QUANTUM OR NON-QUANTUM, CLASSICAL OR NON-CLASSICAL STATES OF LIGHT ???

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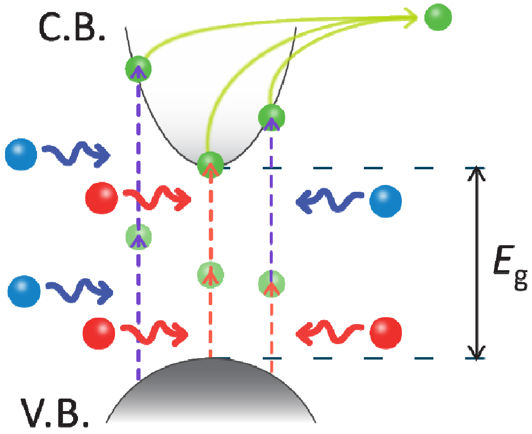
The trigger: Fabien Boitier thesis work

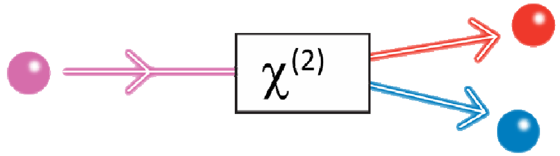
$g^{(2)}$ measurement using two-photon absorption in a semi-conductor

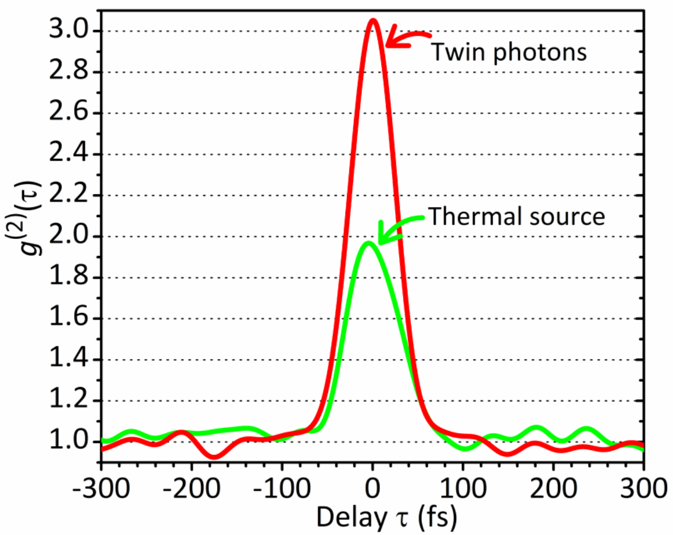
resolution in the femtosecond range

*F. Boitier, A. Godard, E. Rosencher, C. Fabre Nature Physics, **5** 267 (2009)*



measurement on the total light generated by high gain parametric down converter





$$\boxed{g^{(2)}(0) = 3}$$

Evidence of an extrabunching effect

is it a quantum effect ??

Summary:

1- quantum or non-quantum ?

2- classical or non-classical ?

3- the special case of correlations

first part:

QUANTUM OR NON-QUANTUM ?

in 2011,
quantum mechanics
is the general theoretical frame
for the description of physical phenomena

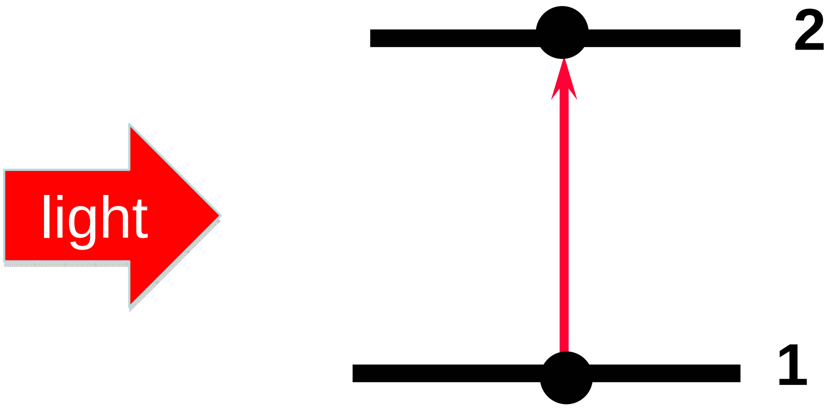
everything is quantum

there are no non-quantum phenomena ← ?

every physical phenomenon, even "classical"
has a quantum explanation

may be, there exist non-quantum phenomena

quantum and classical explanations may coexist



- absorption of a photon
  with conservation of energy and momentum

- quantum jump in the atom induced
  by the classical electromagnetic wave

the coexistence of different pictures often
sheds a new light on the considered phenomenon

a famous example : the dressed atom approach
(Cohen-Tannoudji Haroche)

second part:

CLASSICAL, NON CLASSICAL

or SEMI-CLASSICAL ?

What does classical mean?

Dictionary

"classicality" is a subjective notion,

related to "classes"

i.e. to what we have learnt at the University

2011 non-classicality is different from 1981 non-classicality

there are **different levels** of non-classicality

some phenomena are "**semi-classical"**

Possible definition of a **classical phenomenon**:

can be described by :

Classical electrodynamics (CED):

- Maxwell equations,
- if necessary, statistical fluctuations of the physical parameters

and

Classical mechanics (CM):

- Newton, or Hamilton equations,
- if necessary, statistical fluctuations of the physical parameters

Possible definition of a **non-classical phenomenon**:

there is $\hbar$ somewhere in the expression of its properties

Possible definitions of a **semi-classical phenomenon:**

1) can be described by CED, but not by CM

2) can be described by CM, but not by CED

semi-classical phenomena are not semi-quantum phenomena !!

When is **light** alone non classical ?

when at least one of its properties
cannot be explained by semi-classical theory 1
Classical ElectroDynamics + Quantum matter

$\Longrightarrow$ many quantitative sufficient criteria:

- when intensity fluctuations are sub Poissonian, or sub shot noise

$$\Delta N < \sqrt{\overline{N}}$$

- when normalized intensity correlation is smaller than 1

$$g^{(2)}(\tau) = \frac{\overline{I(0)I(\tau)}}{\left(\overline{I(0)}\right)^2} < 1$$

- when Glauber representation P is non positive

$$\rho = \int d\alpha\, P(\alpha) |\alpha\rangle\langle\alpha|$$

Non classical states of light :

- Fock states $|N\rangle$

- Squeezed states

- Schrödinger cats ...

light states at the border:

- vacuum state $|0\rangle$

vacuum fluctuations, vacuum energy contains $\hbar$

- coherent, or "quasi-classical states" $|\alpha\rangle$

have same fluctuations as vacuum,
can be used in quantum cryptography

small coherent states are non-classical, $|\alpha\rangle, \quad |\alpha| \approx 1$

A criterion using quasi-probability distributions ?

A quantum state of light can also be described by real functions allowing us to determine the probability distributions of different parameters of light

- Glauber distribution $P(\alpha)$
- Wigner distribution $W(\alpha)$
- Husimi distribution $Q(\alpha)$

if the functions are everywhere positive, they have all properties of classical probability distributions :

the quantum fluctuations look like classical fluctuations,
but with a variance proportional to $\hbar$

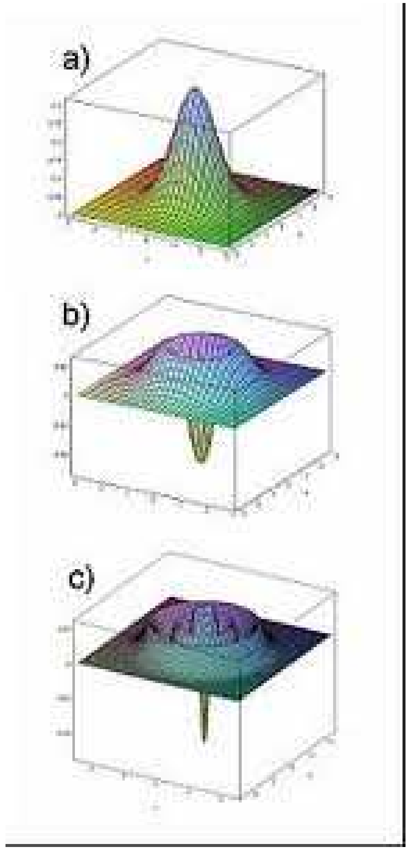
if the functions are somewhere negative

the quantum fluctuations do not look like classical fluctuations

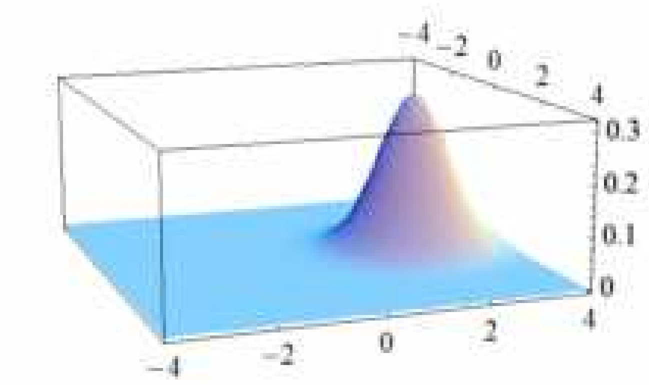
another level of non-classicality

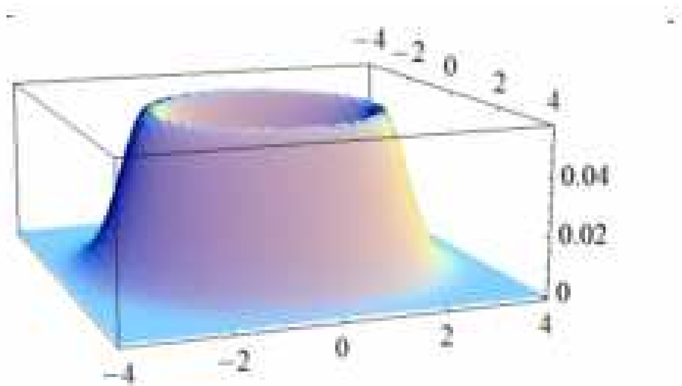
Which probability distribution ?

- Glauber distribution $P(\alpha)$ is often not regular
- Wigner distribution $W(\alpha)$ is regular
  and distinguishes
  between squeezed states or coherent states
  (Gaussian distribution)
  and more non-classical states



- Husimi distribution $Q(\alpha)$
  is regular and always positive

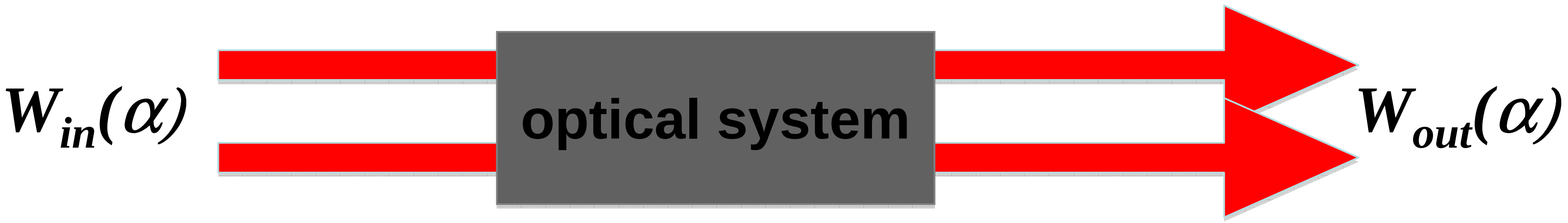




Why is $W(\alpha)$ is generally chosen as the correct quasi-probability distribution ?

directly related to the measurement of field quadratures,
i.e. to the measurement of amplitude and phase of the field

$W(\alpha)$ has unique propagation properties



$$W_{out}(\alpha)=W_{in}(T(\alpha))$$

$T(\alpha)$ is the classical field propagation
for all symplectic transformations,
which includes a large set of non-linear optical devices

third part:

CORRELATIONS:

QUANTUM OR CLASSICAL ?

CORRELATION is a classical concept

- Phenomena that occur statistically at the same time

- implies "mutual information": knowledge on one part gives information on the other

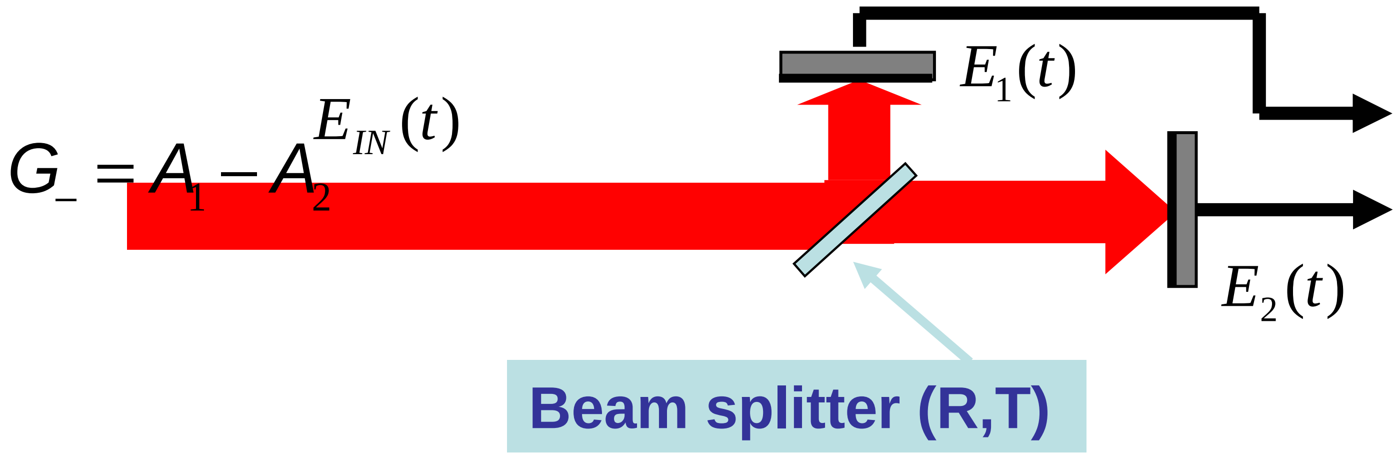
Measured by the correlation function:

$$C_{12} = av\left(A_1 A_2\right) - av\left(A_1\right) av\left(A_2\right)$$

$$c_{12} = \frac{C_{12}}{\sqrt{av\left(\delta A_1^2\right) av\left(\delta A_2^2\right)}} \qquad -1 \leq c_{12} \leq 1$$

even « distant » correlations can be classical

CORRELATION BETWEEN BEAMS PRODUCED BY A BEAM-SPLITTER



$$\boxed{c_{12} = \frac{F-1}{\sqrt{F^2+1+F/RT}}}$$

F : Fano factor of input beam (beam noise normalized to shot noise)

$$F \to +\infty \qquad \Rightarrow \qquad c_{12} \to 1$$

Maximum correlation achieved with the most classical input field !

One does not need quantum correlations to have strong and useful correlations (example : ghost imaging)

WHAT IS A QUANTUM CORRELATION ?

No definite answer to this question : one can define

various degrees of quantum correlations

N. Treps, C. Fabre, Laser Physics **15**, 187 (2005)

1) FIRST QUANTUM LEVEL: twin beams
(technical property of the system)

impossibility of a classical description of the correlated beams

in terms of classical fluctuating fields

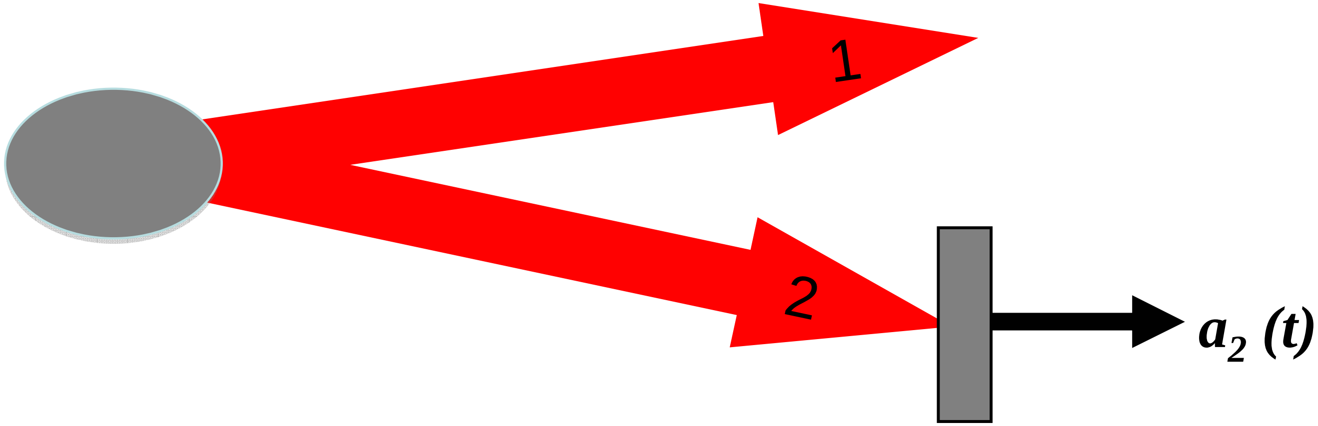
$$G = \frac{F_1 + F_2}{2} - \sqrt{c_{12}^2 F_1 F_2 + (F_1 - F_2)^2 / 4}$$

« Gemellity » noise on the intensity difference when $F_1=F_2$

(characterizes « twin beams »)

$G < 1$ $\Rightarrow$ Impossibility of a classical description of the correlated beams

2) SECOND QUANTUM LEVEL : QND beams (measurement point of view)



Measurement on beam 2 provides information on beam 1 at the quantum level

Quantum Non Demolition measurement criterion

(P. Grangier, JM Courty, S. Reynaud Opt. Commun. **89** 99 (1992))

« Conditional variance » $\rightarrow$ $V_{1|2} = F_1\left(1 - c_{12}^2\right)$

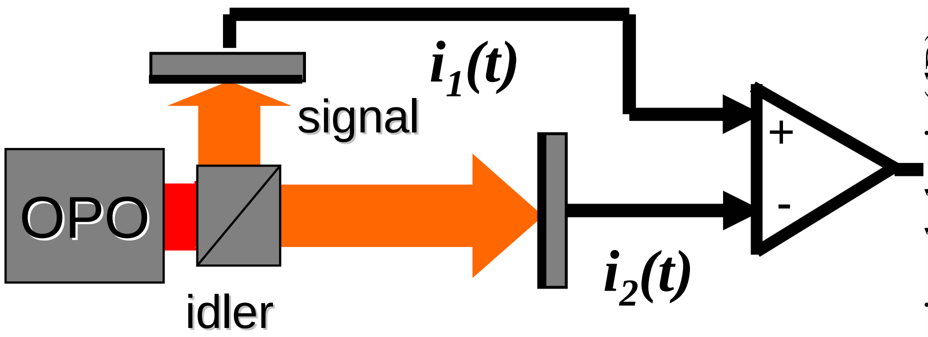
$V_{1|2} < 1 \Rightarrow$ possibility of a QND measurement of beam 1 using the correlation

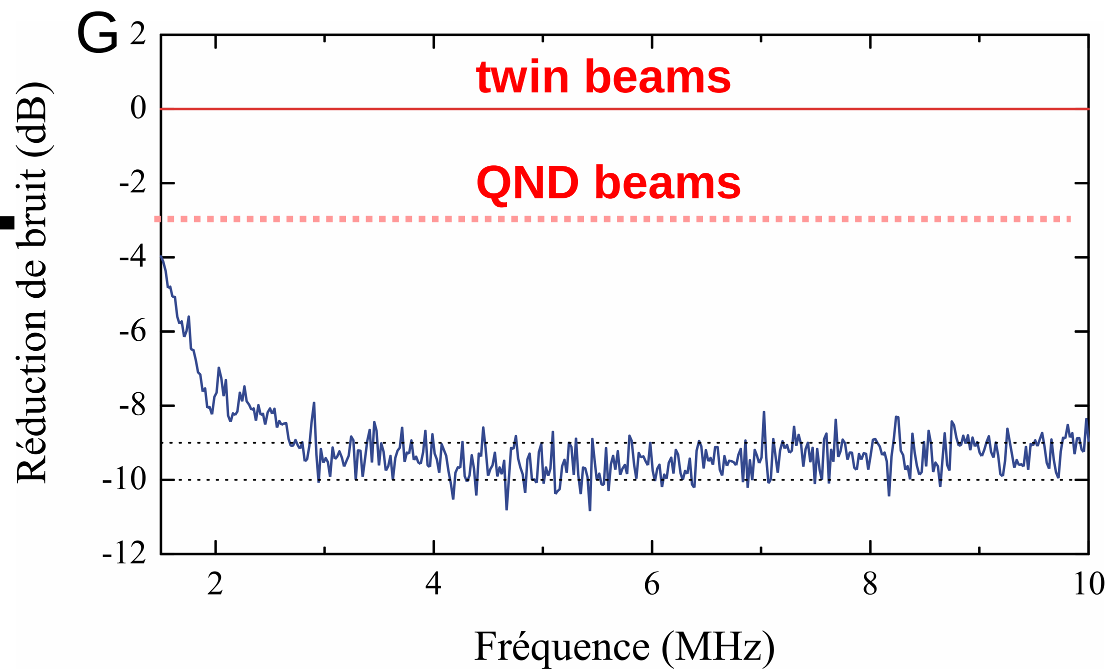
Comparison between the two criteria

$$\Rightarrow \qquad G \le V_{1|2} \le 2G$$

Second level is « stronger » than first level:

GENERATION OF TWIN BEAMS BY OPOS

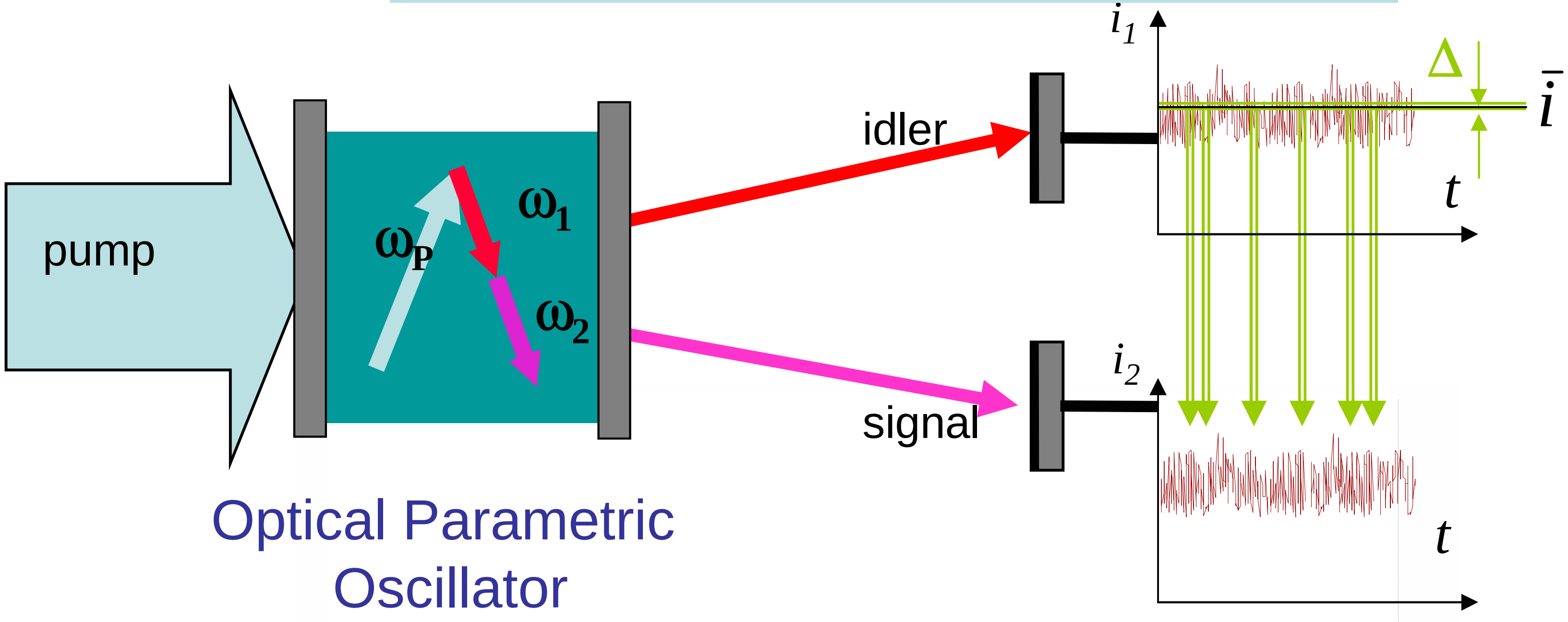




J. Laurat, T. Coudreau, G. Keller, N. Treps, C. Fabre
Phys. Rev. ***A70*** *042315 (2004)*

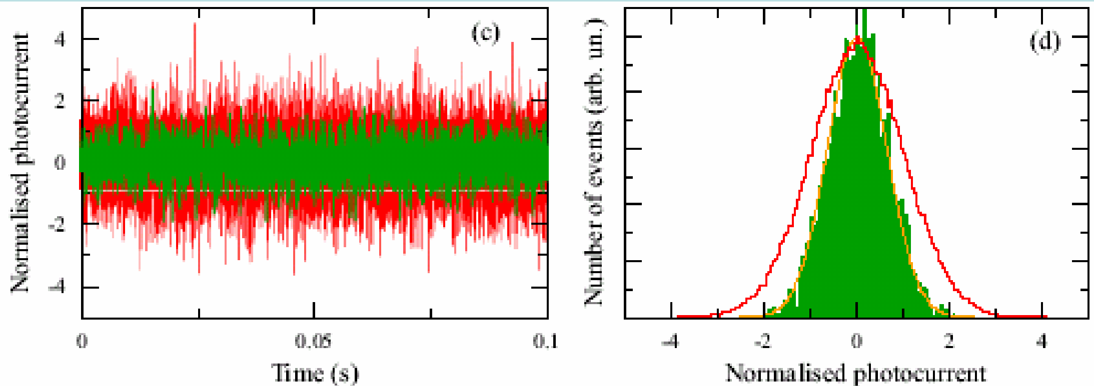
conditional preparation of a non-classical state

preparation of a sub-Poissonian state



Optical Parametric Oscillator

One can show that the remaining noise on the prepared beam is equal to the conditional variance



J. Laurat, T. Coudreau, N. Treps, A. Maître, C. Fabre Phys. Rev. Letters ***91*** *213601 (2003)*

QUANTUM CORRELATION
AND
ENTANGLEMENT

1) non-entangled **pure state:**

$$\left|\Psi\right\rangle = \left|\varphi_1 : 1\right\rangle \otimes \left|\varphi_2 : 2\right\rangle \quad \Longleftrightarrow \quad \boxed{c_{12} = 0}$$

For a pure state :
correlation and entanglement are synonymous

2) non entangled **mixed state, or separable state**

statistical mixture of factorized pure states

For example: a statistical mixture of states $\left|n\right\rangle \otimes \left|n\right\rangle$

gives $V = G = 0$

The existence of quantum correlations, even perfect,
on a single kind of measurement,
does not imply that the mixed state is entangled
The system can be very much « non-classical»
"quantum discord" is one possible quantity
to characterize its non-classicality

2) THIRD QUANTUM LEVEL: Non separable beams
(another technical property of the system)

The system cannot be described by a non-entangled density matrix

Criterion for Gaussian states:

L. Duan, G. Giedke, I. Cirac, P. Zoller, Phys. Rev. Letters **84**, 2722 (2000)

requires the measurement of
(anti)correlations on two non-commuting variables: A, B

$$\Delta A \, \Delta B \geq 1$$

« separability »= ½(gemellity on one quadrature + gemellity on the other)

Two classical beams cannot be entangled

$\exists$ other quantities to characterize inseparability:
entanglement of formation, logarithmic negativity, …

2) FOURTH QUANTUM LEVEL: EPR beams (another measurement point of view)

Einstein Podolsky Rosen point of view: the two correlations may provide two Quantum Non Demolition Measurements:

$$V_{A_1|A_2},\quad V_{B_1|B_2}$$

$$\boxed{EPR = V_{A_1|A_2}\, V_{B_1|B_2} \leq 1} \Leftrightarrow$$

« apparent » violation of the Heisenbeg inequality

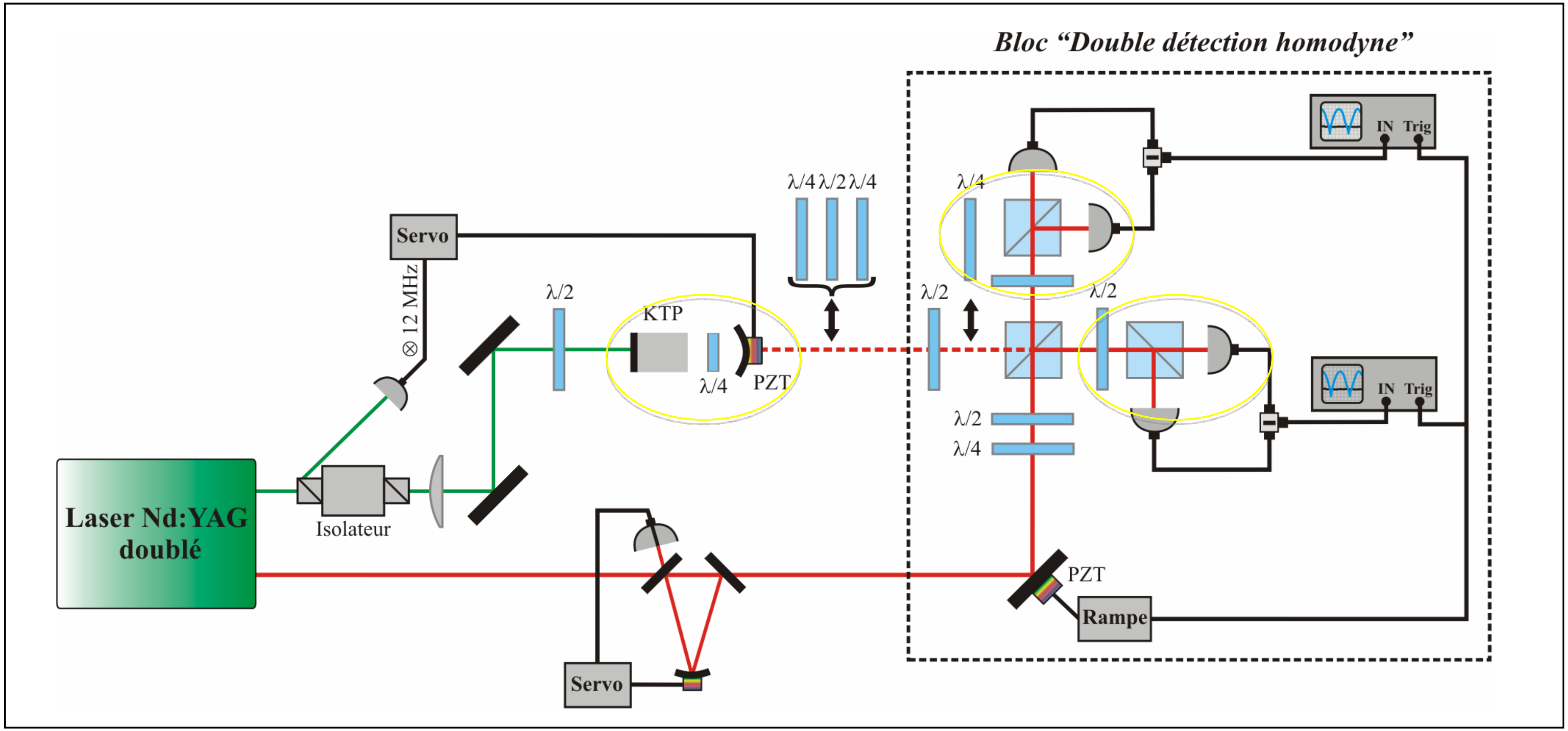
EPR criterion

M. Reid, P. Drummond, Phys. Rev. Letters **60** 2731 (1990)

$$\Leftrightarrow \quad \left(1 - C^{2}_{12\,A}\right)\left(1 - C^{2}_{12\,B}\right) \geq \frac{1}{F_A F_B}$$

All EPR beams are non separable

Experimental set-up

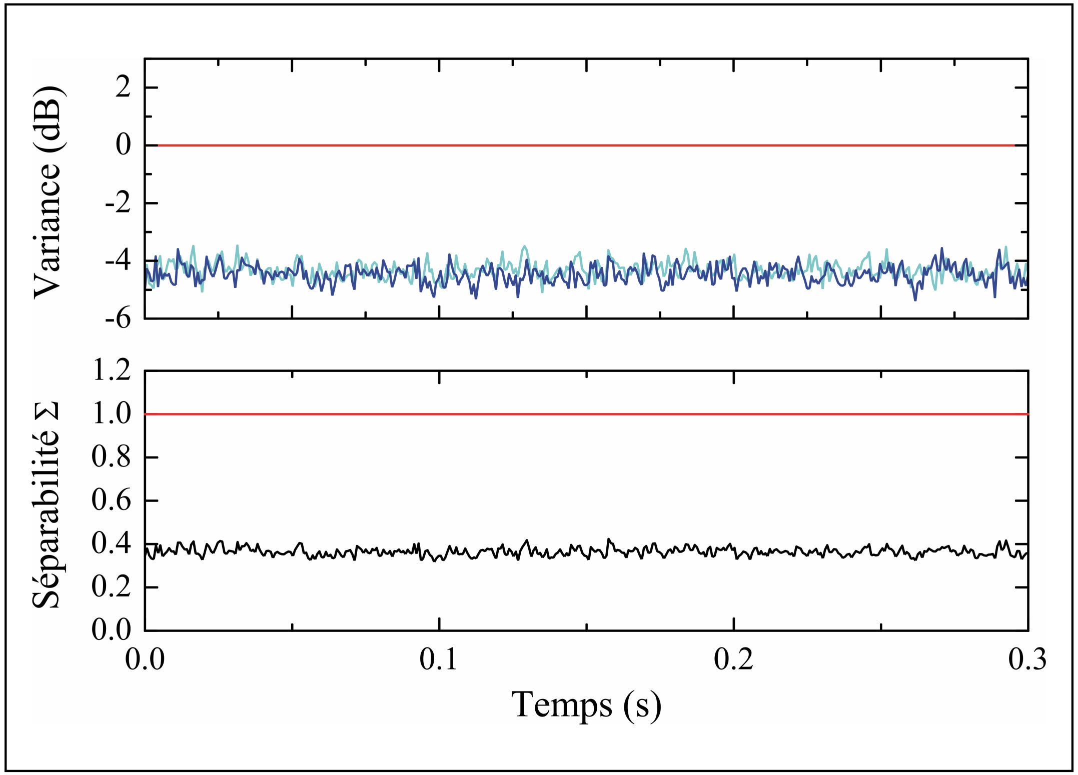


Experimental results below threshold

gemellity$_-$
on the two quadratures

$$G_- = A_1 - A_2$$
$$G_+ = B_1 + B_2$$

separability



$$S_{12} = (V_+ + V_-) / 2 = 0.33$$

$$EPR = V_{A+1|A+2} \, . V_{A-1|A-2} = 0.42$$

J. Laurat, T. Coudreau, G. Keller, N. Treps, C. Fabre, Phys. Rev. ***A70*** *042315 (2004)*

2) FIFTH QUANTUM LEVEL: Bell beams
(another technical property of the system)

(violation of some Bell inequality)

Impossibility of description of the correlation by local « hidden » stochastic variables

All the states described here have positive Wigner functions:
quantum fluctuations propagate classically

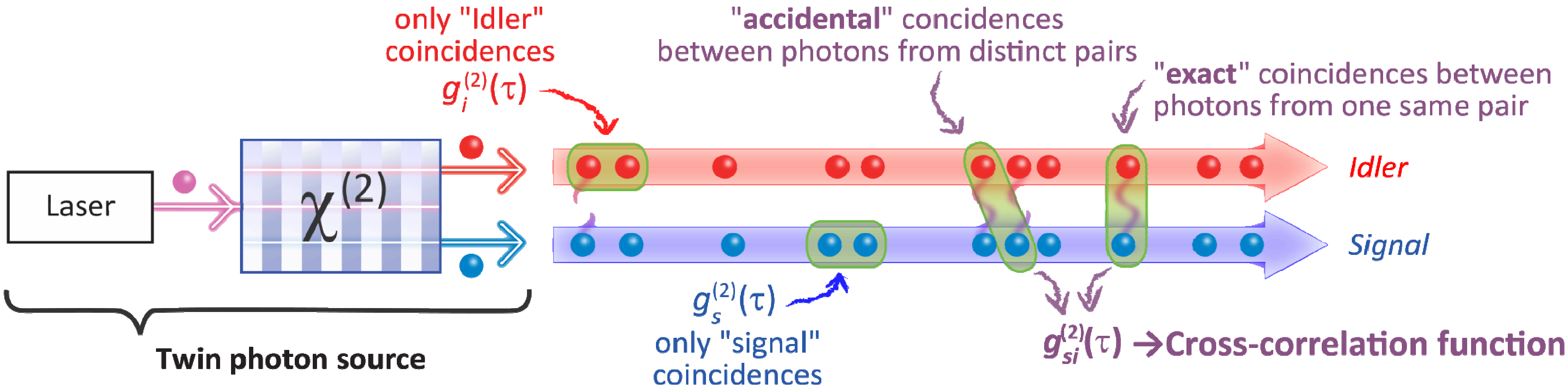
The input instantaneous fluctuations are local hidden variables

For measurements of field quadratures,
this fifth level is never reached

Reached for two-valued observables

What about the $g^{(2)}(0)=3$ experiment ?

1 - quantum explanation



three kinds of photon coincidences:

- accidental

- pairs due to the twin photon source

- linked to the chaotic distribution of pairs

but : photons behave here as classical particles

What about the $g^{(2)}(0)=3$ experiment ?

2 – classical fluctuating field explanation

- The signal and idler fields are classical fields taken as a sum of wavepackets with random phases ϕ_s and ϕ_i.

–the classical equations of parametric mixing imply:

$$\phi_s + \phi_i = \phi_{pump}$$

but : vacuum fluctuations are needed
to trigger the spontaneous parametric fluorescence

CONCLUSION

there are many ways to define non-classicality

concept not restricted to the few photon regime

there are different levels in non-classicality

is this concept really relevant in physics ?

searching for simple physical pictures is always fruitful

having several pictures at the same time
gives more insight to the considered problem

Thank you Emmanuel,
for your inspiration and your dynamism !