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Istituto Nazionale di Ottica

Single-photon-level light manipulation and amplification

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Dipartimento di Fisica

Outline

Manipulating single photons

Measuring light at the quantum level

Single-photon addition and subtraction

Sequences and superpositions of quantum operators

Direct probing of fundamental quantum rules

Noiseless amplification

Investigating the mode structure of ultrashort pulsed quantum light states

Why?

It's fun

Directly "seeing" fundamental quantum mechanical entities and laws at work in a lab

$\hat{a}^\dagger$

$\hat{a}$

$\hat{a}\,|\alpha\rangle = \alpha\,|\alpha\rangle$

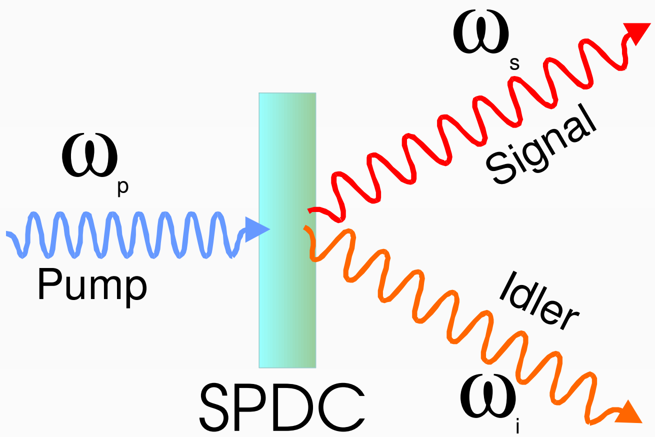
$[\hat{a}, \hat{a}^\dagger] = 1$

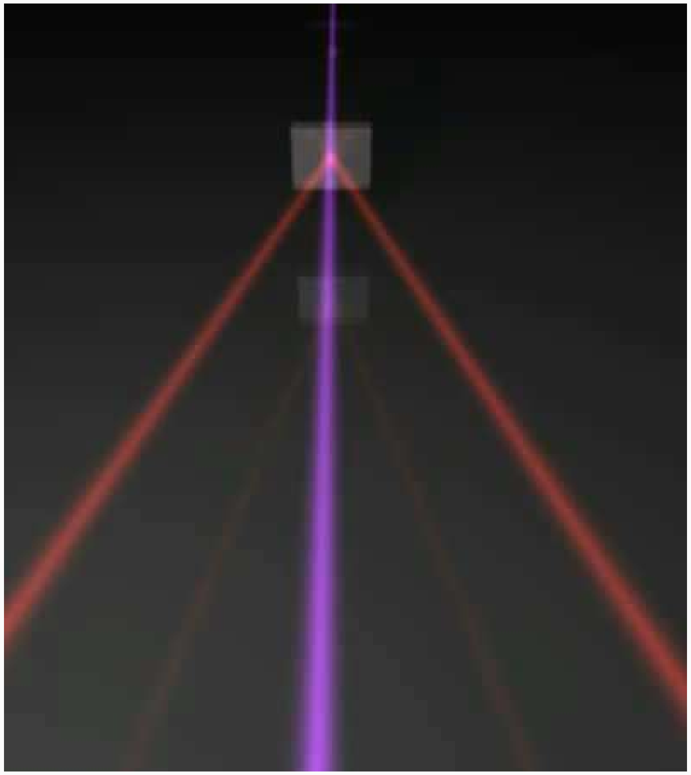
It can be useful

New tools for quantum technologies

Producing single photons

Spontaneous parametric down-conversion in a nonlinear crystal



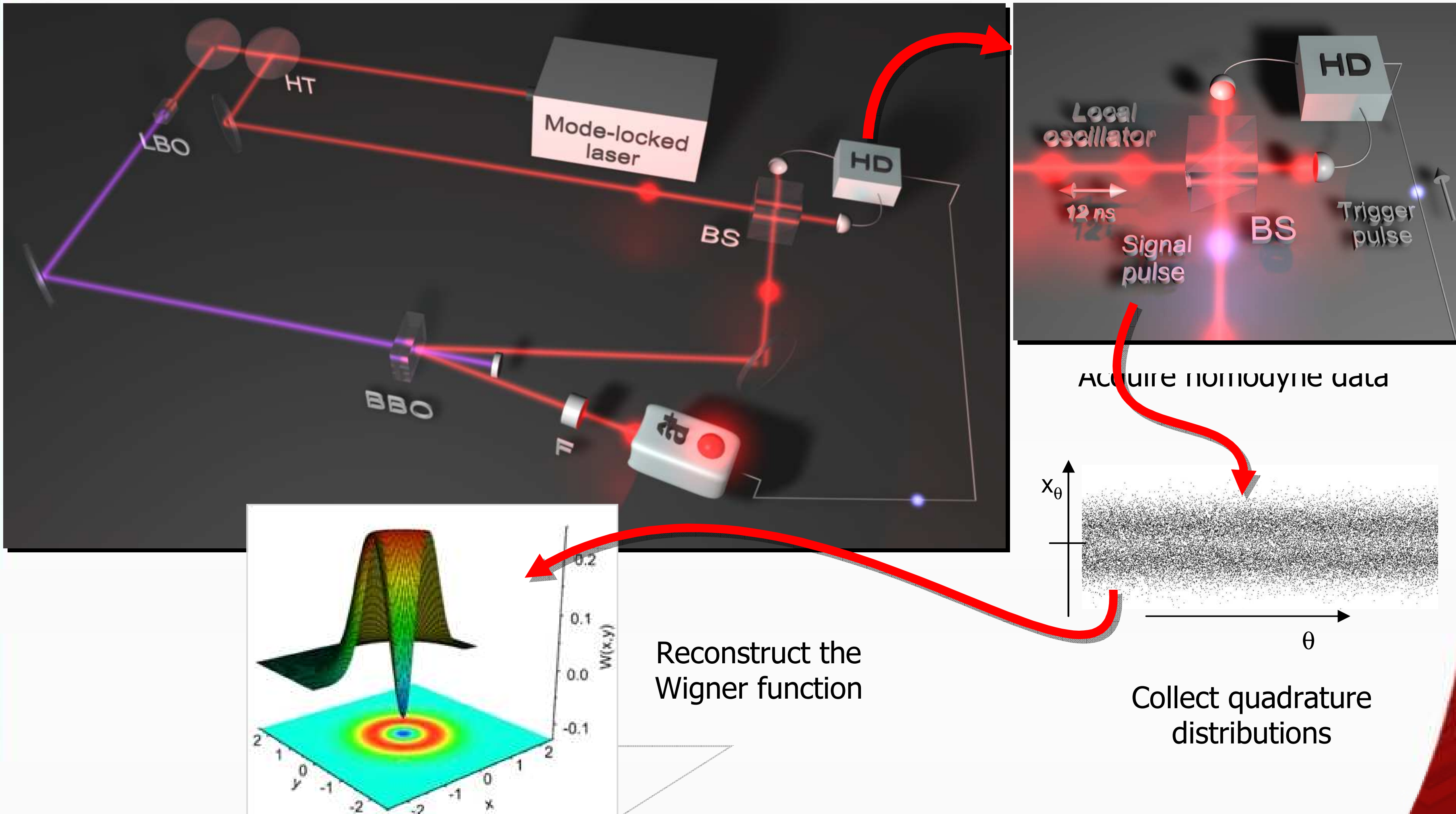


Energy and momentum conservation

$$\omega_p = \omega_i + \omega_s$$

$$\mathbf{k}_p = \mathbf{k}_i + \mathbf{k}_s$$

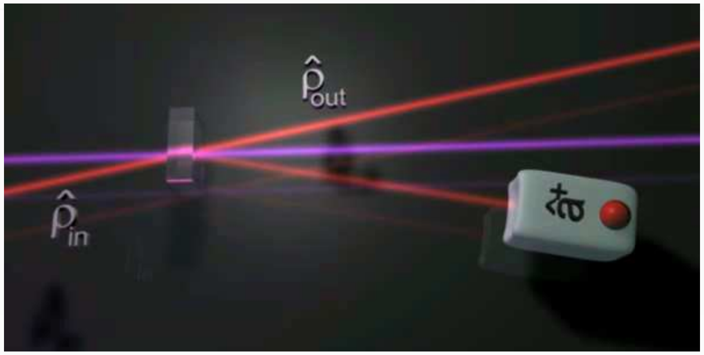
Single photons in the lab



MB, F. Marin, S. Viciani, A. Zavatta and F. T. Arecchi, *Phys. Rev. Lett.*, **90**, 043602 (2003)
S. Viciani, A. Zavatta and MB, *Phys. Rev. A*, **69**, 053801 (2004)

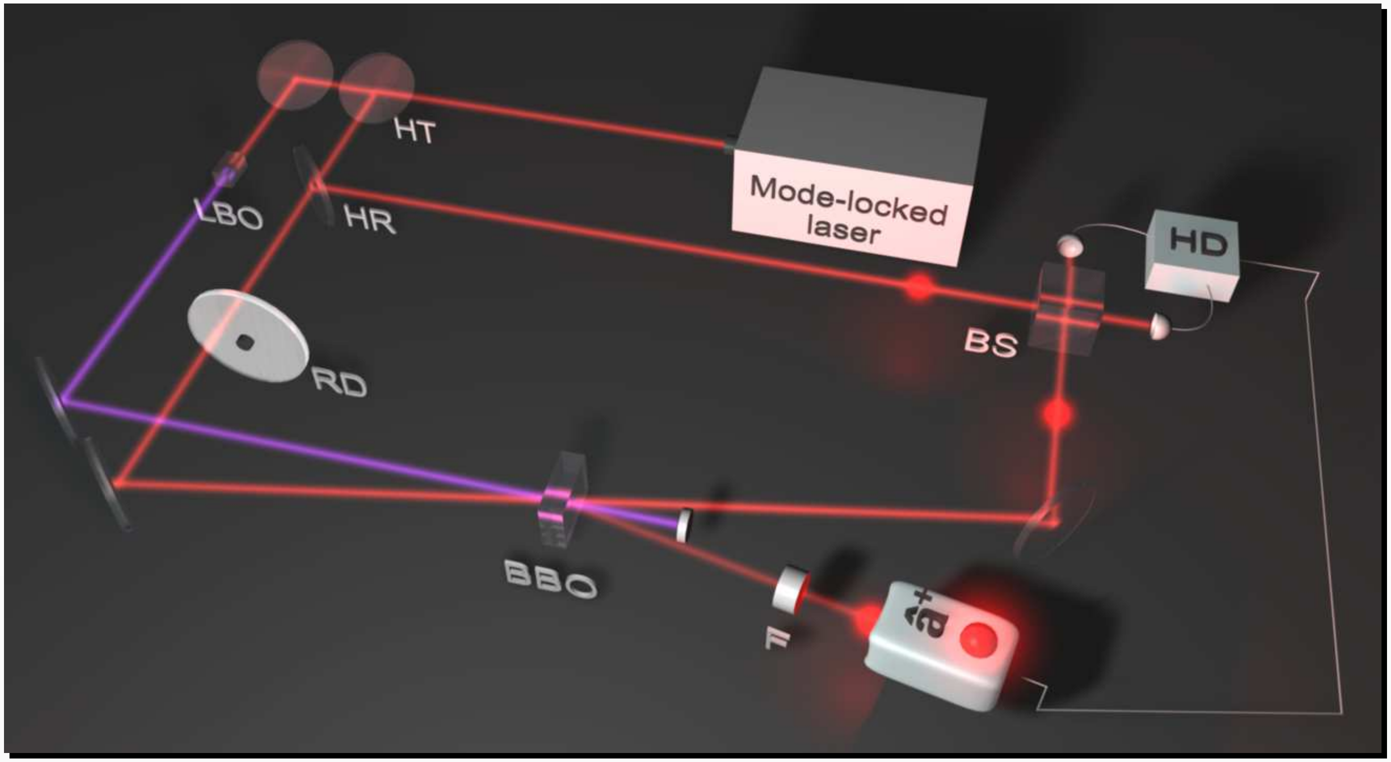
“Adding” photons with PDC

$\hat{a}^\dagger$



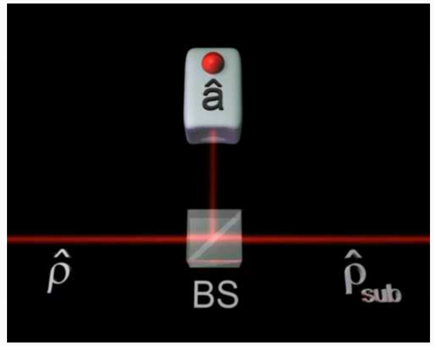
Faithful implementation of the creation operator for:

- small PDC gain
- small photon numbers



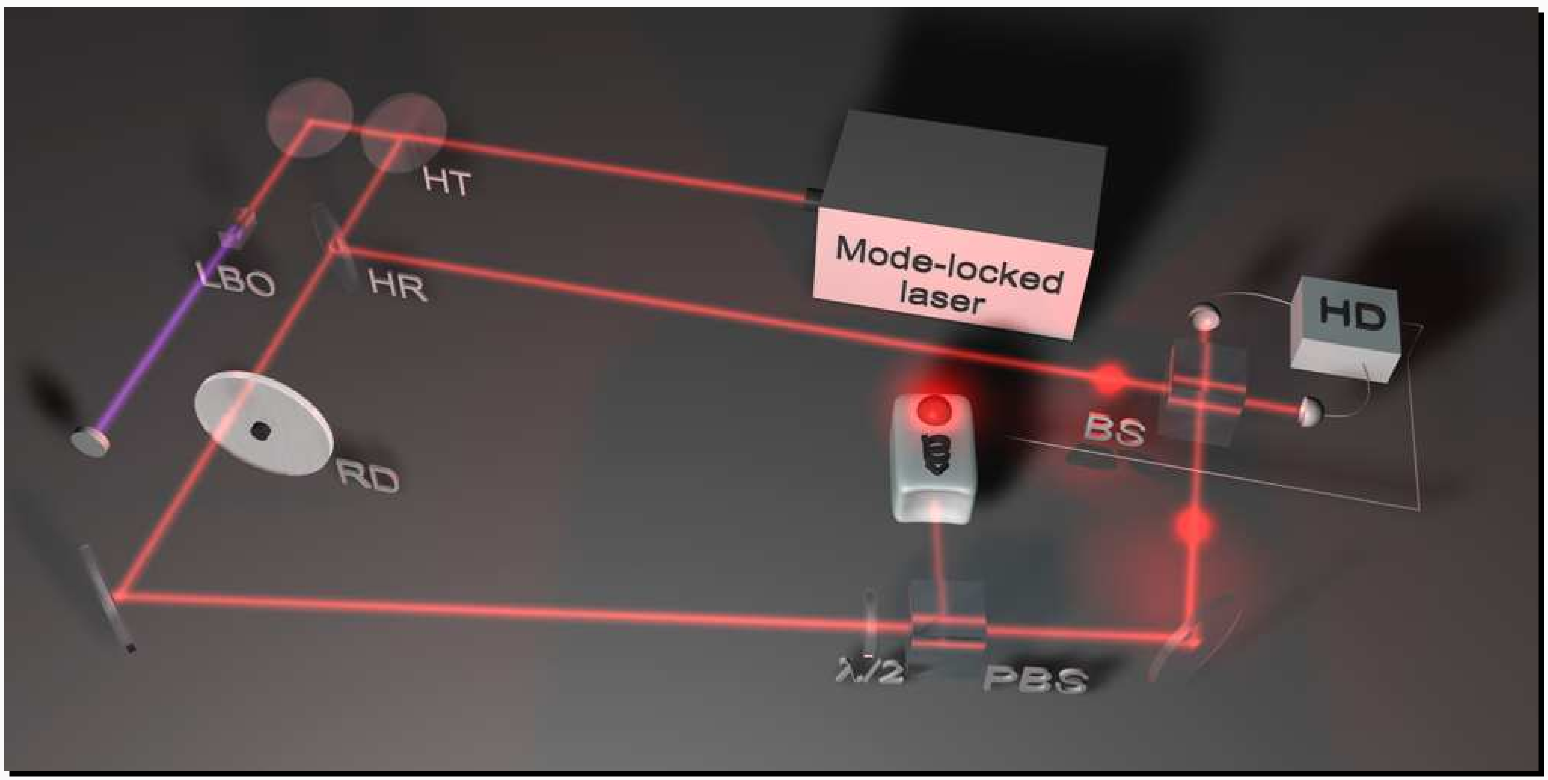
“Subtracting” photons with a beam splitter

$\hat{a}$



Faithful implementation of the annihilation operator for:

- small BS reflectivity
- small photon numbers



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Using photon addition and subtraction

$$\hat{a}^\dagger$$

Particle-to-wave transition

A. Zavatta, S. Viciani, MB, *Science*, 306, 660 (2004)
A. Zavatta, S. Viciani, MB, *PRA* 72, 023820 (2005)

Test of criteria for nonclassicality

A. Zavatta, V. Parigi, MB, *PRA* 75, 052106 (2007)

Reconstruction of nonclassical P-function

T. Kiesel, W. Vogel, V. Parigi, A. Zavatta, MB, *PRA* 78, 021804(R) (2008)

Nonclassical quasiprobabilities

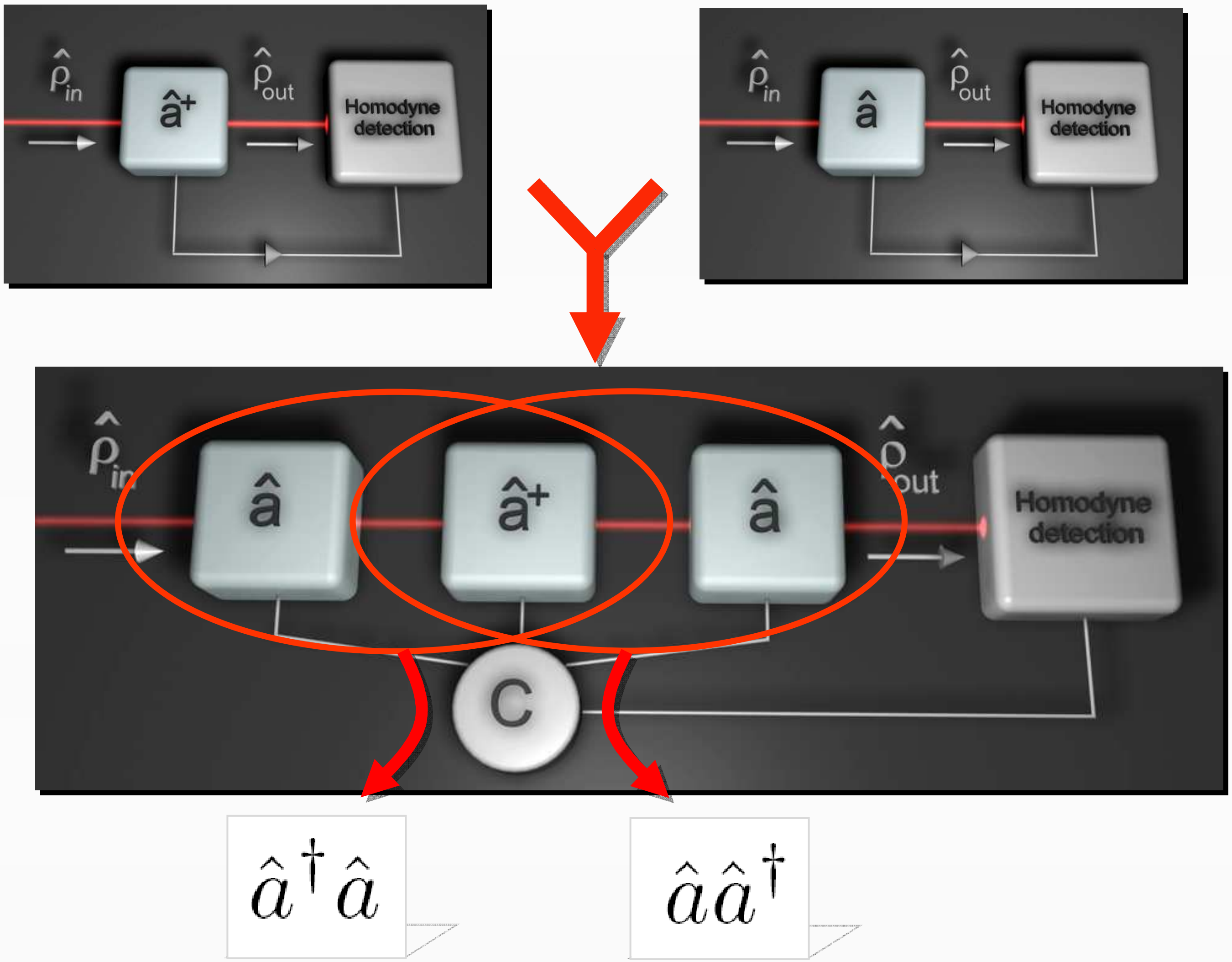
T. Kiesel, W. Vogel, MB, A. Zavatta, *PRA* 83, 032116 (2011)

$$\hat{a}$$

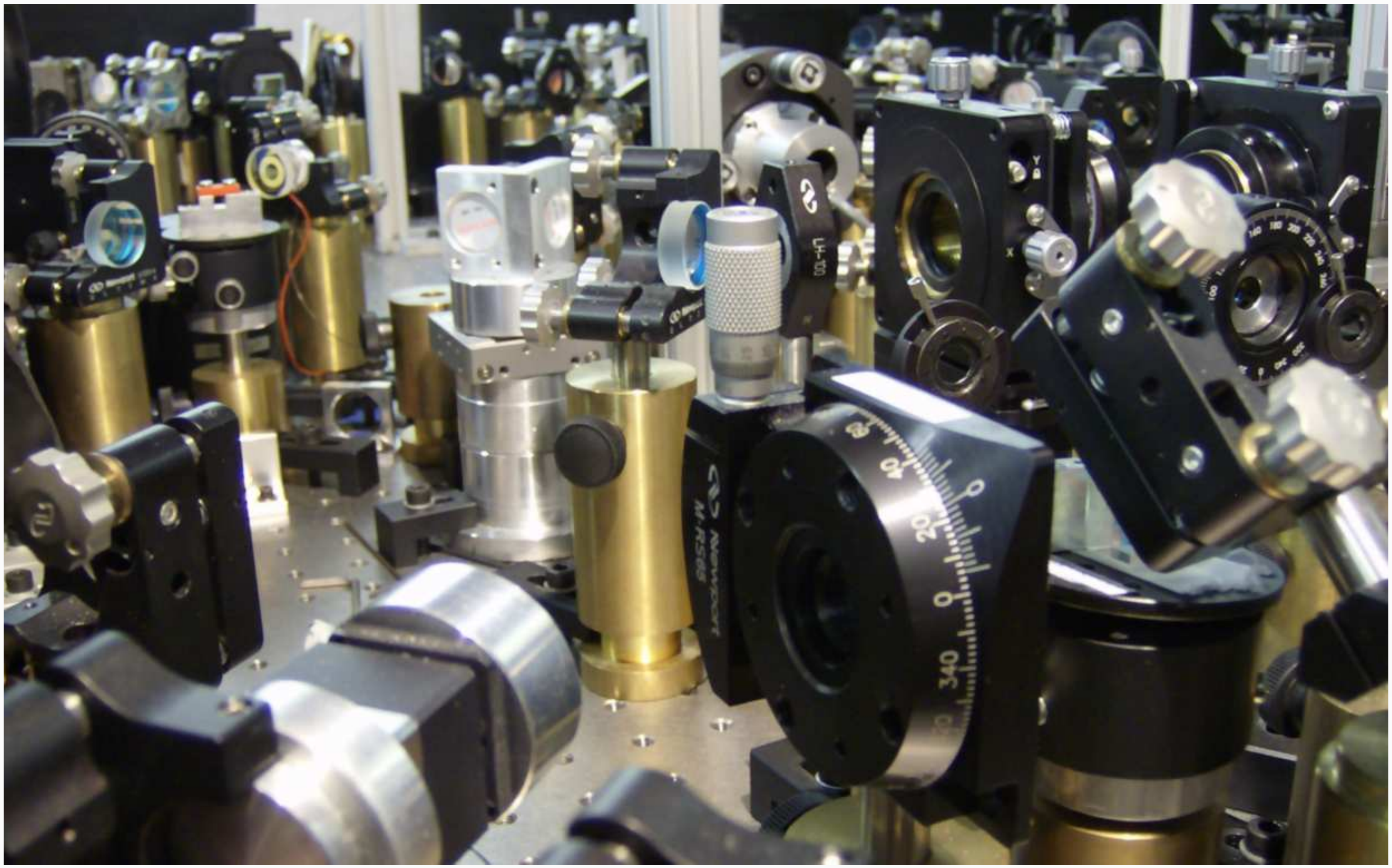
State de-Gaussification
Coherent state invariance
Odd quantum maths

A. Zavatta, V. Parigi, M.S. Kim, MB,
New Journal of Physics **10**, 123006 (2008)

Combining quantum operators



Making sequences of single-photon additions and subtractions



$$[\hat{a}, \hat{a}^\dagger] \neq 0$$

V. Parigi, A. Zavatta, M.S. Kim, MB, *Science* **317**, 1890 (2007)

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Noiseless amplification by addition & subtraction

Apply a sequence of photon addition and subtraction to a weak coherent state

$$\hat{a}\hat{a}^\dagger$$

$$|\alpha\rangle \approx |0\rangle + \alpha\,|1\rangle + \ldots$$

$$\begin{aligned}\hat{a}\hat{a}^\dagger\,|\alpha\rangle &\approx \hat{a}\hat{a}^\dagger(|0\rangle + \alpha\,|1\rangle + \ldots) =\\ &= \hat{a}(|1\rangle + \sqrt{2}\alpha\,|2\rangle + \ldots) =\\ &= |0\rangle + 2\alpha\,|1\rangle + \ldots \approx |2\alpha\rangle\end{aligned}$$

The final state is a coherent state of double amplitude !!!

P. Marek and R. Filip, *PRA*, **81**, 022302 (2010)

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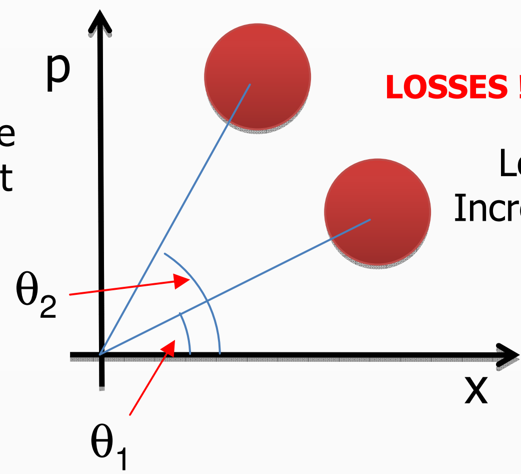
Phase-insensitive noiseless amplification

Suppose we encode information in a set of coherent states



LOSSES !!!

Loss of distinguishability
Increase of phase uncertainty

Phase-insensitive, <u>noiseless,</u> linear amplification of coherent states

$$|\alpha\rangle \to |g\alpha\rangle$$

~~Clone quantum states~~
~~Beat Heisenberg uncertainty~~
~~Send superluminal information~~

Unfortunately, this is not allowed by the linearity and unitary evolution of Quantum Mechanics!

Only a non-deterministic implementation is possible

$$|\alpha\rangle\langle\alpha| \to \rho(\alpha) = P|g\alpha\rangle\langle g\alpha| + (1-P)|0\rangle\langle 0|$$

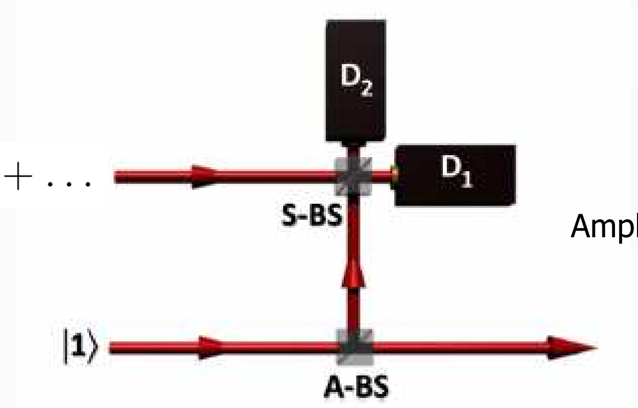
Non-deterministic noiseless amplification

Nondeterministic Noiseless Linear Amplification of Quantum Systems

T.C.Ralph[1] and A.P.Lund[1,2],

Quantum Communication Measurement and Computing
Proceedings of 9th International Conference, Ed. A.Lvovsky, 155-160 (AIP, New York 2009).

$$|\alpha\rangle \approx |0\rangle + \alpha\,|1\rangle + \ldots$$

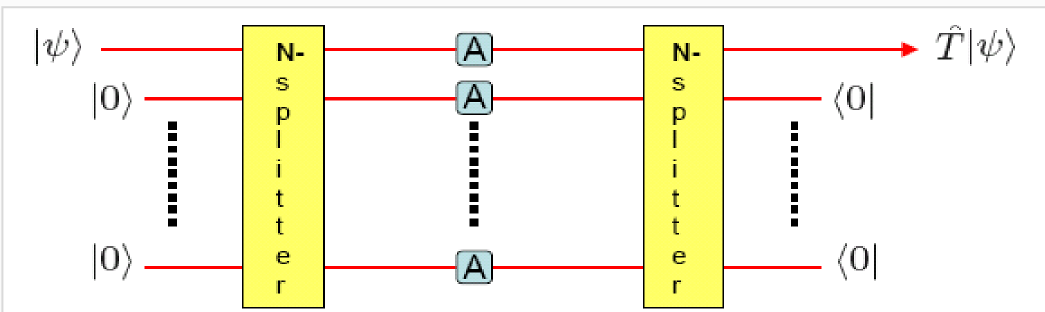


Quantum scissors

Amplified coherent state truncated to the |1> term

$$\left(|0\rangle + \frac{\sqrt{1-r^2}}{r}\alpha|1\rangle\right)$$

It only works well for |gα|<<1



$|\psi\rangle$, $|0\rangle$, $|0\rangle$ → $\hat{T}|\psi\rangle$, $\langle 0|$, $\langle 0|$

Scissors-based noiseless amplification

LETTERS
PUBLISHED ONLINE: 28 MARCH 2010 | DOI: 10.1038/NPHOTON.2010.35
nature photonics

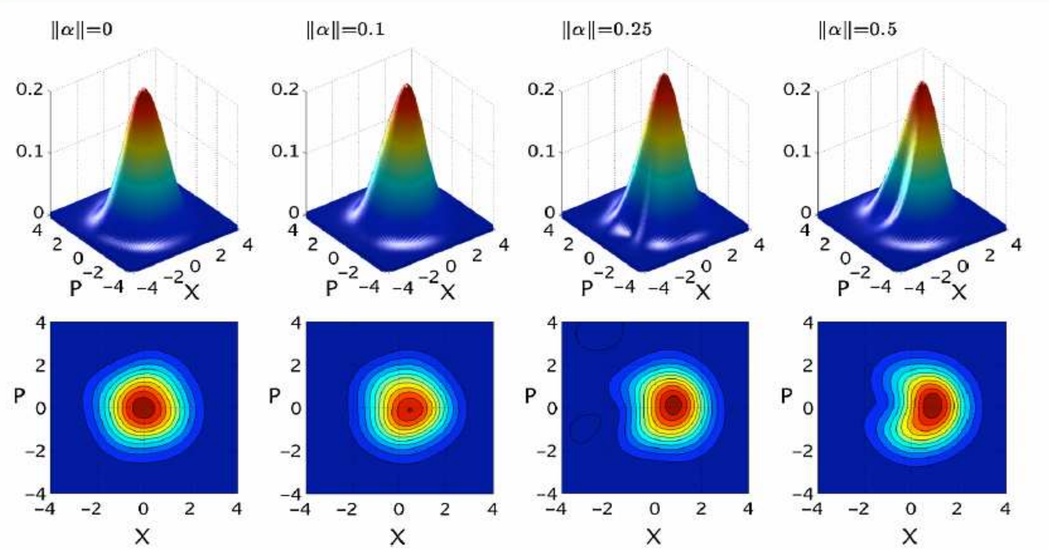
Heralded noiseless linear amplification and distillation of entanglement

G. Y. Xiang[1], T. C. Ralph[2], A. P. Lund[1,2], N. Walk[2] and G. J. Pryde[1]*

PRL 104, 123603 (2010) PHYSICAL REVIEW LETTERS week ending 26 MARCH 2010

Implementation of a Nondeterministic Optical Noiseless Amplifier

Franck Ferreyrol, Marco Barbieri, Rémi Blandino, Simon Fossier, Rosa Tualle-Brouri, and Philippe Grangier
Groupe d'Optique Quantique, Laboratoire Charles Fabry, Institut d'Optique, CNRS, Université Paris-Sud, Campus Polytechnique, RD 128, 91127 Palaiseau cedex, France
(Received 10 December 2009; published 24 March 2010)



Good amplifier only for very low amplitudes

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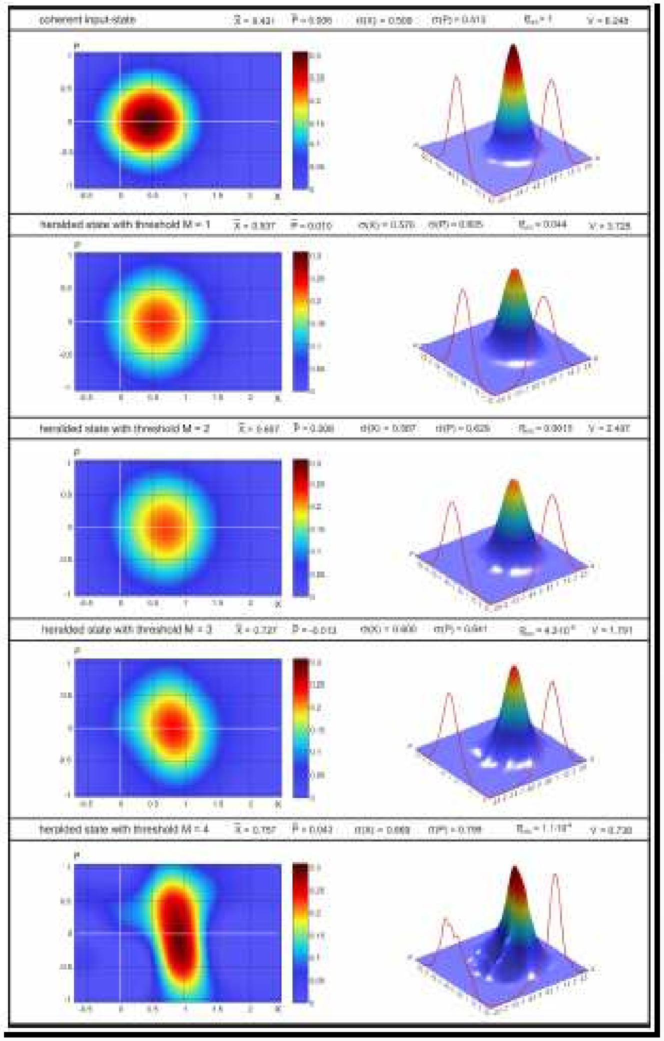
Noise addition and photon subtraction

nature physics
LETTERS
PUBLISHED ONLINE: 15 AUGUST 2010 | DOI: 10.1038/NPHYS1743

Noise-powered probabilistic concentration of phase information

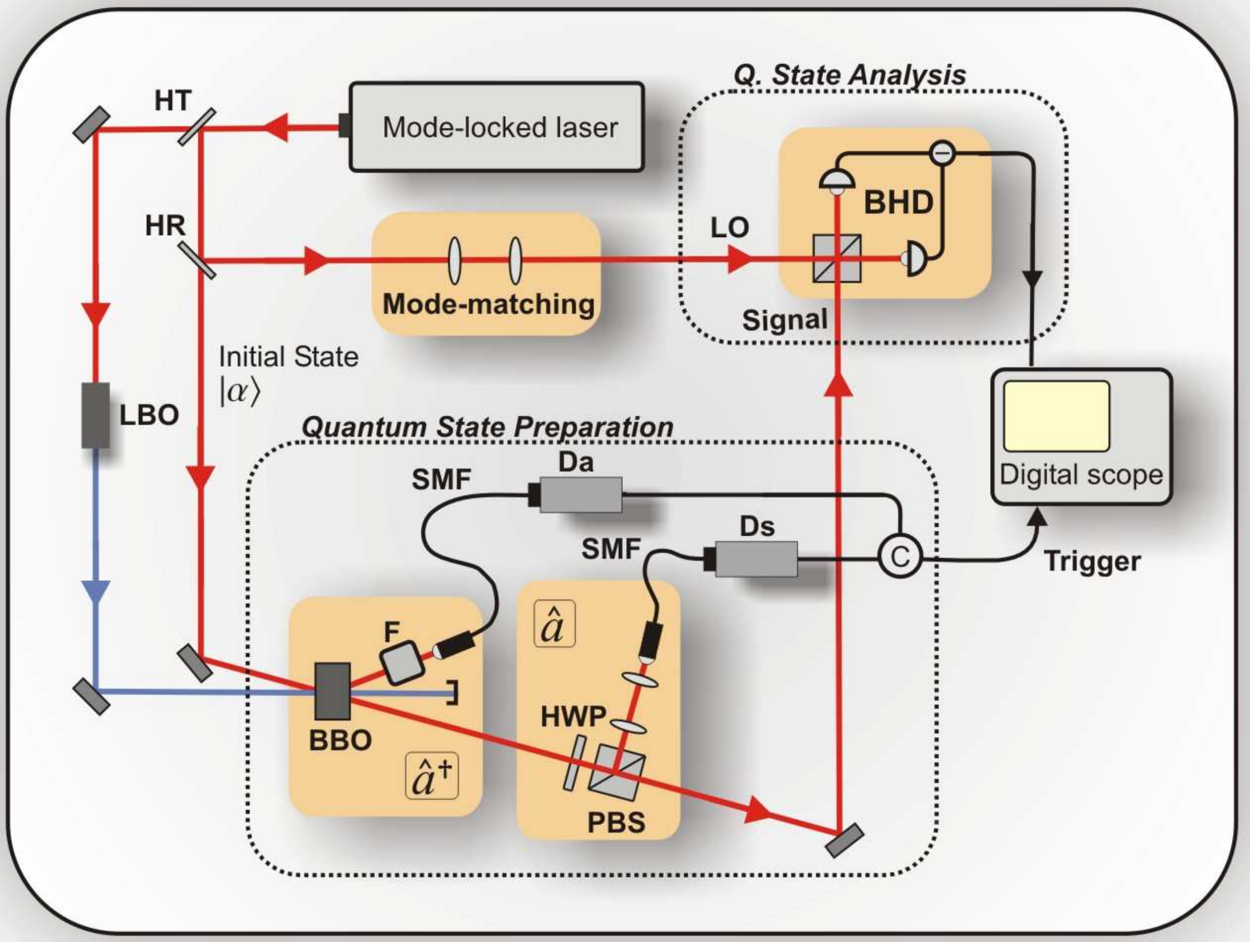
Mario A. Usuga[1,2†], Christian R. Müller[1,3†], Christoffer Wittmann[1,3], Petr Marek[4], Radim Filip[4], Christoph Marquardt[1,3], Gerd Leuchs[1,3] and Ulrik L. Andersen[2*]



The final state can be used for improved phase estimation

...but it is highly deformed and heavily mixed

The hi-fi noiseless amplifier

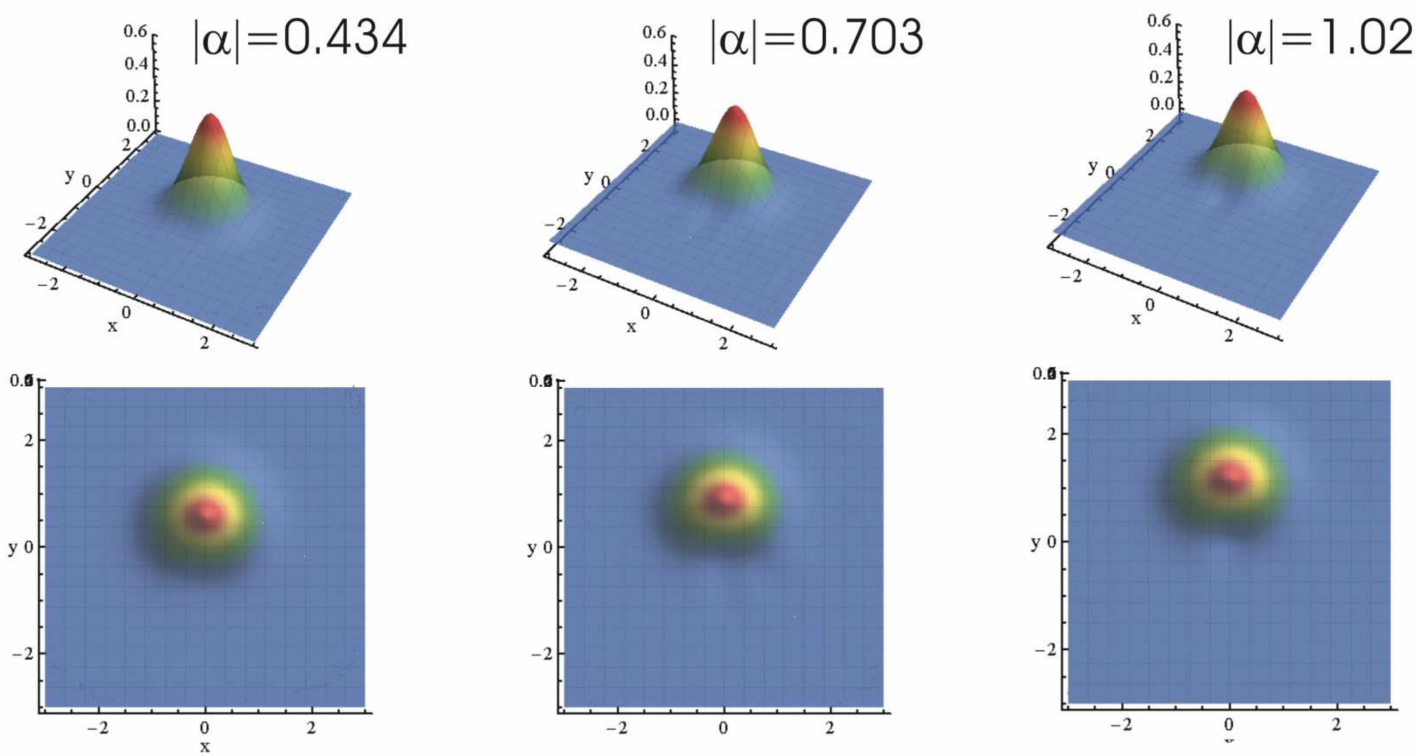


Wigner functions

ARTICLES
PUBLISHED ONLINE: 21 NOVEMBER 2010 | DOI: 10.1038/NPHOTON.2010.260
nature photonics

A high-fidelity noiseless amplifier for quantum light states

A. Zavatta[1,2], J. Fiurášek[3] and M. Bellini[1,2]*



Hi-fi quantum amplification

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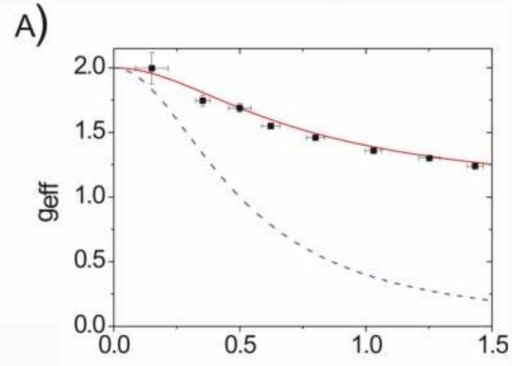
Effective amplitude gain

$$g_{eff} = \frac{\langle x_{amp} \rangle}{\langle x_{in} \rangle}$$



Fidelity

Distortions compared to the ideal coherent state of double amplitude

Noise

How much noise is added in the process?

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Variable-gain amplifier

$$\hat{G}_{g=2} = \hat{a}\hat{a}^\dagger$$

Is just a particular case of a general, variable-gain, noiseless amplifier

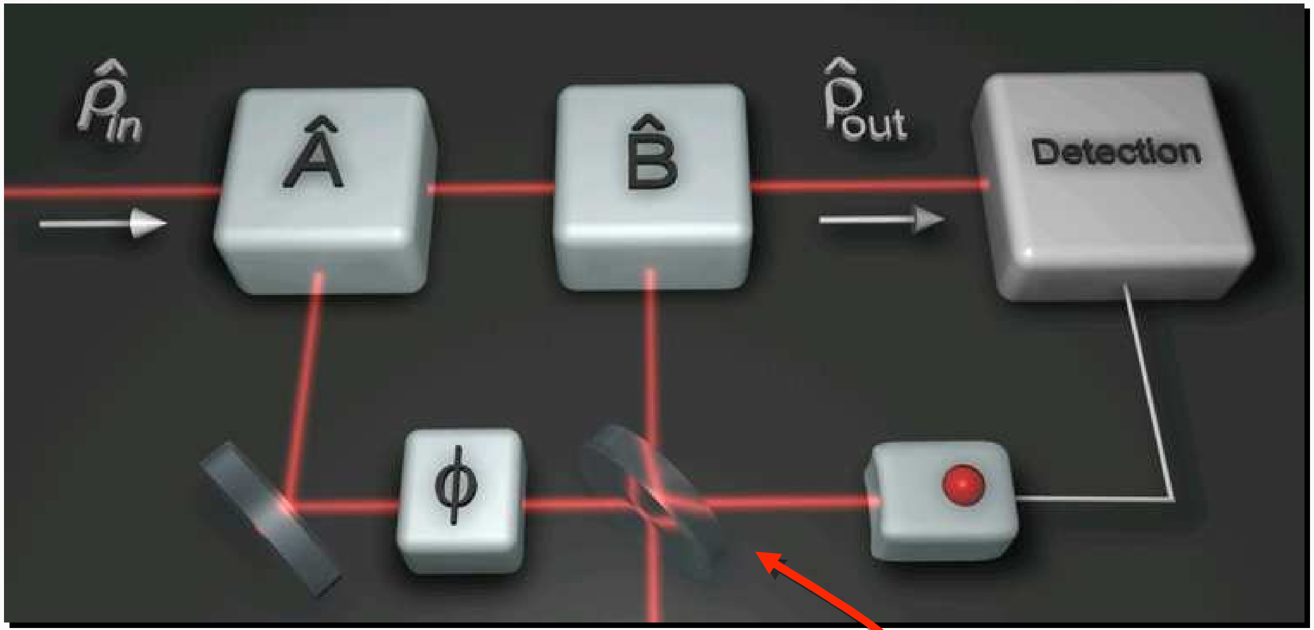
$$\hat{G} = (g-2)\hat{a}^\dagger\hat{a} + \hat{a}\hat{a}^\dagger$$

Amplitude gain

J. Fiurasek, *PRA* **80**, 053822 (2009)

Need a way to produce coherent superpositions of quantum operators

Superpositions of quantum operators



$$|\alpha|\,\hat{A} + e^{i\phi}\,|\beta|\,\hat{B}$$

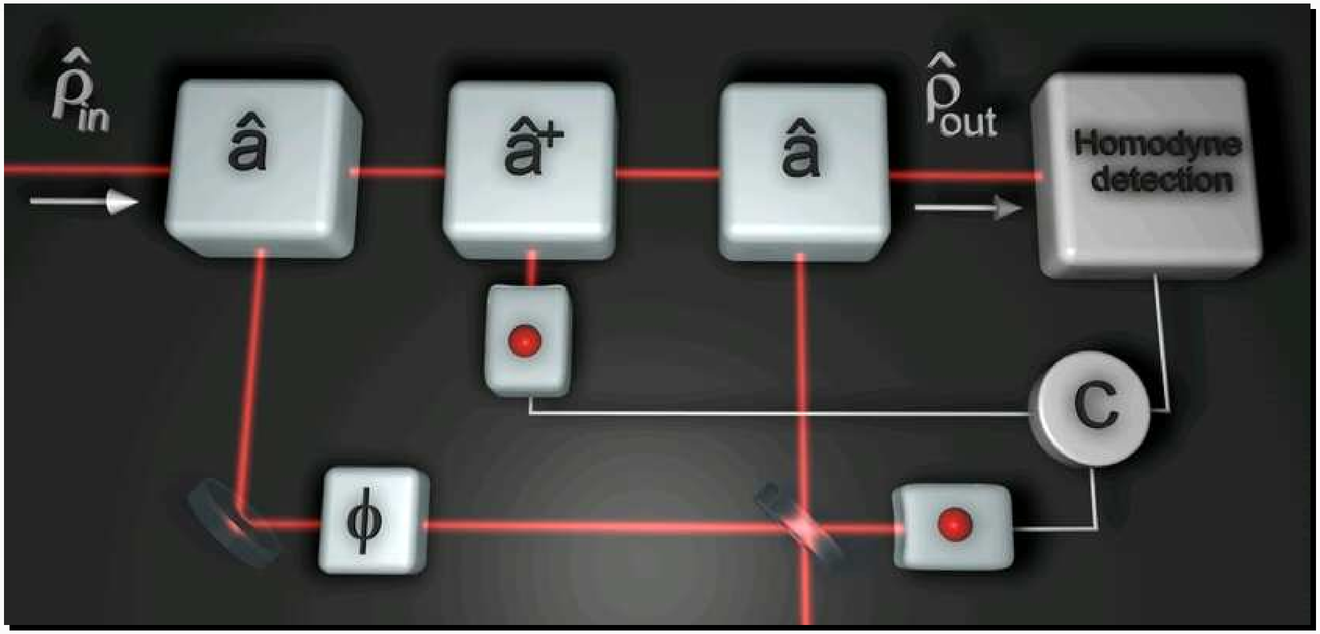
Erases the information about the origin of a "click"

Arbitrary superpositions of operators can be implemented

Apply to any state

Arbitrary state superposition

Experimental operator superpositions



With a variable-reflectivity beam splitter one gets

$$\hat{a}\hat{a}^{\dagger} \quad e^{i\phi}\hat{a}^{\dagger}\hat{a}$$

$$|A|\hat{a}^{\dagger}\hat{a} + e^{i\phi}|B|\hat{a}\hat{a}^{\dagger}$$

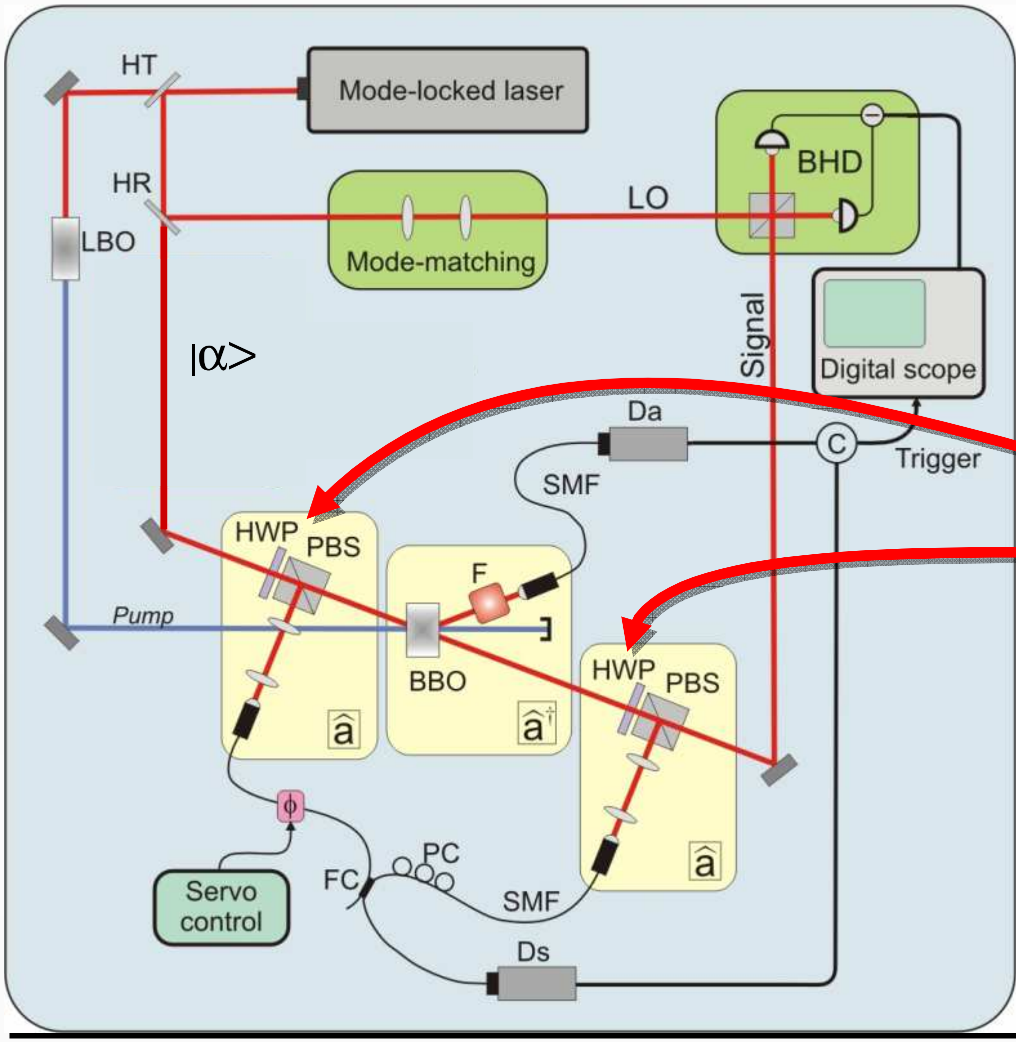
$$[\hat{a}, \hat{a}^{\dagger}] = \hat{a}\hat{a}^{\dagger} - \hat{a}^{\dagger}\hat{a} = 1$$

This complex superposition of operations should do <u>nothing</u> to the state !!

M. S. Kim, H. Jeong, A. Zavatta, V. Parigi, & MB, *PRL* **101**, 260401 (2008) **<u>Theory</u>**

A. Zavatta, V. Parigi, M. S. Kim, H. Jeong, & MB, *PRL* **103**, 140406 (2009) **<u>Experiment</u>**

Setup for a variable-gain noiseless amplifier



$$\hat{G} = (g-2)\hat{a}^\dagger\hat{a} + \hat{a}\hat{a}^\dagger$$

The right weights in the superposition can be tuned by adjusting the waveplate angles

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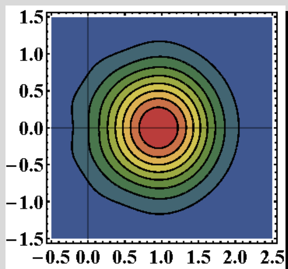
Variable-gain noiseless amplifier

$$\hat{G} = (g-2)\hat{a}^\dagger\hat{a} + \hat{a}\hat{a}^\dagger$$

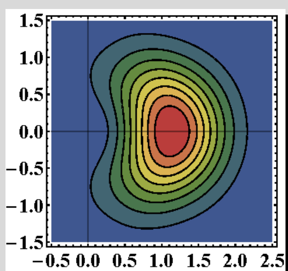
g = 1 $\hat{a}\hat{a}^\dagger - \hat{a}^\dagger\hat{a}$

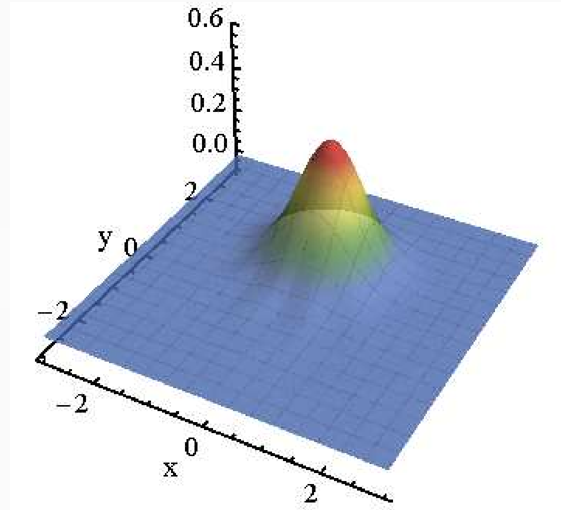
Commutator



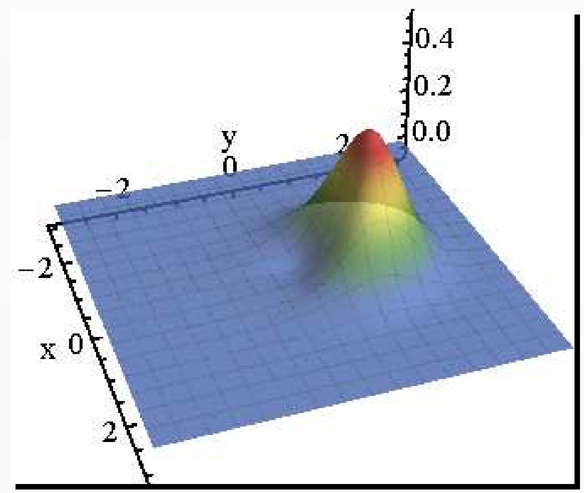
g = 3 $\hat{a}\hat{a}^\dagger + \hat{a}^\dagger\hat{a}$

Anti-Commutator



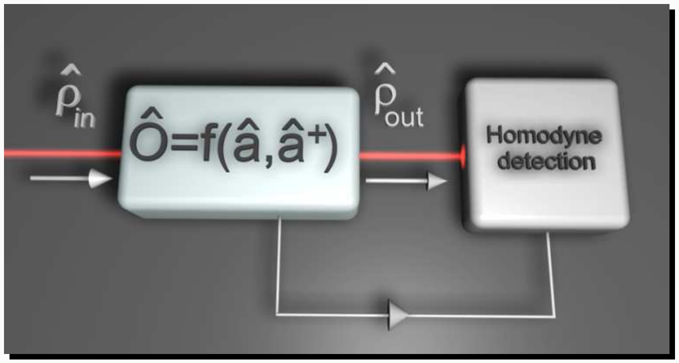


Input coherent state with |α|~1



A. Zavatta, J. Fiurasek, & MB, *in preparation* (2011)

The “shape” of a single photon

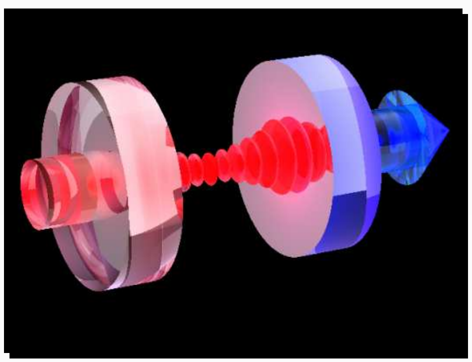


Every operation is performed in a single, well-defined, spatio-temporal mode

↓

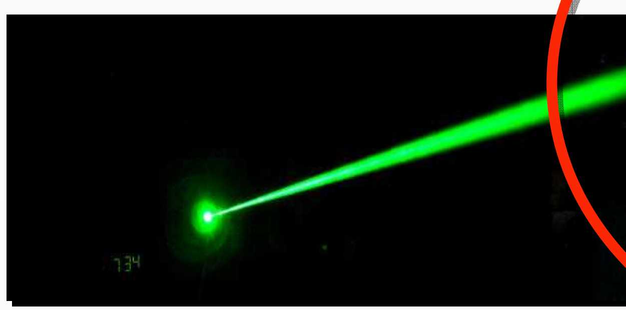
The relevant quantum features of the states can only be accessed if the right mode is properly selected and analyzed

The photon is a single, quantized, excitation of a particular spatio-temporal mode

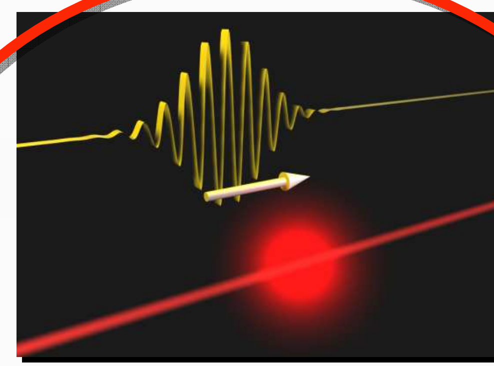


Confined cavity mode

$$|\omega\rangle = \hat{a}^{\dagger}(\omega)\,|0\rangle$$



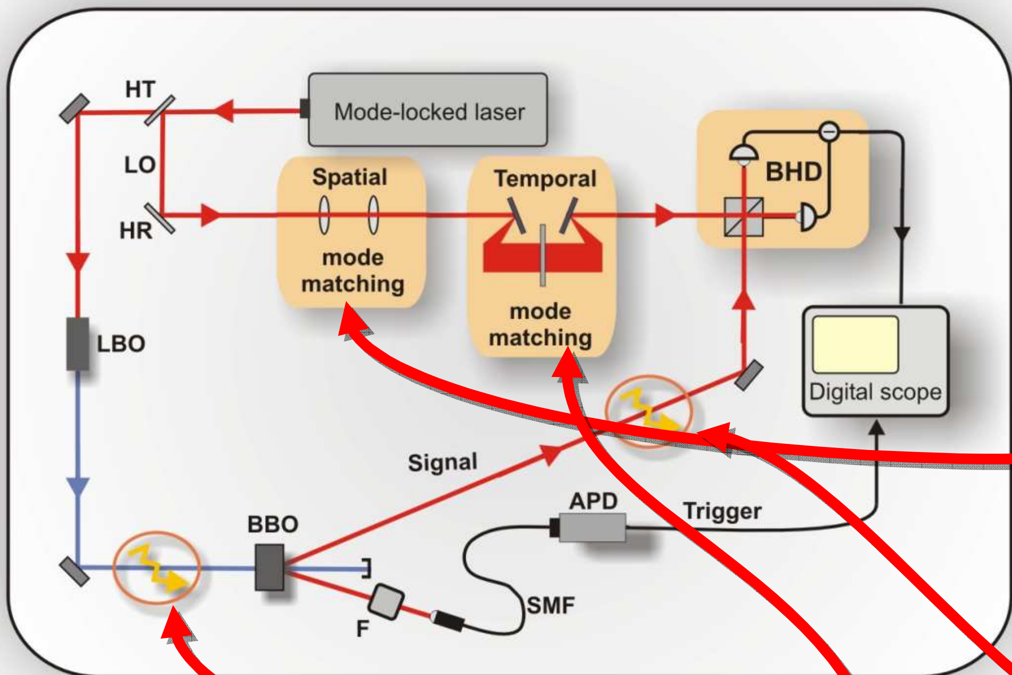
Infinitely extended monochromatic CW mode



Traveling wavepacket mode

$$|1\rangle_{\Psi} = \int d\omega \Psi(\omega)\,|\omega\rangle$$

Measuring the photon wavepacket



A single photon can only be observed if the LO is properly matched in polarization, space, time, spectrum,…

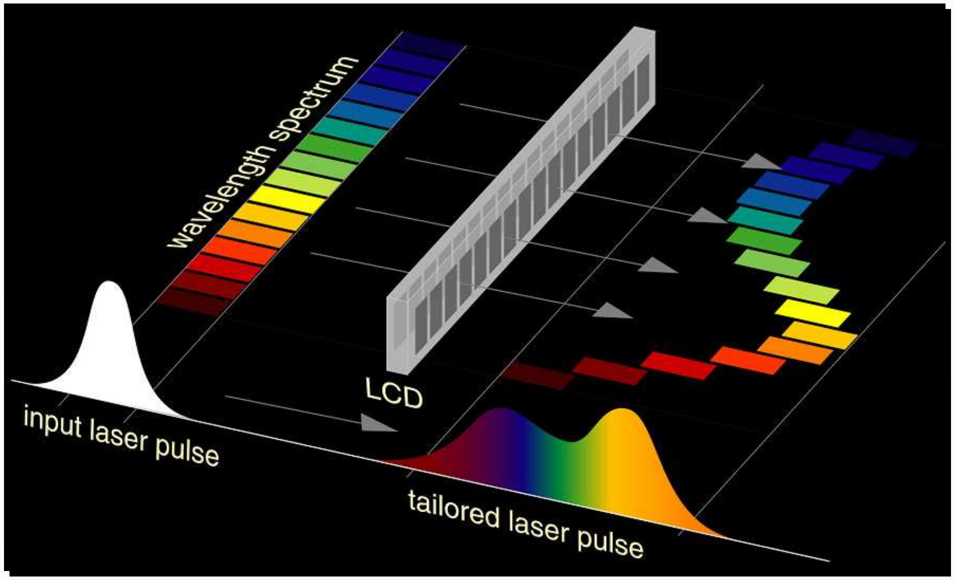
We usually match the LO to the photon spatial mode but assume a Gaussian transform-limited temporal profile

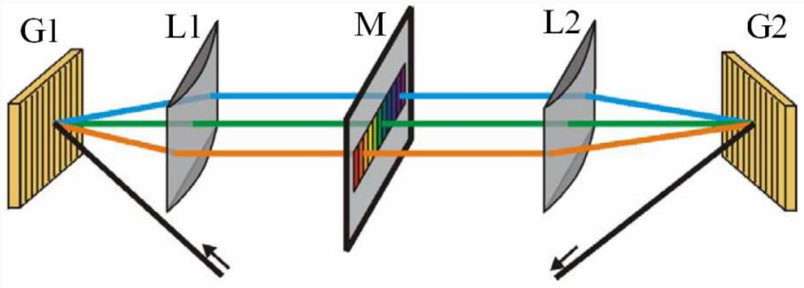
$$\Psi(\omega)$$

What if also the spectral/temporal mode is changed in the propagation or because of pump modulations??
(especially for fs-range wavepacket duration)

Need a spectral/temporal shaping of the LO to reliably measure the mode that contains the single photon

Shaping the local oscillator



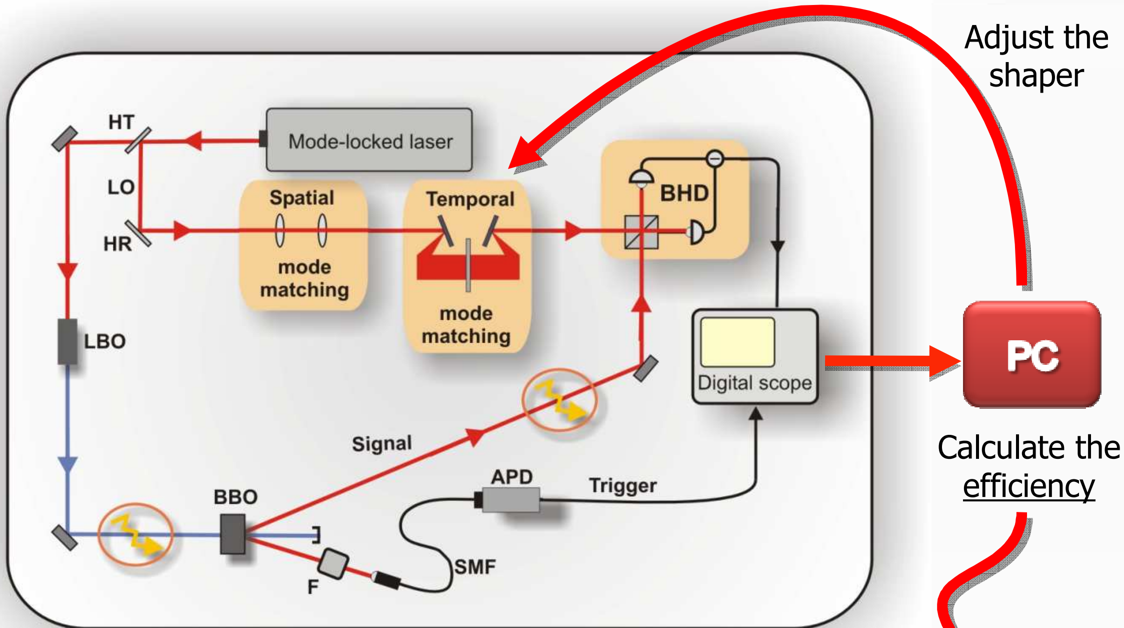


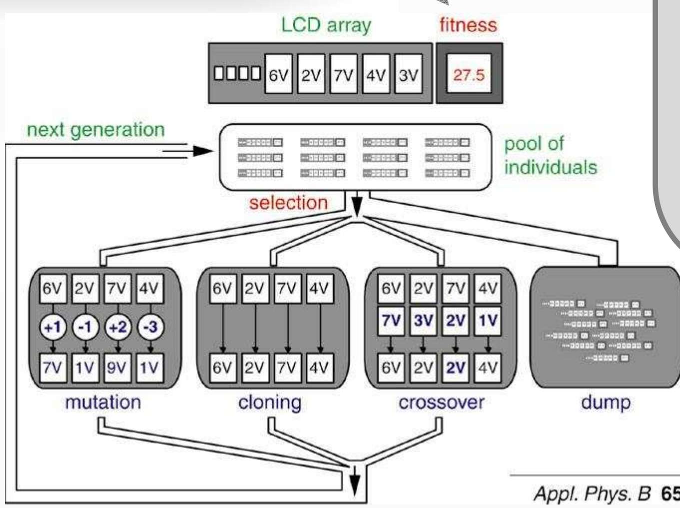
Need to independently modulate each wavelength component in amplitude and phase

SLM: 128 pixels
(pixel width: 97 µm, pixel gap 3 µm)

Widely used technique in ultrafast laser research, particularly in femtochemistry to steer specific reactions, etc.

Genetic search of the photon shape

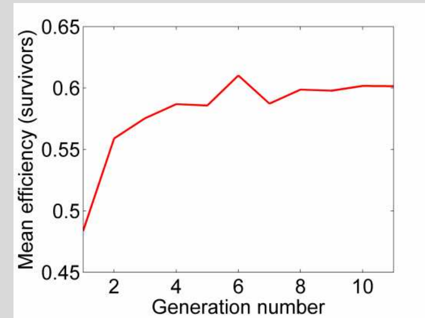


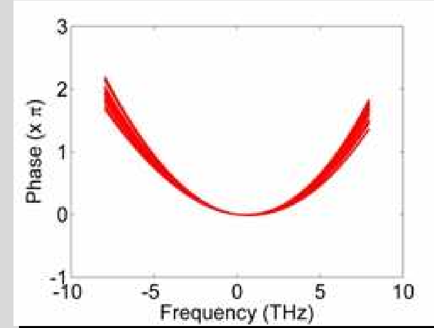


Appl. Phys. B **65**, 779 (1997)

No need of previous knowledge of the correct mode shape

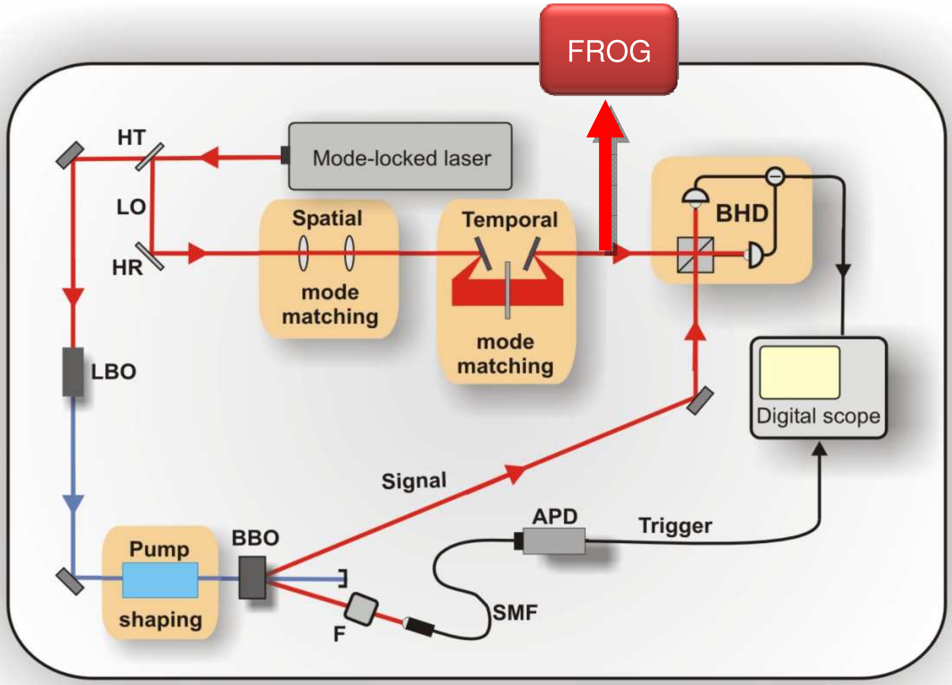
Use an evolutionary algorithm to find the best LO pulse shape



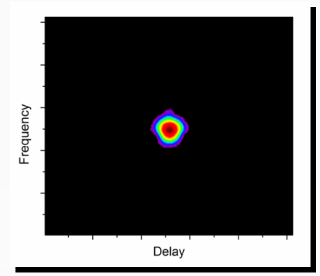


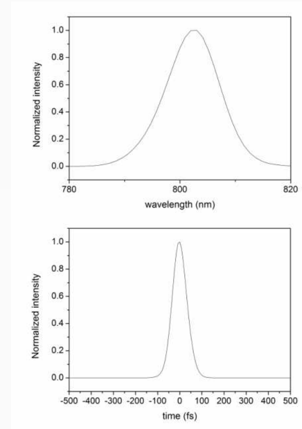
Measuring a frequency-dispersed single photon

Mapping the shape of a single photon onto the LO pulse



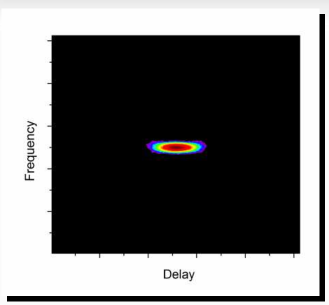
Frequency-Resolved Optical Gating
can fully characterize the LO pulse

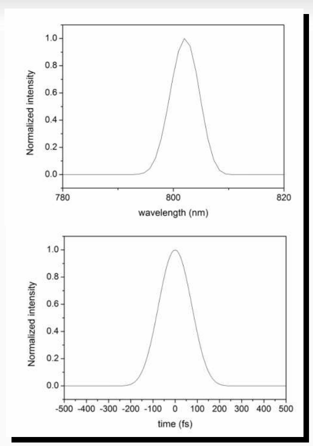




Un-modulated pump

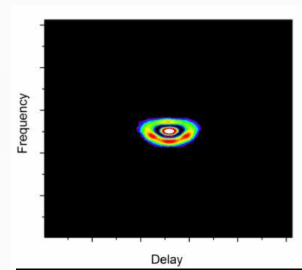
Pulse Width: 76.21 fs
Bandwidth: 5.29 THz
Bandwidth: 11.34 nm

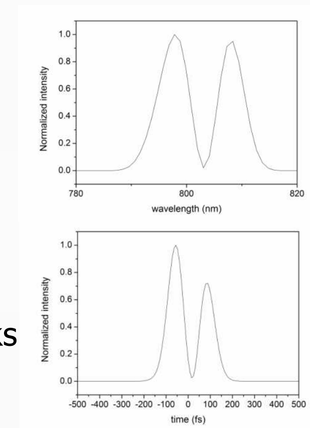




Spectral narrowing

Pulse Width: 172.38 fs
Bandwidth: 2.84 THz
Bandwidth: 6.09 nm





Double
spectral/temporal peaks

The single photon is in a coherent superposition of two distinct spectral/temporal modes

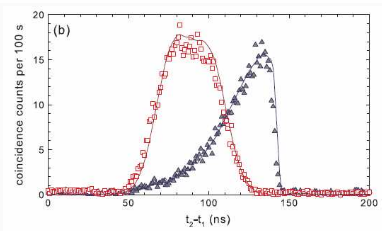
Encoding quantum information in the shape of a single <u>ultrashort</u> photon

Amplitude and phase modulation has been achieved for narrowband (100ns - 1μs long) photons

PRL 101, 103601 (2008) PHYSICAL REVIEW LETTERS week ending 5 SEPTEMBER 2008

Electro-Optic Modulation of Single Photons

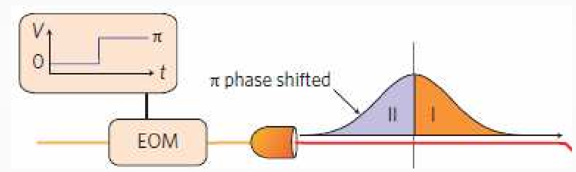
Pavel Kolchin,* Chinmay Belthangady, Shengwang Du, G. Y. Yin, and S. E. Harris



nature photonics LETTERS
PUBLISHED ONLINE: 13 JULY 2009 | DOI: 10.1038/NPHOTON.2009.115

Phase shaping of single-photon wave packets

H. P. Specht, J. Bochmann, M. Mücke, B. Weber, E. Figueroa, D. L. Moehring* and G. Rempe



Both modulation and detection can be performed with standard electronics

Ultrafast optics + Quantum optics

Manipulate and characterize the spectral content of ultrashort (<100 fs) quantum states of light

Multimode encoding and detection for higher dimensional Hilbert spaces:
powerful resource for quantum communication protocols
(i.e., differential phase shift QKD)

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Conclusions and credits

Accurate quantum state engineering

Advanced techniques of analysis

↓

Powerful tools for quantum information processing, communication, and metrology

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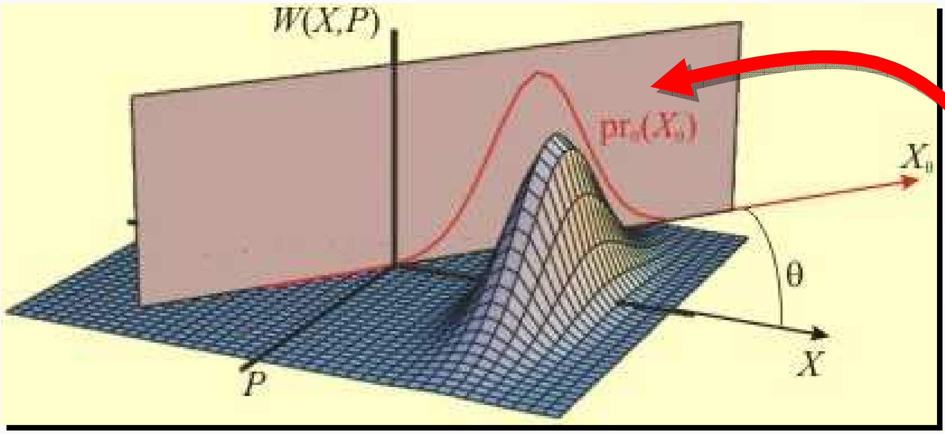
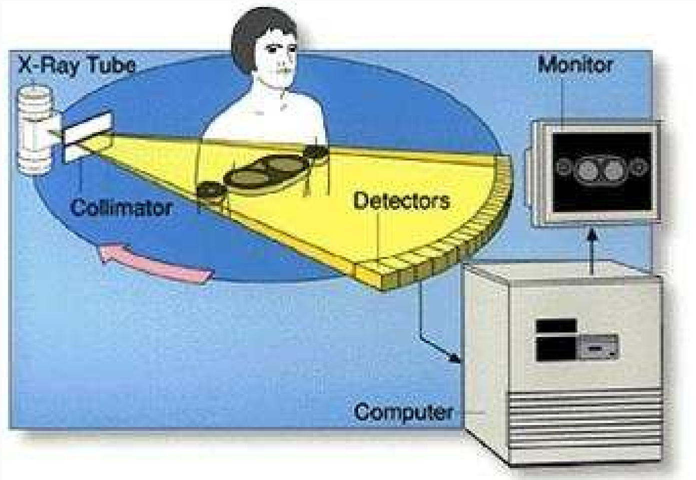
Quantum tomography: reconstructing the Wigner function



W(x,p) contains the full information about the state but cannot be measured directly

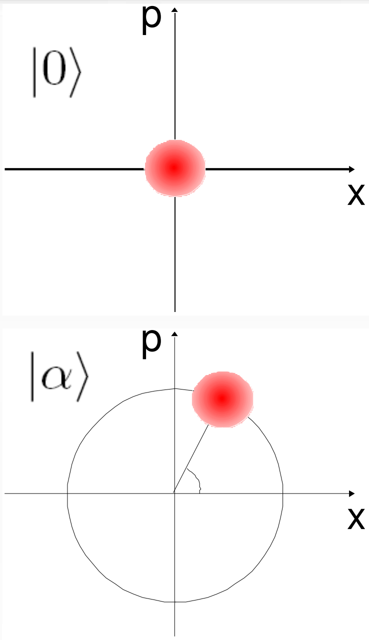
However, all its projections are quadrature distributions that are accessible by balanced homodyne detection

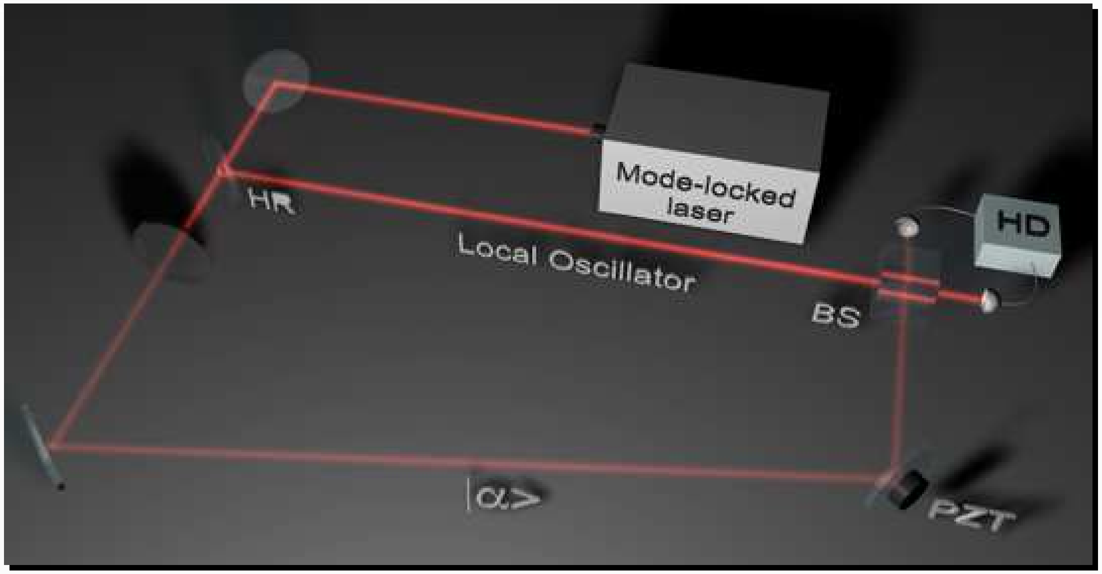
Use a tomographic approach to reconstruct the Wigner function

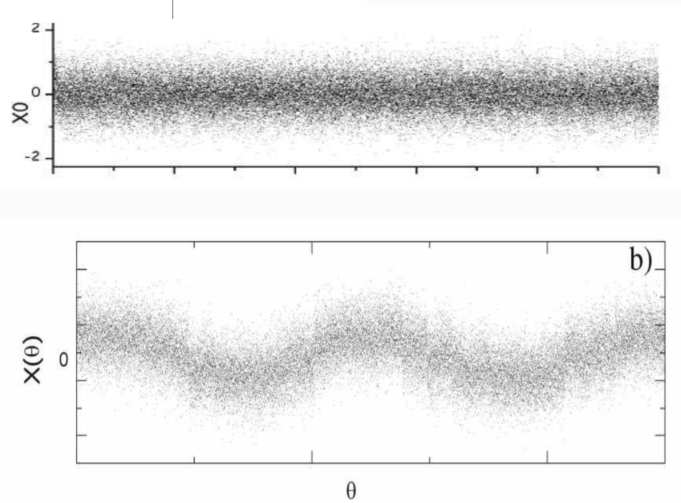


Just like in medical CAT (Computerized Axial Tomography)

Classical coherent states

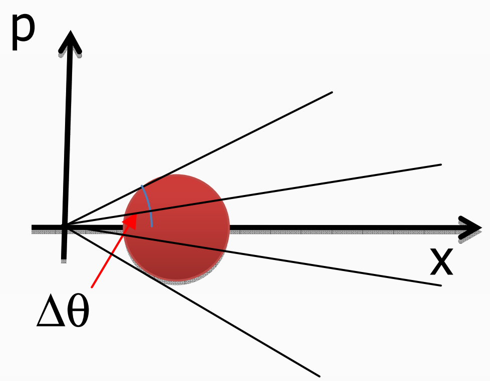






A. Zavatta, MB, P. L. Ramazza, F. Marin and F. T. Arecchi, *JOSA B*, **19**, 1189-1194 (2002)

Improved state/phase discrimination

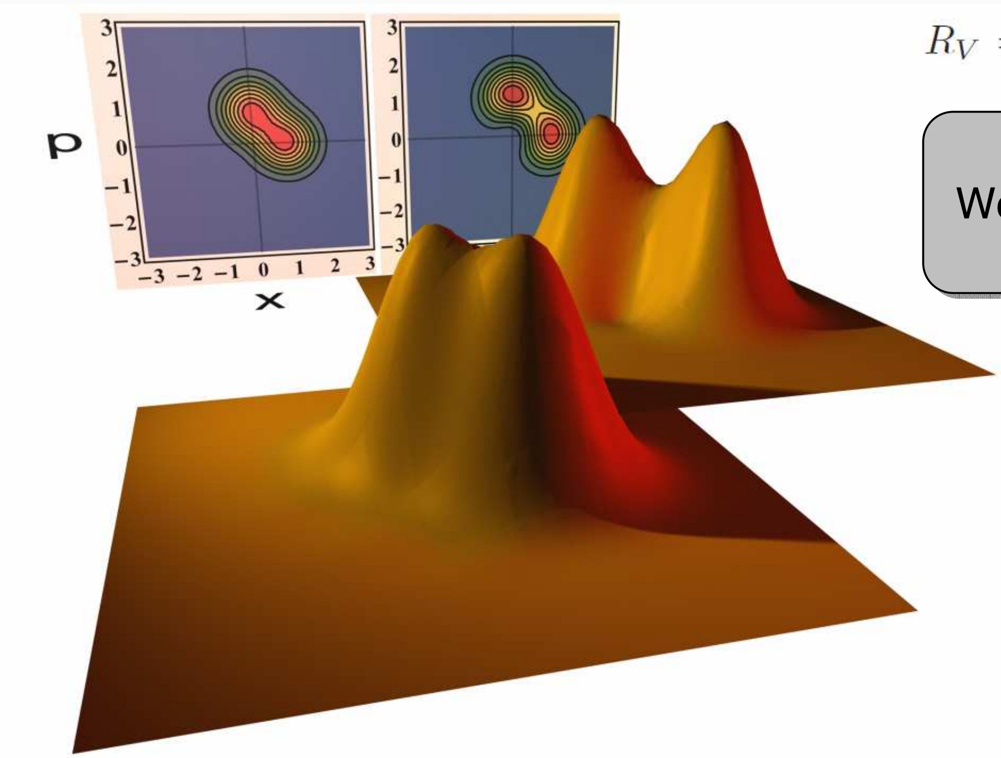


For small θ, the reduction in the phase variance is

$$R_V = \frac{1}{g_{eff}^2}\frac{\langle(\Delta p_{amp})^2\rangle}{\langle(\Delta p_{in})^2\rangle}$$

For ideal noiseless amplification

$$R_V = \frac{1}{g_{eff}^2}$$



$R_V = 0.45, 0.64, 0.76$ for $|\alpha| = 0.4, 0.7, 1.0$

$R_V<1$
We always get a clear improvement in the phase estimation

The “weirdness” of photon subtraction

Subtracting a single photon from a state may increase the resulting mean photon number if the initial state was super-Poissonian.

$$\bar{n}_{sub} = \bar{n} - 1 + F$$

where

<u>Fano parameter</u> $$F \equiv \frac{\overline{(\Delta n)^2}}{\bar{n}}$$

Variance of photon number distribution

Mean photon number

$\bar{n}_{sub} = \bar{n} - 1$ for a Fock state

$\bar{n}_{sub} = \bar{n}$ for a coherent state

$\bar{n}_{sub} = 2\bar{n}$ for a thermal state !!!

Photon creation and annihilation operators <u>do not</u> perform deterministic photon addition and subtraction !

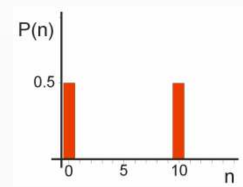
Quantum magic ?

How can the mean number of rabbits in the hat increase by extracting one ??

Do we really need "quantum rabbits" ?

$\langle n_s \rangle \leq \langle n_0 \rangle$ $\langle n_s \rangle > \langle n_0 \rangle$

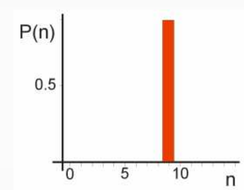
$P_0(0)=1/2$
$P_0(10)=1/2$



$\langle n_0 \rangle = 0*1/2+10*1/2 = 5$

If a rabbit is extracted then:

$P_s(0)=0$
$P_s(9)=1$

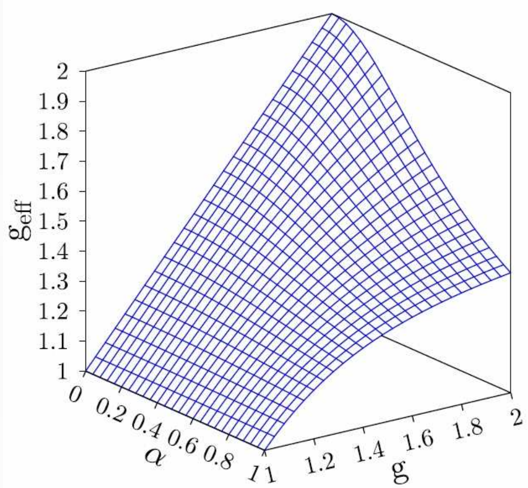


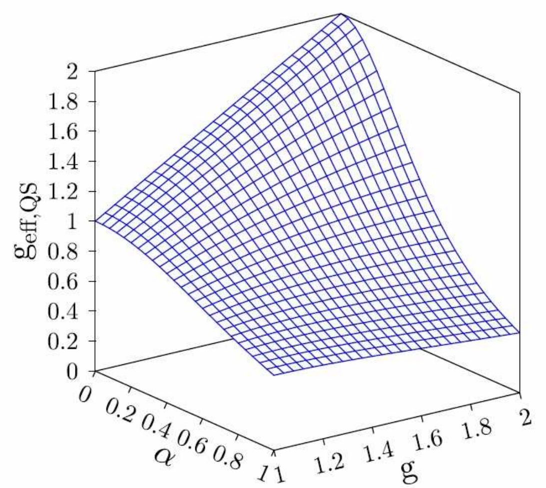
$\langle n_s \rangle = 0*0+9*1 = 9$

Effective amplitude gain and fidelity

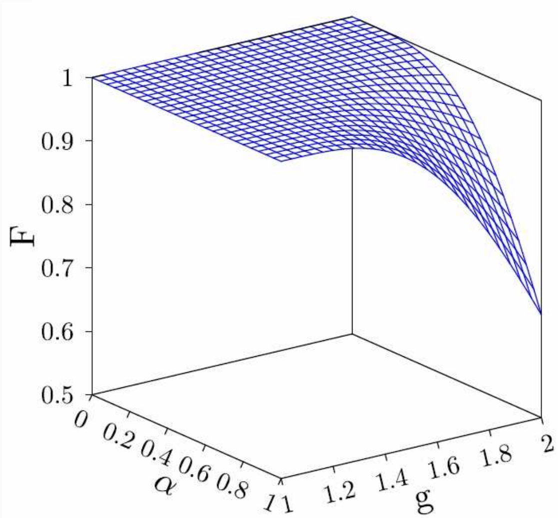
Addition/subtraction	Quantum scissors

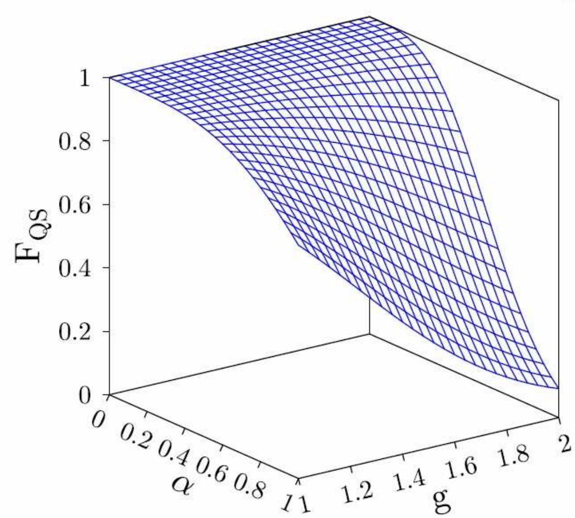
$$g_{\mathrm{eff}} = \frac{1}{\alpha}\frac{\langle\alpha|\hat{G}\hat{a}\hat{G}|\alpha\rangle}{\langle\alpha|\hat{G}^2|\alpha\rangle}$$





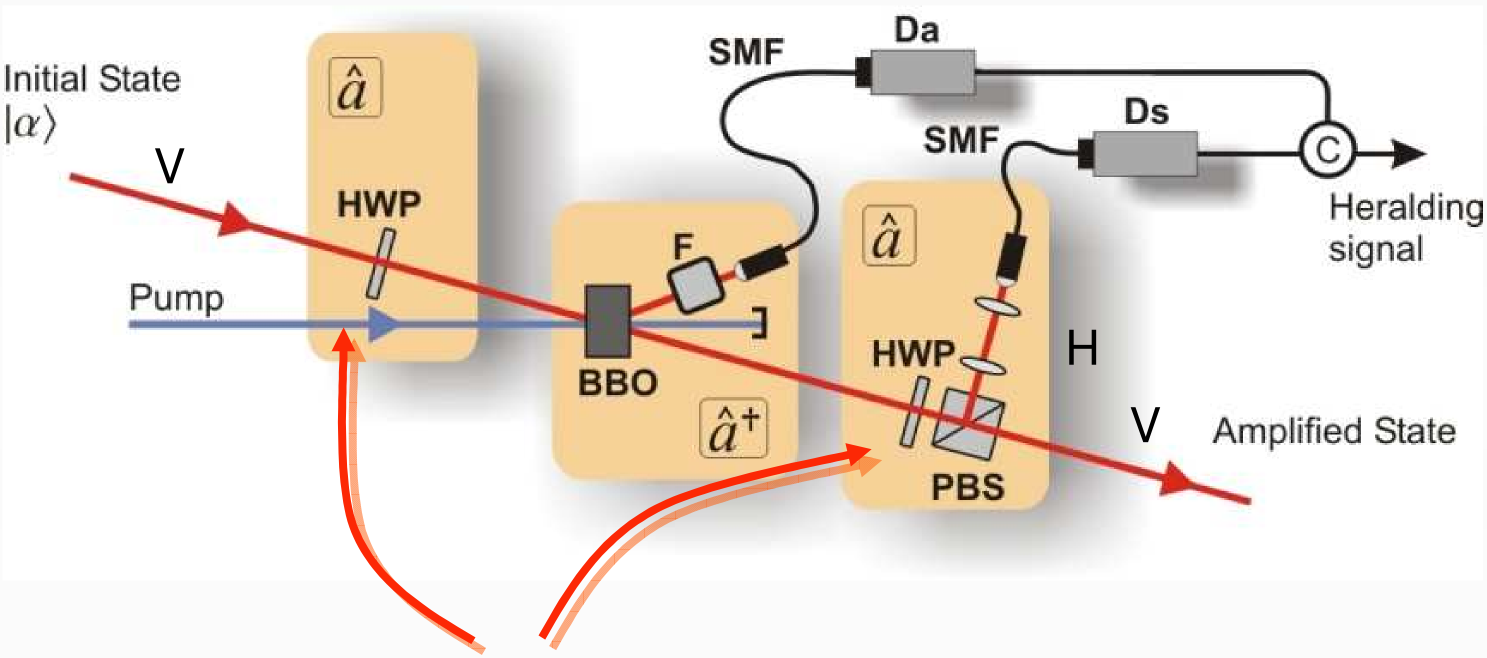
$$F = \frac{|\langle g\alpha|\hat{G}|\alpha\rangle|^2}{\langle\alpha|\hat{G}^2|\alpha\rangle}$$





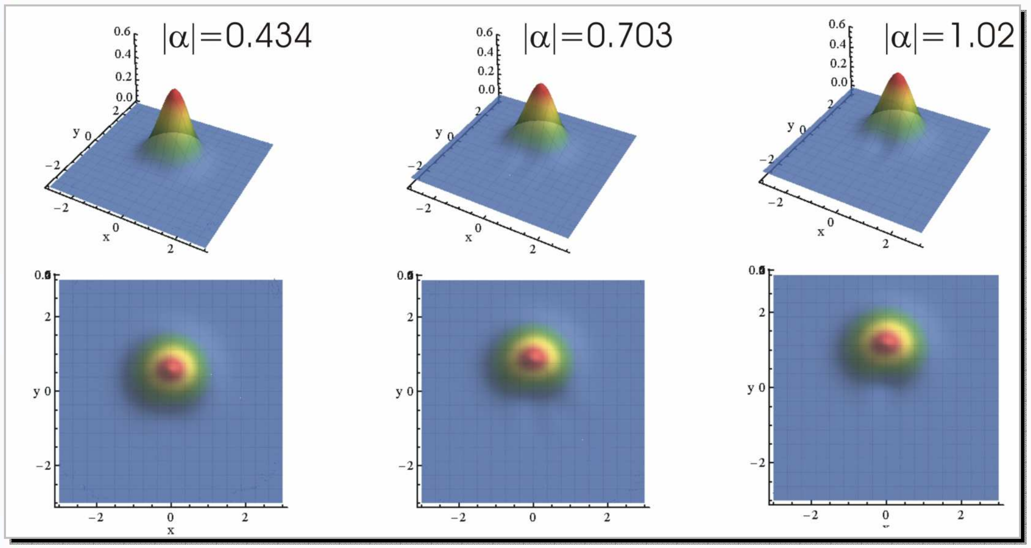
Compact variable-gain noiseless amplifier

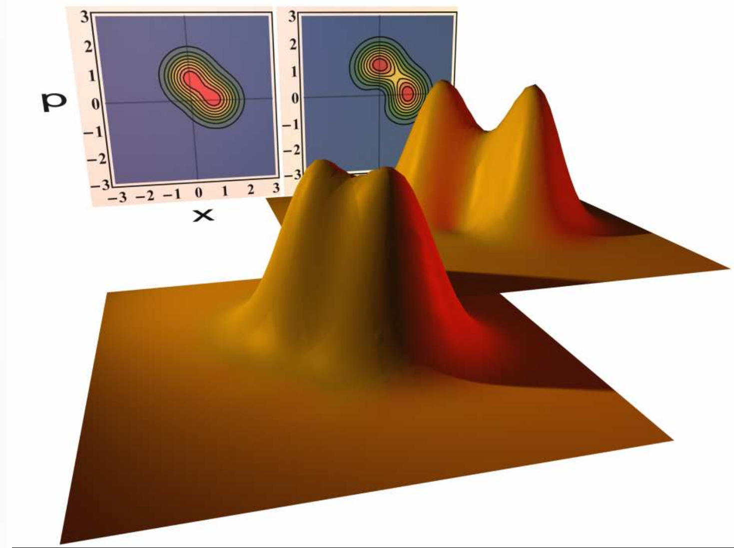
Use a polarization-based interferometer for phase stability



The two HWPs are rotated by very small angles.

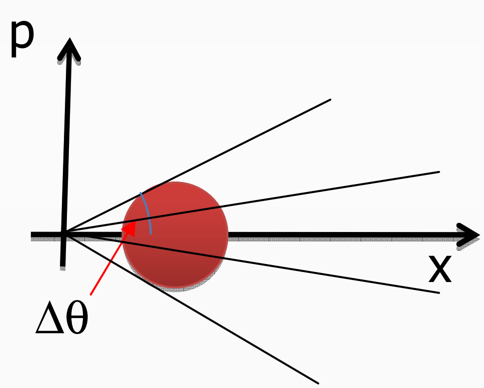
Experimental results





The amplifier does its job without deforming the amplified state

Can be used for better phase estimation and state discrimination



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A high-fidelity noiseless amplifier for quantum light states

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