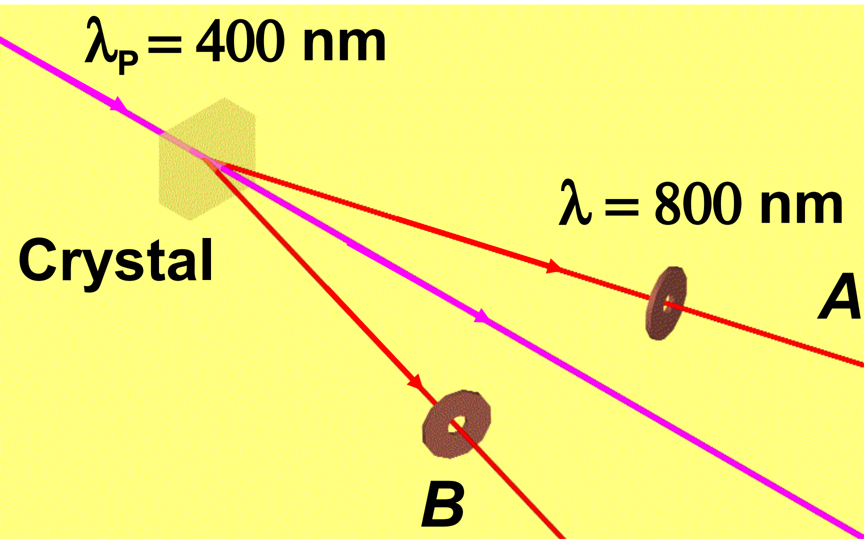
Non-locality tests: violation of
Bell inequalities
Quantum cryptographic applications
Quantum teleportation
Quantum computation



P.G. Kwiat, et al., Phys. Rev. Lett. **75**, 4337 (1995)

Entanglement of a large number of photons via spontaneous parametric down-conversion:

Paradigmatic physical system to investigate the transition from the microscopic to the macroscopic world



Hamiltonian of interaction

$$H_I = i\hbar\chi\left(\hat{a}_V^+\hat{b}_H^+ - \hat{a}_H^+\hat{b}_V^+\right) + h.c.$$

Unitary evolution

$$\hat{U} = \exp\left(-iH_I t/\hbar\right)$$

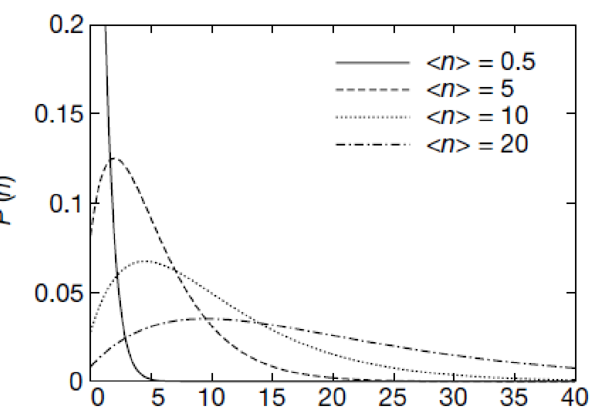
Singlet states superposition

$$\hat{U}|0\rangle_A|0\rangle_B = \frac{1}{\cosh^2(g)}\sum_{n=0}^{\infty}\sqrt{n+1}\tanh^n(g)|\psi_n\rangle$$

$$|\psi_n\rangle = \frac{1}{\sqrt{n+1}}\sum_{m=0}^{n}(-1)^m|(n-m)H, mV\rangle_A|mH,(n-m)V\rangle_B$$

Gain du processus $g = \chi t$

Average photon number per mode $\bar{n} = \sinh^2 g$



Increasing gain implies higher generation probability for terms with higher number of photons

2 photon and 4 photon entanglement

gain parameter $g = \chi t << 1$

g^2 terms neglected (low gain approximation)

Spontaneous emission ⟺ $\hat{U}|0\rangle_A|0\rangle_B \approx |0\rangle_A|0\rangle_B + g\left(|\phi\rangle_A|\phi^\perp\rangle_B - |\phi^\perp\rangle_A|\phi\rangle_B\right)$

n=1 ➡ 1/2 – spin state

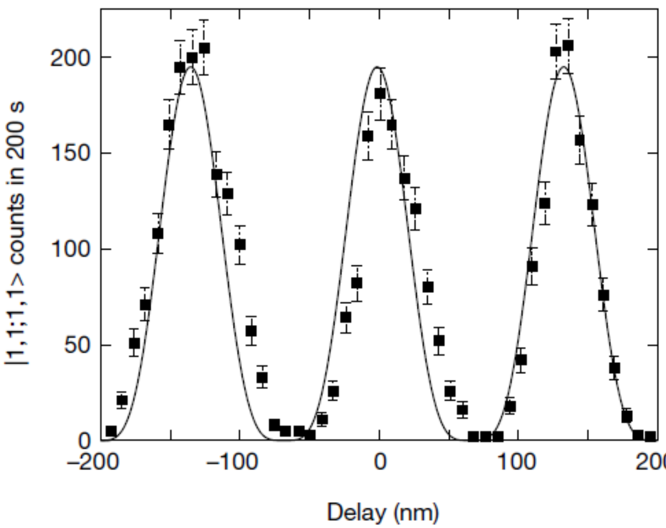
$$|\psi_1\rangle = \frac{1}{\sqrt{2}}\left(|1H\rangle_A|1V\rangle_B - |1V\rangle_A|1H\rangle_B\right)$$

n=2 ➡ 4 photons

➡ 2 systems with spin 1

$$|\psi_2\rangle = \frac{1}{\sqrt{3}}\left(|2H\rangle_A|2V\rangle_B - |1H,1V\rangle_A|1H,1V\rangle_B + |2V\rangle_A|2H\rangle_B\right)$$

- ☺ Quantum metrology applications
- ☺ Higher-bit-rate quantum cryptography

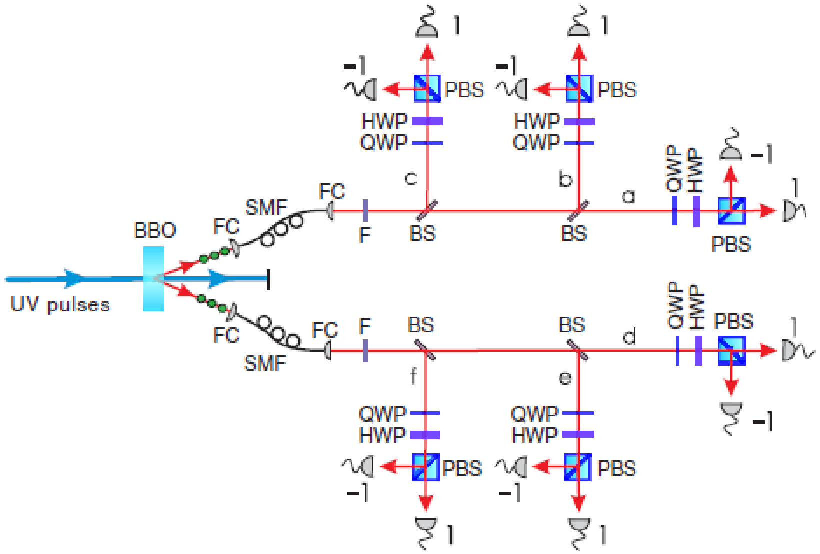


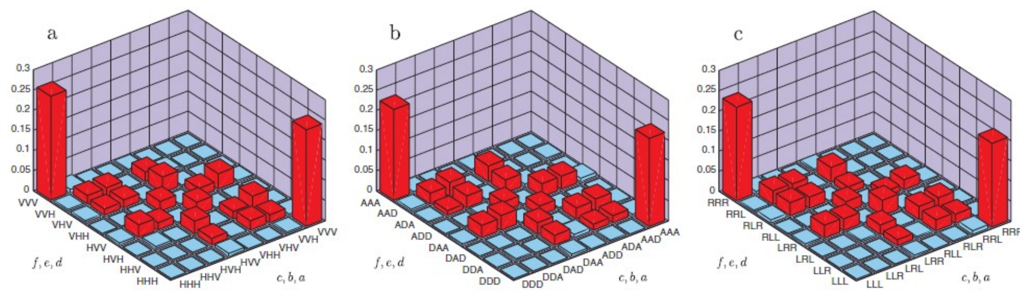
A. Lamas-Linares, et al., Nature **412**, 887 (2001) , M. Bourennane, et al., Phys. Rev. Lett. **92**, 107901 (2005)

6 photon entanglement

n=3 ➡ 6 photons ➡ 2 systems with spin 3/2

$$|\psi_3\rangle = \frac{1}{2}\left(|3H\rangle_A|3V\rangle_B - |2H,1V\rangle_A|1H,2V\rangle_B + |1H,2V\rangle_A|2H,1V\rangle_B - |3V\rangle_A|3H\rangle_B\right)$$





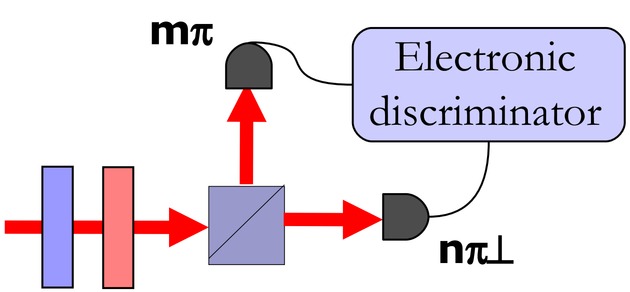
- Secure quantum multiparty cryptographic protocols
- Projective measurements result in various different 4-photon entangled states (GHZ)

M. Radmark, et al., Phys. Rev. Lett. **109**, 150501 (2009).

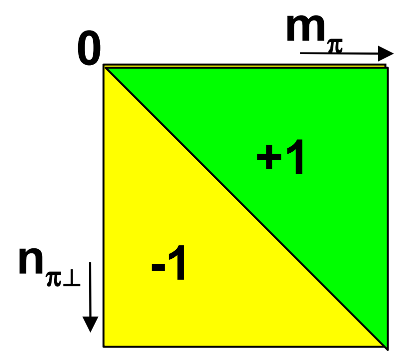
Dichotomic measurements on multiphoton fields

Is it possible to observe quantum correlations by performing dichotomic measurements on a macroscopic state?

DICHOTOMIZATION OF THE MEASUREMENT PROCESS



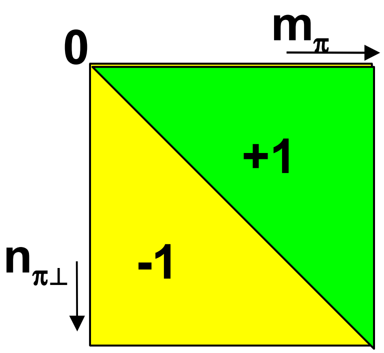
$$m_\pi - n_{\pi\perp} > 0 \rightarrow +1$$
$$n_{\pi\perp} - m_\pi > 0 \rightarrow -1$$

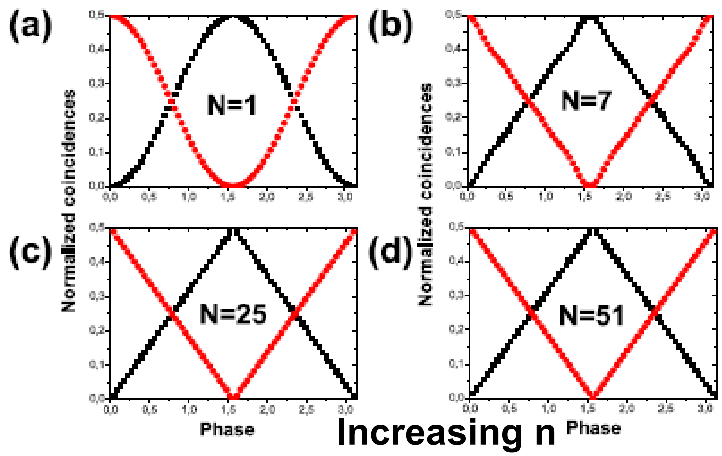


Measurement of the intensity for the two polarization modes ⇨ Signals comparison ⇨ Dichotomic assignement

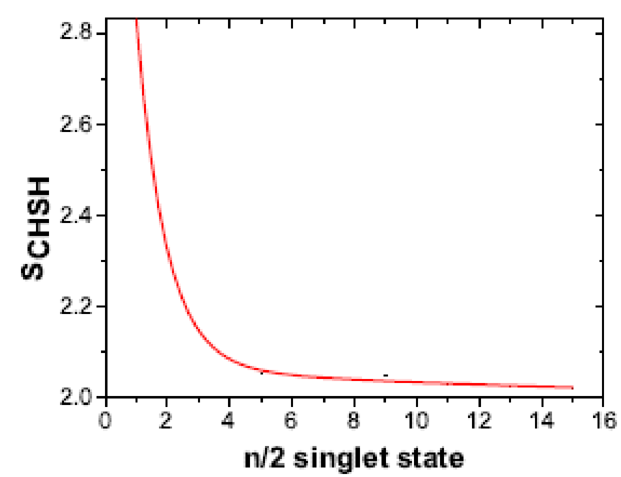
Dichotomic measurements on multiphoton fields

In **theory** a dichotomic measurement applied to a *n/2*–singlet state would asymptotically allow the violation of Bell's inequality even for large *n* :



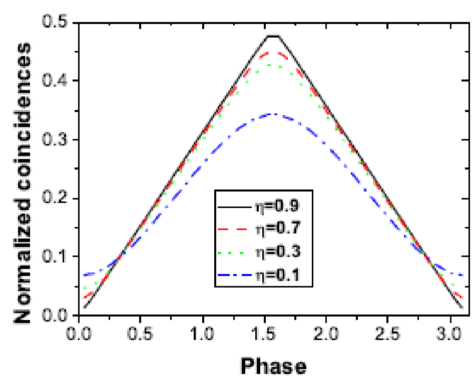


2-photon correlation



Sinusoidal correlation pattern (quantum) → **Linear (classical)**

....And in the real world?
In practice we have the problem of losses.

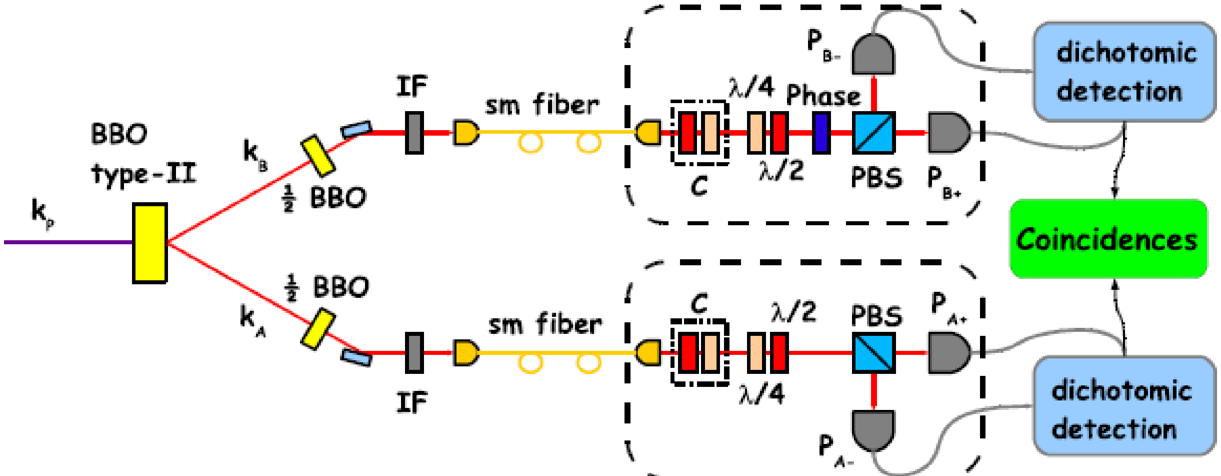


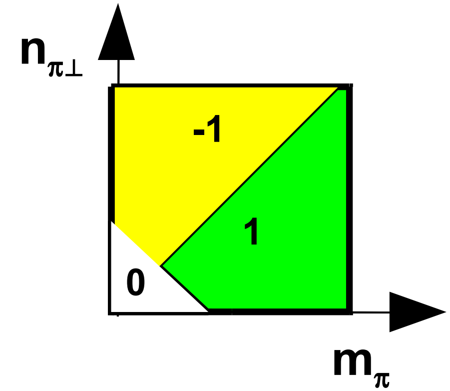
→ Lower visibility

→ Sinusoidal pattern

Generalized measurements on multiphoton fields: experimental results

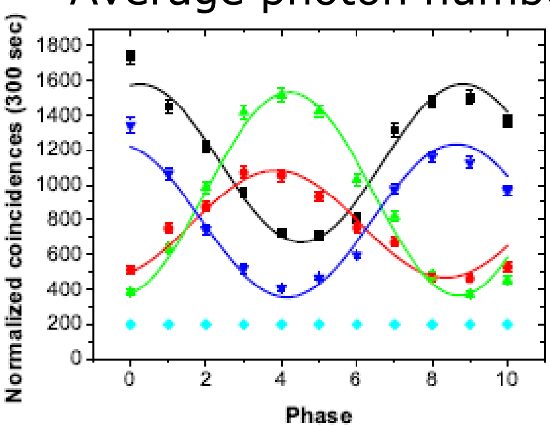
Generalized measurements to beats the losses effects.





NL gain **g=3.5**
mean number **n=270**

Average photon number per mode $\bar{n} = \sinh^2 g$



The visibility obtained by the TD is not enough to violate Bell's inequality tests

Search for entanglement criteria

C. Vitelli, N. Spagnolo, L. Toffoli, F. Sciarrino, and F. De Martini, quant-ph1002.2043

Is it possible to observe quantum phenomena with fuzzy measurement ?

Classical world arising out of quantum physics under the restriction of coarse-grained measurements

Johannes Kofler[1,2] and Časlav Brukner[1,2]
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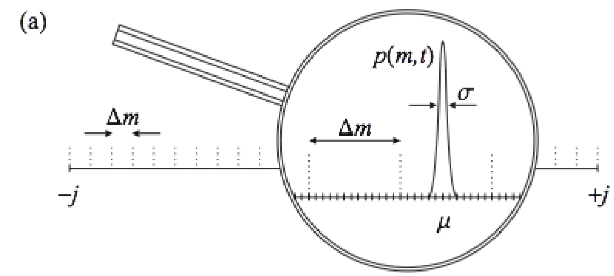
[2]Institut für Quantenoptik und Quanteninformation (IQOQI), Österreichische Akademie der Wissenschaften, Boltzmanngasse 3, 1090 Wien, Austria
(Dated: February 1, 2008)

Conceptually different from the decoherence program, we present a novel theoretical approach to macroscopic realism and classical physics within quantum theory. It focuses on the limits of observability of quantum effects of macroscopic objects, i.e., on the required precision of our measurement apparatuses such that quantum phenomena can still be observed. First, we demonstrate that for unrestricted measurement accuracy no classical description is possible for arbitrarily large systems. Then we show for a certain time evolution that under coarse-grained measurements not only macrorealism but even the classical Newtonian laws emerge out of the Schrödinger equation and the projection postulate.



However there are some theoretical counterexamples..

The conditions for quantum violation of macroscopic realism

Johannes Kofler[1,2] and Časlav Brukner[1,2]

Failure of Local Realism Revealed by Extremely Coarse-Grained Measurements

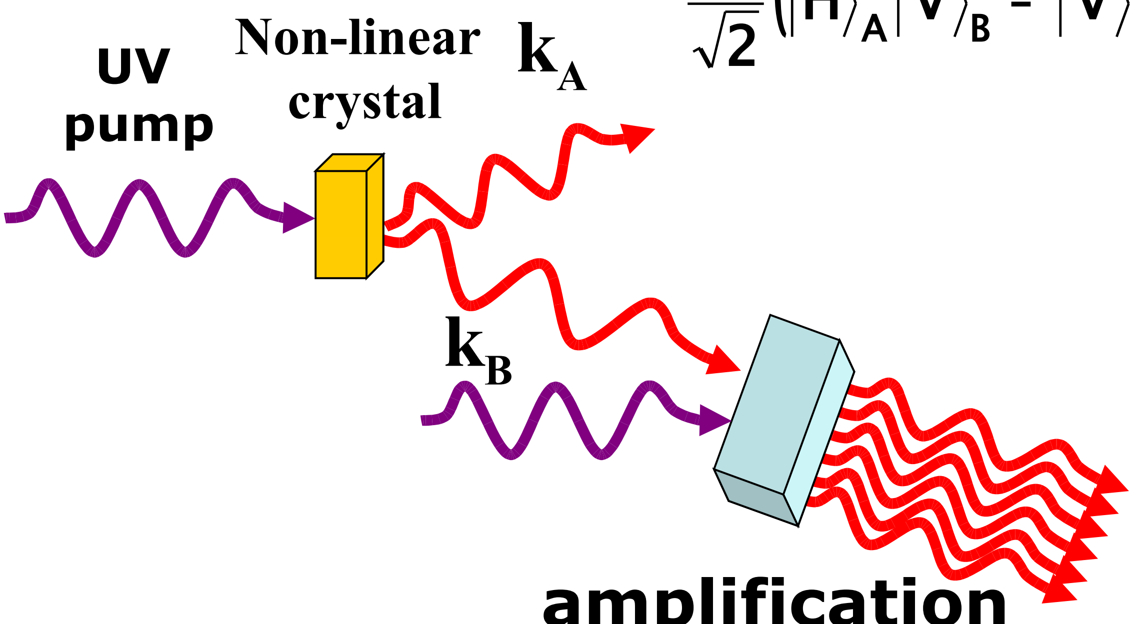
Hyunseok Jeong,[1,2] Mauro Paternostro,[3] and Timothy C. Ralph[1]
[1]Centre for Quantum Computer Technology, Department of Physics, University of Queensland, St Lucia, Qld 4072, Australia
[2]Center for Subwavelength Optics and Department of Physics and Astronomy, Seoul National University, Seoul, 151-742, Korea
[3]School of Mathematics and Physics, The Queen's University, Belfast, BT7 1NN, UK
(Dated: January 23, 2010)

J. Kofler, C. Brukner, Phys. Rev. Lett. **99**, 180403 (2007)
J. Kofler and C. Brukner, Phys. Rev. Lett. **101**, 090403 (2008).
H. Jeong, M. Paternostro, and T. Ralph, Phys. Rev. Lett. **102**, 060403 (2009).

From the microscopic to the mesoscopic-macroscopic world

Entanglement: “the characteristic trait of Quantum Mechanics” (Schrödinger)

$$\frac{1}{\sqrt{2}}\left(|H\rangle_A |V\rangle_B - |V\rangle_A |H\rangle_B\right)$$



Macroscopic Amplificator

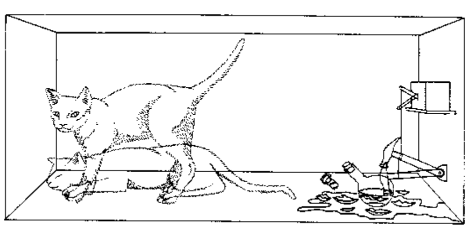
Injection:

Quantum state

(single photon state)

- Multiphoton entanglement: new perspectives in quantum information

-“Schroedinger apologue”: Entanglement between a single photon and a “cat” state



$$|\Sigma\rangle = \frac{1}{\sqrt{2}}\Big(|H\rangle|$$  $$\rangle + |V\rangle|$$  $$\rangle\Big)$$

Quantum cloning ?

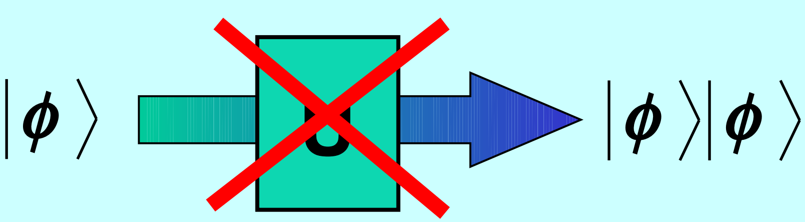
Ideal **Q**uantum **C**loning **M**achine

- Perfect copies of the input state
- Universal: all the state can be cloned

Is it allowed by Quantum Mechanics?

No cloning theorem

“Unknown quantum states cannot be cloned”



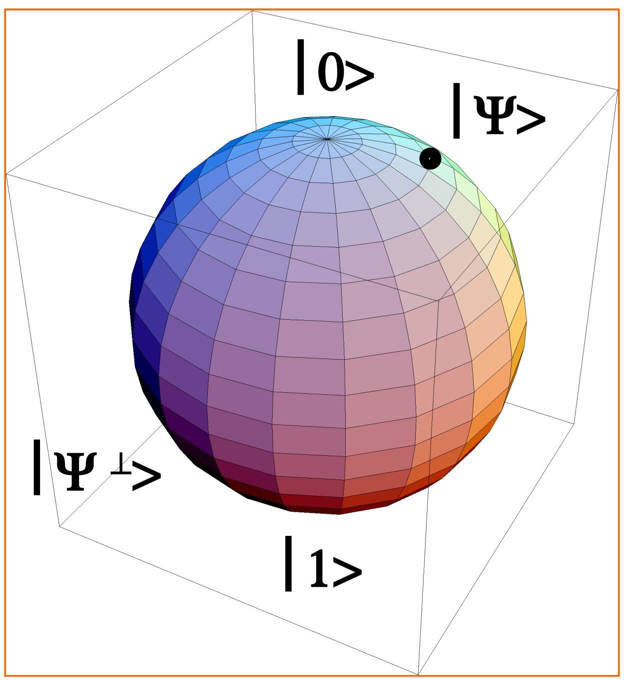
Wootters, Zurek, *Nature* ***299***, 802 (1982)

NOT gate of an unknown qubit

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle \longrightarrow \textbf{NOT GATE} \longrightarrow |\Psi^{\perp}\rangle = \beta^{*}|0\rangle - \alpha^{*}|1\rangle$$

Inversion of the Bloch sphere: Flipping of a qubit on the symmetric point of the Bloch sphere

NOT GATE ANTI-UNITARY not physically realizable with Fidelity = 1



TRANSPOSE

$$\begin{pmatrix} |\alpha|^2 & \alpha\beta^{*} \\ \alpha^{*}\beta & |\beta|^2 \end{pmatrix} \Rightarrow \begin{pmatrix} |\alpha|^2 & \alpha^{*}\beta \\ \alpha\beta^{*} & |\beta|^2 \end{pmatrix}$$

Important for criteria of separability of bipartite state

$$E_{NOT}(\rho) \xleftarrow{\sigma_Y} \rightarrow E_{PT}(\rho)$$

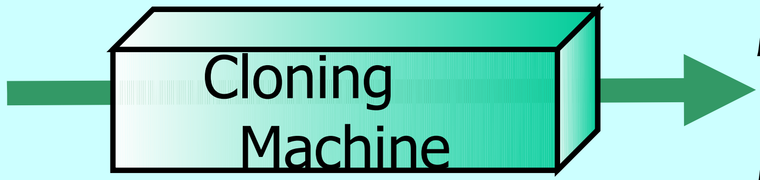
Optimal Quantum Machines

No cloning theorem: "It is not possible to clone an arbitrary unknown quantum state"
No quantum NOT gate: "A universal NOT gate cannot be realized"

What the best physical approximations of the these two machines ?
Fidelity F: $0 \leq F \leq 1$, $F = 1$ perfect realization, forbidden by quantum mechanics

Optimal Universal Quantum Cloning 1→ 2

$|\phi\rangle$



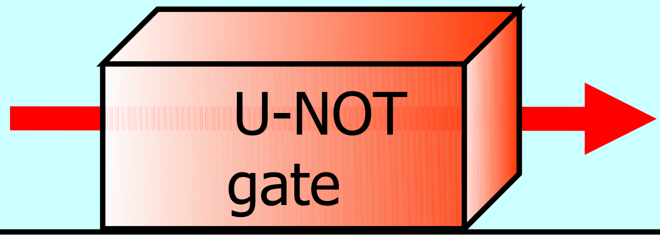
ρ_{out}

ρ_{out}

$$F = \int_{|\phi\rangle \in H} \langle \phi | \rho_{out} | \phi \rangle d\phi$$

Optimal Universal NOT gate 1→1

$|\phi\rangle$



$\tilde{\rho}_{out}$

$$F = \int_{|\phi\rangle \in H} \langle \phi^{\perp} | \tilde{\rho}_{out} | \phi^{\perp} \rangle d\phi$$

Quantum cloning by stimulated emission

Input qubit: polarization state of a single photon

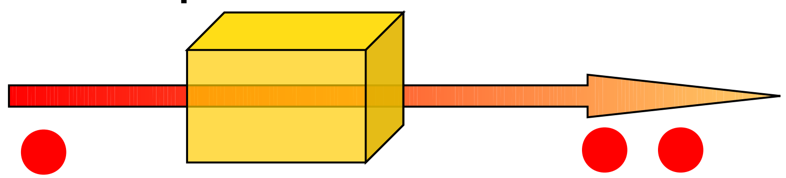
$$|\phi_{IN}\rangle = \alpha|0\rangle + \beta|1\rangle \quad \Leftrightarrow \quad |\phi_{IN}\rangle = \alpha|H\rangle + \beta|V\rangle$$

Implementation based on the stimulated emission process

I) Medium with inverted population: same gain for all the polarizations

II) Optical parametric amplification

Injected photon



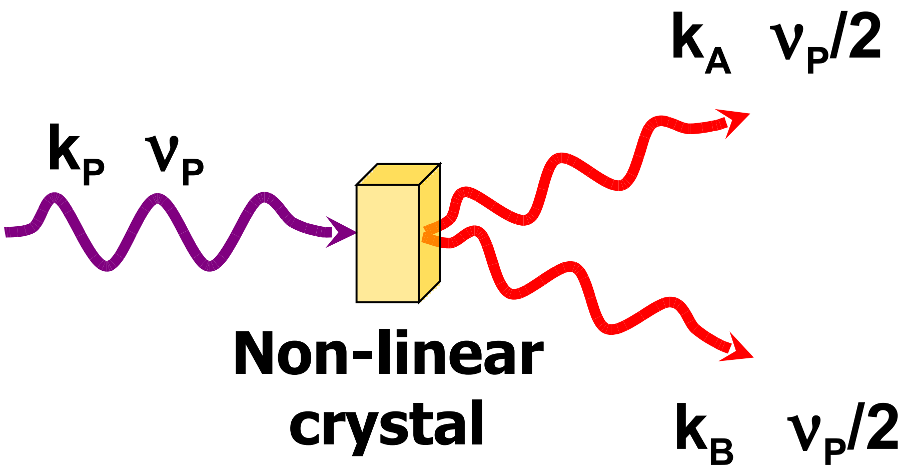
Amplifier

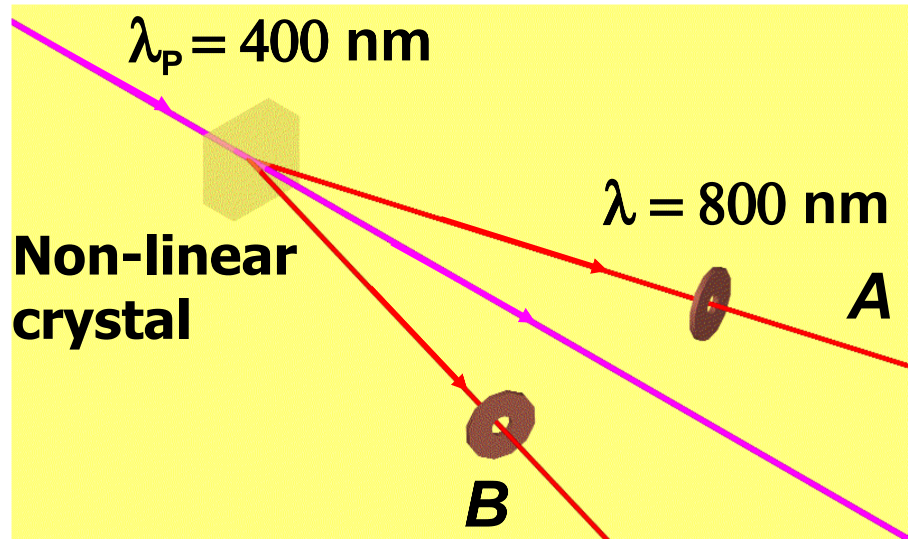
Universality of the cloning
Universality of
the amplification

Spontaneous emission for all the states
Noise → F<1

C. Simon, G .Weihs, and A. Zeilinger, Phys. Rev. Lett. **84**, 2993 (2000)

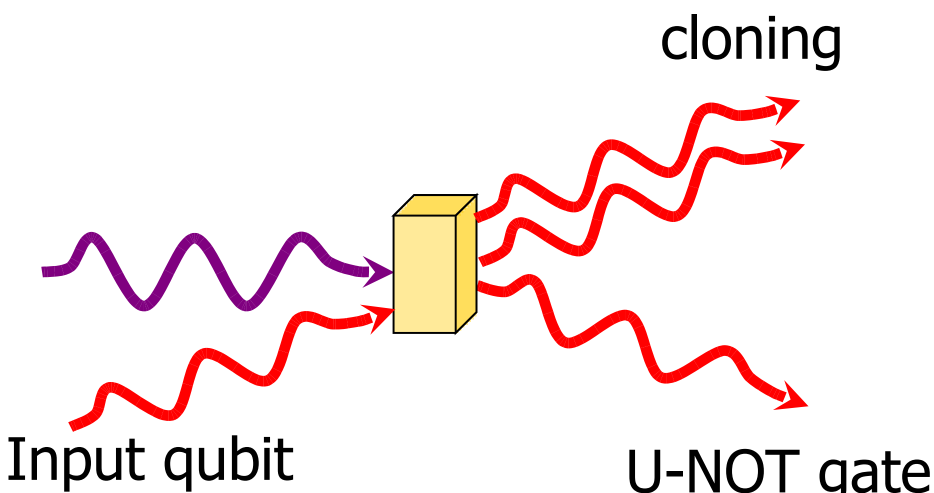
Parametric interaction: generation of entangled states

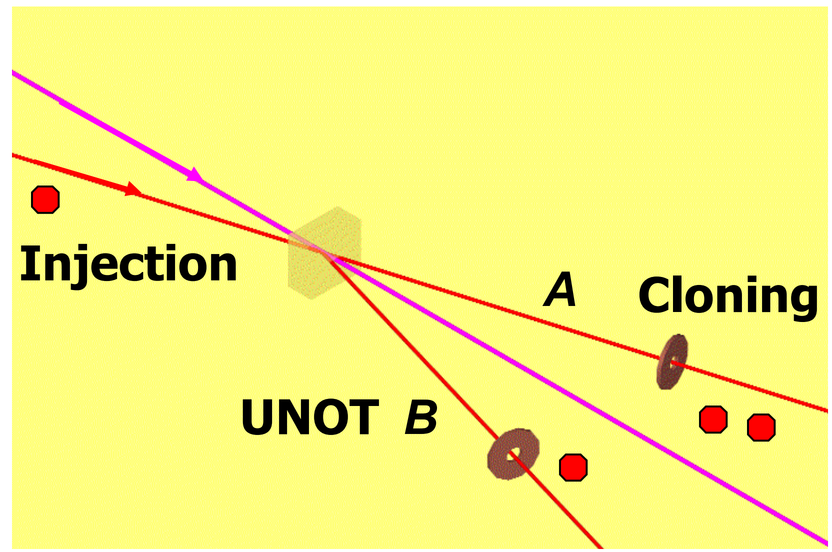




Spontaneous emission ⟺ $\hat{U}|0\rangle_A|0\rangle_B \propto \left(|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B\right)$

Quantum Injected Optical Parametric Amplifier





$$|\phi\rangle_A = \alpha|H\rangle_A + \beta|V\rangle_A$$

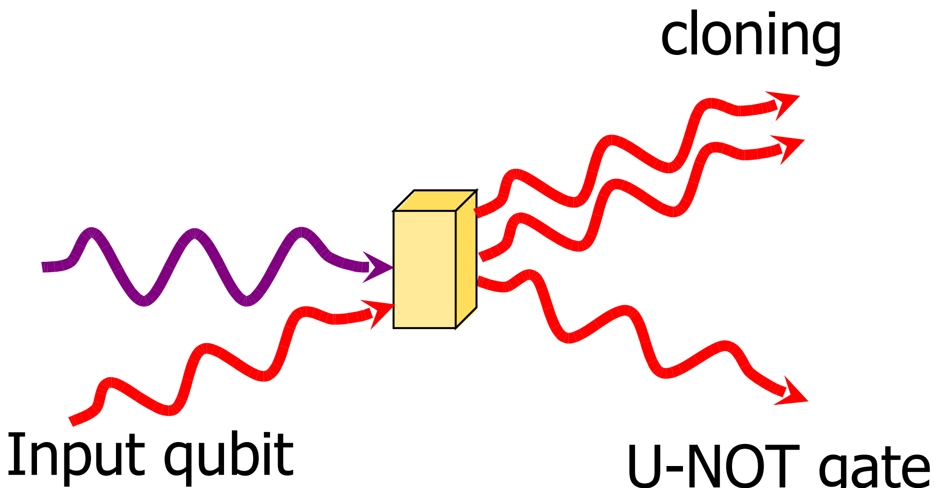
Stimulated emission $\Longleftrightarrow$ $\hat{U}|\phi\rangle_A|0\rangle_B \propto \left(2^{1/2}|\phi\,\phi\rangle_A|\phi^{\perp}\rangle_B - |\phi\,\phi^{\perp}\rangle_A|\phi\rangle_B\right)$

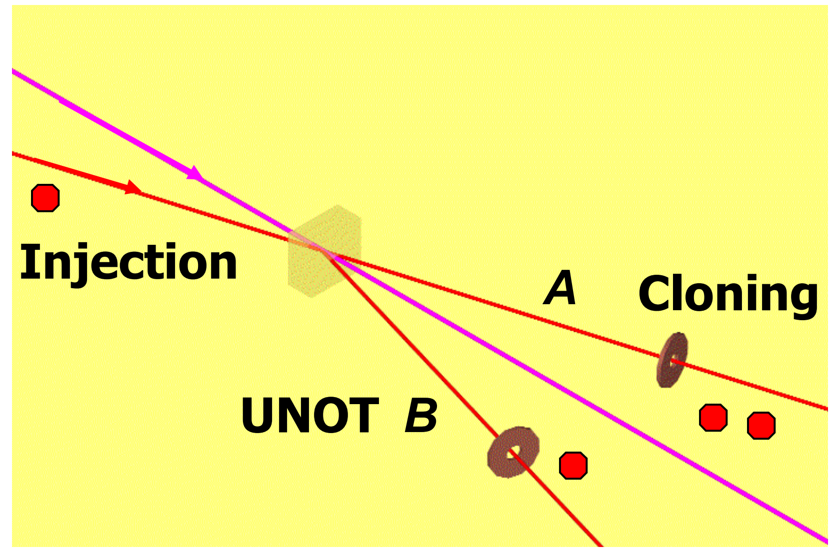
Mode A: Universal cloning process

Mode B: UNOT gate

De Martini, et al., *Nature* **419**, 815 (2002); Lamas-Linares, et al., *Science* **296**, 712 (2002)
De Martini, Pelliccia, Sciarrino, *Phys. Rev. Lett.* **92**, 067901(2004)

Quantum Injected Optical Parametric Amplifier





$$|\phi_{IN}\rangle_A = \alpha|H\rangle_A + \beta|V\rangle_A$$

Stimulated emission $\Longleftrightarrow$ $\hat{U}|\phi\rangle_A|0\rangle_B \propto \left(2^{1/2}|\phi\ \phi\rangle_A|\phi^\perp\rangle_B - |\phi\ \phi^\perp\rangle_A|\phi\rangle_B\right)$

$H_I = i\hbar\chi\left(a_V^+ b_H^+ - a_H^+ b_V^+\right) + h.c.$ classical and undepleted pump $\chi \propto E_P$

Universality of the amplifier : the interaction Hamiltonian can be recast in the following way (SU(2) invariance) $H_I = i\hbar\chi\left(\hat{a}_\phi^+ \hat{b}_{\phi\perp}^+ - \hat{a}_{\phi\perp}^+ \hat{b}_\phi^+\right) + h.c.$

Quantum Injected Optical Parametric Amplifier

$$H_I = i\hbar\chi\left(\hat{a}^+_{\phi}\hat{b}^+_{\phi\perp} - \hat{a}^+_{\phi\perp}\hat{b}^+_{\phi}\right) + h.c.$$

$\hat{U} = \exp\left(-iH_I t/\hbar\right)$ gain parameter $g = \chi t << 1$ g^2 terms neglected

Spontaneous parametric down-conversion

$$\hat{U}|0\rangle_A|0\rangle_B \approx |0\rangle_A|0\rangle_B + g\left(|\phi\rangle_A|\phi^\perp\rangle_B - |\phi^\perp\rangle_A|\phi\rangle_B\right)$$

Stimulated emission by injection of the state $|\Psi_{in}\rangle = |\phi\rangle_A|0\rangle_B$

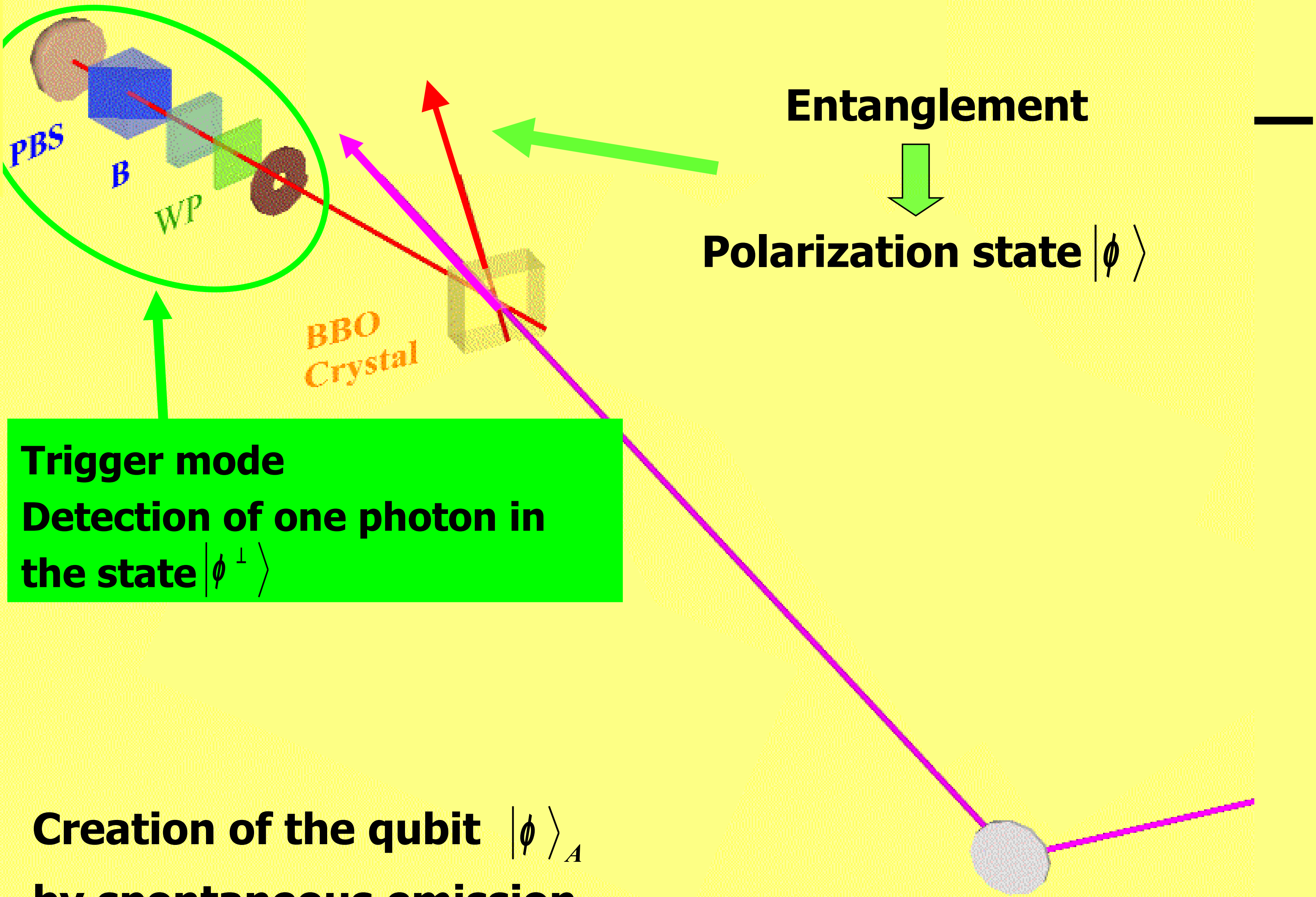
$$\hat{U}|\phi\rangle_A|0\rangle_B \approx |\phi\rangle_A|0\rangle_B + g\,2^{1/2}\left(|\phi\,\phi\rangle_A|\phi^\perp\rangle_B - |\phi\,\phi^\perp\rangle_A|\phi\rangle_B\right)$$

probability of emitting $|\phi\rangle$ **over mode A increased by a factor R=2**

probability of emitting $|\phi^\perp\rangle$ **over mode B increased by a factor R*=2**

A: Cloning mode: 2 photons in the state $\rho_A = \frac{5}{6}|\phi\rangle\langle\phi| + \frac{1}{6}|\phi^\perp\rangle\langle\phi^\perp|$

B: UNOT mode: 1 photon in the state $\rho_B = \frac{1}{3}|\phi\rangle\langle\phi| + \frac{2}{3}|\phi^\perp\rangle\langle\phi^\perp|$

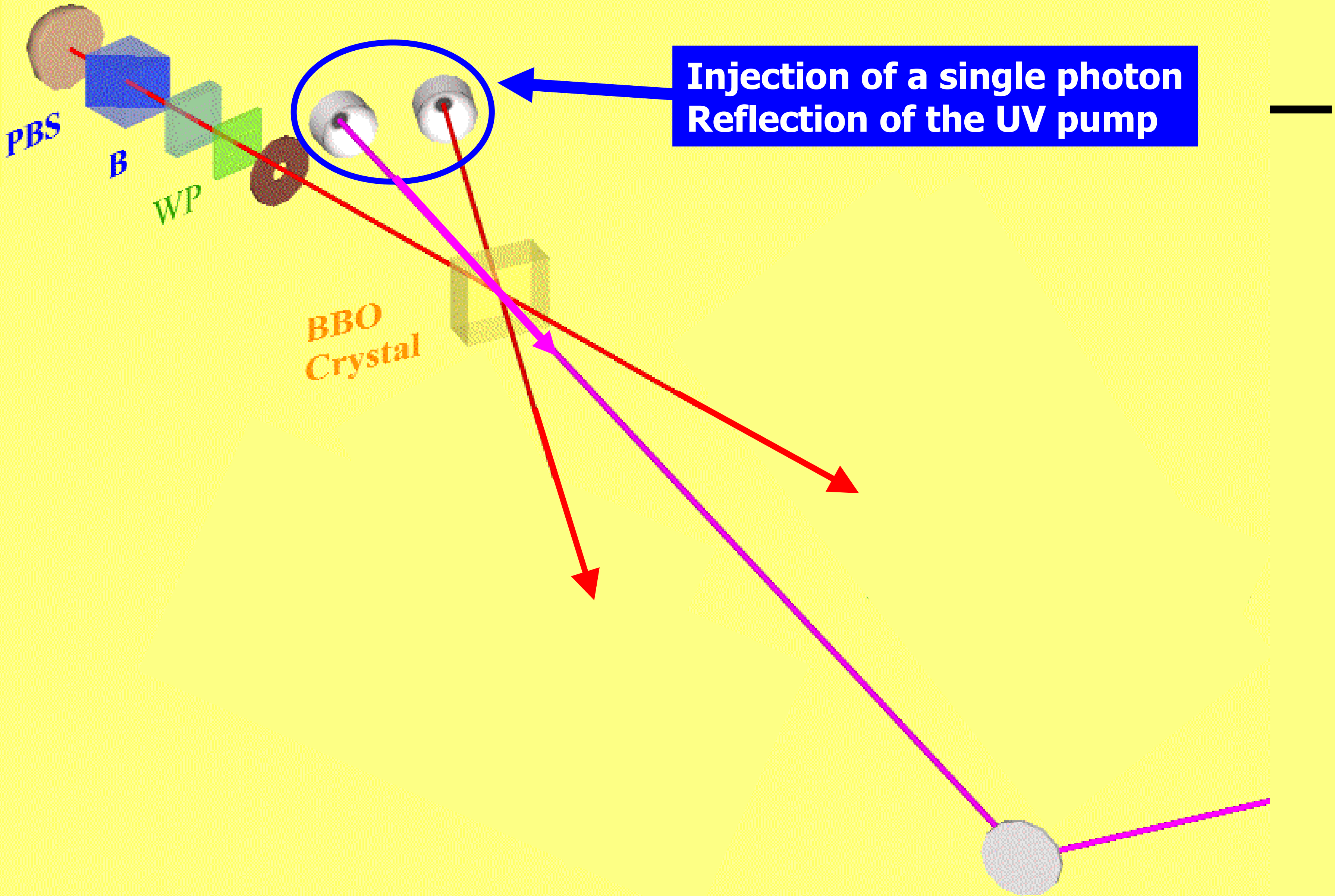


Entanglement

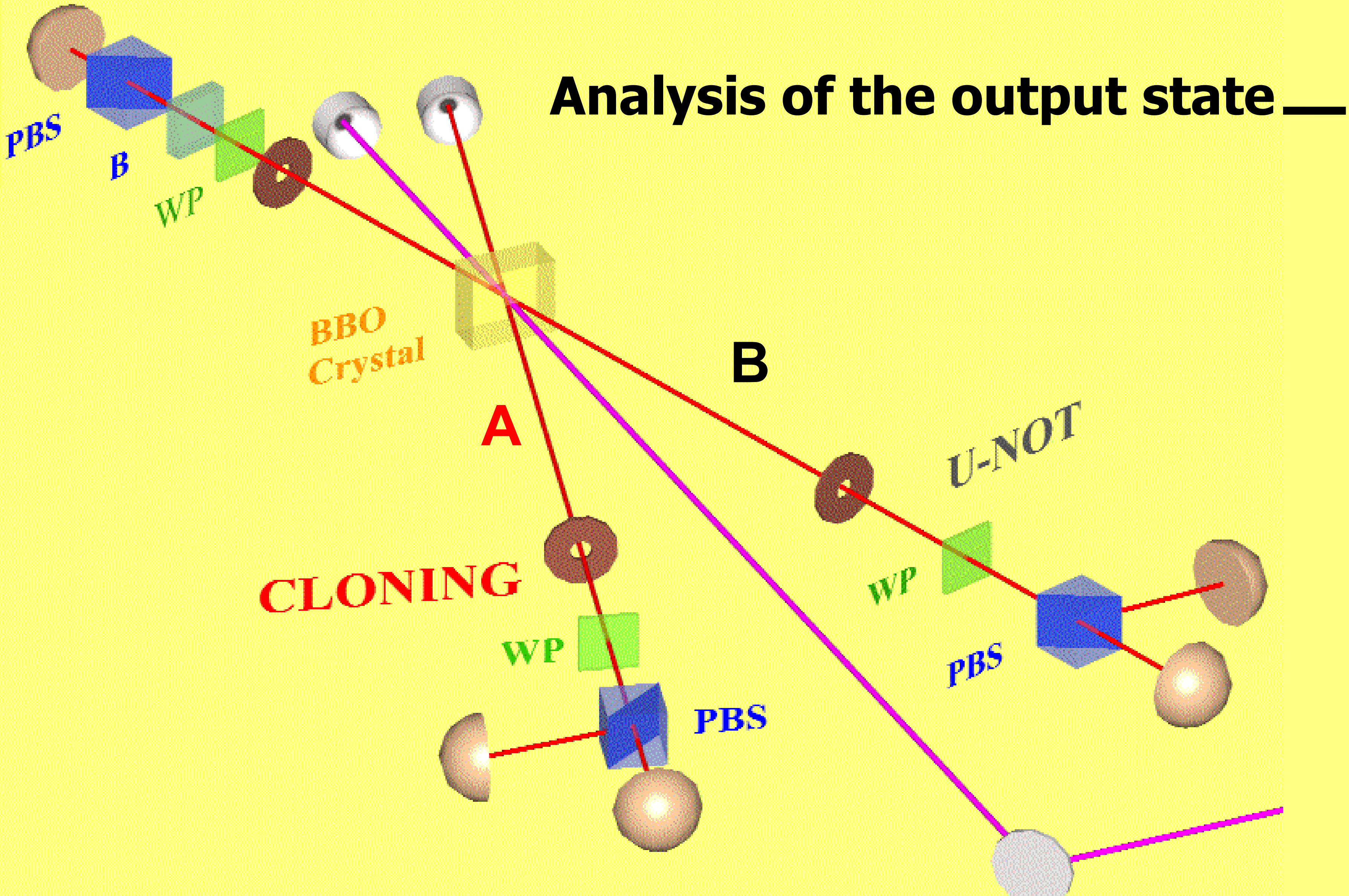
Polarization state $|\phi\rangle$

Trigger mode
Detection of one photon in the state $|\phi^{\perp}\rangle$

Creation of the qubit $|\phi\rangle_A$
by spontaneous emission


Injection of a single photon
Reflection of the UV pump
PBS
B
WP
BBO
Crystal

Analysis of the output state



De Martini, Buzek, Sciarrino, Sias, *Nature (London)* **419**, 815 (2002)
Pelliccia, Schettini, Sciarrino, Sias, De Martini, *Physical Review A* **68,** 042306 (2003)
De Martini, Pelliccia, Sciarrino, *Physical Review Letters* **92**, 067901(2004)

High – gain optical parametric amplification of a single photon state

$$|\phi\rangle_A = \alpha |H\rangle_A + \beta |V\rangle_A$$

Optimal quantum cloning process

Optical parametric amplification (OPA)

$$|\Psi\rangle_{out} = \hat{U}_{OPA}\left(\alpha |H\rangle + \beta |V\rangle\right) = \alpha \hat{U}_{OPA} |H\rangle + \beta \hat{U}_{OPA} |V\rangle = \alpha |\Psi(H)\rangle + \beta |\Psi(V)\rangle$$

Transfer of the quantum superposition condition affecting the input single-particle to a multi-particle quantum state

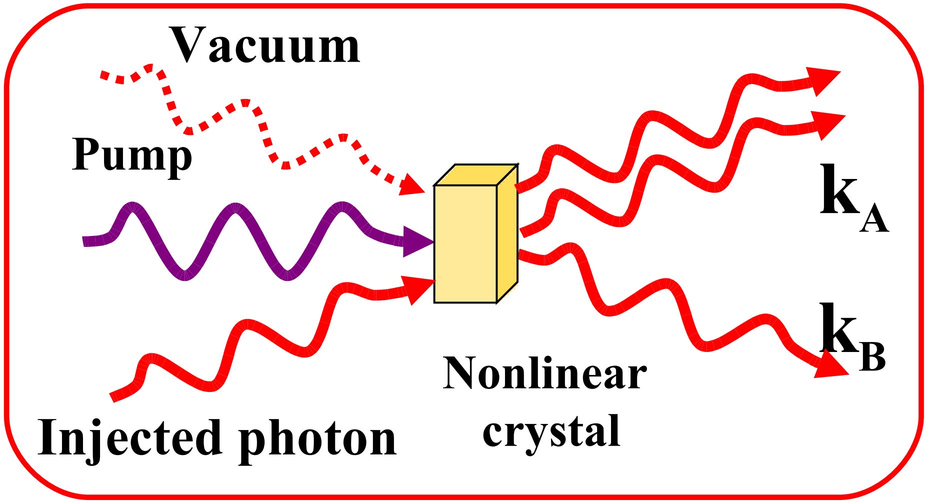
$$|H\rangle \Rightarrow |\Psi(H)\rangle \qquad |V\rangle \Rightarrow |\Psi(V)\rangle$$

$$|\langle\Psi(H)|\Psi(V)\rangle|^2 = 0$$

$$|\Psi(H)\rangle = \frac{1}{C^3}\sum_{i,j=0}^{\infty}(-\Gamma)^i \Gamma^j \sqrt{i+1}\,|i+1, j, j, i\rangle$$

$$|\Psi(V)\rangle = \frac{1}{C^3}\sum_{i,j=0}^{\infty}(-\Gamma)^i \Gamma^j \sqrt{j+1}\,|i, j+1, j, i\rangle$$

Bipartite entangled state



F. De Martini, F. Sciarrino, and V. Secondi, Phys. Rev. Lett. **95**, 240401 (2005)

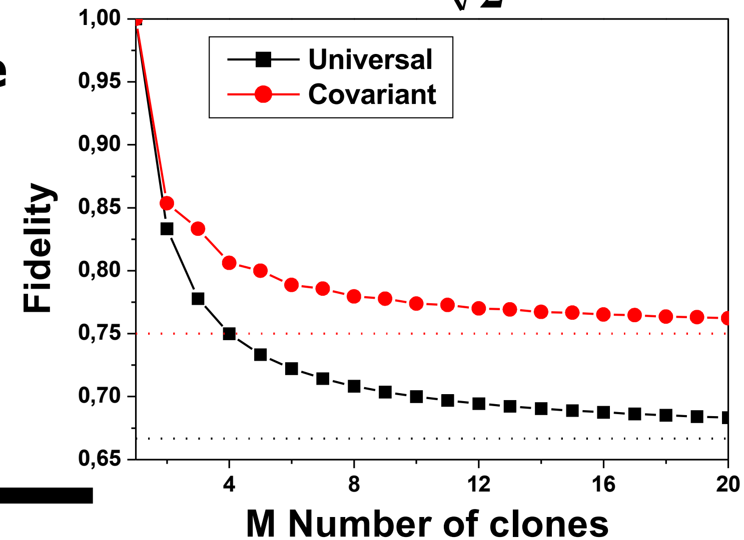
Optimal phase-covariant cloning

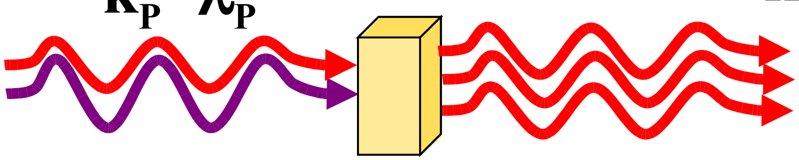
Phase-covariant cloning = cloning of equatorial qubits $|\phi\rangle_{in} = \frac{1}{\sqrt{2}}\left(|0\rangle + e^{i\varphi}|1\rangle\right)$

***a priori* information on the qubit state**

higher fidelity than universal cloning

M odd $F_{cov}^{1\rightarrow M} = \langle\phi|\rho_{out}|\phi\rangle = \frac{1}{2}\left(1 + \frac{M+1}{2M}\right)$





crystal

$k_P \quad \lambda_P$

$k_1 \quad 2\lambda_P$

Input qubit

collinear configuration

$|\phi\rangle_A = 2^{-1/2}\left(|H\rangle_A + e^{i\phi}|V\rangle_A\right)$

$H_I = i\hbar\chi\,\hat{a}_V^{+}\hat{a}_H^{+} + h.c. =$

$= i\hbar\frac{\chi}{2}\left(\hat{a}_{+}^{2+} - \hat{a}_{-}^{2+}\right) + h.c.$

U(1) covariant Hamiltonian

F. Sciarrino, F. De Martini, Phys. Rev. A **72**, 062313 (2005); Phys. Rev. A **76**, 012330 (2007)

Experimental scheme

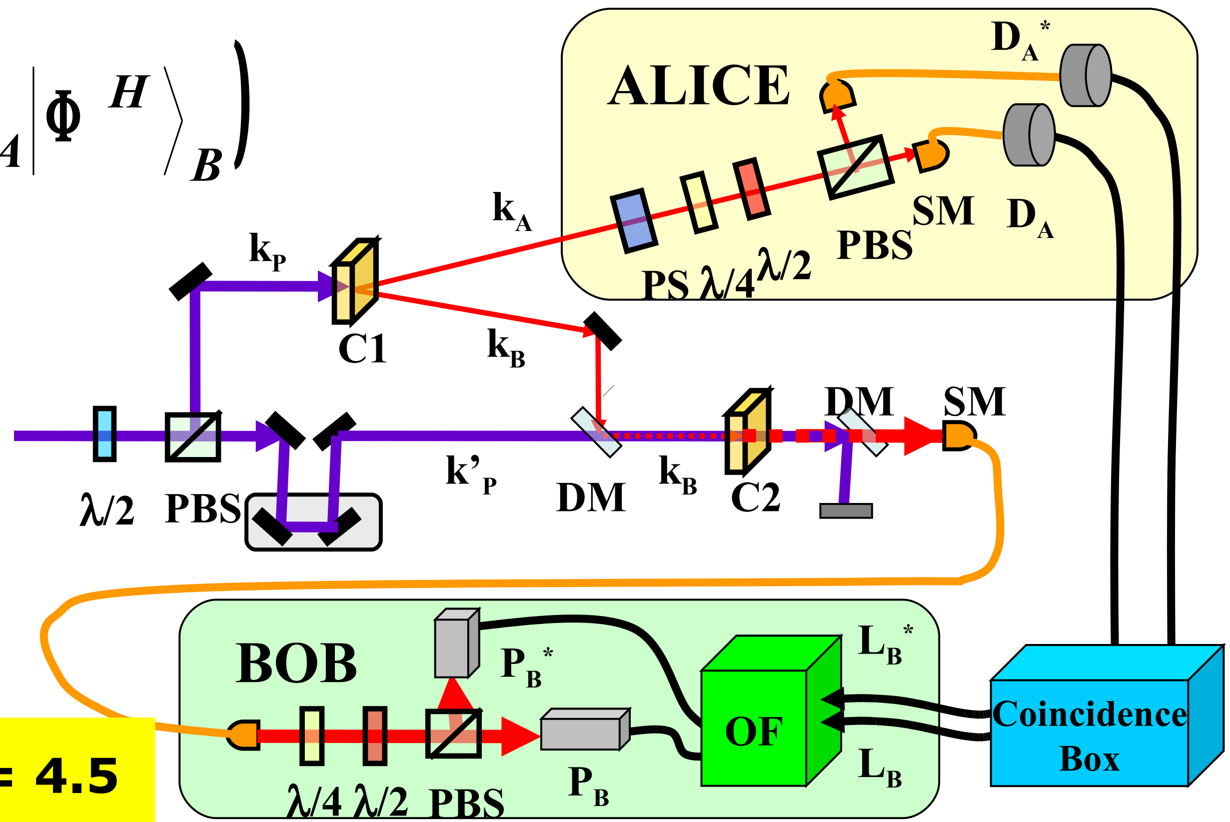
$$\frac{1}{\sqrt{2}}\left(|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B\right)$$

Amplification

$$\frac{1}{\sqrt{2}}\left(|H\rangle_A|\Phi^V\rangle_B - |V\rangle_A|\Phi^H\rangle_B\right)$$

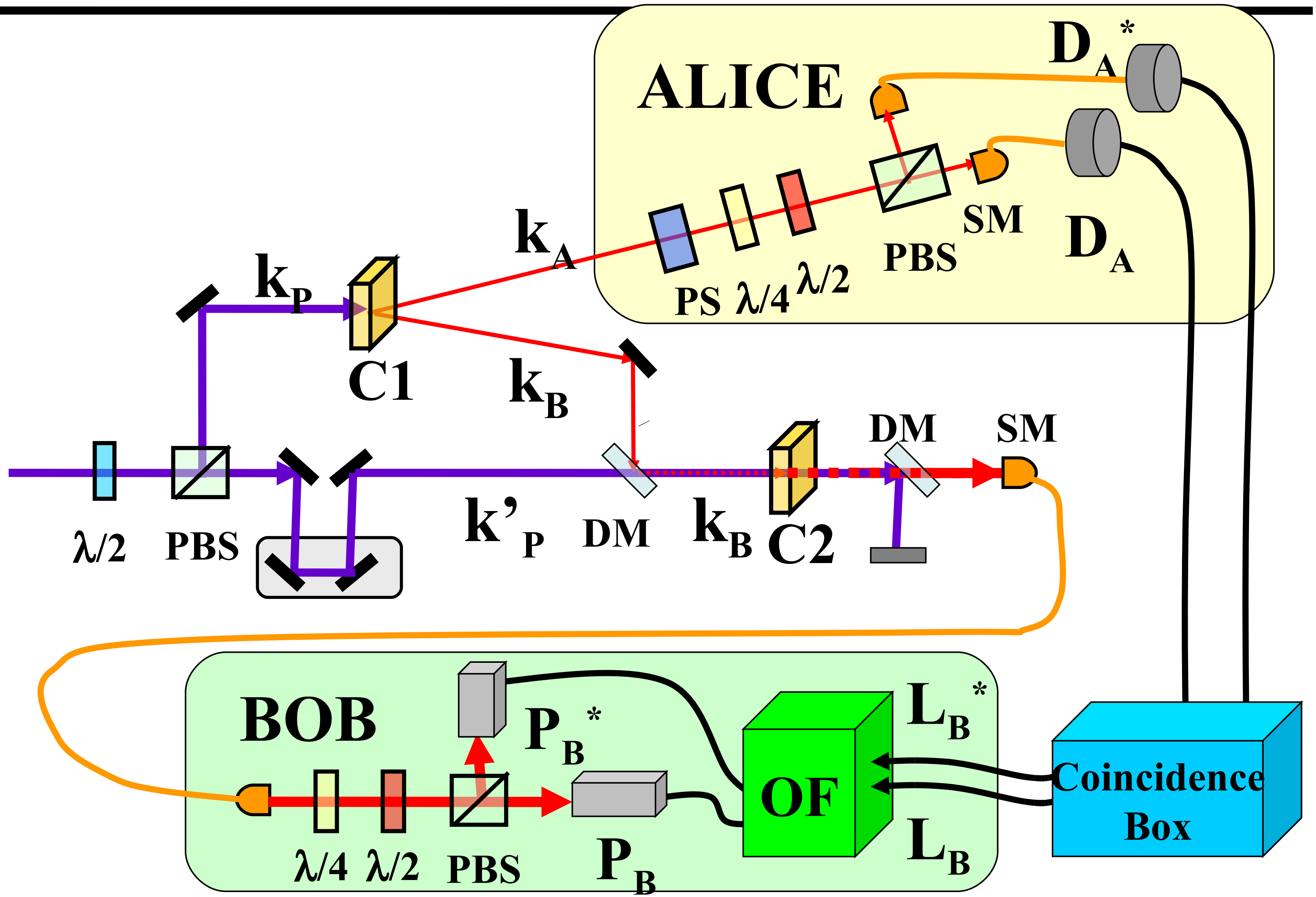
$$|\Phi^V\rangle_B = U_{OPA}|V\rangle_B$$

$$|\Phi^H\rangle_B = U_{OPA}|H\rangle_B$$



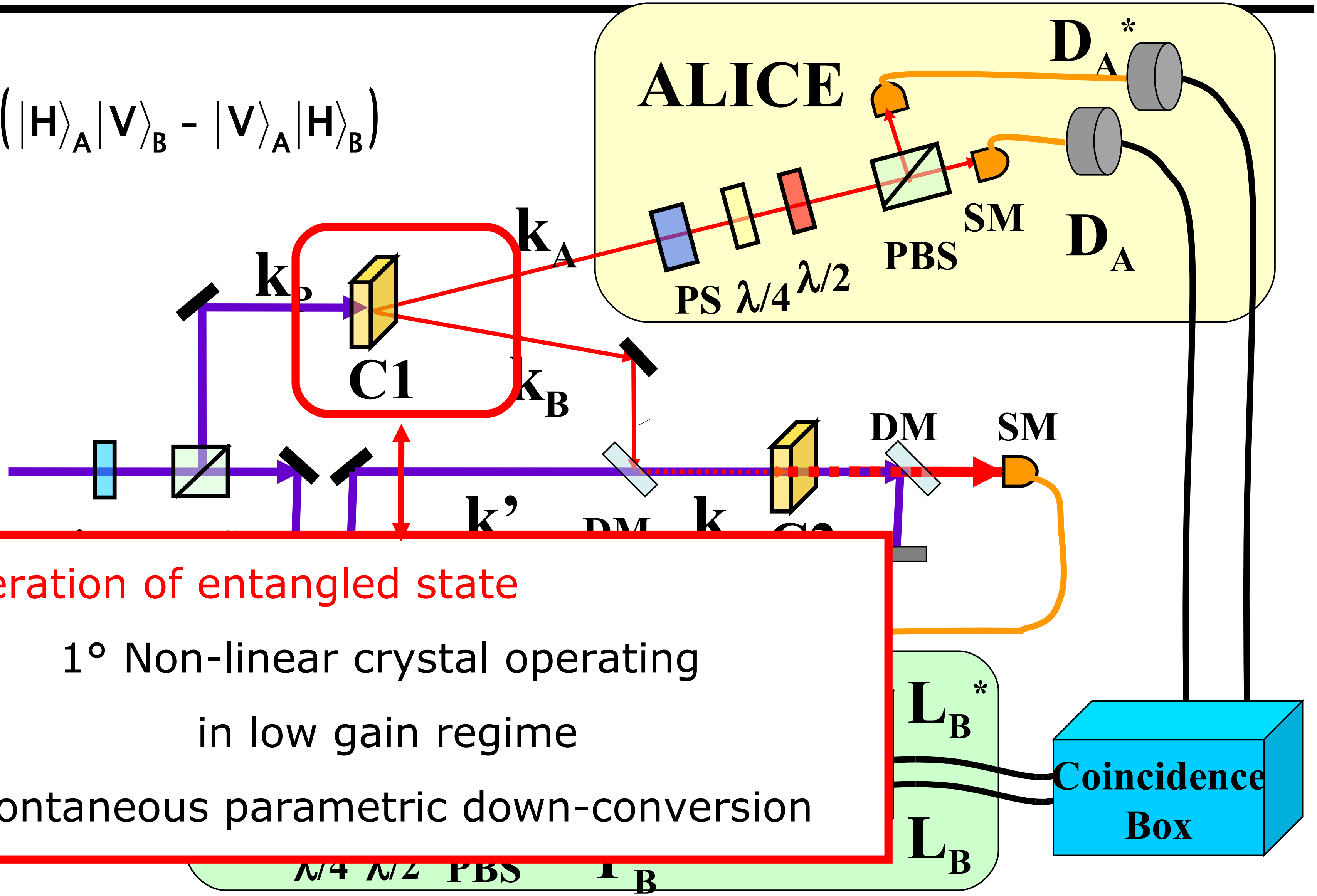
Maximum gain value g = 4.5
Average photon number per mode equal to ~ 1500

Experimental scheme



Experimental scheme

$$\frac{1}{\sqrt{2}}\left(|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B\right)$$



Generation of entangled state

1° Non-linear crystal operating

in low gain regime

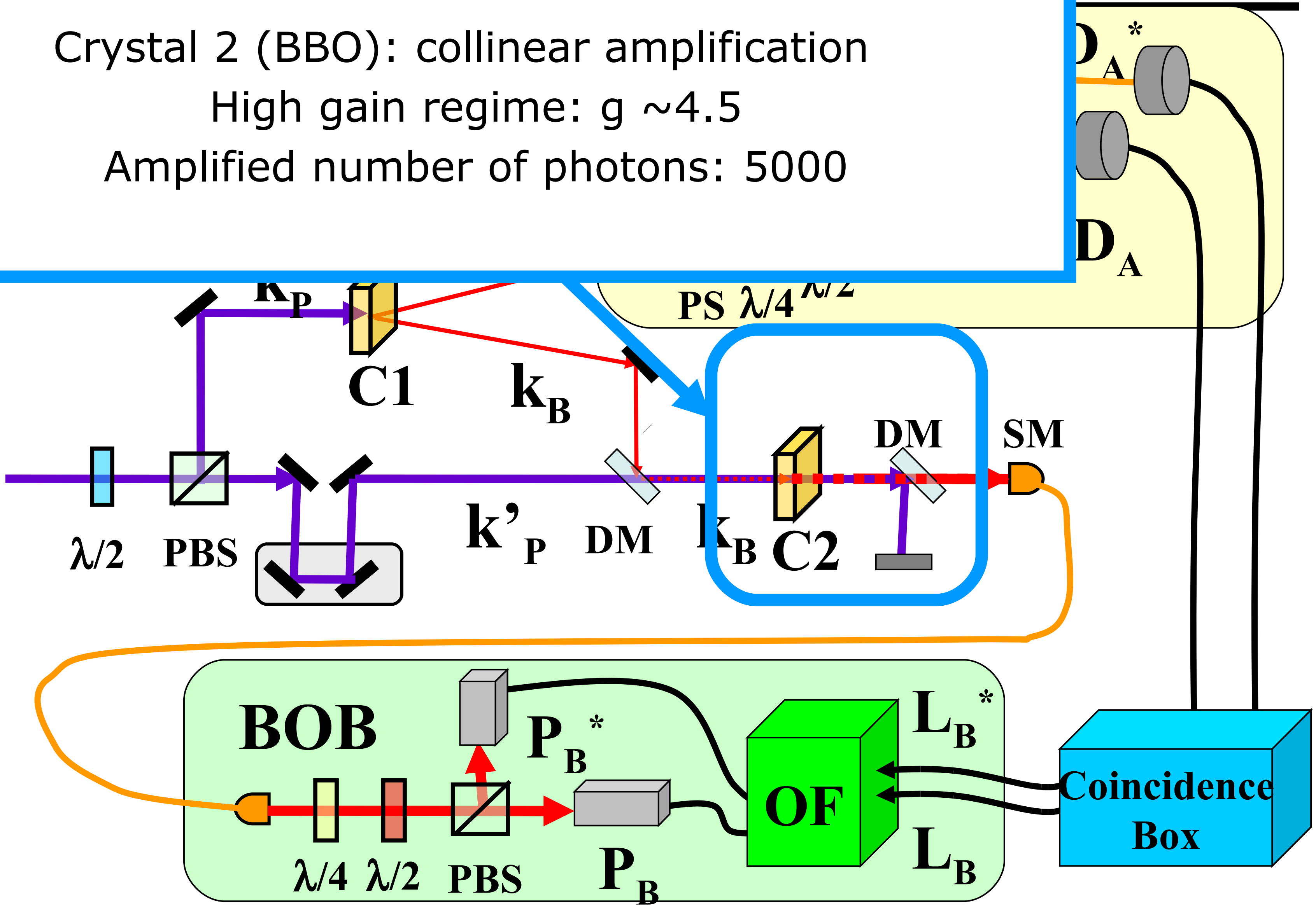
spontaneous parametric down-conversion

Experimental scheme

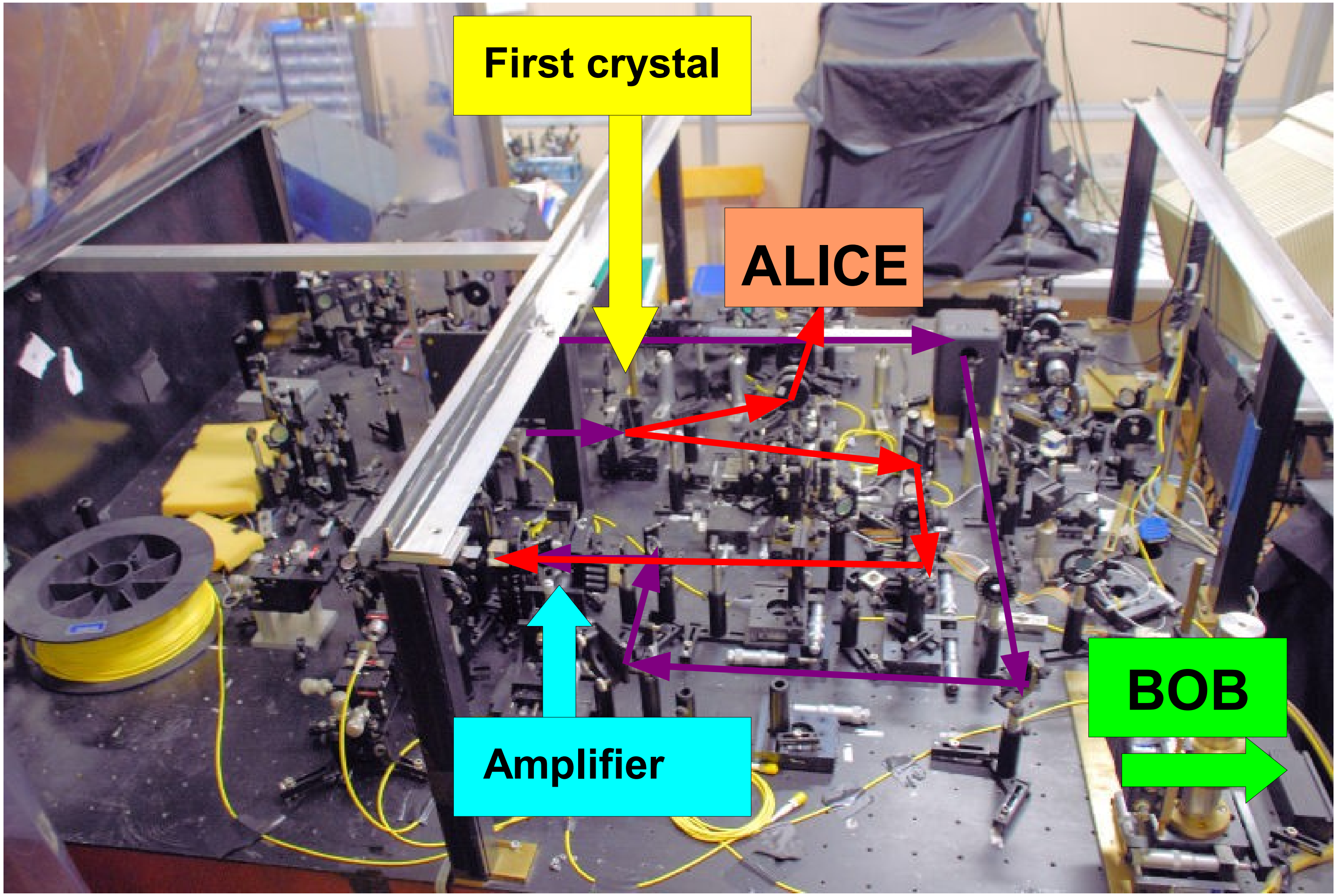
Crystal 2 (BBO): collinear amplification

High gain regime: g ~4.5

Amplified number of photons: 5000



A look to the lab



Experimental characterization

- **Average number of photons over mode k_B**

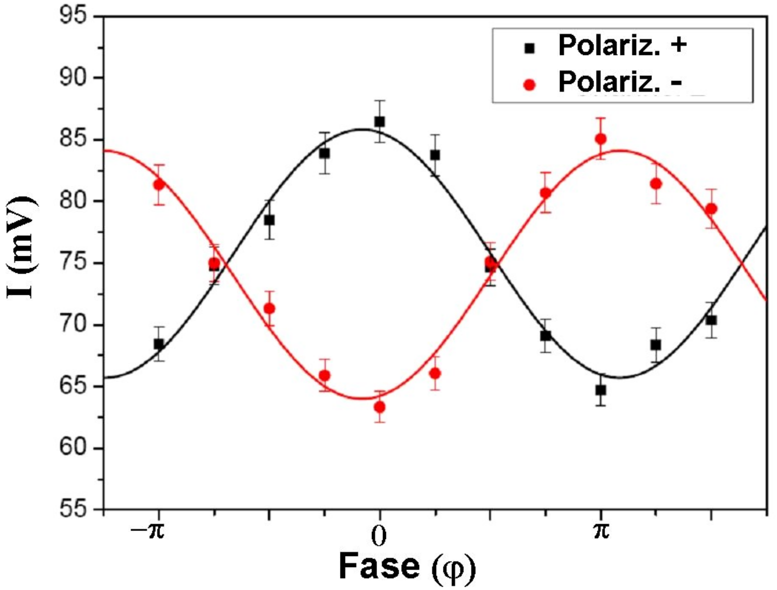
$N \approx 5 \times 10^3$

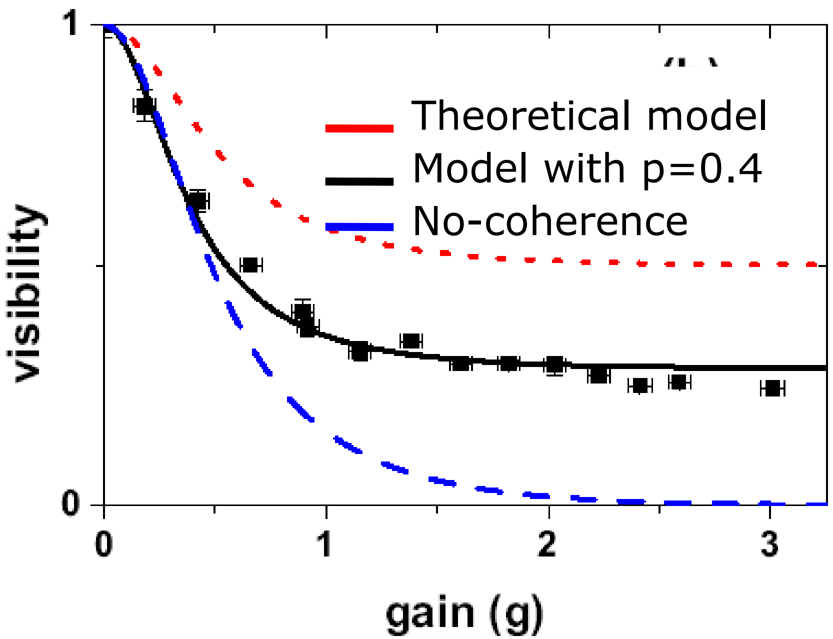
linear detectors: photomultipliers

- **Fringe patterns in any equatorial basis**

experimental visibilities: 15÷20%

main imperfection: injection into the amplified mode with probability p=0.25÷0.40





E. Nagali, T. De Angelis, F. Sciarrino, and F. De Martini, *Physical Review A* **76**, 042126 (2007)

Demonstration of entanglement

Micro-macro wavefunction:

$$\frac{1}{\sqrt{2}}\left(|H\rangle_A|\Phi^V\rangle_B - |V\rangle_A|\Phi^H\rangle_B\right) = \frac{1}{\sqrt{2}}\left(|\varphi\rangle_A|\Phi^{\varphi\perp}\rangle_B - |\varphi^\perp\rangle_A|\Phi^{\varphi}\rangle_B\right)$$

- Alice (A): single photon
- Bob (B): multiphoton field (10^3-10^4)

To experimentally demonstrate the entanglement:

- Observation of correlations in two polarization basis
- Introduction of an appropriate qubit formalism for both the single particle at Alice's site and the multi-particle field at Bob's site
- Application of an entanglement criterion for bipartite system

Main problem to overcome: Discrimination between orthogonal macroscopic states

Criteria for entanglement

Micro–Qubit at Alice's site

- Pauli operator for spin ½: mode $\mathbf{k_A}$

$$\alpha\left|H\right\rangle+\beta\left|V\right\rangle$$

$$\hat{\sigma}_i^{(A)}=\left|\phi_i\right\rangle\left\langle\phi_i\right|-\left|\phi^{\perp}_i\right\rangle\left\langle\phi^{\perp}_i\right|$$

Macro–Qubit at Bob's site

- Macro-spin operator for macro qubit: mode $\mathbf{k_B}$

$$\alpha\left|\Phi^{H}\right\rangle+\beta\left|\Phi^{V}\right\rangle$$

$$\hat{\Sigma}_i^{(B)}=\hat{U}\hat{\sigma}_i\hat{U}^{+}$$

Criterion for two qubit bipartite systems based on the total spin-correlation.

Upper bound criterion for separable state (no entangled)

$$C=V_1+V_2+V_3\leq 1$$

with $V_i=\left|\left\langle\hat{\sigma}_i^{(A)}\cdot\hat{\Sigma}_i^{(B)}\right\rangle\right|$

$$\begin{cases}1\leftrightarrow & \left\{\vec{\pi}_H,\vec{\pi}_V\right\}\\ 2\leftrightarrow & \left\{\vec{\pi}_+=2^{-1/2}\left(\vec{\pi}_H+\vec{\pi}_V\right),\vec{\pi}_-\right\}\\ 3\leftrightarrow & \left\{\vec{\pi}_R=2^{-1/2}\left(\vec{\pi}_H+i\vec{\pi}_V\right),\vec{\pi}_L\right\}\end{cases}$$

Features of the amplified state

Characteristics of the output wave-functions: $\vec{\pi}_{\pm} = \frac{1}{\sqrt{2}}\left(\vec{\pi}_H \pm \vec{\pi}_V\right)$

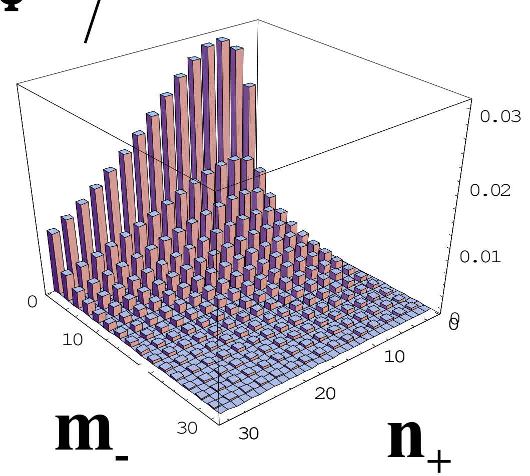
$$\left|\Phi^{\pm}\right\rangle_B = U_{OPA}\left|\pm\right\rangle = \sum_{i,j=0}^{\infty} \gamma_{ij} \frac{\sqrt{(1+2i)!(2j)!}}{i!\,j!}\left|2i+1\right\rangle_{\pm}\left|2j\right\rangle_{\mp} \quad \text{with } \gamma_{ij} = \tanh^{i+j} g$$

Orthogonal states: perfect discrimination requires the detection of all generated photons (equivalent to the measurement of parity operators)

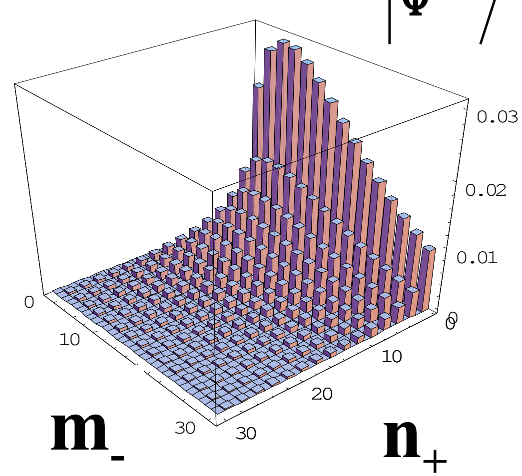
Probabilistic approach exploits difference between the photon number distributions associated to $\left|\Phi^{\pm}\right\rangle$

Probability distribution of the Fock states $\left|n\right\rangle_+ \left|m\right\rangle_-$ *for the two states* $\left|\Phi^{\pm}\right\rangle$

$\left|\Phi^{+}\right\rangle$

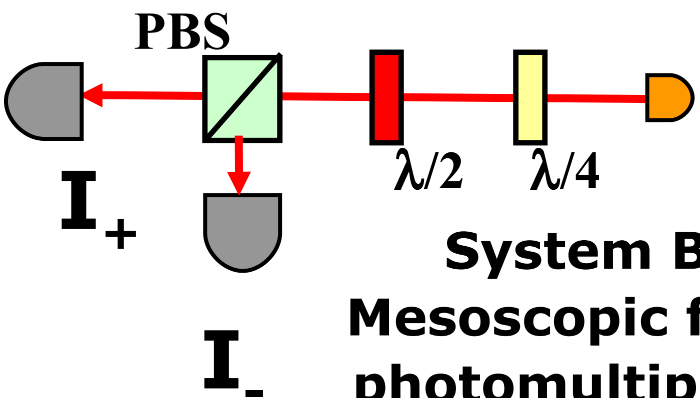


$\left|\Phi^{-}\right\rangle$



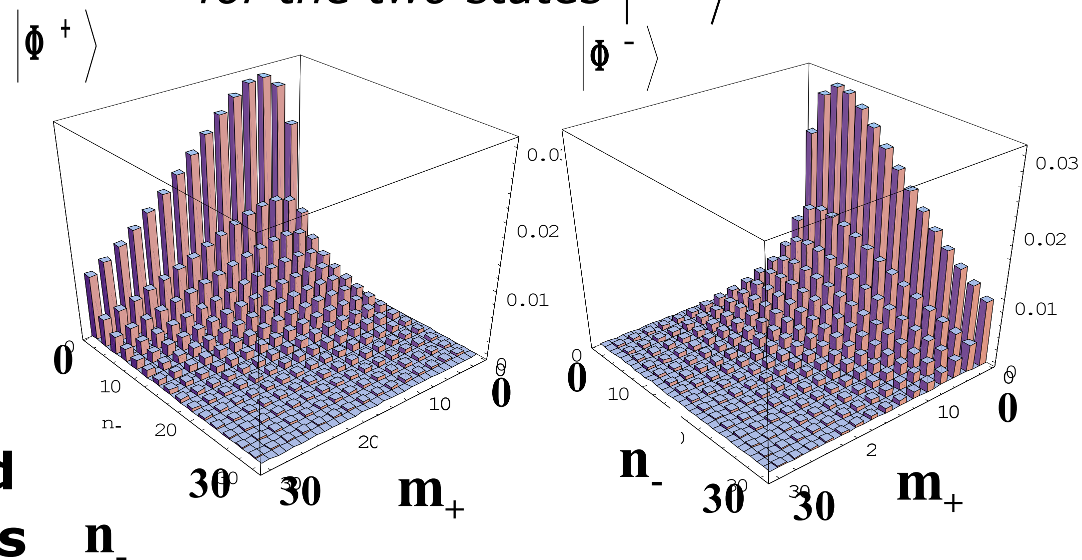
Macro-states identification

Probabilistic identification via ORTHOGONALITY FILTER



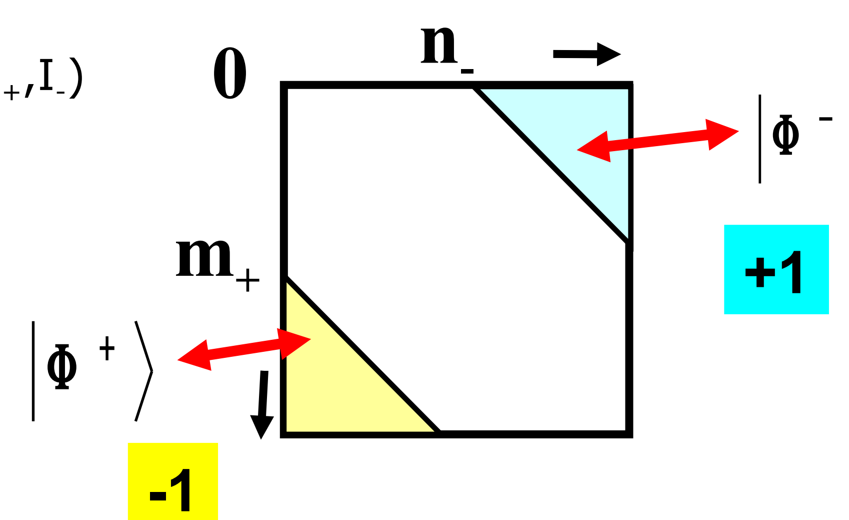
System B: Mesoscopic field photomultipliers

Probability distribution of the Fock states $|n\rangle_+ |m\rangle_-$ *for the two states* $|\Phi^{\pm}\rangle$

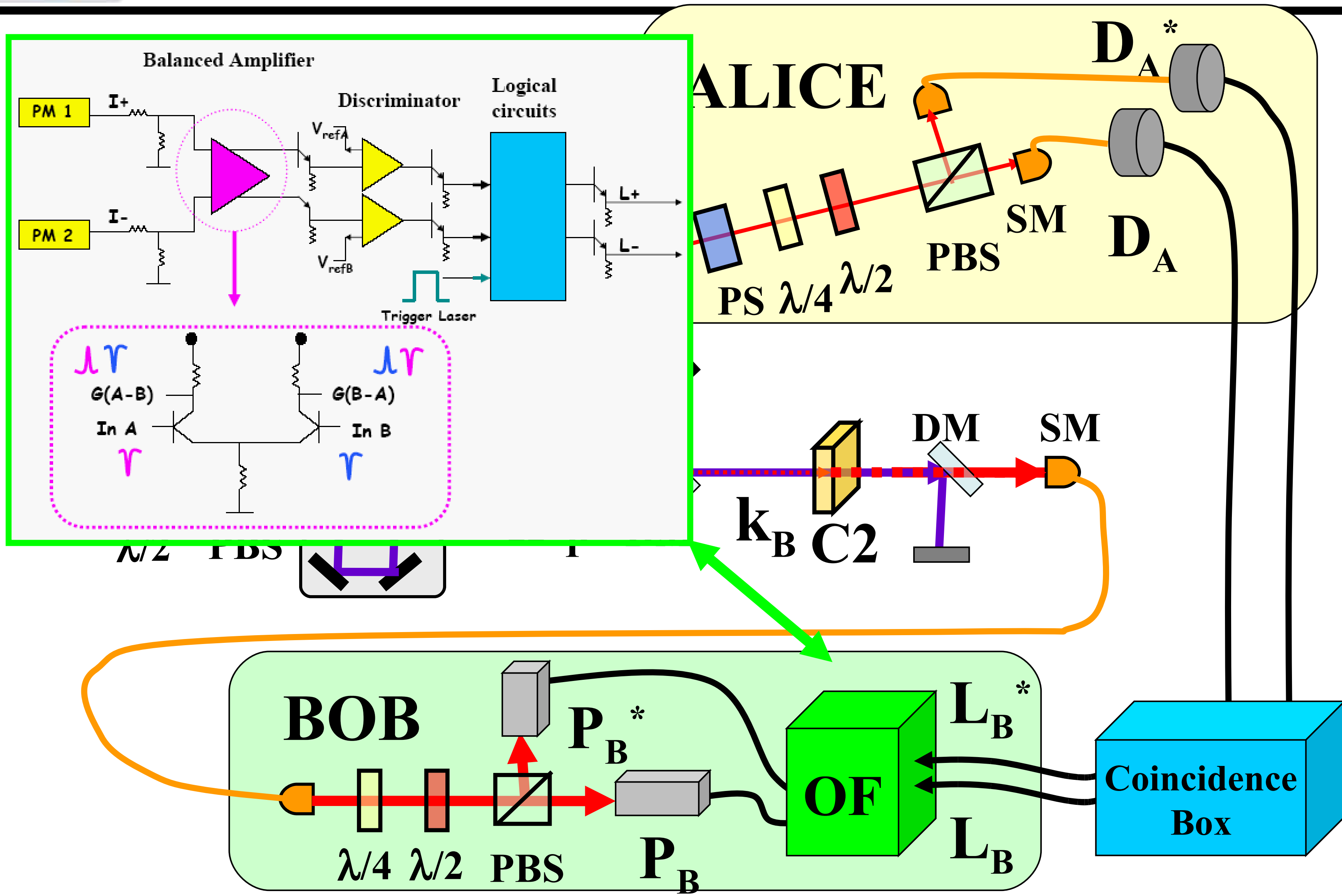


Shot-by-shot we detect continuous signal (I_+, I_-) over mode k_B

- $I_+ >> I_- \Rightarrow$ detection of $|\Phi^+\rangle$
- $I_- >> I_+ \Rightarrow$ detection of $|\Phi^-\rangle$
- $I_+ \sim I_- \Rightarrow$ data discarded

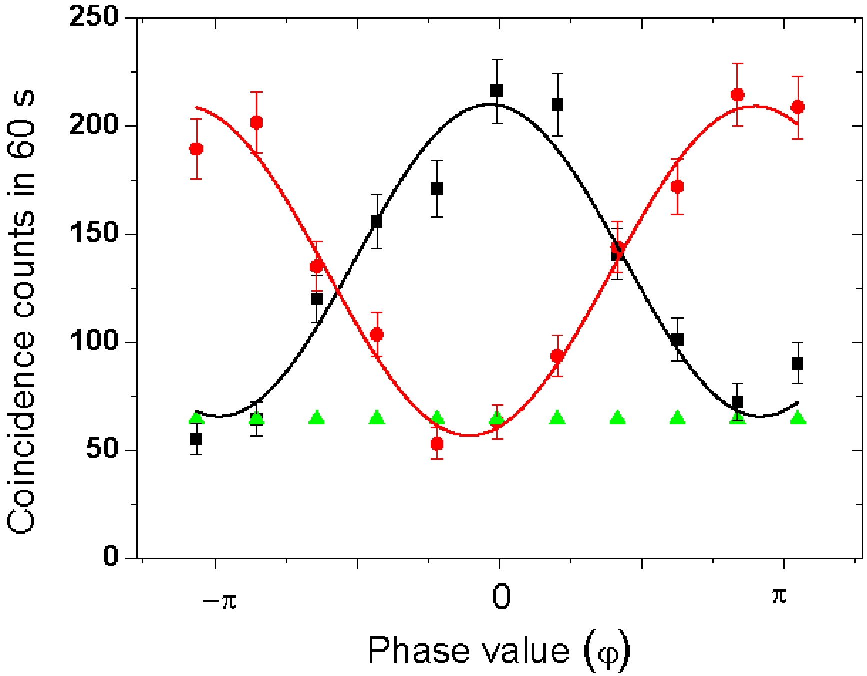


Entanglement observation: experimental scheme



Entanglement observation: experimental results

Correlation pattern between A and B



Filtering probability 10^{-3}

Necessary-Sufficient Entanglement Criterion:

$$C = V_1 + V_2 + V_3 \geq 1$$

$$V_1 = 0; \quad V_2 = (54.0 \pm 0.7)\% ; \quad V_3 = (55.0 \pm 1.0)\%$$

$$C_{exp} = V_1 + V_2 + V_3 = 1.090 \pm 0.012$$

Entanglement between micro and macro photonic systems

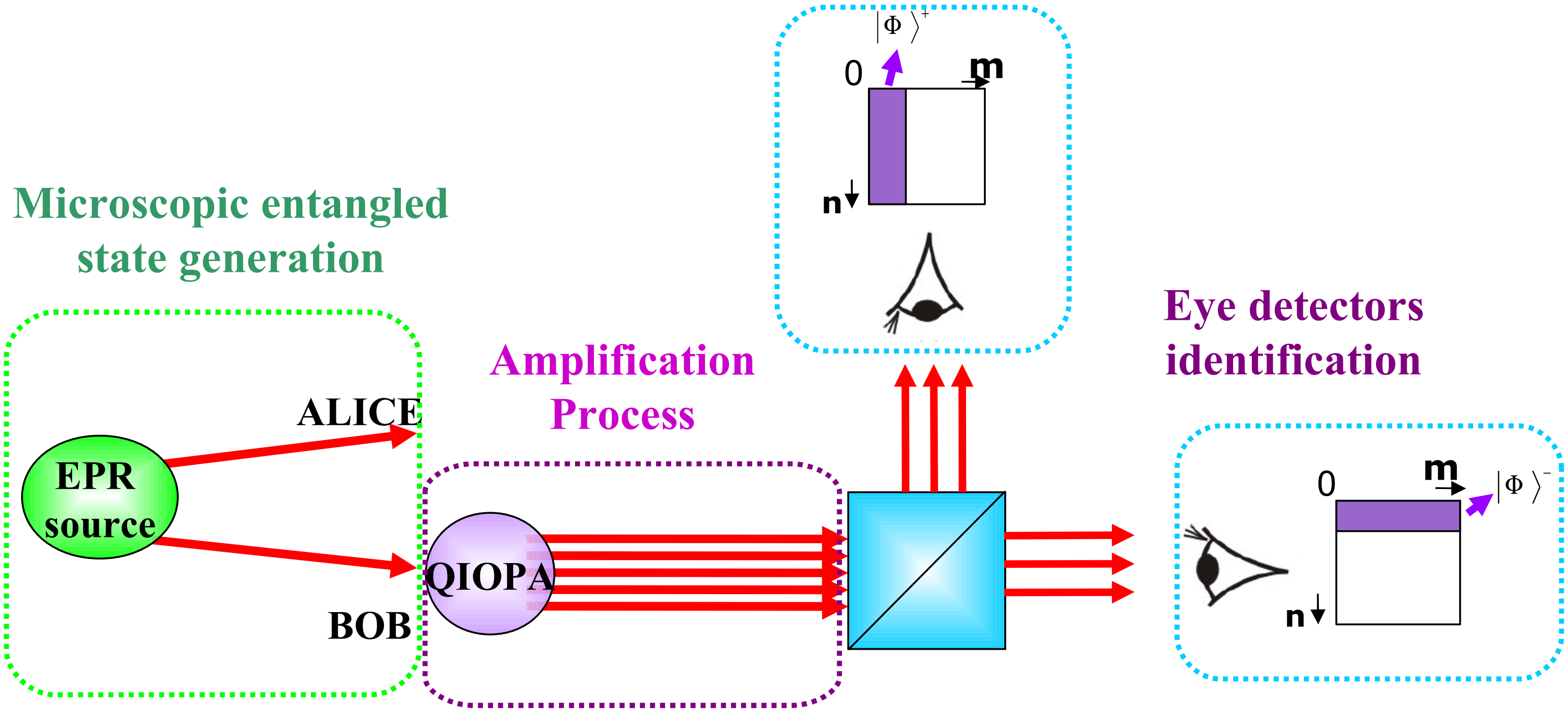
Criteria based in the assumption of local operation on micro system

F. De Martini, F. Sciarrino, and C. Vitelli, *Phys. Rev. Lett.* **100**, 253601 (2008)

Quantum experiments with human eyes as detectors based on optimal cloning ?

Towards Quantum Experiments with Human Eyes as Detectors Based on Cloning via Stimulated Emission

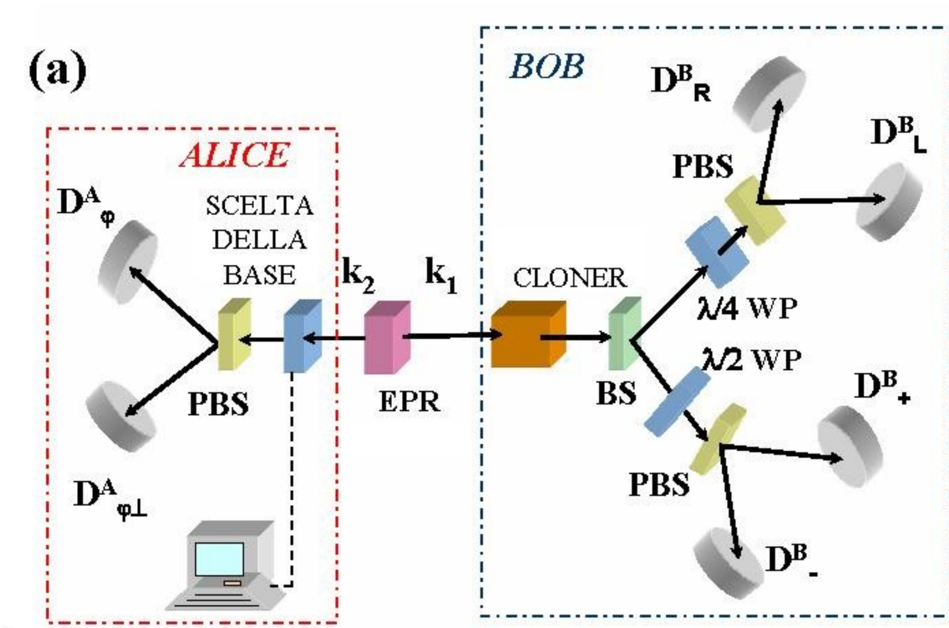
Pavel Sekatski,[1] Nicolas Brunner,[1,2] Cyril Branciard,[1] Nicolas Gisin,[1] and Christoph Simon[1]



To bring the observer much closer to the quantum phenomenon ?

P. Sekatski, et al., *Phys. Rev. Lett.* **103**, 113601 (2009).

FLASH proposal: faster than light comunication?



1981 Nick Herbert
FLASH: First Laser-Amplified Superluminal Hookup

- **Alice chooses the measurement basis either (R,L) or (+,-)**
- **Bob's goal: to guess the basis in which Alice measured the polarization**

New type of measurement: quantum cloning

Bob produces N copies of the quantum states and measures the overall output state in two different basis

ALICE		Perfect cloner / BOB a)	BOB b)
a) $\|+\rangle$	b) $\|-\rangle$	$I_+ = 0$	$I_+ = N/2$
		$I_- = N/2$	$I_- = 0$
		$I_R = N/4$	$I_R = N/4$
		$I_L = N/4$	$I_L = N/4$

Unbalanced signals → $|I_+ - I_-| >> |I_R - I_L|$

N. Herbert, *Found. Phys.* **12**, 1171 (1982)

FLASH proposal: test

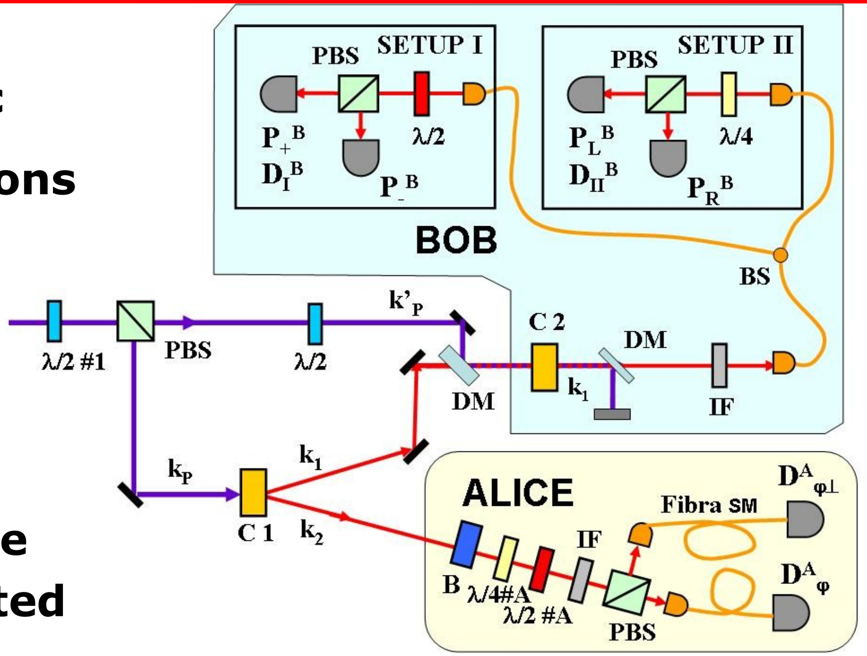
Objection to Herbert proposal → **No cloning theorem**

Wootters and Zurek, Nature **299**, 802 (1982).

Quantum cloning achieved by Optical amplification → **Noisy copies** *but* **Noise not sufficient to rebut Herbert's scheme**

Experimental test by optical parametric amplification of an entangled pair of photons

Characterization of the features of the amplified field



Collective phenomena → **Macroscopic coherence**
Photons highly correlated

T. De Angelis, E. Nagali, F. Sciarrino, F. De Martini, *Physical Review Letters* **99**, 193601 (2007)

Light-matter entanglement

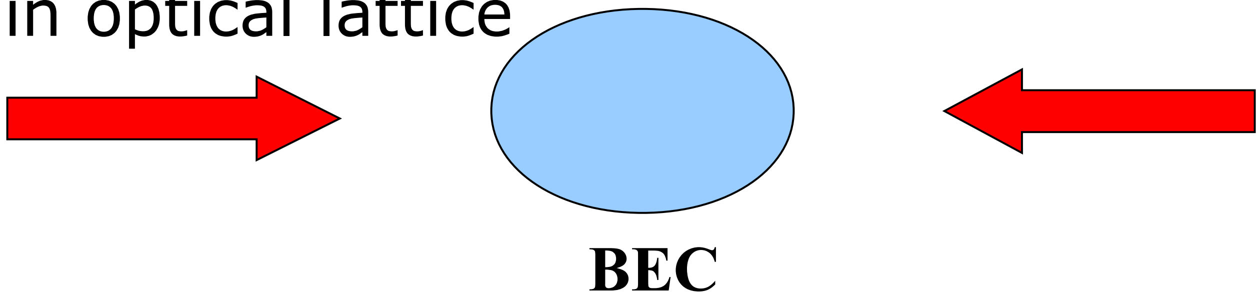
- **Light-matter entanglement**
  - Generation of Schroedinger cat state
  - Test of wavefunction collapse (quantum gravity)
  - Quantum repeater for quantum communication
  - ……

- **Experimental approaches**
  - Interaction of a single photon with a tiny mirror
  - Cooling of micromirror by radiation pressure
  - Quantum memory: interaction between single photon and atom clouds

- **Our approach:**
  - Exploit microscopic-macroscopic entangled field
  - Create micromirror exploiting Bose-Einstein condensate

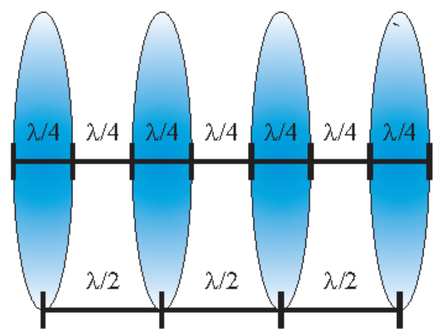
Reflection by a Bragg BEC mirror

I) BEC in optical lattice

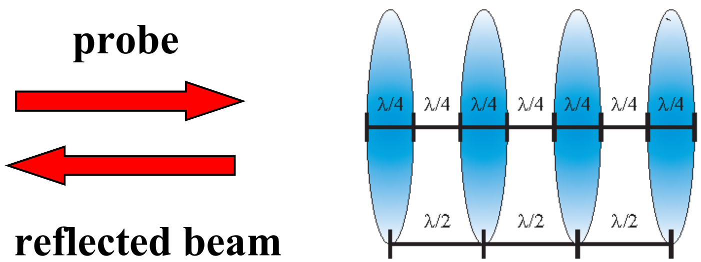


II) Optical lattice turned off

Bragg structured



III) Bragg structured BEC adopted as a mirror



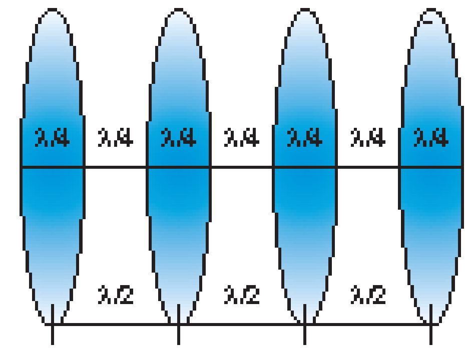
- **Light reflected**
- **Atom acquires momentum kick equal to** $2\hbar k$

Toward light-matter entanglement

I) Micro-macroscopic photonic entanglement by QIOPA

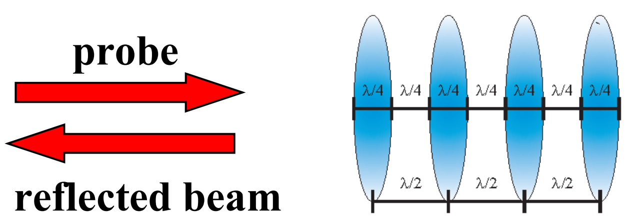
II) BEC mirror

- BEC condensate with 10^5 atoms
- Optical lattices induces a Bragg structure on the BEC
- High reflectivity on bandwidth of GHz



Alternating slabs of condensate and vacuum.

III) Light-matter entanglement by photon scattering



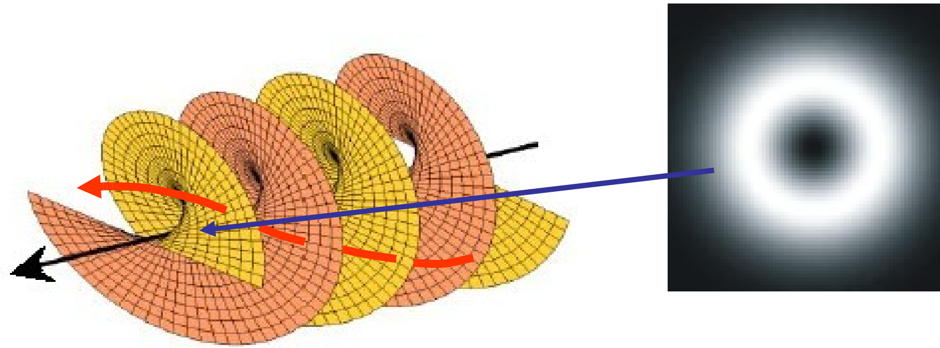
Momentum conservation:
light reflection induces a kick $2\hbar k$
on single atom

F. De Martini, F. Sciarrino, C. Vitelli, and F. Cataliotti, *Phys. Rev. Lett.* **104**, 050403 (2010)

Optimal quantum cloning of images.. Higher dimensional systems (qunit)...

Degree of freedom of light associated with rotationally structured transverse spatial modes

Laguerre–Gauss modes → helicoidal wavefront



nature photonics

LETTERS

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Optimal quantum cloning of orbital angular momentum photon qubits through Hong-Ou-Mandel coalescence

Eleonora Nagali[1], Linda Sansoni[1], Fabio Sciarrino[1,2]*, Francesco De Martini[1,3], Lorenzo Marrucci[4,5]*, Bruno Piccirillo[4,6], Ebrahim Karimi[4] and Enrico Santamato[4,6]

Conclusions

- Investigation on the possibility to observe non-locality on multiphoton state via fuzzy measurement. Search for criteria of entanglement?
- High parametric amplification of entangled states: observation of coherence transfer. Observation of entanglement under assumption of local operation.
- Theoretical investigation on resilience to decoherence of the amplified multiphoton state

F. De Martini, F. Sciarrino, and N. Spagnolo, Physical Review Letters **103**, 100501 (2009)

F. De Martini, F. Sciarrino, and N. Spagnolo, Physical Review A **79**, 052305 (2009).

Perspectives

- Experiment under progress: micro-macro teleportation and measurement induced quantum operations on mesoscopic quantum fields.
- Hybrid quantum information processing: to merge discrete (qubit) and continuous variable (CV) approaches, each one with its own weakness and strengths. Next step: measurement based on homodyne technique.
- Exploit resilience to losses to carry out robust quantum sensing in noisy environment
- Light-matter entanglement: coupling with a Bose-Einstein condensate.