Quantum Optics and Quantum Communications using Gaussian and Non-Gaussian States of the Light

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Content of the Talk

Part 1 : Gaussian and non-Gaussian states

1. Homodyne detection and quantum tomography

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

Part 2 : Continuous variable quantum cryptography (Gaussian !)

1. Continuous variable quantum cryptography : principles
2. Continuous variable quantum cryptography : implementations

Part 3 : Towards quantum networks (non-Gaussian !)

1. Entanglement for continuous variable quantum networks
2. Teleportation of Schrödinger's cats
3. Storing non-Gaussian states : single photon quantum memory

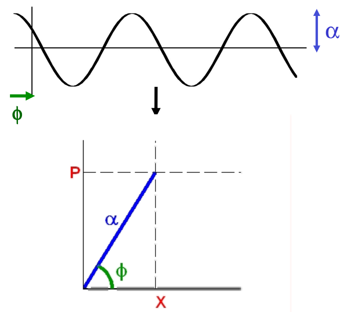
Quantum description of light

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

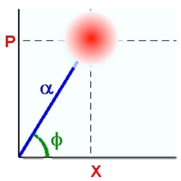
	Discrete – Photons	Continuous – Wave
Parameters :	Number of photons n	Amplitude & Phase (polar)
	Coherences < n | ρ | m >	Quadratures X & P (cartesian)



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)

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



$X = (a + a^+)/\sqrt{2}$

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

$[X, P] = i$

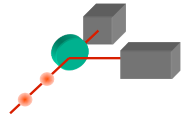
Heisenberg : $\Delta X . \Delta P \geq 1/2$

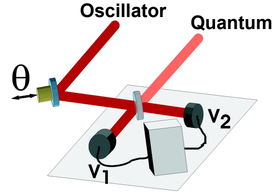
~~measurement of both X and P~~

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 :

$V_1 - V_2 \propto E_{OL} E_{EQ}(\theta)$

$\propto X_\theta = X\cos\theta + P\sin\theta$

Homodyne detection

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

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

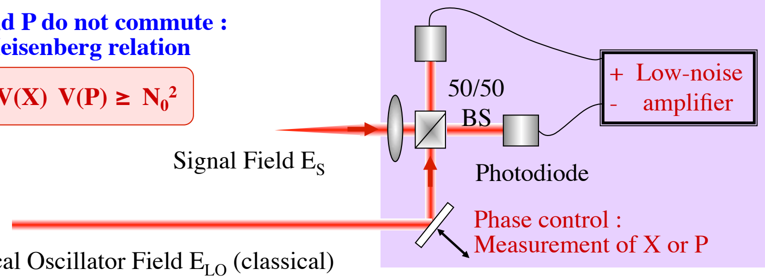
$I_1 - I_2 = |E_{LO}| (E_S e^{-i\theta_{LO}} + E_S^* e^{i\theta_{LO}})$

$= |E_{LO}| (E_S + E_S^*)$ **X meas.**

$= |E_{LO}| \, i (E_S - E_S^*)$ **P meas.**

X and P do not commute :
Heisenberg relation

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



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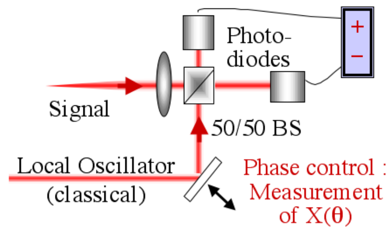
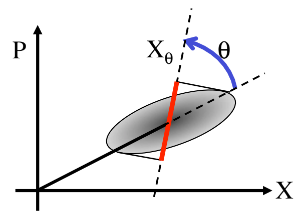
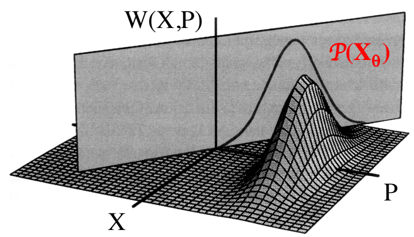
Homodyne detection, Wigner Function and Quantum Tomography

CNRS — QIPC

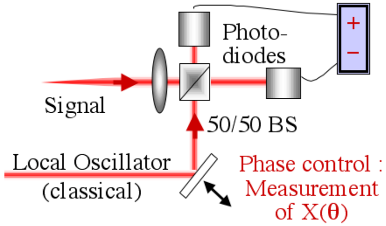


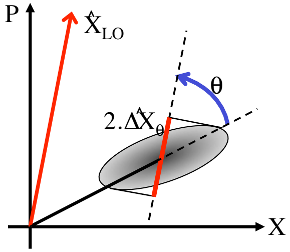
- **Quasiprobability density :**
  Wigner function W(X,P)
- **Marginals of W(X, P)**
  => Probability distributions $\mathcal{P}(X_\theta)$
- **Probability distributions $\mathcal{P}(X_\theta)$**
  => W(X, P) (quantum tomography)

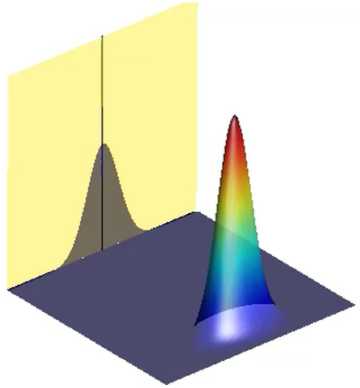




Homodyne detection, Wigner Function and Quantum Tomography







Squeezed State :
Gaussian Wigner Functions

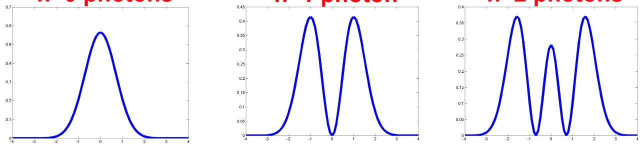
Non-Gaussian States

Basic question :

Consider a single photon : can we measure 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 $|\Psi_n(x)|^2$

$|\Psi_n(x)|^2$

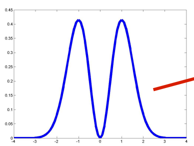


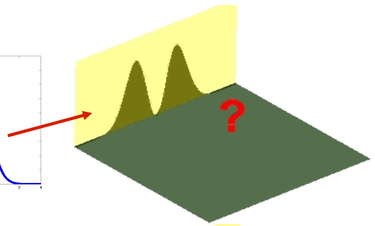
Non-Gaussian States

Basic question :

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

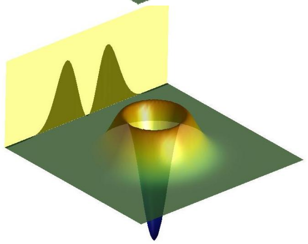
Can the Wigner function of a Fock state n = 1 (with all projections have zero value at origin) be positive everywhere ?





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)

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

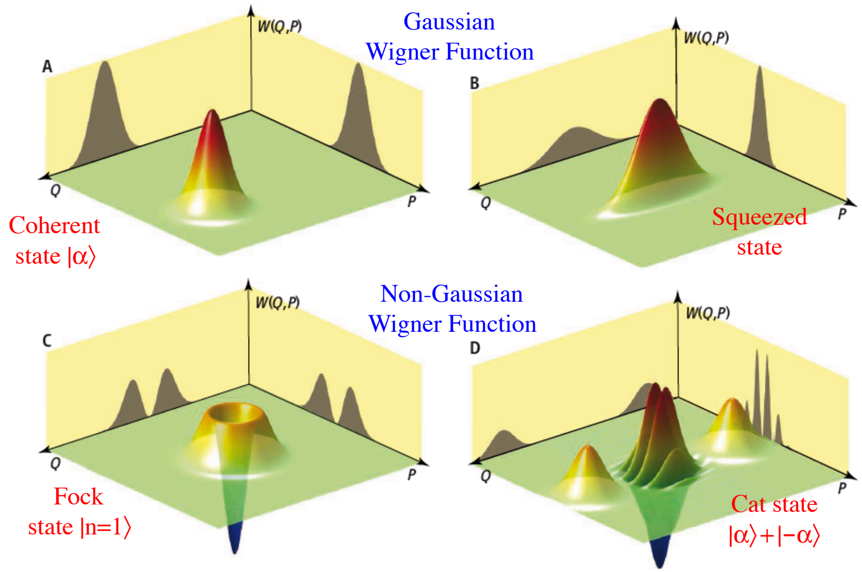
where $\hat{\rho} = |1\rangle\langle 1|$ and N_0 is the variance of the vacuum noise :

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

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 : $\langle q | 1 \rangle = \frac{q}{(2\pi)^{\frac{1}{4}} N_0^{\frac{3}{4}}} e^{-\frac{q^2}{4N_0}}$

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



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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QIPC

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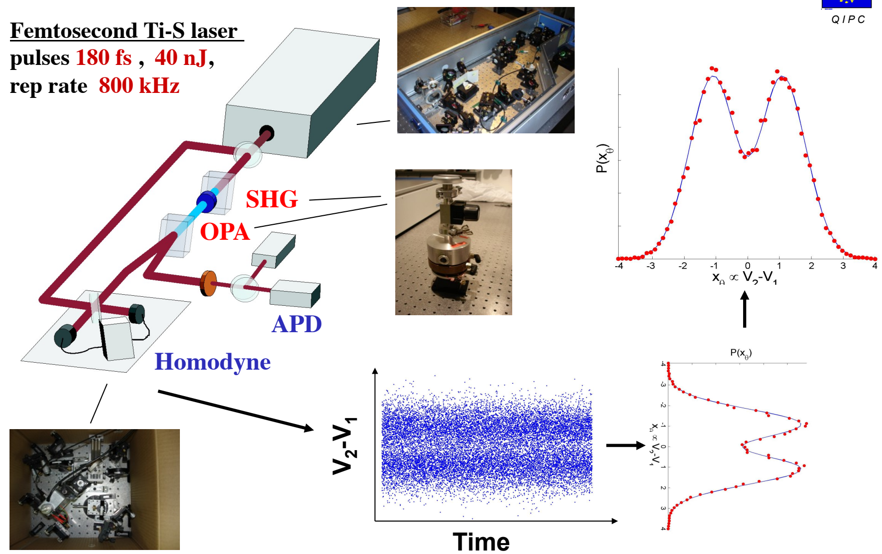
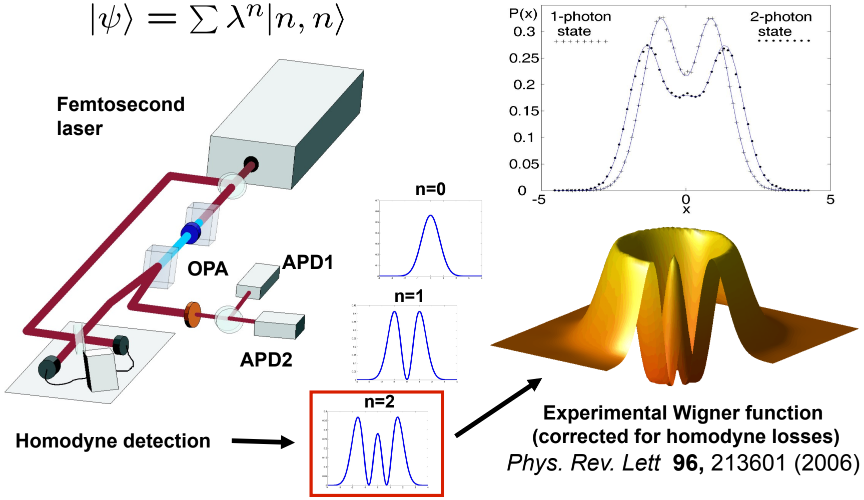
Experimental Set-up



Resource : Two-Photon Fock States

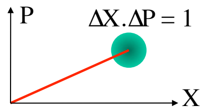
$$|\psi\rangle = \sum \lambda^n |n,n\rangle$$



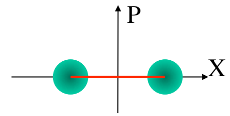
Experimental Wigner function (corrected for homodyne losses)
Phys. Rev. Lett **96,** 213601 (2006)

« Schrödinger's Cat » state

- Classical object in a quantum superposition of distinguishable states
- "Quasi - classical" state in quantum optics : coherent state | α 〉



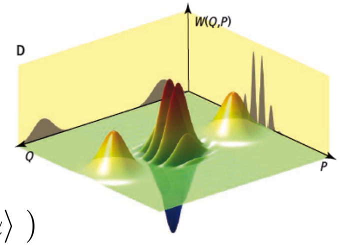
Coherent state



Schrödinger cat state

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

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

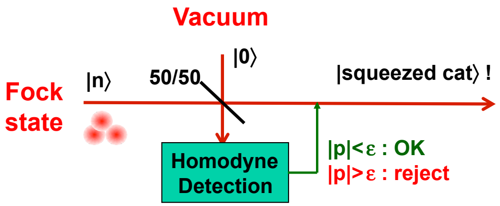


Wigner function of a Schrödinger cat state

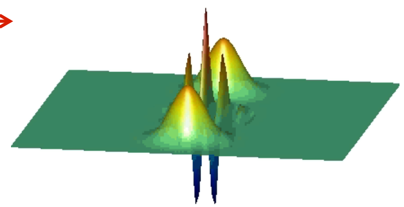
- Resource for quantum information processing
- Model system to study decoherence

How to create a Schrödinger's cat ?

Suggestion by Hyunseok Jeong, calculations by Alexei Ourjoumtsev :



Squeezed Cat state

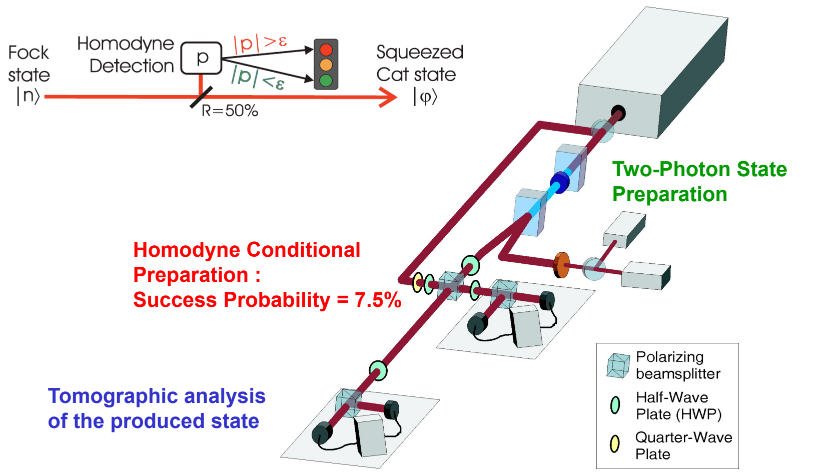


For n ≥ 3 the fidelity of the conditional state with a Squeezed Cat state is F ≥ 99%

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

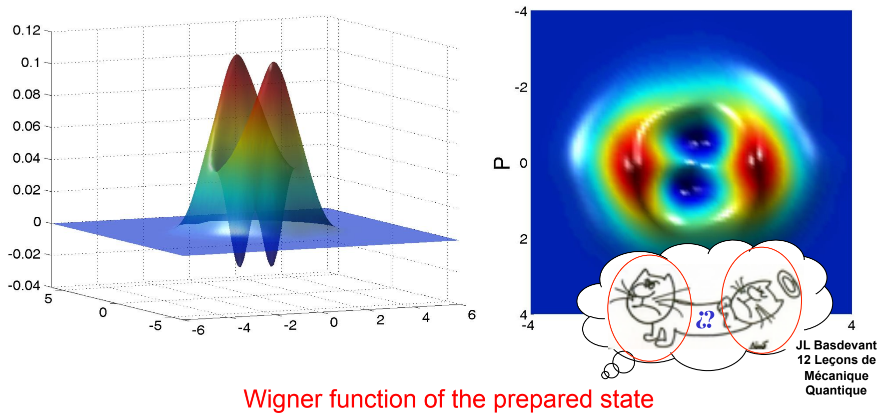
Size :	$\alpha^2 = n$
Same Parity as n :	$\theta = n{*}\pi$
Squeezed by :	3 dB

Squeezed Cat State Generation



Experimental Wigner function

A. Ourjoumtsev et al, Nature 448, 784 (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…

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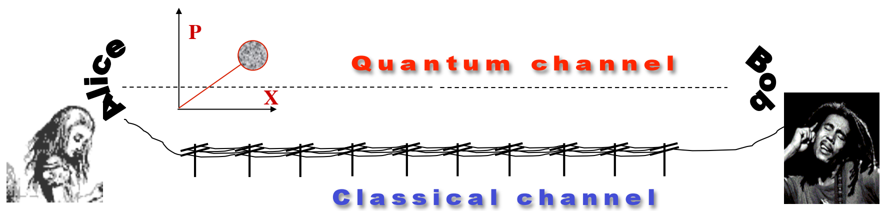
Coherent States Quantum Key Distribution

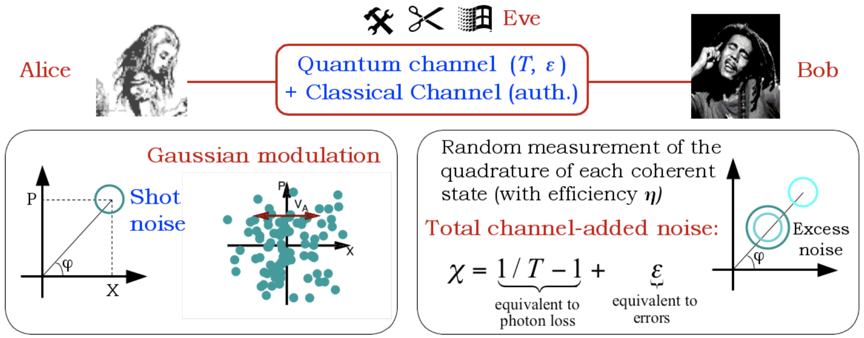


* Essential feature : quantum channel with non-commuting quantum observables
-> not restricted to single photon polarization or phase !

-> Design of Continuous-Variable QKD protocols where :
* The non-commuting observables are the quadrature operators X and P
* The transmitted light contains weak coherent pulses (about 10 photons) with a gaussian modulation of amplitude and phase
* The detection is made using shot-noise limited homodyne detection

Coherent state continuous variables QKD protocol

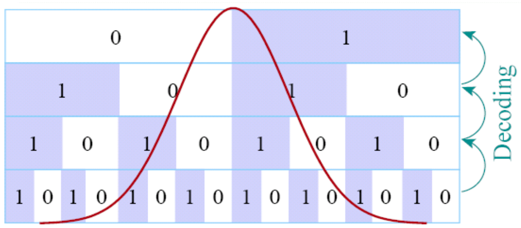
- Key information encoded in both quadratures of a coherent state



- Bob reveals measurement choice
- Alice and Bob share a set of Gaussian correlated data
- Further communication to calculate channel parameters and derive secret key based on Bob's data → **reverse reconciliation**

F. Grosshans et al, Phys. Rev. Lett. 88, 057902 (2002) & Nature 421, 238 (2003)

Reconciliation of correlated Gaussian variables

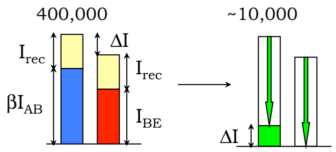


- Each level has a different error rate
- Non-independent levels

→ Error correction performed using multi-level iterative soft decoding with LDPC codes

G. Van Assche et al, IEEE Trans. on Inf. Theory 50, 394 (2004)
M. Bloch et al, arXiv:cs.IT/0509041 (2005)

- Standard privacy amplification based on universal hash functions
- Small processing time



Security of coherent state CV-QKD protocol

- Security initially proven against (arbitrary) individual attacks :
  F. Grosshans et al, Nature 421, 238 (2003)
  F. Grosshans and N. J. Cerf, Phys. Rev. Lett. 92, 047905 (2004)
- Then security proven against arbitrary collective attacks :
  F. Grosshans, Phys. Rev. Lett. 94, 020504 (2005)
  M. Navasqués and A. Acin, Phys. Rev. Lett. 94, 020505 (2005)
- For both individual and collective attacks Gaussian attacks are optimal
  → Alice and Bob consider Eve's attacks Gaussian and estimate her information using the Shannon quantity I_{BE} or the Holevo quantity χ_{BE}
  M. Navasqués et al, Phys. Rev. Lett. 97, 190502 (2006)
  R. García-Patrón et al, Phys. Rev. Lett. 97, 190503 (2006)

proofs of unconditional security (against coherent attacks)
coherent attacks are not better than collective attacks.
R. Renner and J.I. Cirac, Phys. Rev. Lett. 102, 110504 (2009)

Recent results :
Finite size effects : A. Leverrier, F. Grosshans and P. Grangier, Phys. Rev. A 81, 062343 (2010)
Composable security proof : A. Leverrier, Phys. Rev. Lett. (2014)

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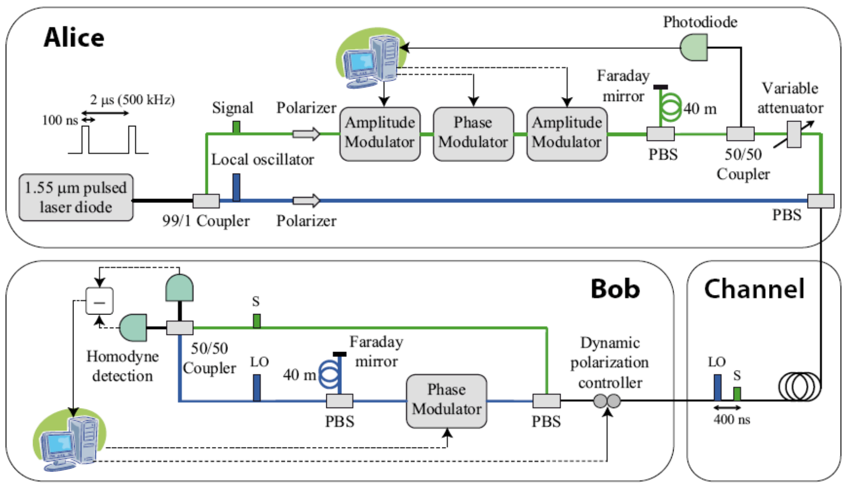
All-fibered CVQKD @ 1550 nm

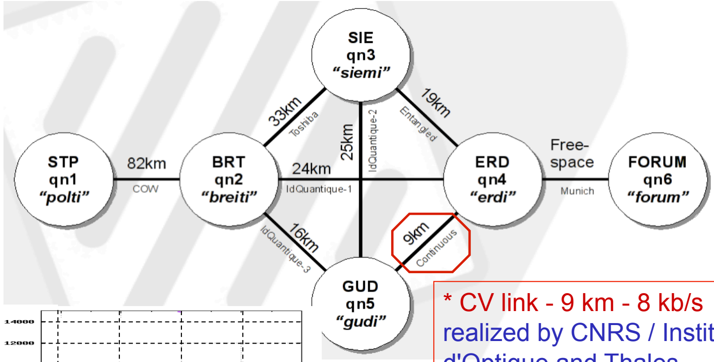
SECOQC



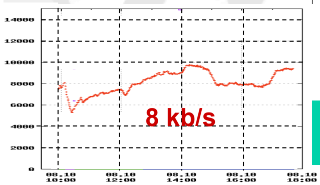
Field test of a continuous-variable quantum key distribution prototype
S Fossier, E Diamanti, T Debuisschert, A Villing, R Tualle-Brouri and P Grangier
New J. Phys. 11 No 4, 04502 (April 2009)

The SECOQC Quantum Back Bone

Real-size demonstration of a **secure quantum cryptography network** by the European Integrated Project SECOQC, Vienna, 8 october 2008

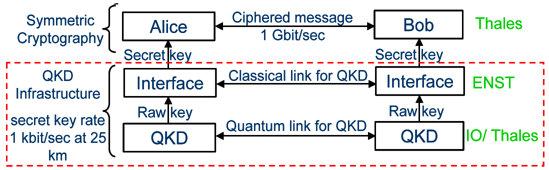


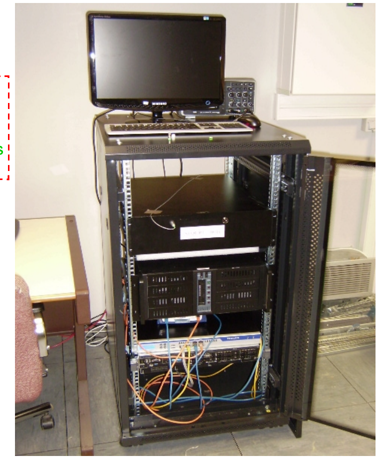
* CV link - 9 km - 8 kb/s realized by CNRS / Institut d'Optique and Thales



CV secret bit rate during the demo (8h)

Symmetric Encryption with QUantum key REnewal SEQURE

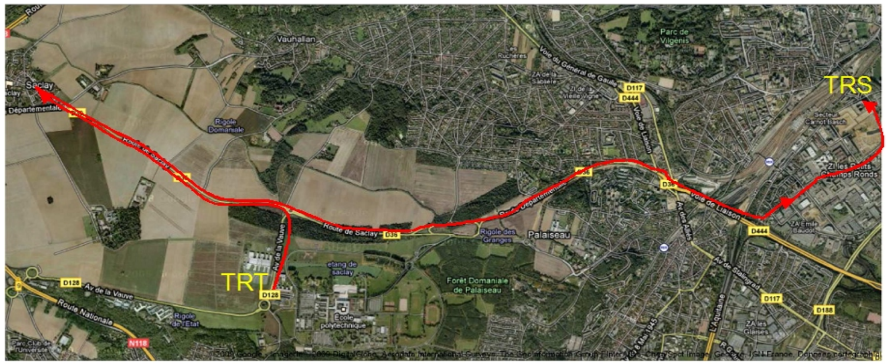




- Thales : Mistral Gbit

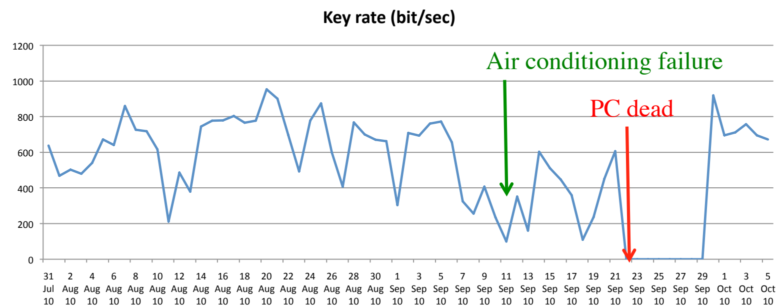
Field implementation

- Fibre link : Thales R&T (Palaiseau) <-> Thales Raytheon Systems (Massy)
- Fiber length about 12 km, 5.6 dB loss



Results

On site, 12 km distance, 5.6 dB loss
Minimal direct action on hardware (feedback loops, remote control)



See http://www.demo-sequre.com

Post-processing at SeQureNet

SEQURENET – A Quantum Key to Network Security

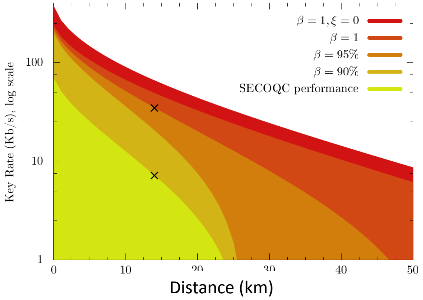
Last version (commercial device, 80 km) : P. Jouguet et al, Nature Phot. 7, 378 (2013)

Paul Jouguet, Sébastien Kunz-Jacques, Romain Alléaume

Optimize LDPC codes, use Graphic Processing Units (GPU) rather than CPU

=> Calculation speed is no more limiting the secret bit rate !

=> β is improved from 89% to 95% for any SNR : **longer distance (80 km) !**

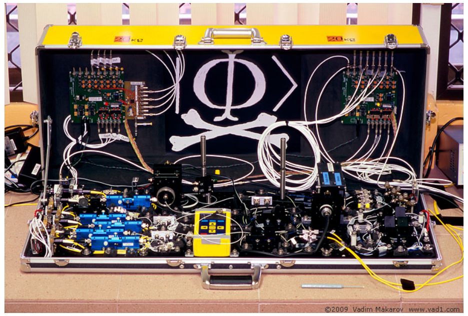


CYGNUS (commercial product)

Quantum Hacking

NTNU Department of Electronics and Telecommunications

UNIK University Graduate Center



- Several recent exemples of "quantum hacking" (e.g. Vadim Makarov et al.)
- Exploits weaknesses in single photon detectors
- Will NOT work against CVQKD (PIN photodiodes, linear regime)
- Hackers will have to work harder...
- ... and Trojan attacks will not make it (work under way, SQN + U. Erlangen)

Many other works on CVQKD !

<= Theory and Experiments : (incomplete list !)

arXiv.org > quant-ph > arXiv:1106.0825
Quantum Physics
Security of Post-selection based Continuous Variable Quantum Key Distribution against Arbitrary Attacks
Nathan Walk, Thomas Symul, Timothy C. Ralph, Ping Koy Lam
(Submitted on 4 Jun 2011)

arXiv.org > quant-ph > arXiv:1011.0304
Quantum Physics
Continuous variable quantum key distribution in non-Markovian channels
Ruggero Vasile, Stefano Olivares, Matteo G A Paris, Sabrina Maniscalco
(Submitted on 1 Nov 2010)

arXiv.org > quant-ph > arXiv:0904.1694
Quantum Physics
Feasibility of continuous-variable quantum key distribution with noisy coherent states
Vladyslav C. Usenko, Radim Filip
(Submitted on 10 Apr 2009 (v1), last revised 21 Jan 2010 (this version, v2))

arXiv.org > quant-ph > arXiv:0904.1327
Quantum Physics
Security bound of continuous-variable quantum key distribution with noisy coherent states and channel
Yong Shen, Jian Yang, Hong Guo
(Submitted on 8 Apr 2009 (v1), last revised 29 Jun 2009 (this version, v2))

arXiv.org > quant-ph > arXiv:0903.0750
Quantum Physics
Confidential direct communications: a quantum approach using continuous variables
Stefano Pirandola, Samuel L. Braunstein, Seth Lloyd, Stefano Mancini
(Submitted on 4 Mar 2009)

arXiv.org > quant-ph > arXiv:1006.1257
Quantum Physics
A balanced homodyne detector for high-rate Gaussian-modulated coherent-state quantum key distribution
Yue-Meng Chi, Bing Qi, Wen Zhu, Li Qian, Hoi-Kwong Lo, Sun-Hyun Youn, A. I. Lvovsky, Liang Tian
(Submitted on 7 Jun 2010 (v1), last revised 16 Jul 2010 (this version, v2))

arXiv.org > quant-ph > arXiv:0910.1042
Quantum Physics
A 24 km fiber-based discretely signaled continuous variable quantum key distribution system
Quyen Dinh Xuan, Zheshen Zhang, Paul L. Voss
(Submitted on 6 Oct 2009)

arXiv.org > quant-ph > arXiv:0811.4756
Quantum Physics
Feasibility of free space quantum key distribution with coherent polarization states
D. Elser, T. Bartley, B. Heim, Ch. Wittmann, D. Sych, G. Leuchs
(Submitted on 28 Nov 2008 (v1), last revised 13 Mar 2009 (this version, v2))

arXiv.org > quant-ph > arXiv:0705.2627
Quantum Physics
Experimental Demonstration of Post-Selection based Continuous Variable Quantum Key Distribution in the Presence of Gaussian Noise
Thomas Symul, Daniel J. Alton, Syed M. Assad, Andrew M. Lance, Christian Weedbrook, Timothy C. Ralph, Ping Koy Lam
(Submitted on 18 May 2007)

Institut d'Optique Graduate School

Content of the Talk

CNRS – QIPC

Part 1 : Gaussian and non-Gaussian states

1. Homodyne detection and quantum tomography
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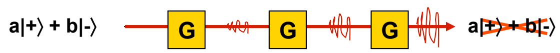
Long distance quantum communications

How to fight against line losses ?

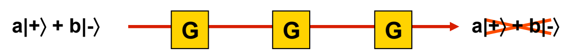
~~Amplification~~



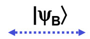
Long distance quantum communications

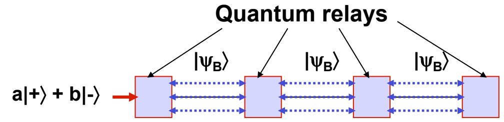
How to fight against line losses ?

~~Amplification~~



1. Exchange of entangled states





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How to fight against line losses ?

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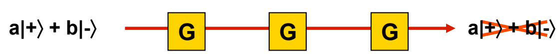

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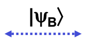
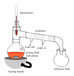
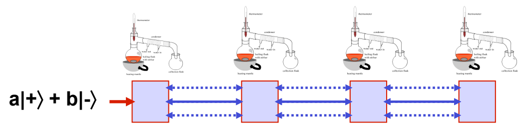


2. Entanglement distillation





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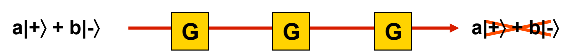
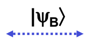
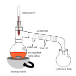
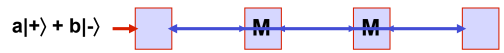


1. Exchange of entangled states



2. Entanglement distillation



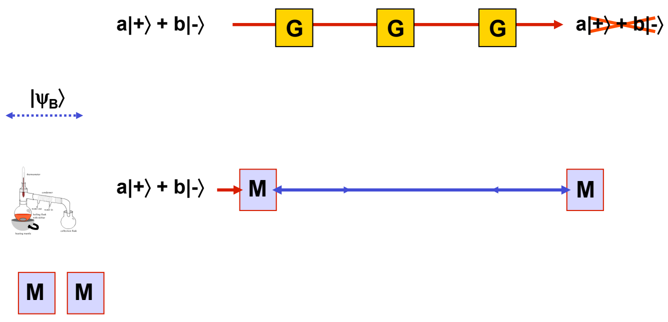


Long distance quantum communications

How to fight against line losses ?

~~Amplification~~

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

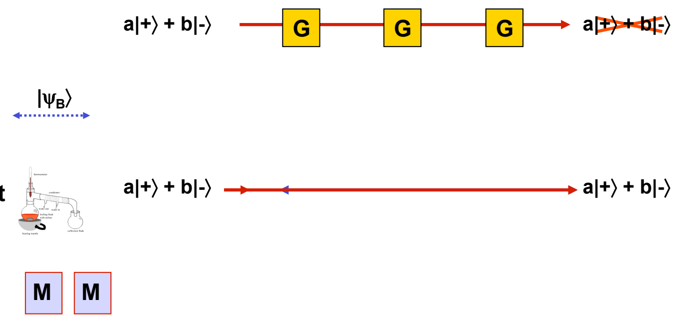


Long distance quantum communications

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)

INSTITUT d'OPTIQUE GRADUATE SCHOOL

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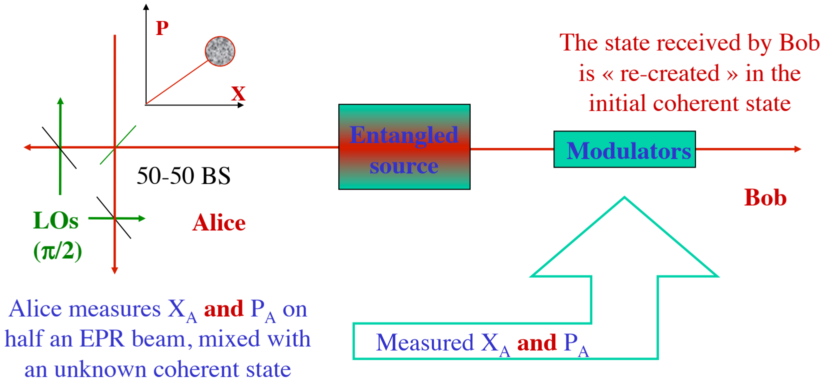
Quantum teleportation of coherent states

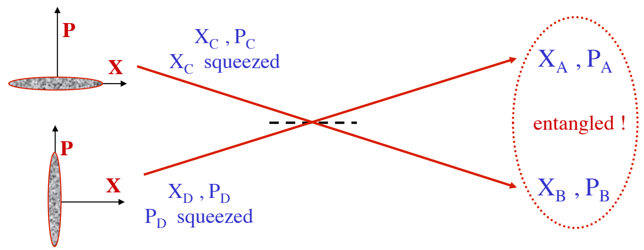


Alice measures X_A **and** P_A on half an EPR beam, mixed with an unknown coherent state

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)

How to produce CV entangled beams ?

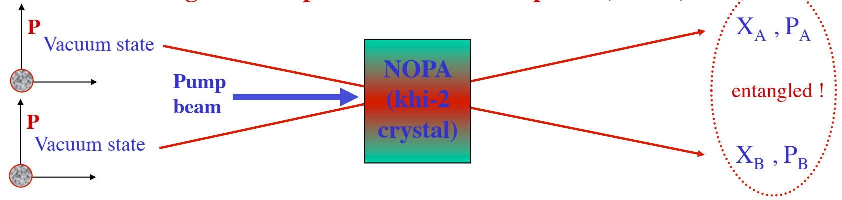
1. Combine two orthogonally squeezed beams



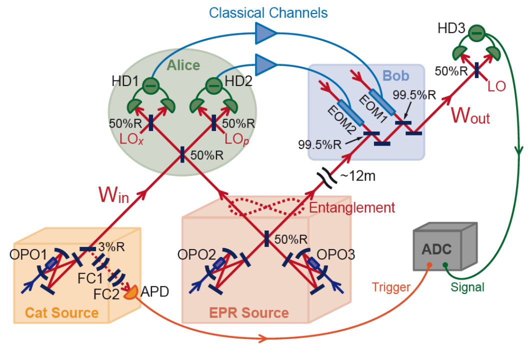
$X_C = (X_A + X_B)/\sqrt{2}$
$P_C = (P_A + P_B)/\sqrt{2}$
$X_D = (X_A - X_B)/\sqrt{2}$
$P_D = (P_A - P_B)/\sqrt{2}$

OK !

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



Quantum teleportation of cat states

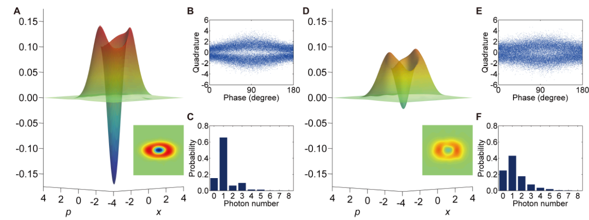


The state received by Bob is « re-created » in the initial cat state (with some loss in fidelity : 0.75 => 0.45)

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)



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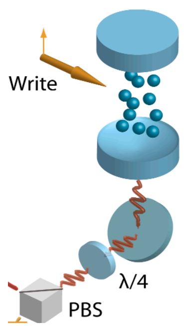
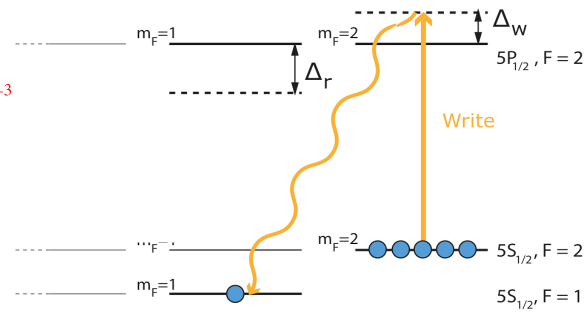
Single Photon from a single polariton (DLCZ protocol)

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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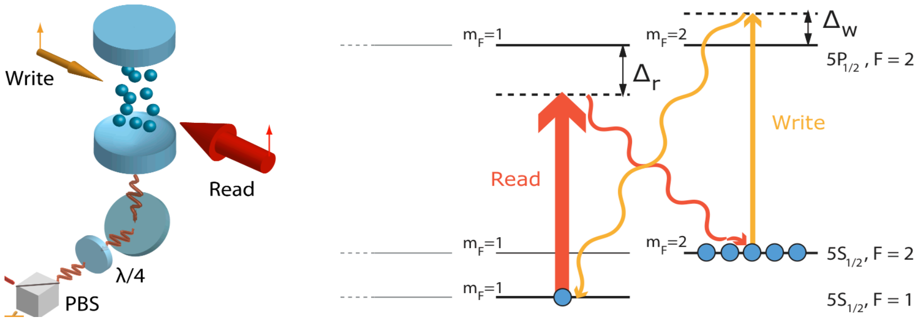

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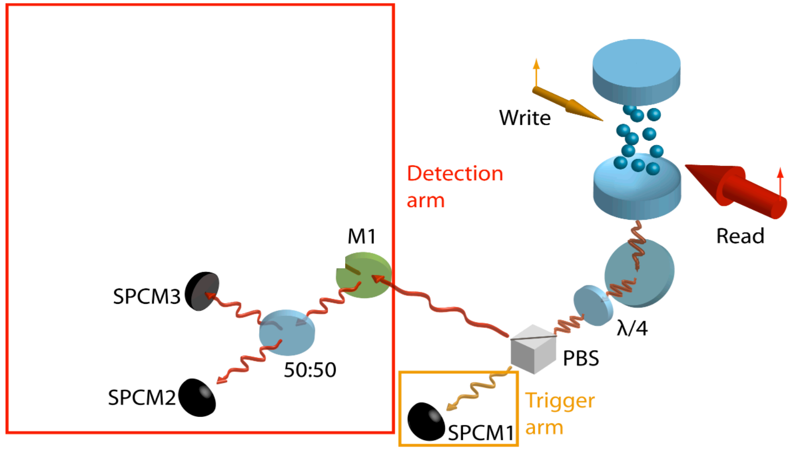

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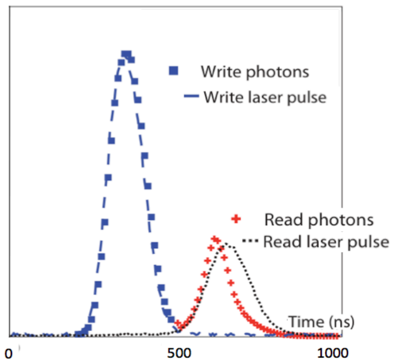

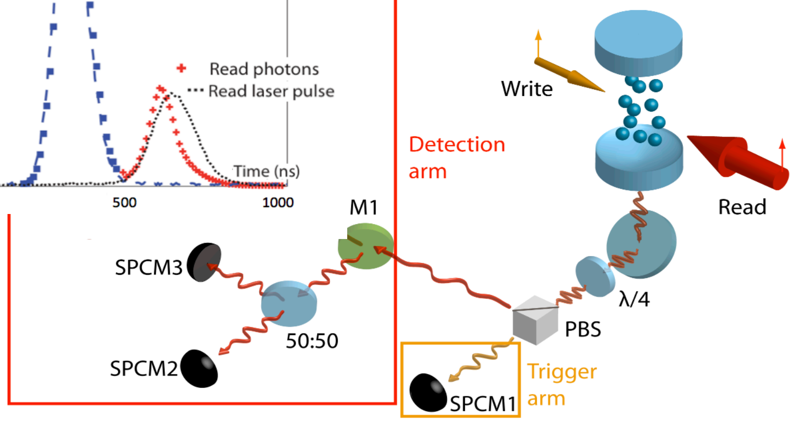

E. Bimbard et al, arXiv:1310.1228 (2013), PRL 112, 033601 (2014)

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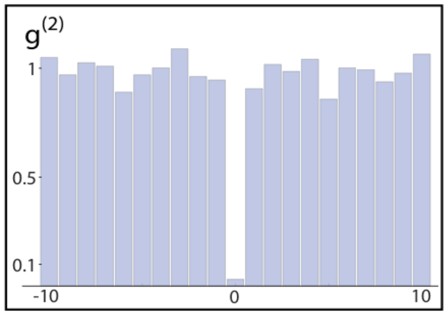

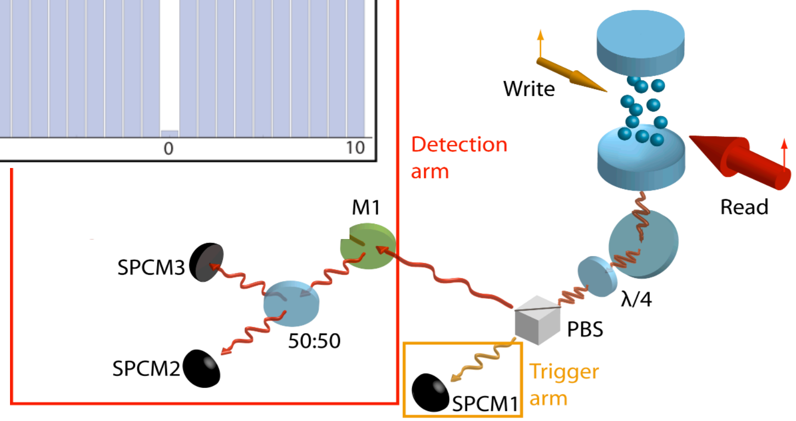

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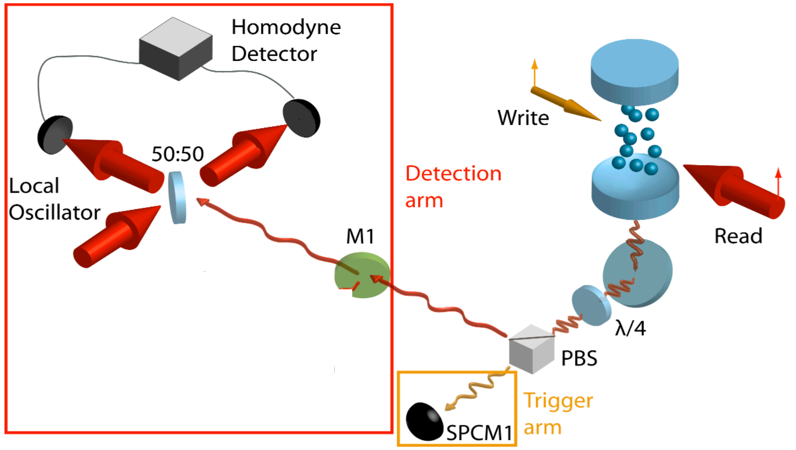
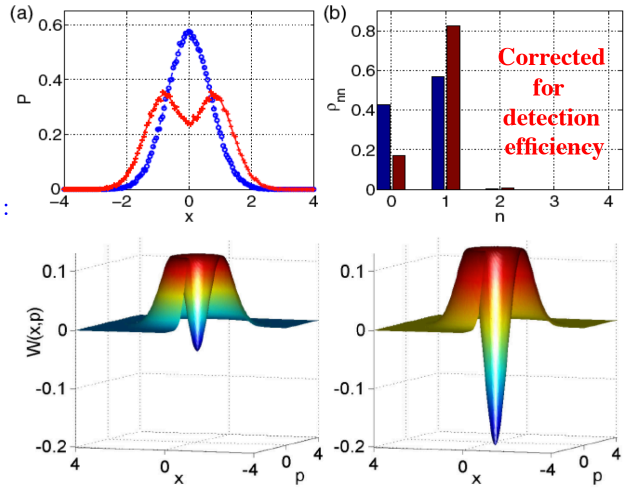


E. Bimbard et al, arXiv:1310.1228 (2013), PRL 112, 033601 (2014)

Single Photon from a single polariton (DLCZ protocol)

Overall detection efficiency : 57%

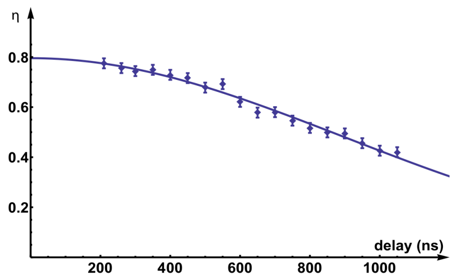


Overall extraction efficiency : 82%

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

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)

Thank you for your attention !

Valentina Parigi (post-doc, exp.)

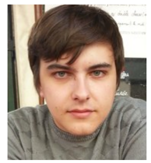
Imam Usmani (post-doc, exp.)

Etienne Brion (CNRS)

Alexei Ourjoumtsev (CNRS)

Jovica Stanojevic (post-doc, th.)

Erwan Bimbard (PhD, exp.)



Andrey Grankin (PhD, th.)

Rajiv Boddeda (PhD, exp.)

Rydberg interactions team (Palaiseau 2014)

erc European Research Council

DELPHI
Deterministic Logical Photon-photon Interactions