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Single-photon-level manipulation and mode analysis of ultrashort quantum light states

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Outline

Manipulating single photons

Measuring light at the quantum level

Single-photon addition and subtraction

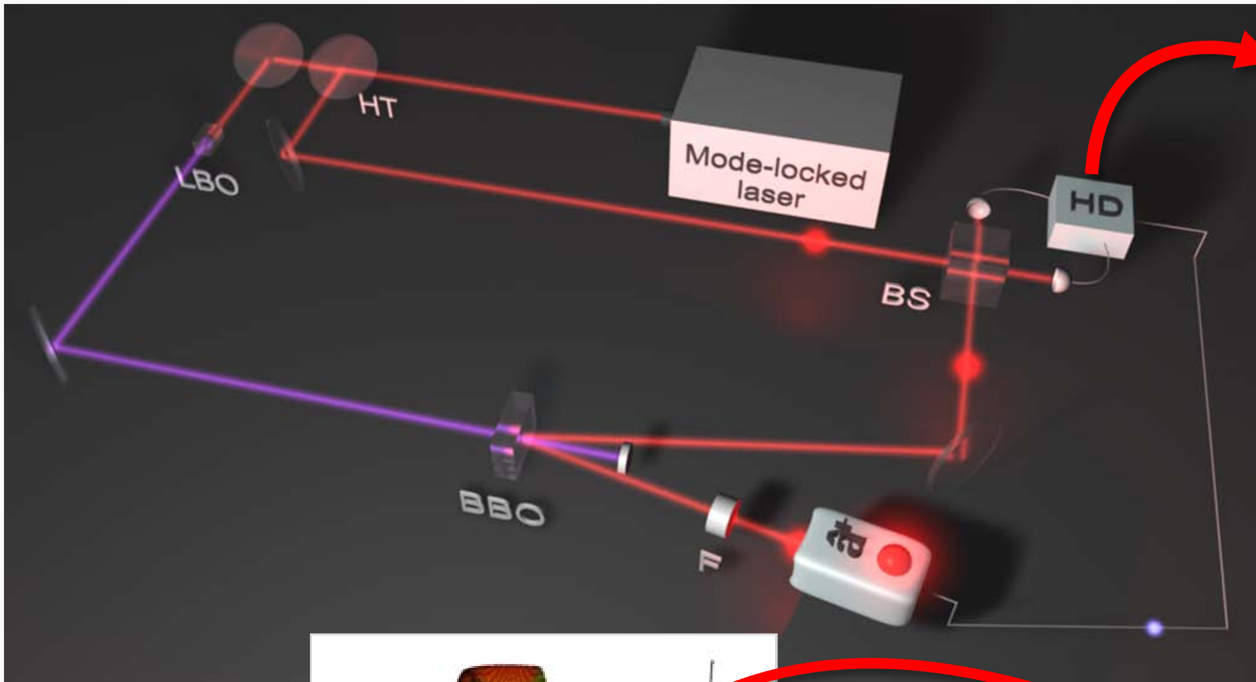
Sequences and superpositions of quantum operators

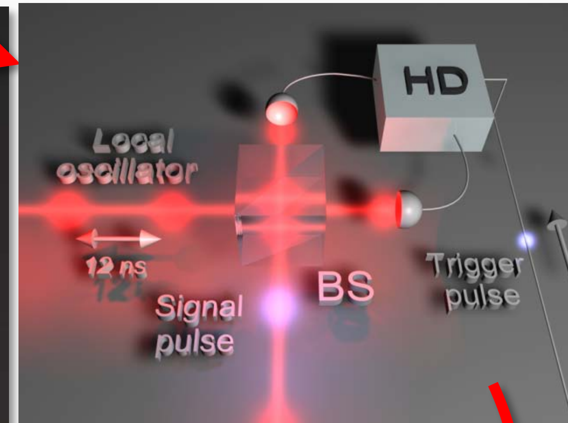
Direct probing of fundamental quantum rules

Noiseless amplification

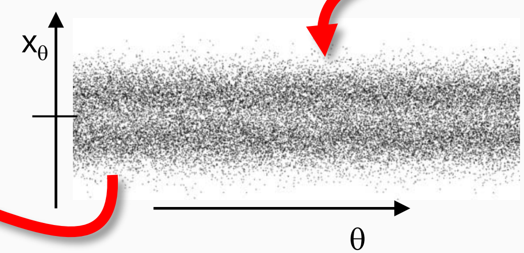
Investigating and exploiting the mode structure of ultrashort pulsed quantum light states

Single photons in the lab

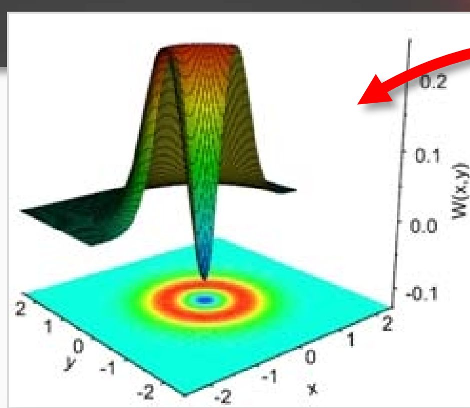




Acquire homodyne data



Collect quadrature distributions



Reconstruct the Wigner function and the density matrix

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)

Photon creation and annihilation operators

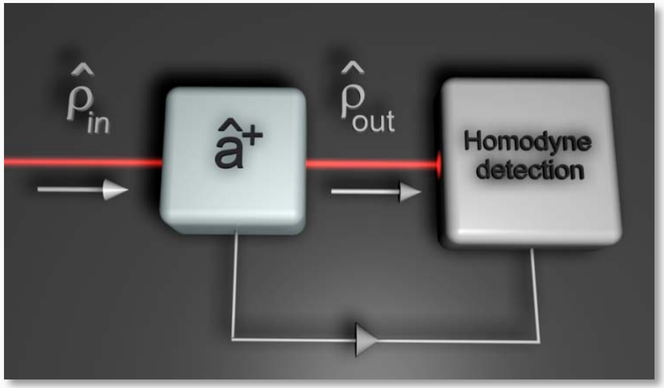
Add and subtract single photons with creation and annihilation operators

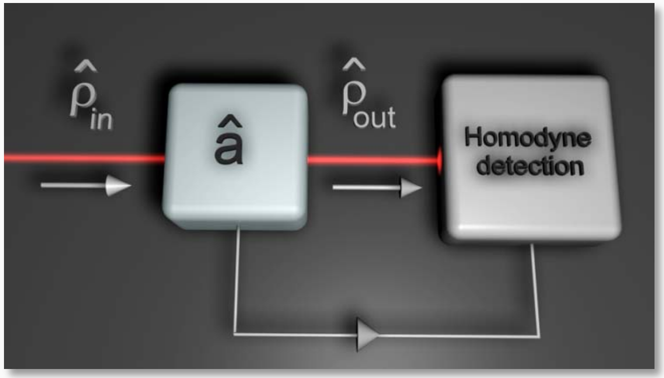
$$\hat{a}^\dagger |n\rangle = \sqrt{n+1}\,|n+1\rangle$$

$$\hat{a}\,|n\rangle = \sqrt{n}\,|n-1\rangle$$

$\hat{a}^\dagger \hat{\rho} \hat{a}$ "Photon-added" state

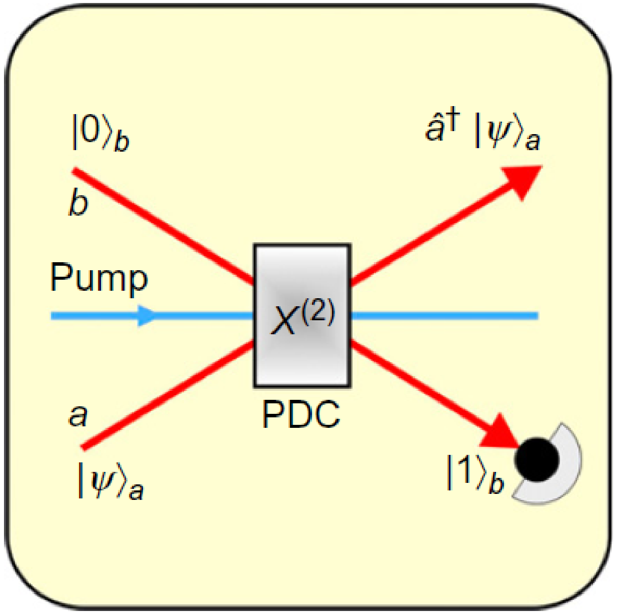
$\hat{a} \hat{\rho} \hat{a}^\dagger$ "Photon-subtracted" state





Conditional generation schemes

Photon addition and subtraction



$$\hat{S} = \mathrm{e}^{-\lambda(\hat{a}\hat{b}-\hat{a}^\dagger\hat{b}^\dagger)}$$

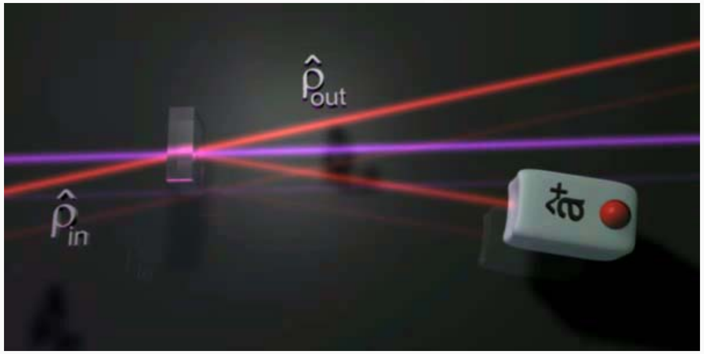
$$\hat{B} = \mathrm{e}^{-\theta(\hat{a}^\dagger\hat{b}-\hat{a}\hat{b}^\dagger)}$$

$$|\psi_{\mathrm{out}}\rangle \approx \left[1-\lambda(\hat{a}\hat{b}-\hat{a}^\dagger\hat{b}^\dagger)\right]|\psi\rangle_a|0\rangle_b \approx |\psi\rangle_a|0\rangle_b + \lambda\hat{a}^\dagger|\psi\rangle_a|1\rangle_b.$$

$$|\psi_{\mathrm{out}}\rangle \approx \left[1-\theta(\hat{a}^\dagger\hat{b}-\hat{a}\hat{b}^\dagger)\right]|\psi\rangle_a|0\rangle_b \approx |\psi\rangle_a|0\rangle_b + \theta\hat{a}|\psi\rangle_a|1\rangle_b$$

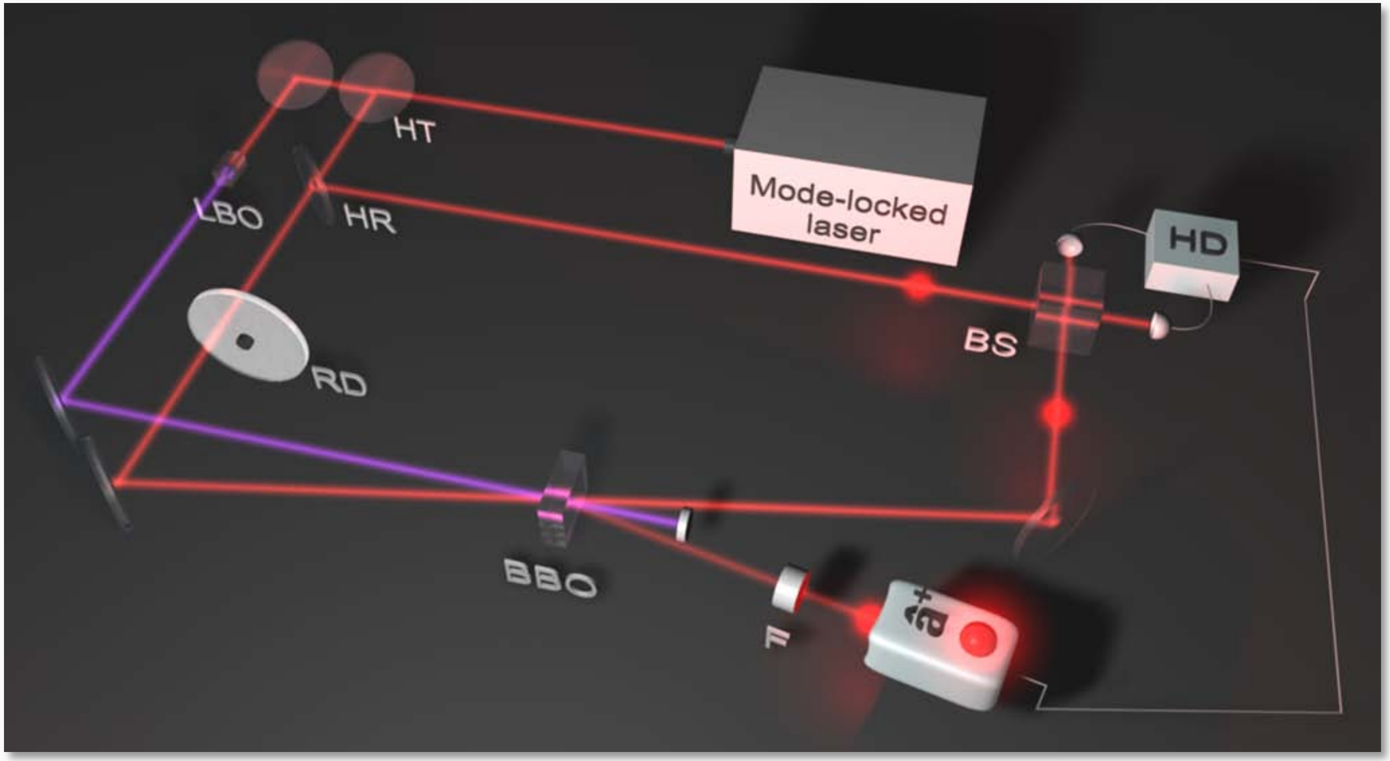
“Adding” photons with PDC

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

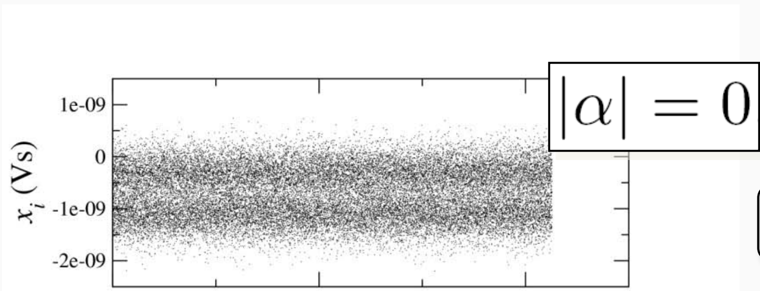


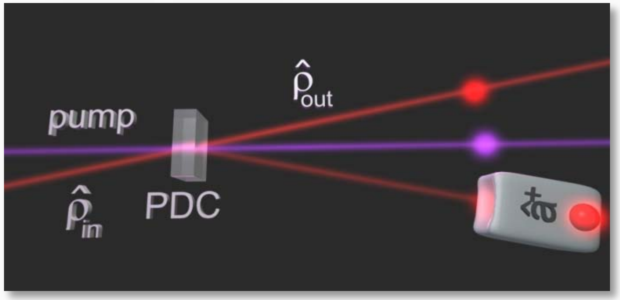
Faithful implementation of the creation operator for:

- small PDC gain
- small photon numbers



Quantum-to-classical transition





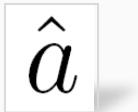
Fock state: phase-invariant

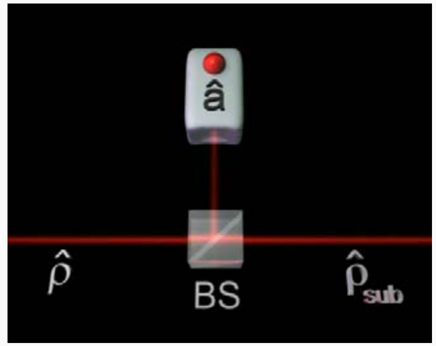
amplitude seed (~1/7 ph/pulse): phase-sensitivity appears

Clear phase dependence

Wave-like behavior

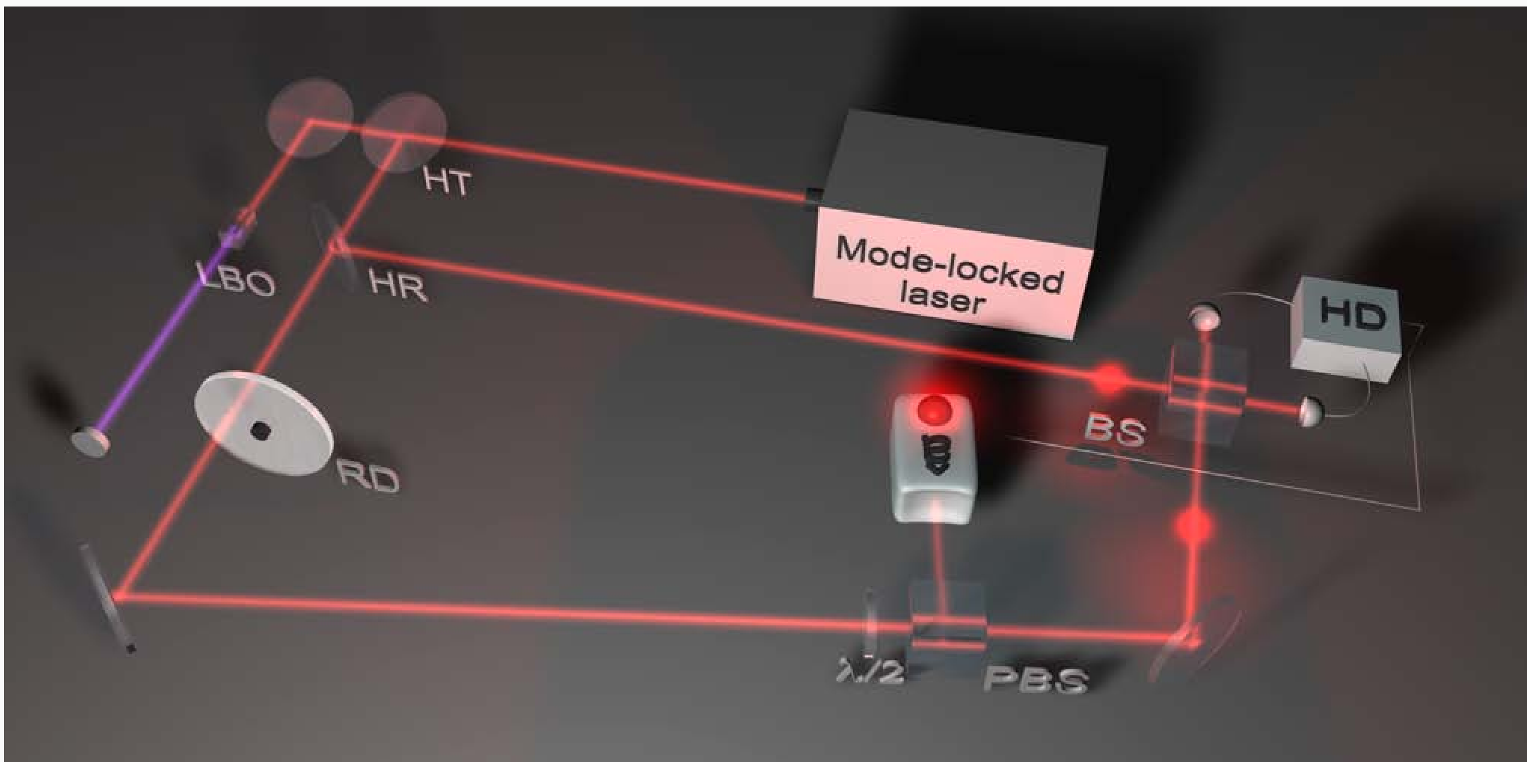
“Subtracting” photons with a beam splitter



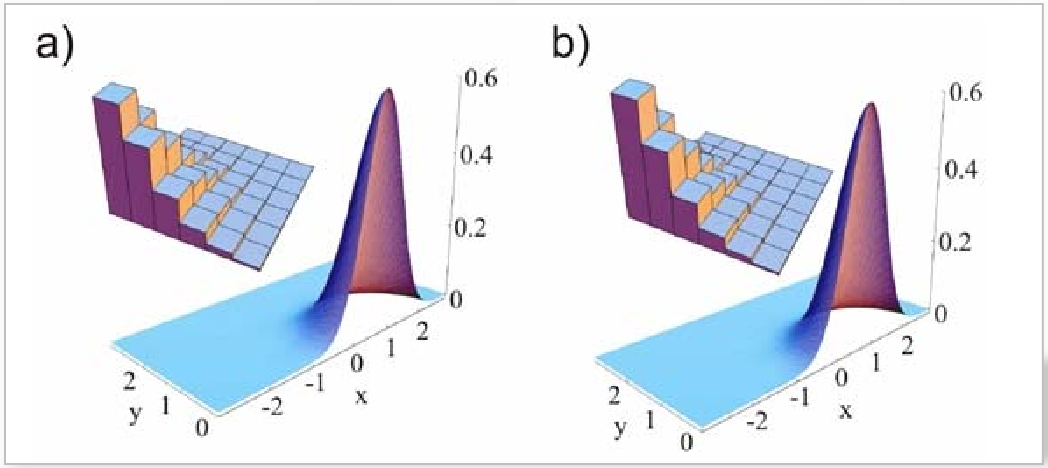


Faithful implementation of the annihilation operator for:

- small BS reflectivity
- small photon numbers



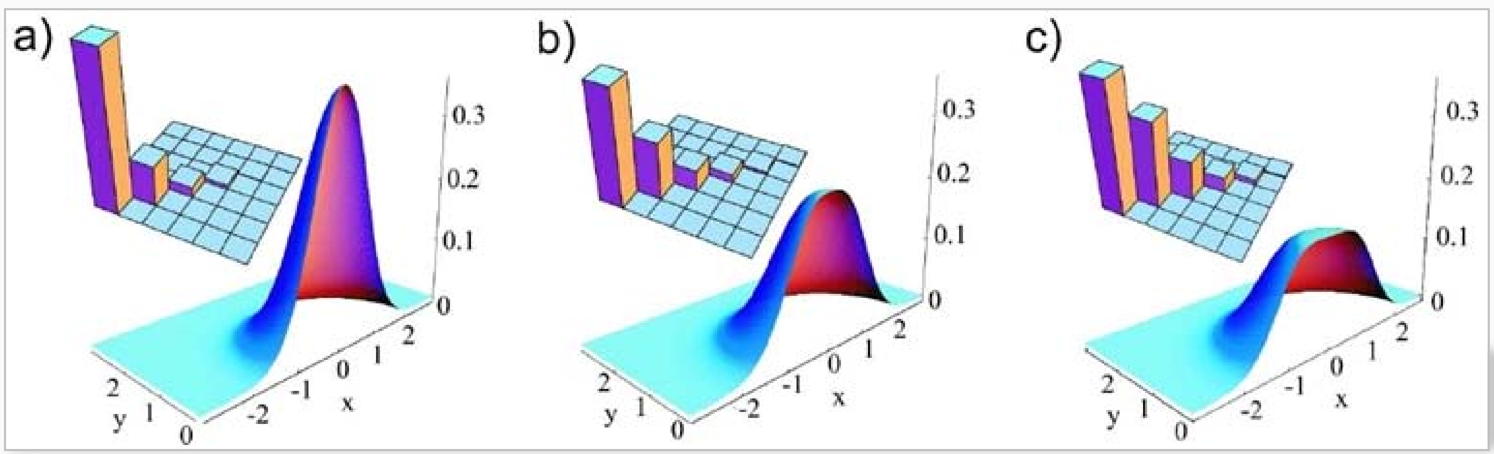
Photon subtraction



Coherent state

Photon-subtracted coherent state

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



Thermal state

Photon-subtracted thermal state

Two-photon-subtracted thermal state

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)

Testing 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)

Quantum process nonclassicality

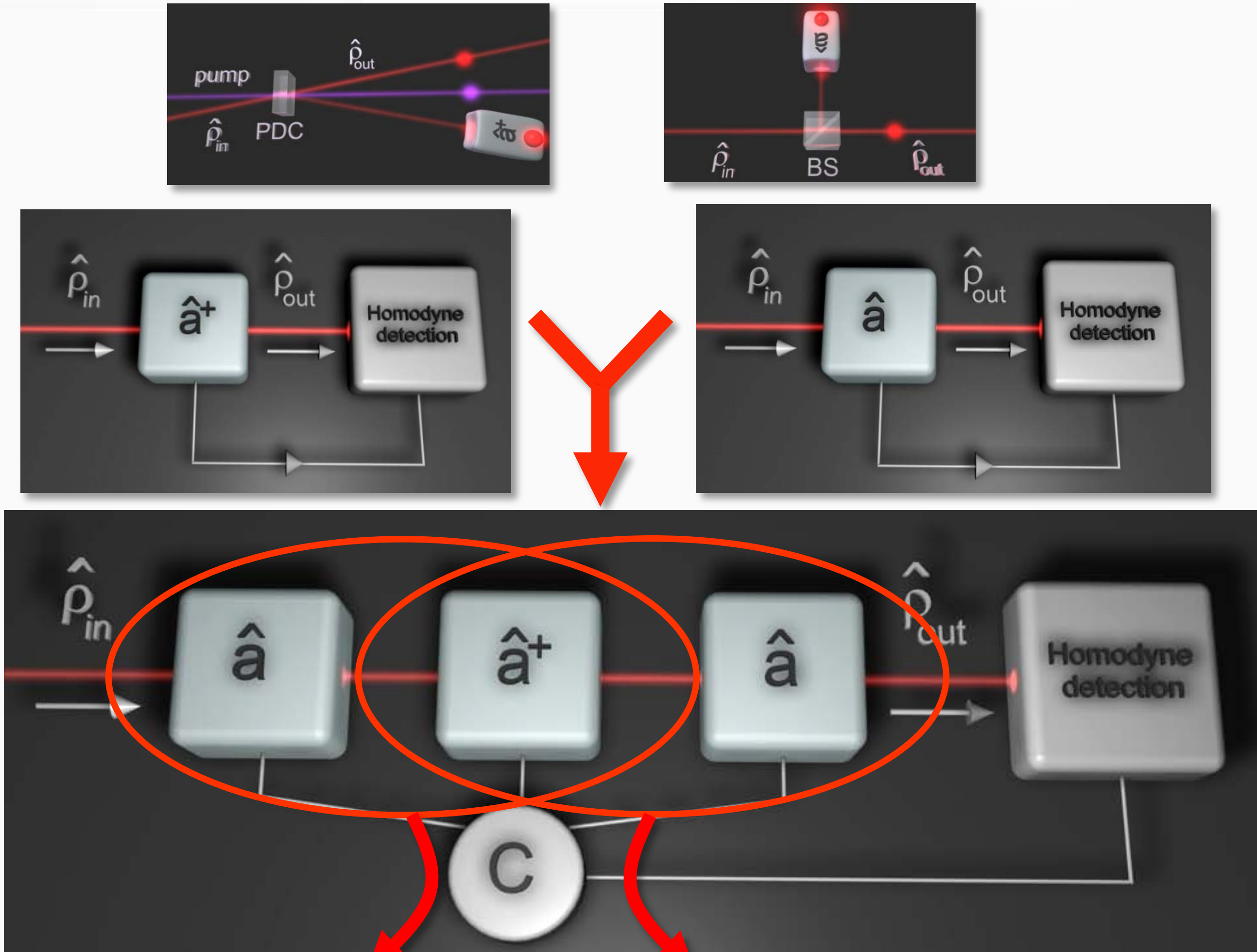
S. Rahimi-Keshari, T. Kiesel, W. Vogel, S. Grandi, A. Zavatta, MB, *PRL,* to appear (2013)

$$\hat{a}$$

State de-Gaussification
Coherent state invariance
Odd quantum maths

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

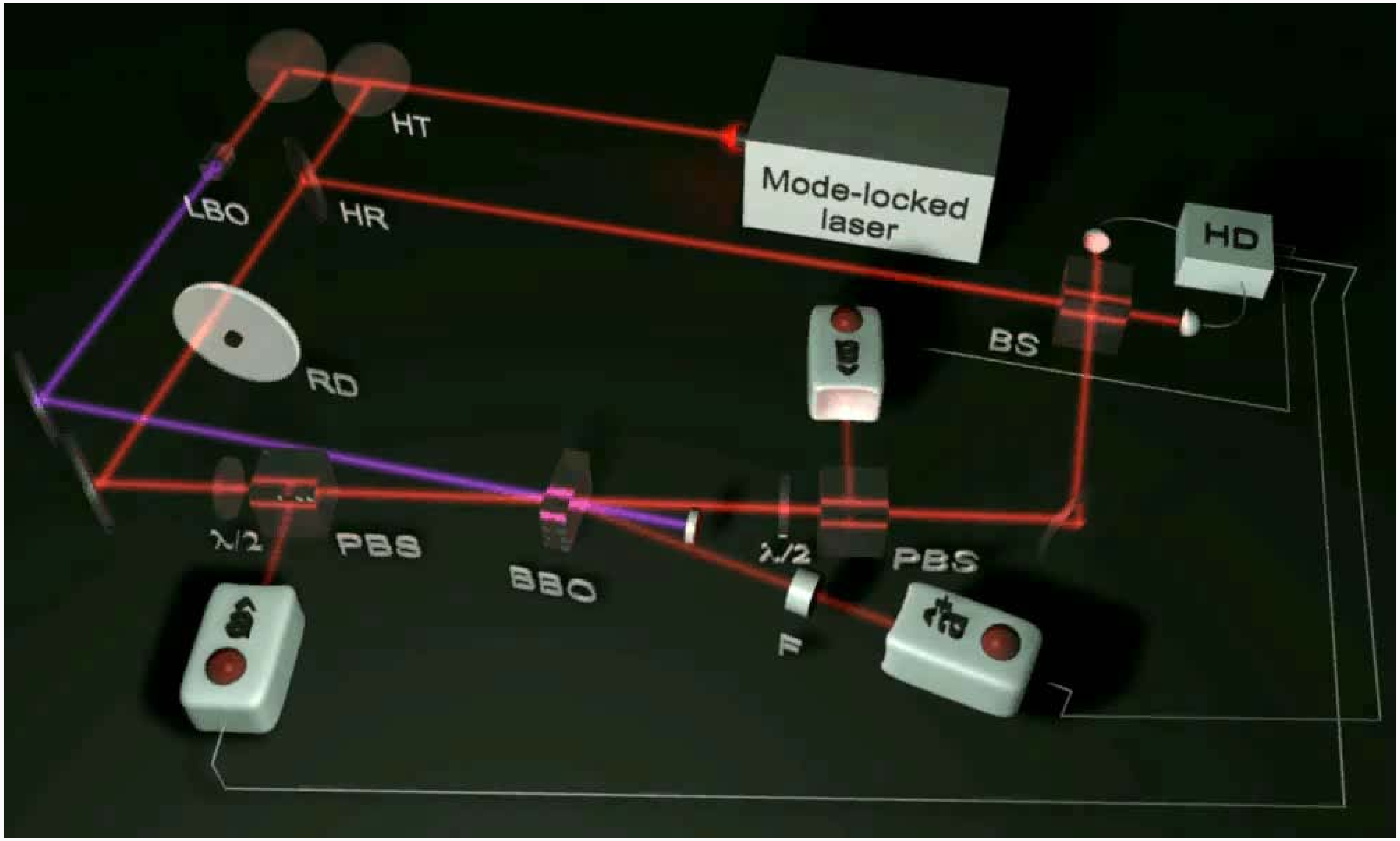
Combining quantum operators



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

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

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)

Noiseless amplification by addition & subtraction

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

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

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

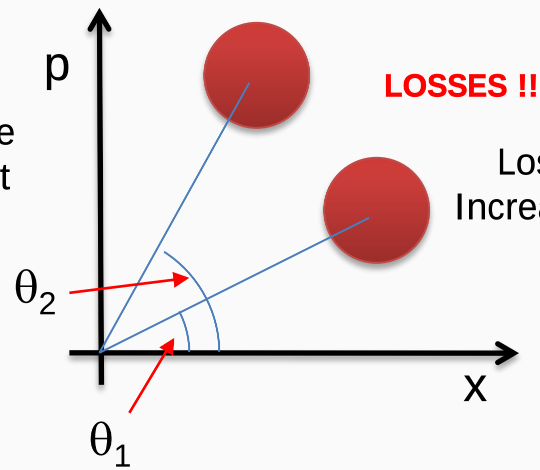
$$\hat{a}\hat{a}^\dagger\,|\alpha\rangle \approx \hat{a}\hat{a}^\dagger(|0\rangle + \alpha\,|1\rangle + \ldots) =$$
$$= \hat{a}(|1\rangle + \sqrt{2}\alpha\,|2\rangle + \ldots) =$$
$$= |0\rangle + 2\alpha\,|1\rangle + \ldots \approx |2\alpha\rangle$$

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

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

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

$$\cancel{|\alpha\rangle \to |g\alpha\rangle}$$

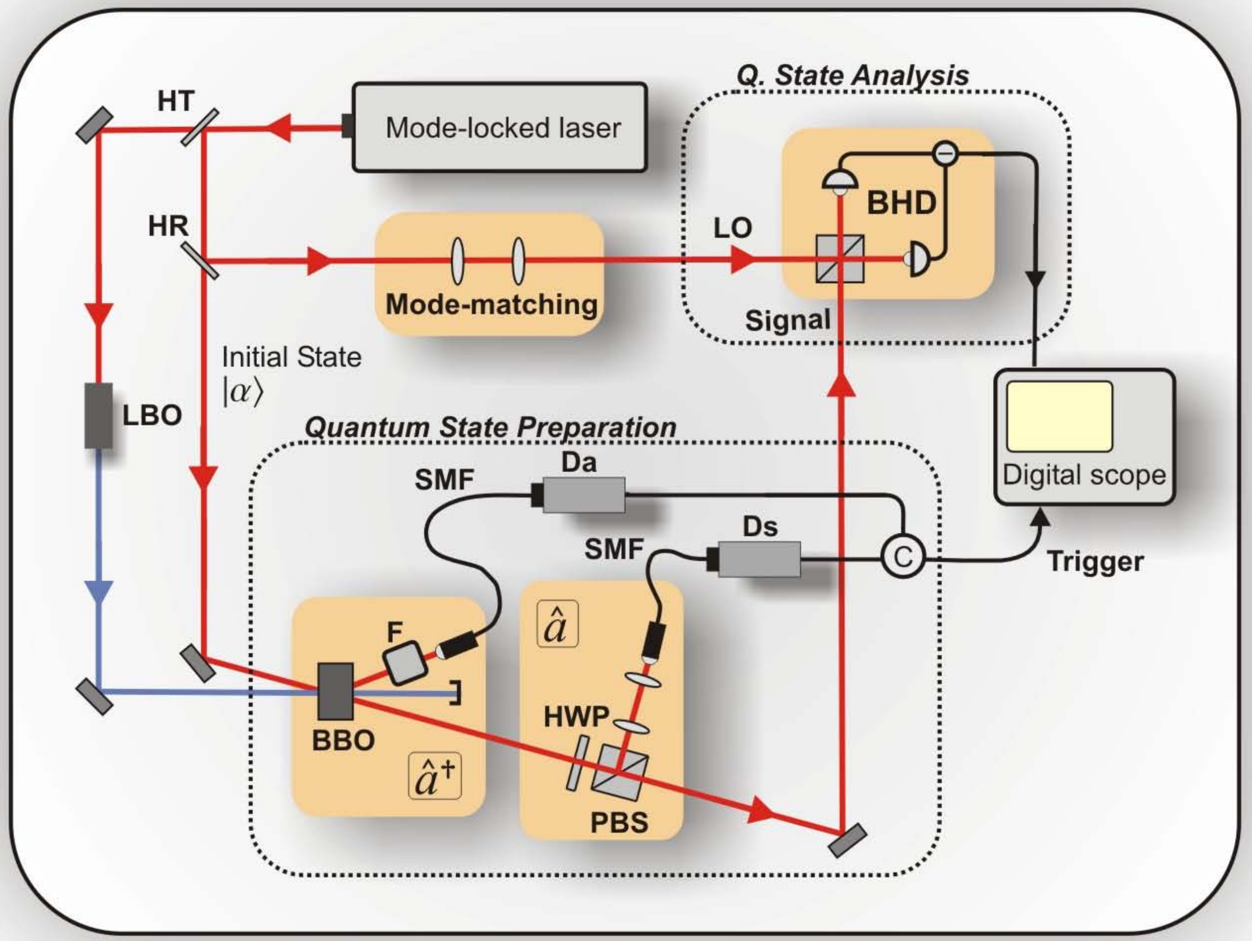
~~Clone quantum states~~
~~Beat Heisenberg uncertainty~~
~~Send superluminal information~~

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

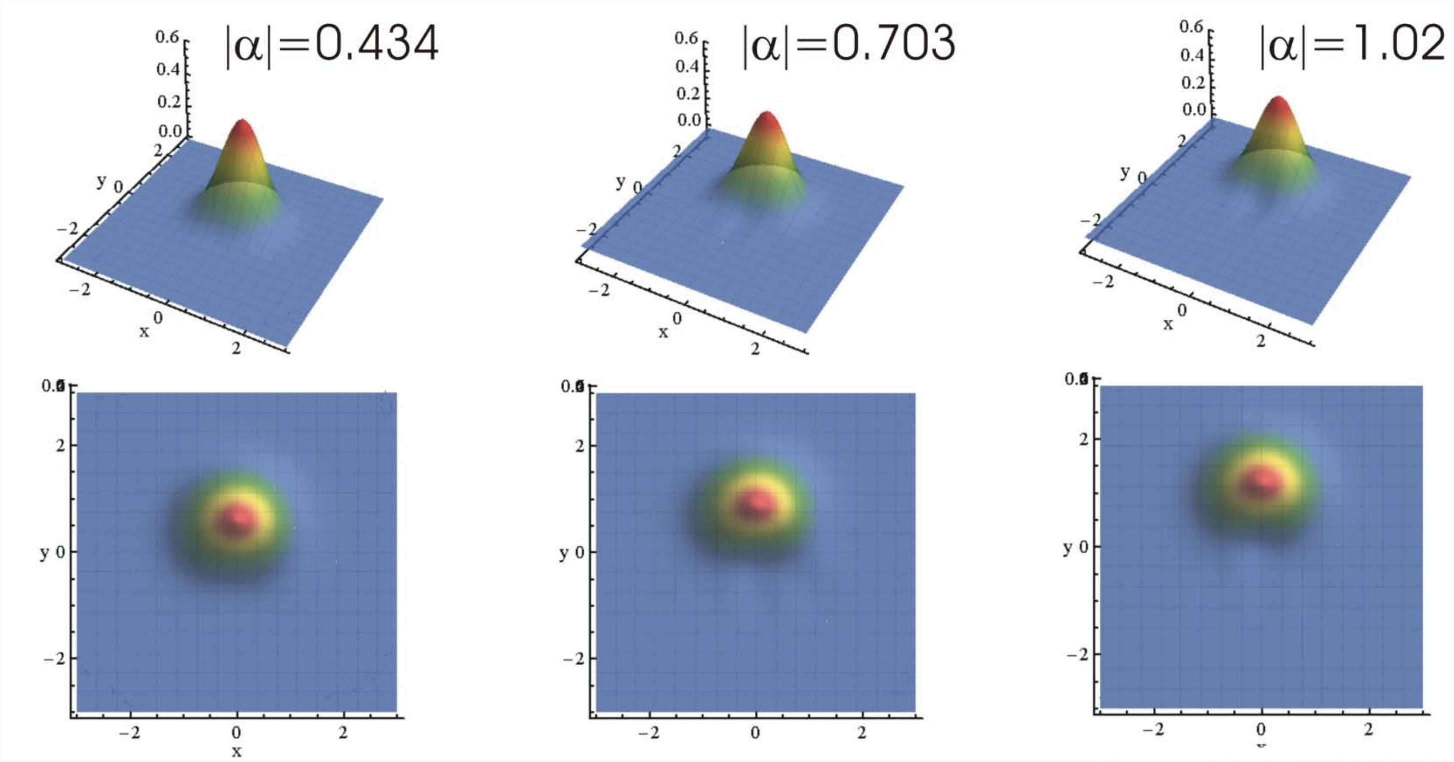
Only a non-deterministic implementation is possible

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

The hi-fi noiseless amplifier



Wigner functions



ARTICLES
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nature photonics

A high-fidelity noiseless amplifier for quantum light states

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

Variable-gain amplifier

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

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

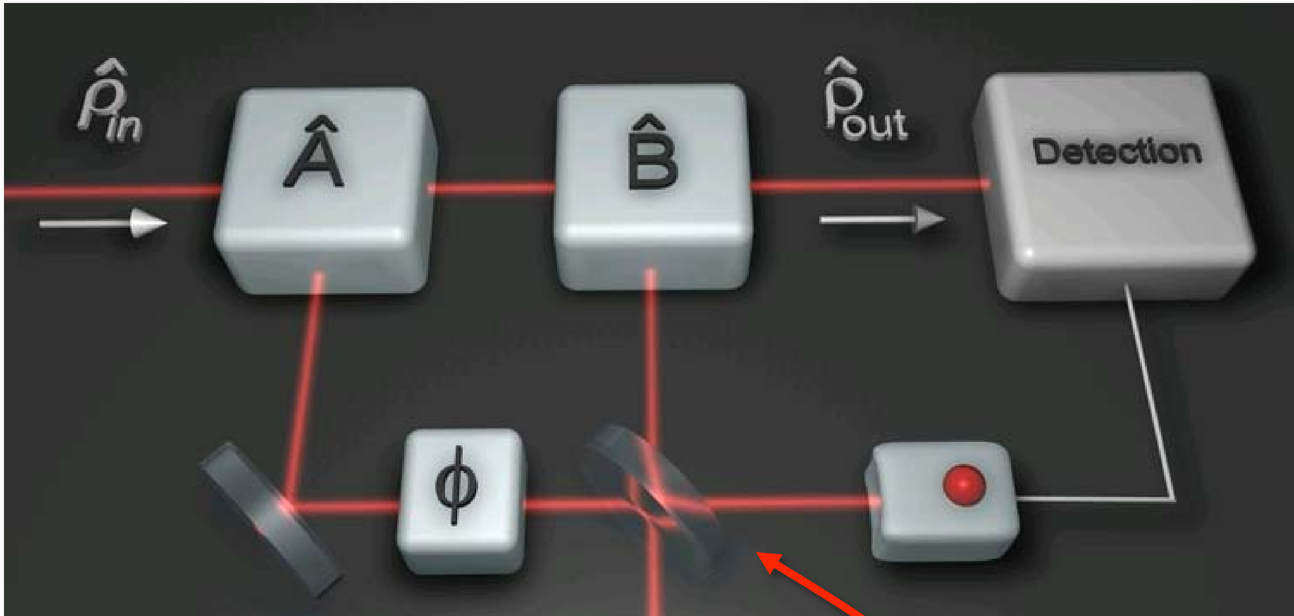
$$\hat{G} = (g-2)\hat{a}^\dagger\hat{a} + \hat{a}\hat{a}^\dagger$$

Amplitude gain

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

Need a way to produce coherent superpositions of quantum operators

Superpositions of quantum operators



Erases the information about the origin of a “click”

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

Arbitrary superpositions of operators can be implemented

Apply to any state

Arbitrary state superposition

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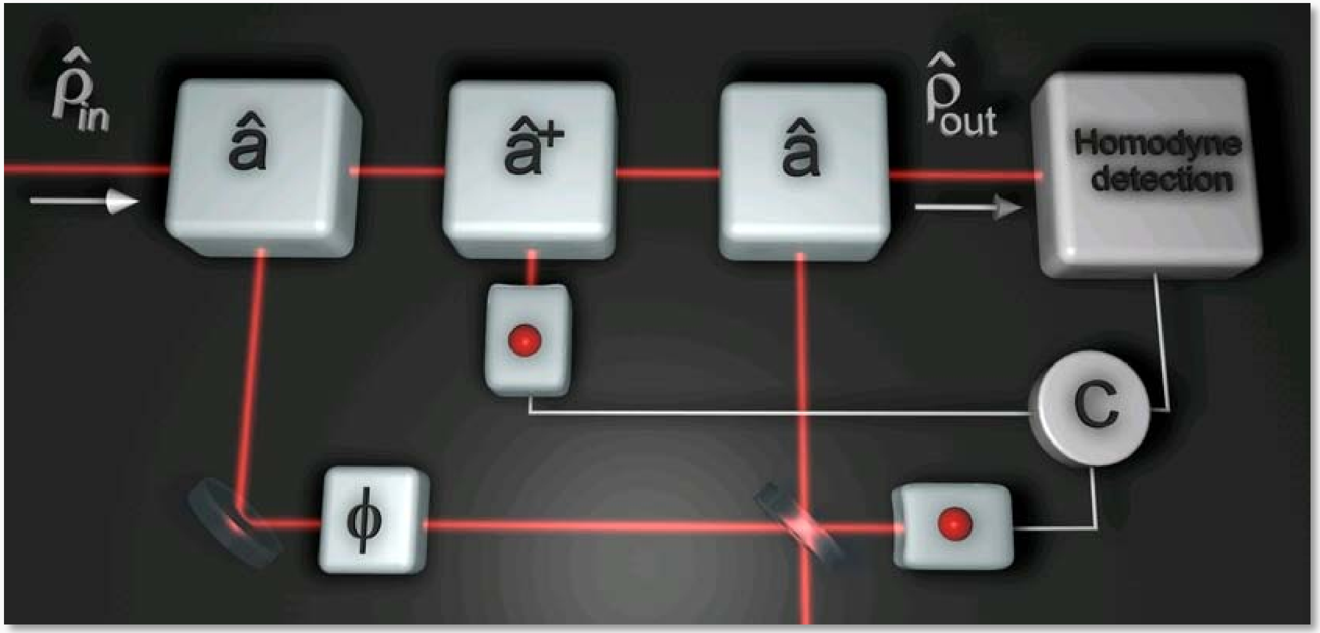
Experimental test of commutation rules



$$\hat{a}\hat{a}^\dagger - e^{i\phi}\,\hat{a}^\dagger\hat{a}$$

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

M. S. Kim, H. Jeong, A. Zavatta, V. Parigi, & MB, *PRL* **101**, 260401 (2008) **Theory**
A. Zavatta, V. Parigi, M. S. Kim, H. Jeong, & MB, *PRL* **103**, 140406 (2009) **Experiment**

Operator sequences and superpositions

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

Heralded noiseless amplifier

A. Zavatta, J. Fiurasek, & MB, *Nature Photonics*, **5**, 52 (2011)

Proof of quantum noncommutativity

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

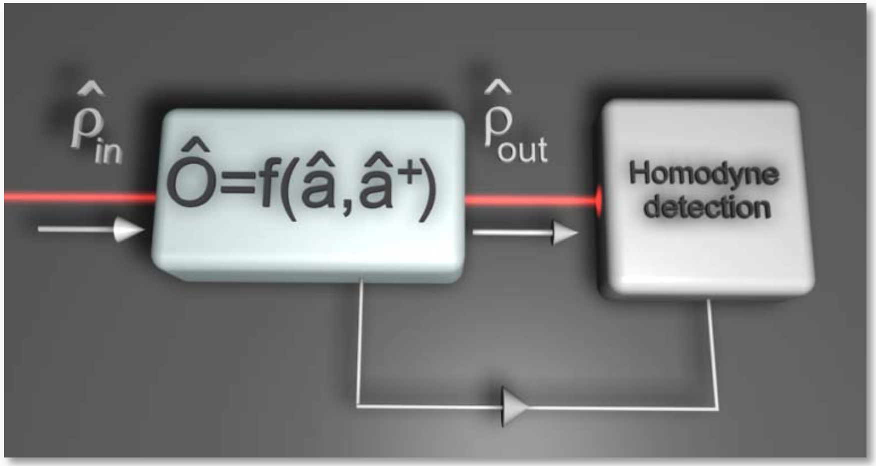
$$[\hat{a}, \hat{a}^\dagger] \neq 0$$

Test of quantum commutation rules

M. S. Kim, H. Jeong, A. Zavatta, V. Parigi, & MB, *PRL* **101**, 260401 (2008)
A. Zavatta, V. Parigi, M. S. Kim, H. Jeong, & MB, *PRL* **103**, 140406 (2009)

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

Working in the right mode

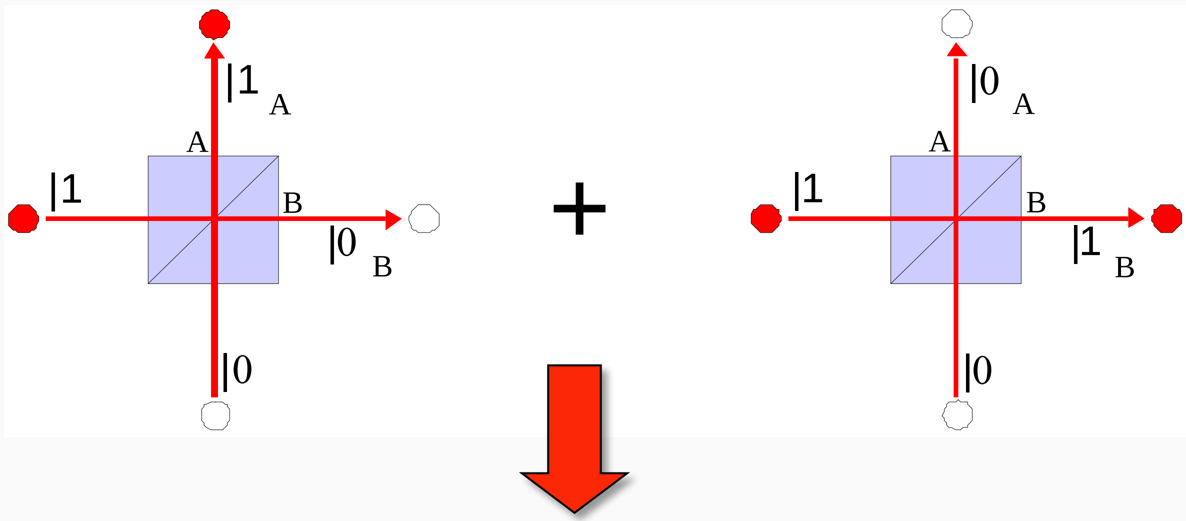


Every operation is performed in a **single, well-defined, mode**

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

A single photon in two spatial modes

Indistinguishable alternatives



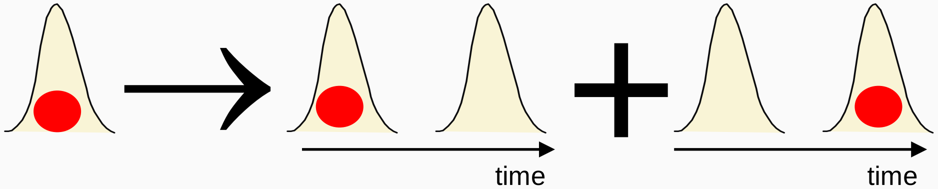
$$\frac{1}{\sqrt{2}}\left(|1\rangle_A|0\rangle_B + |0\rangle_A|1\rangle_B\right)$$

Single-photon path-entangled state

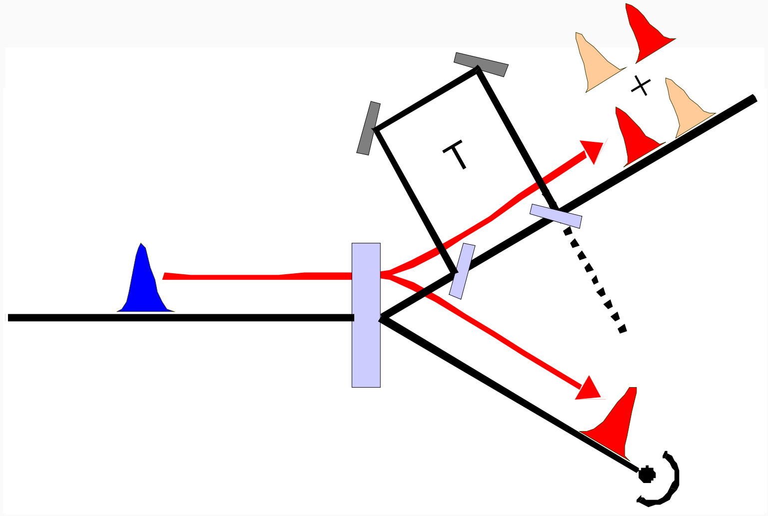
Two distinct spatial modes can get entangled by sharing a single photon

Time-delocalized single photons

Spatial modes → Temporal modes

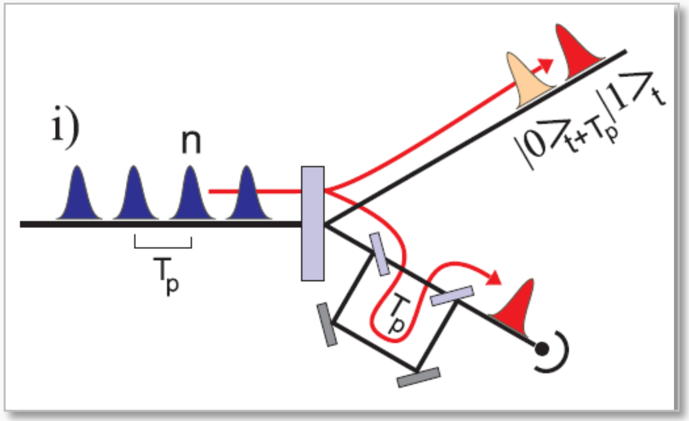


$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|1\rangle_t\,|0\rangle_{t+T} + |0\rangle_t\,|1\rangle_{t+T})$$

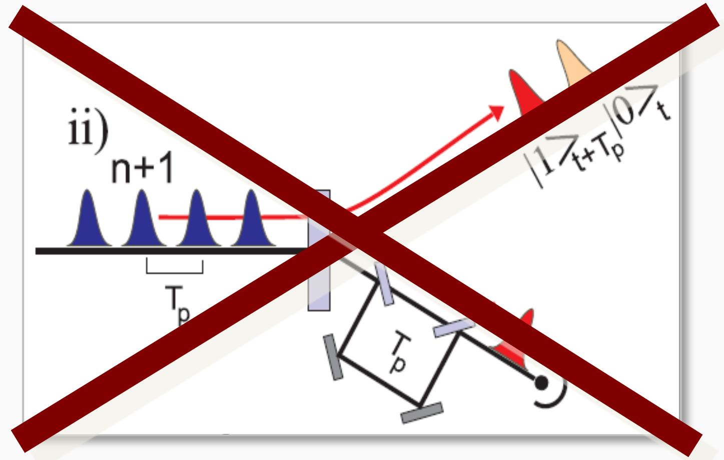


High losses ...

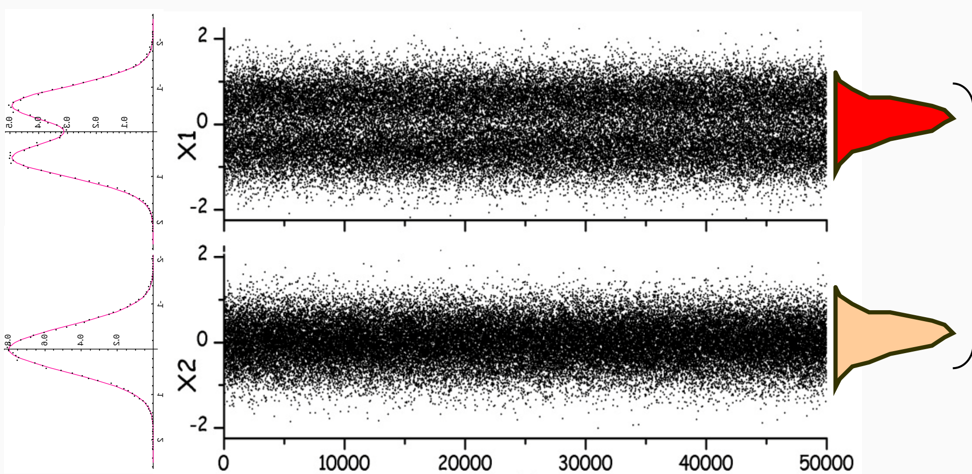
Conditional time delocalization



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



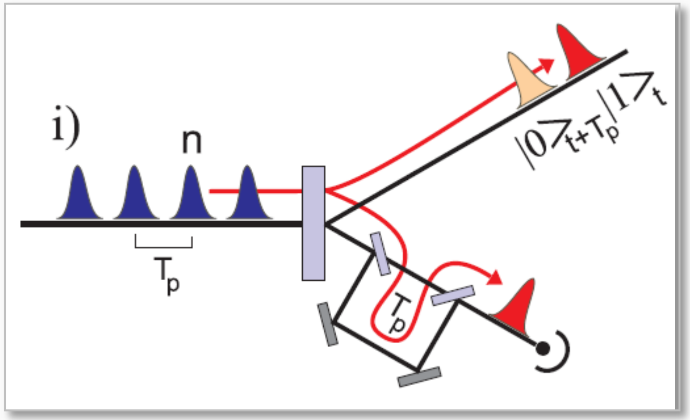
Only one possible path



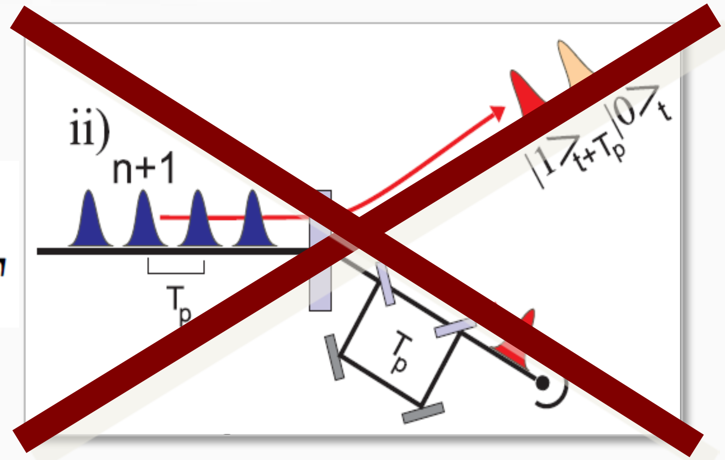
The photon is well localized in the first temporal mode

$$\hat{a}_t^\dagger \, |0\rangle_t \, |0\rangle_{t+T} = |1\rangle_t \, |0\rangle_{t+T}$$

Conditional time delocalization

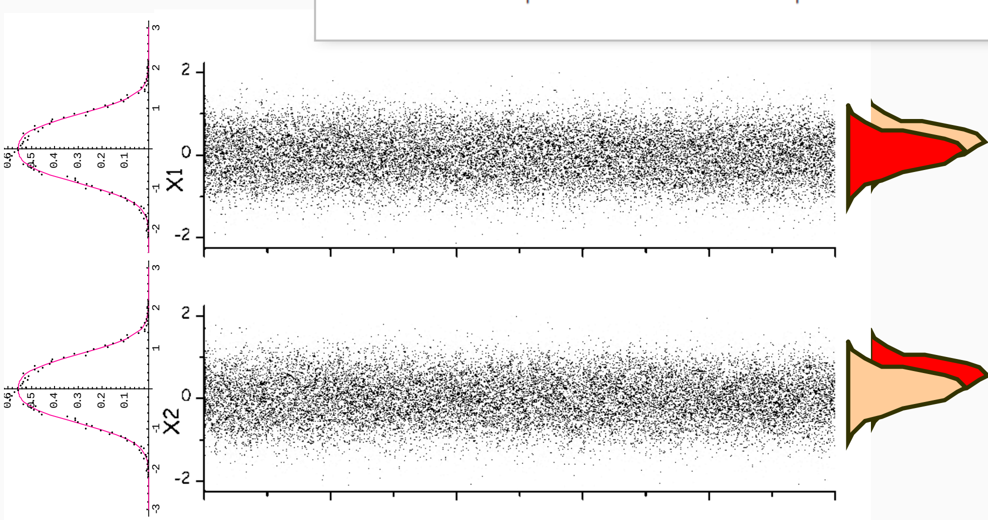


$$\hat{a}_t^\dagger + \hat{a}_{t+T}^\dagger$$



Two possible paths

$$\left(\hat{a}_t^\dagger + \hat{a}_{t+T}^\dagger\right)|0\rangle_t\,|0\rangle_{t+T} = |1\rangle_t\,|0\rangle_{t+T} + |0\rangle_t\,|1\rangle_{t+T}$$



Each temporal mode contains a statistical mixture of vacuum and single photon

Correlations between the modes

Statistical mixture of localized states

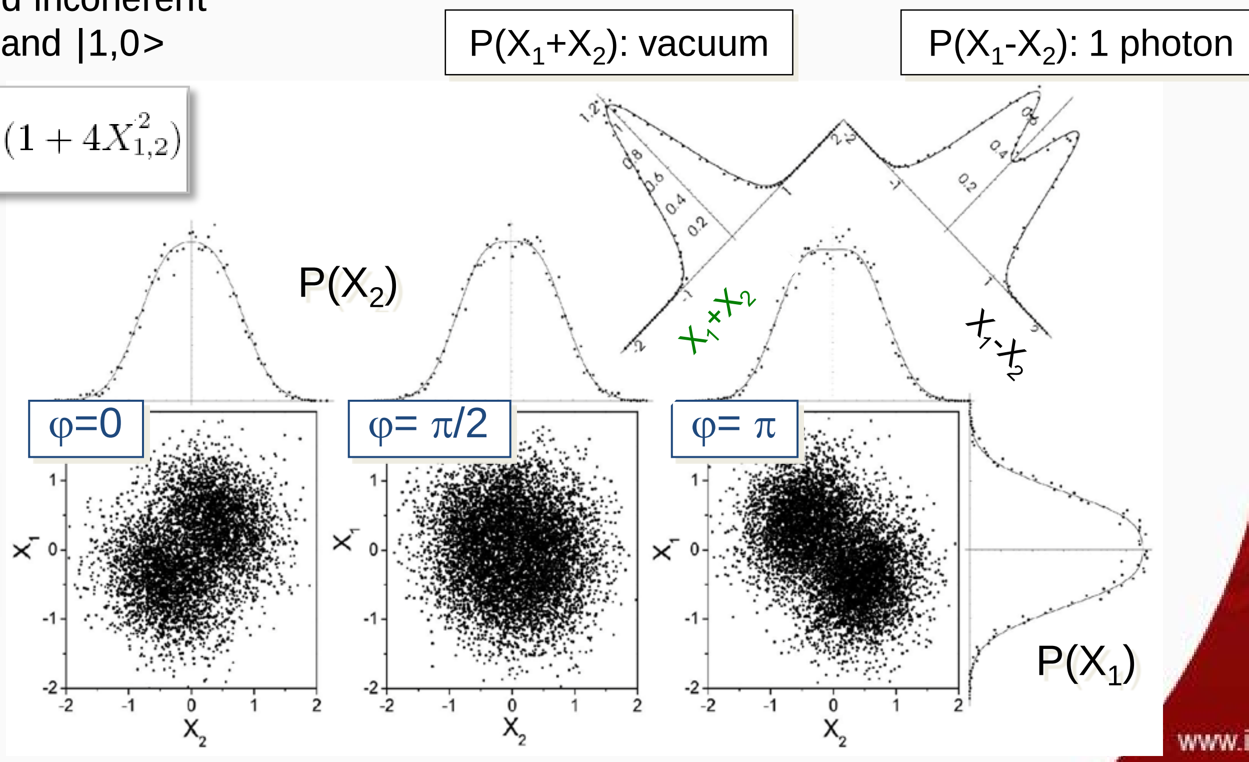
$$\hat{\rho}_{mi} = \frac{1}{2}\Big(|1,0\rangle\langle 1,0| + |0,1\rangle\langle 0,1|\Big)$$

Coherently-delocalized single photon

$$\hat{\rho}_s = \frac{1}{2}\Big(|1,0\rangle\langle 1,0| + |0,1\rangle\langle 0,1| + e^{-\imath\varphi_i}|1,0\rangle\langle 0,1| + e^{\imath\varphi_i}|0,1\rangle\langle 1,0| \Big)$$

Single-mode quadrature distributions are the same for both coherent and incoherent superpositions of |0,1> and |1,0>

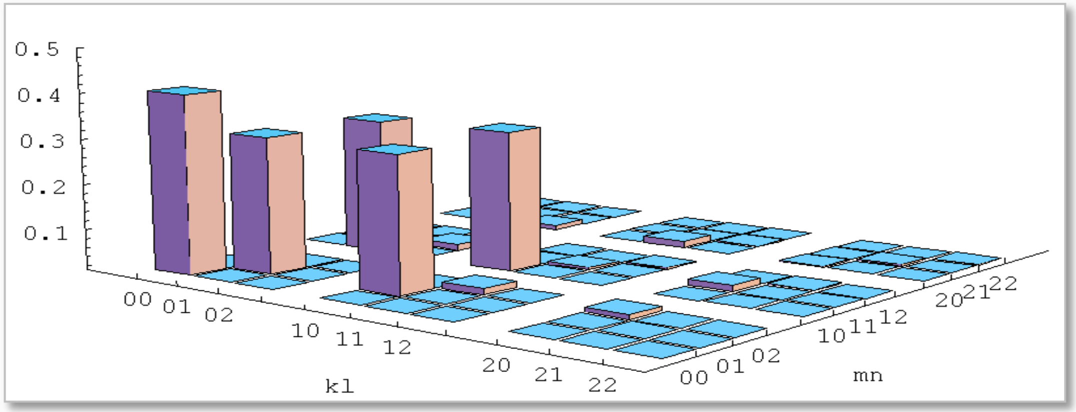
$$P(X_{1,2}) = \frac{1}{\sqrt{2\pi}}\exp[-2X_{1,2}^2](1+4X_{1,2}^2)$$



Look for correlations: phase-dependent joint quadrature distributions

Entanglement and nonlocality

Reconstructed two-mode density matrix



Entanglement verified by means of Peres’ criterion (negativity of partial transpose)

A. Peres, *Phys. Rev. Lett*. 77, 1413 (1996)
G. Vidal and R. F. Werner, *Phys. Rev. A* 65, 032314 (2002)

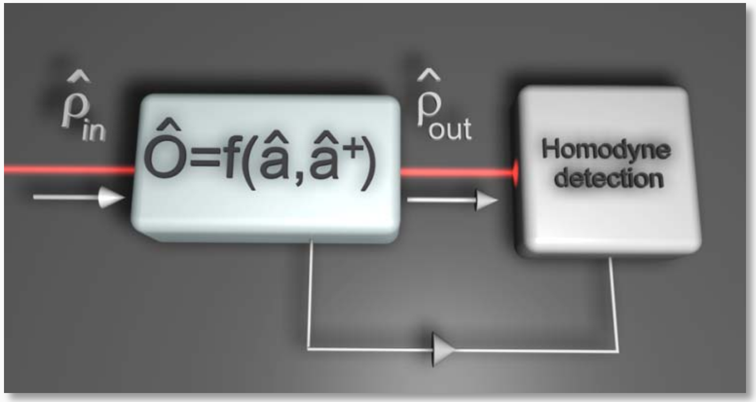
Within some assumptions, Bell’s-type inequalities are violated (use a “tomographic” approach via the Wigner function)

No dichotomization of CV

K. Banaszek and K. Wodkiewicz, *Phys. Rev. A* **58**, 4345 (1998)
K. Banaszek and K. Wodkiewicz, *Phys. Rev. Lett.* **82**, 2009 (1999)

A. Zavatta, M. D'Angelo, V. Parigi and MB, *Phys. Rev. Lett.*, **96**, 020502 (2006)
M. D’Angelo, A. Zavatta, V. Parigi and MB, *Phys. Rev. A*, **74**, 052114 (2006)

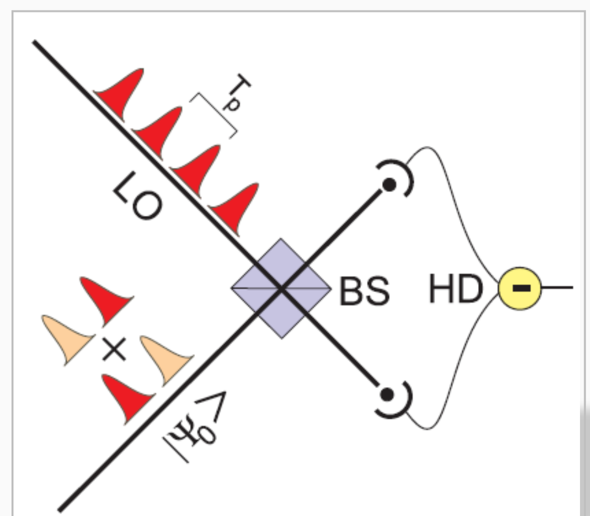
Working in the right mode



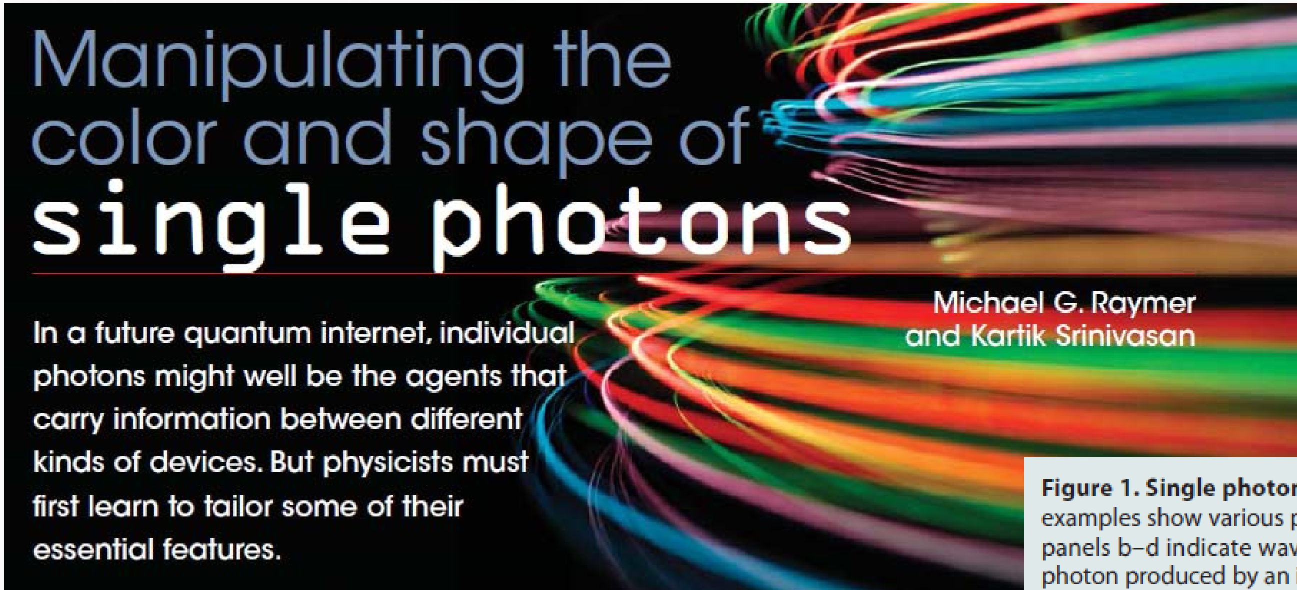
Every operation is performed in a **~~single~~, well-defined, mode**

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

A shaped LO mode allows mode-selective homodyne detection



The shape of a single photon


Manipulating the color and shape of single photons

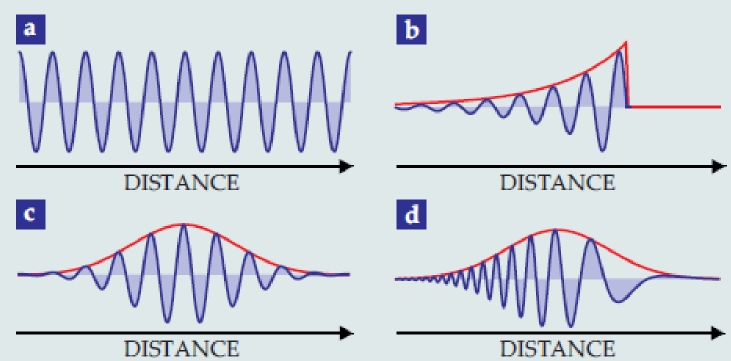
Michael G. Raymer and Kartik Srinivasan

In a future quantum internet, individual photons might well be the agents that carry information between different kinds of devices. But physicists must first learn to tailor some of their essential features.

physics today

November 2012

Figure 1. Single photons exist in a variety of shapes. These four examples show various photons at an instant in time; the red lines in panels b–d indicate wavepacket envelopes. (**a**) A monochromatic photon produced by an ideal laser. (**b**) A decaying exponential packet spontaneously emitted from an excited atom. (**c**) A Gaussian packet created by nonlinear optical processes. (**d**) A so-called chirped-frequency packet resulting from dispersive propagation in optical fiber.

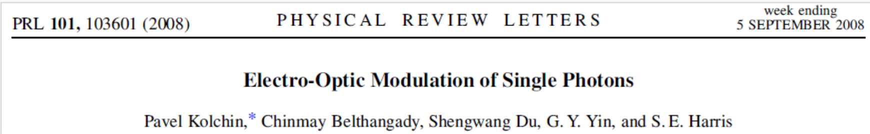


Optimized detection

Efficient coupling to atomic quantum memories

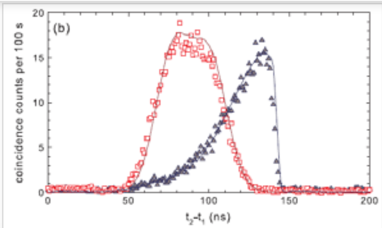
Multimode encoding and detection in higher-dimensional Hilbert spaces

The shape of “long” photons


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

Electro-Optic Modulation of Single Photons

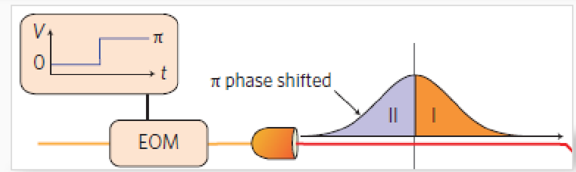
Pavel Kolchin,* Chinmay Belthangady, Shengwang Du, G. Y. Yin, and S. E. Harris




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



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

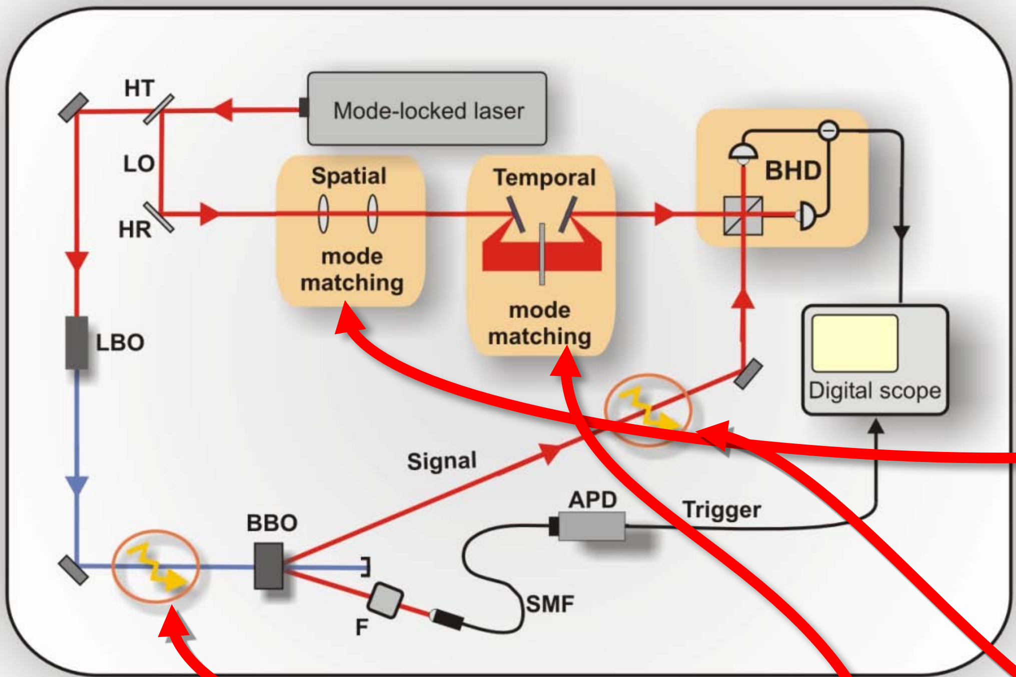
Both modulation and detection can be performed with standard electronics

In our case:

Manipulate and characterize the spectrotemporal mode of ultrashort (<100 fs) quantum states

Ultrafast + Quantum Optics

Measuring the photon wavepacket



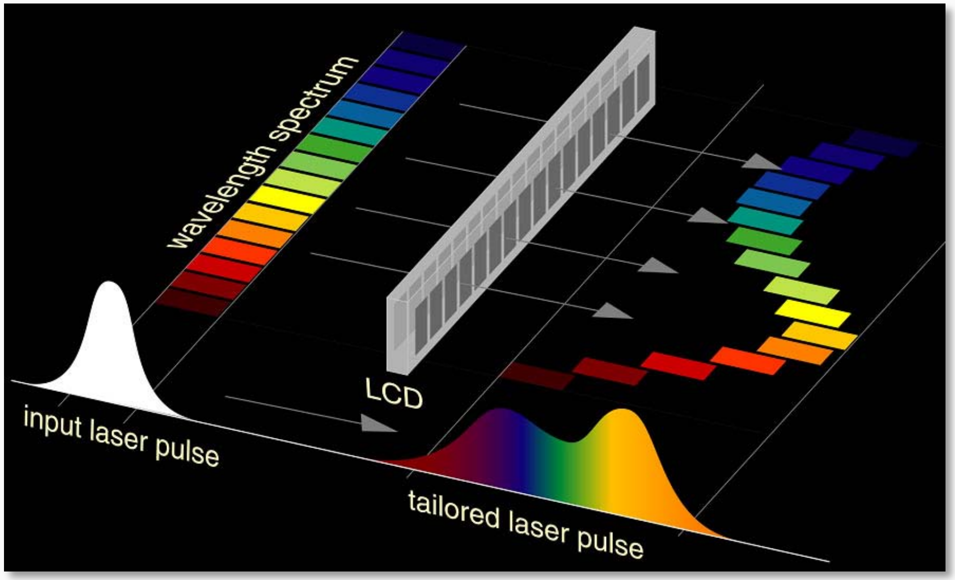
A quantum state can only be efficiently observed by BHD if the LO is properly matched in polarization, space, time, spectrum,...

We usually match the LO to the photon <u>spatial</u> mode but assume a Gaussian transform-limited <u>spectrotemporal profile</u>

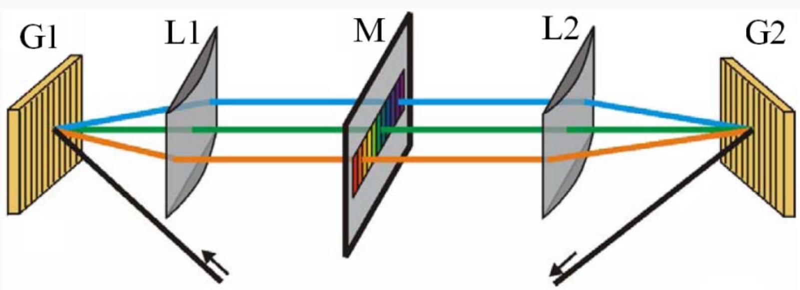
What if also the spectrotemporal mode is changed in the propagation or because of pump modulations??
(especially for fs-range wavepacket duration)

Need a spectrotemporal 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

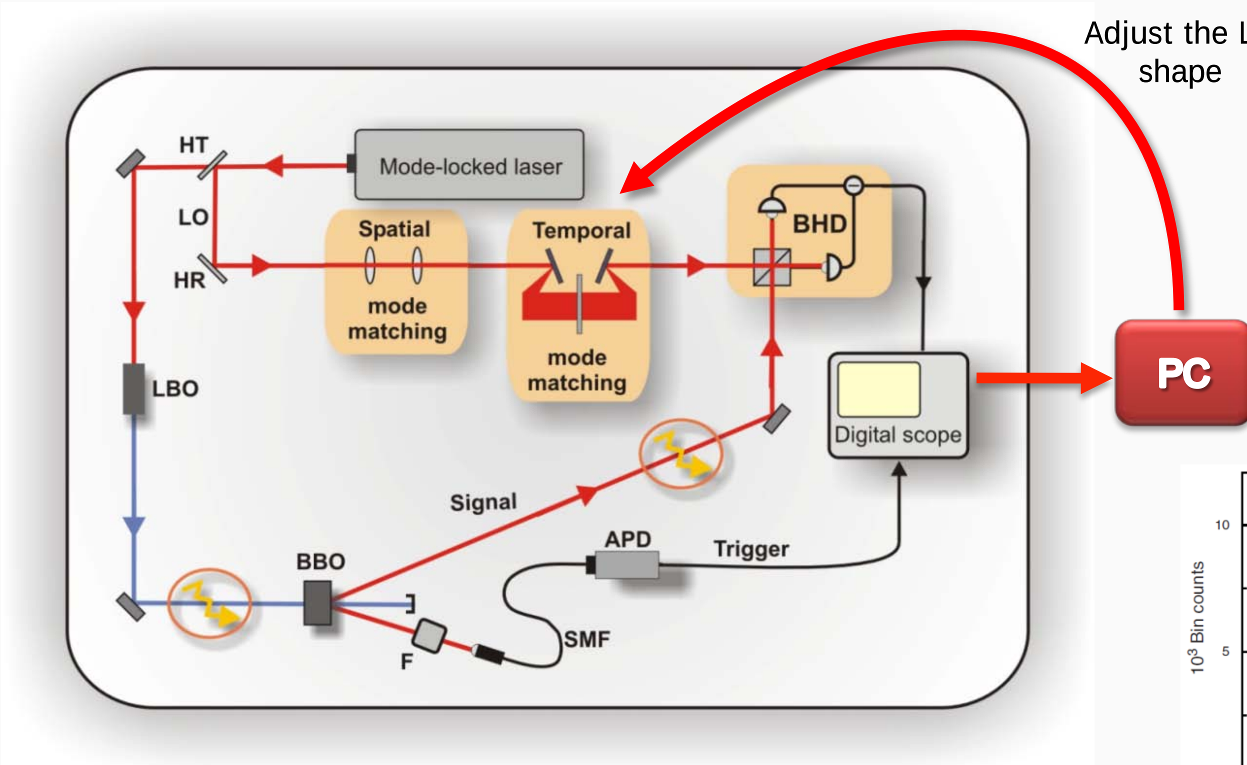


SLM: 2x128 pixels
(pixel width: 97 μm, pixel gap 3 μm)

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

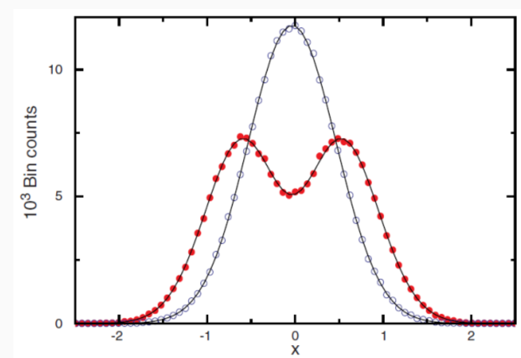
A.M. Weiner, *Rev. Sci. Instrum.* **71**, 1929 (2000)

Searching for the photon shape



Adjust the LO shape

Calculate the efficiency η



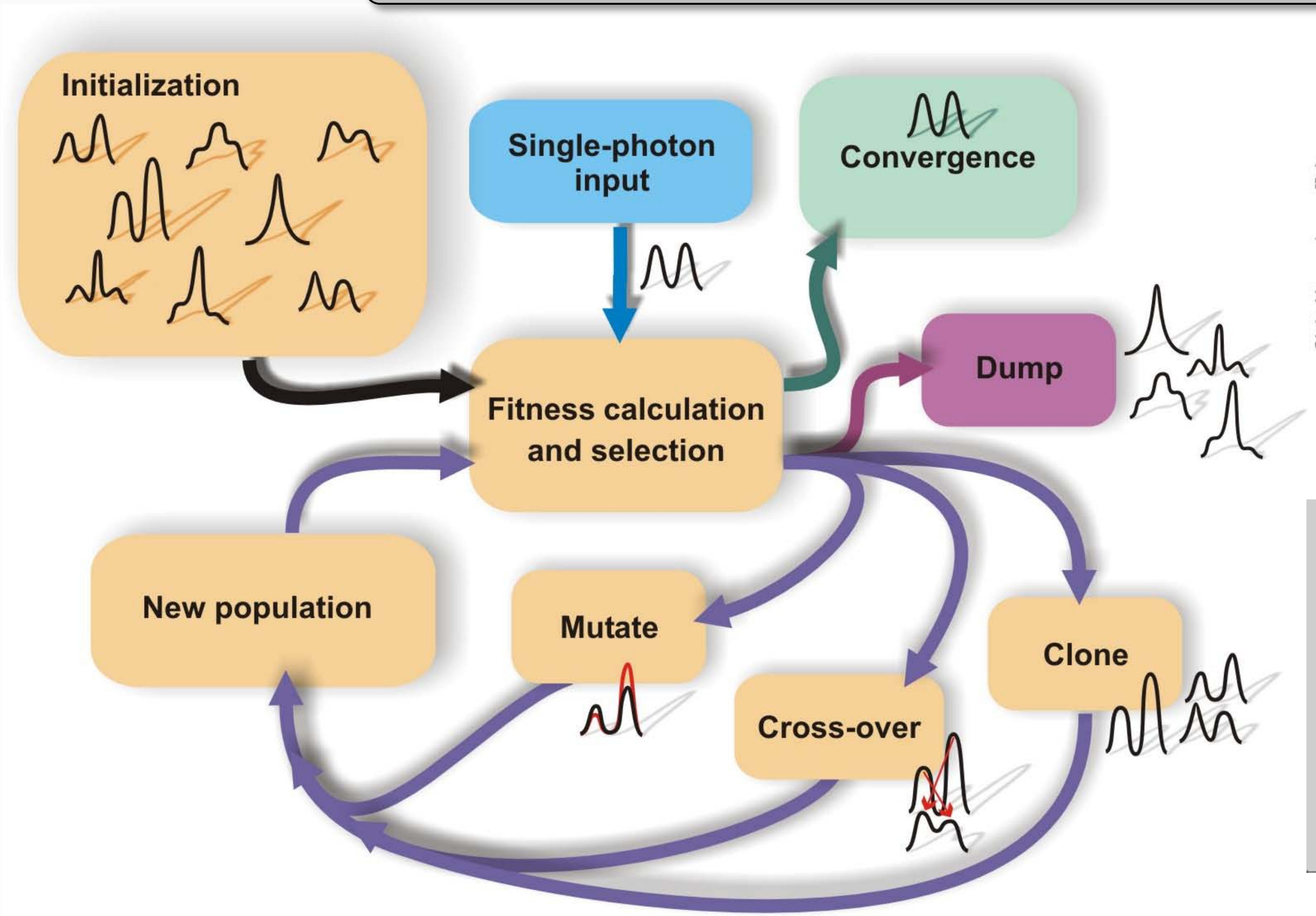
Single-photon quadrature distribution

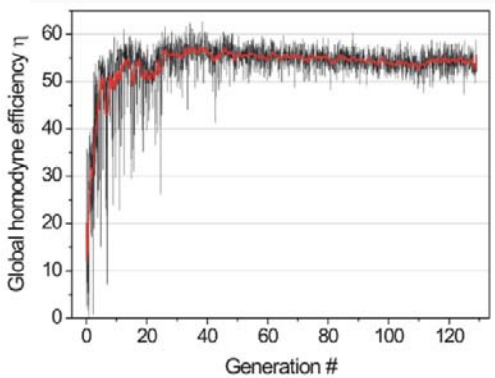
$$\eta \left|1\right\rangle \left\langle 1\right| + (1-\eta) \left|0\right\rangle \left\langle 0\right|$$

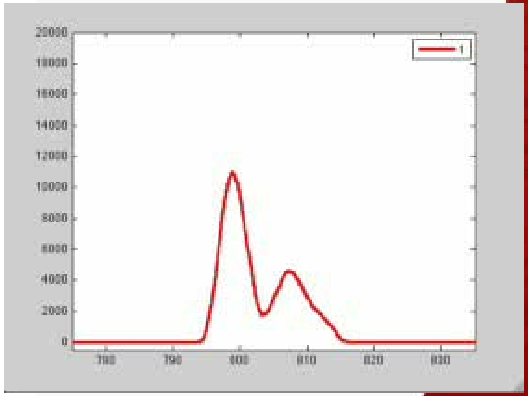
η quantifies the amount of pure single photon in the detected mixed state

Genetic search of the photon shape

Using an evolutionary algorithm to find the best LO pulse shape

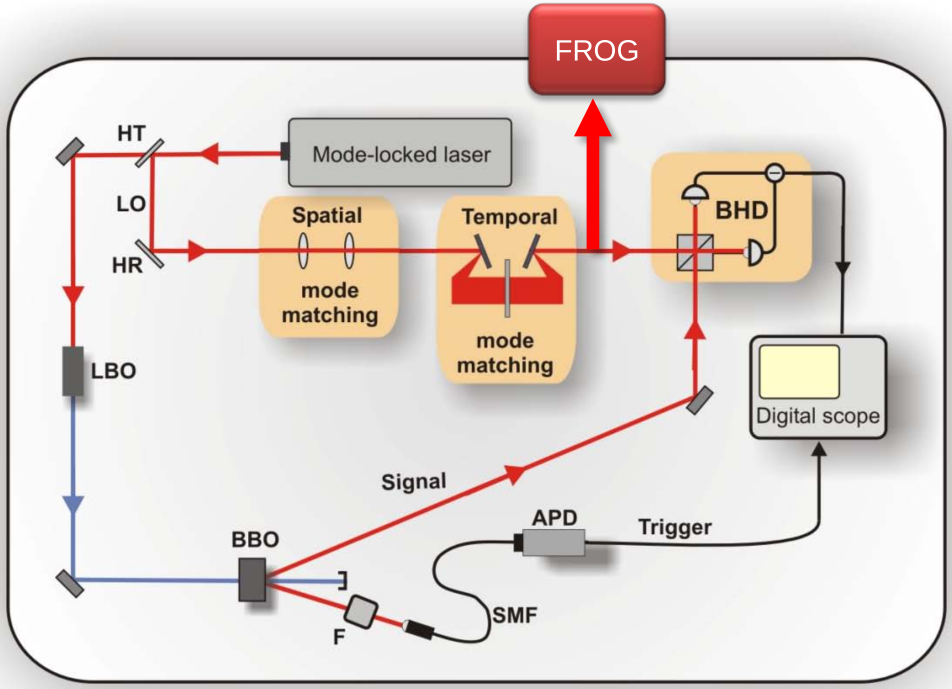




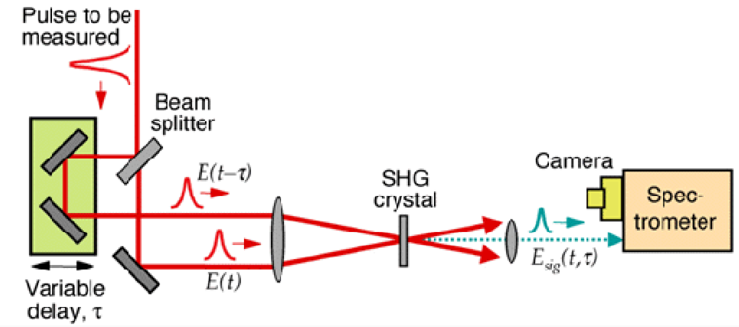


No preliminary information required!

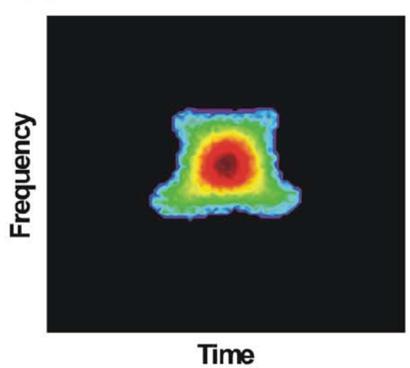
Mapping the shape of a single photon onto the LO pulse

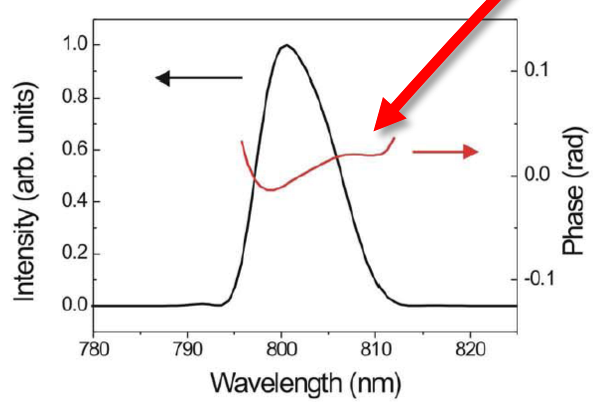


FROG (Frequency-Resolved Optical Gating)
can fully characterize the LO pulse



Un-modulated
single photon

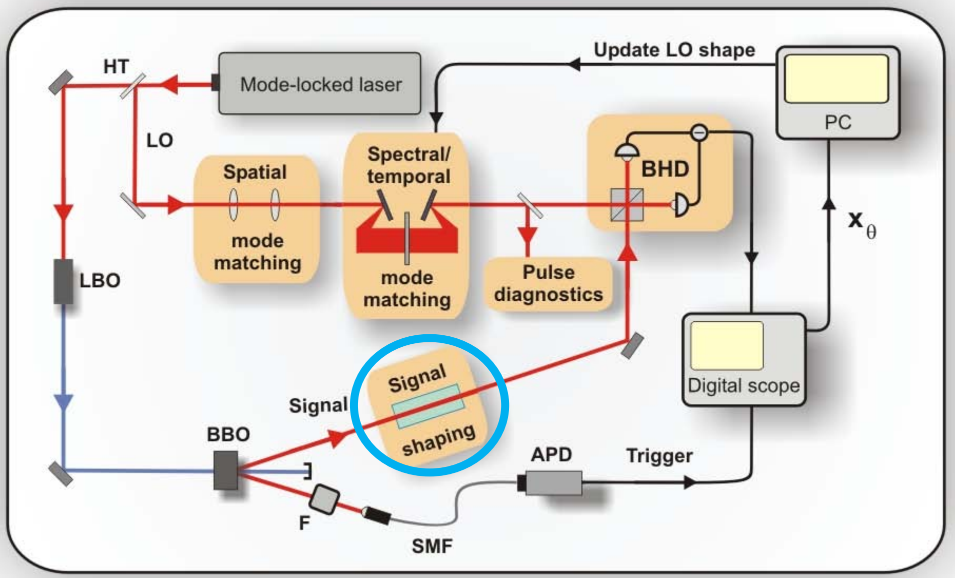




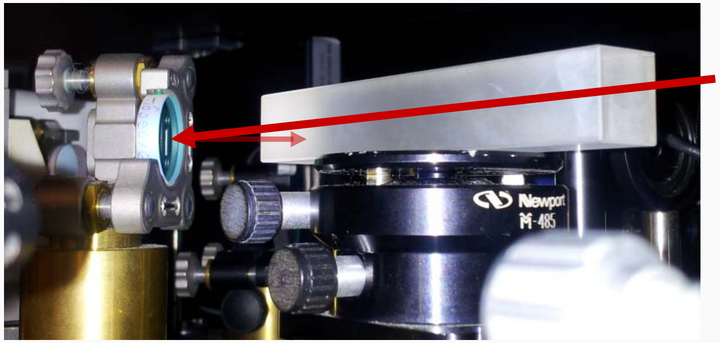
Flat spectral phase
(Fourier-transform-limited
single-photon pulse)

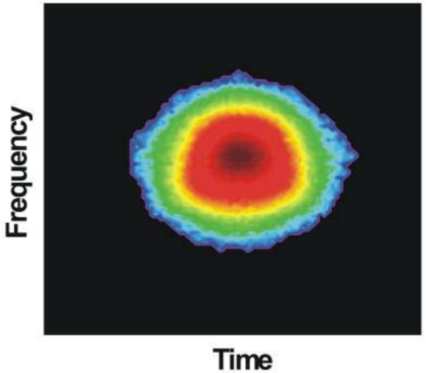
$\Delta\lambda_{FWHM}$~ 9.5 nm
$\Delta\tau_{FWHM}$~100 fs

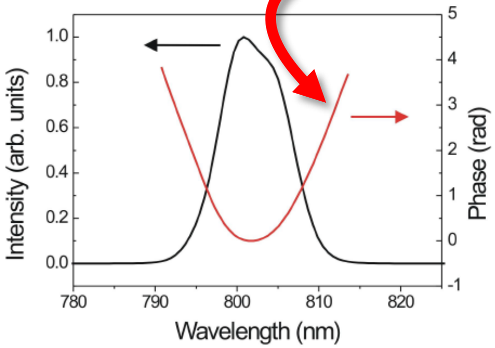
Shaping the photon



Linear dispersion by propagation through a 10-cm-long block of BK7 glass

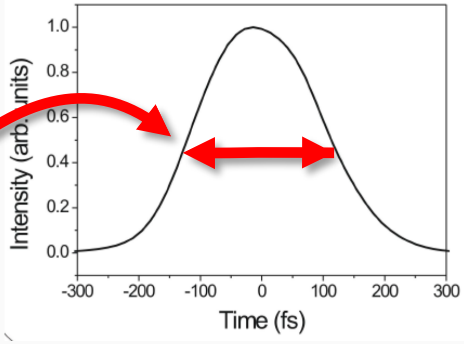






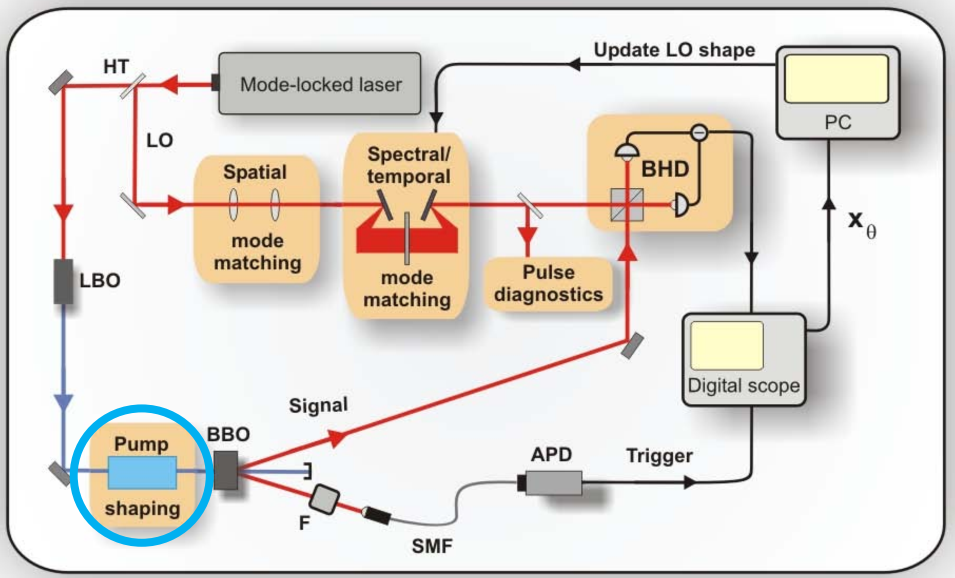
Quadratic spectral phase (positively chirped single-photon pulse)

$\Delta\lambda_{FWHM} \sim 9.5$ nm
$\Delta\tau_{FWHM} > 200$ fs



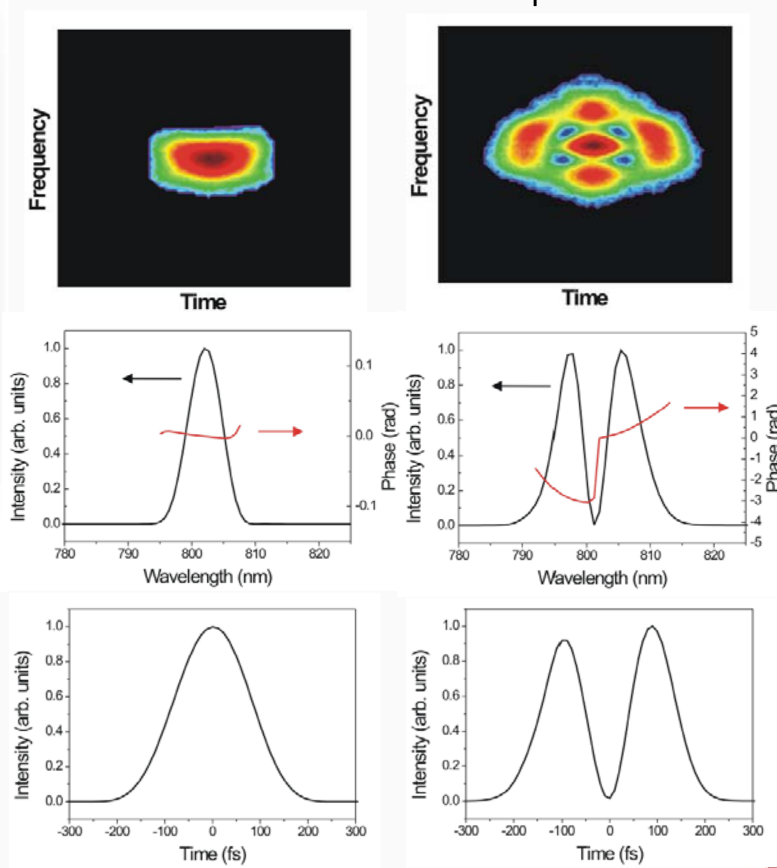
Detection efficiency would drop from ~60% to ~40% without shaping the LO!

More shaping by pump modulation

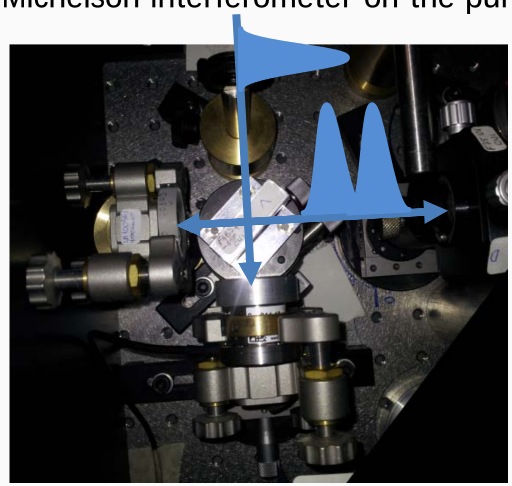


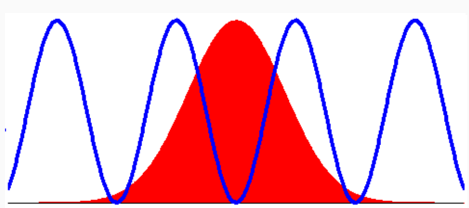
Spectral narrowing

Double spectrotemporal peaks



Michelson interferometer on the pump





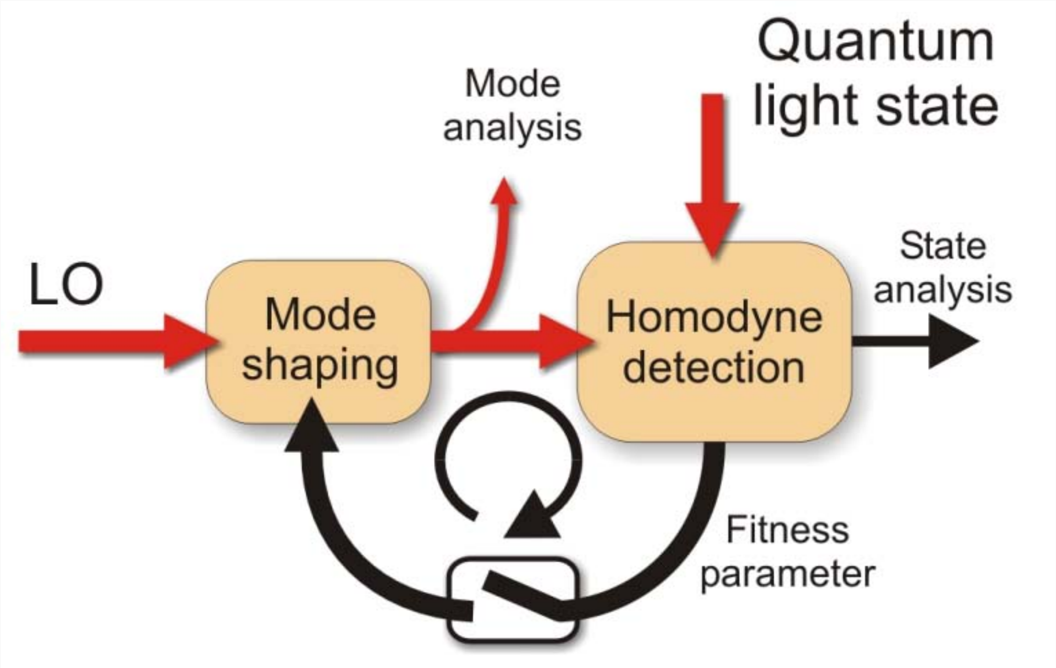
frequency

Sinusoidal modulation
of the pump spectrum

$\Delta\lambda_{FWHM}$~ 6 nm
$\Delta\tau_{FWHM}$~180 fs

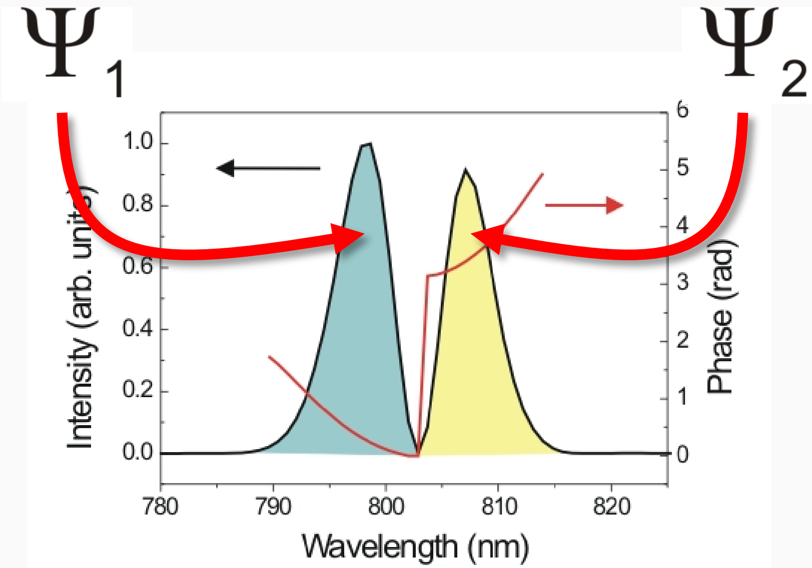
Exploiting the modal selectivity

From the measurement of the mode
to mode-selective analysis of quantum states



Instead of measuring the unknown mode, we can
use a shaped LO to analyze the state in given modes

A single-photon spectral qubit

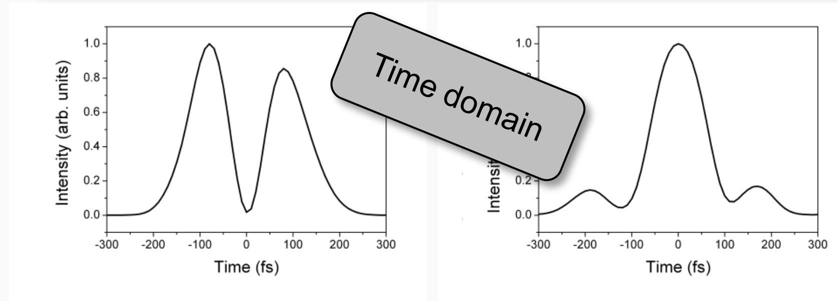


The single photon can be thought of as in a coherent superposition of two distinct spectral modes

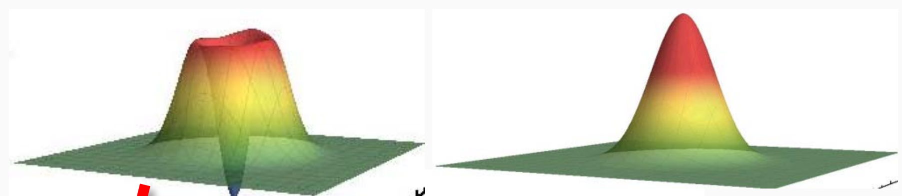
$$\frac{\left(|1\rangle_{\Psi_1}|0\rangle_{\Psi_2} + |0\rangle_{\Psi_1}|1\rangle_{\Psi_2}\right)}{\sqrt{2}}$$

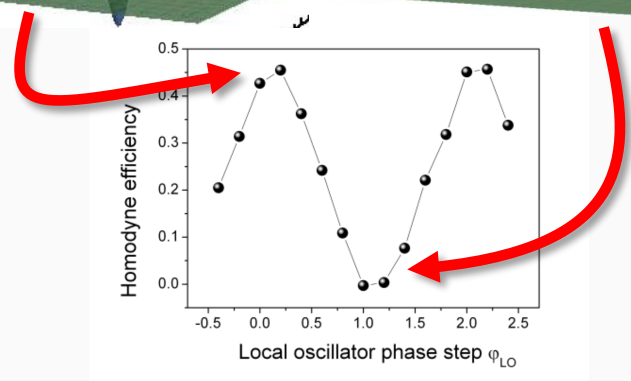
C. Polycarpou, K. Cassemiro, G. Venturi, A. Zavatta, & MB, *Phys. Rev. Lett.* **109**, 053602 (2012)

Probing coherence by HD with shaped LO modes



$$\frac{\left(|1\rangle_{\Psi_1}|0\rangle_{\Psi_2} + |0\rangle_{\Psi_1}|1\rangle_{\Psi_2}\right)}{\sqrt{2}} \qquad \frac{\left(|1\rangle_{\Psi_1}|0\rangle_{\Psi_2} - |0\rangle_{\Psi_1}|1\rangle_{\Psi_2}\right)}{\sqrt{2}}$$





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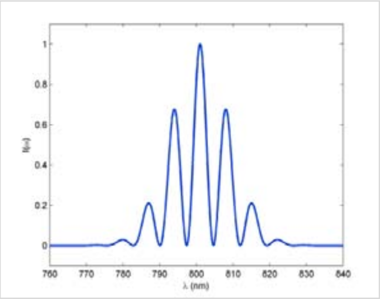
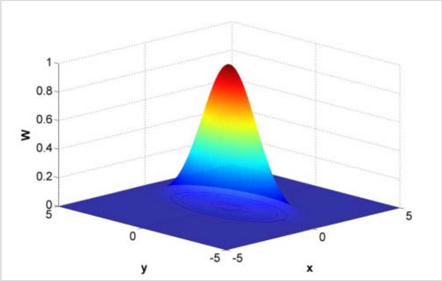
Perspectives

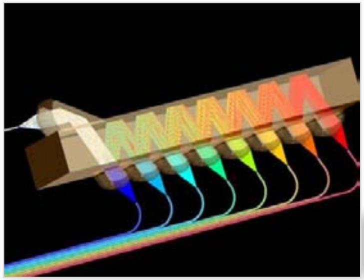
A single-photon spectral qubit

C. Polycarpou, K. Cassemiro, G. Venturi, A. Zavatta, & MB, *Phys. Rev. Lett.* **109**, 053602 (2012)

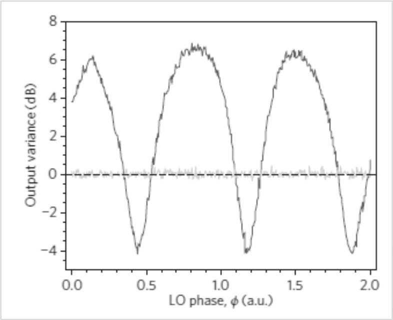


Use multiple “spectral bins” to enlarge the Hilbert space for encoding information on a single photon
(spectral qudits - quantum WDM)





Full spatiotemporal mode analysis by also shaping the LO wavefront



Arbitrary quantum states can be analyzed by choosing the right fitness parameter for the optimization
(squeezing, Schmidt mode content, etc.)

Conclusions

Accurate quantum state engineering

Advanced techniques of analysis

Powerful tools for studying the foundations of physics and for quantum information processing, communication, and metrology

Credits

Alessandro Zavatta
Giovanni Venturi
Constantina Polycarpou

Main collaborations:

Werner Vogel, Rostok, D
Katiuscia Cassemiro, Recife, BR
Myungshik Kim, London, UK
Jaromir Fiurasek, Olomouc, CZ

Thank you!

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