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European Laboratory for
Non-Linear Spectroscopy

Università di Firenze
Dipartimento di Fisica

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Continuous Variable Quantum Information Processing 2012 (CVQIP'12) - Copenhagen
27 April 2012

Manipulation of quantum light at the single-photon level and by ultrafast pulse-shaping techniques

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DI FIRENZE

Outline

Part 1	Manipulating CV quantum states at the single-photon level and quantum homodyne tomography characterization

- Single-photon addition and subtraction
- Sequences and superpositions of quantum operators
- Direct probing of fundamental quantum rules
- Noiseless amplification

Part 2	Investigating the mode structure of ultrashort pulsed quantum light states

- Adaptive homodyne detection
- Spectral-temporal shaping of quantum states

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Photon creation and annihilation operators

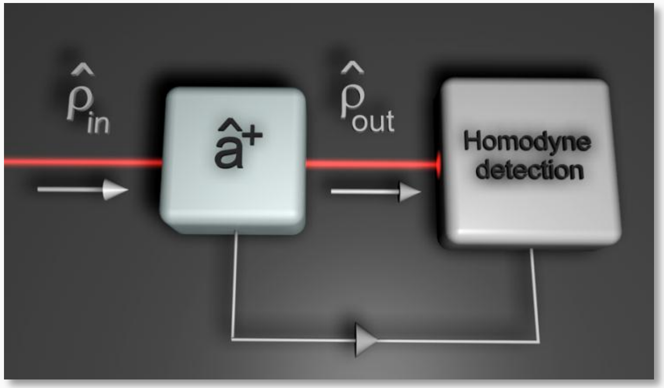
Creation and annihilation operators:

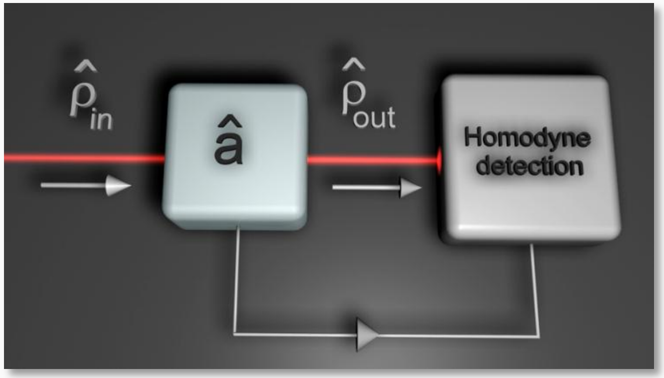
$$\hat{a}^\dagger |n\rangle = \sqrt{n+1}\,|n+1\rangle$$

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

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

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





Conditional generation schemes

Adding a single photon to a state of light

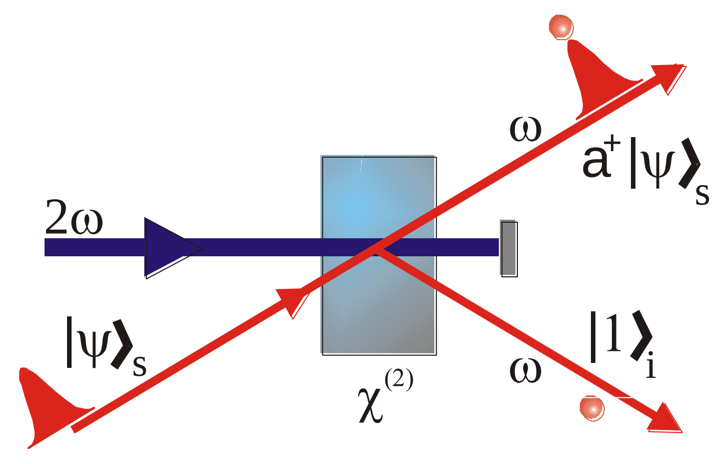
Parametric amplification
in a nonlinear crystal

$$H = i\hbar\chi(\hat{a}_s^\dagger\hat{a}_i^\dagger - \hat{a}_s\hat{a}_i)$$

In the low-gain regime
(eliminates higher-order excitations)

$$g \equiv \chi t \ll 1$$

$$|\psi(t)\rangle \approx [1 + g(\hat{a}_s^\dagger\hat{a}_i^\dagger - \hat{a}_s\hat{a}_i)]\,|\psi(0)\rangle$$



Inject a seed pure state in the signal mode

$$|\psi(0)\rangle \equiv |\psi\rangle_s\,|0\rangle_i$$

$$\Downarrow$$

$$|\psi\rangle_{out} = |\psi\rangle_s\,|0\rangle_i + g\hat{a}_s^\dagger\,|\psi\rangle_s\,|1\rangle_i$$

… whenever an idler photon is detected, the signal is prepared in a *single-photon-excited* version of the initial state

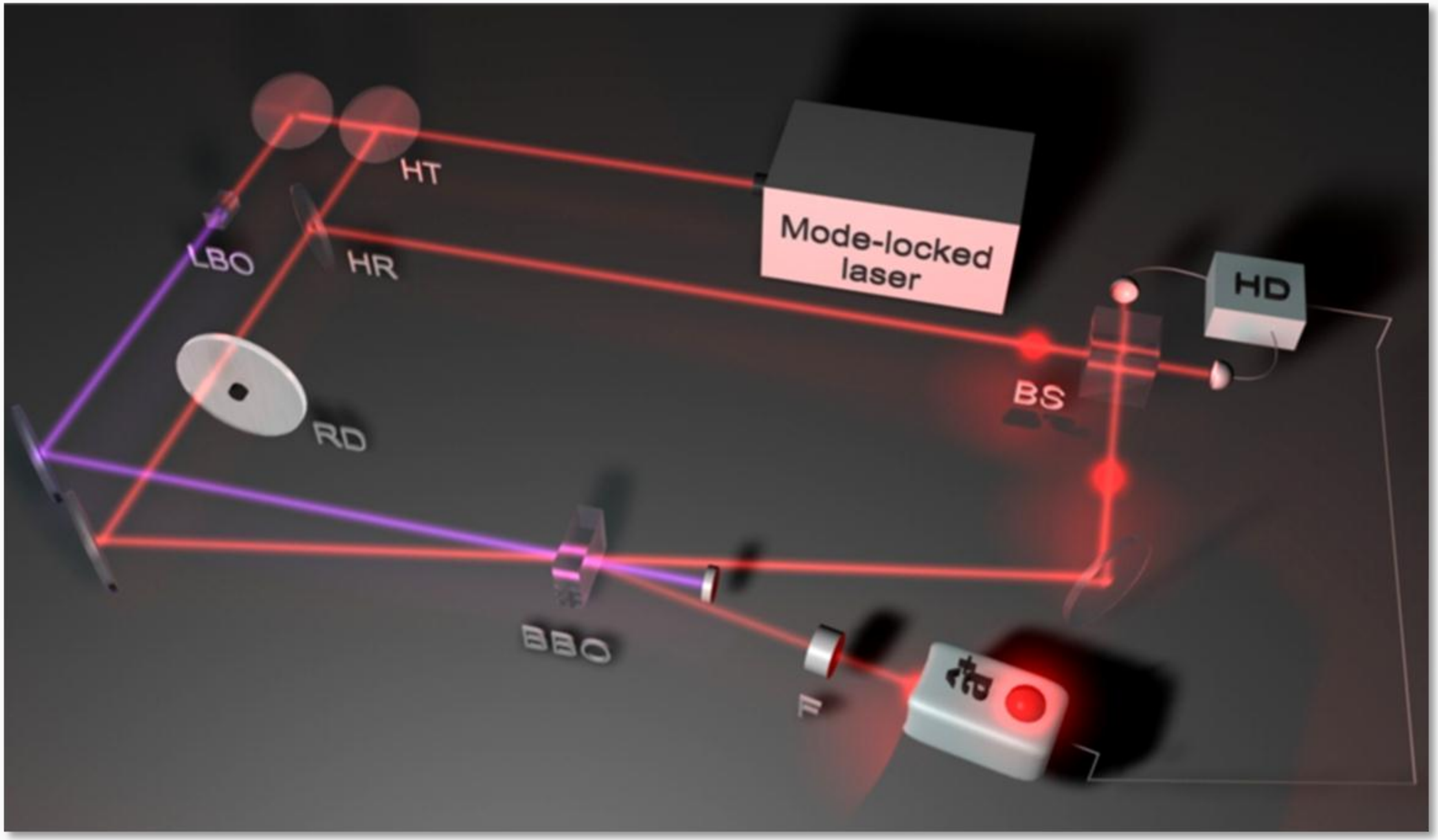
Stimulated emission regime

Emission probability increases with <*n*>

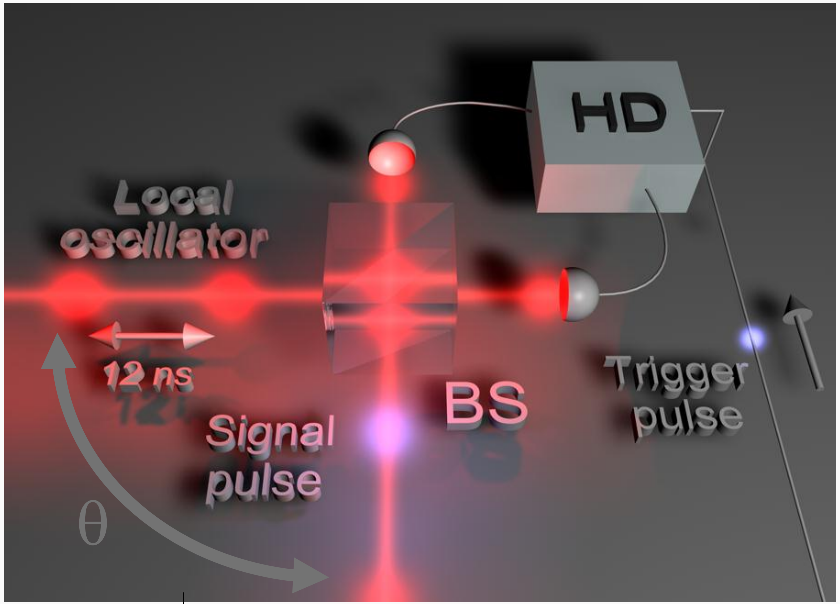
$$p_{st} \propto |g|^2\,\langle\psi|\,\hat{a}\hat{a}^\dagger\,|\psi\rangle = \\ = |g|^2(1 + \langle\psi|\,\hat{n}\,|\psi\rangle) = \\ = |g|^2(1 + \bar{n})$$

A. Zavatta, S. Viciani, M. Bellini, *Science* **306**, 660 (2004)

Experimental single-photon addition



Ultrafast homodyne detection & quantum tomography



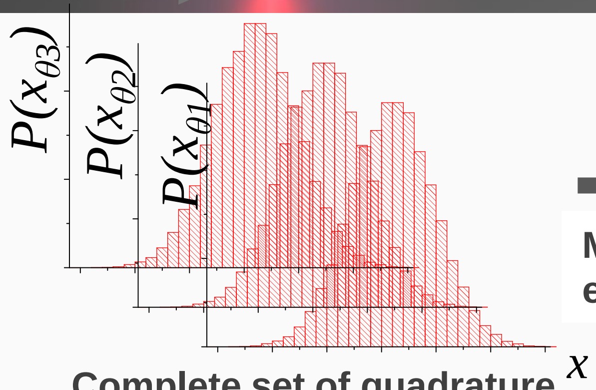
Gated time-domain acquisition

Ultra-high bandwidth (~100 MHz)

Low electronic noise (S/N >10 dB)

High subtraction efficiency
(~60 dB @ 82 MHz)

A. Zavatta, M. Bellini, P.L. Ramazza, F. Marin, F.T. Arecchi, J. Opt. Soc. Am. B 19, 1189 (2001)



Complete set of quadrature measurements

$$\{P(x_\theta)\}_{\theta\in[0\div\pi]}$$

Maximum likelihood estimation

Density matrix elements

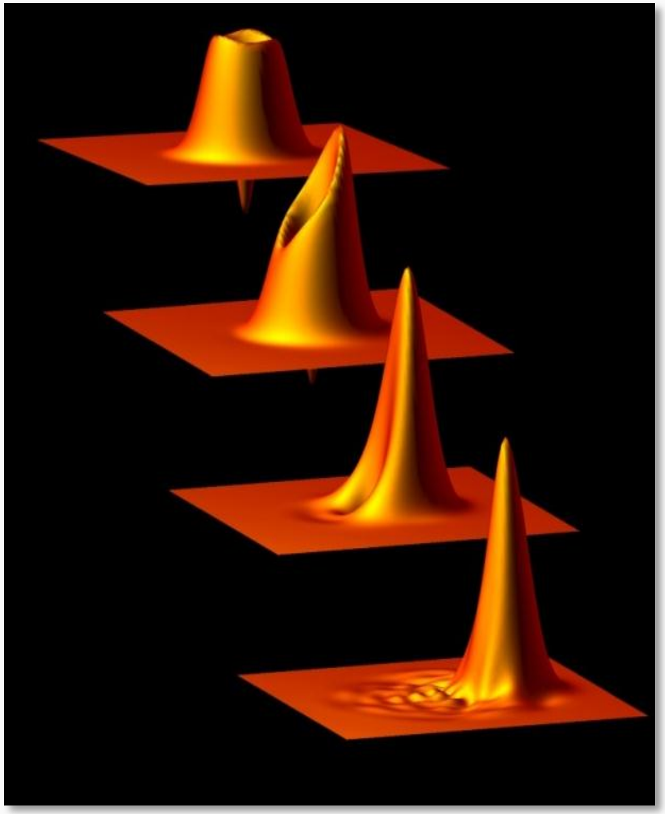
$$\rho_{nm} = \langle n|\hat{\rho}|m\rangle$$

Wigner function

K. Banaszek, G. M. D'Ariano, M. G. A. Paris and M. F. Sacchi, Phys. Rev. A 61, 010304(R) (1999)
Z. Hradil, D. Mogilevtsev, J. Rehacek, Phys. Rev. Lett. 96, 230401 (2006)

Adding a single photon to a state of light

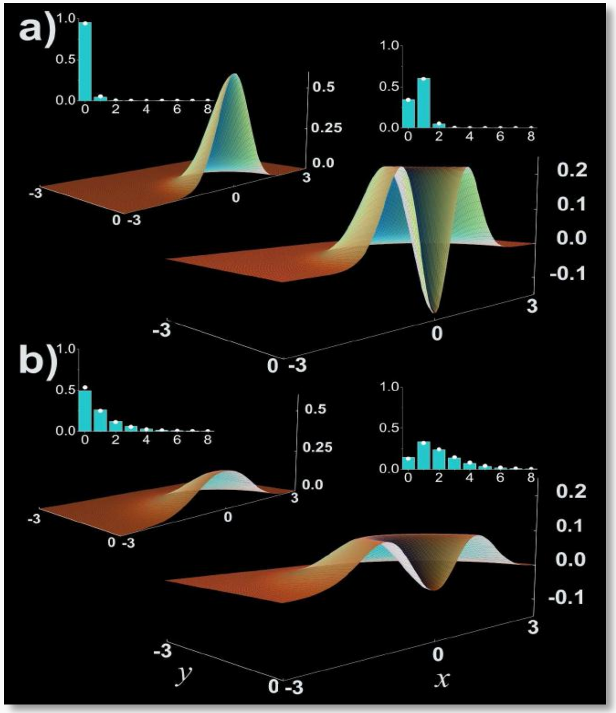
SPACS



Particle-to-wave transition
Spontaneous-to-stimulated emission

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

SPATS



Test of criteria for nonclassicality

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

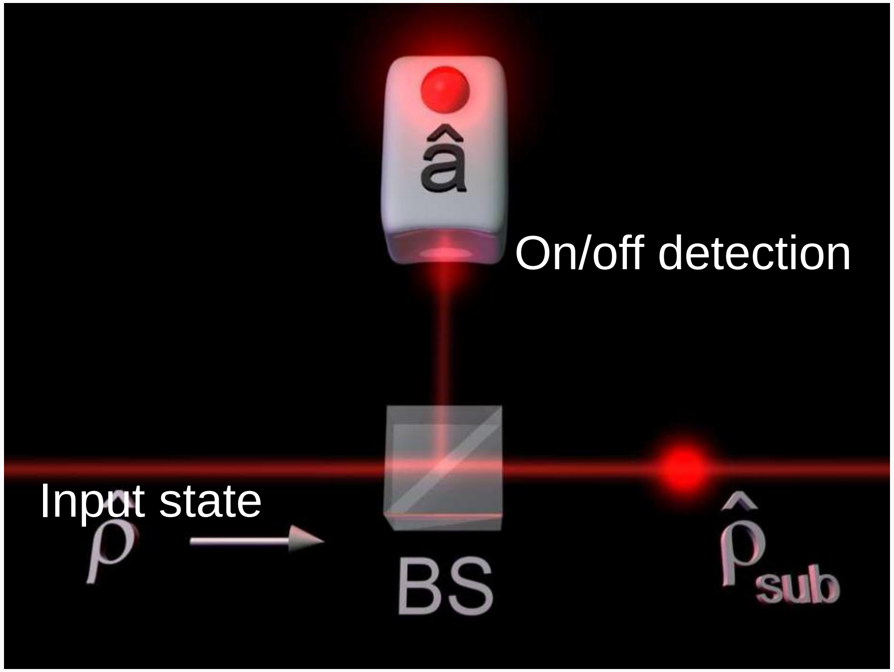
Reconstruction of nonclassical P-function

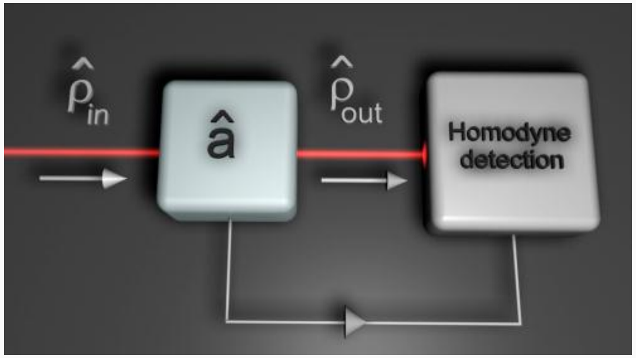
T. Kiesel, W. Vogel, V. Parigi, A. Zavatta, M. Bellini, *PRA* 78, 021804(R) (2008)

Nonclassical quasiprobabilities

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

How to “subtract” a single photon





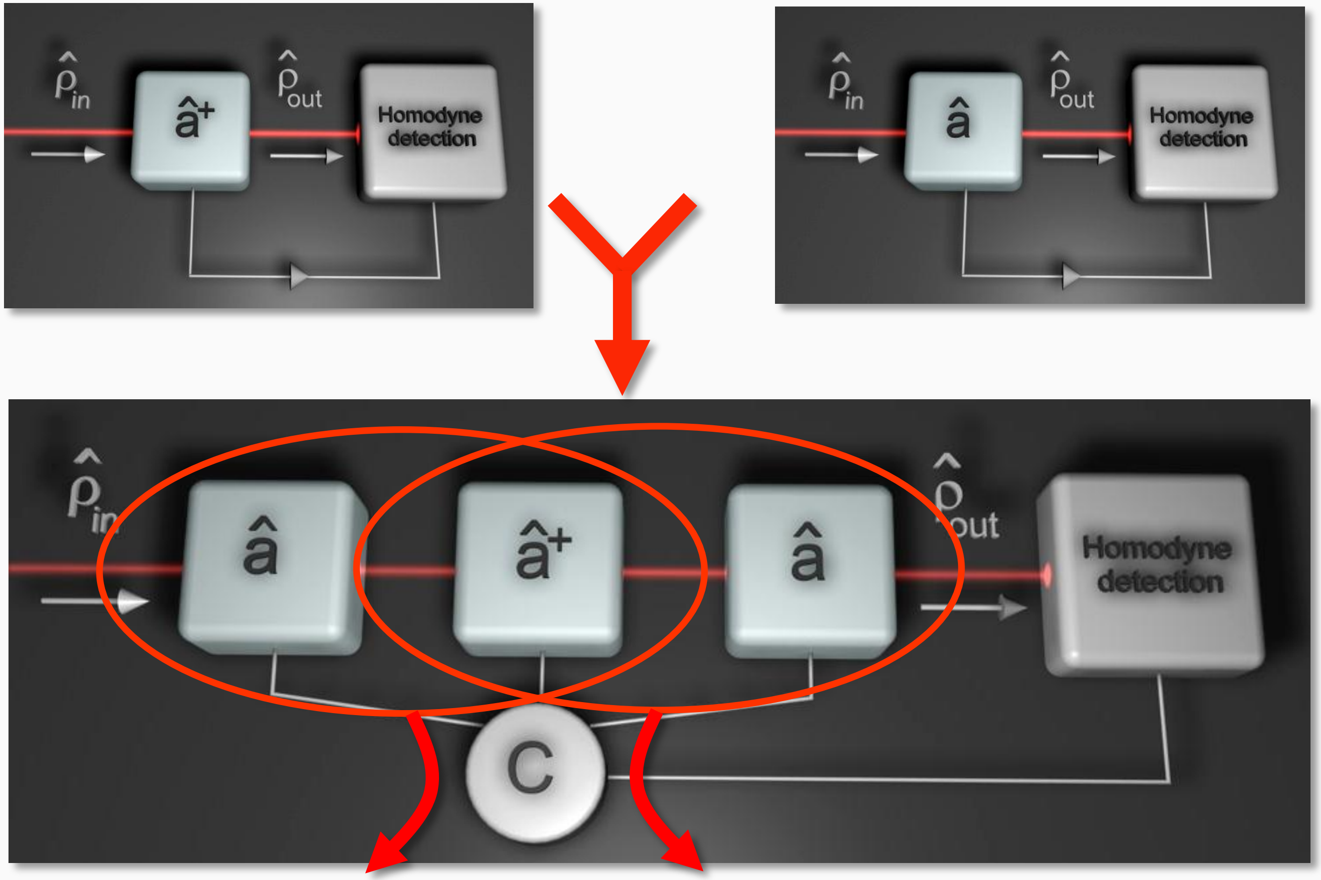
$$\hat{a}$$

Faithful implementation of the annihilation operator for:

- Low BS reflectivity
- Low photon numbers

J. Wenger, R. Tualle-Brouri, and P. Grangier, Phys. Rev. Lett. 92, 153601 (2004)

Combining quantum operators

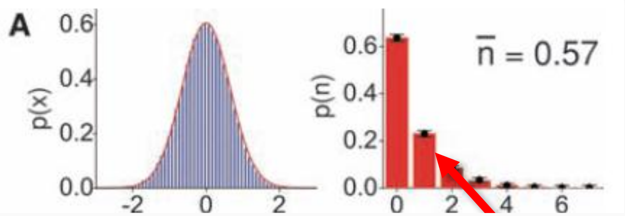


$\hat{a}^\dagger\hat{a}$

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

Homodyne data and reconstructions

1



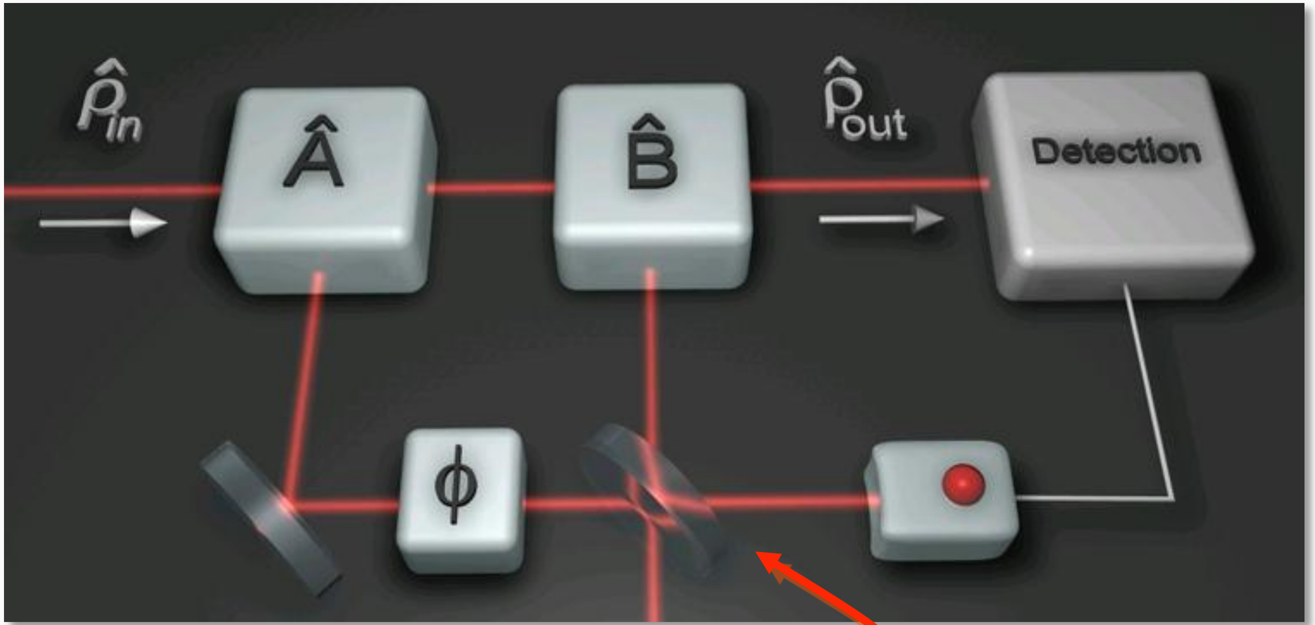
Limited preparation efficiency (ξ=92%) in the photon-addition stage adds small contaminations

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

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

Clearly different final states

Superpositions of quantum operators



Erases the information about the origin of a "click"

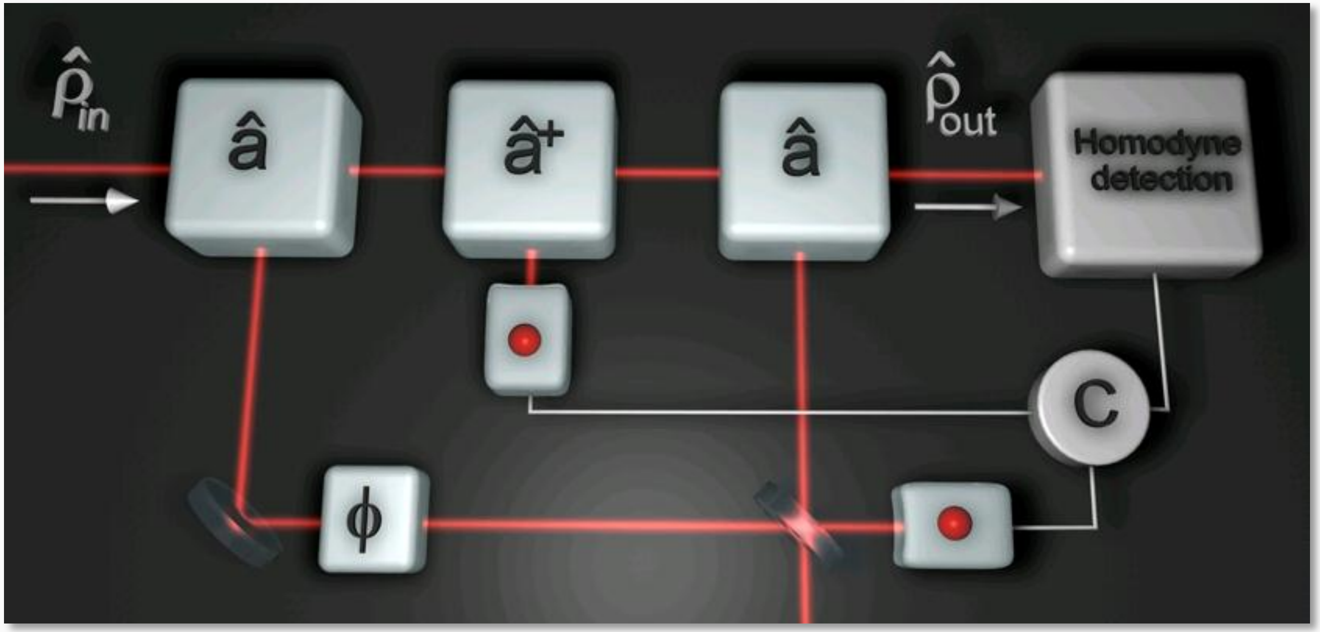
$$|\alpha|\,\hat{A} + e^{i\phi}\,|\beta|\,\hat{B}$$

Arbitrary superpositions of operators can be implemented

Apply to any state

Arbitrary state superposition

Complete test of commutation relations



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

$\phi = 0$

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

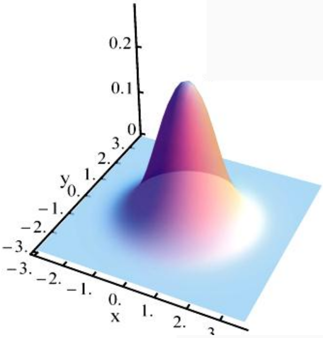
This complex superposition of operations should do <u>nothing</u> to the state !!

M. S. Kim, H. Jeong, A. Zavatta, V. Parigi, & M. Bellini PRL 101, 260401 (2008)

Testing commutation rules

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

Initial thermal state



Experimentally reconstructed Wigner functions

$$F = \left|Tr\sqrt{\sqrt{\hat{\rho}_{in}}\,\hat{\rho}_{out}\,\sqrt{\hat{\rho}_{in}}}\right|^2 > 0.99$$

A. Zavatta, V. Parigi, M. S. Kim, H. Jeong, & M. Bellini, PRL 103, 140406 (2009)

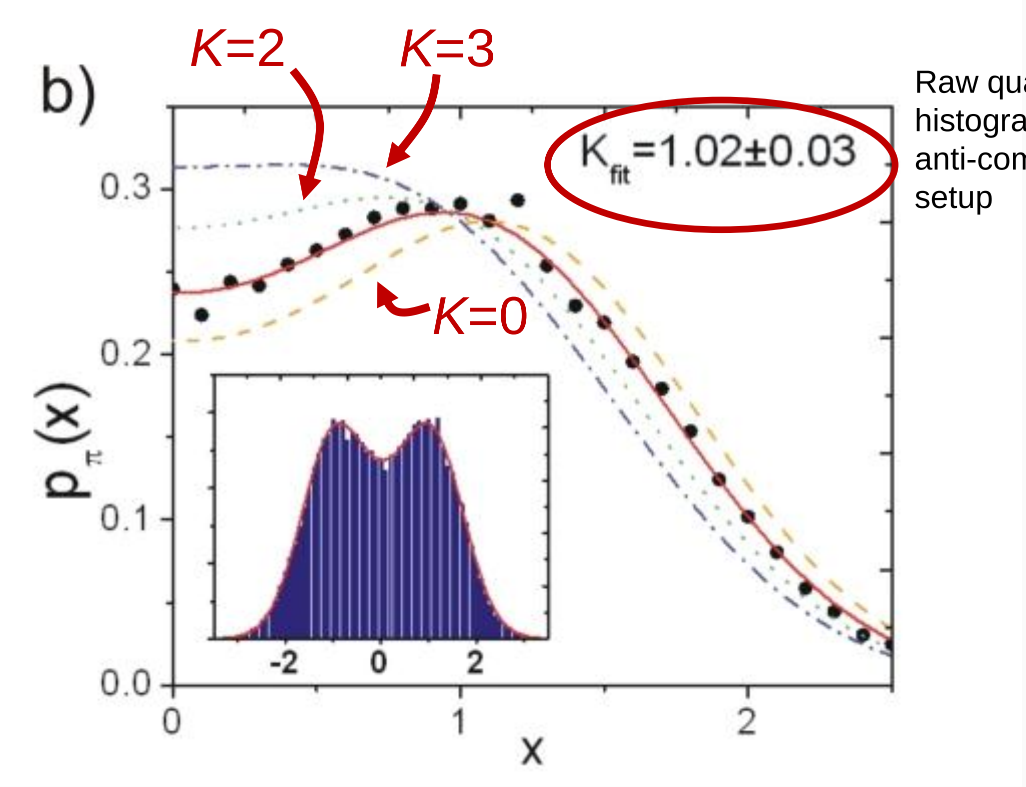
Quantitative test of commutation rules

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

then the anti-commutator would correspond to

$$2\hat{a}^\dagger\hat{a} + K\mathbf{1}$$

The final state strongly depends on the exact value of *K* and can be experimentally tested



Raw quadrature histograms for the anti-commutator setup

The superposition scheme works well and it can be used for QIP

A. Zavatta, V. Parigi, M. S. Kim, H. Jeong, and M. Bellini Phys. Rev. Lett. 103, 140406 (2009)

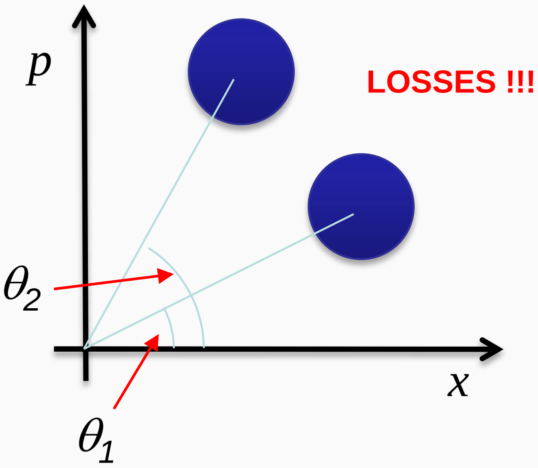
Phase-insensitive noiseless amplification

$$|\alpha\rangle \rightarrow |\alpha e^{i\theta}\rangle$$

Encoding information in the phase of a coherent state

$$V(\theta_{\text{est}}) = \frac{1}{4|\alpha|^2}$$

Standard quantum limit on phase measurements



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

$$|\alpha\rangle \longrightarrow |g\alpha\rangle$$

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

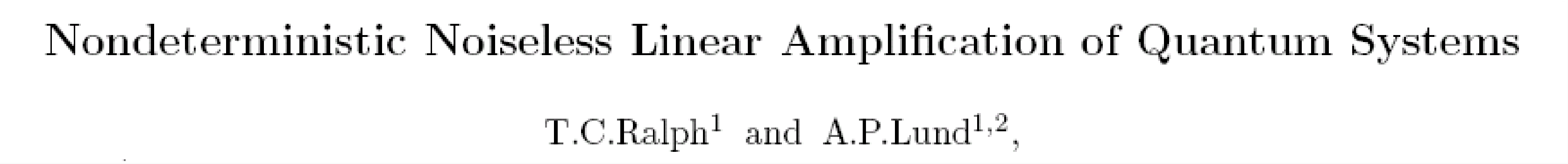
- ✗ Clone quantum states
- ✗ Violation of Heisenberg uncertainty principle
- ✗ Send superluminal information

Non-deterministic noiseless amplification

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

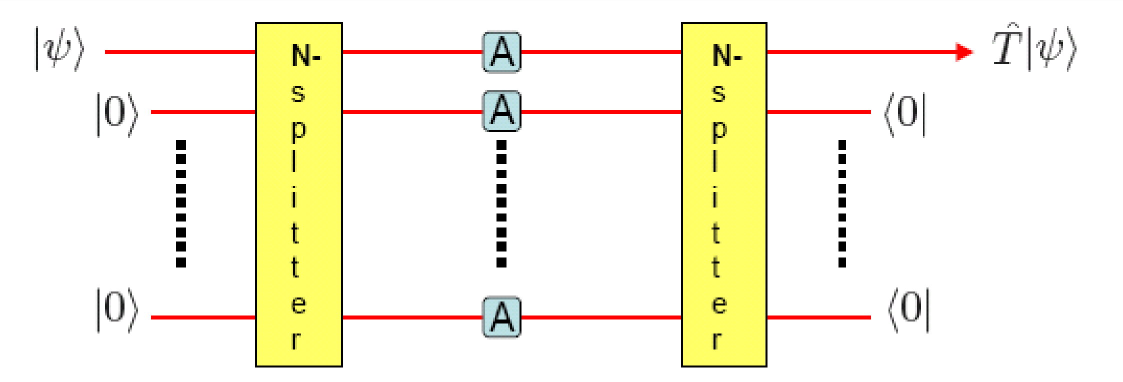
Only a non-deterministic
implementation is possible

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



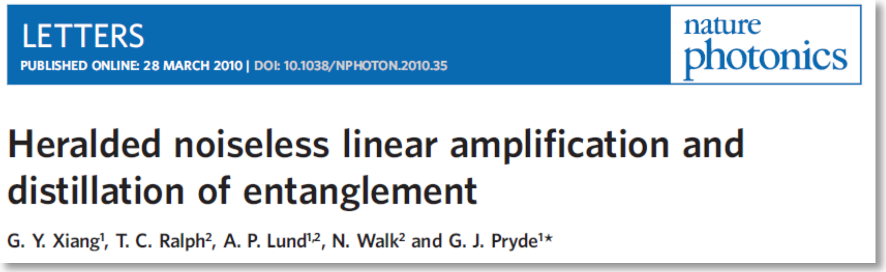
Nondeterministic Noiseless Linear Amplification of Quantum Systems

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



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

Heralded noiseless amplifiers



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]*

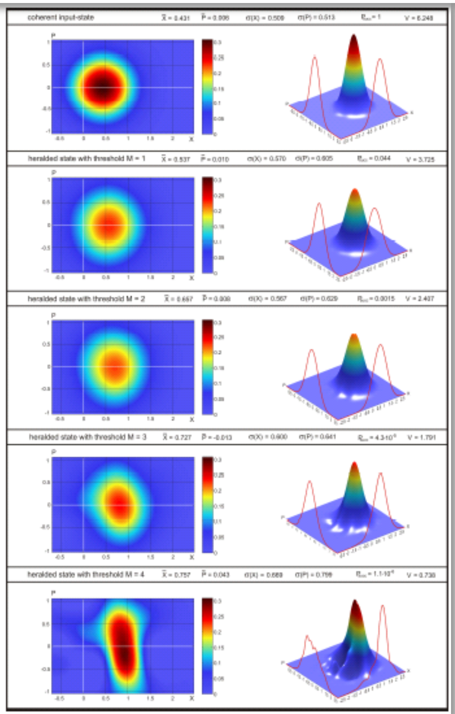
nature physics

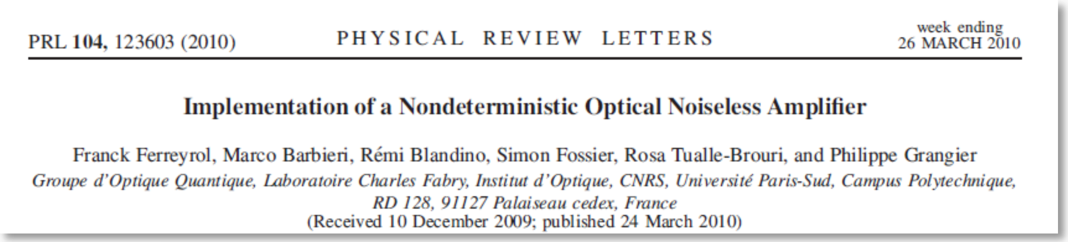
LETTERS

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]*





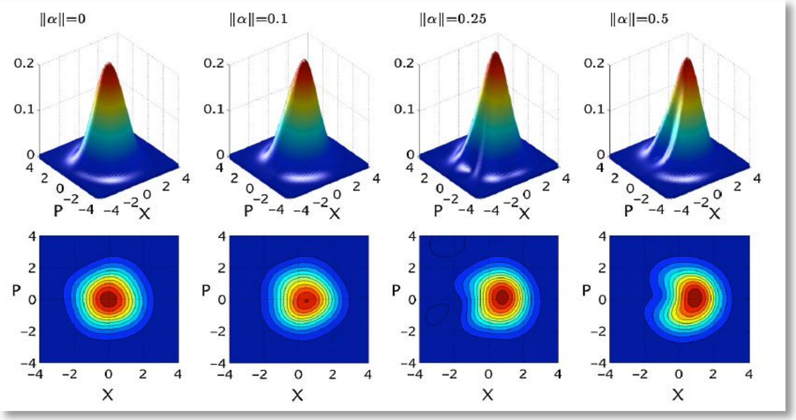
PRL **104,** 123603 (2010) PHYSICAL REVIEW LETTERS week ending 26 MARCH 2010

Implementation of a Nondeterministic Optical Noiseless Amplifier

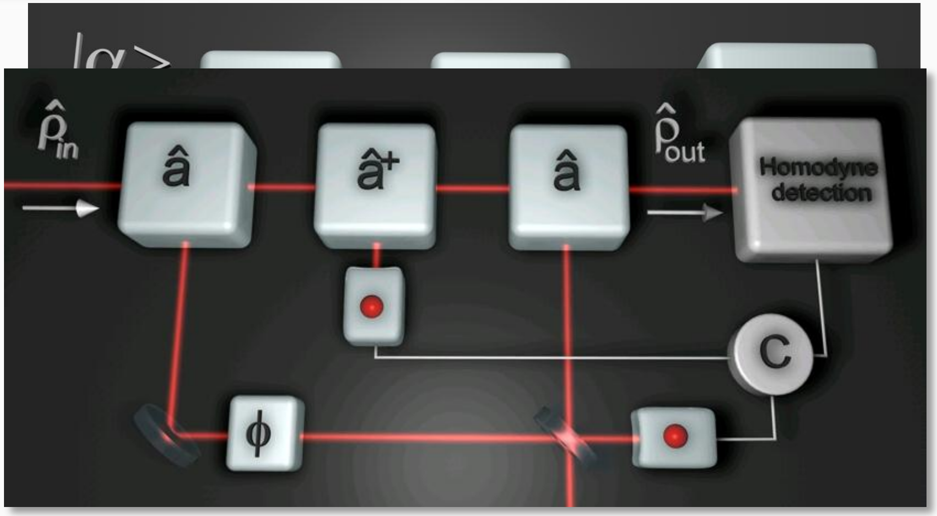
Franck Ferreyrol, Marco Barbieri, Rémi Blandino, Simon Fossier, Rosa Tualle-Brouri, and Philippe Grangier

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)



Noiseless amplification by addition & subtraction



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

$$\downarrow$$

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

$|\alpha| \ll 1$

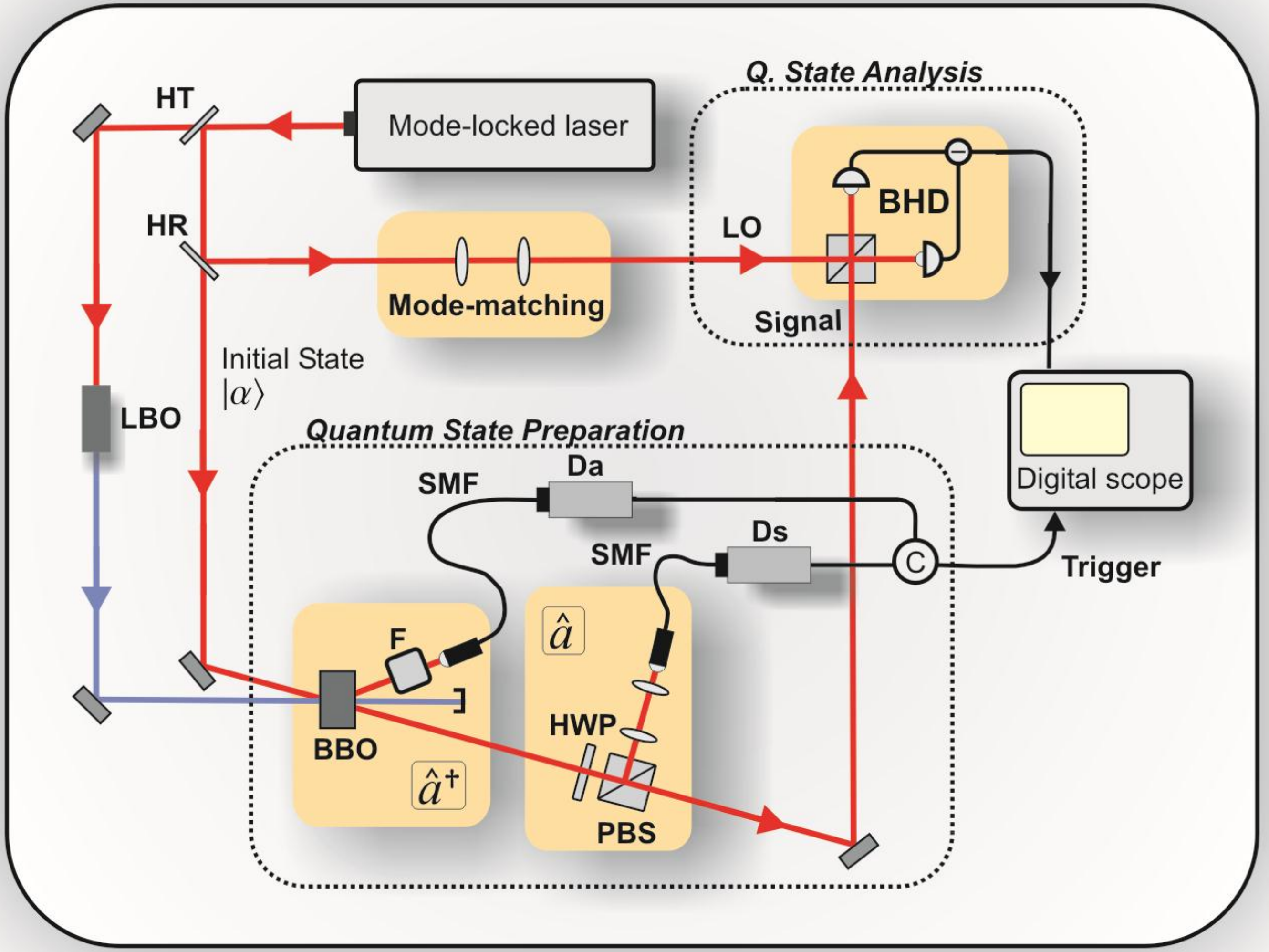
$$|\alpha\rangle \approx |0\rangle + \alpha\,|1\rangle$$

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

The final state is not truncated to the |1> term

J. Fiurasek, Phys. Rev. A 80, 053822 (2009)
P. Marek and R. Filip, Phys. Rev. A 81, 022302 (2010)

Experimental setup

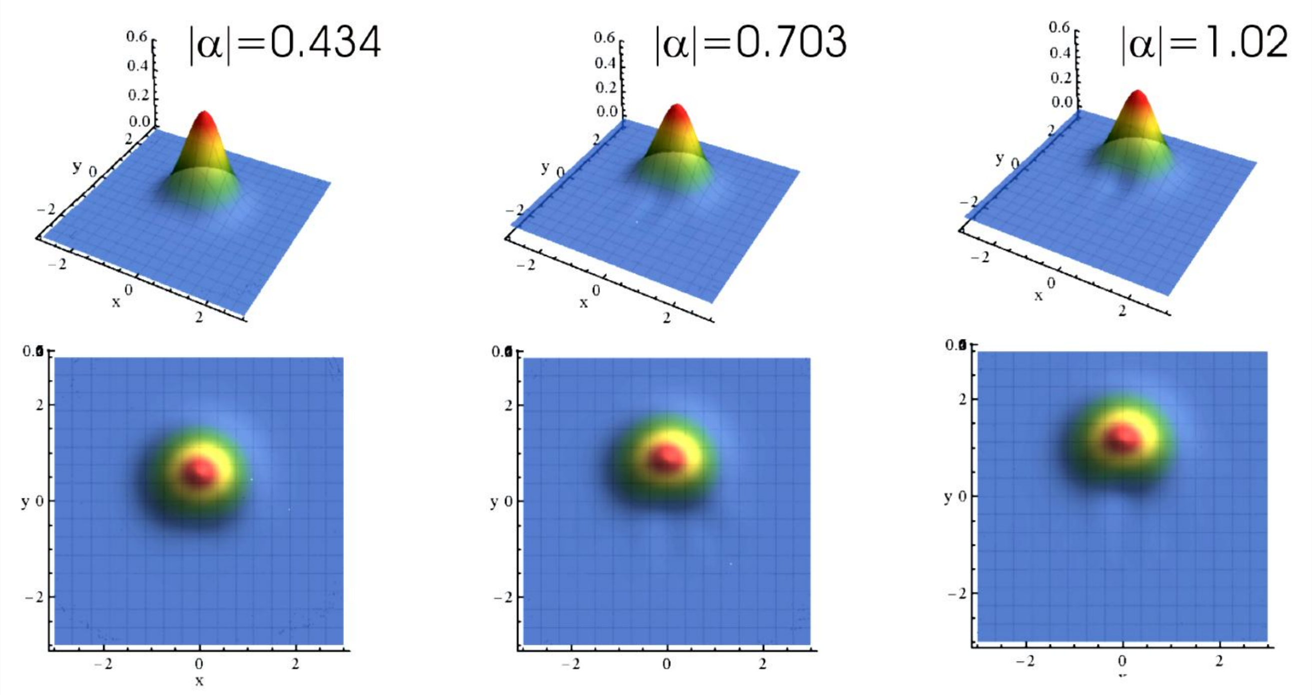


A. Zavatta, J. Fiurasek, and M. Bellini, Nature Phot. 5, 52 (2011)

High fidelity quantum amplification

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

Reconstructed Wigner functions for the amplified coherent states:



High fidelity quantum amplification

Effective amplitude gain

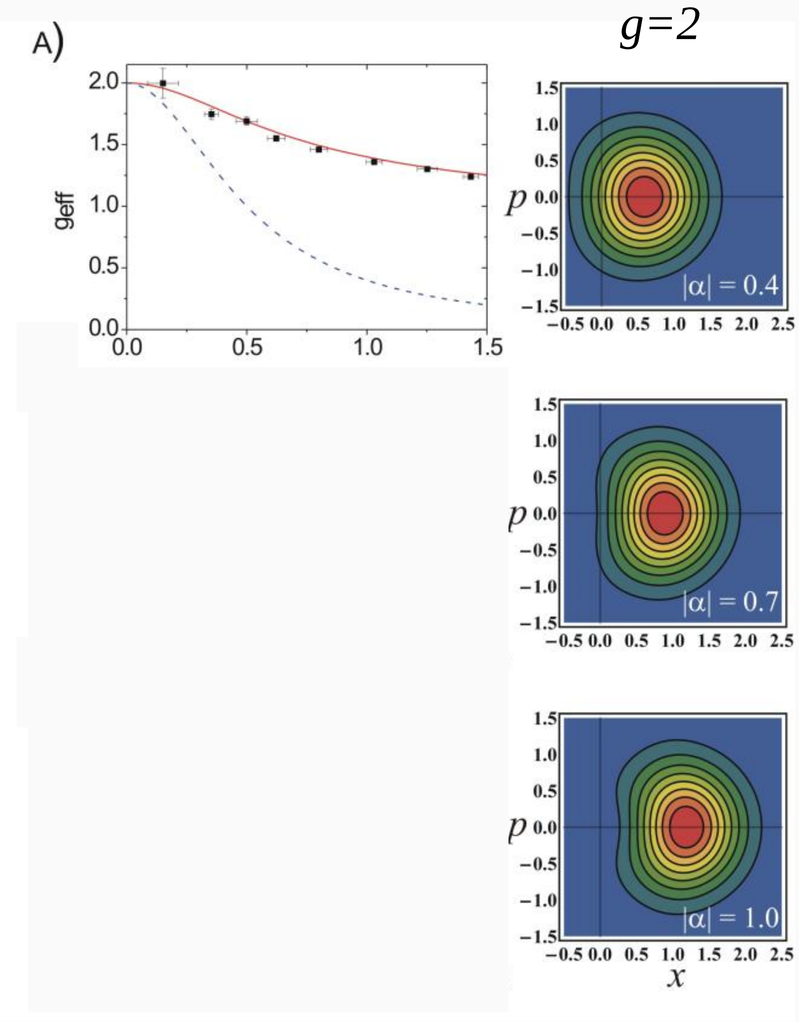
$$g_{eff} = \frac{\langle x_{amp} \rangle}{\langle x_{in} \rangle}$$

Fidelity

Distortions compared to the ideal coherent state of double amplitude

Noise

How much noise is added in the process?



A. Zavatta, J. Fiurasek, and M. Bellini, Nature Phot. 5, 52 (2011)

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

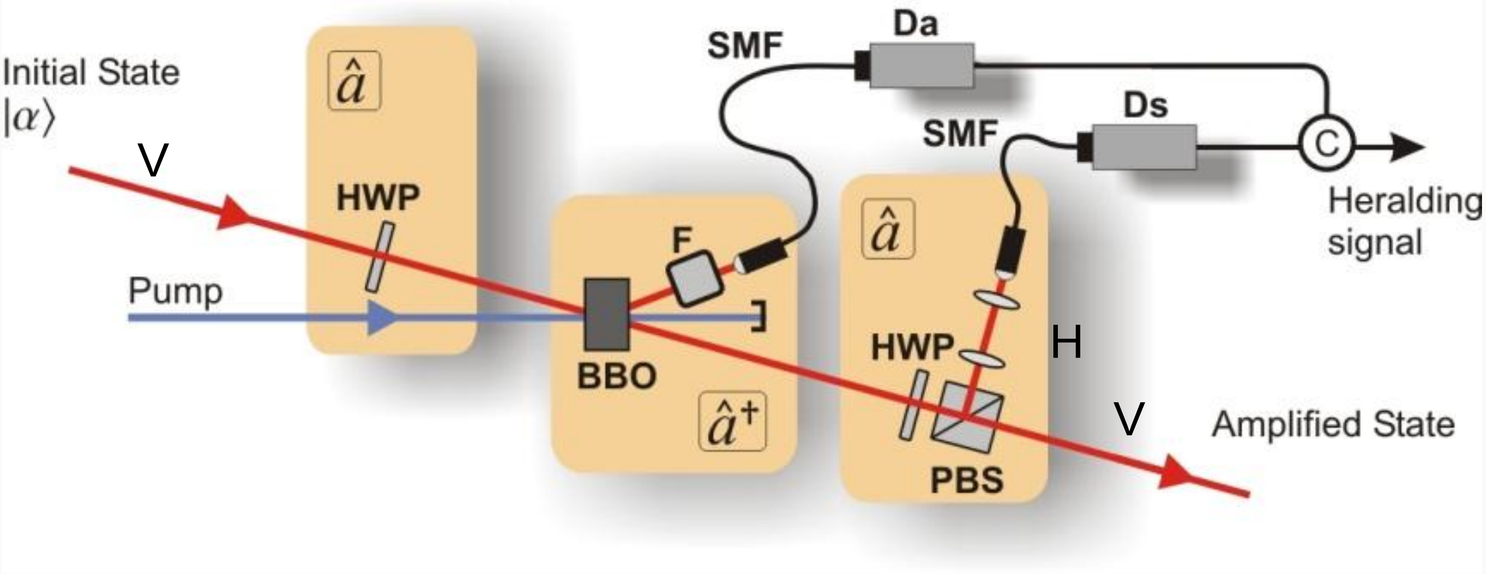
J. Fiurasek, *PRA* **80**, 053822 (2009)

Need a way to produce coherent superpositions of quantum operators

Variable-gain noiseless amplifier

Superposition of two sequences of operators:

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



The two HWPs are rotated by very small angles.

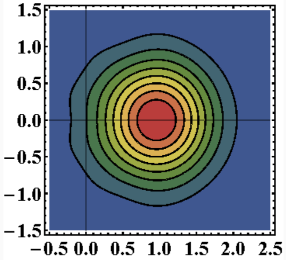
A. Zavatta, J. Fiurasek, and M. Bellini, in preparation (2011)

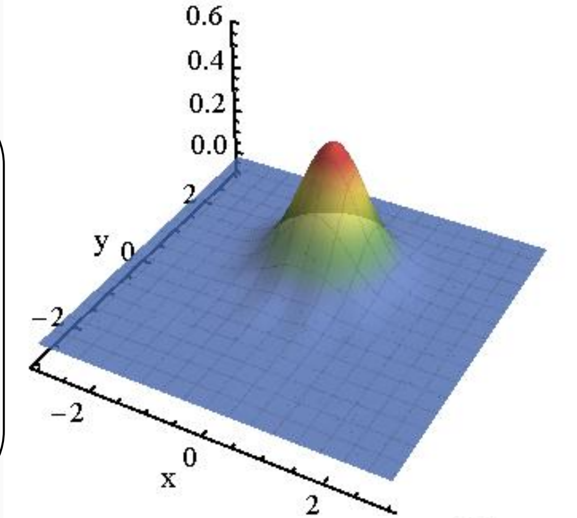
Variable-gain noiseless amplifier

Input coherent state $|\alpha| \approx 1$

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

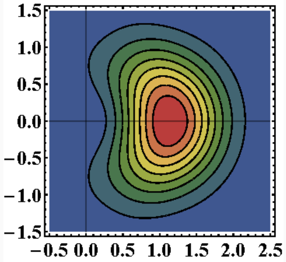
Commutator

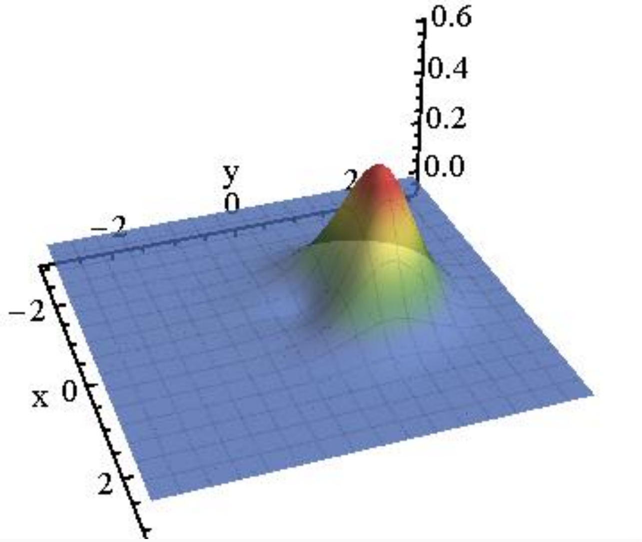




$\boldsymbol{g = 3}$ $\hat{a}\hat{a}^{\dagger} + \hat{a}^{\dagger}\hat{a}$

Anti-Commutator





A. Zavatta, J. Fiurasek, and M. Bellini, in preparation (2011)

Outline

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Part 2	Investigating the mode structure of ultrashort pulsed quantum light states

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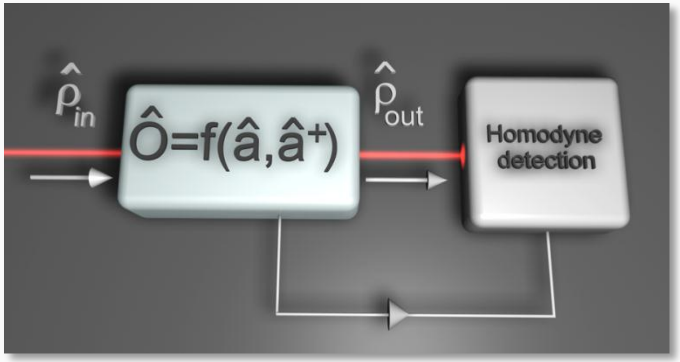
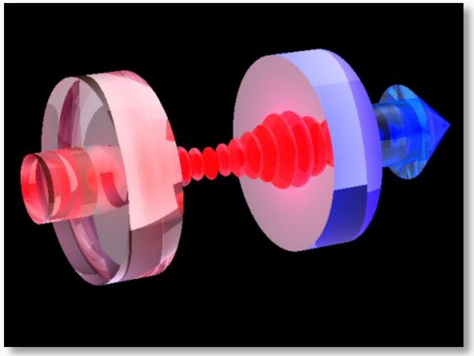
The “shape” of a quantum state



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

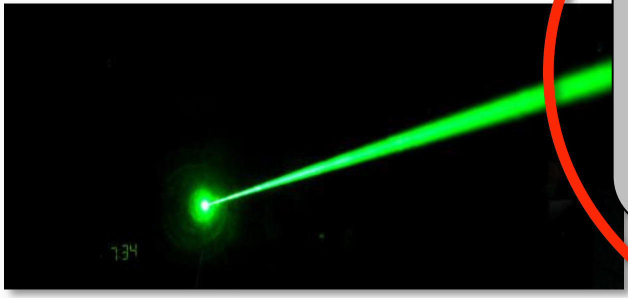
The relevant quantum features of the states can only be accessed if the right mode is properly selected and analyzed

Excitation of a particular spatio-temporal mode

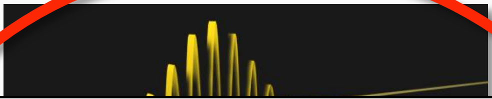


Confined cavity mode

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



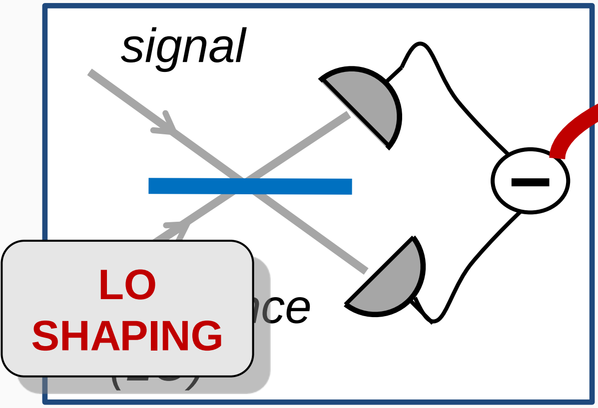
Infinitely-extended monochromatic CW mode



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

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

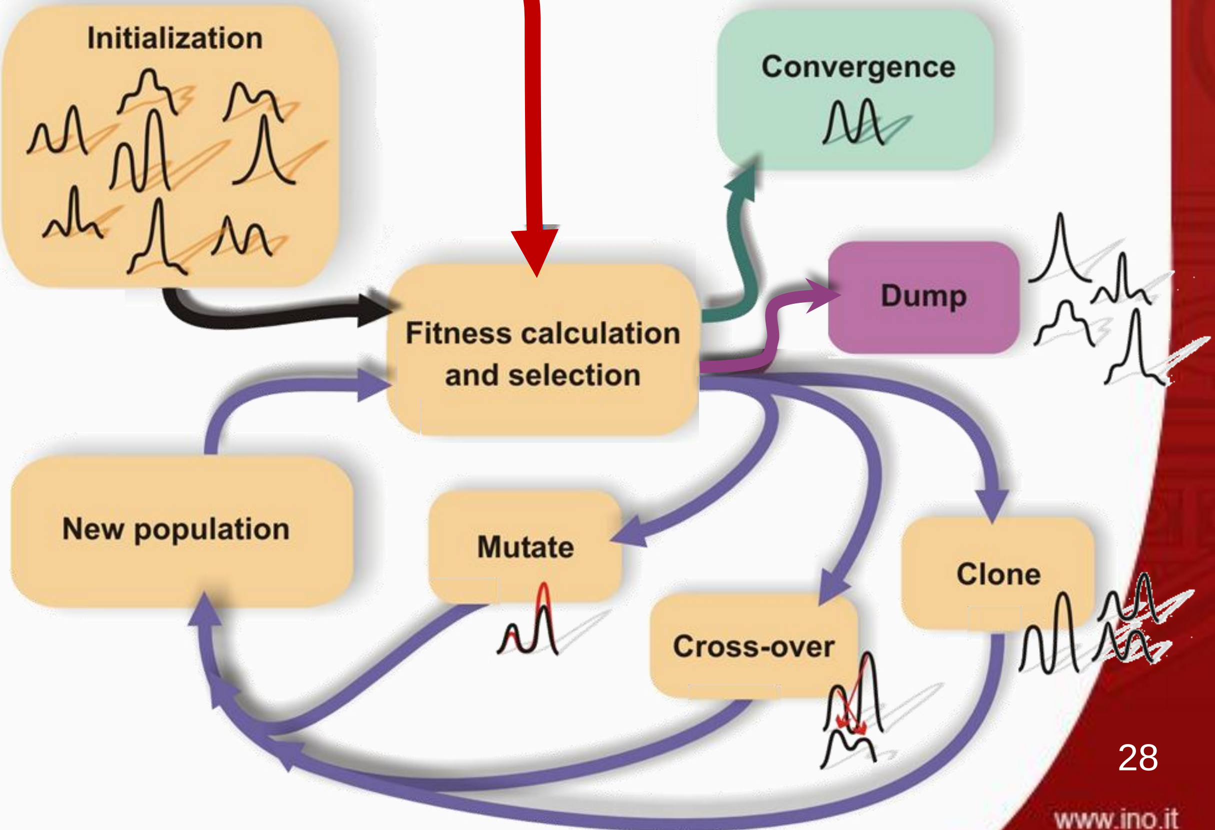
Adaptive measurement scheme



Detection efficiency, squeezing, etc

Genetic algorithm:
Local oscillator

The method works without preliminary information!

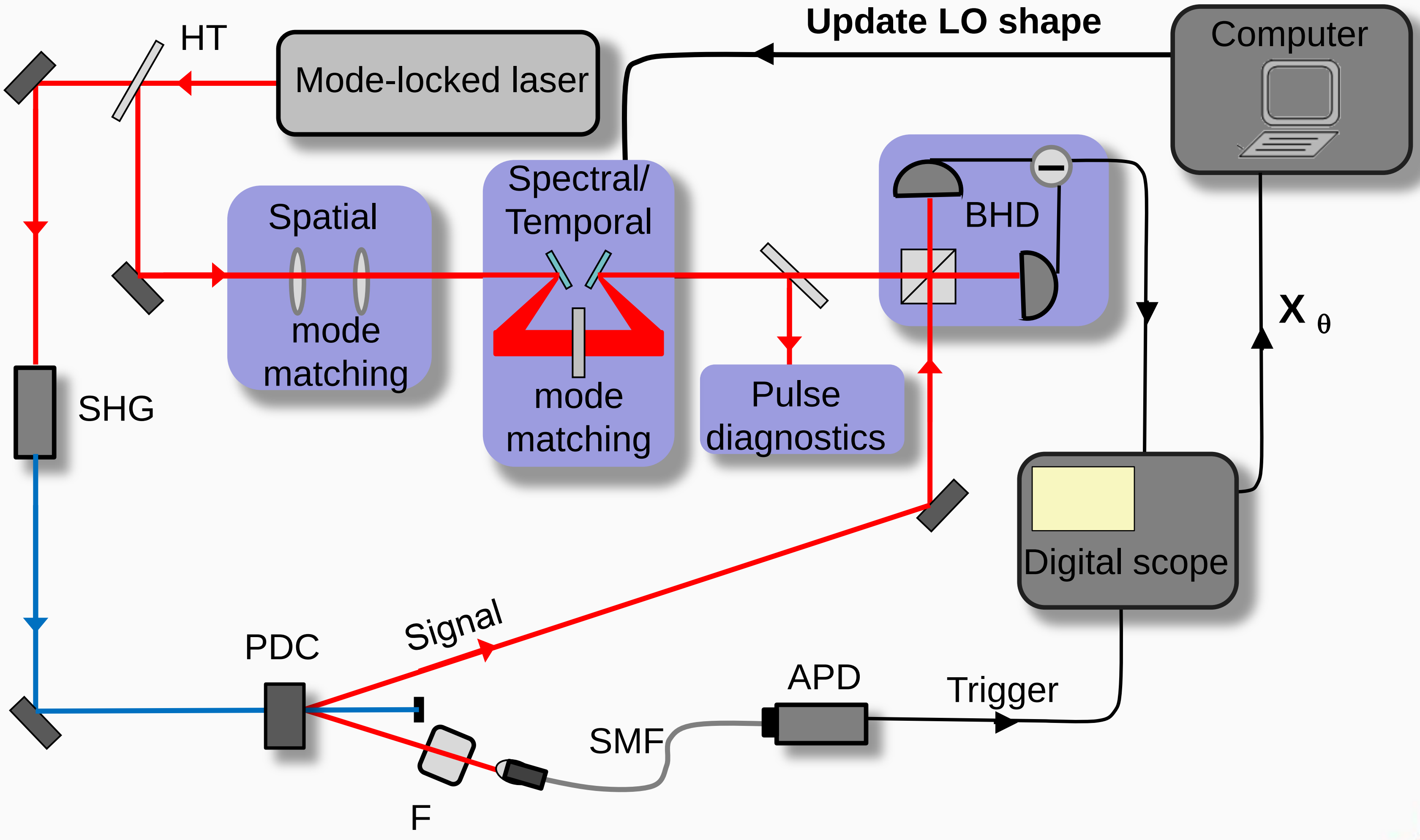


A quantum state can only be efficiently observed if the LO is properly matched in polarization, space, time, spectrum,…

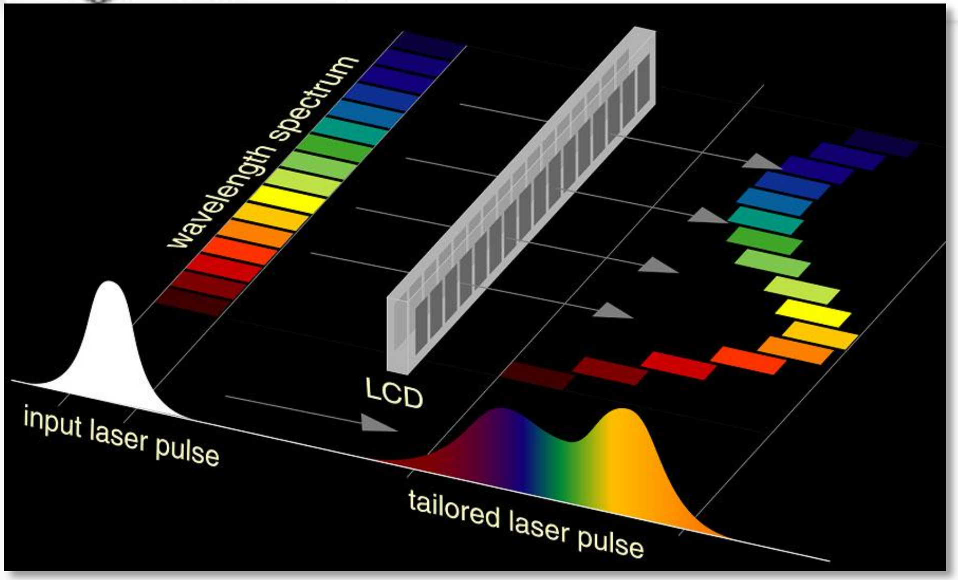
C. Polycarpou, K. Cassemiro, G. Venturi, A. Zavatta, & M. Bellini, arXiv:1111.7161v1 [quant-ph]

Measuring the photon wavepacket

82 MHz, @ 800 nm
$\Delta\tau \sim 70$ fs, $\Delta\lambda \sim 10$ nm



Shaping ultrashort LO pulses



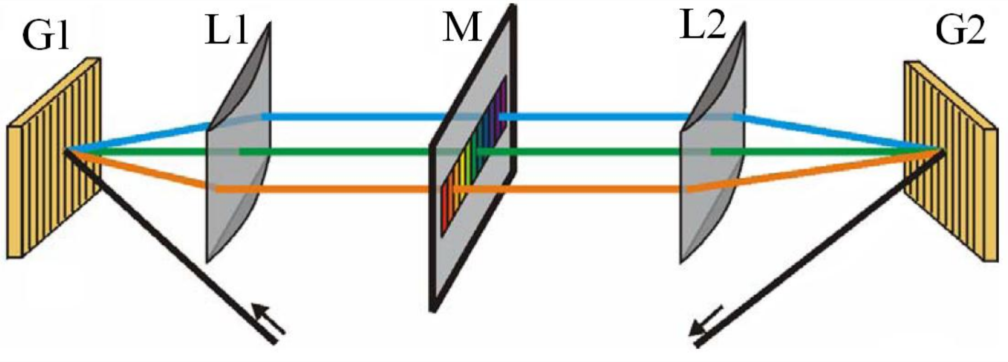
SLM pulse shaper

One needs to independently modulate each wavelength component in amplitude and phase

Two Spatial Light Modulators

128 pixels each

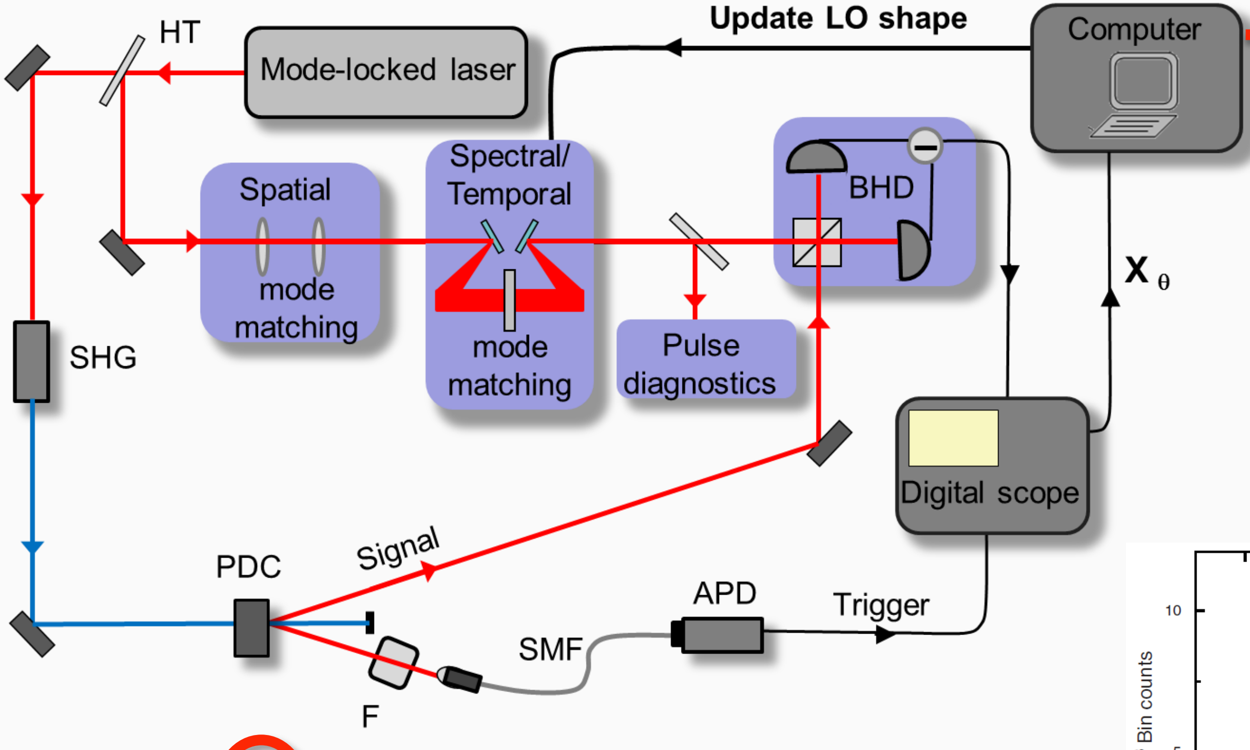
Resolution 0.6 nm



A. M. Weiner, Rev. Sci. Instrum. **71**, 1929 (2000); J. Vaughan, Ultrafast Optics textbook, GeorgiaTech.

Searching for the photon shape

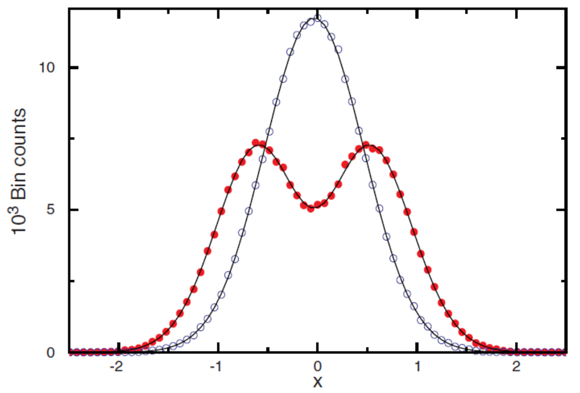
82 MHz, @ 800 nm
Δτ ~ 70 fs, Δλ ~ 10 nm



Calculate the
efficiency η

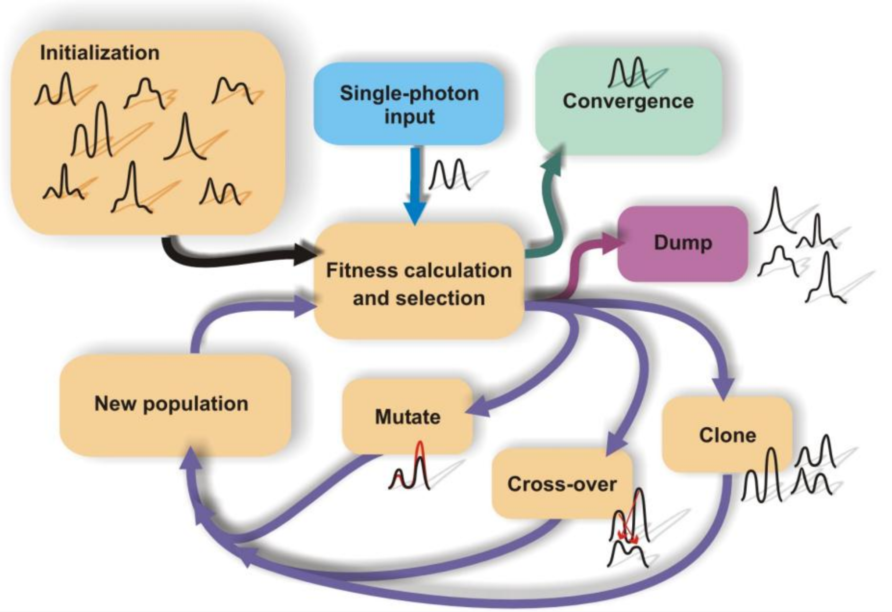
$$\eta\,|1\rangle\langle 1| + (1-\eta)\,|0\rangle\langle 0|$$

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

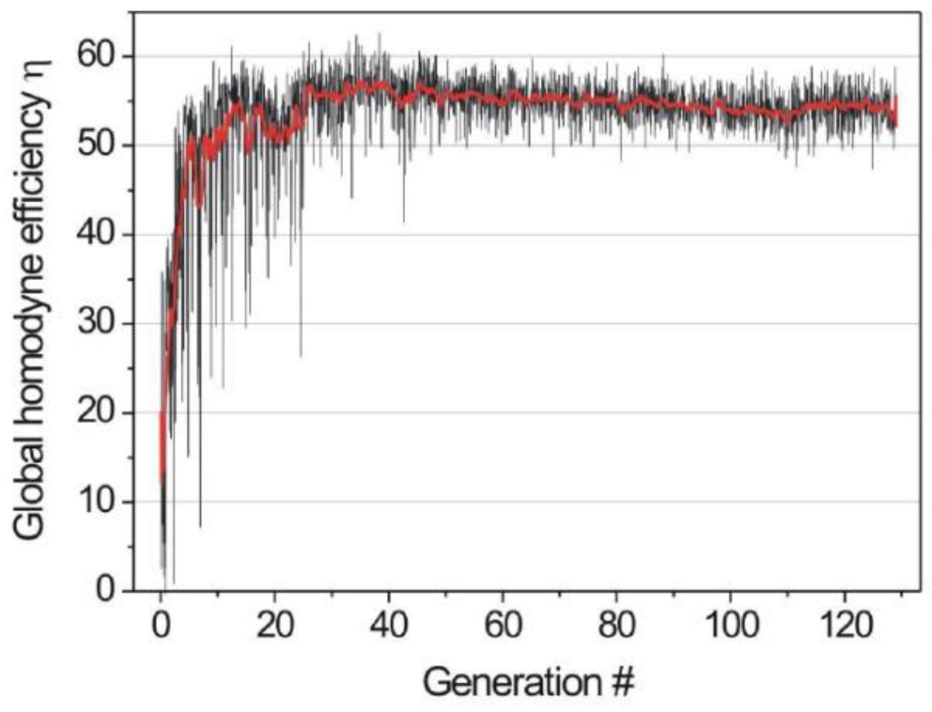


Single-photon
quadrature distribution

Evolutionary search of the photon shape



14 h experiment run



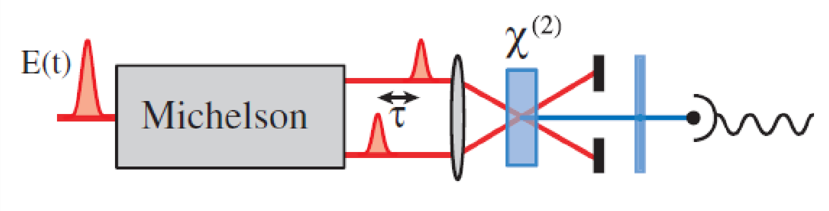
Using the evolutionary algorithm to find the best LO pulse shape

No preliminary information is needed

C. Polycarpou, K. Cassemiro, G. Venturi, A. Zavatta, & M. Bellini, arXiv:1111.7161v1 [quant-ph]

Retrieving the LO shape of light (FROG)

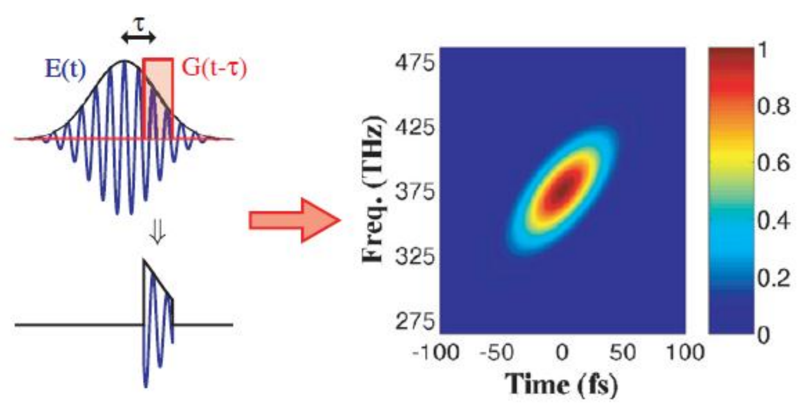
Autocorrelation



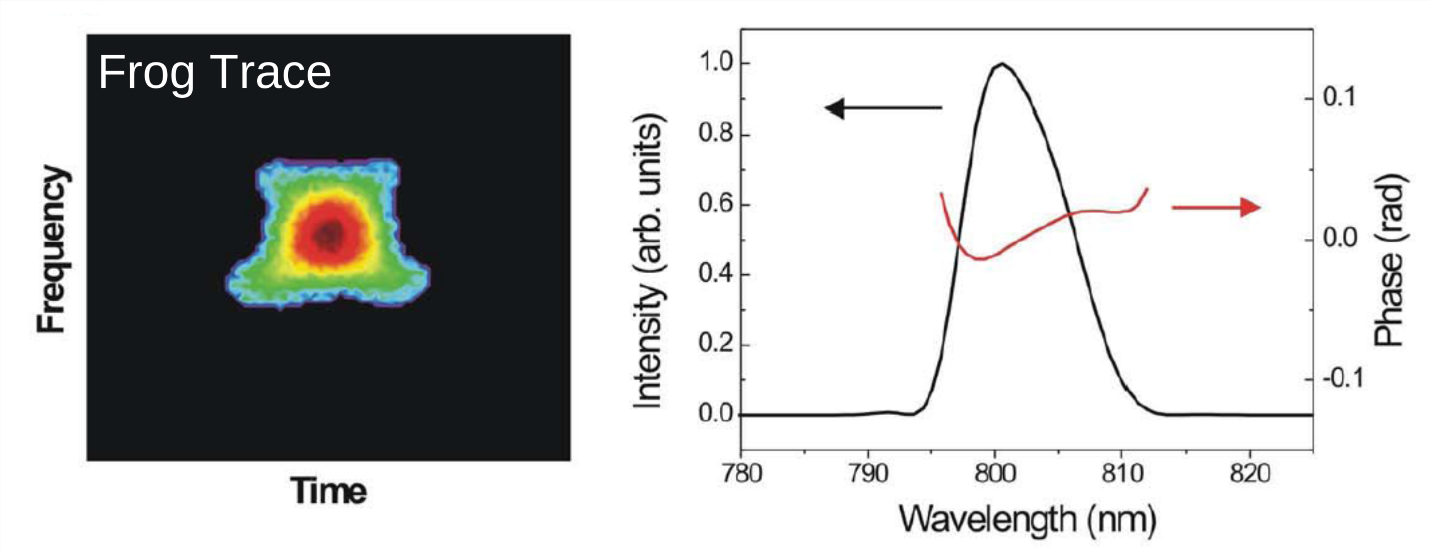
Assuming pulse profile → pulse duration

A. Monmayrant *et al.*, J. Phys. B **43**, 103001 (2010)
I.A. Walmsley and C. Dorrer, Adv. Opt. and Phot. **1**, 308 (2009)

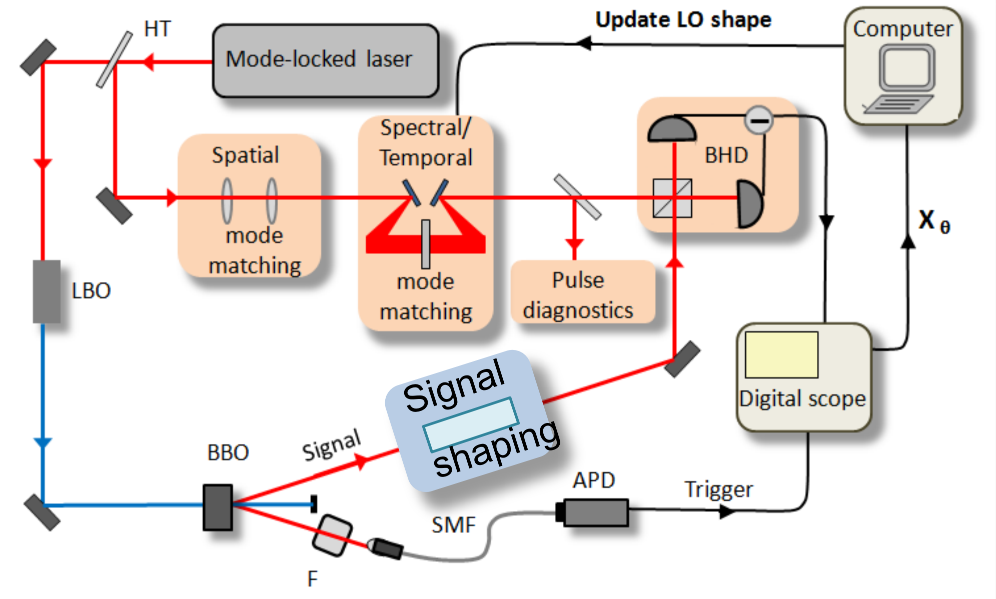
FROG (Frequency Resolved Optical Gating)



Unmodulated single photon shape



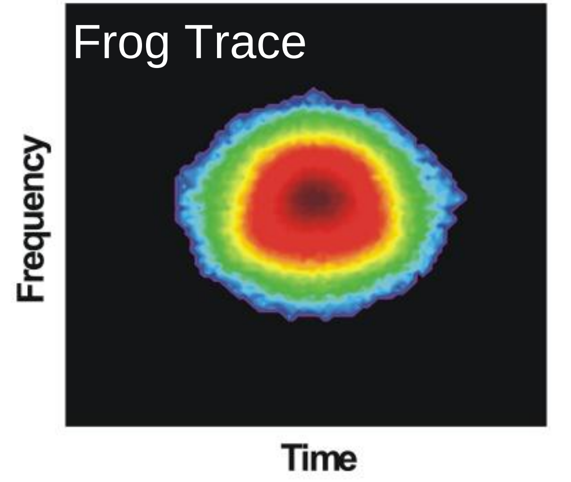
Introducing linear dispersion

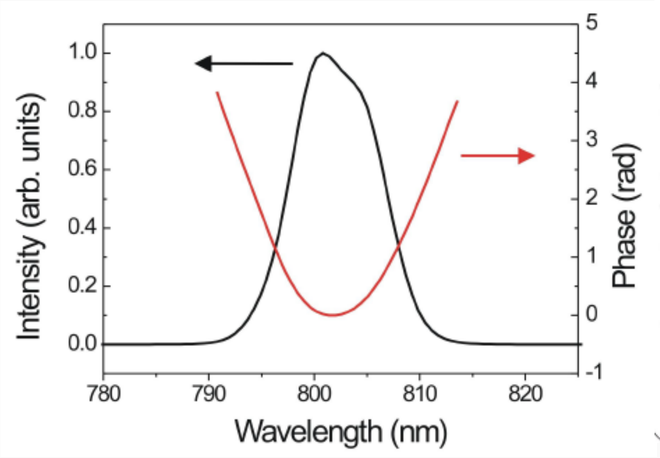


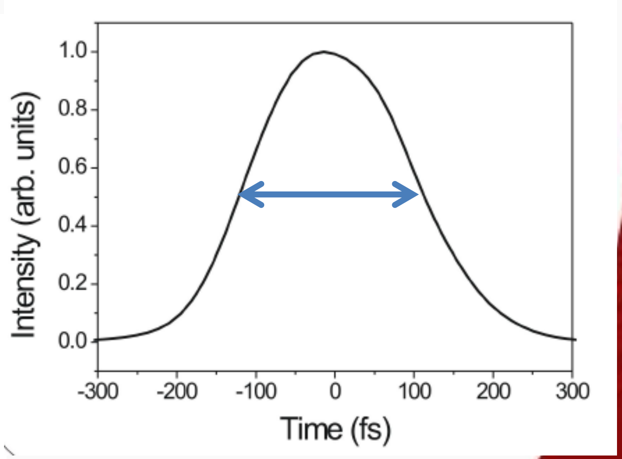
10 cm long BK7 glass

Retrieved mode presents a temporally stretched shape, as expected.

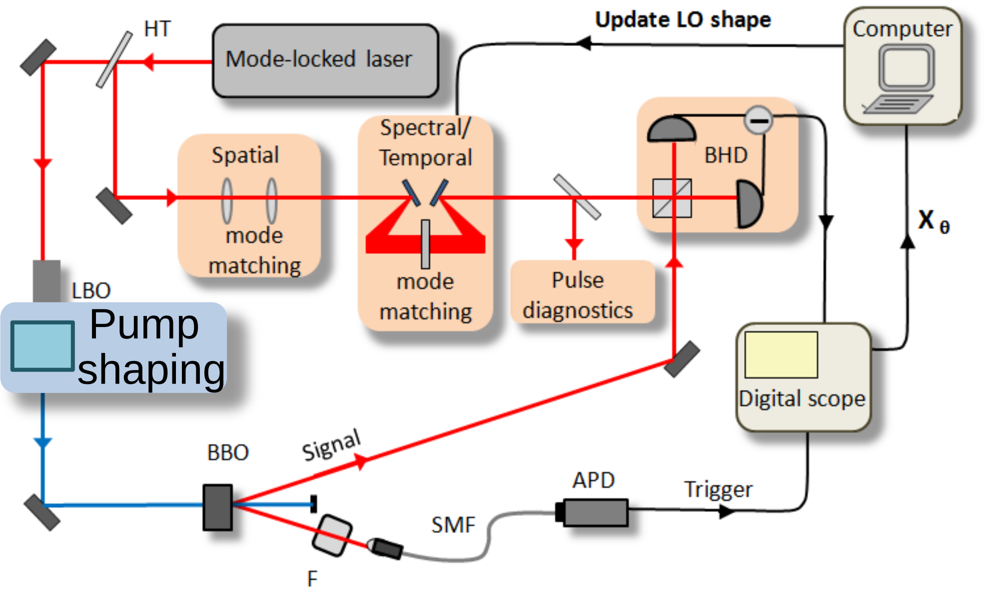
η = 60%





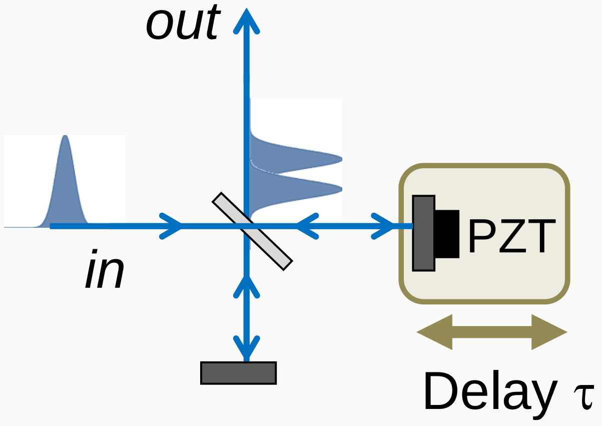


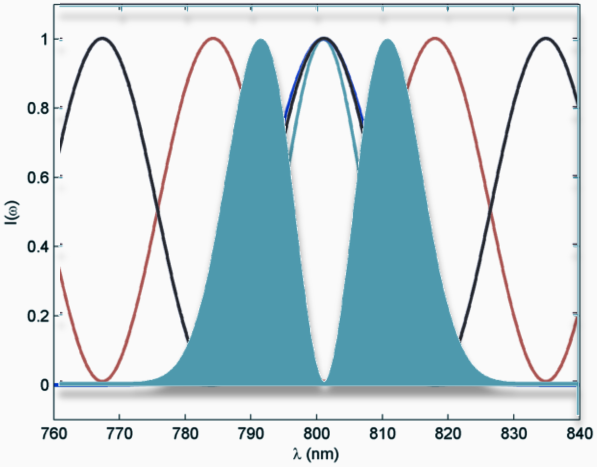
More complex shapes



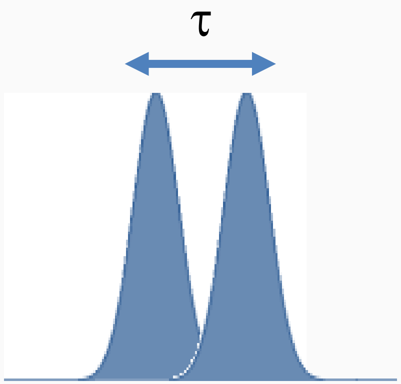
Pump shaping

Michelson interferometer





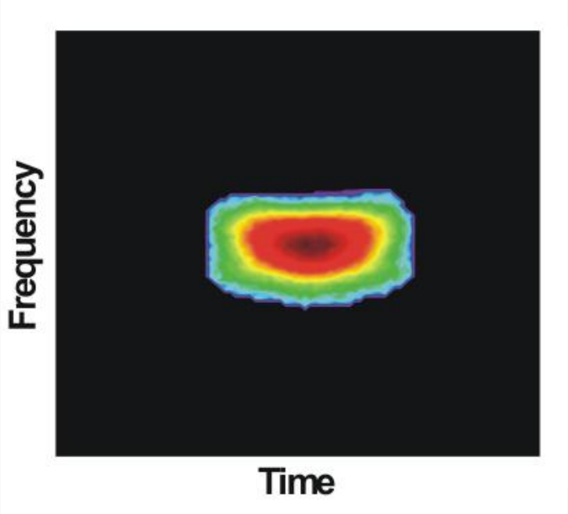
Sinusoidal modulation

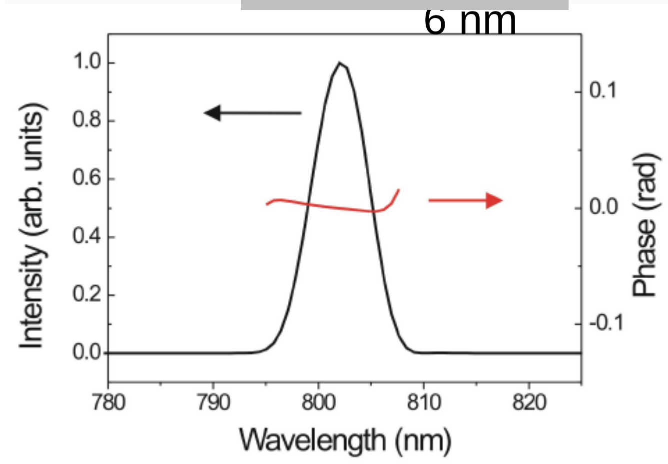


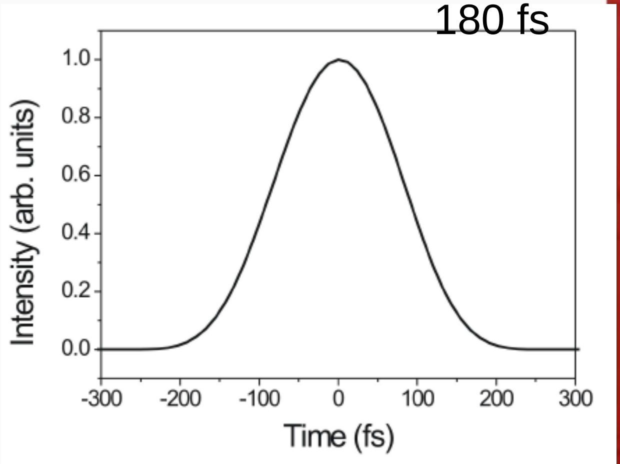
Phase between pulses
(controlled with PZT)

Results – LO optimization

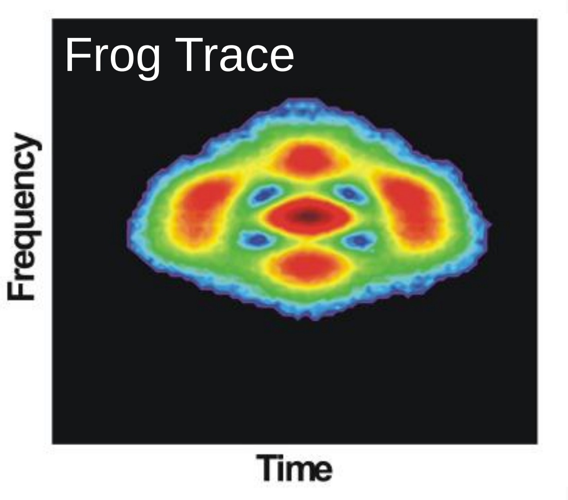
Phase = 0

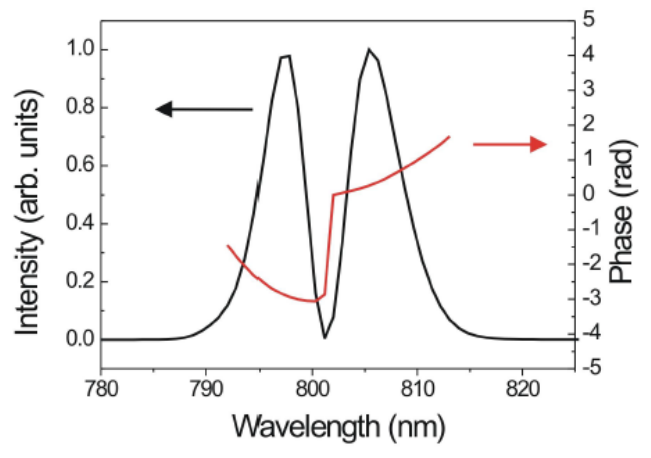


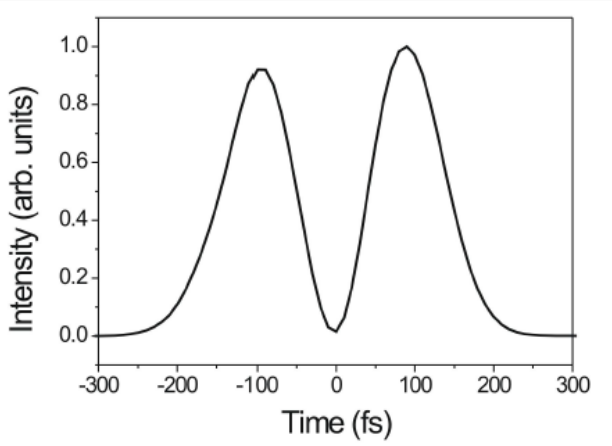




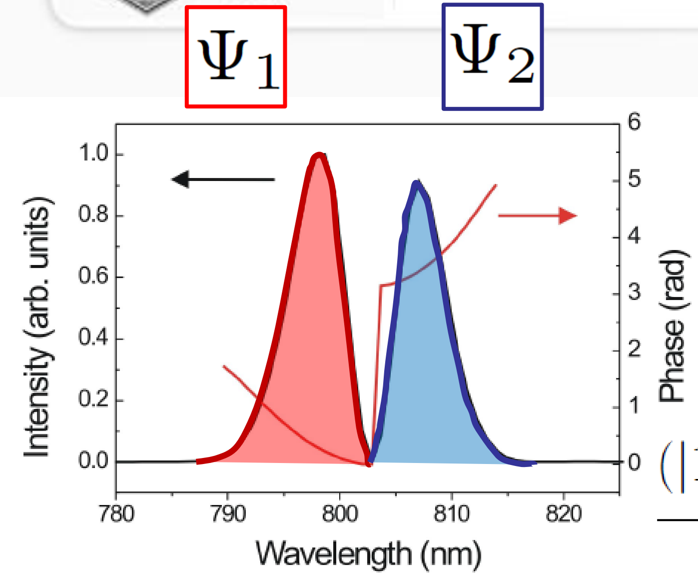
Phase = π



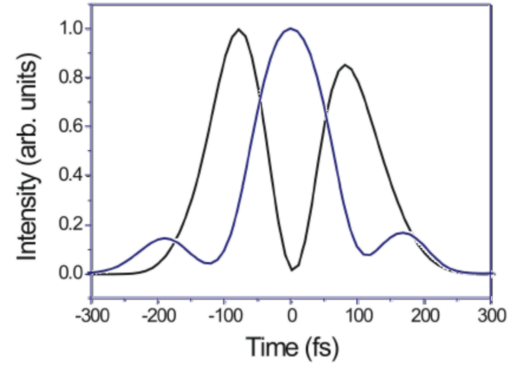


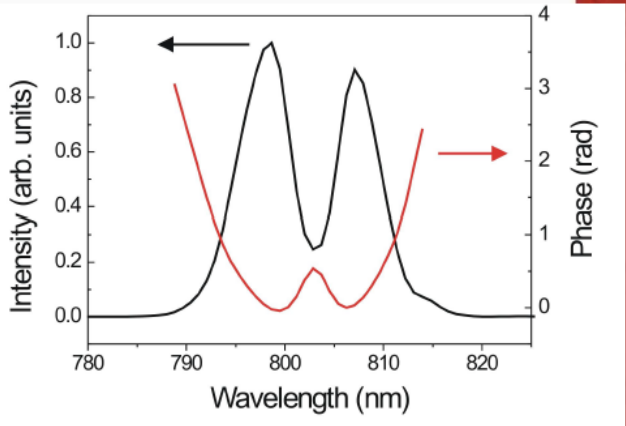


Probing coherence



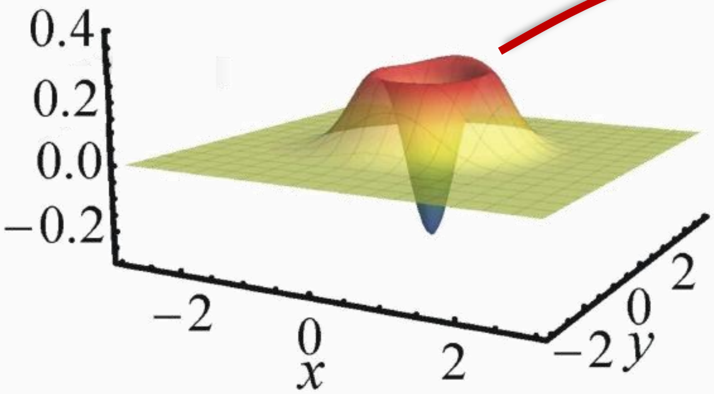
$$\frac{\left(|1\rangle_{\Psi_1}|0\rangle_{\Psi_2} + |0\rangle_{\Psi_1}|1\rangle_{\Psi_2}\right)}{\sqrt{2}}$$

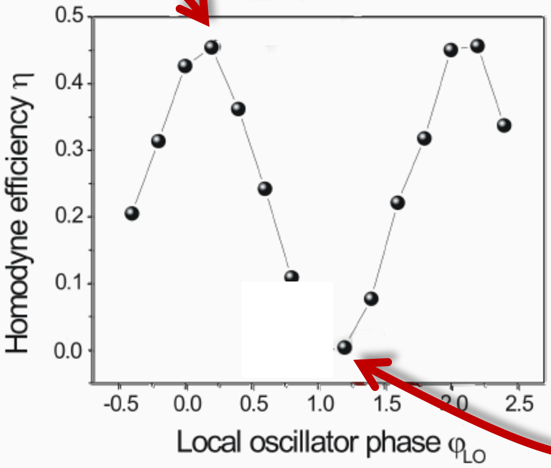




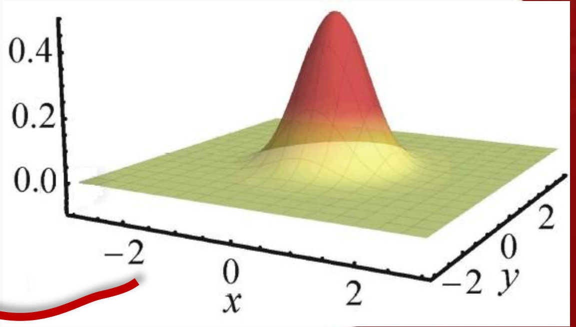
$$\frac{\left(|1\rangle_{\Psi_1}|0\rangle_{\Psi_2} - |0\rangle_{\Psi_1}|1\rangle_{\Psi_2}\right)}{\sqrt{2}}$$

Coherent superposition of two distinct spectral modes



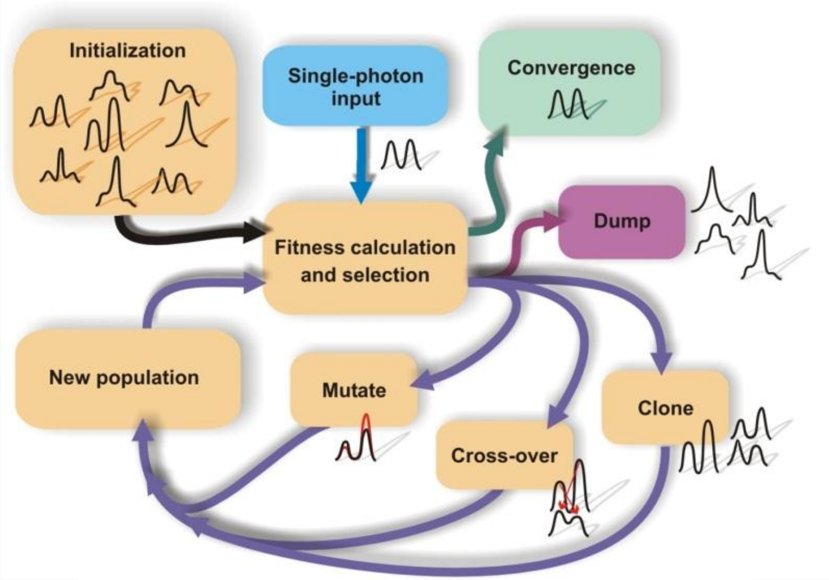


Probe coherence
using shaped LO mode!



What about other quantum states of light?

It is only necessary to have a fitness parameter


Initialization

Single-photon input

Convergence

Fitness calculation and selection

Dump

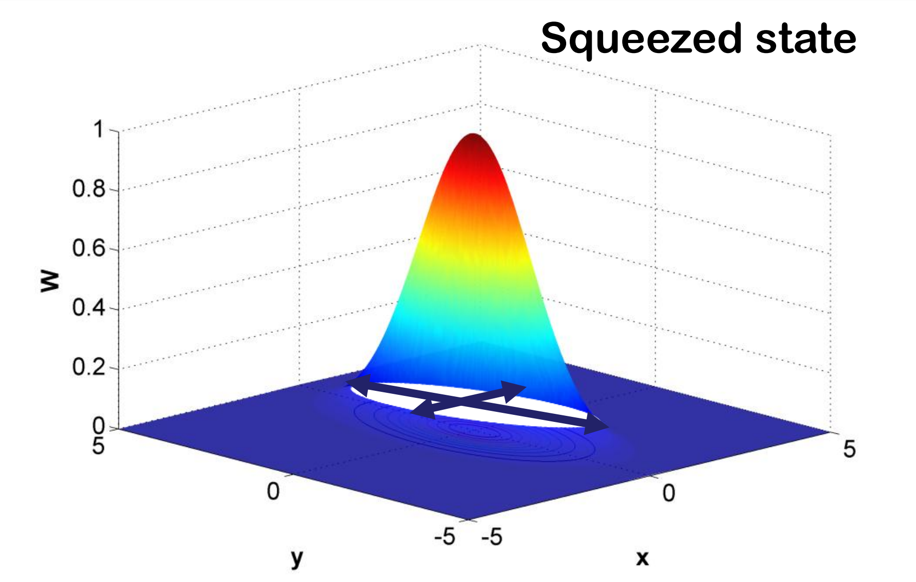
New population

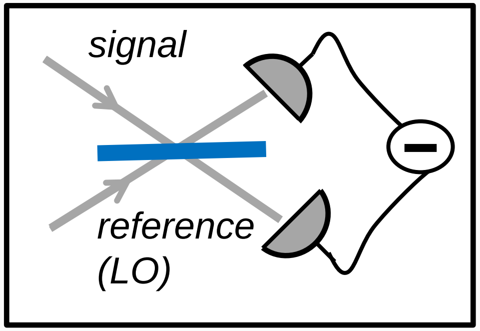
Mutate

Cross-over

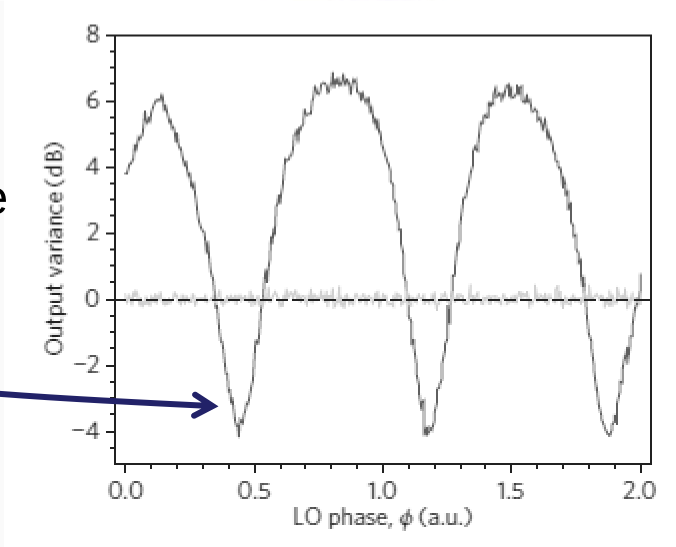
Clone

Can be applied to multiphoton states


Squeezed state

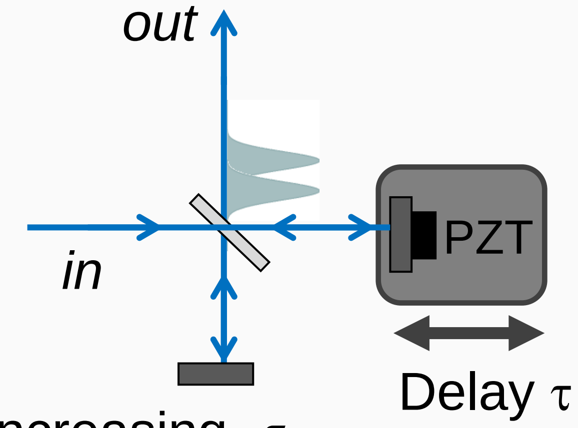


Fitness would be the quantum noise level

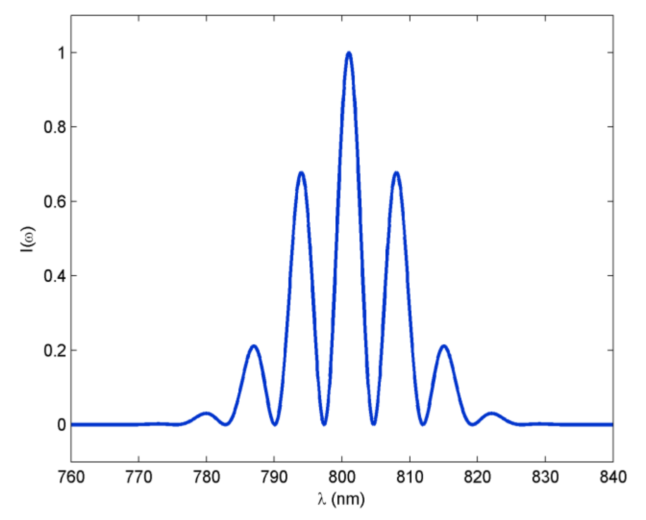


Perspectives: multimode light

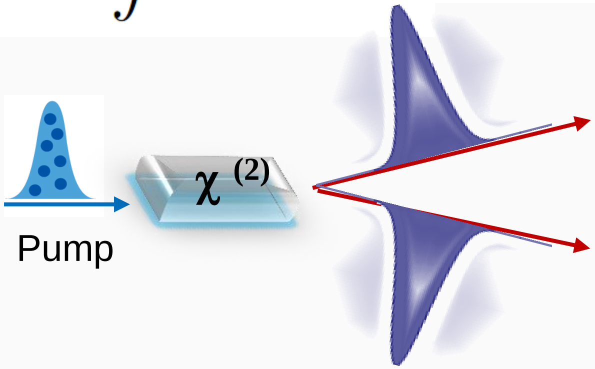
Pump: Michelson interferometer

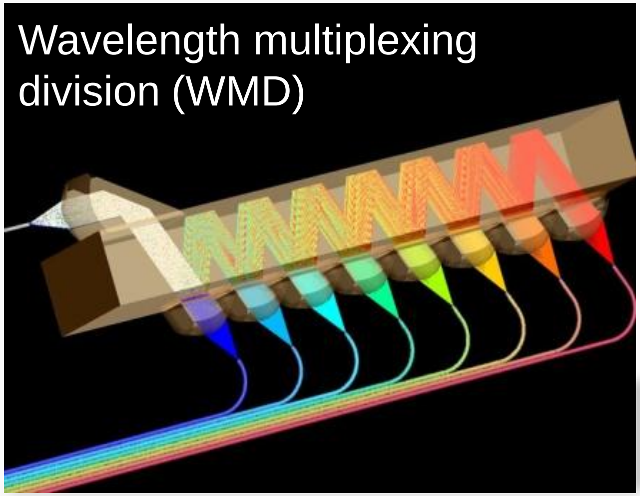


Increasing τ



$$|1\rangle_{\Psi} = \int d\omega \Psi(\omega)\, \hat{a}^{\dagger}(\omega)\, |0\rangle$$

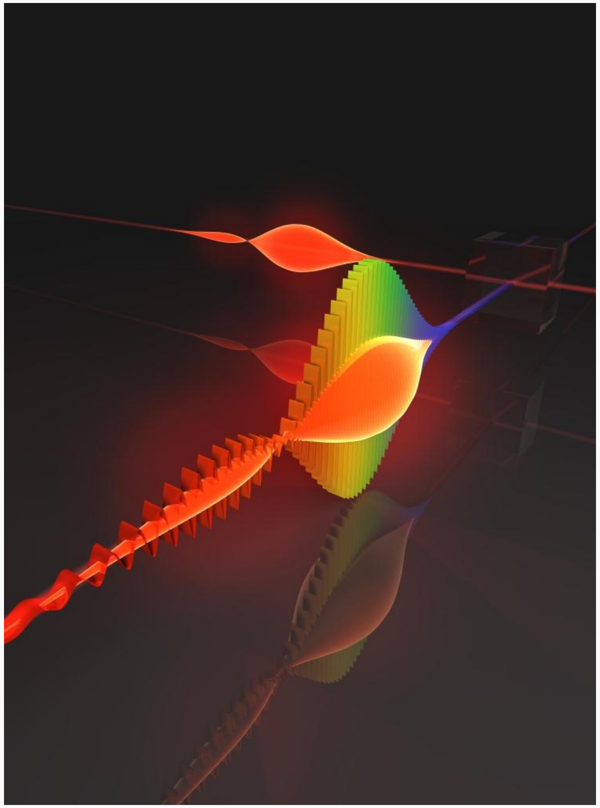




Wavelength multiplexing division (WMD)

Spectro-temporal structure → Platform for encoding quantum information

Conclusions



Tools for CV quantum information processing and quantum metrology

Experimental realization of photon creation and annihilation operators

Noiseless linear amplification

Developed an adaptive homodyne measurement scheme to access and probe a rich multimode structure of quantum states

Florence Quantum Optics Group

- Marco Bellini (INO-CNR, LENS)
- Alessandro Zavatta (INO-CNR, LENS)
- Constantina Polycarpou (Phd Student, LENS)

Active collaborations:

- *Katiuscia Cassemiro, Antonio Sales Coelho (Brasil)*
- Jaromír Fiurášek (Palacký University, CZ)
- Myungshik Kim (Imperial College, UK)
- Werner Vogel, Thomas Kiesel (Uni Rostock, D)

Thank you for your attention!

www.ino.it/home/QOG