Content of the lectures

Lecture 1 Introduction to quantum noise, squeezed light and entanglement generation

Quantization of light, Continuous-variable, Homodyne detection, Gaussian states, Optical parametric oscillators, Entanglement, Teleportation

Lecture 2 Quantum state engineering

Conditional preparation, Non-Gaussian states, Schrödinger cat states, Hybrid approaches, Quantum detectors, POVM and detector tomography

Lecture 3 Optical quantum memories.

Quantum repeaters, atomic ensembles, DLCZ, EIT, Photon-echo, Matter-Matter entanglement

Laboratoire Kastler Brossel
Physique quantique et applications

Lecture 2
Quantum State Engineering

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Taiwan-France joint school, Nantou, May 2011

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Lecture 2

- What is a conditional quantum state preparation ?

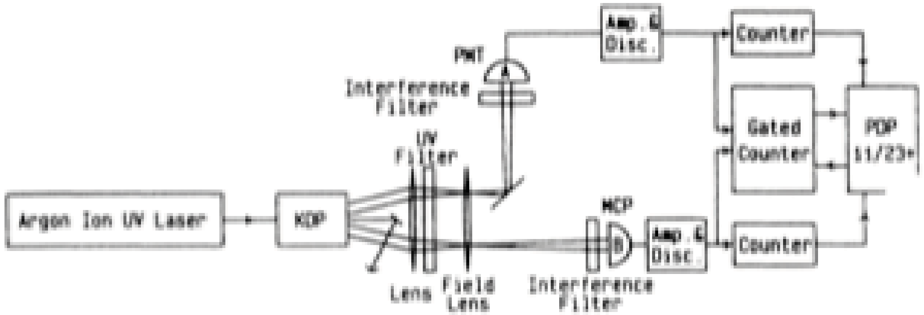
- General strategy for quantum state engineering : Theory

- Illustration : Schrödinger cat state generation

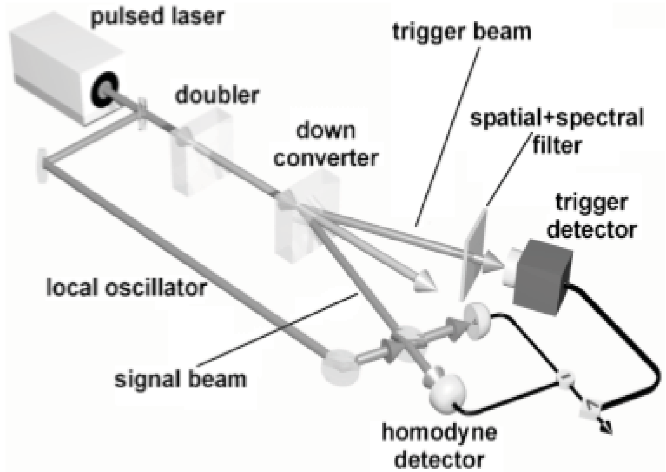
- Quantum detectors, decoherence, and effect on state engineering

What is a Conditional Preparation ?

Example : **Heralded** Single-photon generation



C.K. Hong and L. Mandel, PRL 56, 58 (1986)



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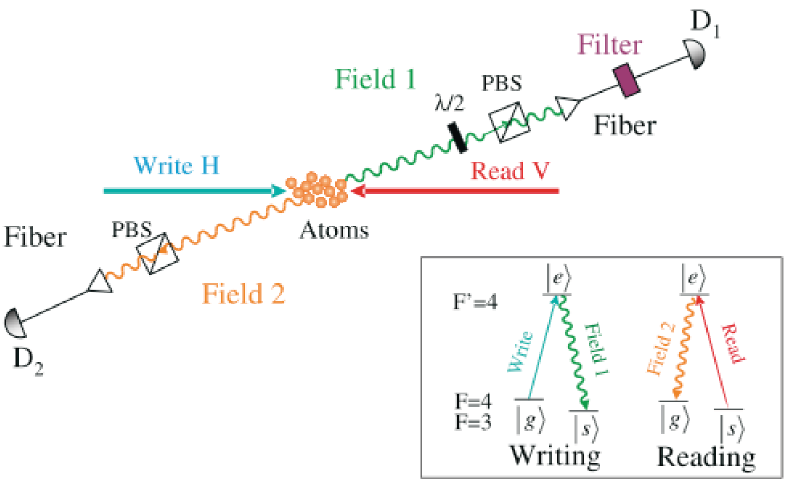
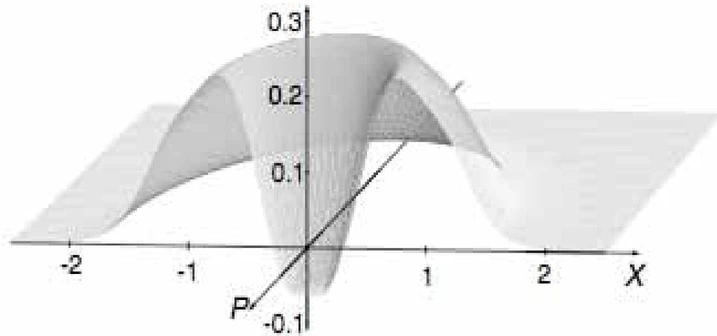


J. Laurat et al., Opt. Express 14, 6912 (2006)



Resource : two-mode state by SPDC or FWM
Heralding : one SPCM (APD)

Quantum State Engineering

Quantum-optical state engineering up to the two-photon level

Nature Photonics **4**, 243 (2010)

Erwan Bimbard[1,2†], Nitin Jain[1,3†], Andrew MacRae[1] and A. I. Lvovsky[1*]

The ability to prepare arbitrary quantum states within a certain Hilbert space is the holy grail of quantum information technology. It is particularly important for light, as this is the only physical system that can communicate quantum information over long distances. We propose and experimentally verify a scheme to produce arbitrary single-mode states of a travelling light field up to the two-photon level. The desired state is remotely prepared in the signal channel of spontaneous parametric down-conversion by means of conditional measurements on the idler channel. The measurement consists of bringing the idler field into interference with two ancilla coherent states, followed by two single-photon detectors, which, in coincidence, herald the preparation event. By varying the amplitudes and phases of the ancillae, we can prepare any arbitrary superposition of zero-, one- and two-photon states.

Goal : heralded generation of the state

$$|\psi\rangle = a_0 |0\rangle + a_1 |1\rangle + a_2 |2\rangle$$

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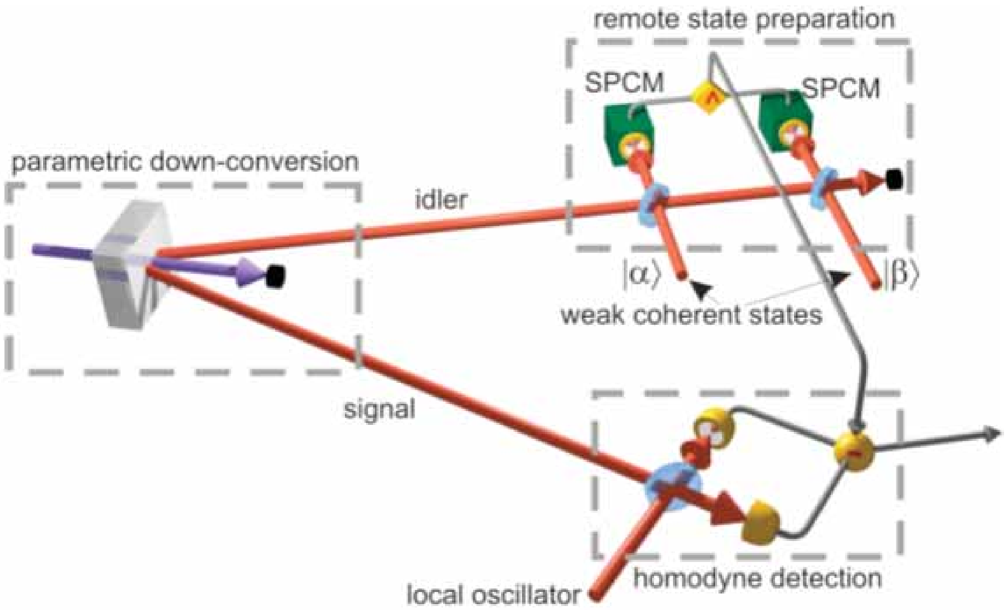


$$|\Psi\rangle = \sqrt{1-\gamma^2}\left[|0_s,0_i\rangle + \gamma|1_s,1_i\rangle + \gamma^2|2_s,2_i\rangle + O(\gamma^3)\right]$$

Resource : two-mode state by SPDC
Heralding : 2 SPCM with two displacements

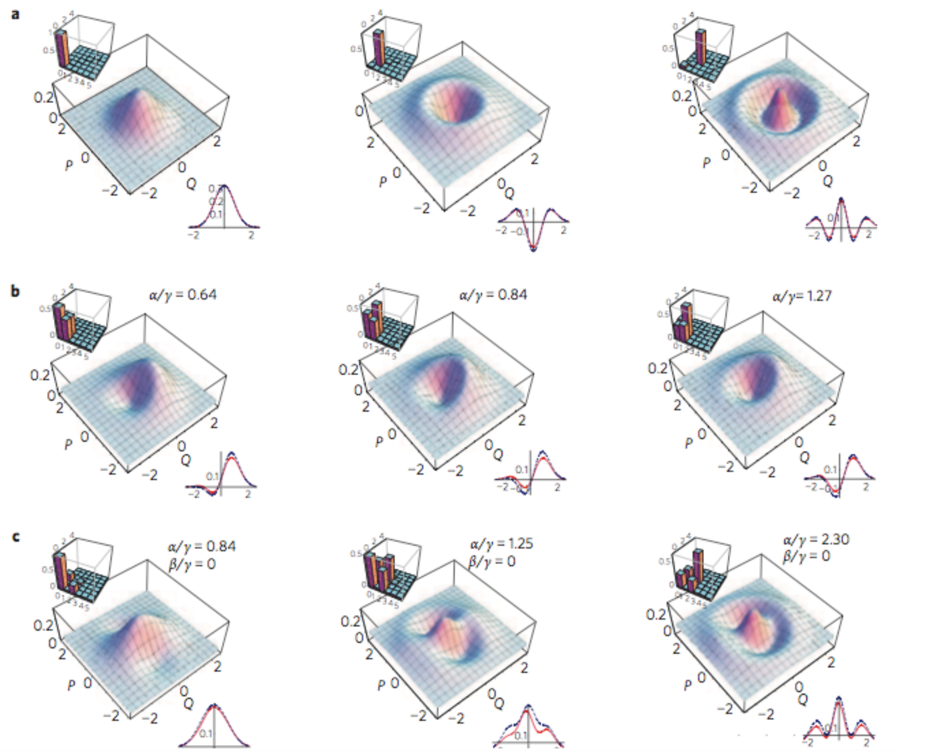


Figure 2 | Various superpositions of photon number states. In each panel, the Wigner function and the density matrix (absolute values) of the reconstructed states are displayed, as well as the cross-section of the Wigner function along the $P=0$ plane. In the cross-sections, the solid red line shows the experimental result and the dashed blue line shows the theoretical fit (see text). All state reconstructions feature correction for 55% detection efficiency. **a**, Results for Fock states $|0\rangle$ (left), $|1\rangle$ (centre) and $|2\rangle$ (right). **b**, Superpositions of states $|0\rangle$ and $|1\rangle$. The single-photon fraction increases from left to right. **c**, Superpositions of states $|0\rangle$ and $|2\rangle$. The two-photon fraction increases from left to right.

Lecture 2

• What is a conditional quantum state preparation ?

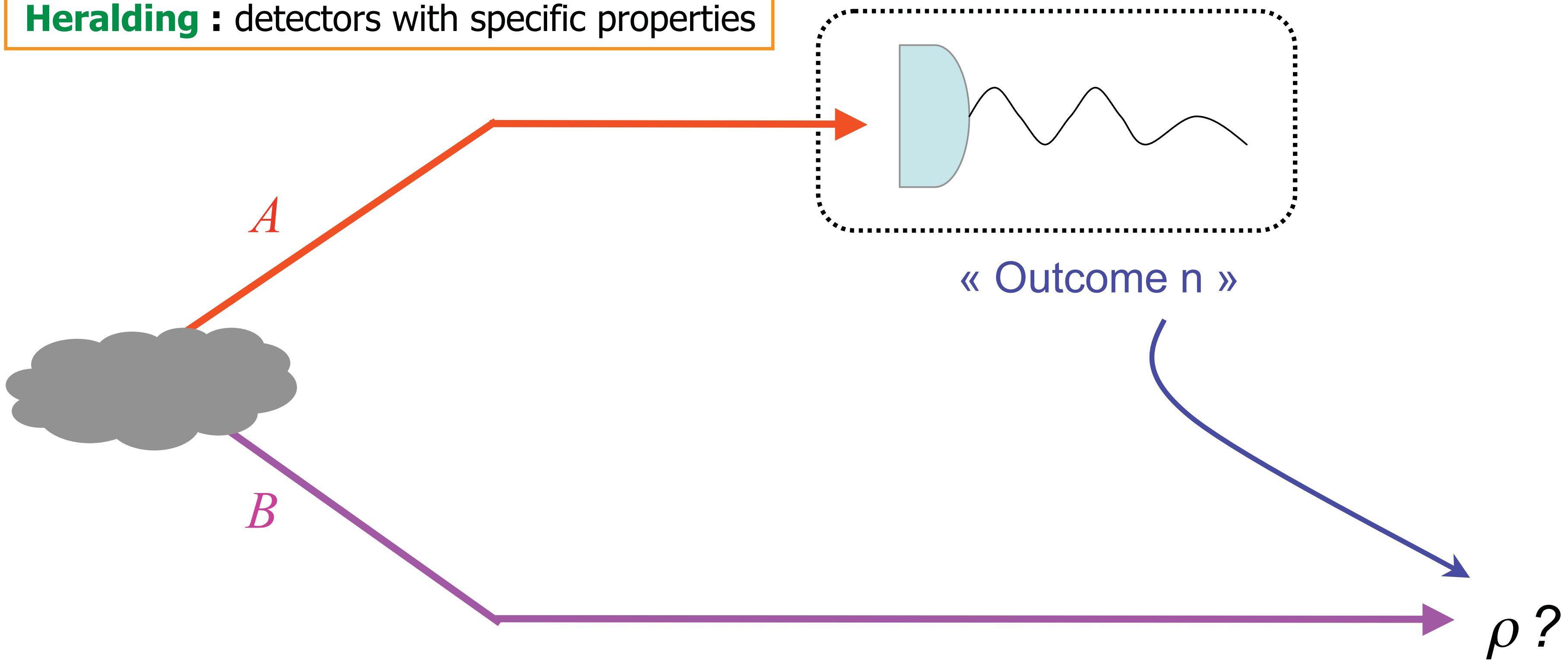
• General strategy for quantum state engineering : Theory

• Illustration : Schrödinger cat state generation

• Quantum detectors, decoherence, and effect on state engineering

General Strategy for QSE

Resource : quantum correlated beams
Heralding : detectors with specific properties



General Strategy for QSE

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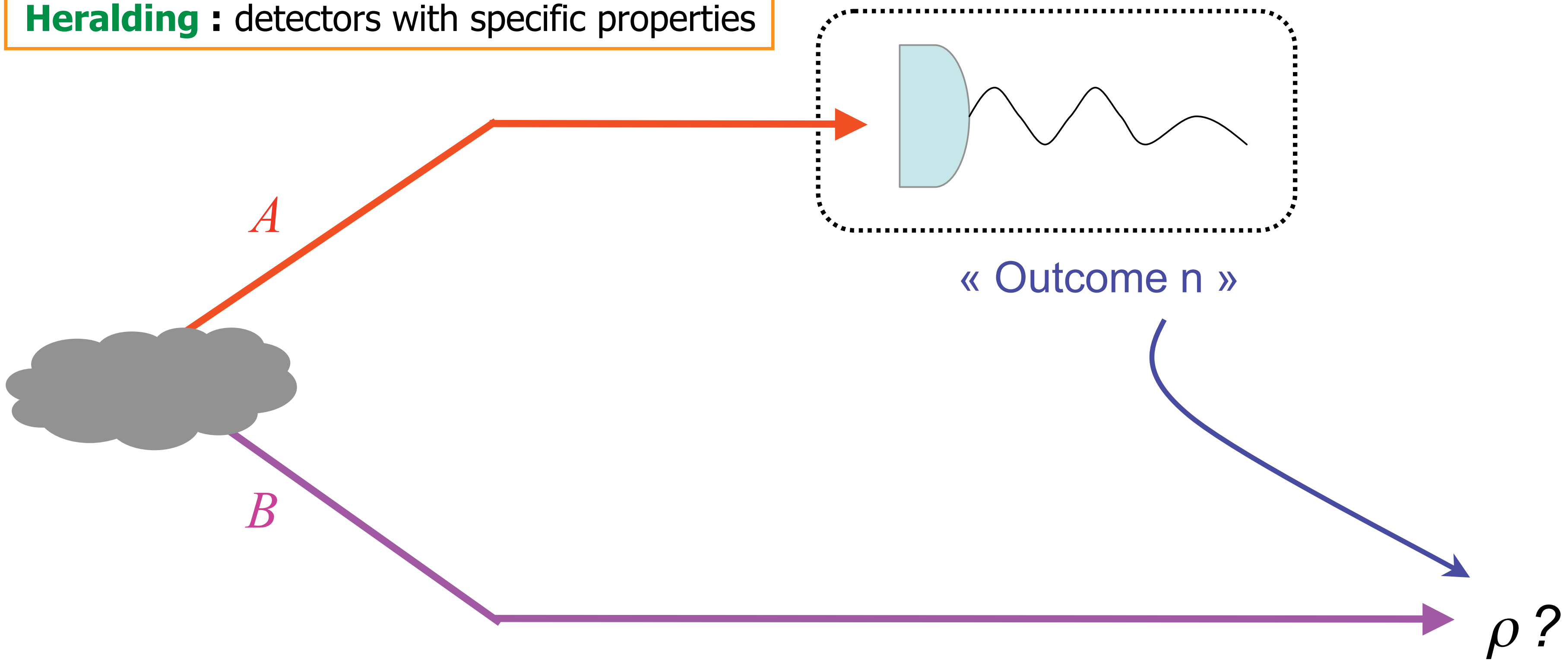


How to describe the heralding detector?

Single-Photon Detectors

REVIEW ARTICLES | FOCUS
PUBLISHED ONLINE: 30 NOVEMBER 2009 | DOI: 10.1038/NPHOTON.2009.230

nature photonics

Single-photon detectors for optical quantum information applications

Robert H. Hadfield

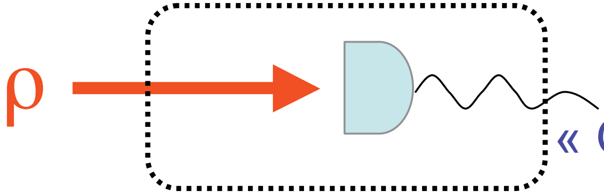
The past decade has seen a dramatic increase in interest in new single-photon detector technologies. A major cause of this trend has undoubtedly been the push towards optical quantum information applications such as quantum key distribution. These new applications place extreme demands on detector performance that go beyond the capabilities of established single-photon detectors. There has been considerable effort to improve conventional photon-counting detectors and to transform new device concepts into workable technologies for optical quantum information applications. This Review aims to highlight the significant recent progress made in improving single-photon detector technologies, and the impact that these developments will have on quantum optics and quantum information science.

Single-photon counting module (SPCM or APD), Transition-edge sensor (TES), Superconducting single-photon detectors (SSPD),…

Key parameters : Quantum efficiency, deadtime, Photon-number resolution, dark noise…

Measurement Apparatus and POVM

Giving an incident state ρ, what is the probability to obtain the outcome “n”?



« Outcome n »

POVM :

- Positive operator valued measure -

The set of POVM elements $\{\Pi_n\}$ fully

e

$$W_n(x,p) = \frac{1}{\pi\hbar}\int_{-\infty}^{\infty} dy\,\langle\, x - y \,|\, \hat{\Pi}_n \,|\, x + y \,\rangle\, e^{(2ipy/\hbar)}$$

Ex.

detectors (n click = n photons)

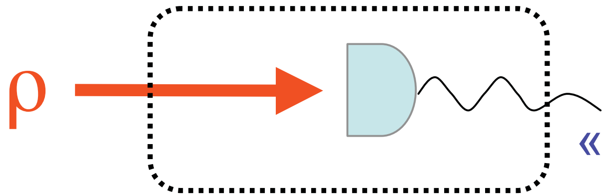
$$\hat{\Pi}_n = |n\rangle\langle n|$$

Ex. 2 : On/Off detector, APD with η=1

$$\hat{\Pi}_{off} = |0\rangle\langle 0|$$

$$\hat{\Pi}_{on} = \hat{1} - |0\rangle\langle 0|$$

such as single-photon detectors



« n clicks »

$$\hat{\Pi}_n = \sum_{k=0}^{\infty} \theta_{n,k} |k\rangle\langle k|$$

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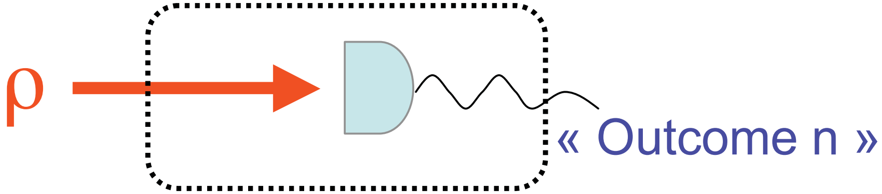


$$Pr\left(n\,|\,\hat{\rho}\right) = Tr\left(\hat{\rho}\,\hat{\Pi}_n\right)$$

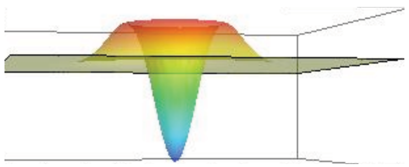
POVM :

\- Positive operator valued measure -

The set of POVM elements $\{\Pi_n\}$ fully describe the possible outcomes of the measurement

Ex. 1 : "Ideal" Photon-number resolving detectors (n click = n photons)

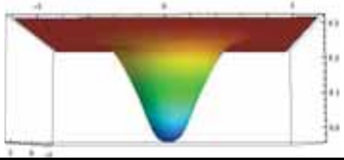
$$\hat{\Pi}_n = |n\rangle\langle n|$$



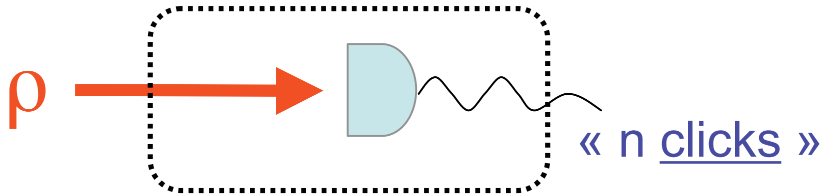
Ex. 2 : On/Off detector, APD with $\eta=1$

$$\hat{\Pi}_{off} = |0\rangle\langle 0|$$

$$\hat{\Pi}_{on} = \hat{1} - |0\rangle\langle 0|$$



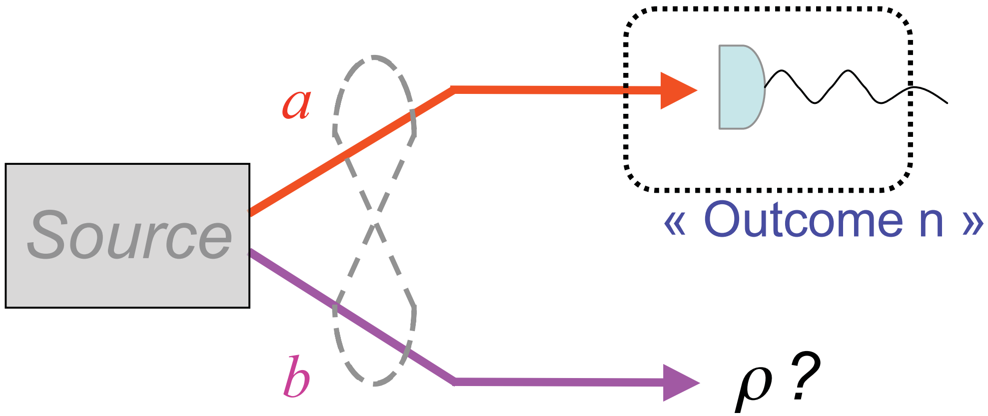
Phase-insentive detectors, such as single-photon detectors



$$\hat{\Pi}_n = \sum_{k=0}^{\infty} \theta_{n,k} |k\rangle\langle k|$$

Conditional State Preparation with SPDC

Giving two entangled modes, what is the prepared state for the outcome “n”?



$$|\Psi\rangle_{ab} = \sqrt{1-|\lambda|^2}\sum_{m=0}^{\infty}\lambda^m |m\rangle_a |m\rangle_b$$

$$\hat{\Pi}_n = \sum_{k=0}^{\infty}\theta_{n,k}|k\rangle\langle k|$$

$$\longrightarrow \quad \rho_n = \frac{\sum_k \lambda^{2k}\,\theta_{n,k}|k\rangle\langle k|}{\sum_k \lambda^{2k}\,\theta_{n,k}}$$

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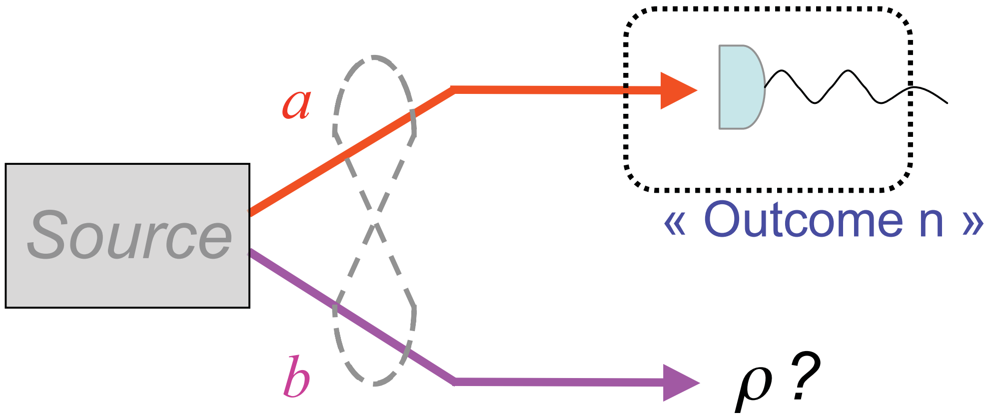

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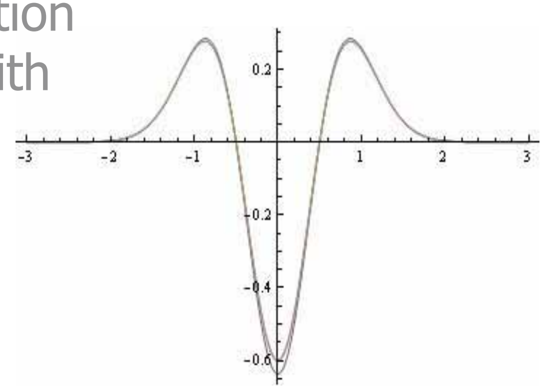
Example: Detectors and Single-Photon Generation

With no photon number resolution ability, POVM coefficients with n>1 still important!

$$\rho_1 \propto \lambda^2\,\theta_{1,1}|1\rangle\langle 1| + \lambda^4\,\theta_{1,2}|2\rangle\langle 2| + \ldots$$

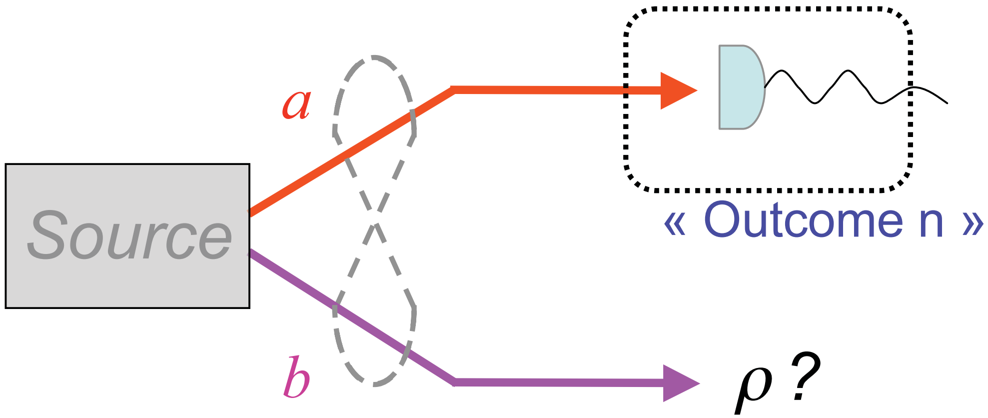
Need thus to use very small λ

Simulations of the Wigner function obtained with
- APD
- TMD
No noise
λ=0.1



Understand POVM : With Entanglement

Giving two entangled modes, what is the prepared state for the outcome "n"?



$$|\Psi\rangle_{ab} = \sqrt{1-|\lambda|^2}\sum_{m=0}^{\infty}\lambda^m |m\rangle_a |m\rangle_b$$

For $\lambda \rightarrow 1$ (perfect entanglement) and a measurement on mode a described by Π_n:

$$\rho = \frac{\Pi_n}{\mathrm{Tr}(\Pi_n)}$$

Non-classicality :

The non-classicality of the prepared states for perfect photon-number correlations.

Ex. : "Ideal" Photon-number resolving detectors (n click = n photons)

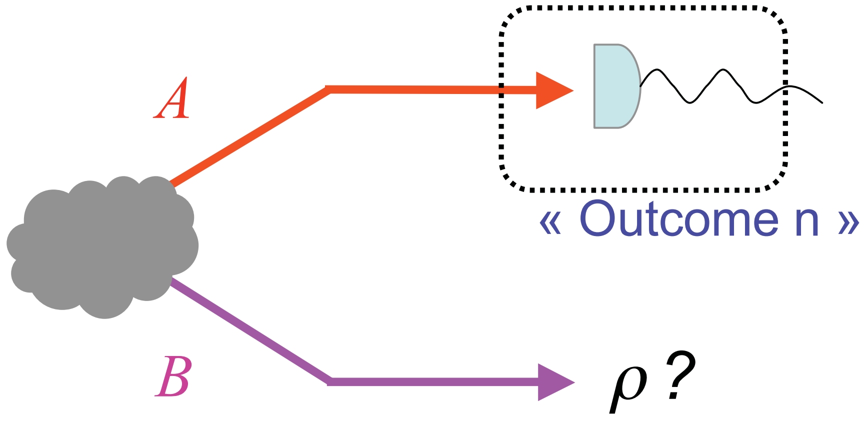
$$\hat{\Pi}_n = |n\rangle\langle n| \longrightarrow \rho = |n\rangle\langle n|$$

Conditional preparation of Fock states

Generalization : Ressource and Detectors

We consider a two-mode state ρ_{AB}, which can be described by the two-mode Wigner function W_{AB}. We operate a measurement on the mode A described by the POVM Π_n (with Wigner function W_n).

What's the expression of the Wigner W of the conditional state ρ ?



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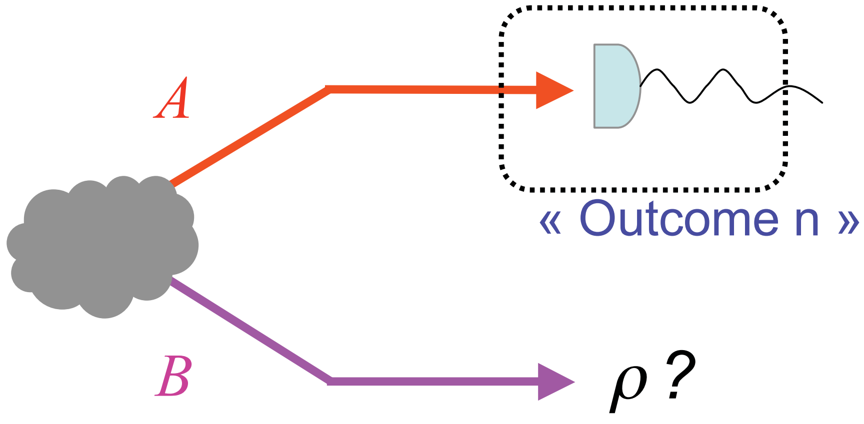

- Probability of outcome n : $$P(n) = Tr\left[\rho_A \hat{\Pi}_n\right] \quad \text{with} \quad \rho_A = Tr_B\left[\rho_{AB}\right]$$

- Expression of the conditional state : $$\rho = \frac{1}{P(n)} Tr_A\left[\rho_{AB}\, \hat{\Pi}_n \otimes I_B\right]$$

- In terms of Wigner function : $$W(p,q) = \frac{\int W_{AB}(p,q,u,v)\, W_n(u,v)\, du dv}{\int W_{AB}(p',q',u,v)\, W_n(u,v)\, du dv dp' dq'}$$

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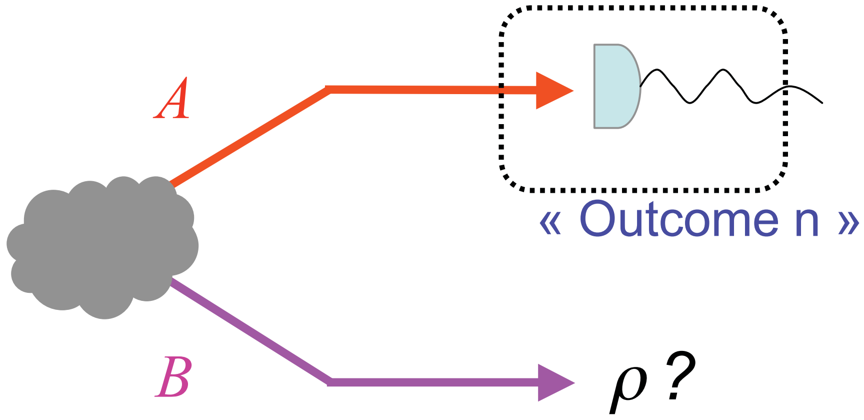

- Probability of outcome n : $P(n) = Tr\left[\rho_A \hat{\Pi}_n\right]$ with $\rho_A = Tr_B\left[\rho_{AB}\right]$

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To have a negative Wigner function, there are 2 possibilities.
1/ Positive resource and a detector with negative Wigner function. (M1)
2/ Negative resource and a detector with positive Wigner function. (M2)

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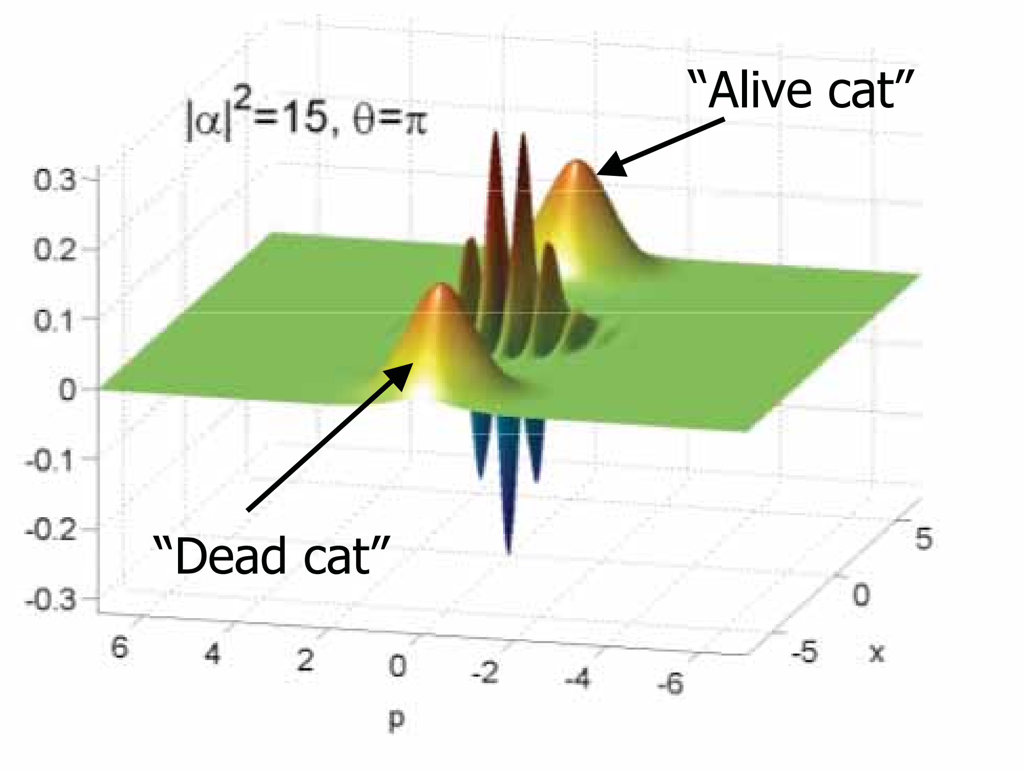
- Quantum detectors, decoherence, and effect on state engineering

Optical Schrödinger Cat

Schrödinger cat : superposition of two distinguishable macroscopic states.
Here: two coherent states.

$$|\alpha\rangle = e^{-|\alpha|^2/2} \sum_{n=0}^{+\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

$$|\alpha\rangle - |-\alpha\rangle = \sum c_n |2n+1\rangle$$



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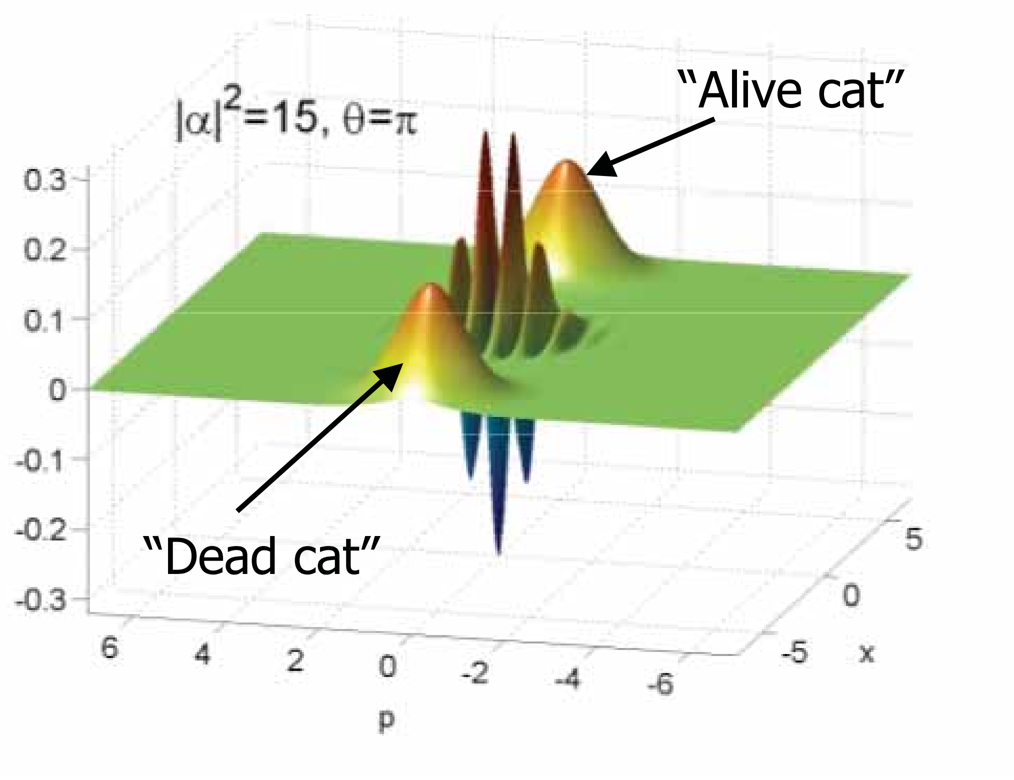
Why generating such states ?

- Non-Gaussian states for Bell violation without loopholes
- Entanglement distillation
- Quantum metrology
- Coherent state quantum computing (CSQC)

$$a|\alpha\rangle + b|-\alpha\rangle = a|0\rangle + b|1\rangle$$



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INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF OPTICS B: QUANTUM AND SEMICLASSICAL OPTICS

J. Opt. B: Quantum Semiclass. Opt. **6** (2004) S828–S833 PII: S1464-4266(04)72410-6

Schrödinger cats and their power for quantum information processing

A Gilchrist[1], Kae Nemoto[2], W J Munro[3], T C Ralph[1], S Glancy[4], Samuel L Braunstein[5] and G J Milburn[1]

Optical Schrödinger Cat

(Feasible) gates
for qubits in the coherent
state basis

$$|\psi_{\text{in}}\rangle = x|\alpha\rangle + y|-\alpha\rangle$$

PHYSICAL REVIEW A **82**, 014304 (2010)

Elementary gates for quantum information with superposed coherent states

Petr Marek and Jaromír Fiurášek
Department of Optics, Palacký University, 17. Listopadu 1192/12, CZ-771 46 Olomouc, Czech Republic
(Received 30 April 2010; published 27 July 2010)

We propose an alternative way of implementing several elementary quantum gates for qubits in the coherent-state basis. The operations are probabilistic and employ single-photon subtractions as the driving force. Our schemes for single-qubit PHASE gate and two-qubit controlled PHASE gate are capable of achieving arbitrarily large phase shifts with currently available resources, which makes them suitable for the near-future tests of quantum-information processing with superposed coherent states.

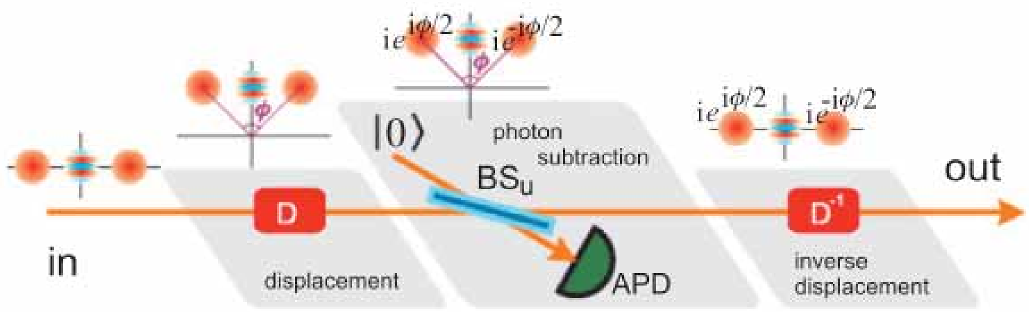


FIG. 1. (Color online) Schematic representation of the single-mode PHASE gate. BS stands for a mostly transmitting strongly unbalanced beam splitter, APD stands for avalanche photodiode, and *D* represents the displacement operation.

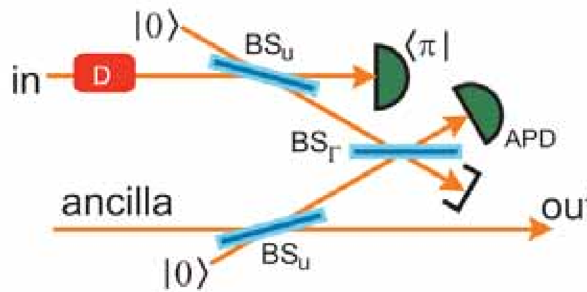


FIG. 4. (Color online) Schematic representation of the approximate single-mode Hadamard gate. BS_u stands for a highly unbalanced weakly reflecting beam splitter, while BS_Γ is a beam splitter with transmission coefficient t_Γ used to set the parameter Γ. APD stands for a avalanche photodiode and $\langle\pi|$ represents the suitable projective measurement (see text).

Schrödinger Cat Preparation (M1)

Method 1 :
positive resource and detector with negative Wigner function

$$|\alpha\rangle - |-\alpha\rangle = \sum c_n |2n+1\rangle$$

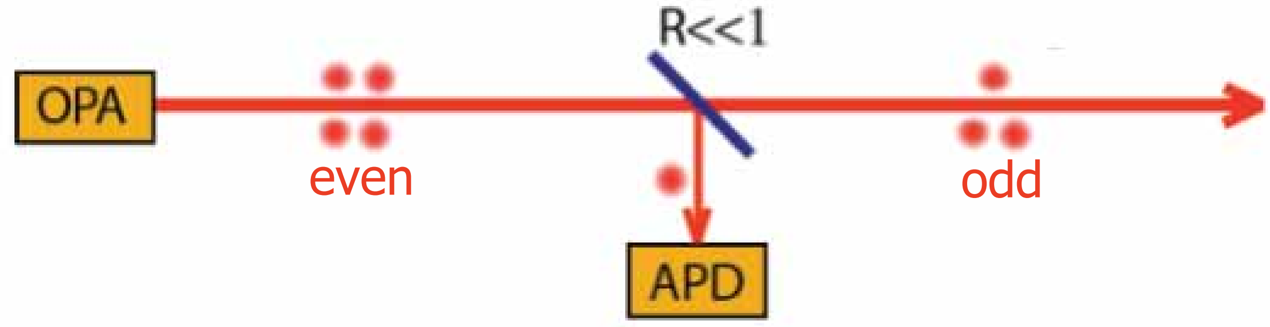
Generating Optical Schrödinger Kittens for Quantum Information Processing

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

We present a detailed experimental analysis of a free-propagating light pulse prepared in a "Schrödinger kitten" state, which is defined as a quantum superposition of "classical" coherent states with small amplitudes. This kitten state is generated by subtracting one photon from a squeezed vacuum beam, and it clearly presents a negative Wigner function. The predicted influence of the experimental parameters is in excellent agreement with the experimental results. The amplitude of the coherent states can be amplified to transform our "Schrödinger kittens" into bigger Schrödinger cats, providing an essential tool for quantum information processing.

Science 312, 83 (2006)

Kittens ($|\alpha|$~1) look very similar to a photon-subtracted squeezed vacuum state.
F>0.9 up to $|\alpha|$~2.



$$\alpha|0\rangle + \beta|2\rangle + \gamma|4\rangle + \ldots \longrightarrow \beta|1\rangle + \sqrt{2}(1-R)\gamma|3\rangle + \ldots$$

Schrödinger Cat Preparation (M1)

Method 1 :
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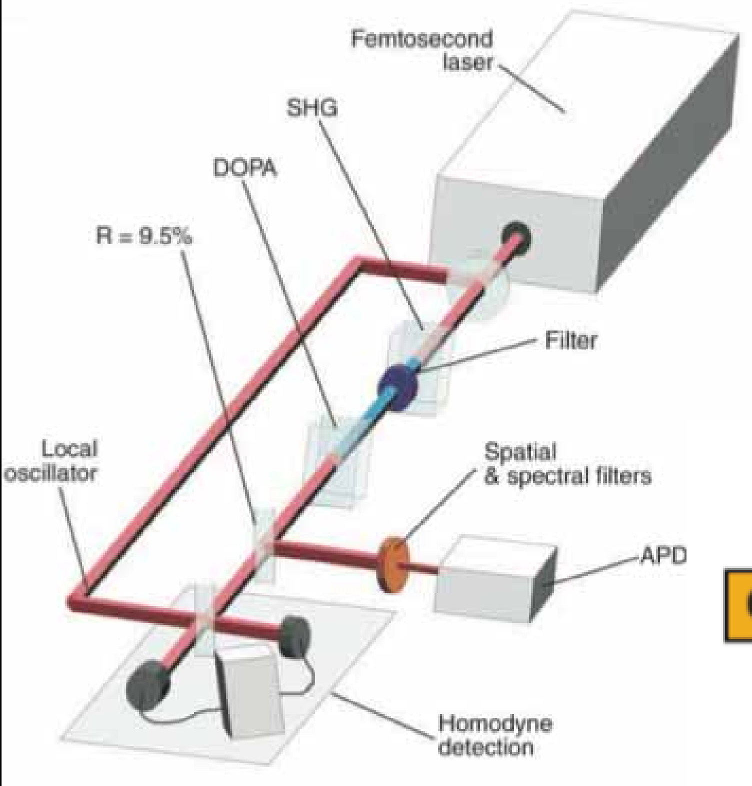

Single-photon subtraction from a pulsed squeezed state

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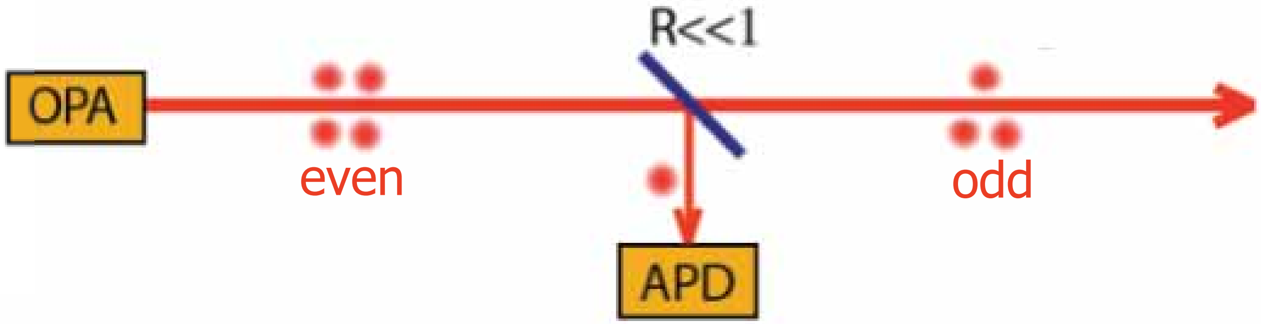

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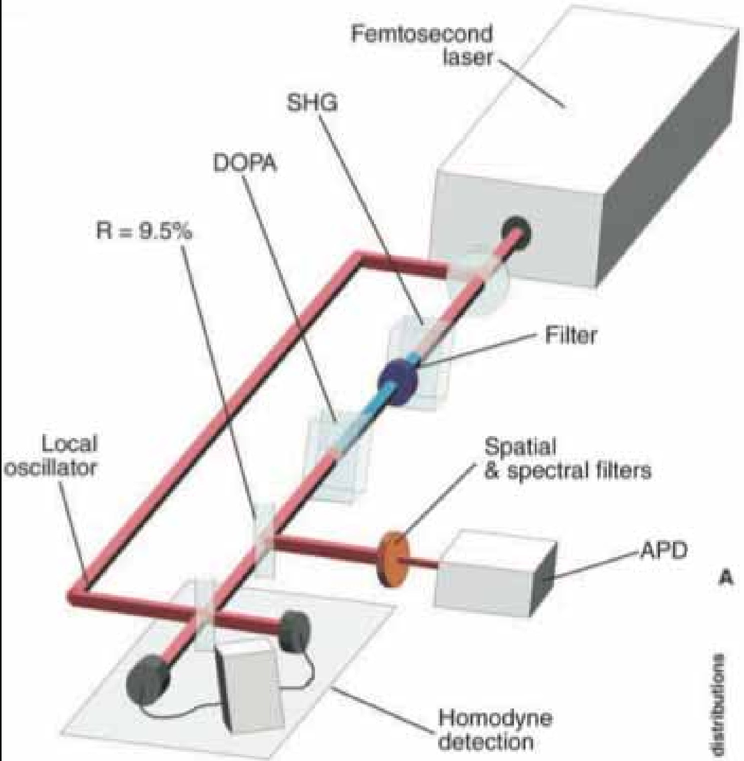
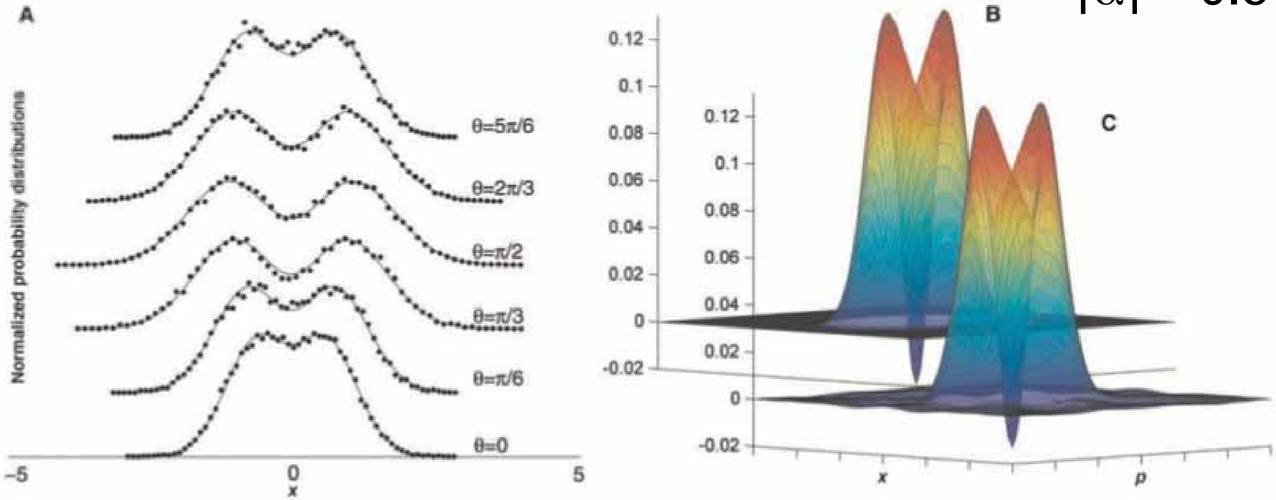
Science 312, 83 (2006)



Single-photon subtraction from a pulsed squeezed state

$|\alpha|^2 \sim 0.8$



Schrödinger Cat Preparation (M1)

Method 1 :
positive resource and detector with negative Wigner function

Generation of Optical Coherent State Superpositions by Number-Resolved Photon Subtraction from Squeezed Vacuum

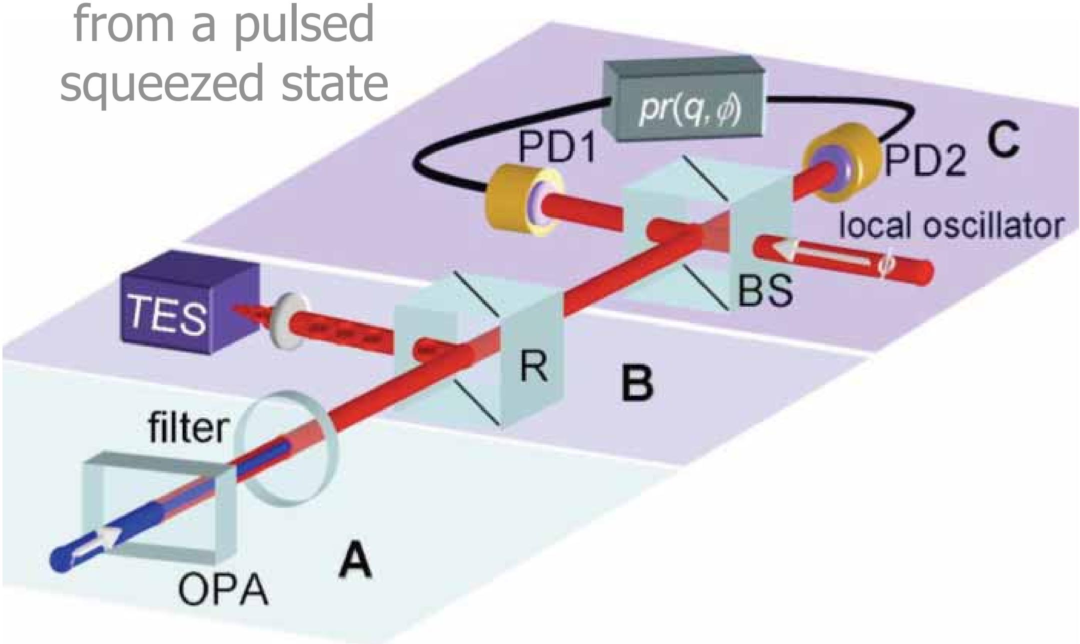
Thomas Gerrits,[1] Scott Glancy,[1] Tracy S. Clement,[1] Brice Calkins,[1] Adriana E. Lita,[1] Aaron J. Miller,[2] Alan L. Migdall,[3,4] Sae Woo Nam,[1] Richard P. Mirin,[1] and Emanuel Knill[1]

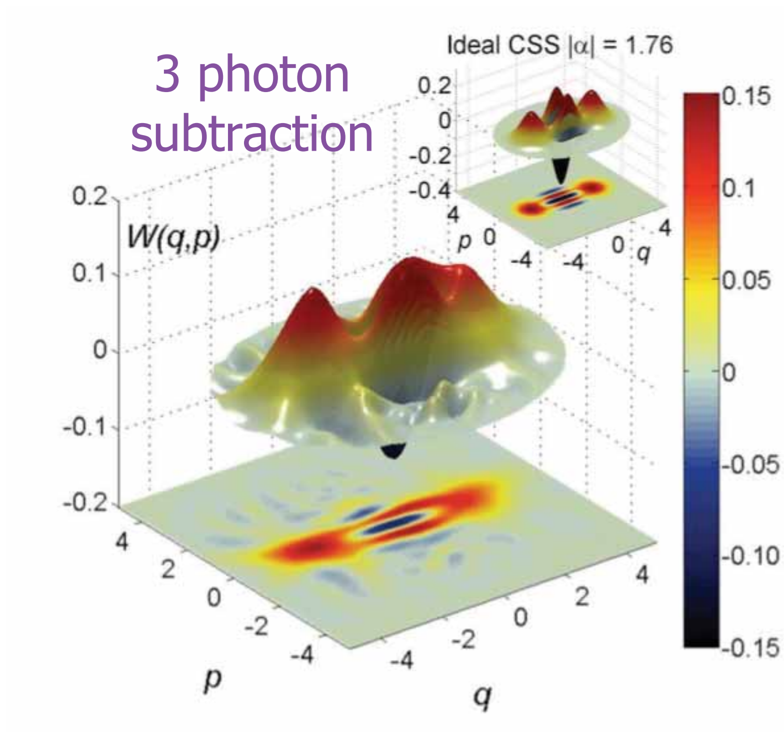
[1]*National Institute of Standards and Technology, Boulder, CO, 80305, USA*

We have created heralded coherent state superpositions (CSS), by subtracting up to three photons from a pulse of squeezed vacuum light. To produce such CSSs at a sufficient rate, we used our high-efficiency photon-number-resolving transition edge sensor to detect the subtracted photons. This is the first experiment enabled by and utilizing the full photon-number-resolving capabilities of this detector. The CSS produced by three-photon subtraction had a mean photon number of $2.75^{+0.06}_{-0.24}$ and a fidelity of $0.59^{+0.04}_{-0.14}$ with an ideal CSS. This confirms that subtracting more photons results in higher-amplitude CSSs.

Phys. Rev. A 82, 031802 (2010)

Number-resolved photon subtraction from a pulsed squeezed state

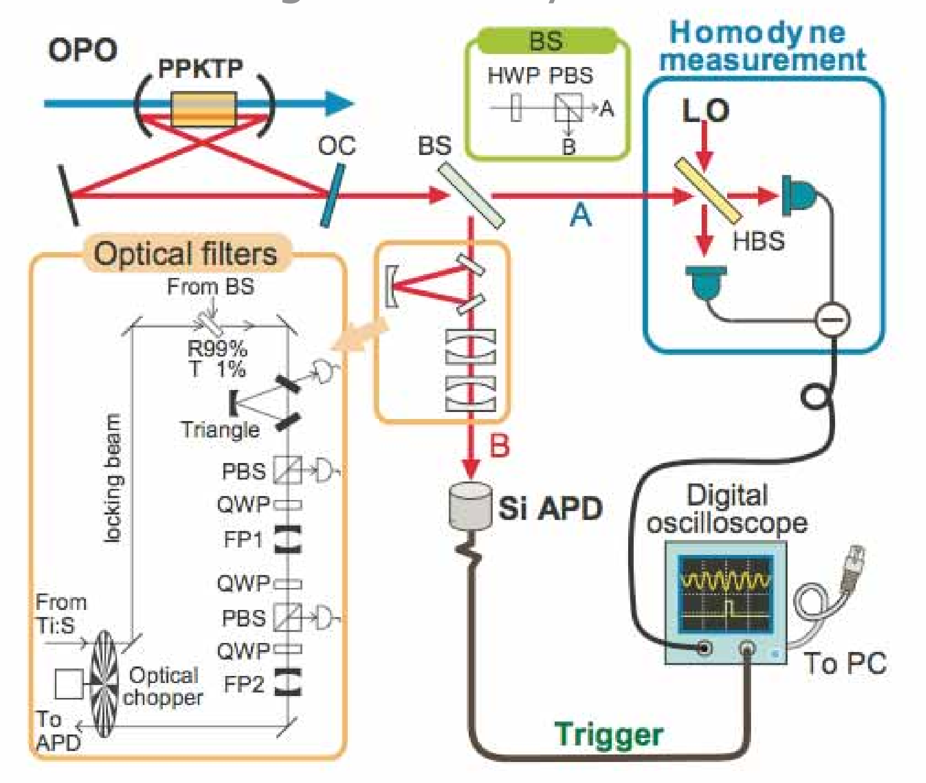




Schrödinger Cat Preparation (M1)

Method 1 :
positive resource and detector
with negative Wigner function

Photon subtraction from a squeezed
state generated by an OPO



See also works from Copenhagen, Paris…

Photon subtracted squeezed states generated with periodically poled KTiOPO$_4$

Opt. Express 15, 3568 (2007)

Kentaro Wakui, Hiroki Takahashi

National Institute of Information and Communications Technology (NICT), 4-2-1 Nukui-Kita, Koganei, Tokyo 184-8795, Japan and Department of Applied Physics, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

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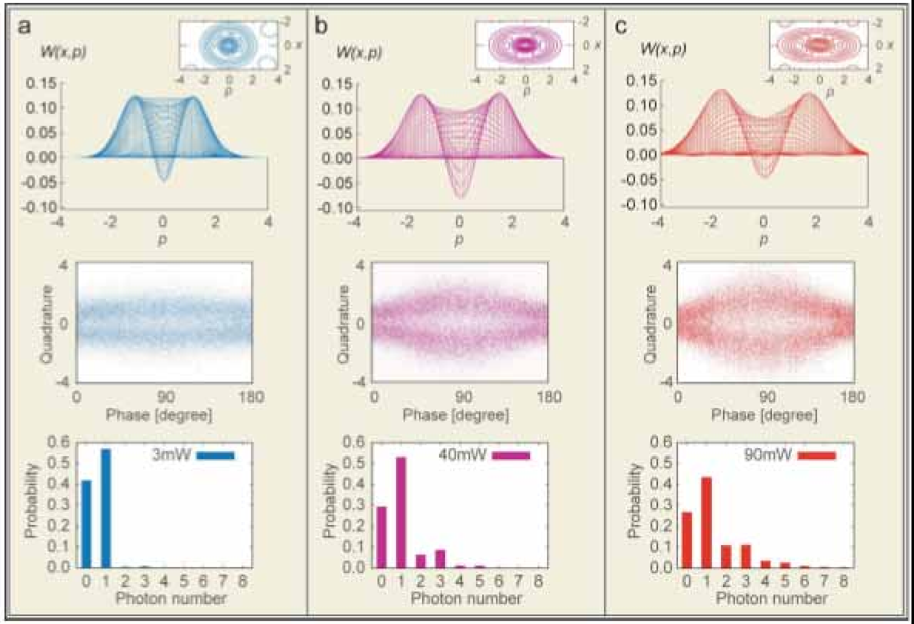
Akira Furusawa

Department of Applied Physics, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

Masahide Sasaki

National Institute of Information and Communications Technology (NICT), 4-2-1 Nukui-Kita, Koganei, Tokyo 184-8795, Japan

By varying the squeezing



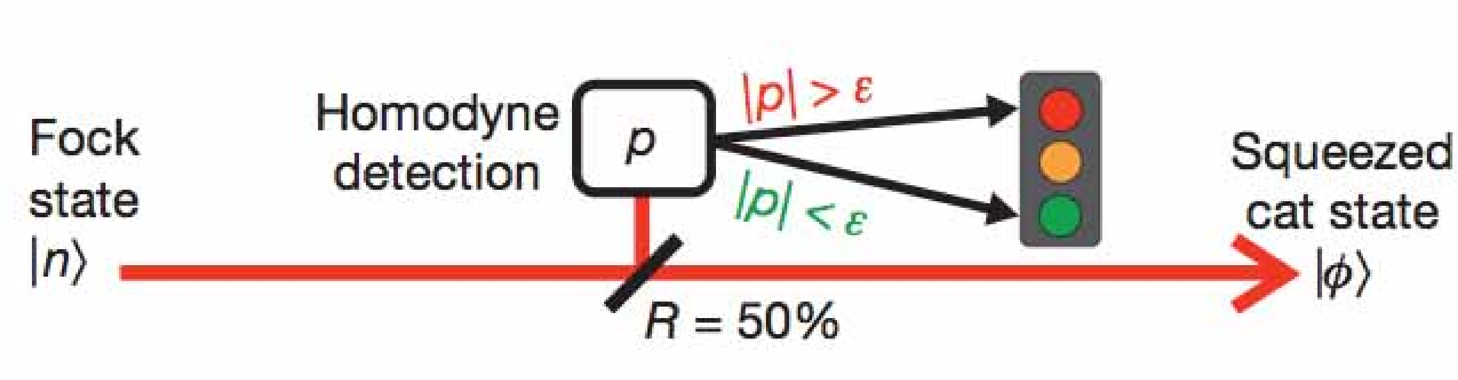
Schrödinger Cat Preparation (M2)

Method 2 :
negative resource and detector with positive Wigner function

Generation of optical 'Schrödinger cats' from photon number states

Nature 448, 784 (2007)

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



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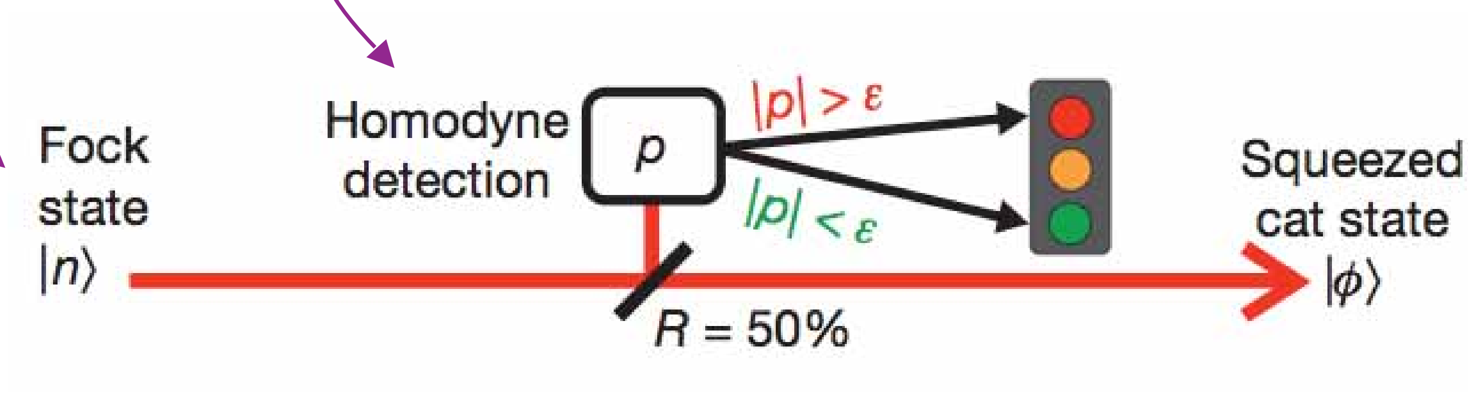

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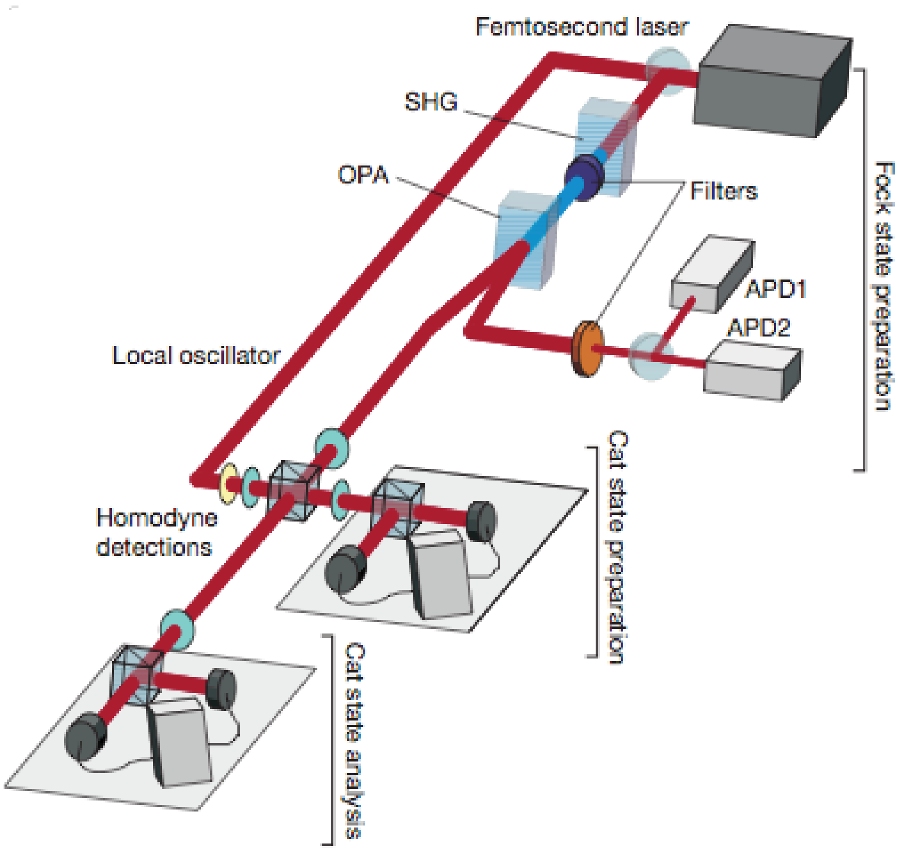
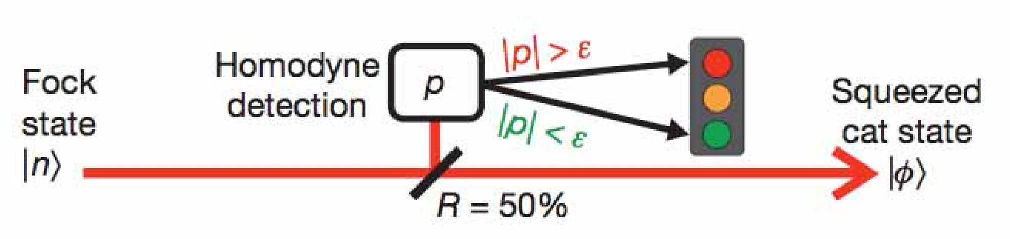
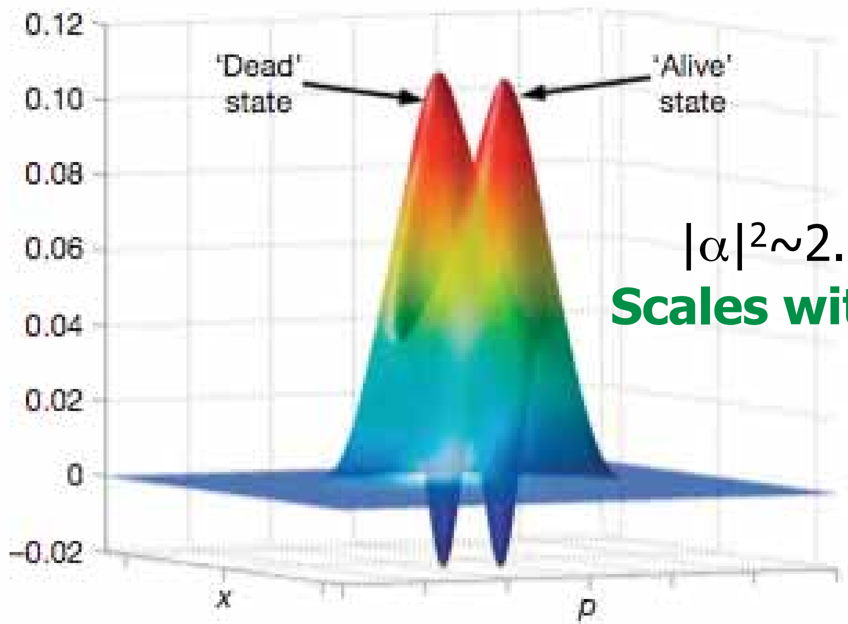






$|\alpha|^2 \sim 2.6$

Scales with n

Lecture 2

- What is a conditional quantum state preparation ?

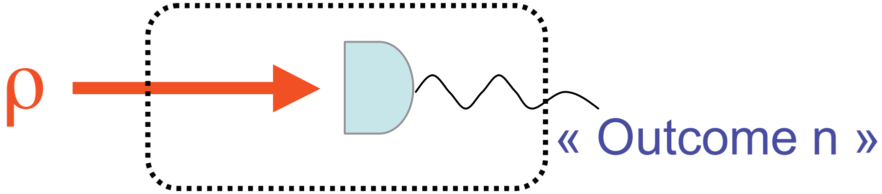
- General strategy for quantum state engineering : Theory

- Illustration : Schrödinger cat state generation

- Quantum detectors, decoherence, and effect on state engineering

Measurement Apparatus and POVM

Giving an incident state ρ, what is the probability to obtain the outcome "n"?



$$Pr\left(n\,|\,\hat{\rho}\right) = Tr\left(\hat{\rho}\,\hat{\Pi}_n\right)$$

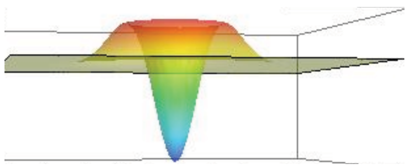
POVM :

- Positive operator valued measure -

The set of POVM elements $\{\Pi_n\}$ fully describe the possible outcomes of the measurement

Ex. 1 : "Ideal" Photon-number resolving detectors (n click = n photons)

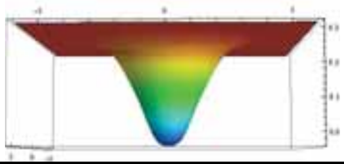
$$\hat{\Pi}_n = |n\rangle\langle n|$$



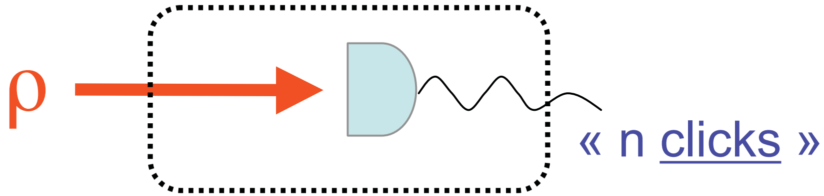
Ex. 2 : On/Off detector, APD with η=1

$$\hat{\Pi}_{off} = |0\rangle\langle 0|$$

$$\hat{\Pi}_{on} = \hat{1} - |0\rangle\langle 0|$$



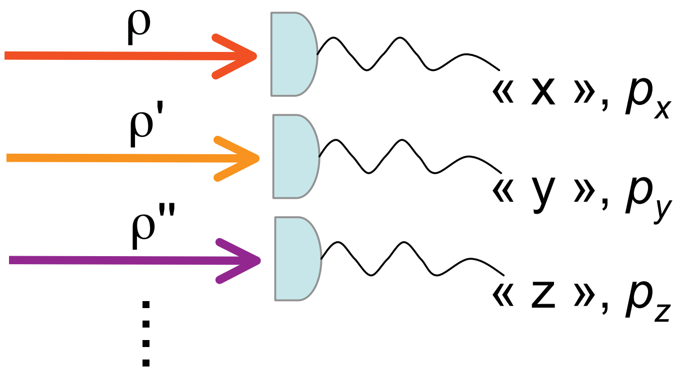
Phase-insentive detectors, such as single-photon detectors



$$\hat{\Pi}_n = \sum_{k=0}^{\infty} \theta_{n,k} |k\rangle\langle k|$$

Quantum Detector Tomography

Giving a "black-box" detector with N possible outcomes, what is the POVM ?



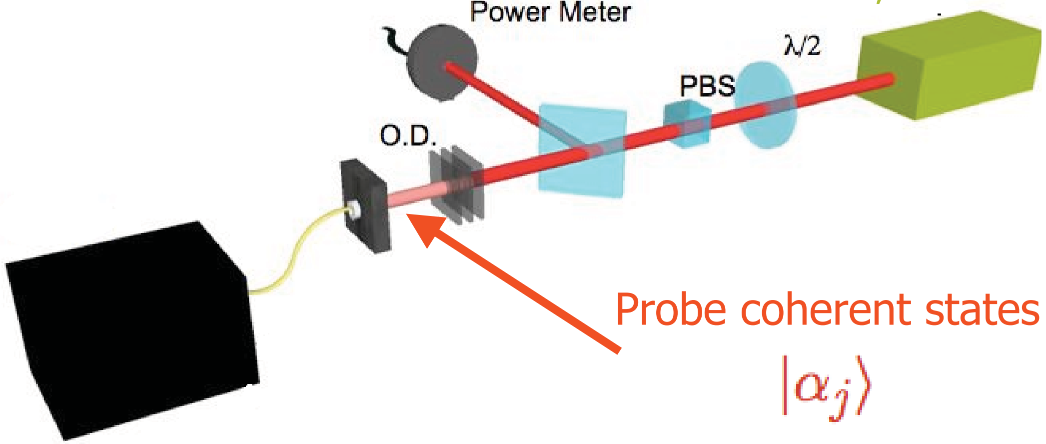
1) Send known states and measure the probability of outcomes $f_1, f_2, \ldots$

2) Reconstruction of the POVM by Maximum-likelihood algorithm

Experimental QDT :

\- Quantum Detector Tomography -

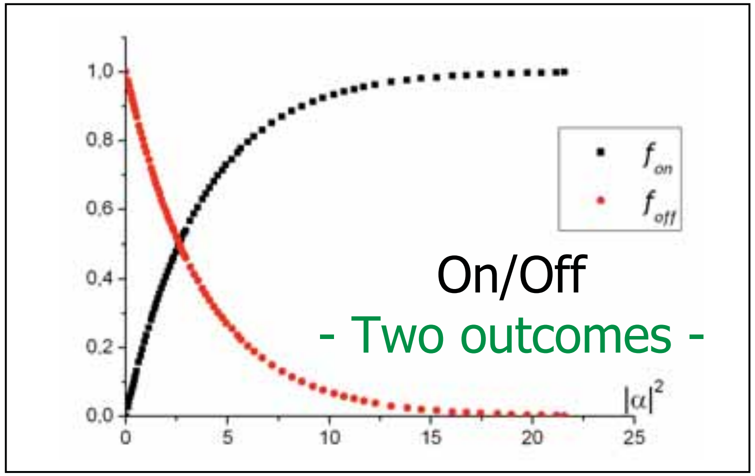
By probing the detector with a tomographically complete set of states, QDT aims at reconstructing the POVM of the device without assumptions on its inner functioning.



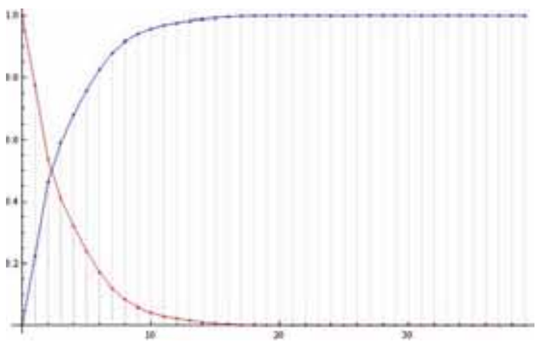
J.S. Lundeen et al., Nature Phys. **5**, 27 (2009)
J. Fiurasek, Phys. Rev. A. **64**, 024102 (2001)

Experimental QDT of Two Detectors

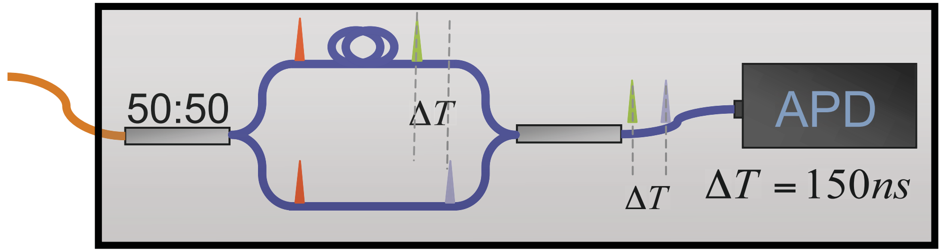
Avalanche Photodiode

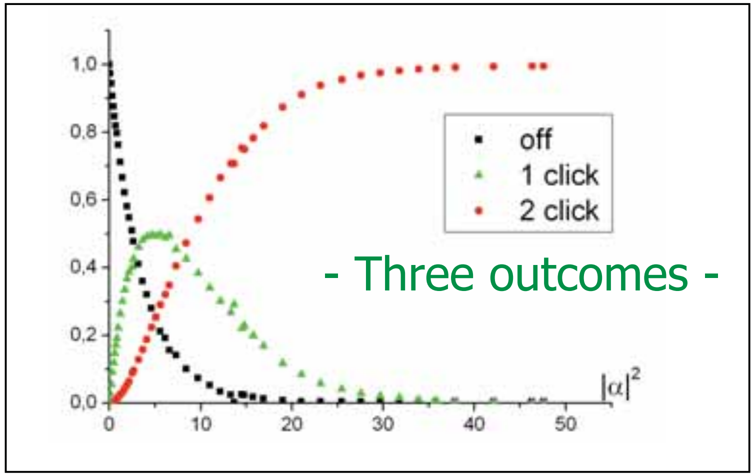


Π_{ON}, Π_{OFF}



Time-multiplexed detector

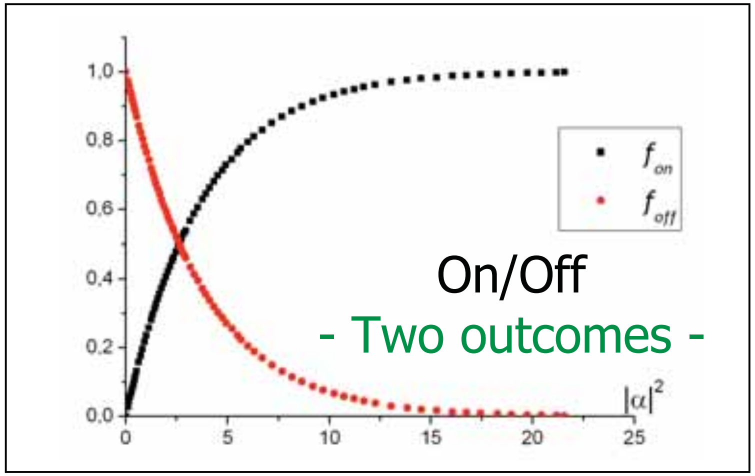




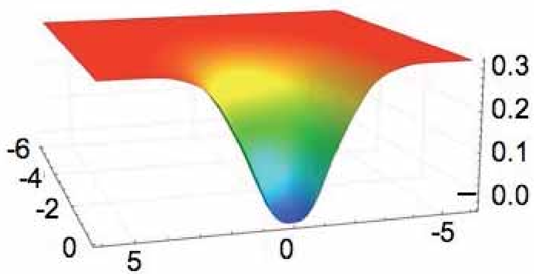
Π_0, Π_1, Π_2

Experimental QDT of Two Detectors

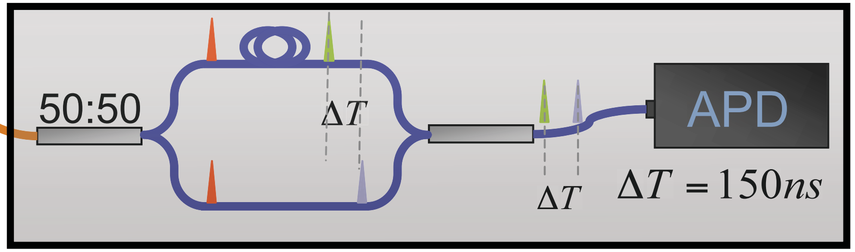
Avalanche Photodiode

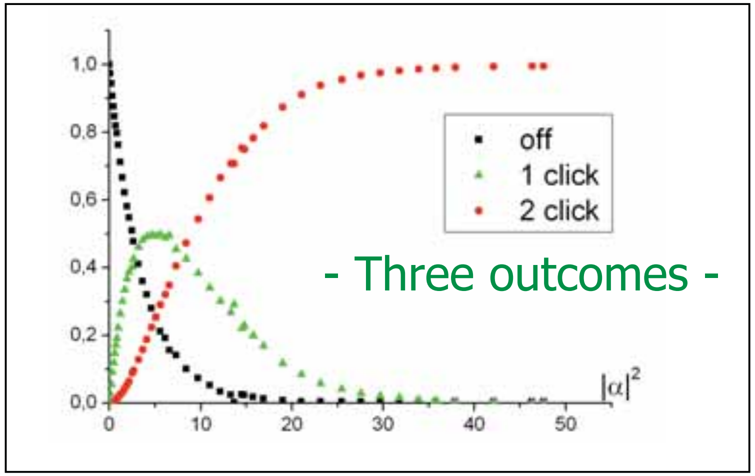


Π_{ON}

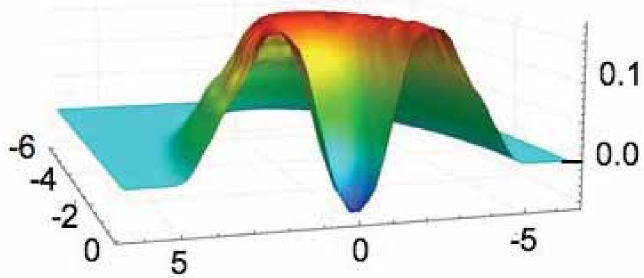


Time-multiplexed detector





Π_1



Quantum Decoherence of Counters

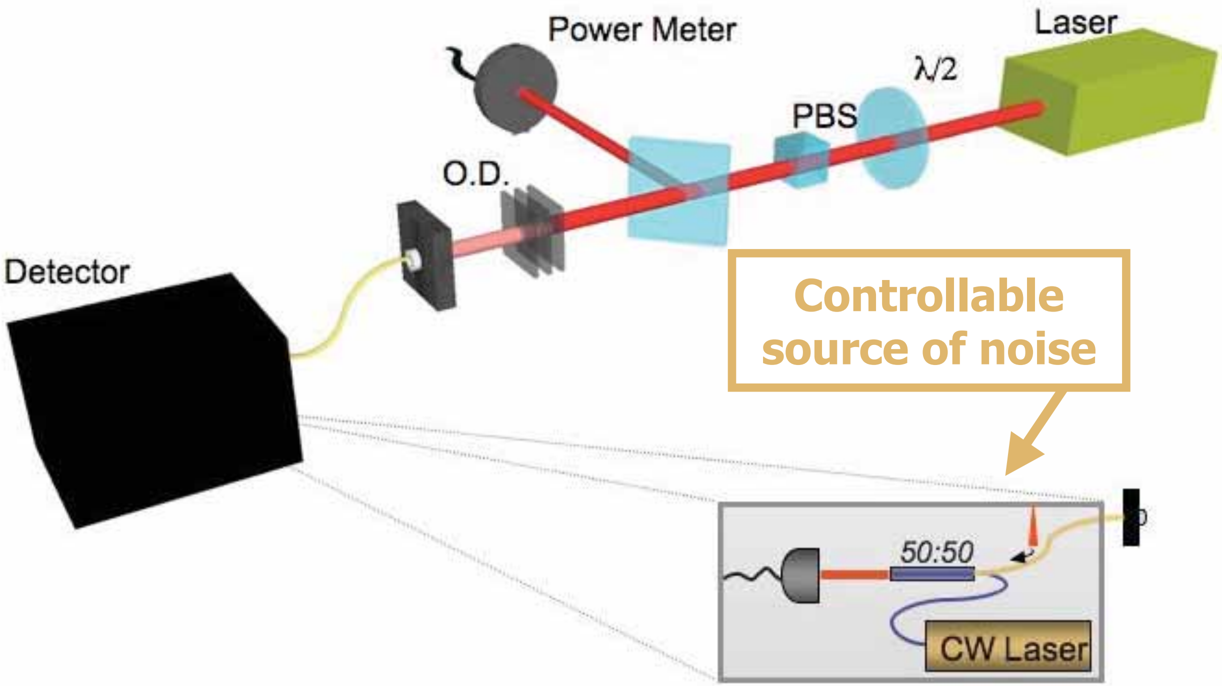
Quantum Decoherence of Single-Photon Counters

V. D'Auria, N. Lee, T. Amri, C. Fabre and J. Laurat
Laboratoire Kastler Brossel, Université Pierre et Marie Curie, Ecole Normale Supérieure, CNRS, Case 74, 4 place Jussieu, 75252 Paris Cedex 05, France
(Dated: April 1, 2011)

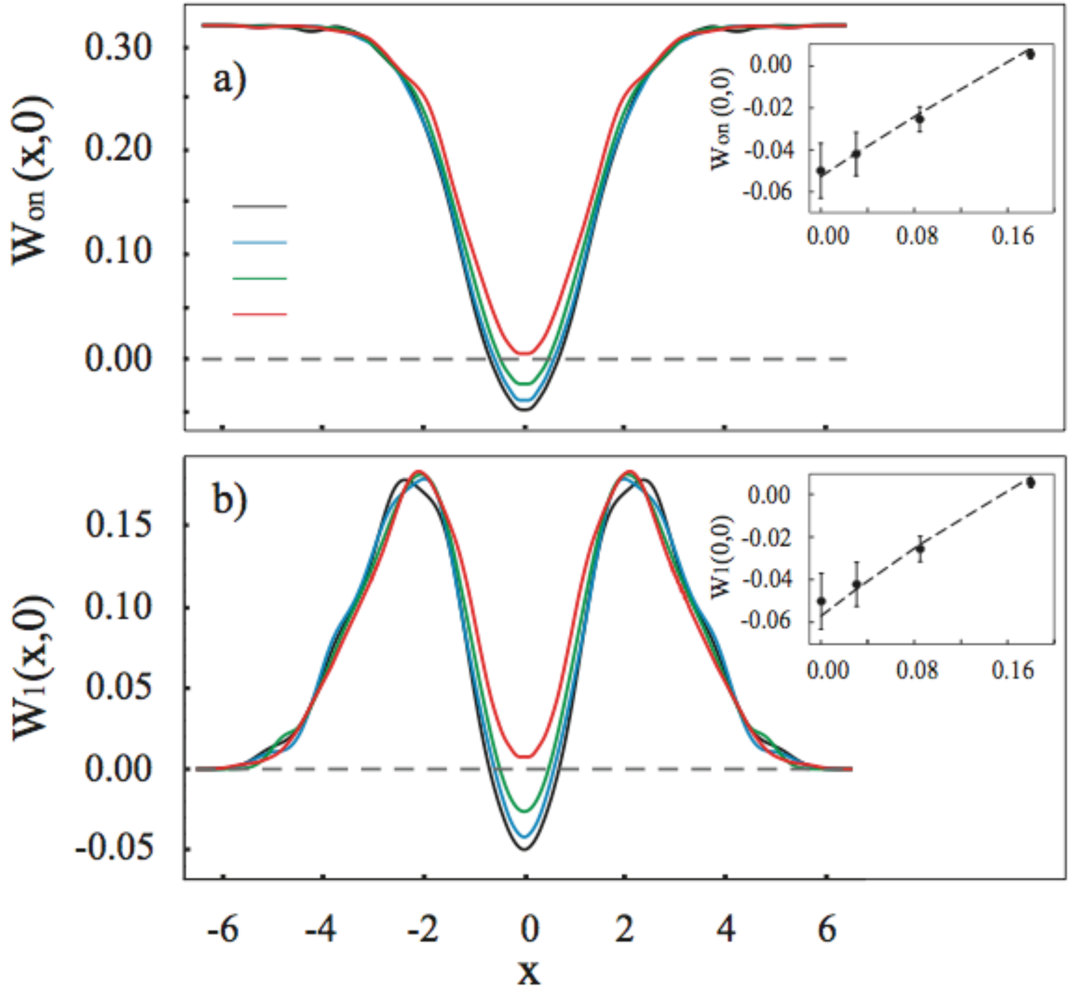
The interaction of a quantum system with the environment leads to the so-called quantum decoherence. Beyond its fundamental significance, the understanding and the possible control of this dynamics in various scenarios is a key element for mastering quantum information processing. Here we report the quantitative probing of what can be called the quantum decoherence of detectors, a process reminiscent of the decoherence of quantum states in the presence of coupling with a reservoir. We demonstrate how the quantum features of two single-photon counters vanish under the influence of a noisy environment. We thereby experimentally witness the transition between the full-quantum operation of the measurement device, where the probabilities have no classical equivalent, to the "semi-classical regime", described by a positive Wigner function, where the quantum fluctuations can be in principle classically described. The exact border between these two regimes is determined.

What is the effect of noise on the quantum capability of the counters ?

Many practical situations: dark noise, additional background, non desired emission in the detected mode…



Quantum-to-Classical Transition



Avalanche Photodiode

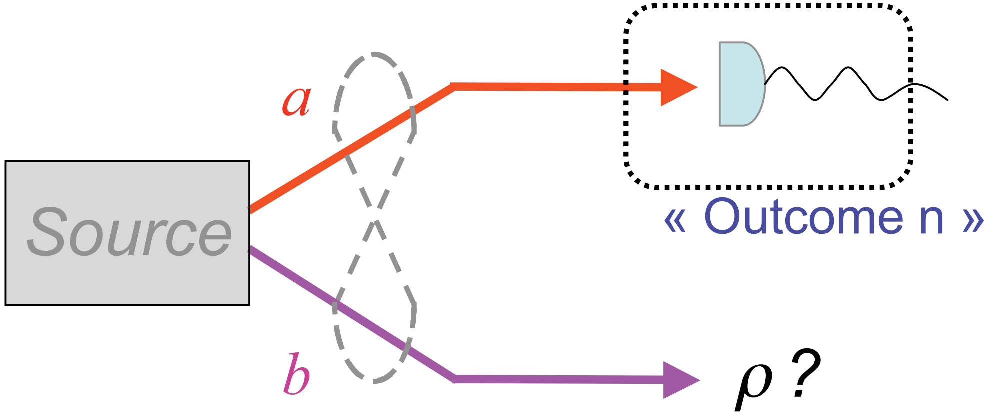
Time-multiplexed detector

Model discrete convolution of the dark count probability distribution and the probability of 'n' clicks in the absence of noise

Transition for $\nu=\eta/2$

Effect on Quantum State Engineering

Giving two entangled modes, what is the prepared state for the outcome "n"?



$$|\Psi\rangle_{ab} = \sqrt{1-|\lambda|^2}\sum_{m=0}^{\infty}\lambda^m |m\rangle_a |m\rangle_b$$

$$\hat{\Pi}_n = \sum_{k=0}^{\infty}\theta_{n,k}|k\rangle\langle k|$$

$$\longrightarrow \quad \rho_n = \frac{\sum_k \lambda^{2k}\,\theta_{n,k}|k\rangle\langle k|}{\sum_k \lambda^{2k}\,\theta_{n,k}}$$

Effect on Quantum State Engineering

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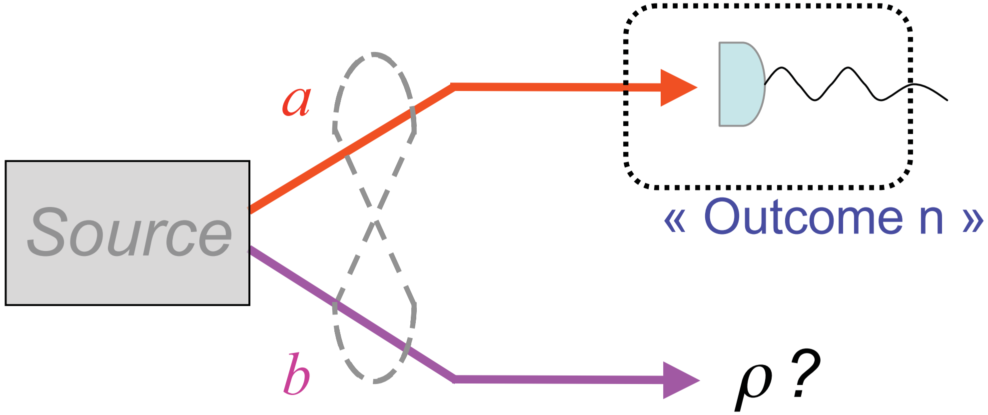

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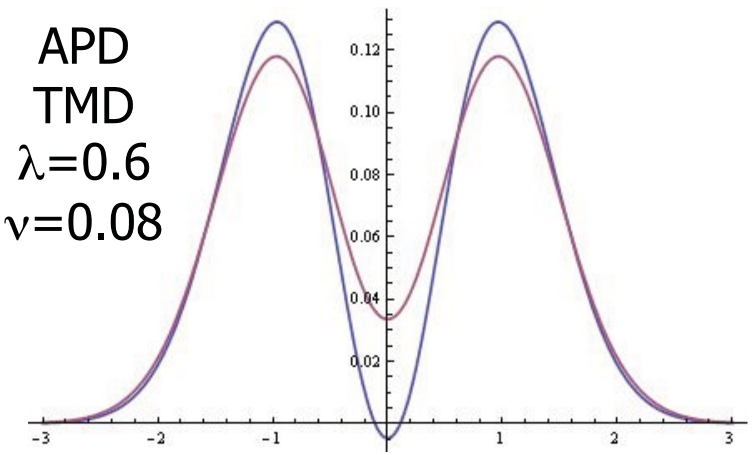
QSE simulation

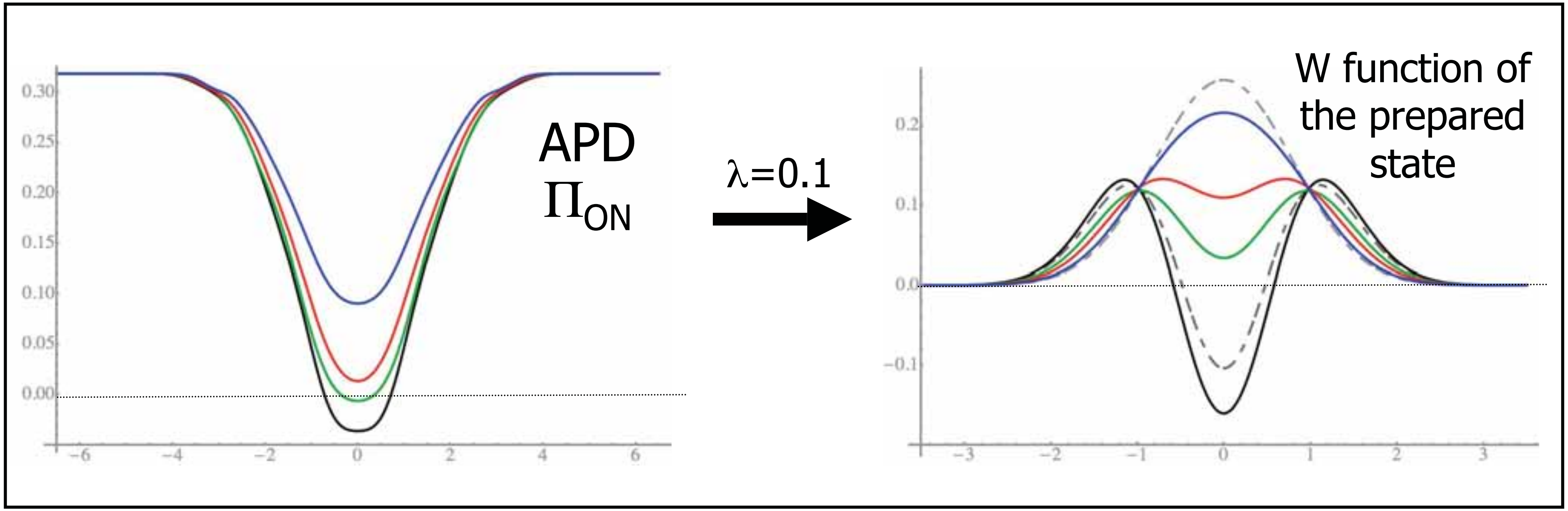
We numerically simulate two-mode entanglement and use the experimentally reconstructed POVMs.

Ex.: Detectors and Single-Photon Generation

APD
TMD
λ=0.6
ν=0.08



Effect on Quantum State Engineering

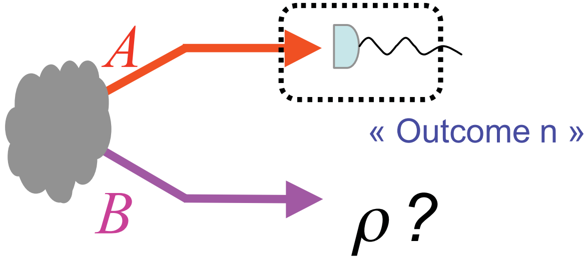


The quantum decoherence transition of the detector directly translates into such transition for the prepared state.

It gives a gradual transition between a state with negative Wigner function to a state with a positive Wigner function approaching a gaussian shape and corresponding to the classical thermal state generated by SPDC.

Summary

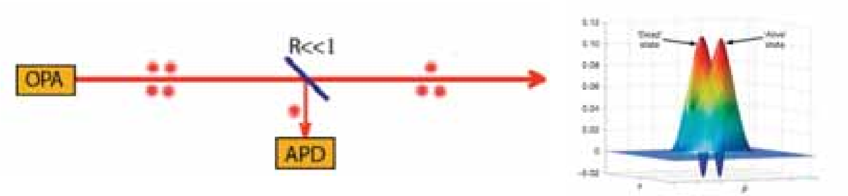
- Conditional state preparation



- 'General' theory of QSE

$$W(p,q) = \frac{\int W_{AB}(p,q,u,v)\, W_n(u,v)\, du dv}{\int W_{AB}(p',q',u,v)\, W_n(u,v)\, du dv dp' dq'}$$

- Schrodinger cat state preparation



- Decoherence of single-photon counters and effect on QSE