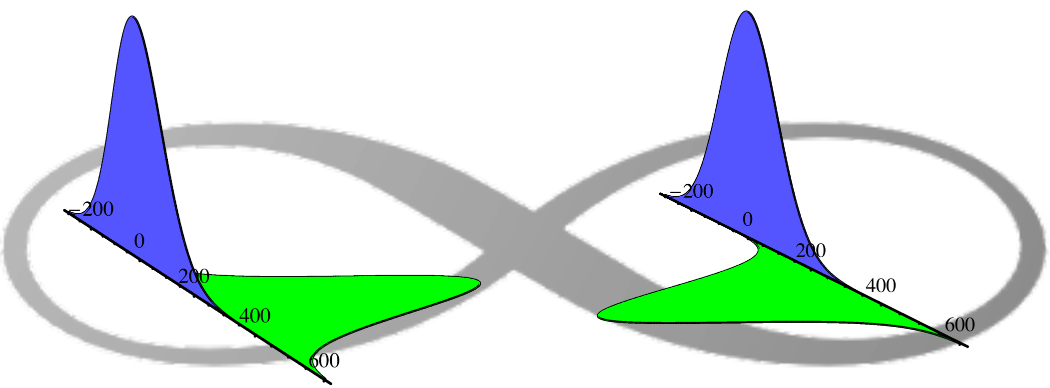
# Quantum multimode resources based on optical frequency combs and simulation of complex quantum network


Valentina Parigi

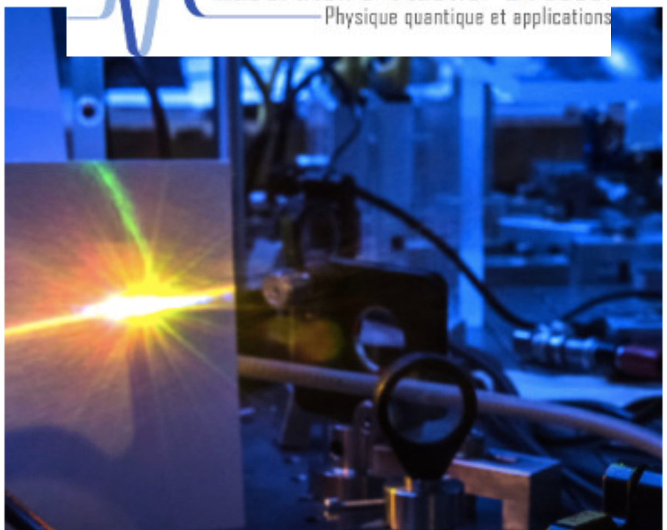
Multimode quantum optics group


*QuProCSII 07 April 2017*

# Our group at LKB

Laboratoire Kastler Brossel
Physique quantique et applications



MULTIMODE
QUANTUM OPTICS
NICOLAS TREPS, CLAUDE FABRE,
VALENTINA PARIGI

QCUMbER
Quantum Controlled Ultrafast Multimode Entanglement and Measurement

ANR

SORBONNE UNIVERSITÉS

*C. Fabre, N. Treps*

## Femto Lab

- Quantum Frequency Combs
- Quantum Information Processing
- Multimode analysis of laser dynamics
- Quantum metrology
- Complex quantum networks

## Optical Fiber Networks

CAILabs
Shaping the light

# Outline

***Multimode quantum optics in Quantum Information technologies***

*Introduction*

*Multicolor entanglement*

*Towards measurement based quantum computing*

***Simulation of complex quantum networks***

**Probing a structured environment**

*Energy transport: some ideas*

# Outline

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***Towards measurement based quantum computing***

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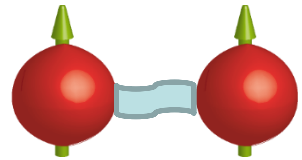
**Probing a structured environment**

***Energy transport: some ideas***

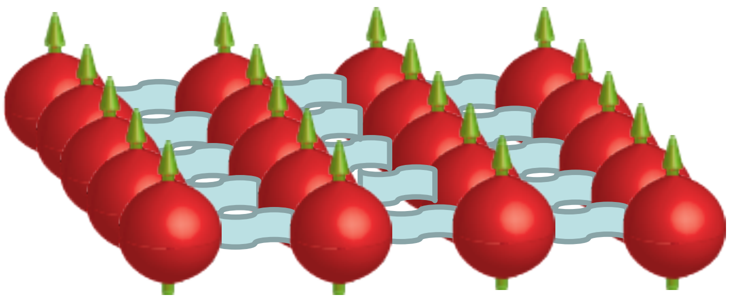
# Quantum information protocols

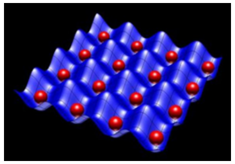
+



**Quantum systems** (q-bits) **Quantum Correlations** (entanglement)

Quantum systems on large scale





Example atoms

| Technology | **Real** advantage over classical |
|---|---|
| Quantum communications | Safer (cryptography) |
| Quantum computation | Faster (prime factorization) |
| Quantum simulation | Solution to hard problem |
| Quantum metrology | More sensitive |

# Quantum information protocols

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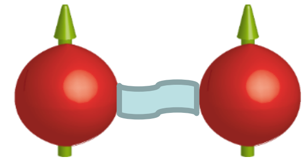

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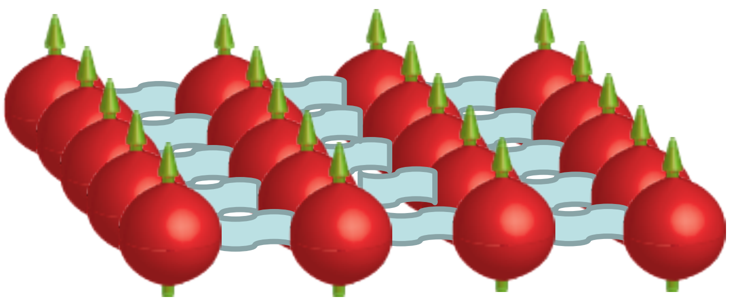

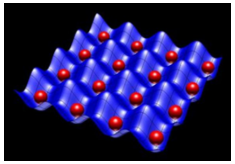

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# Quantum information protocols

## …with multimode quantum optics

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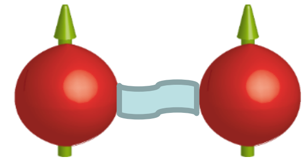
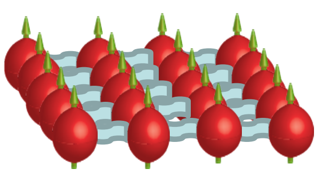


**Quantum systems**

spatial-temporal modes
of the electromagnetic field
= independent harmonic oscillators

**Quantum Correlations** (entanglement)

Entanglement between quadratures
(i.e. amplitude and phase)



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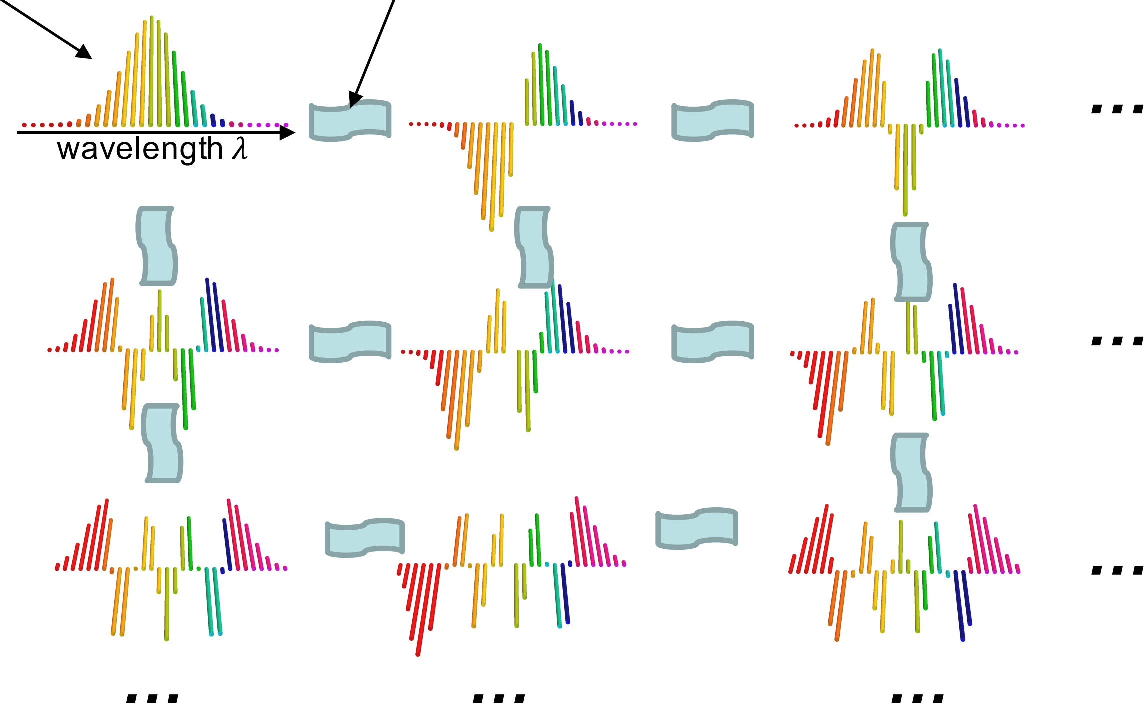

# Quantum information protocols

## …with multimode quantum optics

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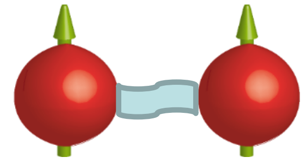

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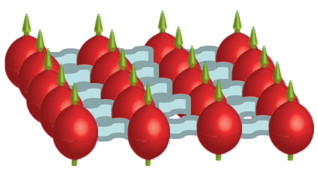

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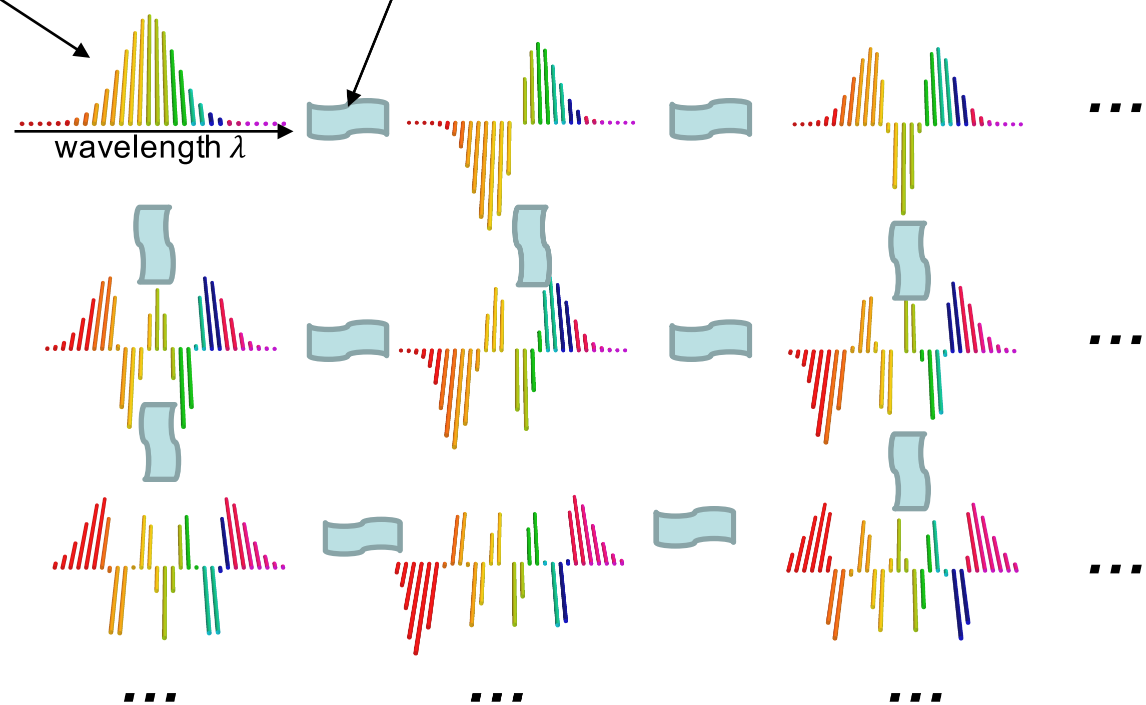


+
*Non - Gaussian operations*

# Outline

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### Introduction

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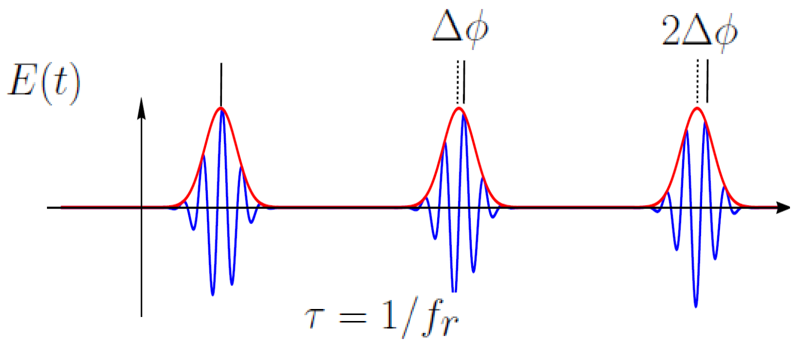
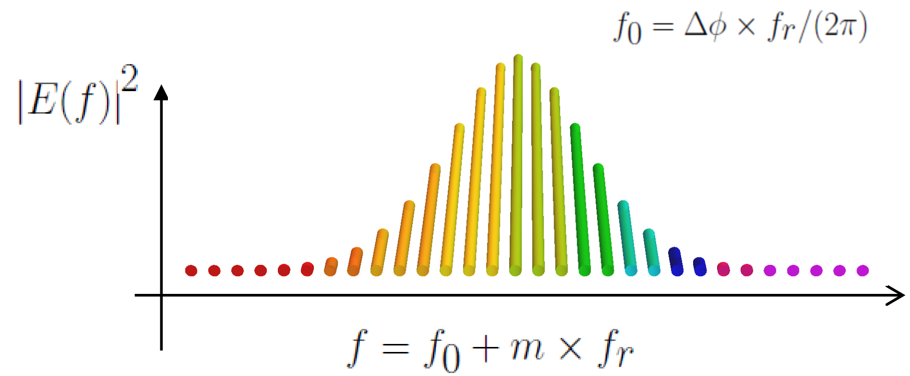
# Multimode quantum optics

**Optical frequency comb** + quantum optics




time

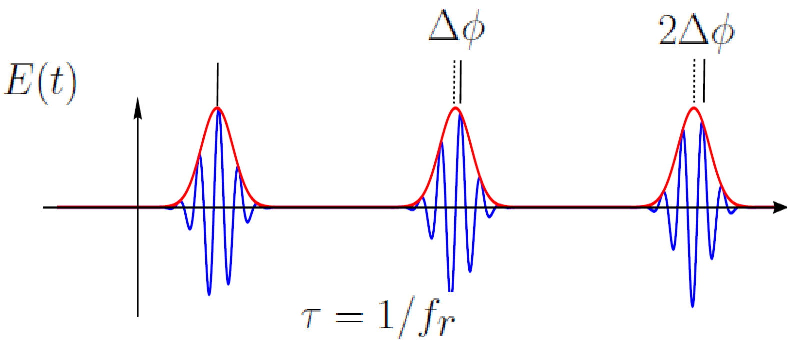



frequency

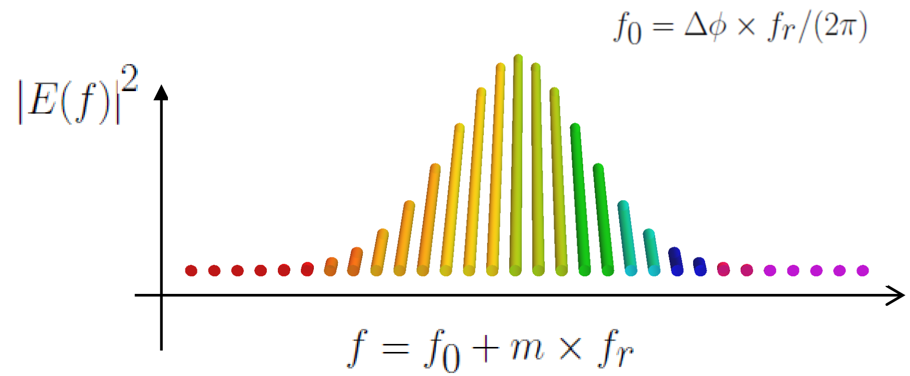
Femtosecond mode-locked laser -> Huge number of modes (~ $10^6$ frequencies)

# Multimode quantum optics

Optical frequency comb + **quantum optics**




time

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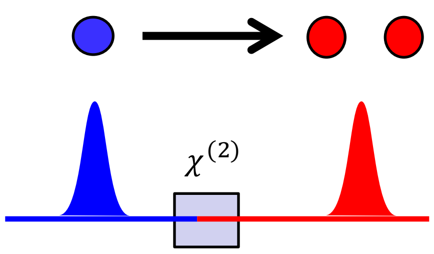
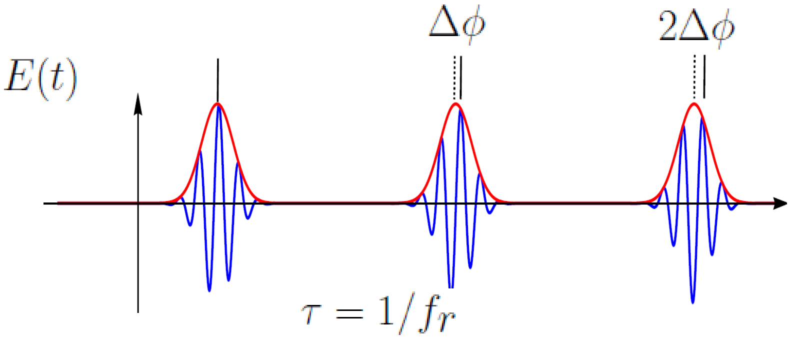



$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$

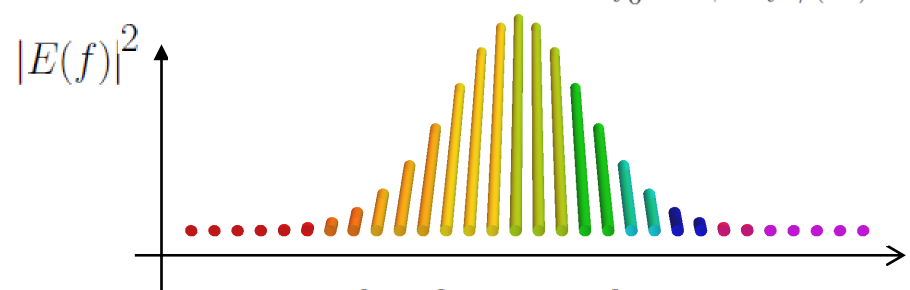
Parametric process

# Multimode quantum optics

Optical frequency comb + **quantum optics**

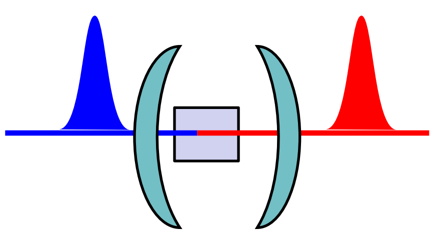



time




frequency

$$\omega_s \neq \omega_i$$



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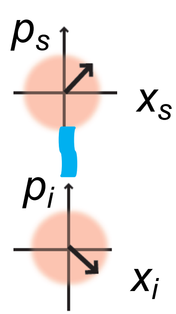
Parametric process



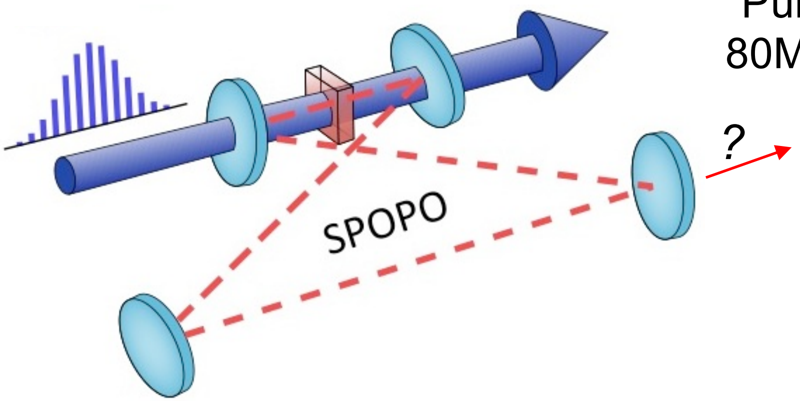

Quadrature entangled states

$x_s$ et $x_i$ correlated
$p_s$ et $p_i$ anti-correlated

# Multimode quantum optics

## Optical frequency comb + quantum optics

Synchronously pumped OPO



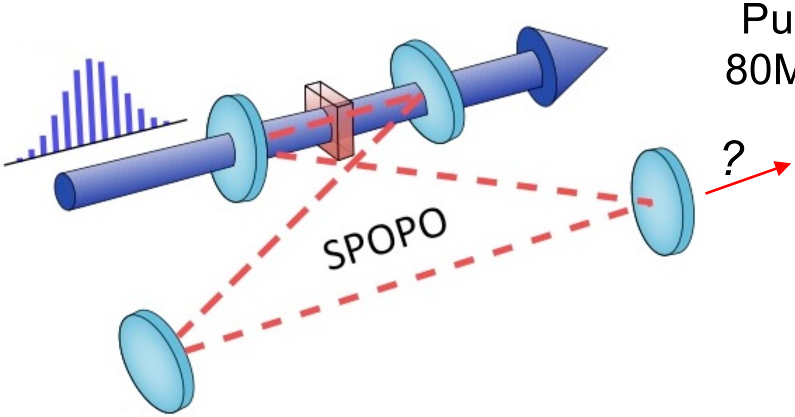

Pump : 200fs
80Mhz rep rate
400nm

# Multimode quantum optics

LKB

## Optical frequency comb + quantum optics

### Synchronously pumped OPO

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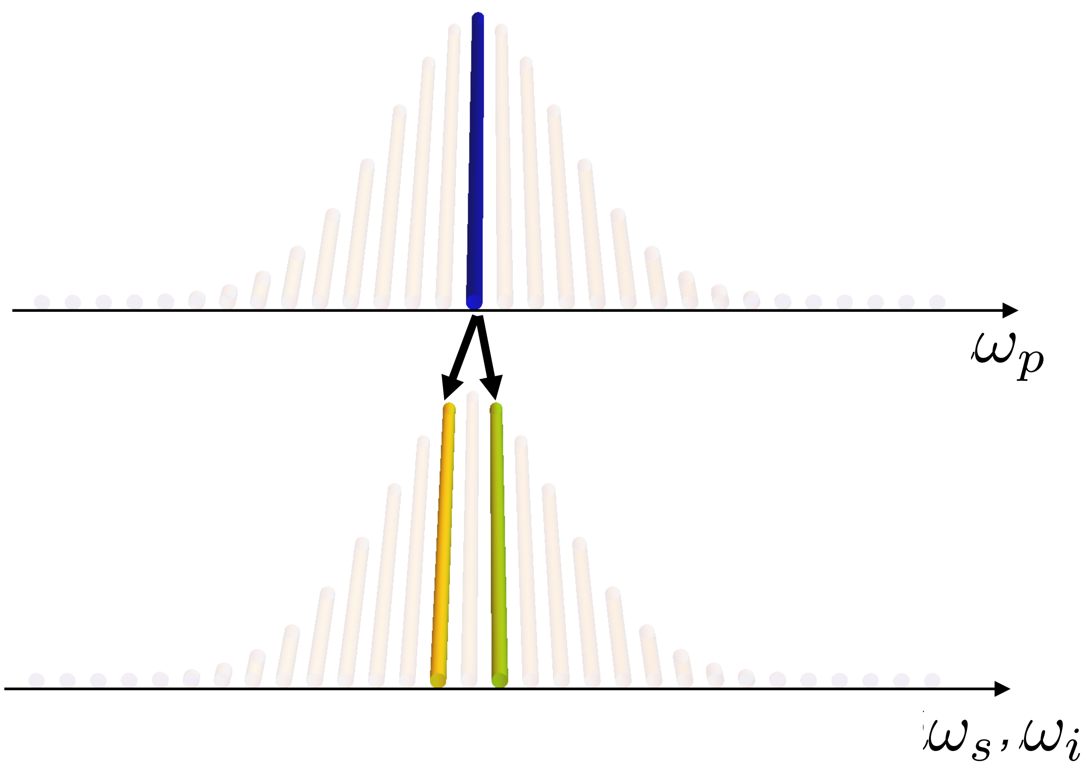
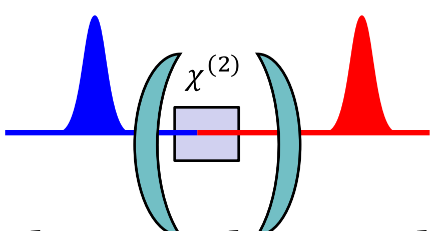
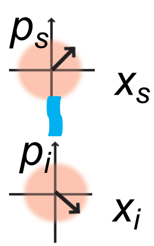



**Symmetric** Frequency Correlations
(quadratures entanglement)

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Parametric process

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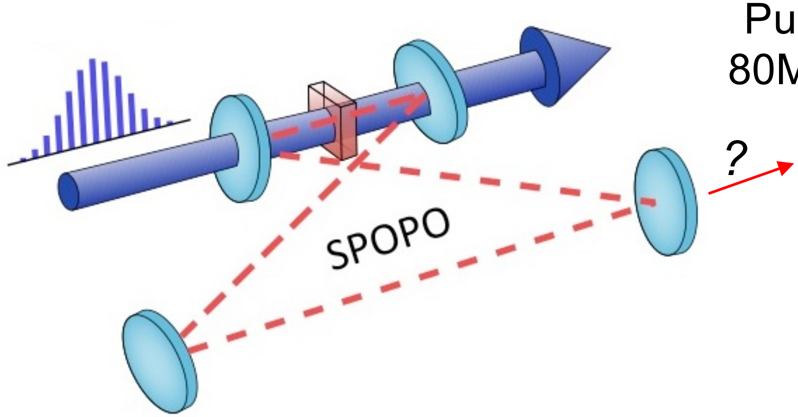


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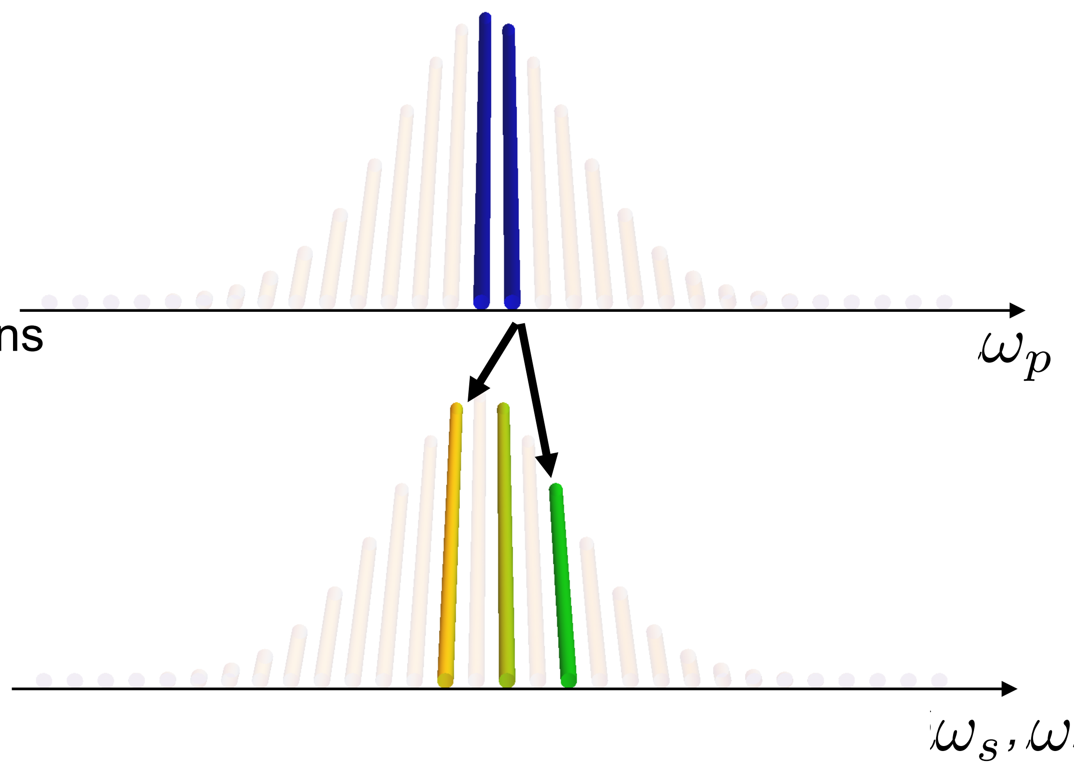
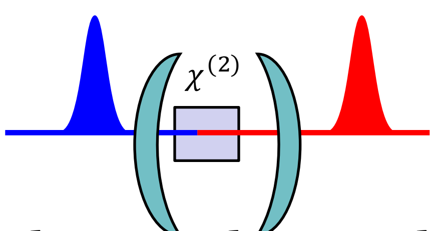



**Asymmetric** Frequency Correlations
(quadratures entanglement)

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Parametric process

# Multimode quantum optics

## Optical frequency comb + quantum optics

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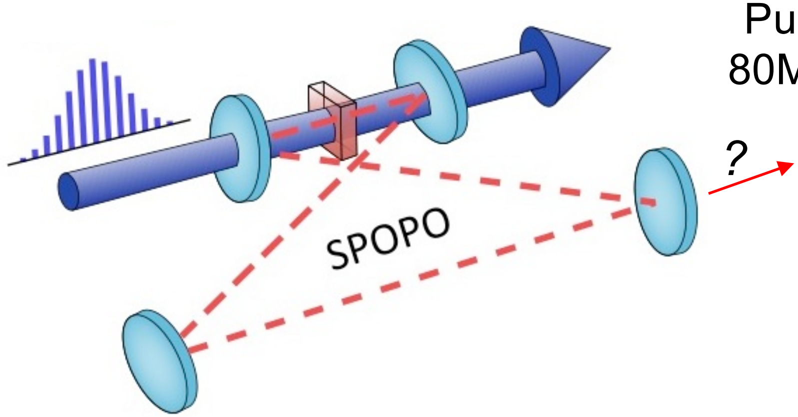


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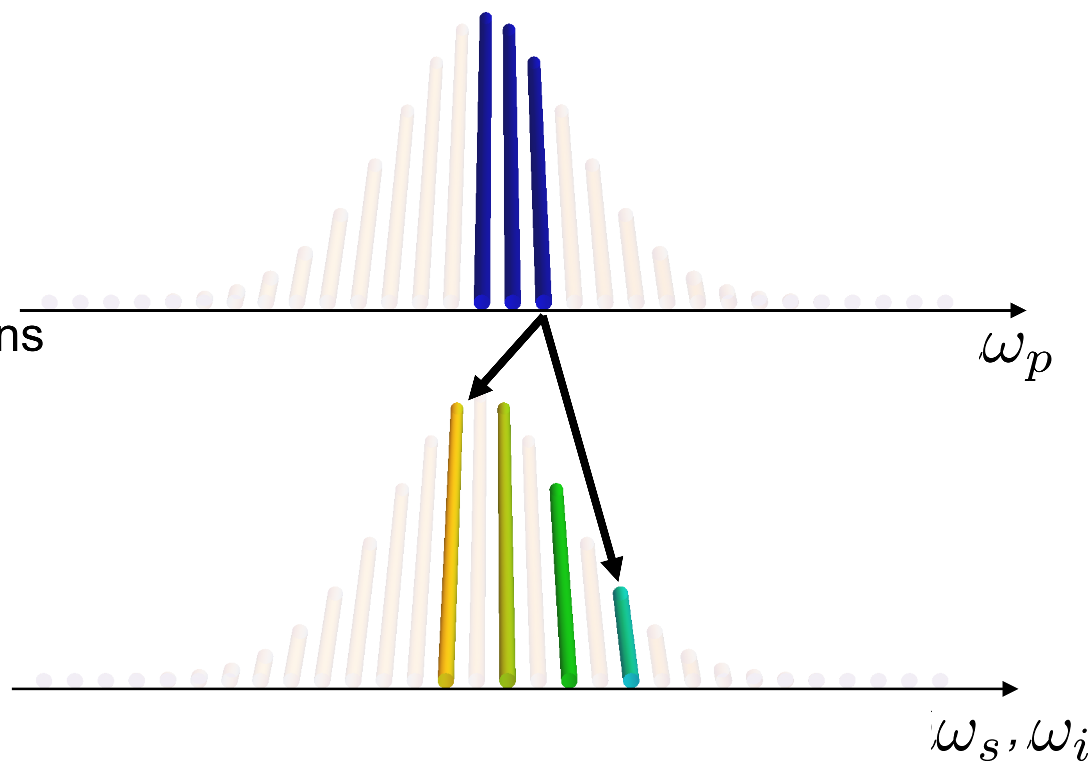


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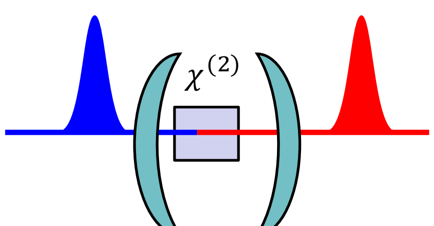


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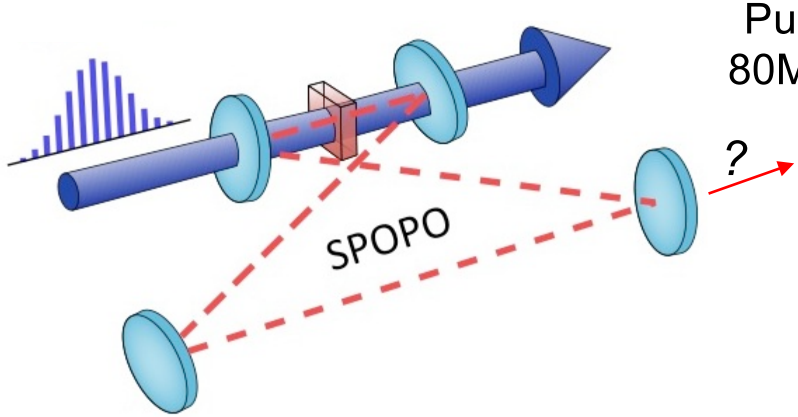
Parametric process

# Multimode quantum optics

## Optical frequency comb + quantum optics

Synchronously pumped OPO

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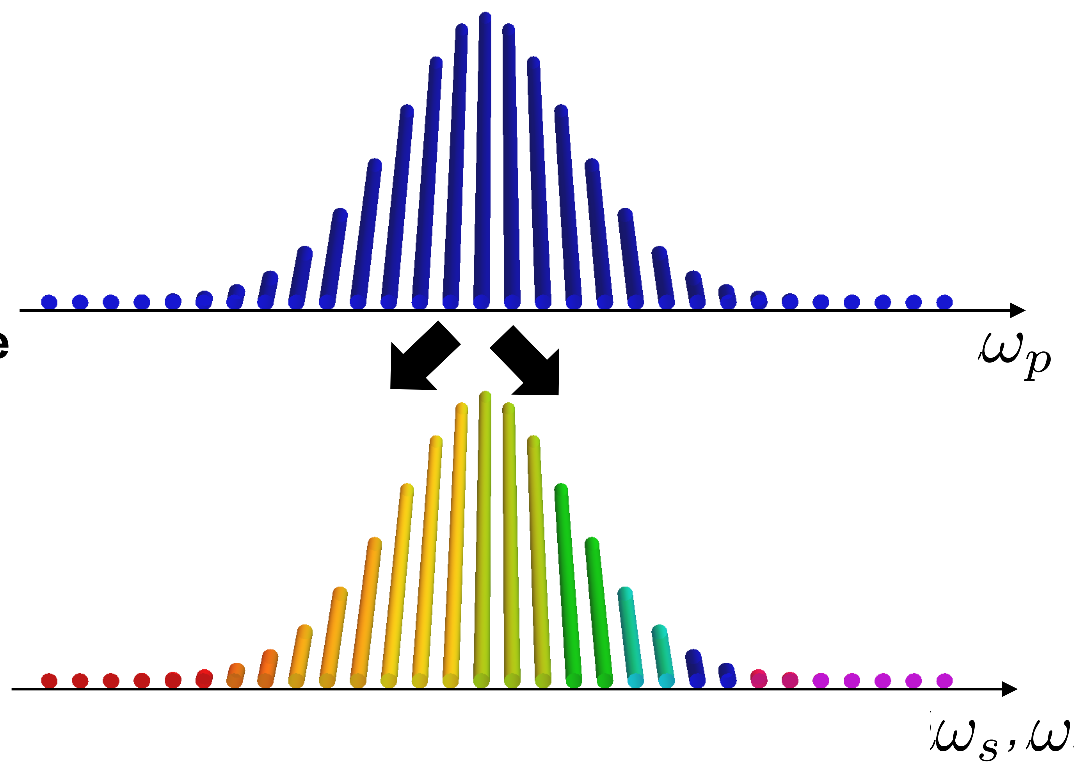
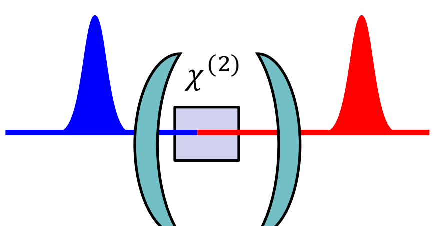



**Complex entanglement structure**
(quadratures entanglement)

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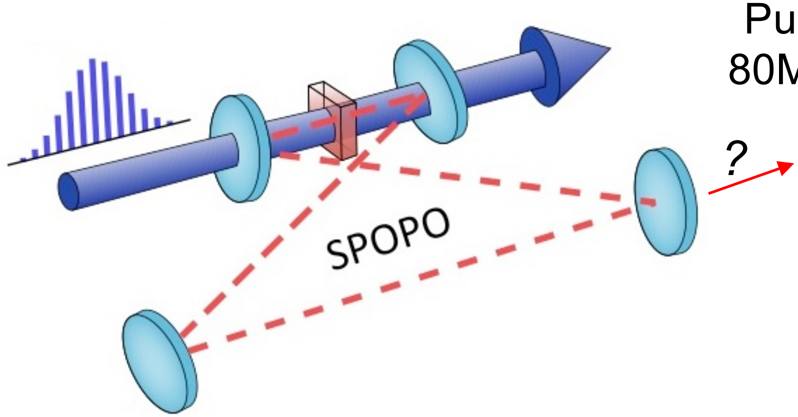
Parametric process

# Multimode quantum optics

## Optical frequency comb + quantum optics

Synchronously pumped OPO

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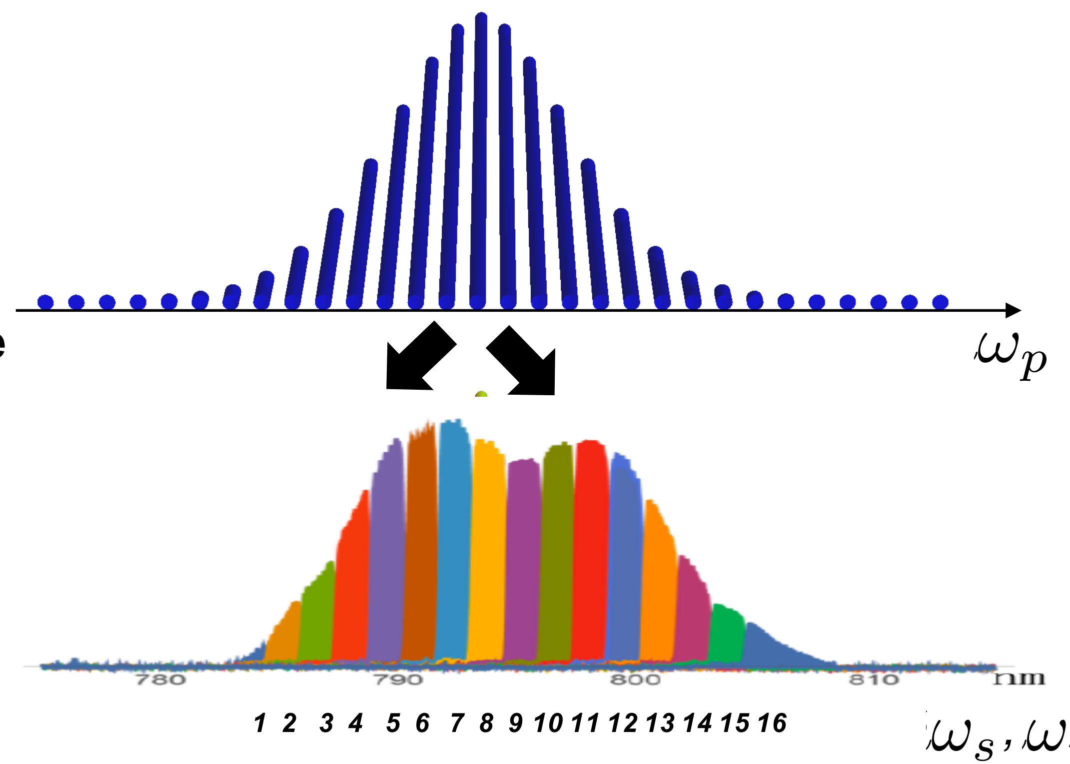


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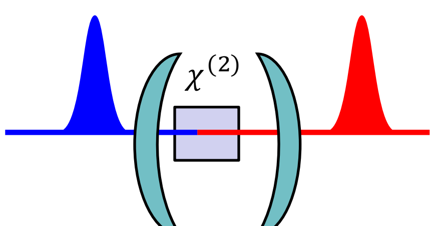
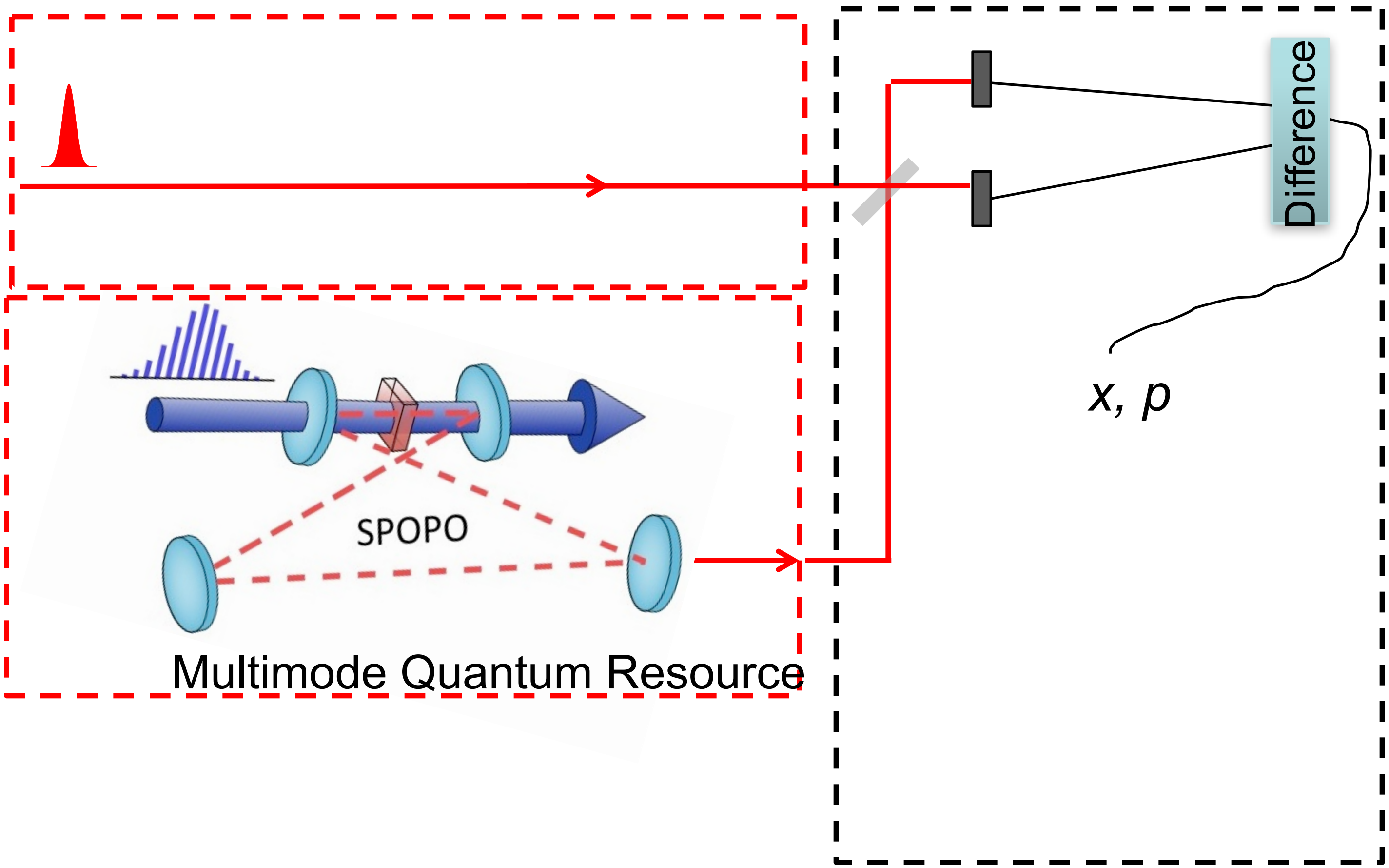



$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$

Parametric process

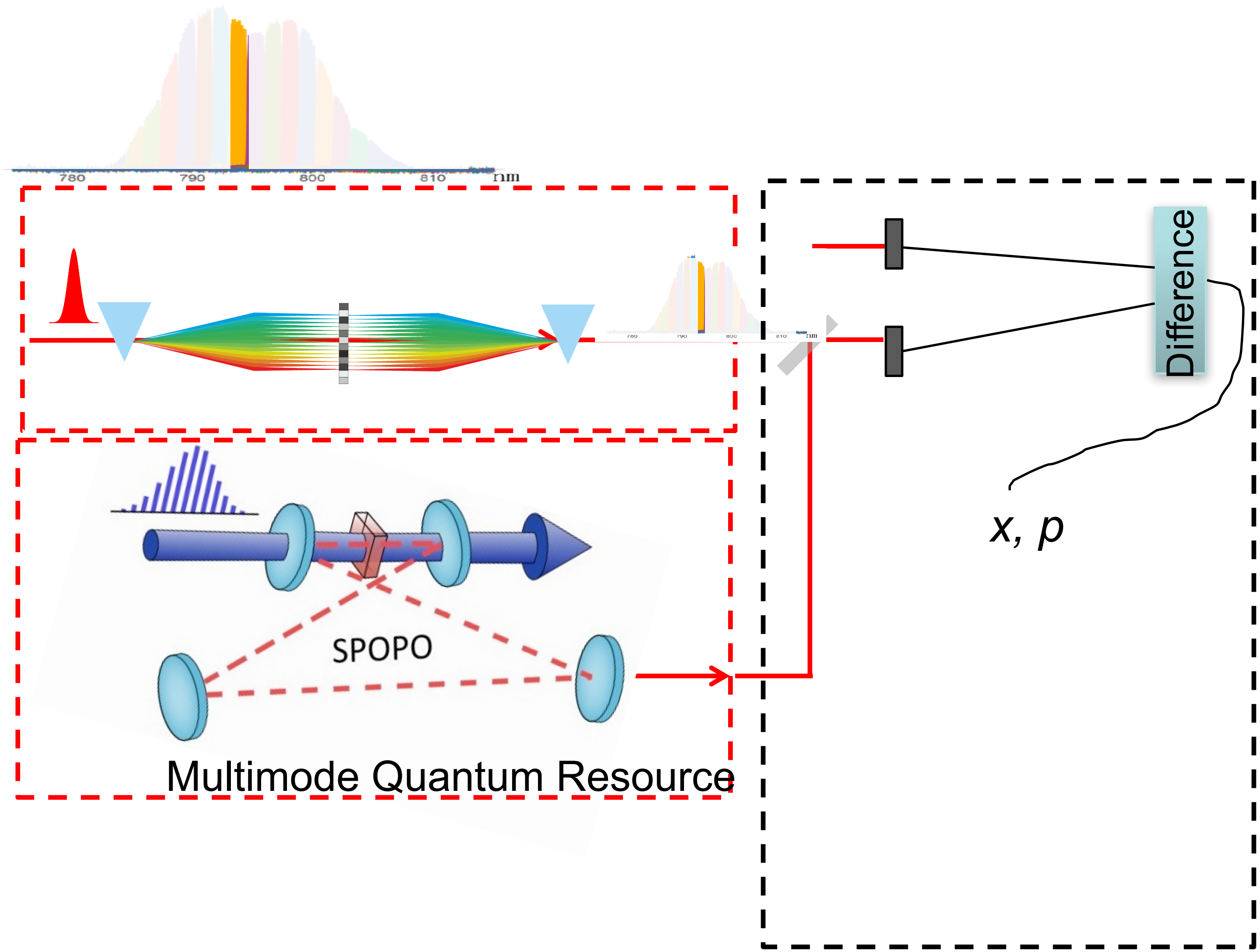
# Characterization

*Characterization :* *homodyne detection*



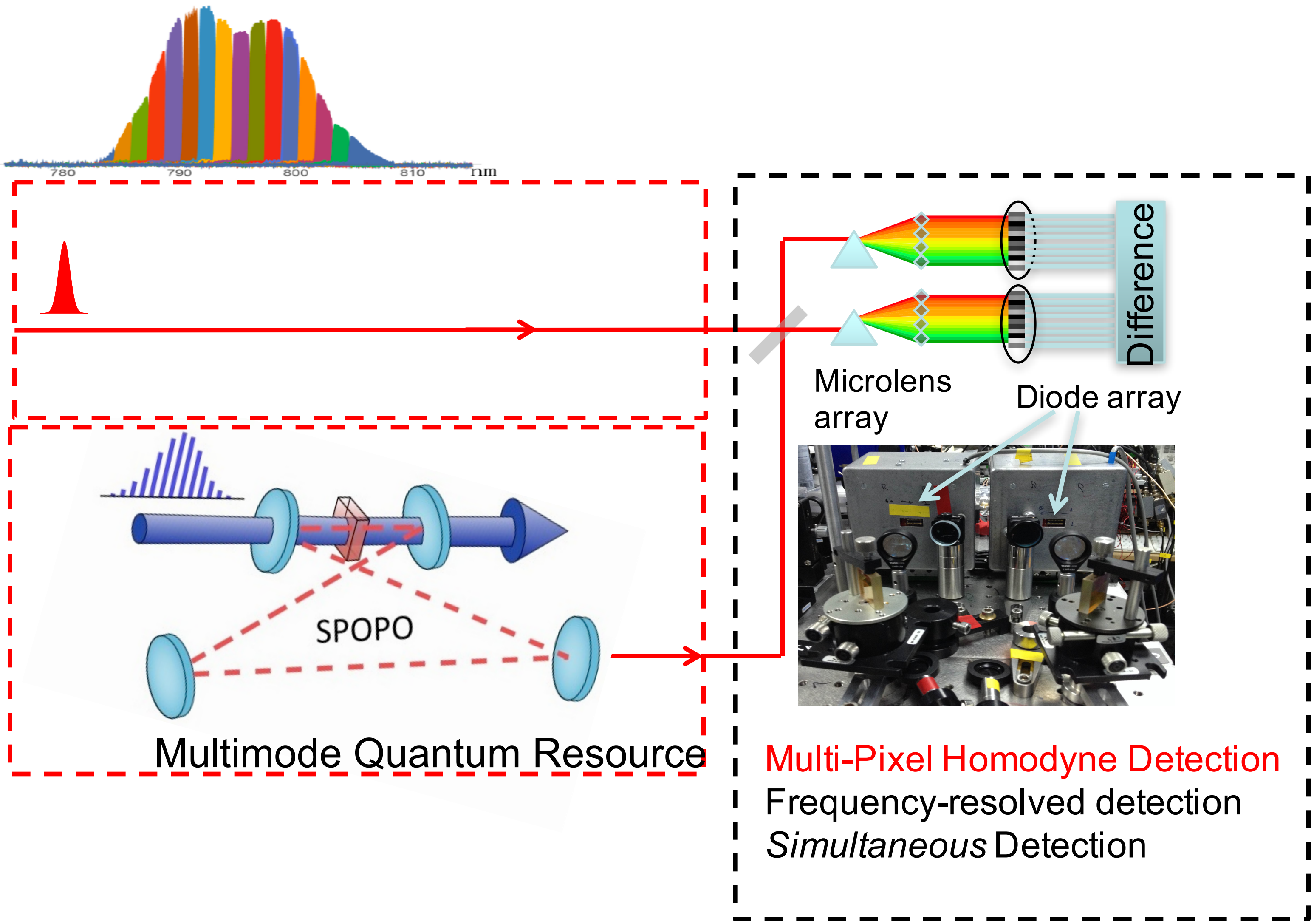
# Characterization 1: pulse shaping

<u>*Characterization : mode-selective homodyne detection*</u>

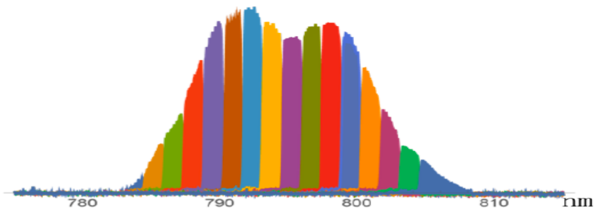


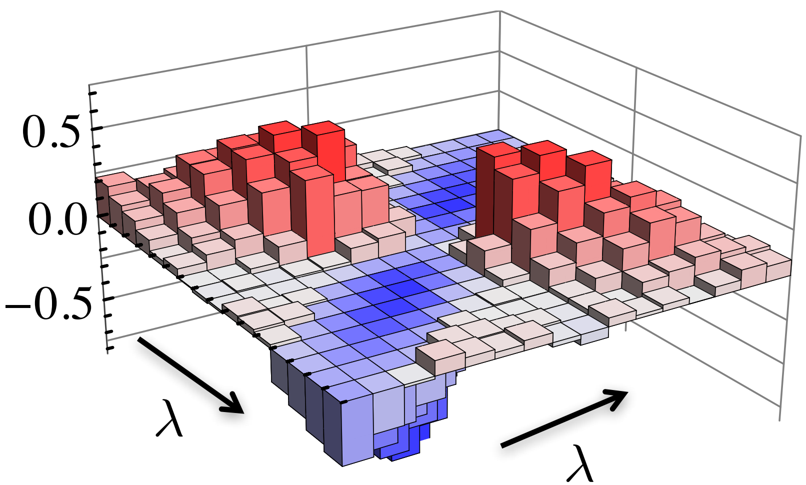
# Characterization 2: multi-pixel

*Characterization : multi-mode homodyne detection*

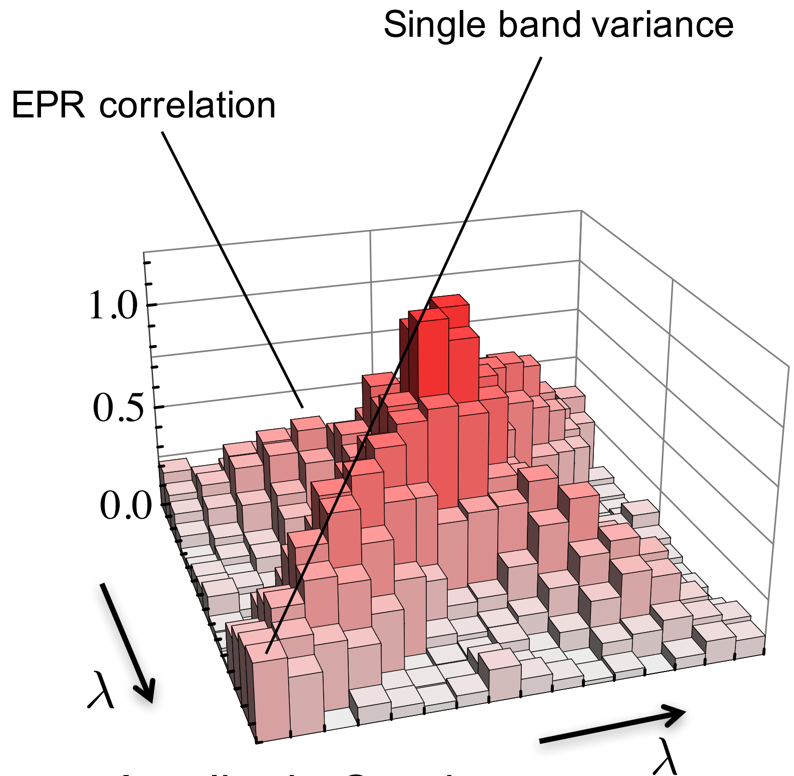


# Characterization: covariance matrix




16-mode Covariance matrix
of Phase Quadrature

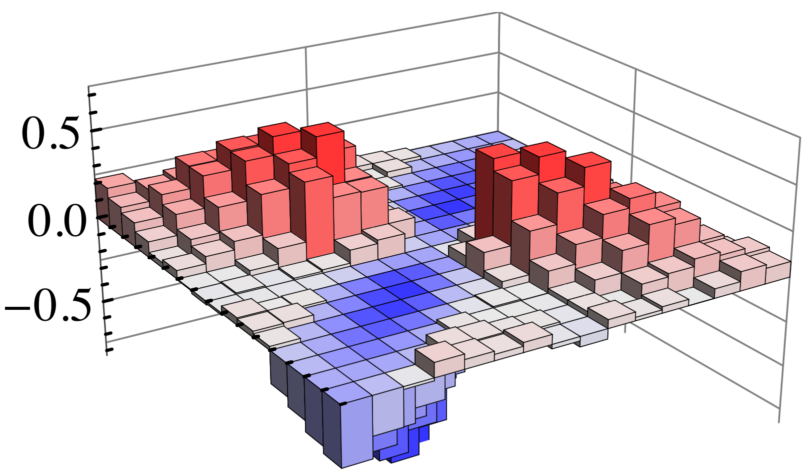


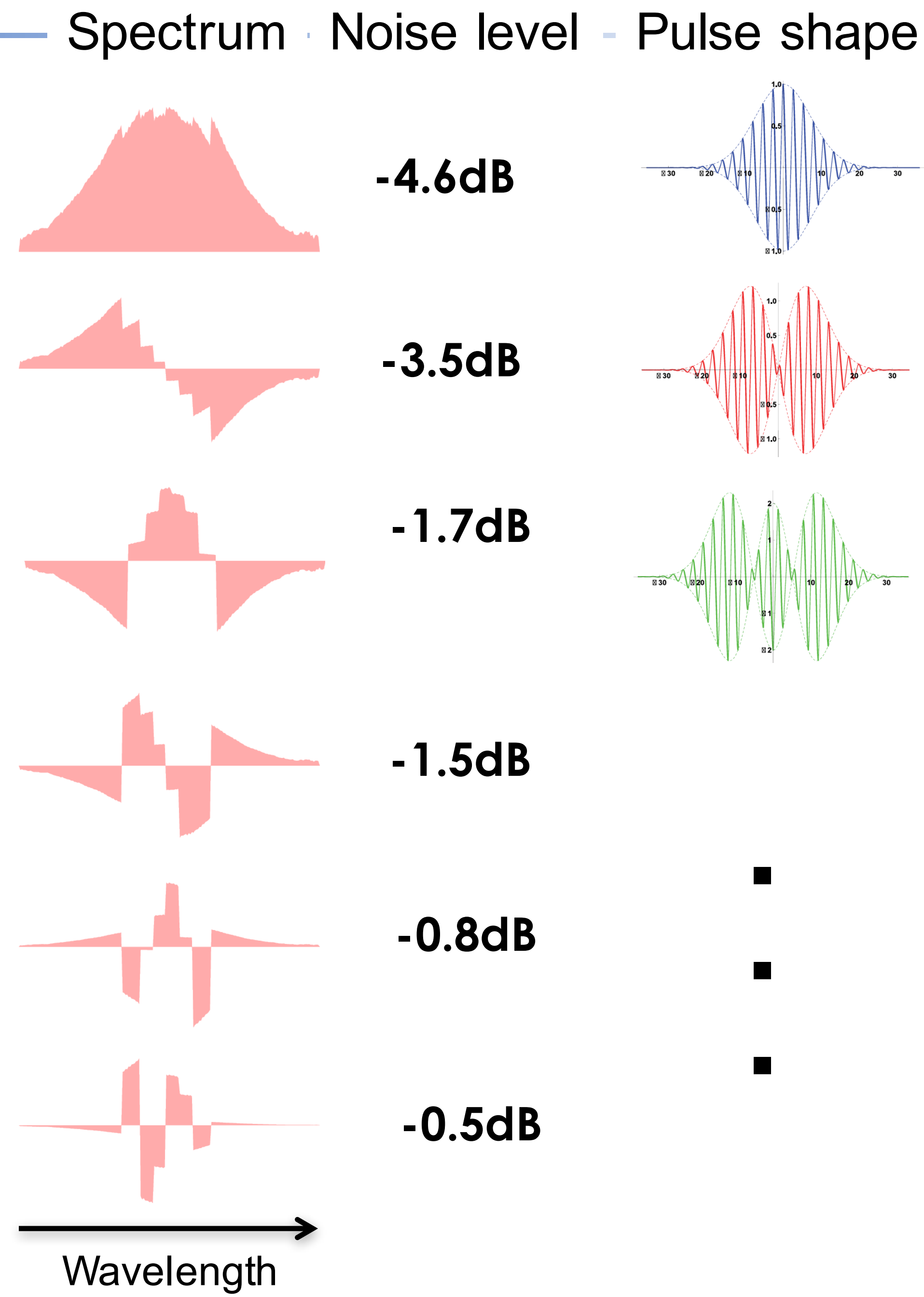

Amplitude Quadrature

# Eigenmodes

## Diagonalization

- Independent Squeezers
- Unique temporal / spectral pulse shapes




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

# Eigenmodes

LKB

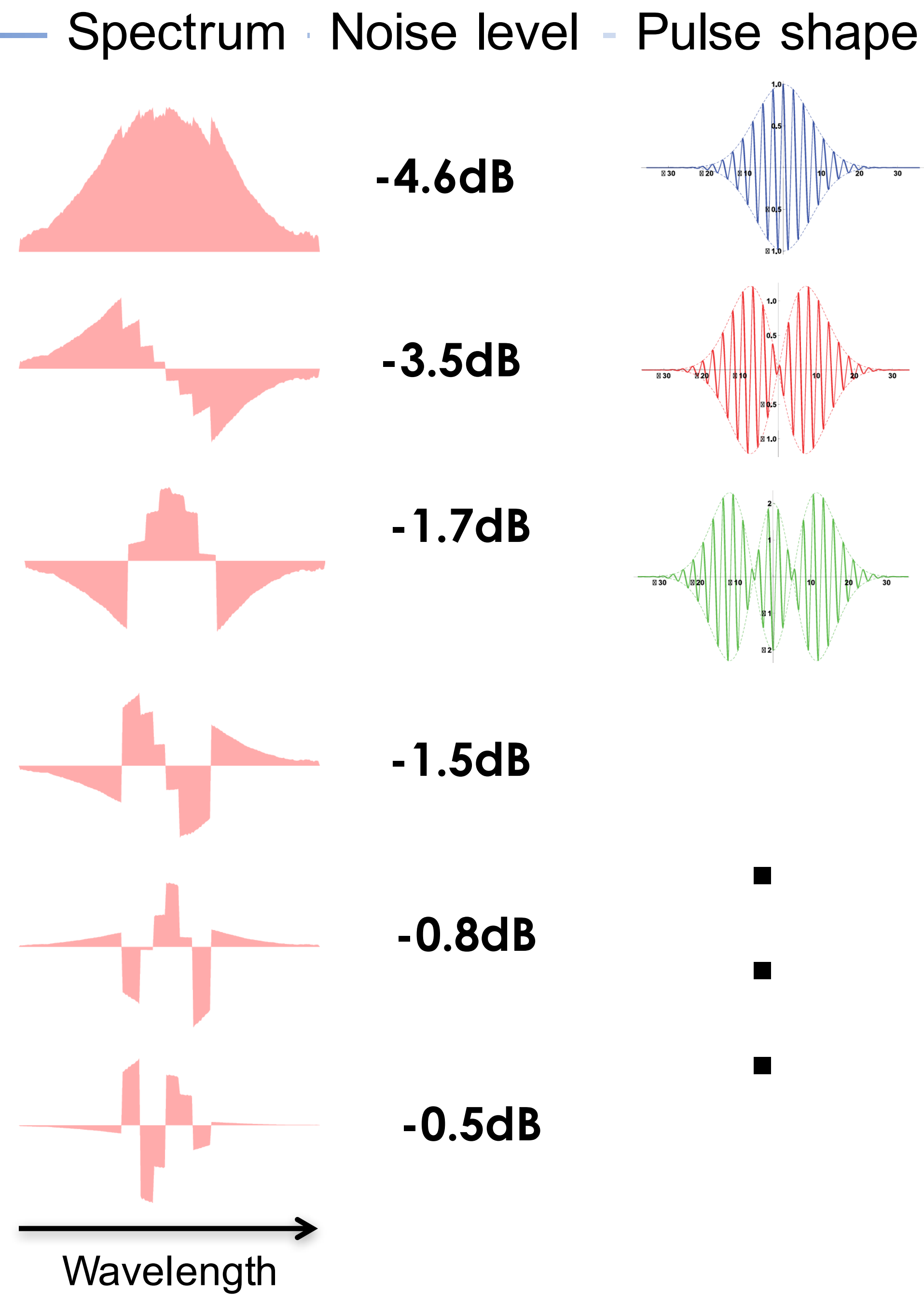
## Diagonalization

- Independent Squeezers
- Unique temporal / spectral pulse shapes

It corresponds to

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

$$H = i\hbar \sum_{k} \Lambda_k \hat{S}_k^{\dagger 2}$$



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**Probing a structured environment**

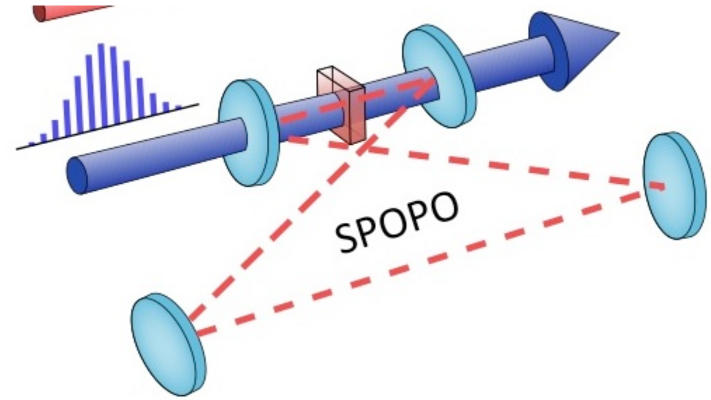
***Energy transport: some ideas***

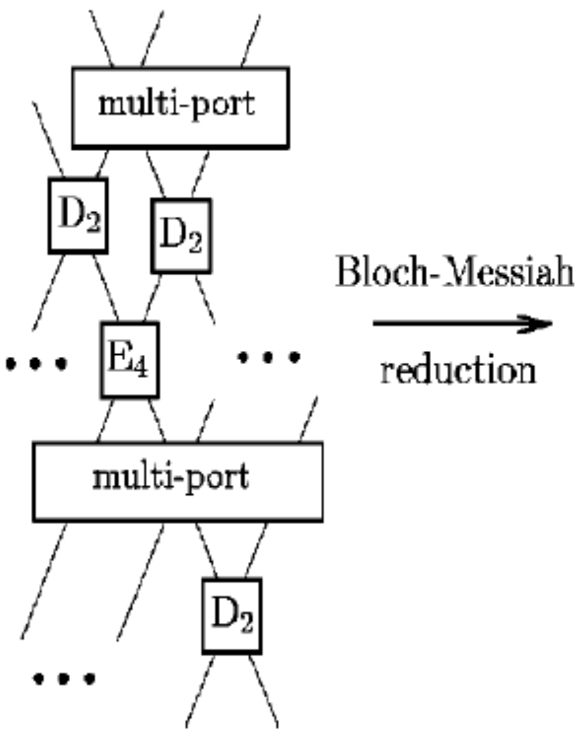
# Multimode quantum Gaussian resource

PHYSICAL REVIEW A **71**, 055801 (2005)

**Squeezing as an irreducible resource**

Samuel L. Braunstein
*Computer Science, University of York, York YO10 5DD, United Kingdom*
(Received 6 March 2005; published 31 May 2005)




$$\vec{a} = (a_1, a_2, \dots, a_N).$$

*collection of input modes*

$$\vec{a}_{out} = V^\dagger S U \vec{a}$$

*squeezing*

*basis change*

***Bloch-Messiah decomposition***

# Multimode quantum Gaussian resource

LKB

PHYSICAL REVIEW A **71**, 055801 (2005)

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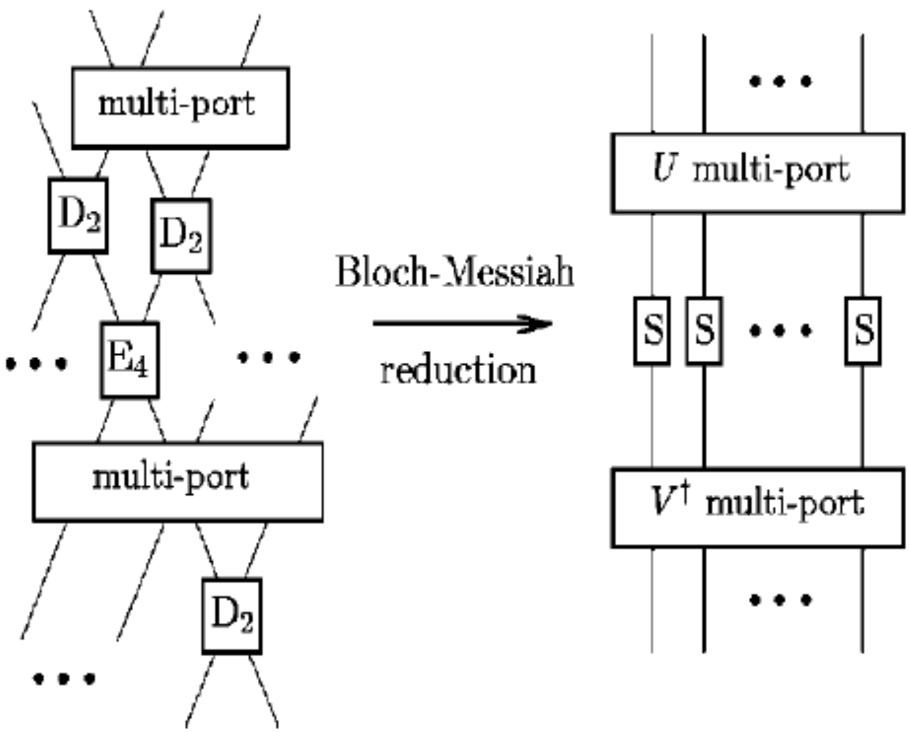
multimode quantum Gaussian ressource = Squeezed modes + basis change

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*squeezing*

*basis change*

***Bloch-Messiah decomposition***

# Multimode quantum Gaussian resource

$$\vec{a}_{out} = V^{\dagger} S U \vec{a}$$

*squeezing*

*basis change*

*if* $\vec{a}$ *collection of vacuum states*

$$\vec{a}_{out} = V^{\dagger} S \vec{a}$$

# Multimode quantum Gaussian resource

$$\vec{a}_{out} = V^{\dagger} S U \vec{a}$$

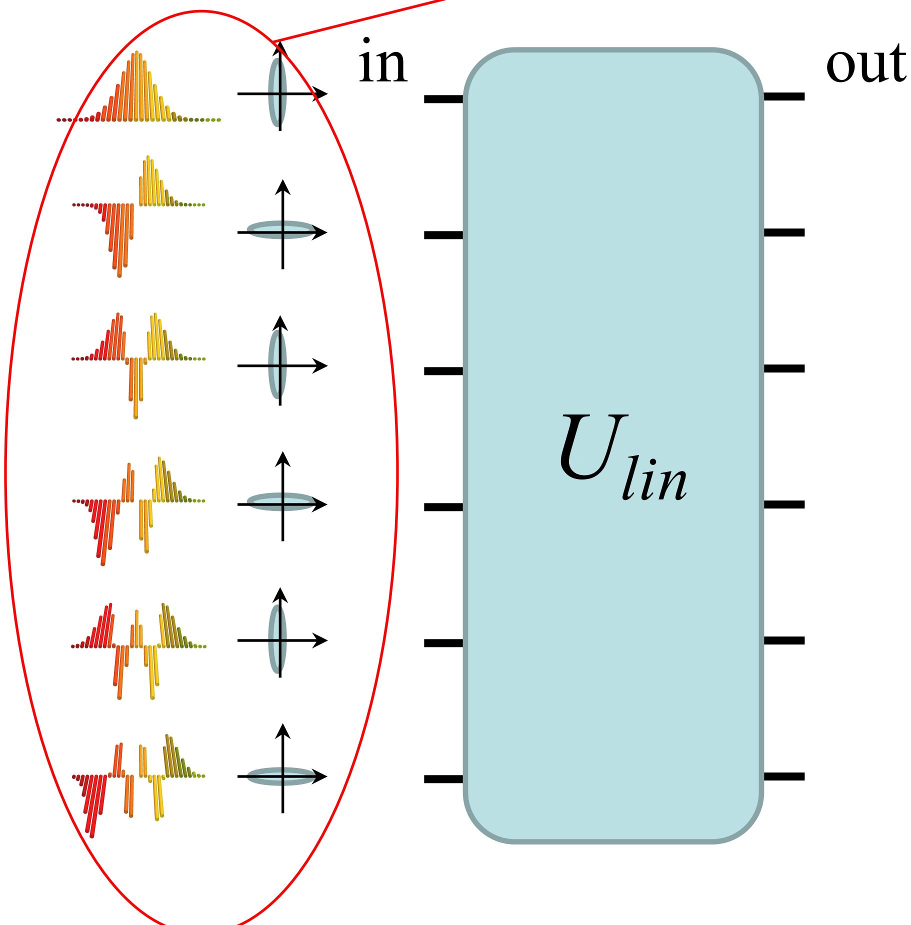
basis change

squeezing

*if* $\vec{a}$ *collection of vacuum states*

$$\vec{a}_{out} = V^{\dagger} S \vec{a}$$

***Supermodes***



# Multimode quantum Gaussian resource

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*squeezing*

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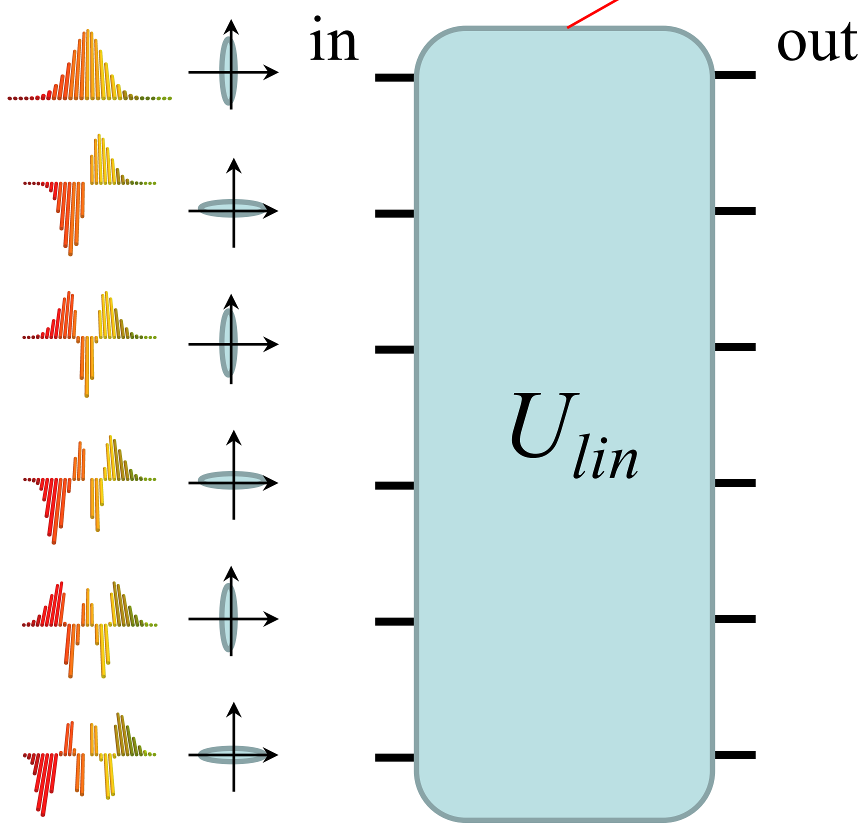
*if* $\vec{a}$ *collection of vacuum states*

$$\vec{a}_{out} = V^{\dagger} S \vec{a}$$

**Supermodes**



# Multimode quantum Gaussian resource

$$\vec{a}_{out} = V^{\dagger} S U \vec{a}$$

basis change

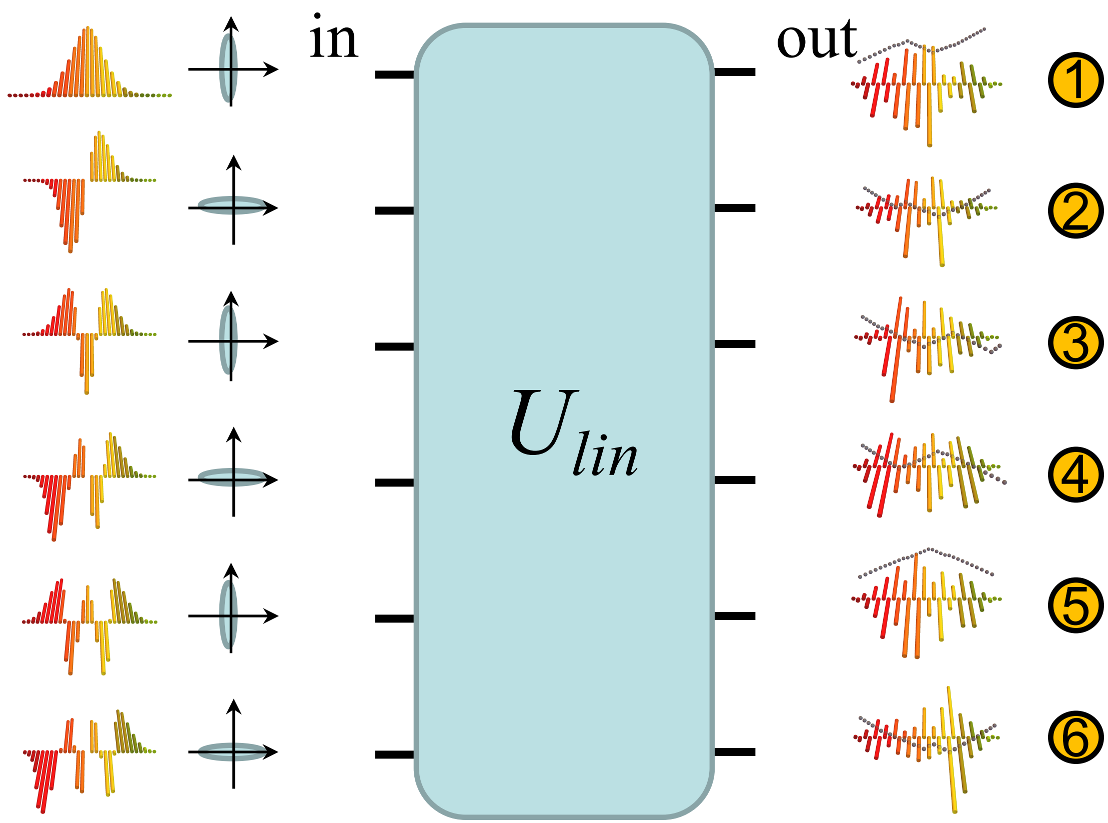
squeezing

*if* $\vec{a}$ *collection of vacuum states*

$$\vec{a}_{out} = V^{\dagger} S \vec{a}$$

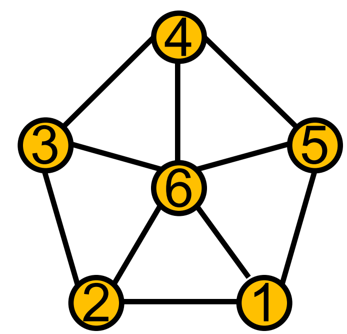
**Supermodes**

**Cluster states**




$$\Delta\left(\hat{p}_n - \sum_b \hat{x}_b\right) \rightarrow 0$$

*nullifier*



# Multimode quantum Gaussian resource

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**Supermodes**

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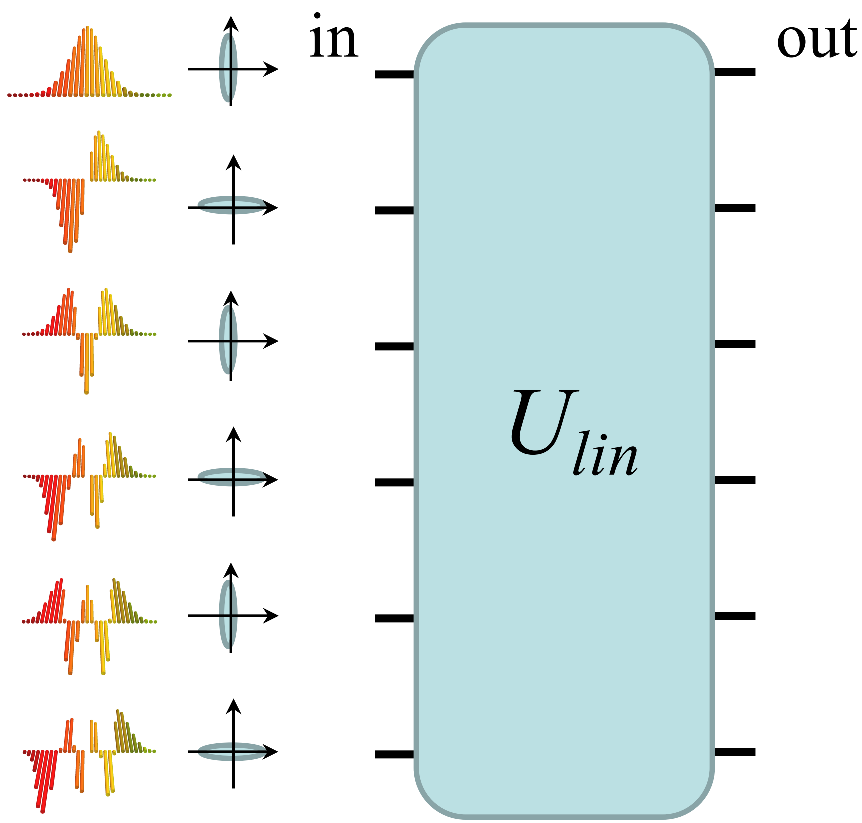
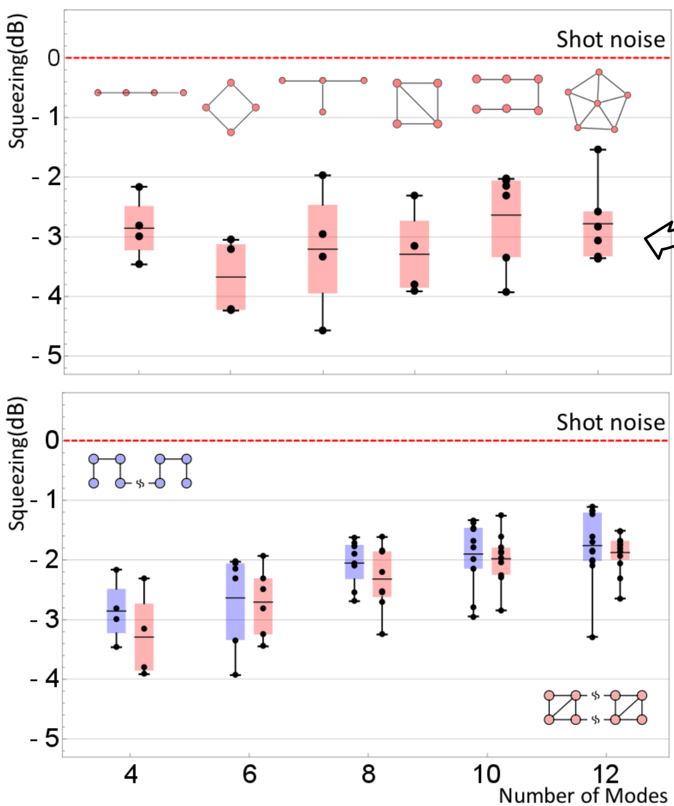
*nullifiers*



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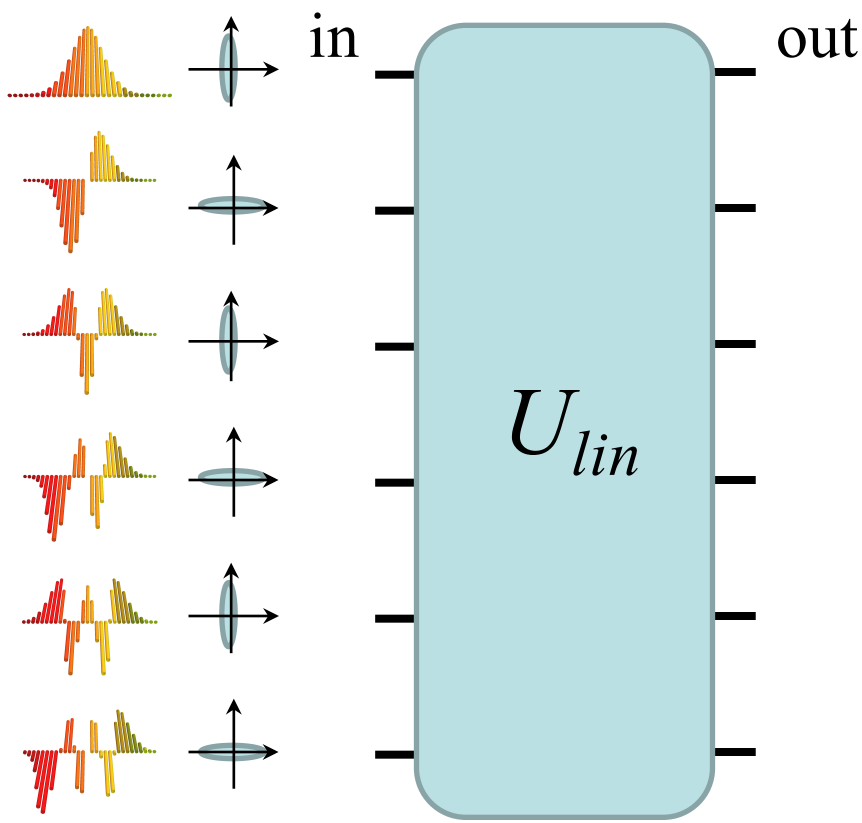
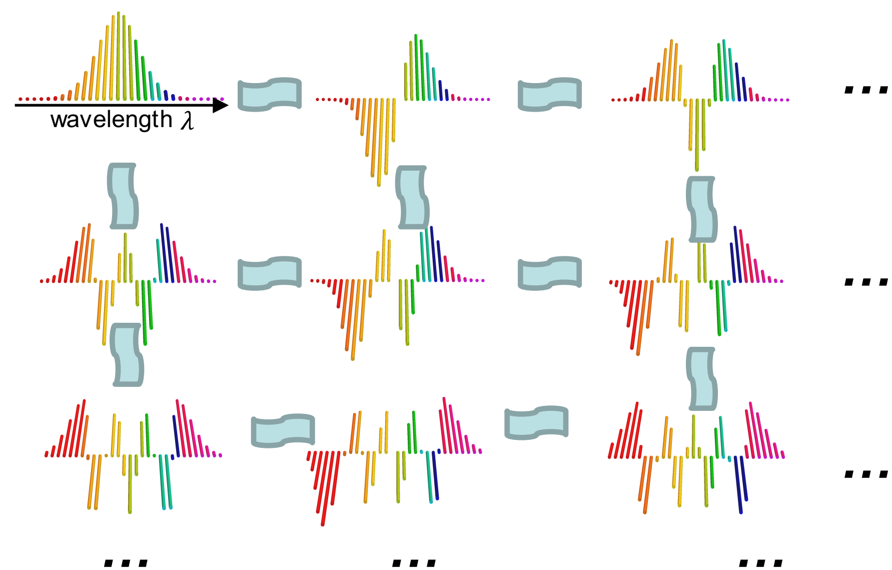
**Supermodes**

***Cluster states***



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$$\vec{a}_{out} = V^{\dagger} S U \vec{a}$$

*squeezing*

*basis change*

*if* $\vec{a}$ *collection of vacuum states*

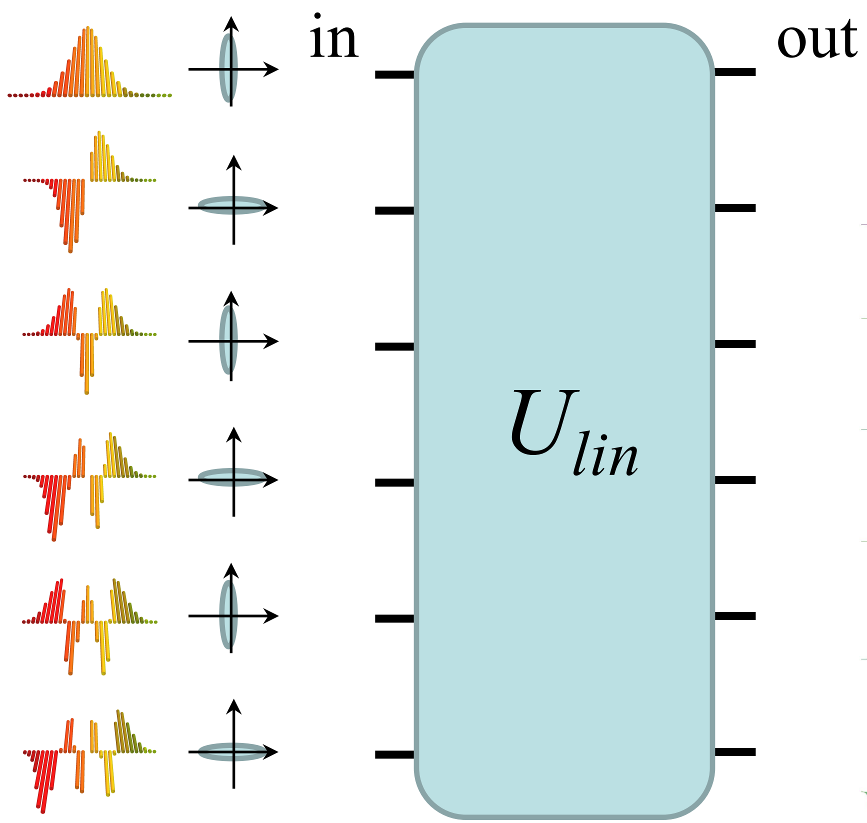
$$\vec{a}_{out} = V^{\dagger} S \vec{a}$$

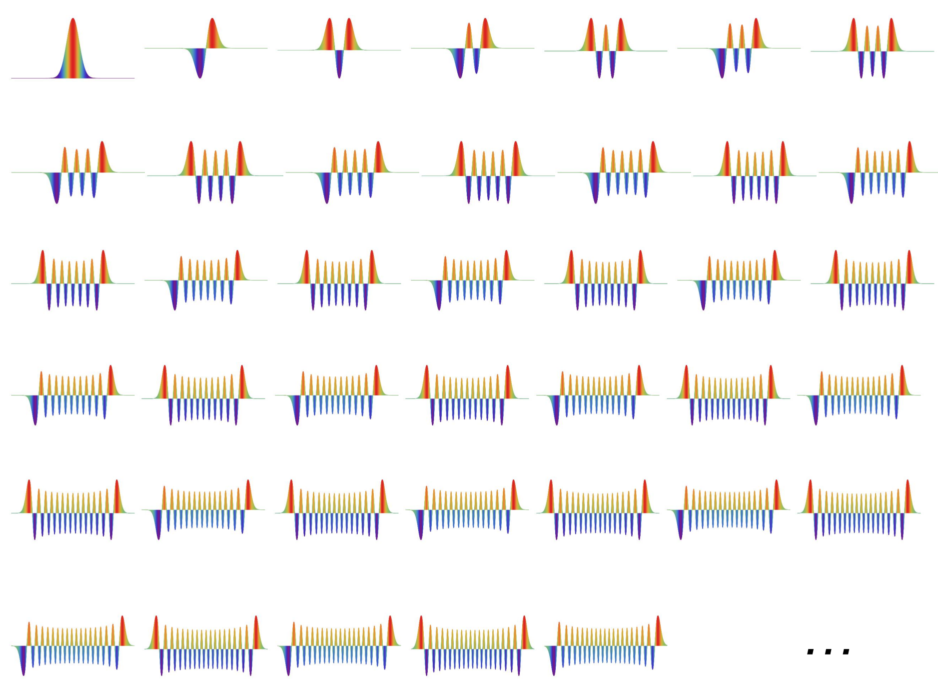
***Supermodes***

***Cluster states***

**Current setup**

**At least 40 Hermite-Gauss modes with quantum properties are generated (we can go up to 100)**



# Multimode quantum Gaussian resource

$$\vec{a}_{out} = V^{\dagger} S U \vec{a}$$

*basis change* *squeezing*

*if* $\vec{a}$ *collection of vacuum states*

$$\vec{a}_{out} = V^{\dagger} S \vec{a}$$

***Supermodes***

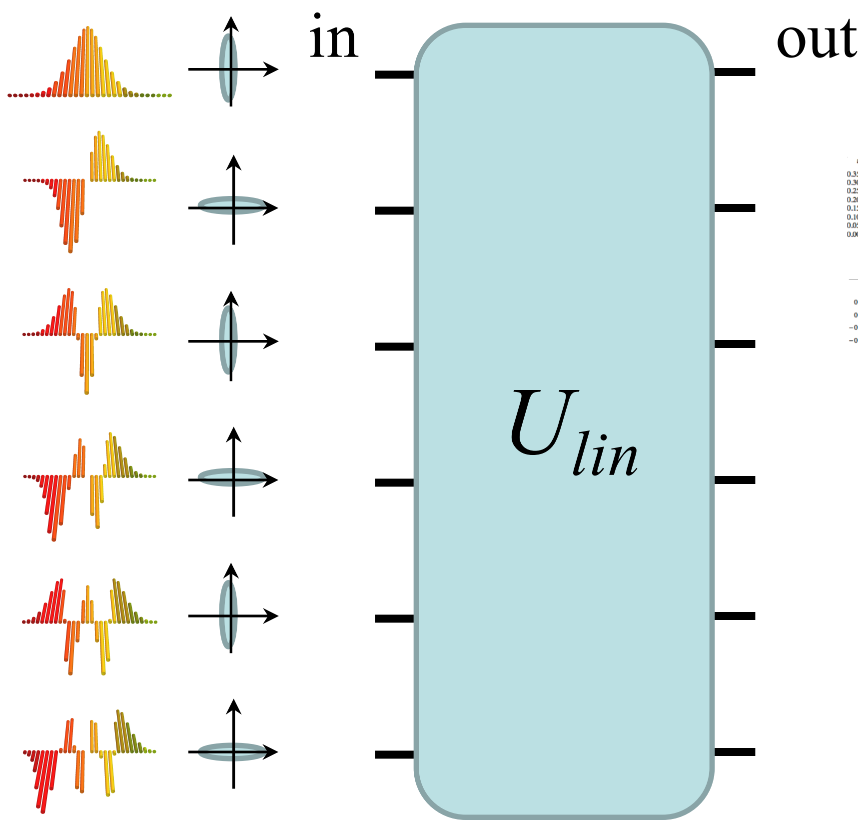
***Cluster states***

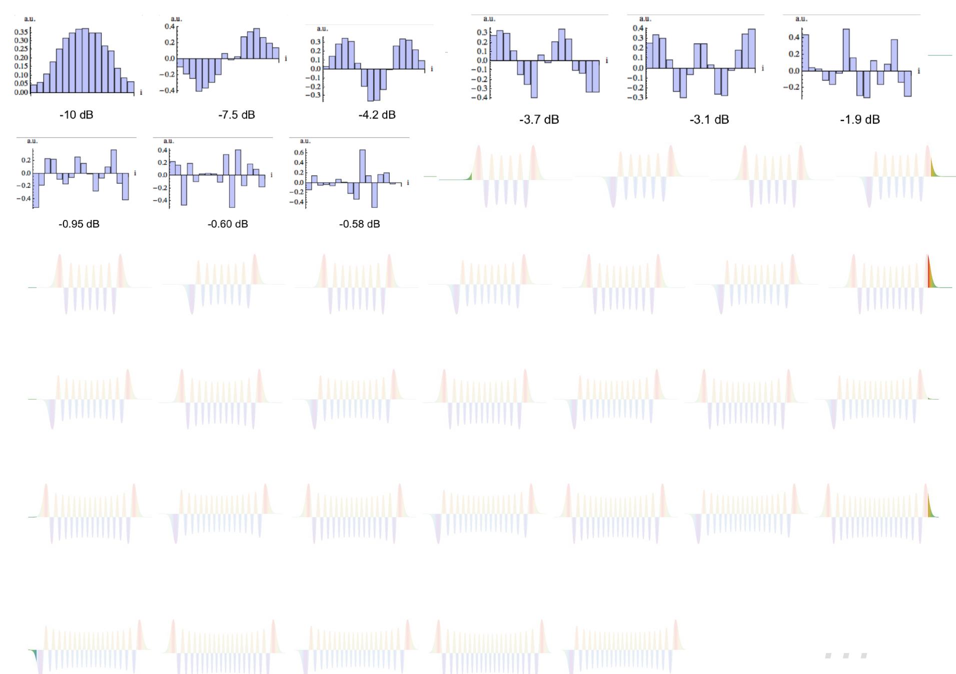
**Current setup**

**At least 40 Hermite-Gauss modes with quantum properties are generated**

But

**We can address them only up to ~ 16..**



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*basis change* *squeezing*

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***Supermodes***

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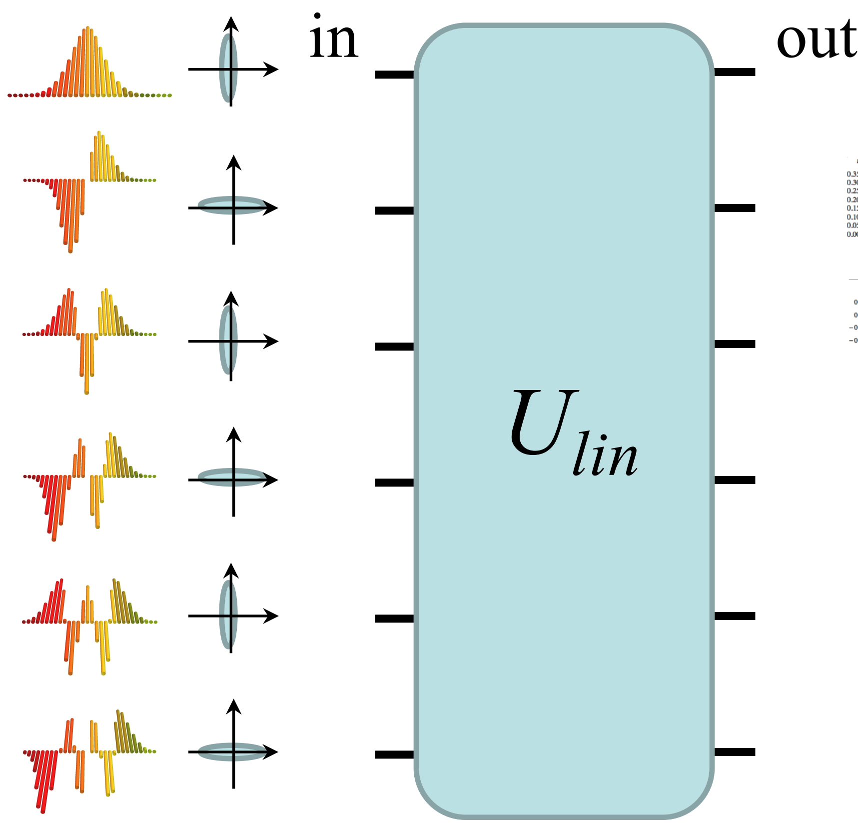


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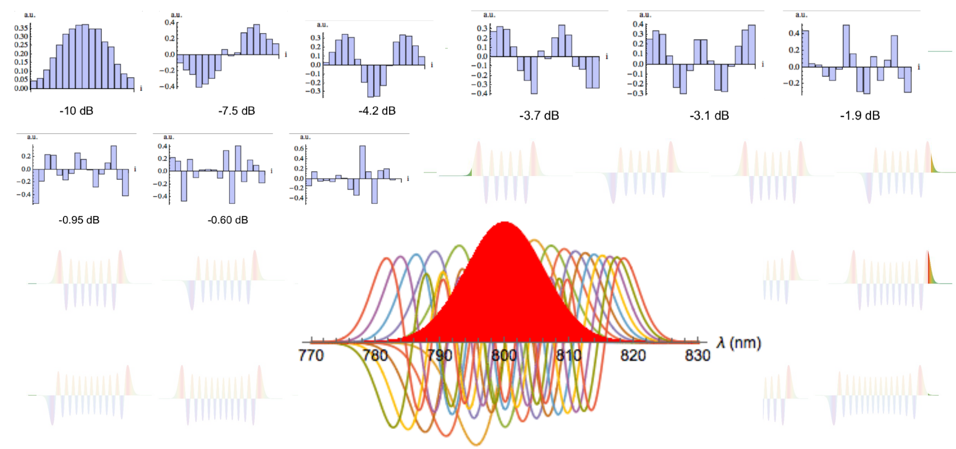
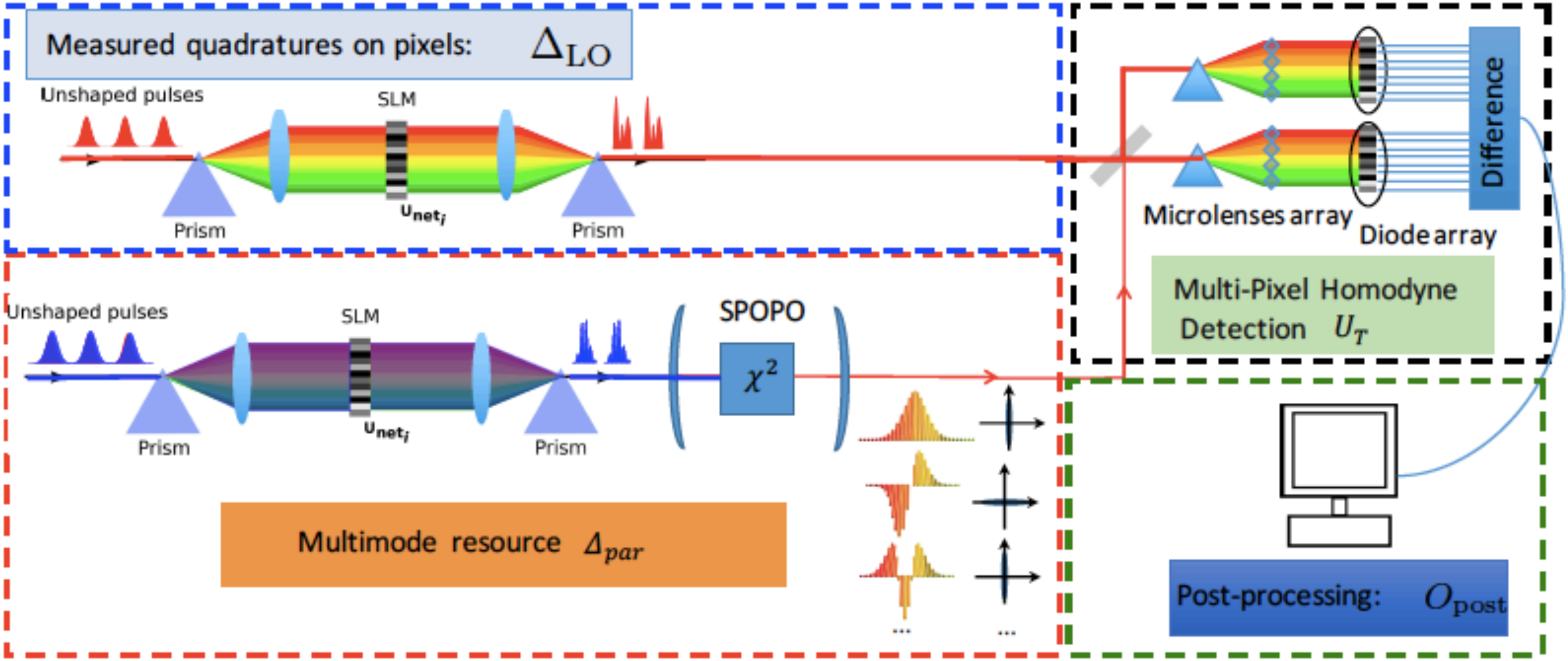



*It is a detection problem: bandwidth of the local oscillator not large enough*

Work in progress on coherent broadening of the laser spectrum

# Experimental control of the parameters



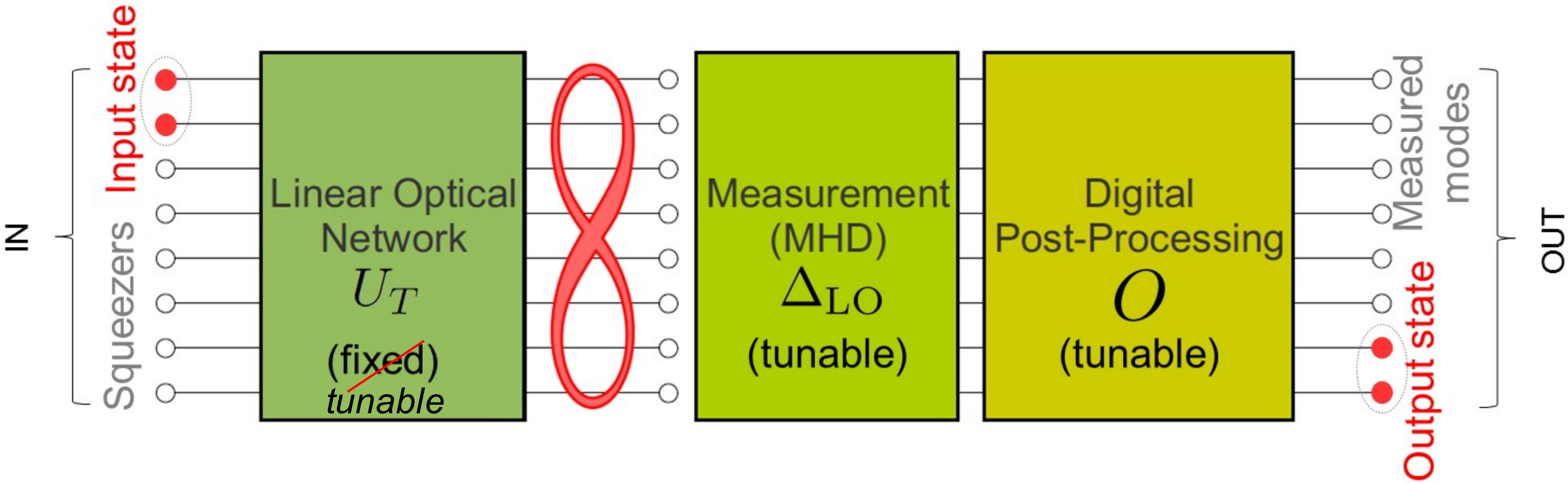

$$\vec{a}_{out} = V^{\dagger} S \vec{a} = O_{post} \Delta_{LO} G \vec{a} = O_{post} \Delta_{LO} U_T \Delta_{par} \vec{a}$$

$G=U_T\Delta_{par}$ parametric process, $\Delta_{par}$ squeezing (basis of supermodes), $U_T$ basis change to pixels

$\Delta_{LO}$ phase of LO components

$O_{post}$ final basis change given by the post-processing

# Direct measurement based QC




System is solved to perform the proper evolution

$$\begin{pmatrix} \vec{x}^{\,\mathrm{out}} \\ \vec{p}^{\,\mathrm{out}} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} \vec{x}^{\,\mathrm{in}} \\ \vec{p}^{\,\mathrm{in}} \end{pmatrix} + \begin{pmatrix} \vec{\delta}_x \\ \vec{\delta}_p \end{pmatrix} + \begin{pmatrix} \vec{\eta}_x \\ \vec{\eta}_p \end{pmatrix}$$

G. Ferrini *et al*, New J Phys 15, 093015 (2013)
G. Ferrini *et al.*, PRA **94**, 062332 (2016)

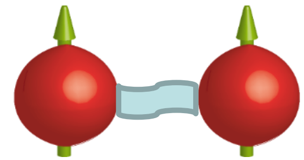
Excess noise due to finite squeezing

Correction factors from post processing

# Quantum information protocols

## …with multimode quantum optics

+

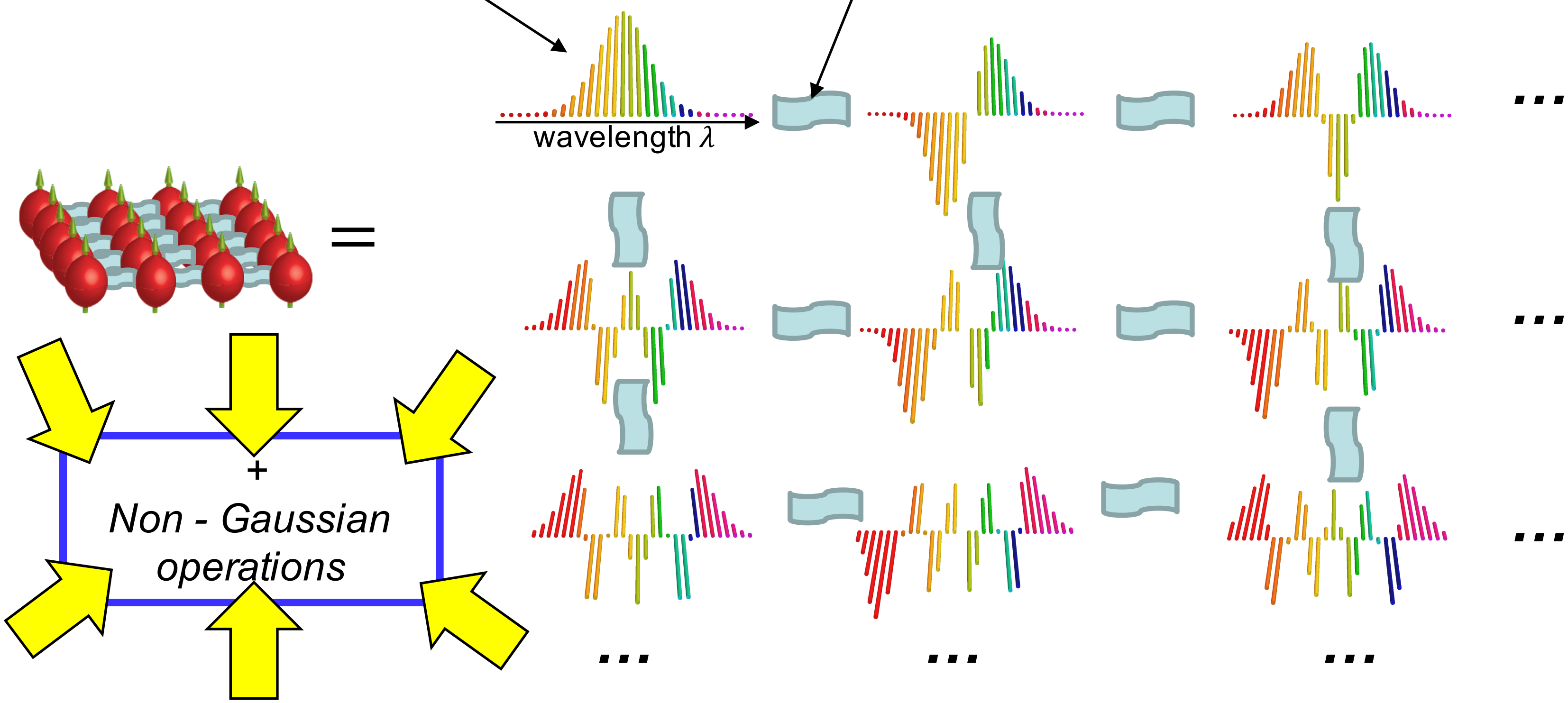


**Quantum systems**

spatial-temporal modes
of the electromagnetic field
= independent harmonic oscillators

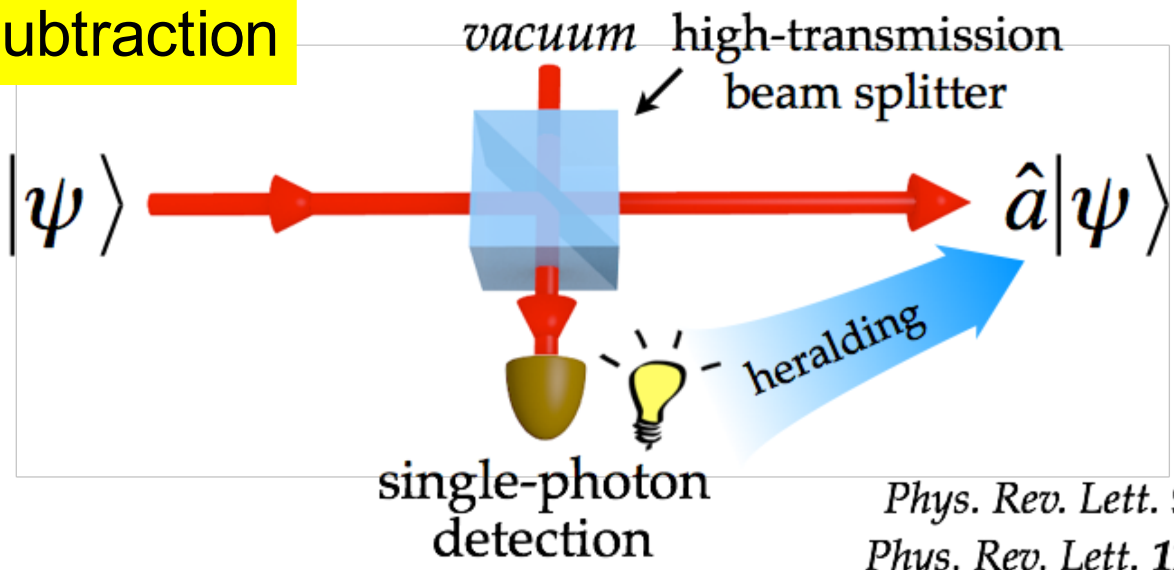
**Quantum Correlations** (entanglement)

Entanglement between quadratures
(i.e. amplitude and phase)

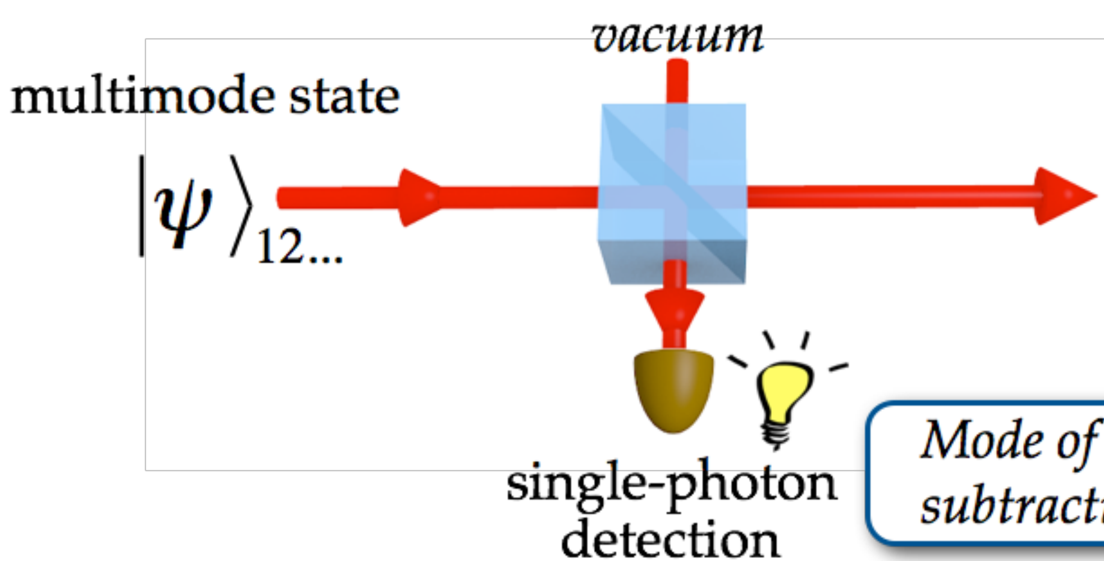


# "Non Gaussian" states

## Photon subtraction




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




a mixed state

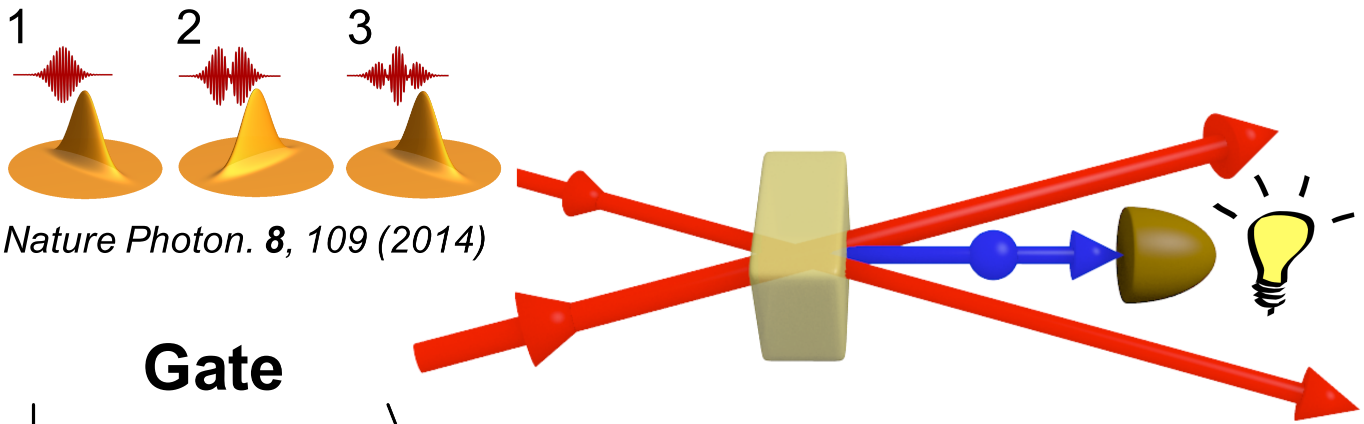
$$\hat{a}_1|\psi\rangle\langle\psi|\hat{a}_1^\dagger + \hat{a}_2|\psi\rangle\langle\psi|\hat{a}_2^\dagger + \ldots \neq (\hat{a}_1 + \hat{a}_2 + \ldots)|\psi\rangle$$

*Mode of single-photon subtraction cannot be selected.*

# Mode-selective single-photon subtractor

Sum Frequency Generation

**Signal**




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

**Gate**

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

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

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).

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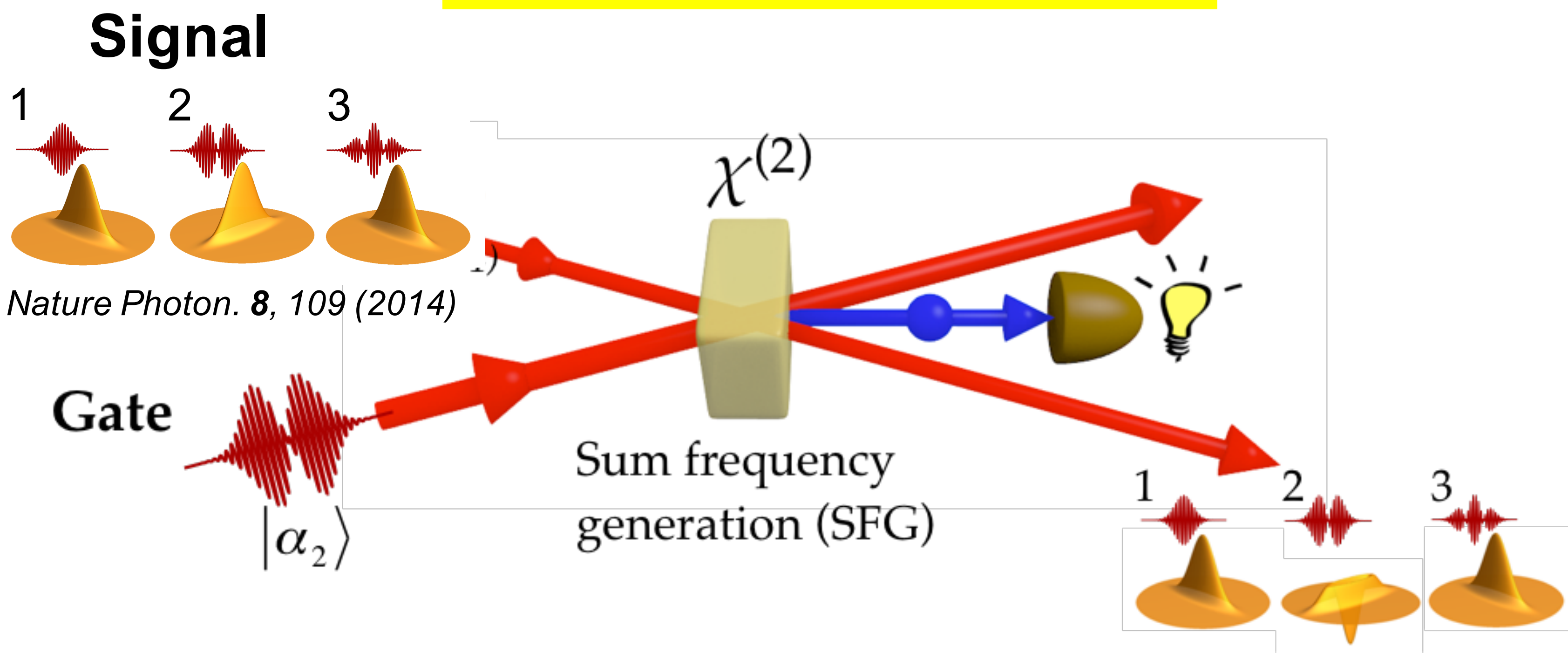


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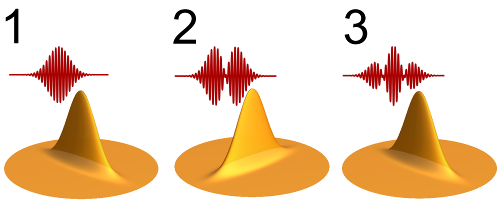
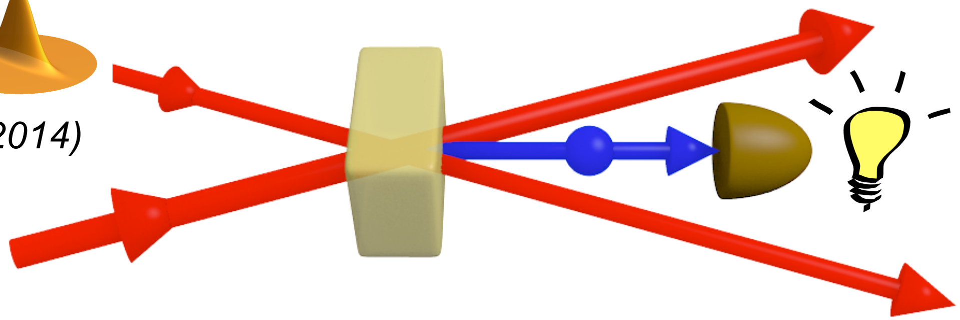



*Nature Photon.* ***8****, 109 (2014)*



**Gate**

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

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

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

Eigenmodes of the process

$$\boxed{\hat{\rho}^{(out)} \propto \sum_k p_k \hat{A}_k \rho^{(in)} \hat{A}_k^\dagger}$$

-> Schmidt number

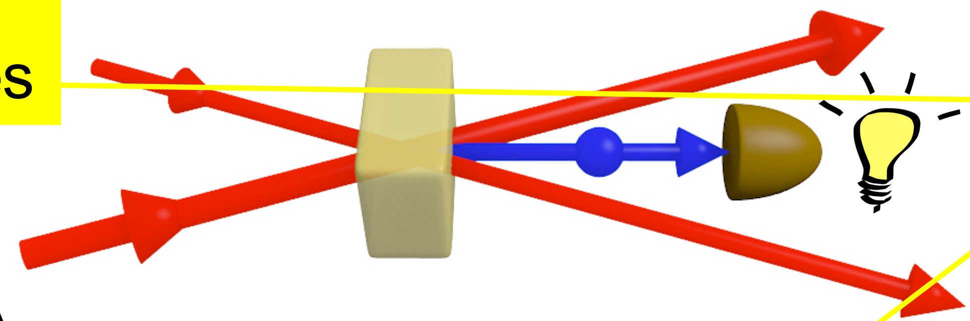
-> purity

# Mode-selective single-photon subtractor

## Sum Frequency Generation

**Signal**

Probe with coherent states



Compute success rate

**Gate**

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

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

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

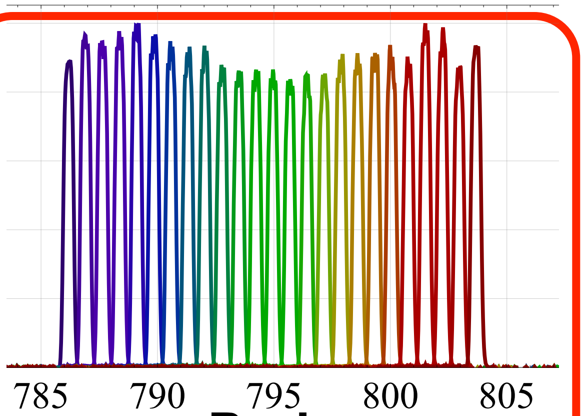
Eigenmodes of the process

-> Schmidt number
-> purity

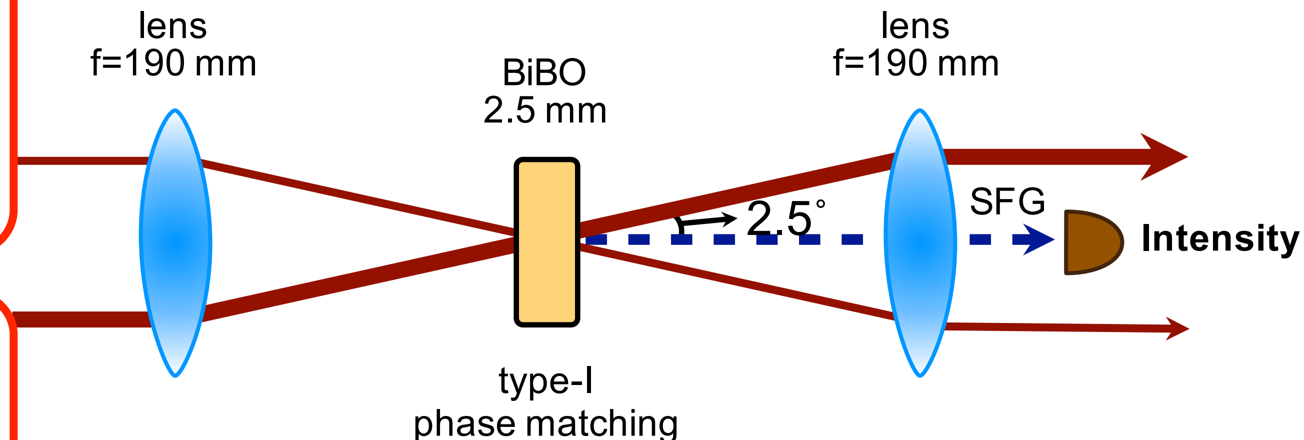
$$\hat{\rho}^{(out)} \propto \sum_k p_k \hat{A}_k \rho^{(in)} \hat{A}_k^\dagger$$

# Quantum Process Tomography

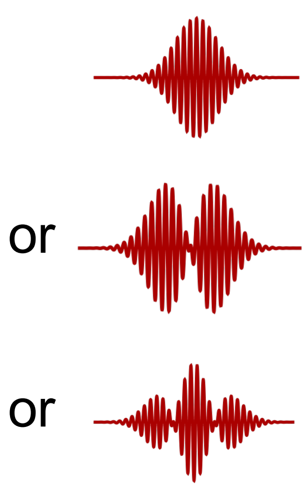
Probe basis: wavelength bands




**Probe (Signal)**




**Gate**



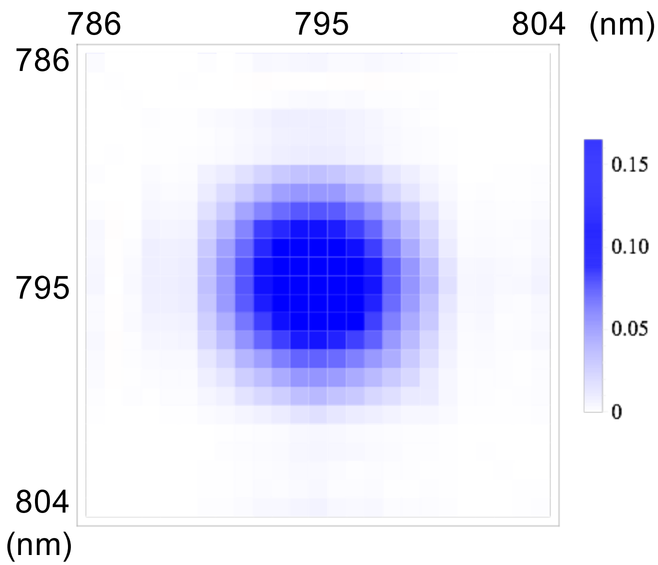

Gate Pulse shape:
Tune the single-photon subtractors.

# Quantum Process Tomography

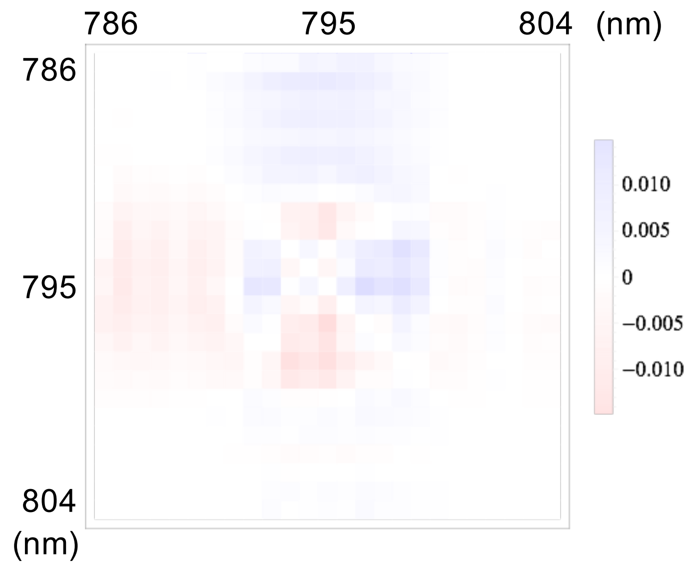
## Reconstruction using Maximum Likelihood Estimation

**Gate**

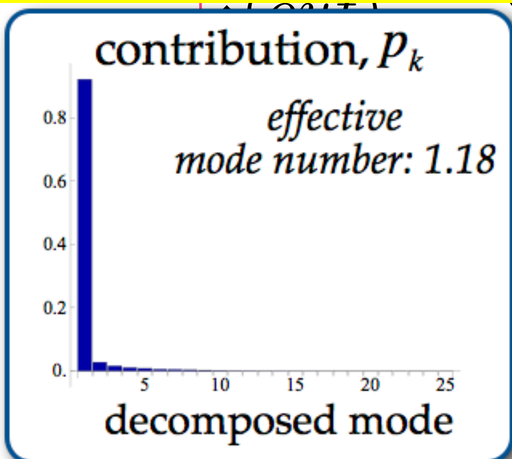
$\mathrm{Re}[\chi]$

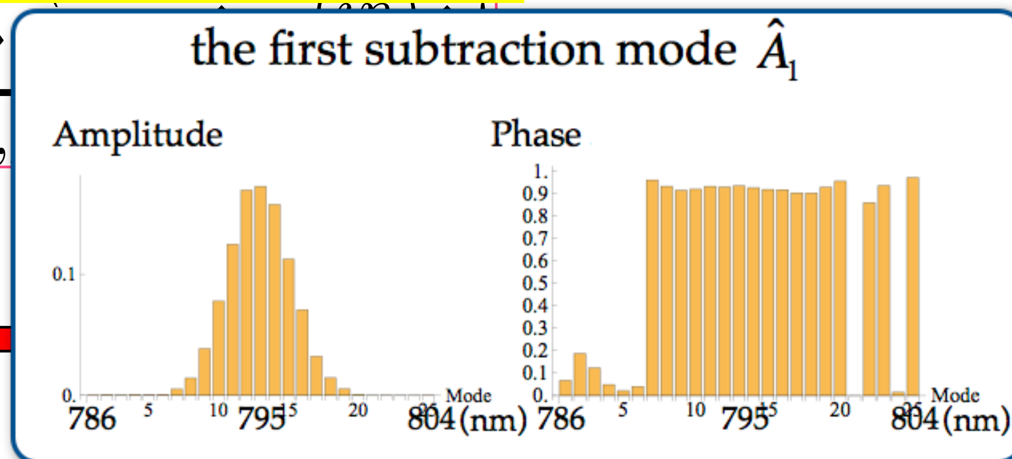



$\mathrm{Im}[\chi]$

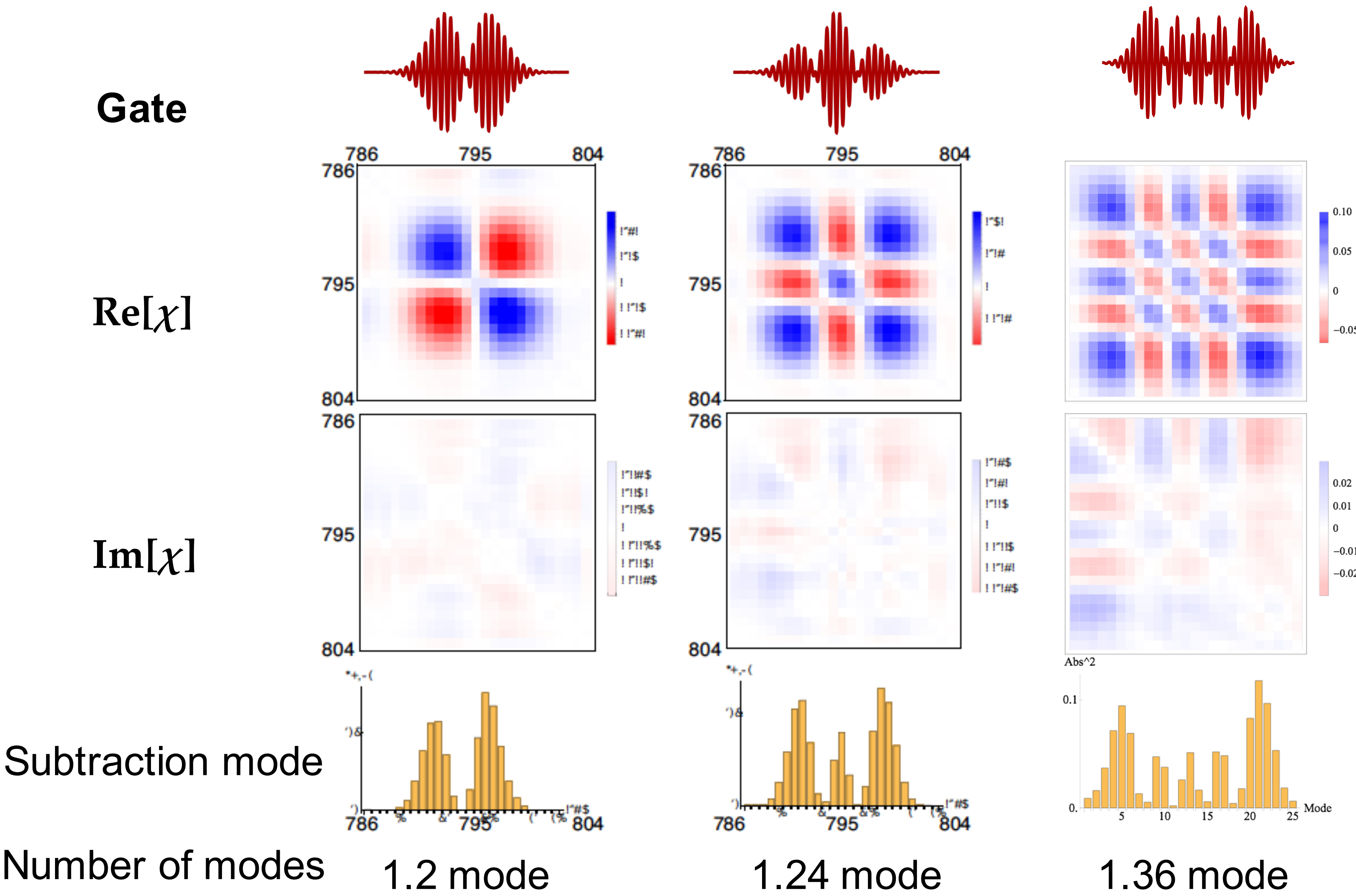



## Diagonalisation: mode eigenvalues and shapes



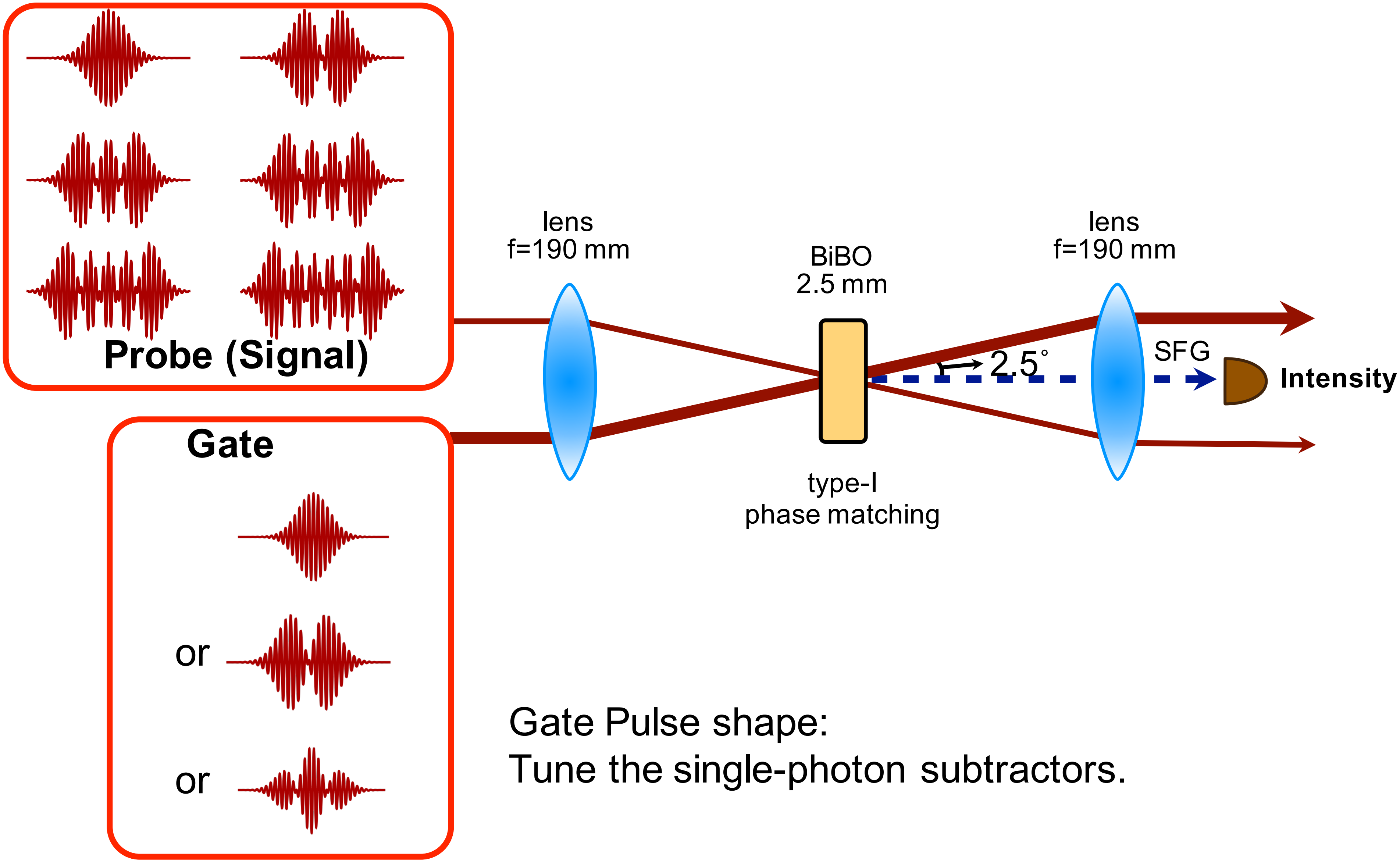



# Quantum Process Tomography



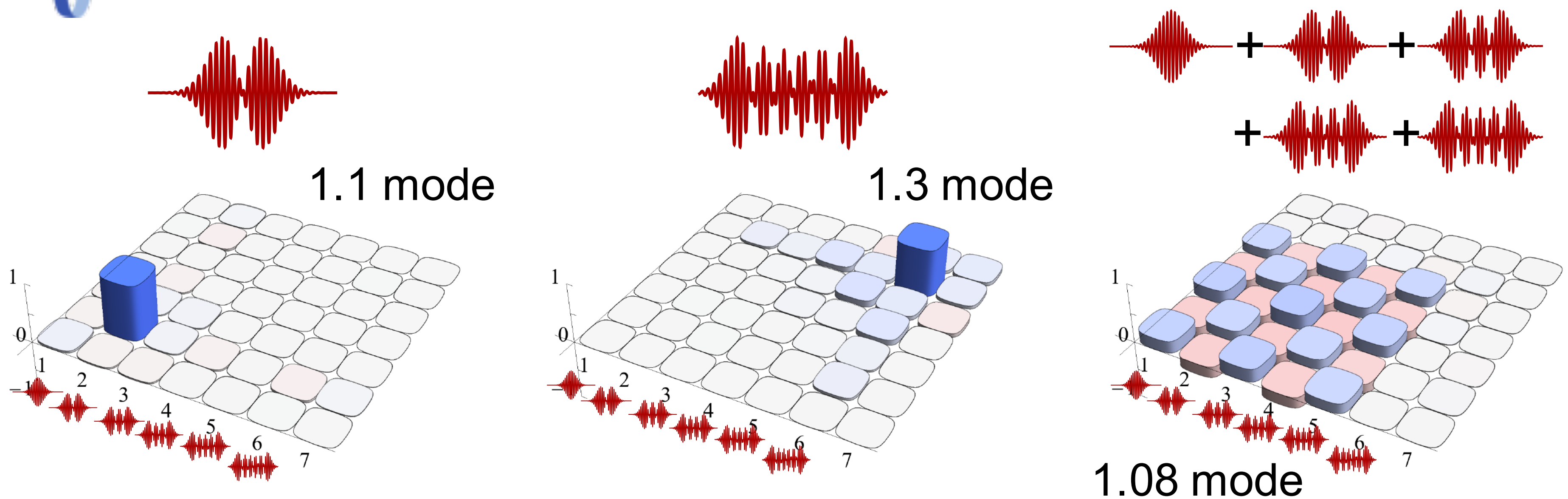
# Quantum Process Tomography

Probe basis: Hermite Gauss modes



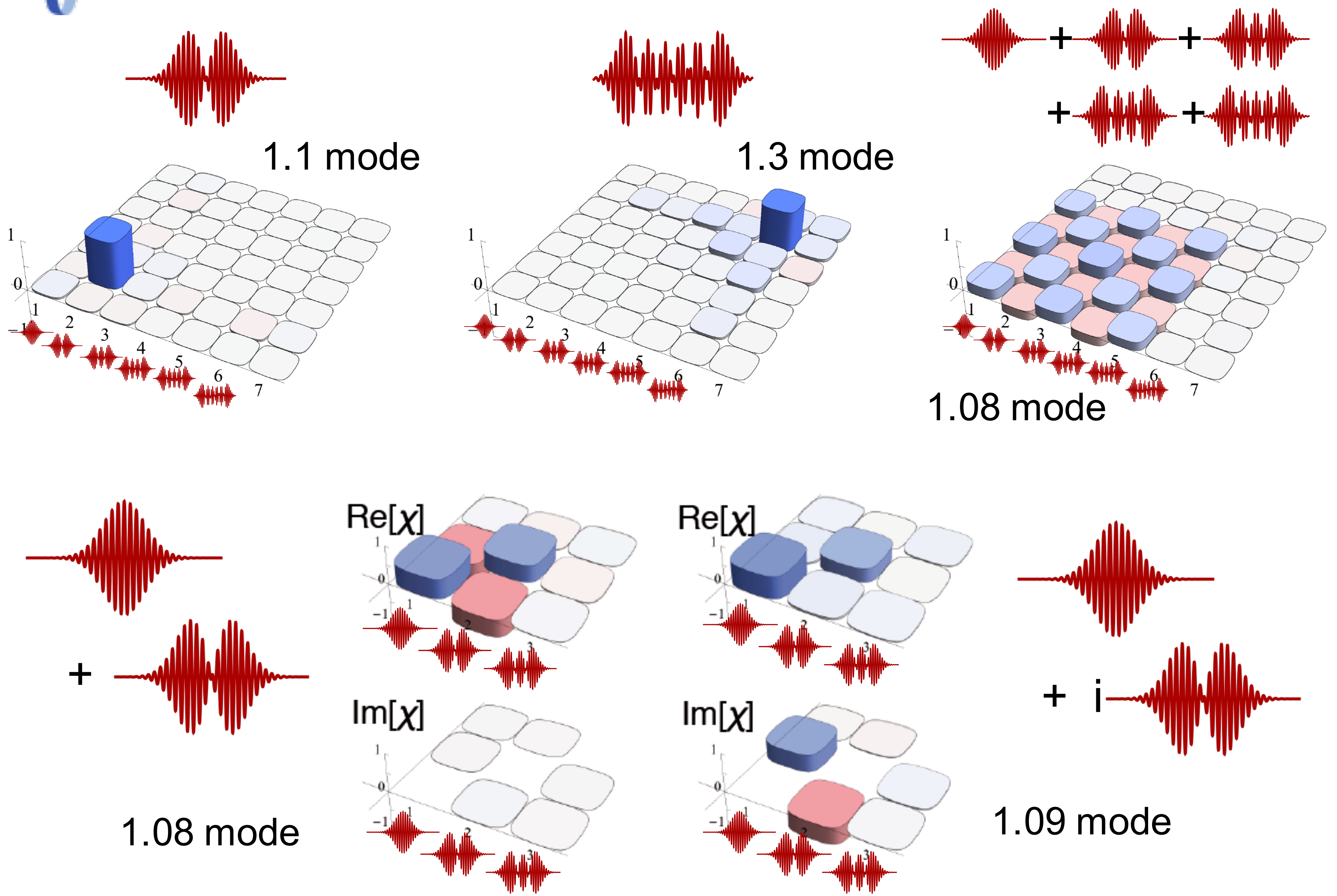

Gate Pulse shape:
Tune the single-photon subtractors.

# Quantum Process Tomography

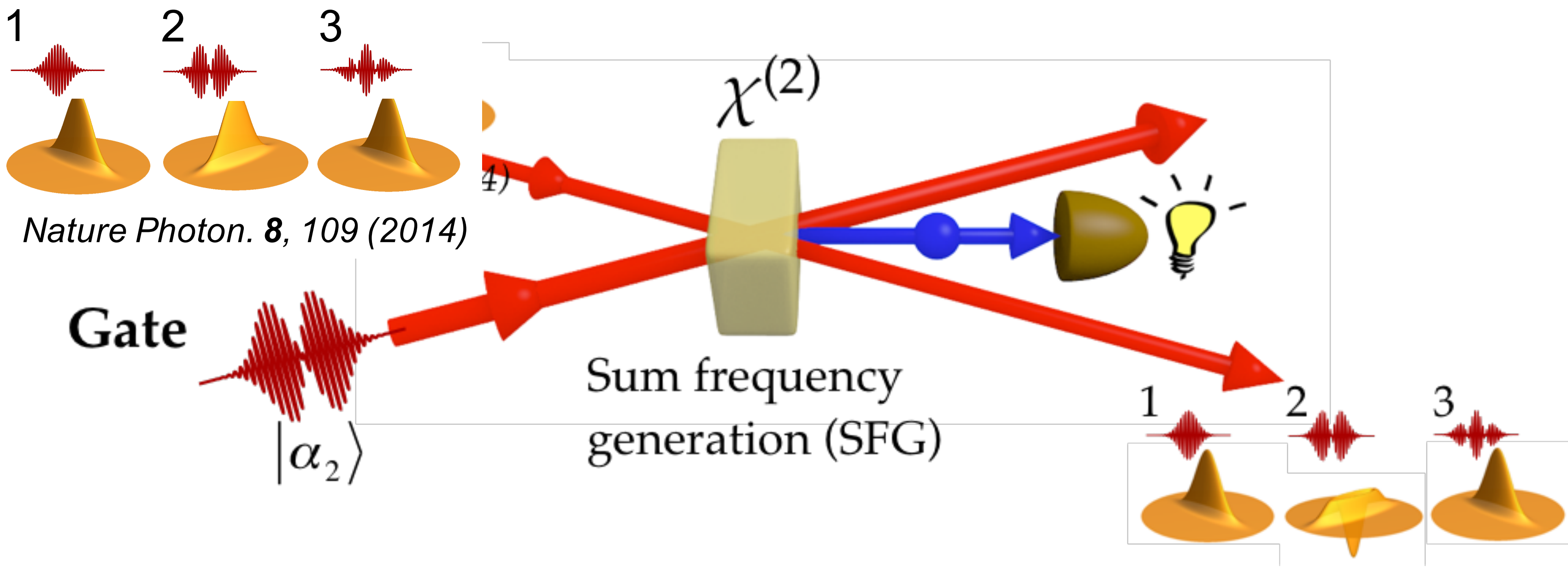


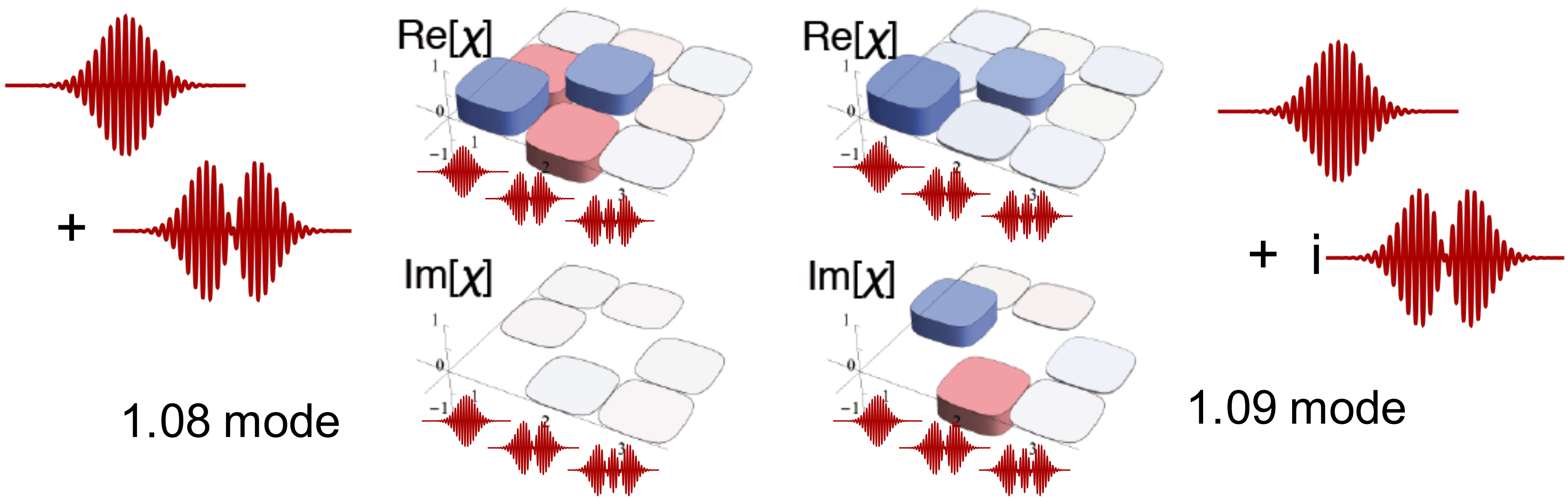

$$\hat{\rho}^{(out)} = \sum_{i,j} \chi_{i,j} \hat{a}_i \rho^{(in)} \hat{a}_j^\dagger$$

# Quantum Process Tomography



# Quantum Process Tomography



Laboratoire Kastler Brossel
Physique quantique et applications

# Outline

## Multimode quantum optics in Quantum Information technologies

*Introduction*

*Multicolor entanglement*

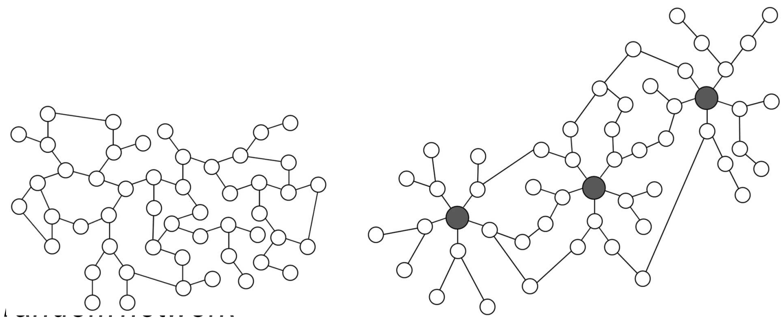
*Towards measurement based quantum computing*

## Simulation of complex quantum networks

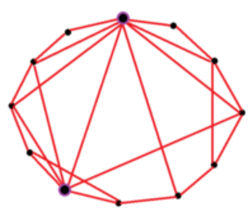
Probing a structured environment

*Energy transport: some ideas*

*in this talk, complex network = not regular lattice*

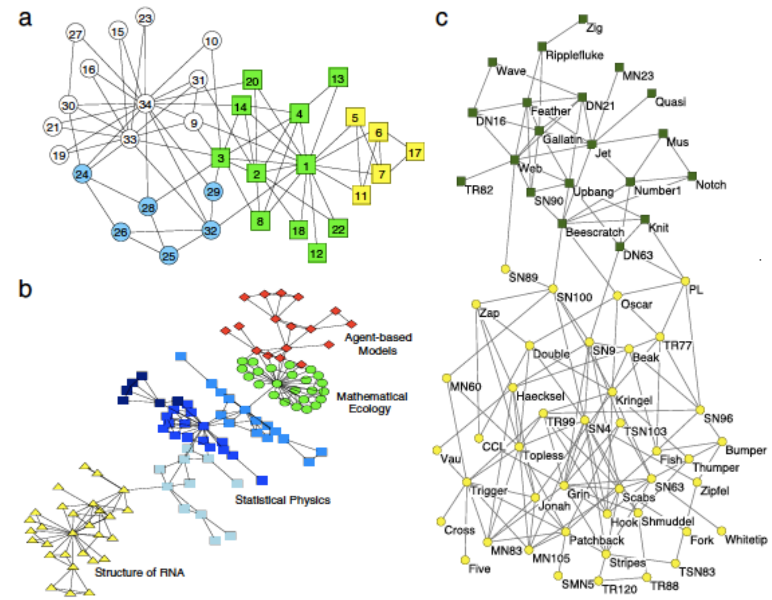


International Journal of Oncology,10.3892/ijo.2013.2114



*small world network*

*wikipedia*




*Community structures*

*S. Fortunato Physiscs Report 486*

# Why?

**Bosonic networks**

- ***Fundamental reasons:***
***understanding the interplay between their complex structure and their quantum properties***
G. Bianconi and C. Rahmede Phys. Rev. E **93**, 032315 (2016)

- ***Quantum networks: at the base of quantum information protocols.***
***Futures quantum technologies : quantum complex networks,***
***ex: quantum communication in a complex www***
G. D. Paparo & M. A. Martin-Delgado, Scientific Reports 2 , 444 (2012)

- ***Open systems: environment described by complex quantum networks***
J. Nokkala, F. Galve, R. Zambrini, S. Maniscalco and J. Piilo, Scientific Reports 6, 26861 (2016)

- ***Energy transfer in quantum complex structures, ex: light harvesting***
M. Walschaers, F. Schlawin, T. Wellens, and A. Buchleitner, Annu. Rev. Condens. Matter Phys. 2016. 7:223–48
M. Faccin, P. Migdał, T. H. Johnson, V. Bergholm, and J. D. Biamonte, Phys. Rev. X **4**, 041012 (2014).

# Multimode quantum Gaussian resource

$$\vec{a}_{out} = V^{\dagger} S U \vec{a}$$

*squeezing*

*basis change*

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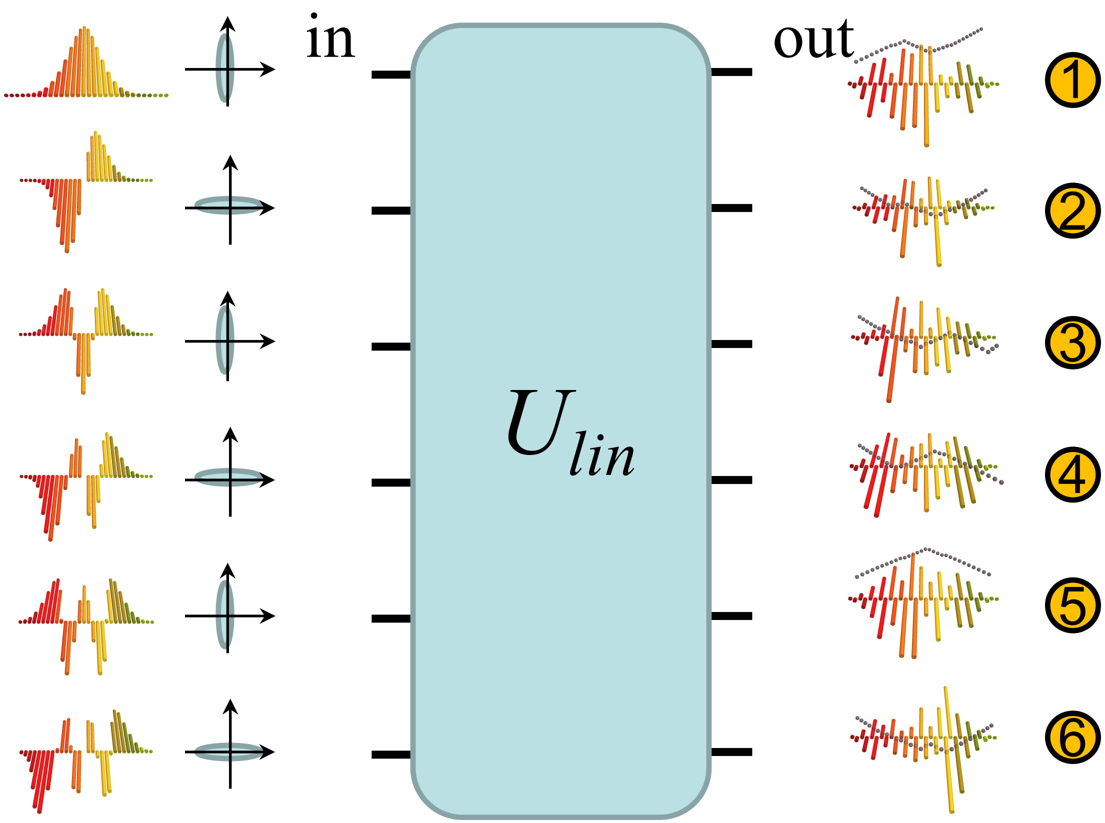
***Supermodes***

***Cluster states***

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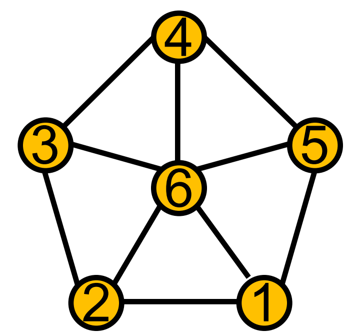
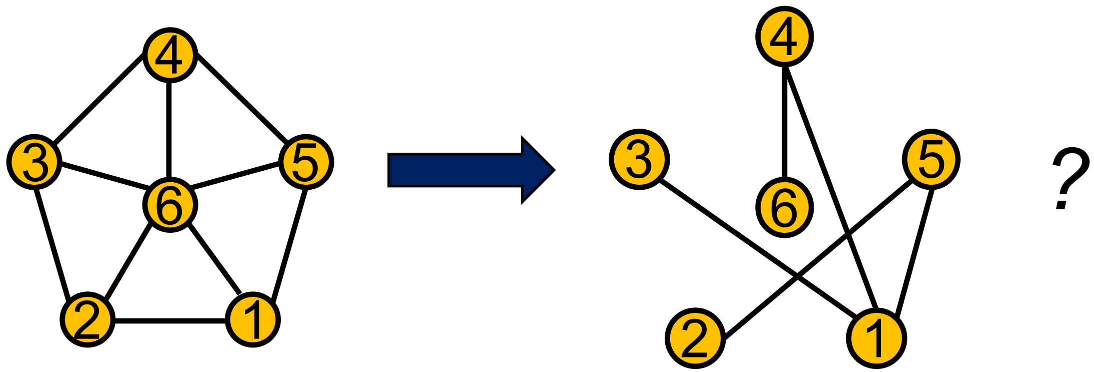
*nullifier*



# Multimode quantum Gaussian resource

*Simulation of complex quantum networks*




$$\vec{a}_{out} = V^{\dagger} S \vec{a}$$

***Find the Bloch-Messiah decomposition of its evolution and experimentally implement V and S***

# Outline

***Multimode quantum optics in Quantum Information technologies***

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*Multicolor entanglement*

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***Simulation of complex quantum networks***

**Probing a structured environment**

*Energy transport: some ideas*

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# Probing a structured environment

LKB

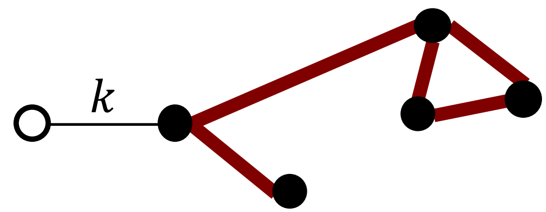
## Simulation of complex structured environment

***+1 system/probe connected to one node***

$$H_E = \frac{\boldsymbol{p}^T \boldsymbol{p}}{2} + \boldsymbol{q}^T \boldsymbol{A} \boldsymbol{q}$$

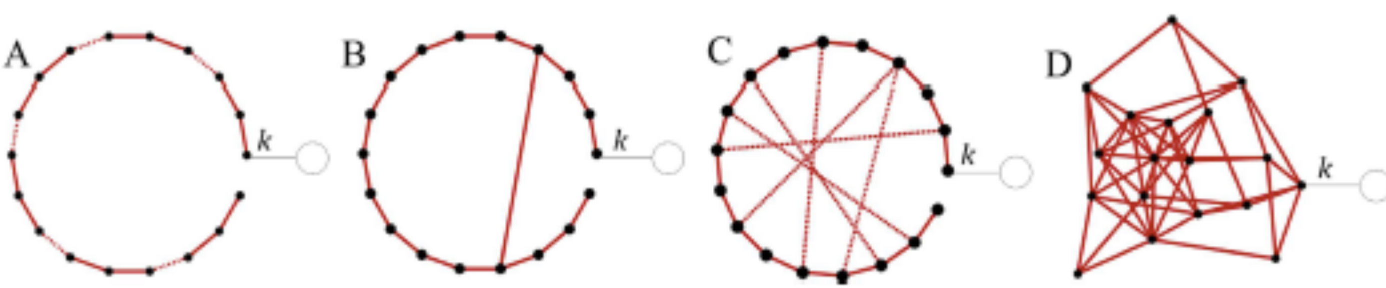
$$H_S = (p_S^2 + \omega_S^2 q_S^2)/2,$$

$$H_I = -k q_S q_i$$




$$A_{ij} = \delta_{ij}\omega_i^2/2 - (1-\delta_{ij})h_{ij}/2$$

*Evolution given by* $H_E + H_S + H_I$ → Measure the state of the probe and recover the structure

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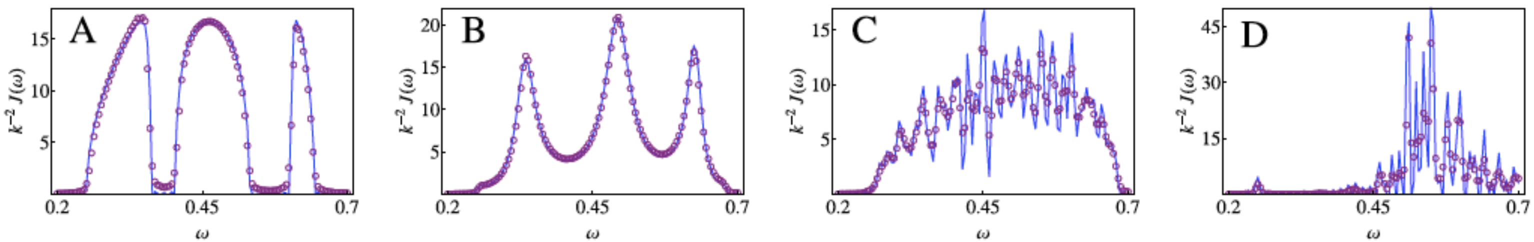
# Probing a structured environment

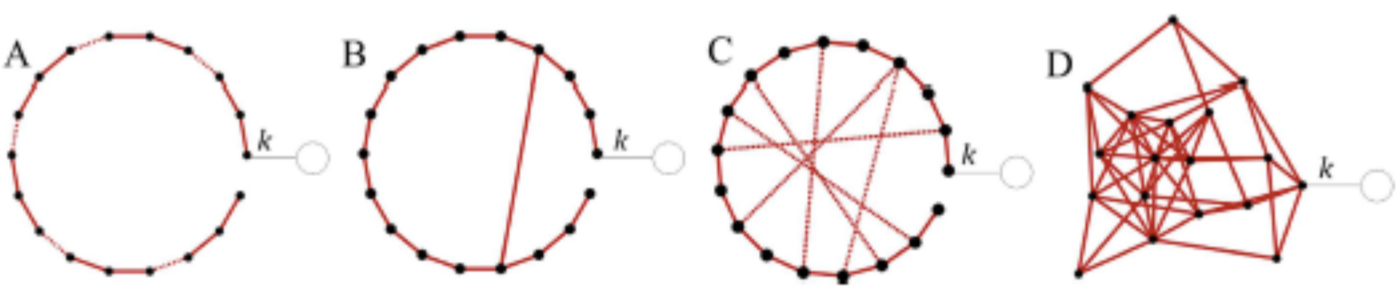
$$J(\omega) = \frac{\pi}{2}\sum_i \frac{k^2 g_i^2}{\Omega_i}\delta(\omega - \Omega_i)$$

*spectral density of environmental coupling*

$$J(\omega) = \omega \int_0^{t_{max}} \gamma(t)\cos(\omega t)\,\mathrm{d}t$$




*Evolution given by* $H_E + H_S + H_I$ → Measure the state of the probe and recover the structure

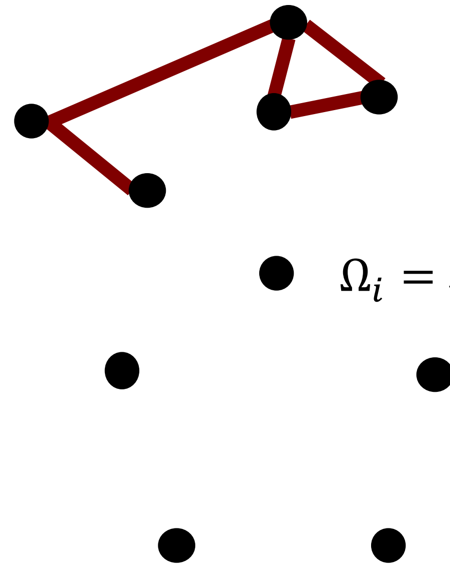



J. Nokkala, F. Galve, R. Zambrini, S. Maniscalco and J. Piilo, Scientific Reports 6, 26861 (2016)

# Probing a structured environment

## Simulation of complex structured environment

$$H_E = \frac{\boldsymbol{p}^T\boldsymbol{p}}{2} + \boldsymbol{q}^T\boldsymbol{A}\boldsymbol{q}$$



$$\Omega_i = \sqrt{2\boldsymbol{D}_{ii}}$$

$$H_E = \frac{\boldsymbol{P}^T\boldsymbol{P}}{2} + \boldsymbol{Q}^T\boldsymbol{D}\boldsymbol{Q}$$

*eigenmodes*

J. Nokkala, F. Galve, R. Zambrini, S. Maniscalco and J. Piilo, Scientific Reports 6, 26861 (2016)

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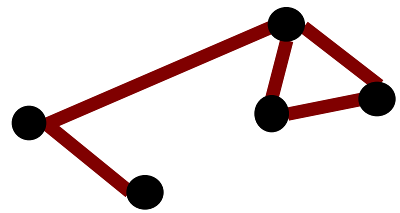
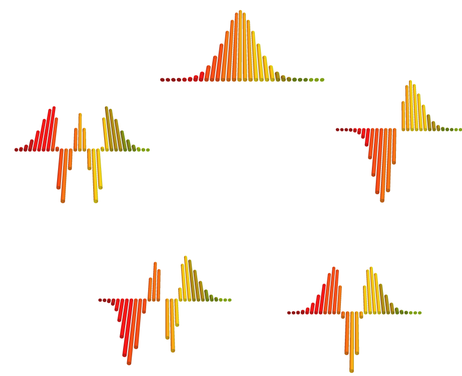




$$H_E = \frac{\boldsymbol{P}^T \boldsymbol{P}}{2} + \boldsymbol{Q}^T \boldsymbol{D} \boldsymbol{Q}$$

*super*
*~~eigen~~modes*

J. Nokkala, F. Arzani, F Galve, R.Zambrini , S Maniscalco,  Jyrki Piilo, C. Fabre, N. Treps, V. Parigi, in preparation

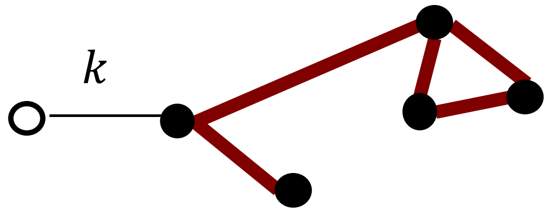
# Probing a structured environment

## Simulation of complex structured environment

***+1 system/probe connected to one node***

$$H_E = \frac{\boldsymbol{p}^T\boldsymbol{p}}{2} + \boldsymbol{q}^T\boldsymbol{A}\boldsymbol{q}$$

$$H_I = -kq_S q_i$$




$$H_E = \frac{\boldsymbol{P}^T\boldsymbol{P}}{2} + \boldsymbol{Q}^T\boldsymbol{D}\boldsymbol{Q}$$

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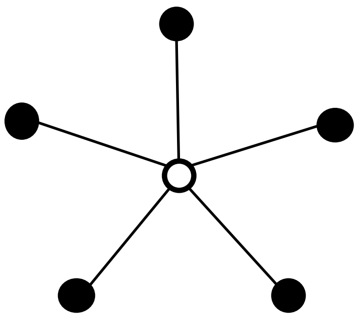

J. Nokkala, F. Galve, R. Zambrini, S. Maniscalco and J. Piilo, Scientific Reports 6, 26861 (2016)

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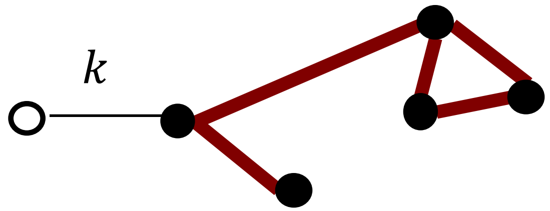


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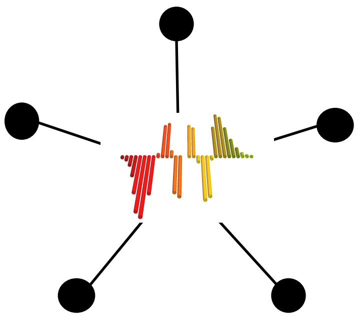

one supplementary supermode

J. Nokkala, F. Arzani, F Galve, R.Zambrini , S Maniscalco, Jyrki Piilo, C. Fabre, N. Treps, V. Parigi, in preparation

# Probing a structured environment

## Simulation of complex structured environment

***+1 system/probe connected to one node***

$$\begin{pmatrix} \mathbf{Q}(t) \\ \mathbf{q_s}(t) \\ \mathbf{P}(t) \\ \mathbf{p_s}(t) \end{pmatrix} = \mathcal{S} \begin{pmatrix} \mathbf{Q}(0) \\ \mathbf{q_s}(0) \\ \mathbf{P}(0) \\ \mathbf{p_s}(0) \end{pmatrix}$$

time evolution of the system + the network
= symplectic matrix acting on the quadratures

J. Nokkala, F. Arzani, F Galve, R.Zambrini , S Maniscalco, Jyrki Piilo, C. Fabre, N. Treps, V. Parigi, in preparation

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*Bloch-Messiah decomposition* $\Longrightarrow$ *Implement experimentally*

$\mathcal{S} = \mathcal{V}\,\mathcal{K}$ *when possible*

*rotation= basis change* *squeezing*

J. Nokkala, F. Arzani, F Galve, R.Zambrini , S Maniscalco, Jyrki Piilo, C. Fabre, N. Treps, V. Parigi, in preparation

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$\Rightarrow$ *Implement experimentally*

*measure the probe*

J. Nokkala, F. Arzani, F Galve, R.Zambrini , S Maniscalco, Jyrki Piilo, C. Fabre, N. Treps, V. Parigi, in preparation

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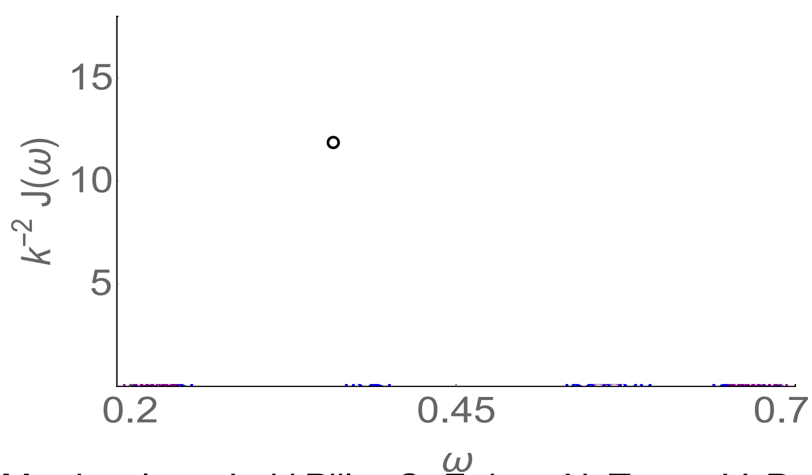


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# Probing a structured environment

LKB

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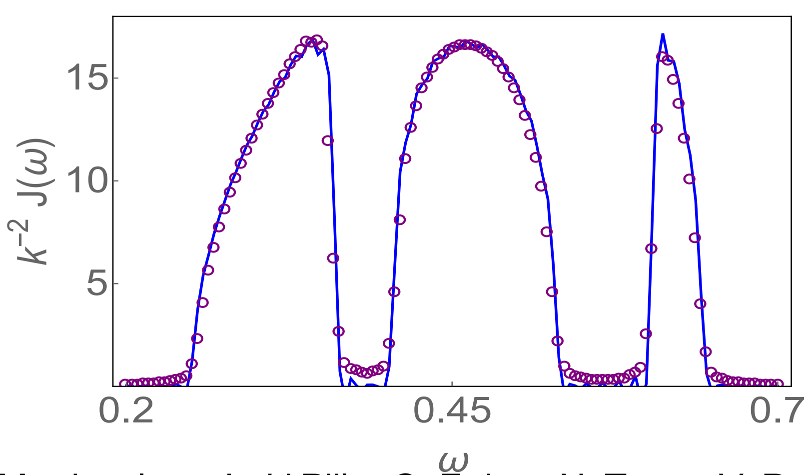


J. Nokkala, F. Arzani, F Galve, R.Zambrini , S Maniscalco, Jyrki Piilo, C. Fabre, N. Treps, V. Parigi, in preparation

# Probing a structured environment

LKB

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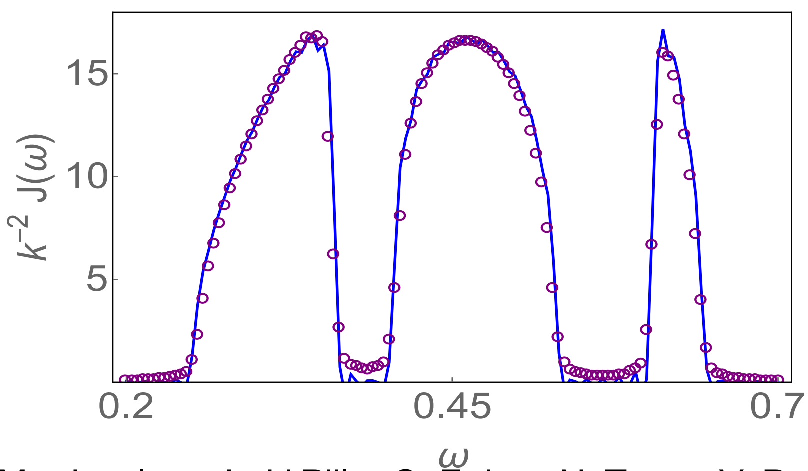



*network structure*
*encoded in the rotation* $\mathcal{V}$

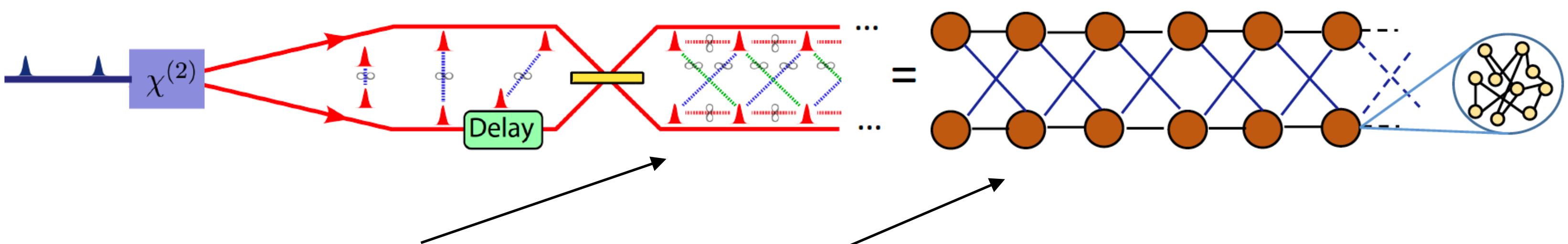
*energy parameters* $\{k, g, \omega_0, \omega_s\}$
*encoded in the squeezing* $\mathcal{K}$

J. Nokkala, F. Arzani, F Galve, R.Zambrini , S Maniscalco, Jyrki Piilo, C. Fabre, N. Treps, V. Parigi, in preparation

# Towards larger complex networks ?

- ***Number of modes :16*** *at the moment but they are only limited by the measurement procedure -> they could be around* ***40*** *if we increase the spectral bandwidth of LO*

- *Exploring new experimental setup -> "big-states"* ***10^5*** *modes*




*dual-rail cluster:*
*entanglement structure*
*in the pulses (time) basis*

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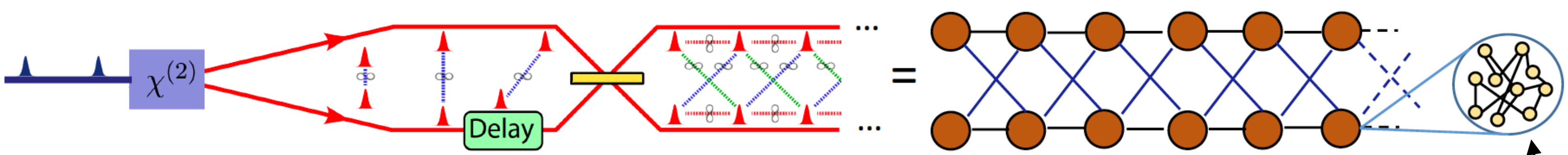


*dual-rail cluster: entanglement structure in the pulses (time) basis*

*the multimode structure in the frequency domain is maintained . Community structures*

S.Yokoyama, R. Ukai, S. C. Armstrong, C. Sornphiphatphong, T. Kaji, S. Suzuki, J. Yoshikawa, H. Yonezawa, N. C. Menicucci & A. Furusawa Nature Photonics 7, 982–986 (2013); APL Photonics 1, 060801 (2016)

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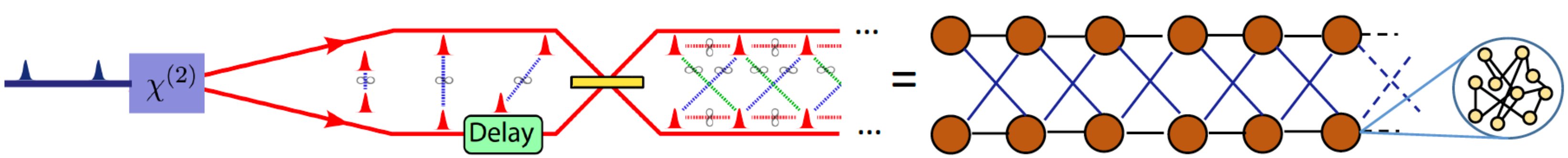
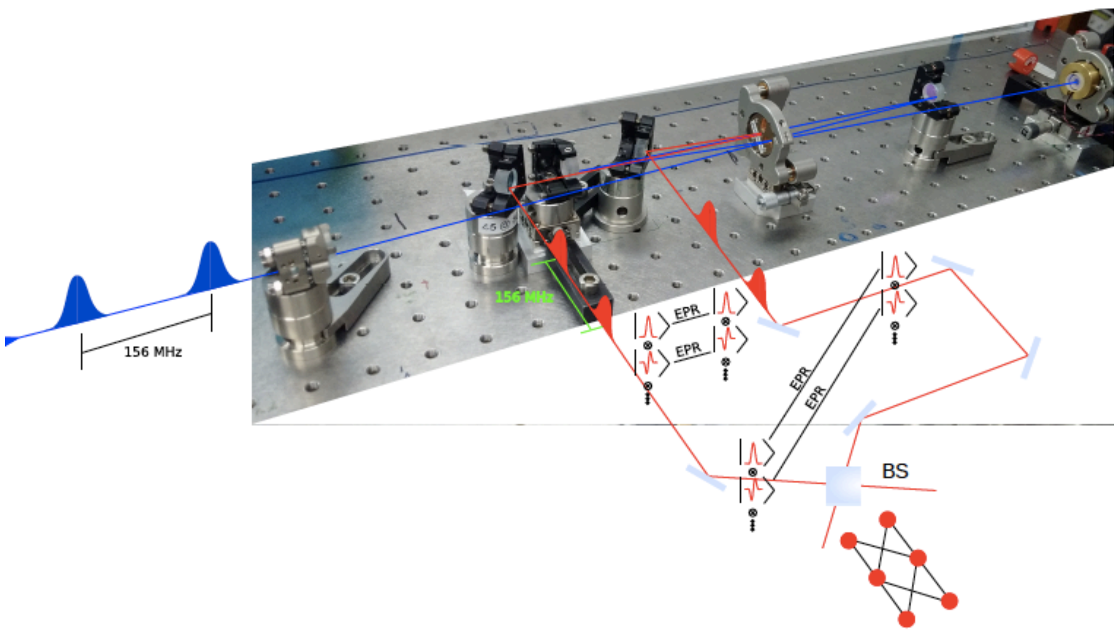


# Outline

## ***Multimode quantum optics in Quantum Information technologies***

***Introduction***

***Multicolor entanglement***

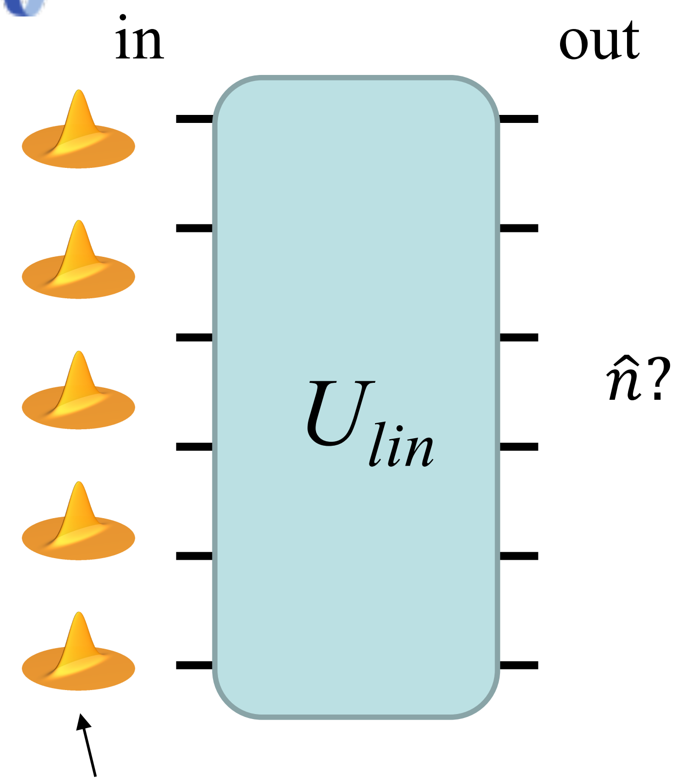
***Towards measurement based quantum computing***

## ***Simulation of complex quantum networks***

**Probing a structured environment**

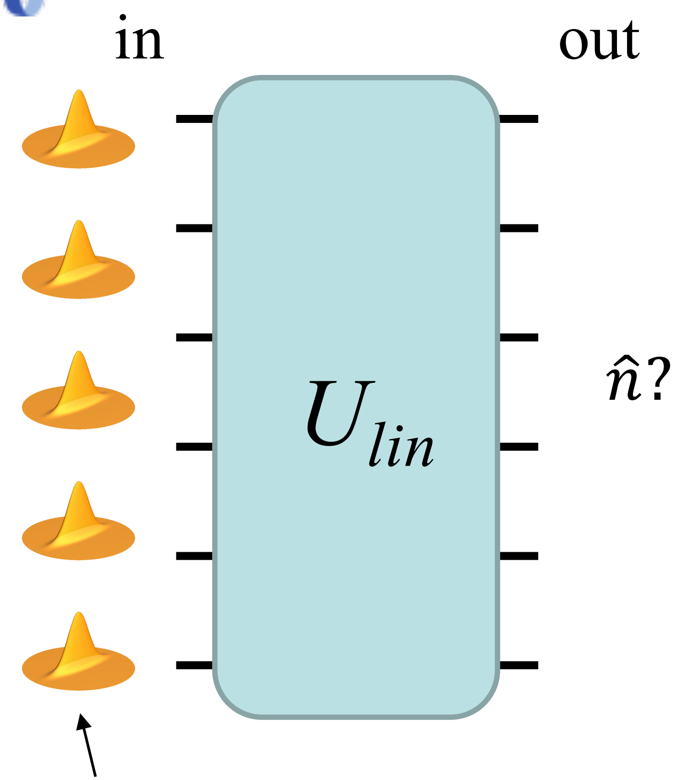
***Energy transport: some ideas***

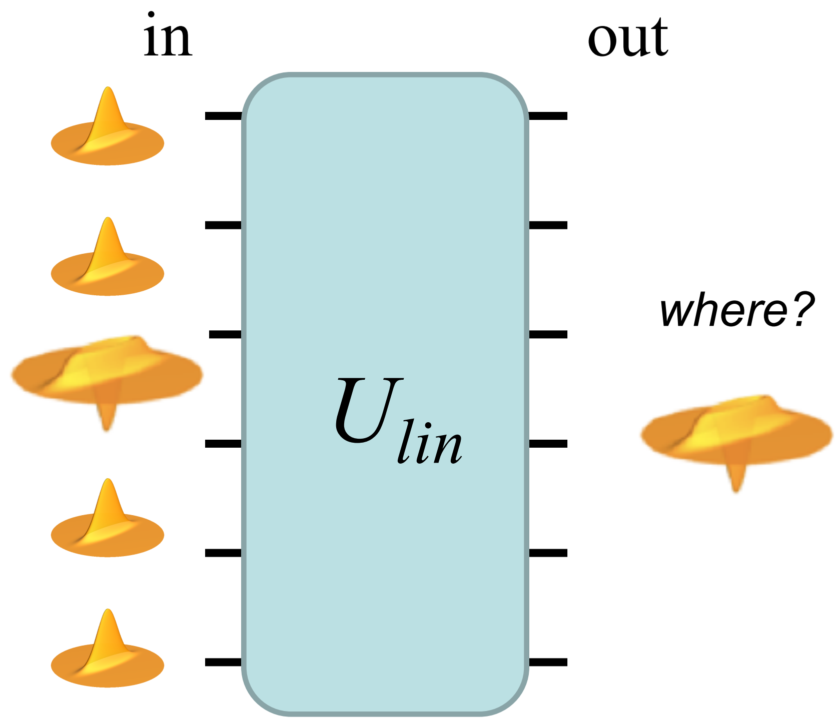
# Energy transport: some ideas




$$\frac{1}{\sqrt{\cosh r}}\sum_{n=0}^{\infty}\sqrt{\binom{2n}{n}}\left(-\frac{\tanh(r)}{2}\right)^{n}|2n\rangle$$

# Energy transport: some ideas

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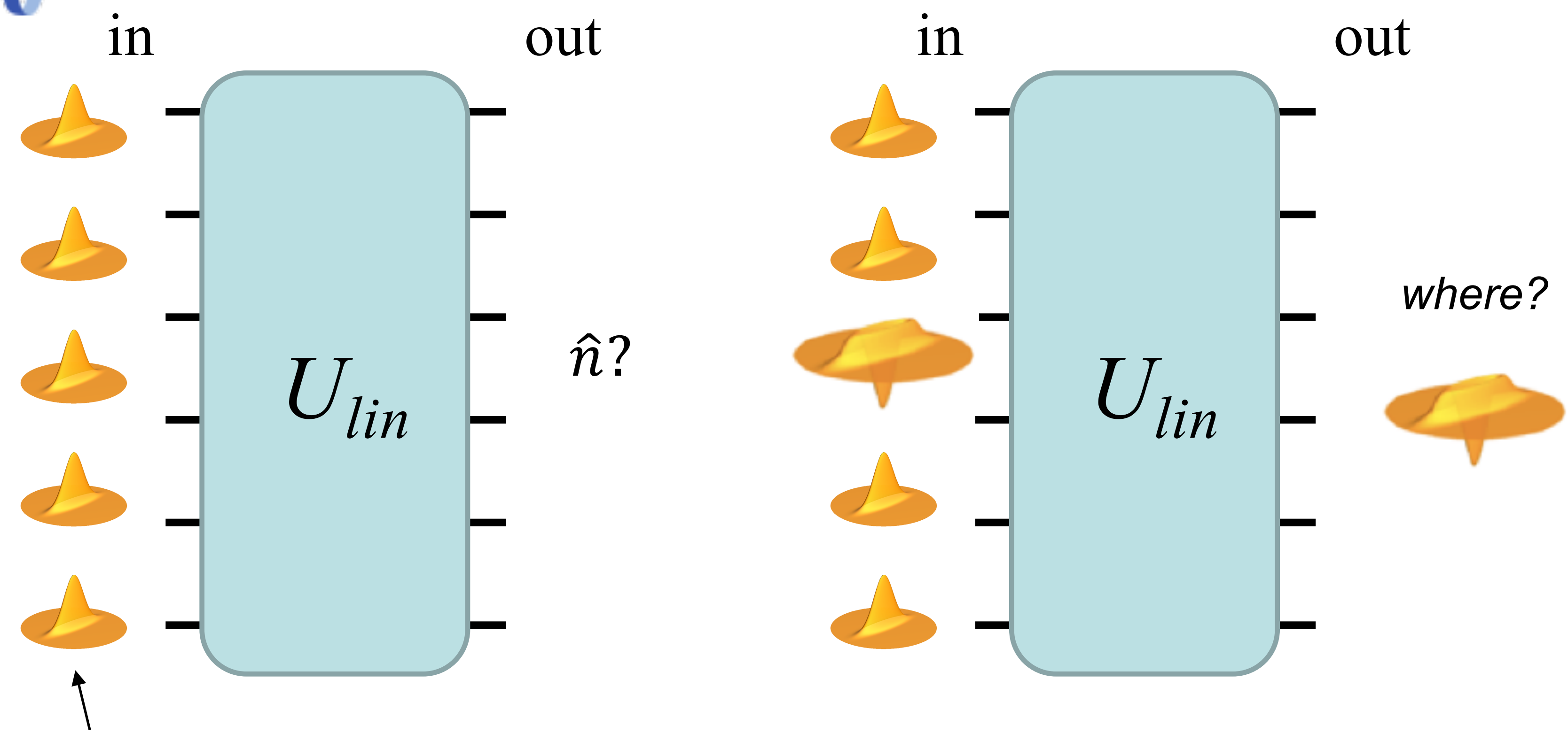


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*Connection with boson sampling problems*

C S. Hamilton, R. Kruse, L. Sansoni, S. Barkhofen, C. Silberhorn, I. Jex , arXiv:1612.01199
R. N. Alexander, N. C. Gabay, P. P. Rohde, and N. C. Menicucci,
Phys. Rev. Lett. **118**, 110503 (2017)

# *Thank you!*

LKB