INO-CNR
ISTITUTO NAZIONALE DI OTTICA

“Photons beyond qubits”, Olomouc, 16/04/2014

Multimode state generation and detection & hybrid quantum-classical entanglement

Marco Bellini

Istituto Nazionale di Ottica (INO) - CNR
European Laboratory for Nonlinear Spectroscopy (LENS)
Department of Physics, University of Florence

Florence, Italy

lens European Laboratory for Non-Linear Spectroscopy

INO-CNR ISTITUTO NAZIONALE DI OTTICA

STUDIORUM UNIVERSITAS FLORENTINA

www.ino.it

Photons beyond qubits

How to go beyond?

New forms of qubit encodings

Continuous variables
Spatial, temporal, spectral modes

More modes (qudits)

Hybrid discrete/CV entangled qubits

Our tools

Single-photon-level light manipulation

Measuring light at the quantum level

Single-photon addition and subtraction

Balanced homodyne detection

Sequences and superpositions of quantum operators

Multi-mode state analysis and m-m operator superpositions

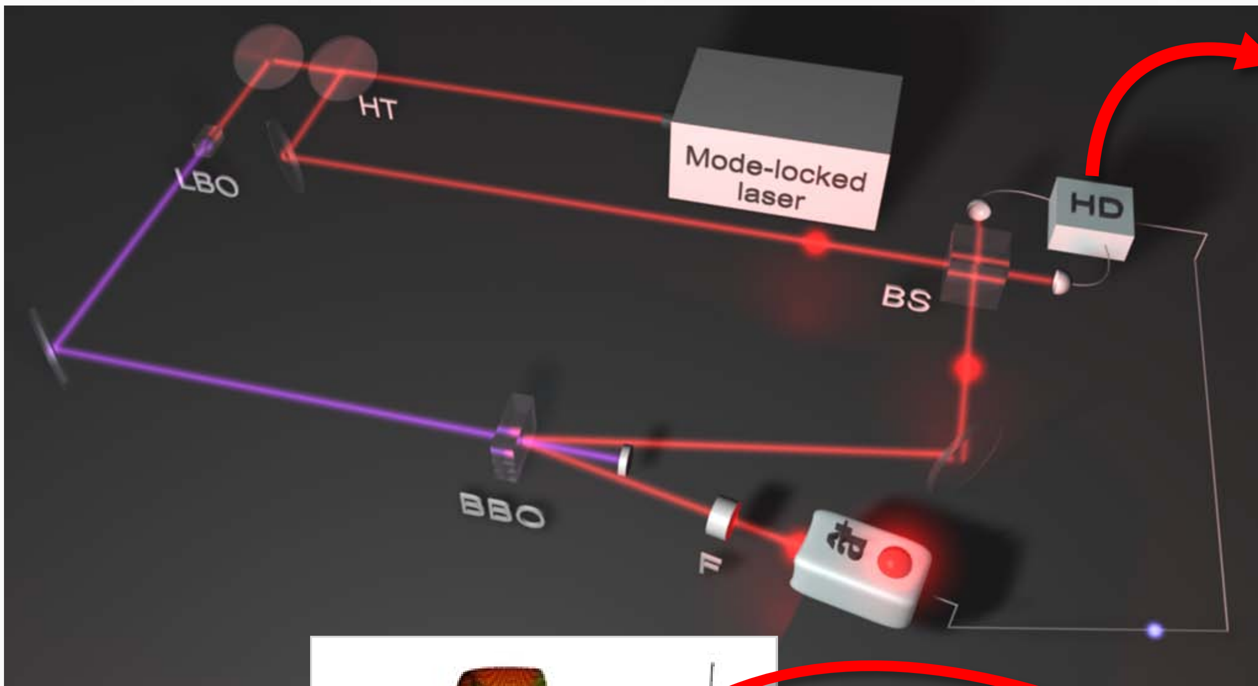
Direct probing of fundamental quantum rules

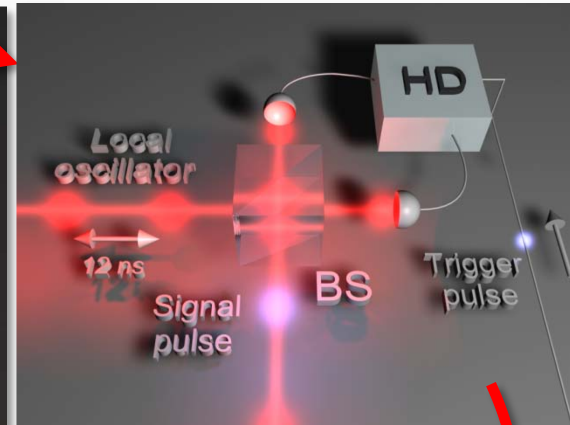
Quantum processes: noiseless amplification, …

Accessing states in arbitrary spectro-temporal modes

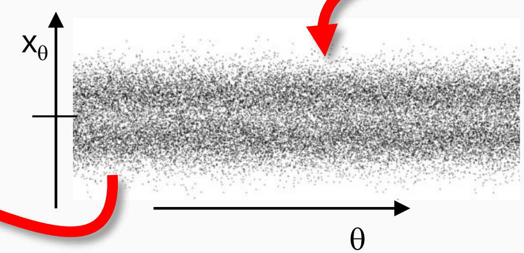
Generating hybrid quantum-classical entangled states

Single photons in the lab

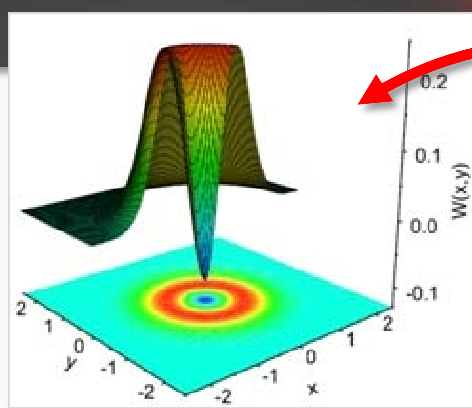




Acquire homodyne data



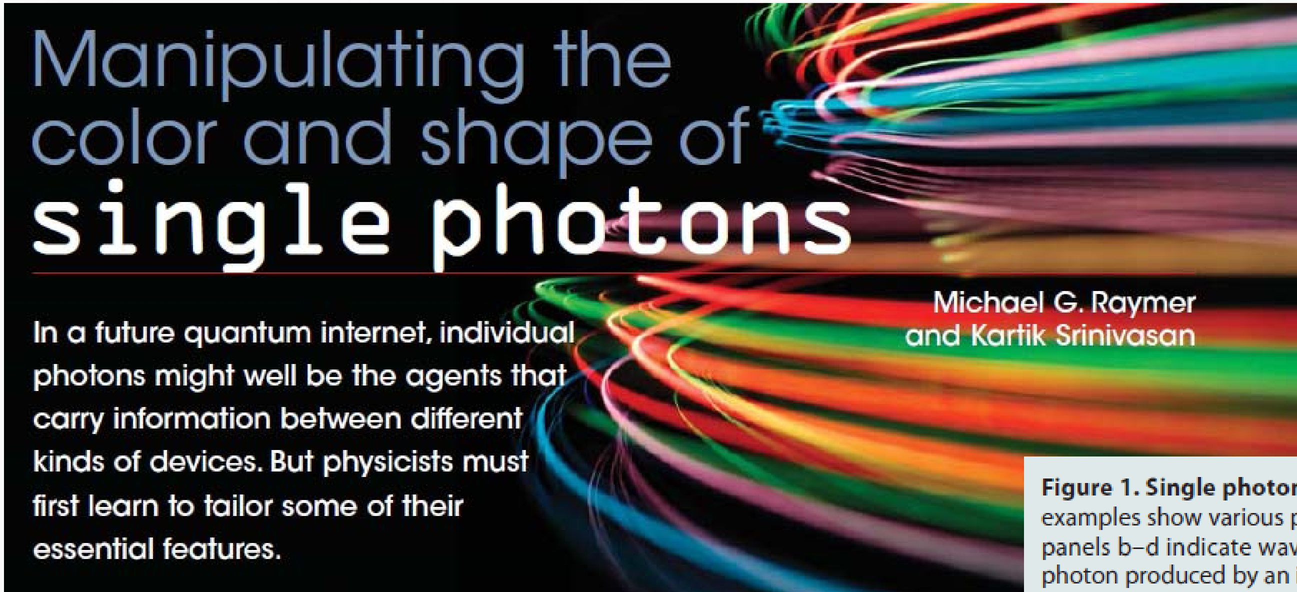
Collect quadrature distributions



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)

The shape of a single photon



Manipulating the color and shape of **single photons**

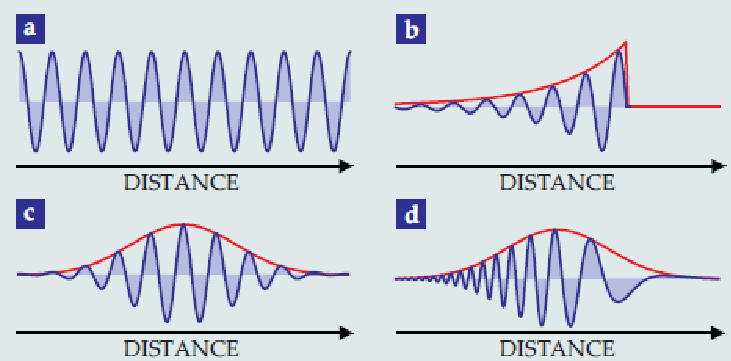
Michael G. Raymer and Kartik Srinivasan

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

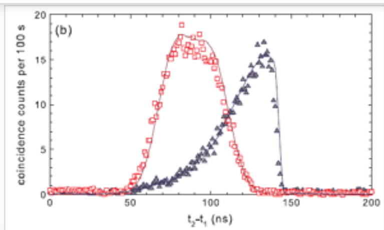
Multimode encoding and detection in higher-dimensional Hilbert spaces

The shape of “long” photons

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

Electro-Optic Modulation of Single Photons

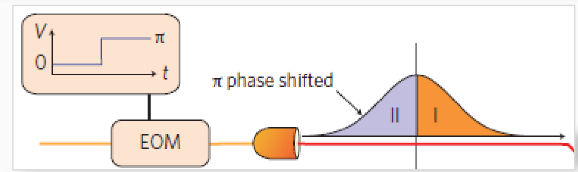
Pavel Kolchin,* Chinmay Belthangady, Shengwang Du, G. Y. Yin, and S. E. Harris



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

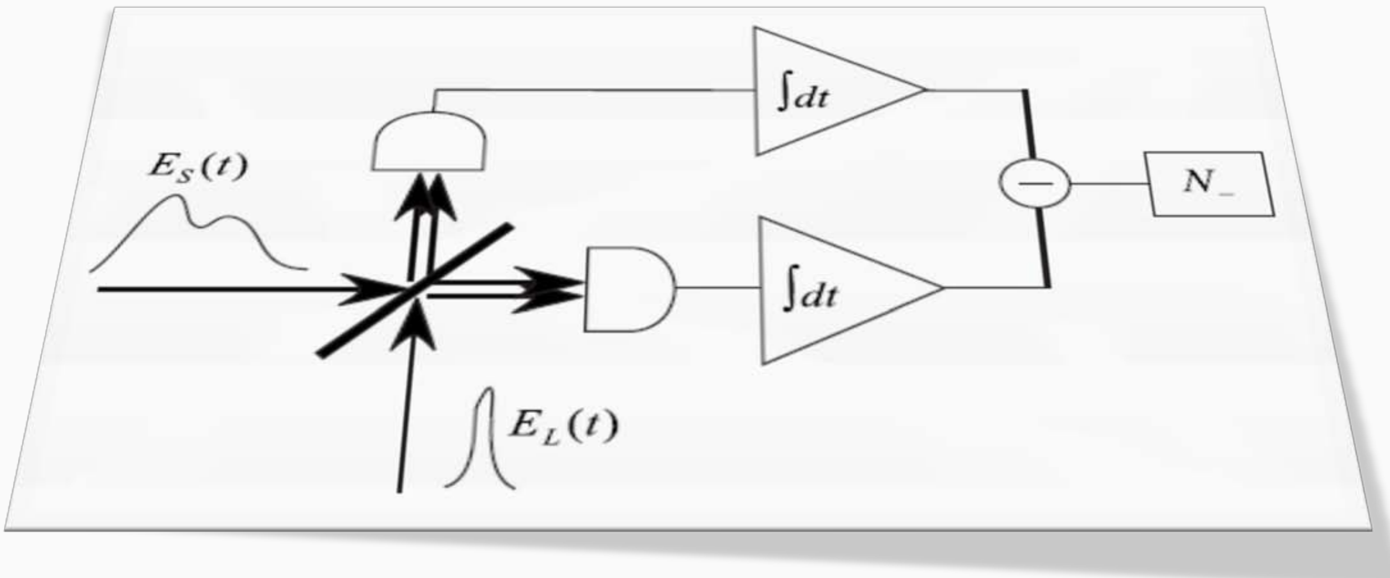
In our case:

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

Ultrafast + Quantum Optics

Modal selectivity of homodyne detection

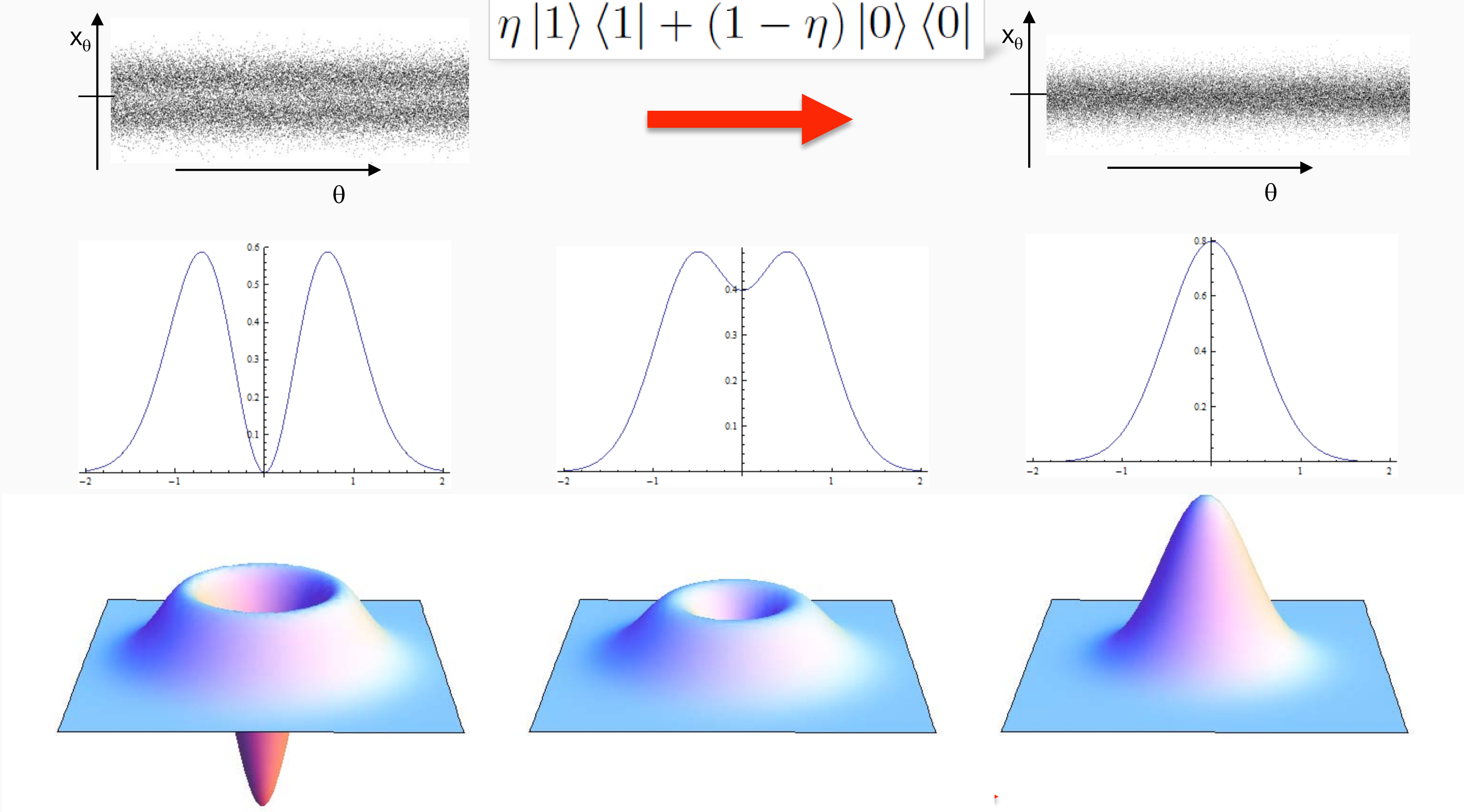
Homodyne detection only extracts information from the signal field in the mode defined by the local oscillator



The (spatial, temporal, spectral, polarization) mode of the local oscillator has to be perfectly matched to that of the state to be measured, otherwise detection efficiency rapidly drops to zero

Wigner function of a single photon

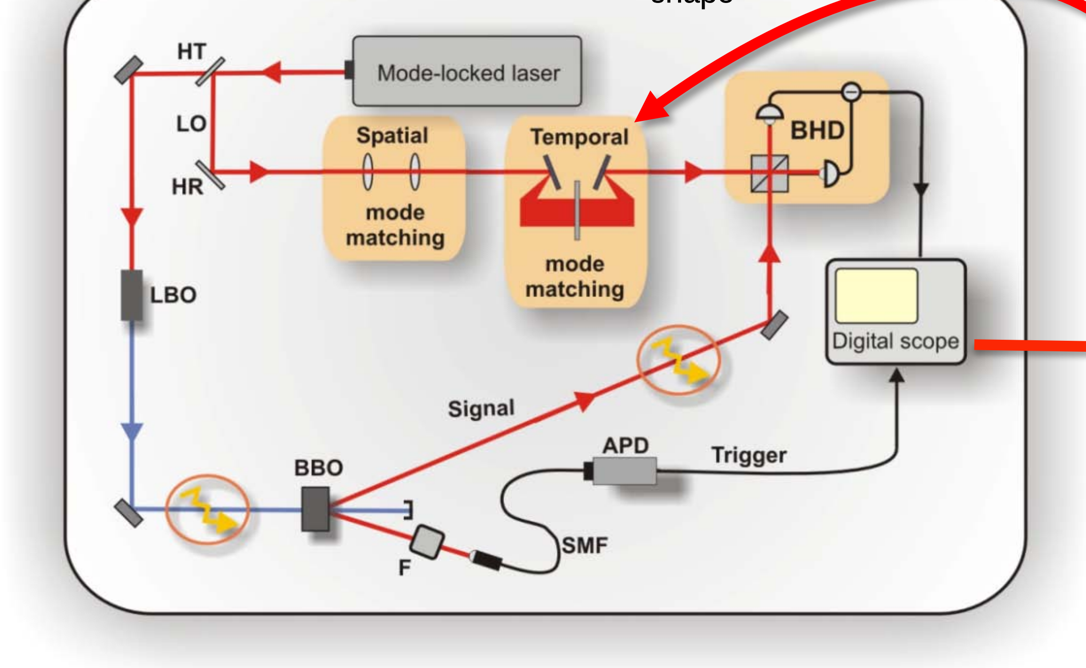
$$\eta \left|1\right\rangle \left\langle 1\right| + (1-\eta) \left|0\right\rangle \left\langle 0\right|$$



Single photon | **decreasing detection efficiency** | **Vacuum**

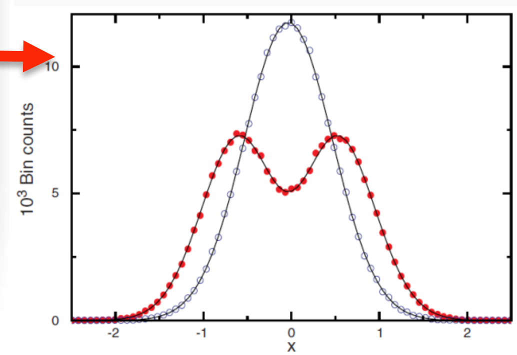
Searching for the photon shape

Adjust the LO shape



Shaping the LO to maximize the homodyne detection efficiency

Calculate the efficiency η



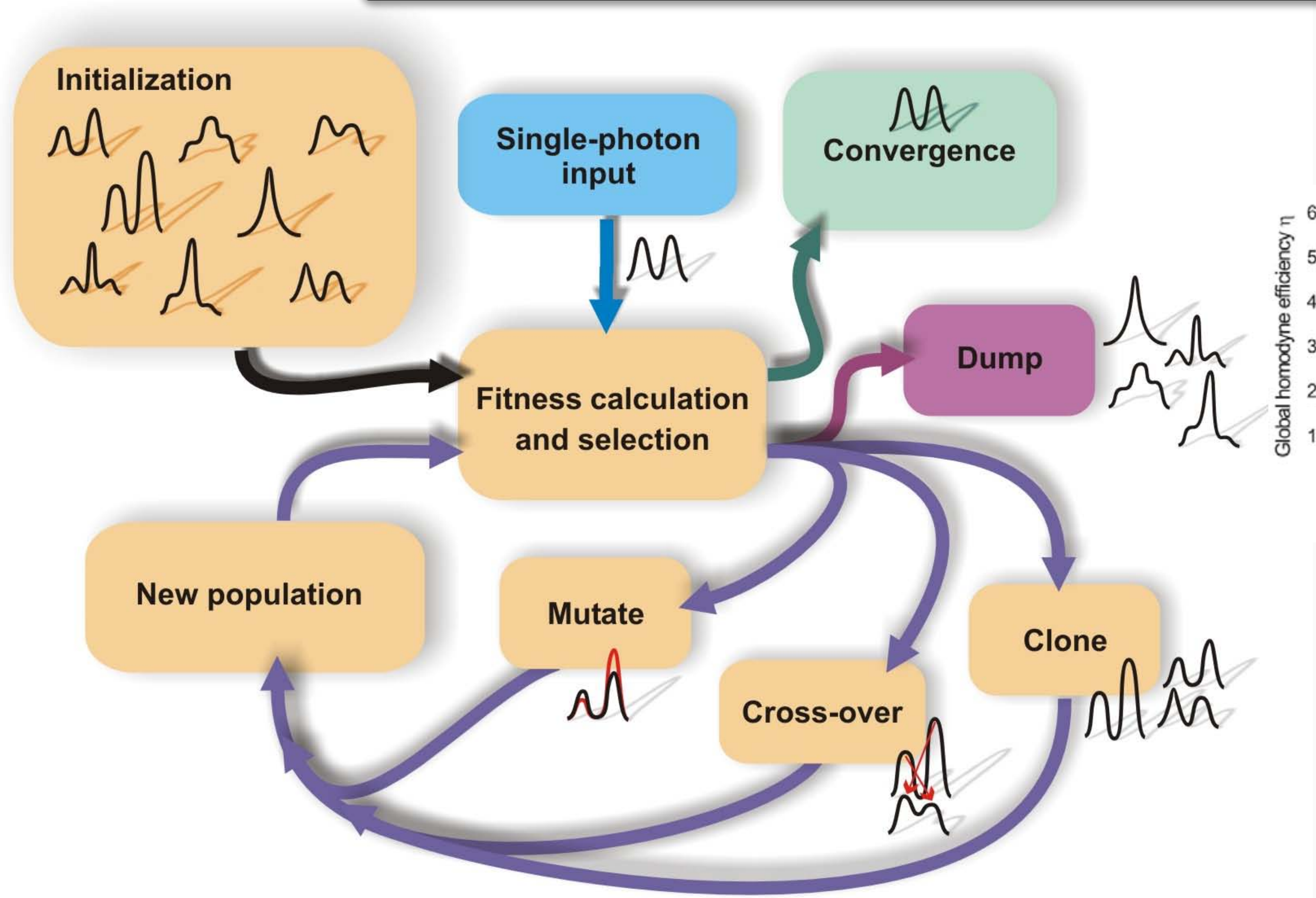
Single-photon quadrature distribution

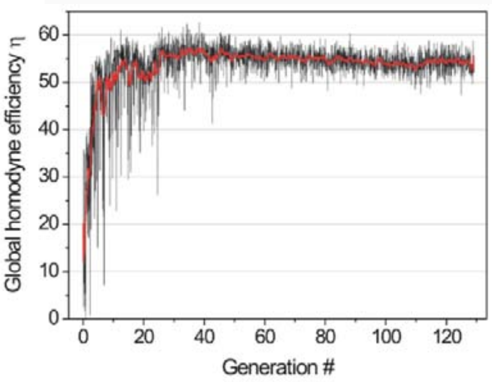
$$\eta |1\rangle\langle 1| + (1-\eta)|0\rangle\langle 0|$$

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

Genetic search of the photon shape

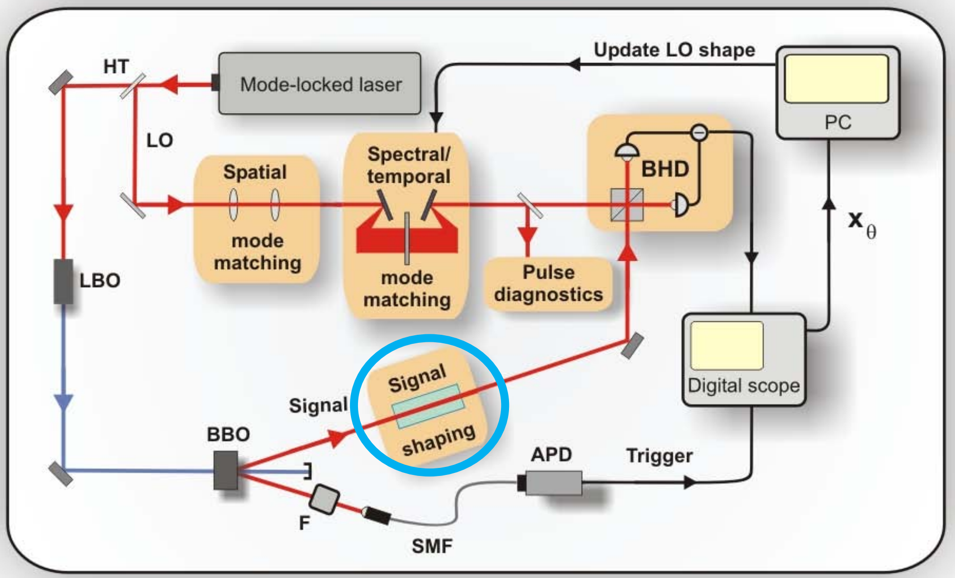
Using an evolutionary algorithm to find the best LO pulse shape



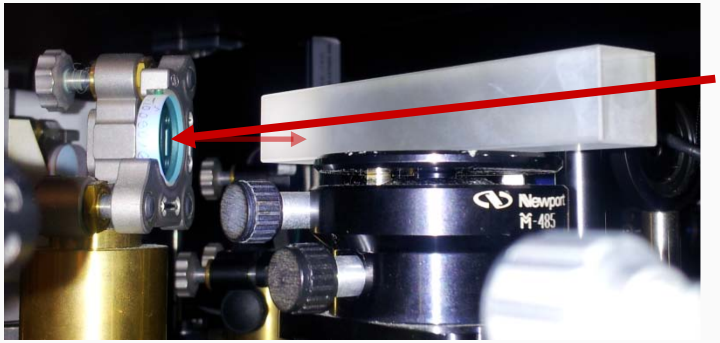


No preliminary information required!

Shaping the photon

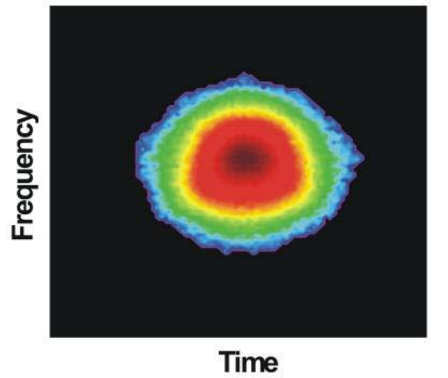


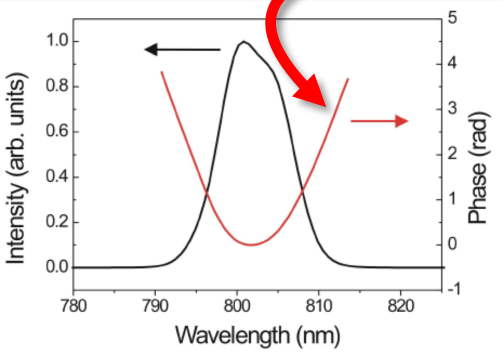
Linear dispersion by propagation through a 10-cm-long block of BK7 glass

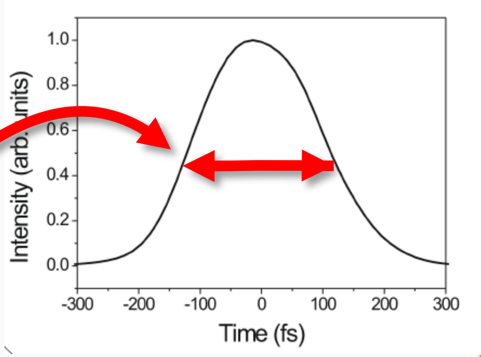


Quadratic spectral phase (positively chirped single-photon pulse)

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

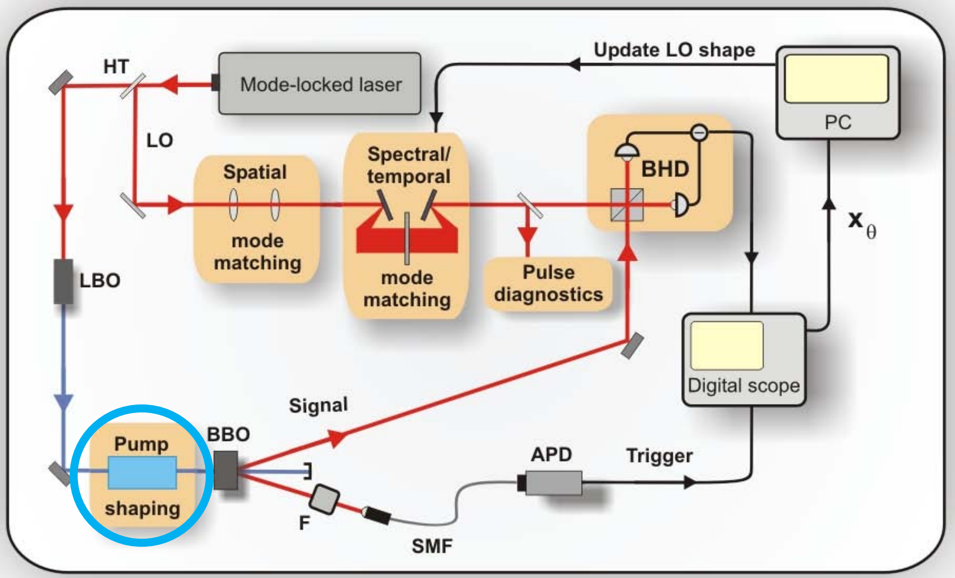






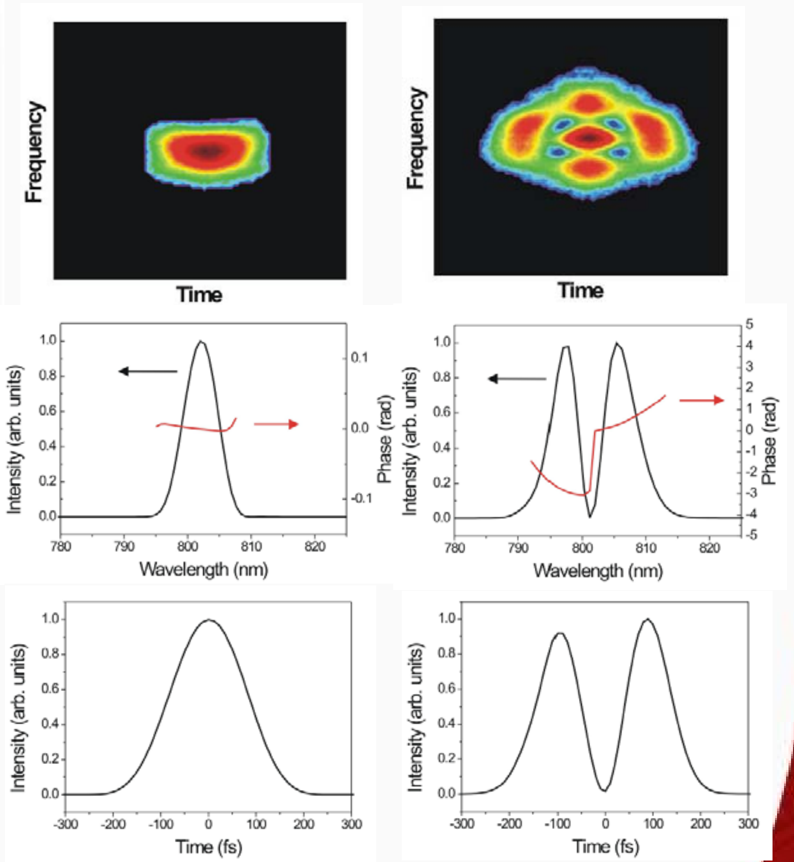
Detection efficiency would drop from ~60% to ~40% without shaping the LO!

More shaping by pump modulation

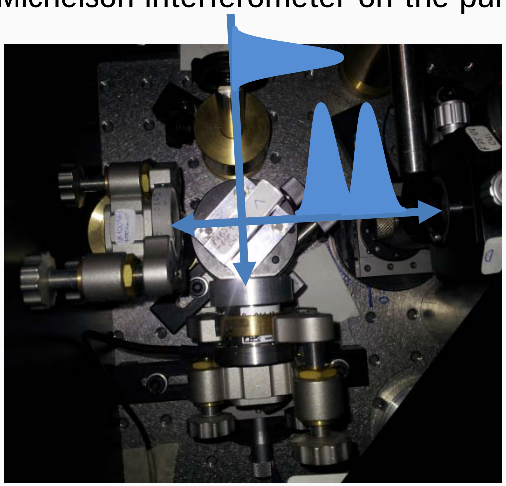


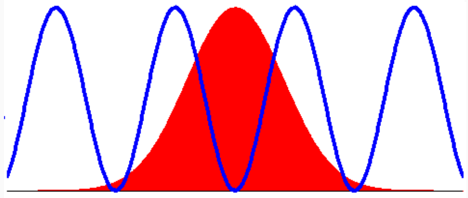
Spectral narrowing

Double spectrotemporal peaks



Michelson interferometer on the pump





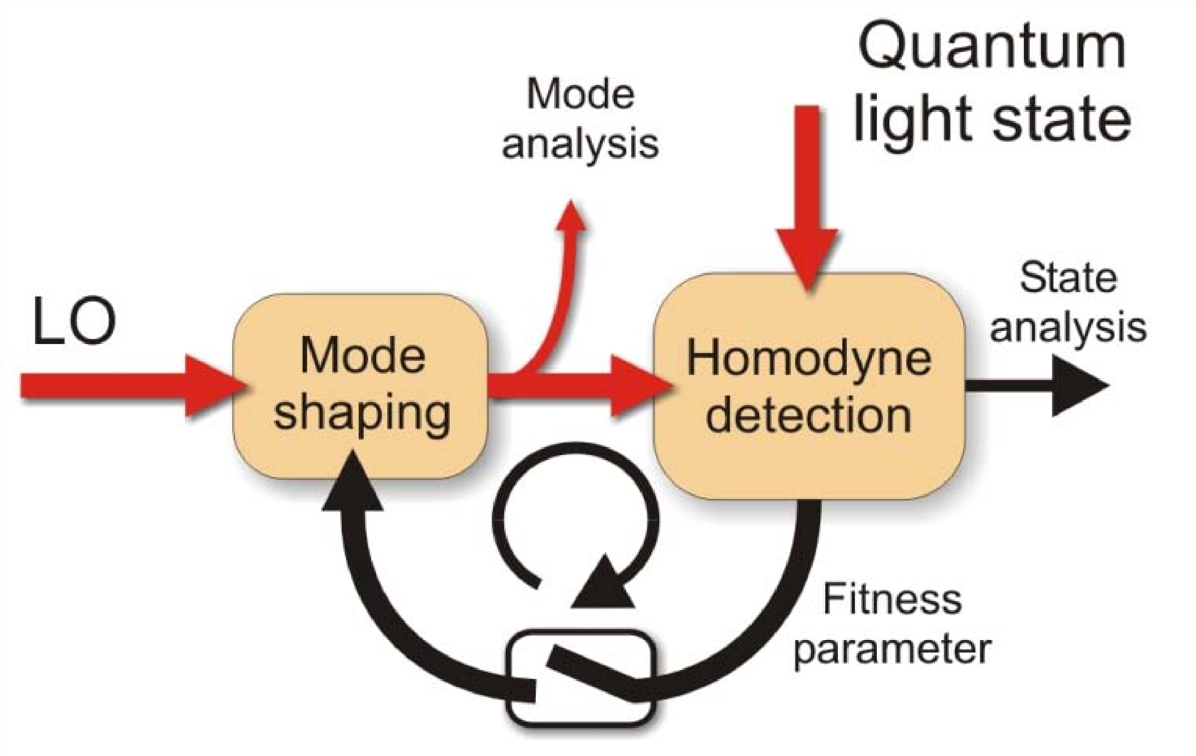
frequency

Sinusoidal modulation of the pump spectrum

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

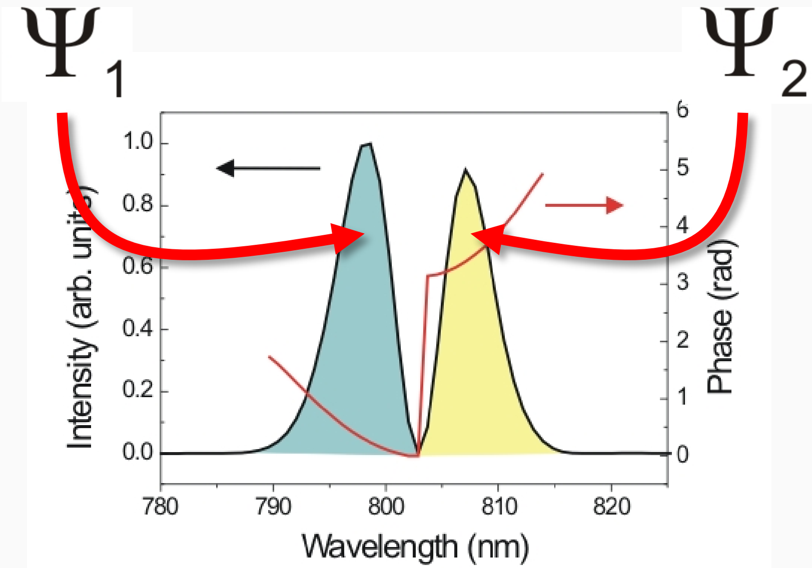
Exploiting the modal selectivity

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

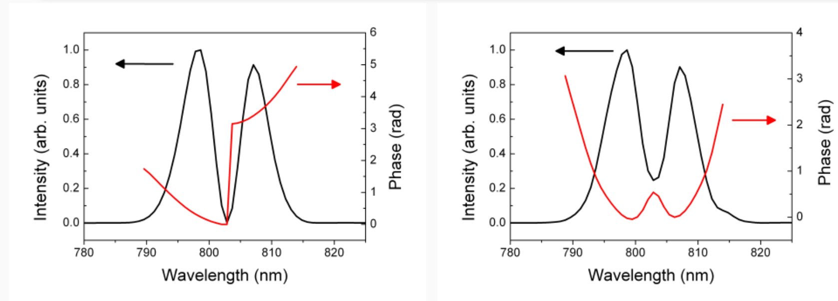
A single-photon spectral qubit



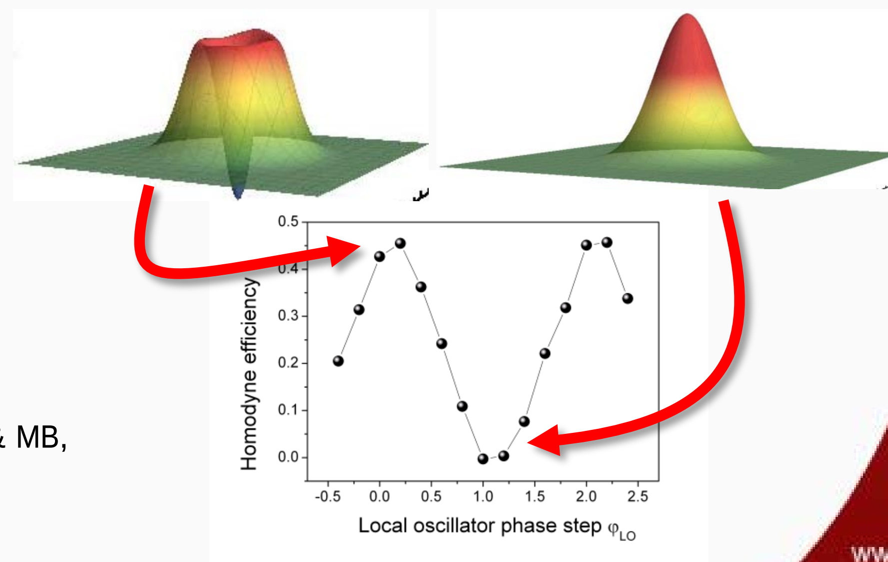
The single photon is in a coherent superposition of two distinct spectral modes

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

Probing coherence by HD with shaped LO modes



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

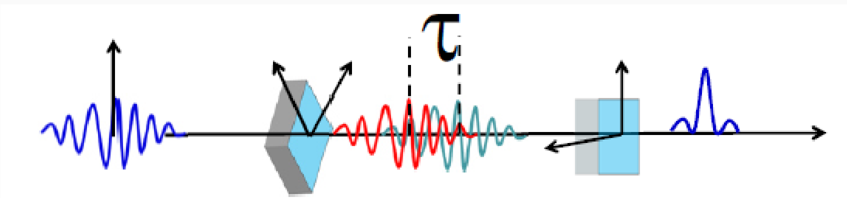


C. Polycarpou, K. Cassemiro, G. Venturi, A. Zavatta, & MB, *Phys. Rev. Lett.* **109**, 053602 (2012)

INO-CNR
Istituto Nazionale di Ottica

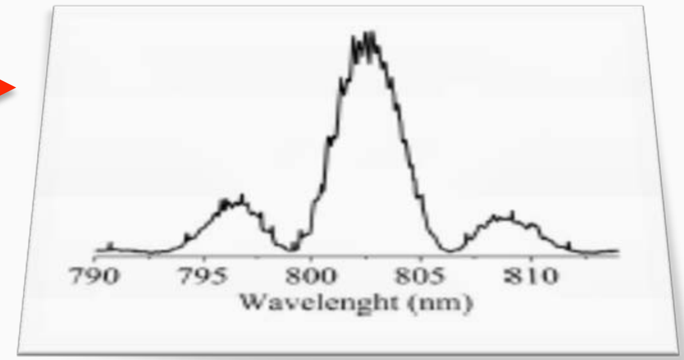
Exploring single-photon spectral **qudits**

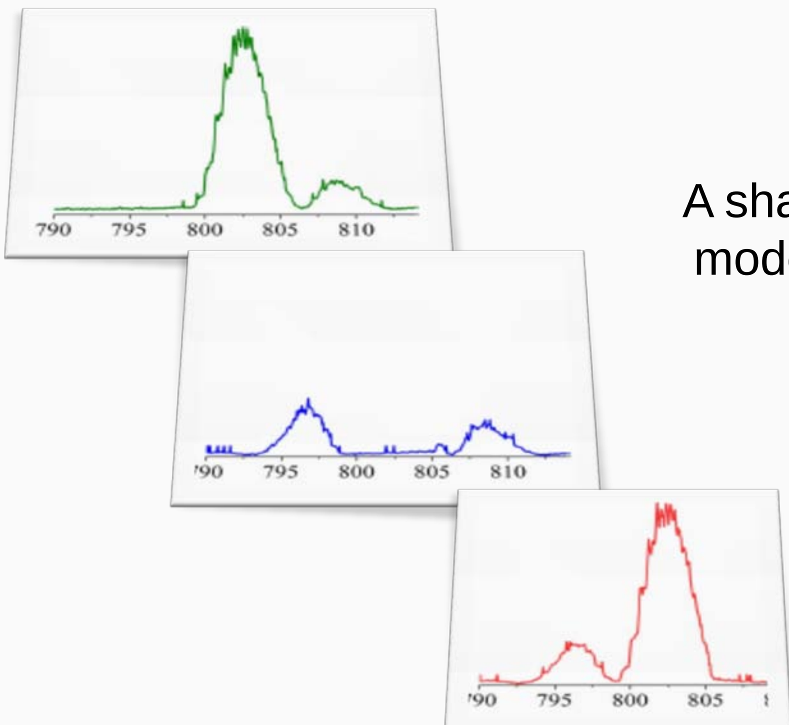
Generating more frequency bins by properly shaping the pump



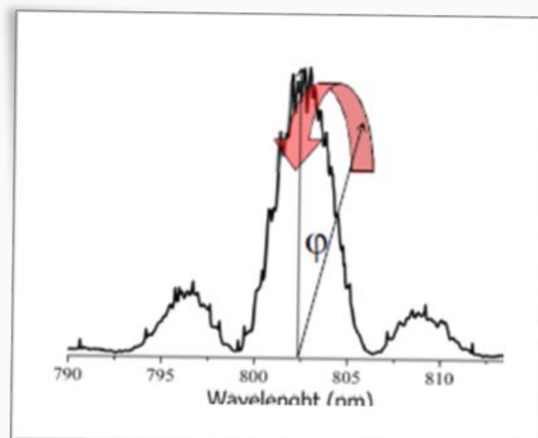
Use a birefringent crystal for stable pump shaping

A 3-peaked single photon





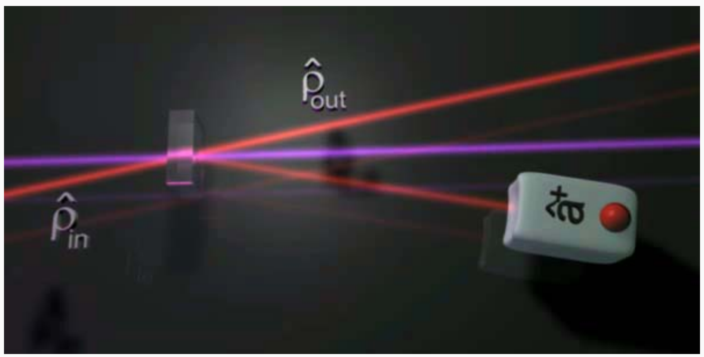
A shaped LO can probe combinations of the three modes with different relative weights and phases



work in progress...

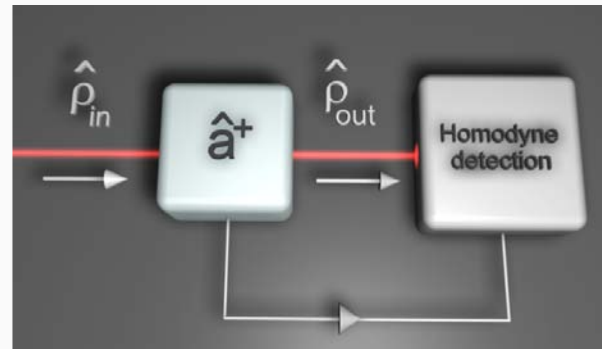
Beyond the single photon

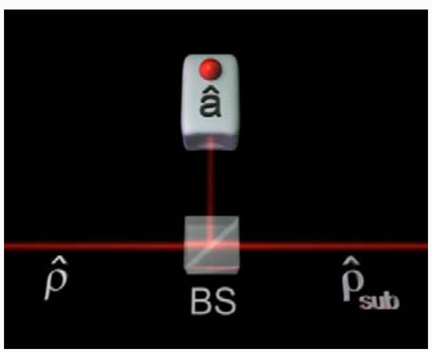
Introducing our (single mode) quantum toolbox



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

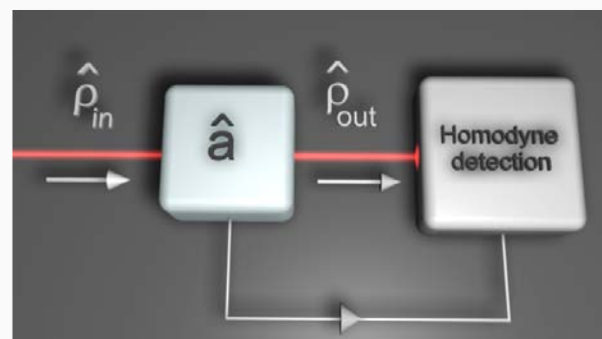
- small PDC gain
- small photon numbers





$$\hat{a}$$

- small BS reflectivity
- small photon numbers

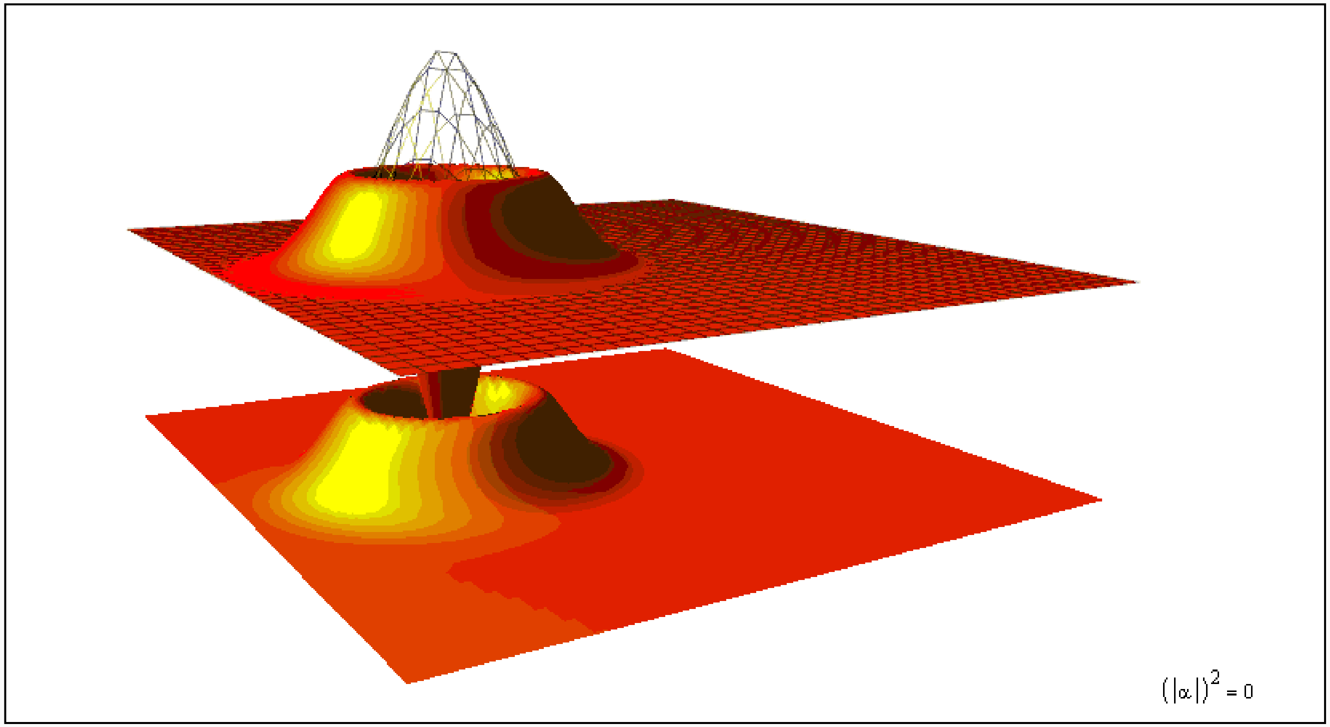


Non-deterministic (heralded) generation schemes

INO-CNR Istituto Nazionale di Ottica

Single-photon-added coherent states

$$\hat{a}^{\dagger}\,|\alpha\rangle$$



The SPACS resembles a coherent state for large input amplitudes $|\alpha|$

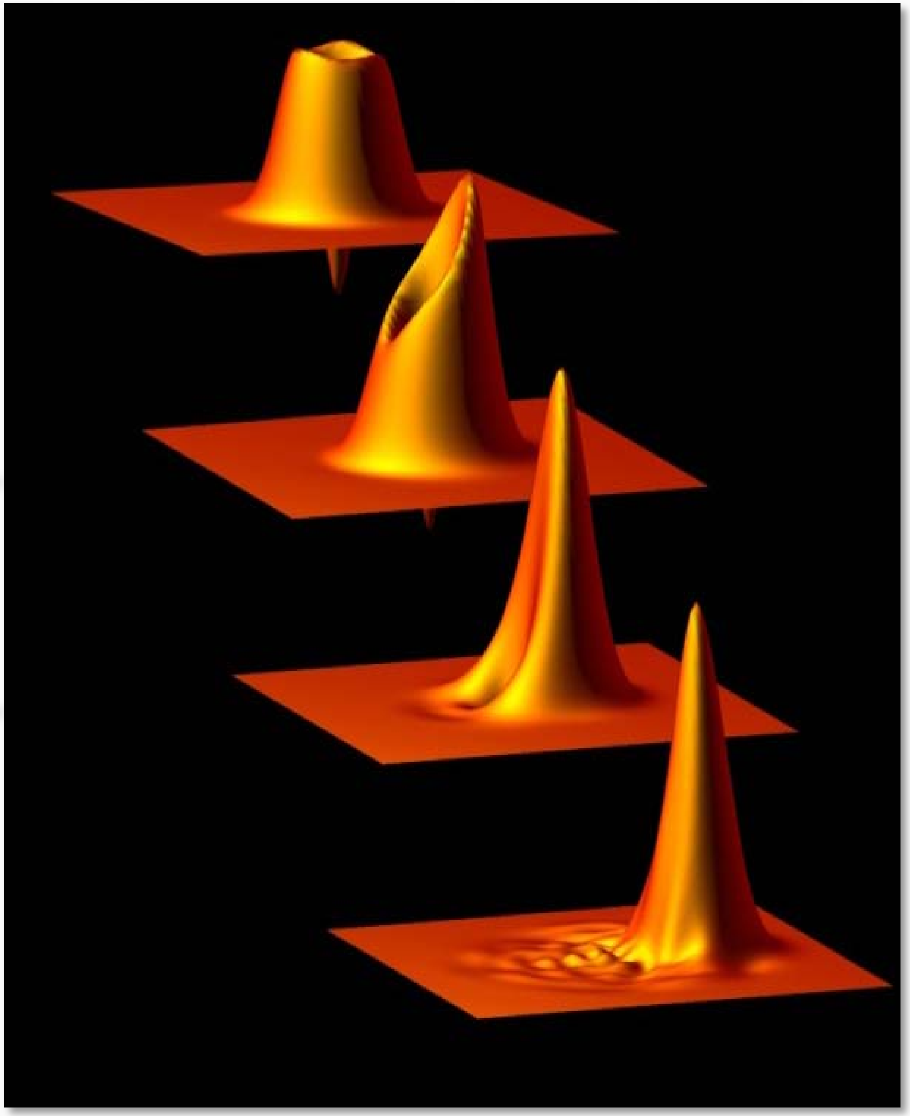
Quantum-to-classical transition

$|\alpha| = 0$

$|\alpha| = 0.387$

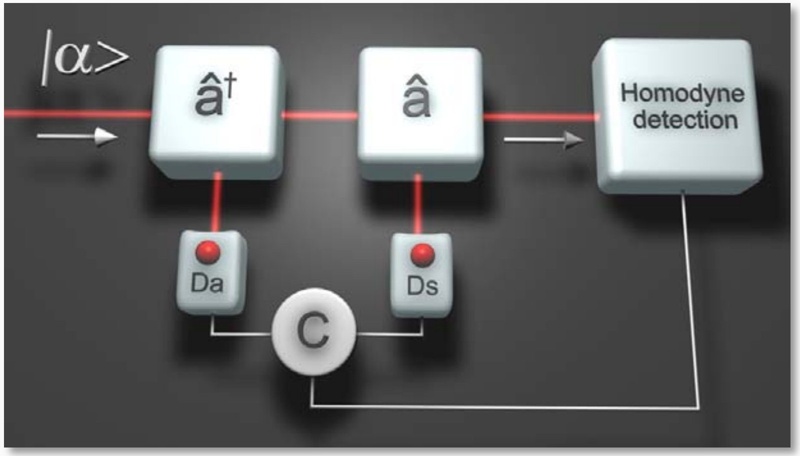
$|\alpha| = 0.723$

$|\alpha| = 3.74$



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

Sequences of quantum operators



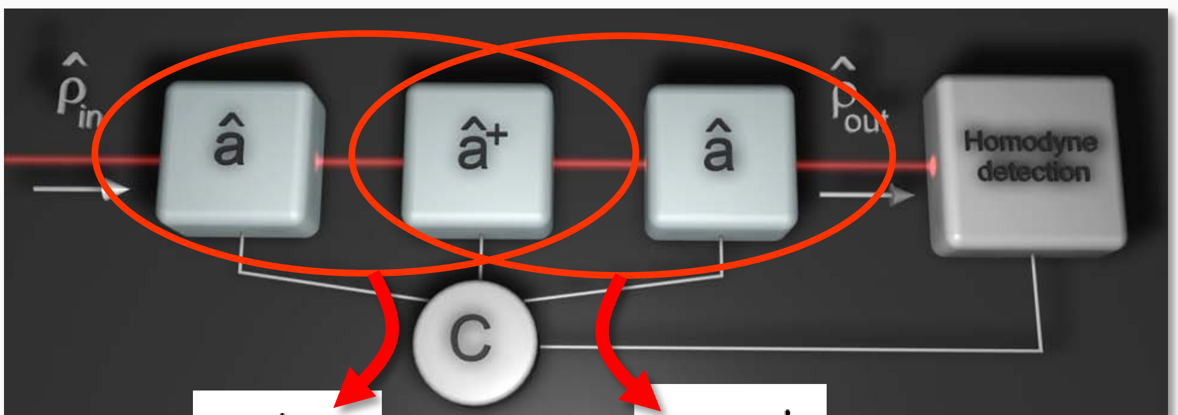
Noiseless amplification

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]*

Direct test of quantum non-commutativity



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

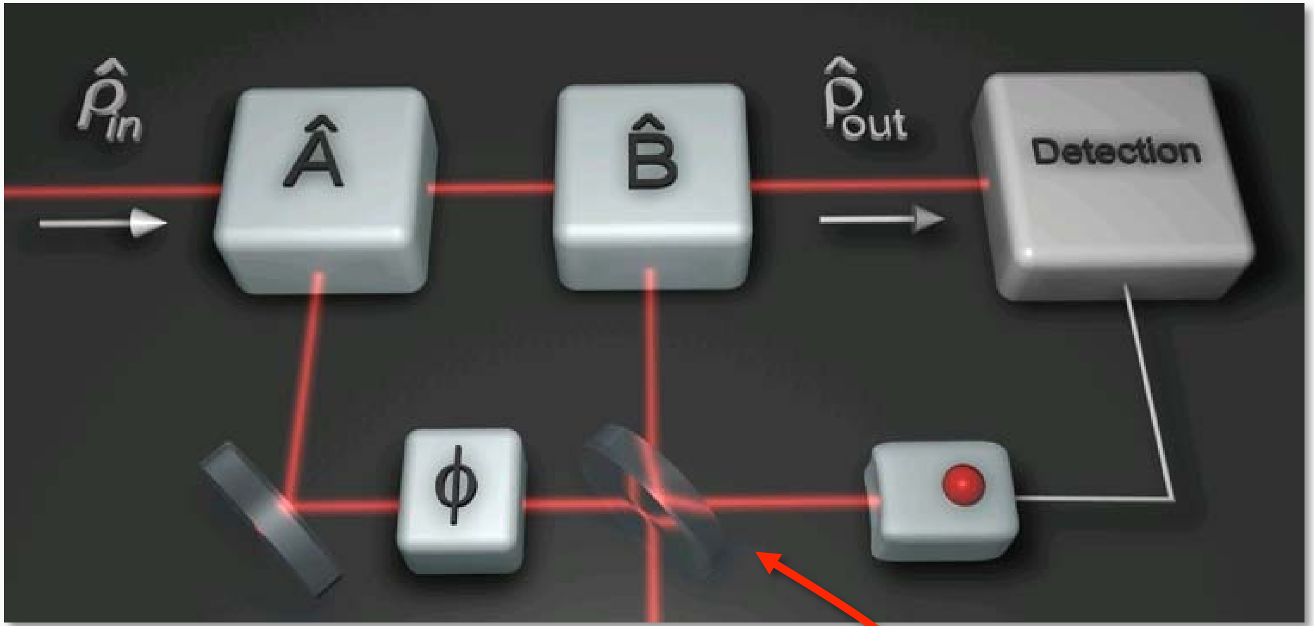
$$\hat{a}\hat{a}^\dagger$$

Science

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

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

Superpositions of quantum operators

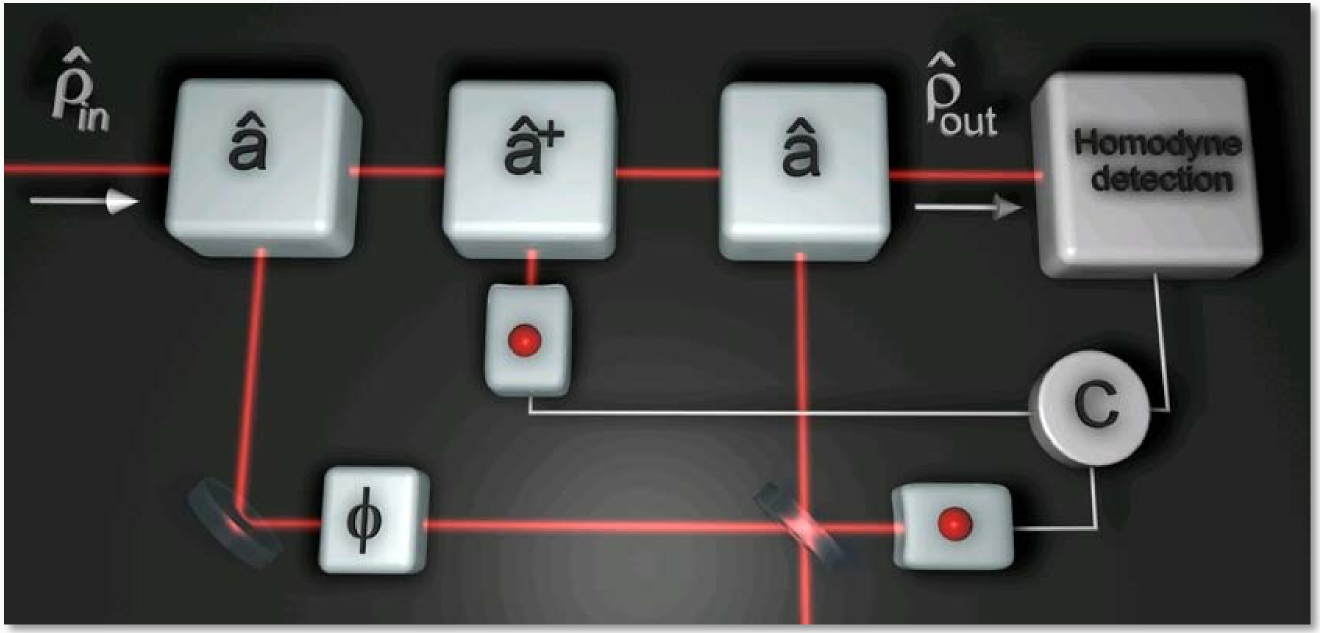


Erases the information about the origin of a "click"

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

Arbitrary superpositions of operators can be implemented

Experimental test of commutation rules

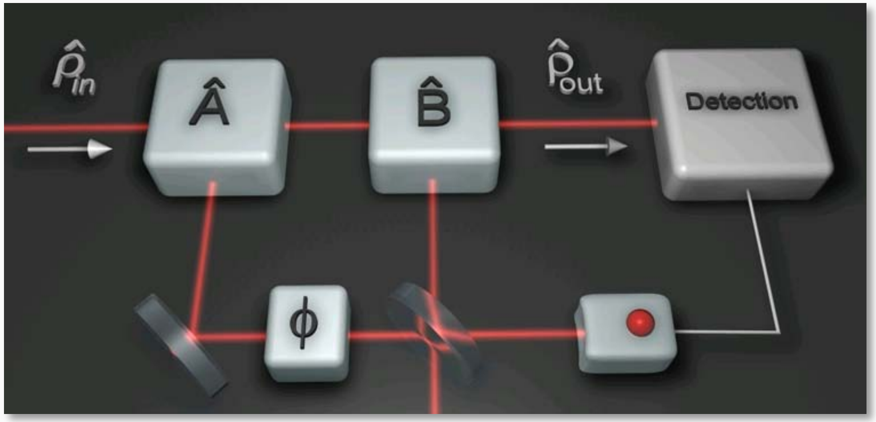


$$[\hat{a}, \hat{a}^\dagger] = \hat{a}\hat{a}^\dagger - \hat{a}^\dagger\hat{a} = \mathbf{1}$$

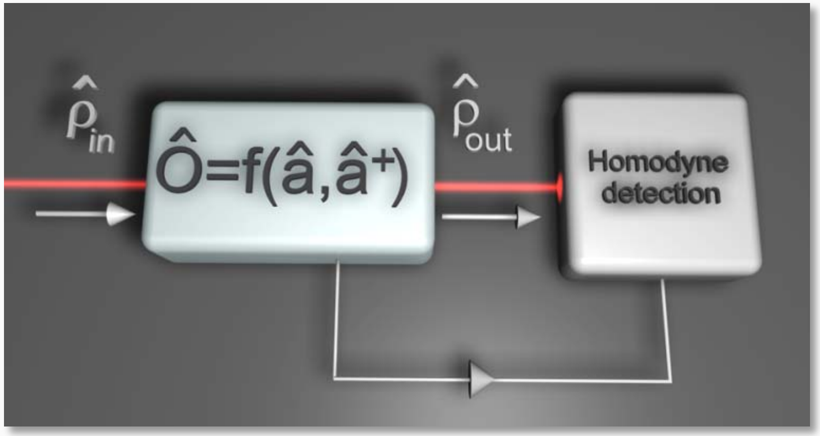
M. S. Kim, H. Jeong, A. Zavatta, V. Parigi, & MB, *PRL* **101**, 260401 (2008) **Theory**
A. Zavatta, V. Parigi, M. S. Kim, H. Jeong, & MB, *PRL* **103**, 140406 (2009) **Experiment**

Going multi-mode

So far, all operations have been performed in a **~~single~~, ~~well-defined~~, mode**



Single-mode superposition of quantum operators



Generic combination of sequences and superpositions of basic operators

How to extend our quantum tools to work in a multi-mode regime?

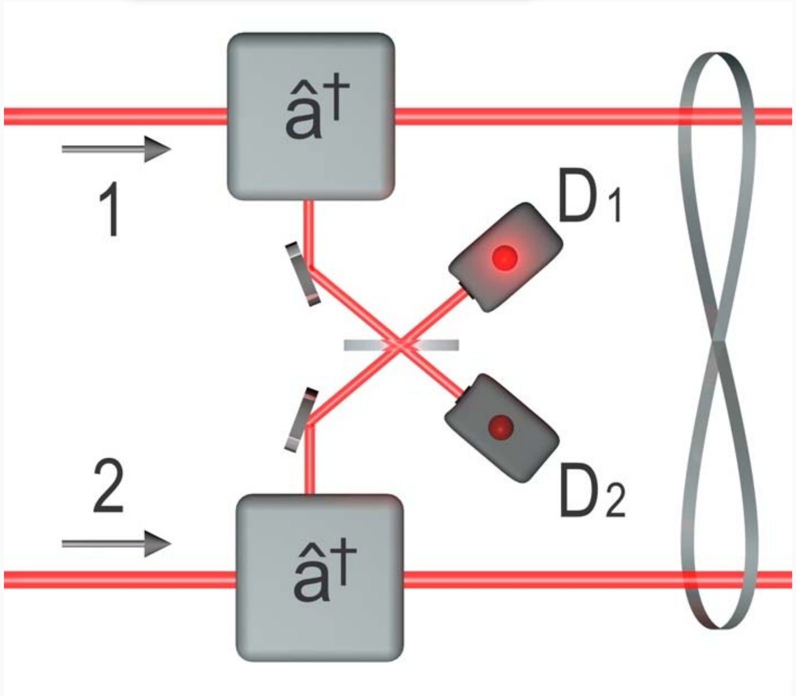
Superposition of operators on two modes

$$r\hat{a}_1^\dagger + t\hat{a}_2^\dagger$$

Delocalized photon addition on modes 1 and 2

$$|0\rangle_1$$

$$|0\rangle_2$$



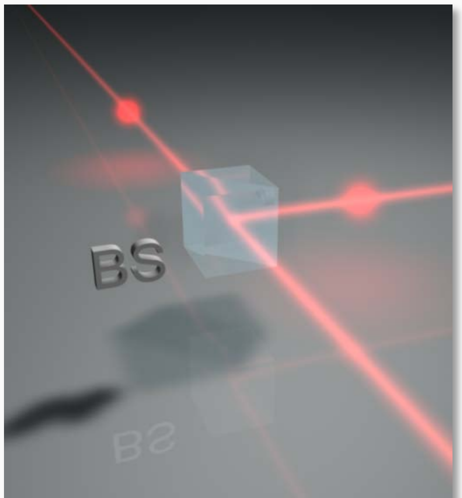
$$\frac{1}{\sqrt{2}}(|1\rangle_1 |0\rangle_2 + |0\rangle_1 |1\rangle_2)$$

Single-photon path-entangled state

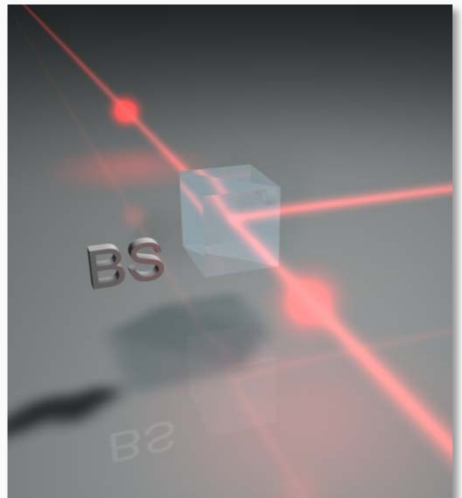
Two distinct spatial modes get entangled by sharing a single photon

Single-photon entanglement

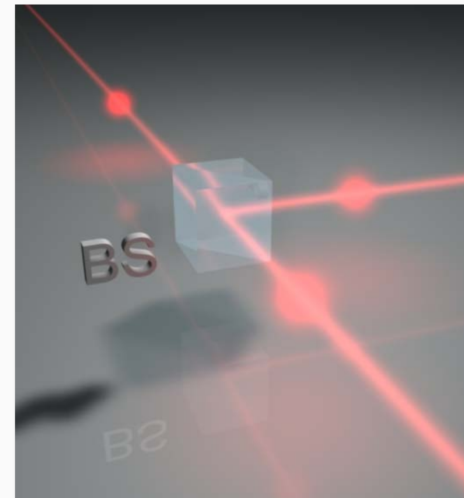
Indistinguishable alternatives



+



=



Classical particle

Quantum particle

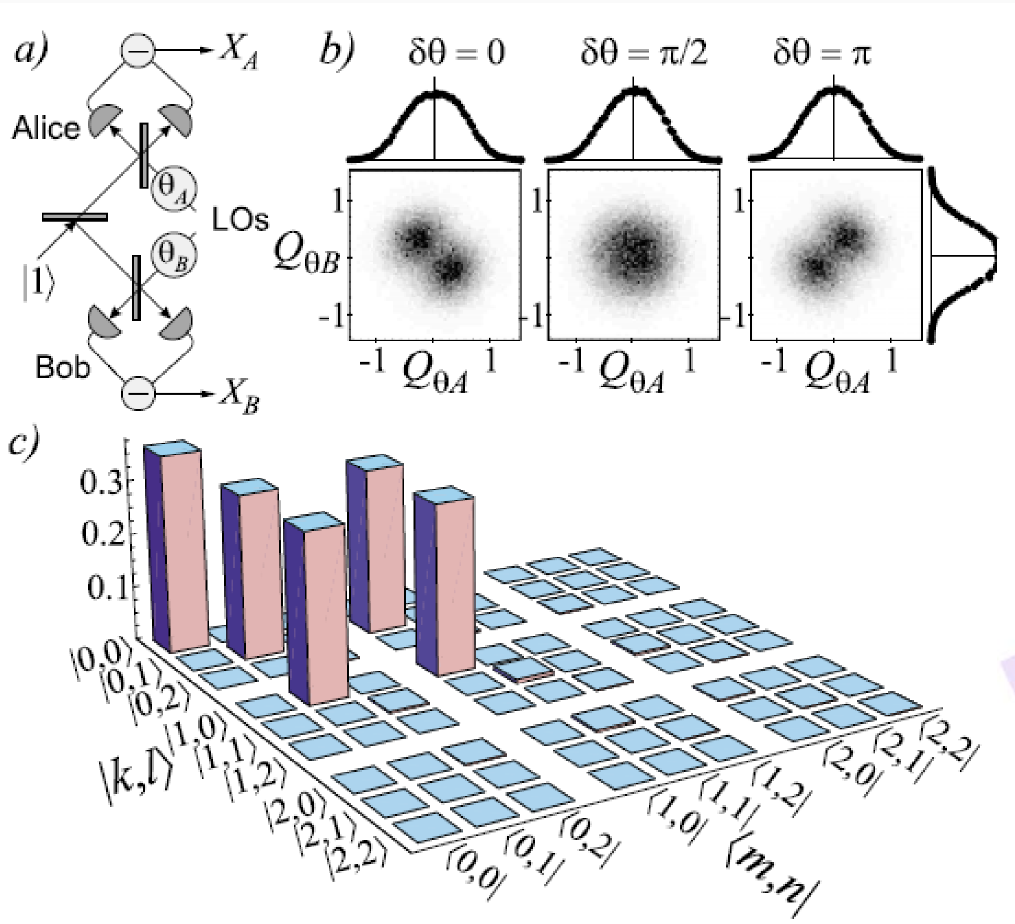
$$\frac{1}{\sqrt{2}}\left(|1\rangle_A|0\rangle_B + |0\rangle_A|1\rangle_B\right)$$

Single-photon path-entangled state

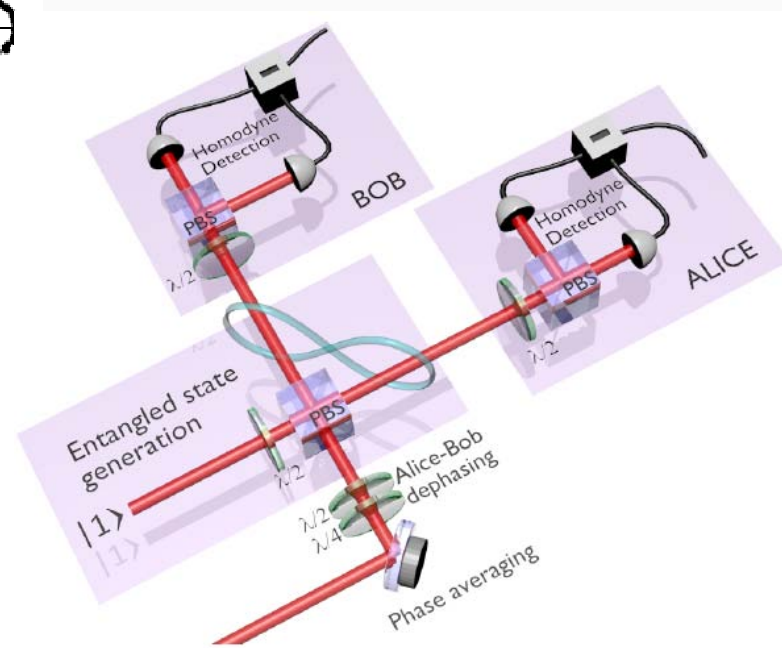
"Here" and "there" at the same time

Experimental single-photon entanglement

Babichev S. A., J. Appel, and A. I. Lvovsky, 2004, Phys. Rev. Lett. **92**, 193601.



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



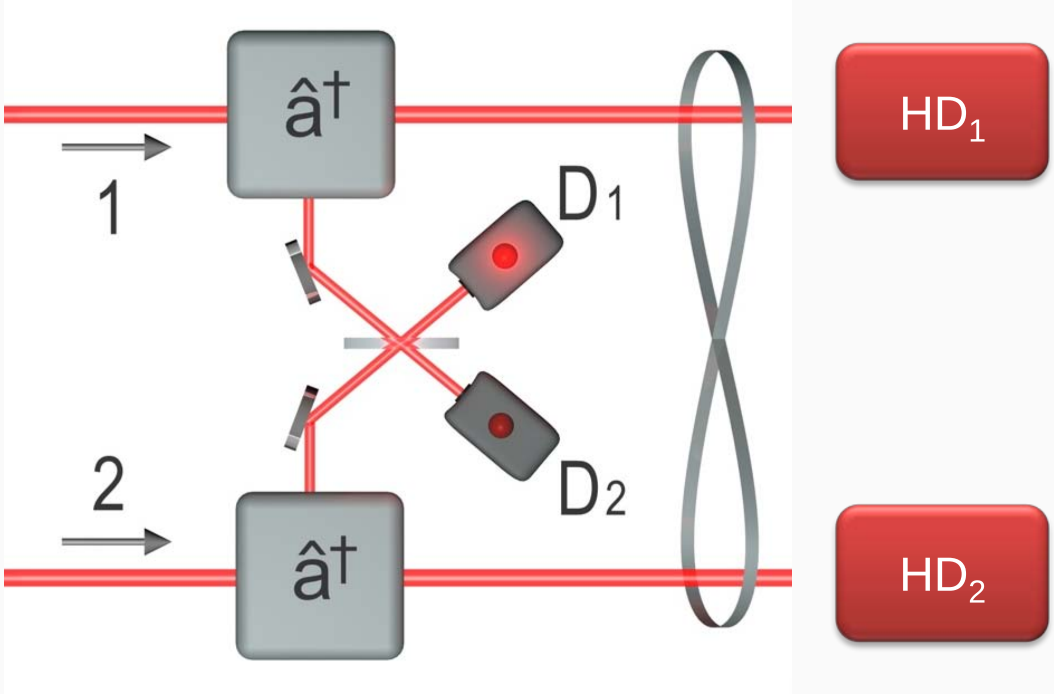
O. Morin, J.-D. Bancal , M. Ho, P. Sekatski, V. D'Auria, N. Gisin, J. Laurat and N. Sangouard . 2013 Phys. Rev. Lett. 110, 130401

Superposition of operators on two modes

$$\frac{1}{\sqrt{2}}(|1\rangle_1 |0\rangle_2 + |0\rangle_1 |1\rangle_2)$$

$|0\rangle_1$

$|0\rangle_2$

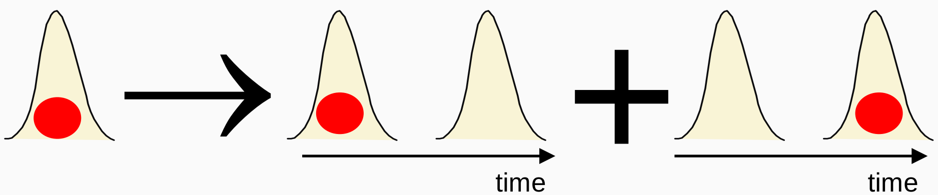


It requires two PDC sources and two homodyne detectors

Not a very clever solution...

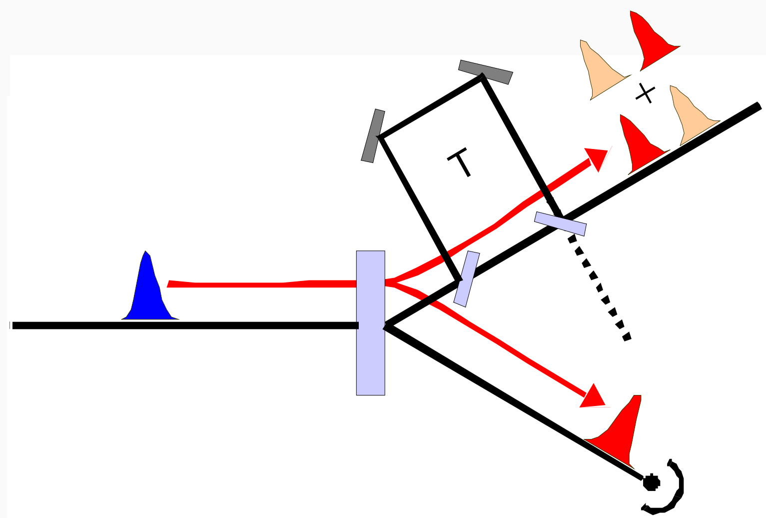
Time-delocalized single photons

Spatial modes → Temporal modes



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

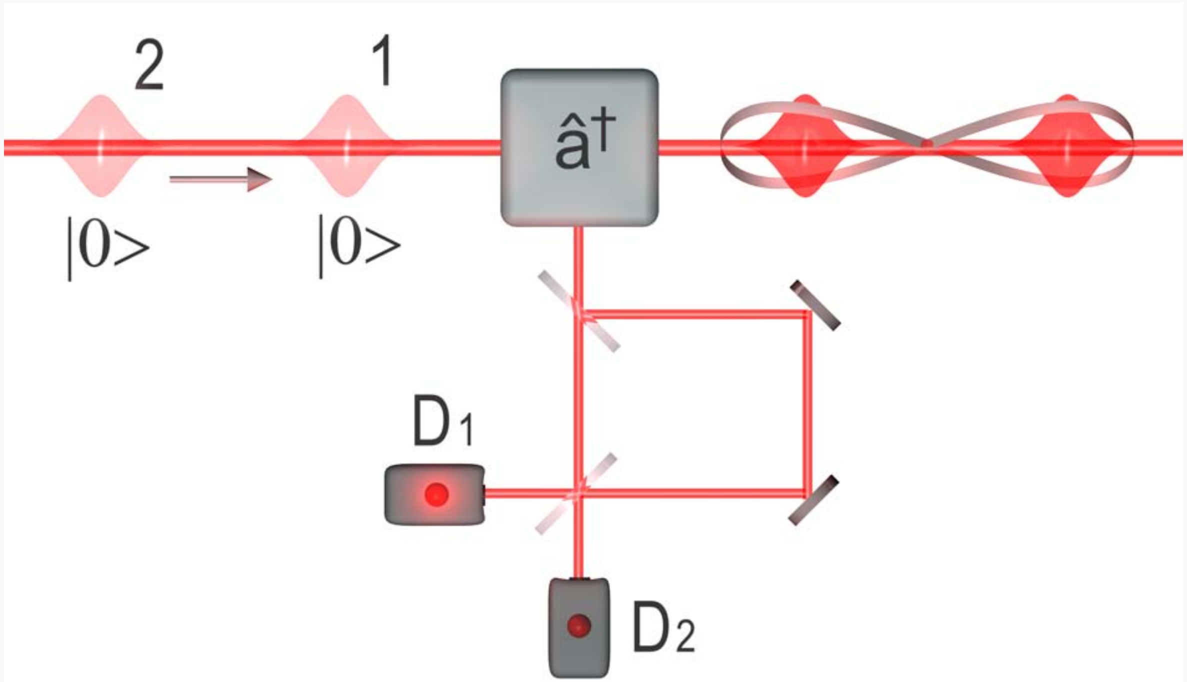
"Sooner" and "later" at the same time (?!?)



High losses ...

A single-photon time-bin qubit

Coherent superposition of two photon-addition processes onto two different traveling wavepacket temporal modes



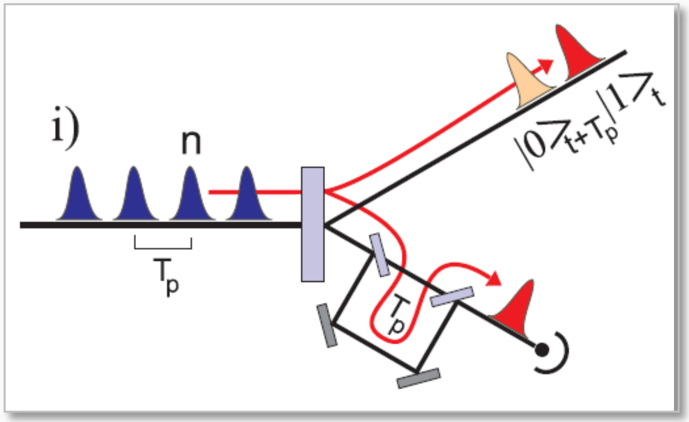
$$(\hat{a}_t^\dagger + \hat{a}_{t+T}^\dagger)\,|0\rangle_t\,|0\rangle_{t+T} = |1\rangle_t\,|0\rangle_{t+T} + |0\rangle_t\,|1\rangle_{t+T}$$

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

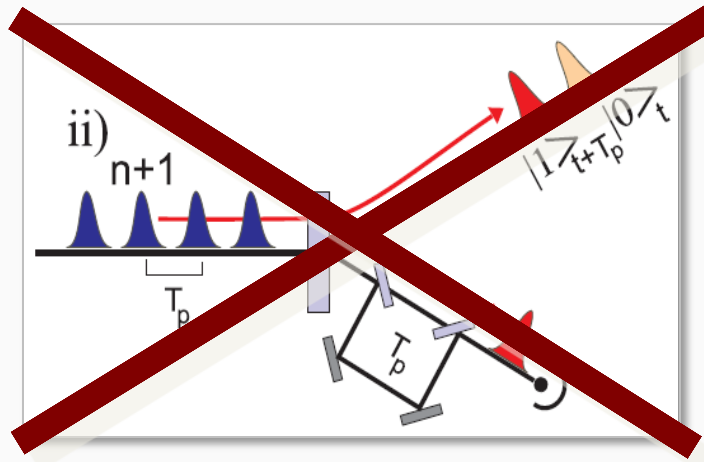
M. D'Angelo, A. Zavatta, V. Parigi and MB, *Phys. Rev. A*, **74**, 052114 (2006)

S. Takeda, T. Mizuta, M. Fuwa, J. Yoshikawa, H. Yonezawa, and A. Furusawa, *Phys. Rev. A* **87**, 043803 (2013)

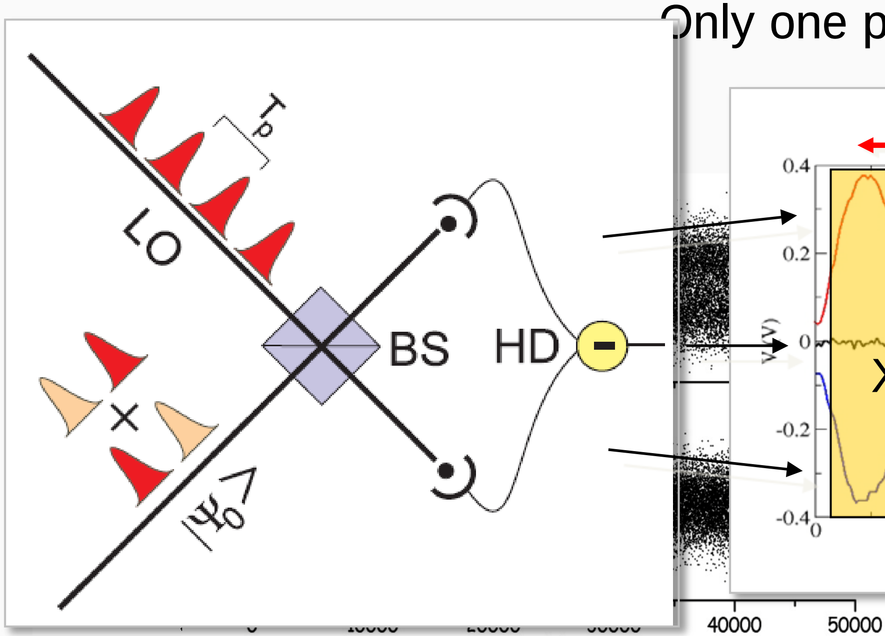
Conditional delocalization & multimode HD

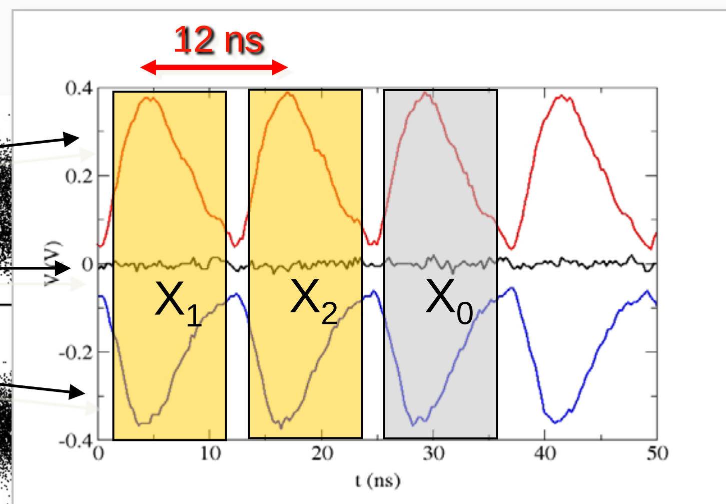


$$\hat{a}_t^\dagger$$



Only one possible path





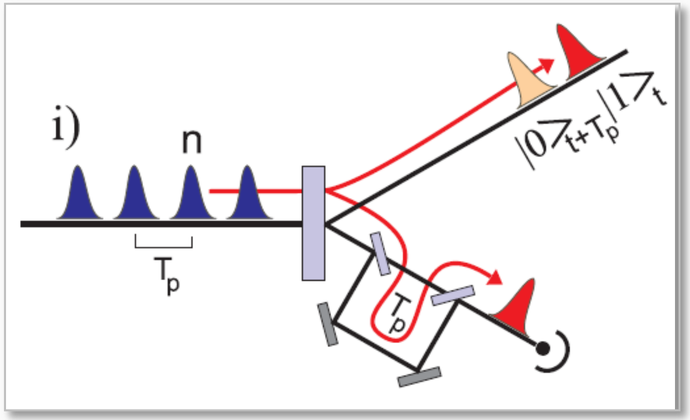
ll localized
oral mode

Three consecutive time-bins are analyzed for each trigger event

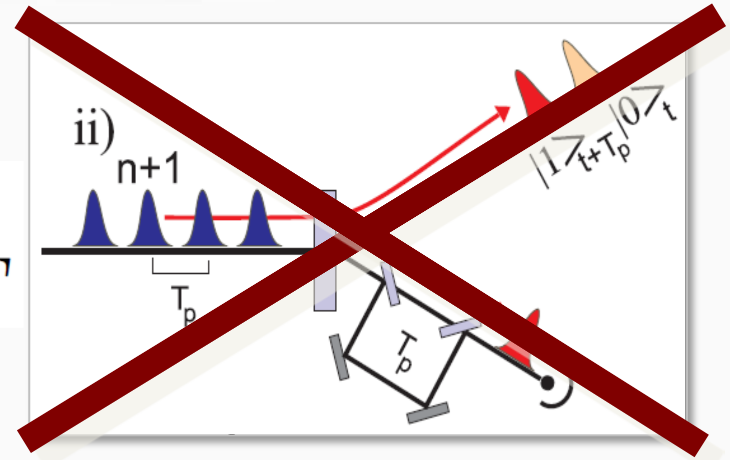
$= |1\rangle_t |0\rangle_{t+T}$

INO-CNR ISTITUTO NAZIONALE DI OTTICA

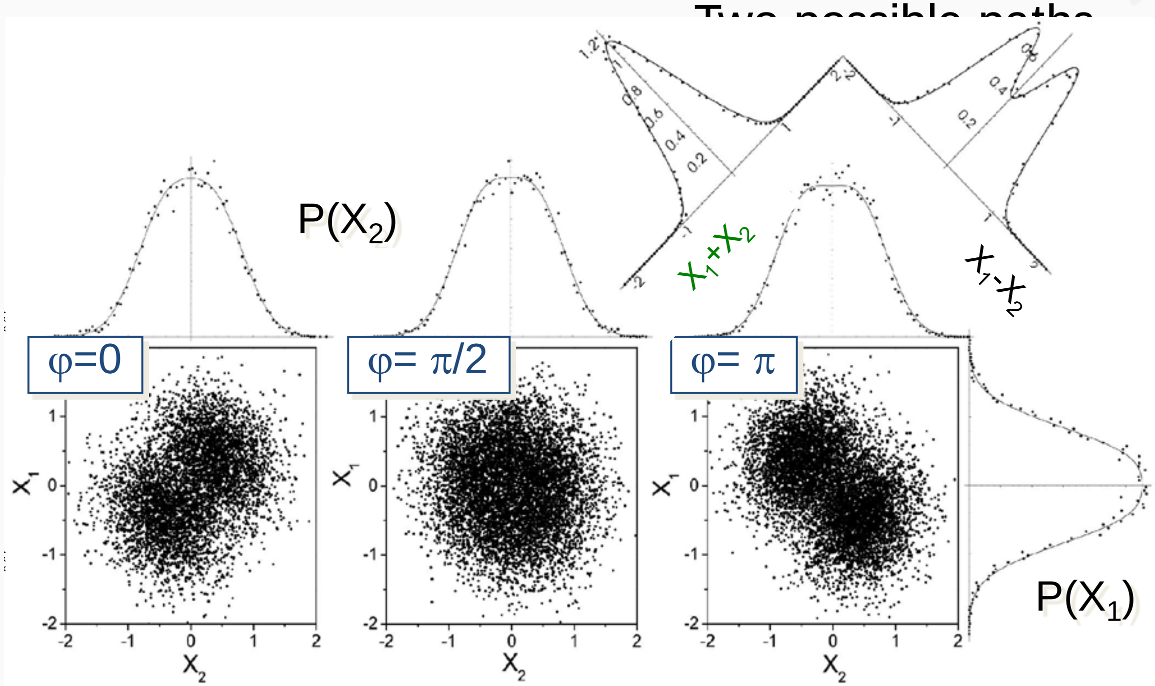
Conditional time delocalization



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



Two possible paths

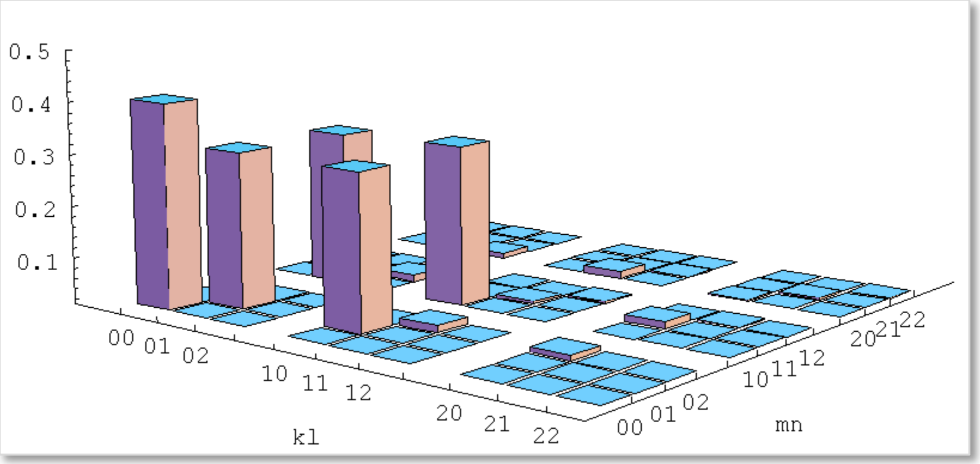


$+ |0\rangle_t |1\rangle_{t+T}$

Coherence manifests in the correlations between the quadrature of the two modes

...atistical mixture of vacuum and single photon

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)

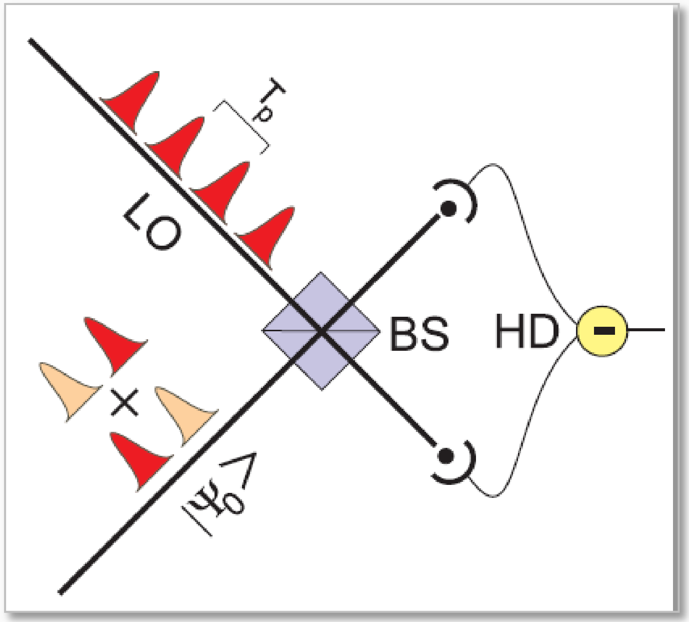
INO-CNR
ISTITUTO NAZIONALE DI OTTICA

Going hybrid

$$\frac{1}{\sqrt{2}}\left(|1\rangle_1\,|0\rangle_2 + |0\rangle_1\,|1\rangle_2\right)$$

Discrete variable entangled state

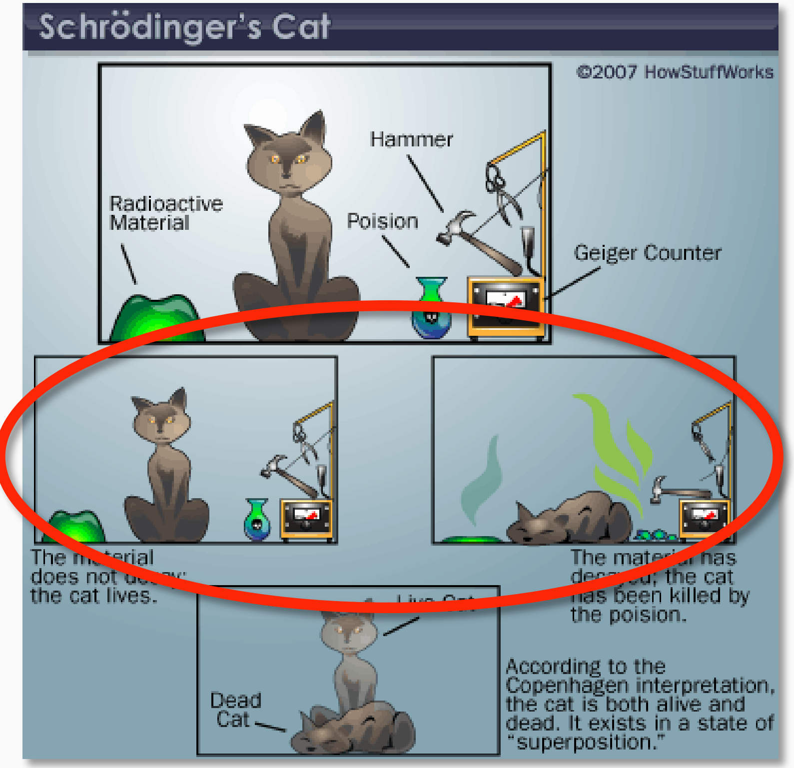
+



Multi-mode homodyne detection (continuous variables)

DV entanglement analyzed with CV detection

Hybrid quantum-classical entanglement



Schrödinger's cat paradox

Entanglement of quantum and classical objects

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle\,|☺\rangle + |\downarrow\rangle\,|☹\rangle\right)$$

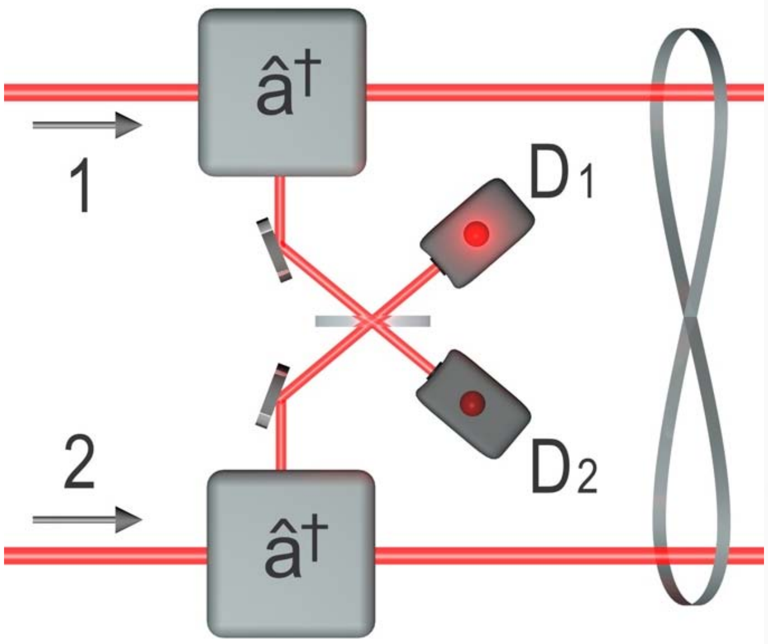
Most quantum state
Particle-like
Discrete variables

Most classical state
Wave-like
Continuous variables

Fundamental importance
Useful resource for optical quantum information processing

Hard to produce (cross-Kerr nonlinearity,...)

Creating a hybrid entangled state



Using the appropriate beam-splitter ratio:

$$t = \sqrt{1 - |r|^2} = \frac{1}{\sqrt{1 + |\alpha|^2}}$$

$$\frac{1}{\sqrt{2}}\left(|1\rangle|\alpha\rangle + |0\rangle\frac{\hat{a}^\dagger|\alpha\rangle}{\sqrt{|\alpha|^2 + 1}}\right)$$

If α is not too small $\quad \frac{\hat{a}^\dagger|\alpha\rangle}{\sqrt{1 + |\alpha|^2}} \approx |\alpha'\rangle$

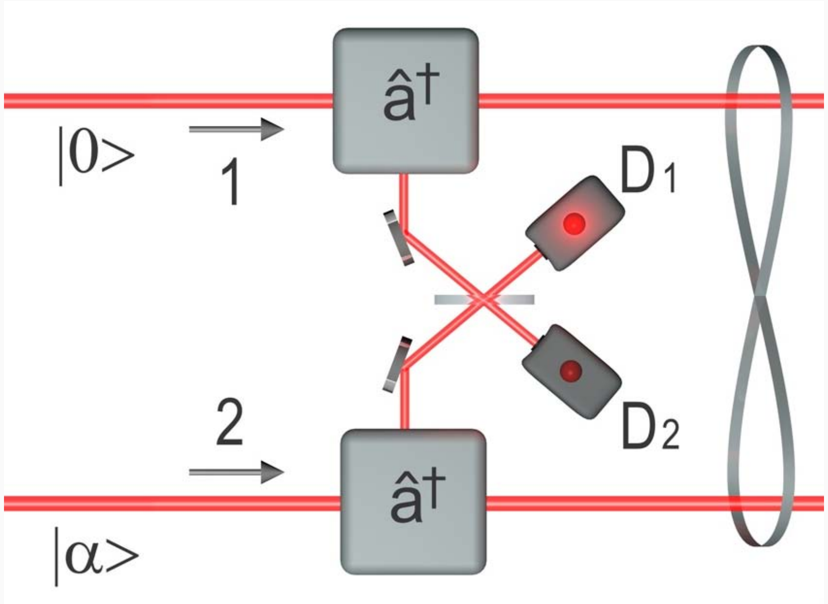
$\mathcal{F} \approx 0.98$ for $\alpha = 2$ and $g\alpha = 2.414$

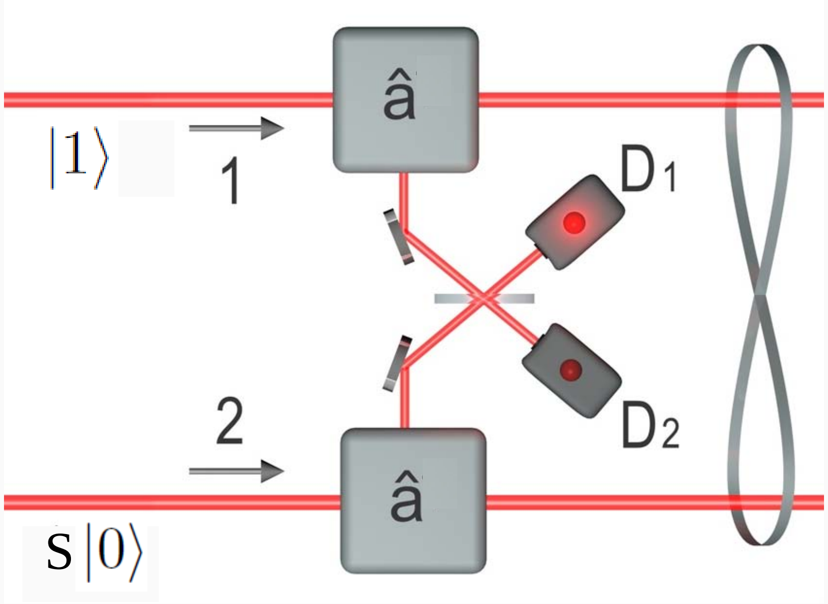
$\mathcal{F} \approx 0.998$ for $\alpha = 4$ and $g\alpha = 4.236$

$$\approx \frac{1}{\sqrt{2}}\left(|1\rangle|\alpha\rangle + |0\rangle|\alpha'\rangle\right)$$

Hybrid single-photon (discrete) and coherent state (continuous variable) entangled qubits

Different approaches to hybrid entanglement





$$\approx \frac{1}{\sqrt{2}}\Big(|1\rangle|\alpha\rangle + |0\rangle|\alpha'\rangle\Big)$$

see Julien's and Ulrik's schemes for hybrid entanglement generation

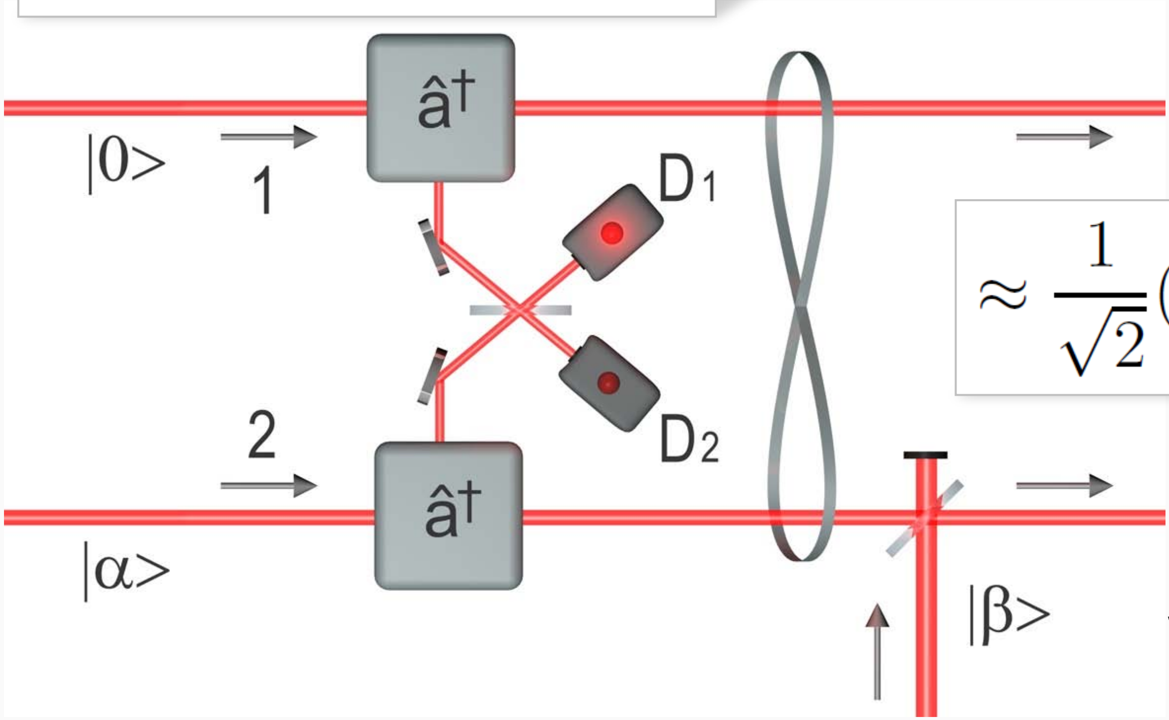
Need some nonclassical resources somewhere

Symmetric hybrid entangled state

$$\approx \frac{1}{\sqrt{2}}\Big(|1\rangle|\alpha\rangle + |0\rangle|\alpha'\rangle\Big)$$

The right amount of phase-space displacement in the second mode can produce a symmetric hybrid state

$$D(-\frac{\alpha+\alpha'}{2})$$



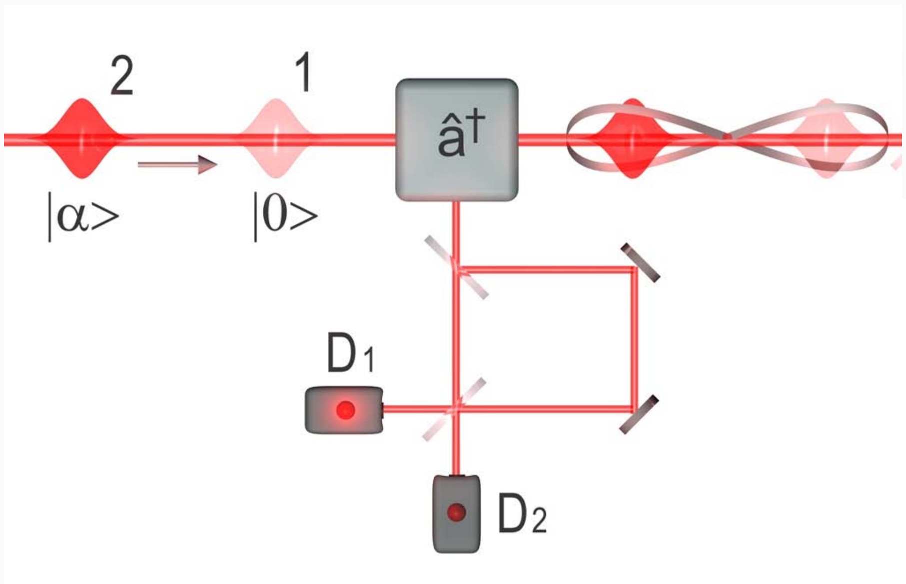
$$\approx \frac{1}{\sqrt{2}}(|0\rangle|\alpha_f\rangle + |1\rangle|-\alpha_f\rangle)$$

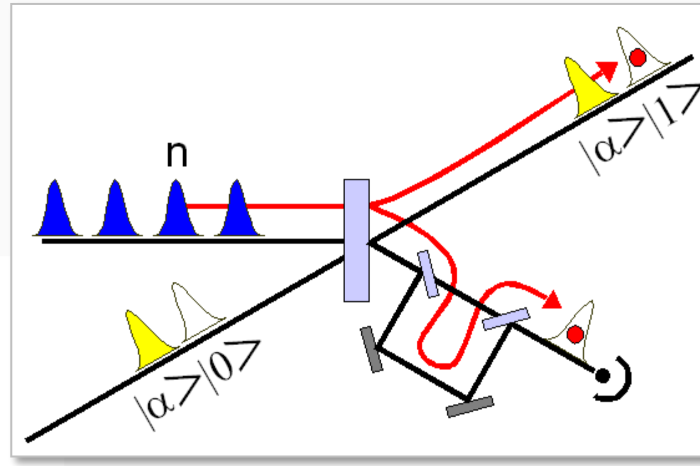
with a final (small) coherent state amplitude of

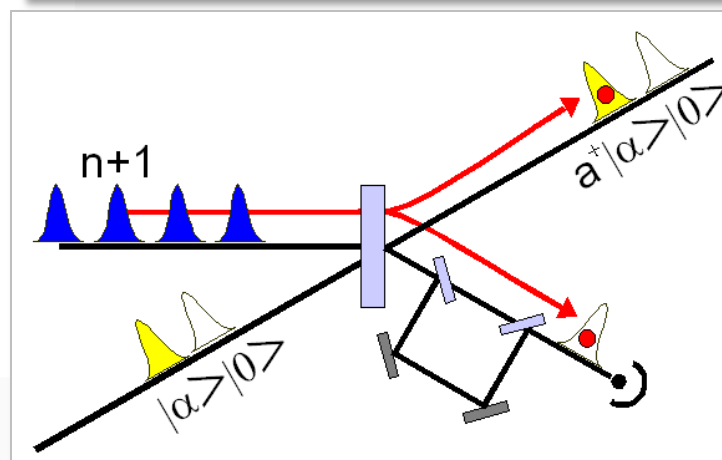
$$\alpha_f = (\alpha' - \alpha)/2$$

In principle the coherent state amplitude can be made larger (and with higher fidelity) by tele-amplifying mode 2

Creating a time-bin hybrid entangled state



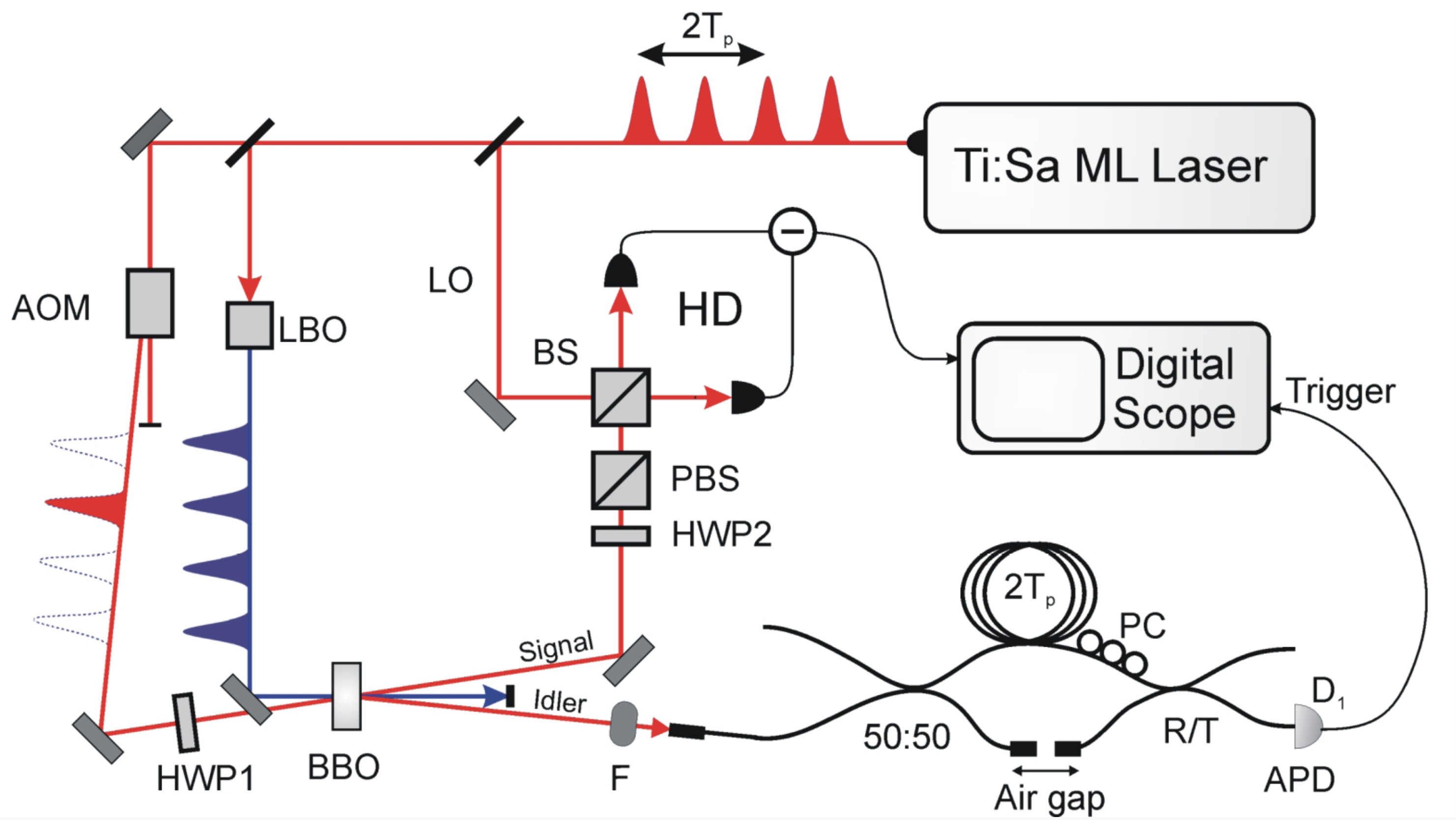




Temporal-mode version of the hybrid entangled state

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

Experimental setup



Entangling quantum and classical states of light
arXiv 1309:6192

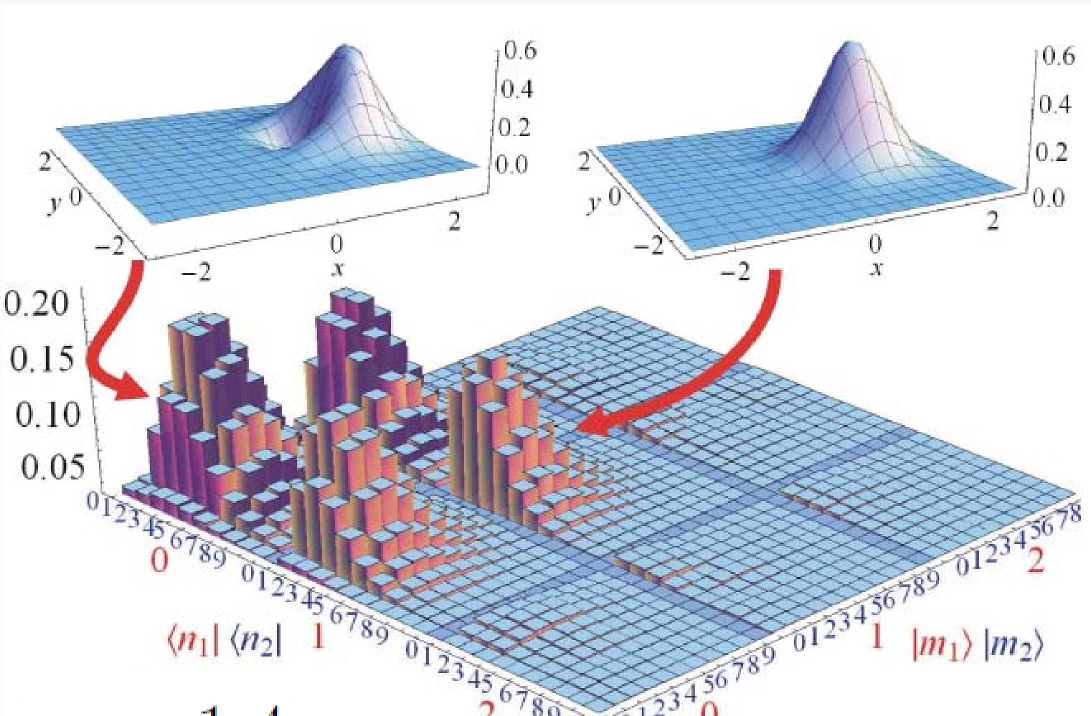
Experimental hybrid entangled state

$$\approx \frac{1}{\sqrt{2}}\Big(|1\rangle|\alpha\rangle + |0\rangle|\alpha'\rangle\Big)$$

Off-diagonal terms prove the coherent superposition character of the state

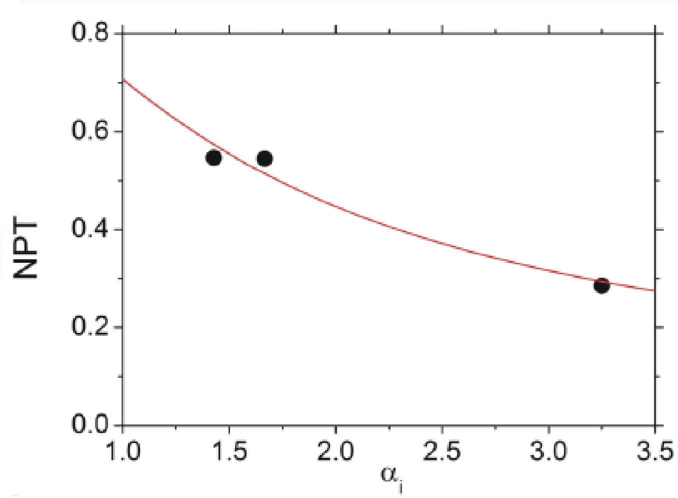
$$\mathrm{NPT}=0.55$$

Entangled hybrid state



$\alpha_i \approx 1.4$

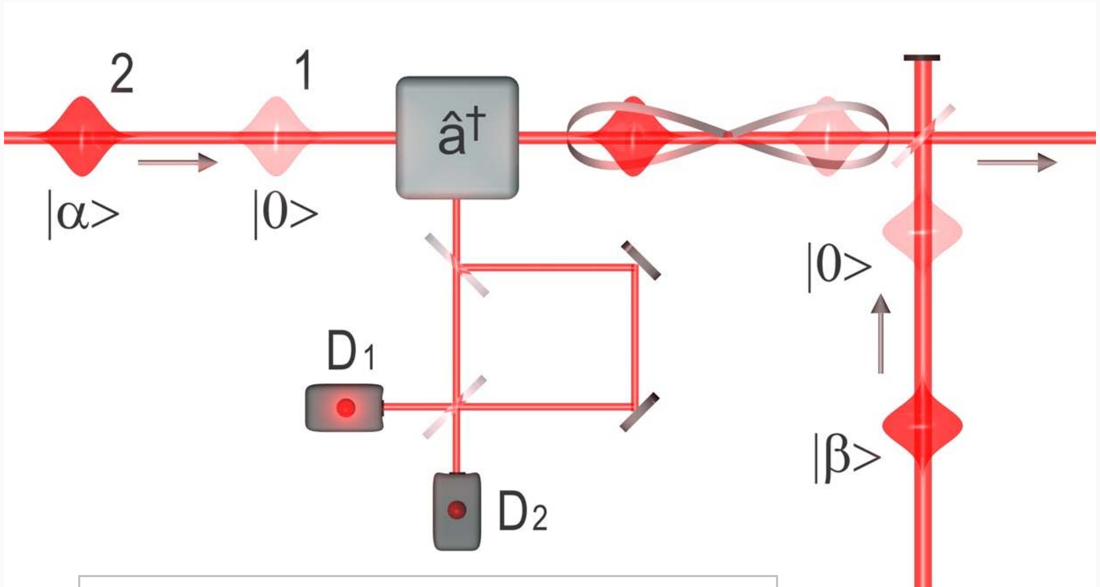
Reconstructed two-mode density matrix
(corrected for detection efficiency)



Measured negativity of the partial transpose

INO-CNR
Istituto Nazionale di Ottica

Symmetric time-bin hybrid entangled state



$$\approx \frac{1}{\sqrt{2}}\Big(|1\rangle|\alpha\rangle + |0\rangle|\alpha'\rangle\Big)$$

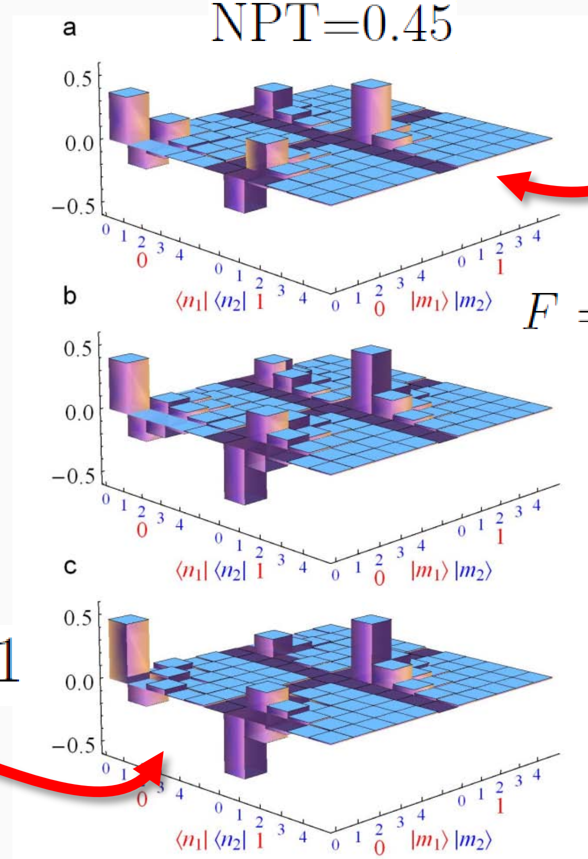
Displace the second mode

$$\approx \frac{1}{\sqrt{2}}(|0\rangle|\alpha_f\rangle + |1\rangle|-\alpha_f\rangle)$$

$\alpha_f \approx 0.31$

Reconstructed two-mode density matrix
(corrected for detection efficiency)

NPT=0.45



$F = 0.92$

Entangling quantum and classical states of light
arXiv 1309:6192

Conclusions

New quantum state engineering tools

New multi-mode techniques

Accessing unknown and multiple modes

Experimental Schmidt mode retrieval

Higher-dimensionality encoding of quantum information

Generating (small-scale) optical hybrid entanglement

Explore quantum-classical entanglement

Interface qubits encoded in discrete and continuous variables

Deterministic linear-optical gate operations and teleportation

Extend to larger amplitudes (tele-amplification)

Credits

- ❖ **Alessandro Zavatta**

- ❖ **Samuele Grandi**
- ❖ **Luca Costanzo**
- ❖ **Antonio Sales Coelho**
- ❖ **Katiuscia Cassemiro**
- ❖ **Constantina Policarpou**

- ❖ **Myungshik Kim**
- ❖ **Jaromir Fiurasek**
- ❖ **Werner Vogel**
- ❖ **Hyunseok Jeong**
- ❖ **Timothy C. Ralph**

Thank you!

www.ino.it/home/QOG

INO-CNR Istituto Nazionale di Ottica

chist-era

ENTE CASSA DI RISPARMIO DI FIRENZE

Consiglio Nazionale delle Ricerche

REGIONE TOSCANA

LaserlabEurope

The "Integrated Initiative" of European Laser Infrastructures in the 7th Framework Programme of the European Union