MULTIMODE QUANTUM PHYSICS

Claude Fabre

Laboratoire Kastler Brossel
Physique quantique et applications

PLAYING WITH

QUANTUM MODES

Claude Fabre

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Quantum computing now involves a few qubits
(7 qubits to factorize 15 !)

Useful quantum computing in the future

will require many entangled qubits or quantum variables

Necessity of investigations on quantum properties of systems with many degrees of freedom

This talk : multimode quantum states of light

What is a mode ?

A normalized solution of Maxwell equations $\mathbf{f}_1(\mathbf{r},t)$

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}-\frac{1}{c^2}\frac{\partial^2}{\partial x^2}\right)\mathbf{f}_1(\mathbf{r},t)=0 \qquad \nabla.\mathbf{f}_1=0$$

$$\int d^3r dt\,\left|\mathbf{f}_1\right|^2=1$$

single mode field: $\mathbf{E}_1^+(\mathbf{r},t)=E_1\,\mathbf{f}_1(\mathbf{r},t)$

E_1 complex amplitude of the single mode field

What is a mode **basis** ?

A complete, orthonormal, set of Maxwell equations solutions

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}-\frac{1}{c^2}\frac{\partial^2}{\partial x^2}\right)\mathbf{f}_m(\mathbf{r},t)=0 \qquad \nabla.\mathbf{f}_m = 0$$

$$\int d^3r dt\, \mathbf{f}_m^*.\mathbf{f}_n = \delta_{mn}$$

most general complex field : $\mathbf{E}^+(\mathbf{r},t)=\sum_m E_m\, \mathbf{f}_m(\mathbf{r},t)$

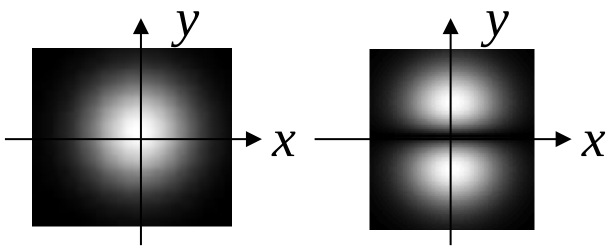
$\{E_m\}$: set of complex amplitudes

any Maxwell equation solution $\mathbf{f}_m$ can be considered as the first element of a mode basis

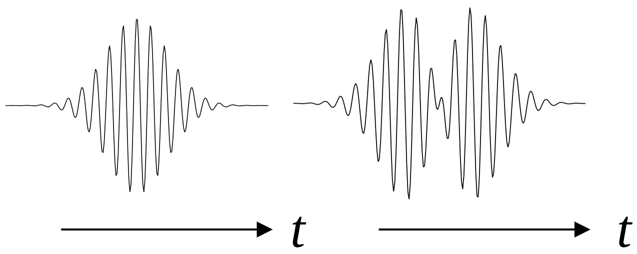
Examples of modes

$$\mathbf{u}_{\ell}(\mathbf{r},t)=\frac{1}{\sqrt{V}}\varepsilon_{\ell}e^{i(\mathbf{k}_{\ell}\cdot\mathbf{r}-\omega_{\ell}t)}$$ Travelling plane wave

Spatial Hermite-Gauss modes



Temporal Hermite-Gauss modes



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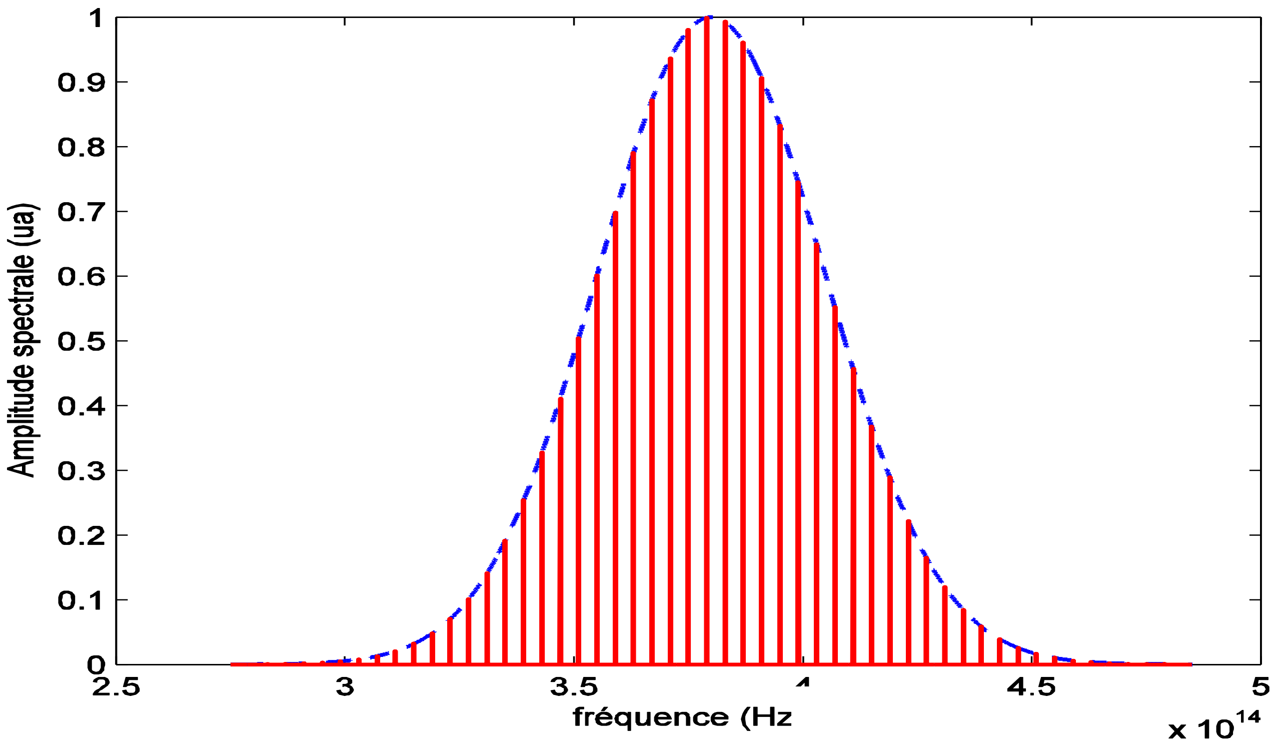
a highly multimode optical system: the frequency comb

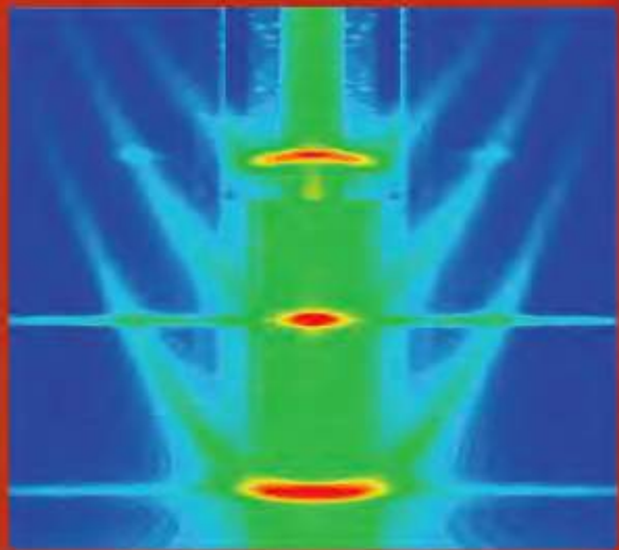


trains of 100fs pulses from Ti:Sapph lasers:
pulsed field spans over 10^4 10^5 frequency modes

quantization of the electromagnetic field

Introduction to QUANTUM OPTICS

From the Semi-classical Approach to Quantized Light



Gilbert Grynberg, Alain Aspect
and Claude Fabre

field quantization on the plane wave mode basis

classical complex field: $\mathbf{E}^{+}(\mathbf{r},t) = \sum_{l} E_l \mathbf{u}_l(\mathbf{r},t)$

complex field operator $\hat{\mathbf{E}}^{+}(\mathbf{r},t) = \sum_{l} E_{0l}\, \hat{a}_l\, \mathbf{u}_l(\mathbf{r},t)$

$\hat{a}_l$: annihilation operator of a photon in plane wave mode *l*

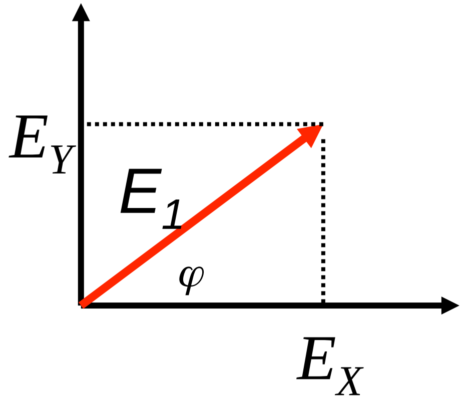
$\hat{a}_l^{+}$: creation operator of a photon in plane wave mode *l*

$|0\rangle$: vacuum state (no photons, ground state of system)

$|1\rangle$: single photon in mode *l*

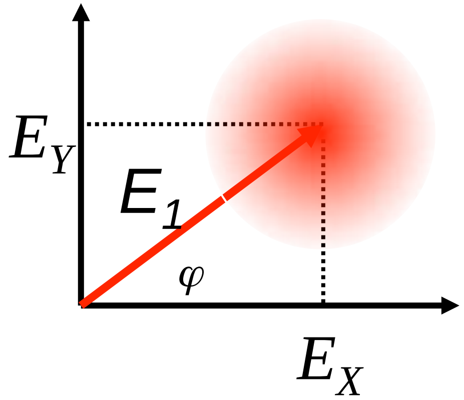
$E_{0l} = \sqrt{\dfrac{\hbar\omega_l}{2\varepsilon_0 V}}$: electric field of a single photon in mode *l*

Classical single mode field phasor représentation



E_x, E_y : Quadratures

Quantum single mode field phasor représentation



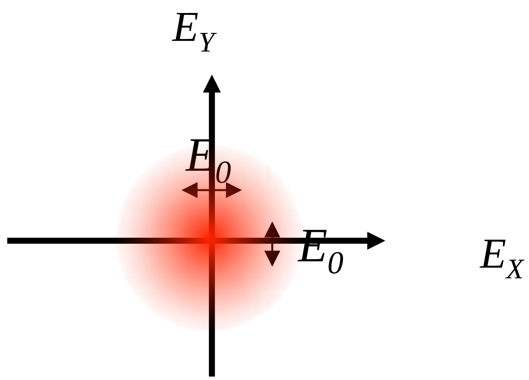
E_x, E_y : Quadratures

E_X and E_Y correspond to non commuting operators

$$\hat{E}_X \quad \hat{E}_Y$$

Heisenberg inequality: $\Delta E_X \Delta E_Y \geq E_0^2$

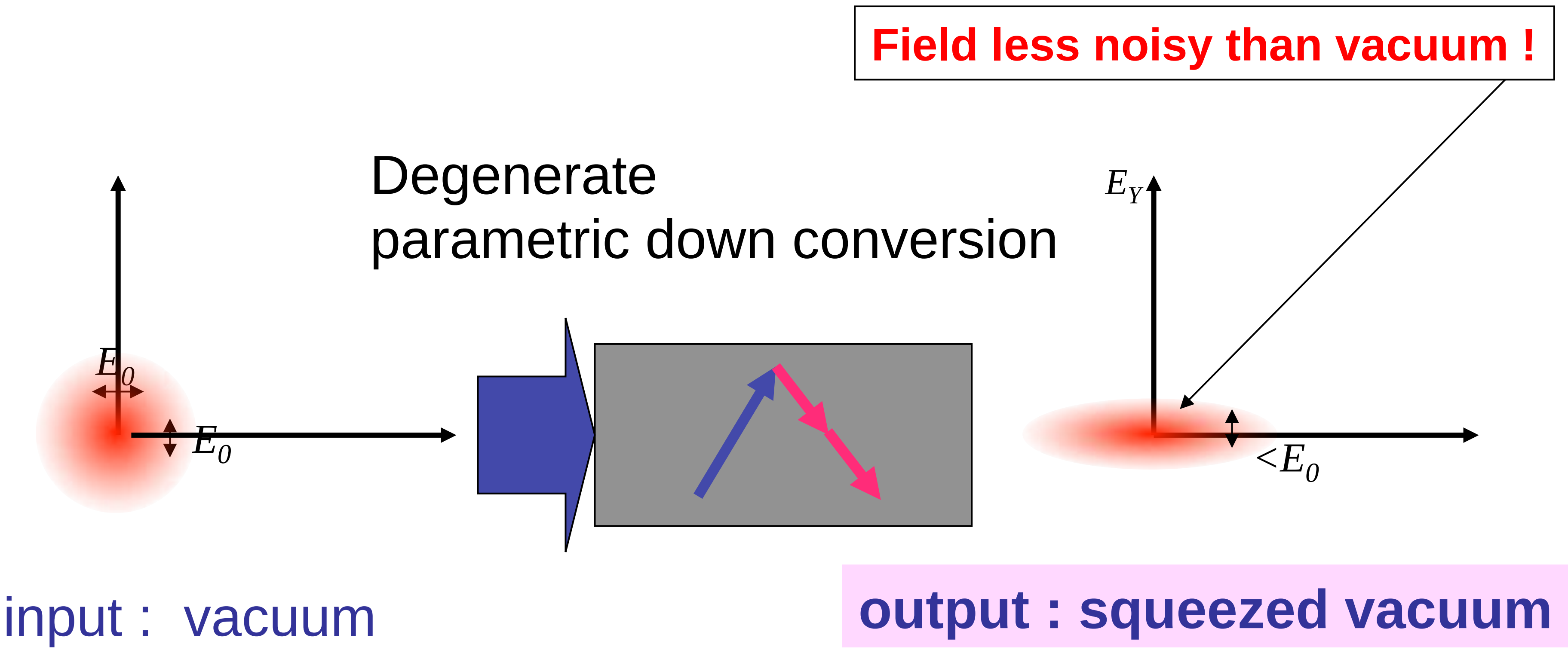
zero photon state: « obscurity » or « vacuum»



$$\Delta E_X = E_0 \quad \Delta E_Y = E_0$$

« vacuum fluctuations »

The other quantum property of light



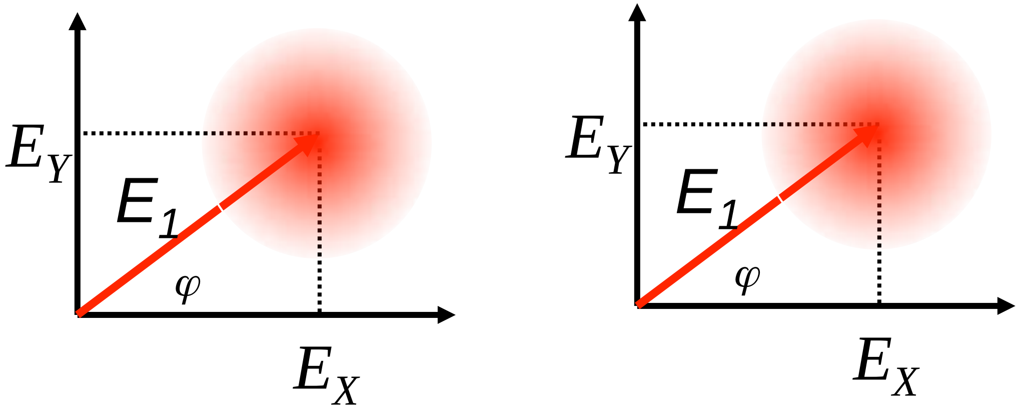
Heisenberg does not forbid $\Delta E_X \leq E_0 \quad \Delta E_Y \geq E_0$

provided that $\Delta E_X \Delta E_Y \geq E_0^2$

Best experiments : 94% reduction

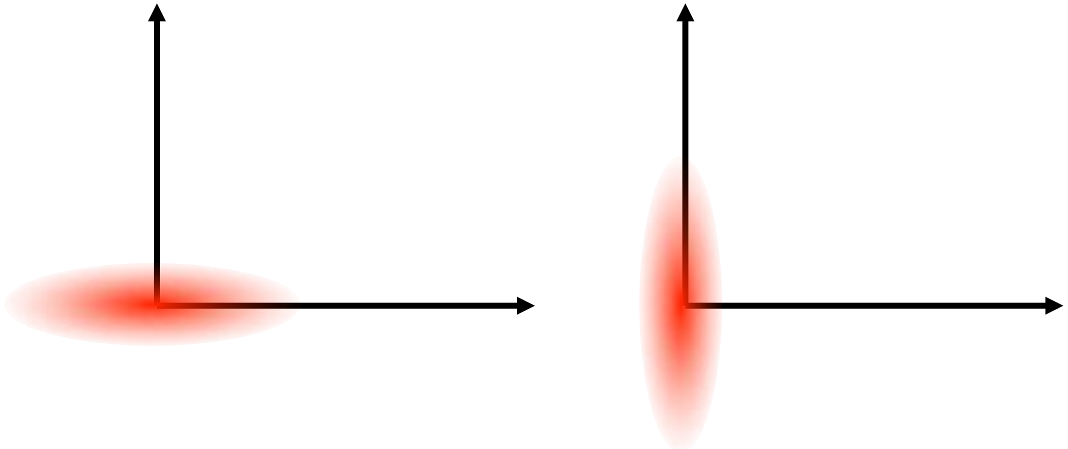
vacuum and squeezed states have Gaussian quantum fluctuations

Quantum multimode field



E_{lx}, E_{ly} : Quadratures
for each mode

E_{lX} and $E_{l'Y}$ commute



possibility of
multiple squeezing

possibility
of **quantum correlations**
between quadratures
in different modes

signature of **entanglement** :
simultaneous correlations
on X quadratures and anticorrelations on Y quadrature
(like in Einstein Podolsky Rosen famous paper)

change of mode basis

Unitary matrix $\mathbf{U} = \left\{ \mathbf{U}_m^l \right\}$

$$\hat{b}_m^+ = \sum_l \mathbf{U}_m^l \, \hat{a}_l^+ \qquad \left[\hat{b}_m , \hat{b}_{m'}^+ \right] = \delta_{m,m'}$$

$\hat{b}_m$: annihilation operator of a photon in a new mode « *m* »

$\hat{b}_m^+ \left| 0 \right\rangle = \left| 1 : m \right\rangle$: single photon in a new mode « *m* »

$$\boxed{\hat{\mathbf{E}}^+(\mathbf{r},t) = \sum_m F_{0m} \, \hat{b}_m \, \mathbf{f}_m(\mathbf{r},t)}$$

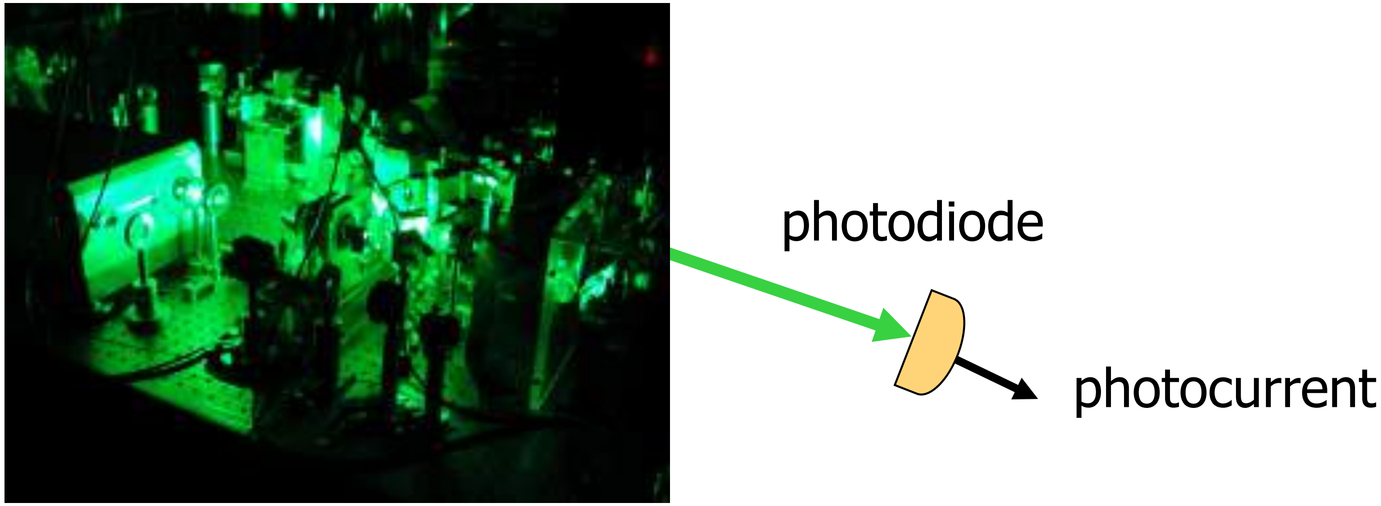
F_{0m} : electric field of a single photon in mode « *m* »

Spatio-temporal shape of new mode:

$$\mathbf{f}_m(\mathbf{r},t) = \frac{1}{F_{0m}} \sum_l E_{0l} \, \mathbf{U}_m^l \, \mathbf{u}_l(\mathbf{r},t)$$

« usual quantum state of light 1 »

continuous variable regime



single mode, possibly many photons

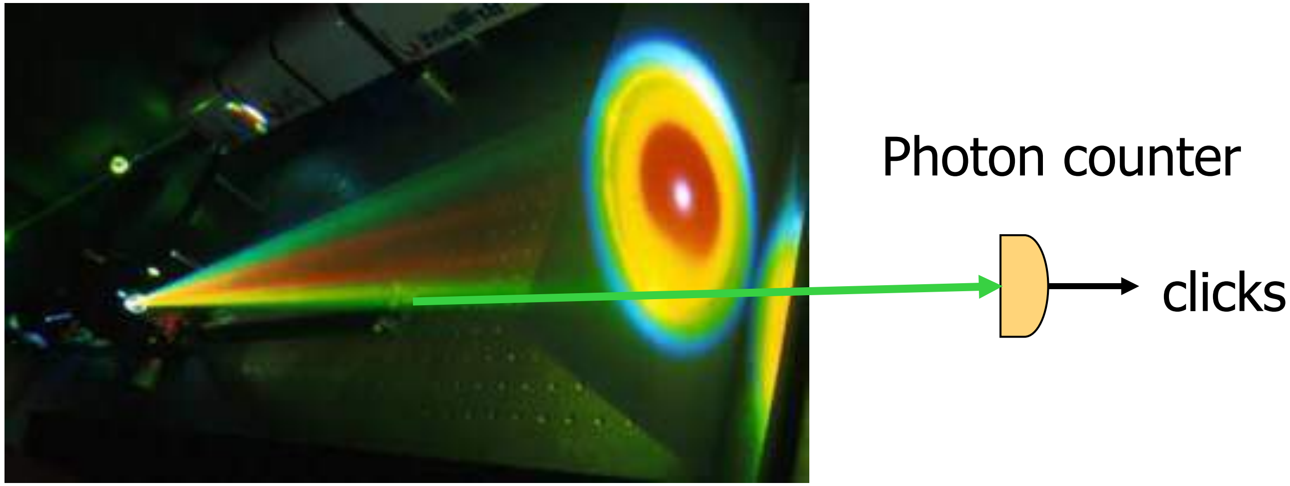
$$\left|\Psi\right\rangle = \sum_n c_n \left|n : \ell = \ell_0\right\rangle$$

Photon number

mode label

« usual quantum state of light 2 »

photon counting regime



single photon, possibly many modes

$$\left|\Psi\right\rangle = \sum_{\ell} c_{\ell} \left| n = 1 : \ell \right\rangle$$

Photon number

mode label

Most general state of light

$$\left|\Psi\right\rangle = \sum_{n_1} .. \sum_{n_\ell} .. c_{n_1,..,n_\ell,..} \left| n_1 : 1, .., n_\ell : \ell, .. \right\rangle$$

Photon number

Mode label

Influence of mode basis change

The same quantum state $\left|\Psi\right\rangle$

may have quite different forms

when expressed in different modal bases

In this talk : **total freedom** in change of mode basis

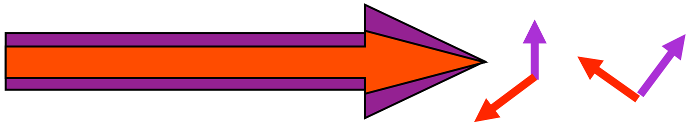
A related problem: bipartite entanglement

Part 1: subset $\left\{\mathbf{u}_{1p}\right\}$

Part 2: subset $\left\{\mathbf{u}_{2m}\right\}$

Only « local operations » allowed

Example 1 : change of polarization modes



$$\left|\Psi\right\rangle = \left|\psi_x^{squeezed}\right\rangle \otimes \left|\varphi_y^{squeezed}\right\rangle$$

Separable state in the basis of Ox,Oy polarizations

$$\left|\Psi\right\rangle = \alpha\left|\varphi_{45}\right\rangle \otimes \left|\psi_{-45}\right\rangle + \beta\left|\chi_{45}\right\rangle \otimes \left|\xi_{-45}\right\rangle$$

Entangled state on the basis of O_{+45} O_{-45} polarizations

Example 2 : multimode single photon state

$$\left|\Psi\right\rangle = \sum_{\ell} c_{\ell} \left| n = 1 : \ell \right\rangle$$

One defines $\quad \mathbf{v}_1(\mathbf{r},t) = \sum_{\ell} c_{\ell} \mathbf{u}_{\ell}(\mathbf{r},t)$

Completed basis: $\quad \{\mathbf{v}_j\}$

$$\left|\Psi\right\rangle = \left|1 : j = 1\right\rangle \otimes \left|0 : j \neq 1\right\rangle$$

Multimode on one basis, single mode in another

Example 3 : multimode coherent state

$$\left|\Psi\right\rangle = \left|\alpha_0 : 0, \alpha_1 : 1, \ldots, \alpha_\ell : \ell, \ldots\right\rangle$$

One defines $\mathbf{w}_1(r,t) = \dfrac{1}{\beta}\sum_\ell \alpha_\ell \mathbf{u}_\ell(r,t)$

with: $|\beta|^2 = \sum_\ell |\alpha_\ell|^2$

Completed basis: $\left\{\mathbf{w}_k\right\}$

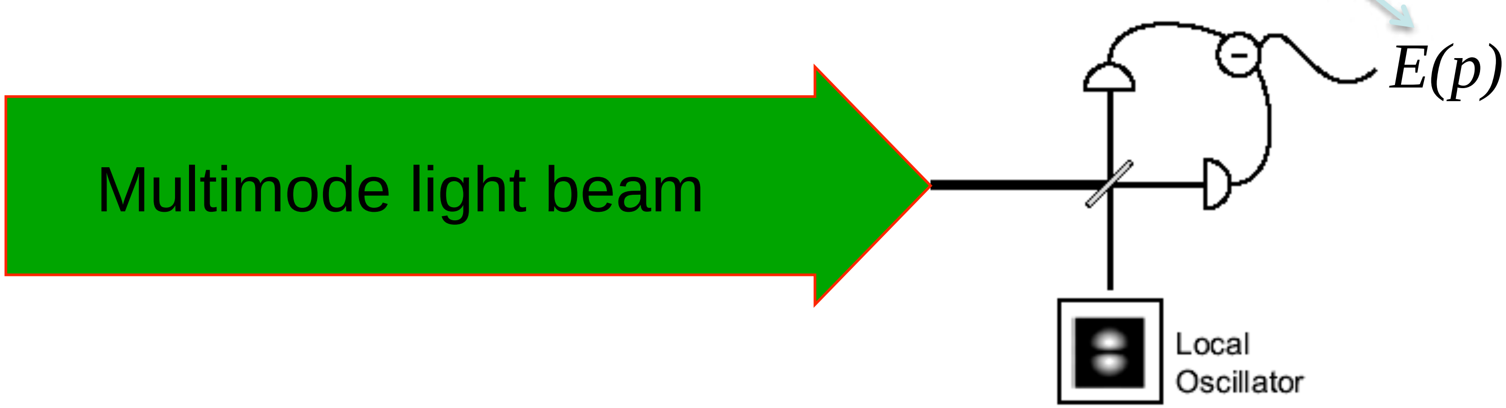
$$\left|\Psi\right\rangle = \left|\beta : k = 1\right\rangle \otimes \left|0 : k \neq 1\right\rangle$$

Multimode on one basis, single mode in another

How to measure the properties of a given mode in a multimode light ?

By using an appropriate **homodyne detection**

Quantum fluctuations of quadratures operators of mode $\mathbf{f}_m$



Local oscillator in mode $\mathbf{f}_m$

problem : it is a destructive measurement

Queries

Are there ***mode independent, or « intrinsic »*** *properties of quantum states of light ??*

To solve a given problem,
is there a ***preferred mode basis*** *that simplifies it ??*

-I-

Intrinsic properties

of light states

Invariants with change of mode basis

- The vacuum state $\left|0\right\rangle = \left|0,..,0,..\right\rangle$

- The total number of photons

$$\hat{N} = \sum_{\ell} \hat{a}_{\ell}^{+} \hat{a}_{\ell} = \sum_{j} \hat{b}_{j}^{+} \hat{b}_{j}$$

Definition of an **intrinsic** single mode state

an **intrinsic single mode state** is a state for which there exists a mode basis $\left\{\mathbf{u}_i\left(\mathbf{r}\right)\right\}$

In which the quantum state is written as:

$$\left|\Psi\right\rangle = \left|\phi : \mathbf{u}_1\right\rangle \otimes \left|0, \ldots 0, 0, \ldots\right\rangle$$

For an **intrinsic multimode state**,
there is no such basis

Criteria for an intrinsic single mode state

N. Treps, V. Delaubert, A. Maître, J.M. Courty, C. Fabre Phys. Rev A**71** 013820 (2005)

(1) $\forall \ell \quad \hat{a}_\ell \left| \Psi \right\rangle$ are proportional to each other

(2) $\left| g^{(1)}(\mathbf{r}, \mathbf{r}', t, t') \right| = 1$

where

$$g^{(1)}(\mathbf{r}, \mathbf{r}', t, t') = \frac{\left\langle \hat{E}^{(-)}(\mathbf{r}, t) \hat{E}^{(+)}(\mathbf{r}', t') \right\rangle}{\sqrt{\left\langle \hat{E}^{(-)}(\mathbf{r}, t) \hat{E}^{(+)}(\mathbf{r}, t) \right\rangle \left\langle \hat{E}^{(-)}(\mathbf{r}', t') \hat{E}^{(+)}(\mathbf{r}', t') \right\rangle}}$$

gives a contrast 1 to interference fringes in any interferometer

Definition of the **intrinsic number of modes**

intrinsic number of modes =

dimension of space spanned by $\left\{ \hat{a}_\ell \left| \Psi \right\rangle \right\}$

Example $\left| \Psi \right\rangle = \left| 1,1 \right\rangle$ is an intrinsic two-mode state

- cannot be written as $\left| 2,0 \right\rangle$

-will not produce perfect first order interference fringes

unsolved problem : specific properties of two-mode states ?

How to determine the **intrinsic number of modes ?**

Difficult task experimentally

(1) A sufficient criterion for a non-single mode state:

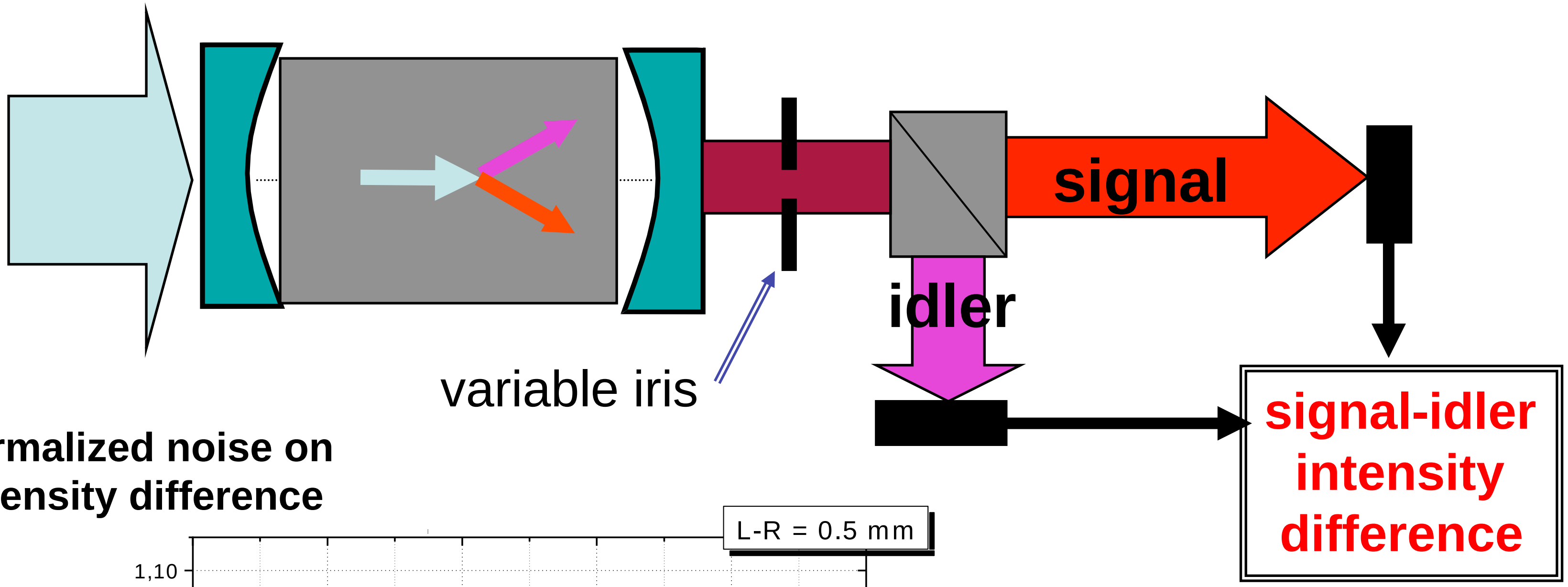
In a single mode field, all the observables
have the same spatio-temporal variation

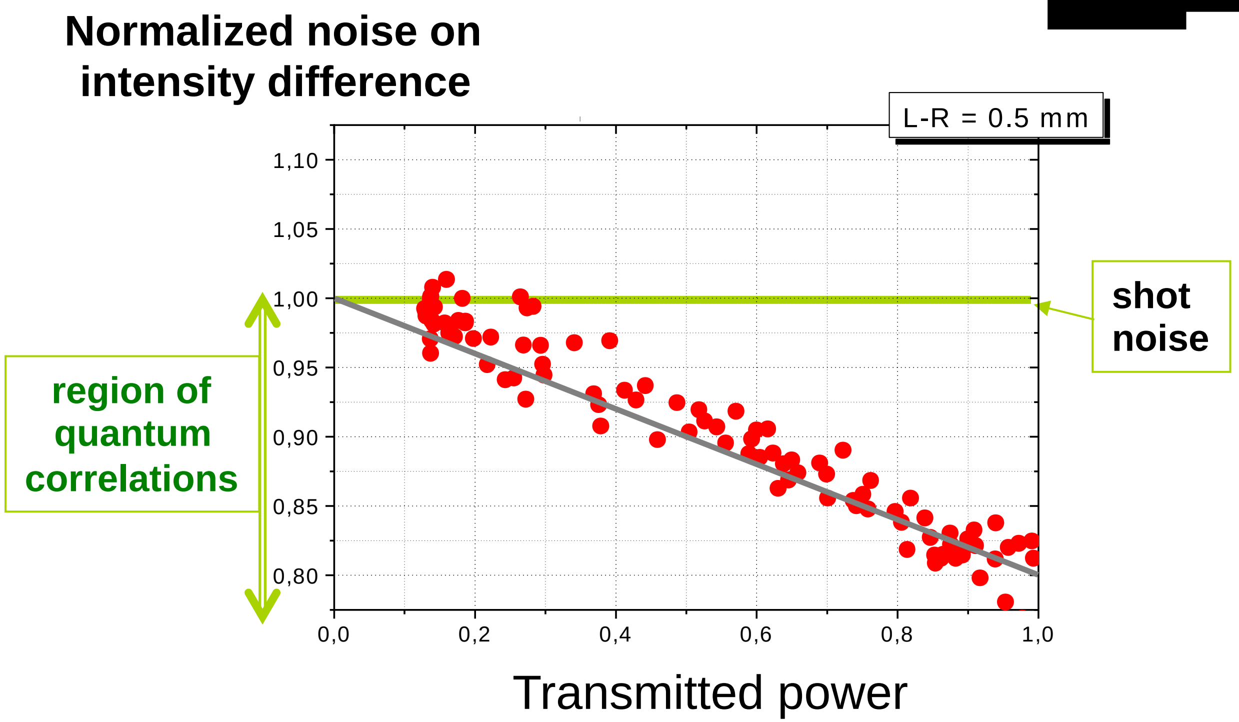
In a non-single mode field
the noise and the mean have not the same variation

(2) Possible for **Gaussian fields**,
that are completely characterized
by the second order moments,
done by **diagonalizing the covariance matrix**
(matrix of variances and cross correlations
in a given mode basis)

Non single mode non-classical light

M. Martinelli, et al Phys. Rev. ***A67****, 023808 (2003)*

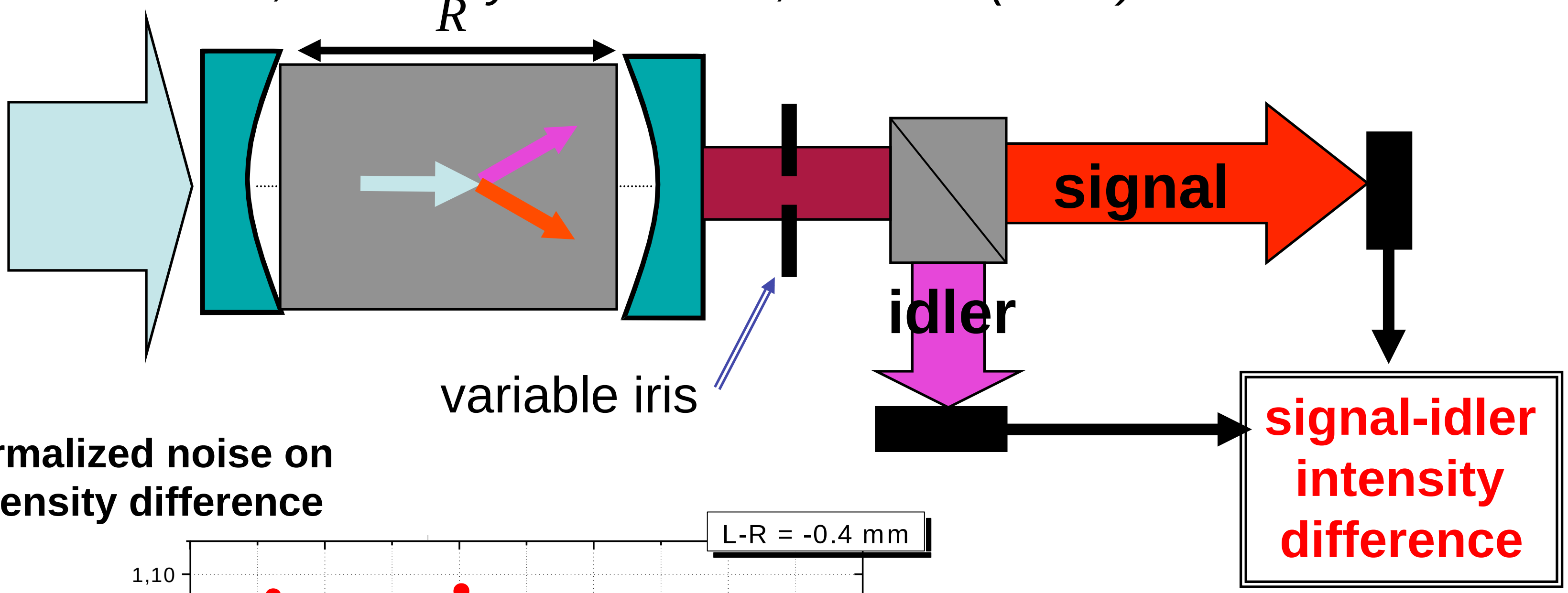


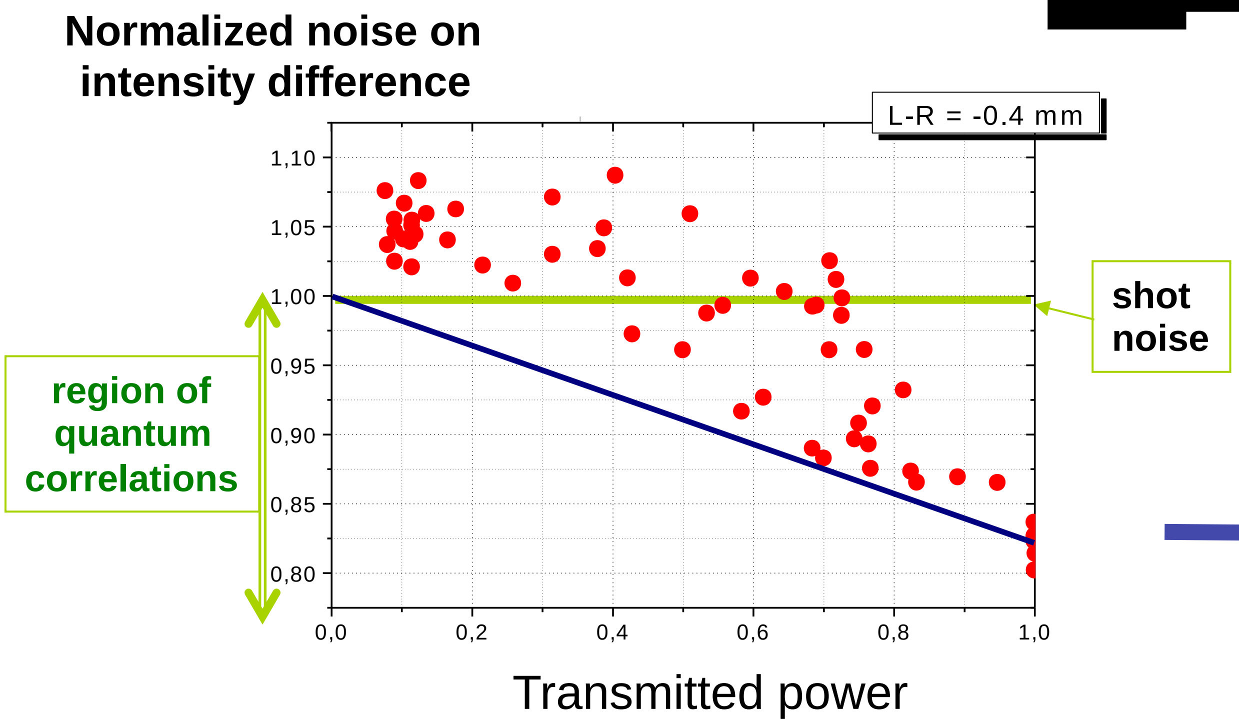


single transverse mode cavity

Non single mode non-classical light

M. Martinelli, et al Phys. Rev. ***A67****, 023808 (2003)*

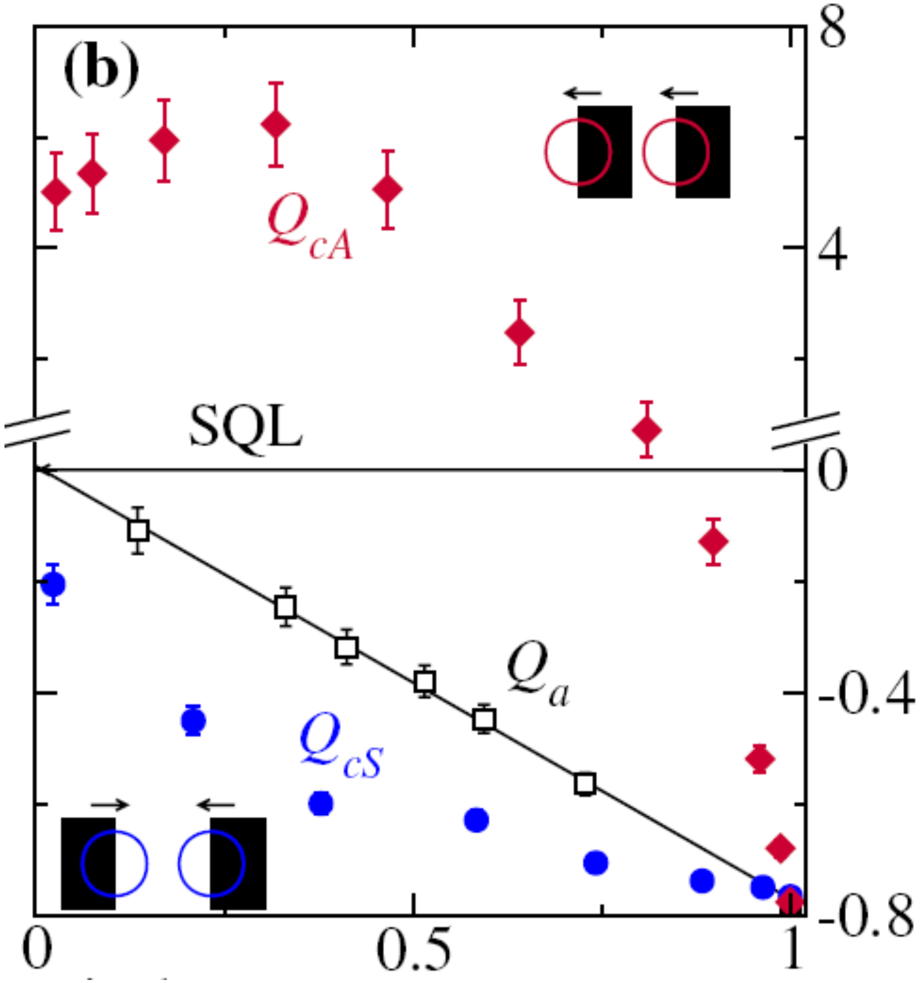




confocal cavity

➡ *non single mode non classical state*

NIST 4 wave mixing experiment



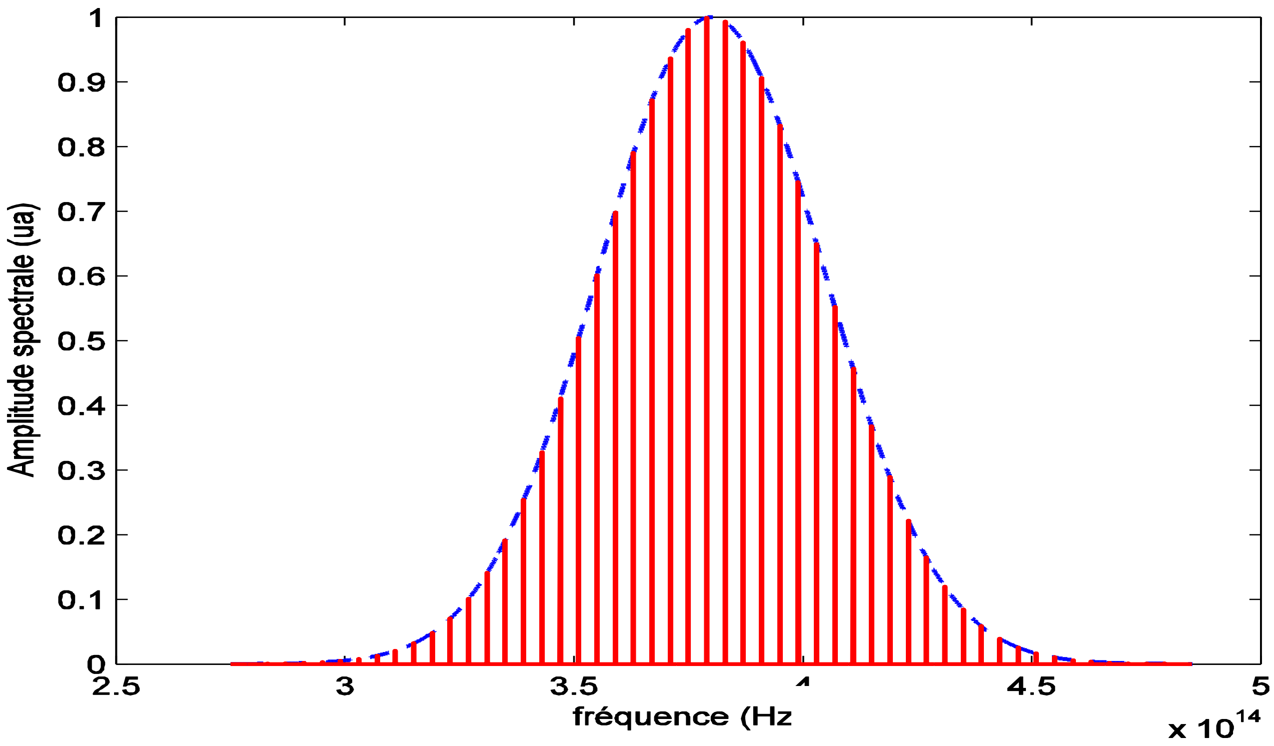
*V. Boyer, A. Marino, P. Lett, PRL **100,** 143601 (2008)*

-II-

Definition and use of preferred modal bases

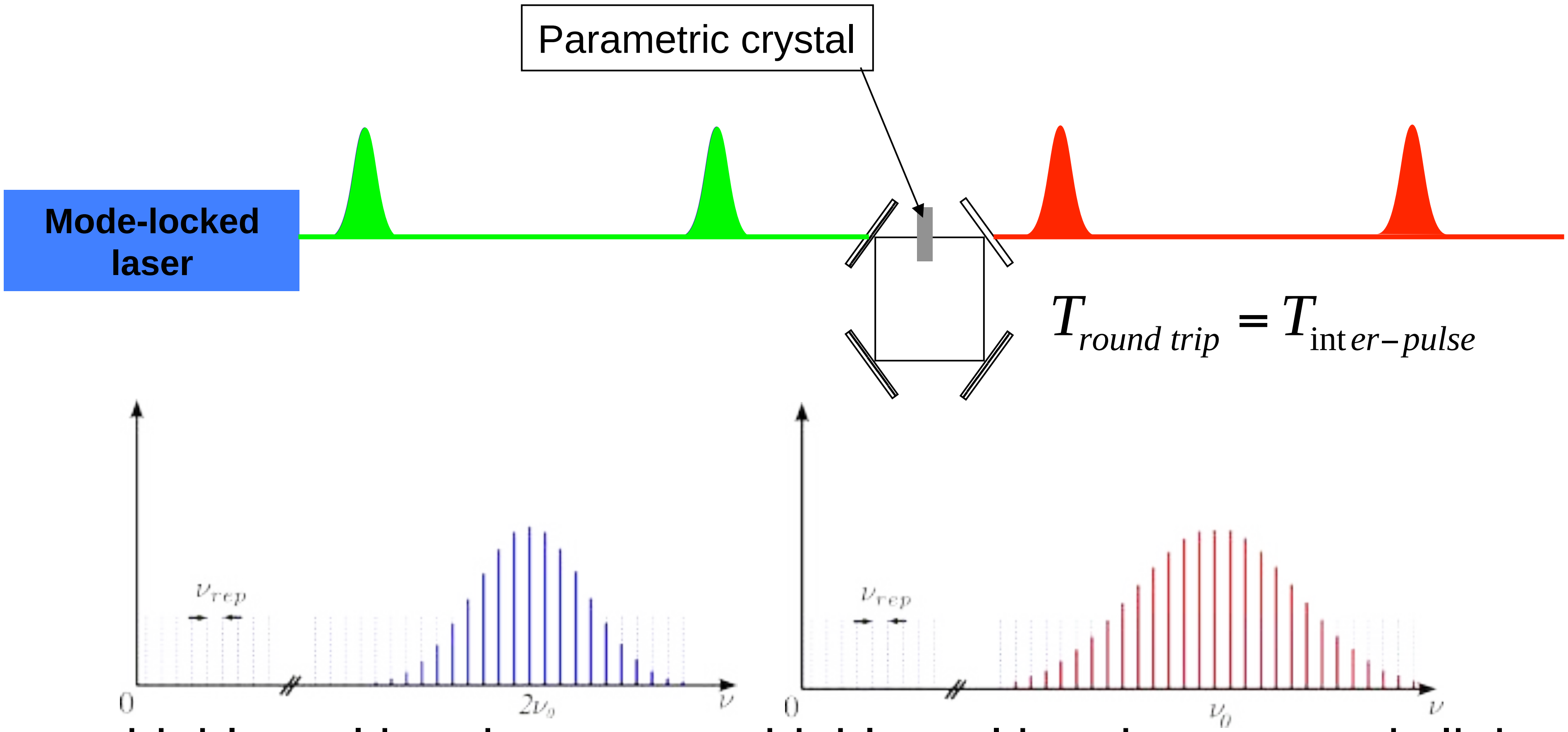
II a : supermodes in parametric interaction

a highly multimode optical system: the frequency comb



trains of 100fs pulses from Ti:Sapph lasers:
pulsed field spans over 10^4 10^5 frequency modes

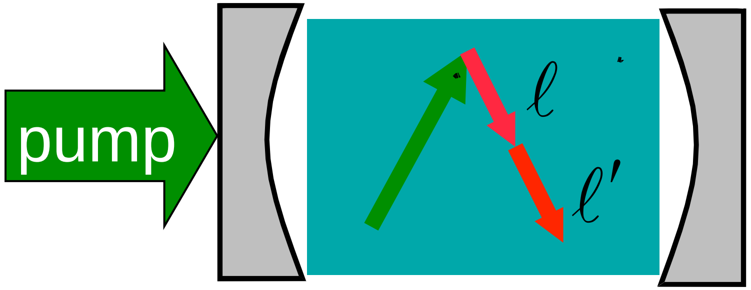
a quantum frequency comb:
the Synchronously Pumped Optical Parametric Oscillator (SPOPO)



highly multimode pump

highly multimode parametric light

Quantum description of multi-pump-mode parametric interaction



G. de Valcarcel et al.
*PRA **74** 061801 (2006)*

G. Patera et al.
*EPJD **56** 123 (2010)*

$$\hat{H} = \sum_{\ell,\ell'} \chi(\omega_\ell, \omega_{\ell'}) \; \alpha_{pump}(\omega_\ell + \omega_{\ell'}) \left(\hat{a}_\ell^+ \hat{a}_{\ell'}^+ + \hat{a}_\ell \hat{a}_{\ell'}\right)$$

Crystal phase matching coefficient

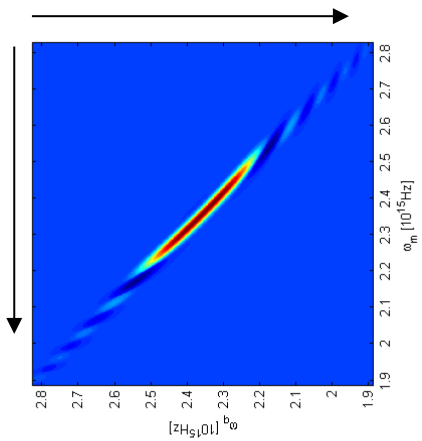
pump spectral amplitude

$$\hat{H} = \sum_{\ell,\ell'} G_{\ell,\ell'} \left(\hat{a}_\ell^+ \hat{a}_{\ell'}^+ + \hat{a}_\ell \hat{a}_{\ell'}\right)$$

Symmetrical matrix

ℓ'

ℓ



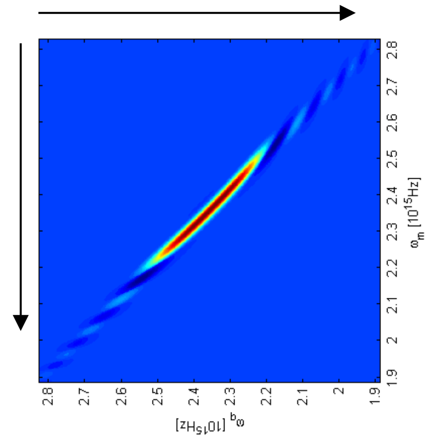
$G_{\ell,\ell'}$

Diagonalization of the parametric interaction

ℓ'

$G_{\ell,\ell'}$

ℓ

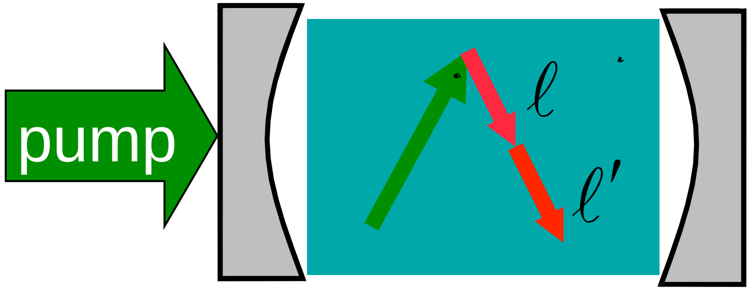


Eigenstates: « supermodes »

$$\hat{b}_k = \sum_{\ell} U_k^{\ell} \hat{a}_{\ell}$$

Eigenvalues: Λ_k

Quantum state generated below threshold



$$\hat{H} = \hbar \sum_{k=1}^{N_m} \Lambda_k \left(\hat{b}_k^2 + \hat{b}_k^{+2} \right)$$

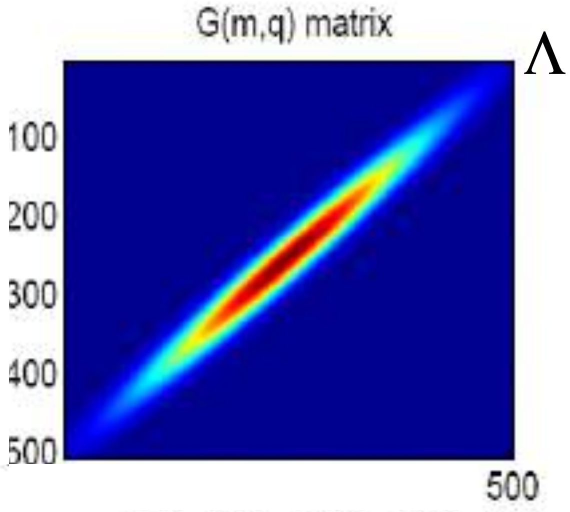
$$\left| \Psi_{out} \right\rangle = \prod_{k=1}^{N_m} e^{-i\ell\Lambda_k \left(\hat{b}_k^2 + b_k^{+2} \right)/c} \left| 0 \right\rangle$$

squeezing transformation

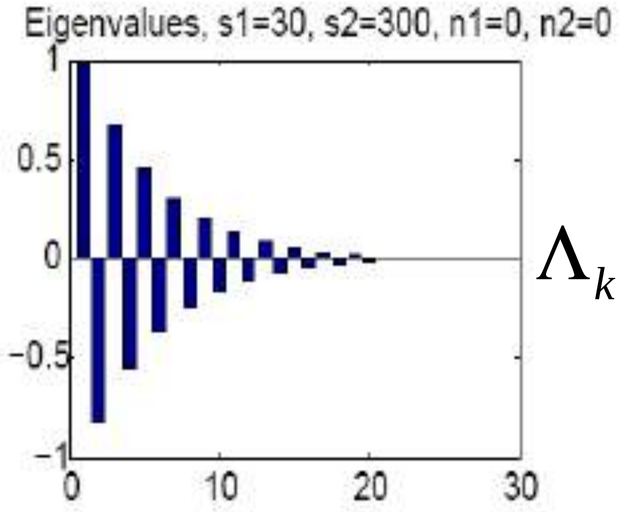
$\left| \Psi_{\text{out}} \right\rangle$: tensor product of squeezed states in supermodes with non-zero eigenvalues

Eigenvalues and eigenmodes

Simple example: Gaussian variation of $G_{\ell,\ell'}$



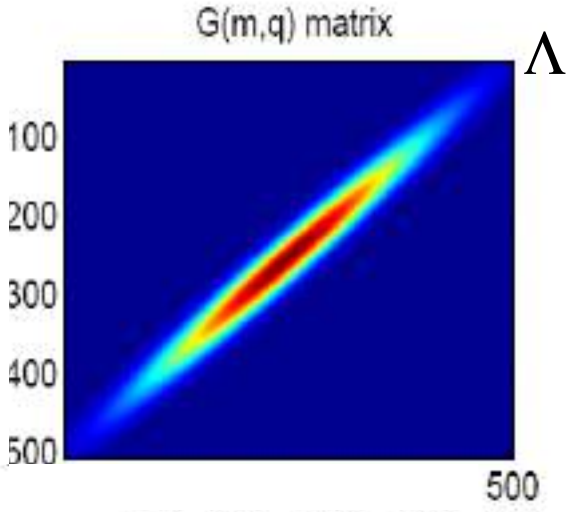
Λ_k



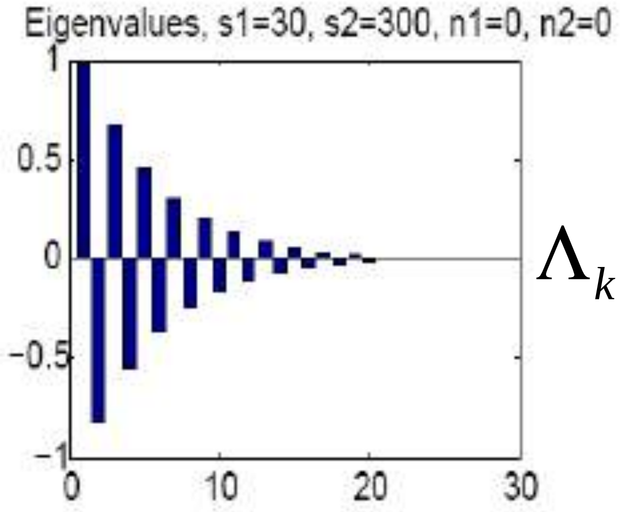
$$\Lambda_k = \Lambda_0 \left(-r\right)^k$$

Eigenvalues and eigenmodes

Simple example: Gaussian variation of $G_{\ell,\ell'}$

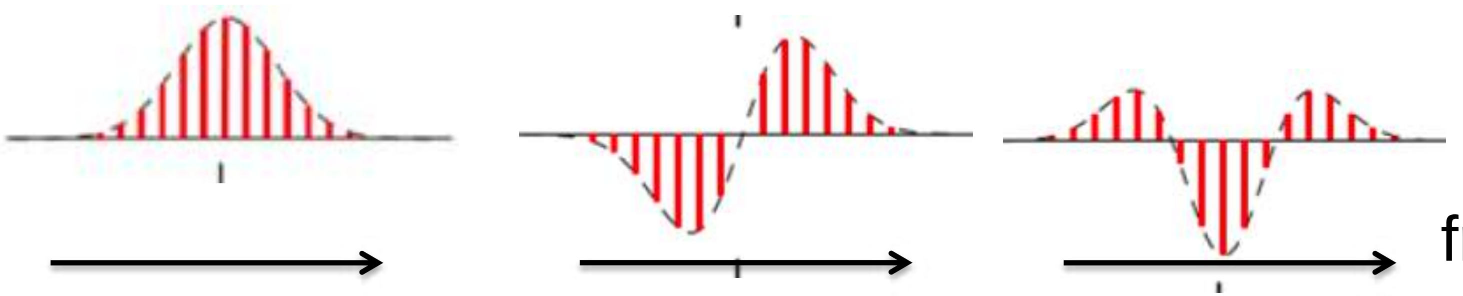


Λ_k



$$\Lambda_k = \Lambda_0 (-r)^k$$

Eigenmodes: combs with Hermite-Gauss modal amplitudes

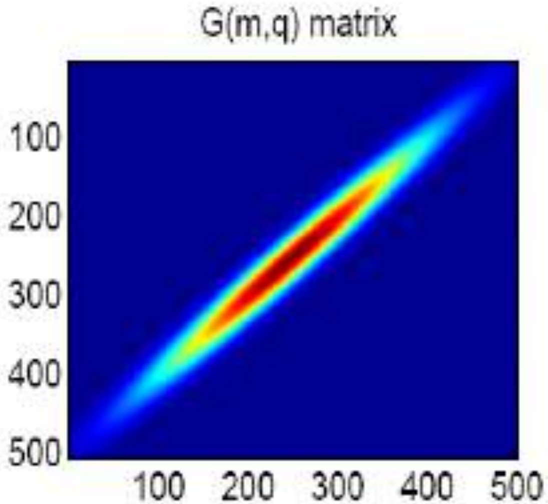


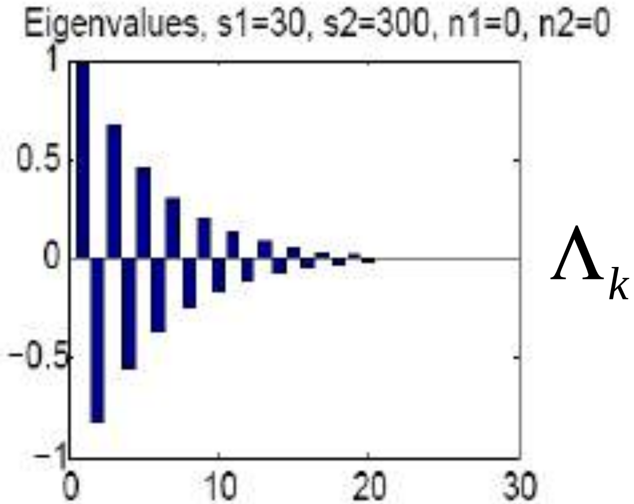
frequency

HG_0 HG_1 HG_2

Eigenvalues and eigenmodes

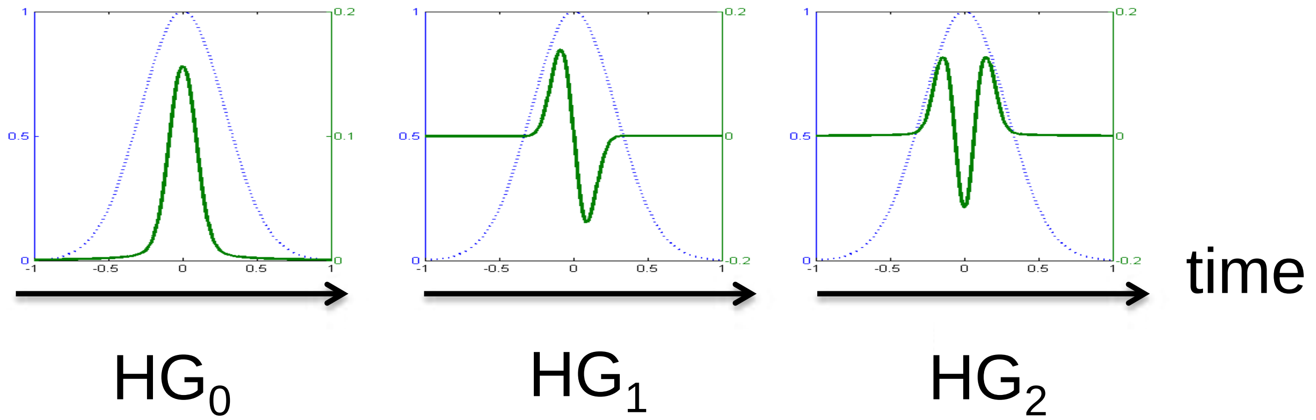
Simple example: Gaussian variation of $G_{\ell,\ell'}$





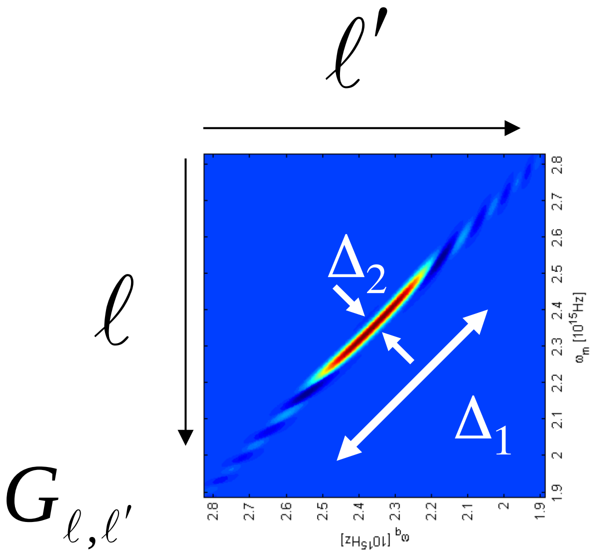
$$\Lambda_k = \Lambda_0 (-r)^k$$

Eigenmodes: trains of Hermite-Gauss pulses in time



How many non-classical modes ?

number of squeezed modes = rank of the G matrix
is of the order of the aspect ratio of the G matrix



Δ_1: phase matching

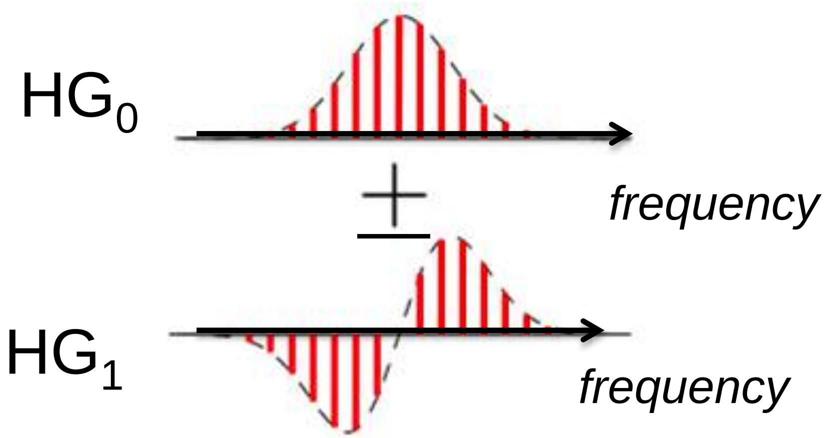
Δ_2: laser linewidth

what about multipartite entanglement ?

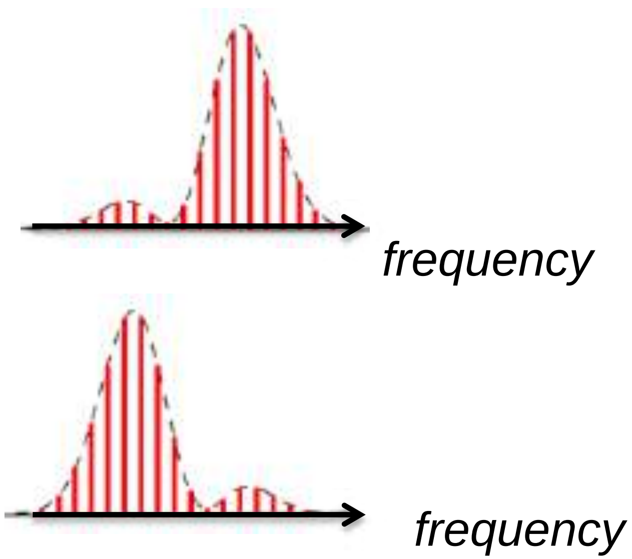
Starting from two squeezed supermodes $v_1(t)$ $v_2(t)$

the mixed modes $v_\pm(t) = \frac{1}{\sqrt{2}}\left(v_1(t) \pm v_2(t)\right)$

are EPR entangled



squeezed



entangled

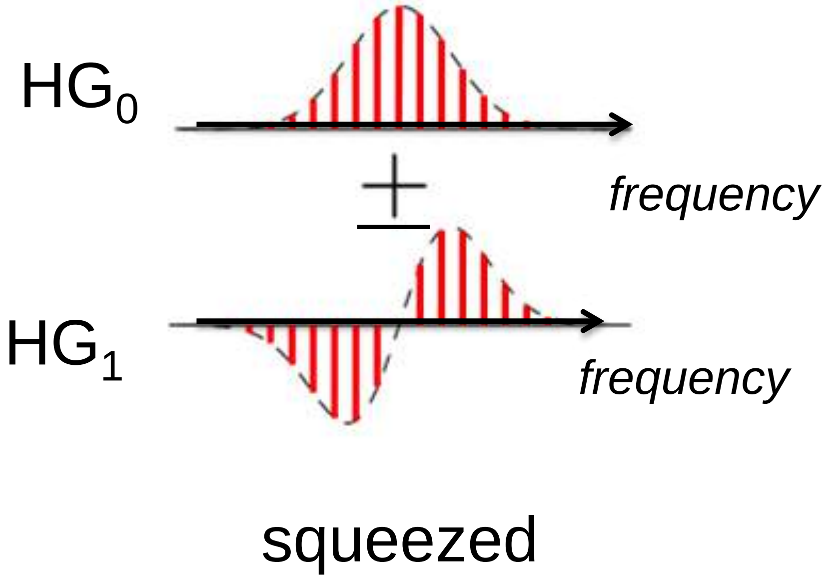
there will be **quantum correlations**
between different **spectral parts** of the comb

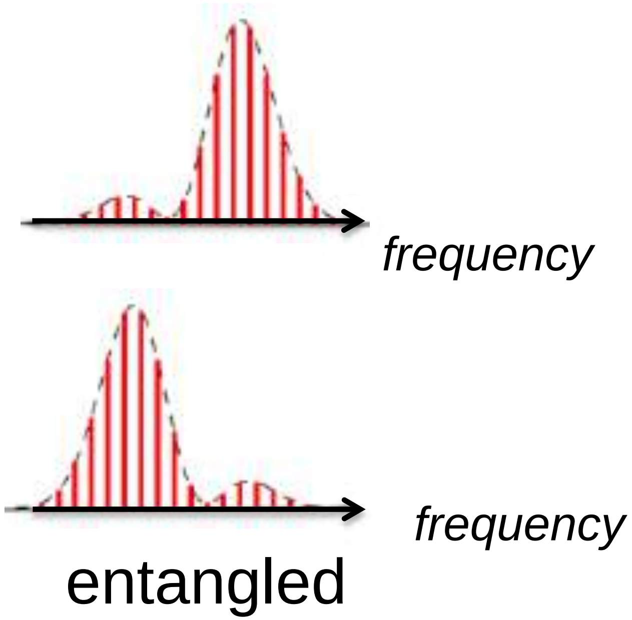
what about multipartite entanglement ?

Starting from two squeezed supermodes $v_1(t) \quad v_2(t)$

the mixed modes $$v_\pm(t) = \frac{1}{\sqrt{2}}\left(v_1(t) \pm v_2(t)\right)$$

are EPR entangled

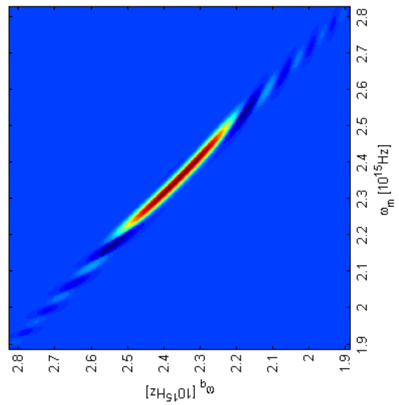




there will **quantum correlations**
between different **temporal parts** of the pulses

How to tailor the multimode quantum state generated by the SPOPO ?

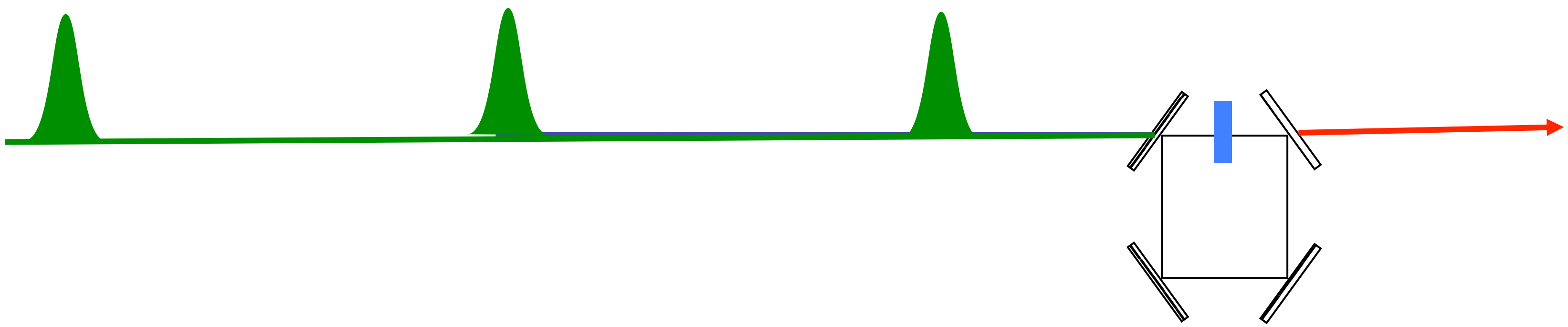
$G_{\ell,\ell'}$



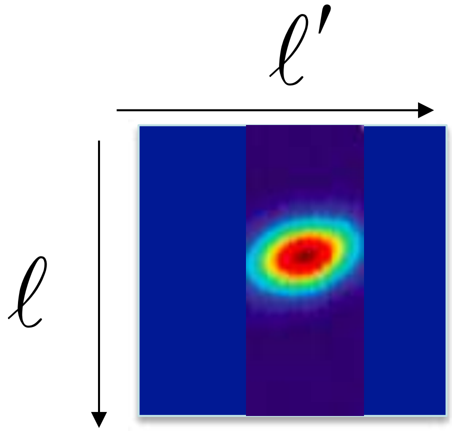
$$G_{\ell,\ell'} = \chi^{crystal}_{\ell,\ell'} \alpha^{pump}_{\ell,\ell'}$$

By changing pump and/or nonlinear medium shape
It is possible to tailor at will the number and the
spectrum of eigenvalues

single mode situation

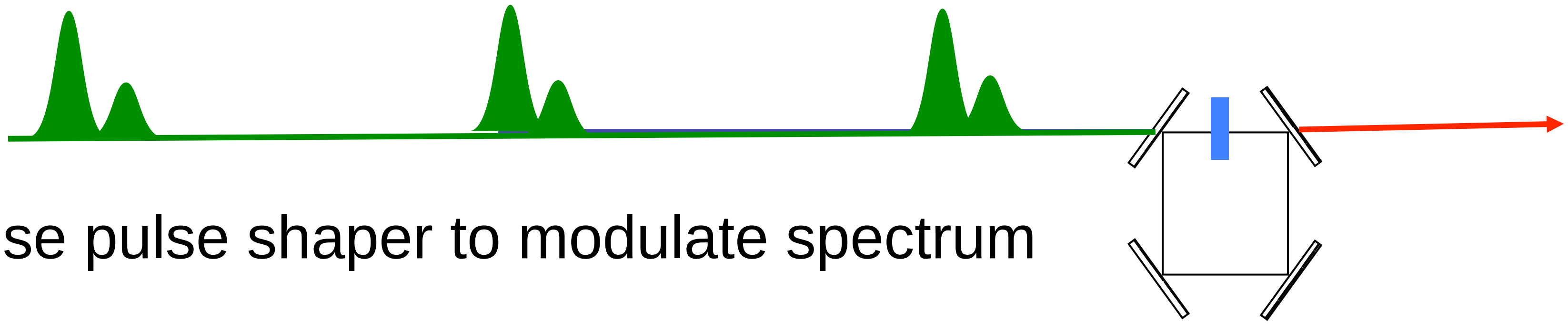


$G_{\ell,\ell'}$



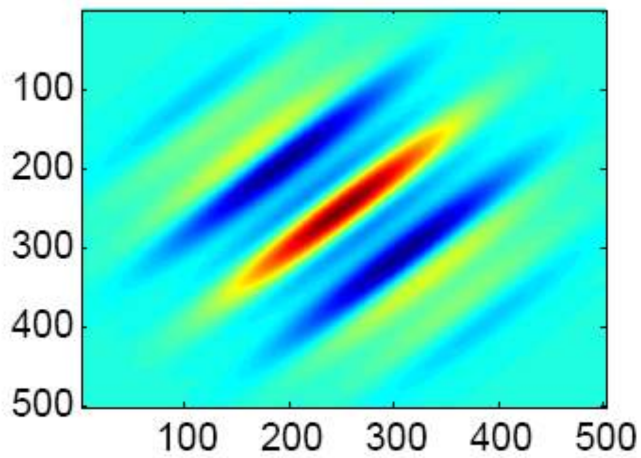
matched pump and
phase matching widths :
single squezed mode

modulation of pump spectrum

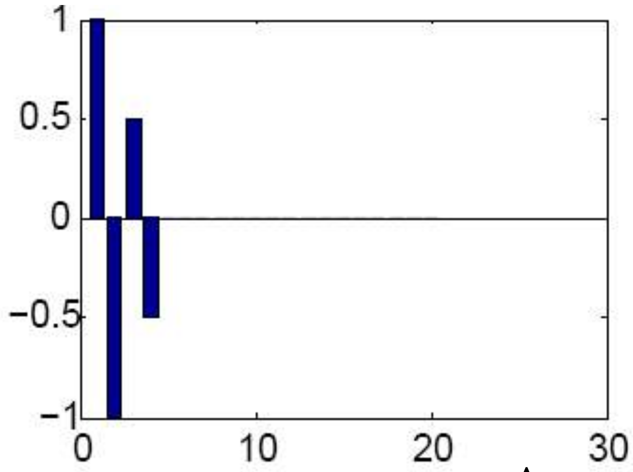


use pulse shaper to modulate spectrum

use delay lines to create delayed pulses



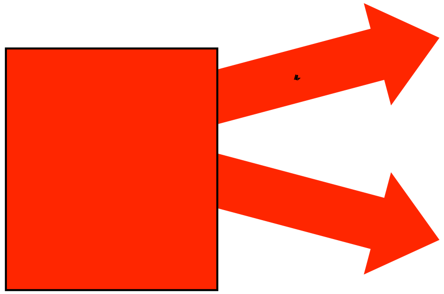
$G_{\ell,\ell'}$ matrix



eigenvalues Λ_k

Link with Schmidt modes

Case of the bipartite system



Part 1: modes $\left\{ \mathbf{u}_{1p} \right\}$

Part 2: modes $\left\{ \mathbf{u}_{2m} \right\}$

$$\hat{H} = \sum_{m,p} \left(G_{m,p} \hat{a}_{1m} \hat{a}_{2p} + G^{*}{}_{m,p} \hat{a}_{1m}^{+} \hat{a}_{2p}^{+} \right)$$

Bloch-Messiah decomposition, singular value decomposition

Parker et al PRA **61**, 032305 (2000) Law Eberly, PRL **92**, 127903 (2004)

$$\hat{H} = C \sum_{i} \lambda_i \left(\hat{b}_{1i} \hat{b}_{2i} + H.c. \right)$$

Schmidt modes defined in each part

Degree of entanglement : Schmidt number $K \approx 2N_S$

-II-

Definition and use of preferred modal bases

II b : « detection mode » for optimized quantum measurements

example 1 of precise measurement: moon ranging

estimation of **distance**

by LIDAR technique;

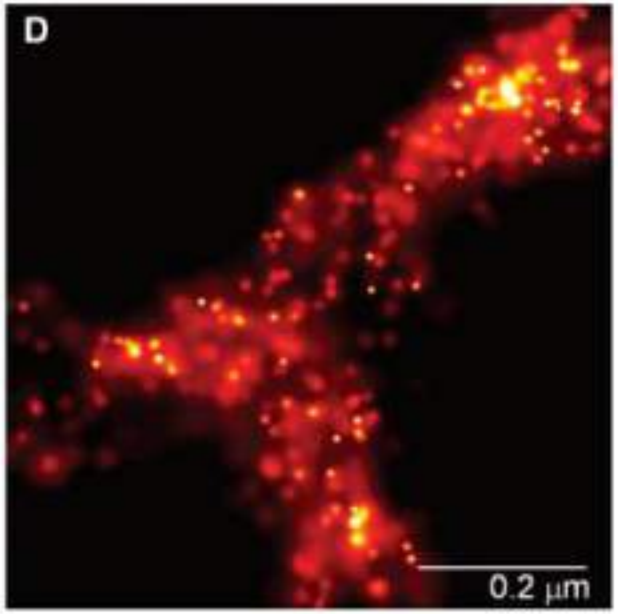
measurement of **a time delay**

of the light pulse

absolute accuracy better than 1 cm
sensitivity to distance change on the order of 1mm

the moon distance increases by 3.2 cm/year !

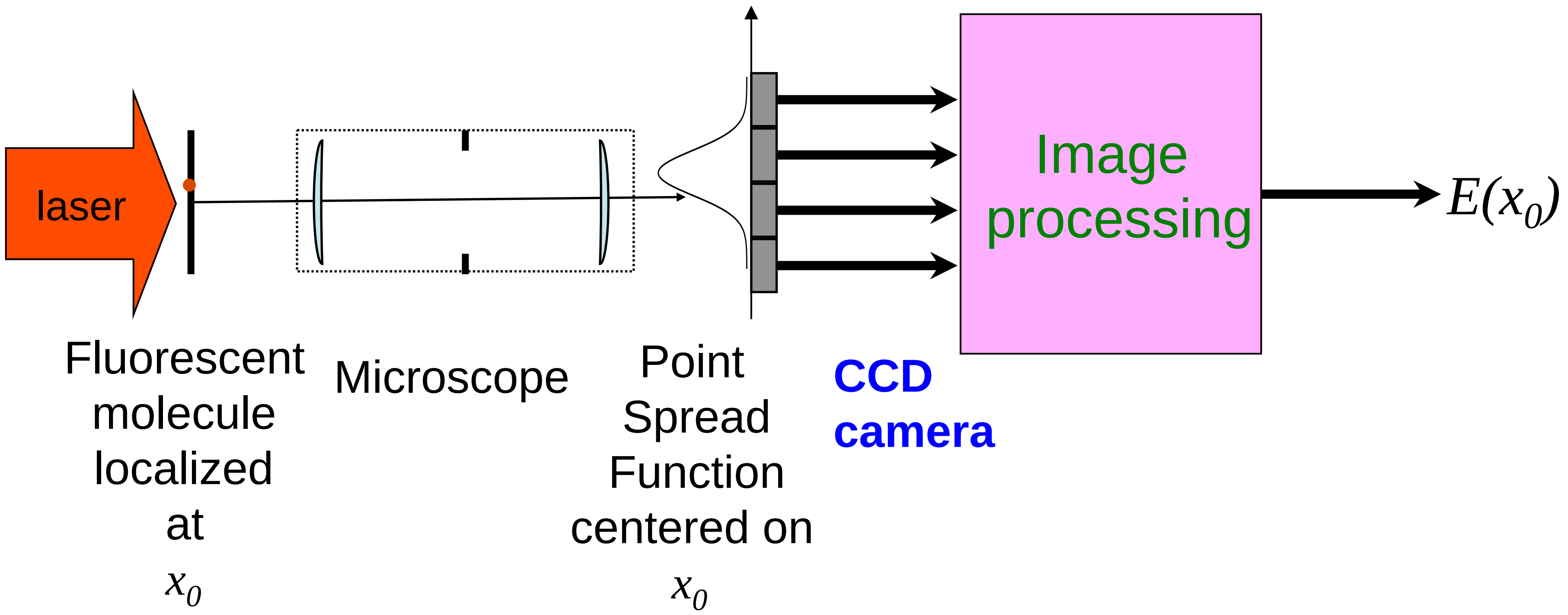
example 2 of precise meaurement : estimation of transverse position x_0, y_0 of nano-objects



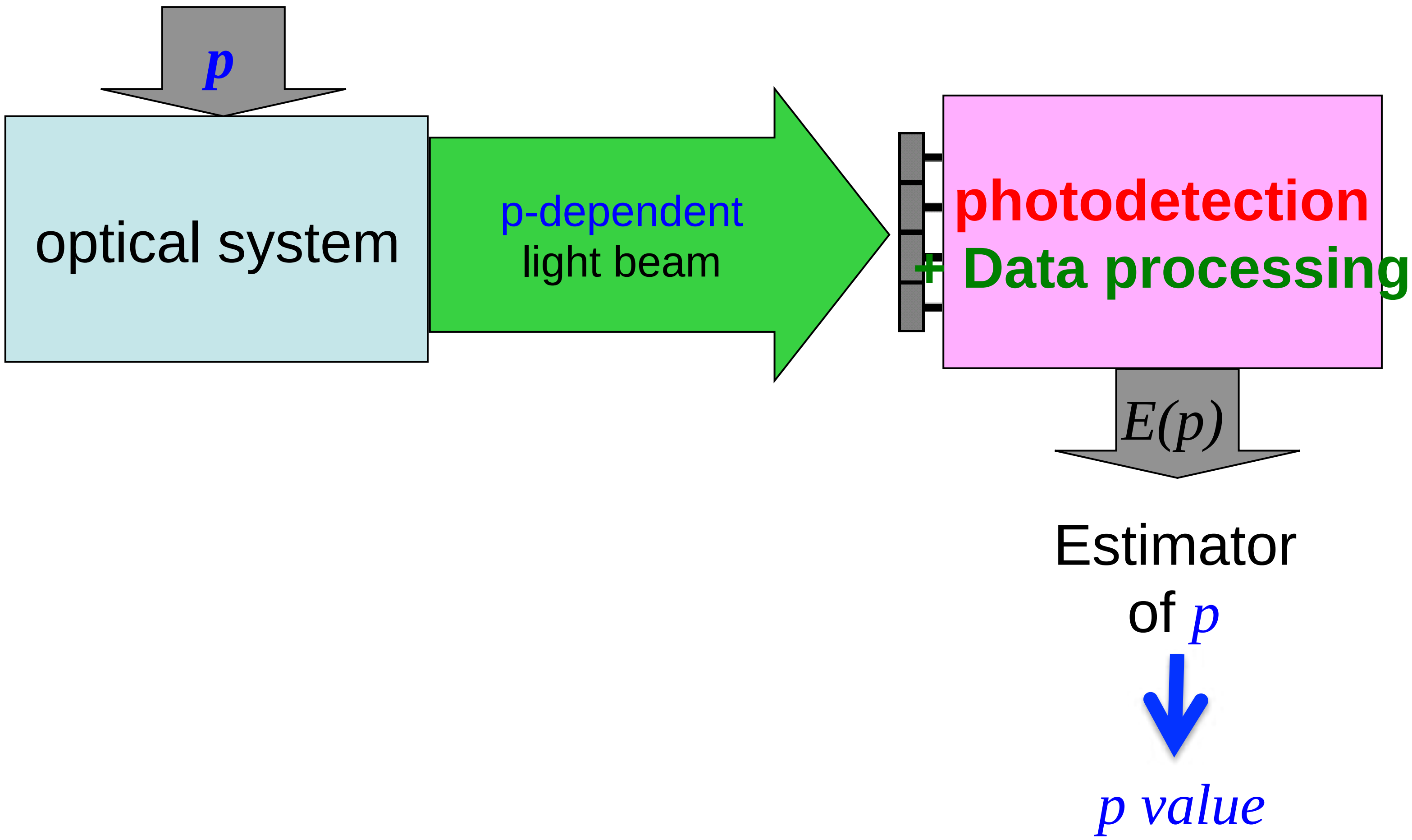
Imaging Intracellular Fluorescent
Proteins at Nanometer Resolution
E. Betzig et al Science **313** 1642 (2006)

Resolution much better than the wavelength:
about 2 nm

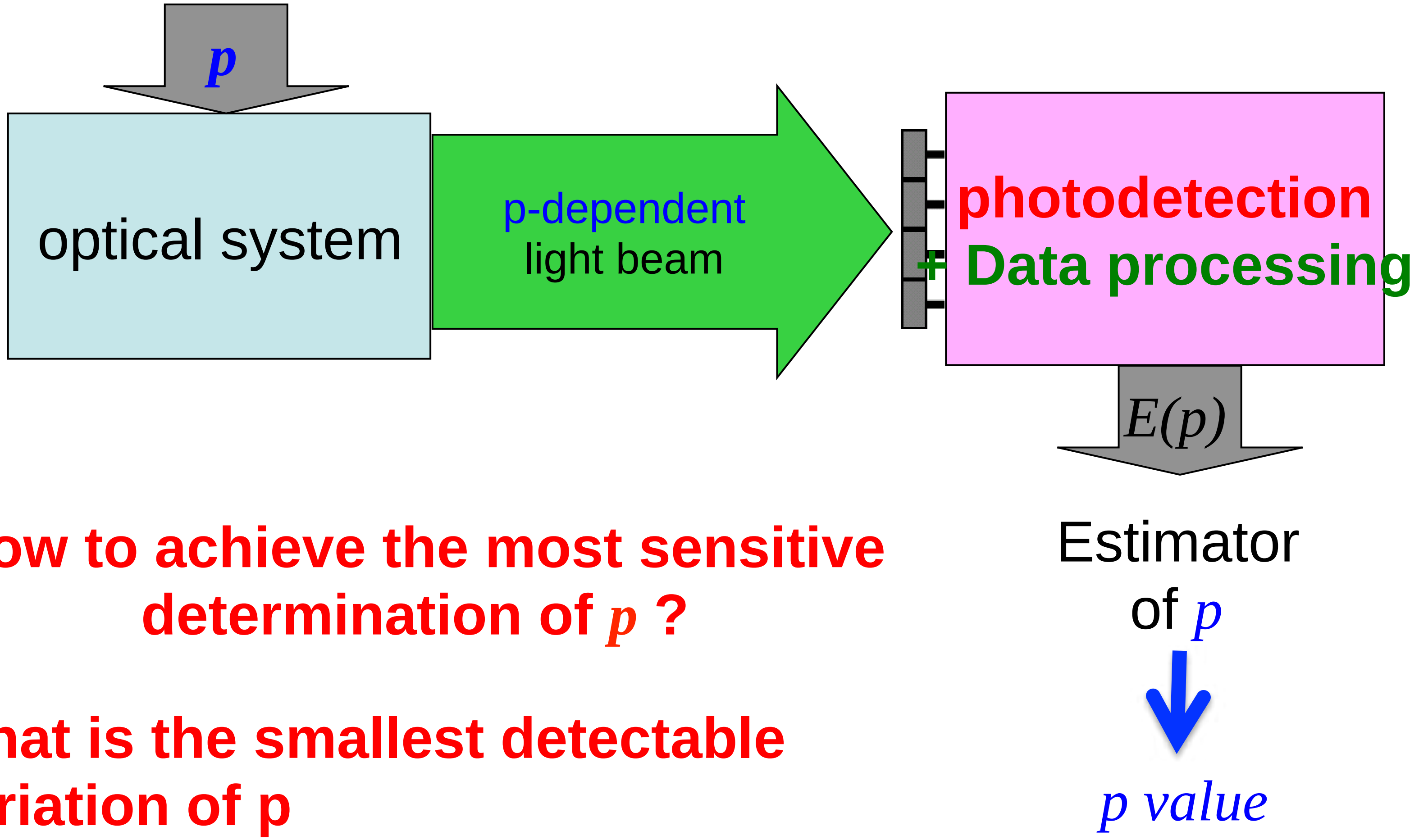
method for transverse position measurement:



General scheme for estimating a parameter p using information carried by light



General scheme for estimating a parameter p using information carried by light



How to achieve the most sensitive determination of p ?

What is the smallest detectable variation of p due to quantum uncertainty ?

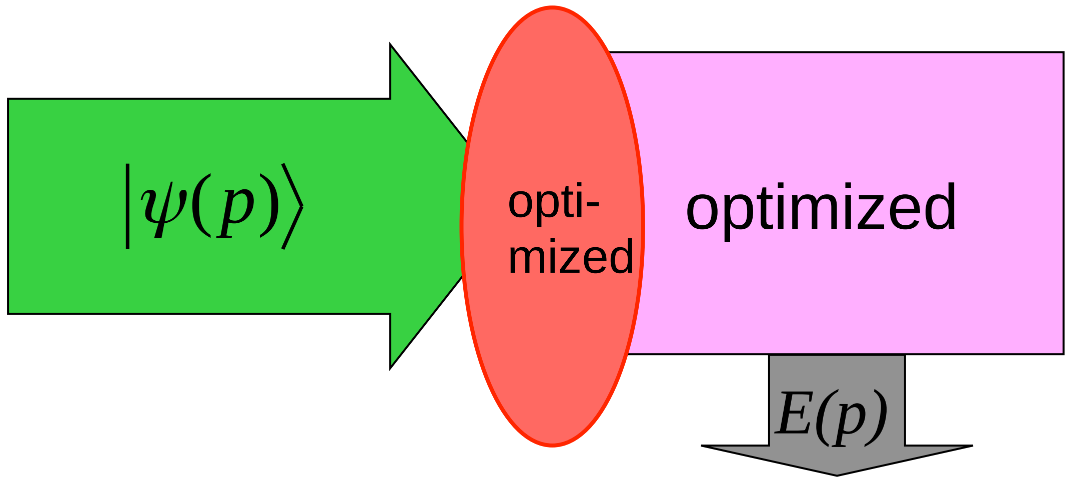
Quantum estimation theory

Helstrom (1976)
Caves, Braunstein (1994)

gives the limit optimized
over all possible data processing procedures
and over all possible measurements operated on light

Quantum Cramer-Rao bound

depends only on the **quantum state of light**
on which the measurement is done

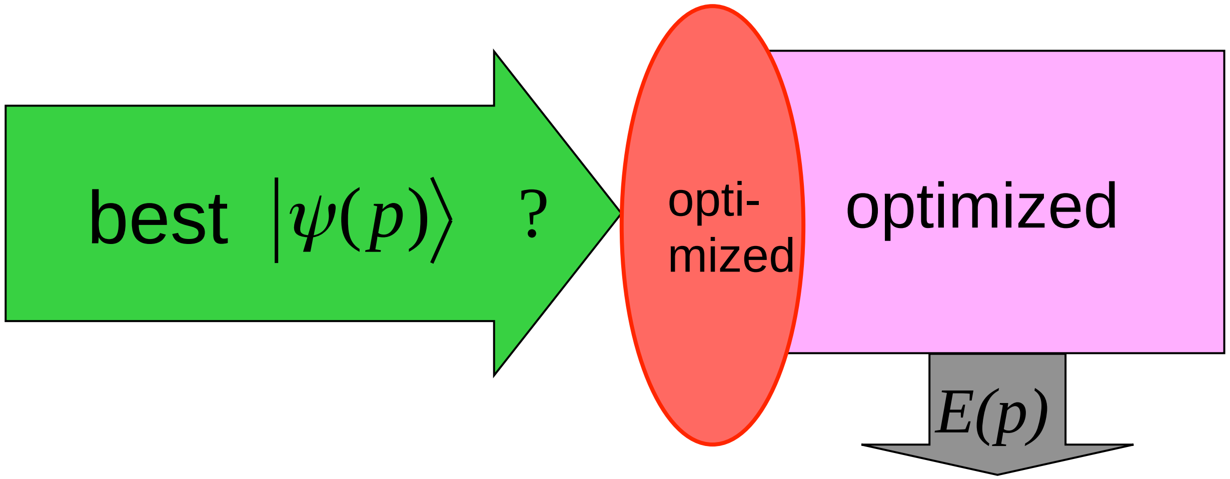


What remains to be chosen to improve further the estimation :

the quantum state of light

$$\left|\Psi(p)\right\rangle$$

used to carry the information in the experiment



a practical choice : the multimode Gaussian pure state

includes **a wide class of non-classical states**

- single and multimode squeezed states
- Einstein Podolsky Rosen paper state
- multipartite quadrature entangled states
- if it includes a coherent state in one mode:

  $\langle N \rangle = 10^{15}$ easy to reach
- readily available (12 dB squeezing)

multimode Gaussian pure state

M modes of arbitrary shape, with quadratures X_i , Y_i

$$\mathbf{Q} = \left(X_1,\ldots,X_M,Y_1,\ldots,Y_M\right)^T$$

entirely defined by the 2M*2M covariance matrix
in a given mode basis

choice of: - number of modes,
- covariance matrix
- **the spatio-temporal shape of modes**

Introduction of relevant modes

average mode :
spatio-temporal dependence of the average field value

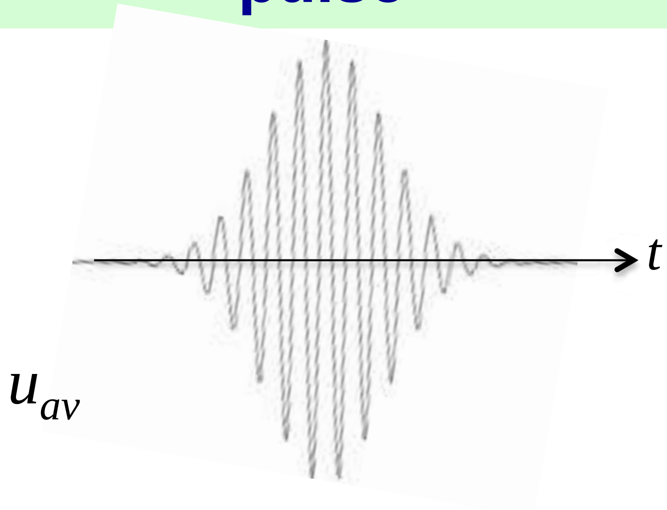
$$u_{av}(x,y,t,p)=\frac{1}{\sqrt{N}}\left\langle\psi\left(p,t\right)\middle|\hat{E}^{(+)}(x,y)\middle|\psi(p,t)\right\rangle$$

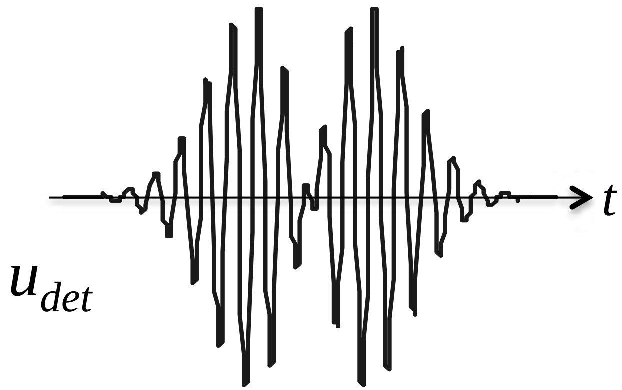
detection mode :
sensitivity of illumination mode to the parameter variation

$$u_{\det}(x,y,t)=p_c\left.\frac{\partial u_{av}}{\partial p}\right|_{p=p_0}$$

normalizing factor

Moon ranging example using Gaussian light pulse





Quantum Cramer Rao bound for Gaussian pure states

p-sensitivity

expression in the high N limit:

$$\Delta p_{QCRb} = \frac{p_c}{2\sqrt{N}} \frac{1}{\sqrt{\left(\Gamma^{-1}\right)_{11}}}$$

« shot noise »

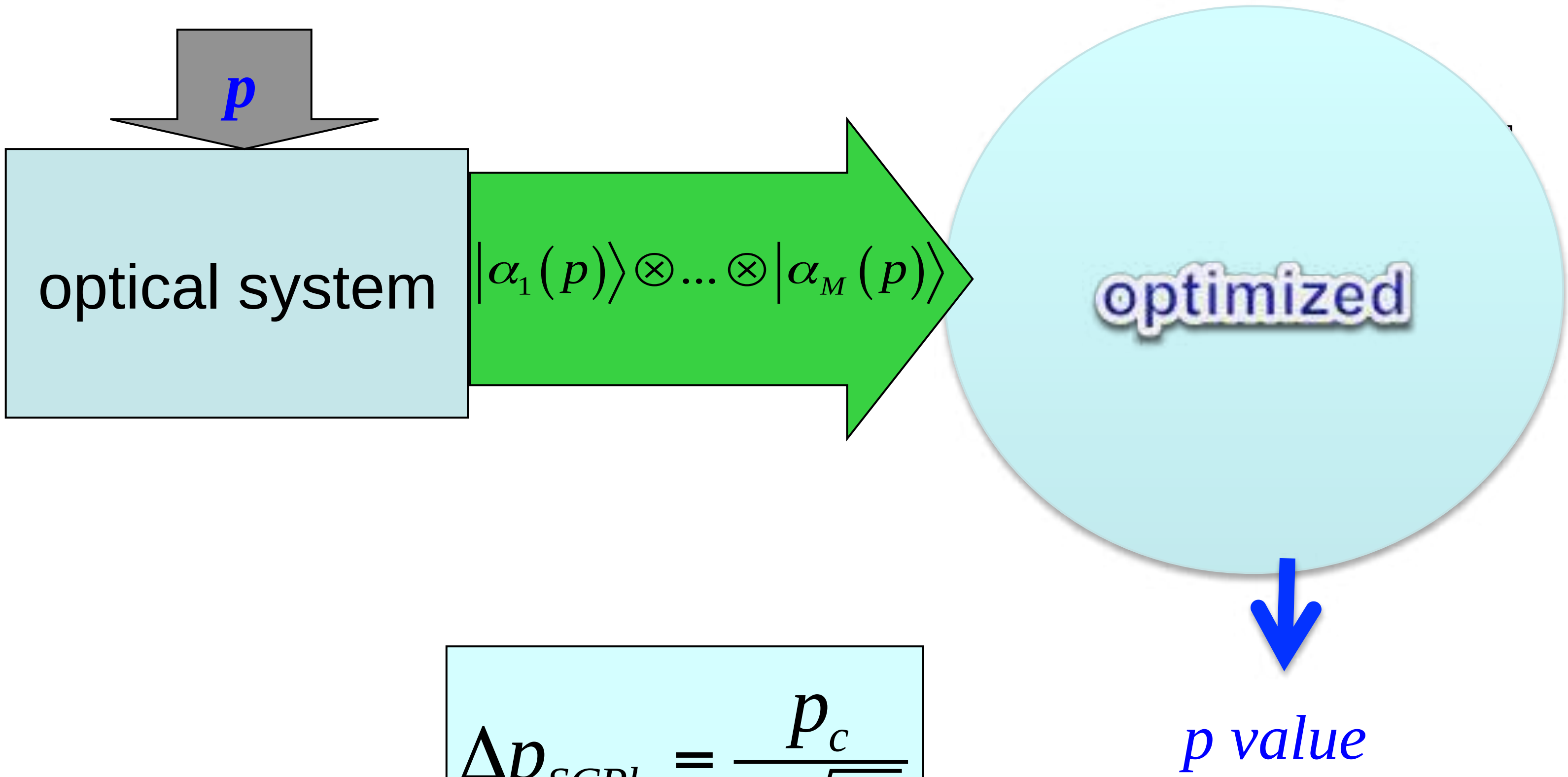
noise term

Diagonal element of the inverse covariance matrix in the detection mode u_{det}

value independent
of the fluctuations of all modes orthogonal to u_{det}

Standard Quantum Cramer Rao bound

When only coherent states are used

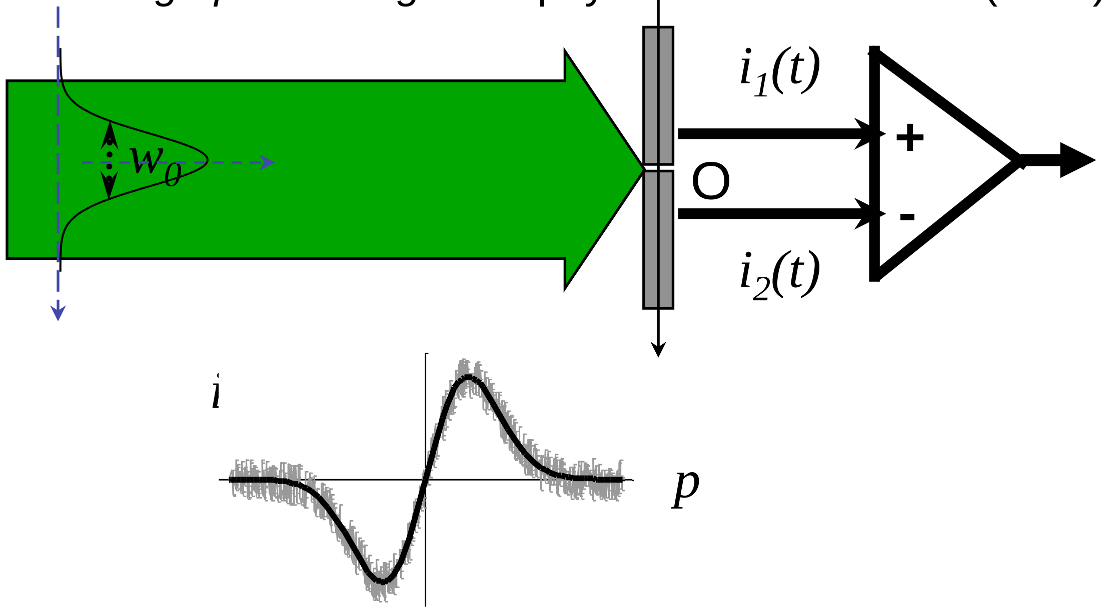


$$\Delta p_{SCRb} = \frac{p_c}{2\sqrt{N}}$$

optimized shot noise limit

Usual technique for beam positioning
split detector technique

V. Delaubert, N. Treps, C. Fabre, H. Bachor, P. Réfrégier,
"*Quantum limits in image processing*" Europhys. Letters **81** 44001 (2008)

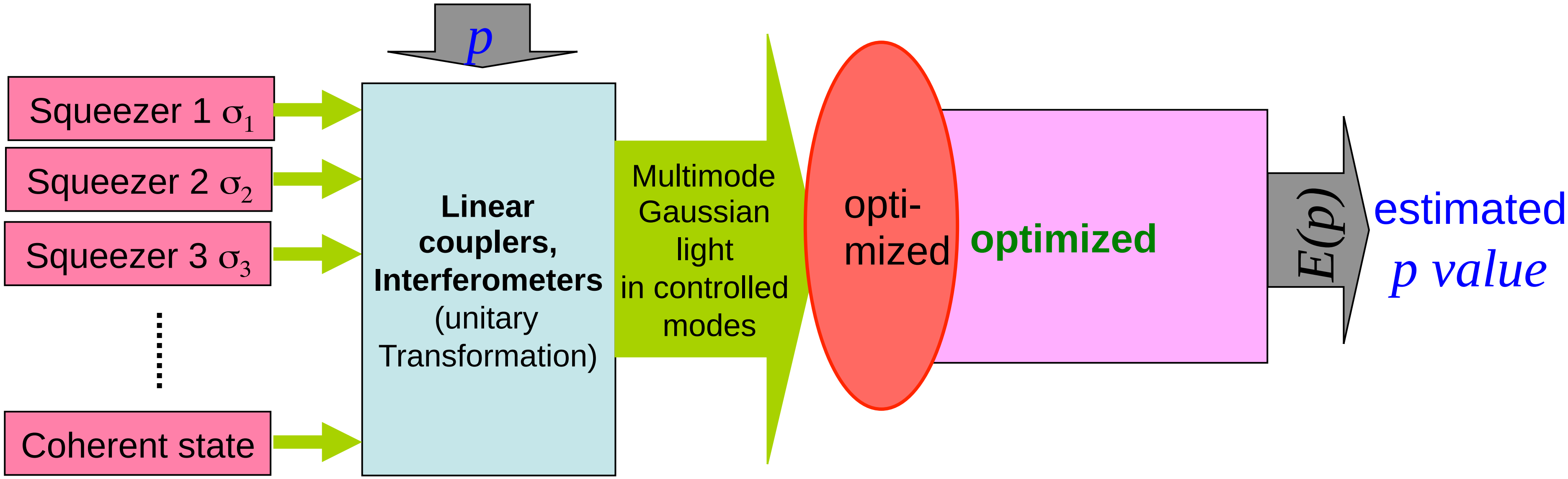


sensitivity limit in split detector technique using a coherent state:

$$(\Delta p)_{\text{split}} = \frac{\sqrt{8}}{\pi}\frac{w_0}{\sqrt{N}} = 1.22(\Delta p)_{\text{S-CRb}}$$ > Cramer Rao limit

split detector technique is not the optimum technique !

Quantum Cramér Rao bound using non-classical Gaussian resources



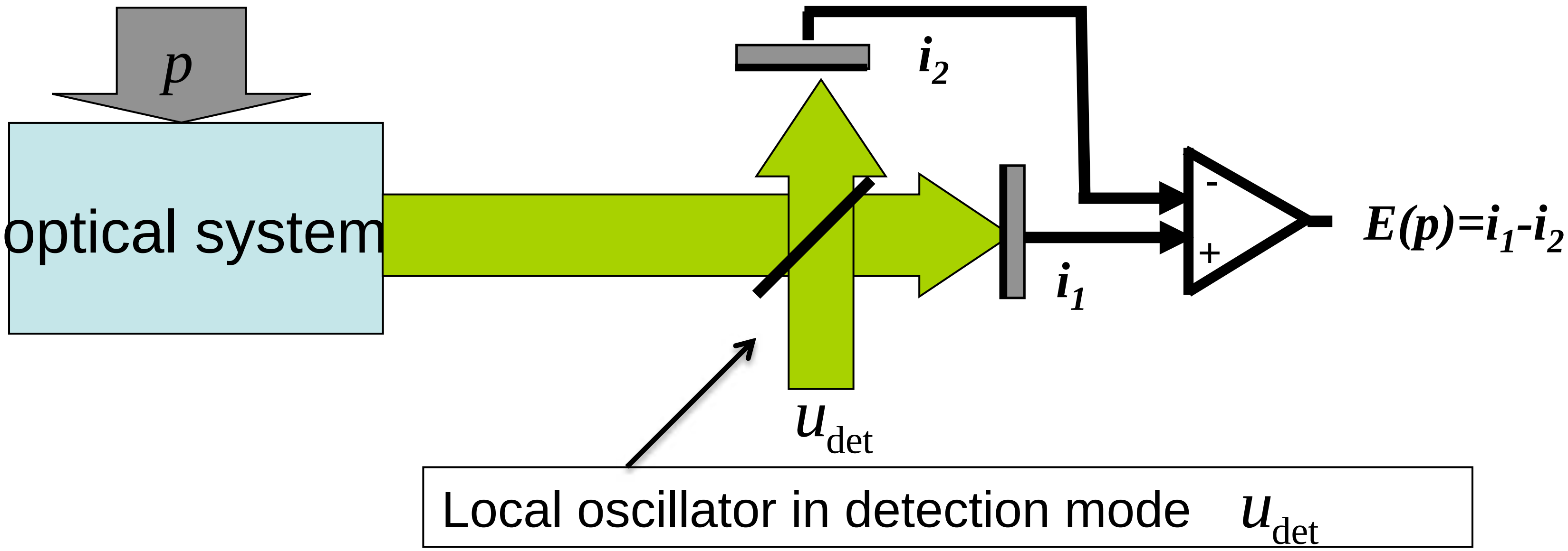
$$\Delta p_{CRb} = \frac{p_c}{2\sqrt{N}}\sqrt{\sigma_{\min}} \qquad \sigma_{\min} = Min\{\sigma_1, \sigma_2, \ldots, \sigma_s\}$$

The lowest Quantum Cramér Rao bound is obtained when the most squeezed beam available is put in the detection mode :

single mode squeezing is enough when it is put on the right mode

One possible way to reach the Quantum Cramer Rao bound

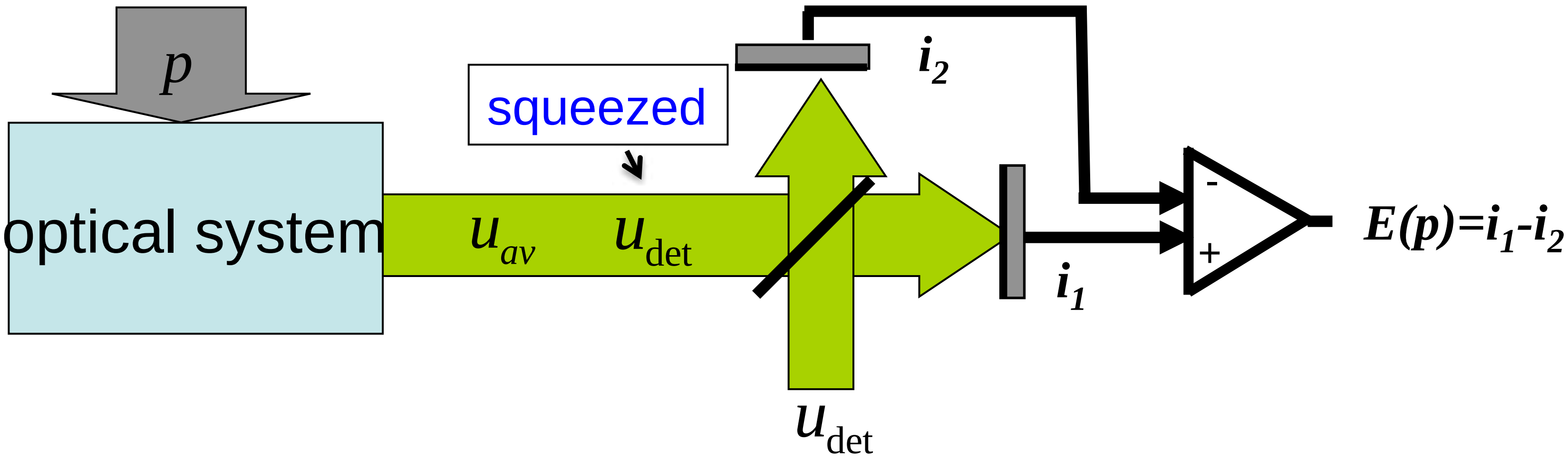
use balanced homodyne detection
with the local oscillator in the detection mode



How to make an estimation below the standard QCR bound ?

use a two-mode non-classical state, tensor product of :

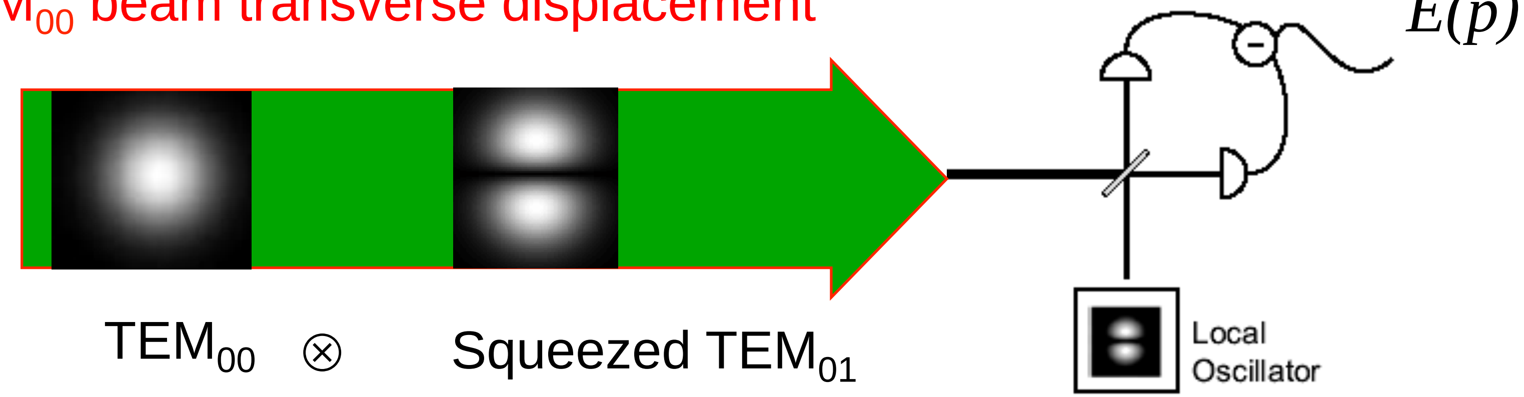
- coherent state in mode u_{av}
- a squeezed vacuum in mode $u_{\det}$



no other measurement starting from u_{av} (given mean field) can do better

Experimental implementations

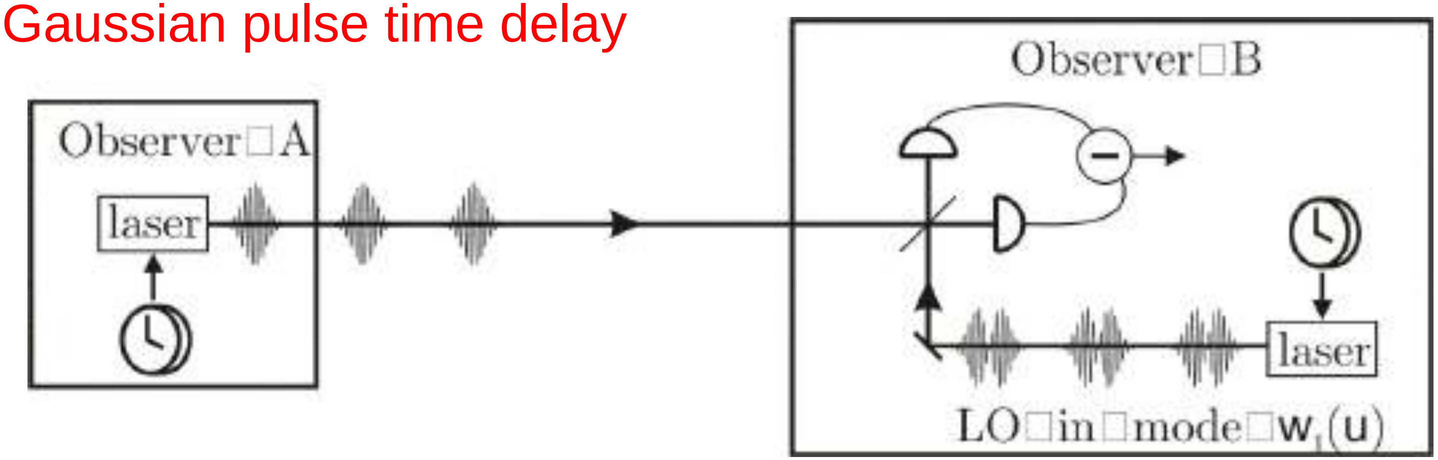
TEM$_{00}$ beam transverse displacement



TEM$_{00}$ $\otimes$ Squeezed TEM$_{01}$

experiment done in Canberra (ANU LKB collaboration) M. Lassen et al. PRL98, 083602 (2007)

Gaussian pulse time delay



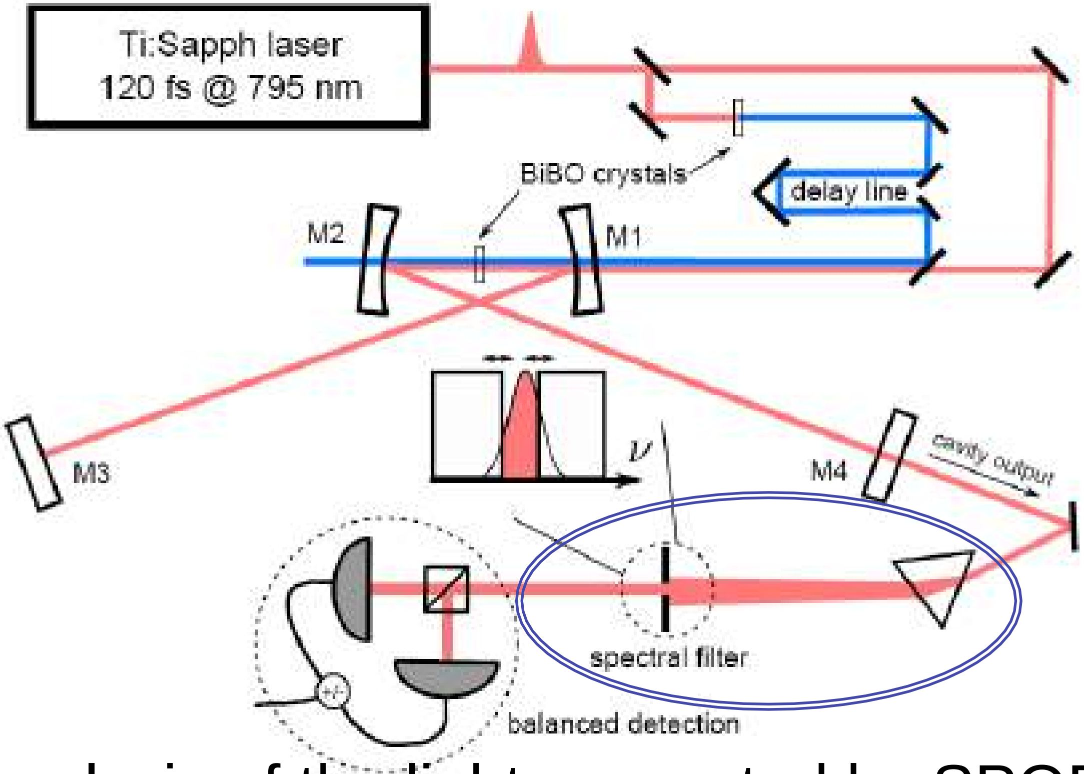
experiment in progress in Paris (Nicolas Treps)

-III-

Experiments on quantum frequency combs

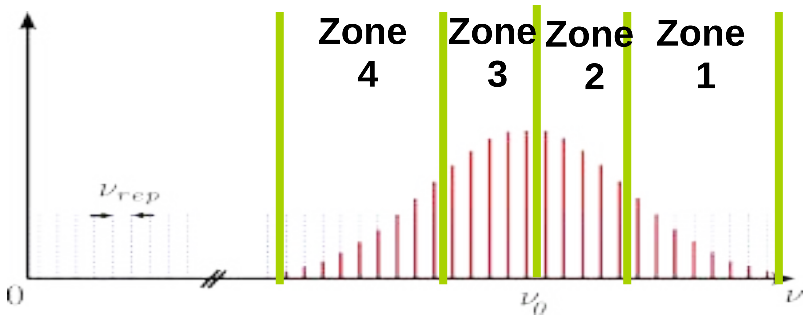
Experiment at LKB

Generation and characterization of multimode quantum frequency combs
O. Pinel, Pu Jian, R. Medeiros, Jingxia Feng, B. Chalopin, C. Fabre, N. Treps
Phys. Rev. Letters **108,** 083601 (2012)

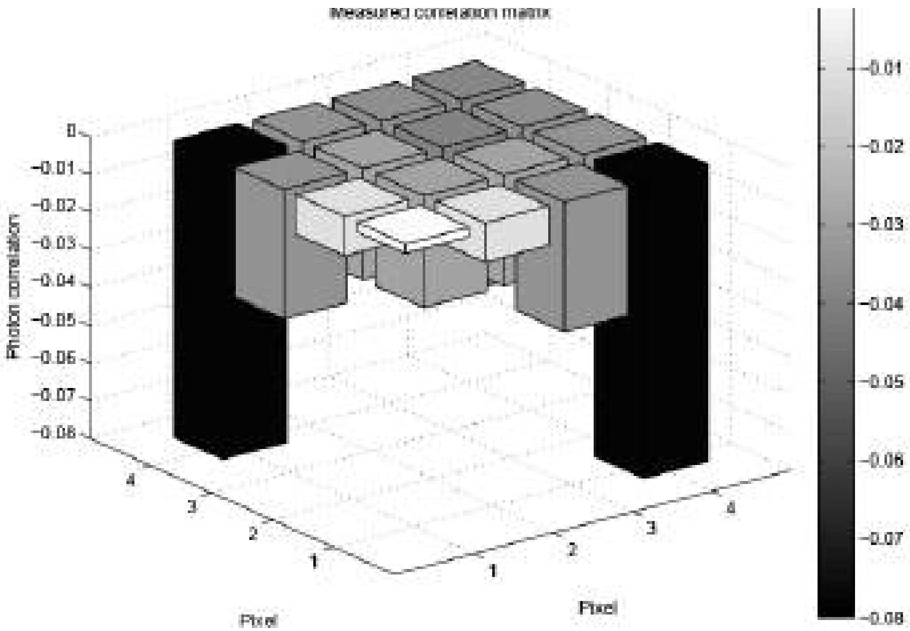


spectral analysis of the light generated by SPOPO

Existence of quantum intensity correlations between different frequency zones of the SPOPO



Experimental intensity correlation matrix



generation of multimode non classical state

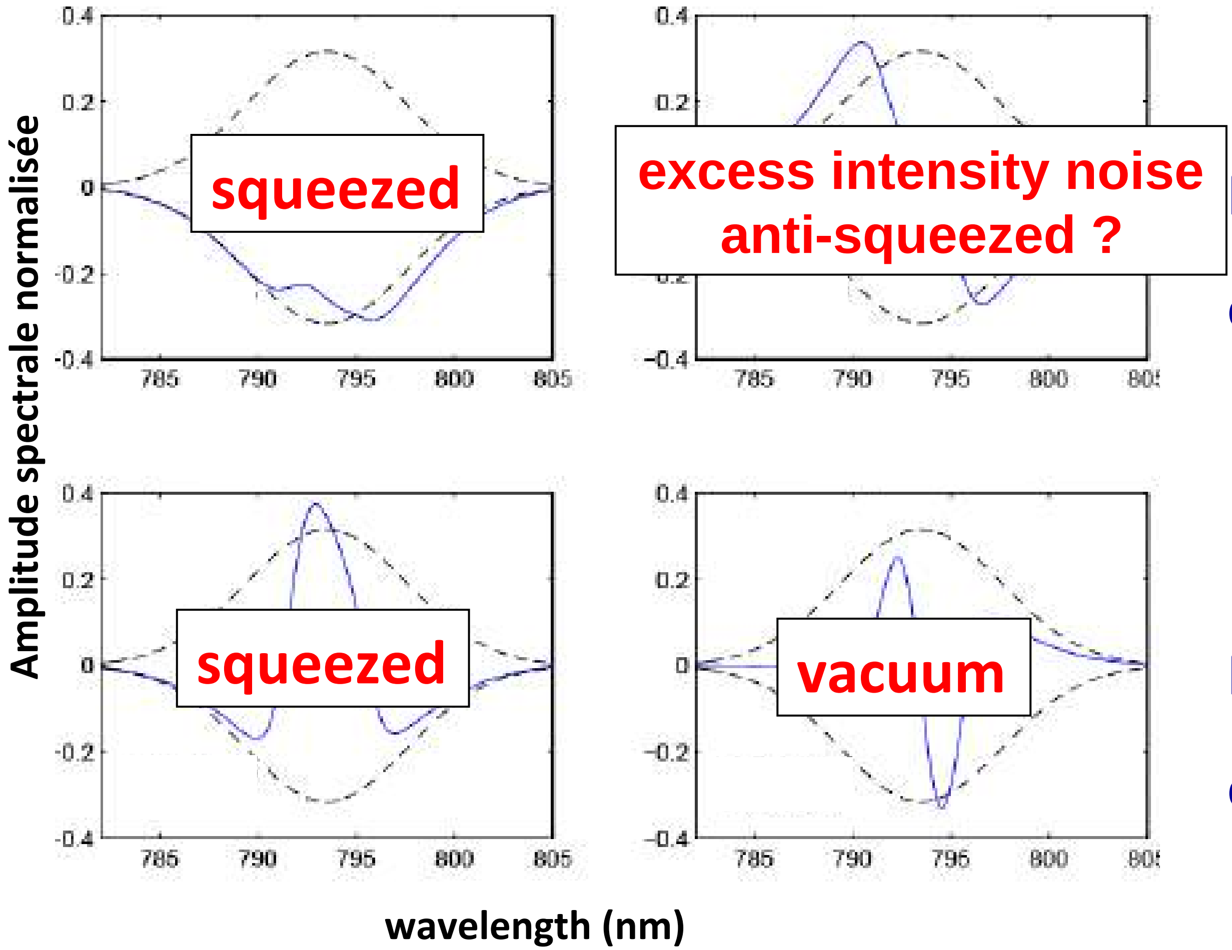
diagonalization of the covariance matrix

P=96%

σ^2=0.86

P=1%

σ^2=1.06



P=3%

σ^2=0.98

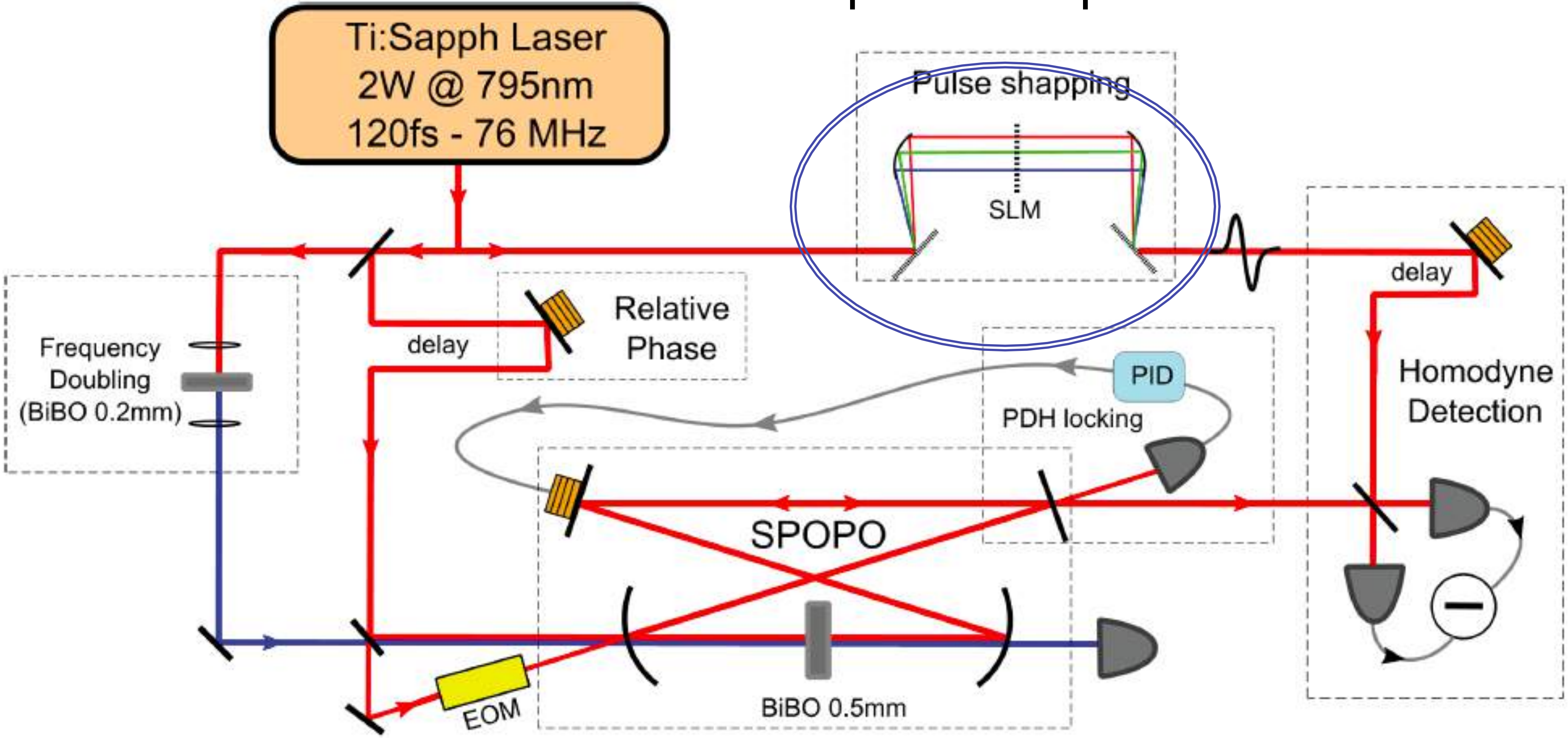
P=0%

σ^2=0.99

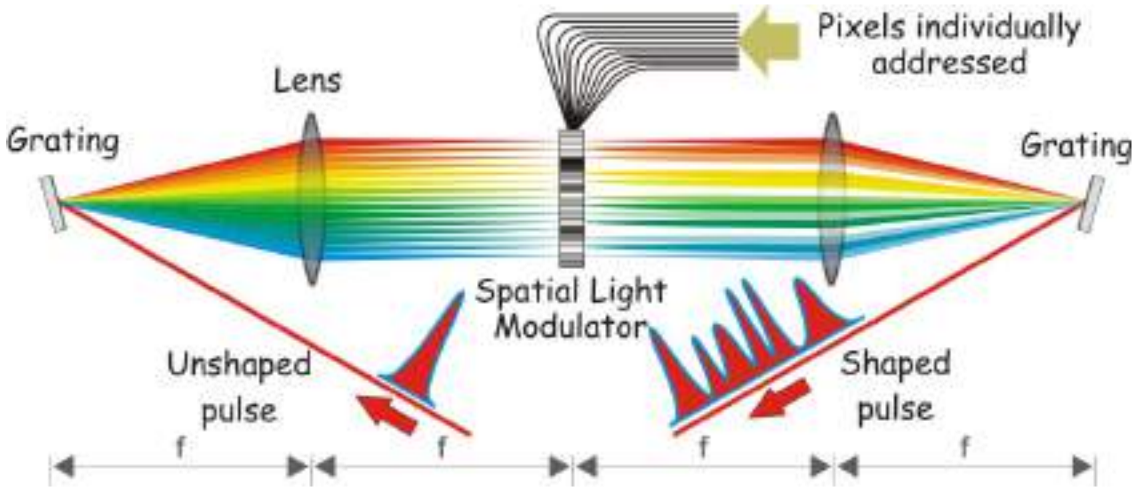
at least three modes involved

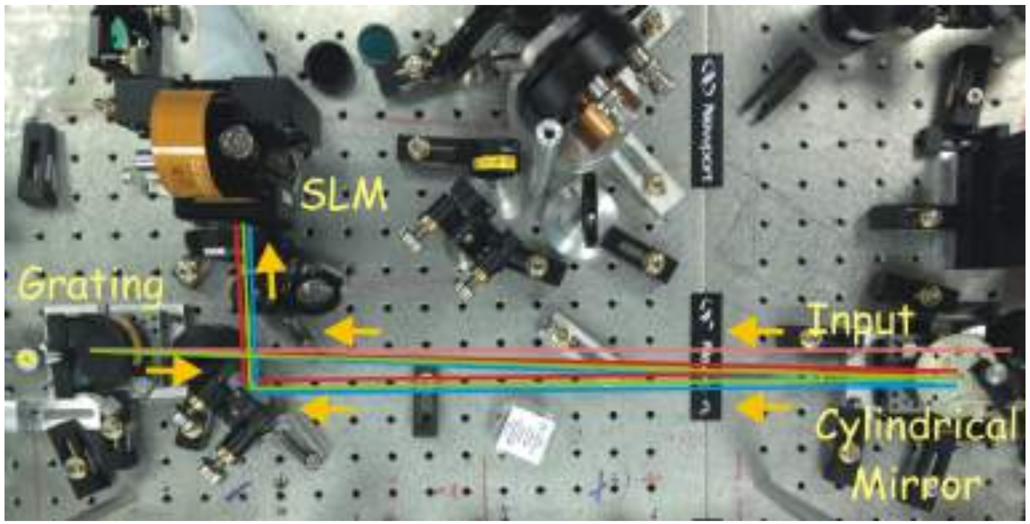
New experimental set-up

homodyne detection
with pulse shaped local oscillator

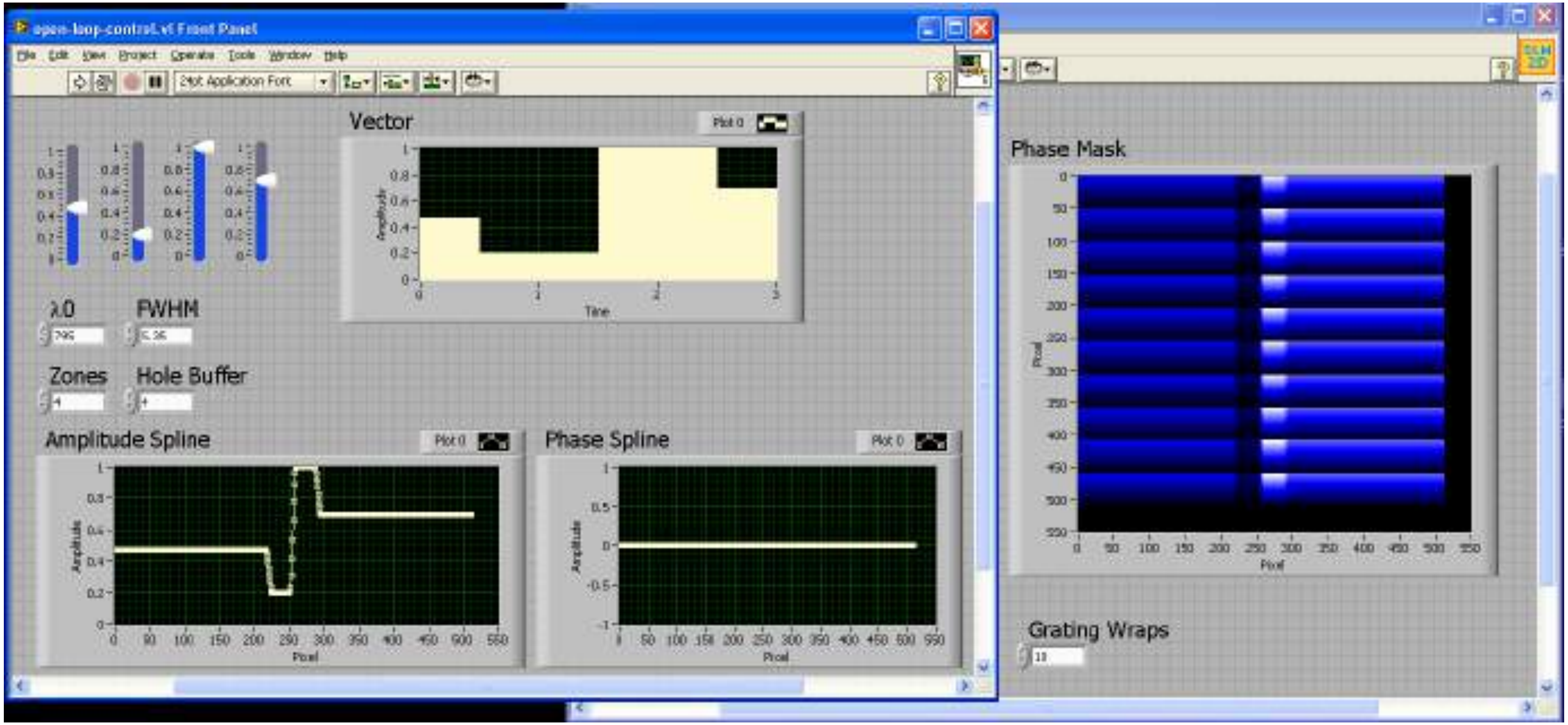


800nm near-infrared Pulse Shaper



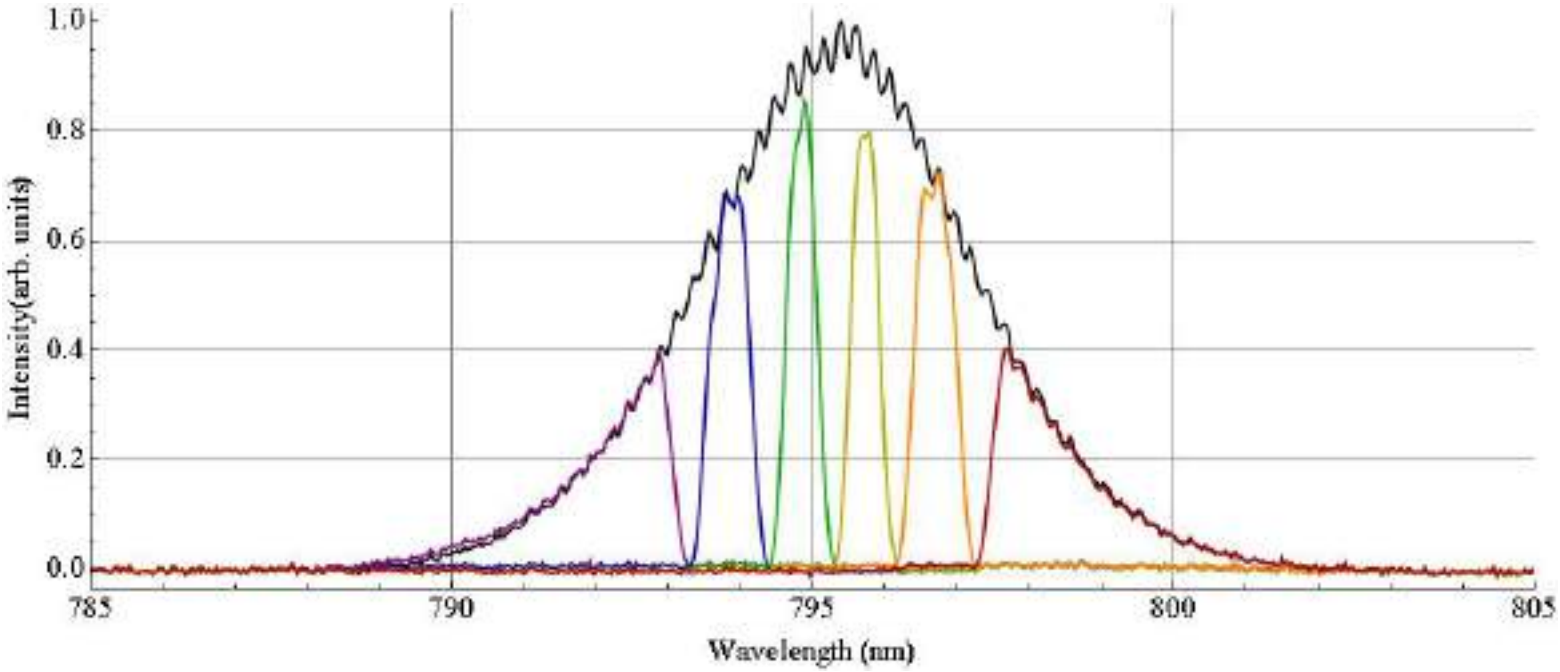


Arbitrary Amplitude Shaping achieved with SLM



Pixelization of Spectral Amplitude

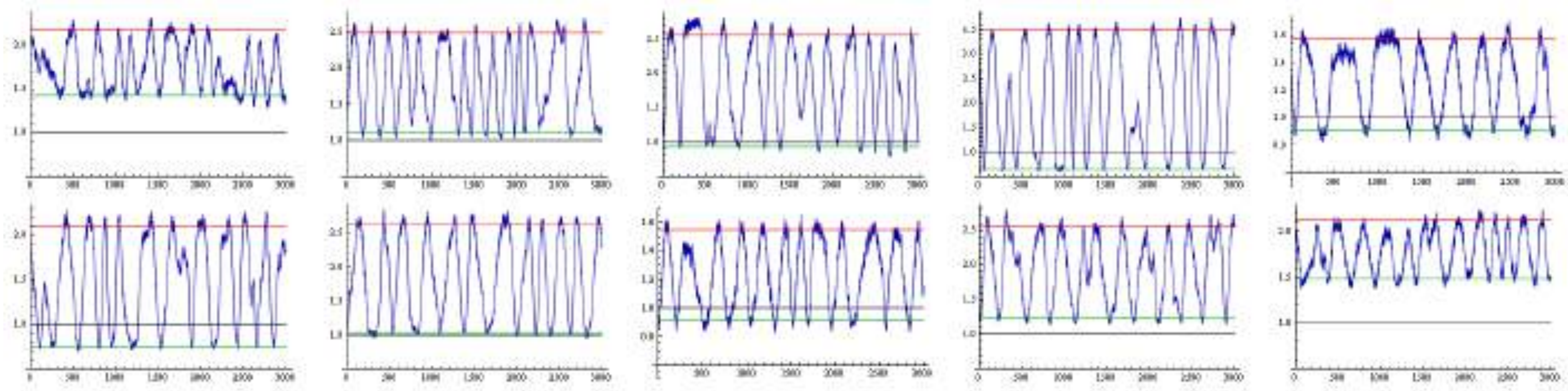
- Divide spectrum into multiple zones (e.g., 4,6,8,10) of equal energy with amplitude shaping



- Measure the noise variance associated with each zone and pair of zones:

$$\mathrm{var}\left[\sqrt{r}\cdot a+\sqrt{t}\cdot b\right]=r\cdot\mathrm{var}(a)+t\cdot\mathrm{var}(b)+2\cdot\sqrt{r\cdot t}\cdot C_{ab}$$

Squeezing Curves for 4 Pixels



- **Red** = Anti-squeezed mean value
- **Black** = Shot noise
- **Green** = Squeezed mean value

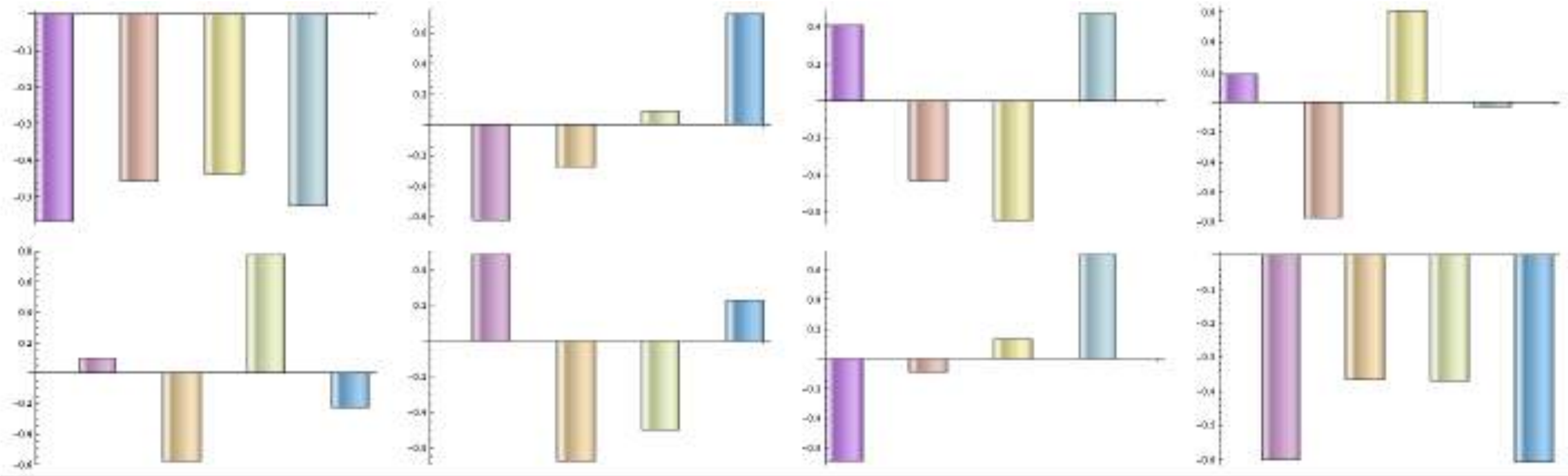
4 Pixel Covariance Matrix

$$\begin{pmatrix}
1.42916 & 0 & -0.0671537 & 0 & -0.246325 & 0 & -0.808429 & 0 \\
0 & 2.18208 & 0 & 0.59928 & 0 & 0.687822 & 0 & 1.35501 \\
-0.0671537 & 0 & 0.910803 & 0 & -0.161434 & 0 & -0.206797 & 0 \\
0 & 0.59928 & 0 & 1.57547 & 0 & 0.53196 & 0 & 0.751954 \\
-0.246325 & 0 & -0.161434 & 0 & 0.91524 & 0 & 0.00674628 & 0 \\
0 & 0.687822 & 0 & 0.53196 & 0 & 1.54957 & 0 & 0.690594 \\
-0.808429 & 0 & -0.206797 & 0 & 0.00674628 & 0 & 1.48186 & 0 \\
0 & 1.35501 & 0 & 0.751954 & 0 & 0.690594 & 0 & 2.1208
\end{pmatrix}$$

4 Pixel Eigenvalues / Eigenvectors

- Matrix Eigenvalues (dB):

(-3.6106, -1.17252, -0.182924, 0.191394, 0.1937, 1.07816, 3.61313, 6.37203)



- 3 squeezed modes in 4 pixel case...

done also for 8 pixels : 7 squeezed modes measured

next step : tailor the squeezed modes by pulse shaping the pump


Nicolas Treps
docs :
Gaelle Keller
Vincent Delaubert
Benoit Chalopin
Giuseppe Patera
Olivier Pinel
Jean-François Morizur
Renné Medeiros
Pu Jian
Roman Schmeissner
Cai Yin
postdocs :
Jinxia Feng
Shifeng Jiang
Jonathan Rosslund
Giulia Ferrini


RESTAURANT
TRADITIONNE
docs :
Gaelle Keller
Vincent Delaubert
Benoit Chalopin
Giuseppe Patera
Olivier Pinel
Jean-François Morizur
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Benoit Chalopin
Giuseppe Patera
Olivier Pinel
Jean-François Morizur
Renné Medeiros
Pu Jian
Roman Schmeissner
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postdocs :
Jinxia Feng
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Jonathan Rosslund
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