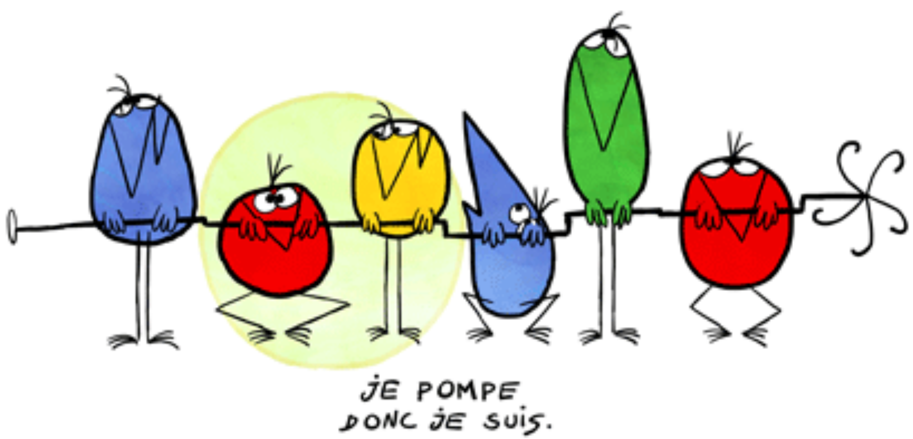
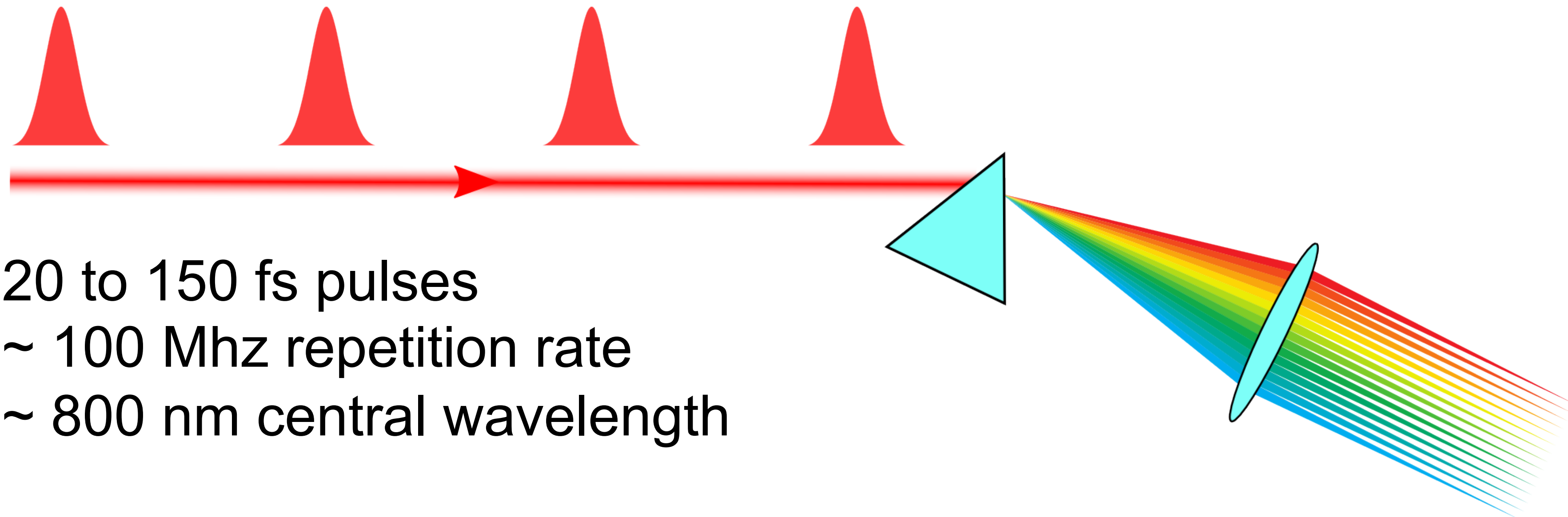
Laboratoire Kastler Brossel
Physique quantique et applications

Tailored Non-Gaussian Multimode States

Nicolas Treps

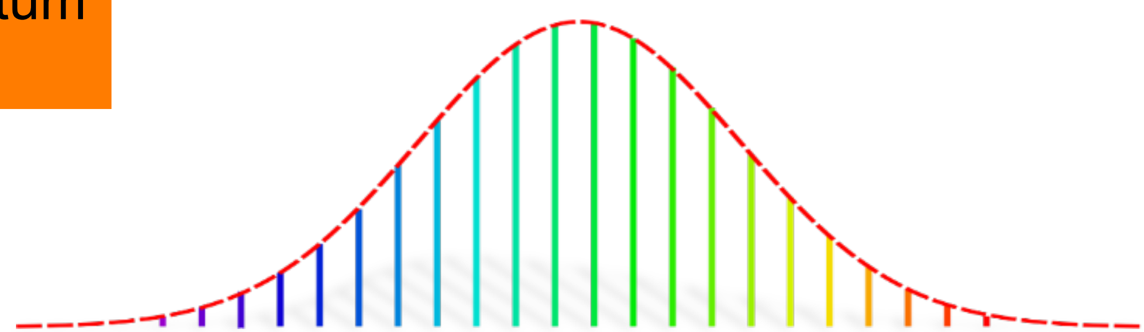


Optical Frequency Combs



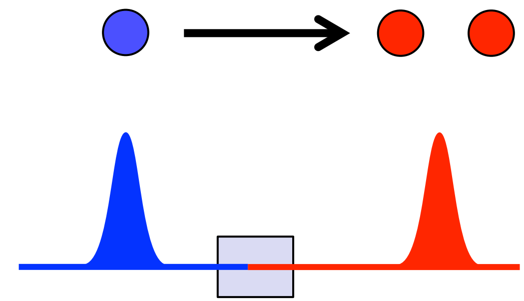
20 to 150 fs pulses
~ 100 Mhz repetition rate
~ 800 nm central wavelength

10^5-10^6 longitudinal modes



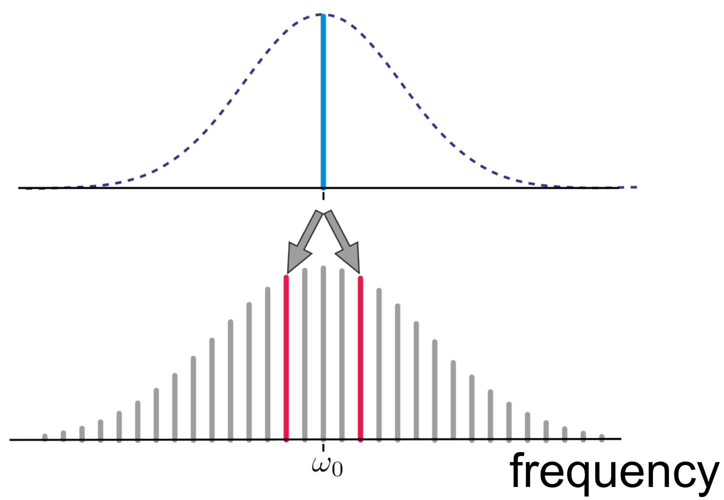
Tool for metrology and quantum information

Optical Frequency Combs

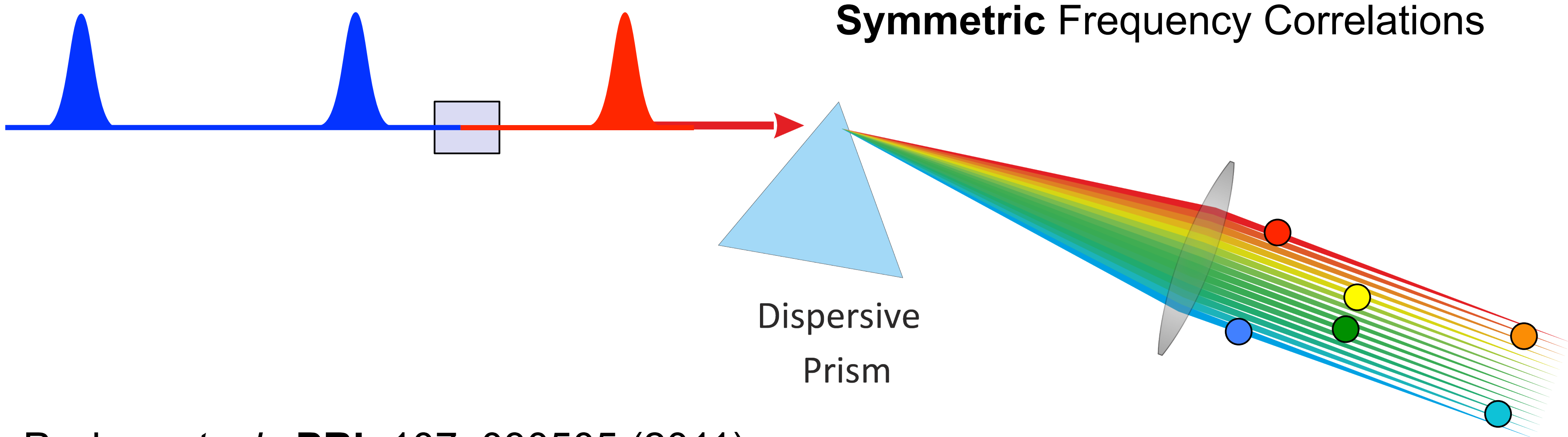


$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$

Femtosecond Downconversion

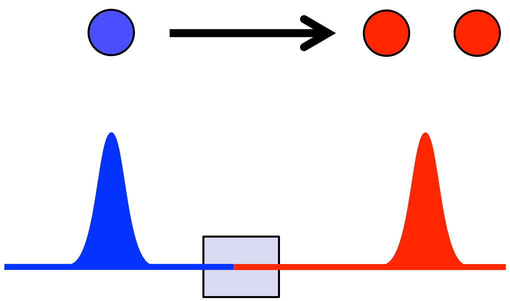


Symmetric Frequency Correlations



Pysher, *et. al.*, **PRL** 107, 030505 (2011)

Optical Frequency Combs



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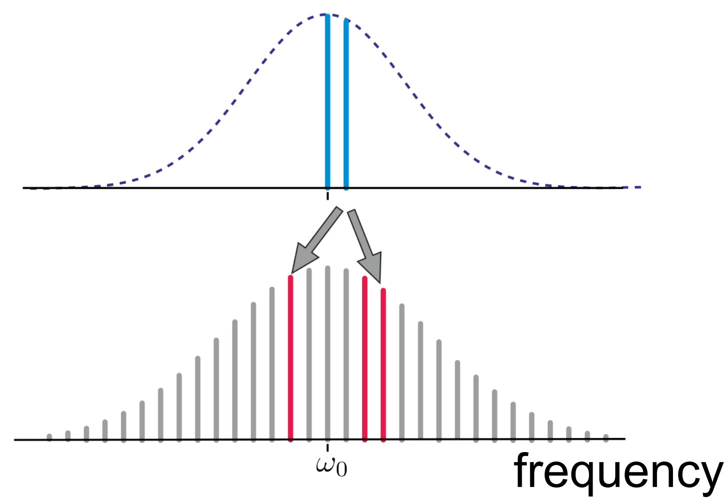
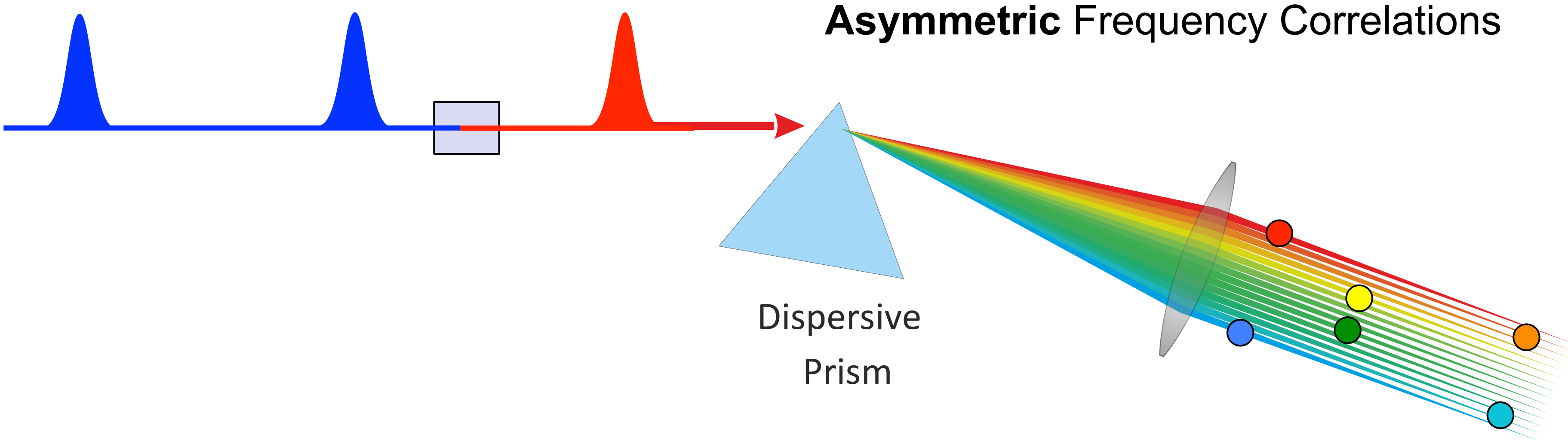
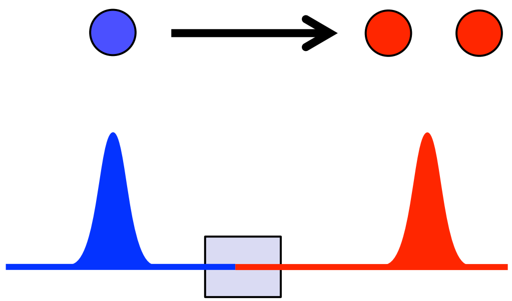


Asymmetric Frequency Correlations



Optical Frequency Combs



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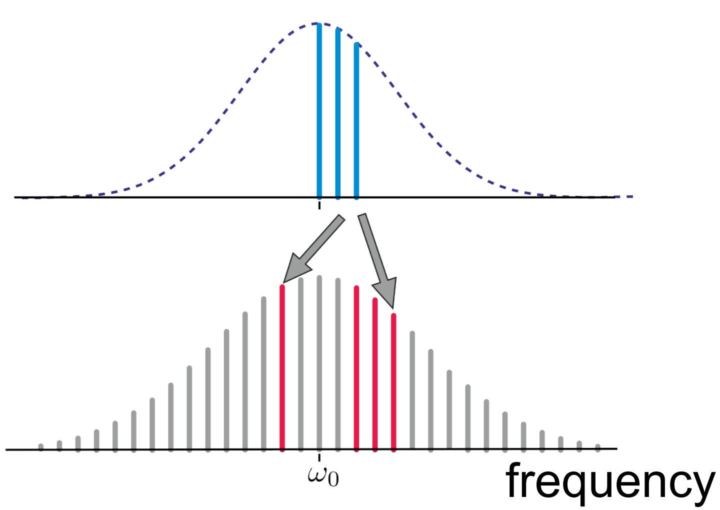
Femtosecond Downconversion



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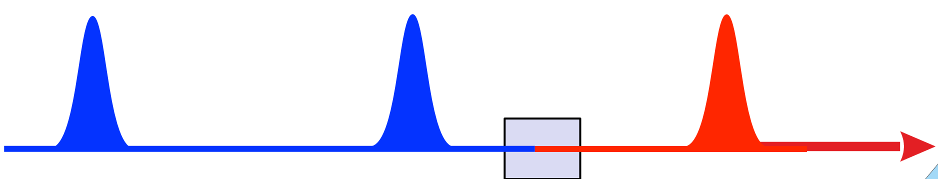
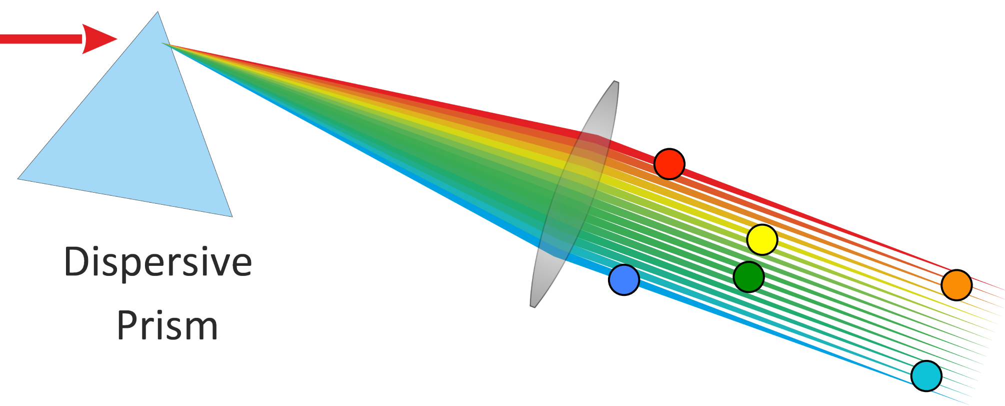
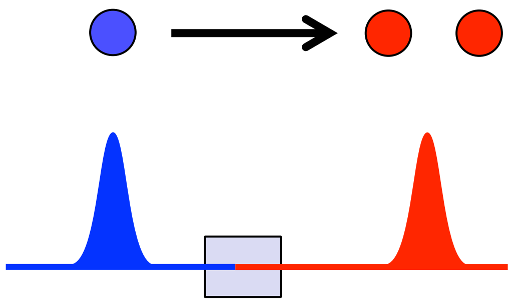




Optical Frequency Combs



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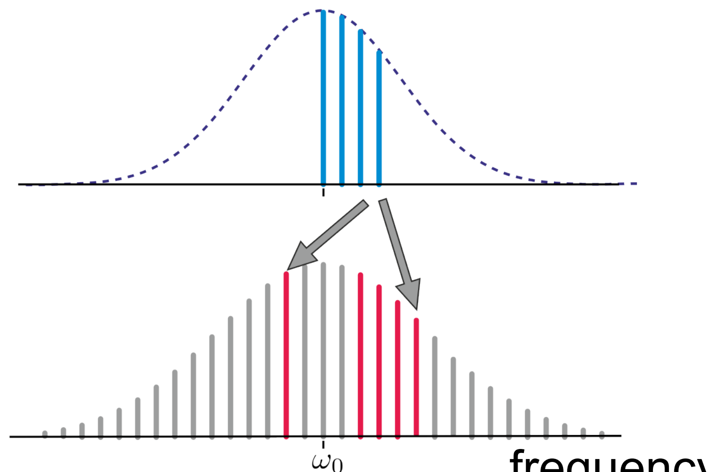
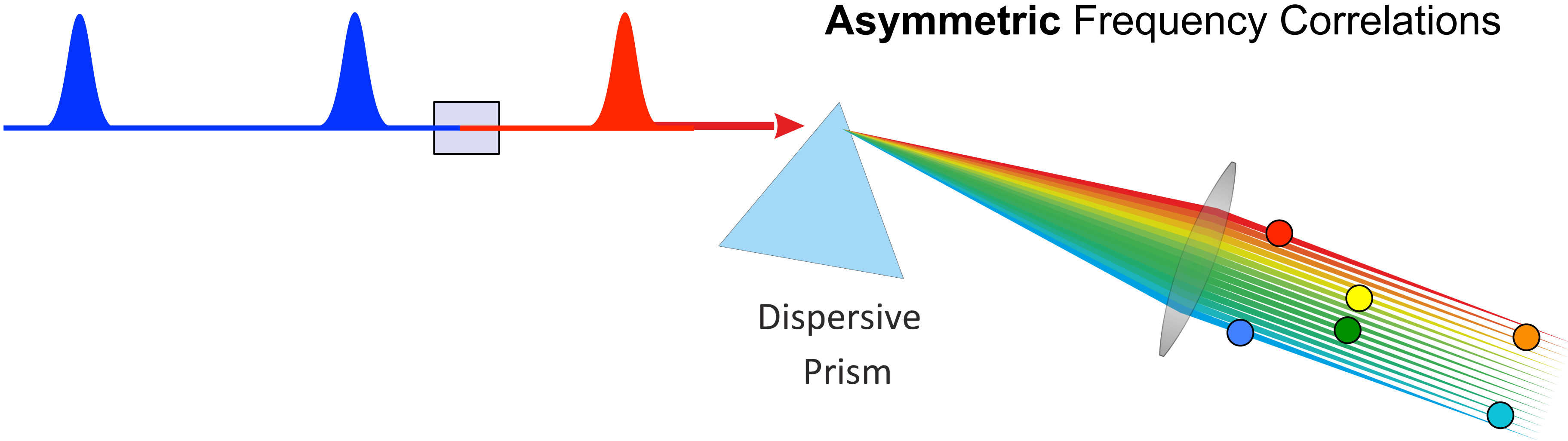
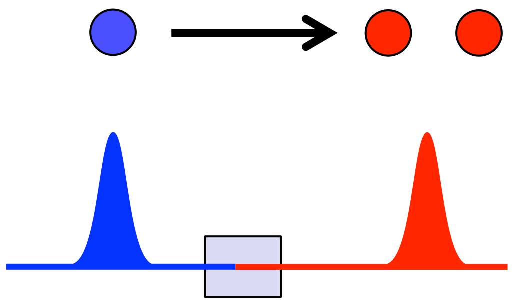


Asymmetric Frequency Correlations



Optical Frequency Combs



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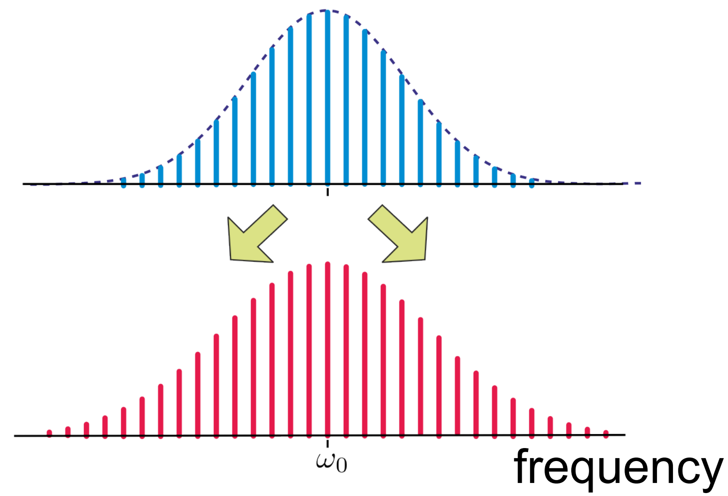
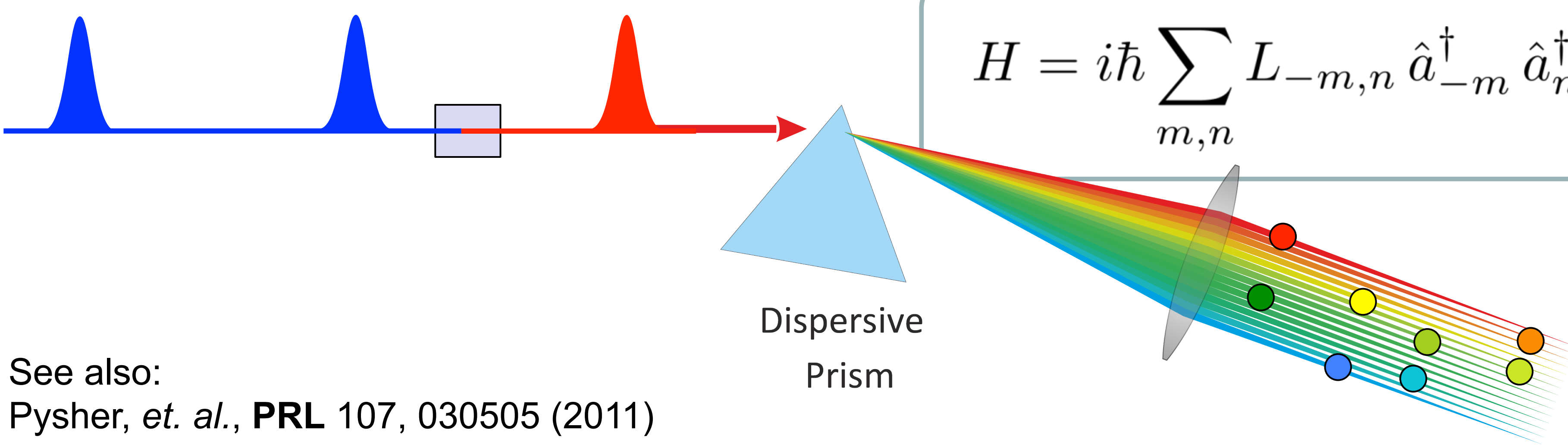
Femtosecond Downconversion

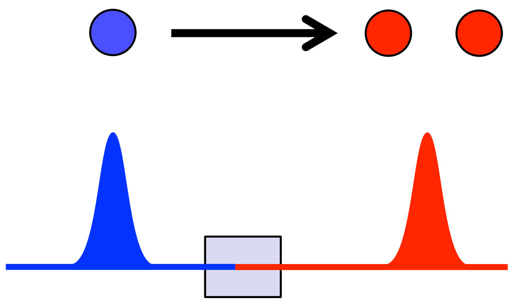


$$H = i\hbar \sum_{m,n} L_{-m,n}\, \hat{a}^{\dagger}_{-m}\, \hat{a}^{\dagger}_{n}$$



See also:
Pysher, *et. al.*, **PRL** 107, 030505 (2011)
Chen, *et. al.*, **PRL** 112, 120505 (2014)

Optical Frequency Combs



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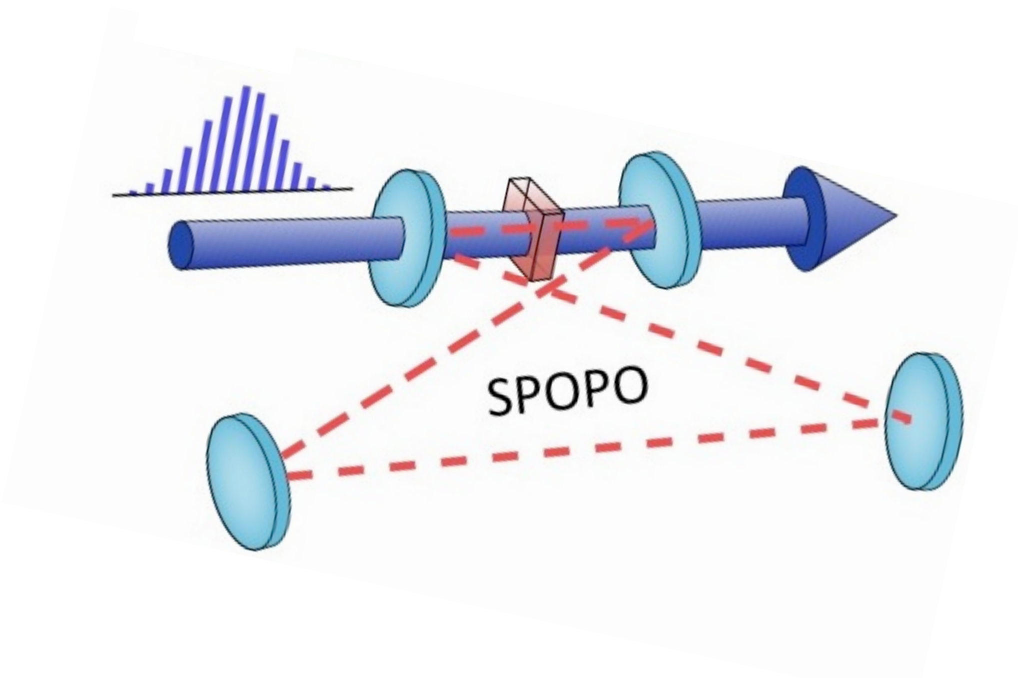
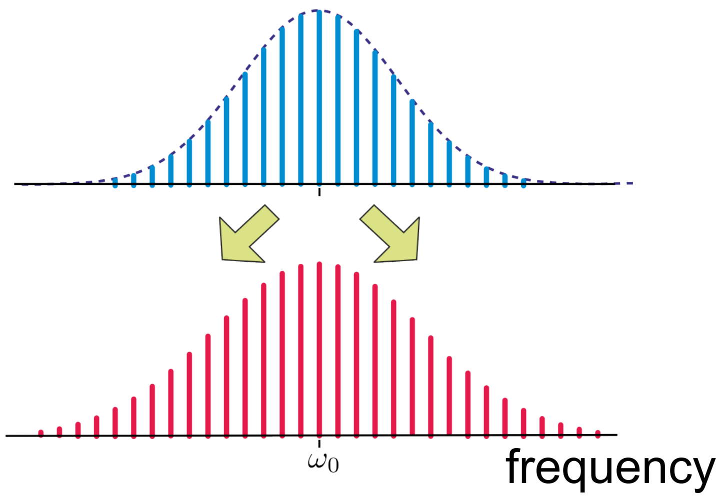


Femtosecond Downconversion



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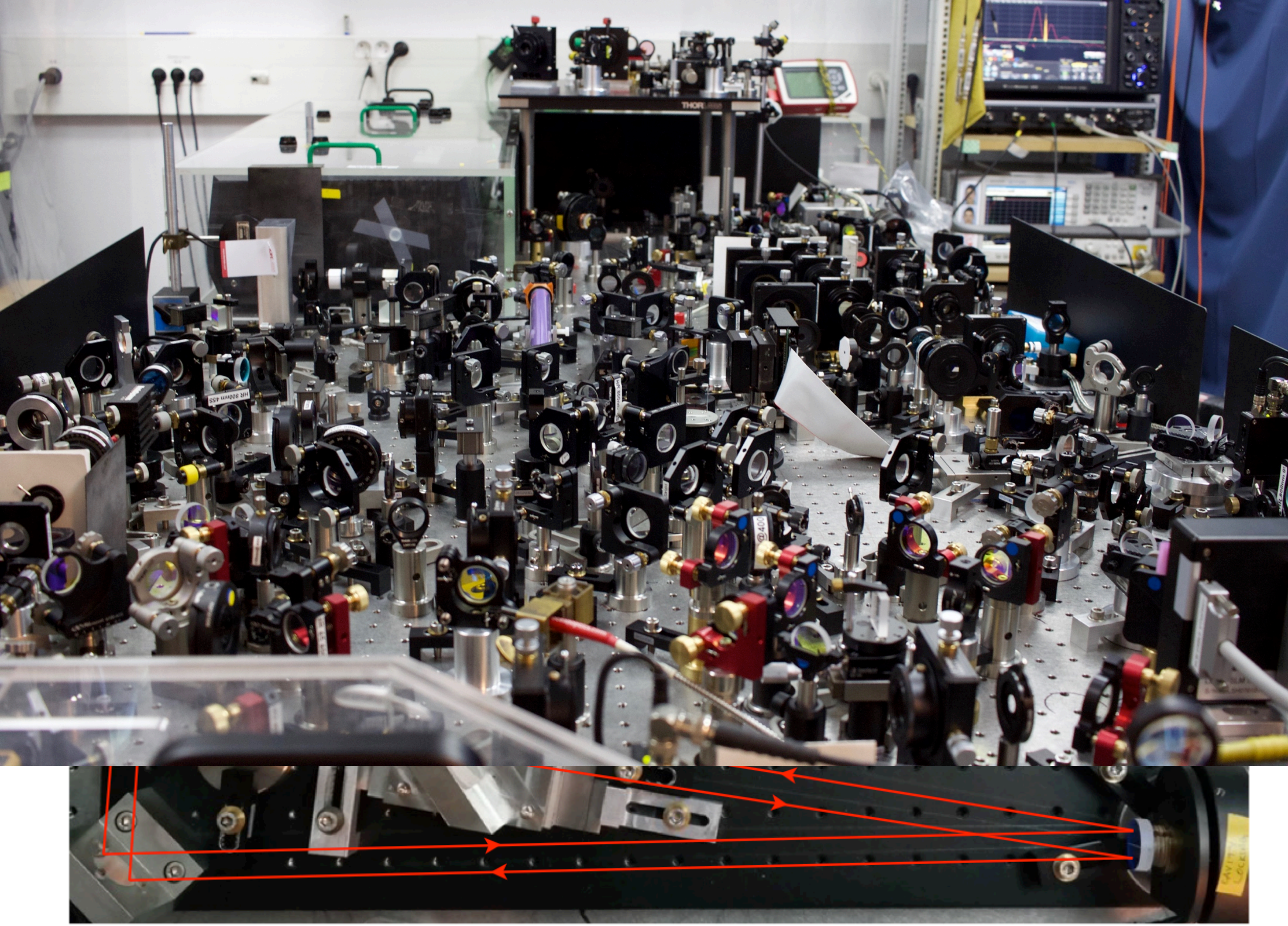


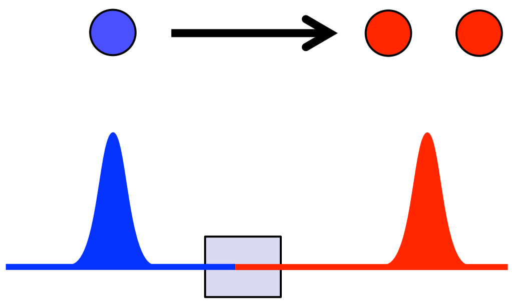
Menu

- Generation of versatile graph-states
- What photon subtraction can do
- Tailored non-Gaussian states

LKB

Measuring the fluctuations of an optical frequency comb

Optical Frequency Combs



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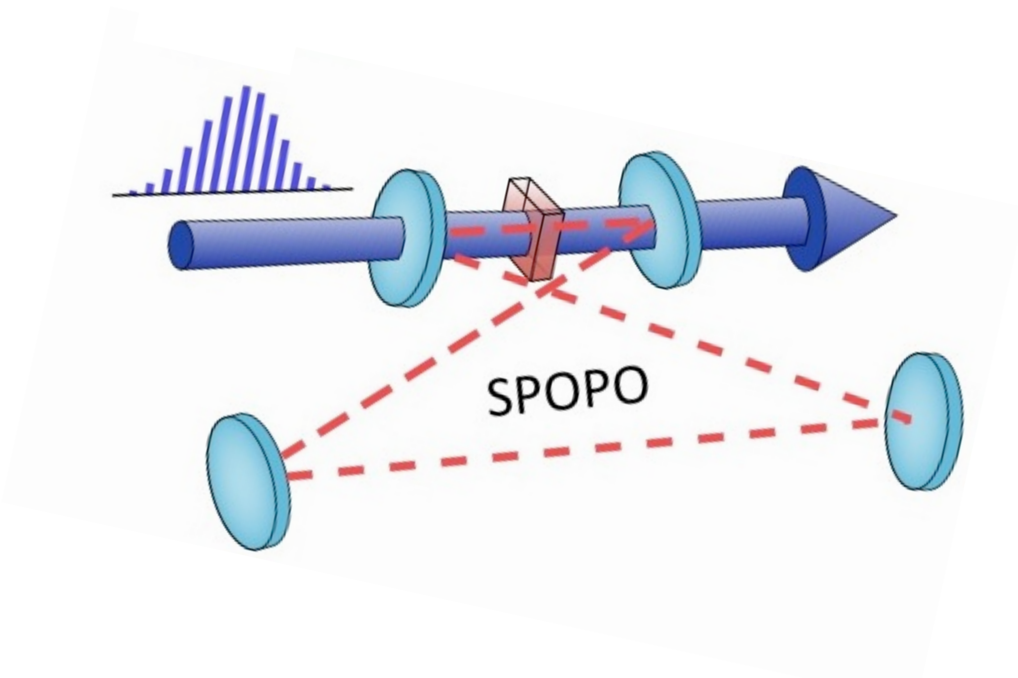
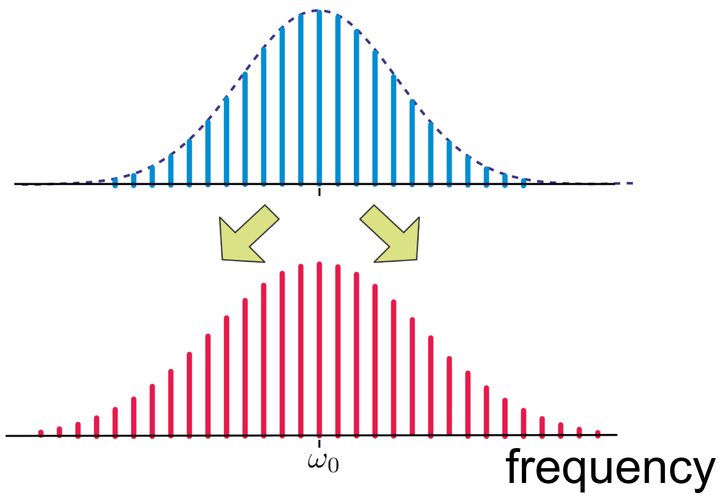
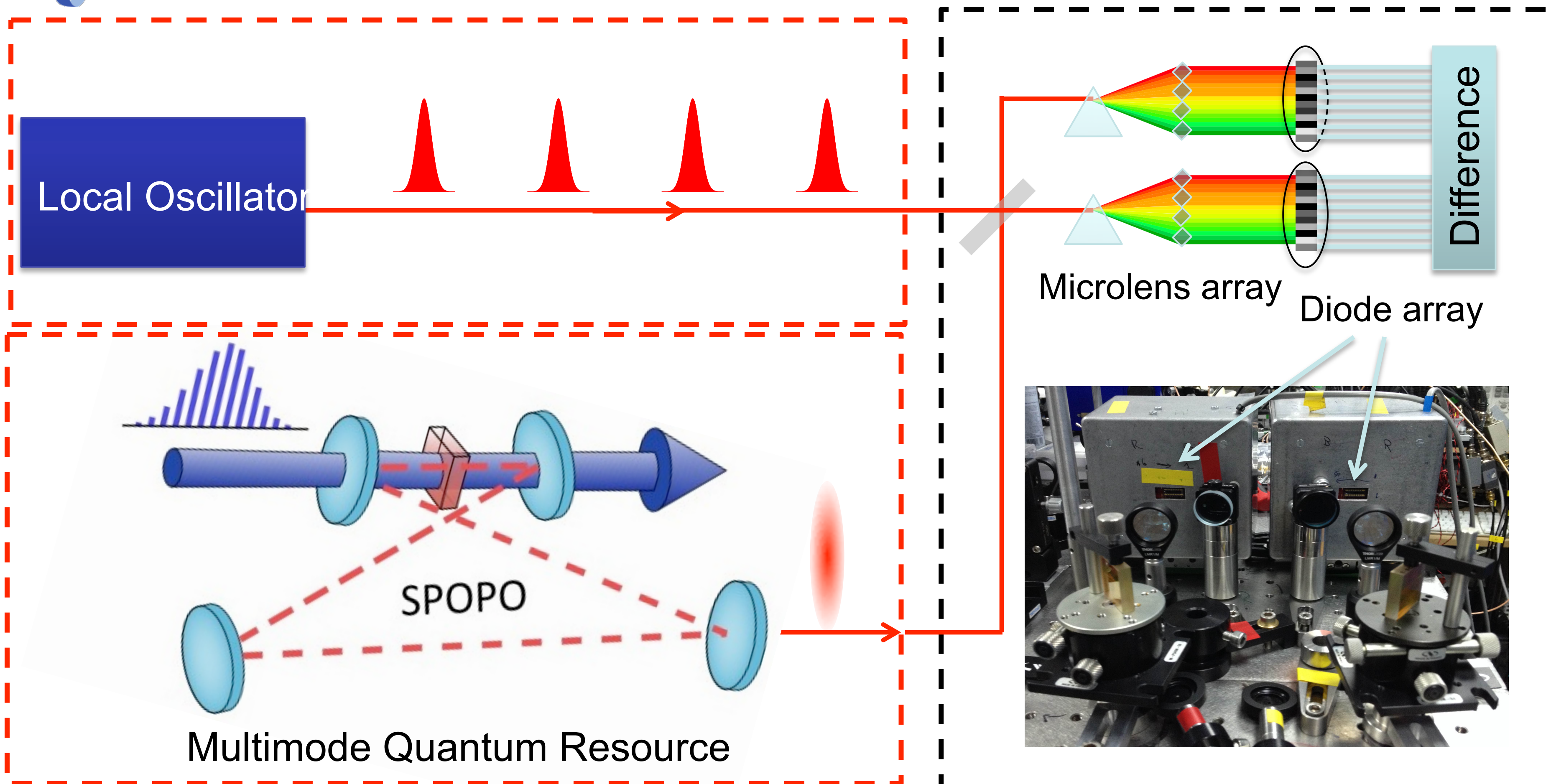


Femtosecond Downconversion



$$H = i\hbar \sum_{m,n} L_{-m,n}\, \hat{a}^\dagger_{-m}\, \hat{a}^\dagger_n$$

Multi-Pixel Homodyne Detection



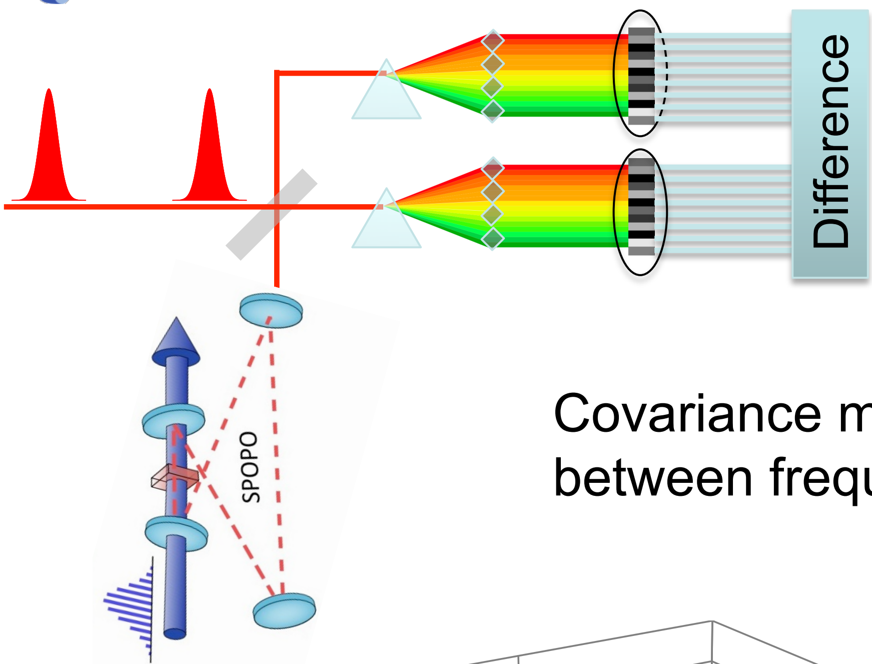
R. Medeiros de Araújo, et al, Phys. Rev. A 89,053828(2014).
See also : C. Polycarpou, K. Cassemiro, G. Venturi, A. Zavatta, and M. Bellini, Phys Rev Lett 109, 053602 (2012).

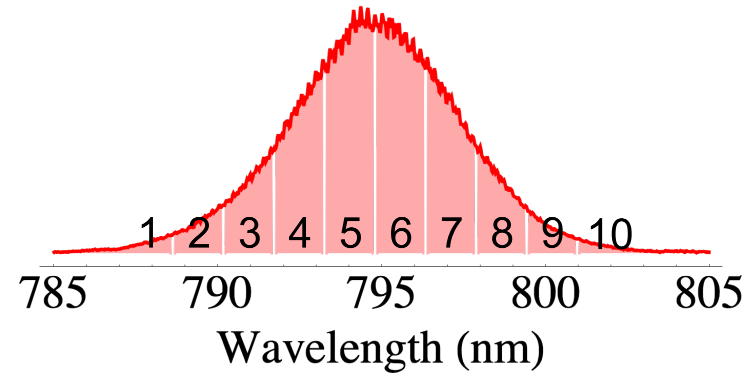
Multi-Pixel Homodyne Detection

Frequency-resolved detection

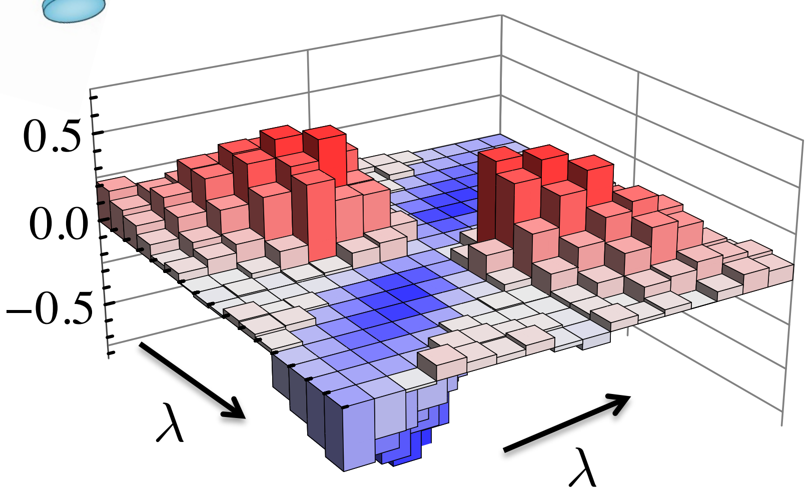
Simultaneous Detection

Multi-Pixel Homodyne Detection

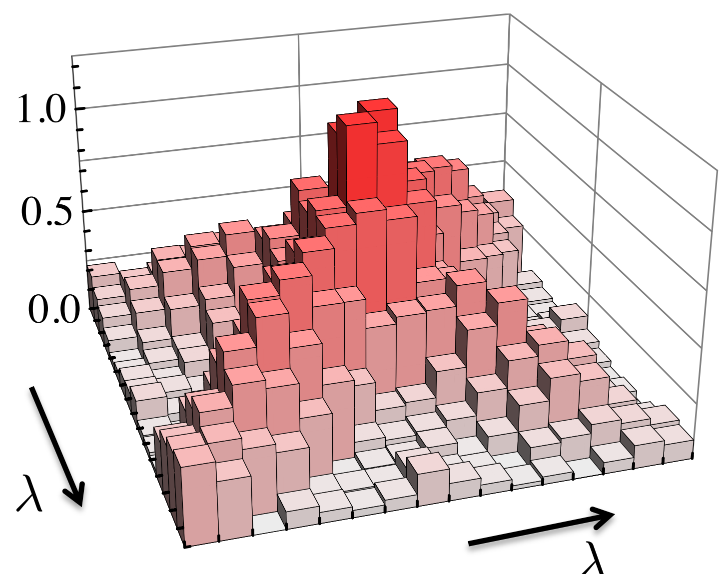




Covariance matrix: normalized correlations between frequency modes

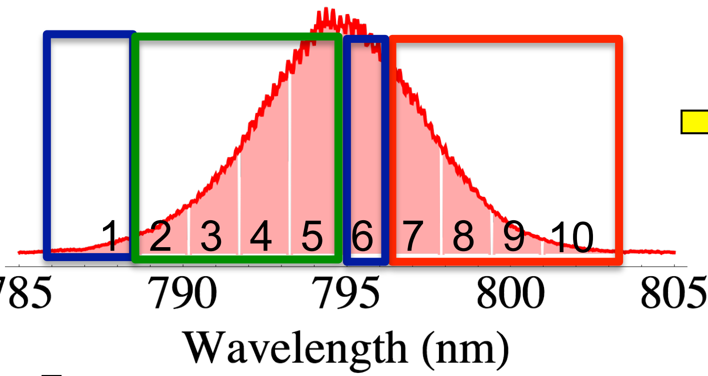


16-mode Covariance matrix of Phase Quadrature

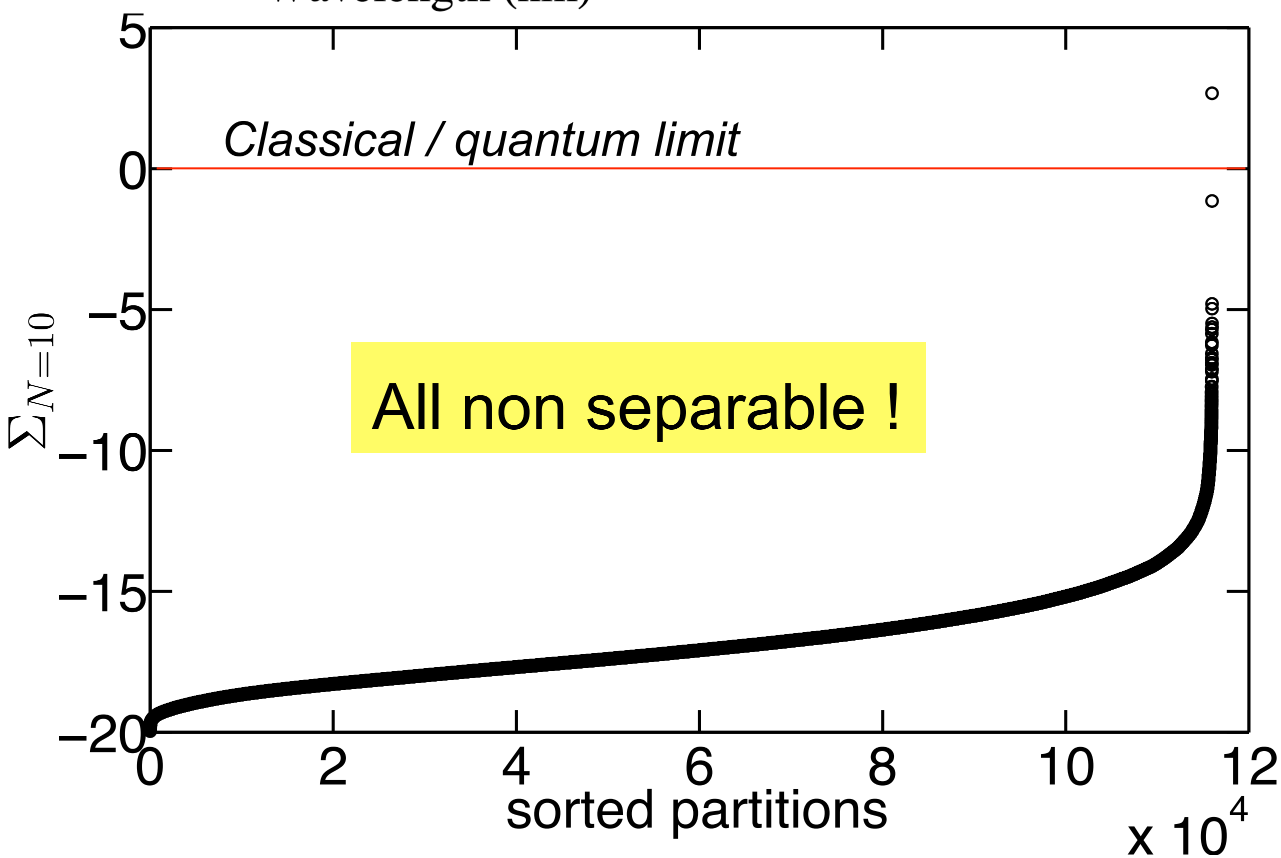


Amplitude Quadrature

Multimode entangled state



10 frequency bands
115 974 possible partitions

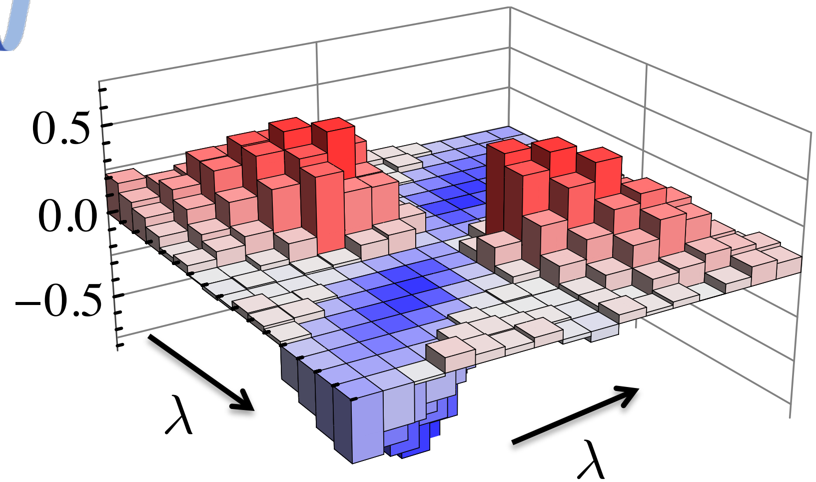


S. Gerke, J. Sperling, W. Vogel, Y. Cai, J. Roslund, N. Treps, and C. Fabre, Phys Rev Lett **114**, 050501 (2015).

Our state is genuinely *K*>2 entangled

S. Gerke, J. Sperling, W. Vogel, Y. Cai, J. Roslund, N. Treps, and C. Fabre, Phys Rev Lett 117, 110502 (2016).

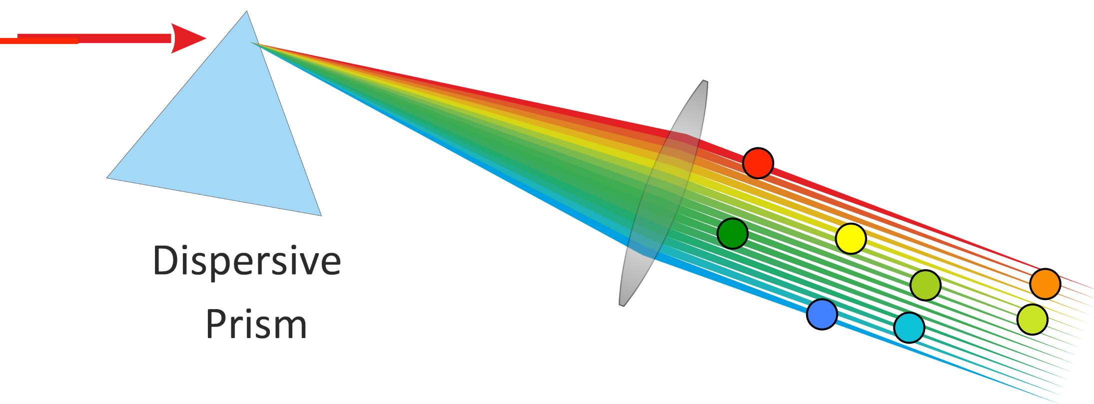
Eigenmodes

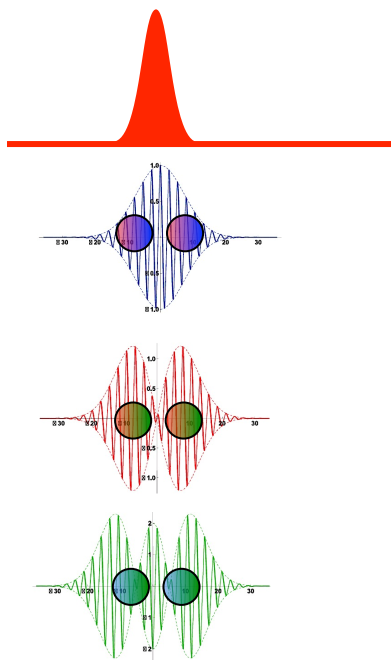


$$H = i\hbar \sum_{m,n} L_{-m,n}\, \hat{a}^{\dagger}_{-m}\, \hat{a}^{\dagger}_{n}$$

diagonalization

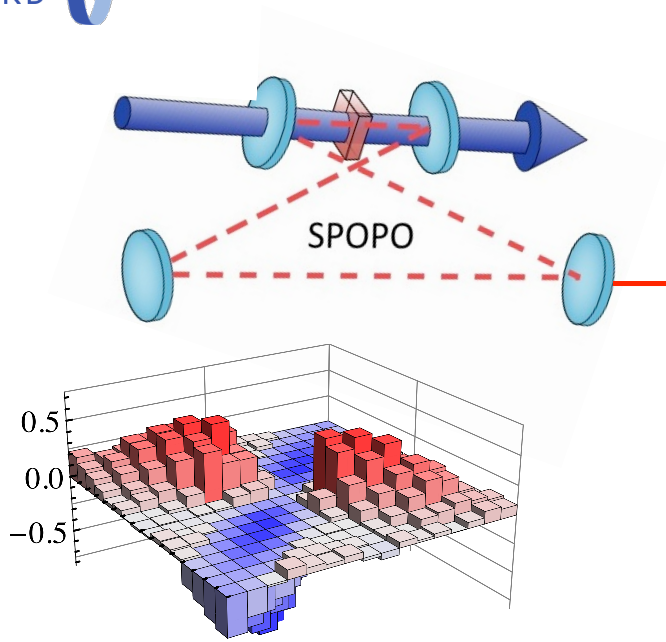
$$H = i\hbar \sum_{k} \Lambda_k S_k^{\dagger 2}$$

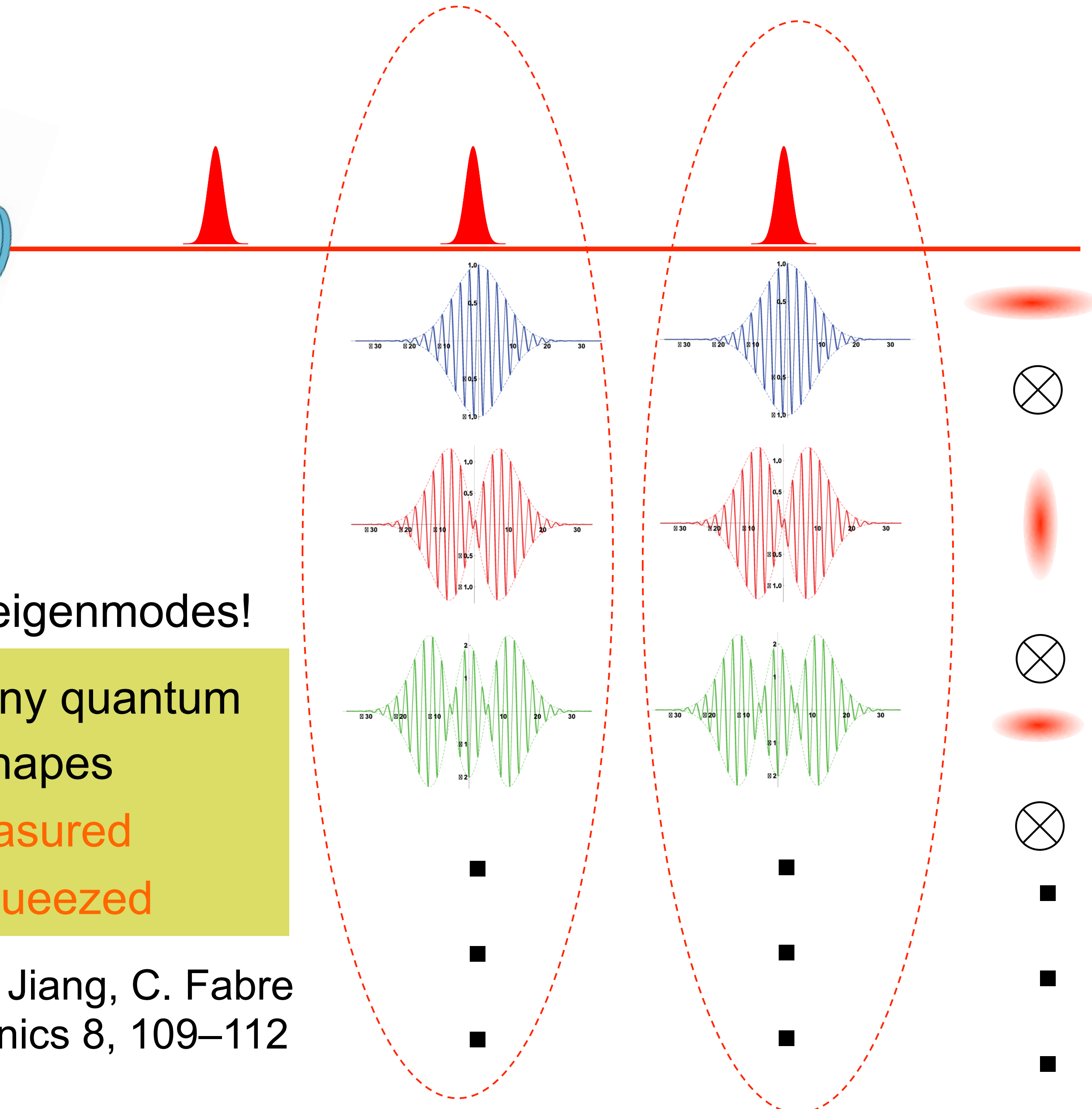




It exists a basis of modes which are not correlated but individually *squeezed*

Multimode squeezing





Diagonalize to find the eigenmodes!

Superposition of many quantum pulses of different shapes

Up to 16 modes measured

More than 12 are squeezed

J. Roslund, R. Medeiros, S. Jiang, C. Fabre and N. Treps, Nature Photonics 8, 109–112 (2014)

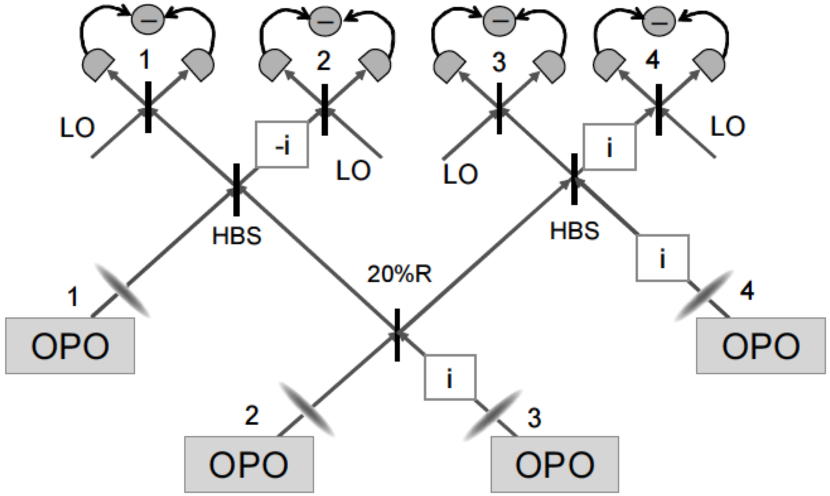
Gaussian « Quantum network »

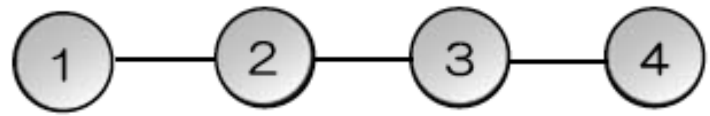
Any gaussian quantum circuit =

Squeezed modes + basis change

S. Braunstein, PRA 71, Squeezing as an irreducible resource 055801 (2005)

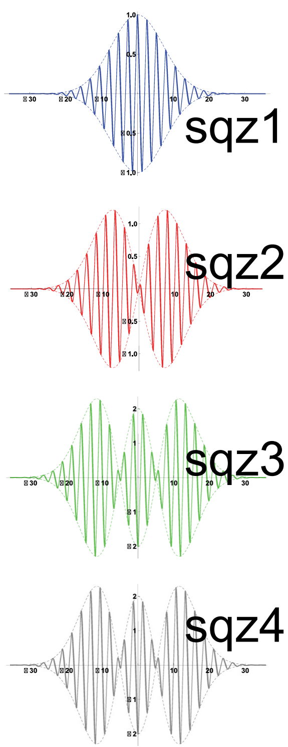
Cluster states



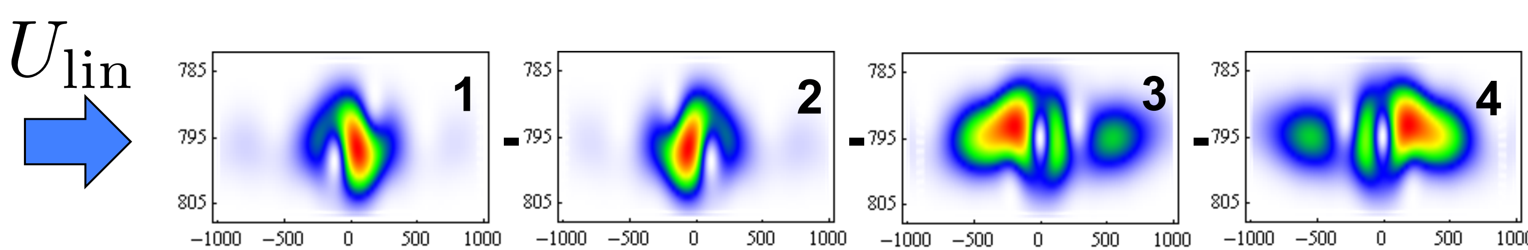


Cluster state matrix:

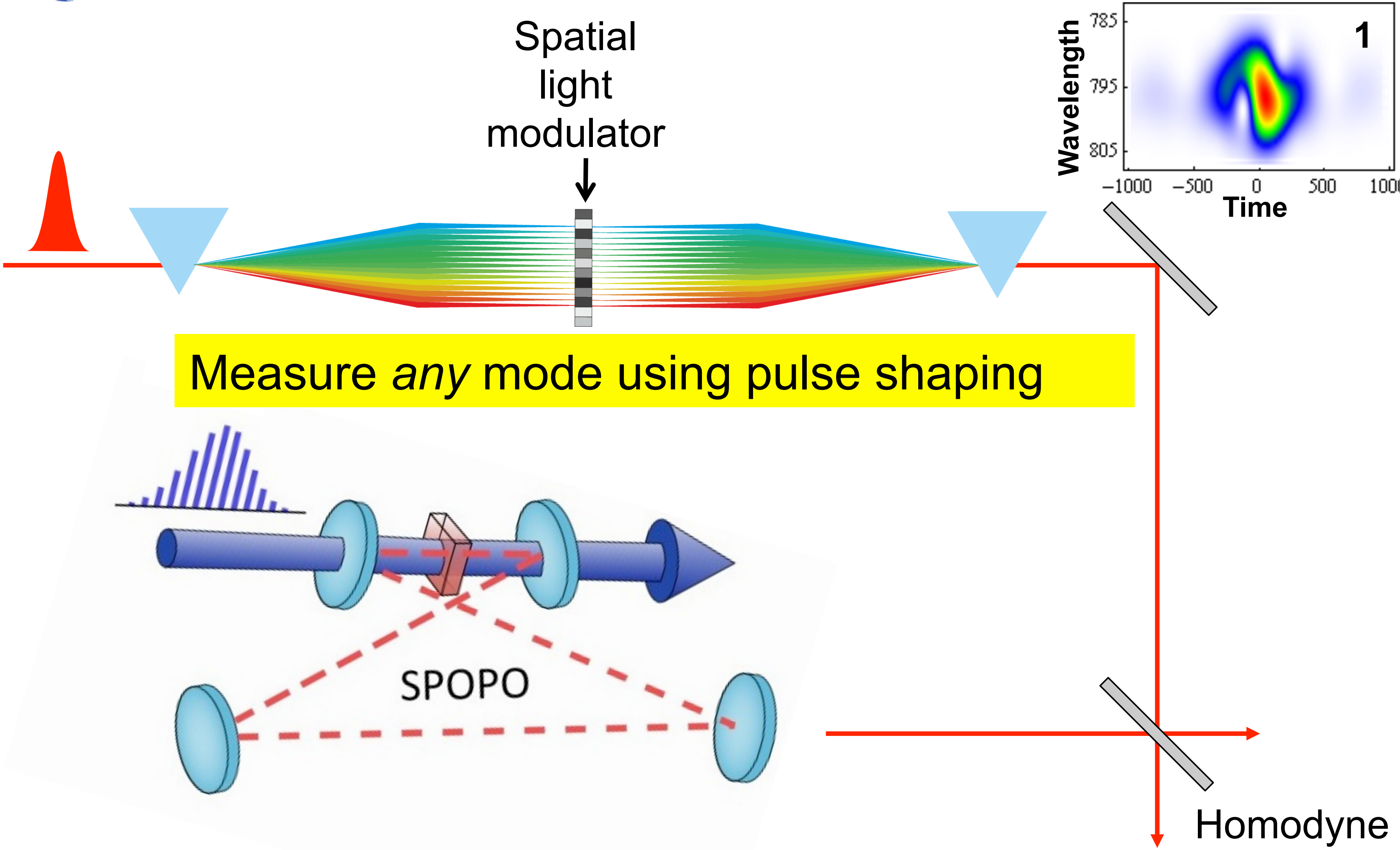
$$U_{\mathrm{lin}} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{10}} & \frac{2i}{\sqrt{10}} & 0 \\ \frac{i}{\sqrt{2}} & -\frac{i}{\sqrt{10}} & \frac{2}{\sqrt{10}} & 0 \\ 0 & -\frac{2}{\sqrt{10}} & \frac{i}{\sqrt{10}} & \frac{i}{\sqrt{2}} \\ 0 & -\frac{2i}{\sqrt{10}} & -\frac{1}{\sqrt{10}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$



X. Su et al., Phys Rev Lett 98, 070502 (2007).
M. Yukawa el al, Phys. Rev. A 78, 012301 (2008).



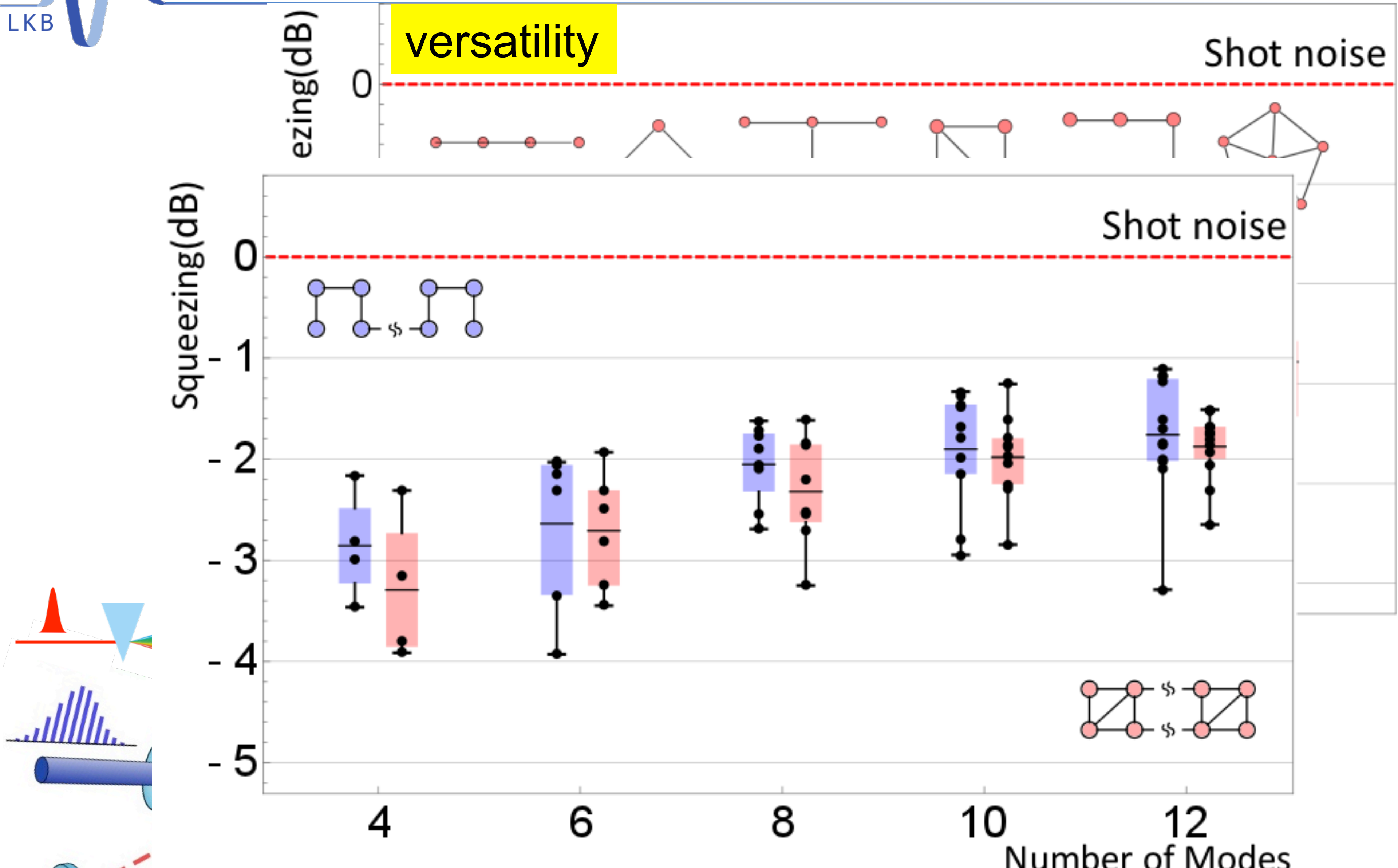
Basis change = Pulse Shaping



Measure *any* mode using pulse shaping

See also : C. Polycarpou, K. Cassemiro, G. Venturi, A. Zavatta, and M. Bellini, Phys Rev Lett 109, 053602 (2012).

Many, many, cluster states…



Y. Cai, J. Roslund, G. Ferrini, F. Arzani, X. Xu, C. Fabre, and N. Treps, Nat Comms **8**, 15645 (2017).

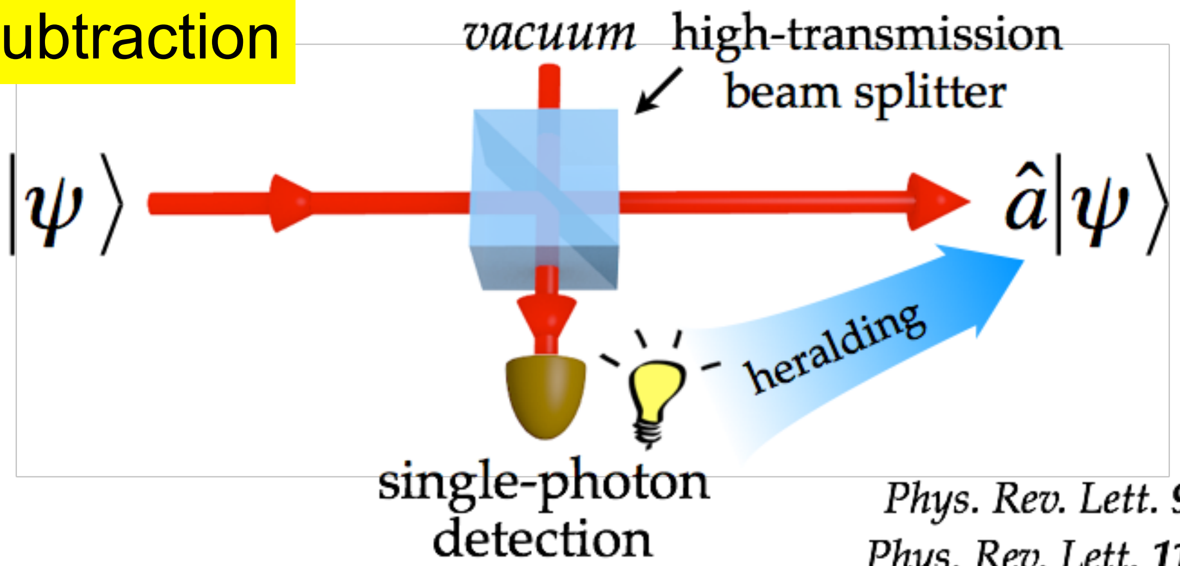
Going non Gaussian:

Mode dependent photon subtraction

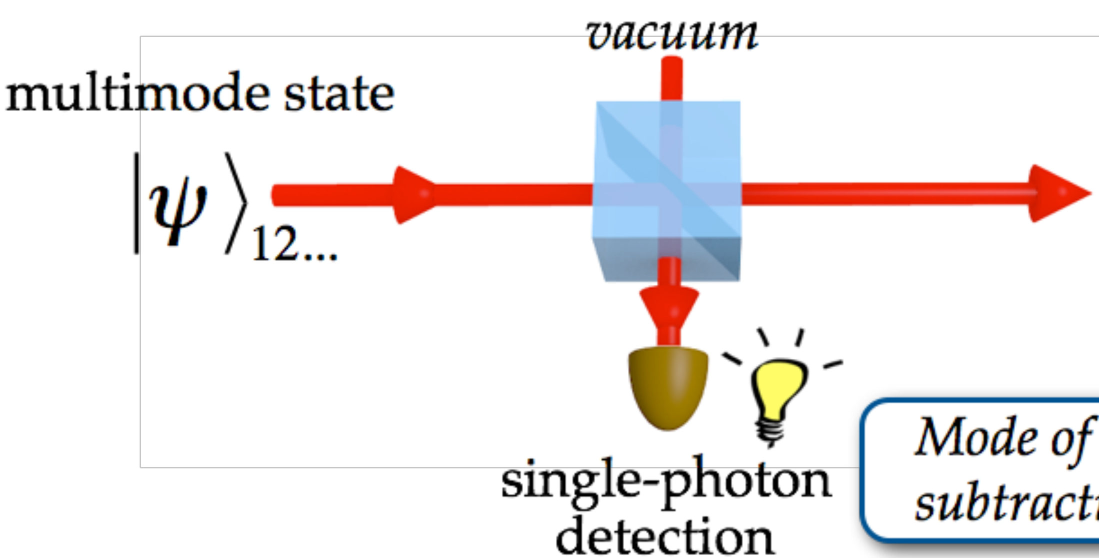
Theoretical approach

"Non Gaussian" states

Photon subtraction



Phys. Rev. Lett. **92**, 153601 (2004)
Phys. Rev. Lett. **110**, 130403 (2013)



a mixed state

$$\hat{a}_1|\psi\rangle\langle\psi|\hat{a}_1^\dagger + \hat{a}_2|\psi\rangle\langle\psi|\hat{a}_2^\dagger + \ldots \neq (\hat{a}_1 + \hat{a}_2 + \ldots)|\psi\rangle$$

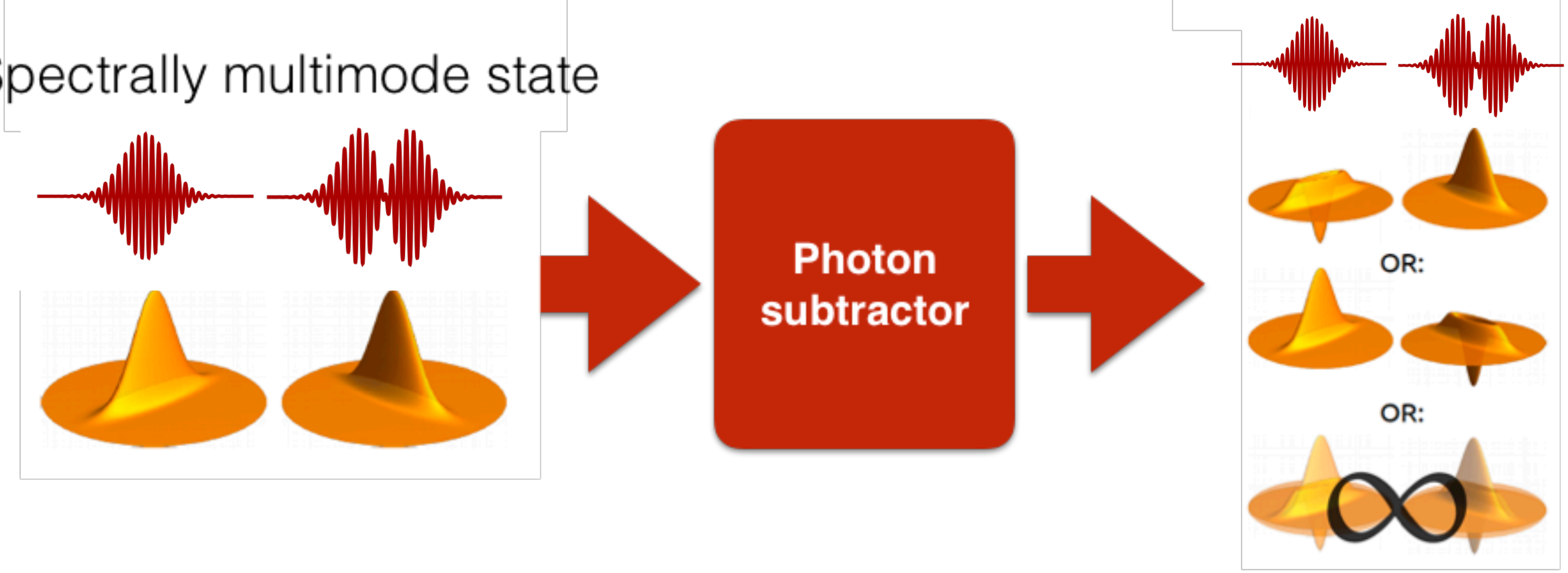
Mode of single-photon subtraction cannot be selected.

"Non Gaussian" states

Gaussian

non-Gaussian

Spectrally multimode state



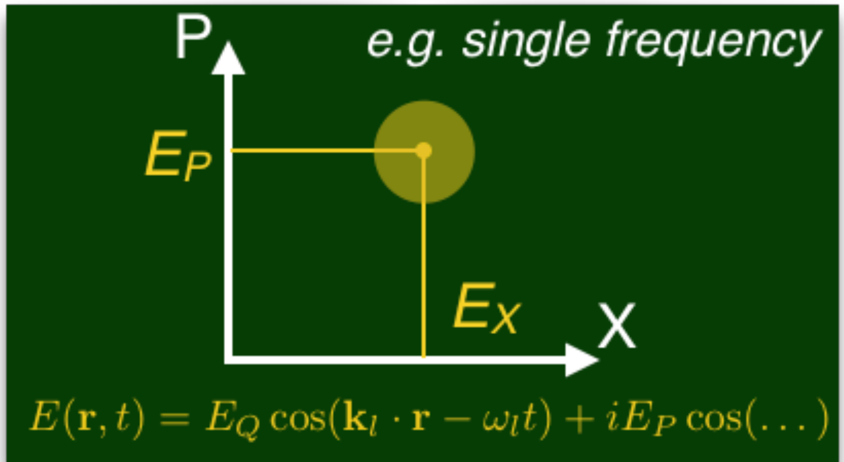
Averchenko *et al*, NJP **18** 083042 (2016)

Ra *et al*, PRX **7** 031012 (2017)

$$\rho_G \longrightarrow \sim a(g)\rho_G a^\dagger(g)$$

"Non Gaussian" states

Single mode optical phase space:



Quantisation

Normalise shot noise to 1

$$[X, P] = 2i$$

Field quadratures

Generalised field quadratures

$$Q(f) = \sum_{j}^{m} f_j X_j + f_{j+m} P_j$$

Multimode optical phase space:

high-dimensional space

$$\mathbb{R}^{2m}$$

symplectic

$$J = \begin{pmatrix} 0 & -\mathbb{1} \\ \mathbb{1} & 0 \end{pmatrix}$$

“Non Gaussian” states

Ingredients

Initial Wigner function $W_0(\beta), \quad \beta \in \mathbb{R}^{2m}$

Mode of subtraction g

Calculate $\langle Q(\alpha)^n \rangle$ for all $\alpha \in \mathbb{R}^{2m}$

Find characteristic function $\chi(\alpha) = \langle \exp[iQ(\alpha)] \rangle$

Fourier transform

Multimode Wigner Function

Walschaers et al, PRL 119, 183601 (2017); PRA 96, 053835 (2017)

“Non Gaussian” states

Initial Wigner function $W_0(\beta), \quad \beta \in \mathbb{R}^{2m}$

Mode of subtraction g

Initial Gaussian state's covariance matrix

$$W(\beta) = \frac{1}{2}\Big[(\beta, V^{-1} A_g V^{-1} \beta) - \mathrm{tr}(V^{-1} A_g) + 2\Big] W_0(\beta)$$

Additional correlation

With

$$A_g \sim (V - \mathbb{1})(P_g + P_{Jg})(V - \mathbb{1})$$

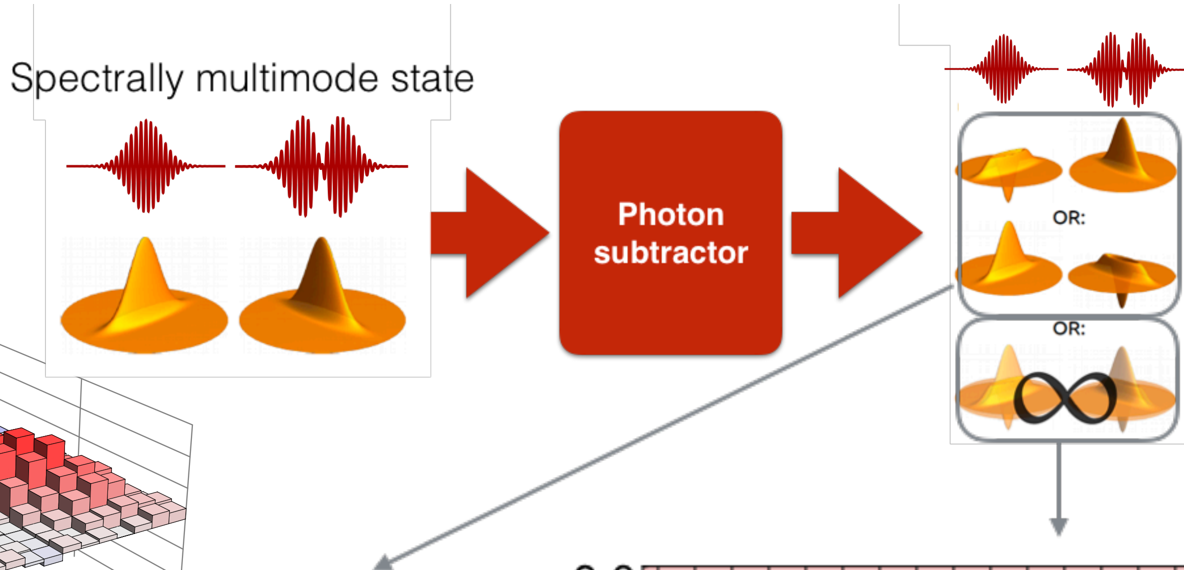
Projector on phase space of mode in which we subtract

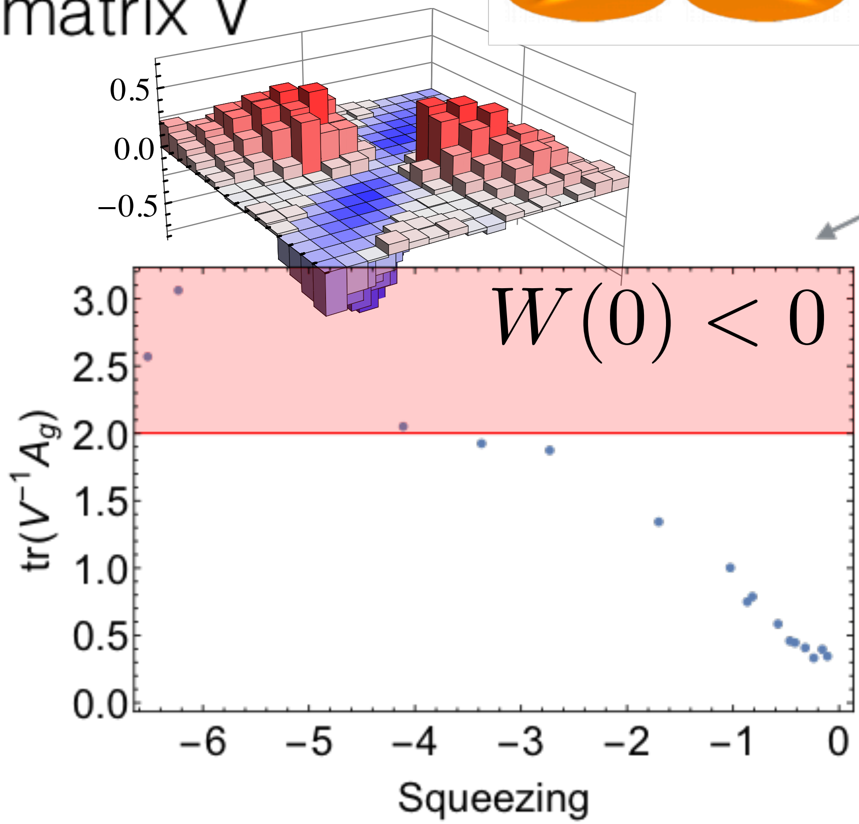
Negativity condition $(g, V^{-1} g) + (Jg, V^{-1} Jg) > 2$

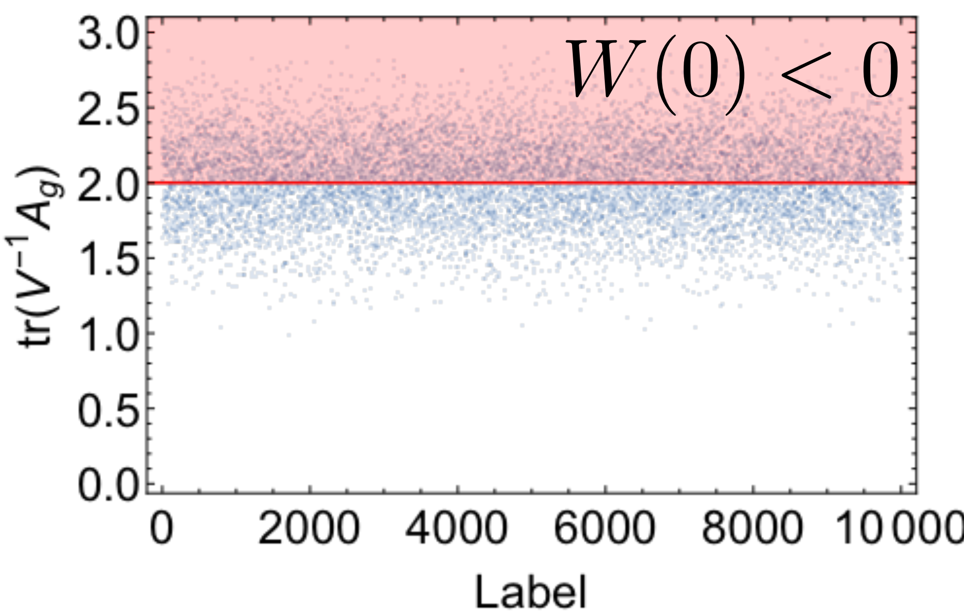
Walschaers et al, PRL 119, 183601 (2017); PRA 96, 053835 (2017)

Simulation on experimental data

16 mode **experimental** covariance matrix V

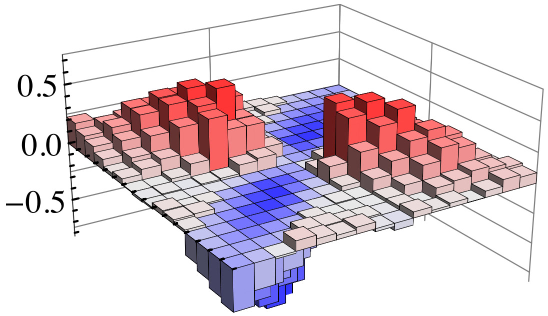




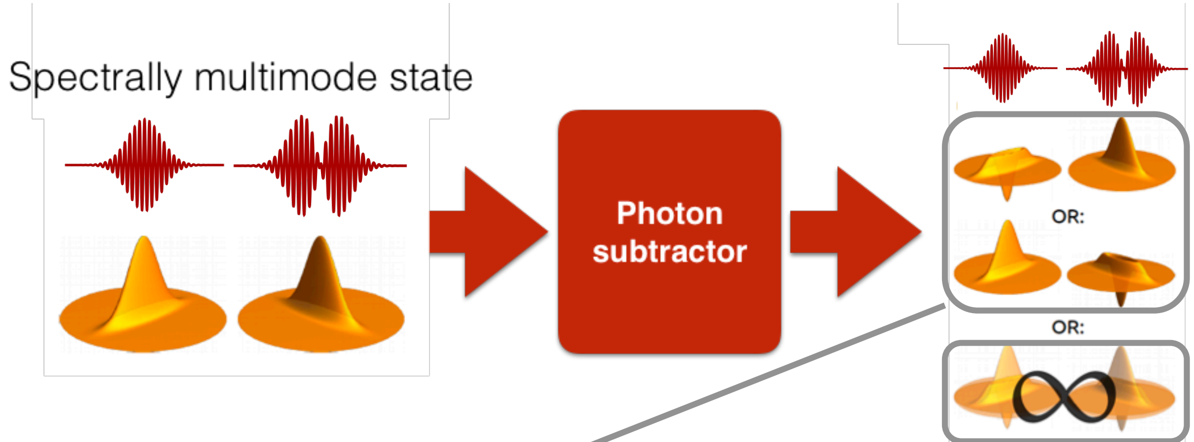


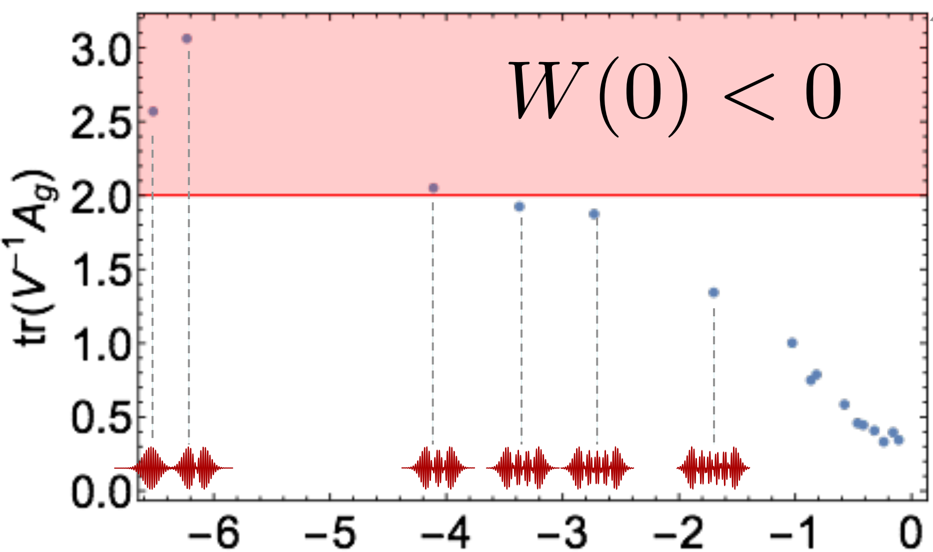
Get negative Wigner function ~50% of the cases

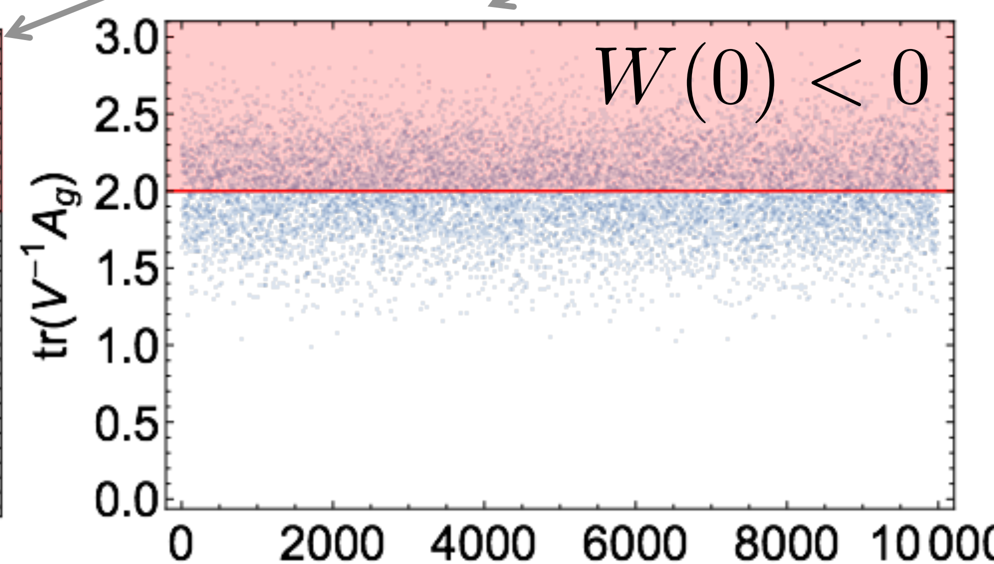
Simulation on experimental data



16 mode experimental covariance matrix V







Get negative Wigner function ~50% of the cases

Inherent entanglement

A state **is inherently entangled** when no mode basis exists in which the Wigner function takes the form

$$W(x_1,\ldots,x_m,p_1,\ldots,p_m)=\sum_k \lambda_k \prod_{i=1}^{m} W_k(x_i,p_i),$$

A Gaussian state cannot be inherently entangled!

Braunstein PRA 71, 055801 (2005)

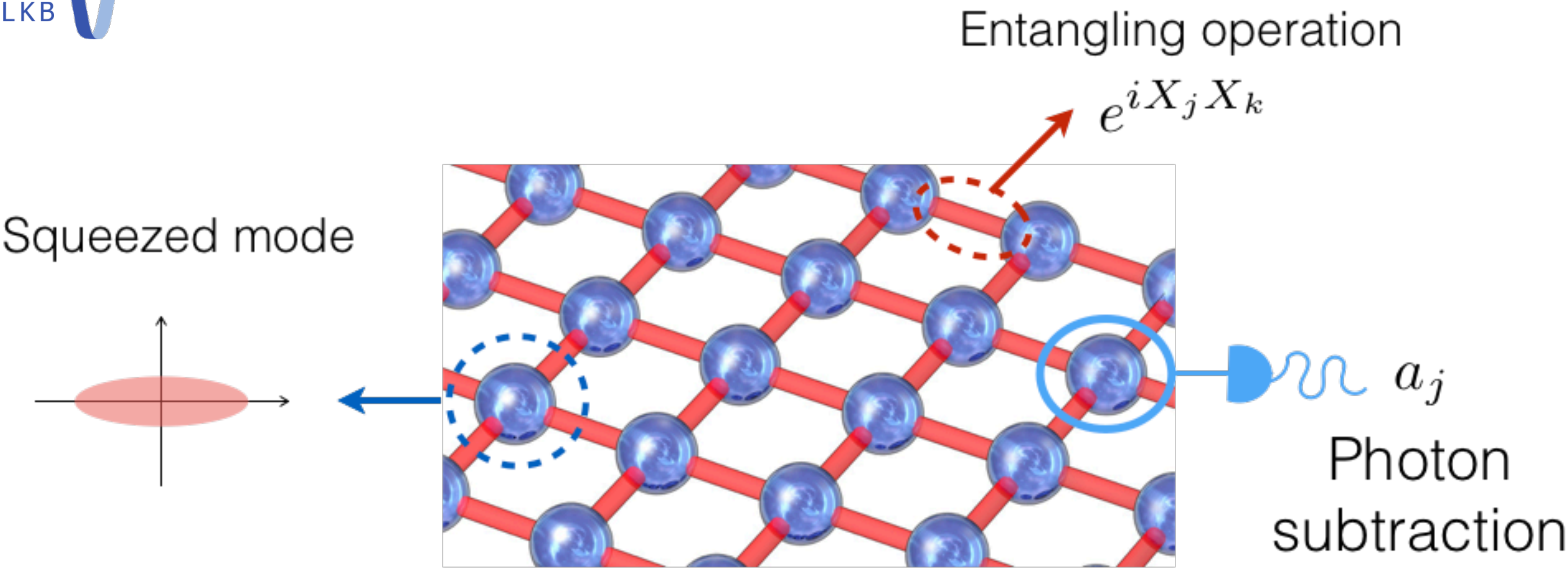
Detailed discussion: PRA 96, 053835 (2017)

Photon subtraction in superposition of eigenmodes can create inherent entanglement

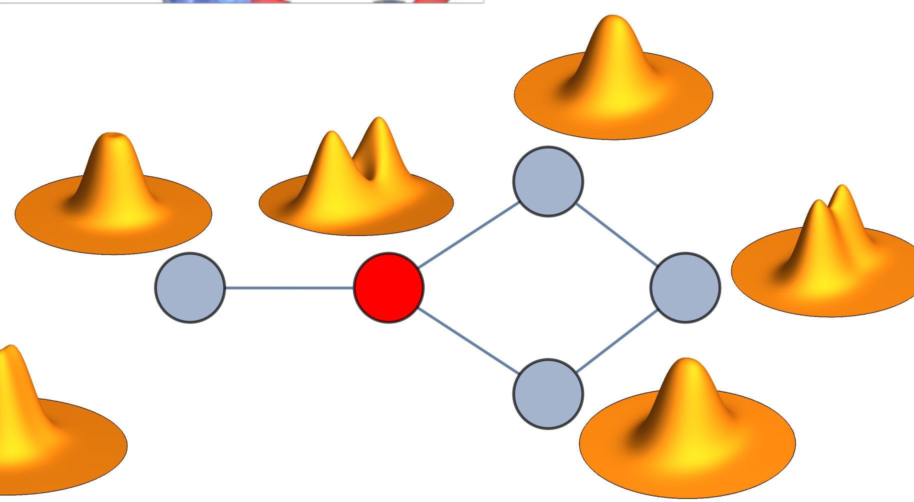
Always the case when the states are pure

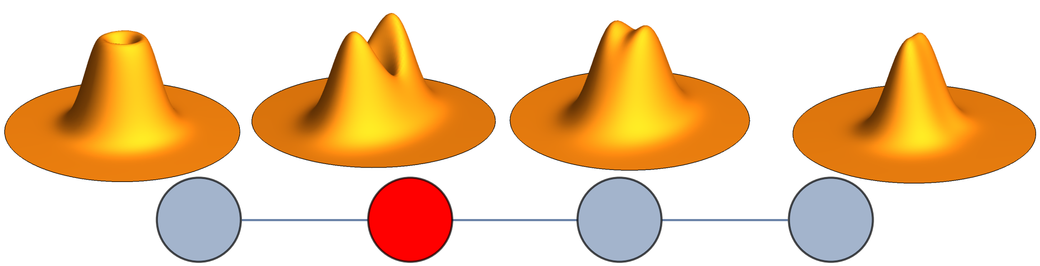
Detailed discussion: PRL 119, 183601 (2017); PRA 96, 053835 (2017)

Effect on graph states

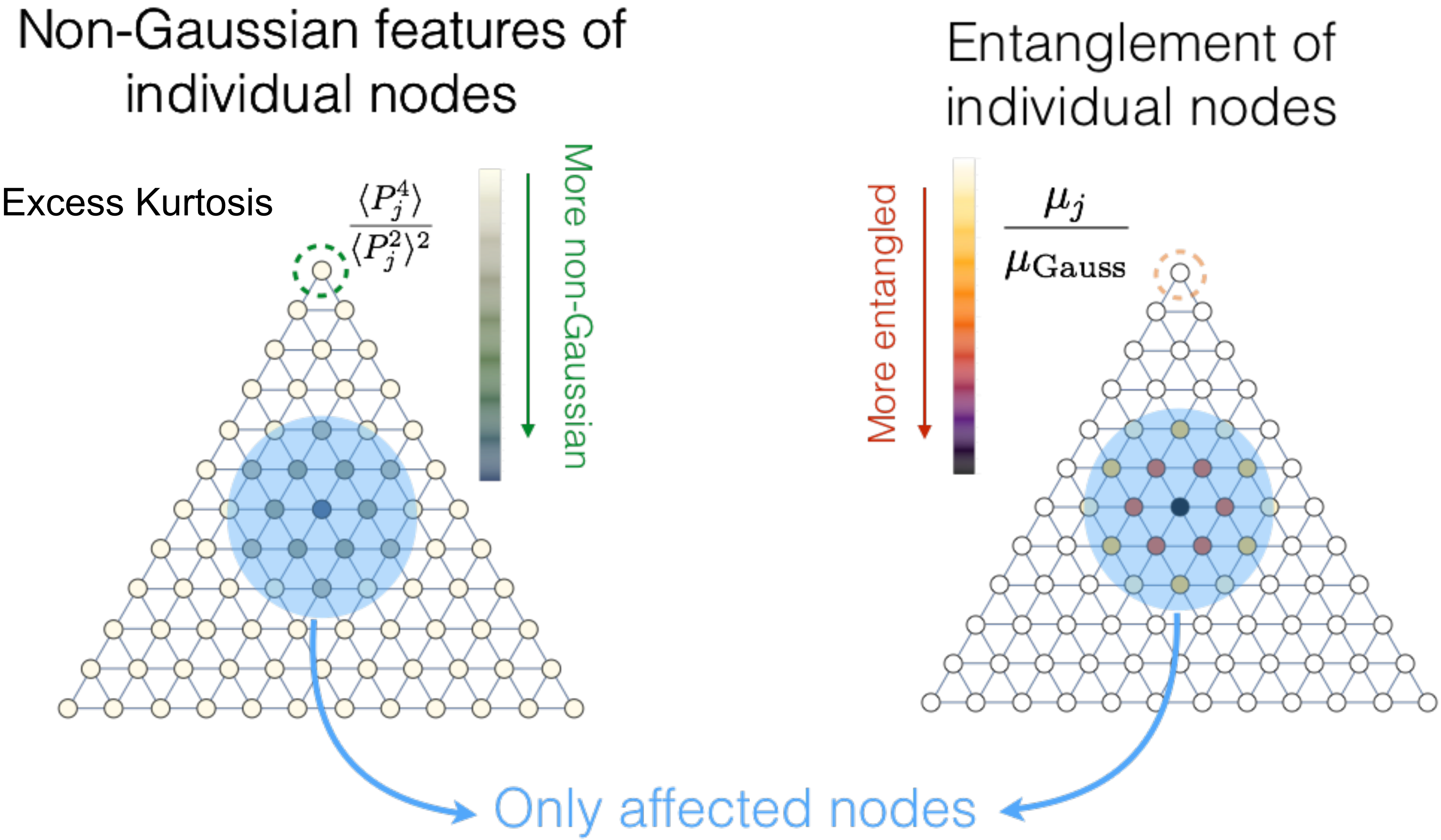


Non-Gaussian graph:





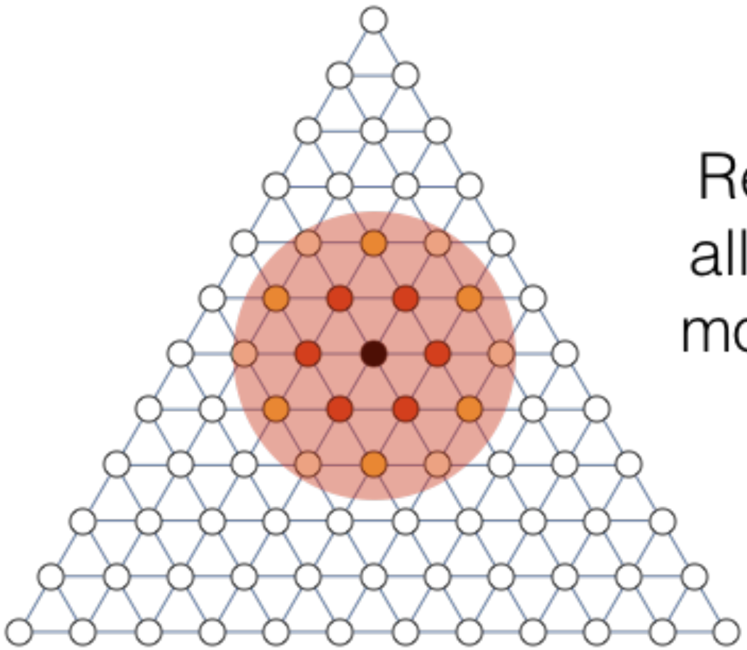
Effect on graph states



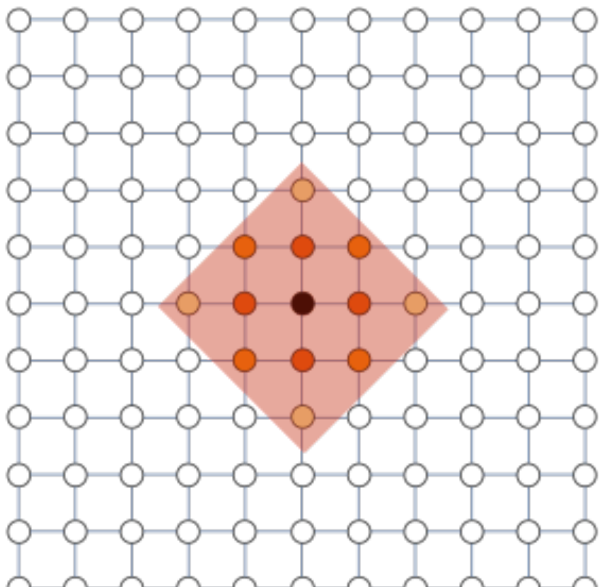
Effect on graph states

General result for any graph state

The reduced state for all modes which are more than two steps removed from the subtraction point is completely unchanged

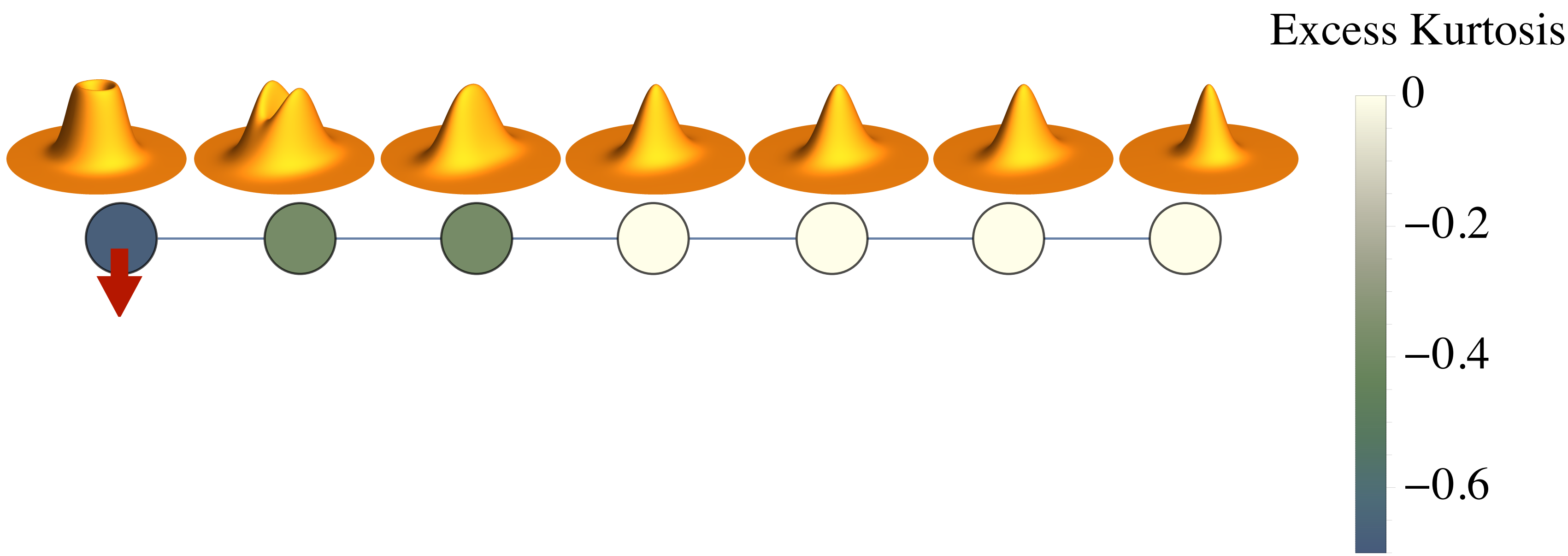


Reduced state for all non-highlighted modes is Gaussian graph state



Effect on graph states

Example on a long linear cluster



Delocalized photon subtraction:

more non-Gaussian modes

less non-Gaussianity

-> strategy for non-Gaussien MBQC?

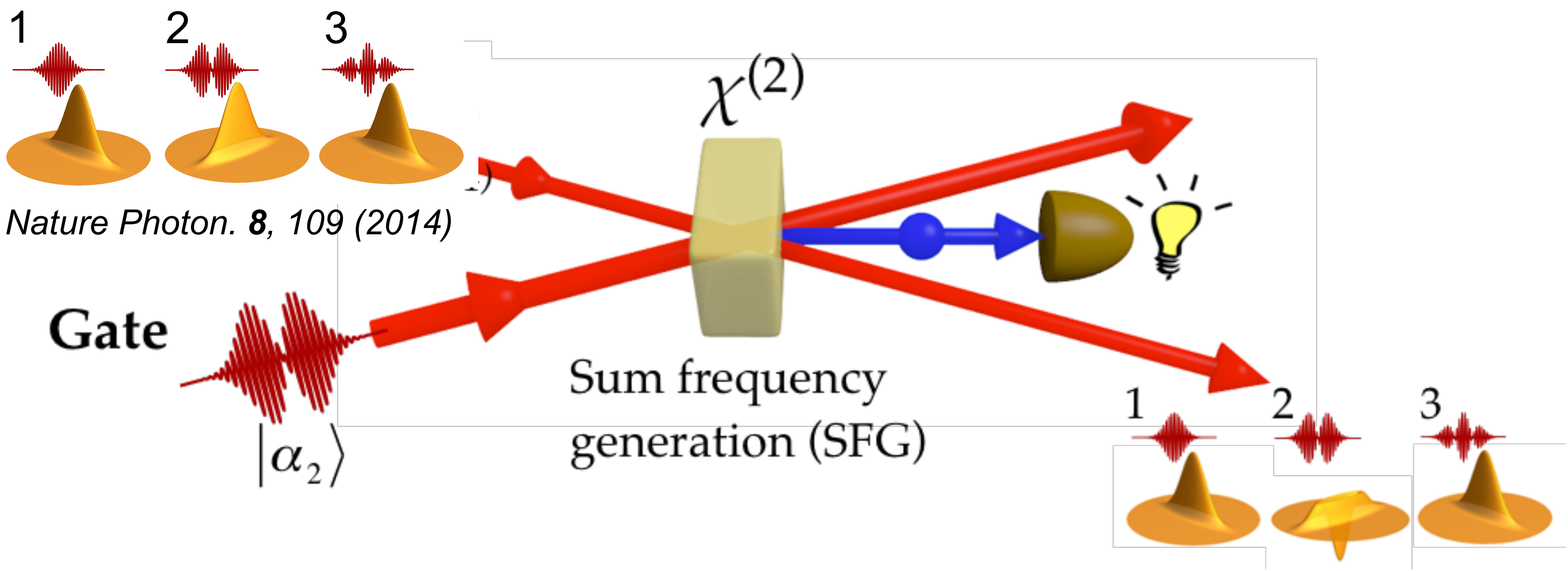
Going non Gaussian:

Mode dependent photon subtraction

Experimental implementation

Mode-selective single-photon subtractor

Sum Frequency Generation



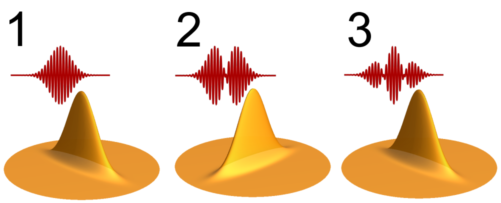
A. Eckstein, B. Brecht, and C. Silberhorn, Opt Express **19**, 13770 (2011).
V. A. Averchenko, V. Thiel, and N. Treps, Phys Rev A **89**, 063808 (2014).

Mode-selective single-photon subtractor

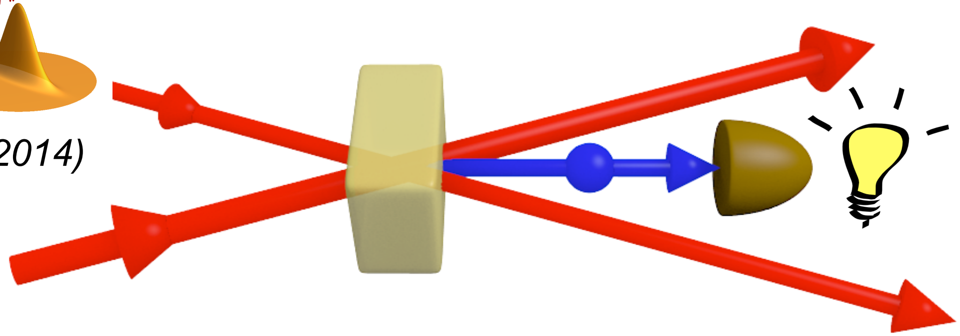
LKB

Sum Frequency Generation

Signal



Nature Photon. ***8****, 109 (2014)*



Gate

$$|\alpha_1, \alpha_2, \ldots\rangle$$

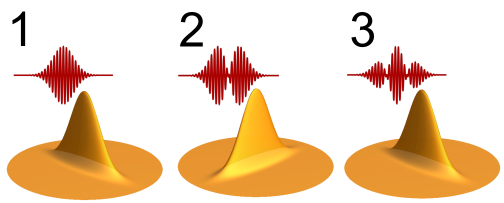
$$\propto (\alpha_1 \hat{a}_1 + \alpha_2 \hat{a}_2 + \ldots)|\psi_s\rangle$$

$$\hat{\rho}^{(out)} = \sum_{i,j} \chi_{i,j} \hat{a}_i \rho^{(in)} \hat{a}_j^\dagger$$

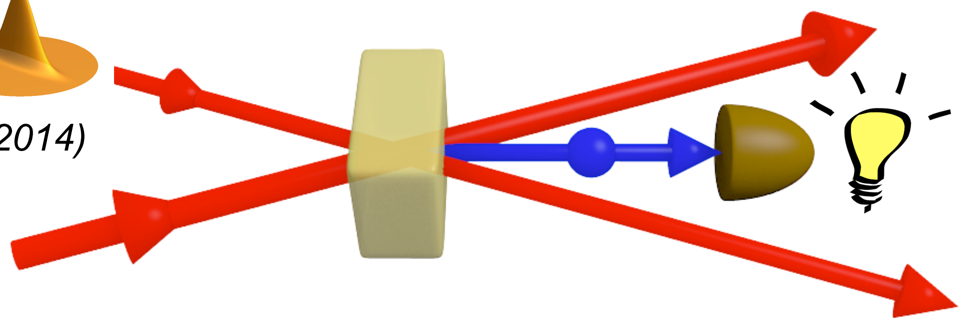
Mode-selective single-photon subtractor

Sum Frequency Generation

Signal



Nature Photon. ***8****, 109 (2014)*



Gate

$$|\alpha_1, \alpha_2, \ldots\rangle$$

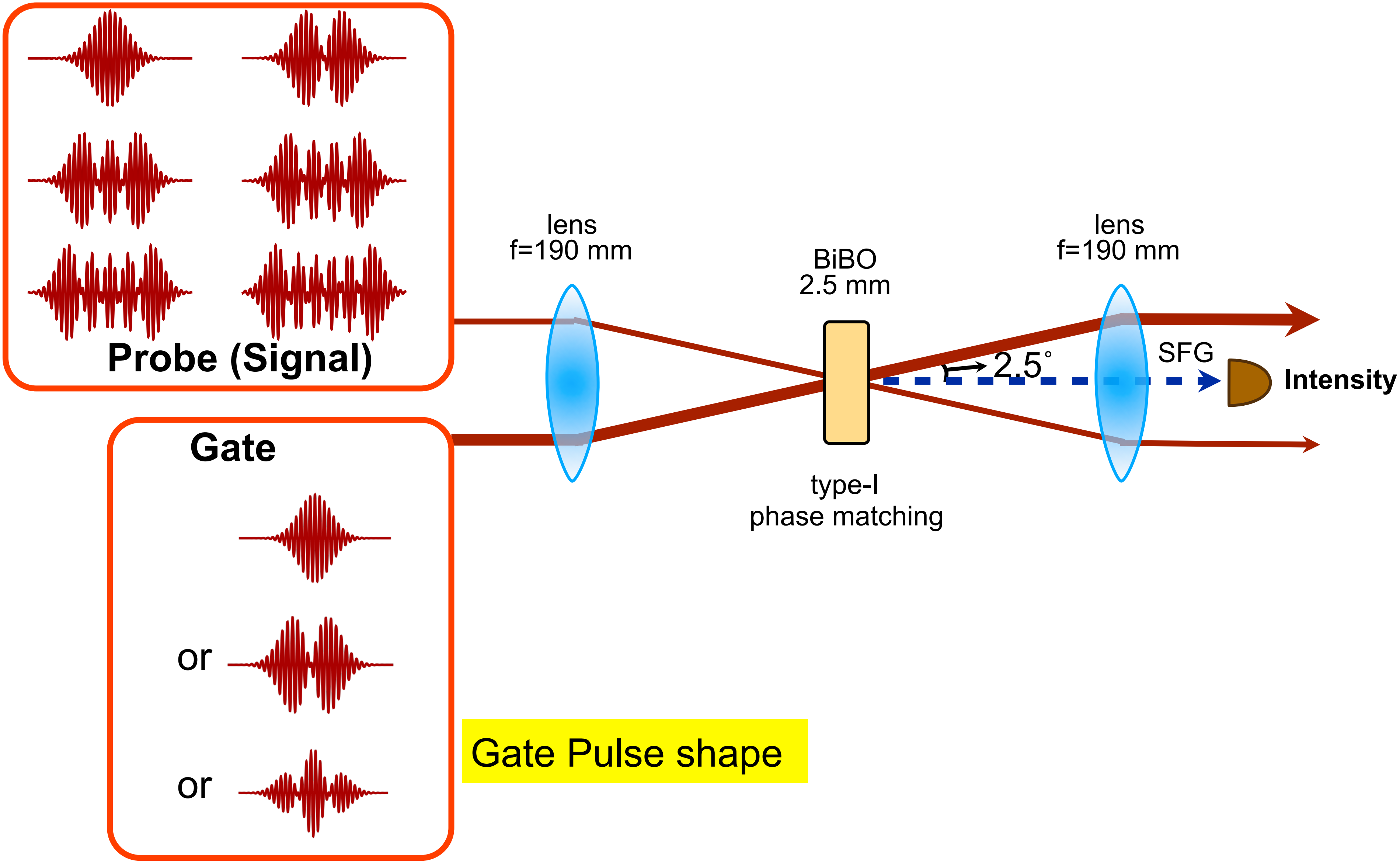
$$\propto (\alpha_1 \hat{a}_1 + \alpha_2 \hat{a}_2 + \ldots)|\psi_s\rangle$$

$$\hat{\rho}^{(out)} = \sum_{i,j} \chi_{i,j} \hat{a}_i \rho^{(in)} \hat{a}_j^\dagger$$

Probe with coherent states

Quantum Process Tomography

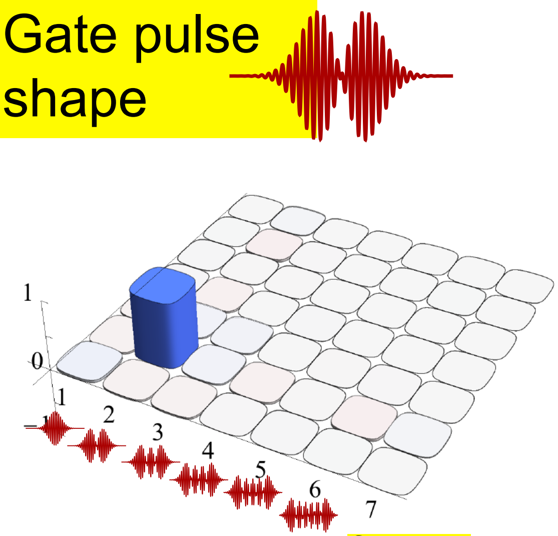
Probe basis: Hermite Gauss modes



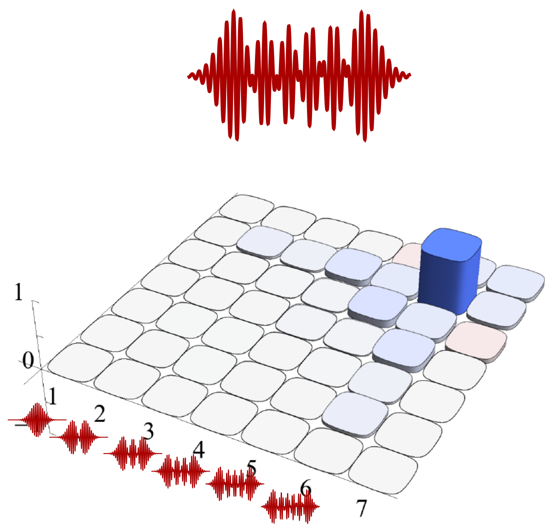
Gate Pulse shape

Quantum Process Tomography

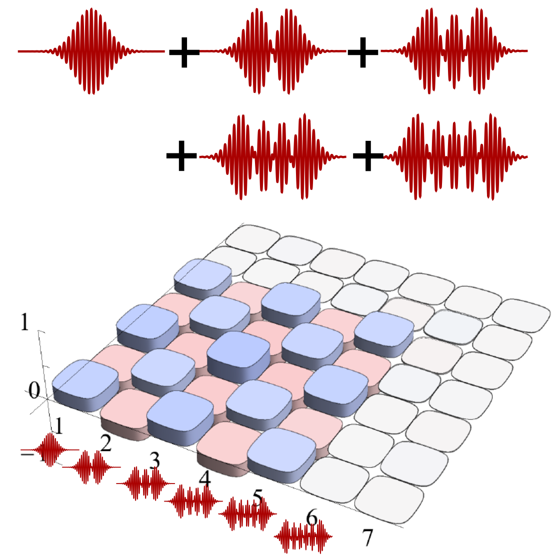
Gate pulse shape



$\chi_{i,j}$



$\chi_{i,j}$



$\chi_{i,j}$

$$\hat{\rho}^{(out)} = \sum_{i,j} \chi_{i,j} \hat{a}_i \rho^{(in)} \hat{a}_j^\dagger$$

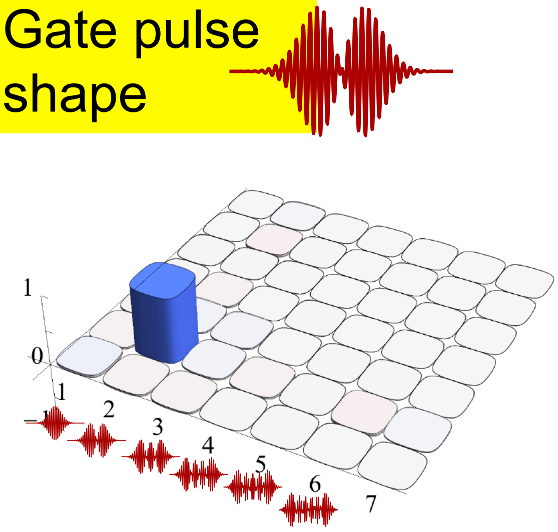
Purity of the photon subtractor (~Schmidt number)

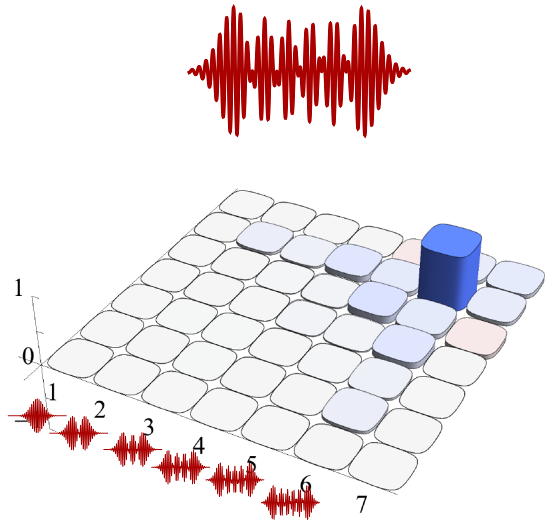
1.1 mode 1.3 mode 1.08 mode

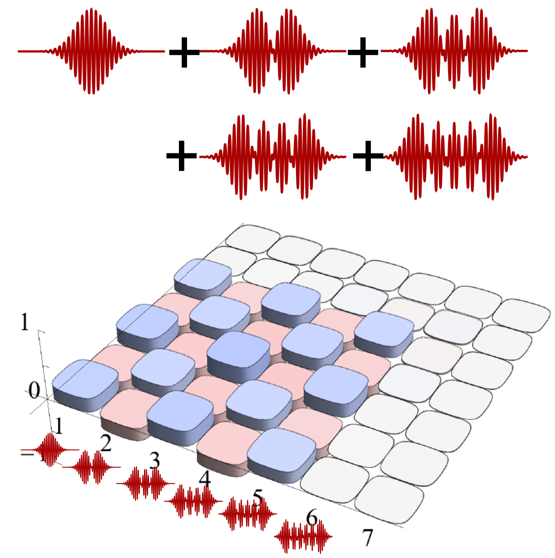
Y.-S. Ra, C. Jacquard, A. Dufour, C. Fabre and N. Treps, PRX 7, 031012 (2017)

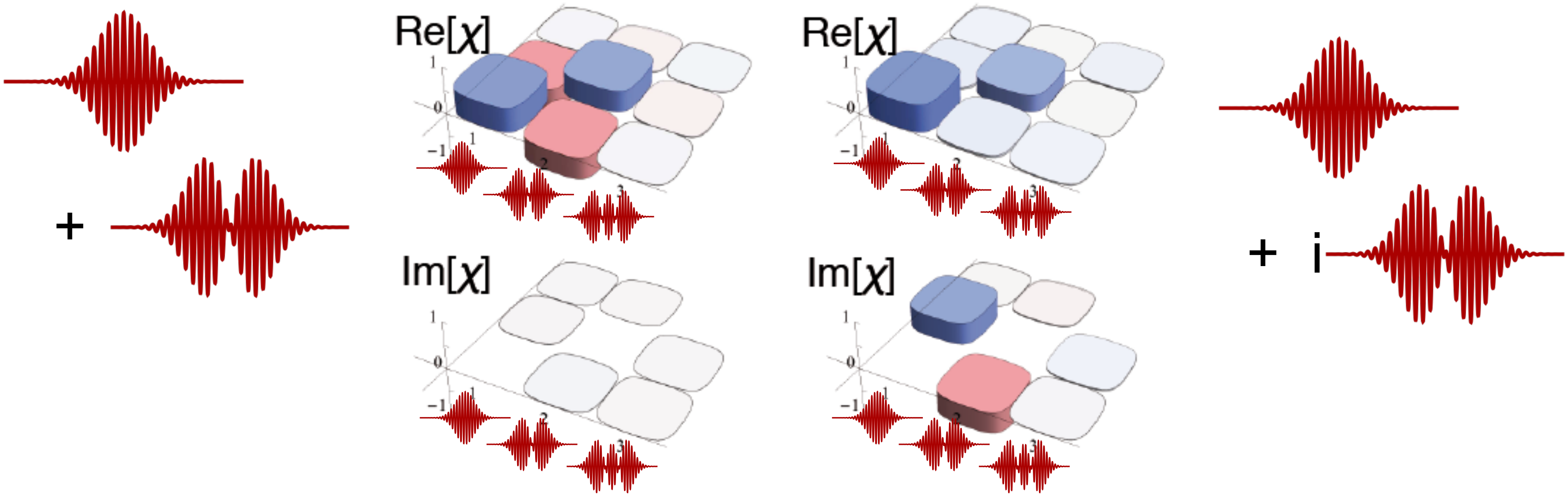
Quantum Process Tomography

Gate pulse shape

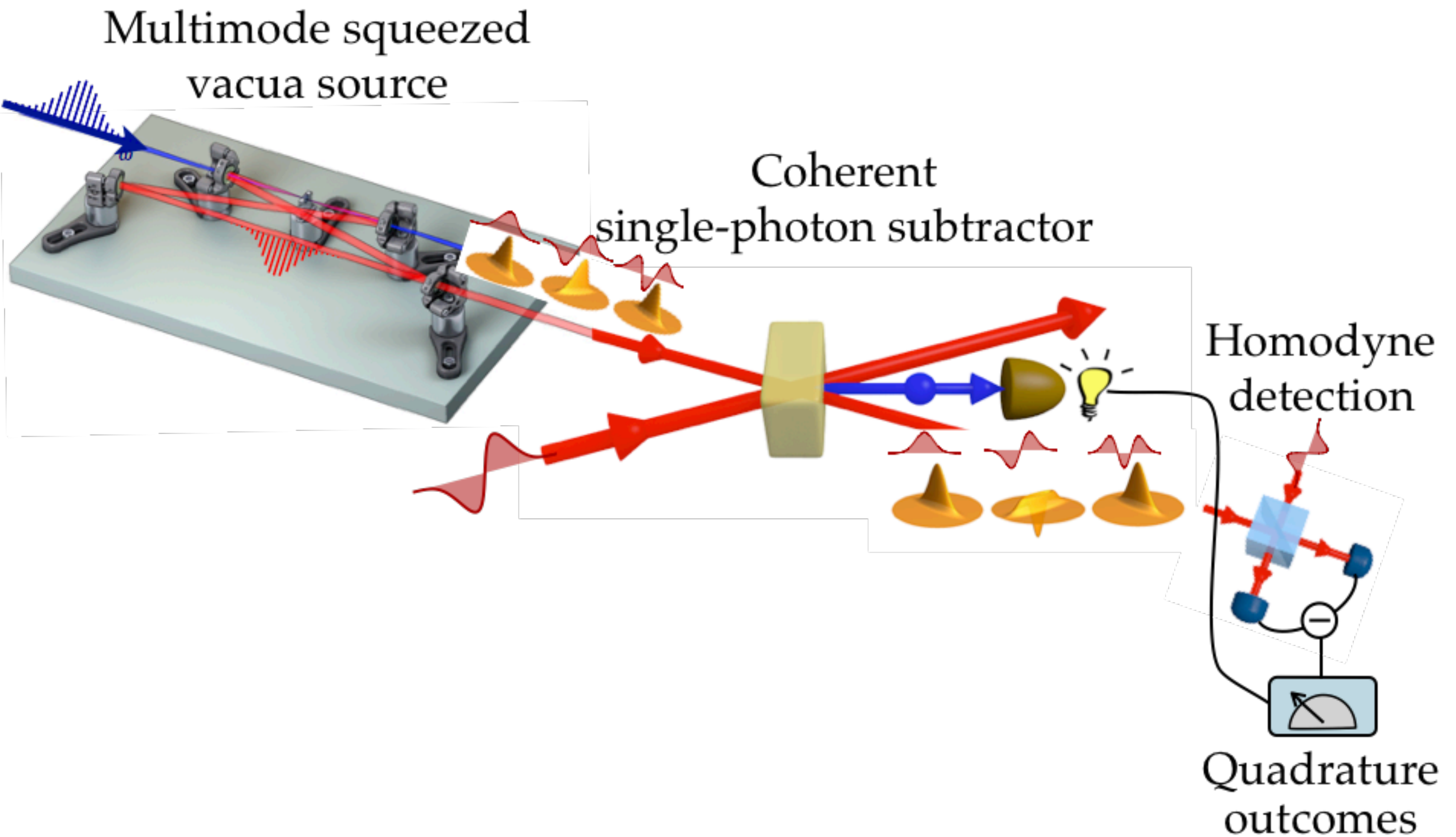




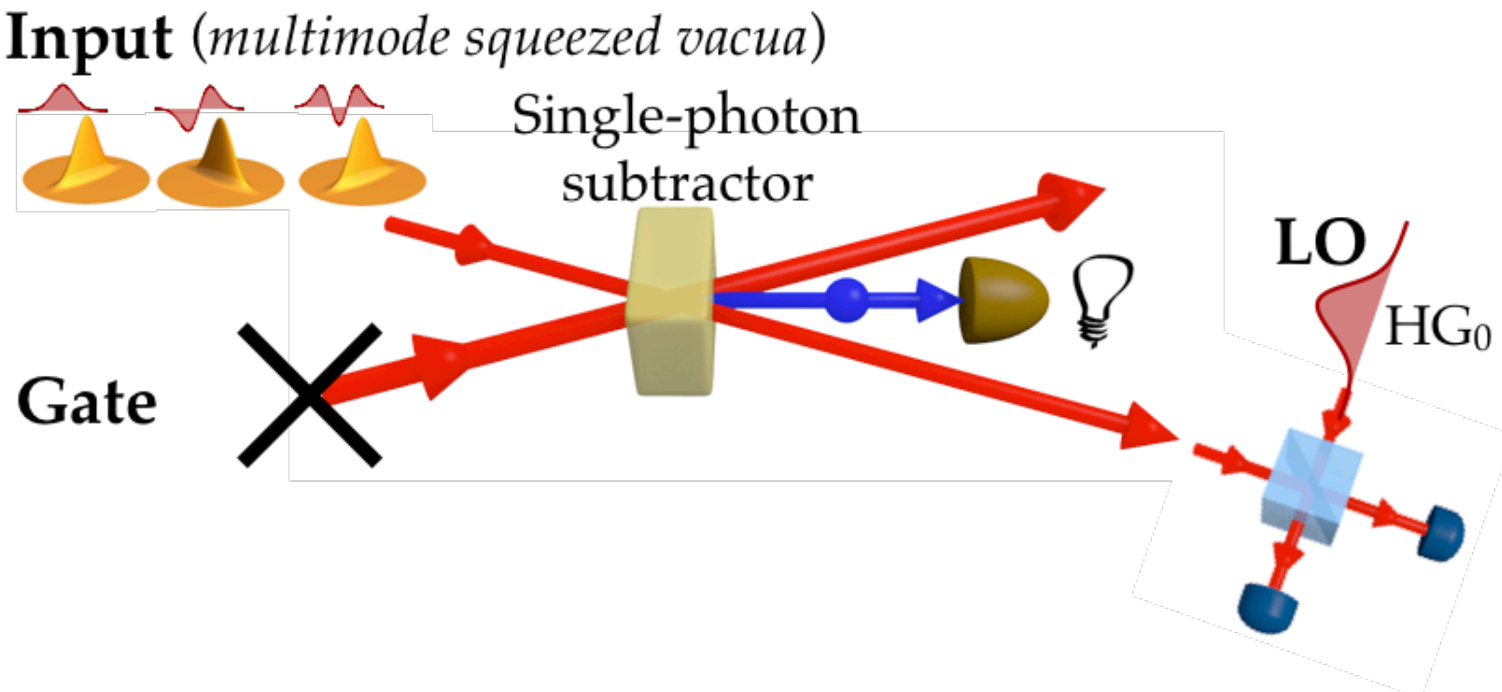


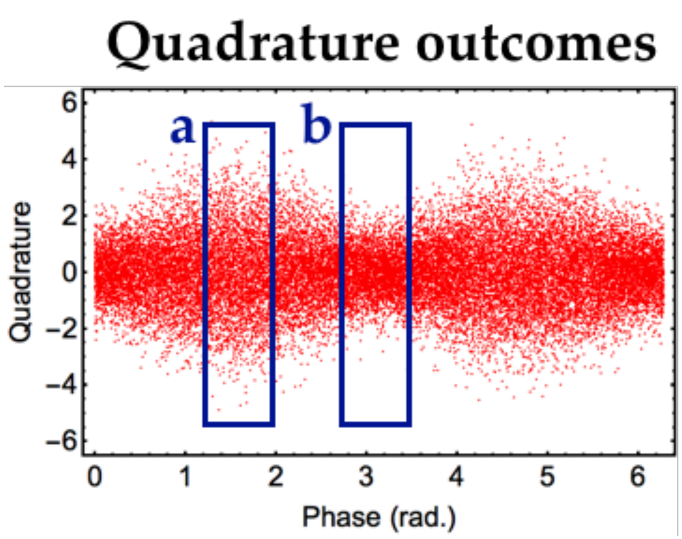


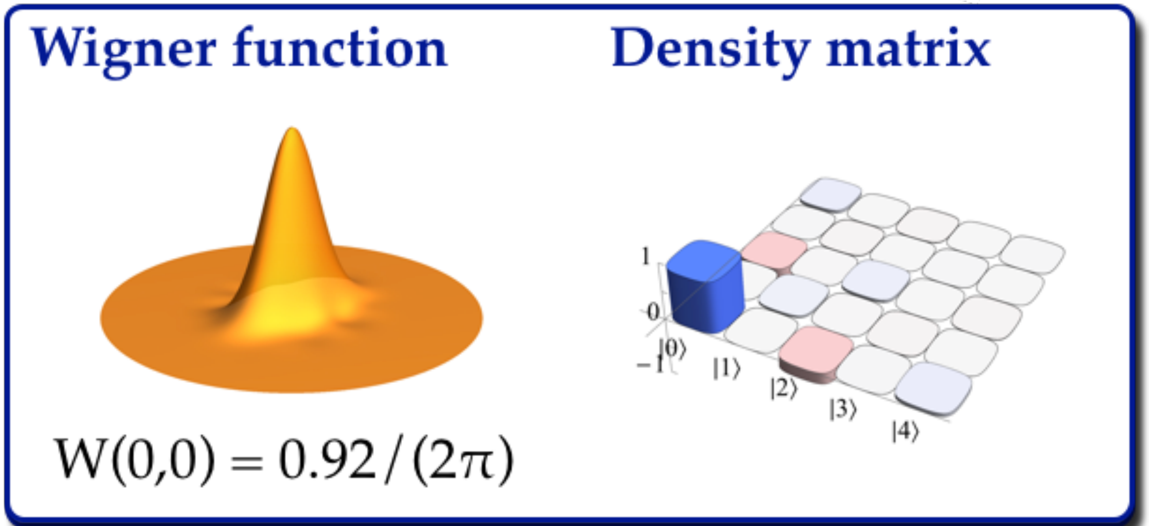
Quantum State Tomography



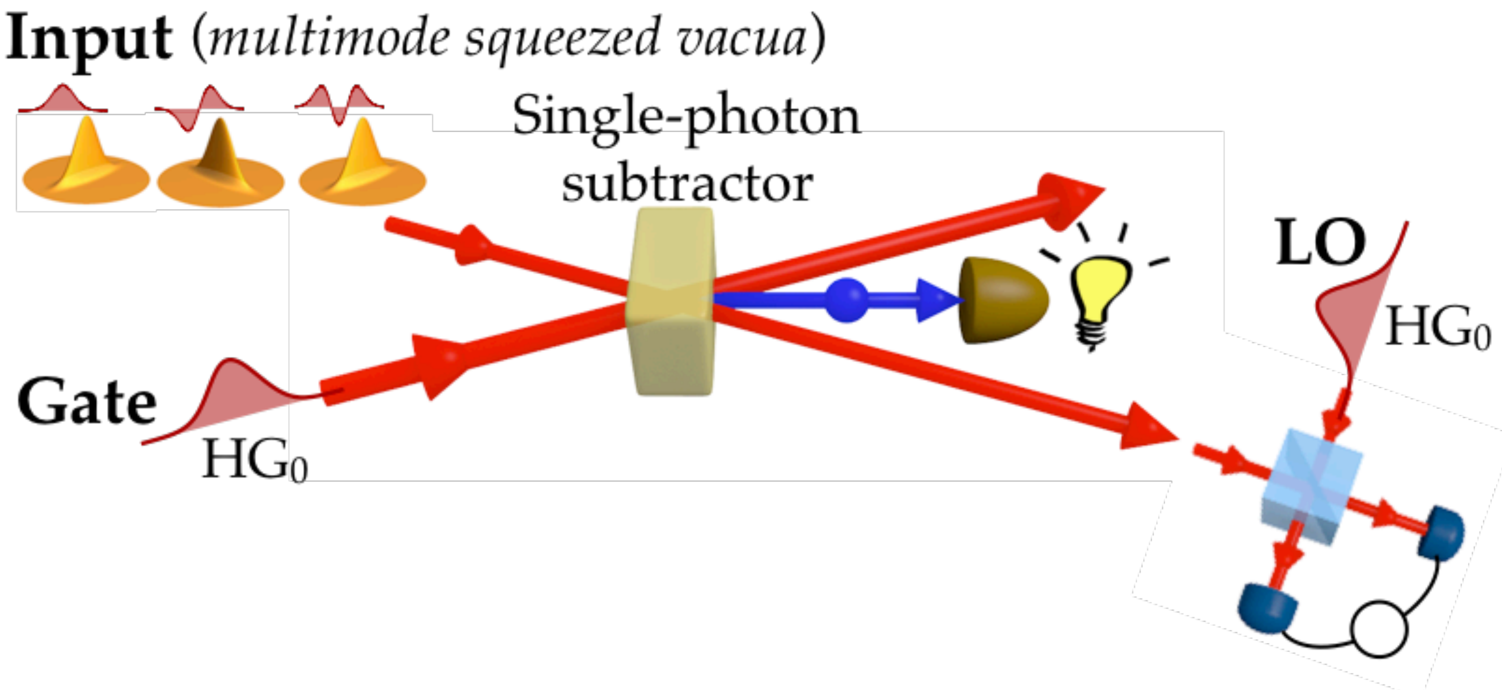
Quantum State Tomography



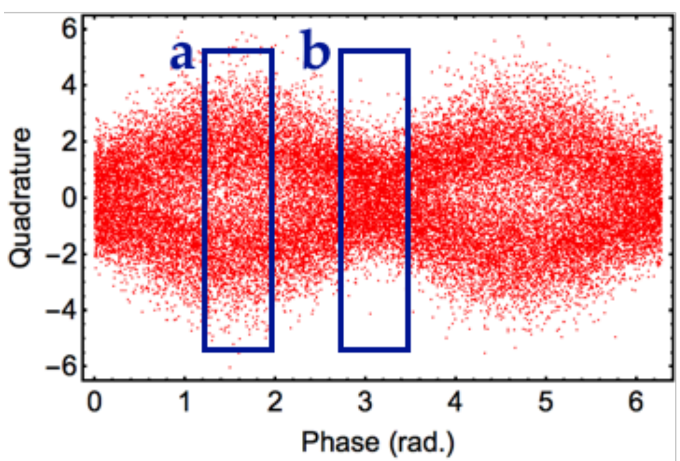




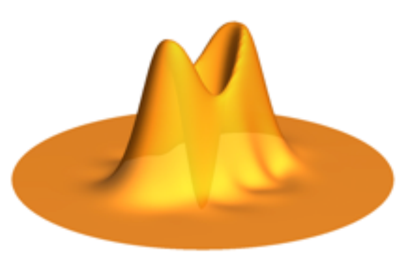
Quantum State Tomography

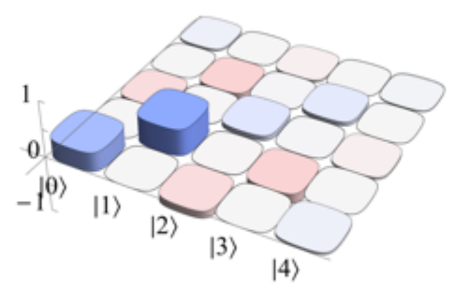


Quadrature outcomes



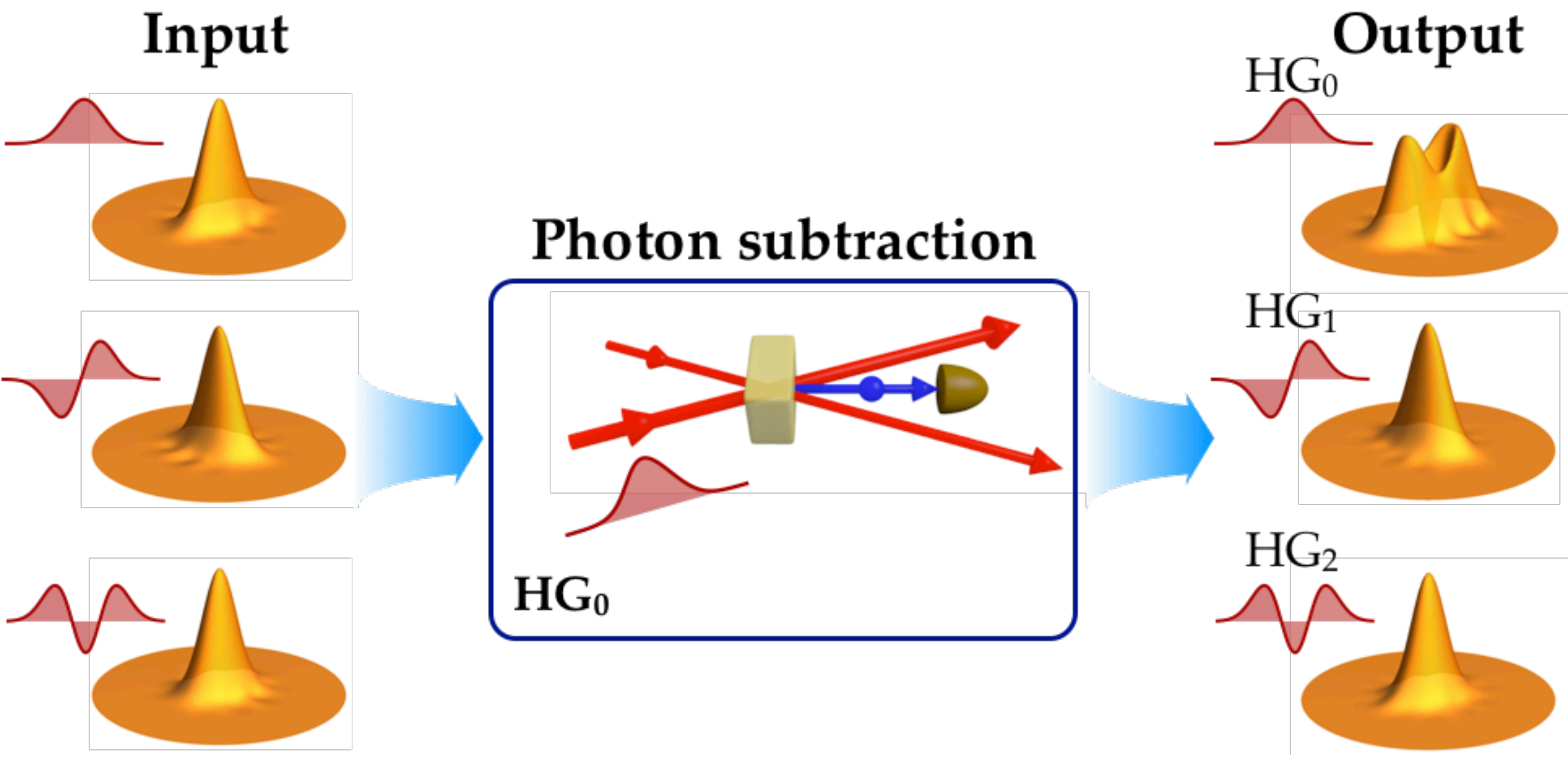
Wigner function | **Density matrix**





$W(0,0) = -0.11/(2\pi)$

Quantum State Tomography



Summary

LKB

- It is possible to tailor non-Gaussian multimode states.
  But many questions remain:

- How to use them for Quantum Information?
- How to demonstrate Inherent entanglement?
- How to make a more complete tomography?
- How…?

People

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Giulia Ferrini
Clément Jacquard
Jonathan Roslund
Cai Yin