Quantum Optics and Quantum Information with Continuous Variables

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Content of the Tutorial

Part 1 : Gaussian and non-Gaussian states

1. Homodyne detection and quantum tomography
2. Generating non-Gaussian Wigner functions : kittens, cats and beyond

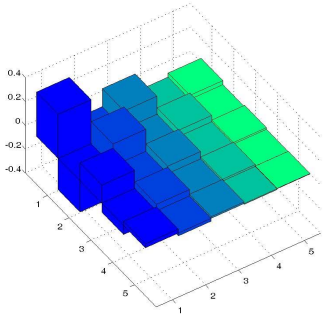
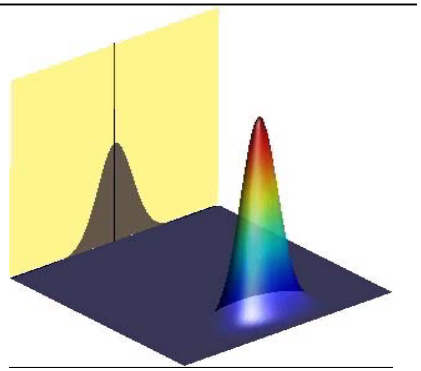
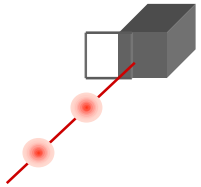
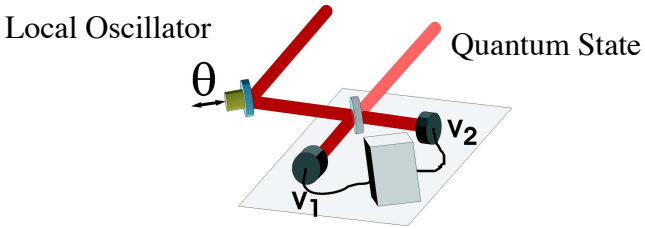
Part 2 : Continuous variable quantum cryptography (Gaussian !)

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

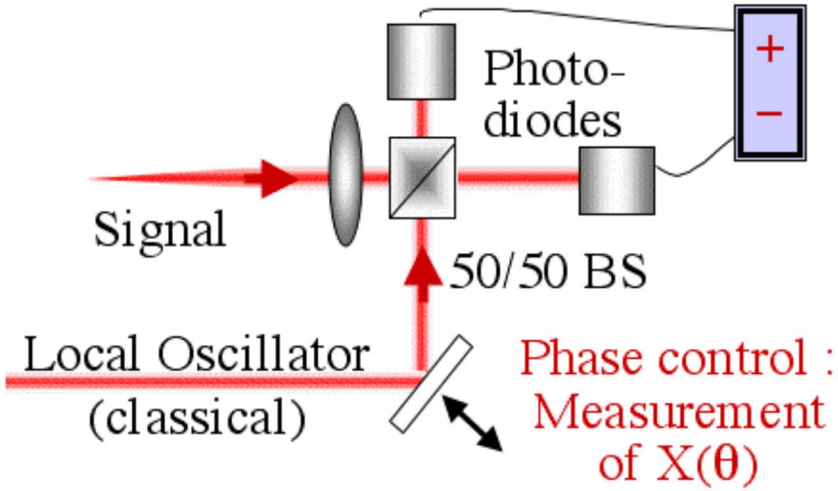
Part 3 : Towards quantum networks (non-Gaussian !)

1. Entanglement for continuous variable quantum networks
2. Deterministic photon-photon interactions

« Discrete » vs « continuous » Light

Light is :	Discrete Photons	Continuous Wave
We want to know :	their Number & Coherence	its Amplitude & Phase (polar) its Quadratures X & P (cartesian)
We describe it with :	Density matrix $\rho_{n,m}$ 	Wigner function W(X,P) 
We measure it by :	Counting: APD, VLPC, TES… 	Demodulating : Homodyne Detection  $V_1 - V_2 \propto X_- = X\cos\theta + P\sin\theta$
« Simple » States	Fock States	Gaussian States

Coherent (Homodyne) Detection, Wigner Function and Quantum Tomography



- **Quasiprobability density :**

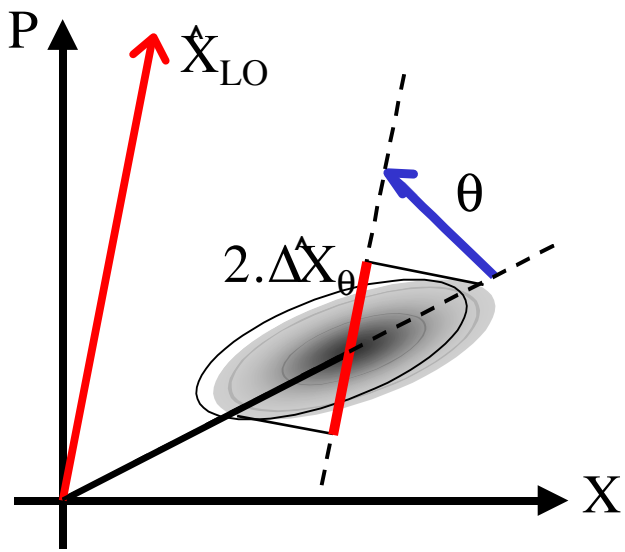
  Wigner function W(X,P)

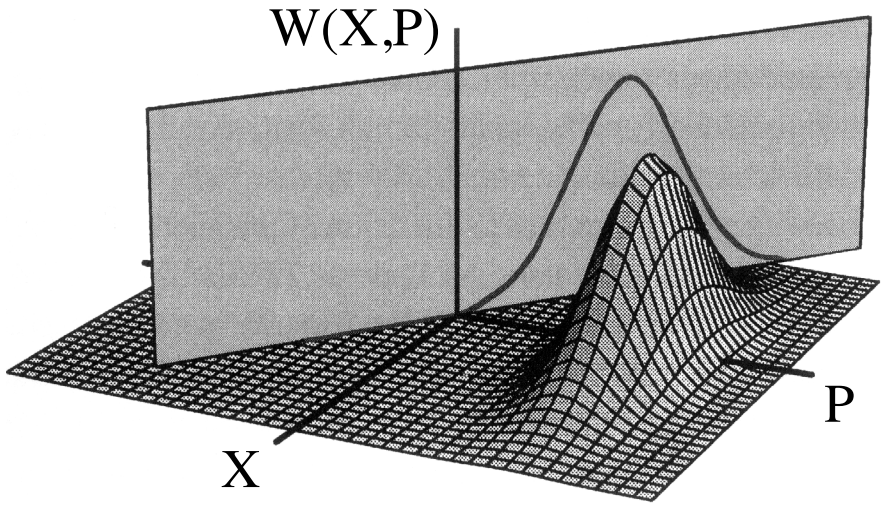
- **Marginals of W(X, P)**

  => Probability distributions $\mathcal{P}(X\theta)$

- **Probability distributions $\mathcal{P}(X\theta)$**

  => W(X, P) (quantum tomography)





Non-Gaussian States

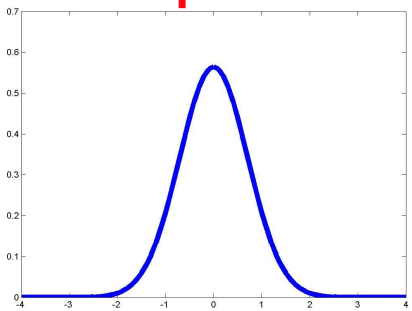
Basic question :

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

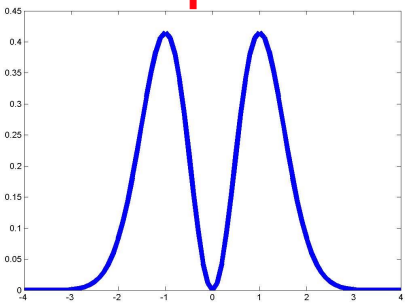
Single mode light field		**Harmonic oscillator**
Photons		**Quanta of excitation**
n photon state	$\Longleftrightarrow$	**n^{th} eigenstate**
Probability $P_n(X)$		**Probability $\lvert\Psi_n(x)\rvert^2$**

$\lvert\Psi_n(x)\rvert^2$

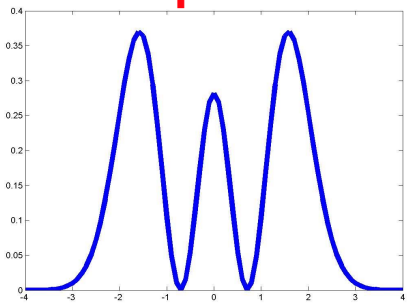
n=0 photons



n=1 photon



n=2 photons

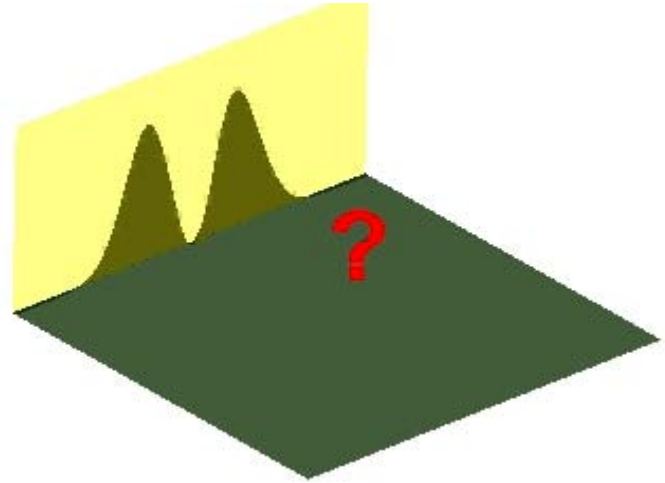


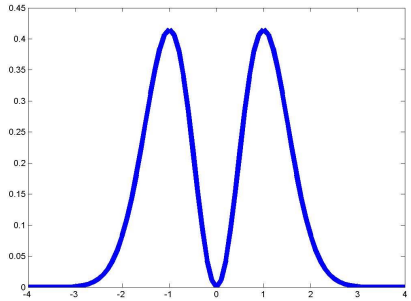
Non-Gaussian States

Basic question :

Consider a single photon : can we speak about 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 ?





Non-Gaussian States

Basic question :

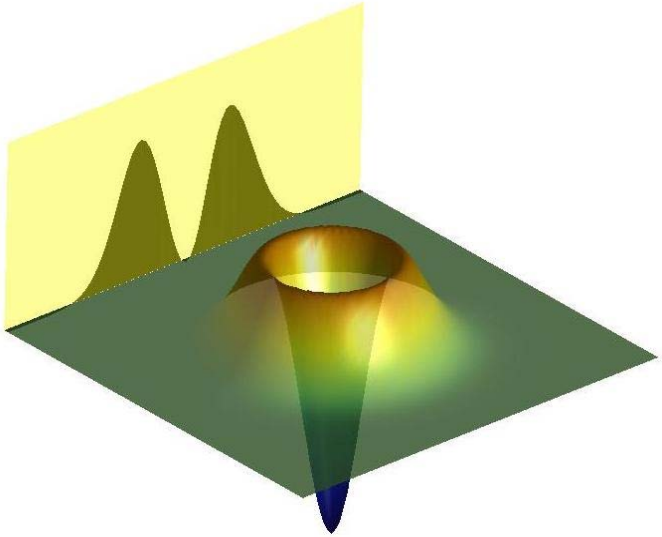
Consider a single photon : can we speak about its **amplitude & phase?**
quadratures X & P ?

NO !

The Wigner function must be negative

↓

~~**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)

$$\boxed{W(p,q) = \frac{1}{2\pi\, 2N_0} \int \mathrm{d}x\, \mathrm{e}^{\frac{\mathrm{i}xp}{2N_0}} \left\langle\, q - \tfrac{x}{2} \,\middle|\, \hat{\rho} \,\middle|\, q + \tfrac{x}{2} \,\right\rangle}$$

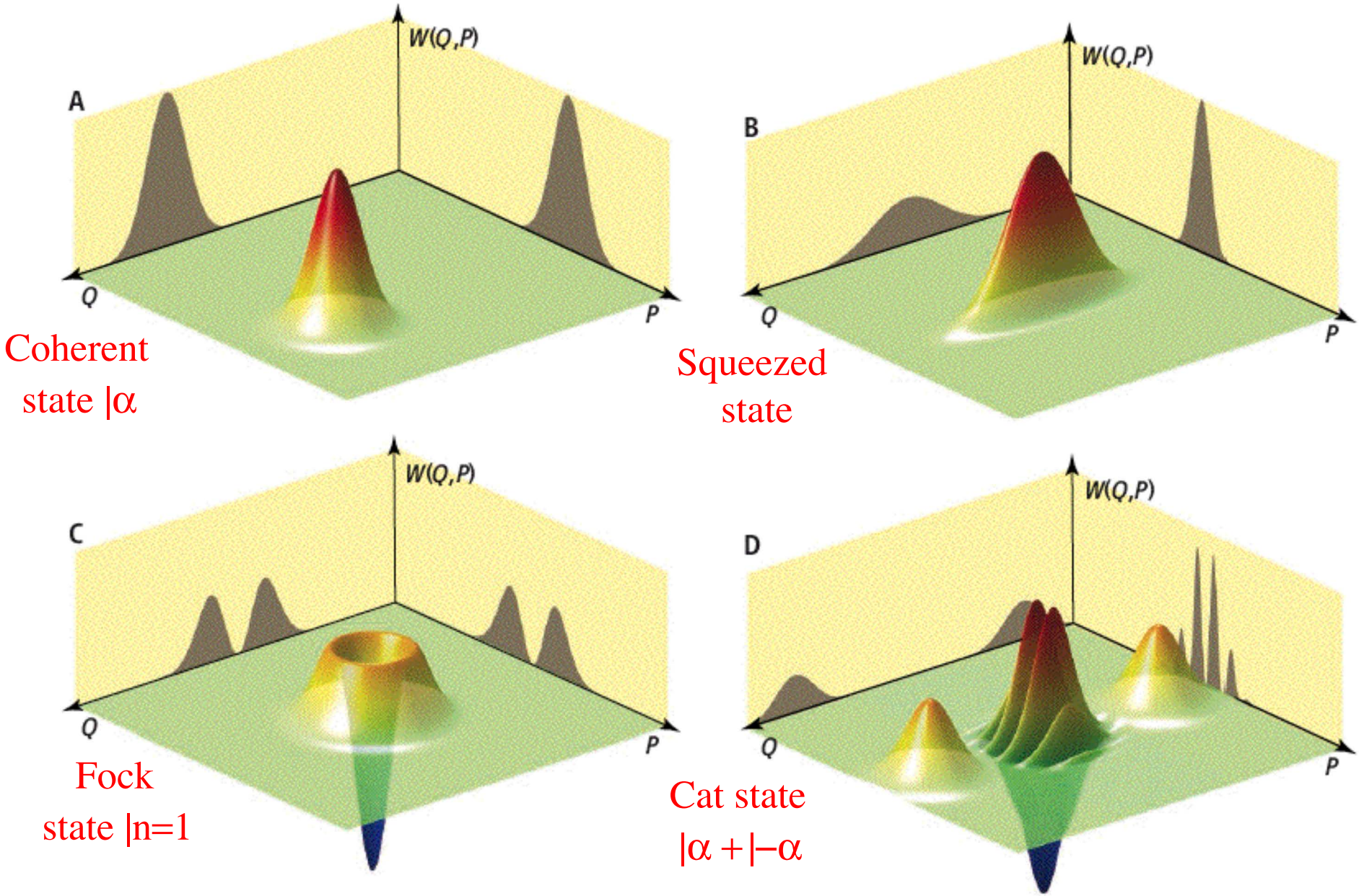
where $\hat{\rho} = |1\rangle\langle 1|$ and N_0 is the variance of the vacuum noise :

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

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



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 Ourioumtsev, 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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1. Homodyne detection and quantum tomography
2. **Generating non-Gaussian Wigner functions : kittens, cats and beyond**

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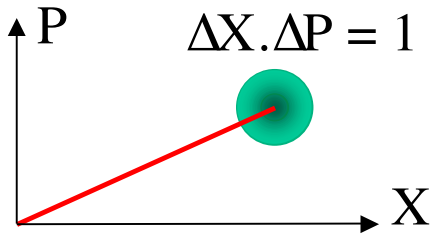
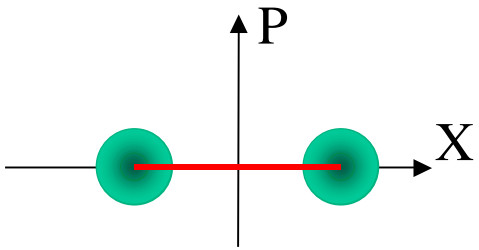
« Schrödinger's Cat » state

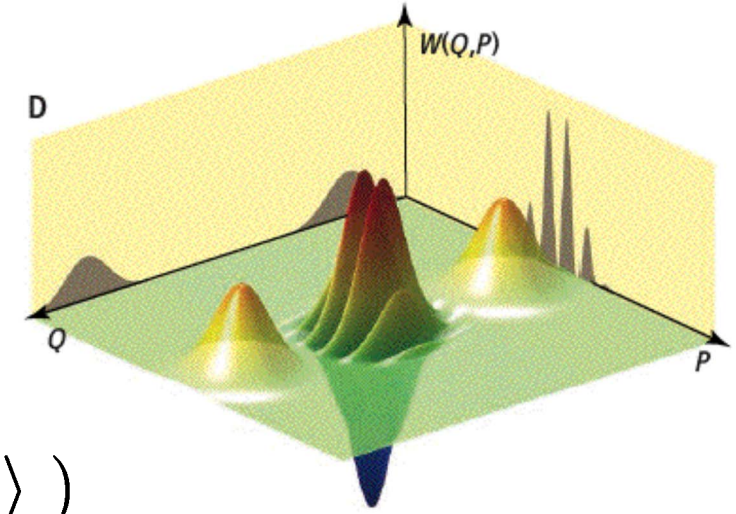
- Classical object in a quantum superposition of distinguishable states
- "Quasi - classical" state in quantum optics : coherent state $|\alpha\rangle$



Coherent state



Schrödinger cat state



Wigner function of a Schrödinger cat state

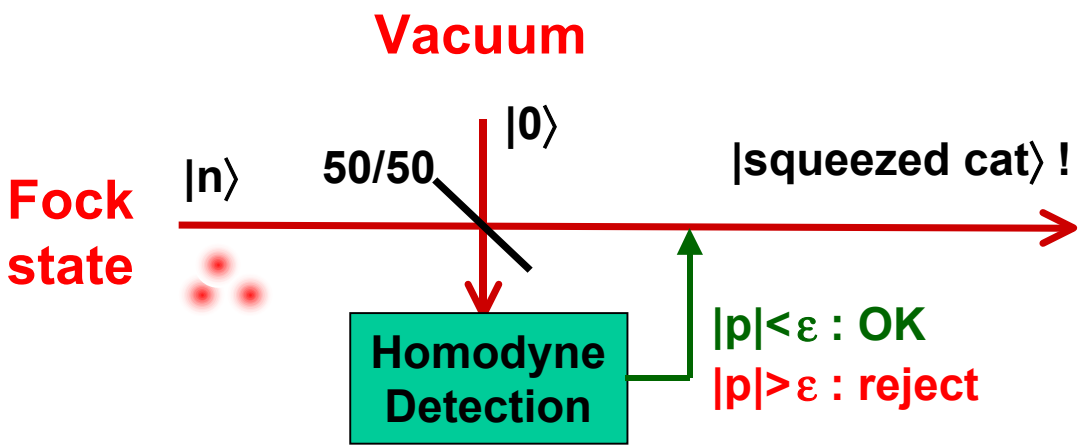
$$|\psi_{odd\ cat}\rangle = c_o(\ |\alpha\rangle - |-\alpha\rangle\ )$$

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

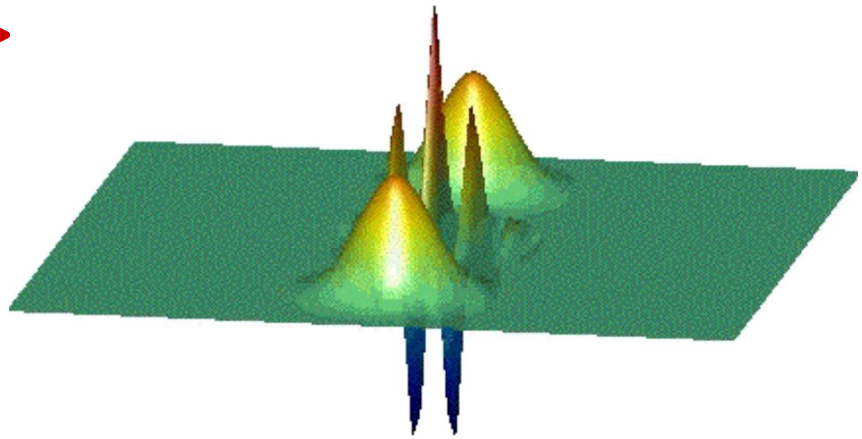
- Resource for quantum information processing
- Model system to study decoherence

How to create a Schrödinger's cat ?

Suggestion by Hyunseok Jeong, calculations by Alexei Ourjoumtsev :



Squeezed Cat state



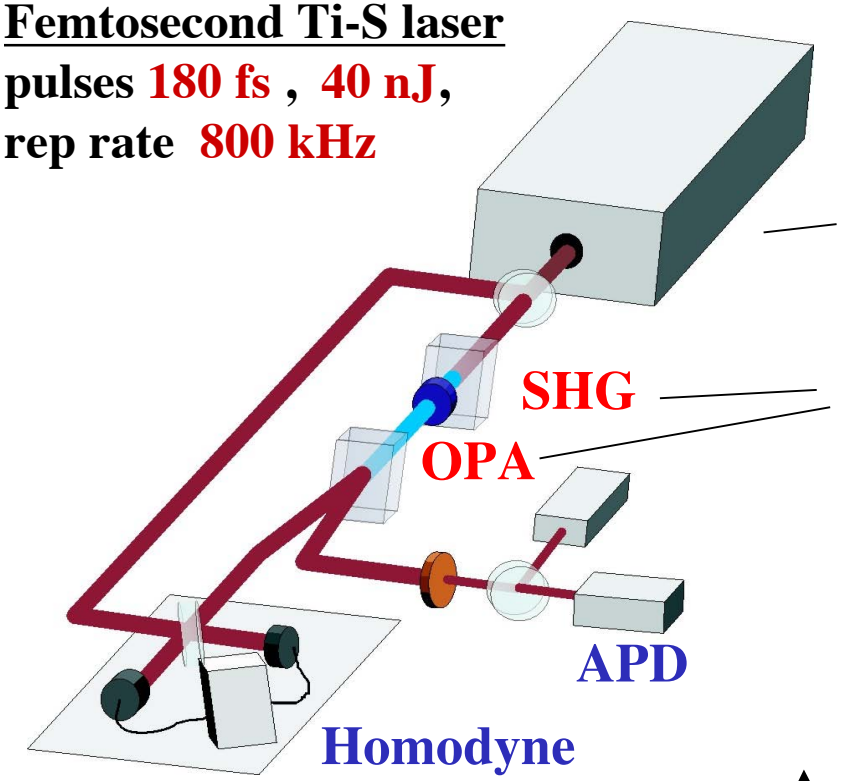
For n ≥ 3 the fidelity of the conditional state with a Squeezed Cat state is F ≥ 99%

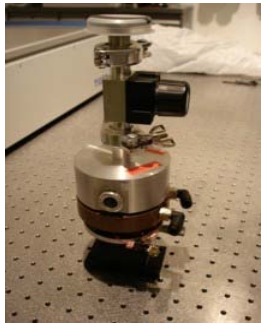
$$S(r)(|\alpha\rangle + e^{i\theta}|-\alpha\rangle)$$

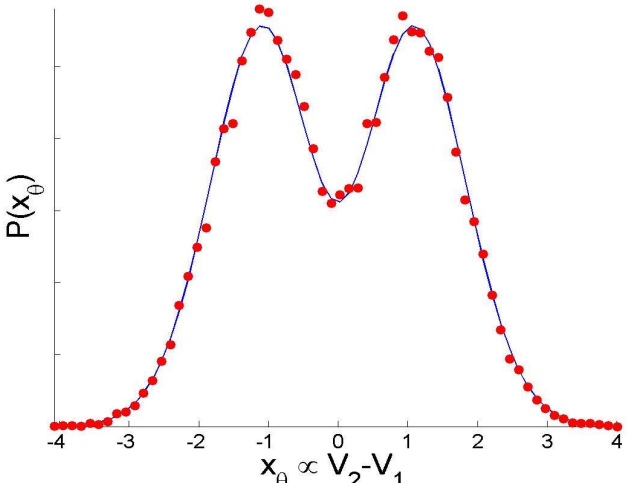
Size :	$\alpha^2 = n$
Same Parity as n :	$\theta = n*\pi$
Squeezed by :	3 dB

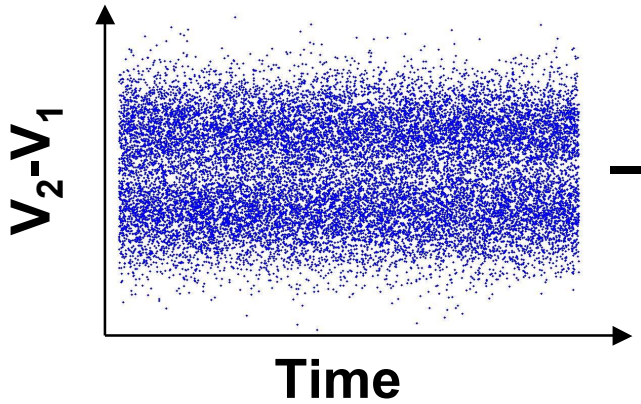
Experimental Set-up

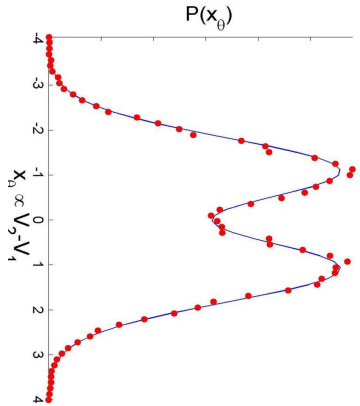
Femtosecond Ti-S laser
pulses 180 fs , 40 nJ,
rep rate 800 kHz





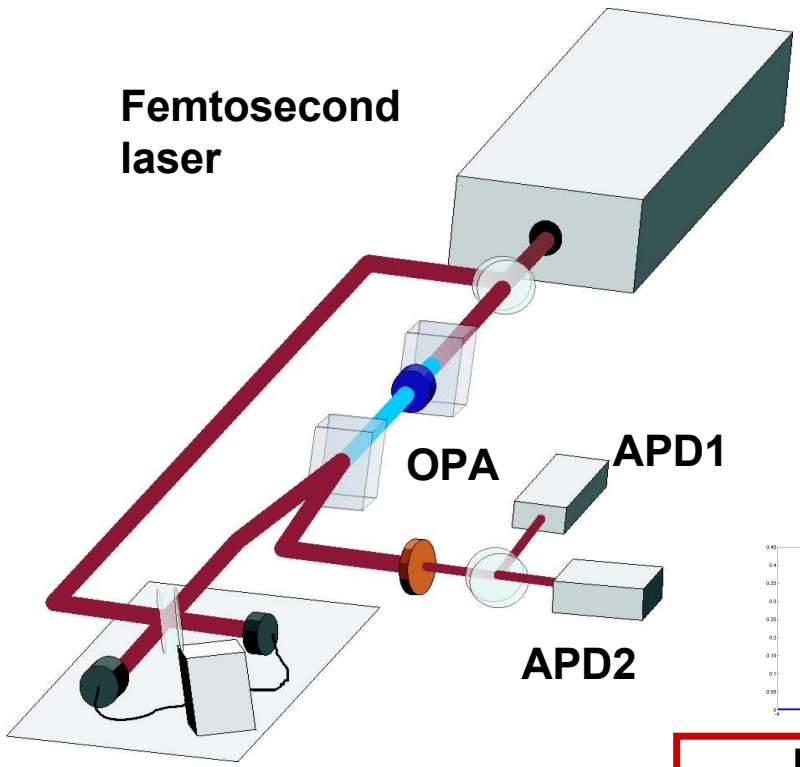


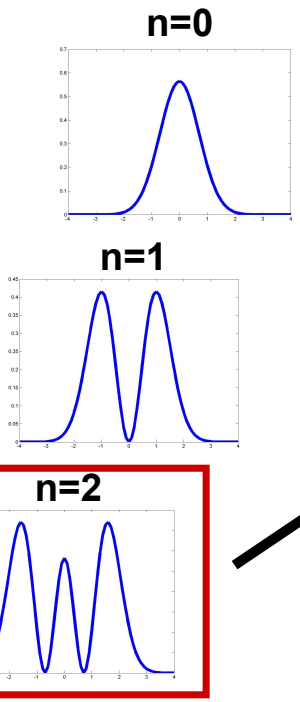




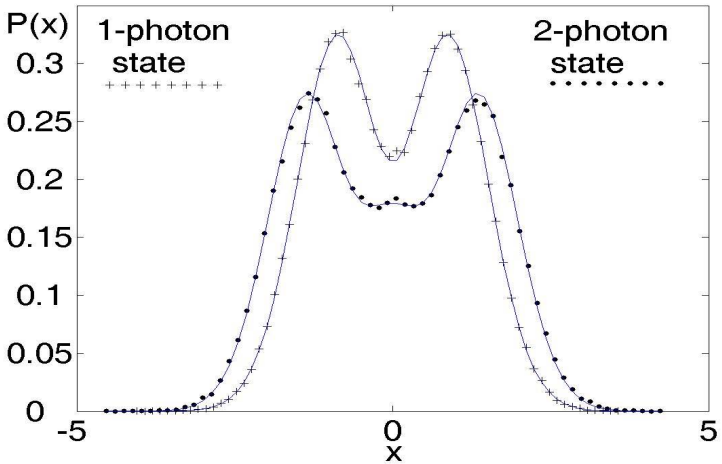
Resource : Two-Photon Fock States

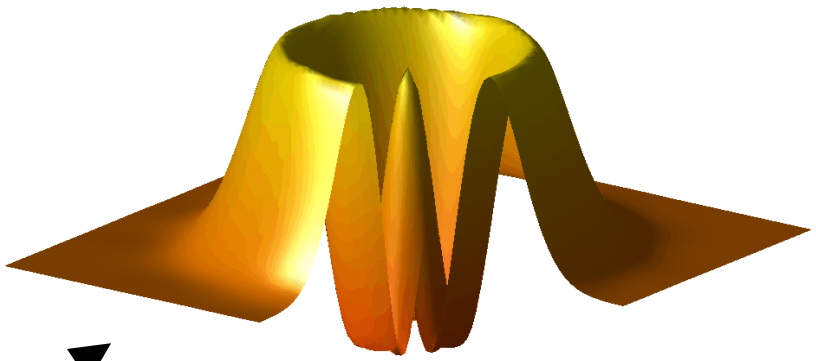
$$|\psi\rangle = \sum \lambda^n |n, n\rangle$$





Homodyne detection

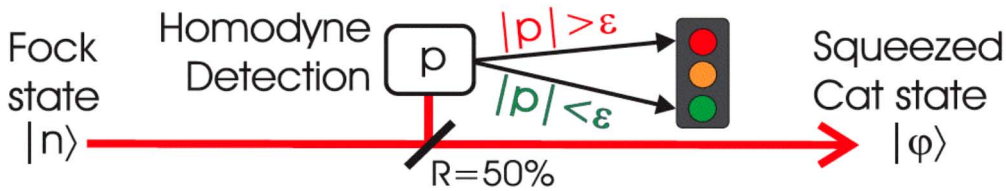


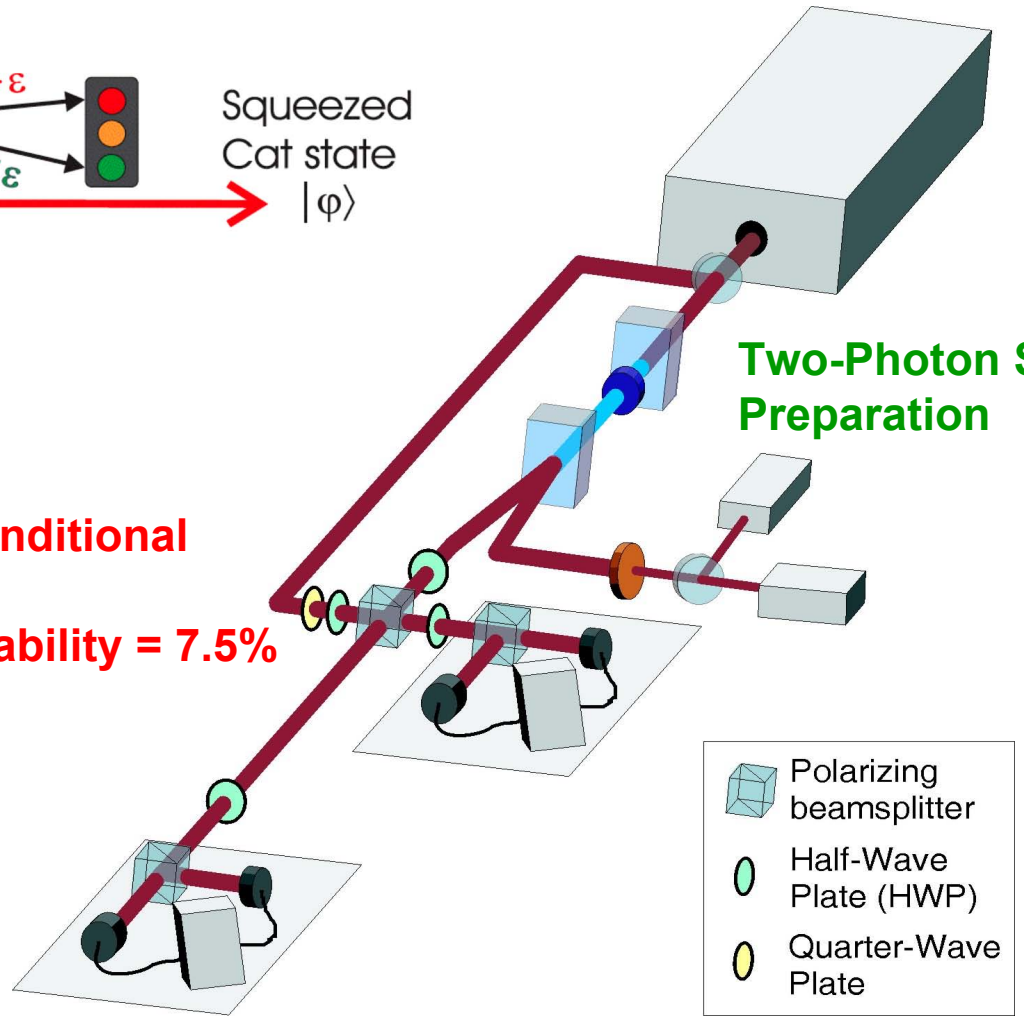


Experimental Wigner function (corrected for homodyne losses)

Phys. Rev. Lett **96,** 213601 (2006)

Squeezed Cat State Generation





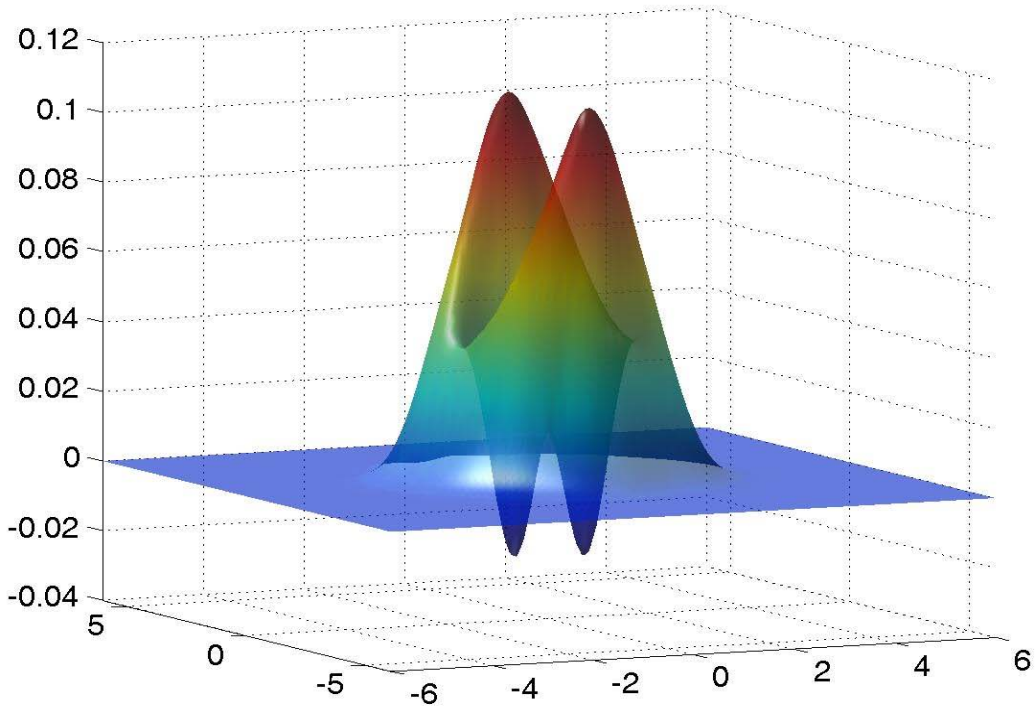
Two-Photon State Preparation

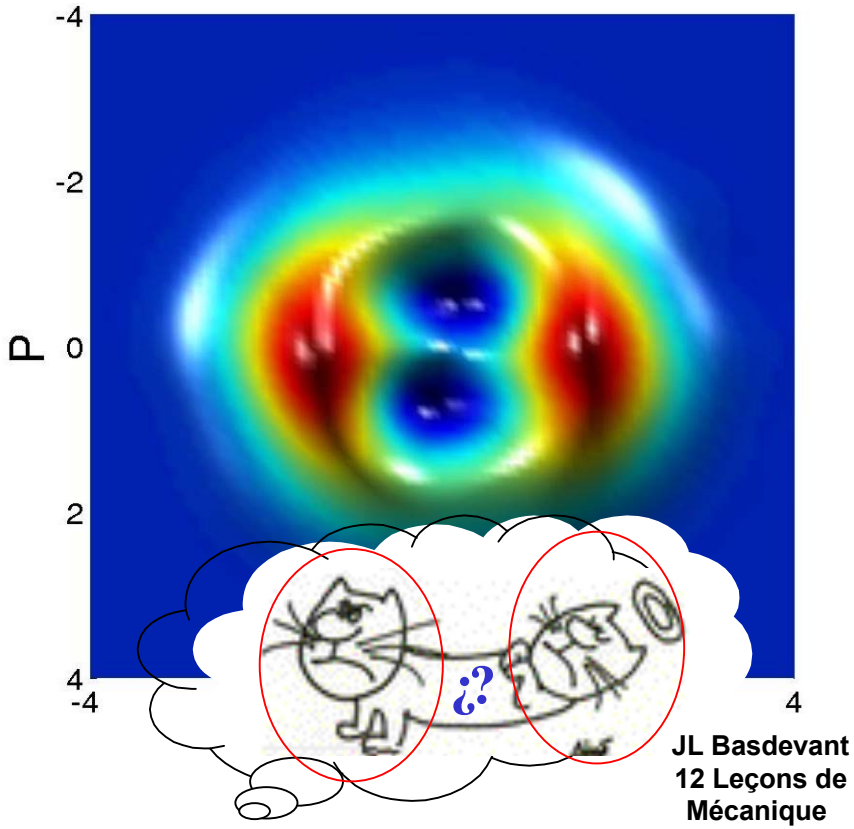
Homodyne Conditional Preparation :
Success Probability = 7.5%

Tomographic analysis of the produced state

Experimental Wigner function

A. Ourjoumtsev et al, Nature 448, 784 (2007)





JL Basdevant
12 Leçons de
Mécanique
Quantique

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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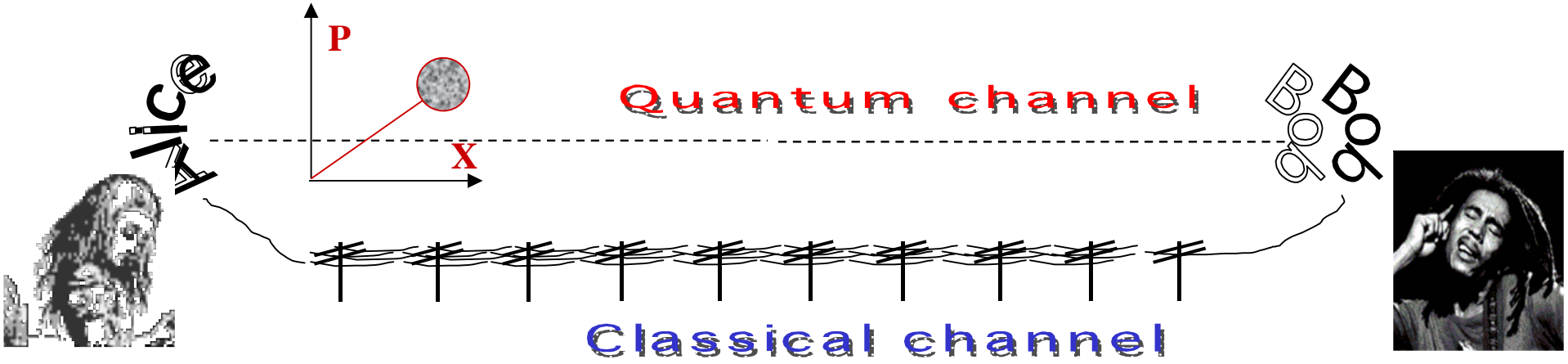
Coherent States Quantum Key Distribution



* 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

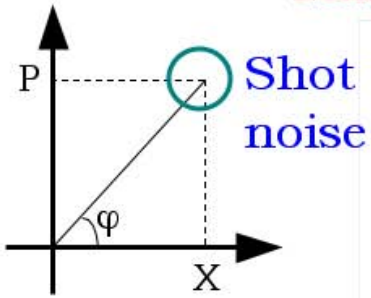
Eve

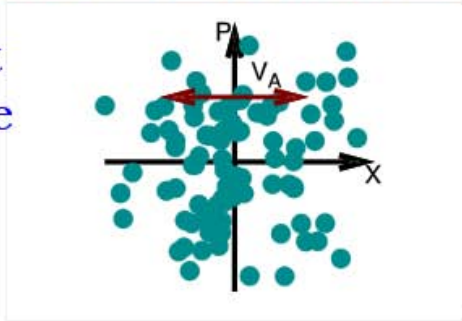
Alice 

Quantum channel (T, ε)
+ Classical Channel (auth.)

Bob

Gaussian modulation

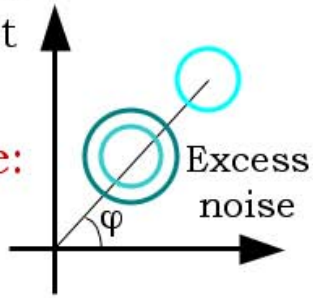




Random measurement of the quadrature of each coherent state (with efficiency η)

Total channel-added noise:

$$\chi = \underbrace{1/T - 1}_{\text{equivalent to photon loss}} + \underbrace{\varepsilon}_{\text{equivalent to errors}}$$



- 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)

QKD protocol using coherent states with gaussian amplitude and phase modulation

Efficient transmission of information using continuous variables ?

-> Shannon's formula (1948) : the mutual information I_{AB} (unit : bit / symbol) for a gaussian channel with additive noise is given by

$$\mathbf{I_{AB} = 1/2 \ \log_2 [\ 1 + V(signal) / V(noise)\ ]}$$

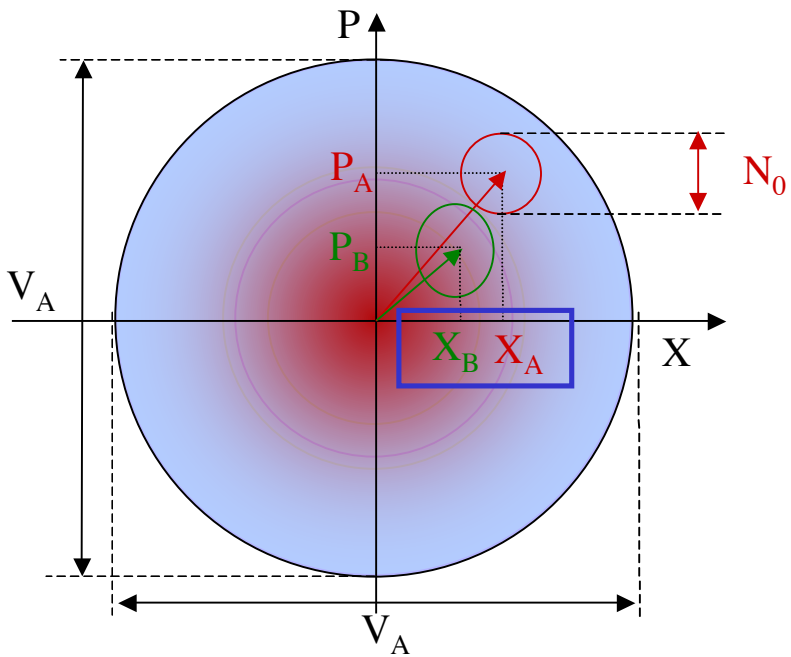
Reminder : I(X; Y) =
H(X) - H(X | Y) =
H(Y) - H(Y| X) =
H(X) + H(Y) - H(X; Y)

(a) Alice chooses X_A and P_A within two random gaussian distributions.

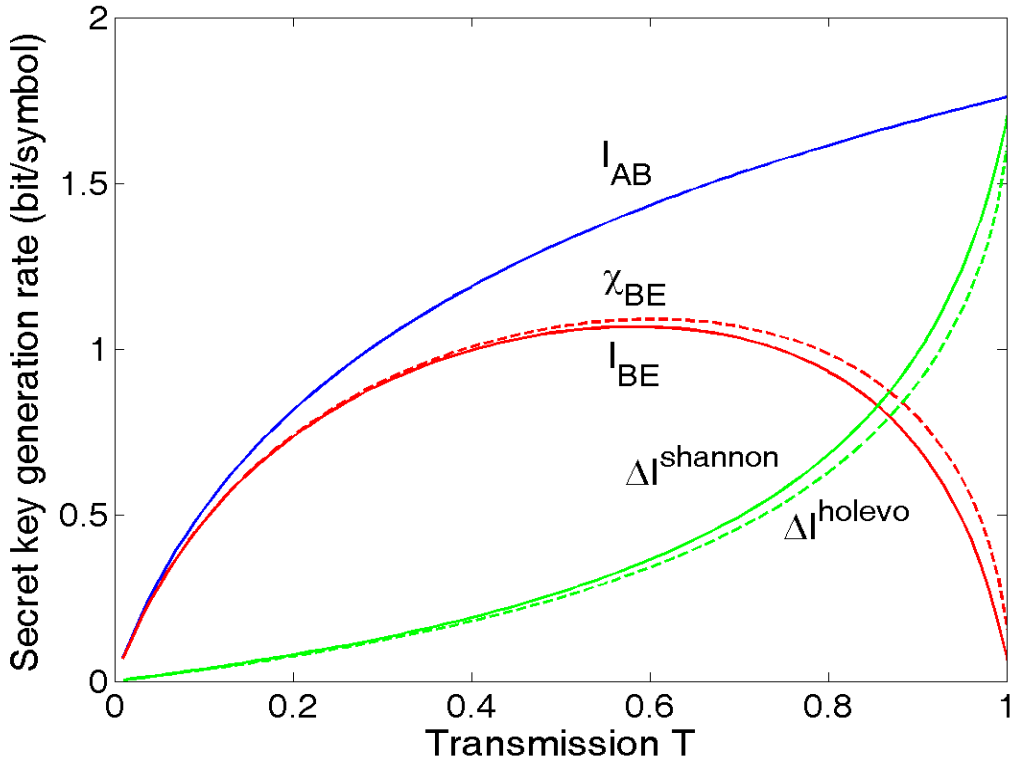
(b) Alice sends to Bob the coherent state $| X_A + i P_A >$

(c) Bob measures either X_B or P_B

(d) Bob and Alice agree on the basis choice (X or P), and keep the relevant values.



Security of coherent state CV-QKD : collective attacks



Alice-Bob mutual information : I_{AB}

Eve-Bob mutual information :

I_{BE} (Shannon : individual attacks)

χ_{BE} (Holevo : collective attacks)

Bounded from channel evaluation !

Secret Key Rate :

$\Delta I = I_{AB} - I_{BE}$ **(Shannon)**

$\Delta I = I_{AB} - \chi_{BE}$ **(Holevo)**

- 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}

Fig : $V_A = 21$ (shot noise units)
$\varepsilon = 0.005$ (shot noise units), $\eta = 0.5$

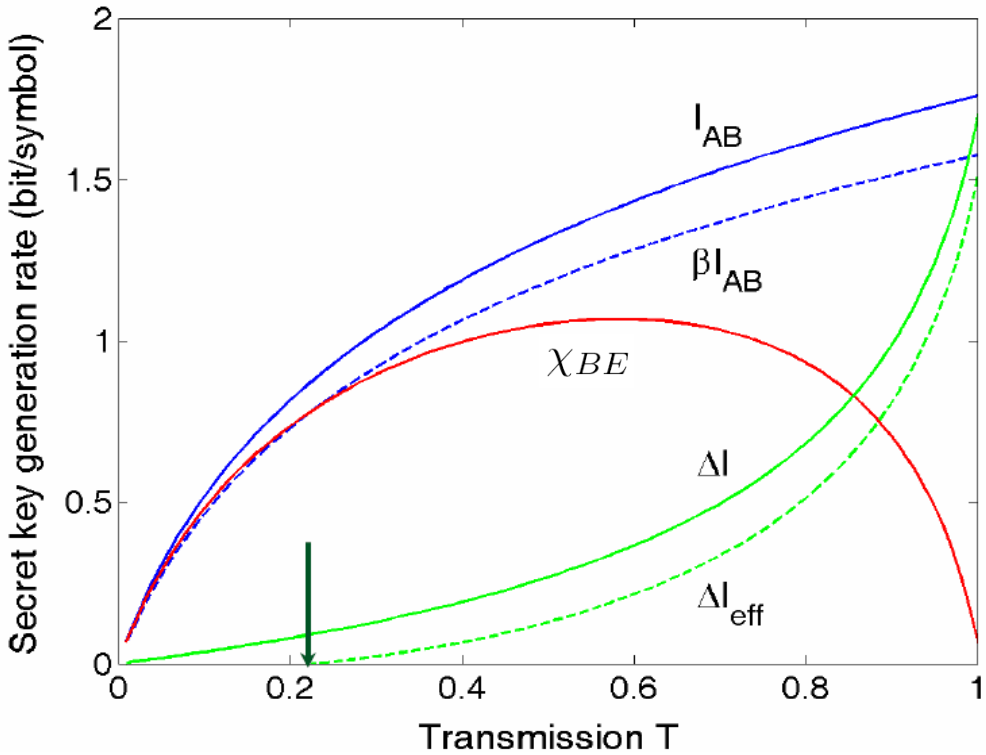
M. Navasqués et al, Phys. Rev. Lett. 97, 190502 (2006)
R. García-Patrón et al, Phys. Rev. Lett. 97, 190503 (2006)

Error correcting codes efficiency

- Errorless bit strings must be extracted from noisy continuous data

- Binning + error correction with very efficient LDPC codes, efficiency $\beta < 1$

$$\Delta I^{eff} = \beta I_{AB} - \chi_{BE}$$



Alice-Bob mutual information : I_{AB}

Available after error correction : $\beta\, I_{AB}$

Eve-Bob mutual information :

χ_{BE} (Holevo : collective attacks)

Imperfect correction efficiency induces a limit to the secure distance

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)

- Very recently 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)

Also : finite size effects, A. Leverrier, F. Grosshans and P. Grangier, Phys. Rev. A 81, 062343 (2010)

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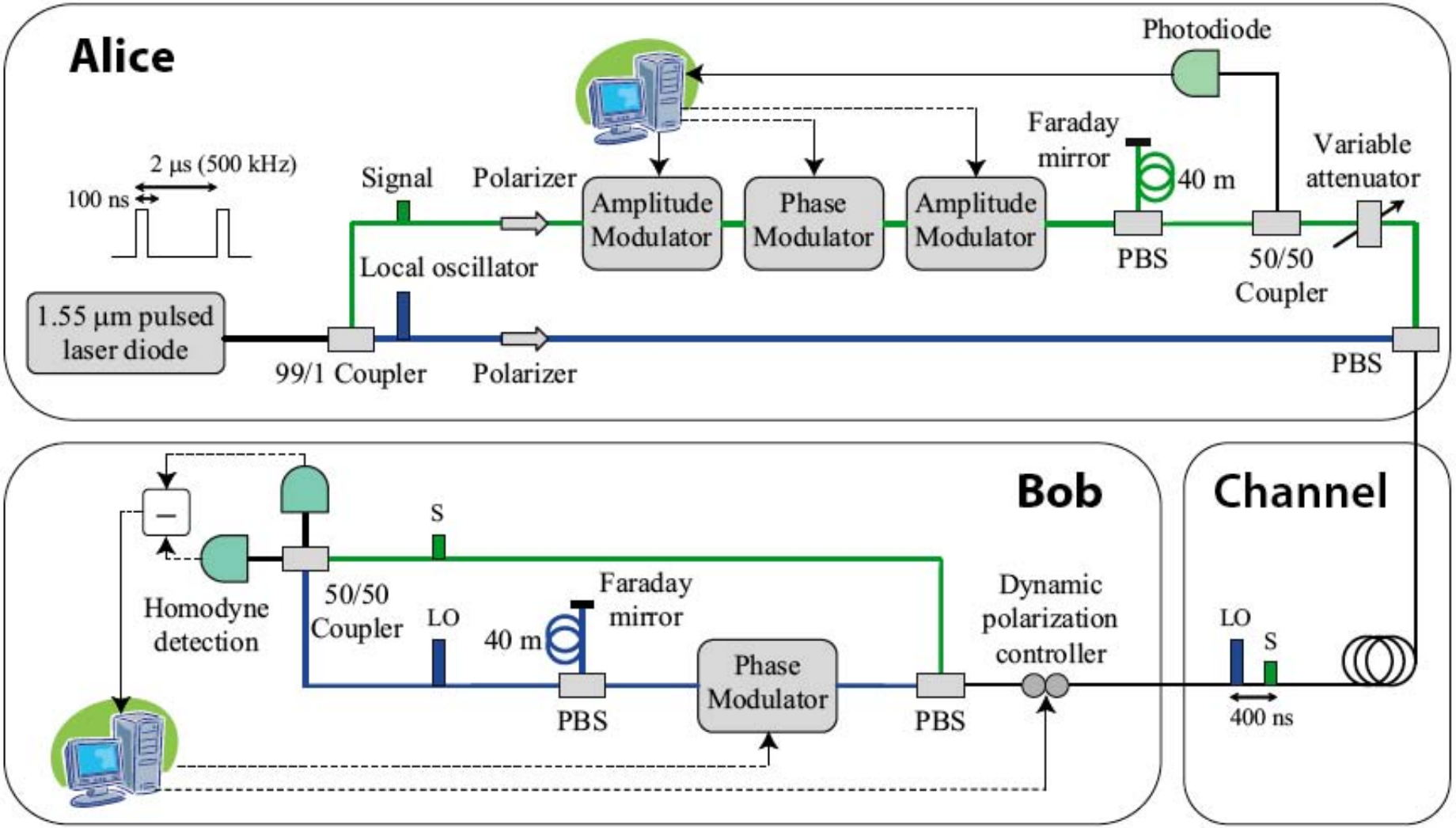
All-fibered CVQKD @ 1550 nm

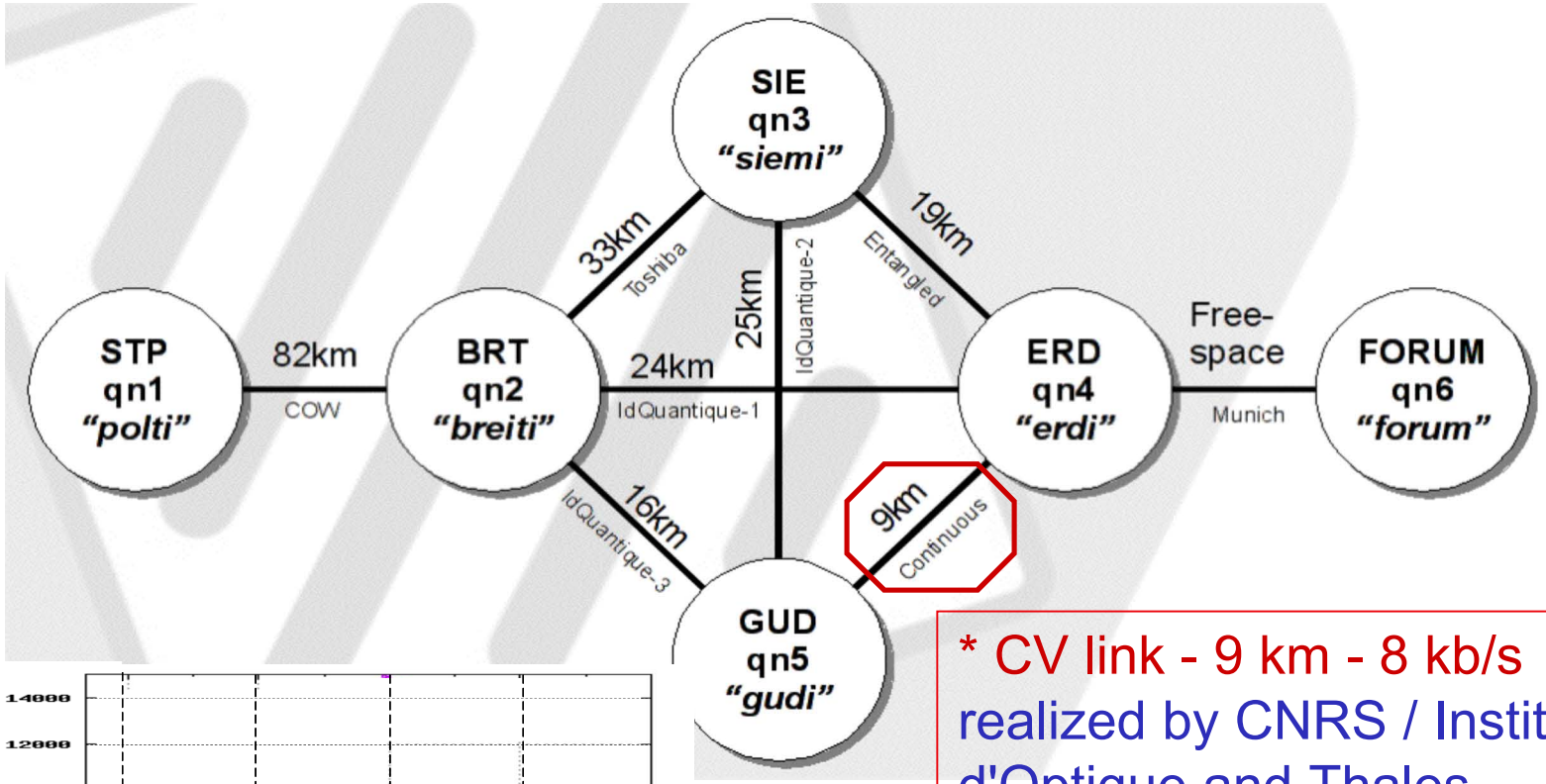


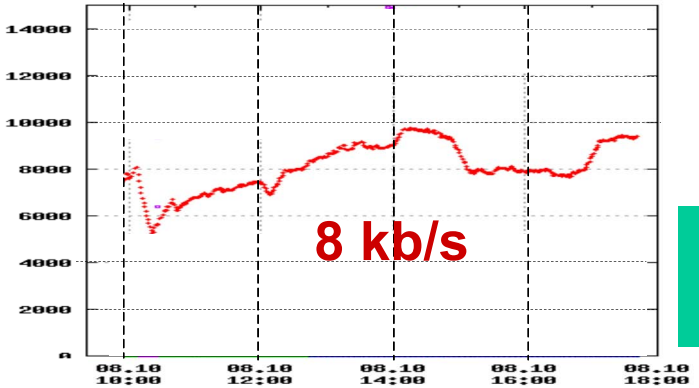
Field test of a continuous-variable quantum key distribution prototype
S Fossier, E Diamanti, T Debuisschert, A Villing, R Tualle-Brouri and P Grangier
New J. Phys. 11 No 4, 04502 (April 2009)

The SECOQC Quantum Back Bone

Real-size demonstration of a **secure quantum cryptography network**

by the European Integrated Project SECOQC, Vienna, 8 october 2008

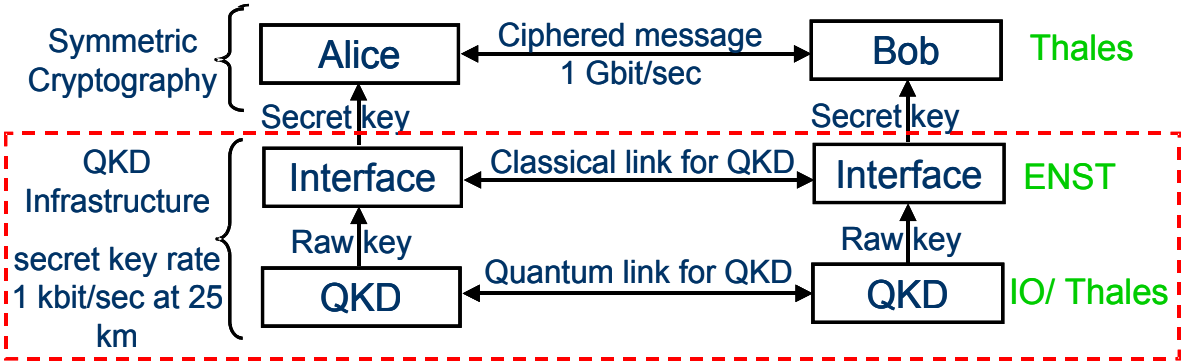


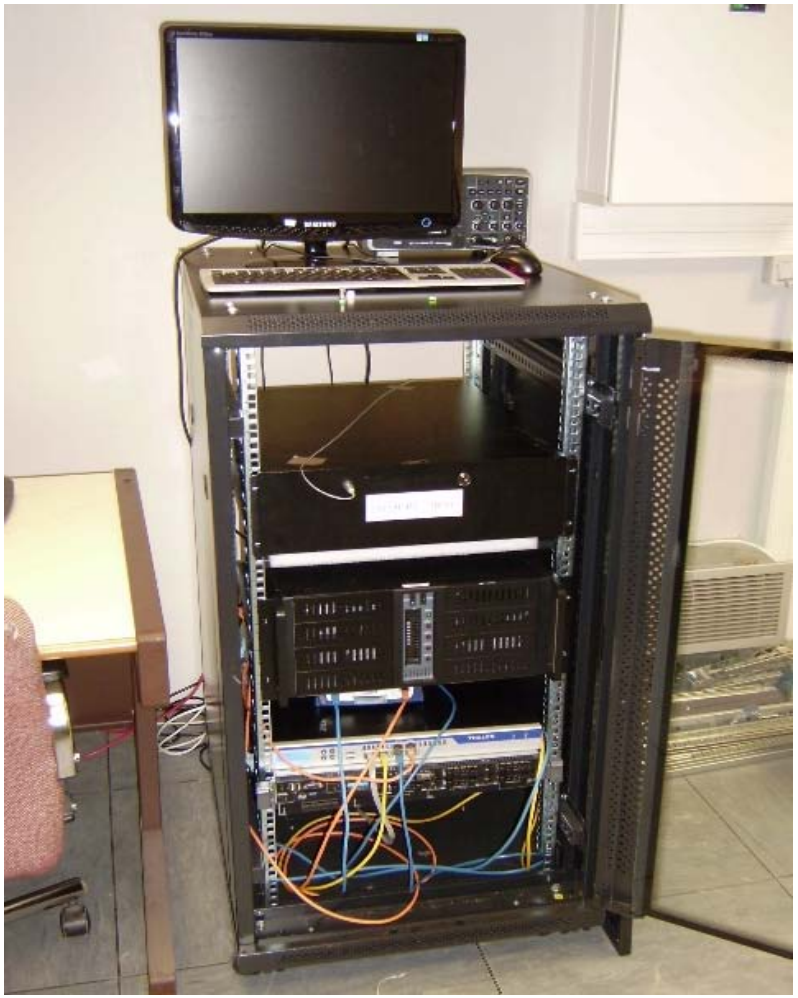


CV secret bit rate during the demo (8h)

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

Symmetric Encryption with QUantum key REnewal SEQURE



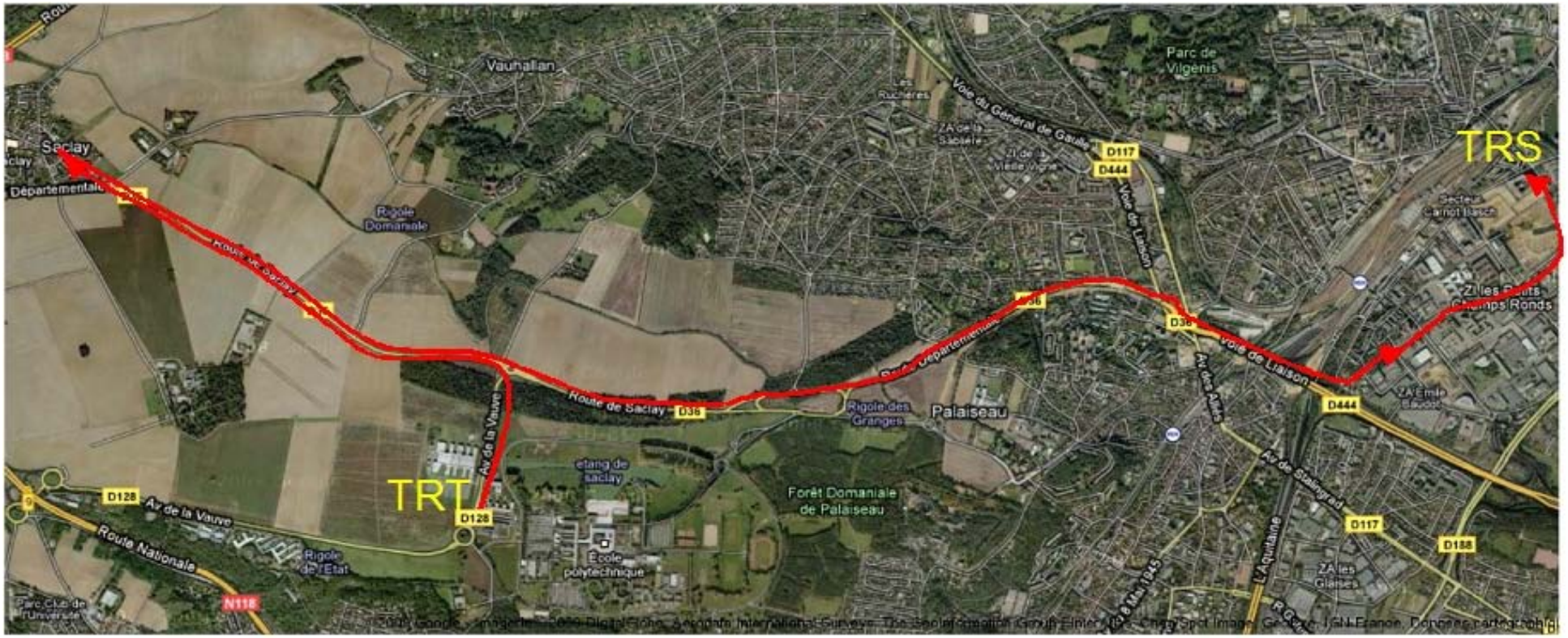


- Thales : Mistral Gbit

SEQURE 1011010111011001010001011 THALES TELECOM ParisTech INSTITUT d'OPTIQUE GRADUATE SCHOOL SEQURENET A QUANTUM KEY TO NETWORK SECURITY

Field implementation

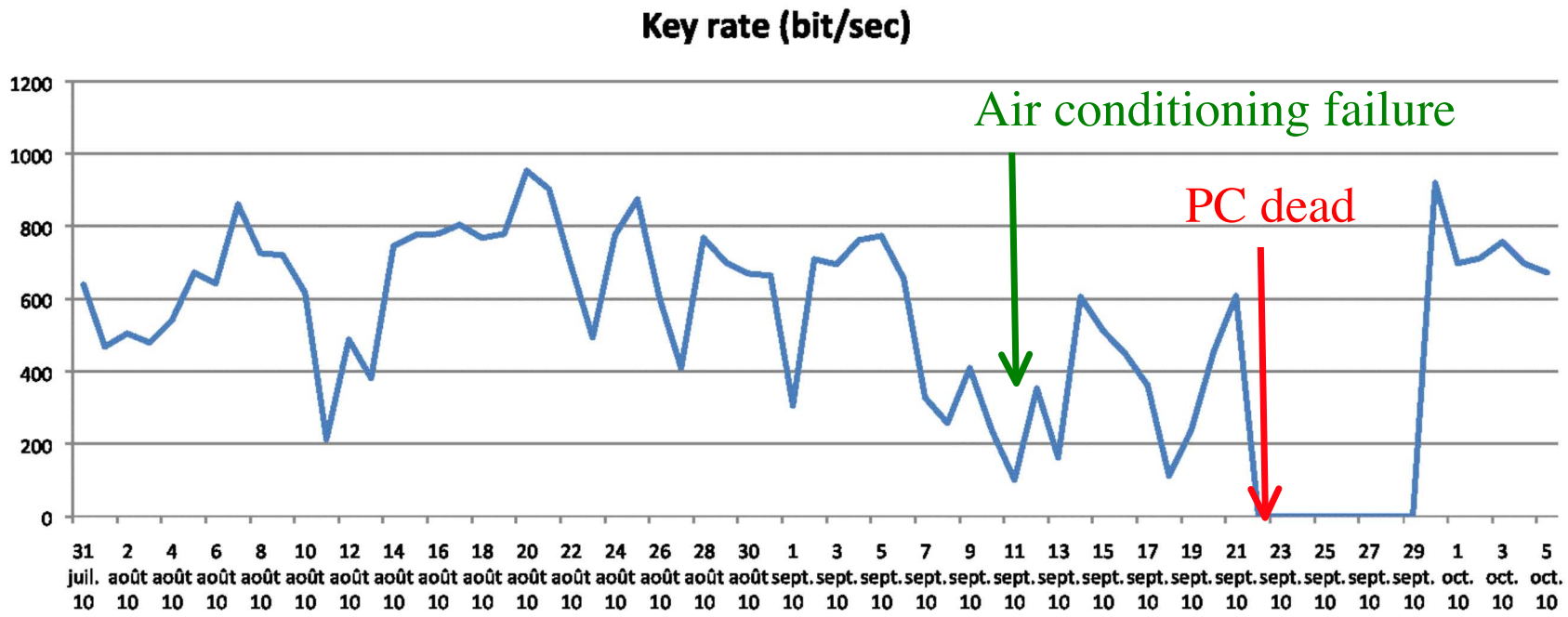
- Fibre link : Thales R&T (Palaiseau) <-> Thales Raytheon Systems (Massy)
- Fiber length about 12 km, 5.6 dB loss



SEQURE 1011010111011001010001011 THALES TELECOM ParisTech INSTITUT d'OPTIQUE GRADUATE SCHOOL SEQURENET A QUANTUM KEY TO NETWORK SECURITY

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

SEQURE 1011010111011001010001011 THALES TELECOM ParisTech INSTITUT d'OPTIQUE GRADUATE SCHOOL SEQURENET A QUANTUM KEY TO NETWORK SECURITY

Post-processing at SeQureNet

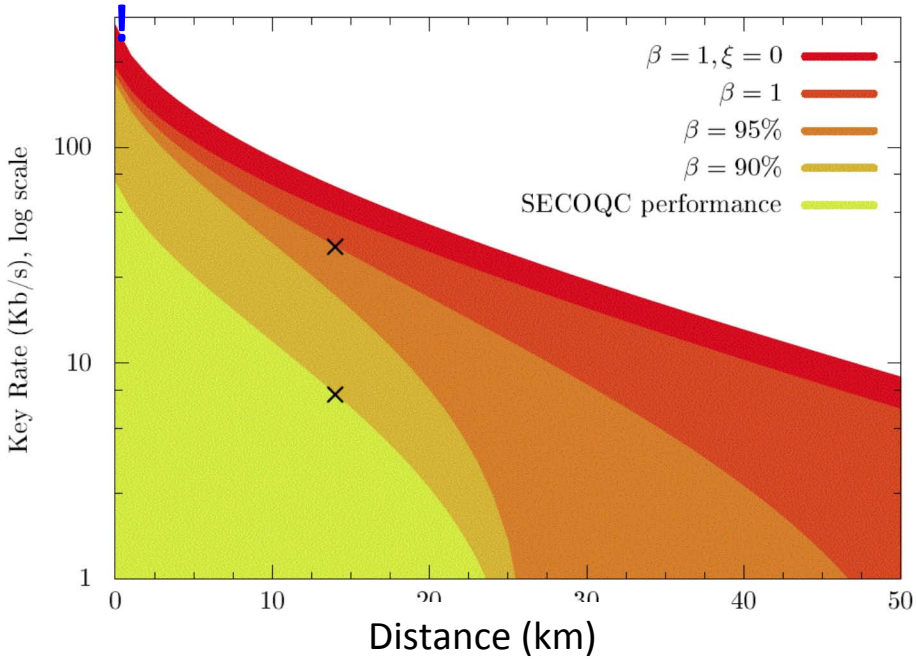
Last version (commercial device, 80 km) : P. Jouguet et al, Nature Phot. 7, 378 (2013)

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 !

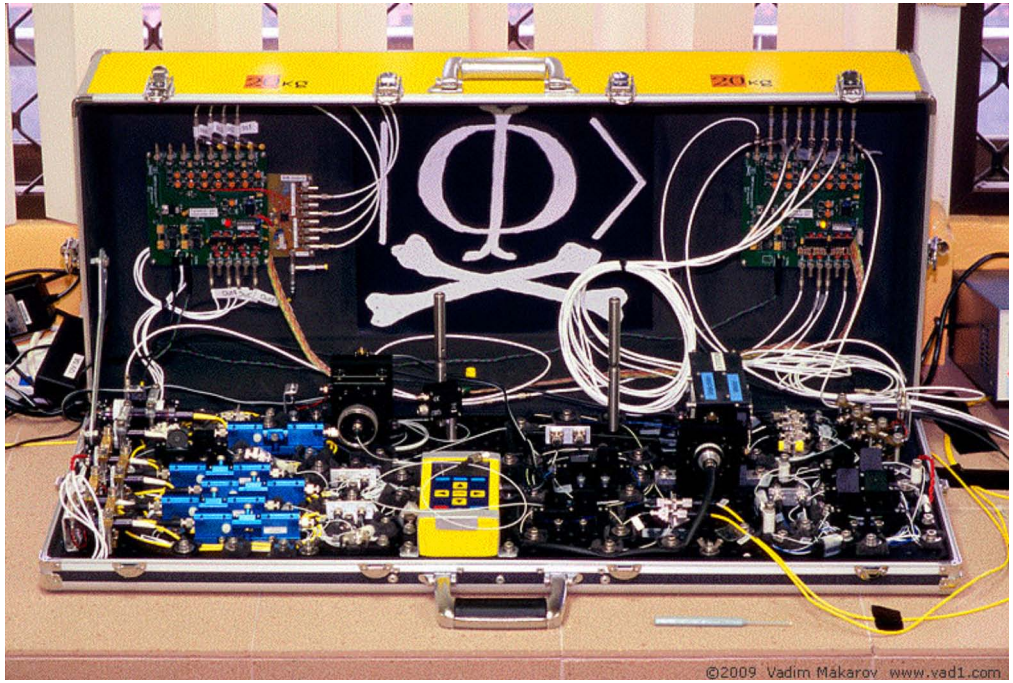
=> β is improved from 89% to 95% for any SNR : **longer distance (80 km)**



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)

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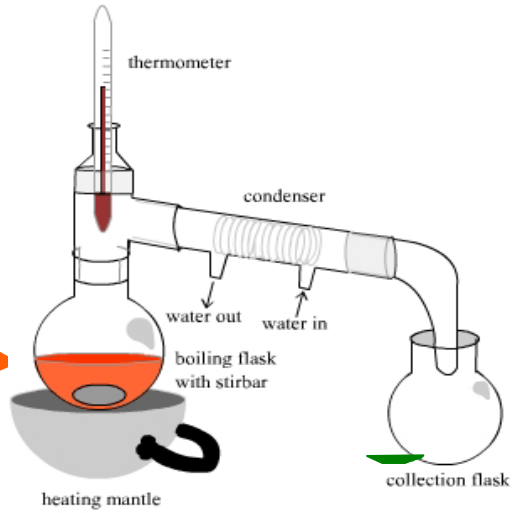
Long-Distance Quantum Communications

- Need to share highly entangled states (cryptography..)
- Problem : losses
- Solution : Entanglement Distillation :

Large number of weakly entangled states

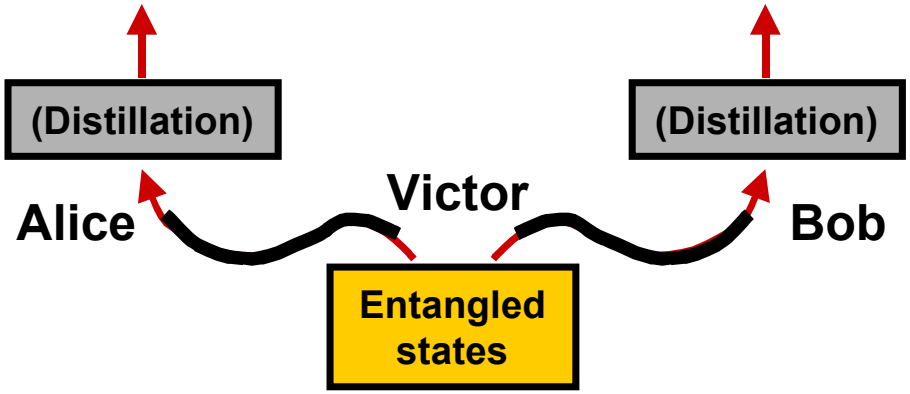


Small number of strongly entangled states

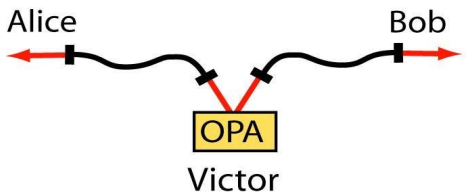
- But impossible to distill Gaussian entanglement with Gaussian means
  $\Rightarrow$ use non-gaussian operations !
  (such as photon subtraction)

How to create entanglement at a large distance ?

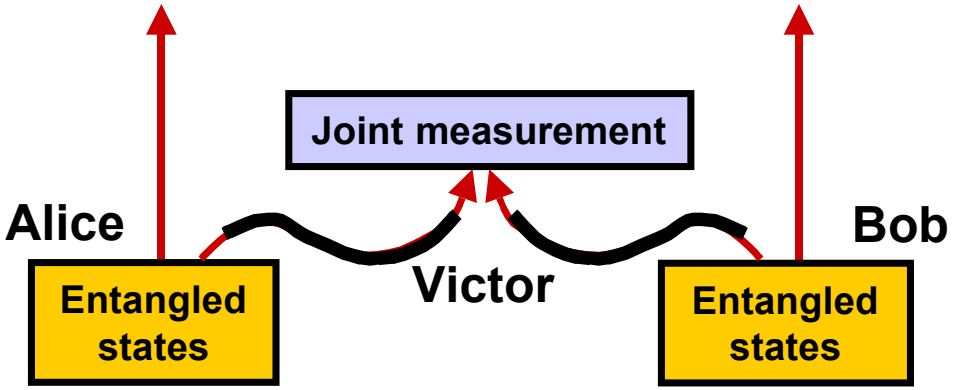
Two main approaches



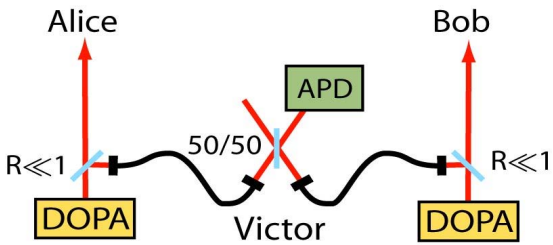
Exemple :



Mostly limites by losses



Exemple :



Mostly limited by noise

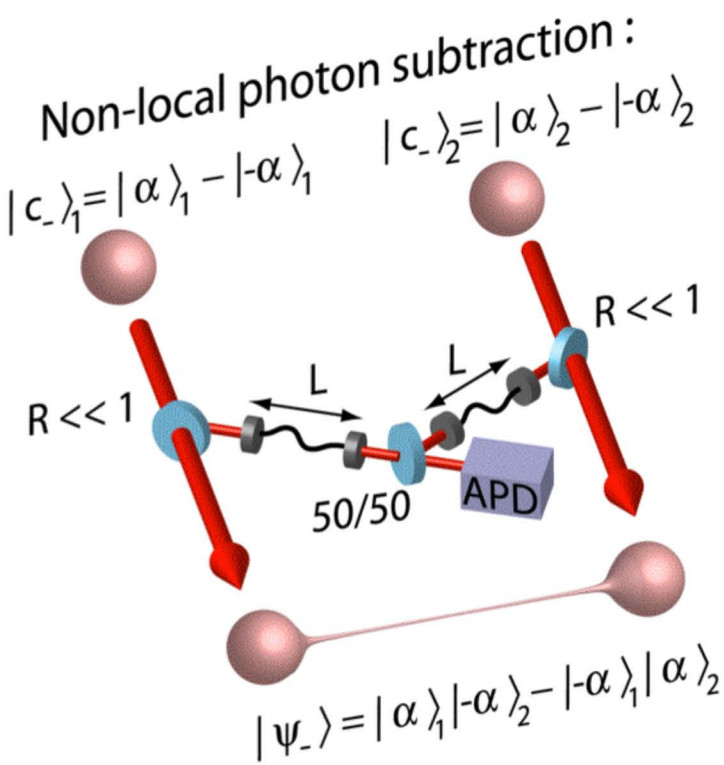
In the present state of technology, this is much more efficient for distances ~ 100 km

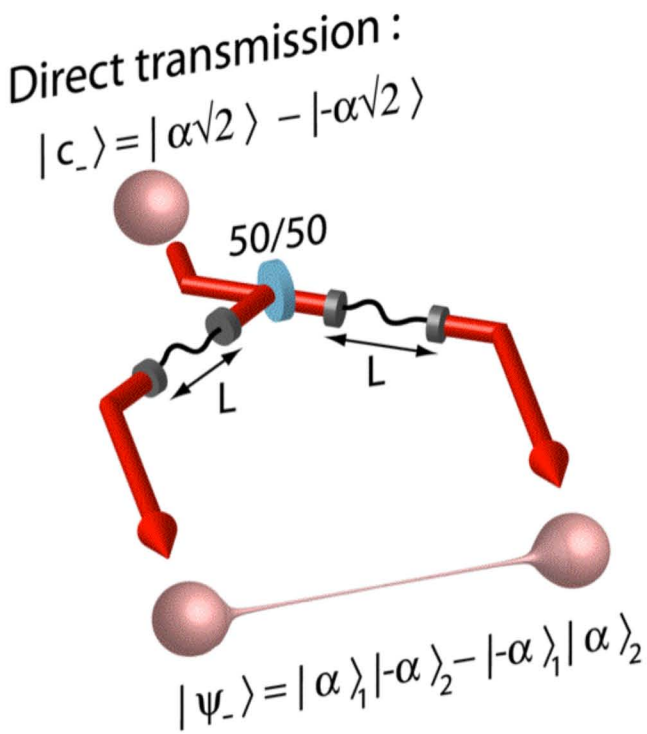
Quantum repeaters with entangled coherent states

Remote entanglement of cat states using "delocalized" photon subtraction

Main advantage of this scheme : **almost insensitive to transmission losses !**

(the non-local cats are never transmitted in the line)

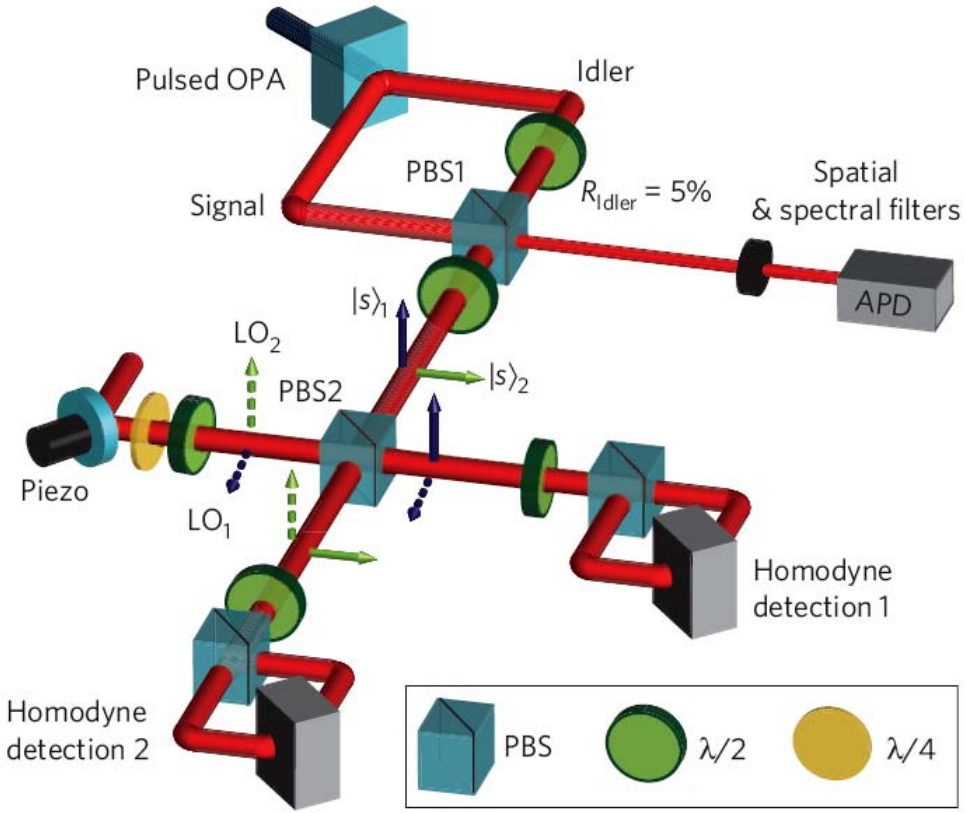




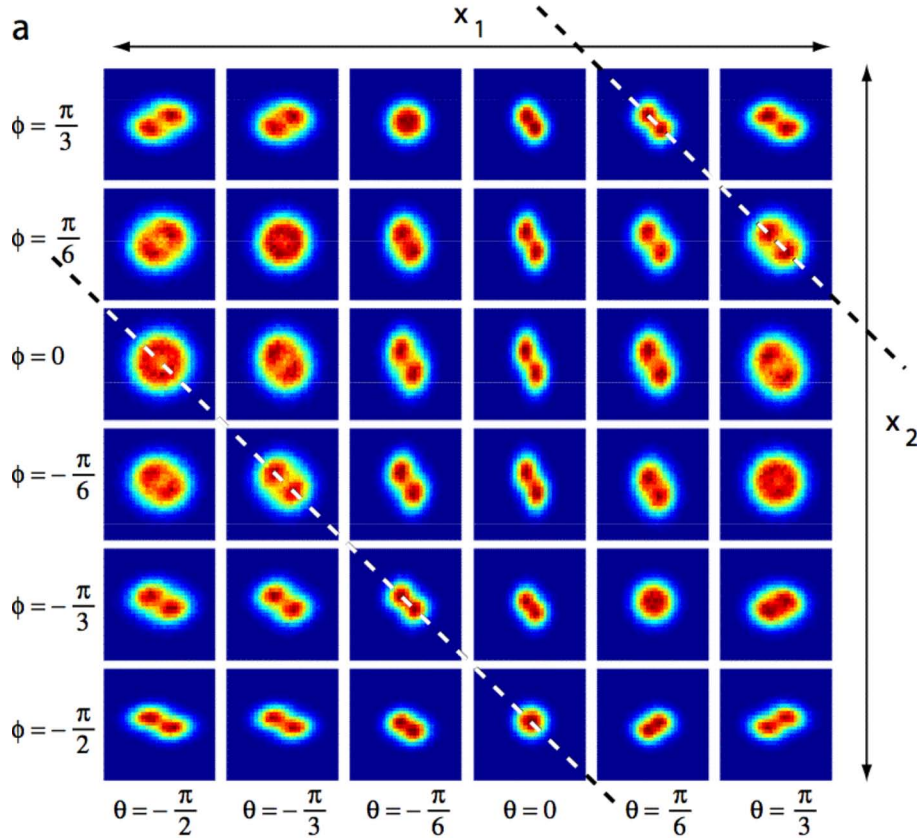
Fidelity for 10 dB losses : **F = 0.4** **F = 0.003**

Experiment

A. Ourjoumtsev et al, Nature Physics, 5, 189, 2009



Experimental set-up



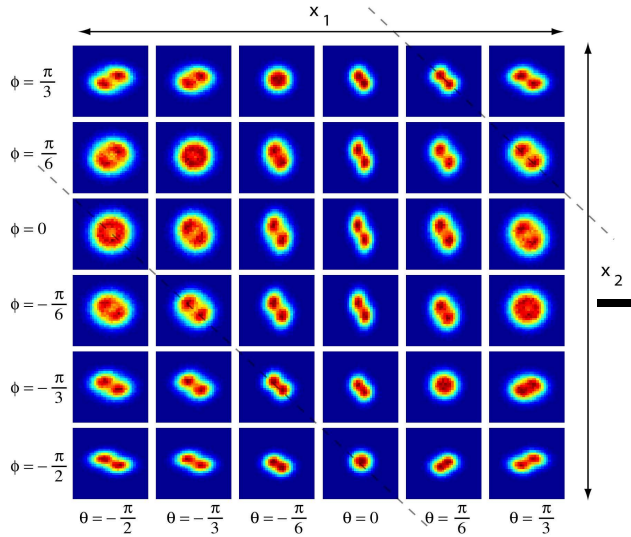
Two-mode probability distributions (two phases ϕ and θ...)

Results

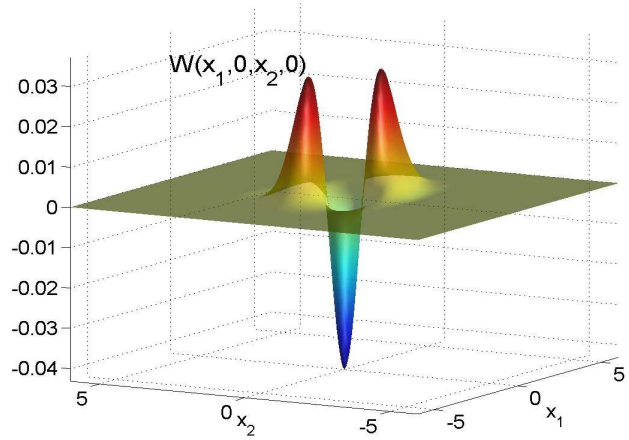
A. Ourjoumtsev et al, Nature Physics, 5, 189, 2009

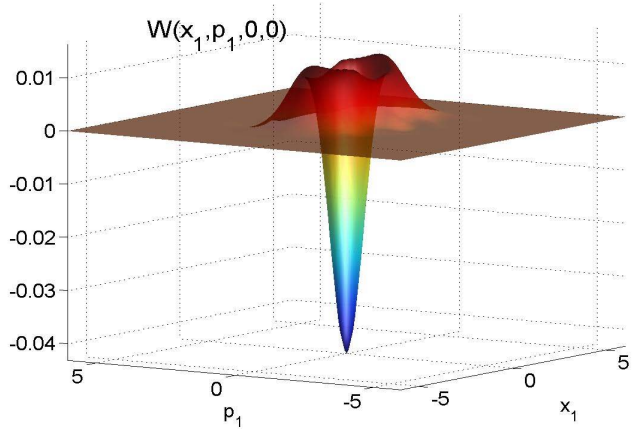
Full two-mode tomography :

$P(x_{1,\theta}, x_{2,\varphi})$



Cuts of the experimental 4D Wigner function, corrected for homodyne losses

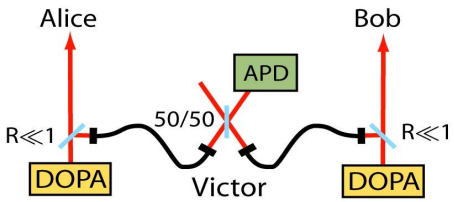




Entanglement : N = 0,25 ± 0,04

Almost insensitive to losses in the quantum channel !

… but still far from a quantum repeater !



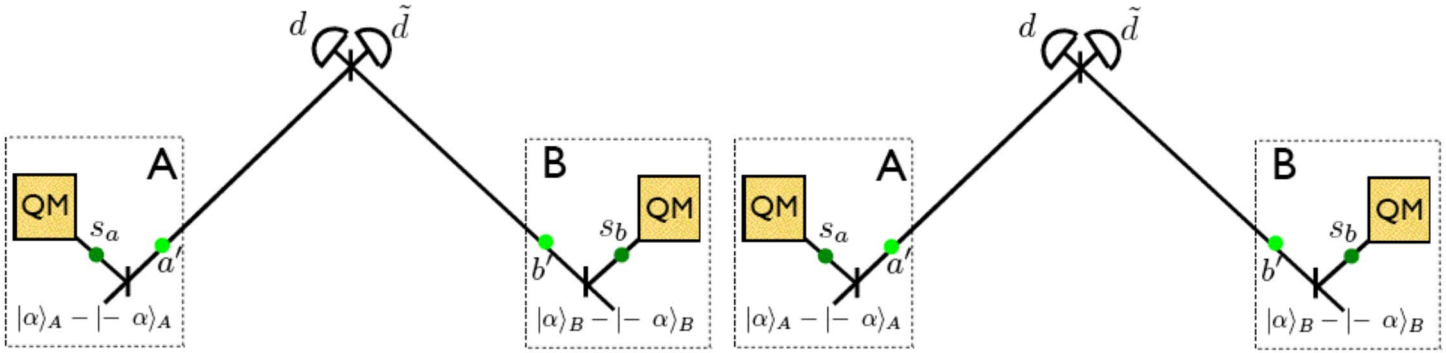
$T_{\text{filters \& APD}}$ ~ 10% :

~ 100 km optical fiber

Quantum repeaters with entangled cats ?

N. Sangouard, C. Simon, N. Gisin, J. Laurat,

R. Tualle-Brouri and P. Grangier, JOSA B 27, 137 (2010)



Bell measurements are deterministic for entangled cats using only BS and photon counters !

$$|\phi_\pm\rangle_{AB} = \frac{1}{\sqrt{M_\pm}}(|\alpha\rangle_A|\alpha\rangle_B \pm |-\alpha\rangle_A|-\alpha\rangle_B)$$

$$|\psi_\pm\rangle_{AB} = \frac{1}{\sqrt{M_\pm}}(|\alpha\rangle_A|-\alpha\rangle_B \pm |\alpha\rangle_A|-\alpha\rangle_B)$$

$\xrightarrow{\text{BS}}$

$$|\phi_+\rangle \rightarrow |\text{even}\rangle_{\text{out1}}|0\rangle_{\text{out2}},$$
$$|\phi_-\rangle \rightarrow |\text{odd}\rangle_{\text{out1}}|0\rangle_{\text{out2}},$$
$$|\psi_+\rangle \rightarrow |0\rangle_{\text{out1}}|\text{even}\rangle_{\text{out2}},$$
$$|\psi_-\rangle \rightarrow |0\rangle_{\text{out1}}|\text{odd}\rangle_{\text{out2}},$$

But parity measurements (even / odd) are extremely sensitive to losses…

-> To avoid errors one has to use kittens rather than cats

-> Increase of the « failure » probability (getting 0 0)

-> Overall not significantly better than using entangled photons :-((

Better hardware needed ! (here : deterministic parity measurement)

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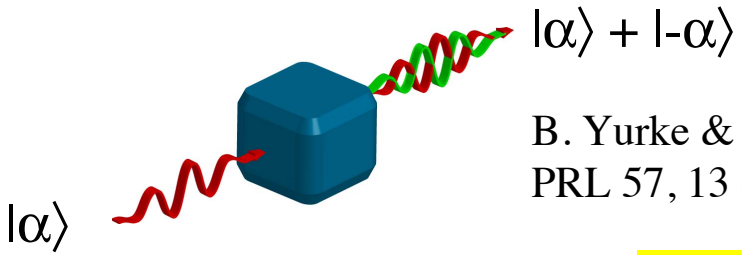
Photon – photon interactions

*** Basic question we want to address :** is it possible to design and manipulate (dispersive and deterministic) **photon-photon interactions ?**

Non-classical state generation



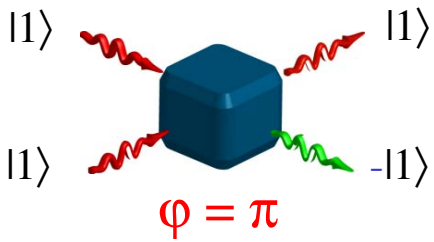
B. Yurke & D. Stoler, PRL 57, 13 (1986)

Self-Kerr effect:

$|n\rangle \rightarrow (e^{i\varphi})^{n(n-1)/2}|n\rangle$

We want $\varphi = \pi$ per photon (aJ !)

Control-phase gate



Cross-Kerr effect

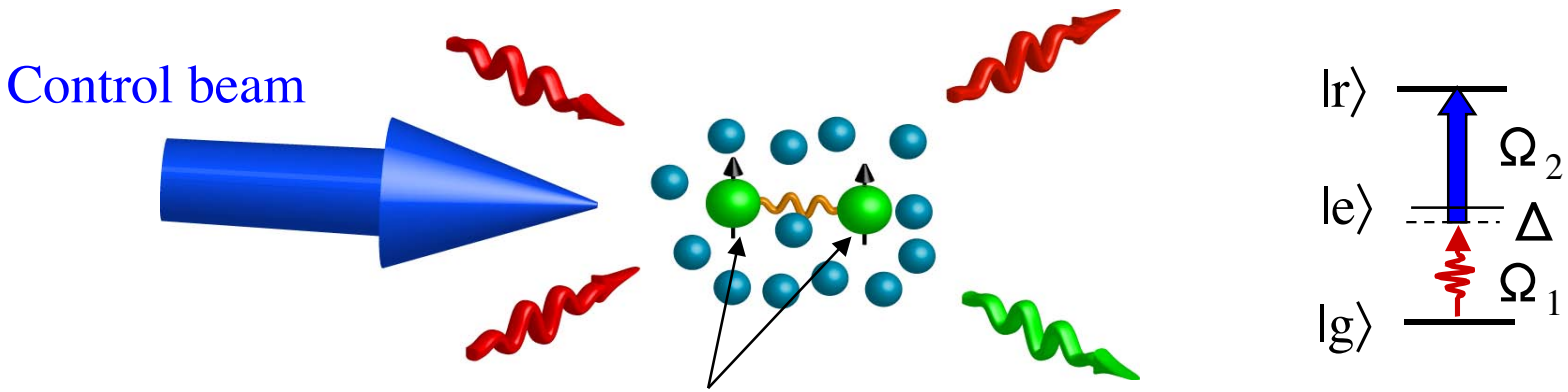
$|n\rangle|m\rangle \rightarrow (e^{i\varphi})^{nm}\, |n\rangle|m\rangle$

*** Present approaches :**

- **measurement-induced non-linearities**, e.g. for KLM, or for producing Fock states, Schrödinger's cat states, noiseless amplification... **Nice expts but their non-deterministic character makes them hardly scalable**

- **cavity QED** : either optical domain or microwave domain (we want optical)

Using Rydberg-Rydberg interactions



Rydberg atoms (^{87}Rb, n~50)

* A possible approach :

- use Rydberg-Rydberg interactions to induce photon-photon interactions

- photons -> (interacting) Rydberg polaritons -> photons

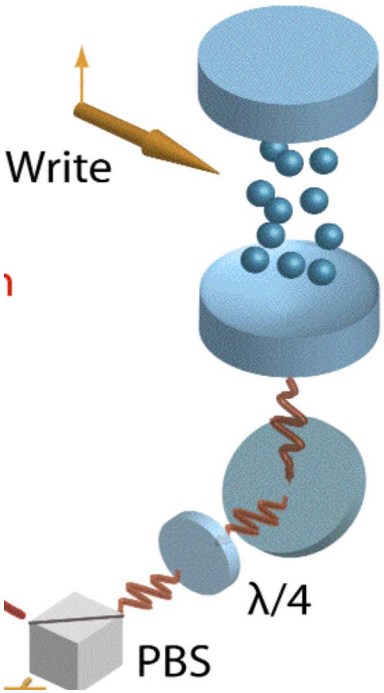
* Lot of ongoing work :

Theory: among recent ones, A. Gorshkov, T. Pohl, F. Bariani, M. Fleischhauer, M. Lukin, G. Kurizki, K. Moelmer & many others

Experiments: groups of C. Adams, A. Kuzmich, V. Vuletic & M. Lukin...

Single Photon from a single polariton (DLCZ protocol)

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



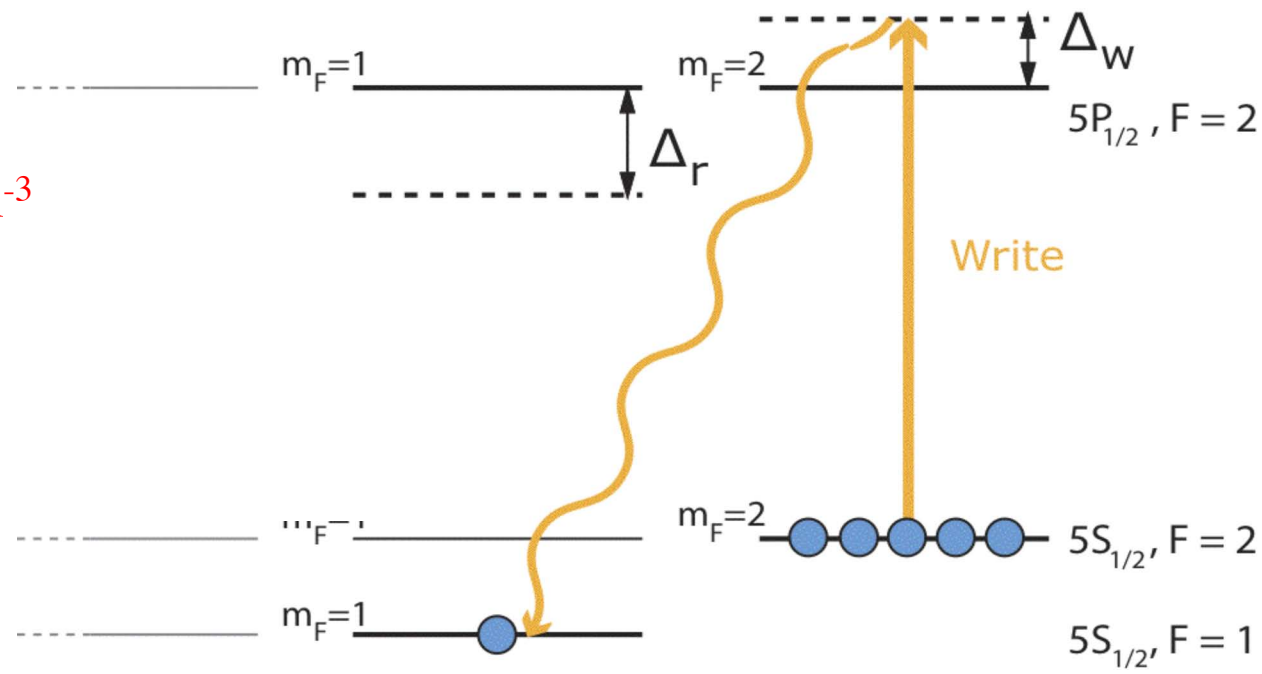
^{87}Rb MOT:

Density

$\rho \approx 4\ 10^{10}$ cm^{-3}

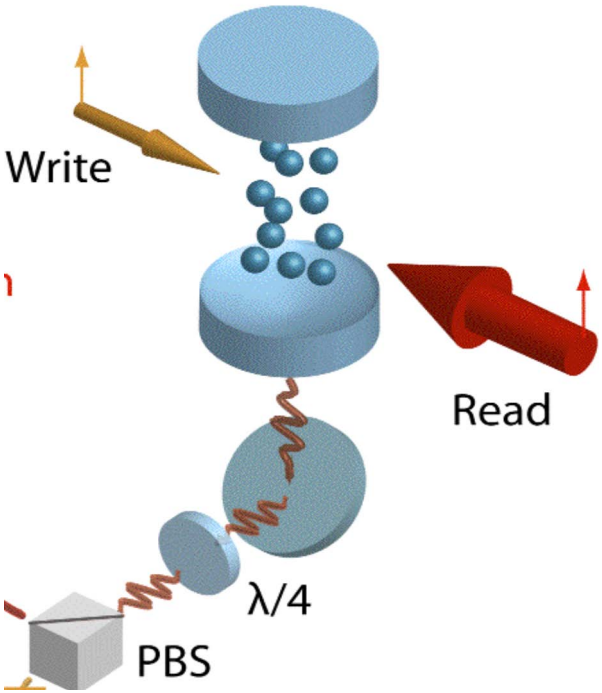
Cooperativity

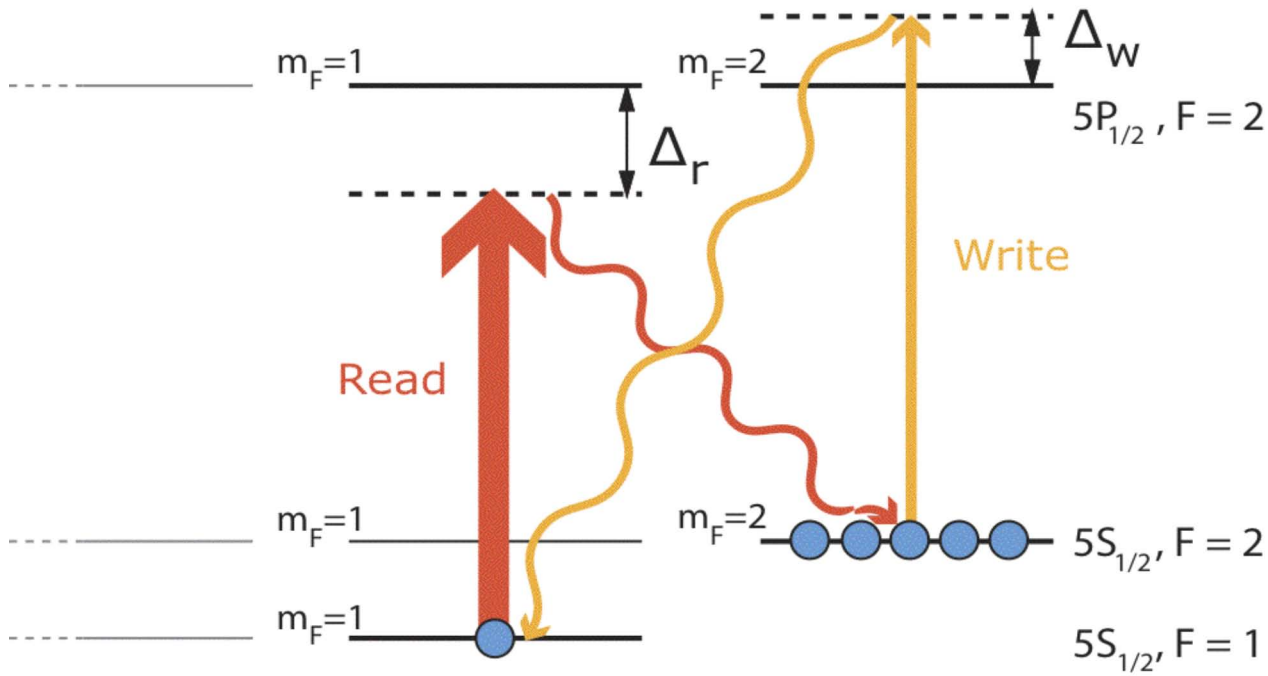
C ≈ 200



E. Bimbard et al, arXiv:1310.1228 (2013)

Single Photon from a single polariton (DLCZ protocol)





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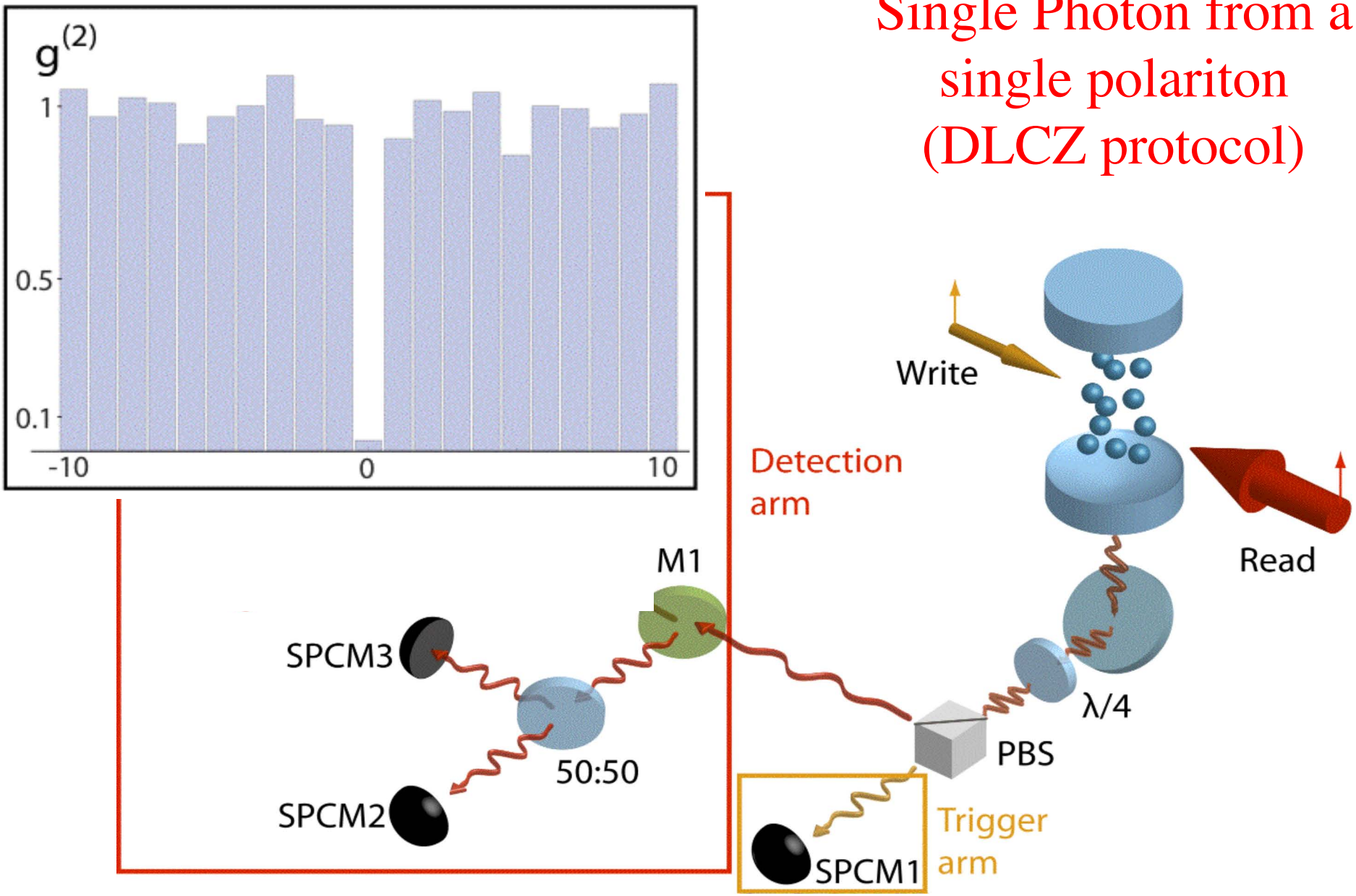

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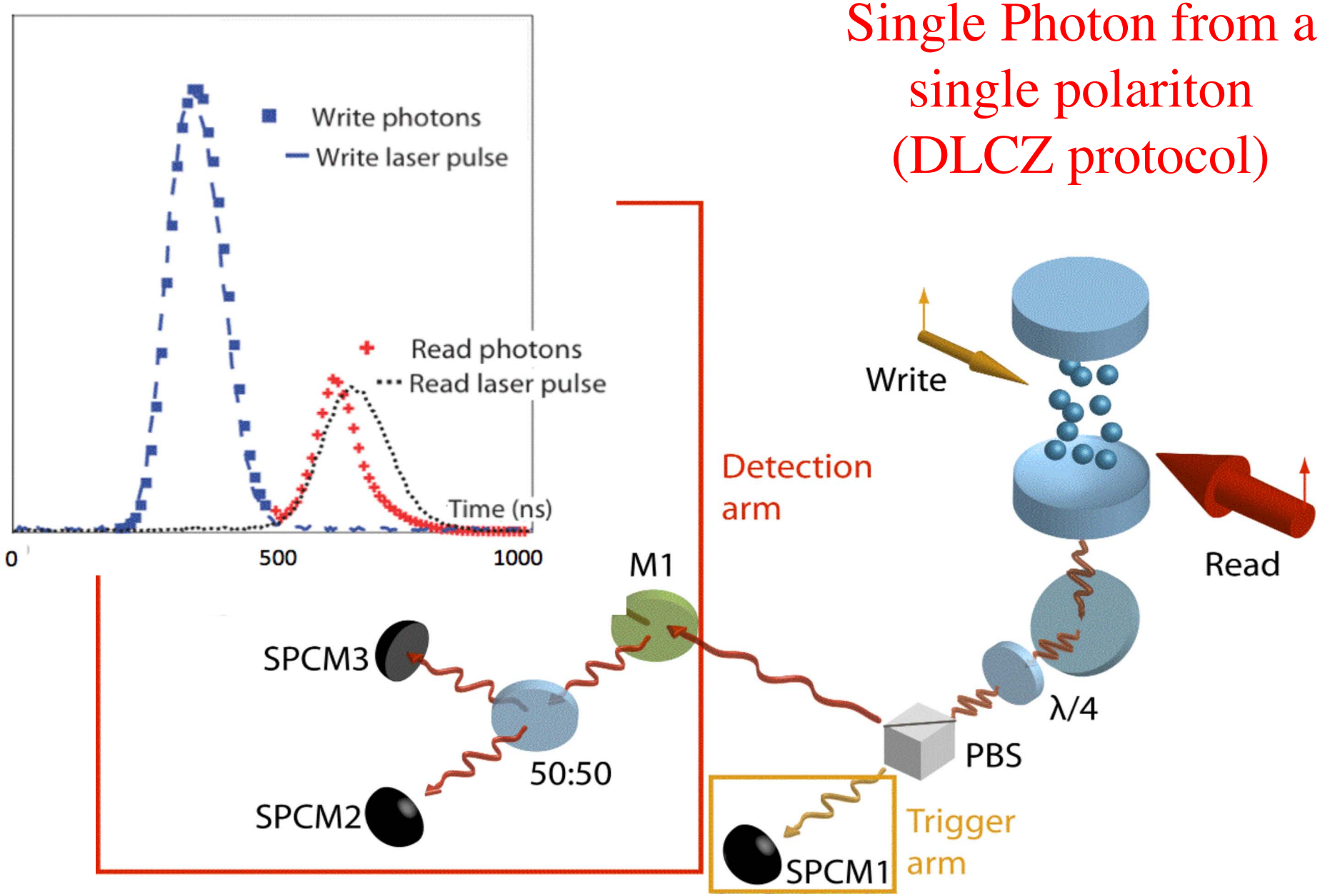

E. Bimbard et al, arXiv:1310.1228 (2013)

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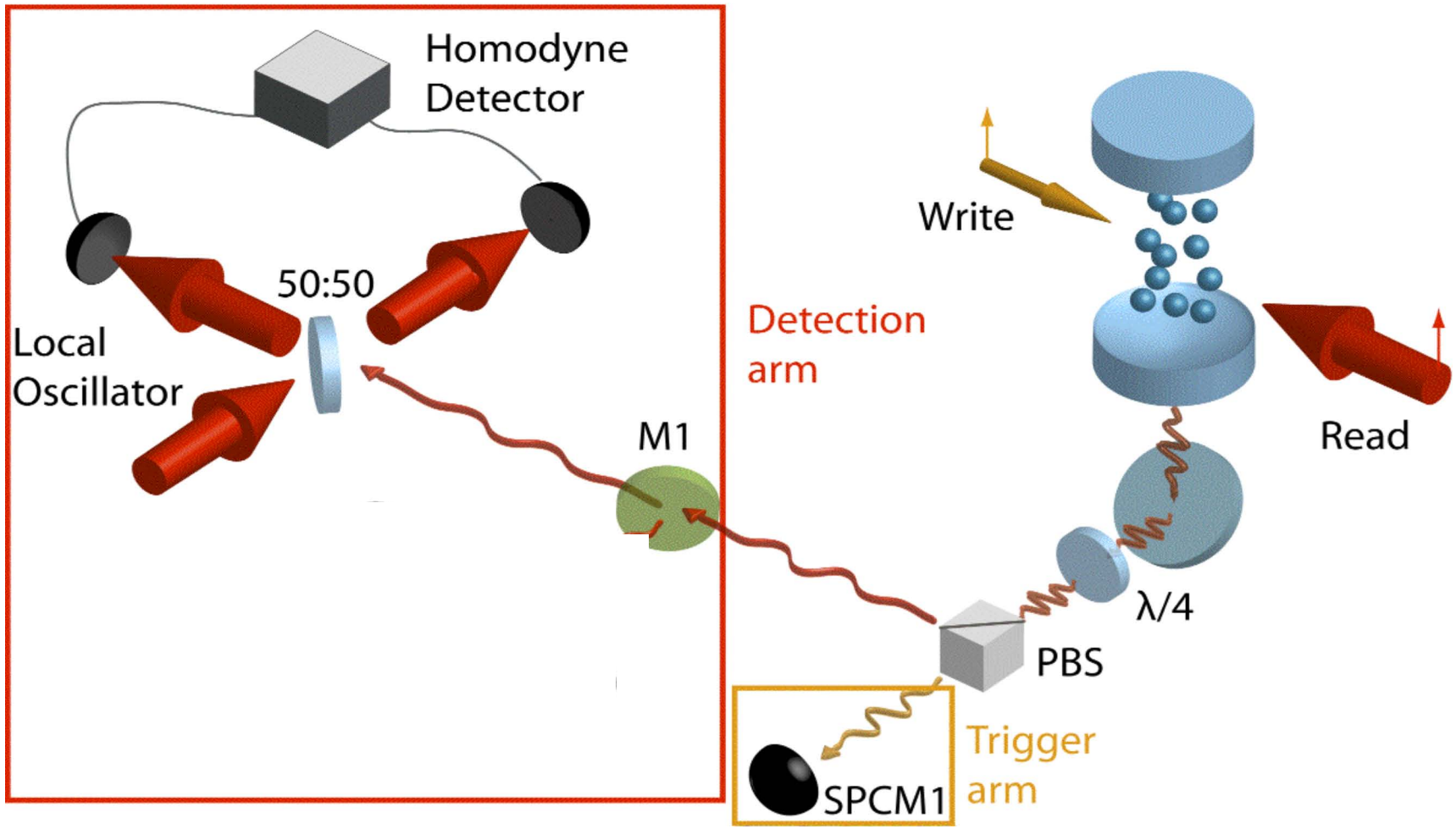
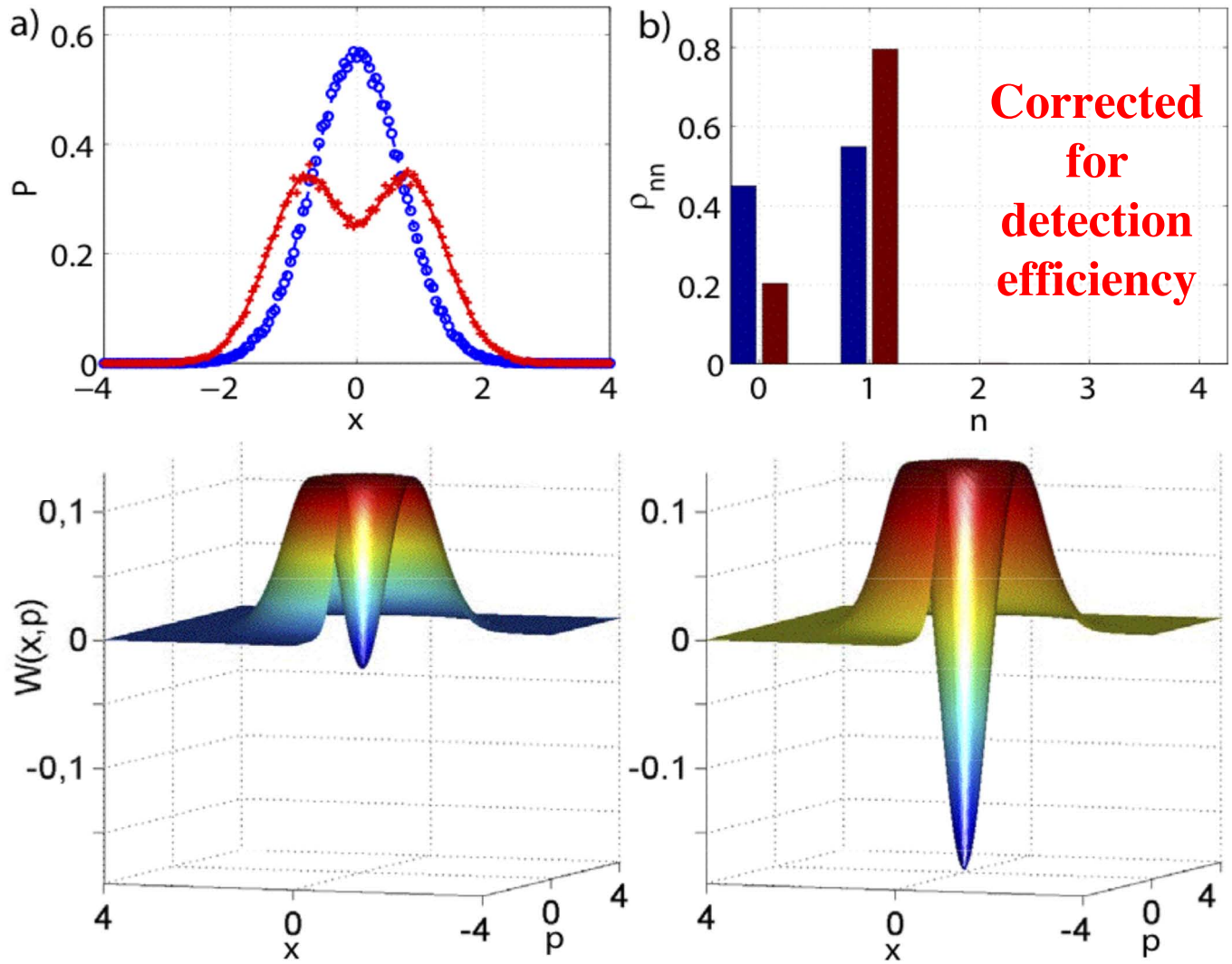


E. Bimbard et al, arXiv:1310.1228 (2013)

Single Photon from a single polariton (DLCZ protocol)

Overall detection efficiency : 55%

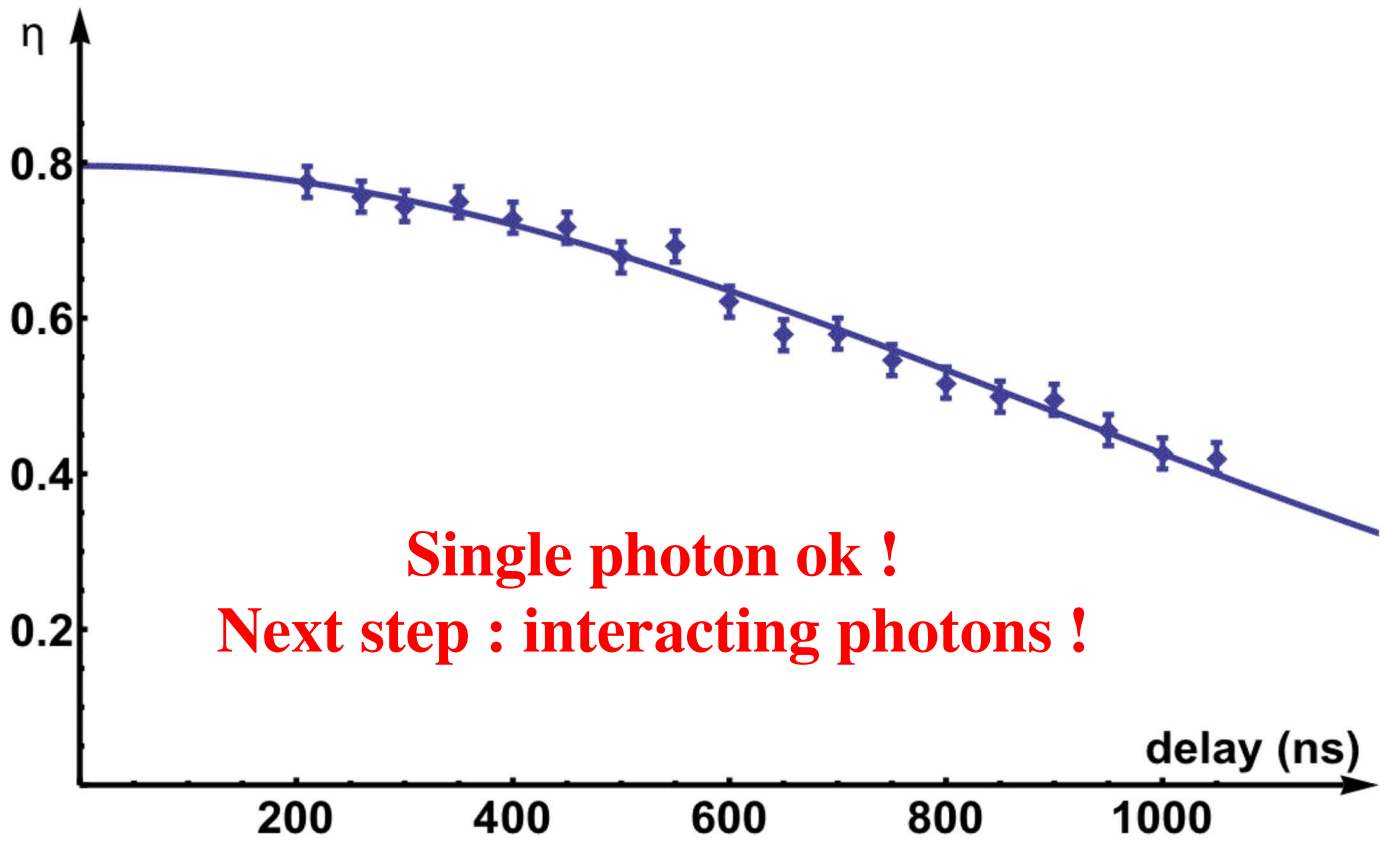


Overall extraction efficiency : 80%

E. Bimbard et al, arXiv:1310.1228 (2013)

Single Photon from a single polariton (DLCZ protocol)

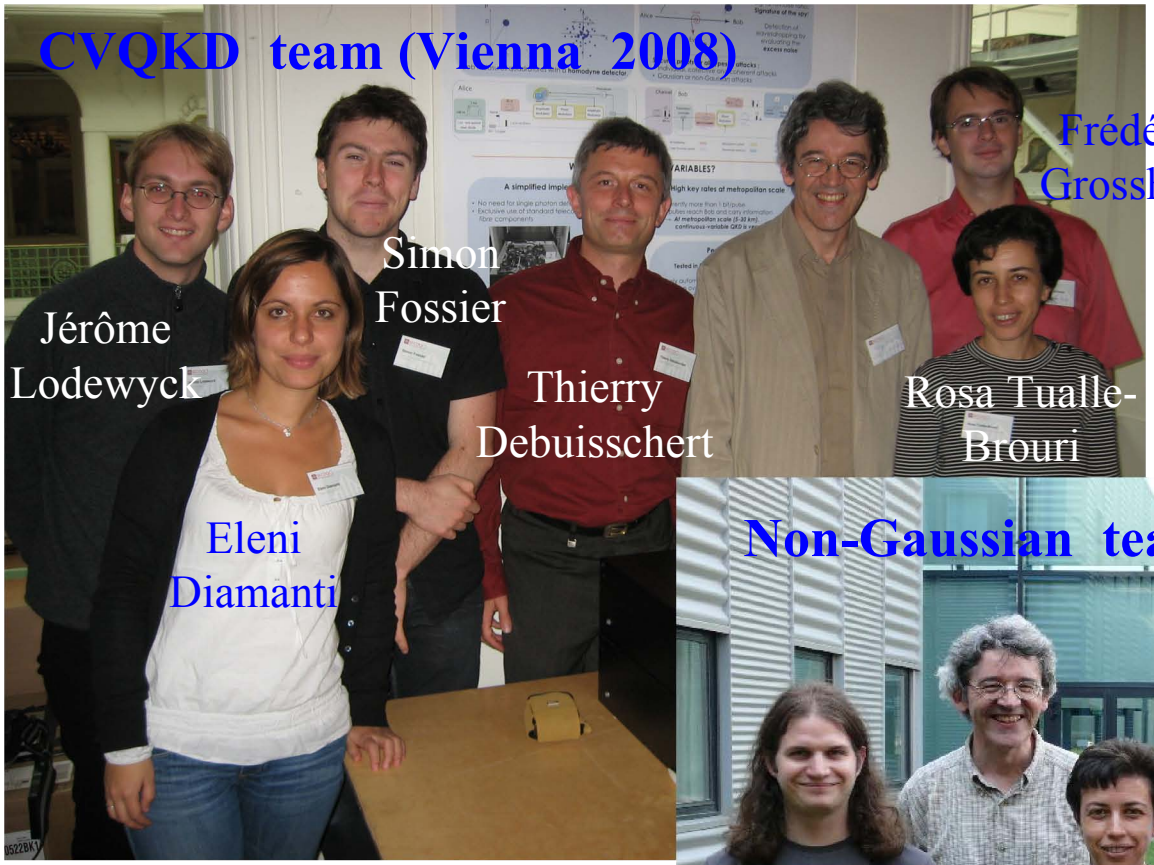
Quantum memory effect : the memory time (1 μs) is limited by motional decoherence due to finite temperature (50 μK)



Single photon ok !
Next step : interacting photons !

E. Bimbard et al, arXiv:1310.1228 (2013)

They did the hard work...



Thank you for your attention !

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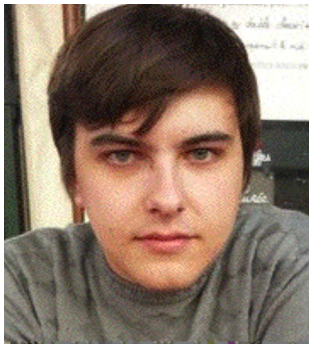

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Rydberg polariton team

Just arrived ! : Rajiv Boddeda, Imam Usmani

Technical staff: F. Fuchs, F. Moron, A. Guilbaud

Collaboration : Pierre Pillet (LAC Orsay)

erc European Research Council

DELPHI

Deterministic Logical Photon-photon Interactions