University Paris-Saclay - IQUPS

Optical Quantum Engineering: From fundamentals to applications

Philippe Grangier,
Institut d'Optique, CNRS, Ecole Polytechnique.

- Lecture 1 (7 March, 9:15-10:45) :
  Qubits, entanglement and Bell's inequalities.
- Lecture 2 (14 March,11:00-12:30) :
  From QND measurements to quantum gates and quantum information.
- Lecture 3 (21 March, 9:15-10:45) :
  Quantum cryptography with discrete and continuous variables.
- Lecture 4 (28 March, 11:10-12:30) :
  Non-Gaussian quantum optics and optical quantum networks.

Content of the Lecture

Part 1 - Quantum optics with discrete and continuous variables

1.1 Homodyne detection and quantum tomography

1.2 Generating non-Gaussian Wigner functions : kittens, cats and beyond

Part 2 - Towards optical quantum networks

2.1 Entanglement, teleportation, and quantum repeaters

2.2 Some experimental achievements

Part 3 - A close look to a nice single photon

3.1 Single photons: from old times to recent ones

3.2 Experimental perspectives

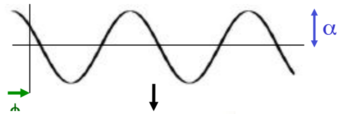
Quantum description of light

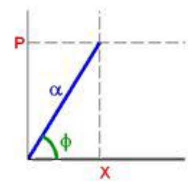
Discrete — Photons	Continuous — Wave

A single "mode" of the quantized electromagnetic field (a plane wave, or a "Fourier transform limited" pulse) is described as a quantized harmonic oscillator : operators a, a^+, $N = a^+ a$, etc...

Quantum description of light

	Discrete — Photons	Continuous — Wave
Parameters :	Number of photons n	Amplitude & Phase (polar)
	Destruction operators a	Quadratures X & P (cartesian)
	Creation operators a^+	
	Number operator $N = a^+a$	





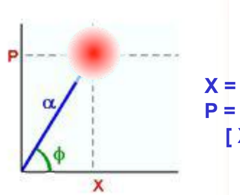
$X = (a + a^+)/\sqrt{2}$
$P = (a - a^+)/i\sqrt{2}$
$[X, P] = i$

Quantum description of light

	Discrete — Photons	Continuous — Wave
Parameters :	Number & Coherence	Amplitude & Phase (polar) Quadratures X & P (cartesian)
Representation:	Density matrix	Wigner function W(X,P)

$$\rho = \begin{bmatrix} \rho_{0,0} & \rho_{0,1} & \rho_{0,2} & \cdots \\ \rho_{1,0} & \rho_{1,1} & \rho_{1,2} & \cdots \\ \rho_{2,0} & \rho_{2,1} & \rho_{2,2} & \cdots \\ \cdots & \cdots & \cdots & \cdots \end{bmatrix}$$

Coherences $< n \mid \rho \mid m >$



$X = (a + a^+)/\sqrt{2}$
$P = (a - a^+)/i\sqrt{2}$
$[X, P] = i$

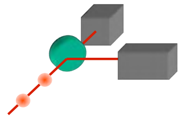
Heisenberg : $\Delta X . \Delta P \geq 1/2$

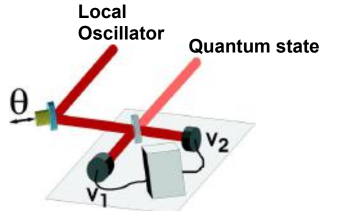
~~measurement of both X and P~~

measurement of $X_\theta = X \cos\theta + P \sin\theta$

Quantum description of light

	Discrete — Photons	Continuous — Wave
Parameters :	Number & Coherence	Amplitude & Phase (polar) Quadratures X & P (cartesian)
Representation:	Density matrix	Wigner function W(X,P)
Measurement :	Counting : APD, VLPC, TES...	Demodulation : Homodyne detection





Interference, then subtraction of photocurrents :

$V_1 - V_2 \quad \propto E_{OL} E_{EQ}(\theta)$
$\propto X_\theta = X\cos\theta + P\sin\theta$

Homodyne detection

$I_1 = |E_{LO} + E_S|^2 /2 = \{ |E_{LO}|^2 + |E_S|^2 + |E_{LO}| (E_S\, e^{-i\theta_{LO}} + E_S^*\, e^{i\theta_{LO}}) \}/2$

$I_2 = |E_{LO} - E_S|^2 /2 = \{ |E_{LO}|^2 + |E_S|^2 - |E_{LO}| (E_S\, e^{-i\theta_{LO}} + E_S^*\, e^{i\theta_{LO}}) \}/2$

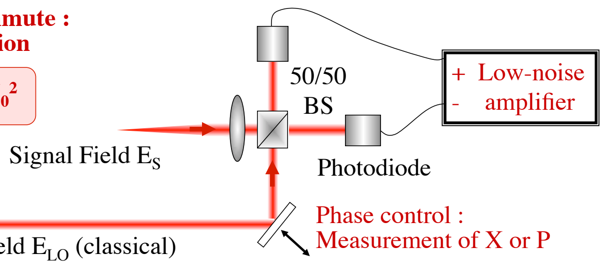
$I_1 - I_2 \quad = |E_{LO}| (E_S\, e^{-i\theta_{LO}} + E_S^*\, e^{i\theta_{LO}})$

$= |E_{LO}| (E_S + E_S^*) \quad \Rightarrow \quad \sqrt{n_{LO}}\,(a + a^+)$ **X meas.** $(\theta_{LO} = 0)$

$= |E_{LO}| (E_S - E_S^*)/i \quad \Rightarrow \quad \sqrt{n_{LO}}\,(a - a^+)/i$ **P meas.** $(\theta_{LO} = \pi/2)$

X and P do not commute : Heisenberg relation

$V(X)\ V(P) \geq N_0^2$



Local Oscillator Field E_{LO} (classical)

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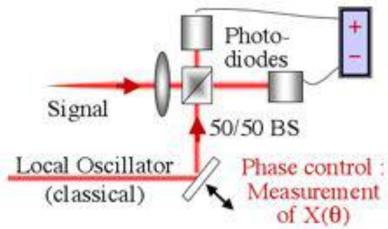
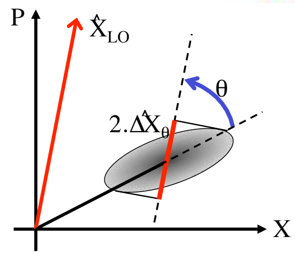
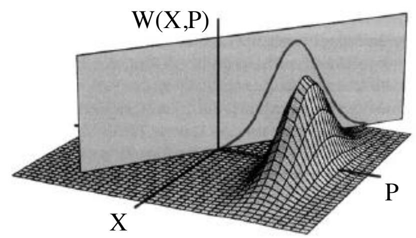
Homodyne detection, Wigner Function and Quantum Tomography

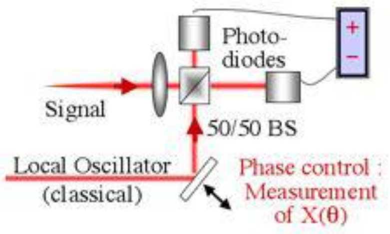


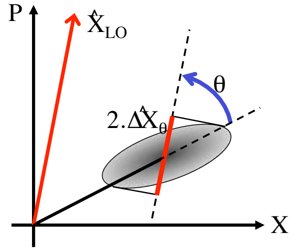
- **Quasiprobability density :**
  Wigner function W(X,P)
- **Marginals of W(X, P)**
  => Probability distributions $\mathcal{P}(X\theta)$
- **Probability distributions $\mathcal{P}(X\theta)$**
  => W(X, P) (quantum tomography)

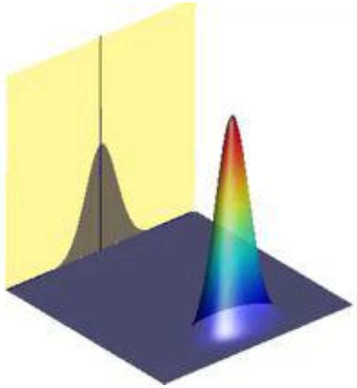




Homodyne detection, Wigner Function and Quantum Tomography



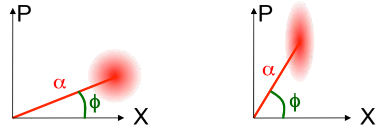




Squeezed State : Gaussian Wigner Functions

Quantum description of light

	Discrete — Photons	Continuous — Wave
Parameters :	Number & Coherence	Amplitude & Phase (polar) Quadratures X & P (cartesian)
Representation:	Density matrix	Wigner function W(X,P)
Measurement :	Counting : APD, VLPC, TES...	Demodulation : Homodyne detection
« Simple » states	Fock states (number states) Sources : - Single atoms or molecules - NV centers in diamond - Quantum dots - Parametric fluorescence	Gaussian states Sources : Lasers : coherent states Non-linear media : squeezed states



$\Delta X . \Delta P \geq 1/2$

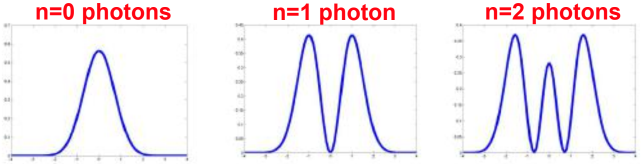
Non-Gaussian States

Basic question :

Consider a single photon : can we speak about its amplitude & phase? quadratures X & P ?

Single mode light field	⟺	Harmonic oscillator
Photons		Quanta of excitation
n photon state		n^{th} eigenstate
Probability $P_n(X)$		Probability $\|\Psi_n(x)\|^2$

$|\Psi_n(x)|^2$

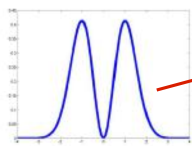


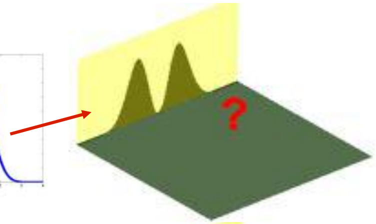
Non-Gaussian States

Basic question :

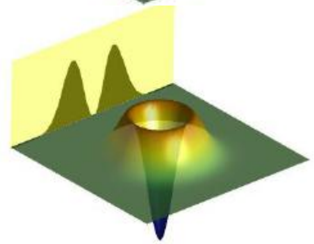
Consider a single photon : can we measure its amplitude & phase? quadratures X & P ?

Can the Wigner function of a Fock state n = 1 (with all projections have zero value at origin) be positive everywhere ?





NO ! The Wigner function must be negative
It is not a classical statistical distribution !



Hudson-Piquet theorem : for a pure state W is non-positive iff it is non-gaussian
Many interesting properties for quantum information processing

Wigner function of a single photon state ? (Fock state n = 1)

$$W(p,q) = \frac{1}{2\pi\, 2N_0} \int dx\, e^{\frac{ixp}{2N_0}} \langle\, q - \tfrac{x}{2} \,|\hat{\rho}|\, q + \tfrac{x}{2} \,\rangle$$

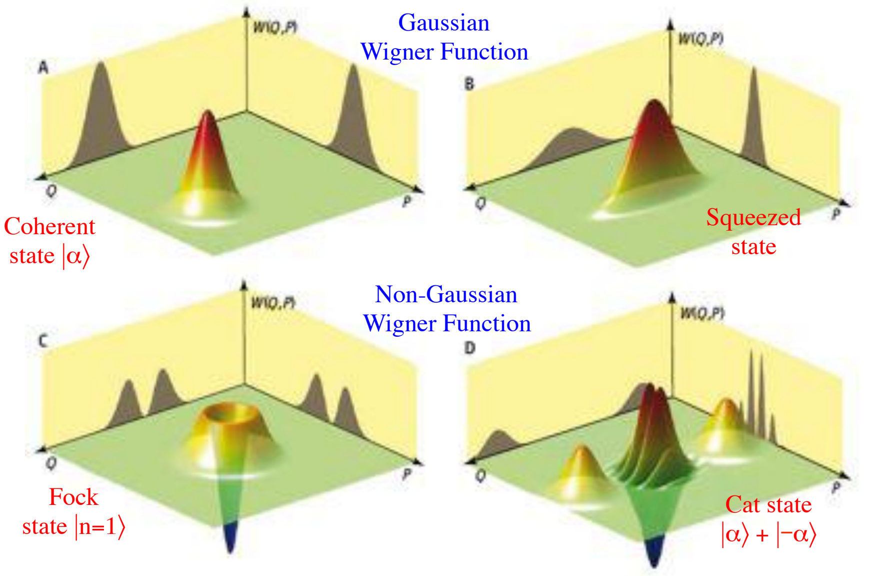
where $\hat{\rho} = |1\rangle\langle 1|$ and N_0 is the variance of the vacuum noise :

$$[\hat{Q}, \hat{P}] \equiv 2iN_0 \qquad \Delta P\, \Delta Q \geq N_0 \qquad N_0 = \Delta P^2 = \Delta Q^2.$$

One may have $N_0 = \hbar/2$, $N_0 = 1/2$ (theorists), $N_0 = 1$ (experimentalists)

Using the wave function of the n = 1 state : $\langle\, q \,|\, 1 \,\rangle = \dfrac{q}{(2\pi)^{\frac{1}{4}} N_0^{\frac{3}{4}}} e^{-\frac{q^2}{4N_0}}$

one gets finally : $W_{|1\rangle}(q,p) = -\dfrac{1}{2\pi N_0} e^{-\frac{r^2}{2N_0}} \left(1 - \dfrac{r^2}{N_0}\right) \qquad r^2 = q^2 + p^2$



P. Grangier, "Make It Quantum and Continuous", Science (Perspective) 332, 313 (2011)

Make It Quantum and Continuous

Philippe Grangier PERSPECTIVES SCIENCE VOL 332 15 APRIL 2011

Unconditional Quantum Teleportation

A. Furusawa, J. L. Sørensen, S. L. Braunstein, C. A. Fuchs, H. J. Kimble,* E. S. Polzik

23 OCTOBER 1998 VOL 282 SCIENCE

Quantum key distribution using gaussian-modulated coherent states NATURE | VOL 421 | 16 JANUARY 2003 |

Frédéric Grosshans*, Gilles Van Assche†, Jérôme Wenger*, Rosa Brouri*, Nicolas J. Cerf† & Philippe Grangier*

NATURE | VOL 432 | 25 NOVEMBER 2004 | www.nature.com/nature

Experimental demonstration of quantum memory for light

Brian Julsgaard[1], Jacob Sherson[1,2], J. Ignacio Cirac[3], Jaromír Fiurášek[4] & Eugene S. Polzik[1]

Vol 443|5 October 2006|doi:10.1038/nature05136

Quantum teleportation between light and matter

Jacob F. Sherson[1,3], Hanna Krauter[1], Rasmus K. Olsson[1], Brian Julsgaard[1], Klemens Hammerer[2], Ignacio Cirac[2] & Eugene S. Polzik[1]

PHYSICAL REVIEW A **68**, 042319 (2003)

Quantum computation with optical coherent states

T. C. Ralph,* A. Gilchrist, and G. J. Milburn
W. J. Munro S. Glancy

Generating Optical Schrödinger Kittens for Quantum Information Processing

Alexei Ourjoumtsev, Rosa Tualle-Brouri, Julien Laurat, Philippe Grangier*

SCIENCE VOL 312 7 APRIL 2006

Vol 448|16 August 2007|doi:10.1038/nature06054

Generation of optical 'Schrödinger cats' from photon number states

Alexei Ourjoumtsev[1], Hyunseok Jeong[2], Rosa Tualle-Brouri[1] & Philippe Grangier[1]

Teleportation of Nonclassical Wave Packets of Light

Noriyuki Lee,[1] Hugo Benichi,[1] Yuishi Takeno,[1] Shuntaro Takeda,[1] James Webb,[2] Elanor Huntington,[2] Akira Furusawa[1]*

15 APRIL 2011 VOL 332 SCIENCE

Small sample, many more papers !

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Content of the Lecture

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Part 1 - Quantum optics with discrete and continuous variables

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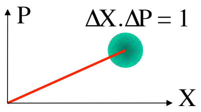
Part 3 - A close look to a nice single photon

3.1 Single photons: from old times to recent ones

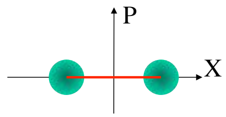
3.2 Experimental perspectives

« Schrödinger's Cat » state

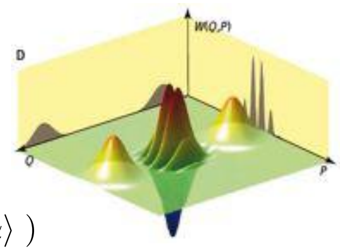
- Classical object in a quantum superposition of distinguishable states
- "Quasi - classical" state in quantum optics : coherent state $|\alpha\rangle$



Coherent state



Schrödinger cat state



$$|\psi_{odd\ cat}\rangle = c_o(\ |\alpha\rangle - |-\alpha\rangle\ )$$

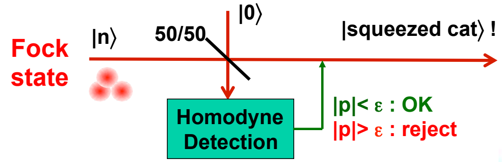
$$|\psi_{even\ cat}\rangle = c_e(\ |\alpha\rangle + |-\alpha\rangle\ )$$

Wigner function of a Schrödinger cat state

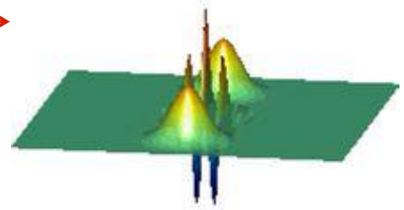
- Resource for quantum information processing
- Model system to study decoherence

How to create a Schrödinger's cat ?

Suggestion by Hyunseok Jeong, proofs by Alexei Ourjoumtsev :



Squeezed Cat state

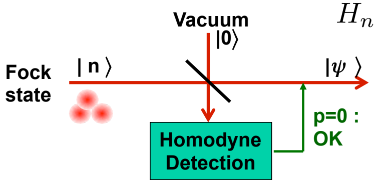


For n ≥ 3 the fidelity of the conditional state with a Squeezed Cat state is F ≥ 99%

$$S(r)(|\alpha\rangle + e^{i\theta}|-\alpha\rangle)$$

Size :	$\alpha^2 = n$
Same Parity as n :	$\theta = n^*\pi$
Squeezed by :	3 dB

Another hint…



$$H_n(p)\ e^{-p^2/2} \otimes H_0(p_0)\ e^{-p_0^2/2} \rightarrow$$

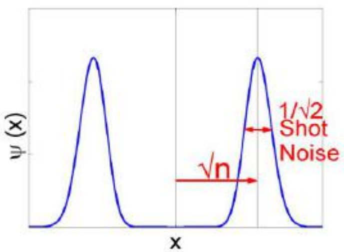
$$H_n((p-p_0)/\sqrt{2})\ e^{-(p-p_0)^2/4}\ e^{-(p+p_0)^2/4} =$$

$$H_n((p-p_0)/\sqrt{2})\ e^{-(p^2+p_0^2)/2}$$

$$H_n(p/\sqrt{2})\ e^{-p^2/2} \rightarrow x^n\ e^{-x^2/2}$$

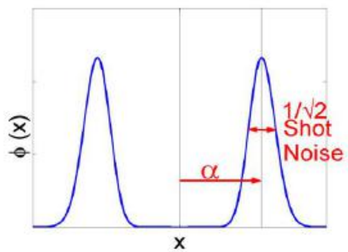
Fourier transform

Prepared state



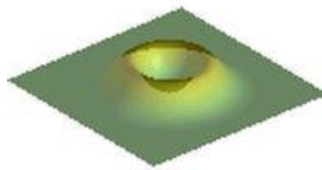
For a large n (n ≥ 3)

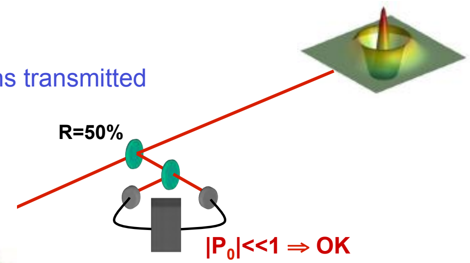
Cat state squeezed by 3 dB



The rebirth of the cat

- Make a n-photon Fock state
- 50/50 : ≈ n/2 photons transmitted



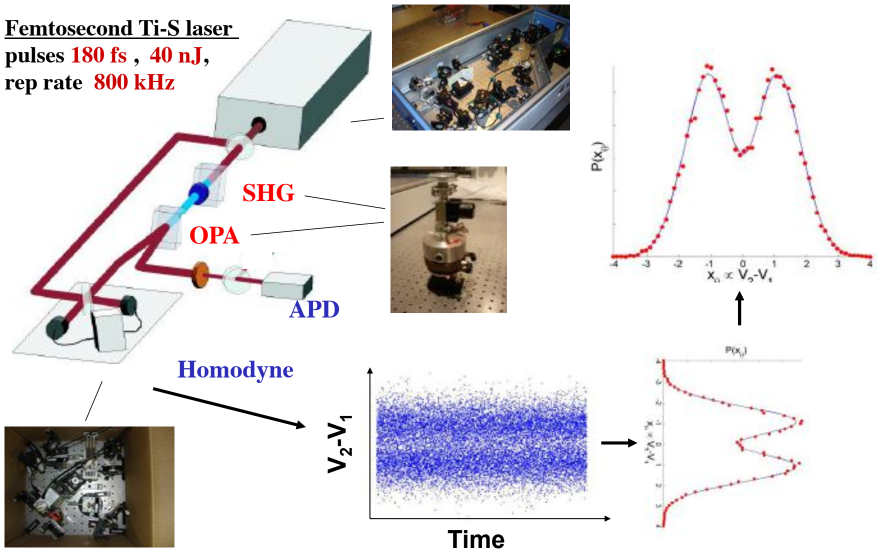


Homodyne measurement
- Phase dependence
- Parity measurement : $\langle P_0=0|2k+1\rangle = 0$
  Reflected : even number of photons
  Transmitted : same parity as n

Squeezed cat state (from n=2) = $\sqrt{2/3}\ |2\rangle - \sqrt{1/3}\ |0\rangle$

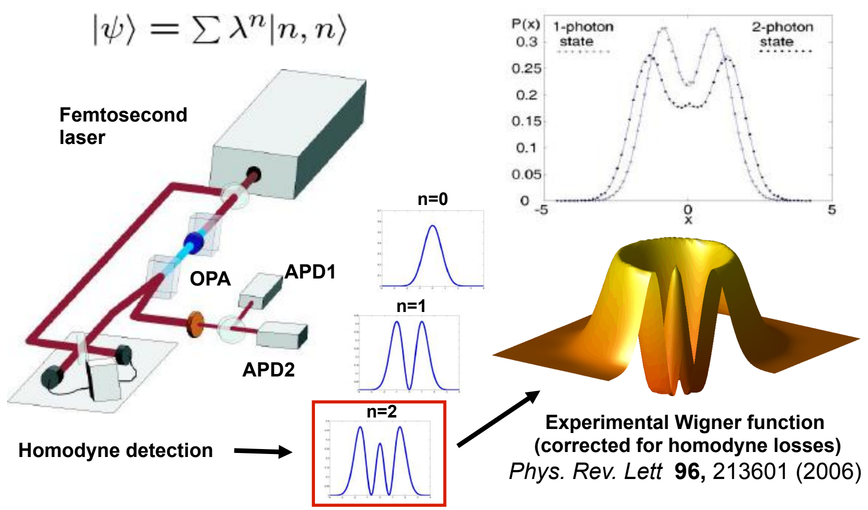
Experimental Set-up

Femtosecond Ti-S laser
pulses 180 fs , 40 nJ,
rep rate 800 kHz



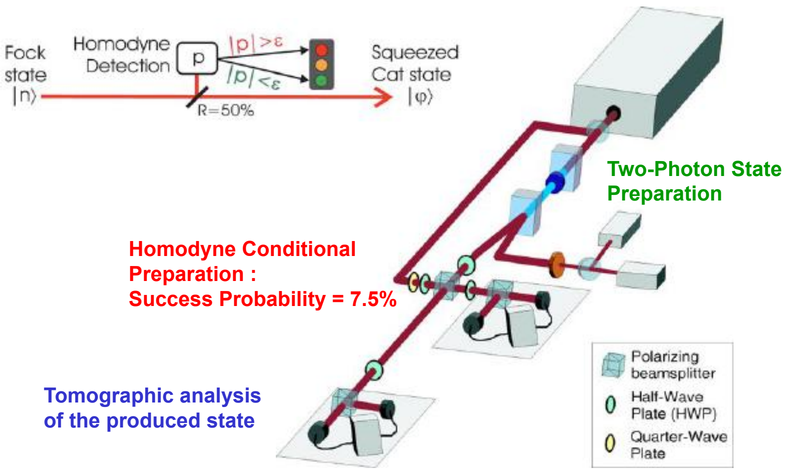
Resource : Two-Photon Fock States

$$|\psi\rangle = \sum \lambda^n |n, n\rangle$$



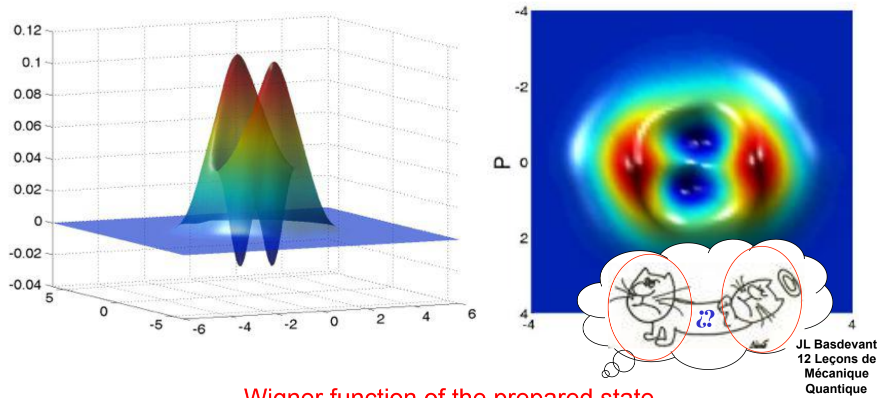
Experimental Wigner function
(corrected for homodyne losses)
Phys. Rev. Lett **96,** 213601 (2006)

Squeezed Cat State Generation



Experimental Wigner function

A. Ourjoumtsev et al, Nature 448, 784, 16 august 2007

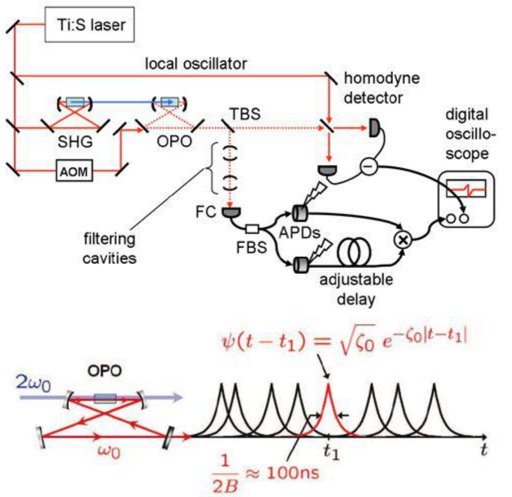


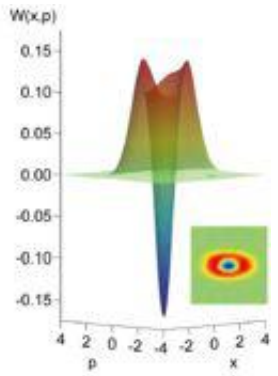
Wigner function of the prepared state
Reconstructed with a Maximal-Likelihood algorithm
Corrected for the losses of the final homodyne detection.

Bigger cats : NIST (Gerrits, 3-photon subtraction), ENS (Haroche, microwave cavity QED), UCSB…

Schrödinger cats with with continuous light beams

Groups of A. Furusawa (Tokyo), M. Sasaki (Tokyo), E. Polzik (Copenhagen), U. Andersen (Copenhagen), J. Laurat (Paris), ...

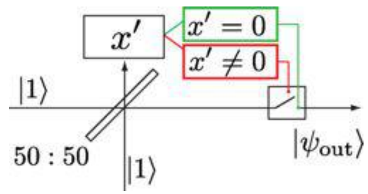




N. Lee et al, Science 332, 330 (2011)

Other methods for bigger / better cats...

J. Etesse, M. Bouillard, B. Kanseri, and R. Tualle-Brouri, Phys. Rev. Lett. 114, 193602 (2015)

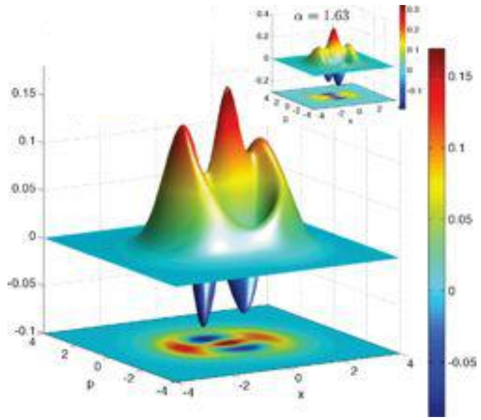


Conditionnally prepared state :

$$\psi_{out}(x)=\frac{1}{\sqrt{3}}|0\rangle+\sqrt{\frac{2}{3}}|2\rangle$$

Fidelity 99% with an even cat state with α = 1.63, squeezed by s = 1.52 along x :

$$\psi_{cat}(x)\simeq 0.61\,|0\rangle+0.79\,|2\rangle+\ldots$$

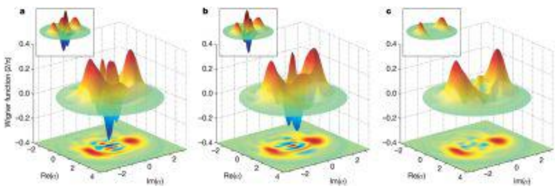


Reconstructed Wigner function, corrected for losses.

Schrödinger cats with microwaves in superconducting cavities

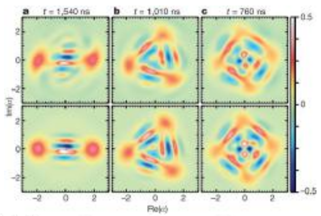
Some examples...

Serge Haroche group
(cacity QED, Paris)
Nature 455, 510 (2008)

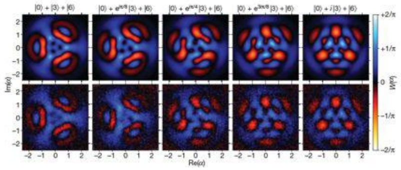


$$W(\alpha)=\frac{2}{\pi}\langle\psi|D^{\dagger}(-\alpha)\Pi\,D(-\alpha)|\psi\rangle$$

Rob Schoelkopf group
(circuit QED, Yale)
Nature 495, 205 (2013)
Cats with 2, 3 or 4 "legs"...



John Martinis group
(circuit QED, Santa Barbara)
Nature 459, 546 (2009)
Quantum state synthetizer



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Content of the Lecture

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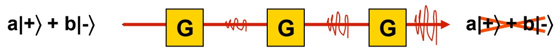
Long distance quantum communications

How to fight against line losses ?

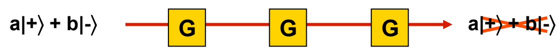
~~Amplification~~



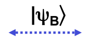
Long distance quantum communications

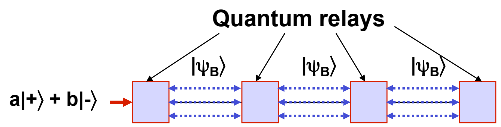
How to fight against line losses ?

~~Amplification~~



1. Exchange of entangled states





Long distance quantum communications

How to fight against line losses ?

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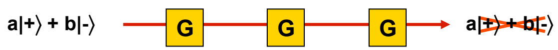

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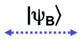
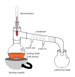
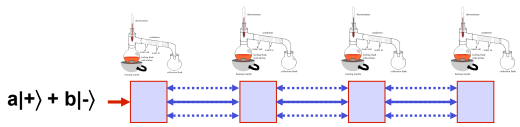


2. Entanglement distillation

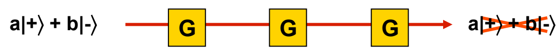




Long distance quantum communications

How to fight against line losses ?

~~Amplification~~



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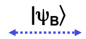

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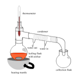
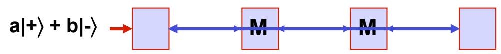


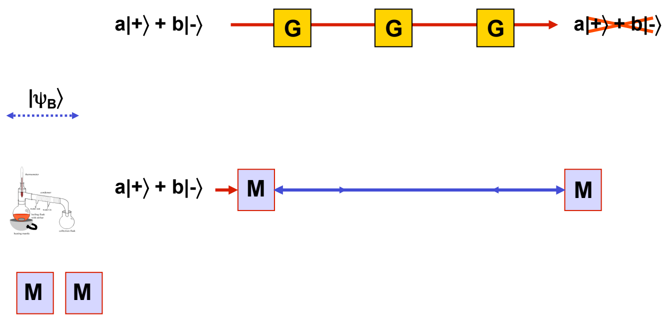


Long distance quantum communications

How to fight against line losses ?

~~Amplification~~

1. Exchange of entangled states
2. Entanglement distillation
3. Entanglement swapping

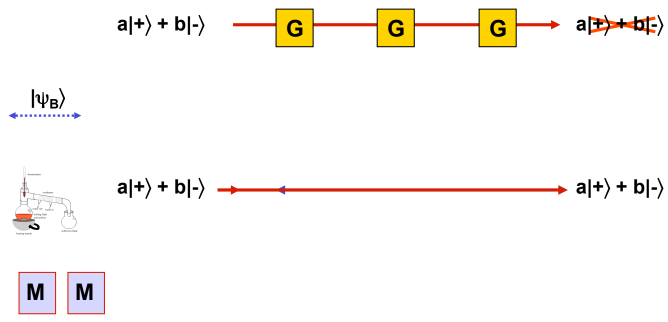


Long distance quantum communications

How to fight against line losses ?

~~Amplification~~

1. Exchange of entangled states
2. Entanglement distillation
3. Entanglement swapping
4. Quantum teleportation



One needs to : * distribute (many) entangled states
*** store them (quantum memories)**
*** process them (distillation)**

Quantum Teleportation

C. H. Bennett et al, 1993

Qubit in an unknown state Ψ

* one cannot « read » it

* one cannot duplicate it

(« non-cloning » theorem)

* but it is possible to « teleport » it ?

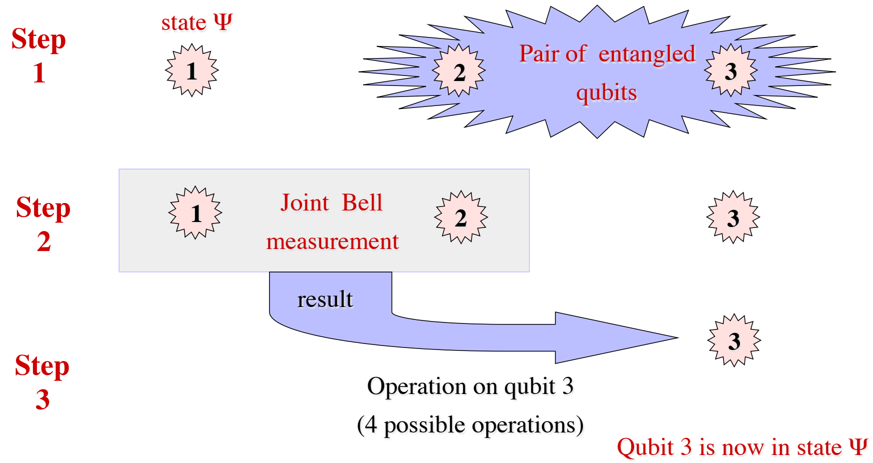
(= to make a remote copy,

destroying the original)

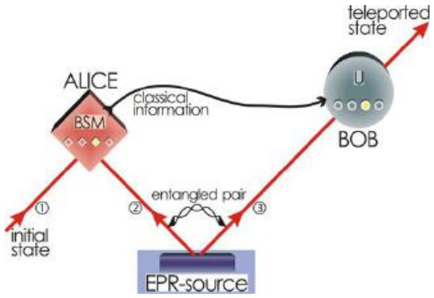
The answer is yes !

Quantum Teleportation

C. H. Bennett et al, 1993



Quantum Teleportation



$$|\Psi\rangle_{123} = |\Phi\rangle_1 \otimes |\Phi^+\rangle_{23}$$
$$= |\Phi^+\rangle_{12} \otimes (\alpha|0\rangle_3 + \beta|1\rangle_3) +$$
$$|\Phi^-\rangle_{12} \otimes (\alpha|0\rangle_3 - \beta|1\rangle_3) +$$
$$|\Psi^+\rangle_{12} \otimes (\alpha|1\rangle_3 + \beta|0\rangle_3) +$$
$$|\Psi^-\rangle_{12} \otimes (\alpha|1\rangle_3 - \beta|0\rangle_3),$$

Initial state

$$|\Phi\rangle_1 = \alpha|0\rangle_1 + \beta|1\rangle_1$$

The shared entangled pair

$$|\Phi^+\rangle_{23} = \frac{1}{\sqrt{2}}(|0\rangle_2|0\rangle_3 + |1\rangle_2|1\rangle_3)$$

where

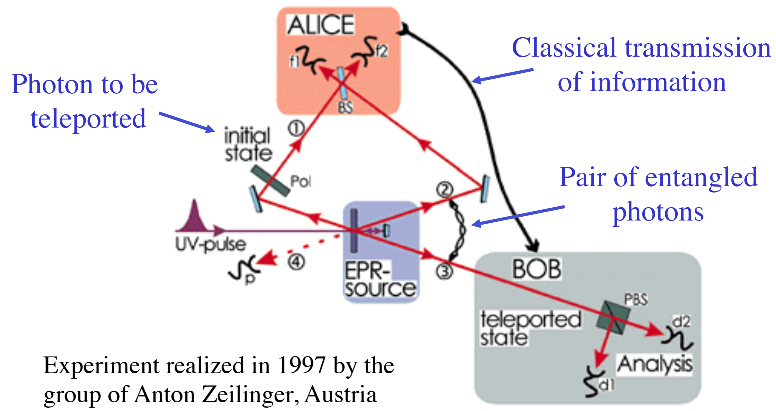
$$|\Phi^\pm\rangle_{12} = \frac{1}{\sqrt{2}}(|0\rangle_1|0\rangle_2 \pm |1\rangle_1|1\rangle_2)$$

$$|\Psi^\pm\rangle_{12} = \frac{1}{\sqrt{2}}(|0\rangle_1|1\rangle_2 \pm |1\rangle_1|0\rangle_2)$$

Bennett, Brassard, Crepeau, Josza, Peres, Wooters 1993

Quantum Teleportation with Photons

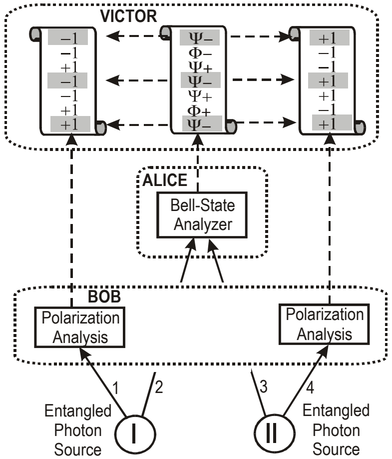
Institut d'Optique



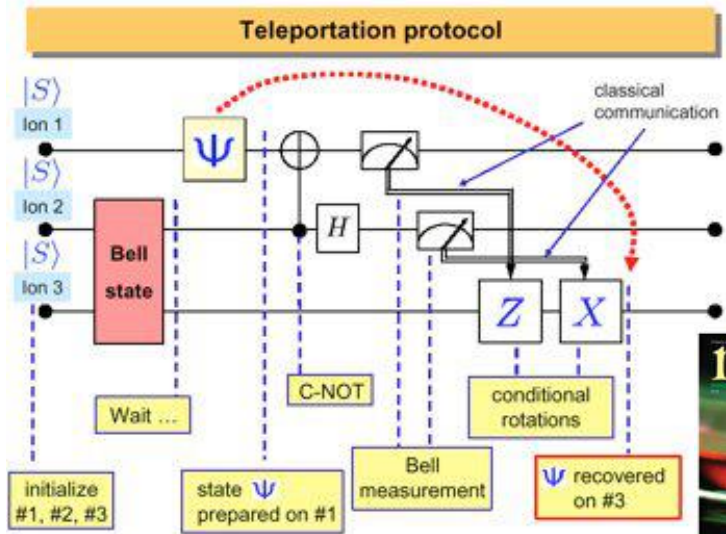
Experiment realized in 1997 by the group of Anton Zeilinger, Austria

Drawback of this scheme: only one Bell state out of 4 can be identified

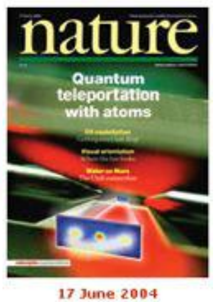
Entanglement swapping



- Two entangled pairs 12 and 34
- Bell measurement by Alice on photons 2 and 3
- Photon 1 and 4 become entangled without having ever met !
- This can be checked using a Bell test between 1 and 4.
- With photons + beam-splitter + counters the Bell state analysis remains incomplete

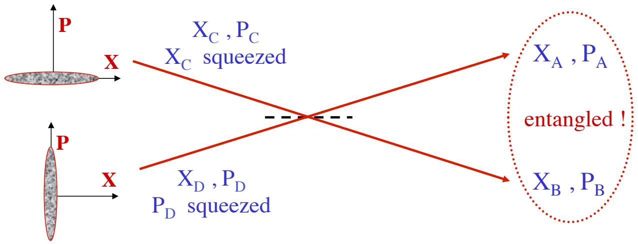


Innsbruck University + NIST Boulder 2004



How to produce CV entangled beams ?

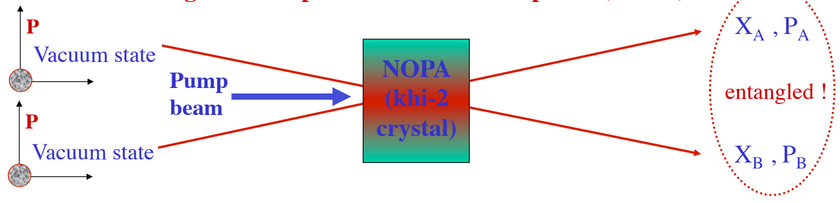
1. Combine two orthogonally squeezed beams



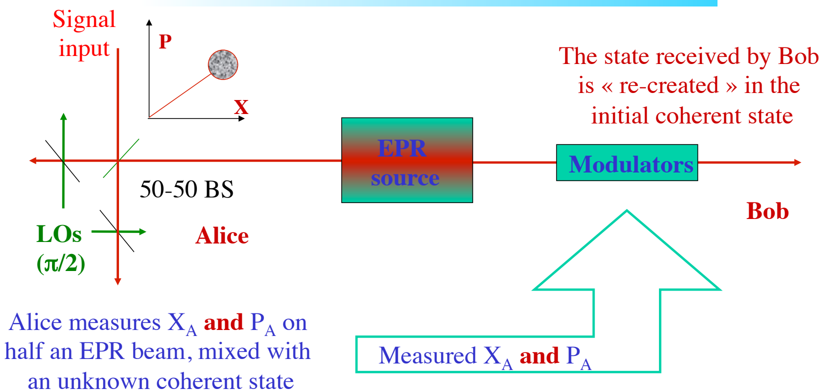
$$X_C = (X_A + X_B)/\sqrt{2}$$
$$P_C = (P_A + P_B)/\sqrt{2}$$
$$X_D = (X_A - X_B)/\sqrt{2}$$
$$P_D = (P_A - P_B)/\sqrt{2}$$

OK !

2. Use a Non-degenerate Optical Parametric Amplifier (NOPA)



Quantum teleportation of coherent states

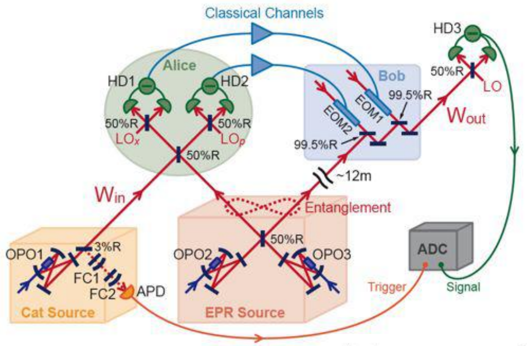


The state received by Bob is « re-created » in the initial coherent state

Alice measures X_A **and** P_A on half an EPR beam, mixed with an unknown coherent state

Experiments :
A. Furusawa et al, Science **282**, 706 (1998)
W. Bowen et al, Phys. Rev. A **67**, 032302 (2003)
T.C. Zhang et al, Phys. Rev. A **67**, 033802 (2003)

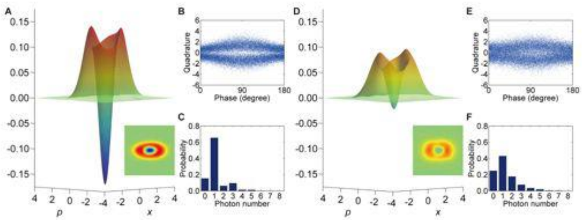
Quantum teleportation of cat states



The state received by Bob is « re-created » in the initial cat state (with some loss in fidelity : 0.75 => 0.45)

Experiment : N. Lee et al, Science **332**, 330-333 (2011).
Remark : the initial squeezed state is CW, not pulsed !

Alice measures X_A **and** P_A on half an EPR beam, mixed with a cat state (obtained from photon subtraction)



Advances in Quantum Teleportation

arXiv:1505.07831

Stefano Pirandola, Jens Eisert, Christian Weedbrook, Akira Furusawa, Samuel L. Braunstein

Quantum Technology		Efficiency	Fidelity	Distance	Memory
Photonic qubits	Polarisation[16,17,21,22]	$\lesssim 50\%^{\dagger}$	$\gtrsim 83\%$ [22]	143 km[22]	N/A‡
	Time-bins [23–25]	25%	81%▲[23]	6 km fibre[24]	
	Dual-rails on chip[26]	1/27	89%◊	On chip	
	Spin-orbital qubits[27]	1/32	$\gtrsim 57\%$▵	Table-top	
NMR[28]		100%	$\simeq 90\%$■	$\simeq$1 Å	$\simeq$ 1 s
Optical modes	CVs[29–36]	100%	83%[36]	12 m[35]	N/A‡
	Hybrid[37]	100%	$\gtrsim 80\%$	Table-top	
Atomic ensembles	(hot) CV light-to-matter[38]	100%	58%	Table-top	4 ms[131]
	(hot) CV matter-to-matter[39]	100%	$\gtrsim 55\%$	0.5 m	
	(cold) DV light-to-matter[40]	50%	78%	7 m fibre	100 ms[132]
	(cold) DV matter-to-matter[41]	50%	88%	150 m fibre	
Trapped atoms	Trapped ions[42–44]	100%	83%[44]	5 μm[43]	$\simeq$ 50 s★[135]
	Trapped ions & photonic carriers[45]	25%	90%	1 m	
	Neutral atoms in an optical cavity[46]	25%	88%	21 m fibre	184 μs[136]
Solid state	Frequency qubit to quantum dot[47]	25%	78%§	5 m	$\gtrsim$ 1 μs★[137]
	Polarisation qubit to rare-earth crystal[48]	25%	89%	10 m, 24.8 km fibre□	1 ms[138], $\simeq$ 6 hours★[133]
	Superconducting qubits on chip[49]	100%	77%, 69%♦	On chip (6 mm)	$\lesssim$ 100 μs★[139,140]
	Nitrogen-vacancy centres in diamonds[50]	100%	86%	3 m	$\simeq$ 0.6 s▽[141], $\gtrsim$ 1 s▼[134]

Content of the Lecture

Part 1 - Quantum optics with discrete and continuous variables

1.1 Homodyne detection and quantum tomography

1.2 Generating non-Gaussian Wigner functions : kittens, cats and beyond

Part 2 - Towards optical quantum networks

2.1 Entanglement, teleportation, and quantum repeaters

2.2 Some experimental achievements

Part 3 - A close look to a nice single photon

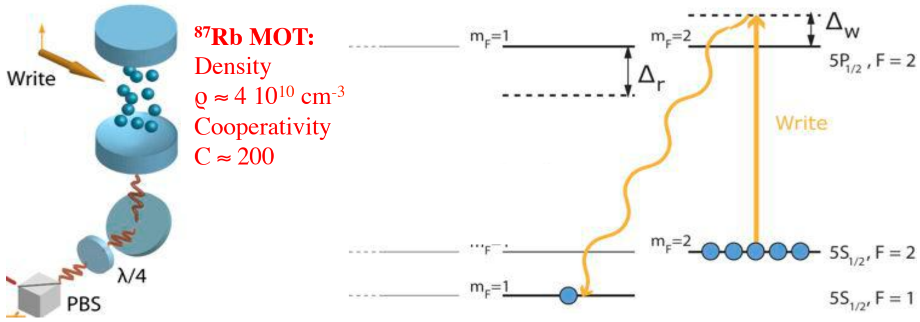
3.1 Single photons: from old times to recent ones

3.2 Experimental perspectives

Single Photon from a single polariton (DLCZ protocol)

L.M. Duan, M.D. Lukin, J.I. Cirac, and P. Zoller, Nature 414, 413 (2001)

^{87}Rb MOT:
Density
$\varrho \approx 4\ 10^{10}$ cm^{-3}
Cooperativity
$C \approx 200$



E. Bimbard et al, arXiv:1310.1228 (2013), PRL 112, 033601 (2014)

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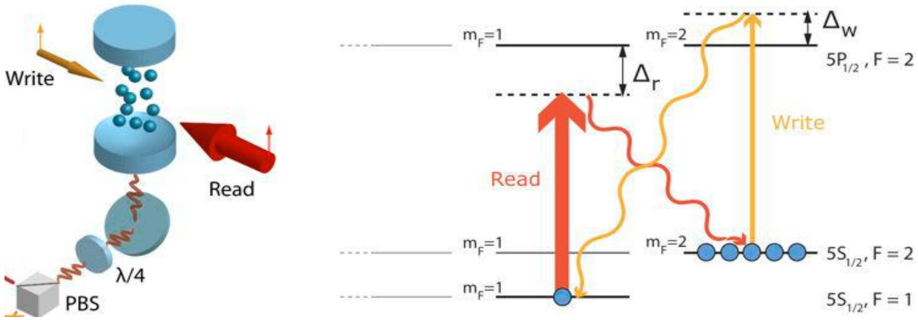

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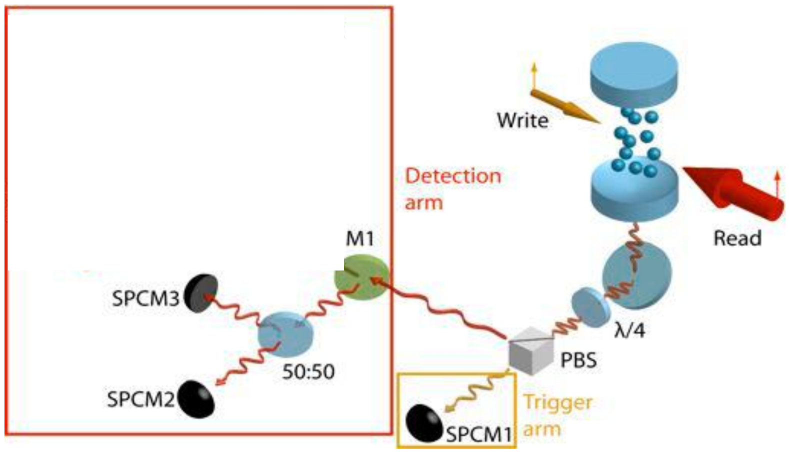

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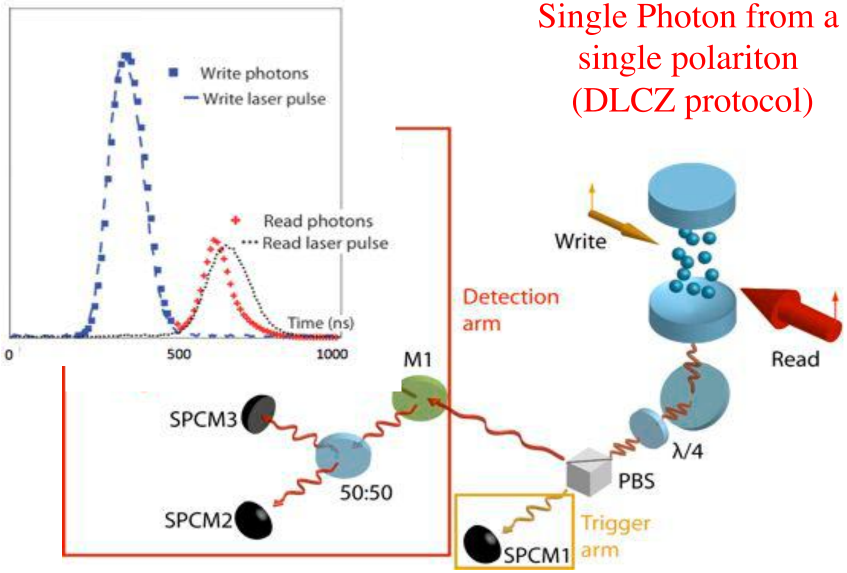

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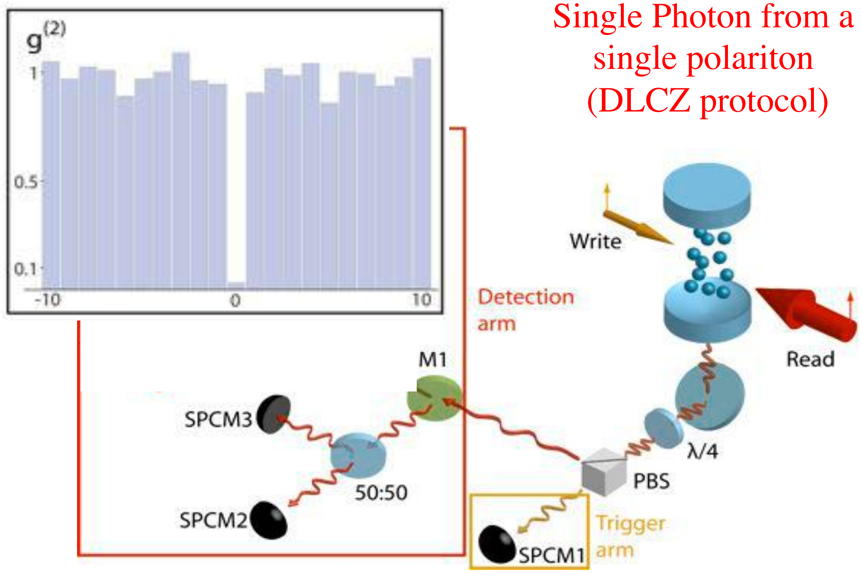

E. Bimbard et al, arXiv:1310.1228 (2013), PRL 112, 033601 (2014)

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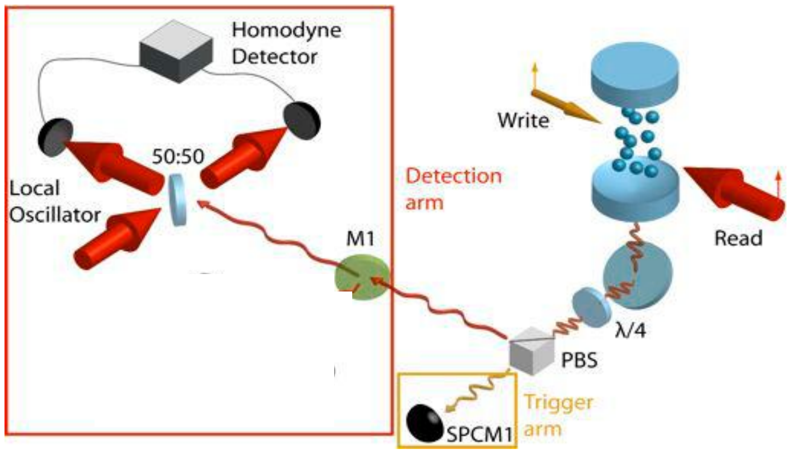
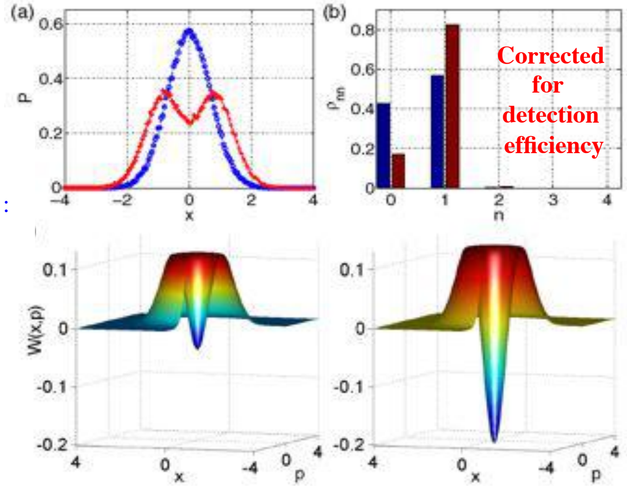


E. Bimbard et al, arXiv:1310.1228 (2013), PRL 112, 033601 (2014)

Single Photon from a single polariton (DLCZ protocol)

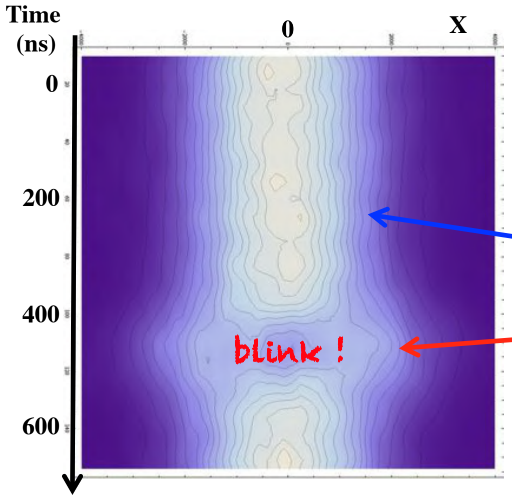
Overall detection efficiency : 57%



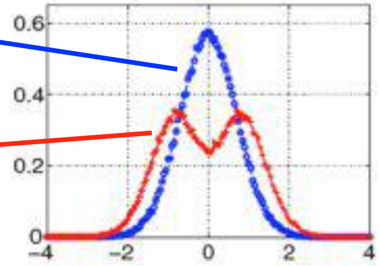
Overall extraction efficiency : 82%

E. Bimbard et al, arXiv:1310.1228 (2013), PRL 112, 033601 (2014)

Looking at the Blinking Photon

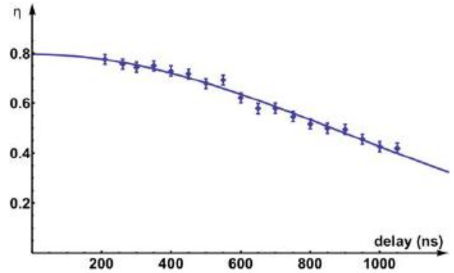


Density plot of homodyne data, time averaged with the expected "photon wave packet" duration



Single Photon from a single polariton (DLCZ protocol)

Quantum memory effect : the memory time (1 μs) is limited by motional decoherence due to finite temperature (50 μK)



$$\eta = P_{Doppler}(t) \times P_{Coop} \times P_{Read} \times P_{Pumping} \times P_{Mode} \times P_{Cav}$$

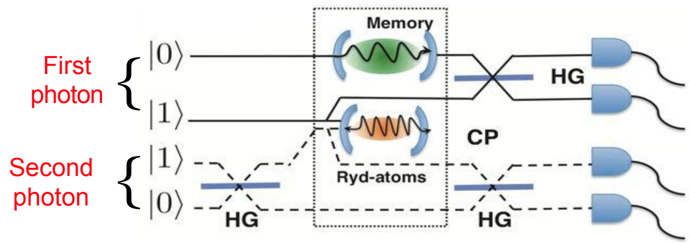
0.94 × 0.97 × 0.96 × 0.965 × 0.97 = 0.82 : ok !

E. Bimbard et al, arXiv:1310.1228 (2013), PRL 112, 033601 (2014)

Photonic Controlled-Phase Gates Through Rydberg Blockade in Optical Cavities

S. Das, A. Grankin, I. Iakoupov, E. Brion, J. Borregaard, R. Boddeda, I. Usmani, A. Ourjoumtsev, P. Grangier, A. S. Sørensen, **arxiv:1506.04300**

Dual-rail photonic gate (used here for a Bell measurement)



Significant increase in the swap efficiency in a quantum repeater scheme, compared to linear quantum gates (with efficiency bounded to 50%)

=> secret bit rate increased by about one order of magnitude.

See also : J. Borregaard et al, arXiv:1504.03703 (2015).

(Temporary) Conclusion

Many potential uses for Quantum Continuous Variables...

* Conditional preparation of « squeezed » non-gaussian pulses / cats
  * Big family of phase-dependant states with negative Wigner functions !
  * Many new experimental results...

* Quantum cryptography
* Coherent states protocols using reverse reconciliation, secure against any (gaussian or non-gaussian) collective attack
* Working fine in optical fibers @1550 nm (SECOQC, SeQureNet...)

* Quantum repeaters
* Basic elements do work in proof-of-principle experiments...
* … but not well enough yet to get a whole system with acceptable efficiency.
* So more work is needed, both on theory and implementations...