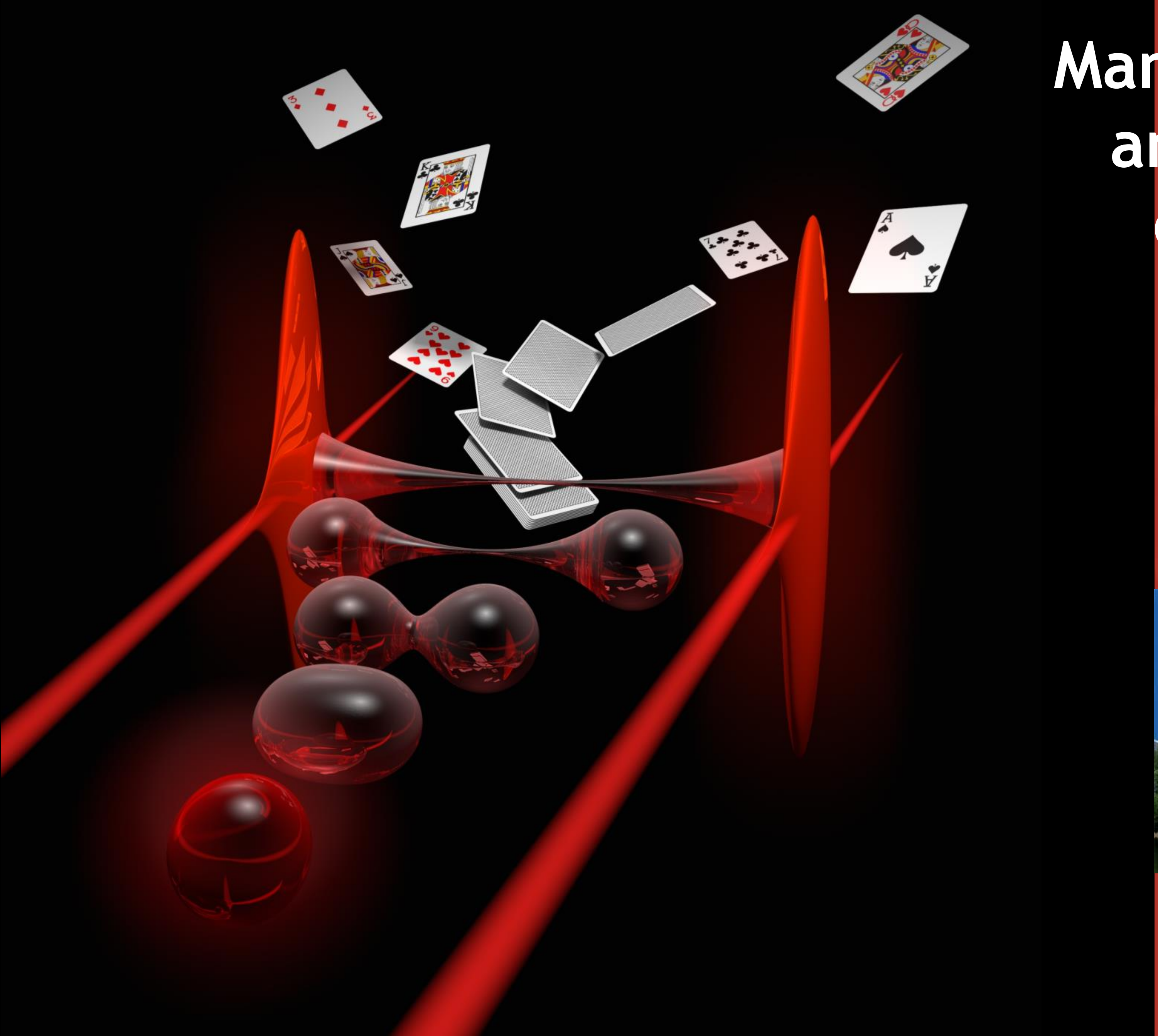


Manipulating the character and shape of ultrashort quantum light states

Marco Bellini

Istituto Nazionale di Ottica - CNR
Florence, Italy

marco.bellini@ino.cnr.it

June 27, 2023

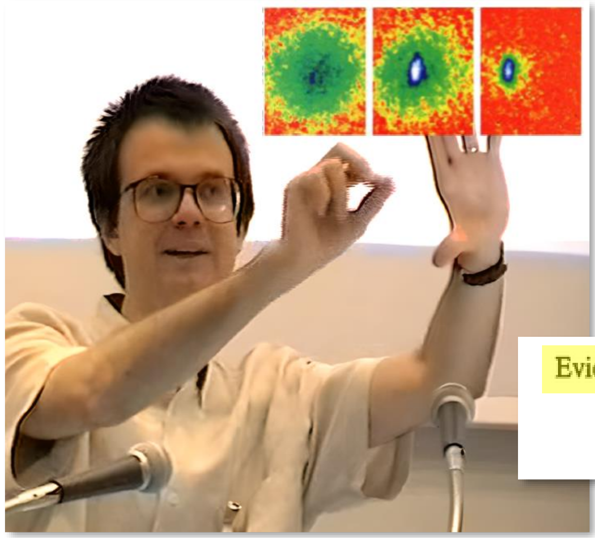
TWICOLS 1995 - Island of Capri

High Precision Measurement of the Dipole Moment of HOCl by Tunable Far Infrared Stark Spectroscopy — 260
G. Modugno, P. De Natale, M. Bellini, M. Inguscio, G. Di Lonardo, L. Fusina and J. Vander Auwera

The only time when I was doing "proper" laser spectroscopy

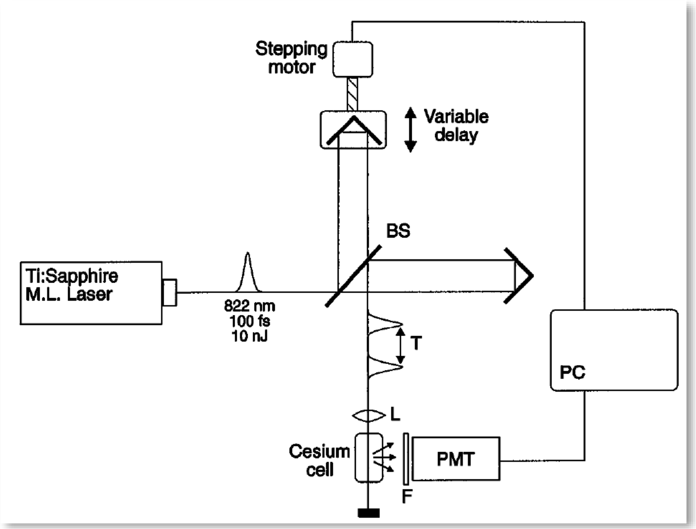
Ultra-stable CW lasers
Extremely narrow spectral emission
Far Infrared (THz)

Ken Evenson



Evidence for Bose–Einstein Condensation in a Dilute Atomic Vapor — 3
M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman and E. A. Cornell

From the ultra-monochromatic to the ultra-short



Start to work with ultrafast
femtosecond lasers

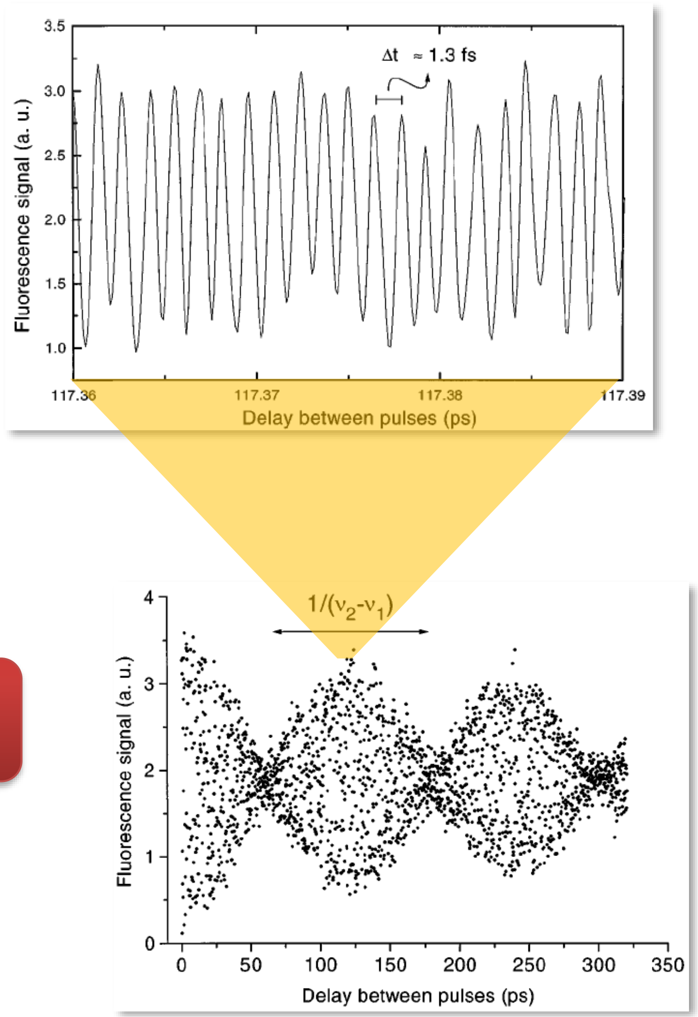
Farewell to spectroscopy?

540 OPTICS LETTERS / Vol. 22, No. 8 / April 15, 1997

Two-photon Fourier spectroscopy with femtosecond light pulses

M. Bellini, A. Bartoli, and T. W. Hänsch*

European Laboratory for Non-Linear Spectroscopy (LENS) and Department of Physics, University of Florence, L.go E. Fermi, 2, I-50125 Firenze, Italy

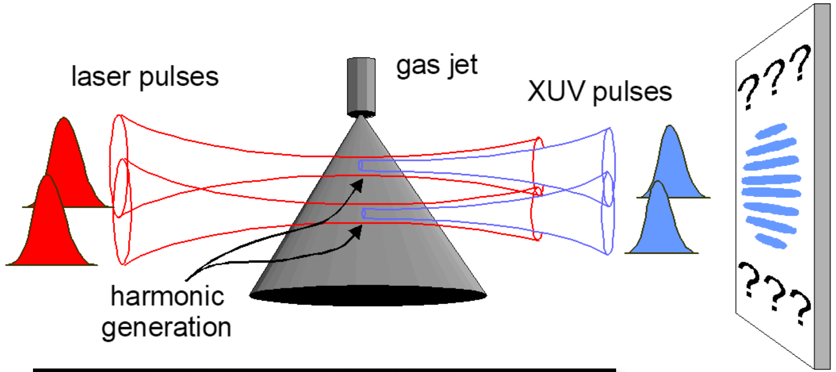


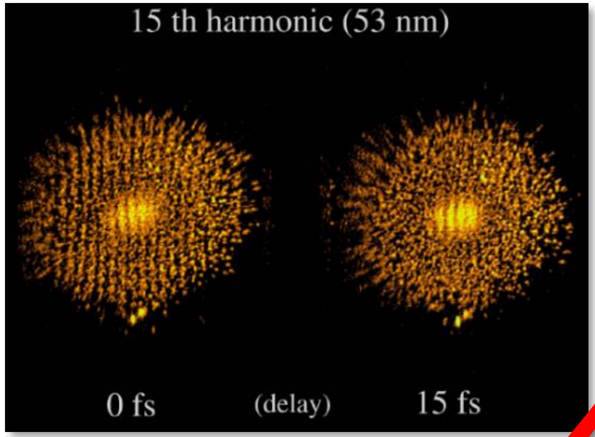
Spectroscopy with ultrashort pulses is possible

Preserve high spectral resolution
+
High peak intensities for highly nonlinear effects

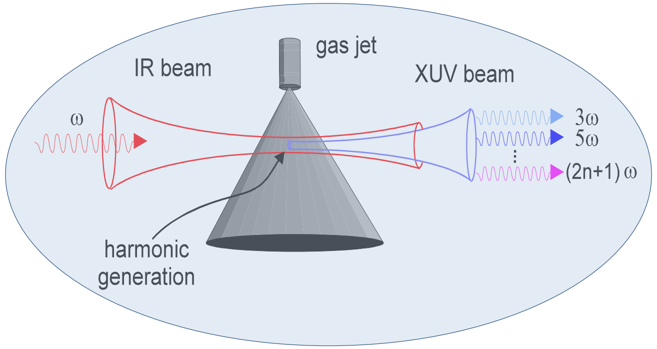
From THz to XUV

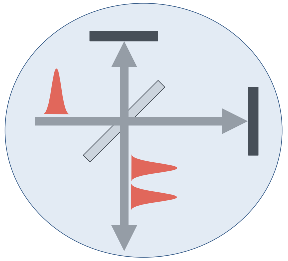
Go more nonlinear: high-order harmonics

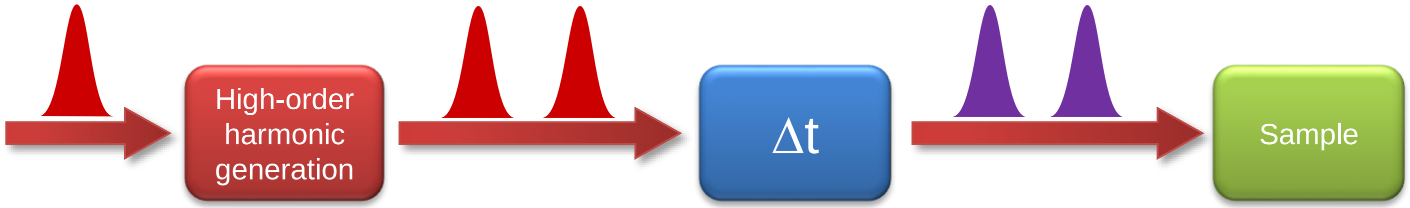




MB et al., *PRL* **81**, 297 (1998)



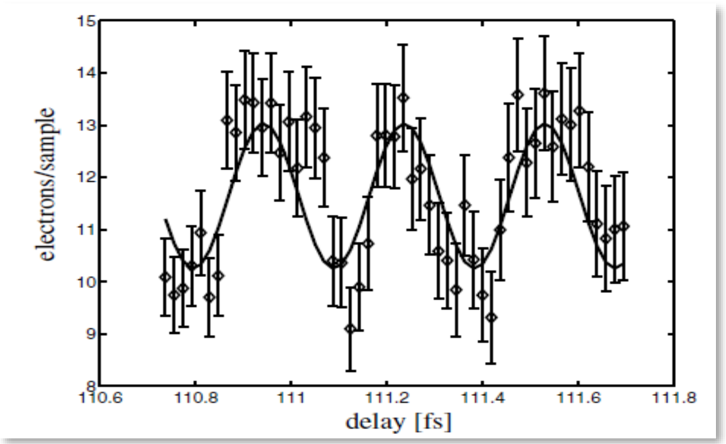




Ramsey spectroscopy with XUV harmonics

Interferometry in the XUV

Attosecond electron dynamics

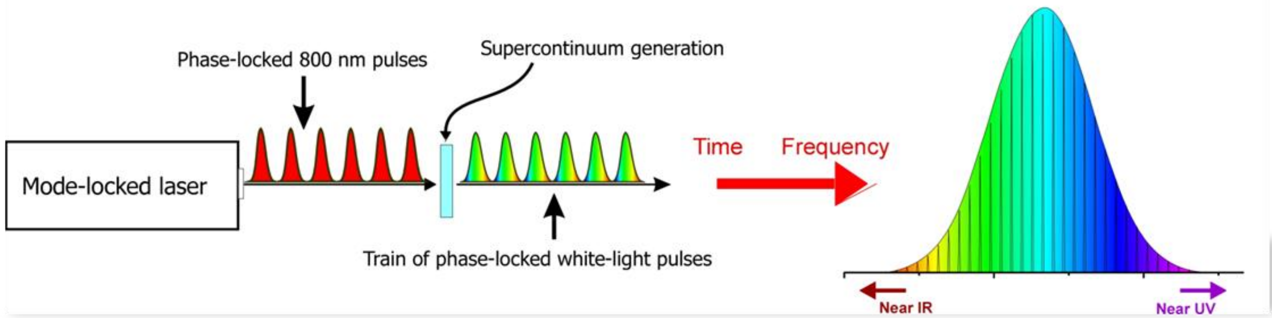


S. Cavalieri et al., *PRL* **89**, 133002 (2002)

Even broader spectra → SC frequency combs

Broader spectra + pulse trains

Supercontinuum frequency combs

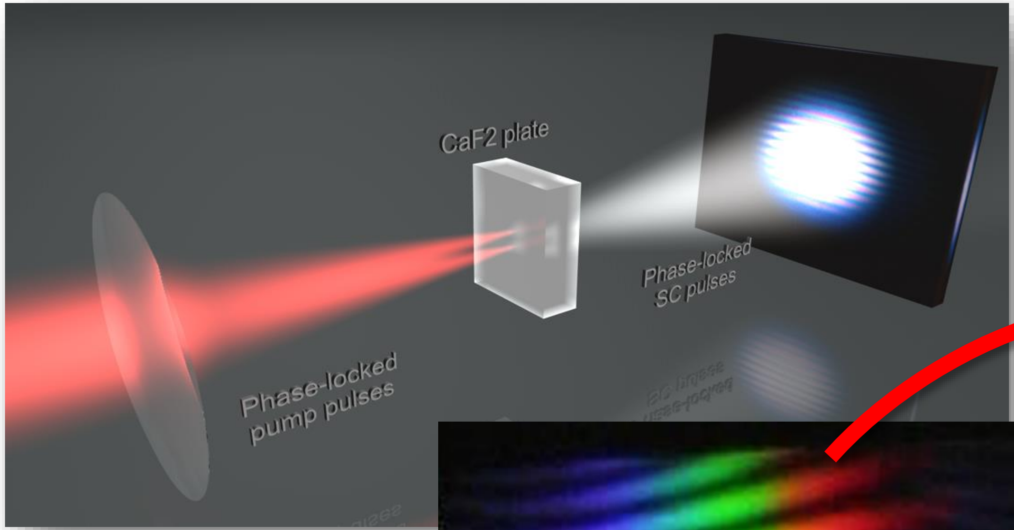


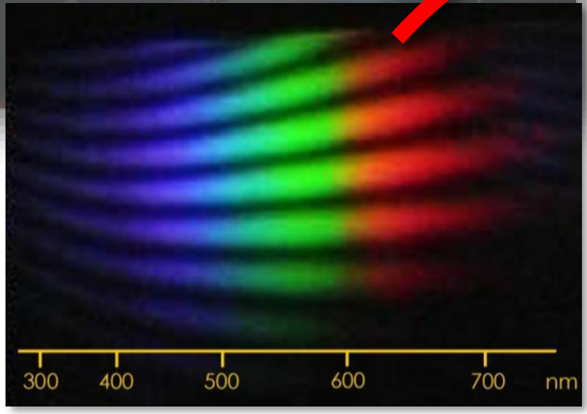
Phase-locked white-light continuum pulses: toward a universal optical frequency-comb synthesizer

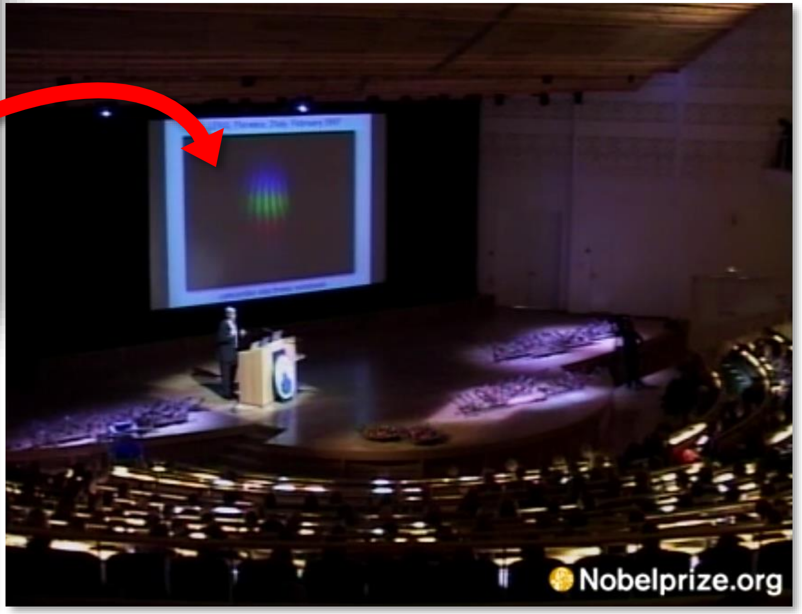
Marco Bellini

Istituto Nazionale di Ottica Applicata, Largo E. Fermi 6, 50125 Florence, Italy, and European Laboratory for Non Linear Spectroscopy and Istituto Nazionale di Fisica della Materia, Largo E. Fermi 2, 50125 Florence, Italy

Theodor W. Hänsch







The Nobel Prize in Physics 2005

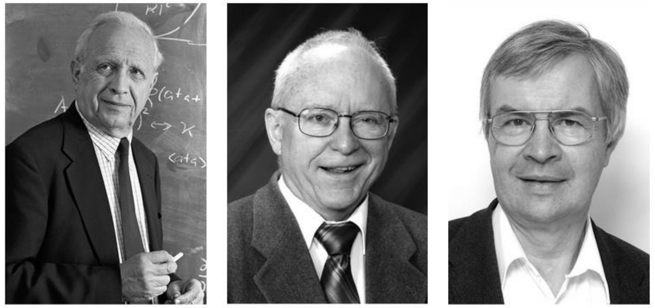
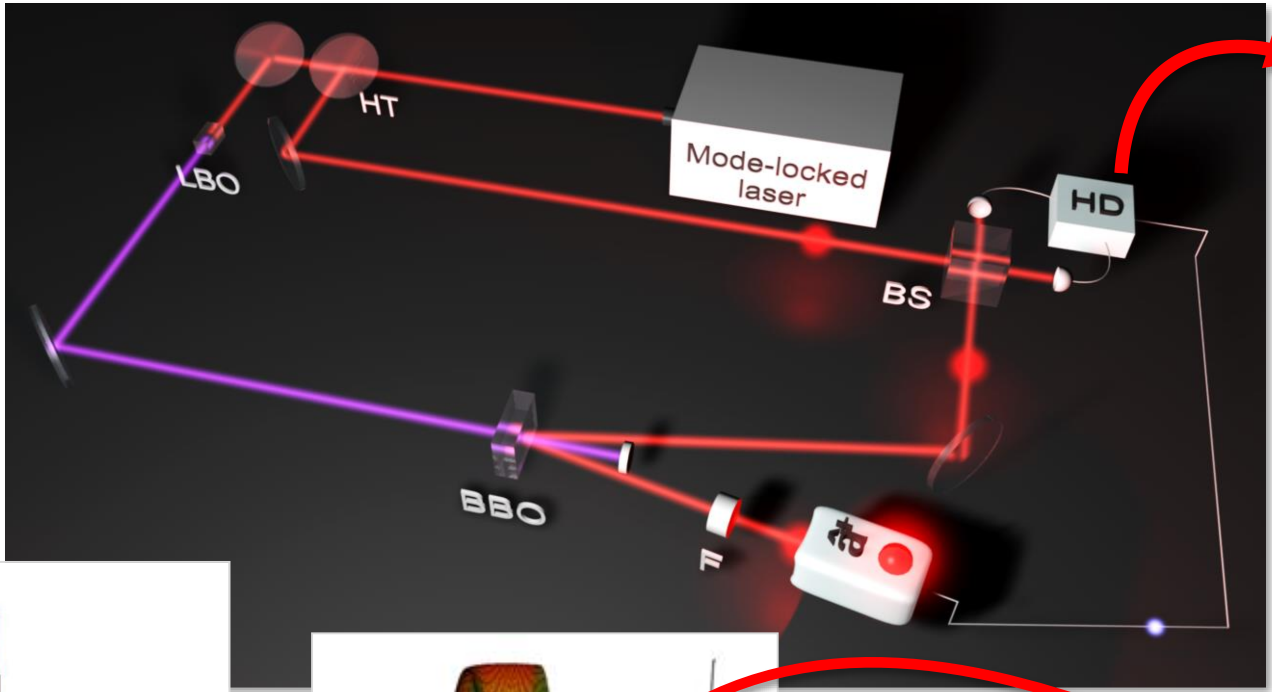


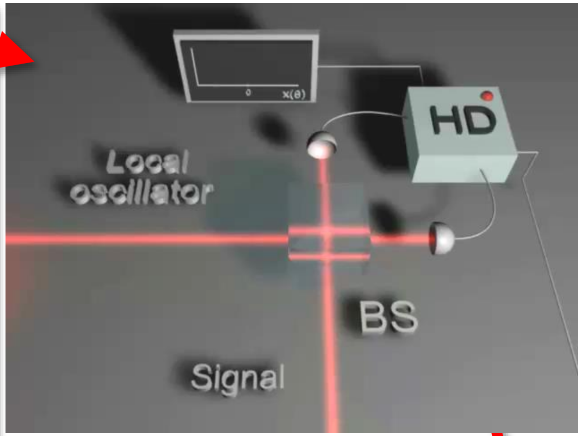
Photo: J.Reed
Roy J. Glauber

Photo: Sears.P.Studio
John L. Hall

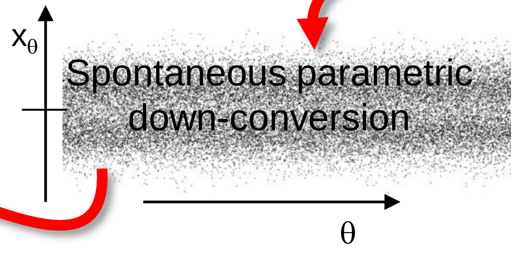
Photo: F.M. Schmidt
Theodor W. Hänsch

From ultrahigh intensities to single photons

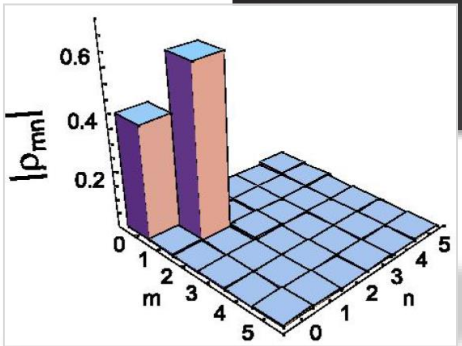


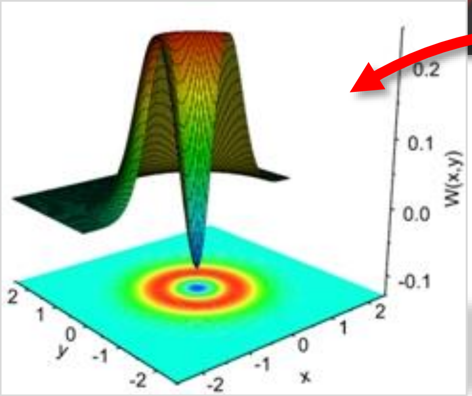


Acquire homodyne data



Collect quadrature
distributions

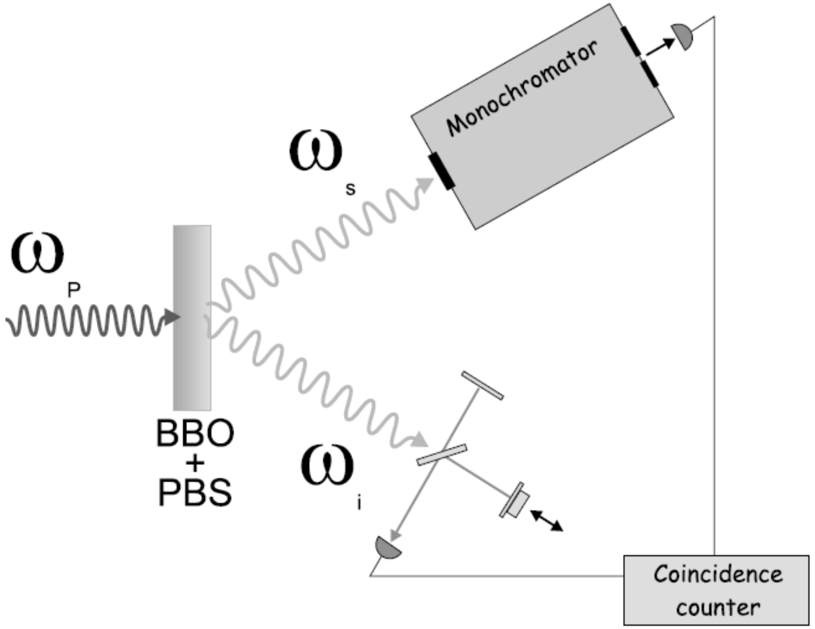


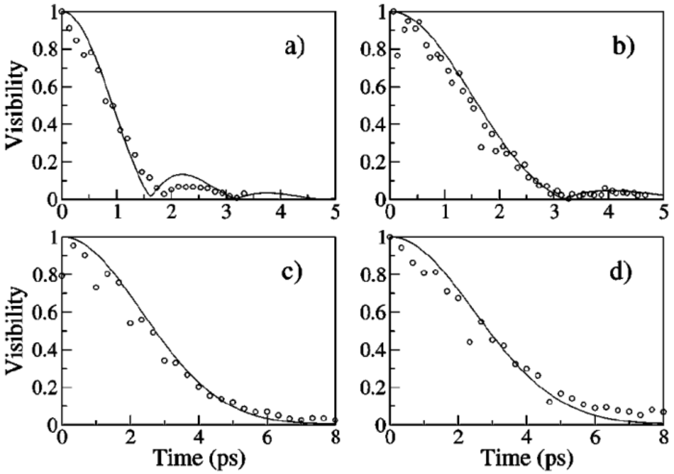


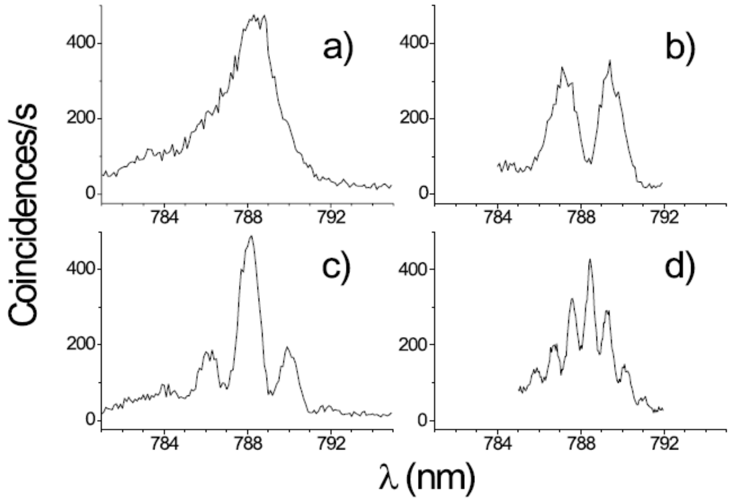
Reconstruct the
Wigner function and
the density matrix

From ultrahigh intensities to single photons

Spontaneous parametric down-conversion







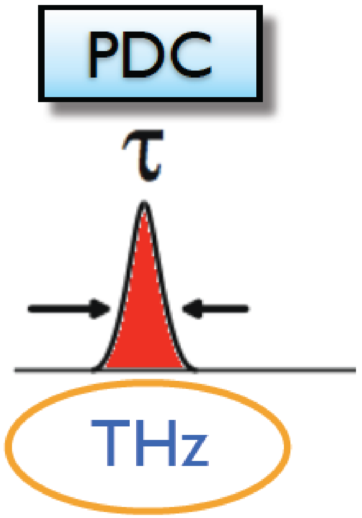
Observation of ghost spectral interferences

VOLUME 90, NUMBER 4 PHYSICAL REVIEW LETTERS week ending 31 JANUARY 2003

Nonlocal Pulse Shaping with Entangled Photon Pairs

M. Bellini,[1,4] F. Marin,[2,4] S. Viciani,[1] A. Zavatta,[3] and F.T. Arecchi[2,4]

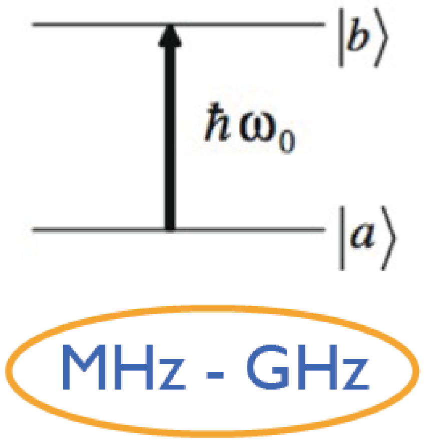
Ultrashort photons and atoms



Extreme bandwidth mismatch

↓

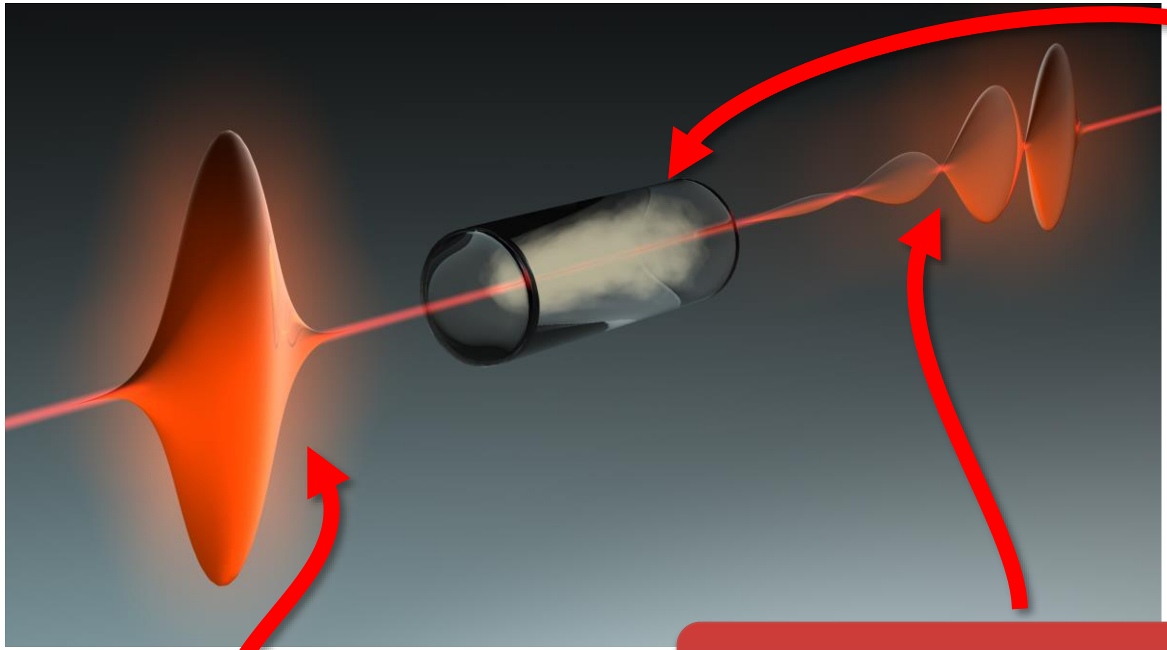
Very low absorption probability

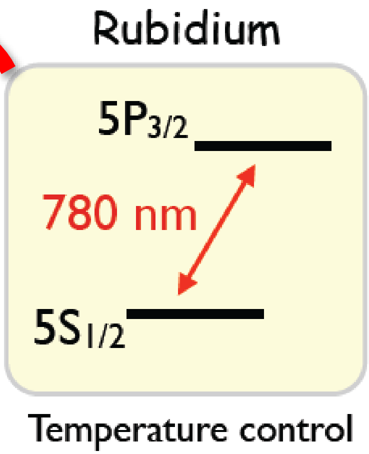


Single-photon 0-π pulses

Shine heralded ultrashort single photons through dense resonant atomic vapors

Successive absorption/emission cycles with a single photon?



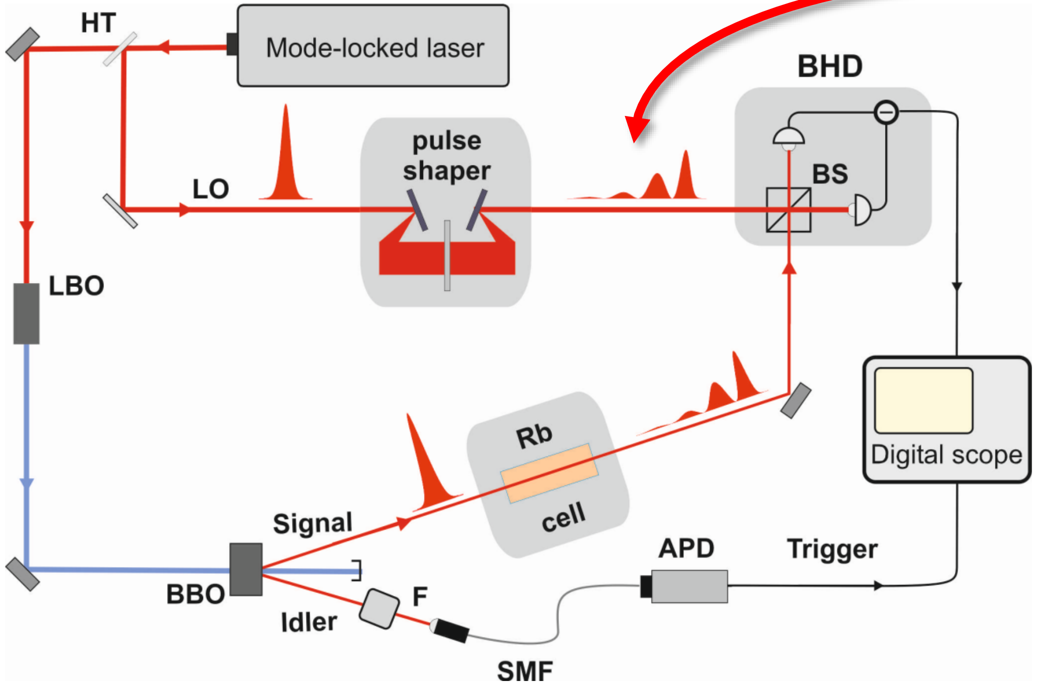


100 fs broadband pure single photon centered @ 780 nm

Still a pure single photon out?

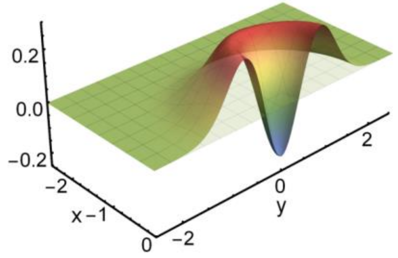
Zero-area temporal mode ?

Measuring the photon in the right mode

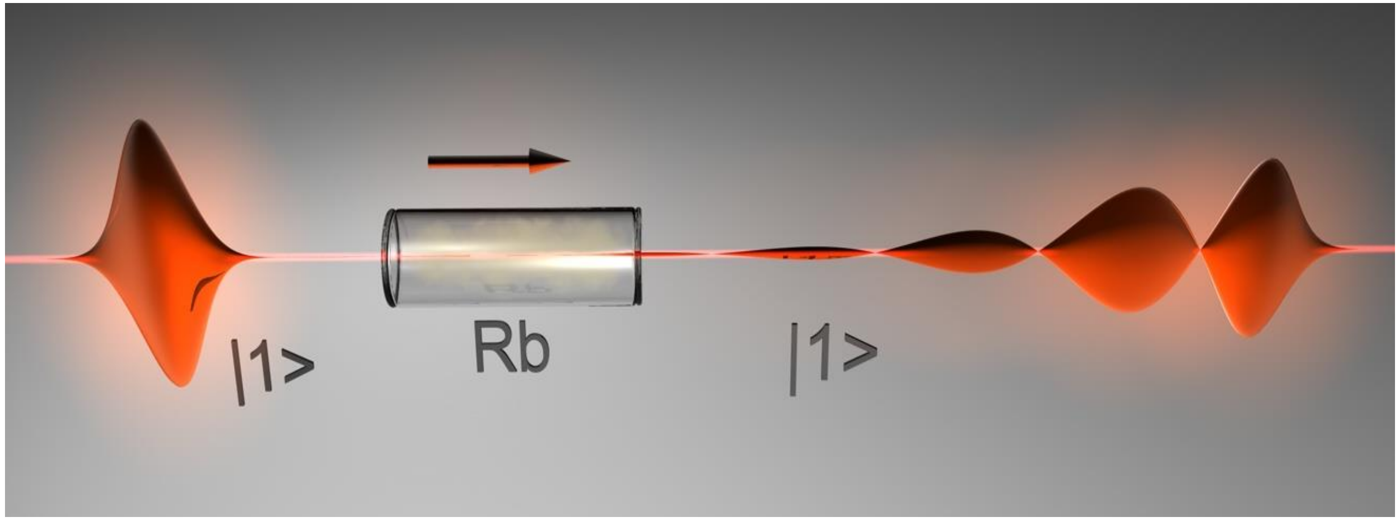


$$E(\omega,l) = E(\omega,0)\exp\left[\frac{-\alpha_0 l}{1-i(\omega-\omega_a)T_2}\right]$$

Use the expected 0π shape for the LO

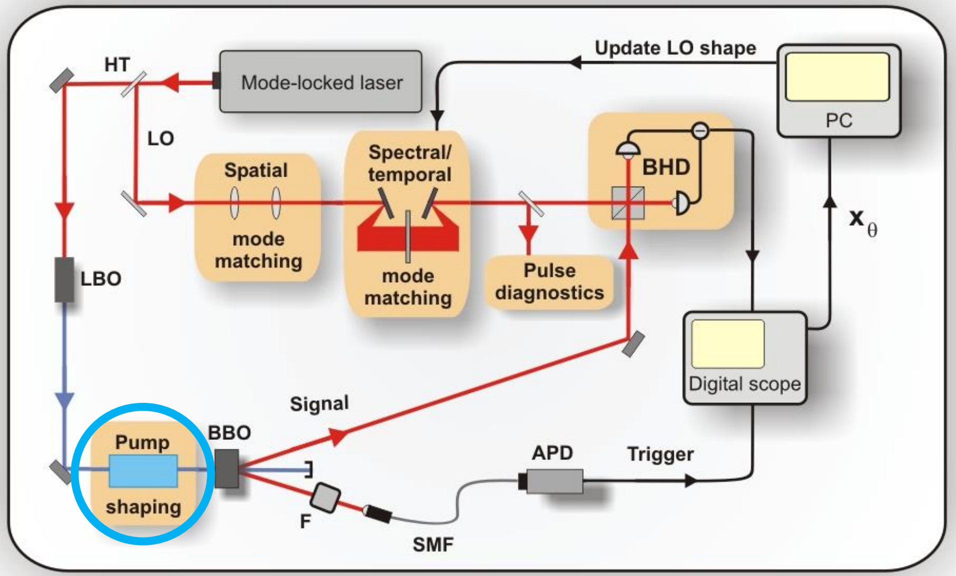


Negative Wigner function

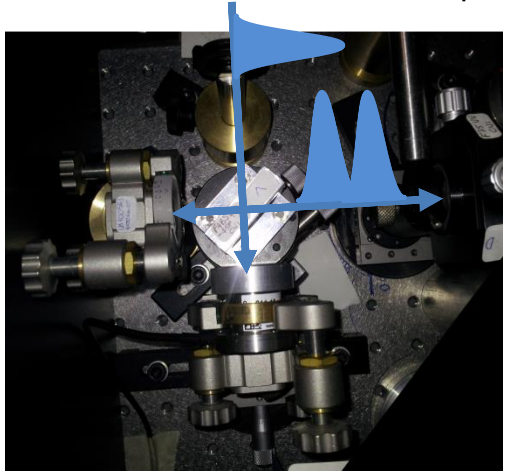


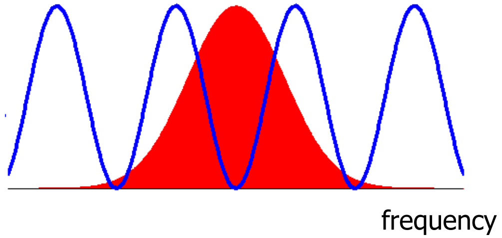
Zero-area single-photon pulses
L.S. Costanzo, A.S. Coelho, D. Pellegrino, M.S. Mendes, L. Acioli, K.N. Cassemiro, D. Felinto, A. Zavatta, & MB
PRL, **116**, 023602 (2016)

Photon shaping by pump modulation



Michelson interferometer on the pump

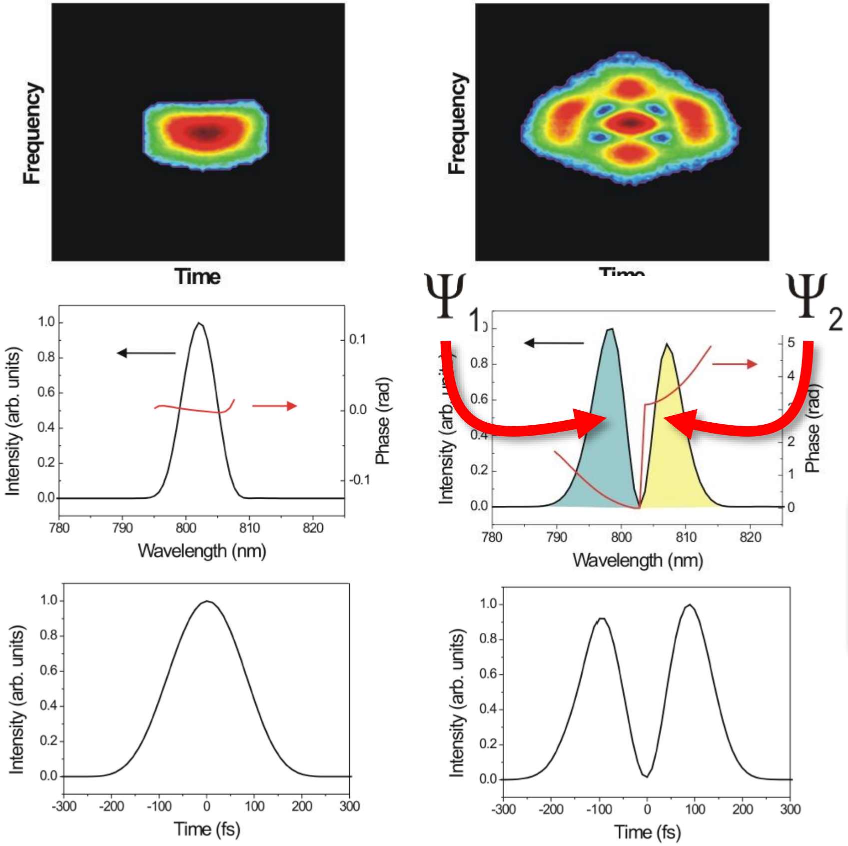




Sinusoidal modulation of the pump spectrum

Spectral narrowing

Double spectrotemporal peaks



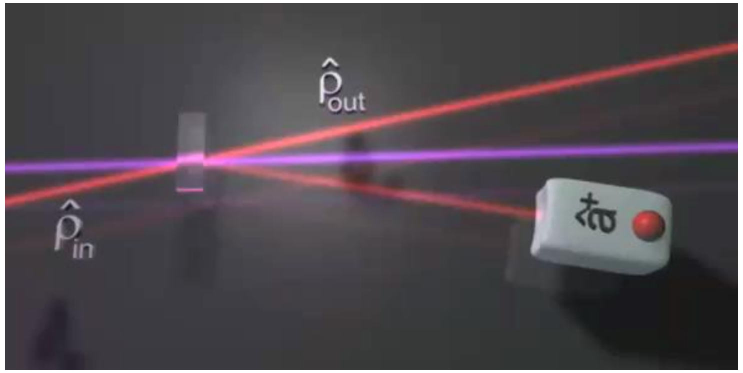
$\Delta\lambda_{FWHM}$~ 6 nm
$\Delta\tau_{FWHM}$~180 fs

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

A single-photon spectral **qudit**

Adaptive detection of arbitrarily-shaped ultrashort quantum light states
C. Polycarpou, K. Cassemiro, G. Venturi, A. Zavatta, & MB
PRL **109**, 053602 (2012)

Photon addition & subtraction

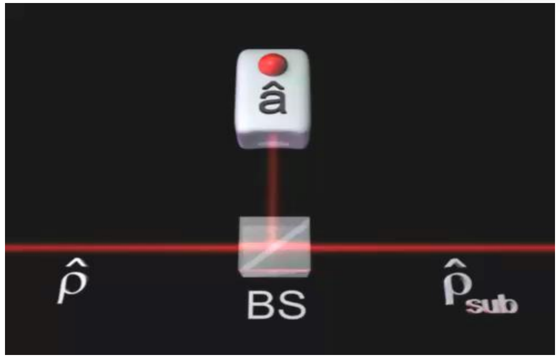


$\hat{a}^{\dagger}$

Photon addition

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

$\hat{a}$



Photon subtraction

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

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

Noiseless amplification

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

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

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)

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

State orthogonalizer and CV qubit generator

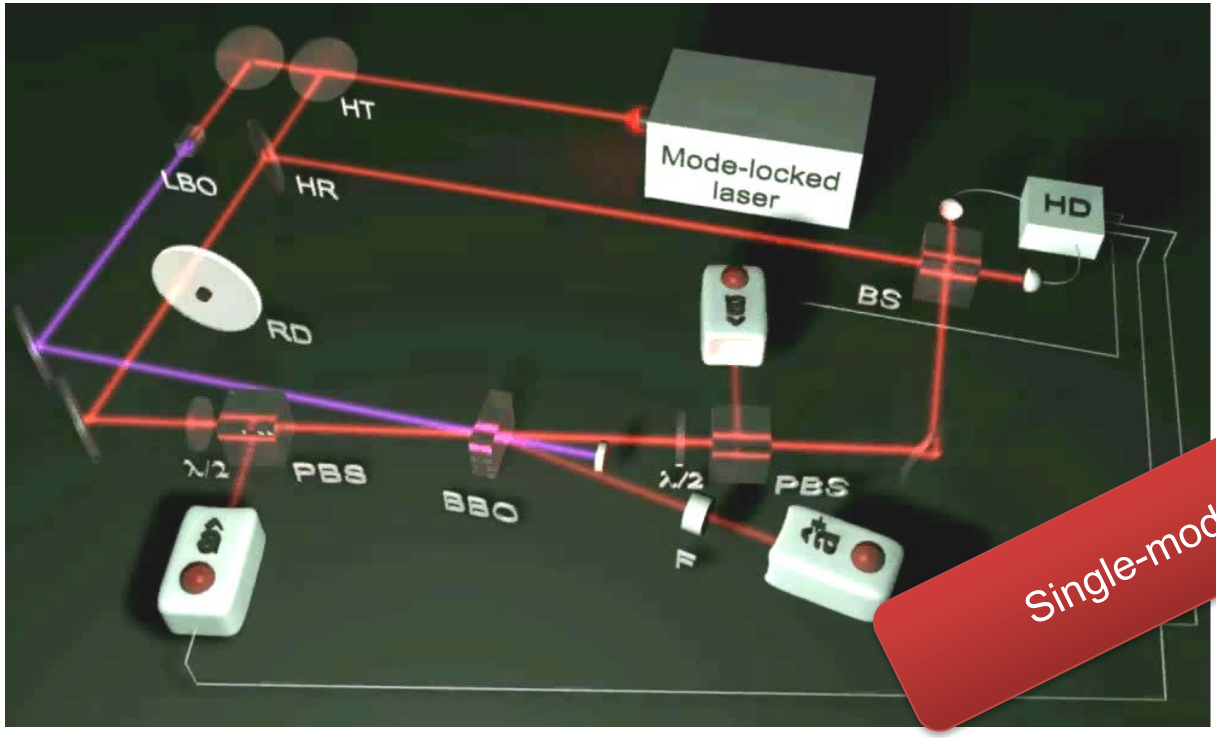
A.S. Coelho, L.S. Costanzo, A. Zavatta, C. Hughes, M.S. Kim, MB
PRL, **116**, 110501 (2016)

$|n\rangle \rightarrow e^{-i\Phi n(n-1)}|n\rangle$

Emulation of Kerr nonlinearities

L.S. Costanzo, A.S. Coelho, N. Biagi, J. Fiurasek, MB, A. Zavatta
PRL, **119**, 013601 (2017)

Testing quantum foundations



Single-mode operations

Quantum commutation rules

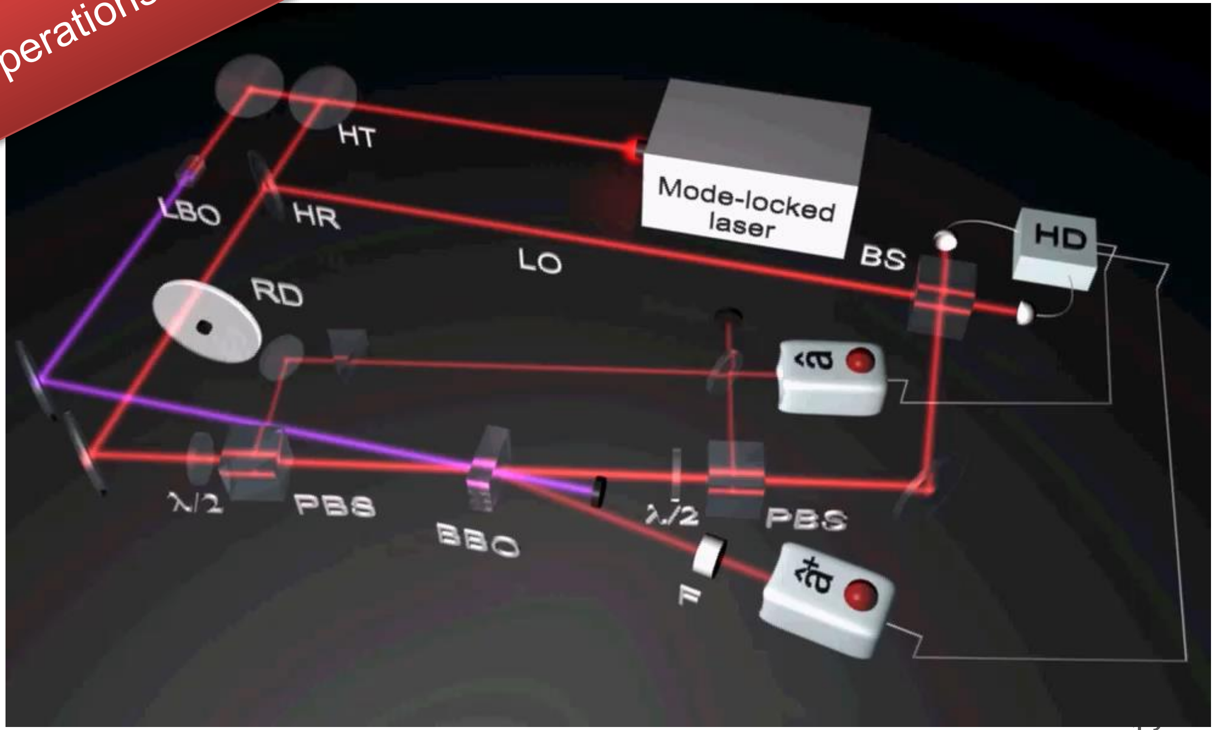
$$[\hat{a}, \hat{a}^\dagger] \neq 0$$

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

Creating operator superpositions

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

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

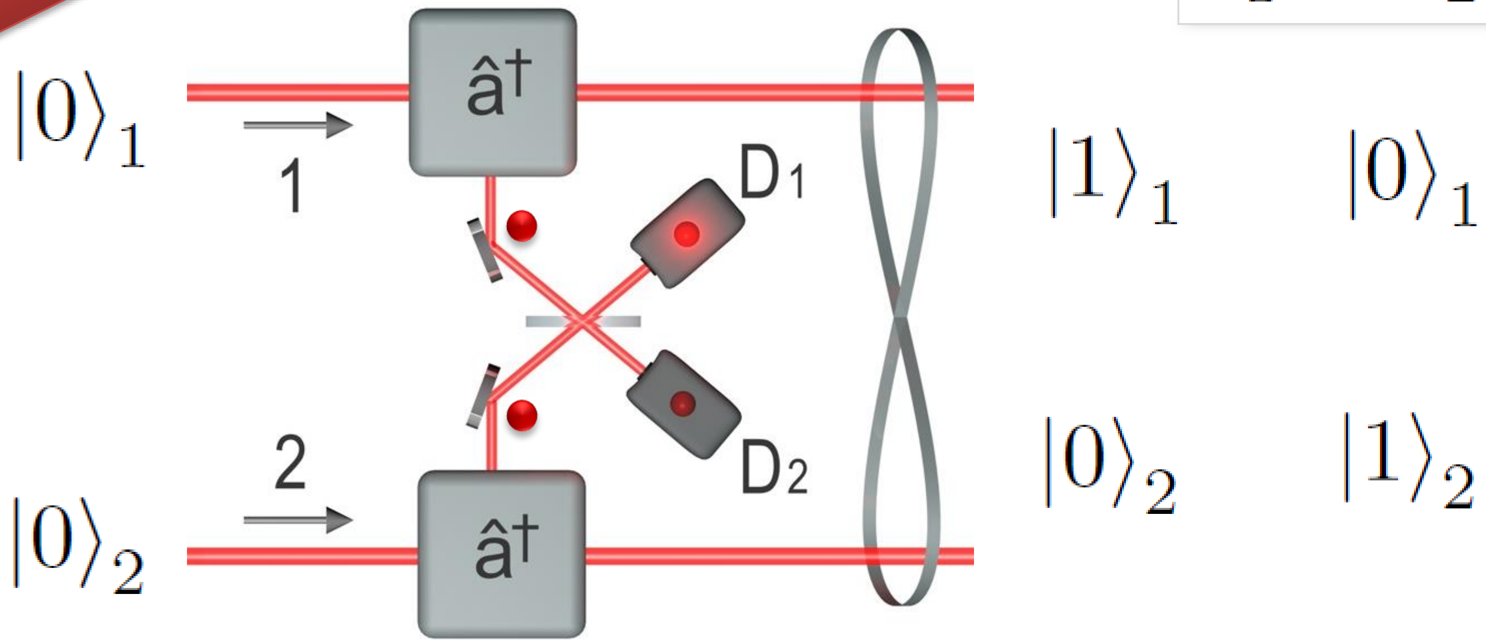


Entanglement by delocalized photon addition

Going multimode

Delocalized photon addition on modes 1 and 2

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

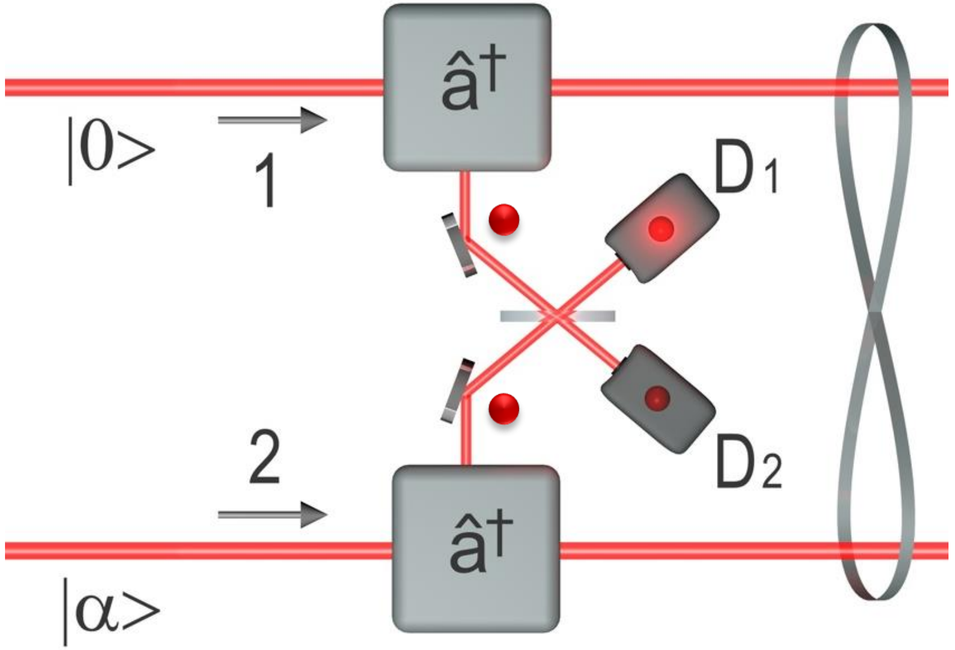


Single-photon path-entangled state

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

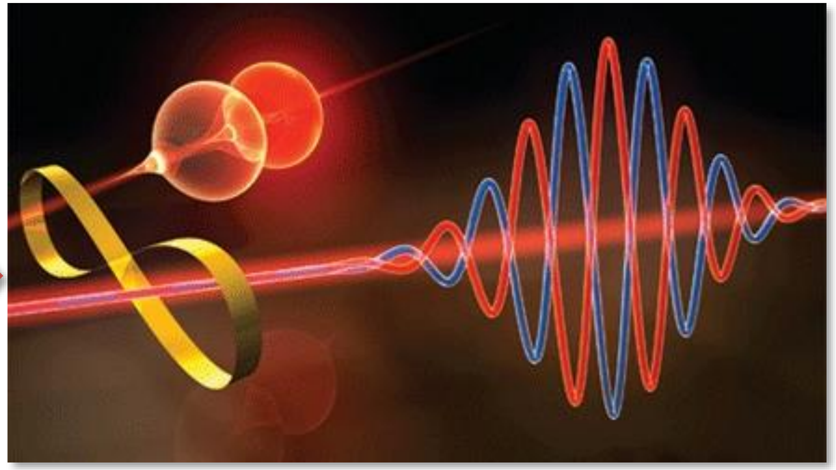
Two distinct spatial modes get entangled by sharing a single photon

Hybrid CV-DV entanglement



$|1\rangle$ $|0\rangle$

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



Displacement on mode 2

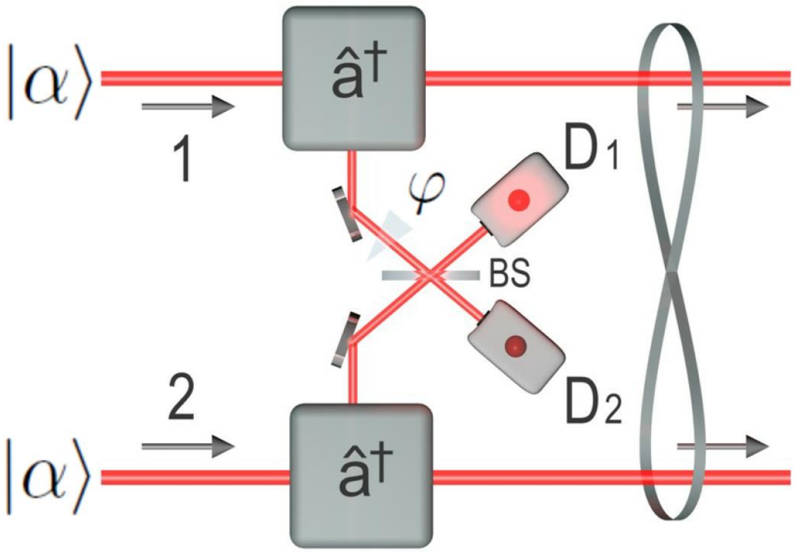
$$\approx \frac{1}{\sqrt{2}}(|0\rangle|\alpha_f\rangle + |1\rangle|-\alpha_f\rangle)$$

Hybrid entanglement between states encoded in discrete and continuous variables

Interfacing quantum information networks relying on different encodings

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



$$|\psi_\varphi(\alpha)\rangle_{12} = \left(\hat{a}_1^\dagger|\alpha\rangle_1|\alpha\rangle_2 + e^{i\varphi}|\alpha\rangle_1\hat{a}_2^\dagger|\alpha\rangle_2\right)/\sqrt{\mathcal{N}}$$

$$= \Big[\hat{D}_1(\alpha)\hat{D}_2(\alpha)\left(|1\rangle_1|0\rangle_2 + e^{i\varphi}|0\rangle_1|1\rangle_2\right)$$

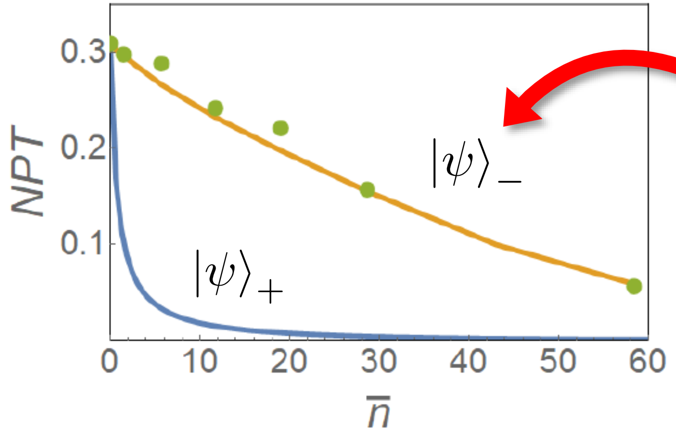
$$+ \alpha^*(1+e^{i\varphi})|\alpha\rangle_1|\alpha\rangle_2\Big]/\sqrt{\mathcal{N}}$$

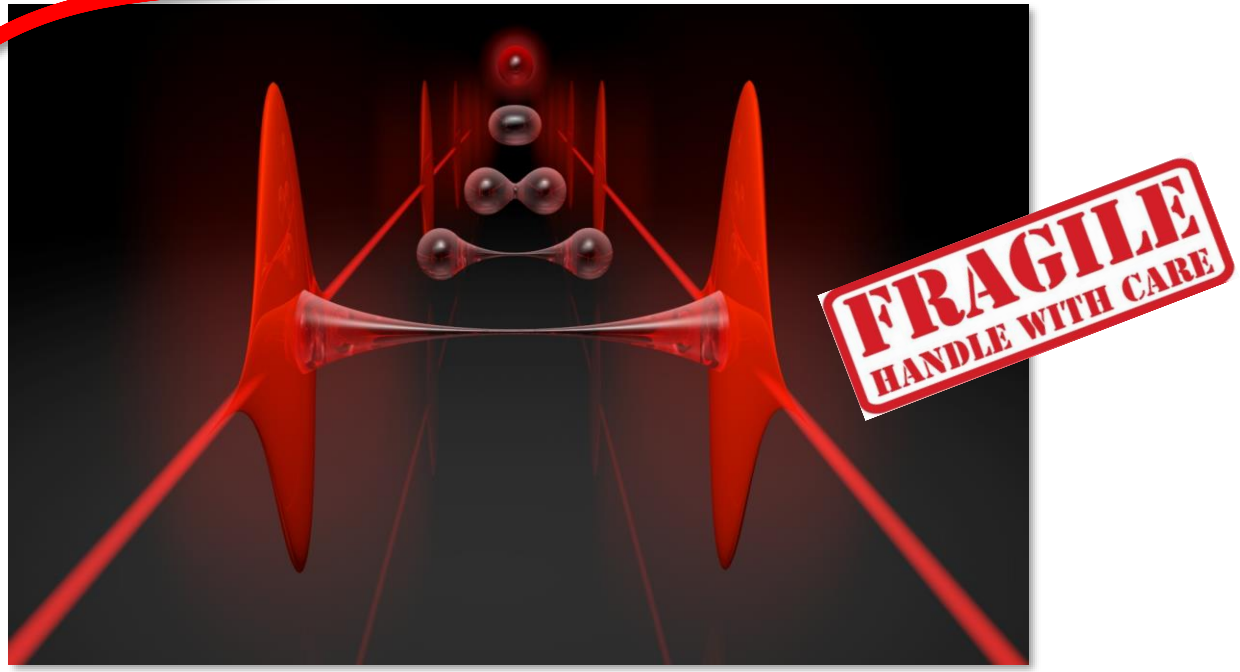
Entangled

Separable

Significant entangelement measured even between **LARGE** coherent states

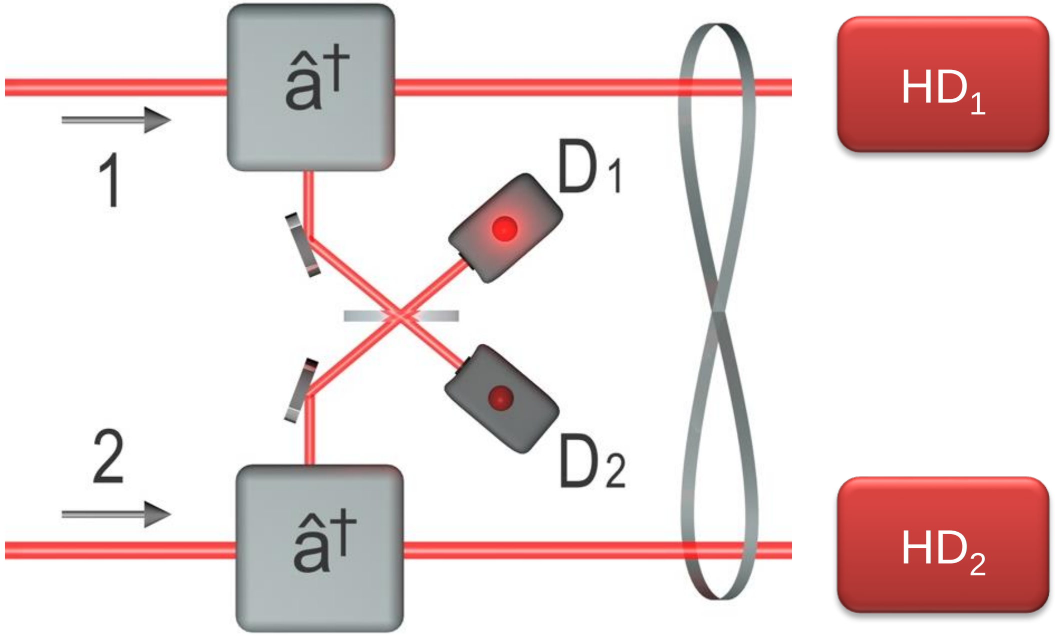
$$\phi = \pi$$





Entangling macroscopic light states by delocalized photon addition
N. Biagi, L.S. Costanzo, MB & A. Zavatta, *PRL* **124**, 033604 (2020)

Superposition of operators on two (spatial) modes

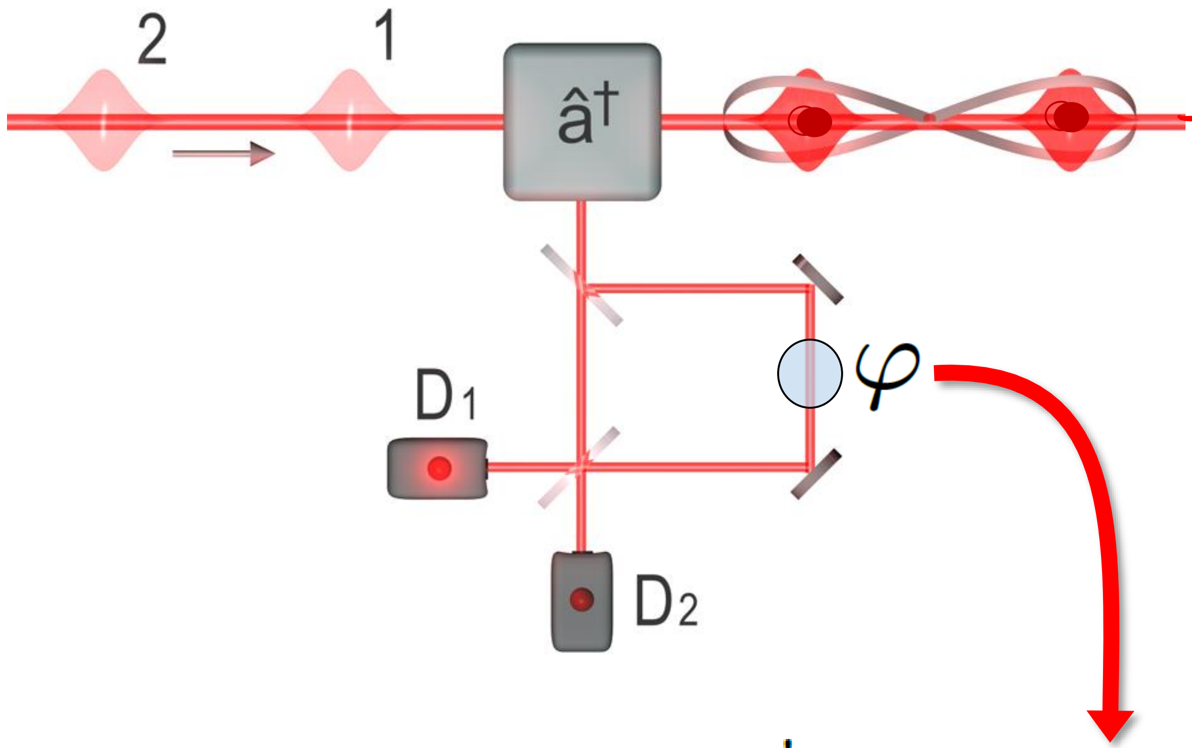


It requires two PDC sources and two homodyne detectors
Hard to scale to more modes

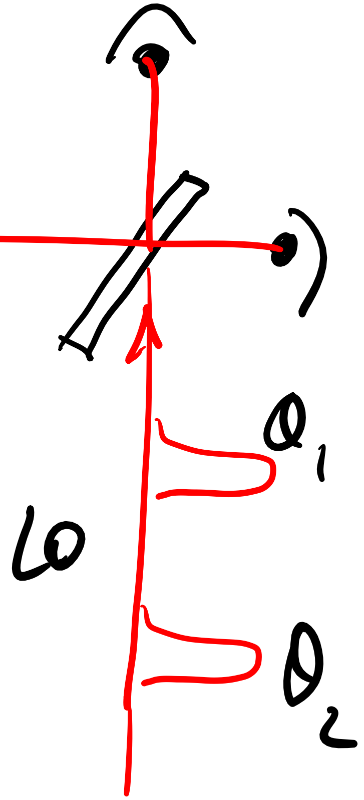
Not so clever...

Superposing operators on two (temporal) modes

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



$$\hat{a}_1^\dagger + e^{i\varphi}\hat{a}_2^\dagger$$



Simple

Compact

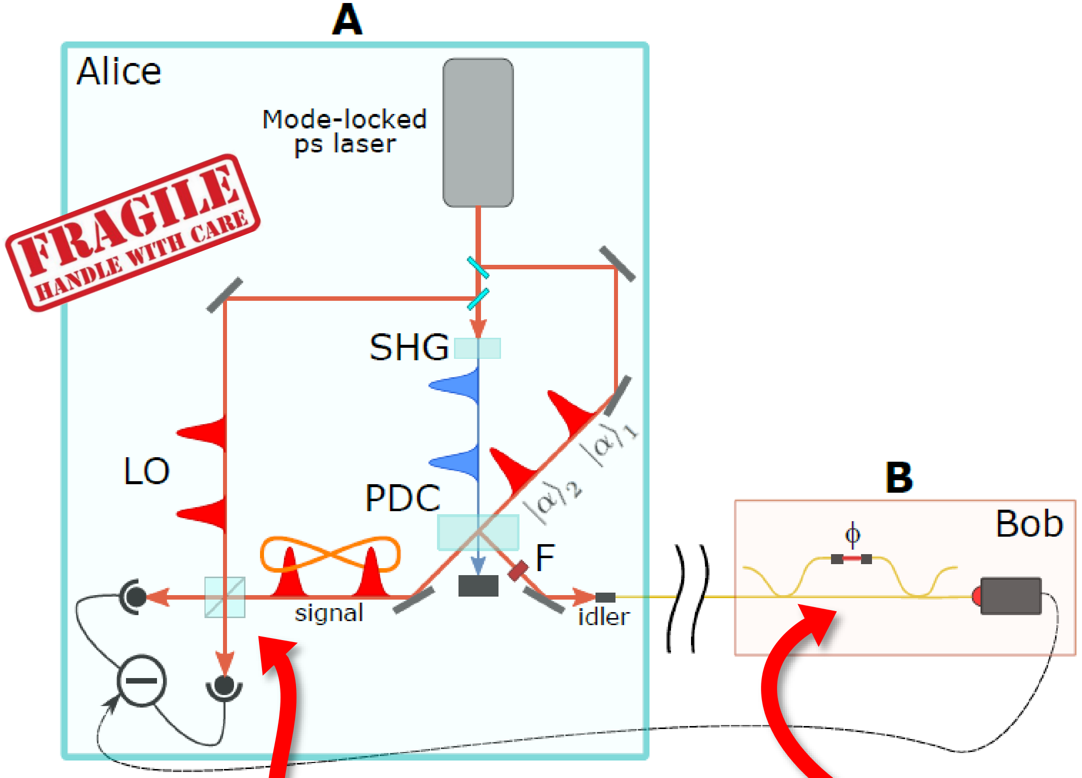
Phase-stable

Scalable to multiple modes

Remote preparation of arbitrary time-encoded single-photon ebits
A. Zavatta, M. D'Angelo, V. Parigi & MB
PRL, **96**, 020502 (2006)

Remote phase sensing

Extreme sensitivity of the **entanglement** on the remote heralding phase

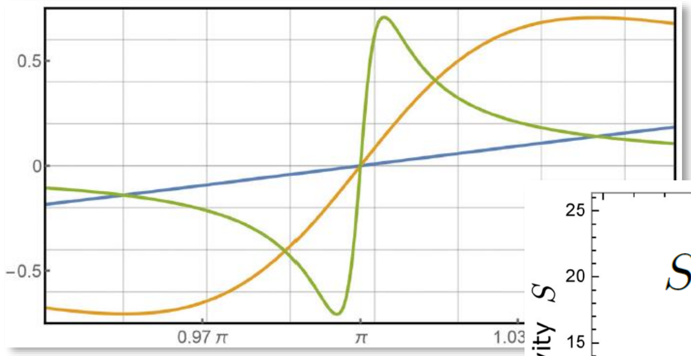


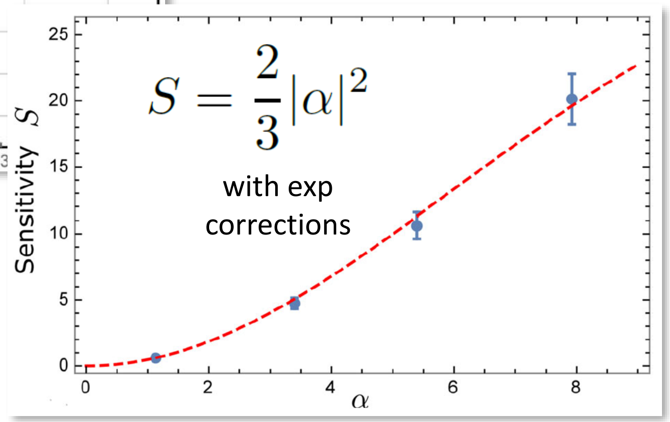
Two-mode (heralded) homodyne detection

Unbalanced Mach-Zehnder interferometer

Highly-sensitive and “easy” observable

$$\hat{X}_{\rm opt} = \hat{p}_1 - \hat{p}_2$$





The phase sensitivity scales with the intensity of coherent states that never interacted with the sample

- Remote sample location
- Losses towards the remote sample unimportant
- Different wavelengths possible
- Single-spatial-mode fiber operation (compactness, phase stability, etc.)

Remote Phase Sensing by Coherent Single Photon Addition
N. Biagi, S. Francesconi, M. Gessner, MB, & A. Zavatta
Advanced Quantum Technologies, **12**, 2200039 (2022)

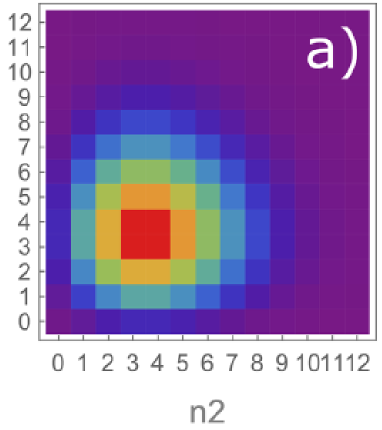
Discorrelation and card games

P_{n_1,n_2}

Joint photon number probability distributions

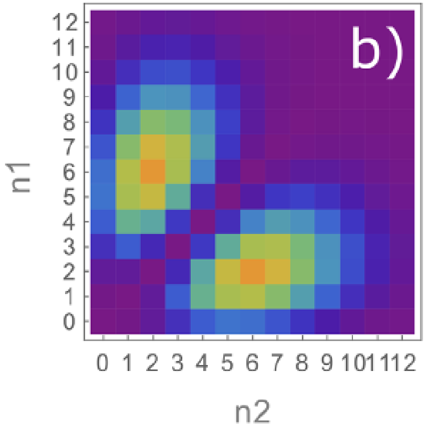
Separable two-mode coherent states

$|\alpha\rangle_1 \, |\alpha\rangle_2$



Delocalized single-photon-added coherent states

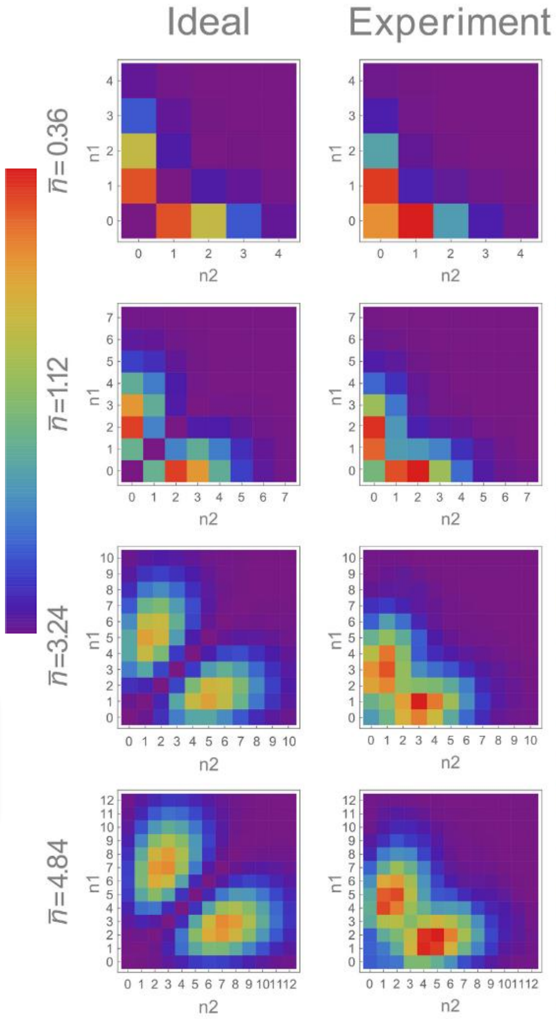
$|\psi\rangle_-$



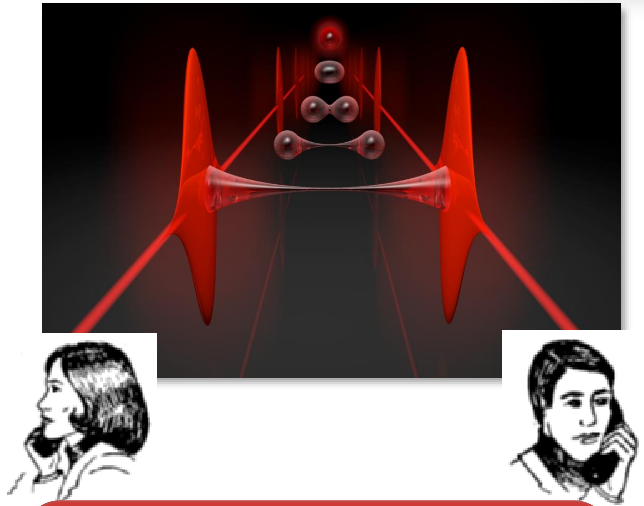
The photon numbers $\boldsymbol{n_1}$ and $\boldsymbol{n_2}$ in the two modes can take any value individually but, when measured together, one never gets $n_1 = n_2$

$$P_{n,n} = 0$$

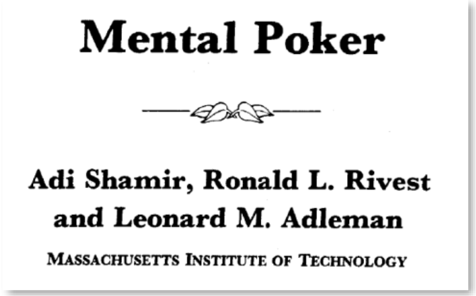
Sharing a discorrelated multimode state may naturally guarantee the uniqueness of the distributed random numbers



Generating discorrelated states for quantum information protocols by coherent multimode photon addition
N. Biagi, L.S. Costanzo, MB, & A. Zavatta
Advanced Quantum Technologies, **2000141** (2021)



Good for mental card games, secure voting, electronic cash, etc.



Mental Poker

Adi Shamir, Ronald L. Rivest and Leonard M. Adleman

Massachusetts Institute of Technology

The Mathematical Gardner
Springer, Boston 1981, pp. 37–43

Playing with quantum light

Photon-by-photon light sculpting

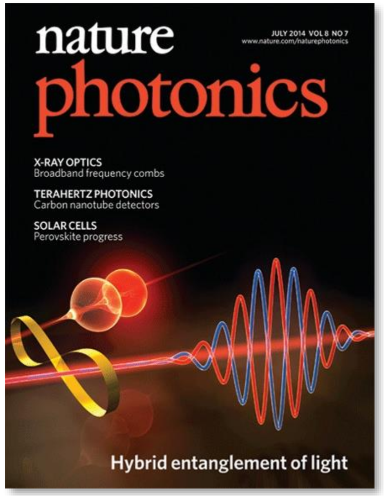
Arbitrary engineering of quantum light states

Textbook-type experiments and fundamental quantum tests

Entanglement generation and control

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

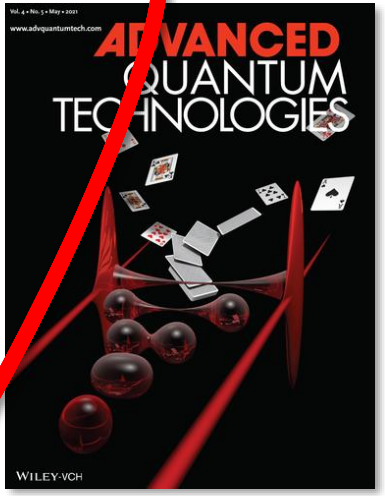
$|\Psi\rangle = \frac{1}{\sqrt{2}}(|🙂\rangle + |🙃\rangle)$

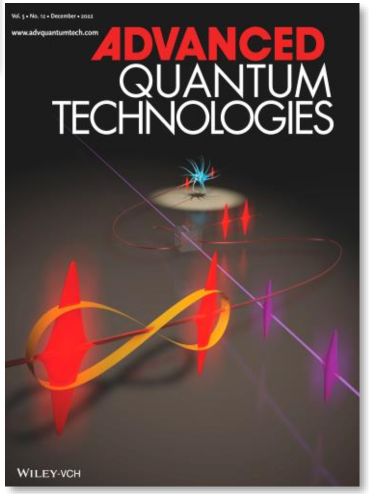


Single-photon mode morphing

Producing single photons of arbitrary shapes

Measuring quantum states in arbitrary ST modes





New tools for quantum technologies

- Noiseless amplification
- Remote sensing
- Novel quantum information processing & communication protocols
- …

Arbitrary quantum state engineering over modes of arbitrary shape

https://quantumlight.ino.cnr.it/

Credits

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