CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

Non-classicality and entanglement by photon addition and subtraction

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PhD in Quantum Technologies, Napoli February 8, 2019

Why playing with quantum light?

It's fun!

Directly "seeing" quantum mechanics at work in a lab

$|1\rangle$

$\hat{a}^\dagger$

$\hat{a}$

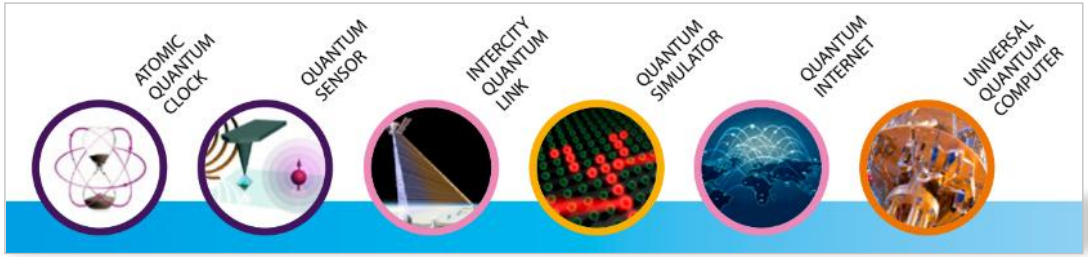
$$[\hat{a}, \hat{a}^\dagger] = 1$$

Fundamental Science

Quantum Technologies

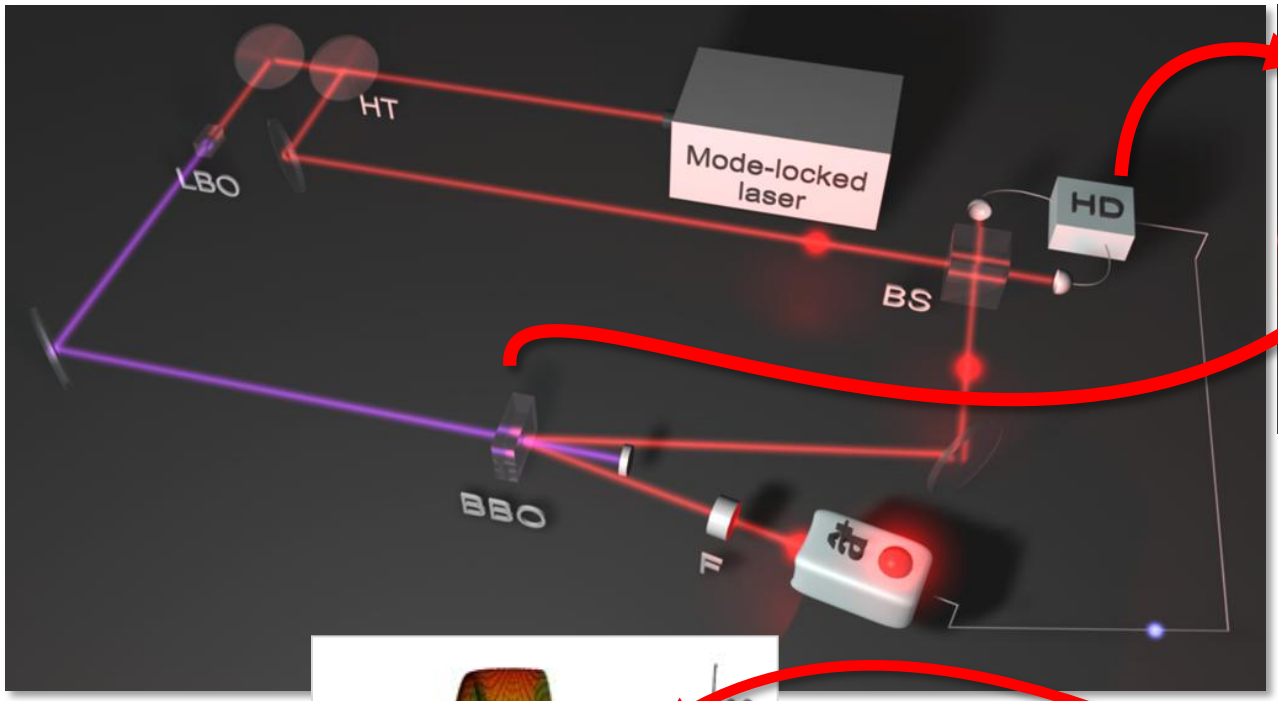
It can be very useful

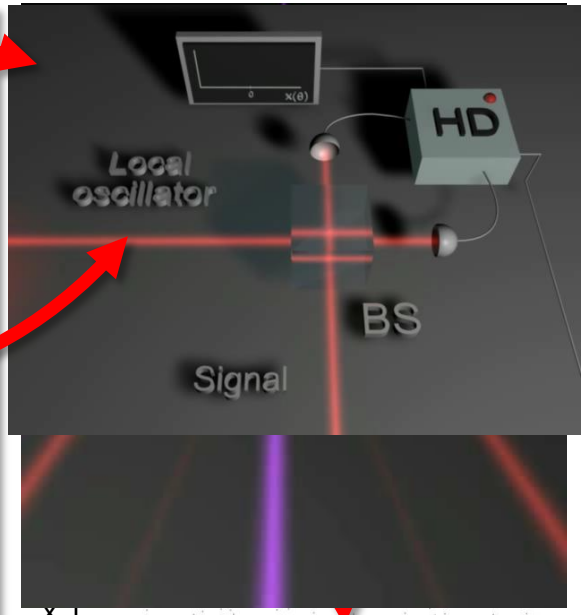
Toolbox for quantum technologies

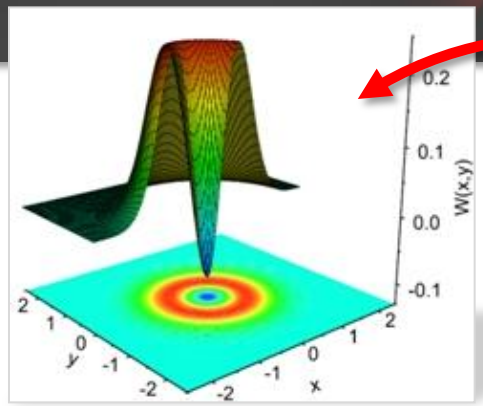


Heralded single photons in the lab

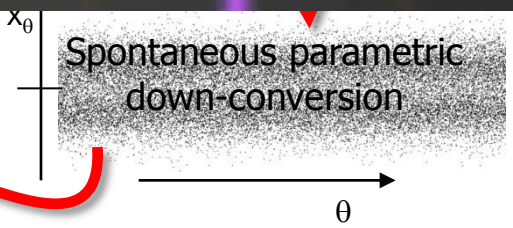
$|1\rangle$







Reconstruct the Wigner function and the density matrix



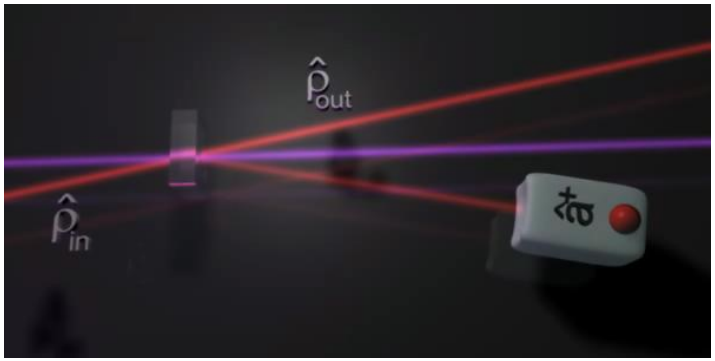
Collect quadrature distributions

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)

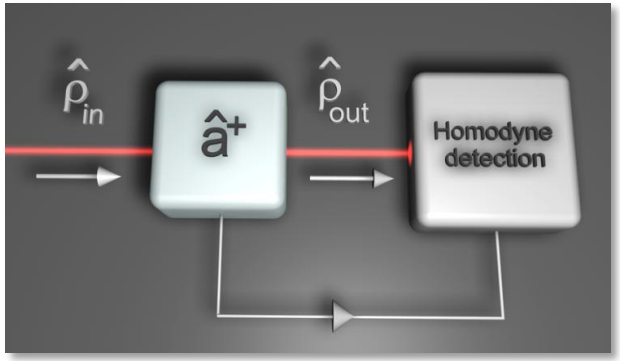
Photon addition & subtraction

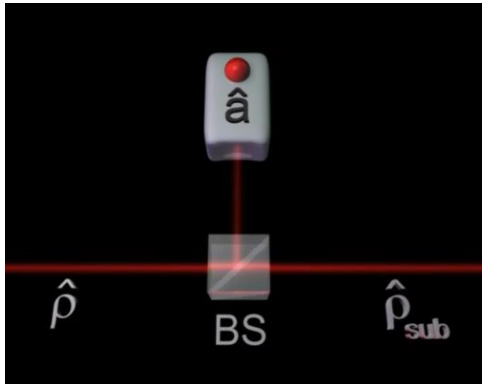
Our quantum toolbox



$\hat{a}^\dagger$

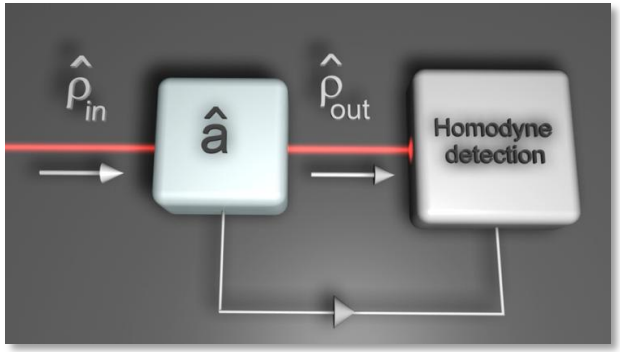
- small PDC gain
- small photon numbers





$\hat{a}$

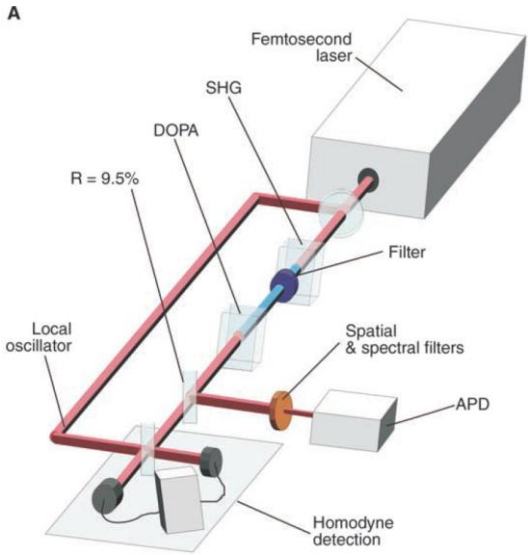
- small BS reflectivity
- small photon numbers

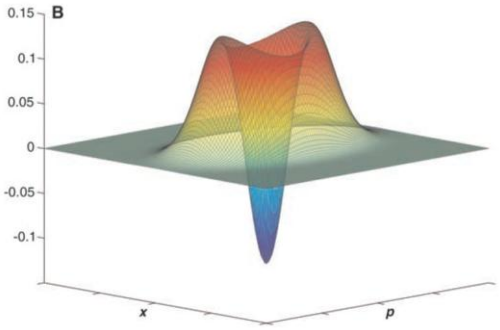


Non-deterministic (heralded) operations

Single-mode photon subtraction

$\hat{a}$



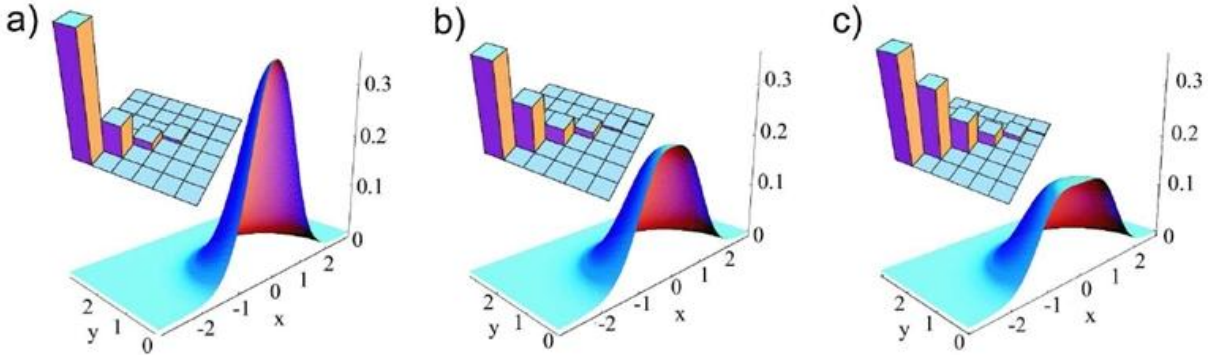


de-Gaussification and cat state generation

A. Ourjoumtsev, R. Tualle-Brouri, J. Laurat, P. Grangier, *Science* **312**, 83 (2006)

Coherent state invariance and effects on photon statistics

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



Thermal state $\bar{n}=0.36$

Subtract one photon $\hat{a}$

Photon-subtracted thermal state $\bar{n}_{sub}=0.69$

Subtract one more photon $\hat{a}$

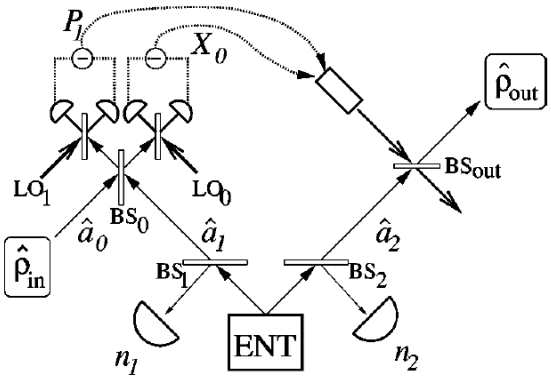
$\bar{n}_{sub_{sub}}=1.03$

Two-mode photon subtraction

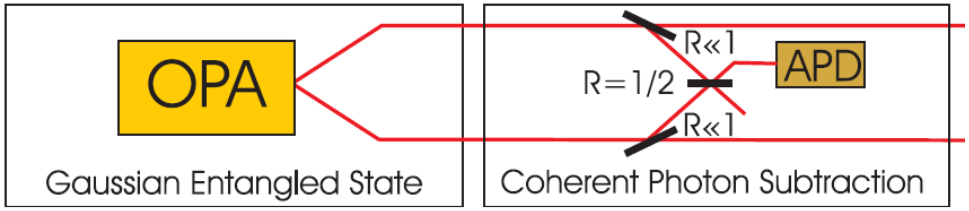
PHYSICAL REVIEW A, VOLUME 61, 032302

Improvement on teleportation of continuous variables by photon subtraction via conditional measurement

T. Opatrný,[1,2] G. Kurizki,[1] and D.-G. Welsch[3]



Non-Gaussian operations (photon subtraction) can distill Gaussian entanglement



$$\hat{a}_1 + \hat{a}_2$$

Experimental entanglement distillation by coherent photon subtraction

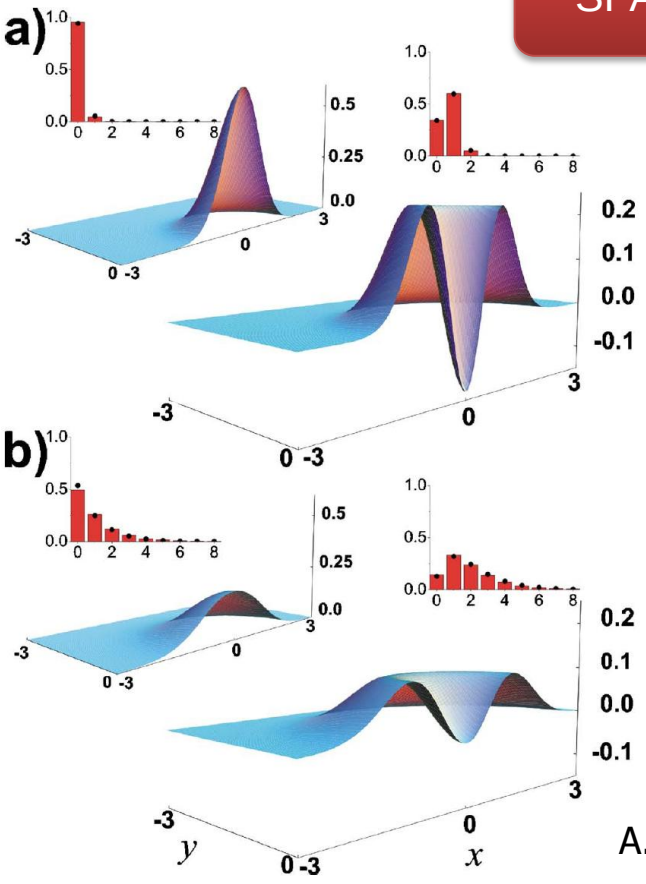
A. Ourjoumtsev, A. Dantan, R. Tualle-Brouri, P. Grangier, *PRL* **98**, 030502 (2007)

Single-mode photon addition

$\hat{a}^\dagger$

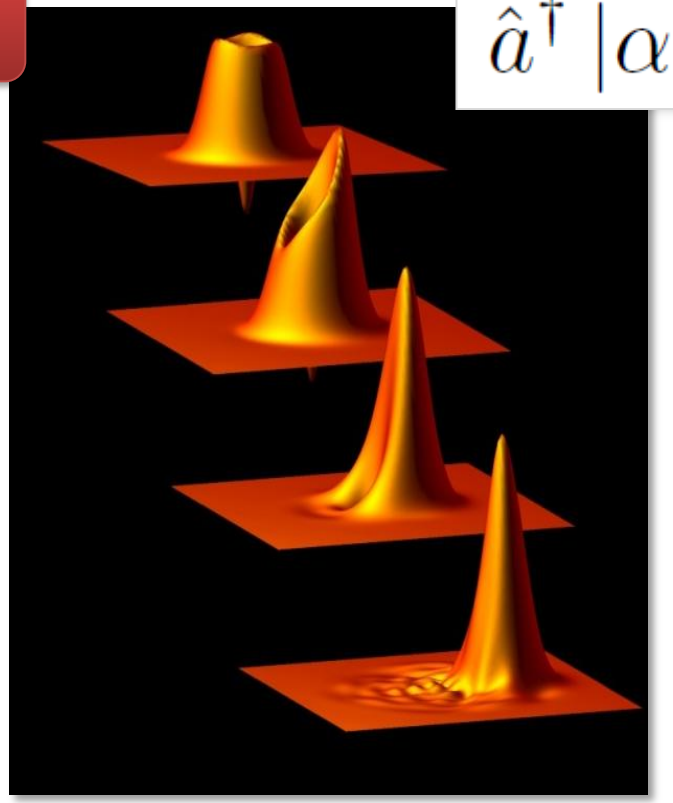
SPACS

SPATS



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

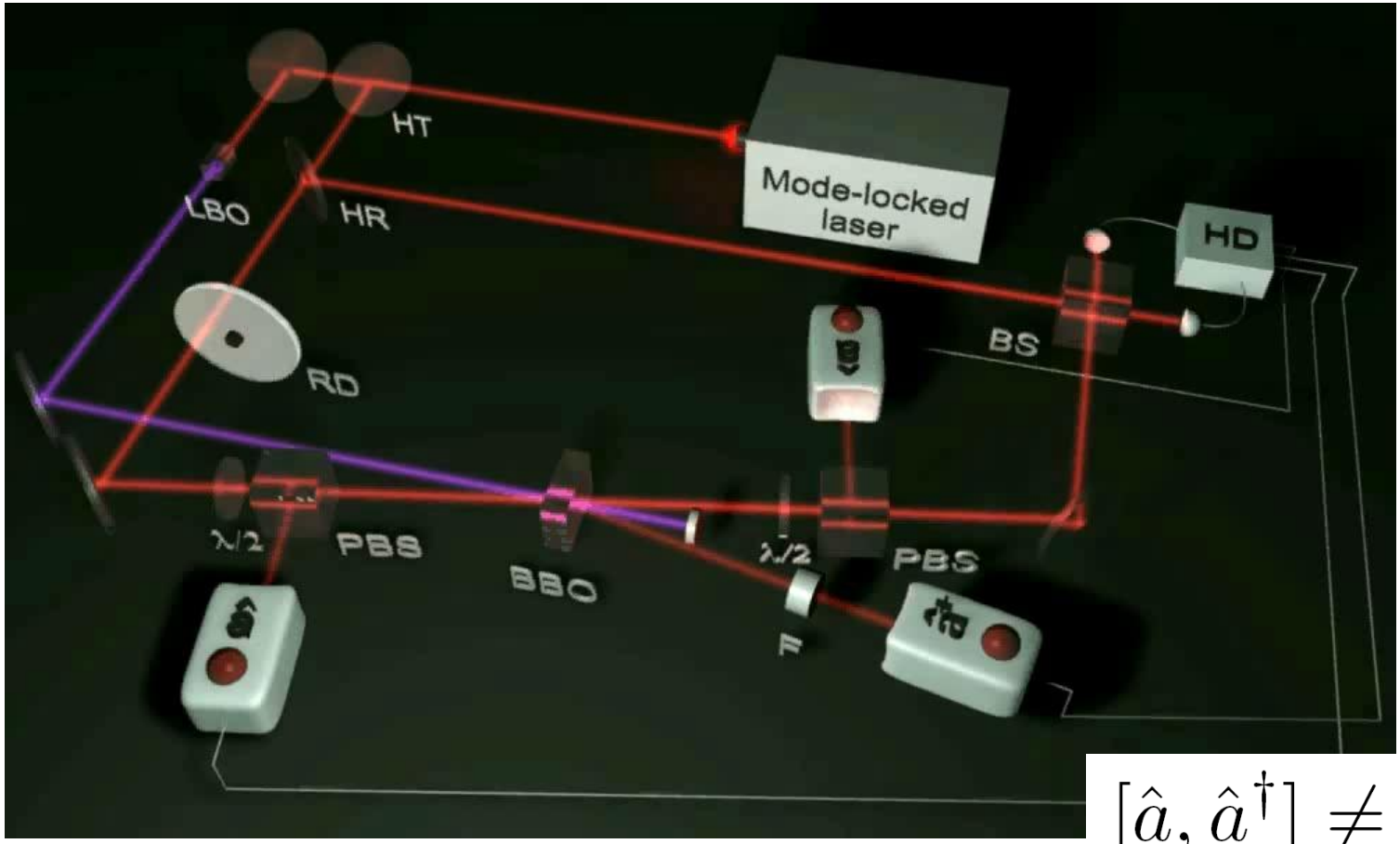
$\hat{a}^\dagger |\alpha\rangle$



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

Sequences of additions and subtractions

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



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

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

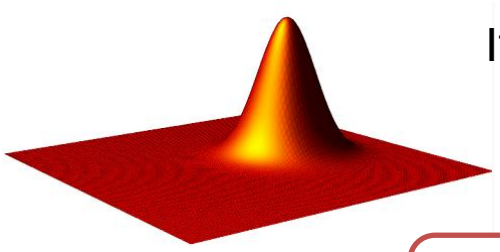
Add or subtract?

Photon subtraction is cool

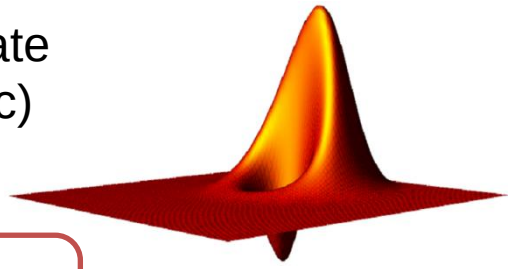
State de-Gaussification
Entanglement distillation

Cannot create non-classicality or entanglement

… but photon addition is even better



It produces a non-classical output state whatever (and however macroscopic) the input one

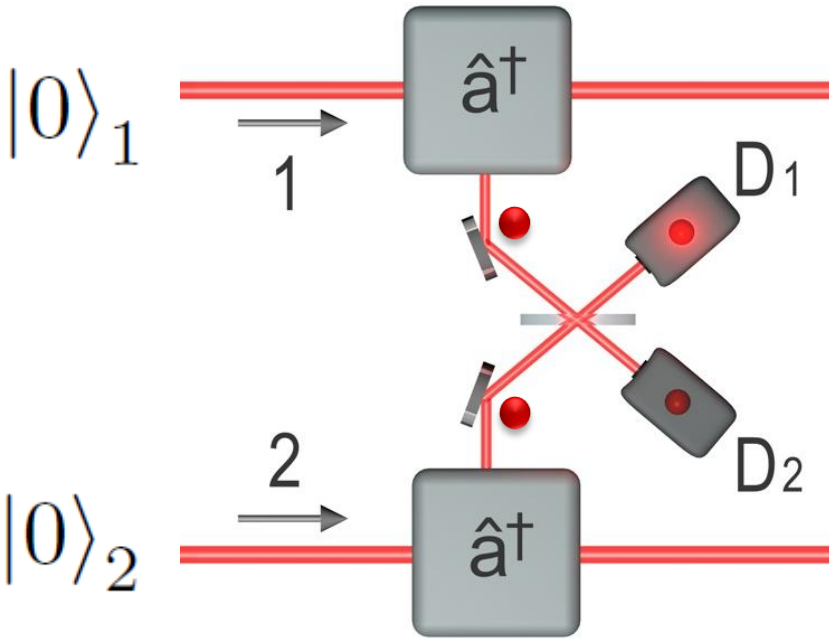


Superpositions of photon additions can entangle arbitrary states

Entanglement by photon addition

Delocalized photon addition on modes 1 and 2

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



$|1\rangle_1 \quad |0\rangle_1$

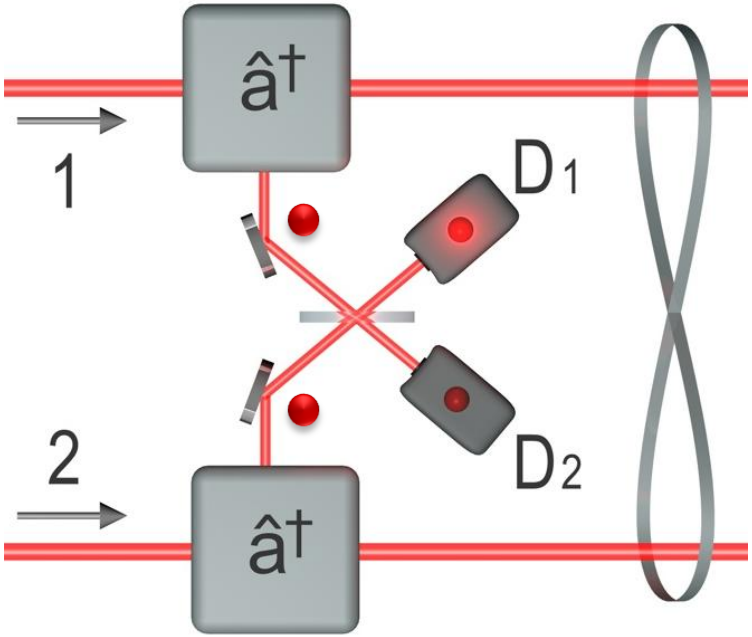
$|0\rangle_2 \quad |1\rangle_2$

Single-photon path-entangled state

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

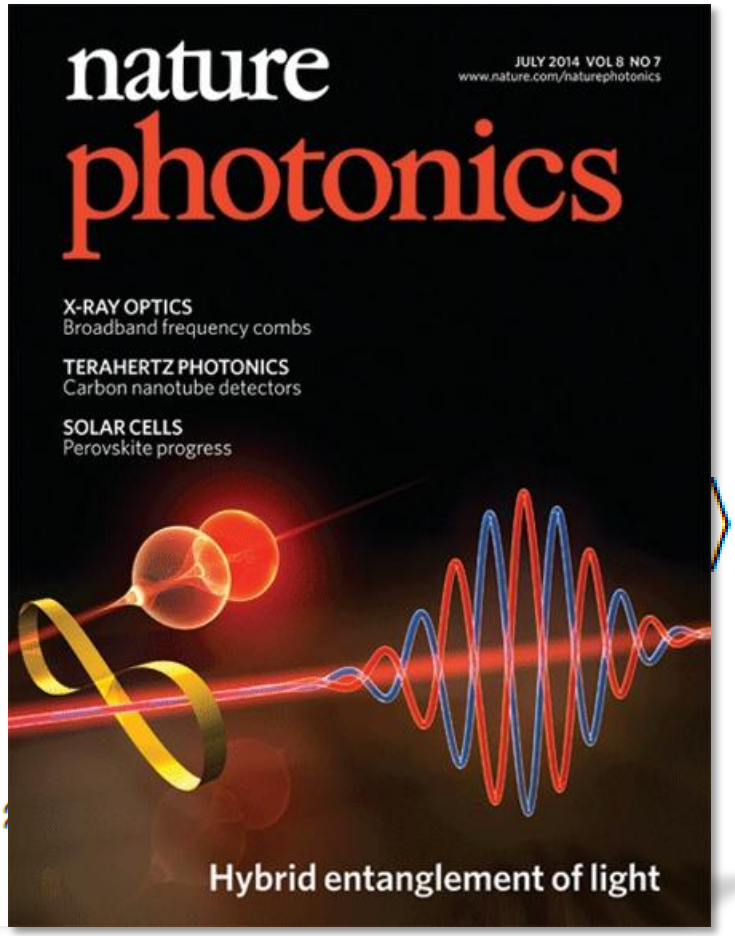
Two distinct spatial modes get entangled by sharing a single photon

Hybrid CV-DV entanglement



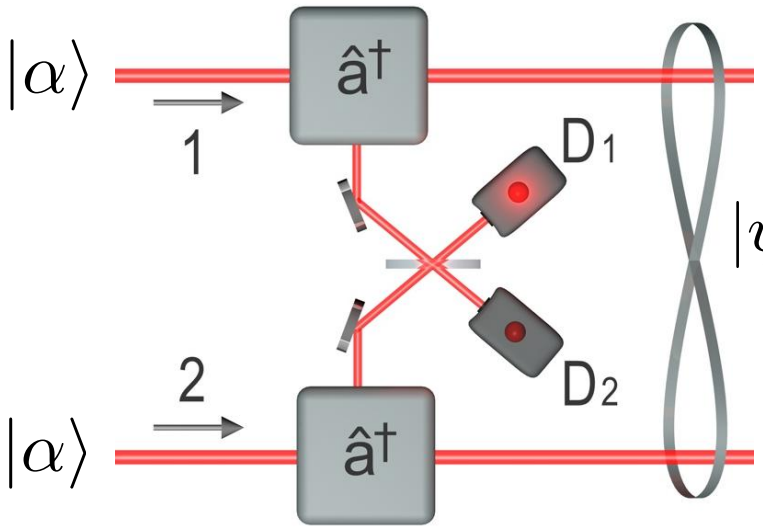
Hybrid single-photon (discrete/quantum) and coherent state (continuous/classical) entangled qubits

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



Generation of hybrid entanglement of light
H. Jeong, A. Zavatta, M. Kang, S. Lee, L.S. Costanzo, S. Grandi, T.C. Ralph, & MB
Nature Photonics, **8**, 564-569 (2014)

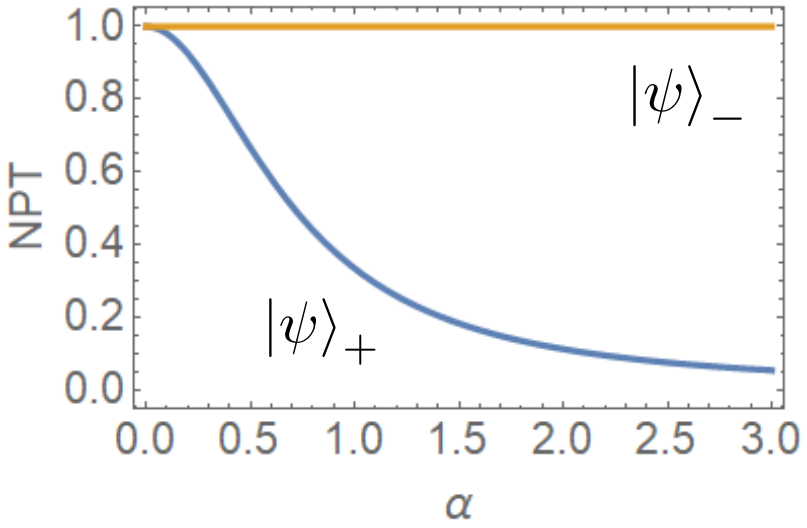
Entangling macroscopic light states



$$|\psi\rangle_{\pm} = \mathcal{N}\left(\hat{a}_1^\dagger |\alpha\rangle_1 |\alpha\rangle_2 \pm |\alpha\rangle_1 \hat{a}_2^\dagger |\alpha\rangle_2\right)$$

NPT Negativity of the partial transpose

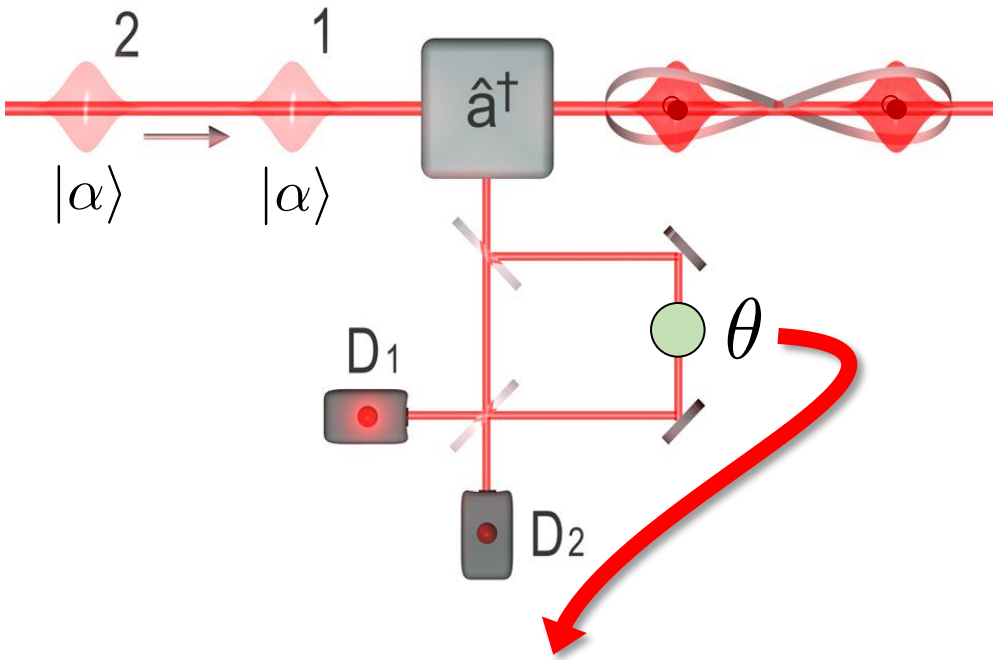
NPT=0 for separable state
NPT=1 for maximally entangled

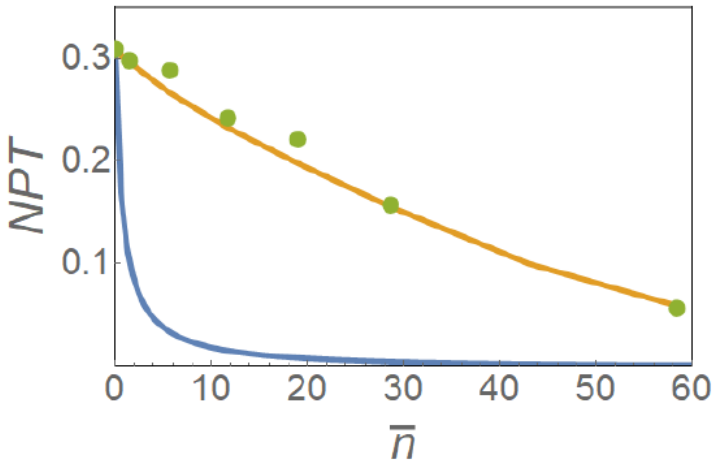


The $|\psi\rangle_-$ state stays highly entangled regardless of the macroscopicity of the component states

Experiment

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





Significant entanglement measured even for **large** coherent states

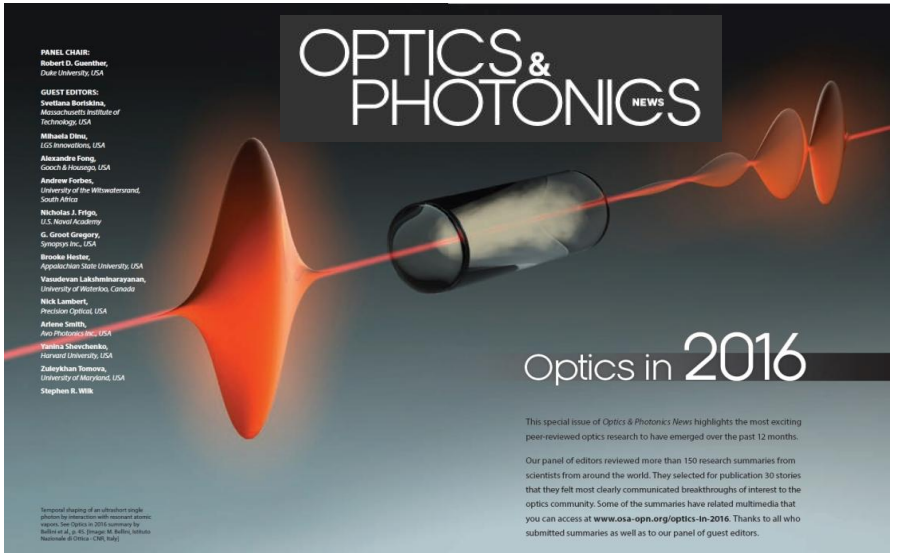
$$|\psi\rangle = (\hat{a}_t^\dagger + e^{i\theta}\hat{a}_{t+T}^\dagger)|\alpha\rangle_t|\alpha\rangle_{t+T}$$

N. Biagi, L.S. Costanzo, MB & A. Zavatta, arXiv:**1811.10466** (2018)

Conclusions & credits

Playing with quantum light is fun!

- Loss-resilient entanglement distribution
- Translate between Q-info encodings
- Homodyne detection for CV-QKD
- Q-info in other degrees of freedom
- ….



Alessandro Zavatta

Nicola Biagi

Luca S. Costanzo

Playing with addition & subtraction

$\hat{a}^\dagger$

$\hat{a}$

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

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

$|\psi\rangle + |\psi_\perp\rangle$

$|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle\,|\alpha\rangle + |1\rangle\,|-\alpha\rangle)$

Photon addition

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

Photon subtraction

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

Noiseless amplification

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

Commutation rules

V. Parigi, A. Zavatta, M.S. Kim, MB, *Science* **317**, 1890 (2007)
A. Zavatta, V. Parigi, M. S. Kim, H. Jeong, MB, *PRL* **103**, 140406 (2009)

State orthogonalizer and CV qubit generator

A.S. Coelho, L.S. Costanzo, A. Zavatta, C. Hughes, M.S. Kim, MB
PRL, **116**, 110501 (2016)

Hybrid entanglement

H. Jeong, A. Zavatta, M. Kang, S. Lee, L.S. Costanzo,
S. Grandi, T.C. Ralph, MB *Nature Photonics*, **8**, 564 (2014)