Anomalous resilience to external Decoherence of Parametric MACROSCOPIC QUANTUM SUPERPOSITIONS

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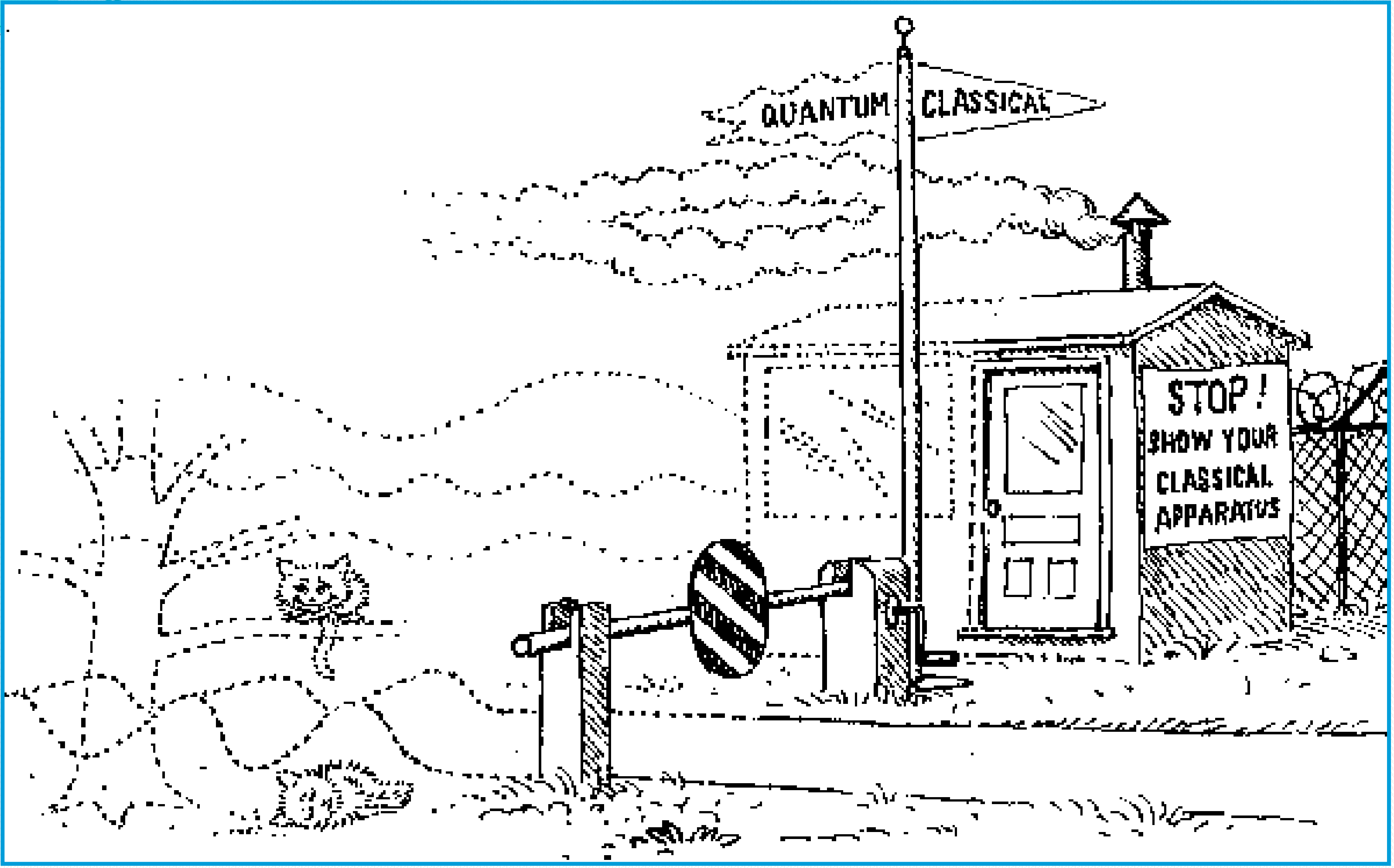
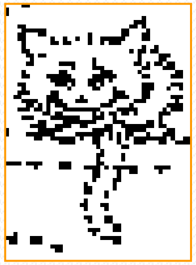
6 – 17 September 2010

The boundary Quantum - Classical

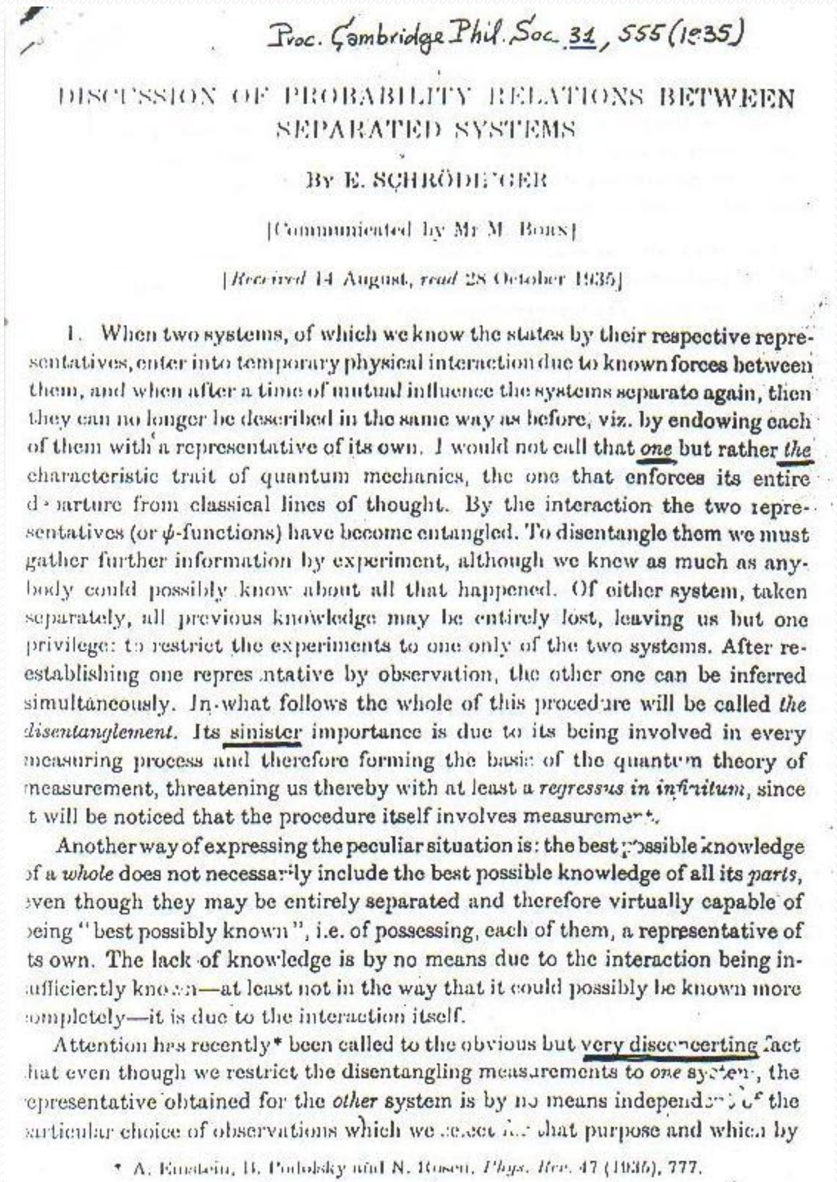


Zurek, Physics Today, October 1991, page 38

Schroedinger's Cat

Cat Entangled State: $|\Phi\rangle = \big(|0\rangle|$  $\rangle + |1\rangle|$  $\rangle\big)$

Remarks on EPR (1935)



Proc. Cambridge Phil. Soc. 31, 555 (1935)

DISCUSSION OF PROBABILITY RELATIONS BETWEEN SEPARATED SYSTEMS

BY E. SCHRÖDINGER

[Communicated by Mr M. BORN]

[*Received* 14 August, *read* 28 October 1935]

1. When two systems, of which we know the states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the same way as before, viz. by endowing each of them with a representative of its own. I would not call that *one* but rather *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought. By the interaction the two representatives (or ψ-functions) have become entangled. To disentangle them we must gather further information by experiment, although we knew as much as anybody could possibly know about all that happened. Of either system, taken separately, all previous knowledge may be entirely lost, leaving us but one privilege: to restrict the experiments to one only of the two systems. After re-establishing one representative by observation, the other one can be inferred simultaneously. In what follows the whole of this procedure will be called *the disentanglement*. Its sinister importance is due to its being involved in every measuring process and therefore forming the basis of the quantum theory of measurement, threatening us thereby with at least a *regressus in infinitum*, since it will be noticed that the procedure itself involves measurement.

Another way of expressing the peculiar situation is: the best possible knowledge of a *whole* does not necessarily include the best possible knowledge of all its *parts*, even though they may be entirely separated and therefore virtually capable of being "best possibly known", i.e. of possessing, each of them, a representative of its own. The lack of knowledge is by no means due to the interaction being insufficiently known—at least not in the way that it could possibly be known more completely—it is due to the interaction itself.

Attention has recently* been called to the obvious but very disconcerting fact that even though we restrict the disentangling measurements to *one* system, the representative obtained for the *other* system is by no means independent of the particular choice of observations which we select for that purpose and which by

* A. Einstein, B. Podolsky and N. Rosen, *Phys. Rev.* 47 (1935), 777.

Erwin Schroedinger
(1887-1961)

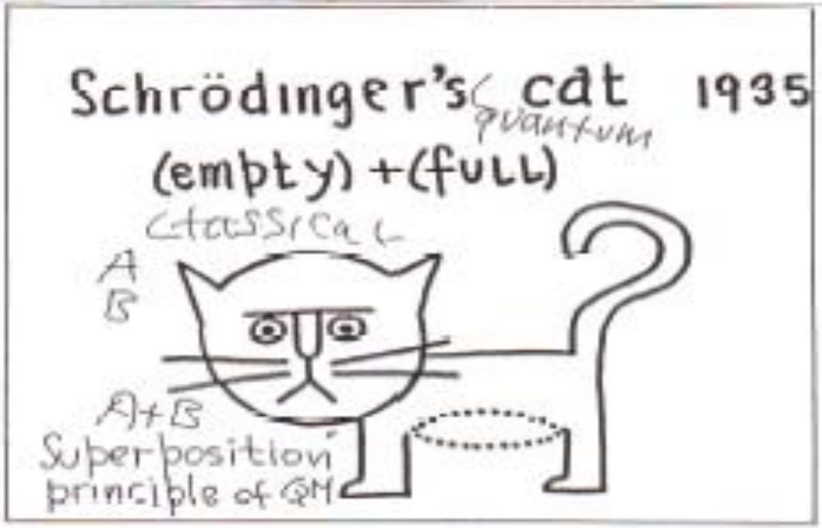


Fig. 2

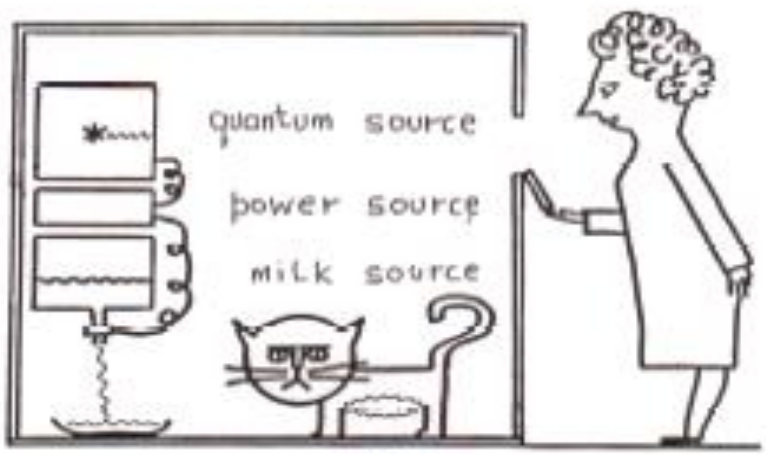
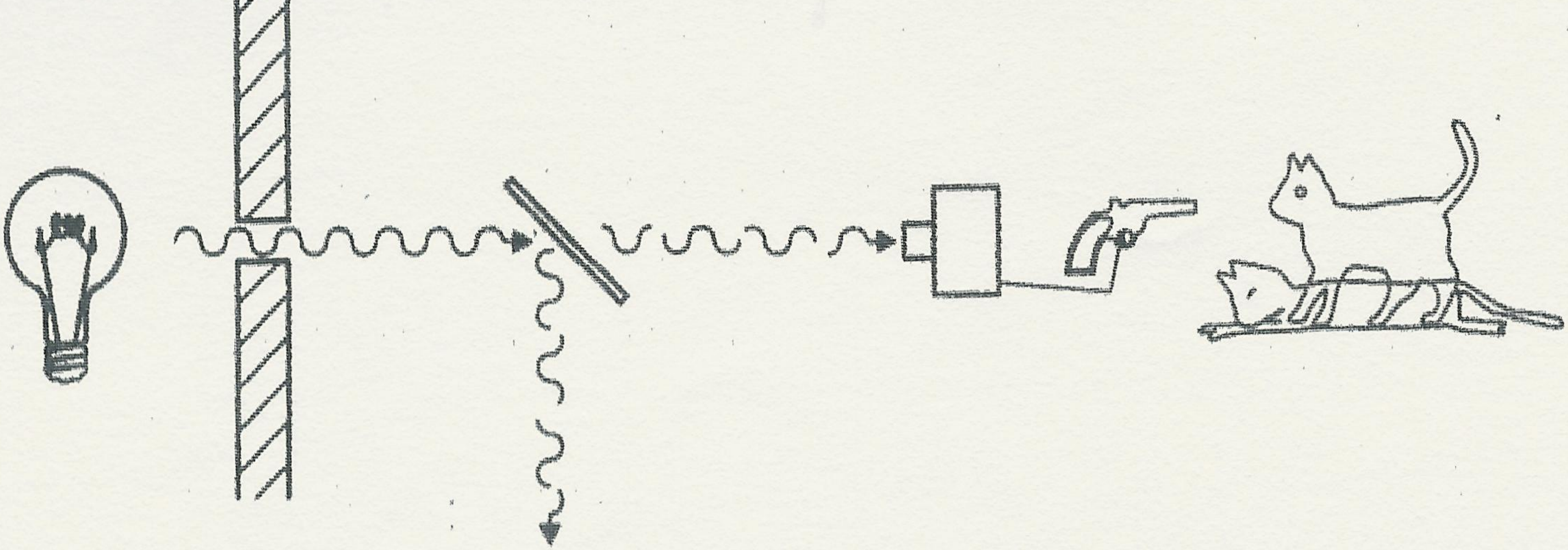
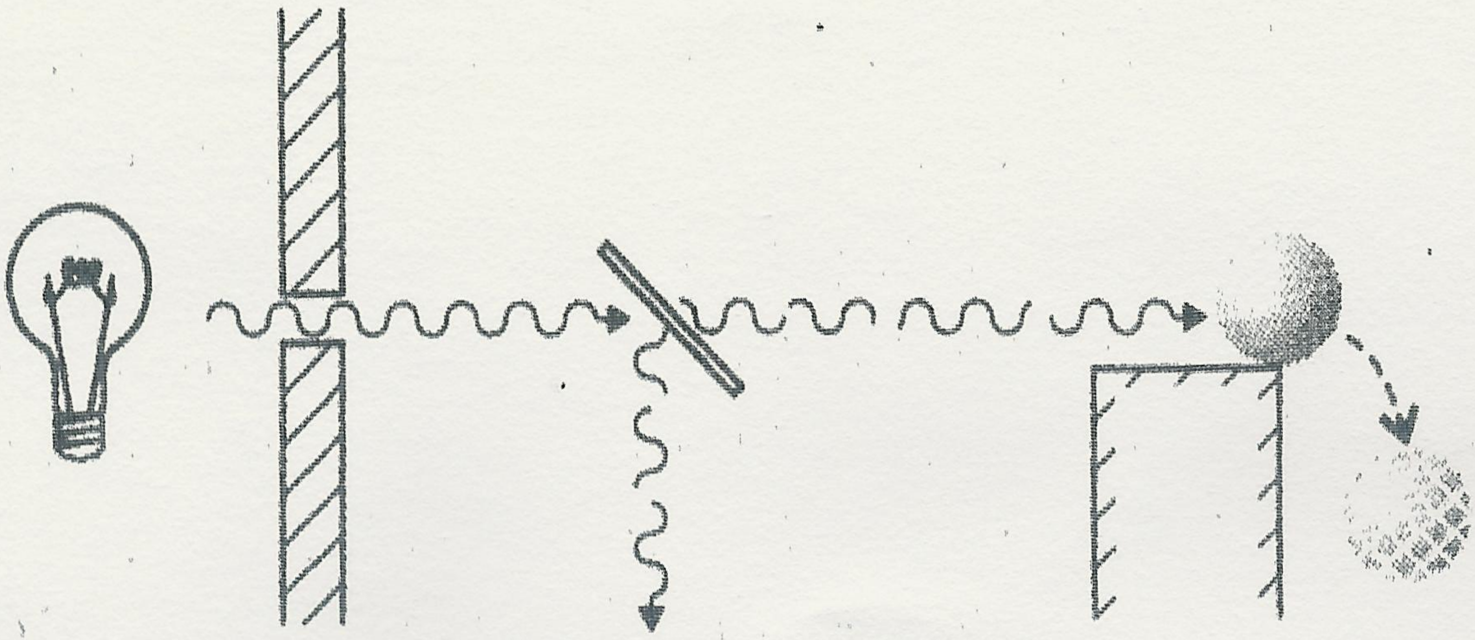


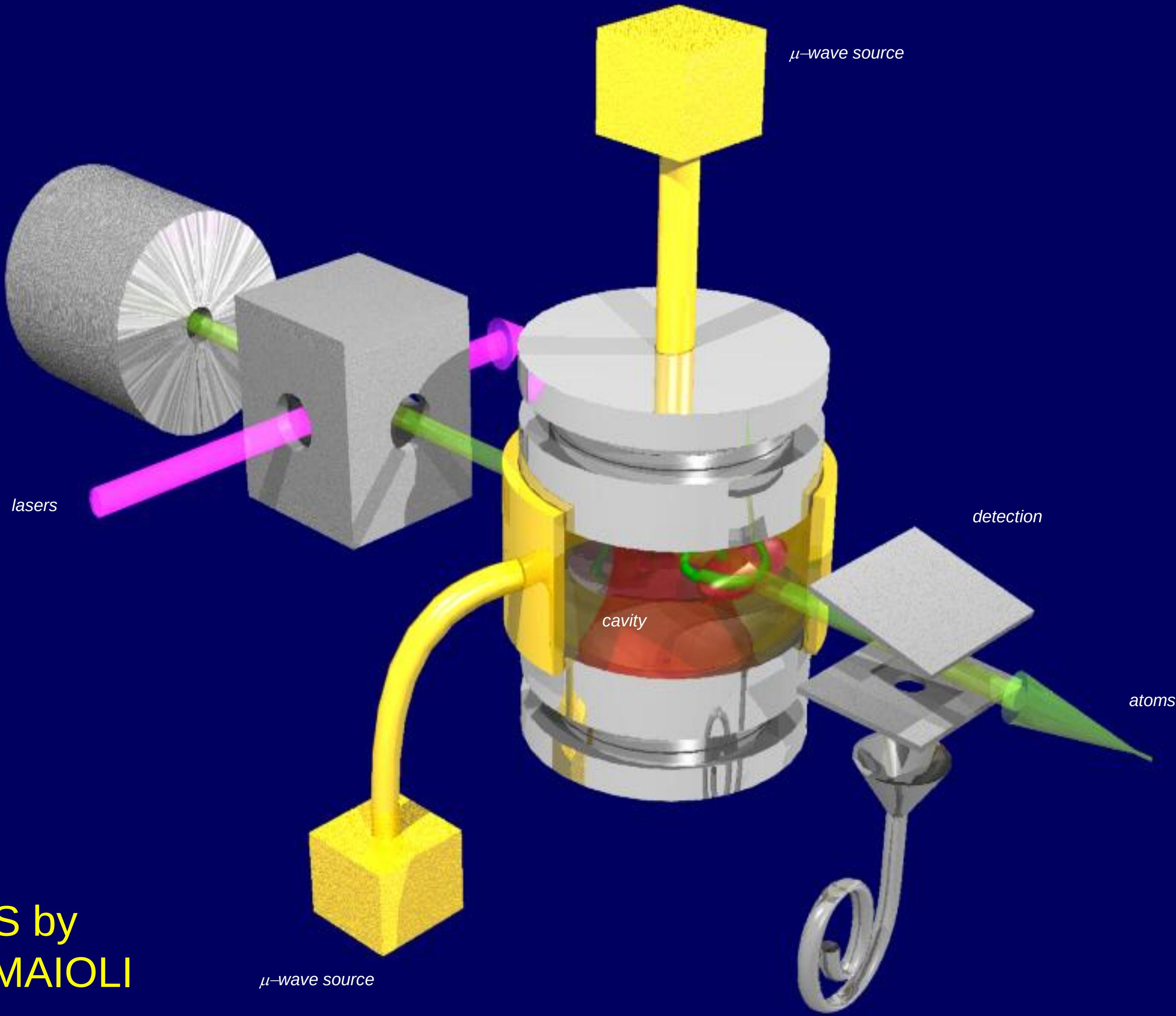
Fig. 3

J. S. Bell
J. Schwinger Festspiel



Roger Penrose (1997)

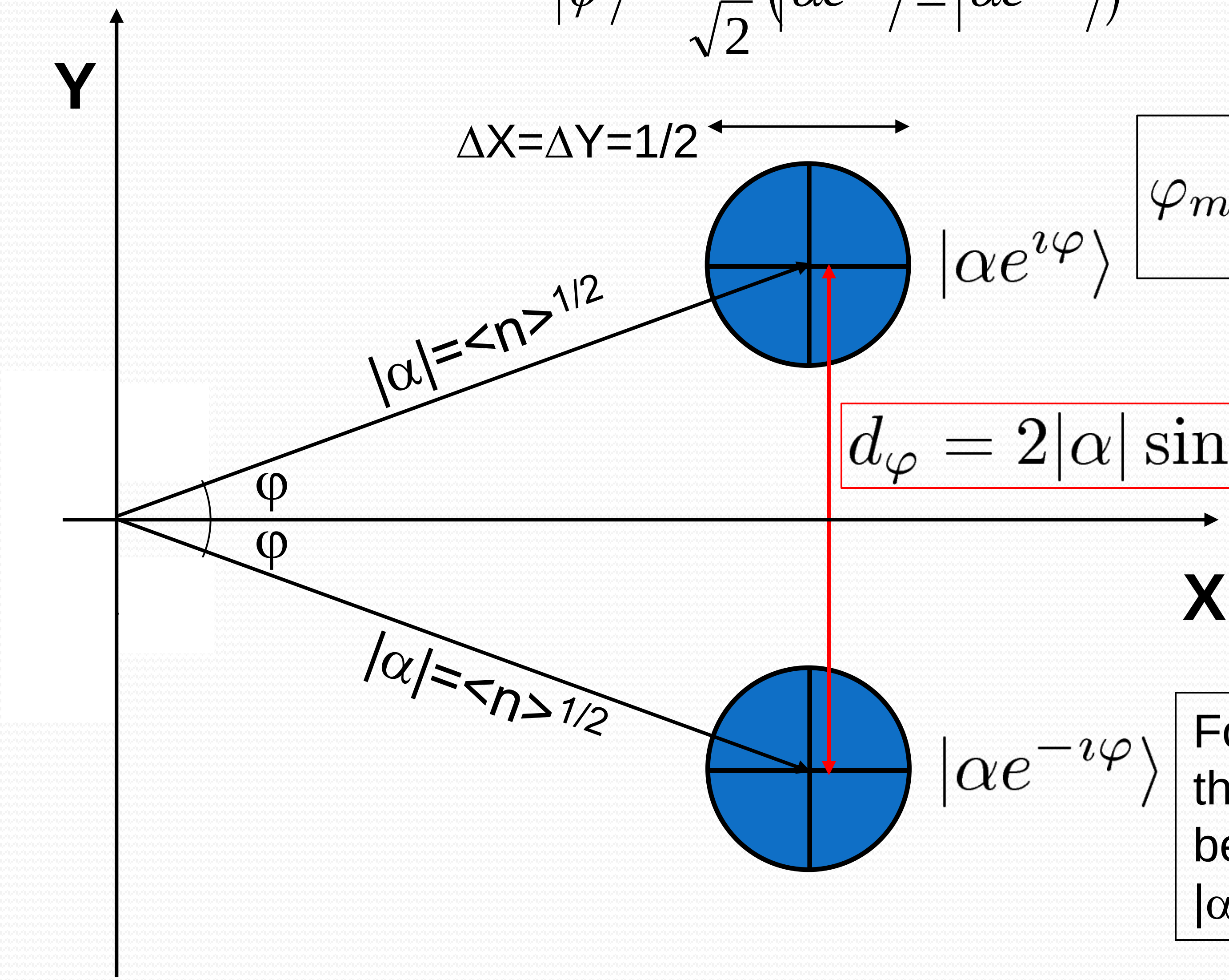




2 SLIDES by
PAOLO MAIOLI
E.N.S. 2004

COHERENT STATES: PHASE SPACE DISTANCE

$$|\psi\rangle = \frac{N}{\sqrt{2}}\left(\left|\alpha e^{i\varphi}\right\rangle \pm \left|\alpha e^{-i\varphi}\right\rangle\right)$$

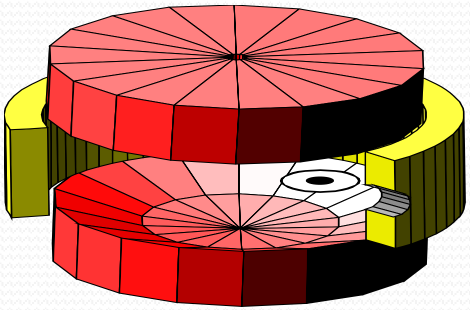


$$d_\varphi = 2|\alpha|\sin\varphi$$

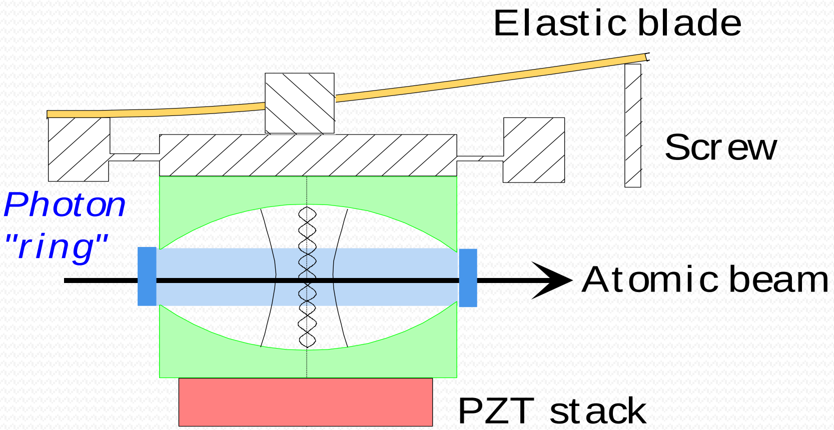
$$\varphi_{min} \sim \frac{1}{|\alpha|} = \frac{1}{\langle n\rangle^{\frac{1}{2}}}$$

For $\varphi < \varphi_{min}$ overlap in the phase space between $|\alpha e^{i\varphi}\rangle$ and $|\alpha e^{-i\varphi}\rangle$

Nb Superconducting cavity (E.N.S. – Paris 2004)

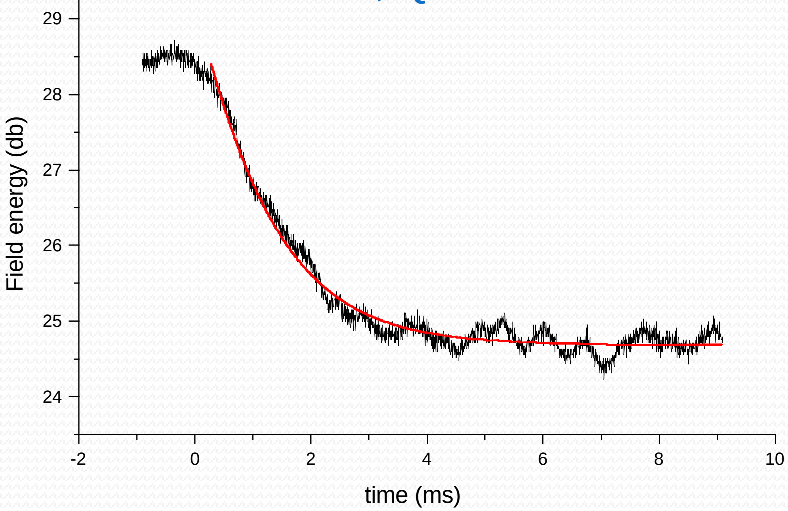


- Open Fabry Perot cavity with a photon "recirculation" ring
- Compatible with a static electric field (circular states stability and Stark tuning)



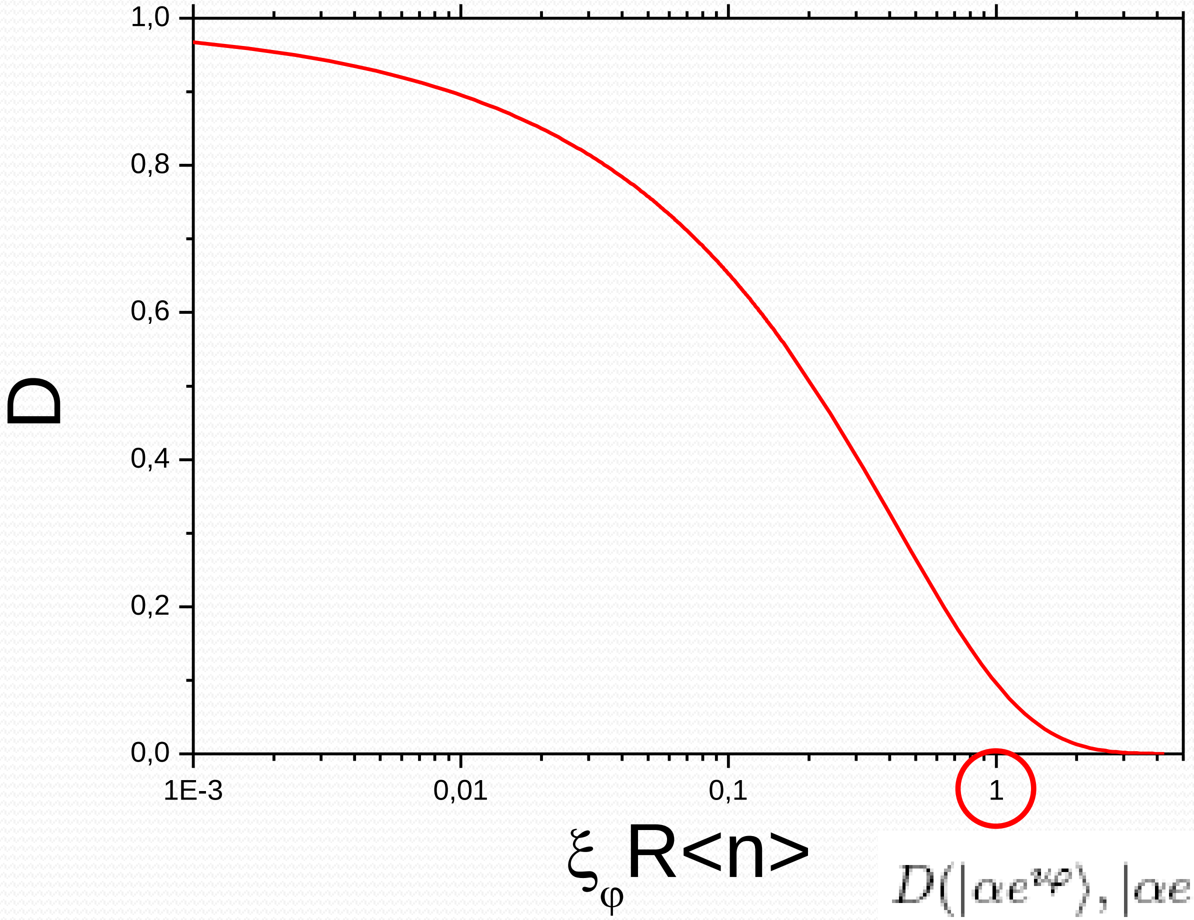
Polished Niobium mirrors

Lifetime: 1 ms ; $Q = 3 \times 10^8$



$$|\varphi\rangle = \mathcal{N}\frac{1}{\sqrt{2}}\left(|\alpha e^{\imath\varphi}\rangle \pm |\alpha e^{-\imath\varphi}\rangle\right) \Rightarrow \mathcal{N}\frac{1}{\sqrt{2}}\left(|\alpha\rangle \pm |-\alpha\rangle\right)$$

$\varphi=\pi/2$



$$\xi_\varphi = \left(\frac{d_\varphi}{d_{\frac{\pi}{2}}}\right)^2 = \sin^2\varphi$$

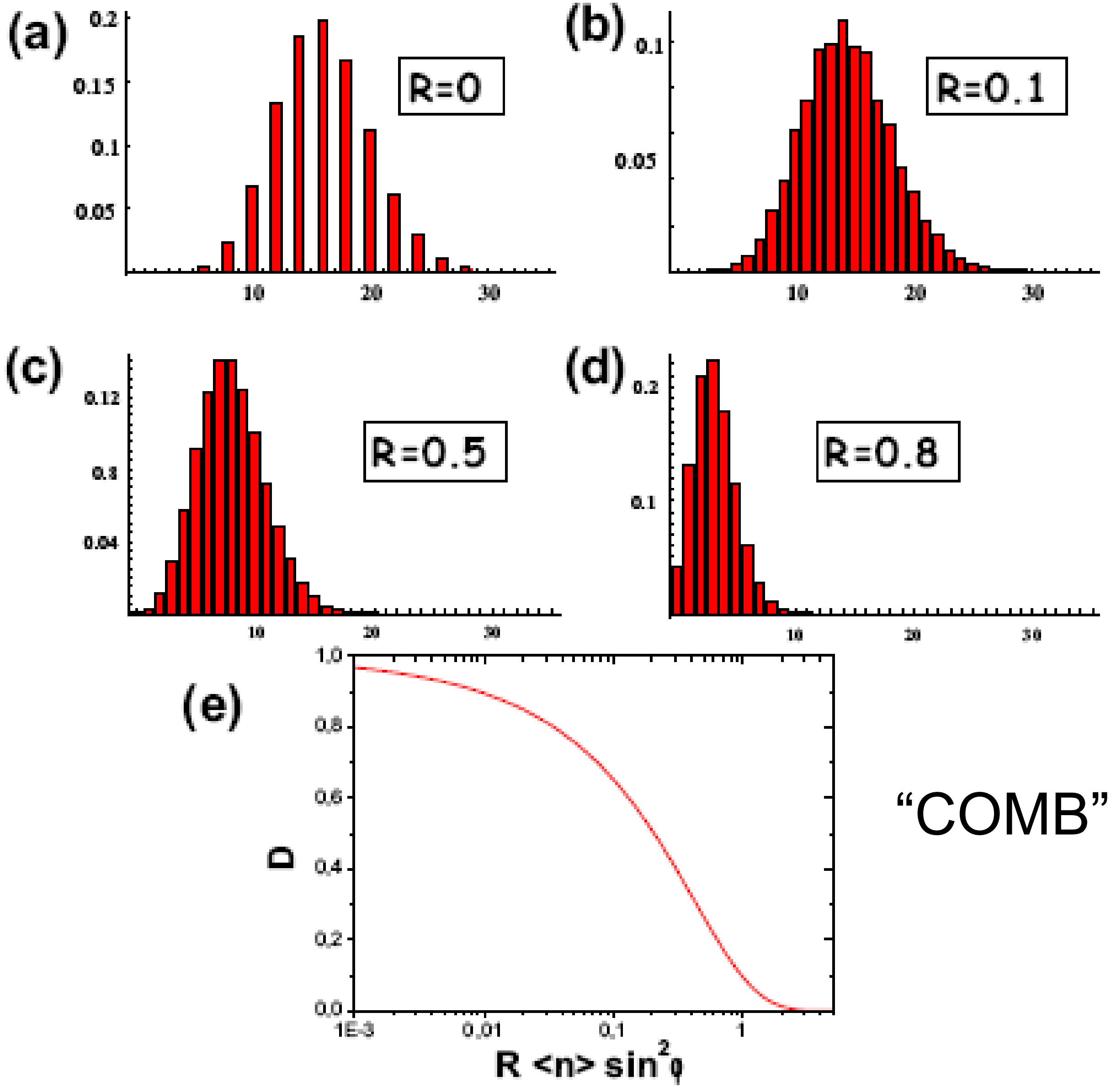
$$(\xi_\varphi)_{min} = \sin^2\frac{1}{|\alpha|} \sim \frac{1}{\langle n\rangle}$$

<u>FOR ANY <n> and φ!</u>

$$D(|\alpha e^{\imath\varphi}\rangle, |\alpha e^{-\imath\varphi}\rangle) = \sqrt{1 - e^{-2T|\alpha|^2 \sin^2\varphi}}$$

$$D(|\phi^+_\varphi\rangle, |\phi^-_\varphi\rangle) = \sqrt{1 - \sqrt{1 - e^{-4R|\alpha|^2 \sin^2\varphi}}}.$$

D: UNIVERSAL FUNCTION FOR COHERENT - STATE MACRO-QUBITS



"COMB" decoherence effect

A question arises:

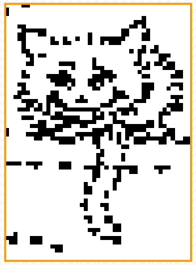
THE SCHROEDINGER CAT REALLY EXISTS ?

SINCE SO FAR IT APPEARS NOT HAVING DIRECTLY OBSERVABLE PROPERTIES

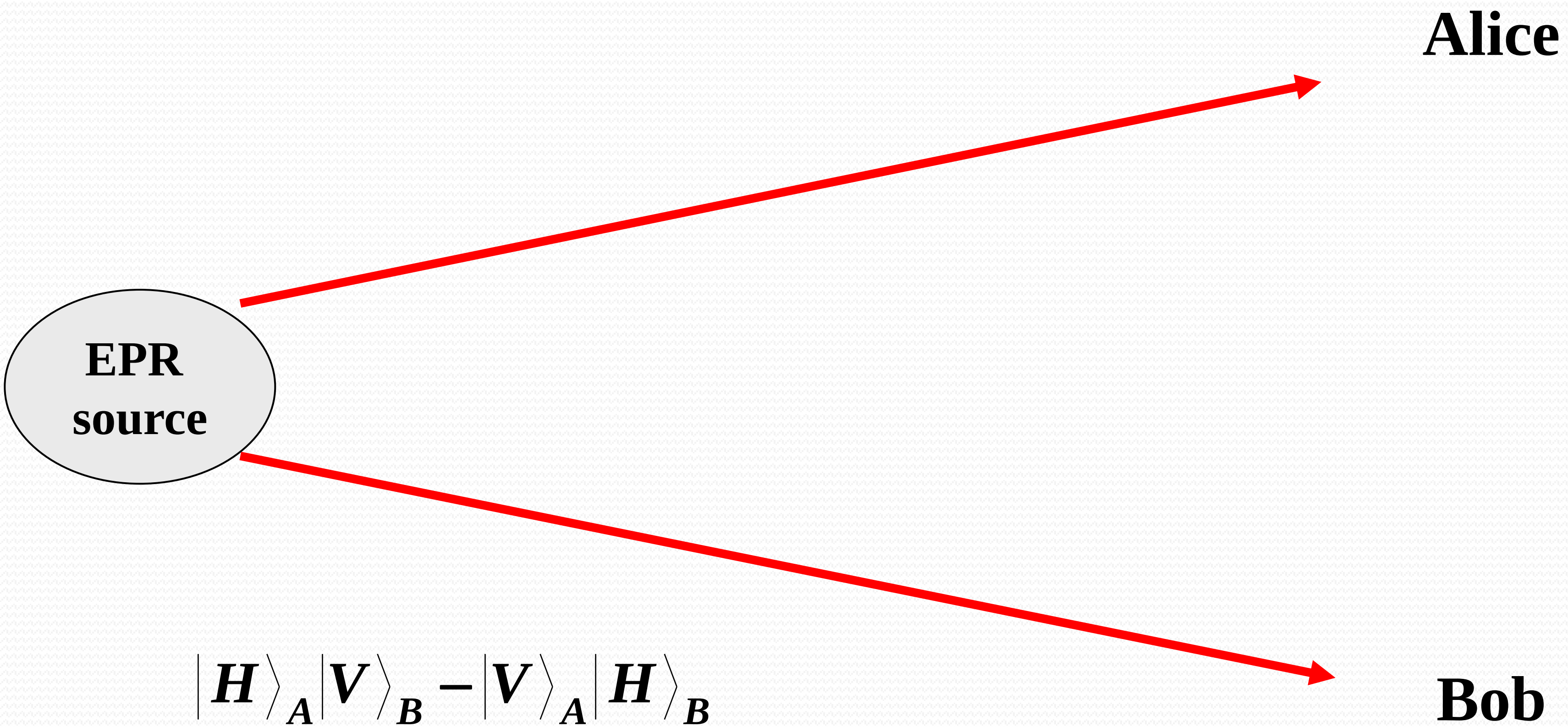
Decoherence is always too large:
I*n general,* loss of one particle spoils Interference

LET'S SEE IF THIS IS REALLY TRUE

Schroedinger's Cat

Cat Entangled State: $|\Phi\rangle = \big(|0\rangle|$  $\rangle + |1\rangle|$  $\rangle\big)$

Entanglement between 2 single photons (EPR, 1935)



$$\frac{|H\rangle_A |V\rangle_B - |V\rangle_A |H\rangle_B}{\sqrt{2}}$$

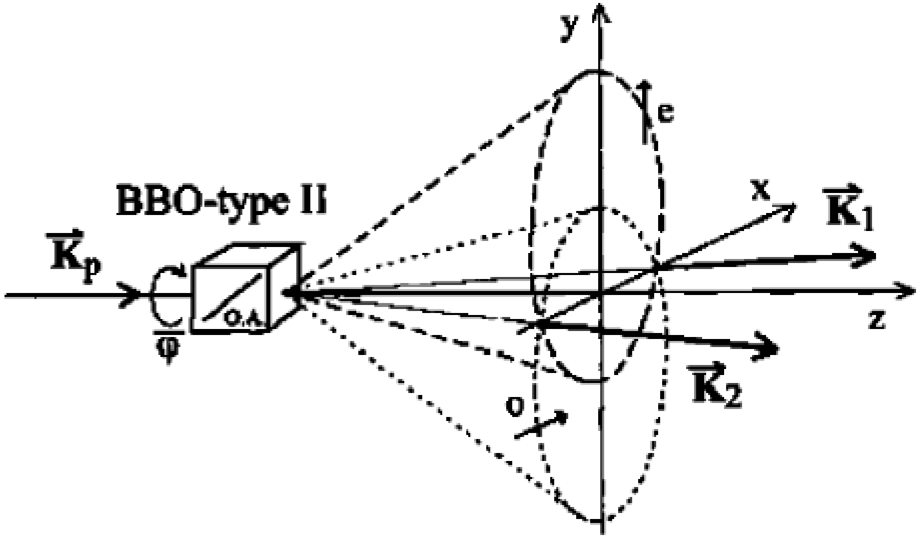
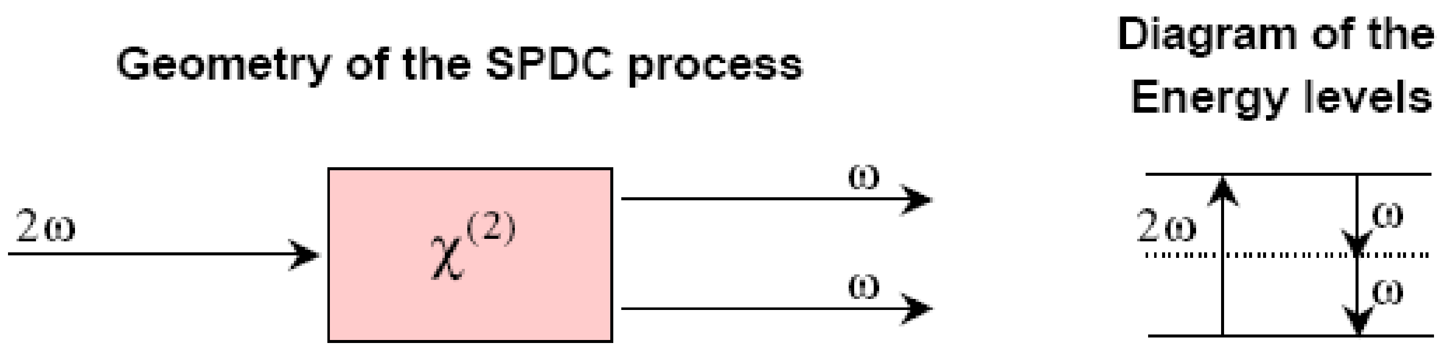


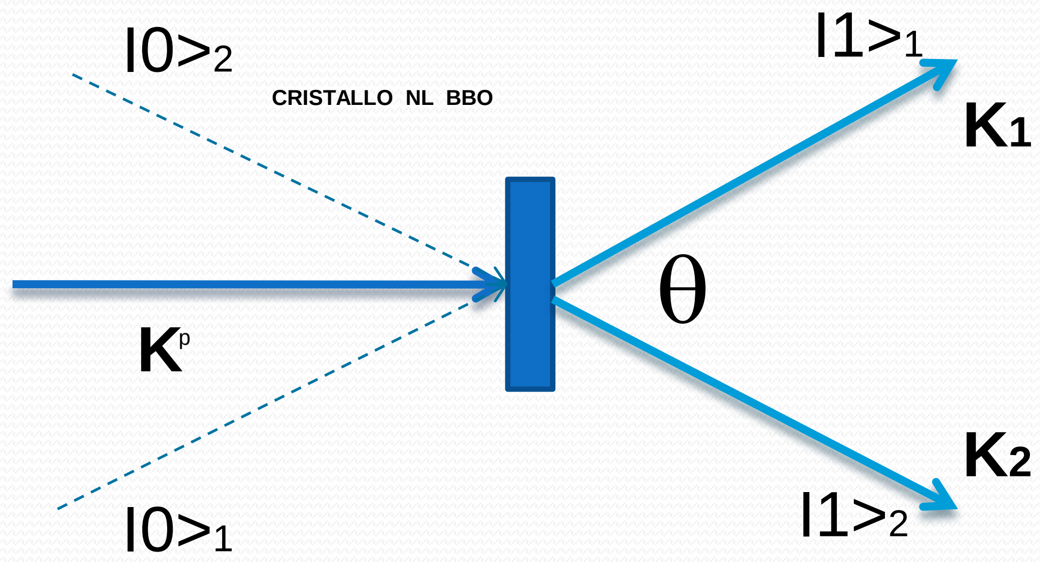
Fig. 13. Generation of polarization entangled states by spontaneous parametric down conversion on modes k_1 and k_2.



. Schematic representation of the spontaneous parametric down-conversion (SPDC) process.

Phase-Matching Conditions:

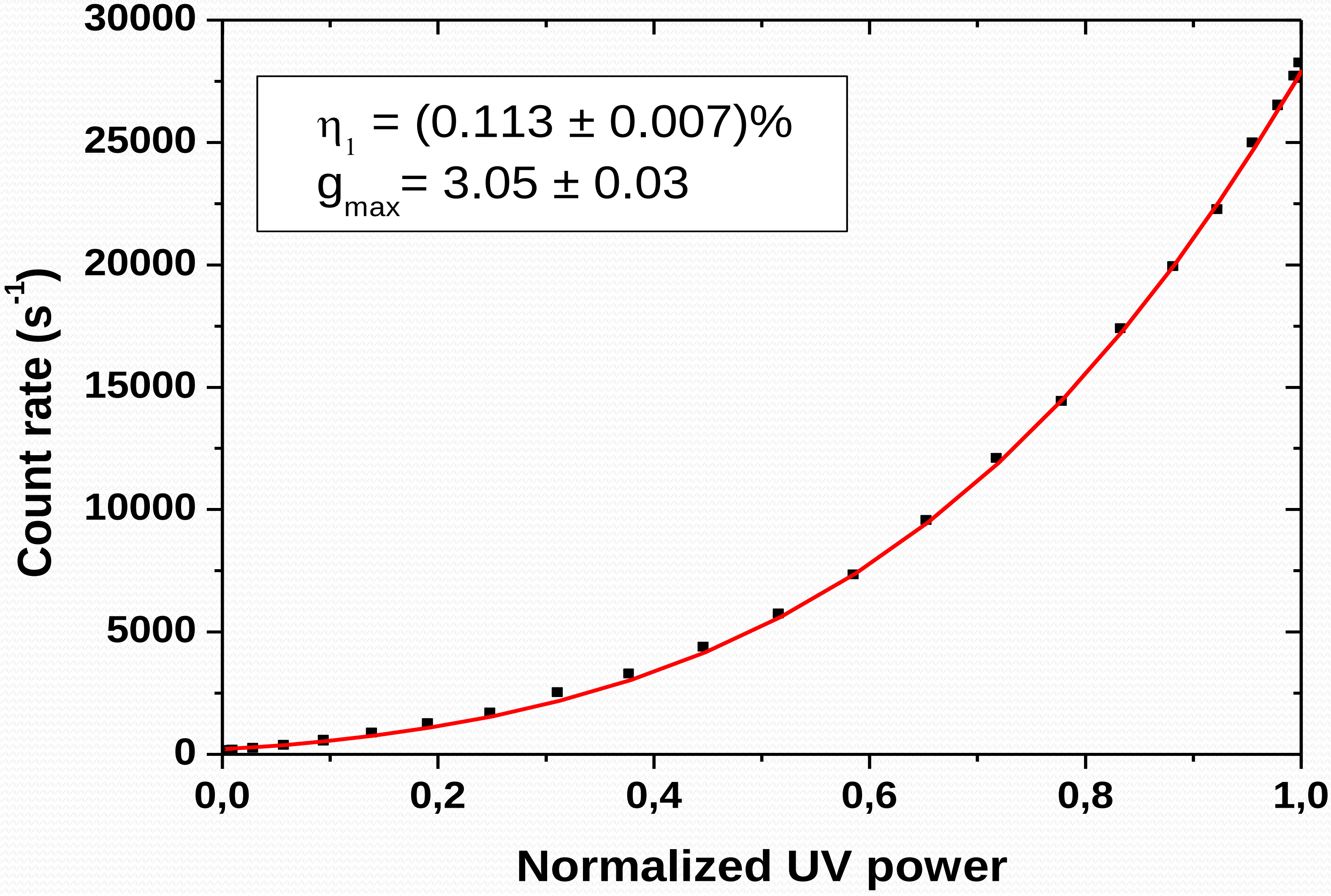
$$\nu_P = \nu_1 + \nu_2,$$
$$\vec{k}_P = \vec{k}_1 + \vec{k}_2,$$



$\lambda_1 = \lambda_2 = 2\lambda_p$

$|K| = 2\pi / \lambda$

High-gain spontaneous parametric down conversion



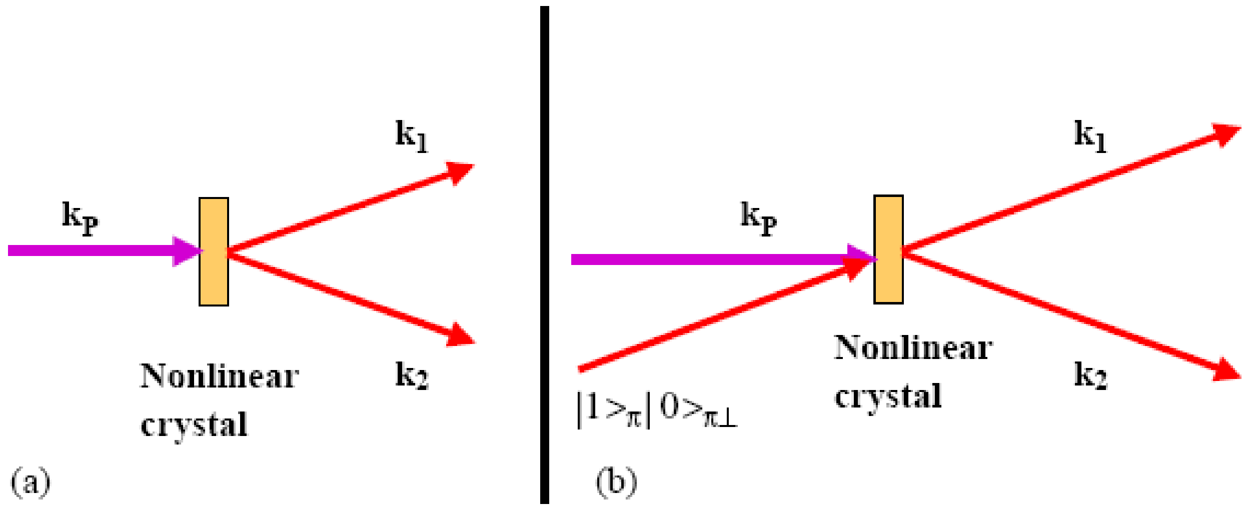


Fig. 20. Optical parametric amplifier working in spontaneous emission regime (a) and stimulated emission regime (b).

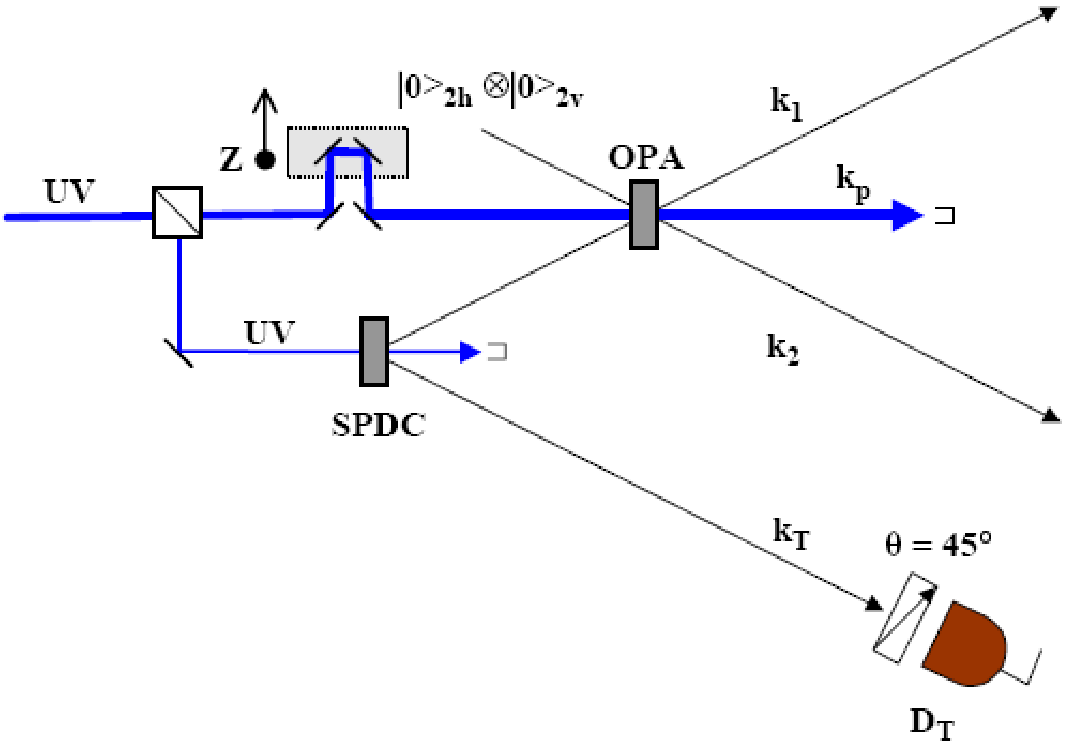


Fig. 21. Schematic diagram of the *quantum injected* optical parametric amplifier (QIOPA) in *entangled configuration*. The injection is provided by an external spontaneous parametric down conversion source of polarization entangled photon states [109].

F. De Martini, Phys.Rev.Lett 81,2842 (1998)

QI-OPA: Quantum - injected Optical Parametric Amplifier

(NL gain g = 4 ÷ 7.8)

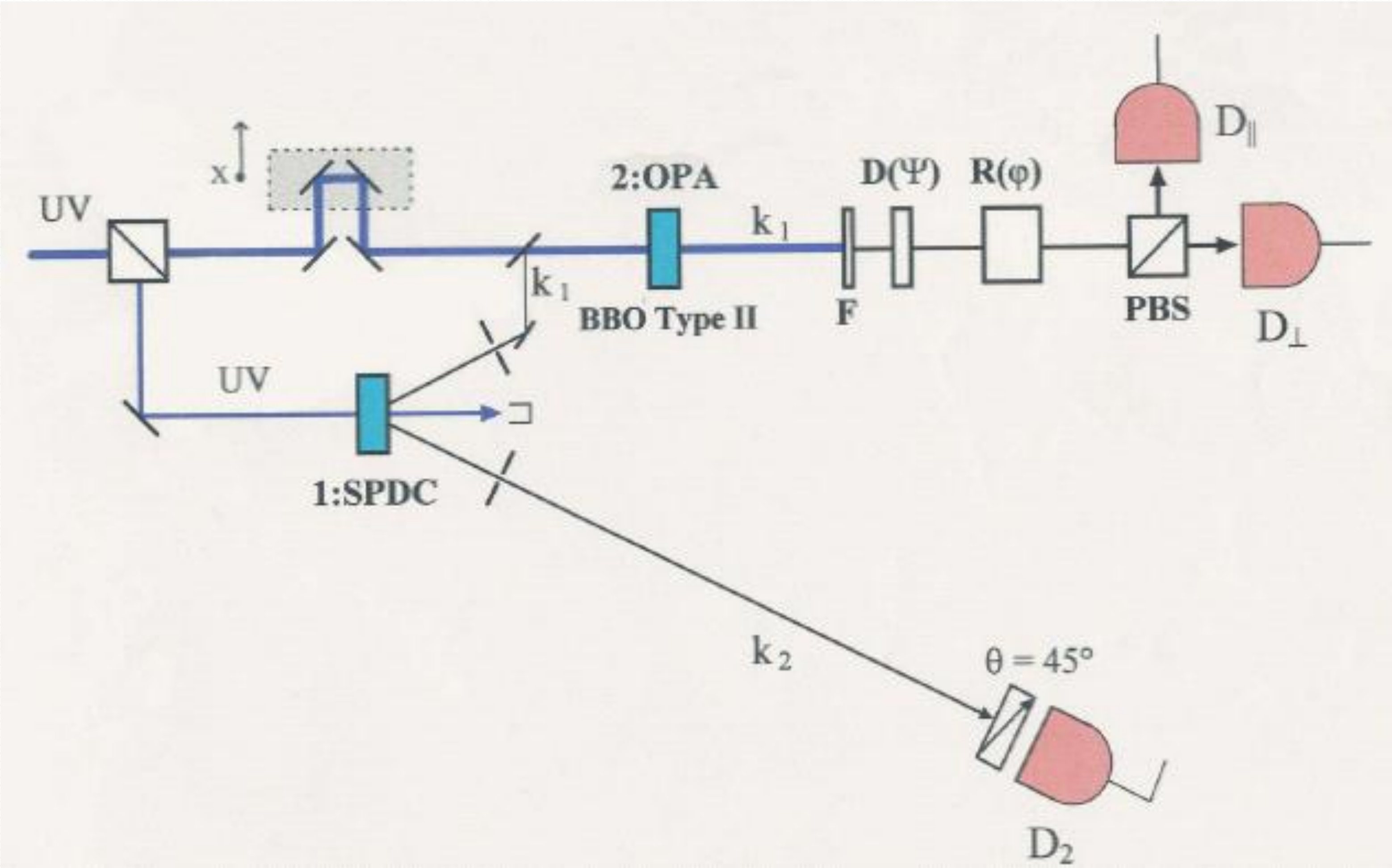
(COLLINEAR STRUCTURE:

Phase-covariant cloning - machine)

QUANTUM INJECTION BY : ONE - PHOTON: (Spin -½)

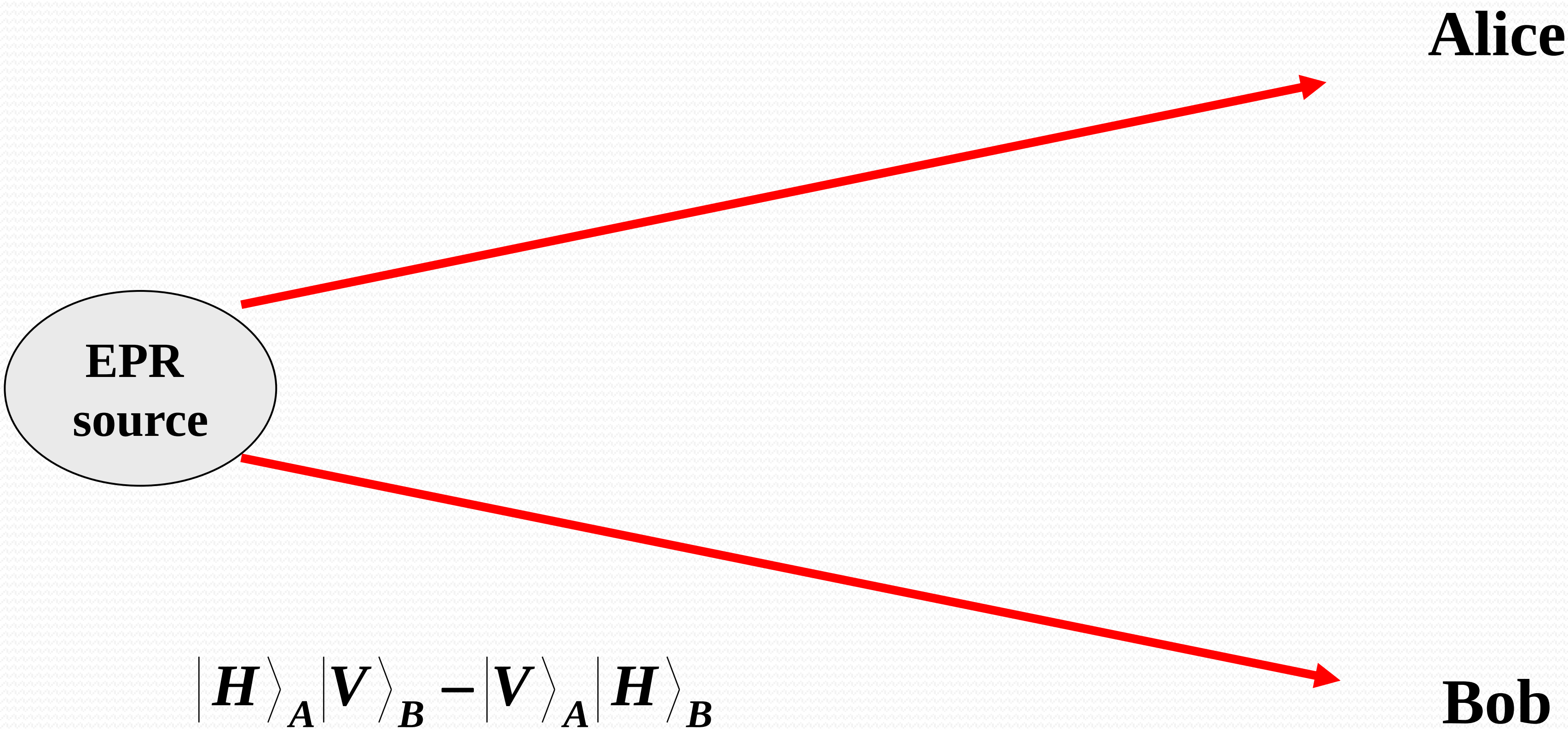
(test of: State Non-separability)

NL gain: g = 6.5 $\rightarrow$ M $\cong$ 4 sinh^{2}g = 350.000



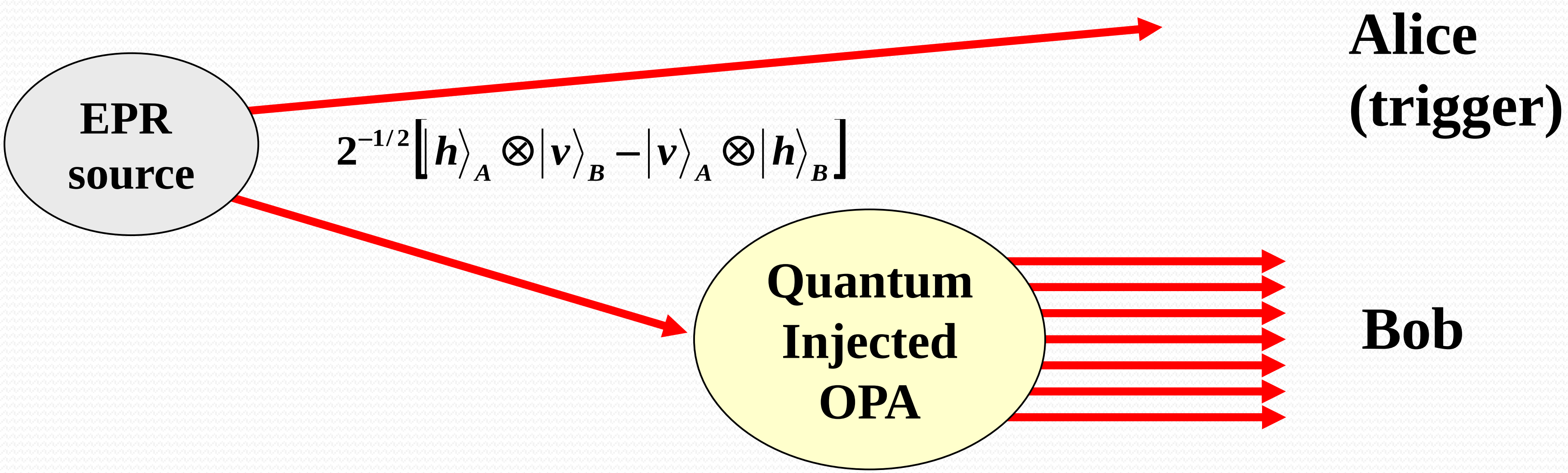
F.De Martini, Phys.Letters A 250, 15 (1998).

Entanglement between 2 single photons (EPR, 1935)



$$\frac{|H\rangle_A |V\rangle_B - |V\rangle_A |H\rangle_B}{\sqrt{2}}$$

Entanglement between a single photon and a mesoscopic field : Micro - Macro (2008)



$$2^{-1/2}\left[\left|h\right\rangle_A \otimes \left|v\right\rangle_B - \left|v\right\rangle_A \otimes \left|h\right\rangle_B\right]$$

$$\left|\Sigma\right\rangle = 2^{-1/2}\left[\left|h\right\rangle_A \otimes \left|\Phi^V\right\rangle_B - \left|v\right\rangle_A \otimes \left|\Phi^H\right\rangle_B\right]:$$

SCHROEDINGER CAT STATE

High – gain stimulated Parametric Amplifier (Quantum-injected OPA: phase-covariant cloning)

$$\left|\Psi_{in}\right\rangle = \alpha\left|+\right\rangle + \beta\left|-\right\rangle \quad ;\left|\pm\right\rangle = 2^{-1/2}(\left|h\right\rangle \pm \left|v\right\rangle)$$

$$;\left|R/L\right\rangle = 2^{-1/2}(\left|h\right\rangle \pm i\left|v\right\rangle)$$

Optimal
Phase-Covariant
Quantum cloning

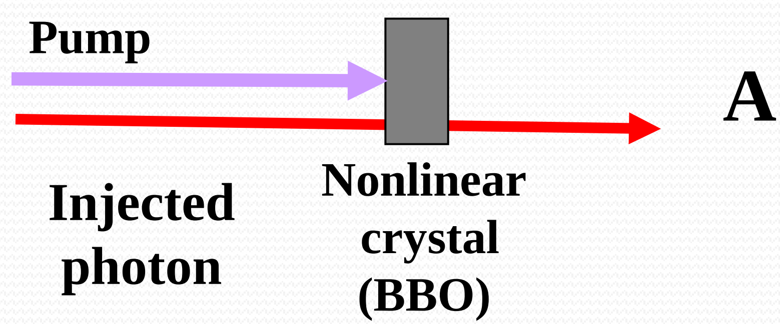
$$\left|\Psi\right\rangle_{out} = \hat{U}_{OPA}\left|\Psi_{in}\right\rangle = \alpha\left|\Psi(+)\right\rangle + \beta\left|\Psi(-)\right\rangle$$

$$\left|+\right\rangle \Rightarrow \left|\Psi(+)\right\rangle; \left|-\right\rangle \Rightarrow \left|\Psi(-)\right\rangle: \; Multi-particle \; (N \approx 10^6)$$

$$\left|\left\langle\Psi(+)\middle|\Psi(-)\right\rangle\right|^2 = \delta_{+,-} : \; Ortho-normal$$

INFORMATION - PRESERVING transfer of quantum superposition from a Microstate into a Macrostate by a Unitary transformation

$$\left|\Psi(\pm)\right\rangle = \sum_{i,j=0}^{\infty}\gamma_{ij}\left(\sqrt{(1+2i)!(2j)!}/i!\,j!\right)\left|2i+1\right\rangle_{\pm}\left|2j\right\rangle_{\mp}$$

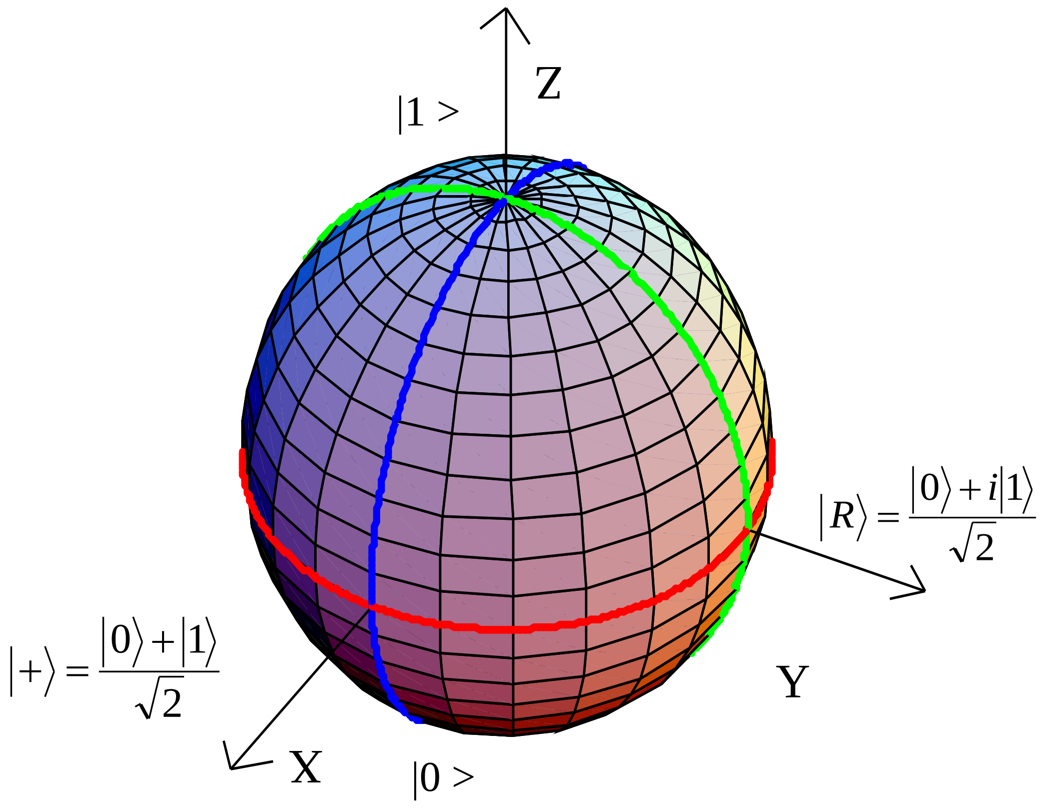


Bipartite entangled state

Change of the injected state by Babinet compensator + λ/2 Wp.

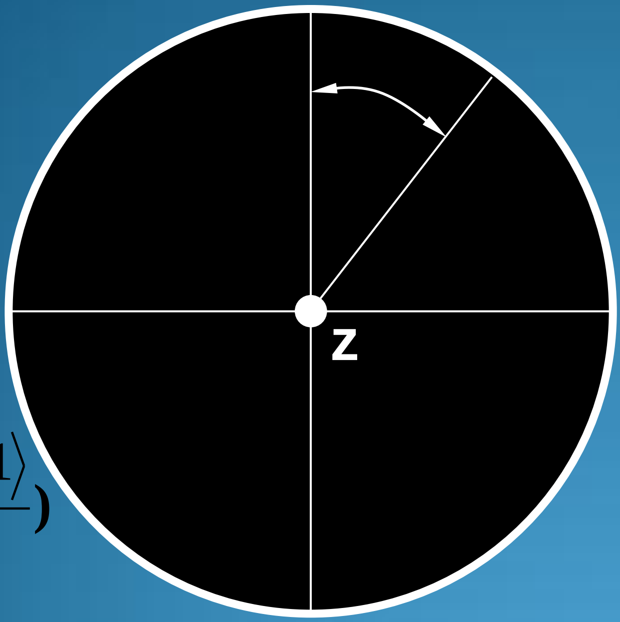
On the Bloch sphere:

$$|\Psi\rangle_{in} = \cos(\theta/2)|0\rangle + e^{i\varphi}\sin(\theta/2)|1\rangle$$



Equatorial z-plane for Collinear QI-OPA: PHASE - COVARIANT CLONING

$$\varphi = 0;\ |+\rangle_A = \left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right)$$



$$\varphi = \frac{3\pi}{2}$$

$$|\mathbf{L}\rangle = \left(\frac{|0\rangle - i|1\rangle}{\sqrt{2}}\right)$$

$$\varphi = \frac{\pi}{2}$$

$$|\mathbf{R}\rangle = \left(\frac{|0\rangle + i|1\rangle}{\sqrt{2}}\right)$$

$$\varphi = \pi;\ |-\rangle = \left(\frac{|0\rangle - |1\rangle}{\sqrt{2}}\right)$$

Input qubit:

$$\frac{|0\rangle + e^{i\varphi}|1\rangle}{\sqrt{2}} = \hat{U}_Z \frac{|0\rangle + |1\rangle}{\sqrt{2}}$$

with: $\hat{U}_Z = e^{i\frac{\varphi}{2}\hat{\sigma}Z}$

COVARIANCE UNDER U $\Rightarrow$ FIDELITY IS INVARIANT UNDER U

$$f_{U|\psi\rangle} = \langle\psi|U^\dagger \, \mathcal{M}\left(U|\psi\rangle\langle\psi|U^\dagger\right) U|\psi\rangle$$
$$= \langle\psi|U^\dagger \, U \, \mathcal{M}\left(|\psi\rangle\langle\psi|\right) U^\dagger \, U|\psi\rangle$$
$$= \langle\psi| \, \mathcal{M}\left(|\psi\rangle\langle\psi|\right) |\psi\rangle$$
$$= f_{|\psi\rangle}$$

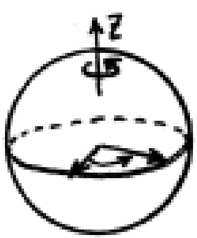
(COVARIANCE)

NON-UNIVERSALLY COVARIANT CLONER

$U \in$ SUBSET OF $SU(2)$ → Abelian Group U(1)

E.G. PHASE-COVARIANT CLONER (D. Bruss et al., PRA, 2000)

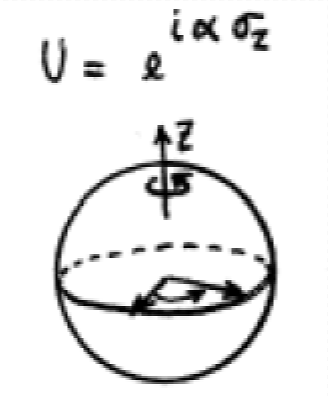
$$U = e^{i\alpha\sigma_z}$$



$$f = \frac{1}{2} + \frac{1}{\sqrt{8}} \simeq 0.854 > \frac{5}{6} \simeq 0.833$$

(UCM)

MICRO-WORLD MIRRORED INTO THE MACRO-WORLD BY THE UNITARY CLONING TRANSFORMATION **U**:



$$\xi\left(\left|\Phi_1\right\rangle+\left|\Phi_2\right\rangle\right)=U\left[\xi\left(\left|\varphi_1\right\rangle+\left|\varphi_2\right\rangle\right)\right];\ \ \xi\equiv 2^{-1/2}$$

MACRO MICRO

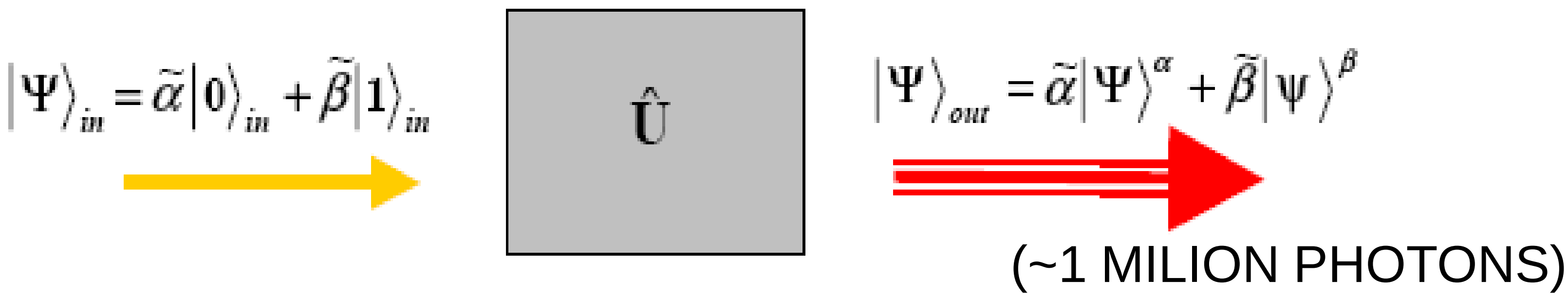
According to original Schroedinger's proposal: properties of the Cat wavefunction:

1) **INTERFERENCE** OF 2 MACROSTATES

2) EXACT **ORTHOGONALITY** OF MACROSTATES
because of mutually exclusive life – death

3) **ENTANGLEMENT** MICRO - MACRO

Quantum Map Micro-Macro



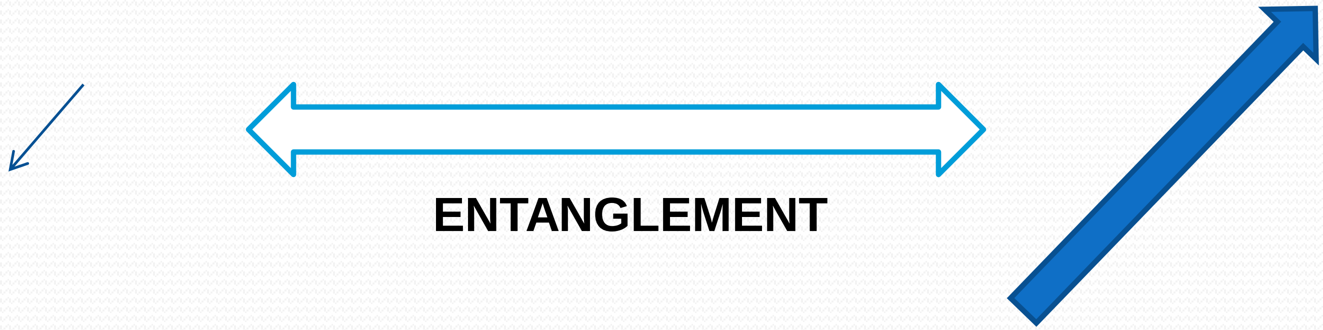
Amplification of the qubit $|\Psi\rangle_{in}$ into $|\Psi\rangle_{out}$ by means of the unitary operation $\hat{U}$.

For phase-covariant cloning: $\hat{U} \equiv \exp[-i(\hat{H}_{int} t/\hbar)]$.

MICRO-MACRO SPIN CORRELATION

ALICE's
MICRO-SPIN
(1 particle)

BOB's
MACRO-SPIN
(≈1.000.000 particles)



Two nonlocally correlated Micro – Macro
Poincaré spheres

PRL **100,** 253601 (2008) PHYSICAL REVIEW LETTERS week ending 27 JUNE 2008

Entanglement Test on a Microscopic-Macroscopic System

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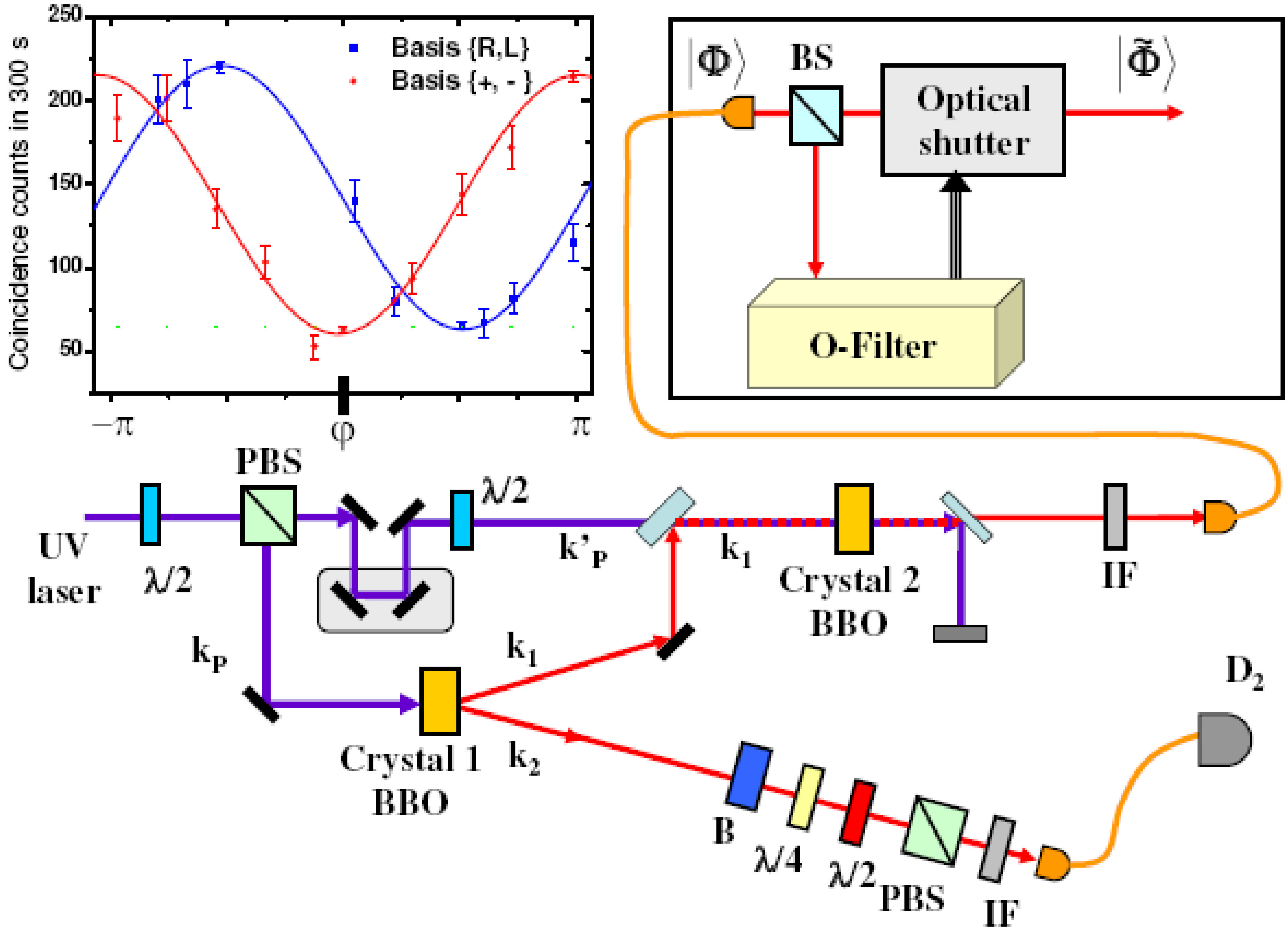
[2]*Accademia Nazionale dei Lincei, via della Lungara 10, I-00165 Roma, Italy*
[3]*Centro di Studi e Ricerche "Enrico Fermi", Via Panisperna 89/A,Compendio del Viminale, Roma 00184, Italy*
(Received 6 March 2008; published 26 June 2008)

A macrostate consisting of $\mathbf{N} \approx 3.5 \times 10^4$ photons in a quantum superposition and entangled with a far apart single-photon state (microstate) is generated. Precisely, an entangled photon pair is created by a nonlinear optical process; then one photon of the pair is injected into an optical parametric amplifier operating for any input polarization state, i.e., into a phase-covariant cloning machine. Such transformation establishes a connection between the single photon and the multiparticle fields. We then demonstrate the nonseparability of the bipartite system by adopting a local filtering technique within a positive operator valued measurement.

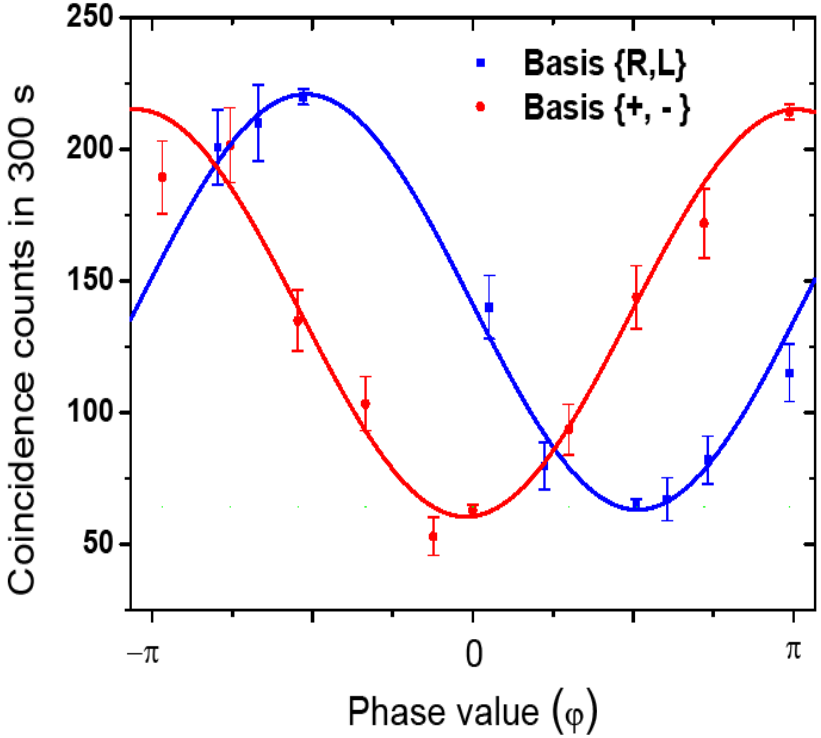
DOI: 10.1103/PhysRevLett.100.253601 PACS numbers: 42.50.Xa, 03.65.Ta, 03.67.Bg, 42.65.Lm

REVEALING HIDDEN NONLOCALITY (S.Popescu, PRL 1995)



MICRO-MACRO NON SEPARABILITY TEST

experimental results

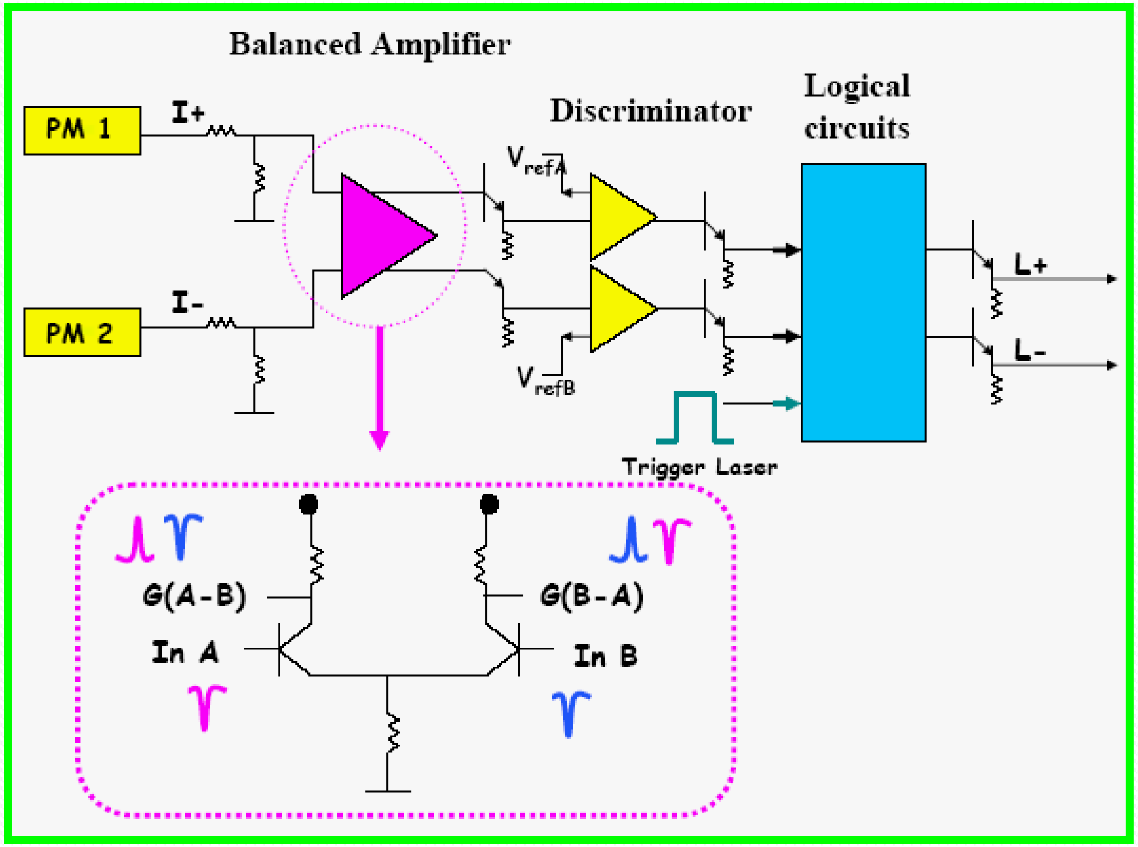


Necessary-Sufficient Non-separability Criterion:

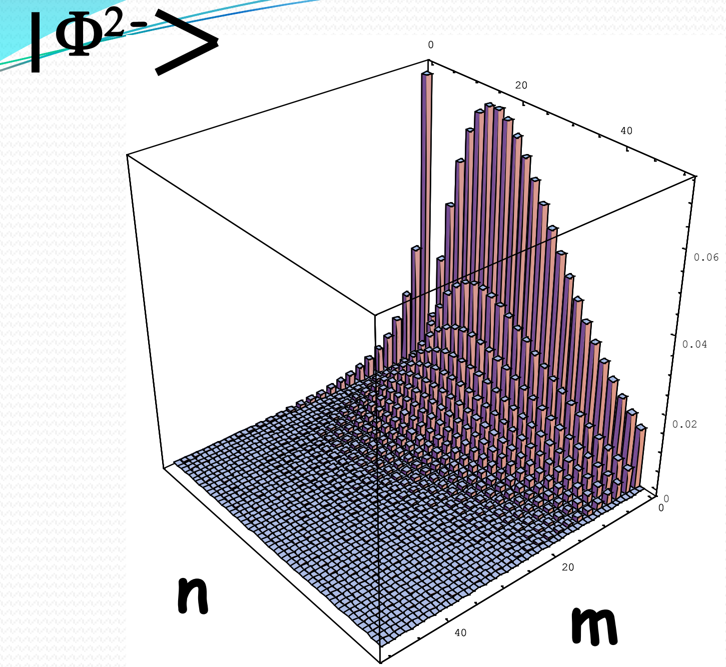
$$C = |V_1 + V_2 + V_3| \geq 1$$

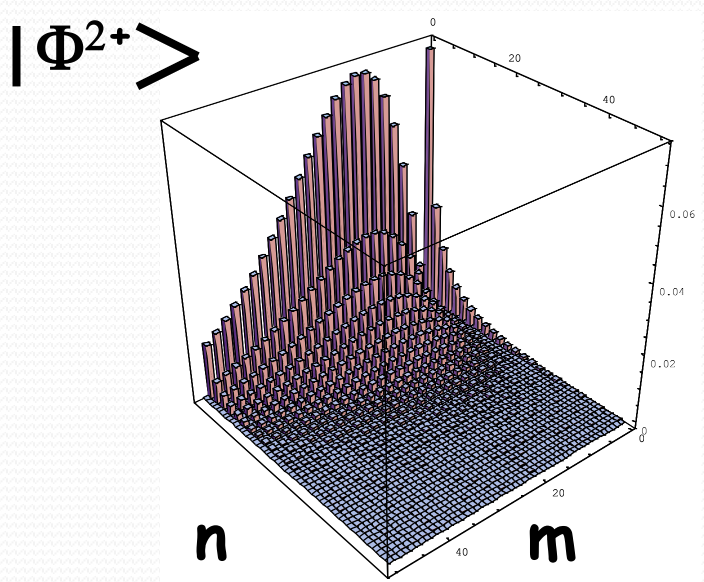
$$V_1 = 0;\ \ V_2 = (54.0 \pm 0.7)\%\ ;\ \ V_3 = (55.0 \pm 1.0)\%$$

$$C_{exp} = |V_1 + V_2 + V_3| = 1.090 \pm 0.012$$

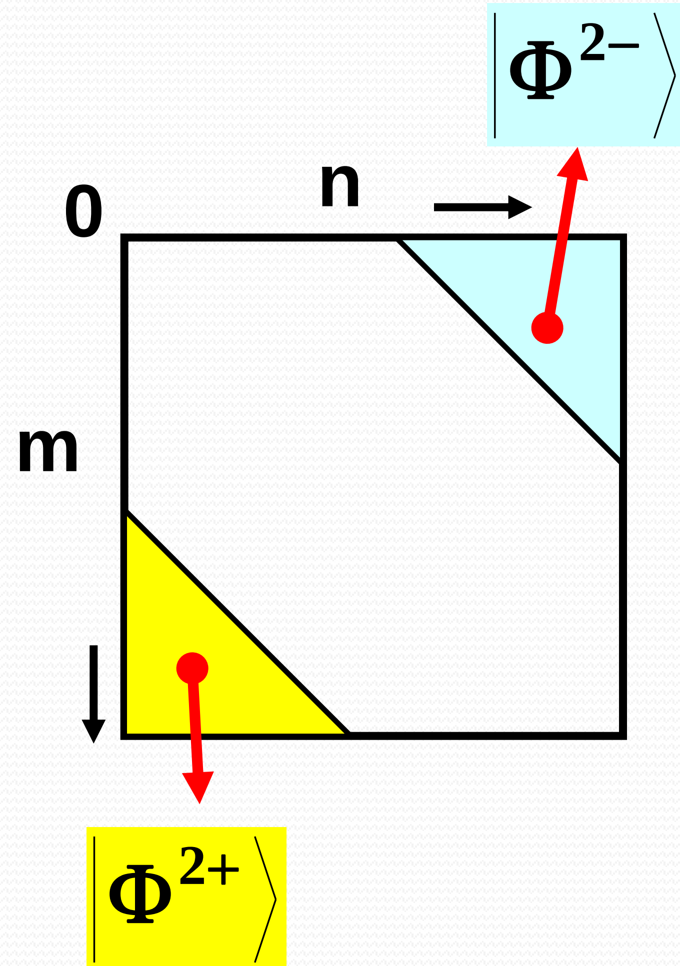


ORTHOGONALITY FILTER (OF)





(OF-Filter)



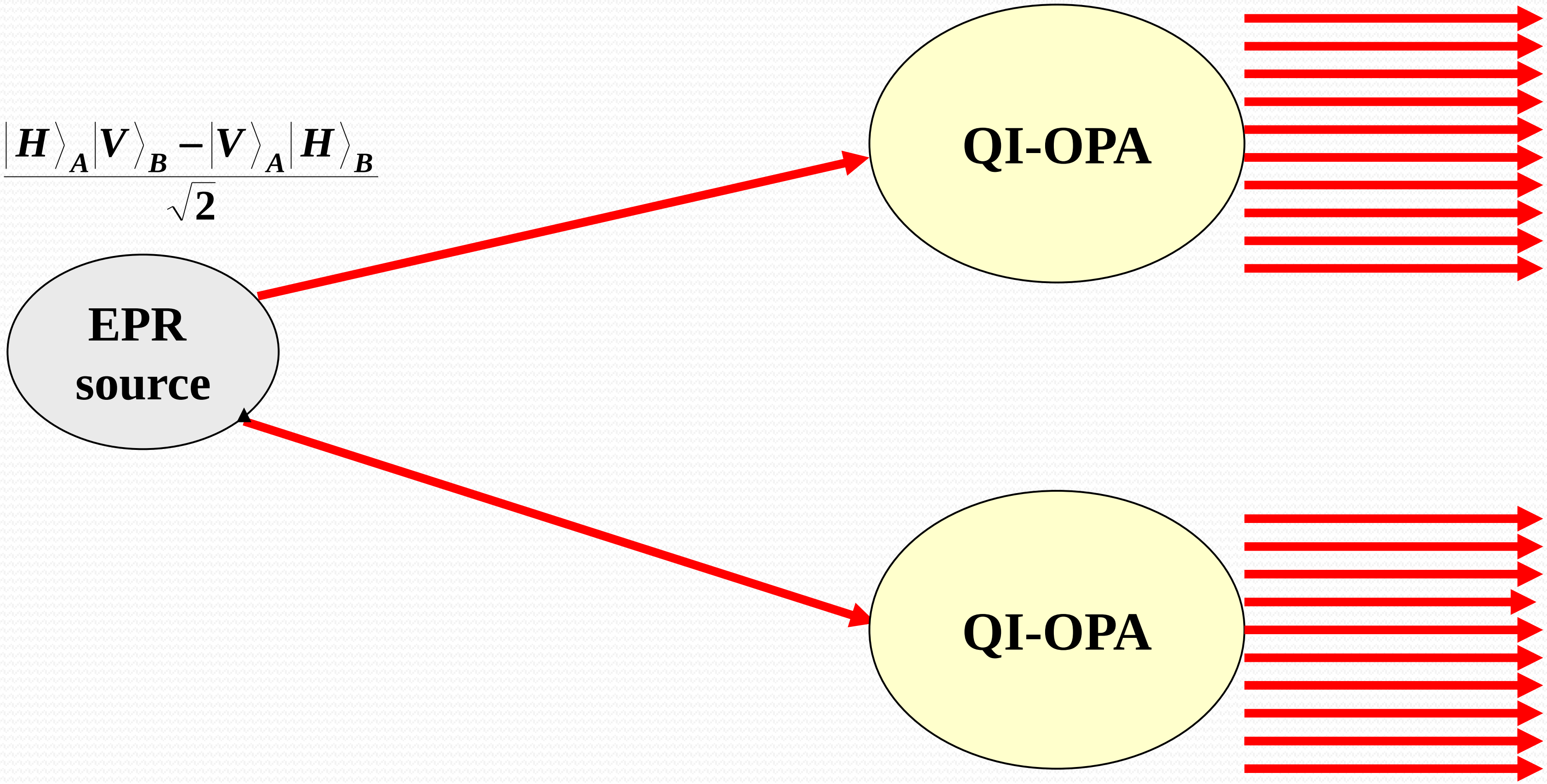
POVM strategy

OUTLINE:

- 1) Our CAT : Micro-Macro entanglement
- 2) Macro-Macro Entanglement
- 3) Decoherence theory: criterion for external and internal decoherence.
- 4) Mirror BEC
- 5) Applications to Long-range Micro-Macro Quantum Teleportation
- 6) Insight into Macrorealism: Conjecture about
- quantum-to-classical transition.

BEYOND THE SCHRODINGER CAT:
Entanglement between 2 mesoscopic fields
MACRO - MACRO ENTANGLEMENT

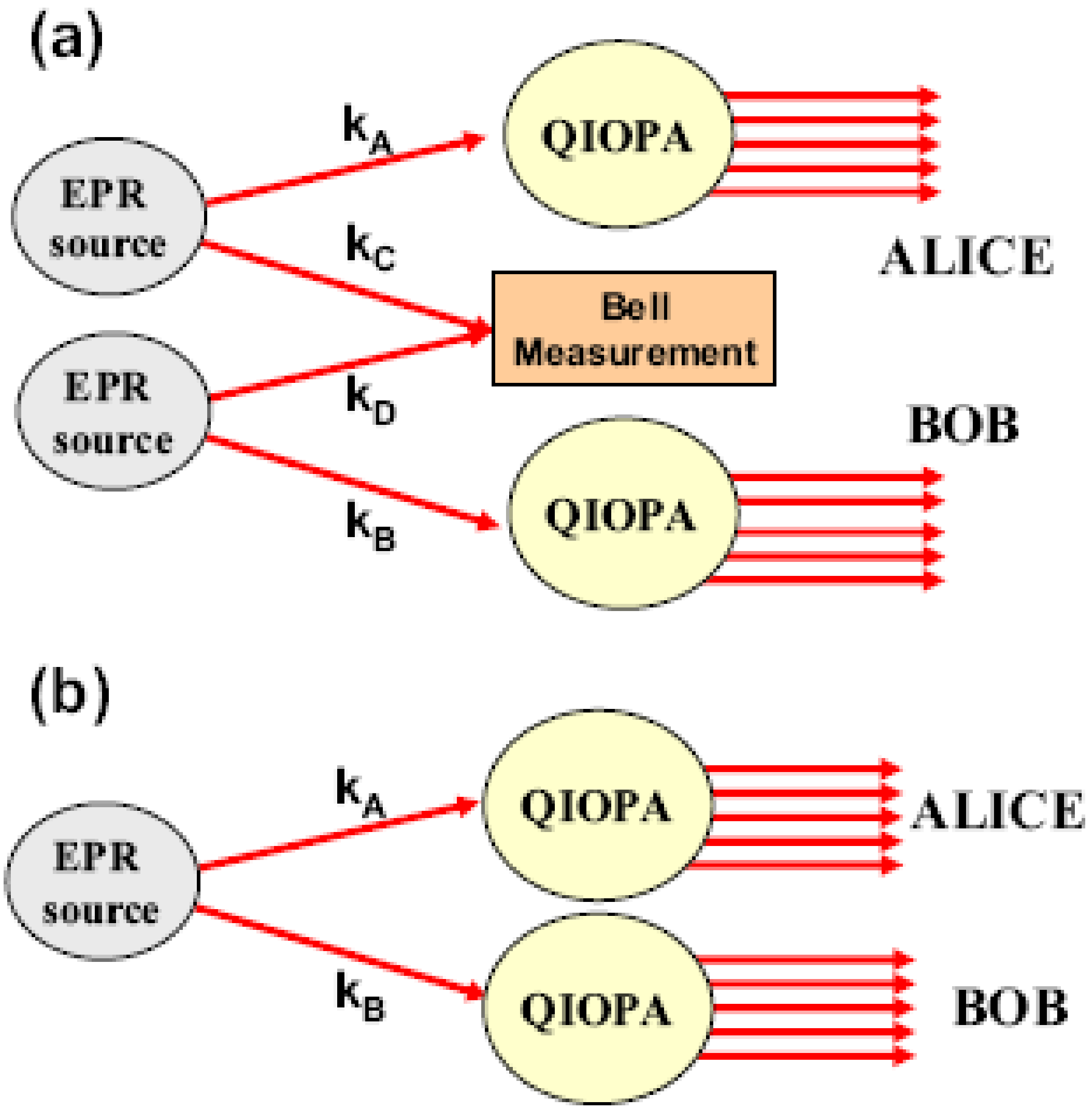
$$\frac{|H\rangle_A |V\rangle_B - |V\rangle_A |H\rangle_B}{\sqrt{2}}$$



$$|\Sigma\rangle = \frac{|\Theta\rangle_A \otimes |\Phi\rangle_B - |\Theta_\perp\rangle_A \otimes |\Phi_\perp\rangle_B}{\sqrt{2}} \quad : (Macro - Macro\ Bell - State)$$

MACRO - MACRO ENTANGLEMENT

quantum repeaters

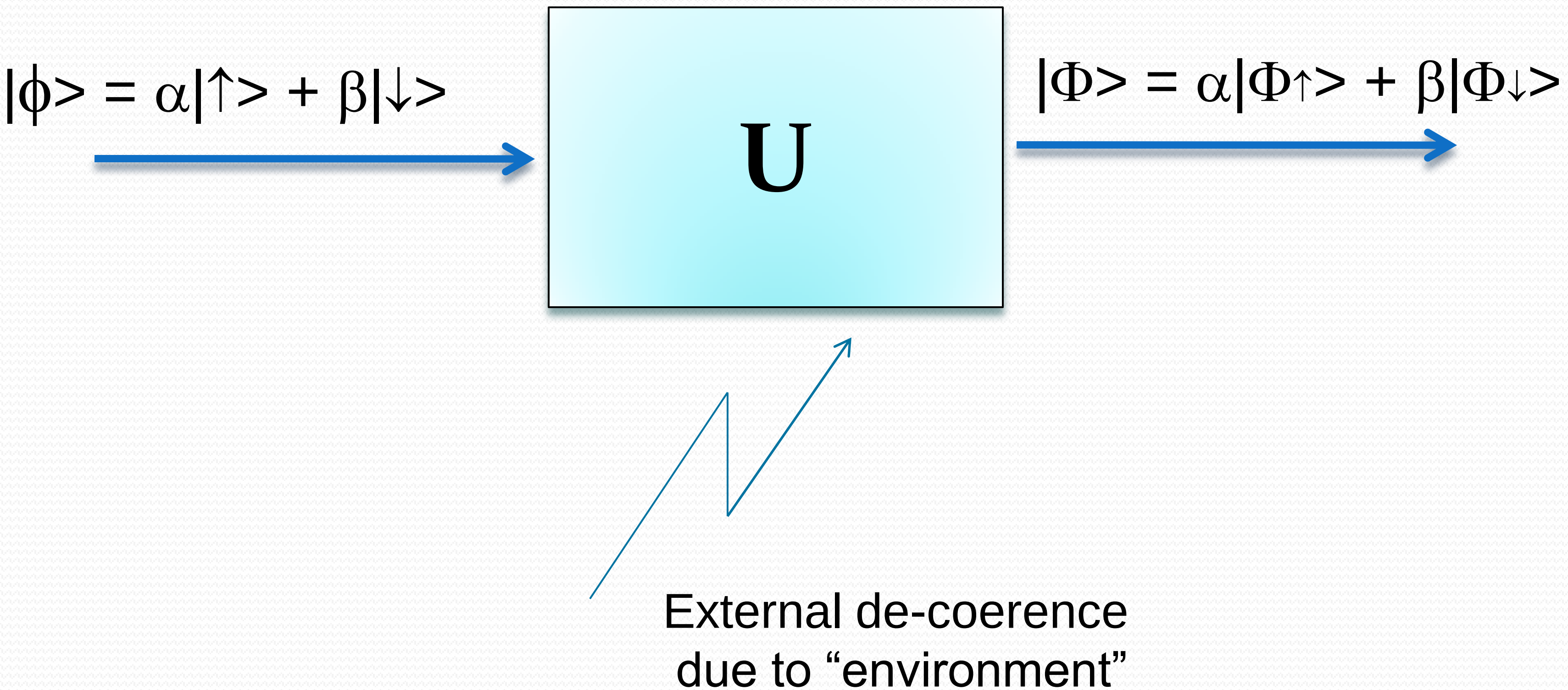


Handwritten note by Einstein on the back of a Greetings Postcard sent to Max Born on January 1, 1954

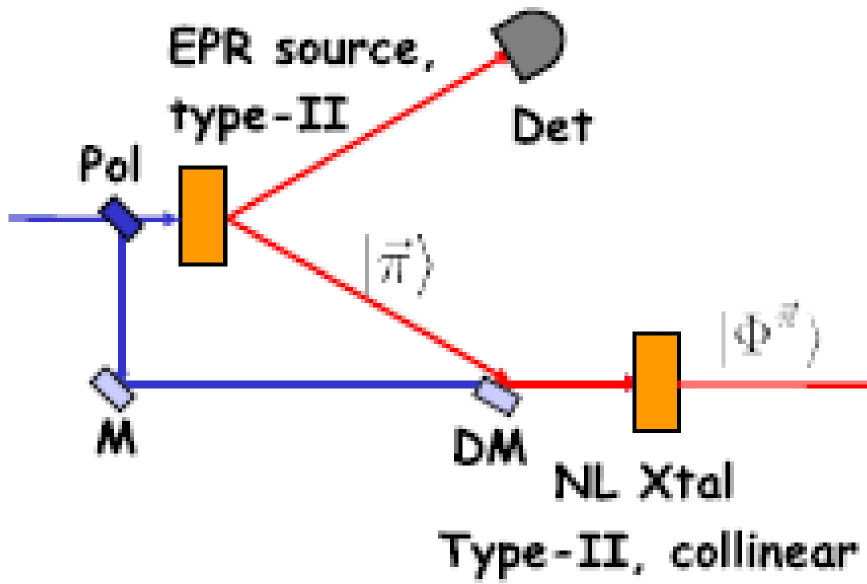
"Let ψ_1 and ψ_2 be solutions of the same Schrödinger equation.... When the system is a macrosystem and when ψ_1 and ψ_2 are 'narrow' with respect to the macrocoordinates, then in by far the greater number of cases this is no longer true for $\psi = \psi_1 + \psi_2$. Narrowness with respect to macrocoordinates is not only *independent* of the principles of quantum mechanics, but, moreover, *incompatible* with them." [The translation from Born (1969) quoted here is due to Joos (1986), p. 7].

Einstein-Born Briefwechsel 1916-1955, Nymphenburger Verlagshandlung GmbH, Munchen (1969)

MICRO - MACRO QUANTUM - MAP



ASSESSMENT OF DECOHERENCE IN QI-OPA: THE LOSSY CHANNEL



R+T = 1

Interference Visibility of Macro-States: Bures distance : $D(\hat{\rho},\hat{\sigma})$

D. Bures, *Trans. Math. Soc. 1969*

R. Jozsa, *J. Mod. Opt. 1994*

A. Uhlmann, *Rep. Math. Phys. 1986*

$$D(\hat{\rho},\hat{\sigma}) = \sqrt{1 - F(\hat{\rho},\hat{\sigma})}$$

where: **STATE FIDELITY**:

$$F(\hat{\rho},\hat{\sigma}) = \mathrm{Tr}\left(\sqrt{\hat{\rho}^{\frac{1}{2}}\hat{\sigma}\hat{\rho}^{\frac{1}{2}}}\right) \Rightarrow \left|\langle\psi|\varphi\rangle\right| \quad \text{(for pure states)}$$

(a) State distinguishability

i.e.

$$\begin{cases} |\alpha\rangle \Leftrightarrow |-\alpha\rangle \\ |\Phi^{+}\rangle \Leftrightarrow |\Phi^{-}\rangle \\ |\Phi^{R}\rangle \Leftrightarrow |\Phi^{L}\rangle \end{cases}$$

→ represents how close two quantum states are

(MQS "Visibility" (i.e. state-orthogonality)

i.e.

$$\begin{cases} \frac{N}{\sqrt{2}}\left(|\alpha\rangle + |-\alpha\rangle\right) \Leftrightarrow \frac{N}{\sqrt{2}}\left(|\alpha\rangle - |-\alpha\rangle\right) \\ \frac{1}{\sqrt{2}}\left(|\Phi^{+}\rangle - |\Phi^{-}\rangle\right) \Leftrightarrow \frac{1}{\sqrt{2}}\left(|\Phi^{+}\rangle + |\Phi^{-}\rangle\right) \\ \frac{1}{\sqrt{2}}\left(|\Phi^{R}\rangle - |\Phi^{L}\rangle\right) \Leftrightarrow \frac{1}{\sqrt{2}}\left(|\Phi^{R}\rangle + |\Phi^{L}\rangle\right) \end{cases}$$

BURES DISTANCE FOR COHERENT STATES

$$\mathrm{D}(|\alpha\rangle, |-\alpha\rangle) = 1 \;\; ; |\alpha\rangle - states : "einselected"$$

"pointer states"

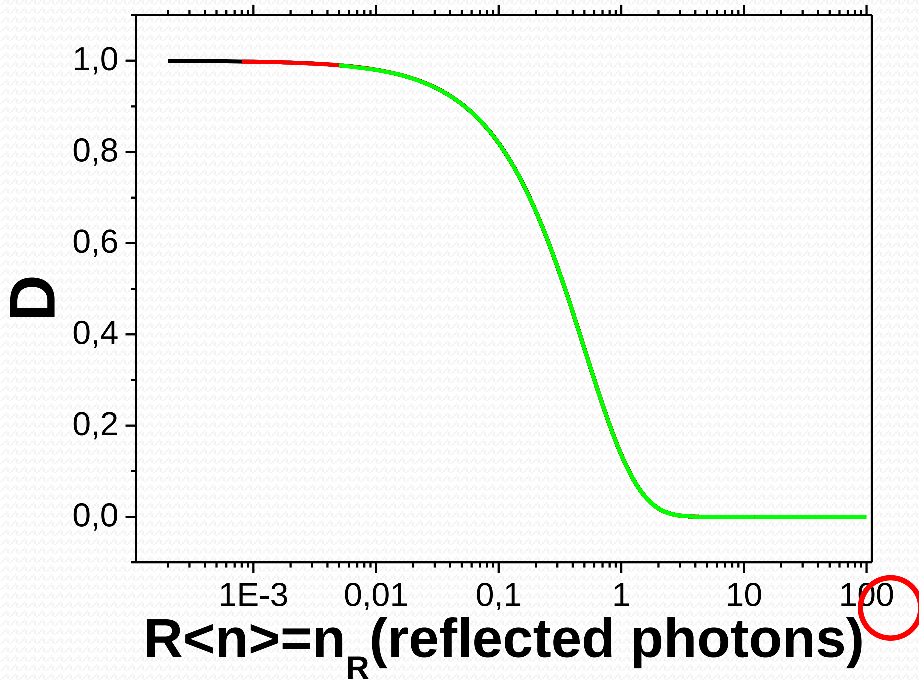
$$\mathrm{D}(\Psi_{+}^{\alpha}, \Psi_{-}^{\alpha}) \approx 0 \;\; ; \left|\Psi_{\pm}^{\alpha}\right\rangle = 2^{-1/2} N(|\alpha\rangle \pm |-\alpha\rangle)$$

Sudden decoherence of all MQS!

W. Źurek, Physics Today, October 1991, pag.36; *Rev. Mod. Phys.* **75**, 715 (2003); *Progr. Math. Phys.* **48**, 1 (2007)

Coherent - State superposition : $\frac{N}{\sqrt{2}}\left(|\alpha\rangle \pm |-\alpha\rangle\right)$

BURES DISTANCE D : $\frac{N}{\sqrt{2}}\left(|\alpha\rangle + |-\alpha\rangle\right) \Leftrightarrow \frac{N}{\sqrt{2}}\left(|\alpha\rangle - |-\alpha\rangle\right)$



$$D_{MQS} = \sqrt{1 - \sqrt{1 - e^{-4R|\alpha|^2}}}$$

Coherence lost after loss of a single photon for **ANY** <n> !

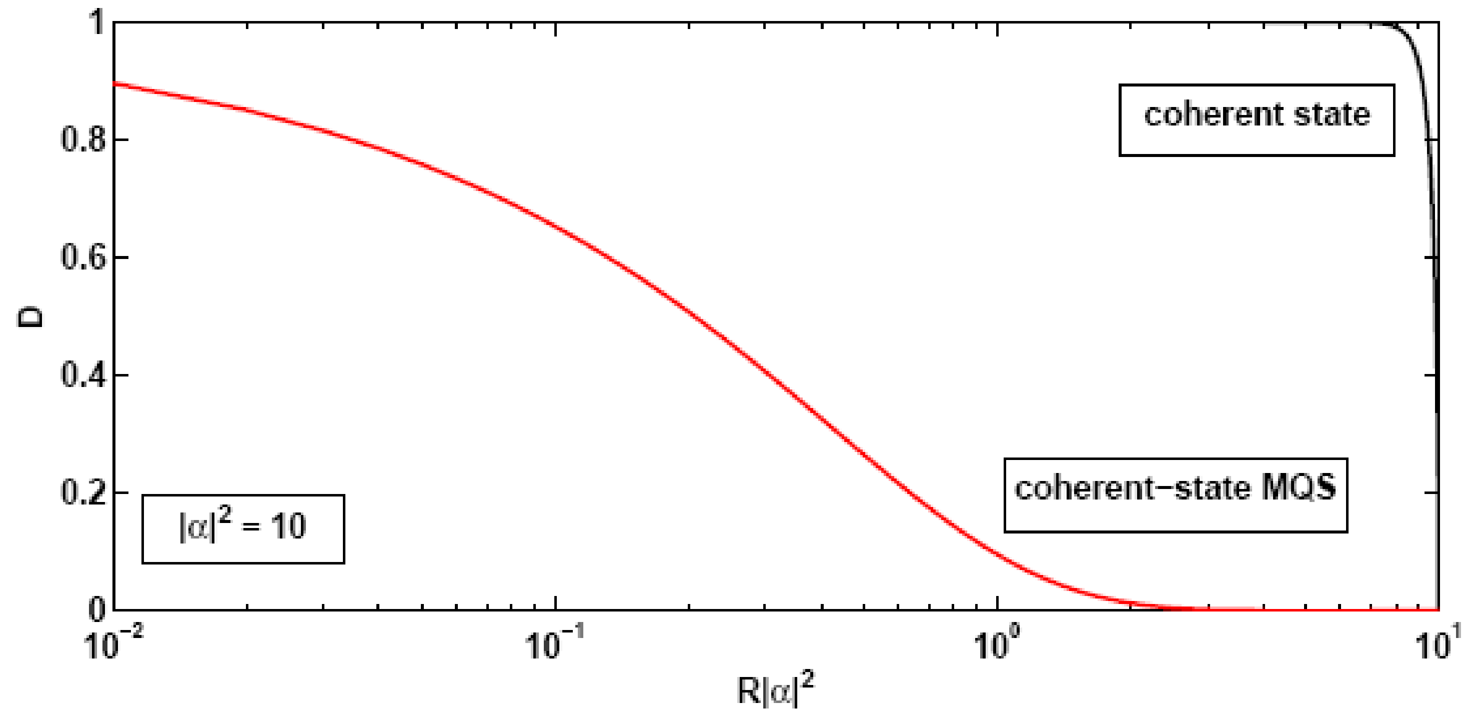
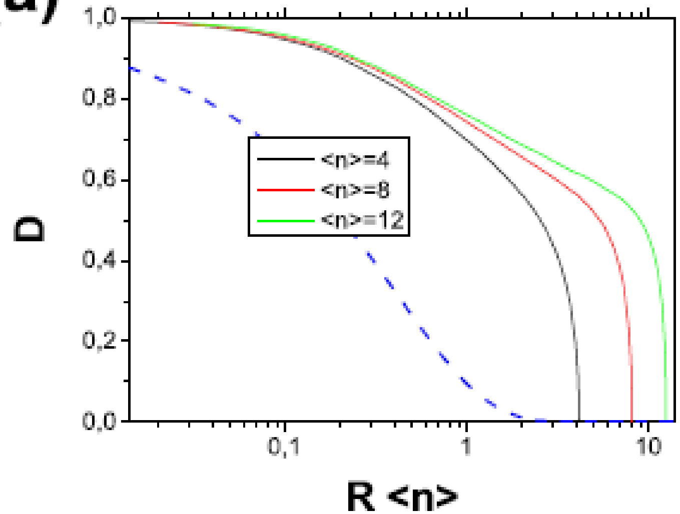


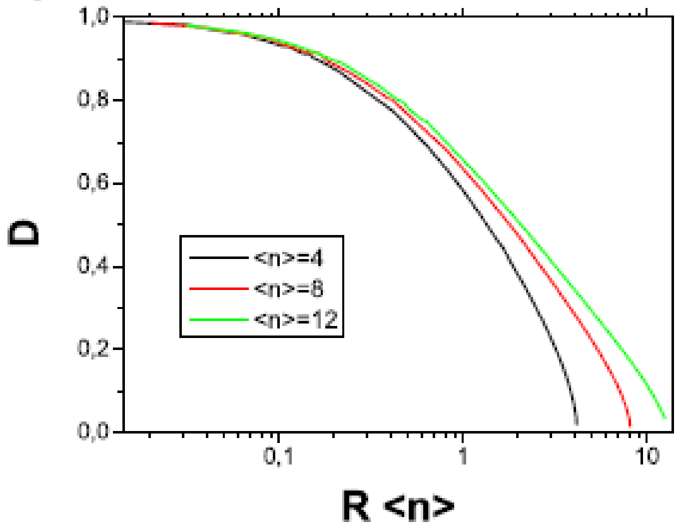
Figure 1: (Loss-robustness comparison between the coherent state distinguishability, $D(|\alpha\rangle, |-\alpha\rangle)$, and the coherent-state MQS distinguishability, $D(|\Phi_{\alpha_+}\rangle, |\Phi_{\alpha_-}\rangle)$.

Decoherence of QI-OPA Macroscopic Quantum Superposition (q-MQS)

(a)

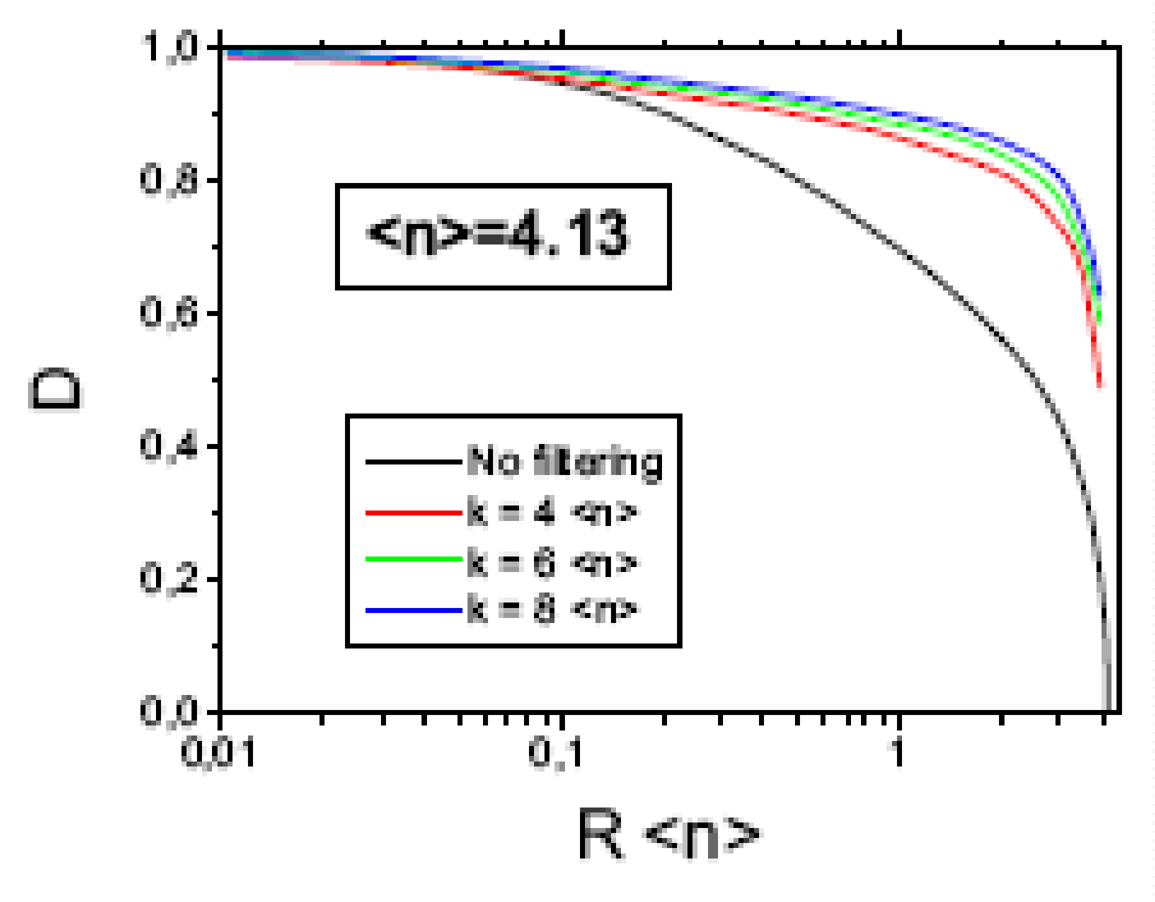


(b)



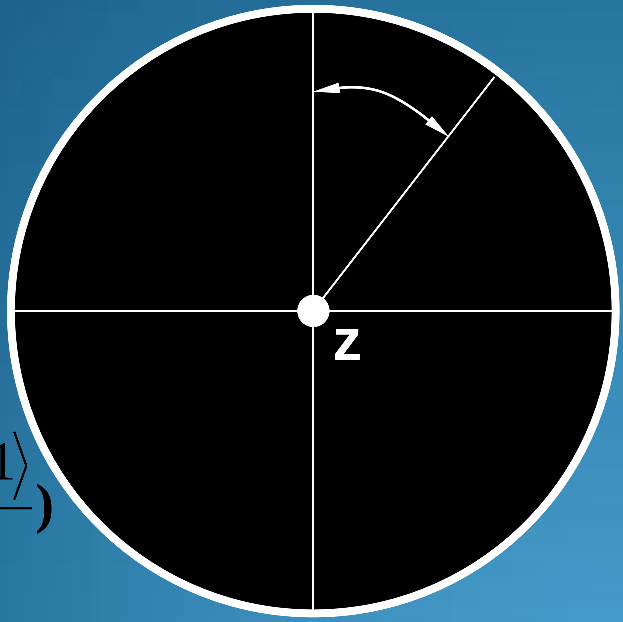
Decoherence of QI-OPA MQS

ORTHOGONALITY FILTER: threshold k



Equatorial z-plane for Collinear QI-OPA: PHASE - COVARIANT CLONING

$$\varphi = 0;\ |+\rangle_A = \left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right)$$



$$\varphi = \frac{3\pi}{2}$$

$$|\mathbf{L}\rangle = \left(\frac{|0\rangle - i|1\rangle}{\sqrt{2}}\right)$$

$$\varphi = \frac{\pi}{2}$$

$$|\mathbf{R}\rangle = \left(\frac{|0\rangle + i|1\rangle}{\sqrt{2}}\right)$$

$$\varphi = \pi;\ |-\rangle = \left(\frac{|0\rangle - |1\rangle}{\sqrt{2}}\right)$$

Input qubit:

$$\frac{|\mathbf{0}\rangle + e^{i\varphi}|\mathbf{1}\rangle}{\sqrt{2}} = \hat{U}_Z \frac{|\mathbf{0}\rangle + |\mathbf{1}\rangle}{\sqrt{2}}$$

with: $\hat{U}_Z = e^{i\frac{\varphi}{2}\hat{\sigma}Z}$

BURES DISTANCE IN THE PREFERRED HILBERT SUBSPACE FOR OPTIMAL PHASE - COVARIANT CLONING

$$\{|\Phi^R\rangle, |\Phi^L\rangle\}: \ |\Phi^R\rangle = \frac{\mathcal{N}_\pm}{\sqrt{2}}\left(|\Phi^+\rangle + i|\Phi^-\rangle\right)$$

$$|\Phi^L\rangle = \frac{\mathcal{N}_\pm}{\sqrt{2}}\left(|\Phi^+\rangle - i|\Phi^-\rangle\right)$$

$$D(|\Phi^R\rangle, |\Phi^L\rangle) = D(|\Phi^+\rangle, |\Phi^-\rangle)$$

MACROSCOPIC BASIS VECTORS AS WELL AS THEIR QUANTUM SUPERPOSITIONS ARE

HIGHLY STABLE STATES !

(I.E. VIRTUALLY DECOHERENCE-FREE MQS)

$$|\Psi^{\pm}\rangle \equiv (|\Phi^{+}\rangle \pm |\Phi^{-}\rangle)/\sqrt{2},$$

FOR COHERENT STATES :

$$|\Phi_{\alpha_{\pm}}\rangle \equiv (|\alpha\rangle \pm |-\alpha\rangle)/\sqrt{2(1 \pm e^{-4|\alpha|^2})},$$

$$D(|\Phi_{\alpha_+}\rangle, |\Phi_{\alpha_-}\rangle) \neq D(|\alpha\rangle, |-\alpha\rangle).$$

$$D(|\alpha\rangle, |-\alpha\rangle) = \sqrt{1 - e^{-2(1-R)|\alpha|^2}}, \quad D(|\Phi_{\alpha_+}\rangle, |\Phi_{\alpha_-}\rangle) = \sqrt{1 - \sqrt{1 - e^{-4R|\alpha|^2}}}$$

FOR q - MQS (covariant) :

$$D(|\Psi^{+}\rangle, |\Psi^{-}\rangle) = D(|\Phi^{+}\rangle, |\Phi^{-}\rangle),$$

COVARIANCE: CRITERIUM FOR DECOHERENCE FREEDOM ?

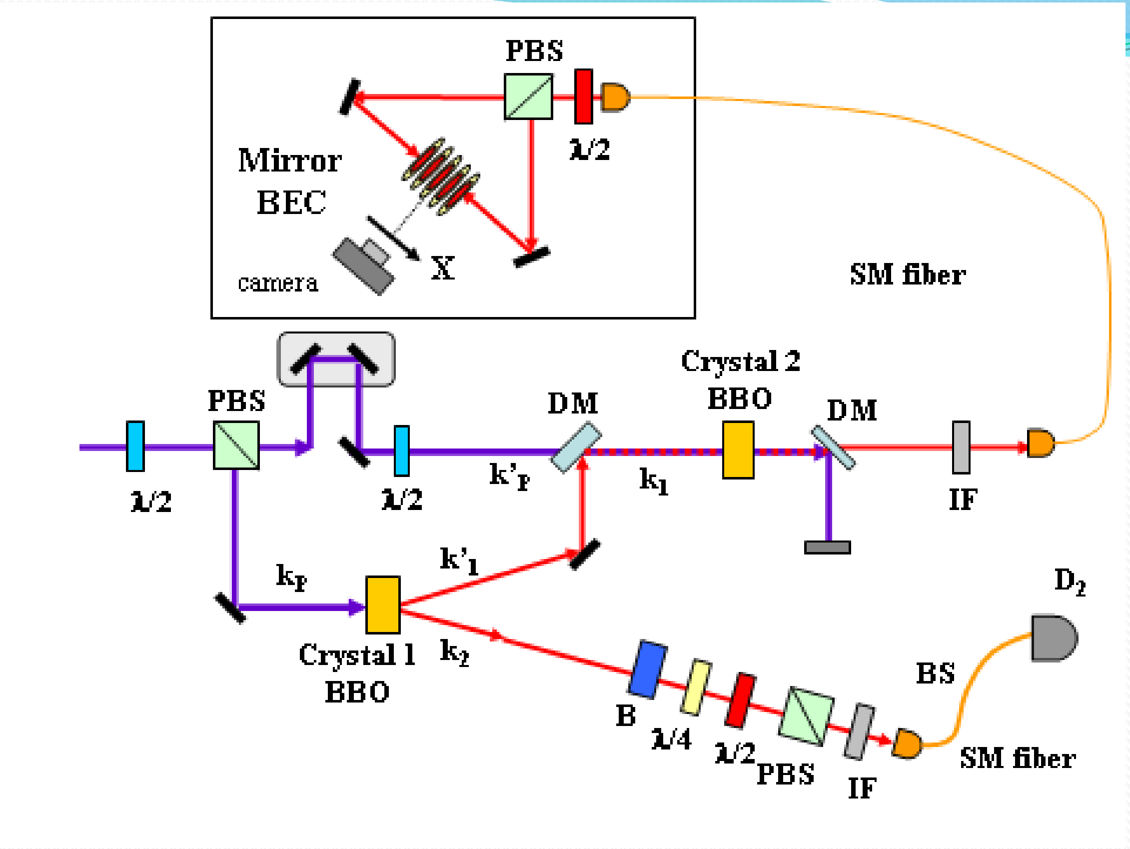
Quantum Injected Optical Parametric Amplifier (QI-OPA):

based on "Optimal Quantum Cloning" :

NOT a "Closed thermodynamic" system BUT:

"**Open, Driven, Far-from-equilibrium**" system

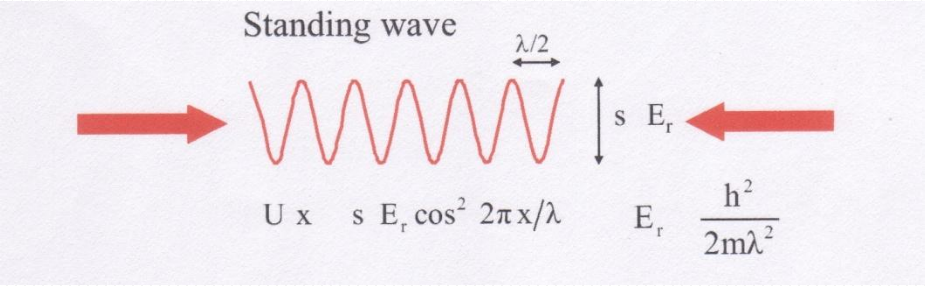
(good model for self- controlled, self–reproductive fundamental processes of biological systems)

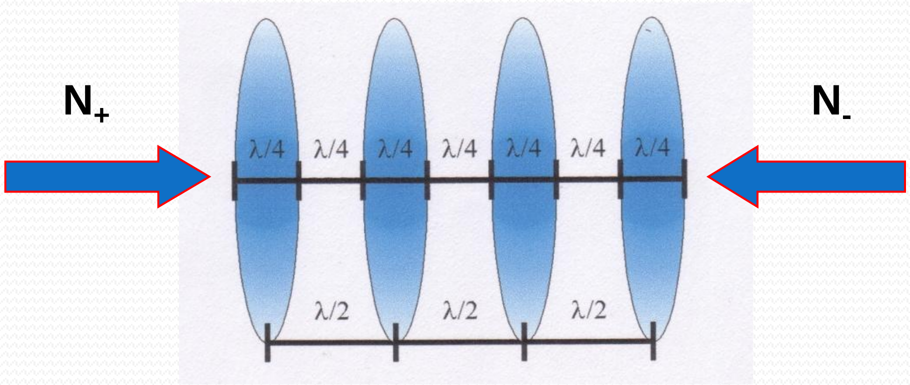


OPTO - MECHANICAL SCHRŐDINGER CAT

F. De Martini, F Sciarrino, C.Vitelli, Phys. Rev. Lett. **100**, 253601, 2008)
F. De Martini, F. Sciarrino, C.Vitelli, F. Cataliotti,
Phys.Rev.Lett. **104**, 050403 (2010).

QI-OPA DRIVEN BEC MECHANICAL OSCILLATIONS

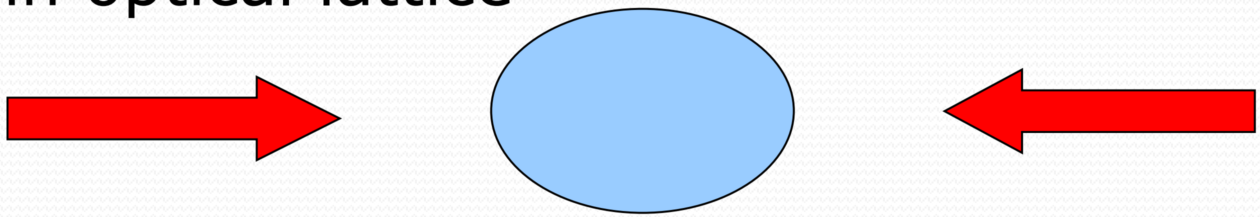




SUPERRADIANT RAYLEIGH SCATTERING → BRAGG SCATTERING:
L.De Sarlo et al (LENS Group) Eur.Phys. J.D. (2004)
L.Fallani et al. (LENS Group) PRA 71, 033612 (2005)

Reflection by a Bragg BEC mirror

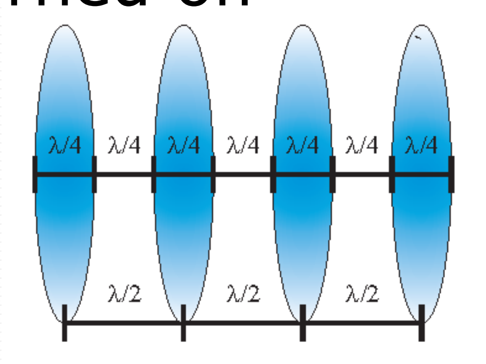
I) BEC in optical lattice



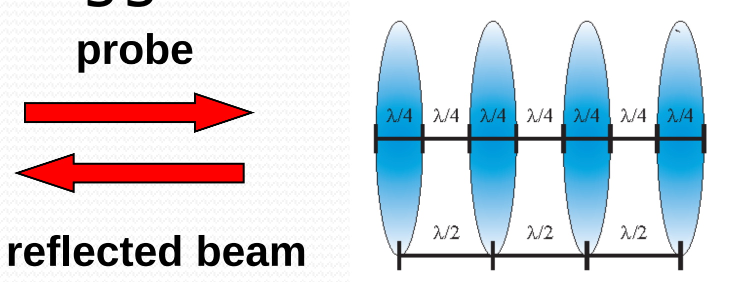
BEC

II) Optical lattice turned off

Bragg structured



III) Bragg structured BEC adopted as a mirror



- **Light reflected**
- **Atom acquires momentum kick equal to**

$$2\hbar k$$

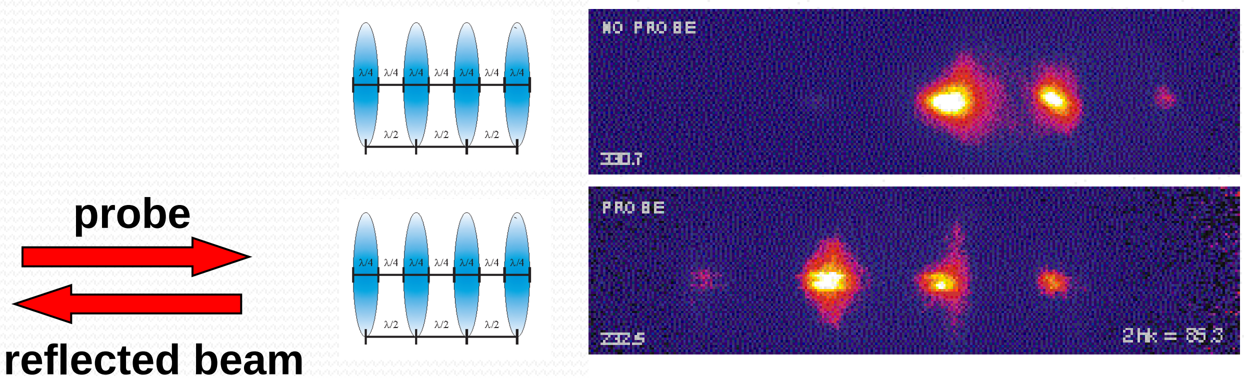
Preliminary results on BEC observed in Florence

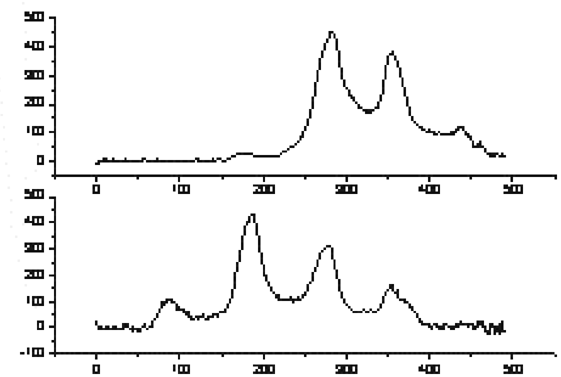
Shadow snapshot of the condensate after expansion: measurement of momentum distribution

Scattering of radiation by a condensate

Measurement performed by F. Cataliotti, C. Fort, … at LENS (January 2008)

Scattering of radiation by a Bragg structured condensate





Momentum distribution

Reflected photon per atom ~1.15

“THE” QUESTION

- WHY IN THE WORLD OF OUR DAILY EXPERIENCE, IN OUR OWN LIVES, WE DON’T PERCEIVE THE QUANTUM PHENOMENA: THE ONES EASILY FOUND MANIPULA-TING FEW PARTICLES IN THE LABORATORY ?

(e.g. INTERFERENCE, ENTANGLEMENT, TELEPORTATION)

- ?

TODAY STANDARD ANSWERS:

1) GRW "DYNAMICAL REDUCTION MODEL".

The Schrödinger equation is modified by a NL term. At a certain vaguely specified level of macroscopicity a kind of "phase transition" leads naturally to the "macroscopic dynamics", i.e. to: "classical" physics (G.Ghirardi, T. Weber, A.Rimini: Lett. Nuovo Cimento 1980).

2) DECOHERENCE (Wojciech H. Zurek, 1991).

Interactions with the "environment" spoil any evidence of quantumness beyond a certain level of system's complexity.

BUT NOW :

1) IF you don't believe in GRW.
2) IF a DECOHERENCE FREE system is found, as in our case another, sensible SOLUTION is needed.

A hint to the solution may be seached in the context of EPR for Large Spins (J>>1)

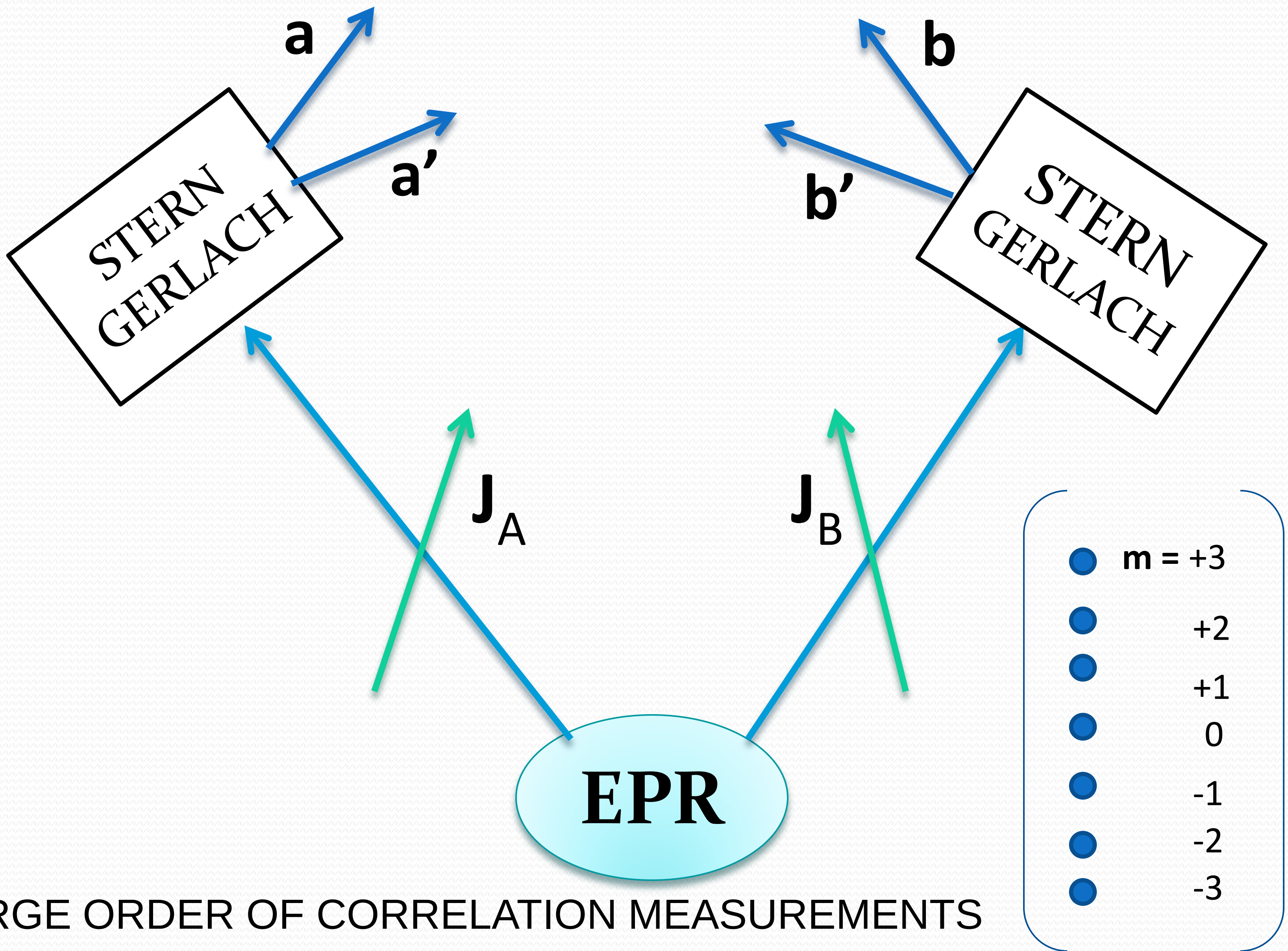
N. D. Mermin, G.M. Schwarz, Founds. of Phys. 1982.
A.Peres, Quantum Theory and Methods (Kluwer, 1983)
J. Kofler , C. Brukner, PRL 99 (2007), and: PRL 101 (2008).

MACROREALISM

Two Postulates (A.J. Leggett , A. Garg, PRL 1985):

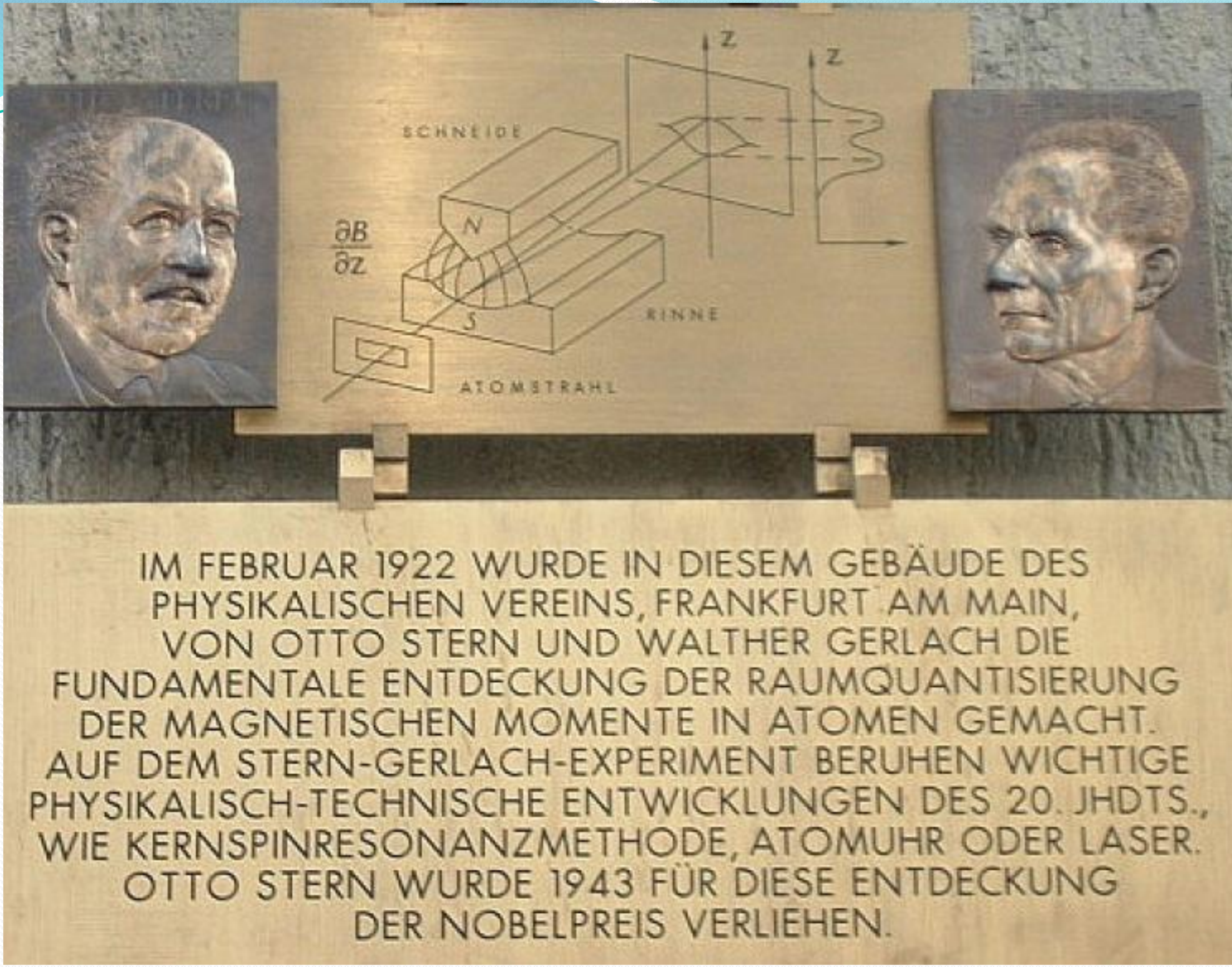
a) A macro system which has available to it two or more macroscopically distinct states, is at any given time in a definite one of these states.

b) It is possible in principle to determine which of these states the system is in without any effect on the state itself or on the subsequent system dynamics”



F10-3

LARGE ORDER OF CORRELATION MEASUREMENTS


Z
Z
SCHNEIDE
∂B/∂z
N
S
RINNE
ATOMSTRAHL
IM FEBRUAR 1922 WURDE IN DIESEM GEBÄUDE DES
PHYSIKALISCHEN VEREINS, FRANKFURT AM MAIN,
VON OTTO STERN UND WALTHER GERLACH DIE
FUNDAMENTALE ENTDECKUNG DER RAUMQUANTISIERUNG
DER MAGNETISCHEN MOMENTE IN ATOMEN GEMACHT.
AUF DEM STERN-GERLACH-EXPERIMENT BERUHEN WICHTIGE
PHYSIKALISCH-TECHNISCHE ENTWICKLUNGEN DES 20. JHDTS.,
WIE KERNSPINRESONANZMETHODE, ATOMUHR ODER LASER.
OTTO STERN WURDE 1943 FÜR DIESE ENTDECKUNG
DER NOBELPREIS VERLIEHEN.

Bell inequalities for higher spins: J>1/2

$J_{1z}u_m = mu_m$; $J_{2z}v_m = mv_m$; $m = j, j-1, \ldots, -j$;

For $(J_{1z}+J_{2z}) = 0$:

$$\left|\Sigma\right\rangle = \sum_m c_m u_m \otimes v_{-m} \quad (Schmidt\ sum)$$

$$\left\langle\Sigma\right|(\alpha \bullet J_1) \otimes (\beta \bullet J_2)\left|\Sigma\right\rangle = -j(j+1)(\alpha \bullet \beta)/3$$

$$Stern-Gerlach\ measures: \quad \exp\left[i\pi\left(j - J_z\right)\right]$$

$$with\ eigenvalues: \pm 1$$

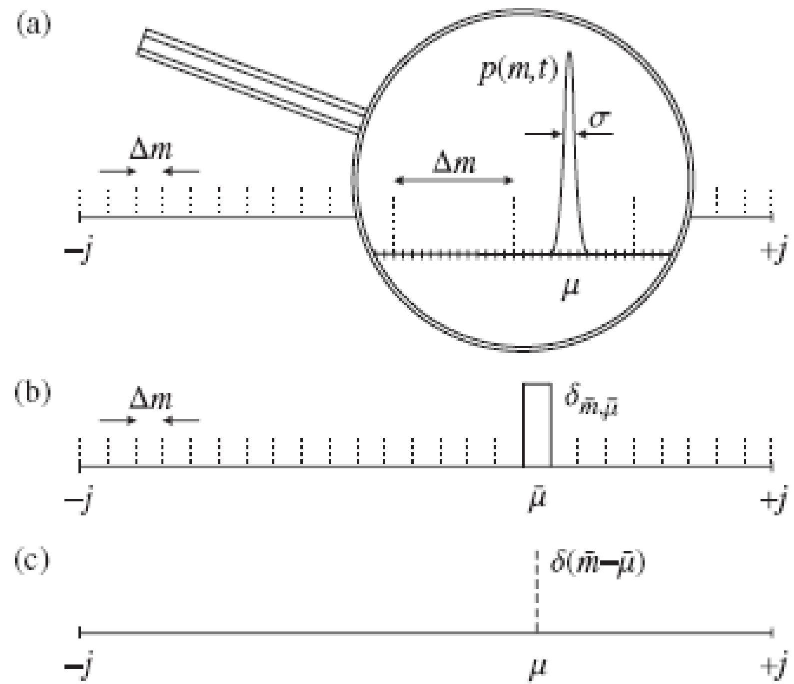
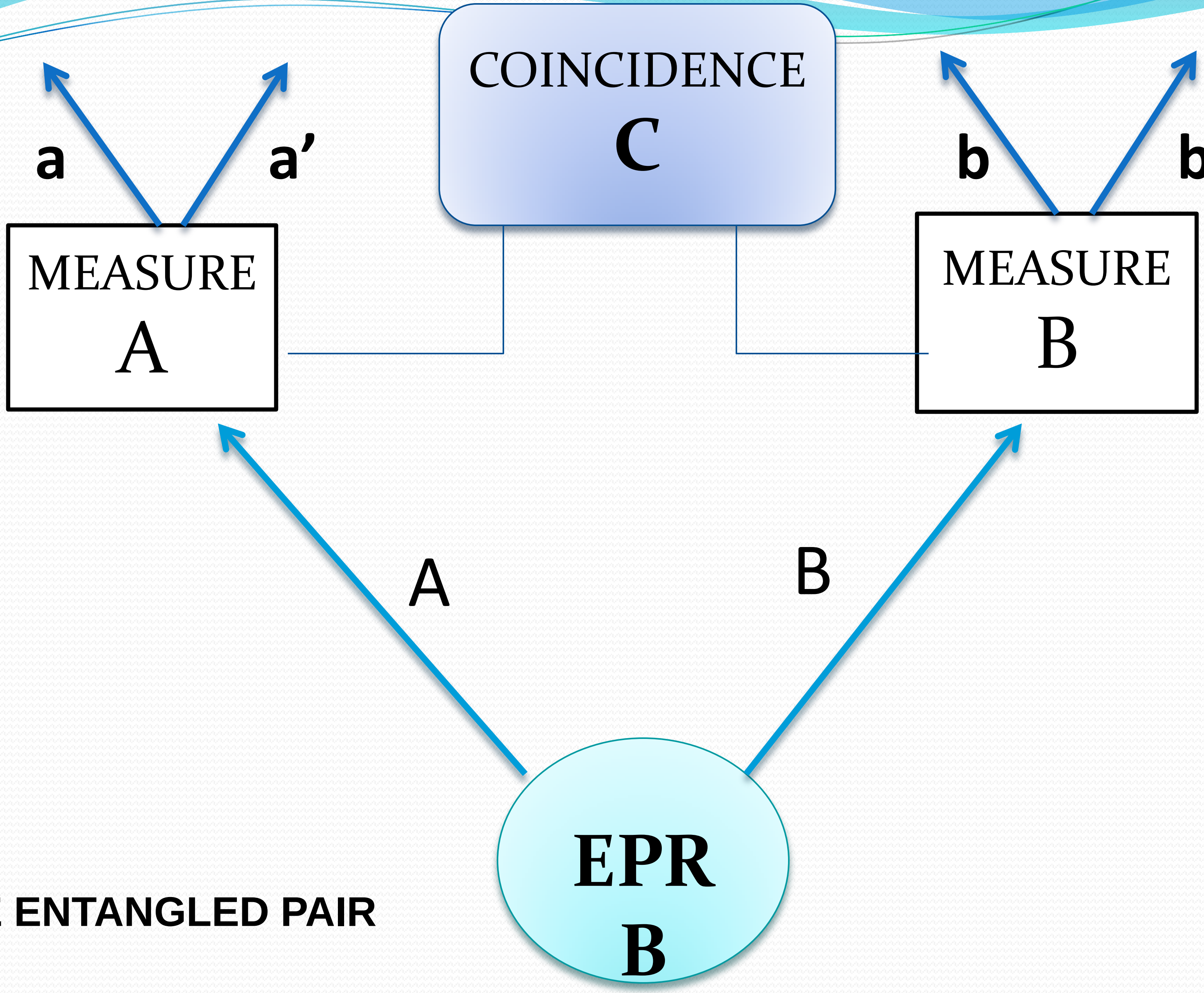


FIG. 1. An initial spin-j coherent state $|\vartheta_0, \varphi_0\rangle$ precesses into the coherent state $|\vartheta, \varphi\rangle$ at time t under a quantum time evolution. (a) The probability $p(m,t)$ for the outcome m in a measurement of the spin's z-component is given by a Gaussian distribution with width σ and mean μ, which can be seen under the magnifying glass of sharp measurements. (b) The measurement resolution Δm is finite and subdivides the $2j+1$ possible outcomes into a smaller number of coarse-grained "slots." If the measurement accuracy is much poorer than the width σ, i.e., $\Delta m \gg \sqrt{j}$, the sharply peaked Gaussian cannot be distinguished anymore from the Kronecker delta $\delta_{\bar{m},\bar{\mu}}$ where $\bar{m}$ is numbering the slots and $\bar{\mu}$ is the slot in which the center μ of the Gaussian lies. (c) In the limit $j \to \infty$, the slots *seem* to become infinitely narrow and $\delta_{\bar{m},\bar{\mu}}$ becomes the delta function $\delta(\bar{m} - \bar{\mu})$.

J.Kofler, C.Brukner
PRL 99, 2007



SINGLE ENTANGLED PAIR

F14-3

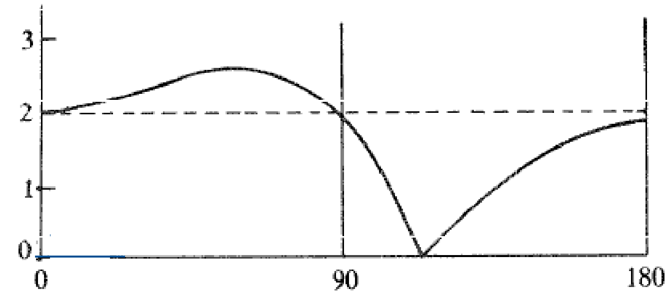
Bell's parameter

$$S \equiv |c(\mathbf{a}, \mathbf{b}) + c(\mathbf{a'},\mathbf{b}) + c(\mathbf{a}, \mathbf{b'}) - c(\mathbf{a'},\mathbf{b'})| \leq 2$$

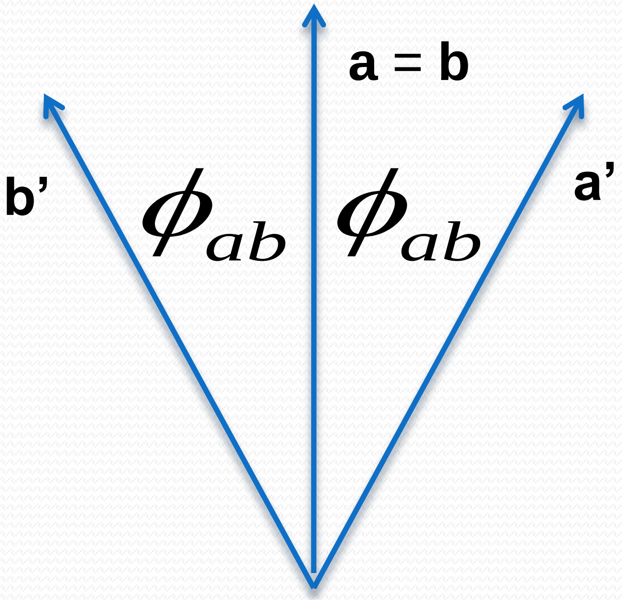
↑

"CLASSICALLY"

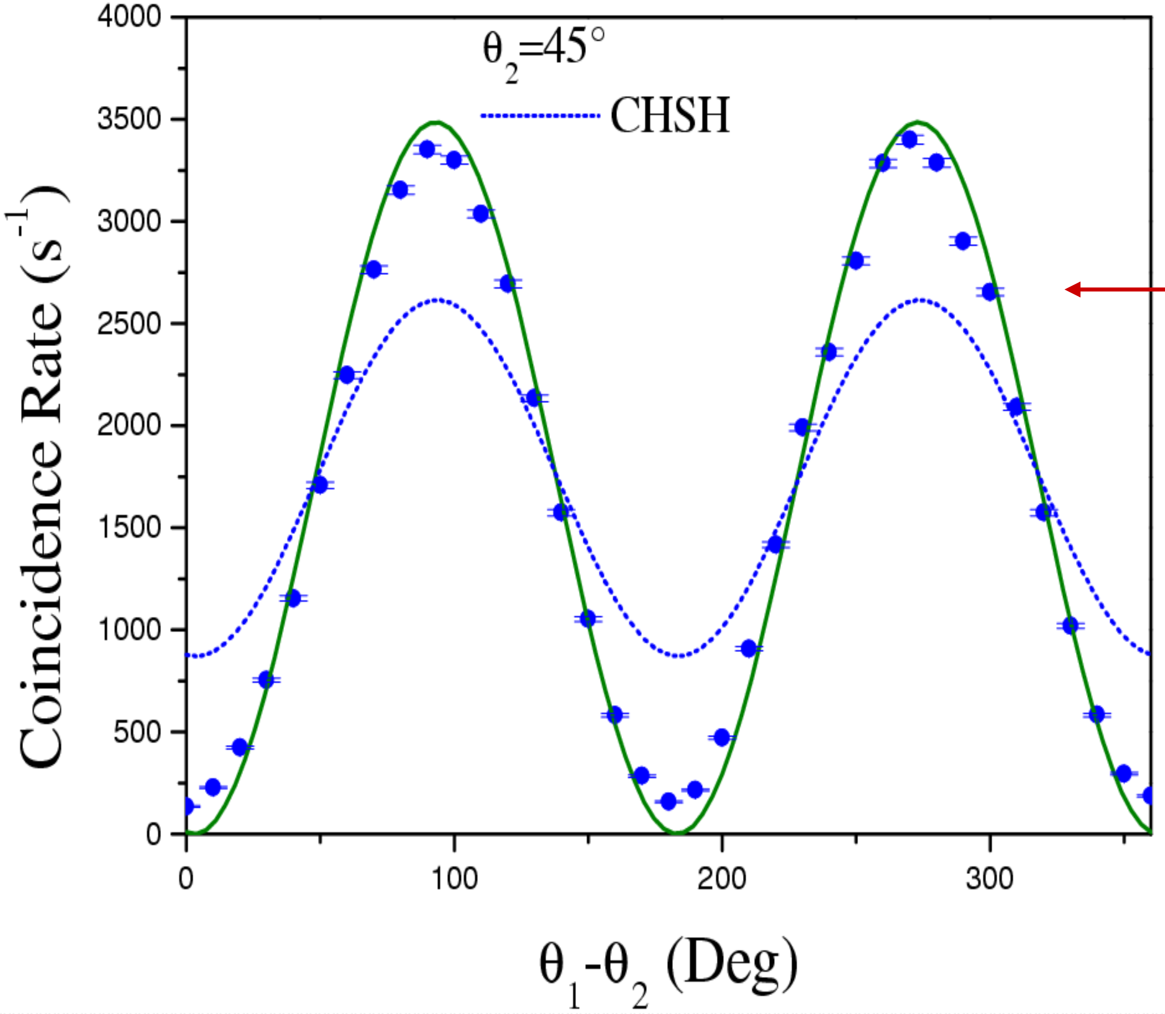
$$S = F(\phi)$$



$\phi_{ab}\,(gradi)$



Singlet state for 2 spin-½: $|\Phi_{AB}\rangle = \xi(|\uparrow_A, \downarrow_B\rangle - |\downarrow_A, \uparrow_B\rangle)$



quantum limit

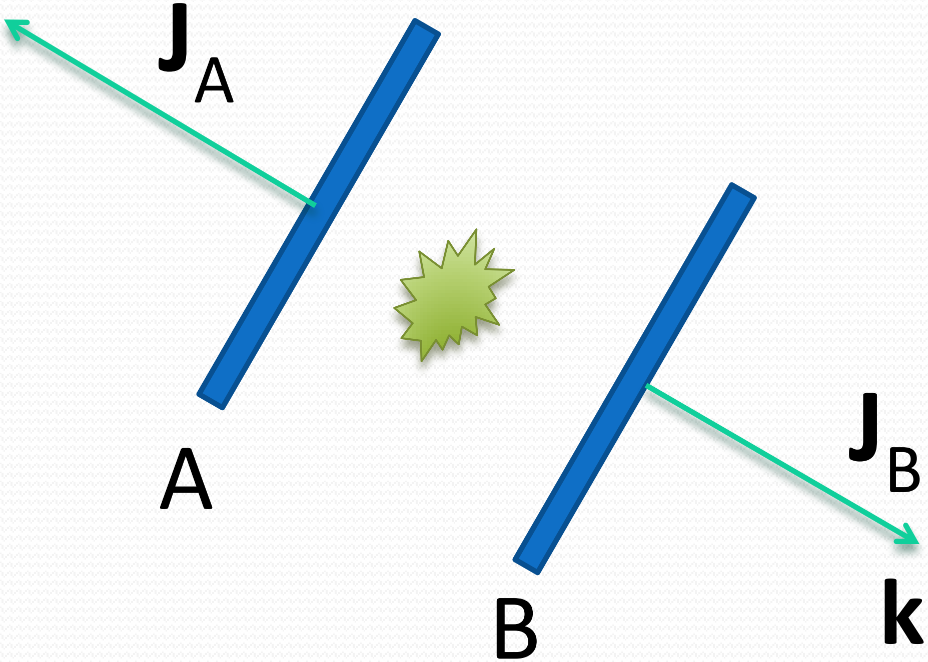
classical limit

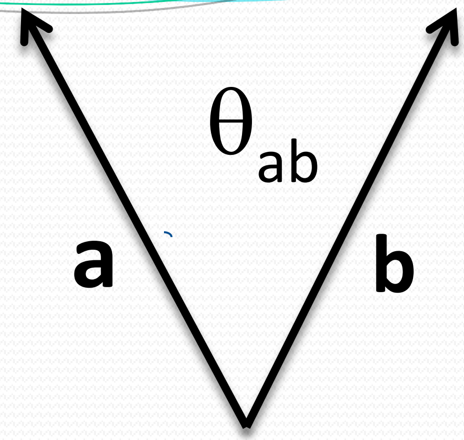
Test of Bell's Inequalities:

Δ = **2.5564 ± .0026** → 213-σ standard deviations

2 HEAVY COUNTER-ROTATING WHEELS

"Classical"



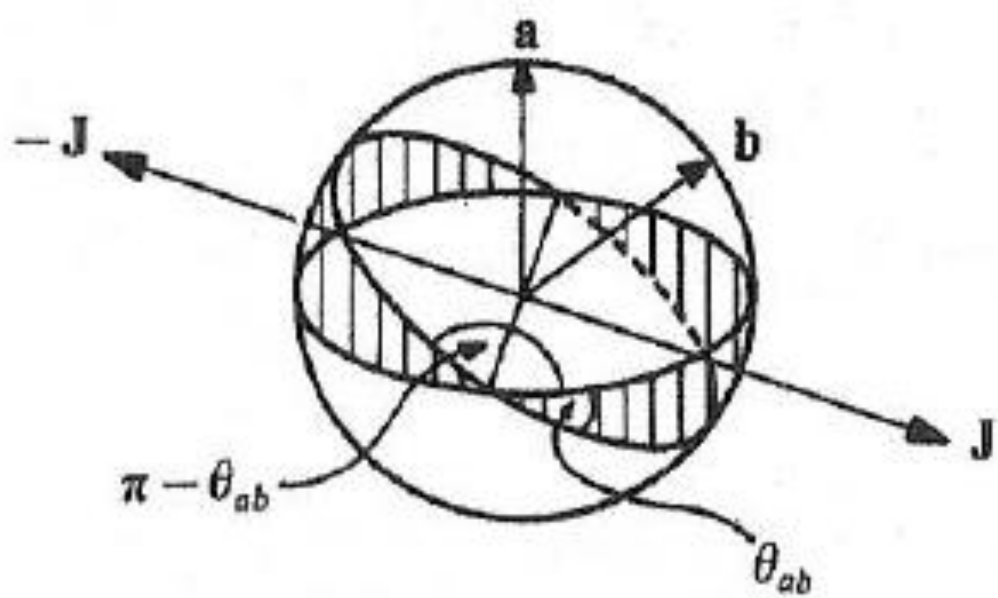


$$\mathbf{J} = (\mathbf{J}_A + \mathbf{J}_B) = 0$$

$$c(\mathbf{a}, \mathbf{b}) = -1 + 2/\pi\theta_{ab}$$

F17-3

DICHOTOMIC MEASUREMENTS: For the n-th launch, register the SIGN of components of **J** and **–J** along arbitrary directions: **a** and **b.** **(**SIGN $\pm \equiv \pm 1$).



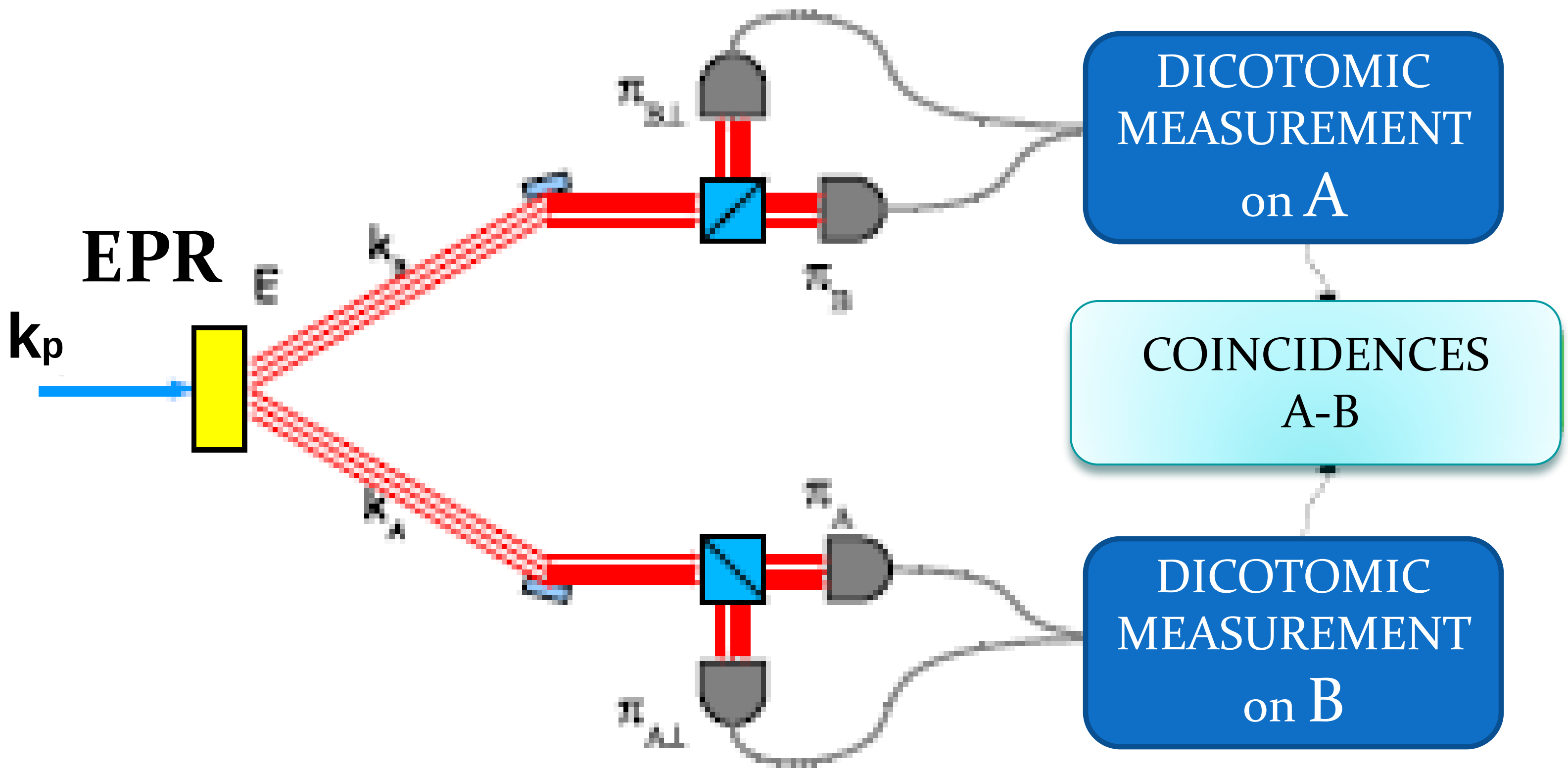
"CLASSICAL": NO - VIOLATION of BELL'S ineq.s: **S = 2**

$$c(\mathbf{a},\mathbf{b}) = \overline{a_n b_n} = \frac{2\theta_{ab}(+1) + 2(\pi - \theta_{ab})(-1)}{2\pi}$$

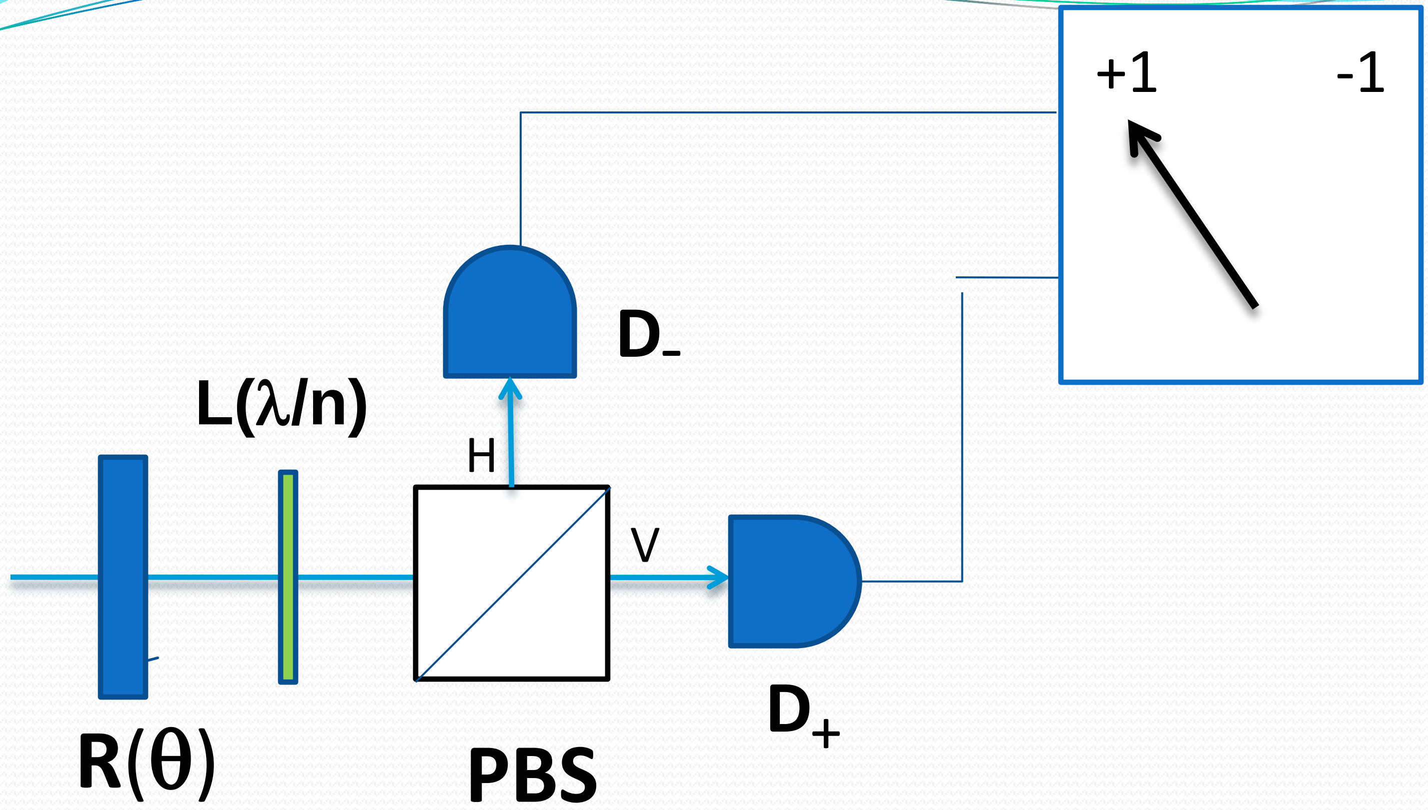
$$= -1 + \frac{2\theta_{ab}}{\pi}$$

VIOLATION of BELL'S ineq.s : **S >2** :

$$c(\mathbf{a},\mathbf{b}) = -\cos\theta_{ab} \simeq -1 + \tfrac{1}{2}\theta_{ab}^2 \ldots$$


EPR
kp
DICOTOMIC MEASUREMENT on A
COINCIDENCES A-B
DICOTOMIC MEASUREMENT on B

OPTICAL STERN - GERLACH (SGO)



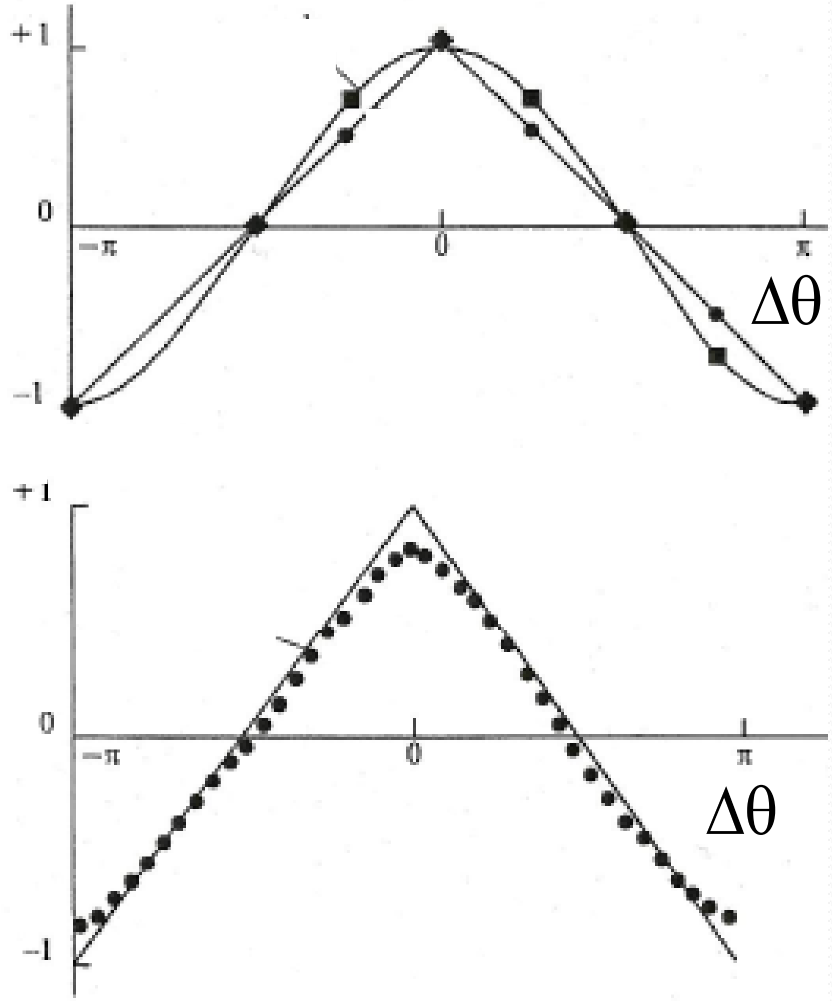
DICHOTOMIC MEASUREMENT of the SINGLE PHOTON POLARIZATION:

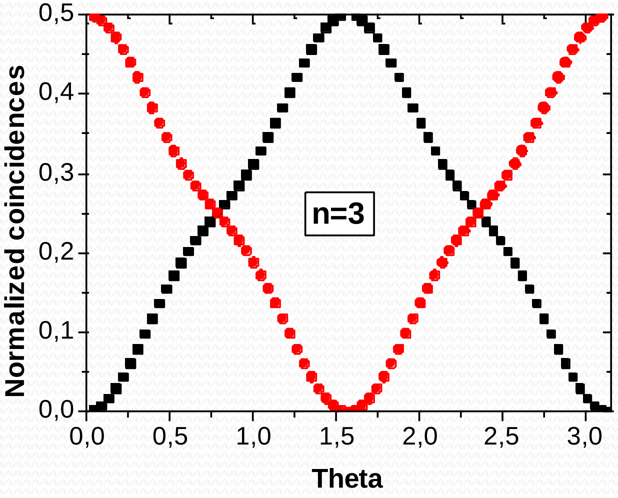
Click (+) : a = +1

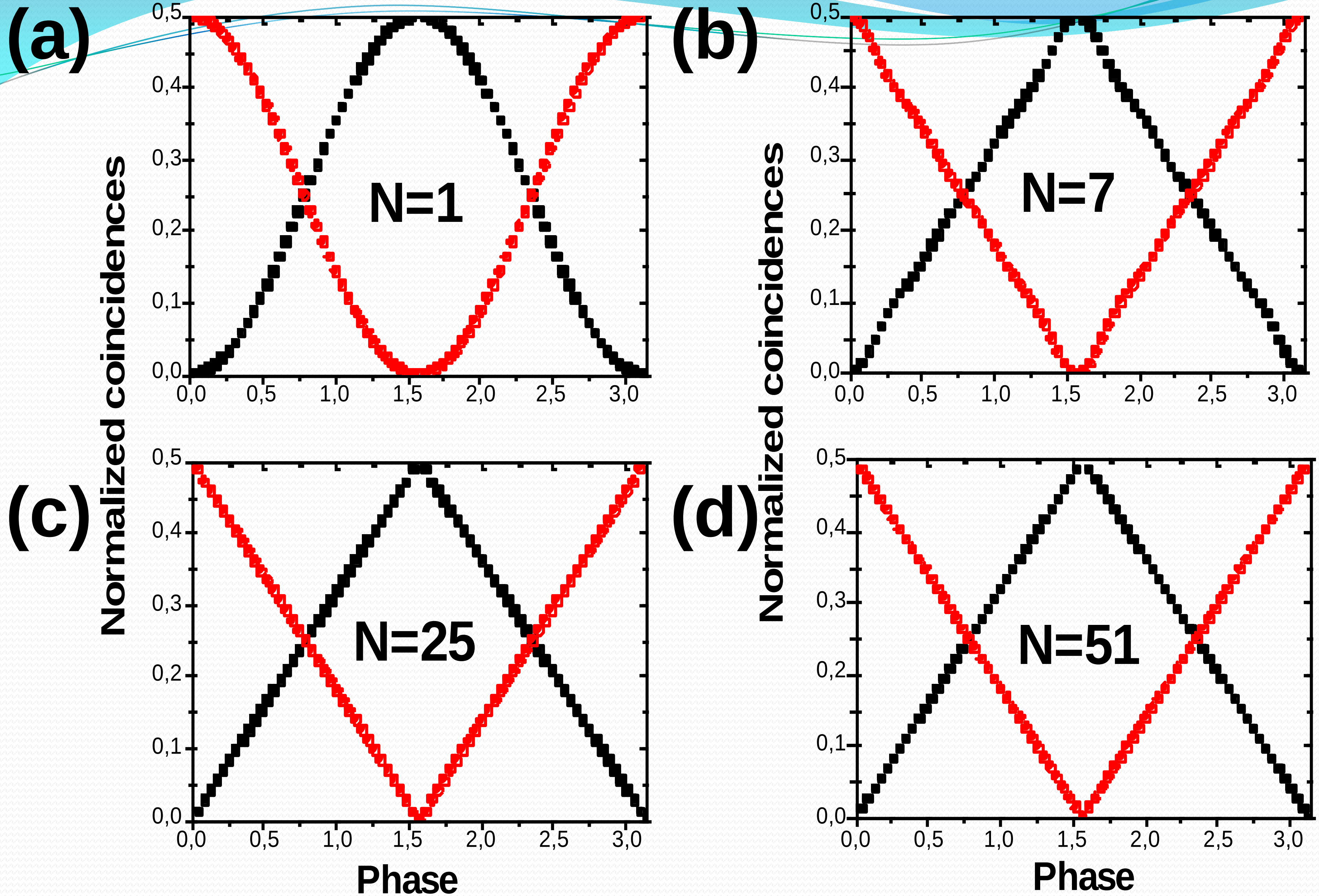
Click (-) : a = -1

CORRELATION COEFFICIENT:

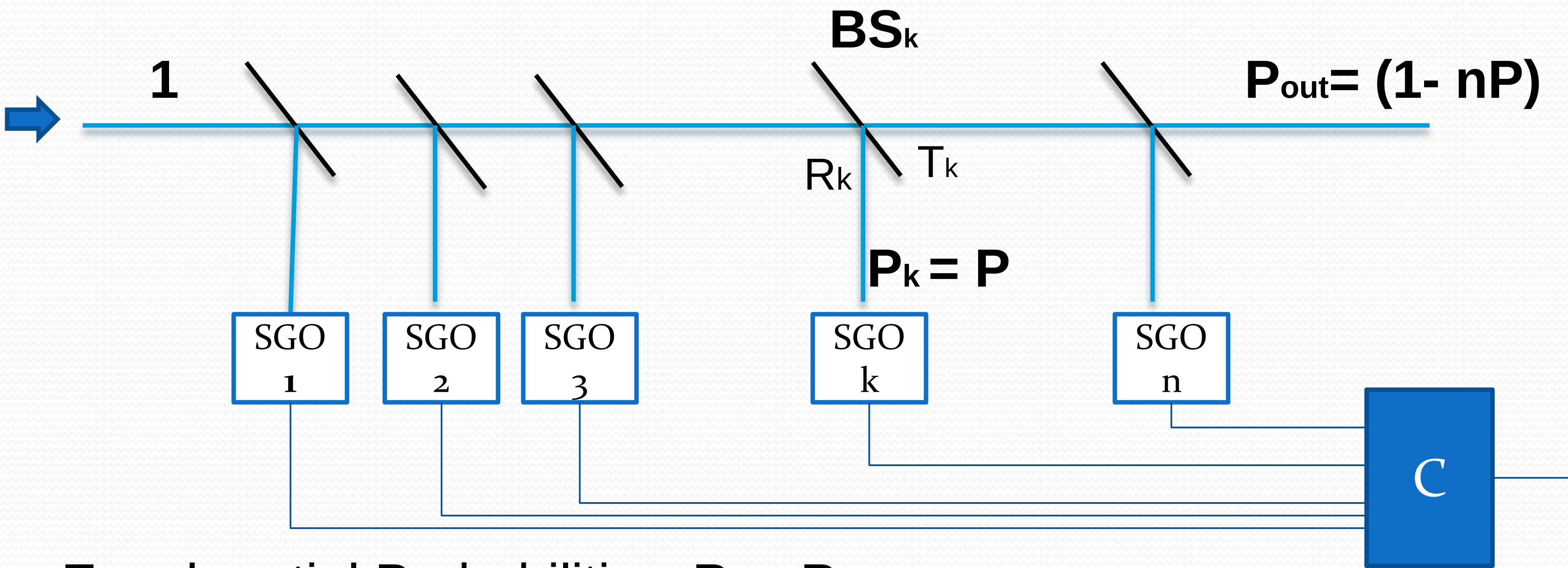
$$\mathbf{c}(\mathbf{a}, \mathbf{b}) = \mathbf{c}(\Delta\theta)$$




n=3
Normalized coincidences
Theta
0,0
0,1
0,2
0,3
0,4
0,5
0,5
1,0
1,5
2,0
2,5
3,0


(a)
N=1
(b)
N=7
(c)
N=25
(d)
N=51
Normalized coincidences
Phase
0,0
0,1
0,2
0,3
0,4
0,5
0,0
0,5
1,0
1,5
2,0
2,5
3,0

OPTICAL STERN – GERLACH *: SGO

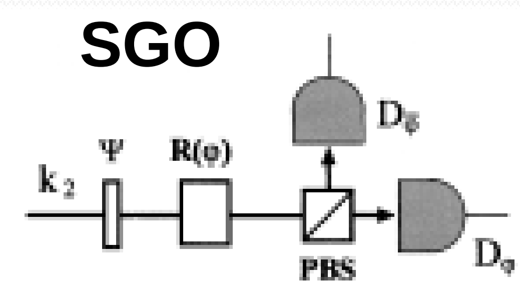


Equal partial Probabilities: $P_k = P$

BS_k

$$R_k = P/[1-(k-1)P]$$

$$T_k = [1-kP]/[1-(k-1)P]$$

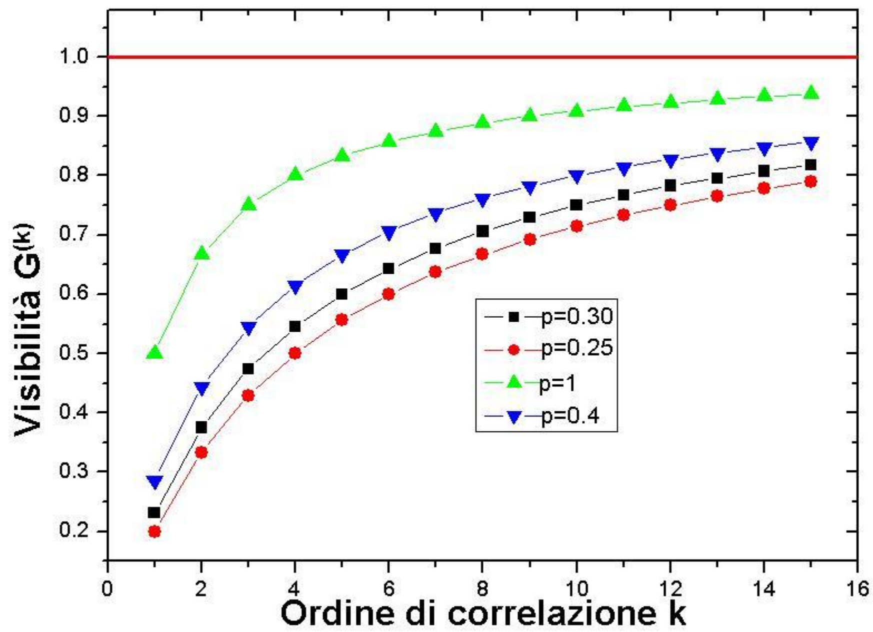


(* single - photon detection)

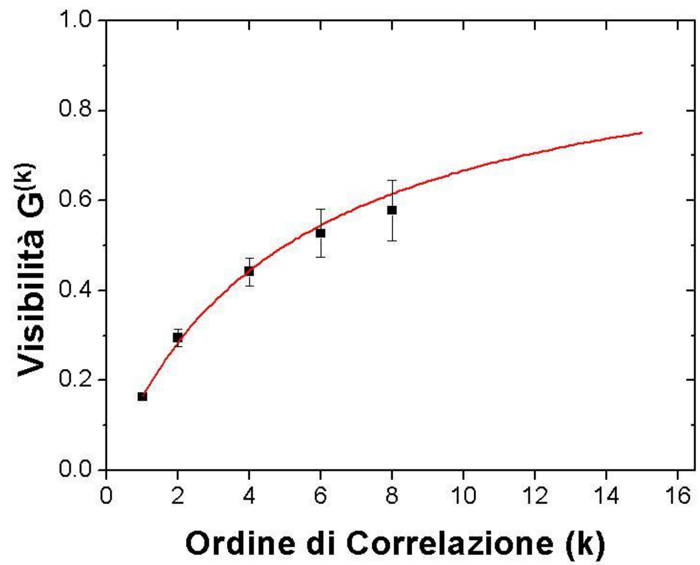
Visibility of Interference Fringes for high-order correlations.

$$G^{(n)} = \langle (a^{+})^{n} (a)^{n} \rangle$$

THEORY



EXPERIMENT



Entanglement criteria for micro-macroscopic systems

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We discuss the conclusions that can be drawn on a recent experimental micro-macro entanglement test [F. De Martini *et. al*, Phys. Rev. Lett. **100**, 253601 (2008)]. The system under investigation is generated through optical parametric amplification of one photon belonging to an entangled pair. The adopted entanglement criterion allows to infer the presence of entanglement before losses, that occur on the macrostate, under specific assumptions. In particular, an a priori knowledge of the system that generates the micro-macro pair is necessary to exclude a class of separable states that can reproduce the obtained experimental results. Finally, we discuss the feasibility of a micro-macro "genuine" entanglement test on the analyzed system by considering different strategies, which show that in principle a fraction ε, proportional to the number of photons that survive the lossy process, of the original entanglement persists in any losses regime.

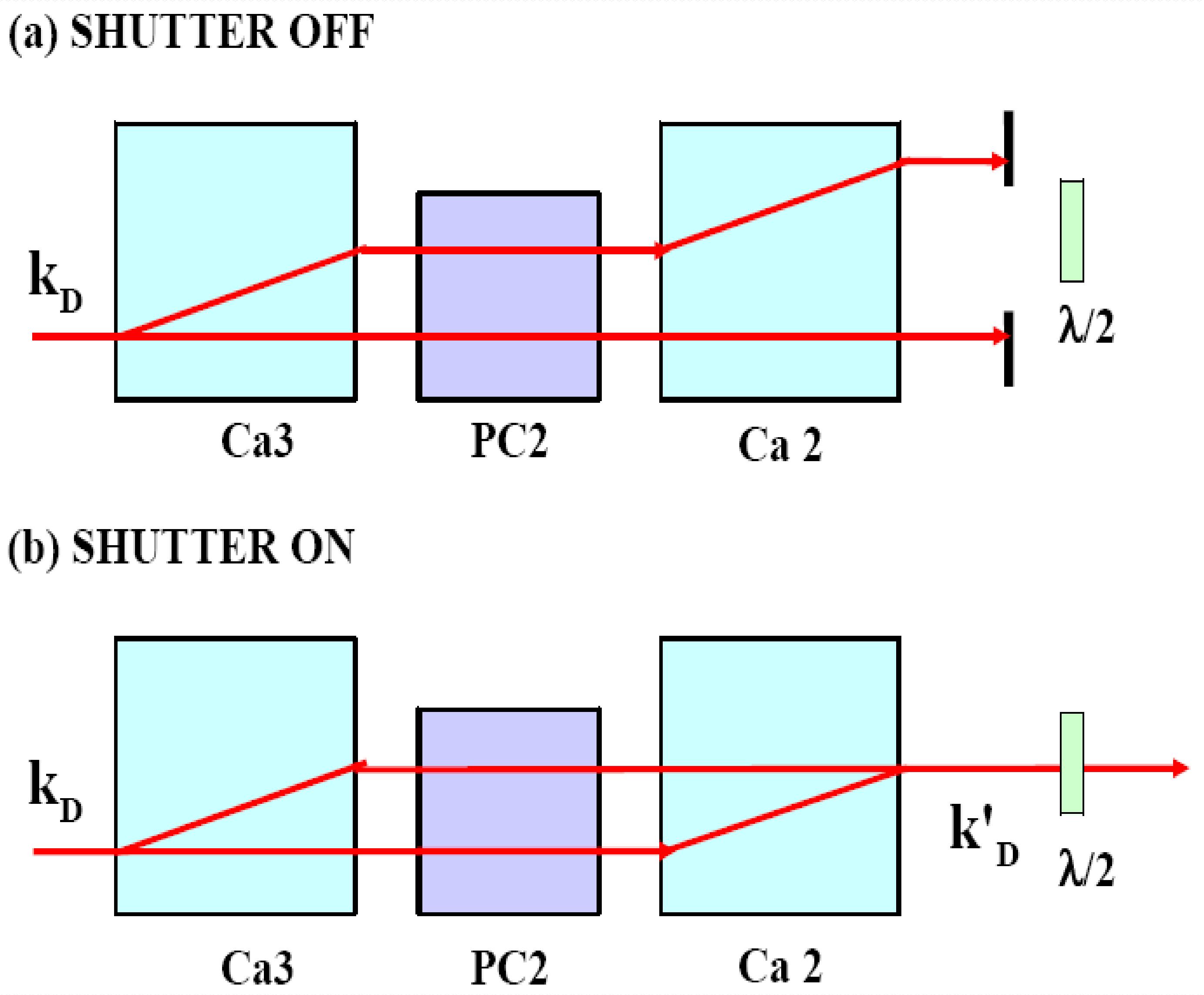
PACS numbers: 03.67.Mn, 03.65.Ud, 03.67.Bg

I. INTRODUCTION

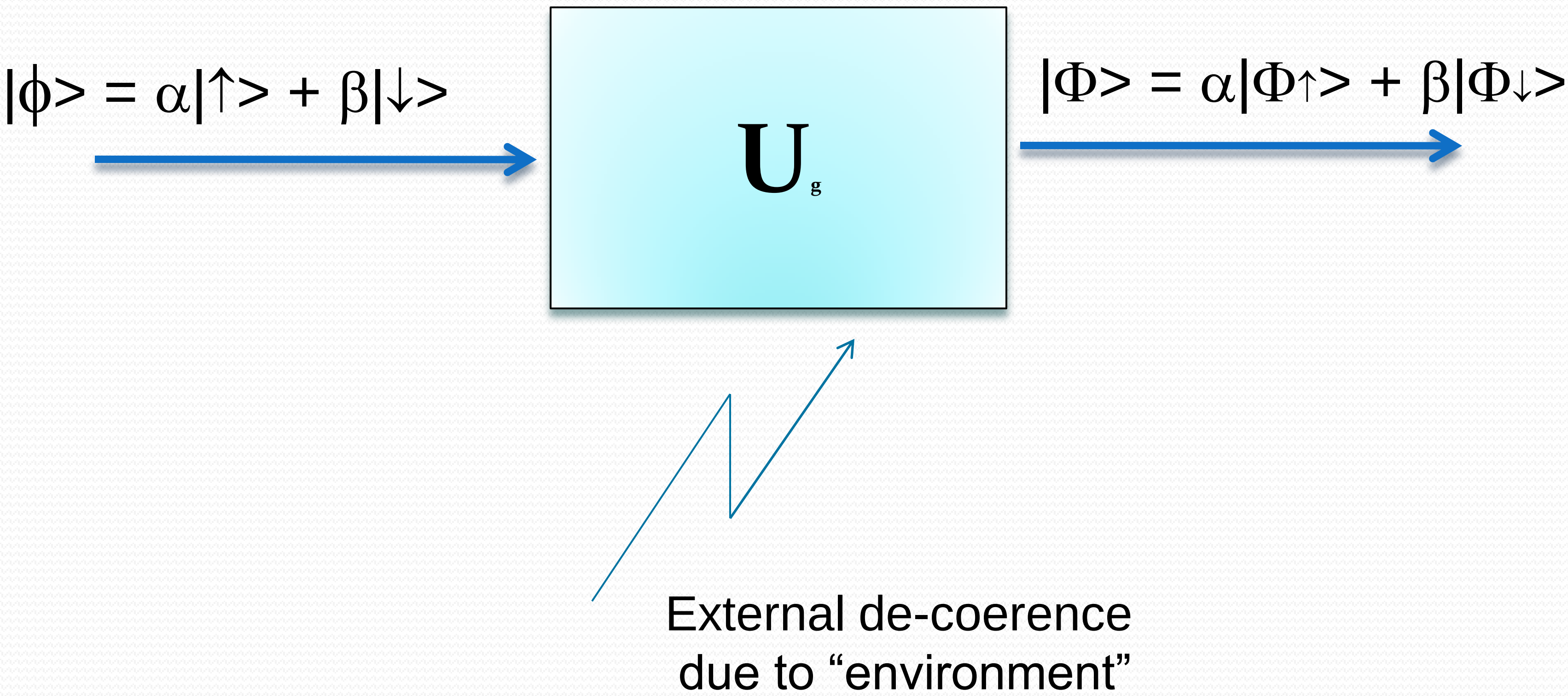
The observation of quantum phenomena, such as quantum entanglement, has been always limited to systems of only few particles. One of the main open challenge for an experimental test in systems of large size is the construction of suitable criteria for the detection of entanglement in bipartite macroscopic systems. A large effort has been devoted in the last few years in this direction. Some of them, such as the partial transpose criterion developed by Peres in Ref.[1], require the tomographic reconstruction of the density matrix, which for system of a large number of particles becomes highly demanding from an experimental point of view. In order to avoid the necessity of the complete reconstruction of the state, a class of tests where only few local measurements are performed has been introduced under the name of "entanglement witness" [2]. For bipartite systems of a large number of particles, this approach has been further investigated

years, and is based on the deliberate attenuation of the analyzed system up to the single photon level. In this way, standard single-photon techniques and criteria can be used to investigate the properties of the field. The verification of the entanglement in the high losses regime is an evidence of the presence of entanglement before the attenuation, since no entanglement can be generated by local operations. Such approach has been exploited in [10, 11] to demonstrate the presence of entanglement in a high gain spontaneous parametric down-conversion source up to 12 photons. Analogous conclusion has been theoretically obtained in Ref.[12] on the same system by exploiting symmetry considerations of the source. The attenuation method has been also applied to a different system, allowing to obtain an experimental proof of the presence of entanglement between a single photon state and a multiphoton state generated through the process of optical parametric amplification in an universal cloning configuration up to 12 photons [13].

FAST OPTICAL SHUTTER FOR QI-OPA OUTPUT PRE-SELECTION



MICRO - MACRO QUANTUM - MAP



MACROSCOPIC QUANTUM SUPERPOSITION:

PERSPECTIVES, RECENT RESULTS AND APPLICATIONS:

.1) Coherent Scattering by a Bragg-shaped BEC: MIRROR-BEC MQS (Collaboration with LENS Laboratories, FI).

.2) Micro-Macro Q- Teleportation (MIMAQT)

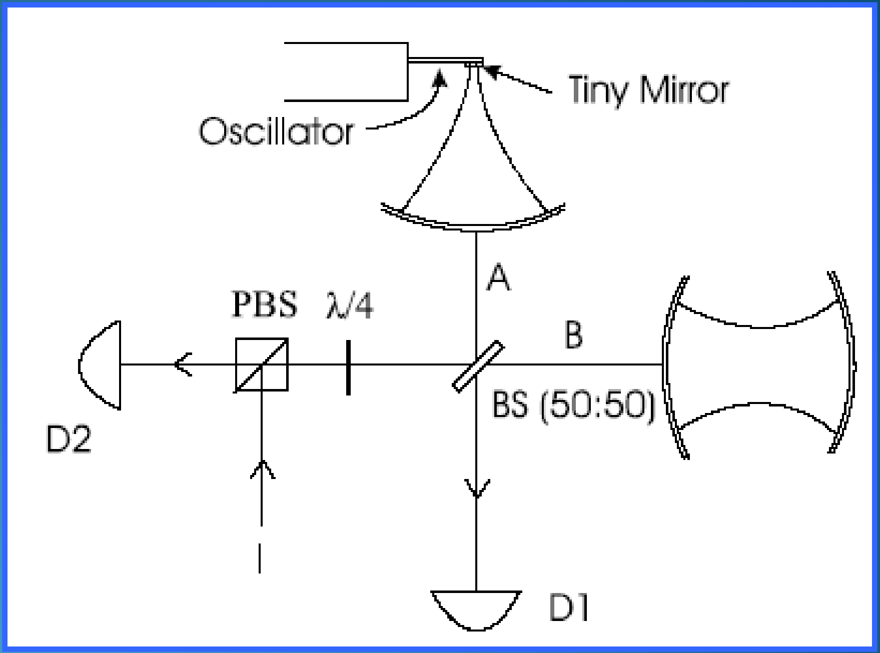
.3) Up-link, long-range and large - efficiency Satellite communication: MIMAQT. (QUEST)

.4) Non-trivial quantum Biological Applications

.5) Enhanced 3d-order N-linearity: C-NOT

Penrose's cat

$$H_{\text{int}} = \hbar\omega_C a^+ a + \hbar\omega_m a^+ a - \hbar G a^+ a(b + b^+)$$



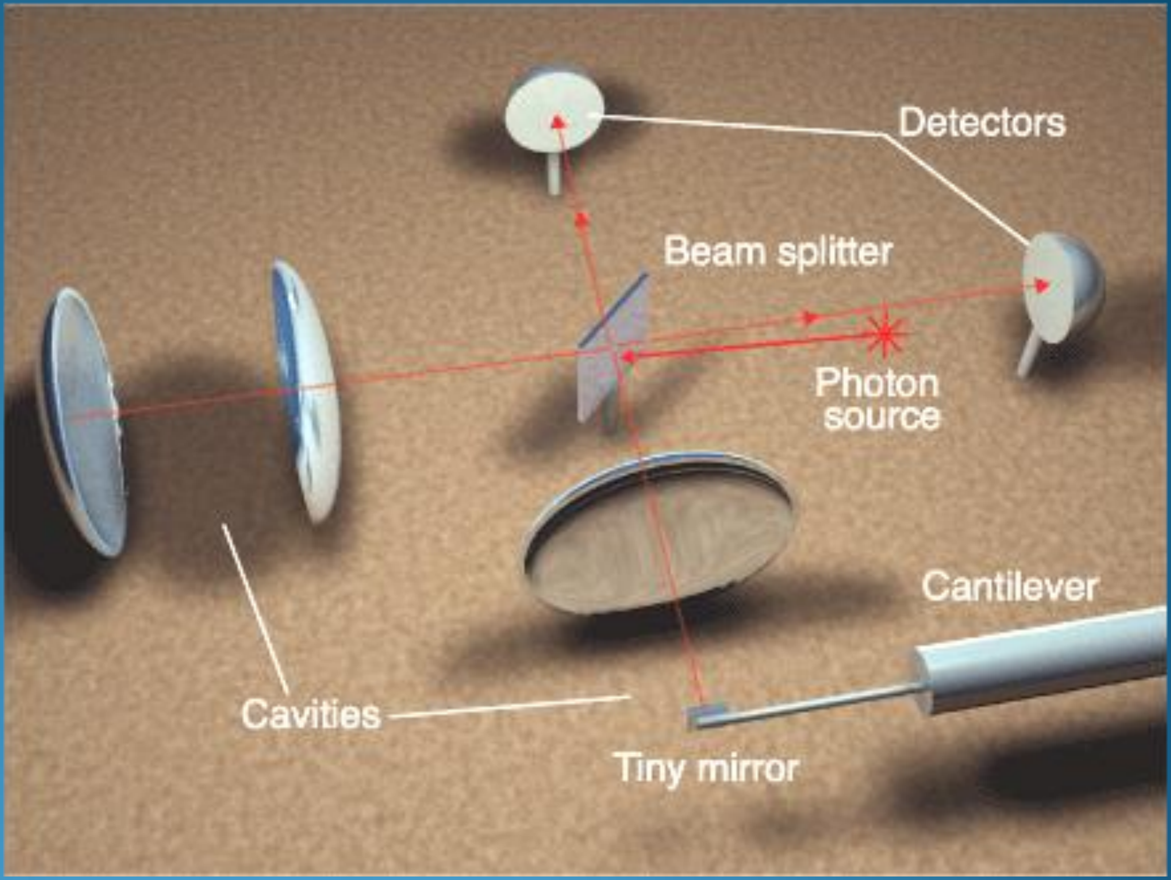
$$|\psi(0)\rangle = \frac{1}{\sqrt{2}}\left(|1\rangle_A |0\rangle_B + |0\rangle_A |1\rangle_B\right)|0\rangle_m$$

$$|\psi(t)\rangle = \frac{1}{\sqrt{2}} e^{-i\omega_c t}\left(|0\rangle_A |1\rangle_B |0\rangle_m + e^{ik^2(\omega_m t - \sin\omega_m t)} |0\rangle_A |1\rangle_B \left|k(1 - e^{-i\omega_m t})\right\rangle_m \right)$$

W. Marshall, C. Simon, R. Penrose, and D. Bouwmeester, *Phys. Rev. Lett.* **91**, 130401 (2003)
C. Seife, "Quantum Experiment Asks 'How Big Is Big?'" *Science* **29**8, 342 (2002)

Penrose's cat (2003)

Mirror: 10 micrometers wide



W. Marshall, C. Simon, R. Penrose, and D. Bouwmeester, *Phys. Rev. Lett.* **91**, 130401 (2003)
C. Seife, "Quantum Experiment Asks 'How Big Is Big?'" *Science* **29**8, 342 (2002)

TWO DIFFERENT STATISTICAL SCHEMES FOR MACROSCOPIC QUANTUM SYSTEMS:

A) **CLOSED QUANTUM SYSTEM**: Thermodynamics,
Extremely rapid Decoherence
(E.N.S. α-states Schroedinger - CAT)

B) **OPEN, DRIVEN QUANTUM SYSTEM FAR FROM EQUILIBRIUM**:

Master - equation evolution with damping and noise. Featuring driving force: Feedback and Error – Correction mechanism.

Virtually: NO-decoherence.

Noise: “reset” mechanism; Dynamic Vs static entanglement;

PARAMETRICALLY DRIVEN, “OPEN” QUANTUM SYSTEMS FAR FROM EQUILIBRIUM leading to:

“NON TRIVIAL” QUANTUM EFFECTS IN BIOLOGICAL AND BIO-CHEMICAL SYSTEMS.

Dynamics of allosteric transitions and of isomeric processes as chromophores in Rhodopsin, of photosyntetic complexes, of catalyzer molecules etc.
Via error-correction, intra-molecular cooling, reset of coherence.

Cfr: “Quantum Aspects of Life” (by Abbott, Davies, Pati, Oxford University Press, 2008).
H. Briegel, S. Popescu

Dynamic entanglement in oscillating molecules

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Institut für Quantenoptik und Quanteninformation der Österreichischen Akademie der Wissenschaften, Innsbruck, Austria
[3]*H.H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, U.K.*
[4]*Hewlett-Packard Laboratories, Stoke Gifford, Bristol BS12 6QZ, U.K.*
(Dated: September 30, 2008)

We demonstrate that entanglement can persistently recur in an oscillating two-spin molecule that is coupled to a hot and noisy environment, in which no static entanglement can survive. The system represents a non-equilibrium quantum system which, driven through the oscillatory motion, is prevented from reaching its (separable) thermal equilibrium state. Environmental noise, together with the driven motion, plays a constructive role by periodically resetting the system, even though it will destroy entanglement as usual. As a building block, the present simple mechanism supports the perspective that entanglement can exist also in systems which are exposed to a hot environment and to high levels of de-coherence, which we expect e.g. for biological systems. Our results furthermore suggest that entanglement plays a role in the heat exchange between molecular machines and environment. Experimental simulation of our model with trapped ions is within reach of the current state-of-the-art quantum technologies.

PACS numbers: 03.65.Yz, 03.67.-a, 05.60-Gg

rections from the nucleus and that impinges continuously on a surrounding luminescent screen over its full expanse. The screen however does not show a more or less constant uniform surface glow, but rather lights up at *one* instant at *one* spot—or, to honor the truth, it lights up now here, now there, for it is impossible to do the experiment with only a single radioactive atom. If in place of the luminescent screen one uses a spatially extended detector, perhaps a gas that is ionised by the α-particles, one finds the ion pairs arranged along rectilinear columns,[5] that project backwards on to the bit of radioactive matter from which the α-radiation comes (C.T.R. Wilson's cloud chamber tracks, made visible by drops of moisture condensed on the ions).

One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following diabolical device (which must be secured against direct interference by the cat): in a Geiger counter there is a tiny bit of radioactive substance, *so* small, that *perhaps* in the course of one hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives *if* meanwhile no atom has decayed. The first atomic decay would have poisoned it. The ψ-function of the entire system would express this by having in it the living and the dead cat (pardon the expression) mixed or smeared out in equal parts.

It is typical of these cases that an indeterminacy originally restricted to the atomic domain becomes transformed into macroscopic indeterminacy, which can then be *resolved* by direct observation. That prevents us from so naively accepting as valid a "blurred model" for representing reality. In itself it would not embody anything unclear or contradictory. There is a difference between a shaky or out-of-focus photograph and a snapshot of clouds and fog banks.

6. The Deliberate About-face of the Epistemological Viewpoint

In the fourth section we saw that it is not possible smoothly to take over models and to ascribe, to the momentarily unknown or not exactly known variables, nonetheless determinate values, that we simply don't know. In Sect. 5. we saw that the indeterminacy is not even an actual blurring, for there are always cases where an easily executed observation provides the missing knowledge. So what is left? From this very hard dilemma the reigning doctrine rescues itself or us by having recourse to epistemology. We are told that no distinction is to be made between the state of a natural object and what I know about it, or perhaps better, what I can know about it if I go to some trouble. Actually—so they say—there is intrinsically only awareness, observation, measurement. If through them I have procured at a given moment the best knowledge of the state of the physical object that is possibly attainable in accord with natural laws, then I can turn aside as *meaningless* any further questioning about the "actual state," inasmuch as I am convinced that no further observation can extend my knowledge of it—at least, not without an equivalent diminution in some other respect (namely by changing the state, see below).

Now this sheds some light on the origin of the proposition that I mentioned at the end of Sect. 2. as something very far-reaching: that all model quantities are measurable in principle. One can hardly get along without this article of belief if one sees himself constrained, in the interests of physical methodology, to call in as dictatorial help the above-mentioned philosophical principle, which no sensible person can fail to esteem as the supreme protector of all empiricism.

Reality resists imitation through a model. So one lets go of naive realism and leans directly on the indubitable proposition that *actually* (for the physicist) after all is said and done there is only observation, measurement. Then all our physical thinking thenceforth has as sole basis and as sole object the results of measurements which can in principle be carried out, for we must now explicitly *not* relate our thinking any longer to any other kind of reality or to a model. All numbers arising in our physical calculations must be interpreted as measurement results. But since we didn't just now come into the world and start to build up our science from scratch, but rather have in use a quite definite scheme of calculation, from which in view of the great progress in Q.M. we would less than ever want to be parted, we see ourselves forced to dictate from the writing-table which measurements are in principle possible, that is, must be possible in order to support adequately our reckoning system. This allows a sharp value for each single variable of the model (indeed for a whole "half set") and so each single variable must be measurable to arbitrary exactness. We cannot be satisfied with less, for we have lost our naively realistic innocence. We have nothing but our reckoning scheme to specify where Nature draws the ignorabimus-line, i.e., what is a *best possible* knowledge of

E. Schroedinger, Naturwissenschaften 23, 807, 1935 described by a master equation of the form

$$\frac{\partial}{\partial t}\rho(t) = -i[H_M(t), \rho] + \mathcal{D}\rho(t) \equiv \mathcal{L}(t)\rho(t) \qquad (2)$$

where $\mathcal{D}\rho = \sum_i 2L_i\rho L_i^\dagger - L_i^\dagger L_i\rho - \rho L_i^\dagger L_i$ is the dissipator from the molecule-environment coupling, and L_i are Lindblad-type generators.

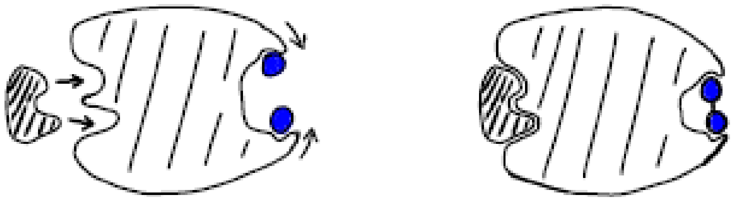

FIG. 1: (a) Conformational changes of a bio-molecule [11], induced e.g. by the interaction with some other chemical, can lead to a time-dependent interaction between different sites (blue) of the molecule. See also [2].

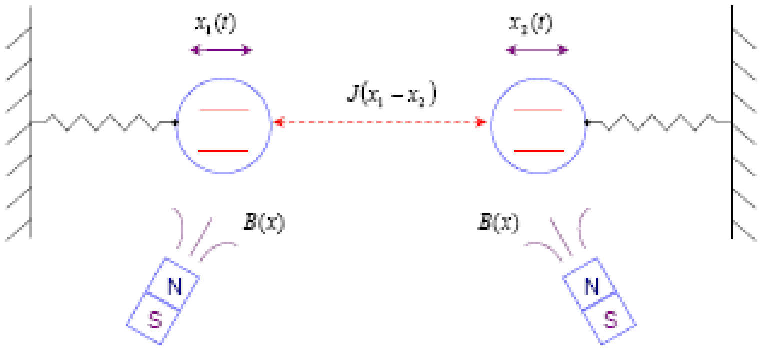

FIG. 2: Model of a two-spin molecule which undergoes conformational changes as a function of time. Both the spin-spin interaction strength J and local fields B are position dependent.

Environment-Assisted Quantum Transport

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[1] *Department of Chemistry and Chemical Biology, Harvard University, 12 Oxford St., Cambridge, MA 02138*

[2] *Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge MA 02139*

(Dated: November 24, 2008)

Transport phenomena at the nano-scale are of interest due to the presence of both quantum and classical behavior. In this work, we demonstrate that quantum transport efficiency can be enhanced by a dynamical interplay of the system Hamiltonian with the pure dephasing dynamics induced by a fluctuating environment. This is in contrast to fully coherent hopping that leads to localization in disordered systems, and to highly incoherent transfer that is eventually suppressed by the quantum Zeno effect. We study these phenomena in the Fenna-Matthews-Olson protein complex as a prototype for larger photosynthetic energy transfer systems. We also show that disordered binary tree structures exhibit enhanced transport in the presence of dephasing.

PACS numbers: 03.65.Yz, 05.60.Gg, 71.35.-y, 03.67.-a

The efficiency of transport in an open quantum system can be substantially affected by the interaction with a fluctuating environment. Noise and decoherence collapse the state generated by quantum hopping and so typically one expects an inhibitory effect on quantum transport. One of the most important classes of quantum transport is the energy transfer in molecular systems [1], for example in the chromophoric light-harvesting complexes [2, 3]. The role of the environment in chromophoric systems [4, 5, 6] and model geometries [7] has been widely studied. The Haken-Strobl model is widely used to describe Markovian bath fluctuations [8]. Gaab and Bardeen used this approach to explore the effect of geometry and coherence in the energy trapping of some model light-harvesting systems [7]. Leegwater [9] uses the survival time to discuss the crossover from hopping to exciton dynamics in the LH1 photosynthetic system of purple bacteria. Quantum transport can also be affected by the well-known Anderson localization [10, 11]. Energy mismatches in disordered materials lead to destructive interference of the electronic wavefunction and subsequently to localization of the quantum particle. Specifically, it has been argued that quantum localization can seriously limit computational power and/or quantum walk properties in binary tree structures [12], where an expo-

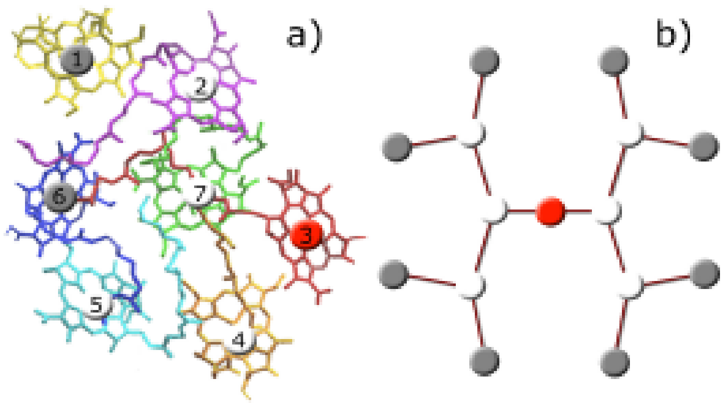

FIG. 1: Quantum transport arises in nature, for example in the energy transfer of photosynthetic complexes and in artificial or engineered systems. In the Fenna-Matthews-Olson protein complex a) quantum coherence has been shown to play a significant role in the exciton dynamics [2]. Binary trees b) are an important concept in many areas of science. Specifically, in quantum physics an exponential speed-up in finding certain target sites (red) make them a potential candidate for the implementation of quantum algorithms [13]. (The grey sites represent initial states for the quantum transport.)

REVIEW ARTICLE

Quantum Dynamics of Electronic Excitations in Biomolecular Chromophores: Role of the Protein Environment and Solvent

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Department of Physics, University of Queensland, Brisbane 4072 Australia

Received: October 23, 2007

A biomolecular chromophore can be viewed as a quantum system with a small number of degrees of freedom interacting with an environment (the surrounding protein and solvent) which has many degrees of freedom, the majority of which can be described classically. The system−environment interaction can be described by a spectral density for a spin−boson model. The quantum dynamics of electronic excitations in the chromophore are completely determined by this spectral density, which is of great interest for describing quantum decoherence and quantum measurements. Specifically, the spectral density determines the time scale for the "collapse" of the wave function of the chromophore due to continuous measurement of its quantum state by the environment. Although of fundamental interest, there very few physical systems for which the spectral density has been determined experimentally and characterized. In contrast, here, we give the parameters for the spectral densities for a wide range of chromophores, proteins, and solvents. Expressions for the spectral density are derived for continuum dielectric models of the chromophore environment. There are contributions to the spectral density from each component of the environment: the protein, the water bound to the protein, and the bulk solvent. Each component affects the quantum dynamics of the chromophore on distinctly different time scales. Our results provide a natural description of the different time scales observed in ultrafast laser spectroscopy, including three pulse photon echo decay and dynamic Stokes shift measurements. We show that even if the chromophore is well separated from the solvent by the surrounding protein, ultrafast solvation can be still be dominated by the solvent. Consequently, we suggest that the subpicosecond solvation observed in some biomolecular chromophores should not necessarily be assigned to ultrafast protein dynamics. The magnitude of the chromophore−environment coupling is sufficiently strong that the quantum dynamics of electronic excitations in most chromophores at room temperature is incoherent, and the time scale for "collapse" of the wave function is typically less than 10 fs.

Quantum coherence in photosyntesis

nature Vol 446|12 April 2007|doi:10.1038/nature05678

LETTERS

Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems

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Photosynthetic complexes are exquisitely tuned to capture solar light efficiently, and then transmit the excitation energy to reaction centres, where long term energy storage is initiated. The energy transfer mechanism is often described by semiclassical models that invoke 'hopping' of excited-state populations along discrete energy levels[1,2]. Two-dimensional Fourier transform electronic spectroscopy[3–5] has mapped[6] these energy levels and their coupling in the Fenna–Matthews–Olson (FMO) bacteriochlorophyll complex, which is found in green sulphur bacteria and acts as an energy 'wire' connecting a large peripheral light-harvesting antenna, the chlorosome, to the reaction centre[7–9]. The spectroscopic data clearly document the dependence of the dominant energy transport pathways on the spatial properties of the excited-state wavefunctions of the whole bacteriochlorophyll complex[6,10]. But the intricate dynamics of quantum coherence, which has no classical analogue, was largely neglected in the analyses—even though electronic energy transfer involving oscillatory populations of donors and acceptors was first discussed more than 70 years ago[11], and electronic quantum beats arising from quantum coherence in photosynthetic complexes have been predicted[12,13] and indirectly observed[14]. Here we extend previous two-dimensional electronic spectroscopy investigations of the FMO bacteriochlorophyll complex, and obtain direct evidence for remarkably long-lived electronic quantum coherence playing an important part in energy transfer processes within this system. The quantum coherence manifests itself in characteristic, directly observable quantum beating signals among the excitons within the *Chlorobium tepidum* FMO complex at 77 K. This wavelike characteristic of the energy transfer within the photosynthetic complex can explain its extreme efficiency, in that it allows the complexes to sample vast areas of phase space to find the most efficient path.

time. The coherence wavelength represents the initial excitation, while the rephasing wavelength can be thought of as the subsequent emission. Without coupling, contributions from excited-state absorption and emission cancel each other, yielding no off-diagonal peaks in the spectrum that signal such coupling. But in the presence of coupling, the cancellation is no longer complete and a so-called cross-peak emerges[16]. Two-dimensional spectroscopy thus provides an excellent probe of the coupling between energy levels.

In the present experiment, we use two-dimensional electronic spectroscopy to observe oscillations caused by electronic coherence evolving during the population time in FMO. Such quantum coherence, a coherent superposition of electronic states analogous to a nuclear wavepacket in the vibrational regime, is formed when the system is initially excited by a short light pulse with a spectrum that spans multiple exciton transitions. Theoretical predictions indicate that both the amplitudes and shapes of peaks will contain beating signals with frequencies corresponding to the differences in energy between component exciton states[17].

To observe the quantum beats, two-dimensional spectra were taken at 33 population times *T*, ranging from 0 to 660 fs. Representative spectra are shown in Fig. 1 and a video of the spectral evolution is included in the Supplementary Information. In these spectra, the lowest-energy exciton gives rise to a diagonal peak near 825 nm that clearly oscillates: its amplitude grows, fades, and subsequently grows again. The peak's shape evolves with these oscillations, becoming more elongated when weaker and rounder when the signal amplitude intensifies. The associated cross-peak amplitude also appears to oscillate. Surprisingly, the quantum beating lasts for 660 fs. This observation contrasts with the general assumption that the coherences responsible for such oscillations are destroyed very rapidly, and that population relaxation proceeds with complete destruction of coher-

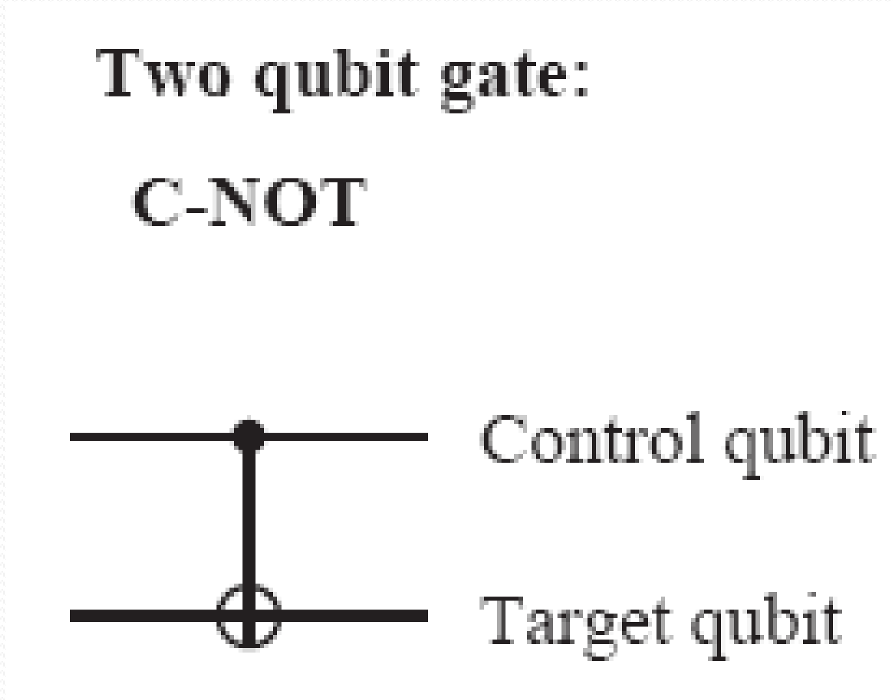
Conclusions:

- The Macro-qubit states obtained through an optical amplification process, consisting in thousands of photons, are high resilient to decoherence and to losses
- The transmission of macro-states results in a higher efficiency of the process respect to the single photon case.
- The Fidelity of the macro-qubit identification is related to the measurement performed on it. By a dichotomic measurement its asymptotic value doesn't allow to perform non locality tests, but is enough to implement a micro-macro teleportation protocol.

OPEN QUESTION: Are these macro-states useful for quantum cryptographic applications ?

$1 \rightarrow$ N particle Qubit:

- The 3d order NL polarization is enhanced by a factor: $\xi = N^{3/2}$
- In our experiment: $\xi \approx 10^9$



(C - Phase Gate)

Achievable non-linearity in a Kerr medium

- Non-linear phase shift induced by the cross-phase modulation:

$$\phi_{NL} = 2b\gamma P L_{eff}$$

$b = \frac{1}{3}$ **beam orthogonally polarized**

polarization parameter associated with the co-propagating modality

$\gamma \approx 60\,\mathrm{W}^{-1} km^{-1}$ **non-linear coefficient (photonic crystal fibre)**

P peak pump power

$\mathrm{L_{eff}} = (1 - e^{-\alpha L})/\alpha$ **effective length of the fibre (α attenuation coefficient)**

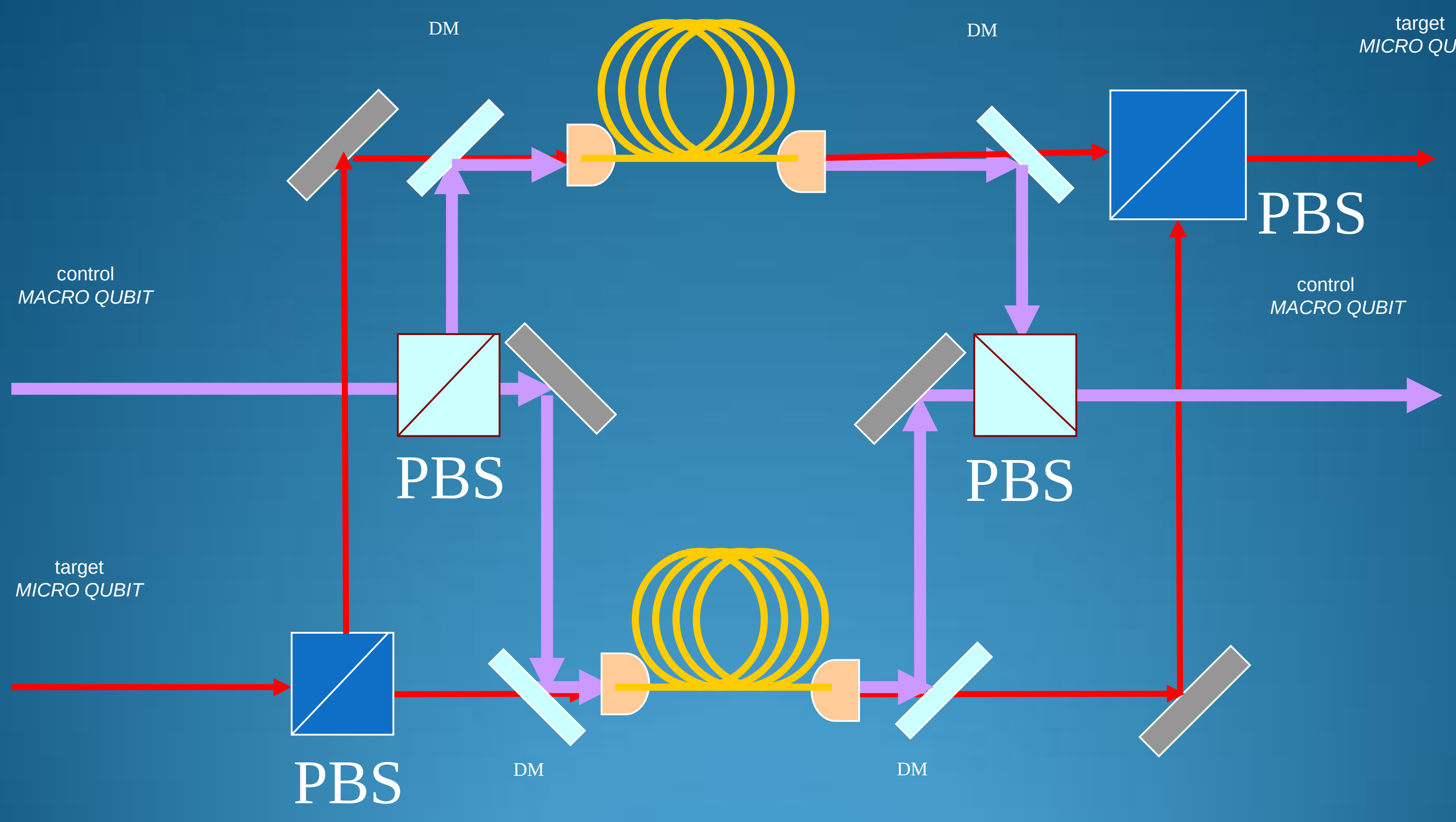
$$1 \text{ photon and } \mathrm{L_{eff}} = 4.5\, m \Rightarrow \phi_{NL} \approx 10^{-7}$$

$$1 \text{ photon and } \mathrm{L_{eff}} = 1\, Km \Rightarrow \phi_{NL} \approx 2 \times 10^{-5}$$

⇓ Multiphoton state

$$10^{6} \text{ photons and } \mathrm{L_{eff}} = 80\, m \Rightarrow \phi_{NL} \approx \frac{\pi}{2}$$

C-PHASE via Kerr non-linearity of optical fibers due to a multi-photon field on a single-photon state

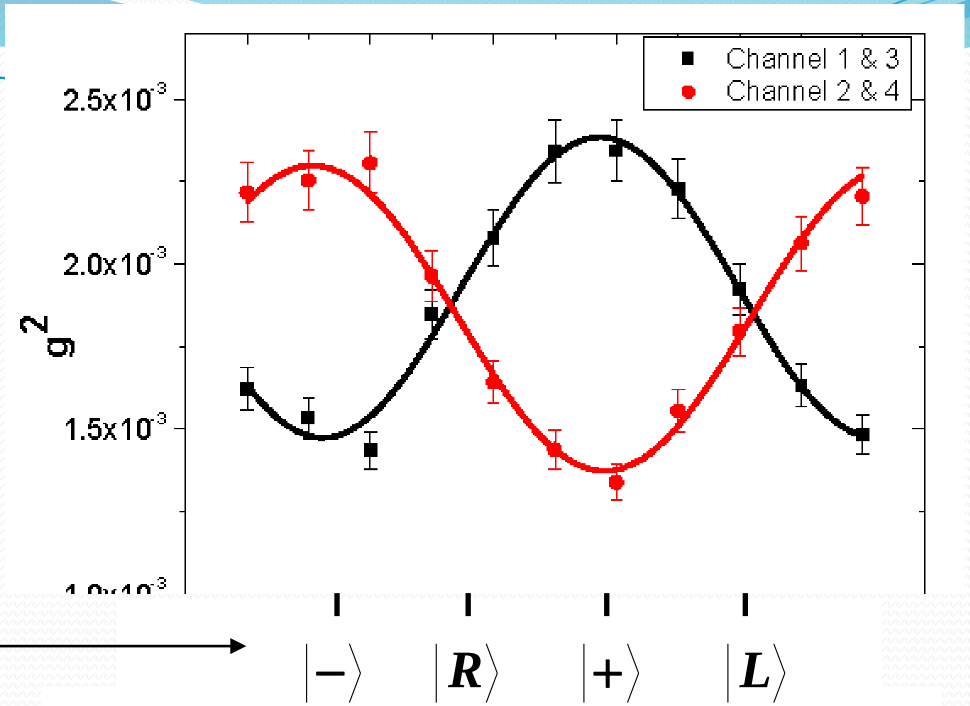


QUANTUM NON-DEMOLITION PROCESS

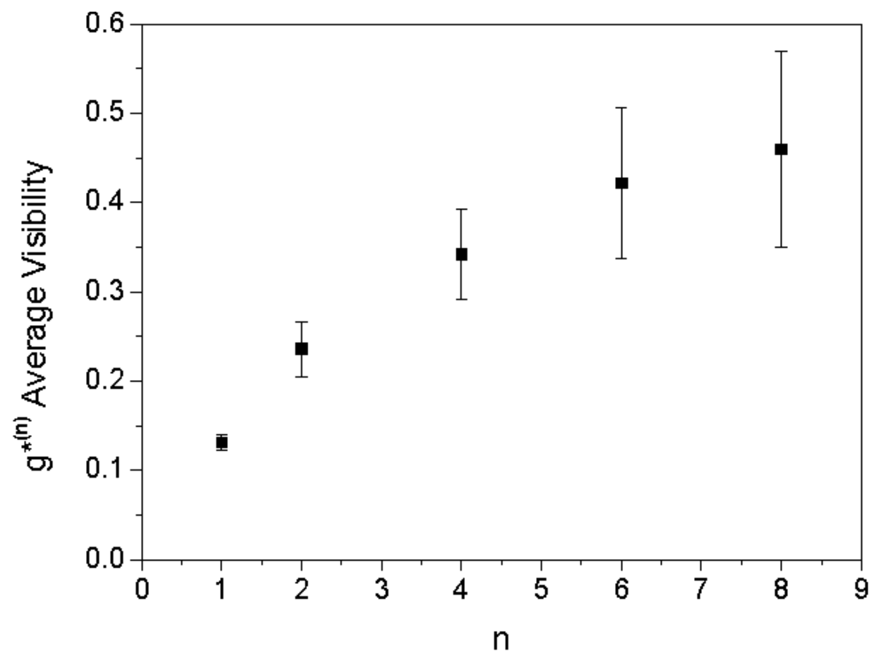
Second order correlation function detected by using four photomultipliers analyzing polarization components $|+\rangle$ and $|-\rangle$

Visibility $\approx (26 \pm 1)\%$

On the *x-axis* is reported the input qubit.



Average visibilities of the n^{th} correlation function.



CONJECTURE N.1

The quantum behavior of a macroscopic body made of **N** particles can be observed and measured in details by an apparatus able to carry out a set of measurements involving a **Nth-order** correlation of the outcomes, i.e. involving a number of detectors ~ **N.**

CONJECTURE N.2

Quantum Mechanics is valid everytime, everywhere, in the real world of our everyday life. Quantum phenomena (interfe-rence, entanglement etc.) are always present around us.

We, humans are not able to follow the quantum dynamics of macroscopic objects because of the poorness of our percei-ving sense apparatus : we have only 2 eyes, 2 ears etc. Then:

The "homo sapiens" was not made for knowing or understan-ding the fine structure of the Universe he lives in. He was made for eating, drinkind and reproducing himself and his species.

SCIENCE is a very noble act of freedom of the man. But Science is also an endless, somewhat desperate , endeavor towards the unknowable.....

CONCLUSION:

We are living in a world whose vastness and richness is beyond the reach of all conceivable measurement apparata.

(and of our most daring imagination)

Towards Quantum Experiments with Human Eyes Detectors Based on Cloning via Stimulated Emission ?

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Dipartimento di Fisica, Sapienza Universitá di Roma, Roma, 00185 Italy and
Accademia Nazionale dei Lincei, via della Lungara 10, I-00165 Roma, Italy

We believe that a recent theoretical work published in Physical Review Letters (103, 113601, 2009) by Sekatsky, Brunner, Branciard, Gisin, Simon, albeit appealing at fist sight, is highly questionable. Furthermore, the criticism raised by these Authors against a real experiment on Micro - Macro entanglement recently published in Physical Review Letters (100, 253601, 2008) is found misleading and misses its target.

PACS numbers:

We believe that the work by P.Sekatsky, N.Brunner, C. Branciard, N. Gisin and C.Simon is highly questionable [1]. The first seed of perplexity is elicited by the title of the paper, the same as the one of the present article (apart from the question mark). For the eye of a human observer, as well as any other human sensory organ, just cannot be adopted as a valid "measurement apparatus" within any experiment involving a quantum mechanical process. As stated many times by Niels Bohr,

scaling algorithm could be adopted in order to transform, in a reliable and reproducible way, the level of the synaptic electric field into one amongst a set of *orthogonal outcomes* expressing the detected light intensity, i.e. the only "observable" accessible to the eye. In facts the "pointer" sitting somewhere within the brain of the observer should be able to single out a definite orthogonal outcome (a), say: a = 3, rather than: a = 2, or a = 4. Third, while the role of the retina and the Na - ion excitation dynamics of the optical nerve may be taken as rather well understood, the complex synaptic trasmission to the "reentrant" talamo - cortical system of the brain

Quant-ph 0912.311v2 (17 december 2009)
To appear in: Foundations of Physics

2

At last, let's stop pondering on the bizarre naked eye detection idea and do consider the detailed micro-macro Bell inequality theory also reported in [1]. There a measurement *loophole* is devised in physical situations implying the calculation of the joint correlation parameters between apparata (OSG_A) and (OSG_B) tuned on different measurement bases, i.e. when the relative angular settings of the corresponding measurement apparata differ from zero: $\Delta\Phi \equiv |\Phi_A - \Phi_B| \neq 0$. Indeed, this is a typical situation realized in all Bell inequality experiments. We don't disagree on several results of the theoretical analysis by [1] but we also want to stress that these ones are quite incorrectly applied to the *real* experiment reported in [12]. In other words, the criticism to our work by Sebatsky *et al*, presumably the true motivation of work [1], is misleading as it misses completely the point. For the following reasons:

(A) The work [12] *is not* a Bell inequality experiment and then no correlations between *different* measurement bases are measured or calculated within the same experiment.. The work [12] merely consists of two totally *independent and uncorrelated* experiments aimed at the evaluation of two *different and uncorrelated* quantities, i.e. the "visibilities" V_2 and V_3 of the two *different and uncorrelated* fringing patterns shown in Figure 1, above. (The other "visibility" was found: $V_1 \simeq 0$). These patterns, drawn as function of Φ_B, represent the jointly correlated detection probabilities when a fixed measurement basis of (OSG_A) is chosen to be either $\{R, L\}$ or $\{+, -\}$, respectively. Consider for instance the measurement of V_2, i.e. the visibility of the fringe pattern determined by the fixed basis $\{R, L\}$ set at the Alice's site. As it is well known V_2 is determined by only two points, the *maximum* and the *minimum* of the pattern, i.e. exactly the points corresponding to the conditions: $\Phi_A = \Phi_B$, or: $\Delta\Phi = 0$.In other words, the two data used to evaluate V_2 are obtained by measuring the joint detection probabilities in the conditions in which the micro-qubit at Alice's site and the macro-qubit at Bob's site are mutually parallel or anti - parallel spin vectors i.e. both belonging to the *same* $\{R, L\}$ basis on the corresponding, equally oriented Poincaré spheres. The same condition: $\Phi_A = \Phi_B$, or: $\Delta\Phi = 0$ is realized within the measurement of V_3 where again the common measurement basis $\{+, -\}$ is realized for both the Alice's and Bob's apparata. Then, because of the common condition: $\Delta\Phi = 0$ affecting both measurements of V_2 and V_3, the "loophole" devised by Sekatsky *et al.* is not applicable to our experiment.

(B) Symmetry considerations based on the *rotational invariance* of the overall micro-macro *singlet* photon pair expressed by Equation 1 in [12], and of the *phase-covariant* and *information preserving* properties of the of the adopted QI-OPA, lead to conclude that the two V_2 and V_3 experiments are really identical, in the sense that the micro and macro states adopted in both cases, albeit formally different, are in fact obtained by relabelling for different polarizations the Fock state components of these micro and macro-states. In facts, the experimental outcomes V_2,V_3 of the two corresponding experiments have been found equal by [12], within the statistical errors.

(C) As presumed by Sekatsky *et al*, photon losses are indeed present in the multi-photon (Bob) side of experiment [12], mostly due to the reduced quantum efficiency $QE < 1$ of the photomultipliers. In any case the effect of losses is a "*local*" one and may be modelled, as shown above in Figure 1, by a Beam Splitter (BS) with a transmission $T \equiv (1 - R)$ placed right at the output of the QI-OPA apparatus. The result of a complete computer simulation of the experiment [12] by adopting the real experimental parameters and by assuming the fixed measurement basis $\{R, L\}$, is shown in Figure 2. There the "visibility" V_2, reported as function of R. is

F. De Martini, quant-ph 0912.3110v2 (17/12/2009) found to be a *decreasing* function of of the amount of photon losses. This result is expected since, being the micro-macro entanglement distributed between all photons emitted by QI-OPA, any photon loss entails a reduction of the amount of entanglement detected on the remaining photons. Furthermore, this behavior agrees with a nice "*entanglement criterion*" expressed in a paper by Eisenberg *et al* [13] that can be expressed as follows: "any *local* transformation cannot enhance the level of entanglement". A photon loss is indeed a *local* transformation, by definition. The work by Eisenberg et al. [13] also dealt with experimental multiphoton etanglement detection with $QE < 1$[17]..

In spite of the entanglement reduction due to the measurement losses, the "*visibility inequality*" $|V_1 + V_2 + V_3| \leq 1$ was violated in the experiment [12]. This *a fortiori* demonstrates the *nonseparability* of our Micro - Macro system.

In summary, all previous considerations fully support our claim asserting that the work [12], taken together with previous works by our Laboratory [11][14] indeed consists of the first *exact* realization of the *Macroscopic Quantum Superposition*, i.e. complying *exactly* with the original definition given by Schrödinger in 1935 [15]. The value of this discovery is further enhanced by the large resilience to decoherence shown by our system, which involves as many as $N \simeq 10^5$ particles [16]. The robustness against any kind of noise makes our system apt to the investigation on several so far inaccessible fundamental issues of quantum mechanics close to the elusive "*quantum - classical boundary*".

We conclude by stressing our deep appreciation for the continuous interest in our work by P.Sekatsky, N.Brunner, C.Branciard, N. Gisin and C. Simon.

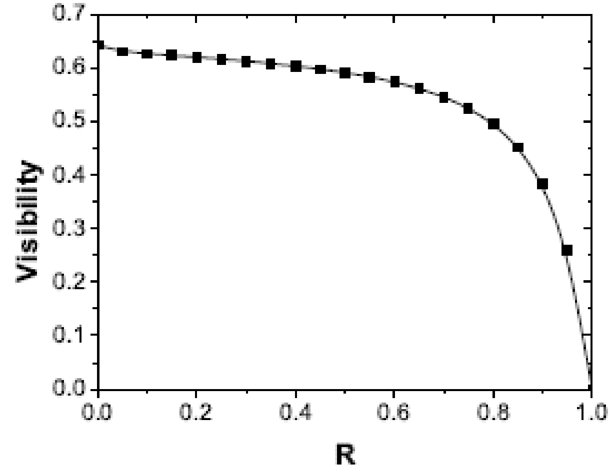

FIG. 2: Complete computer simulation of the experiment [12] showing the decrease of the visibility V_2 due to the reduction of micro - macro entanglement for increasing R, i.e. the amount of photon loss. .

[12] F. De Martini, F.Sciarrino, and C. Vitelli, Phys. Rev. Lett. **100**, 253601 (2008).
[13] H. Eisenberg, G. Khoury, A. Durkin, C. Simon, and D. Bouwmeester, Phys. Rev. Lett. **93**, 193901 (2004).
[14] F. De Martini, F. Sciarrino, and V. Secondi, Phys. Rev. Lett. **95**, 240401 (2005); F. De Martini, and F. Sciarrino, Progr. Quantum Electr. **29**, 165 (2005); F. De Martini, and F. Sciarrino, Journal of Physics A: Math. Theor. **40**, 2977 (2007).
[15] E. Schrödinger, *Naturwissenshaften* **23**, 807 (1935).
[16] F. De Martini, F. Sciarrino and N. Spagnolo, Phys. Rev. Lett. **103**, 100501 (2009).
[17] Since Christoph Simon co-authored both papers [13] and [1] he may perhaps explain why the "*loophole*" problems should be applicable to work [12] and not to [13] and why the "*visibility inequality*" and the "*entanglement criterion*" should be applicable to work [13] and not to [12]

F. De Martini, quant-ph 0912.3110v2 (17/12/09)

Single-particle "loss" test for *Multi*-particle entanglement

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Since the average entanglement cannot be created or enhanced by any *local* (LOCC) operation, e.g. by any loss or filtering mechanism acting on each mode $\mathbf{k_2}$,

Then the realization of entanglement over $\{\mathbf{k_1}, \mathbf{k_2}\}$

at a *single-particle* level implies that entanglement is also realized, in the average, over these modes in the *multi-particle* regime.

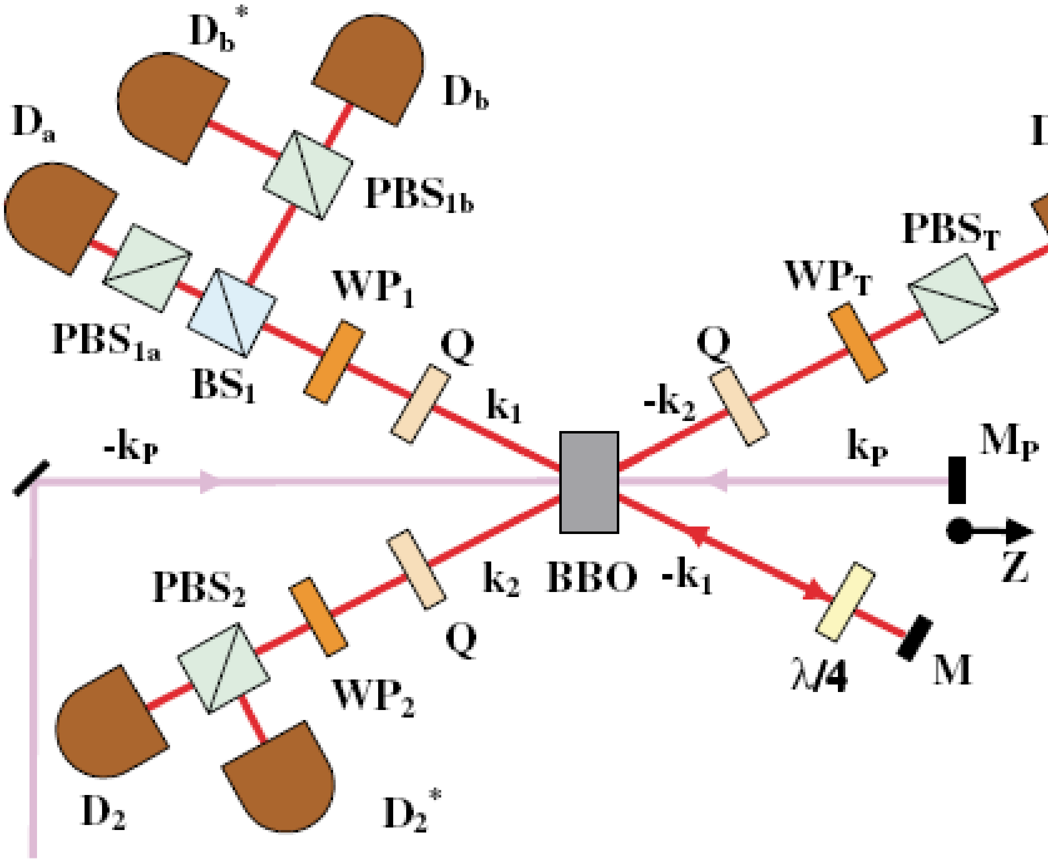


FIG. 1 (color online). Schematic diagram of the universal optimal cloning machine (UOQCM) realized on the cloning (C) channel (mode k_1) of a self-injected OPA and of the Universal NOT (U-NOT) gate realized on the anticloning (AC) channel, k_2.

Outline

Qubit versus Macro-qubit

Macro-qubit measurement

Macro-qubit transmission

Micro-Macro Teleportation

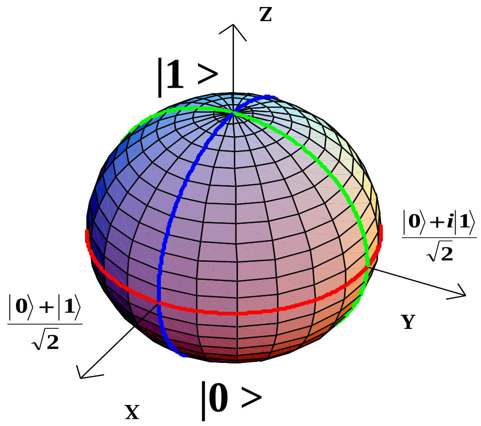
Conclusions

Qubit:

Vector of quantum information:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

- Quantum superposition principle
- No Cloning Theorem



Quantum cryptography applications:

No perturbation → No measurement → No eavesdropping

Optical implementation:
- Single photon polarization
- Single photon path
- Time bin
- Orbital angular momentum

$$|\psi\rangle = \alpha|H\rangle + \beta|V\rangle$$

- Generation through NL optical process
- Manipulation through linear optical elements
- Discrimination through single photon counting detectors

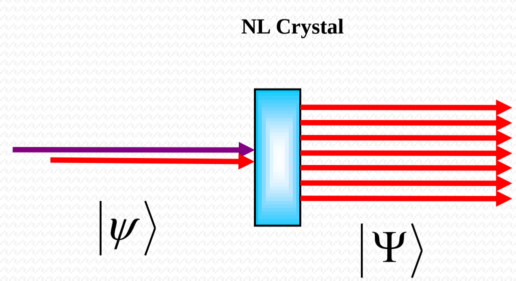
Macro Qubit:

Obtained from a single photon qubit through an optical amplification process: at the exit of the amplifier we have thousands of photons depending on the NL gain of the amplification

Single-photon qubit codified in the polarization degree of freedom → Multi-photon qubit obtained through an amplification process

$$|\psi\rangle = \frac{|H\rangle + |V\rangle}{\sqrt{2}}$$

$$|\Psi\rangle = \frac{|\Phi^H\rangle + |\Phi^V\rangle}{\sqrt{2}}$$

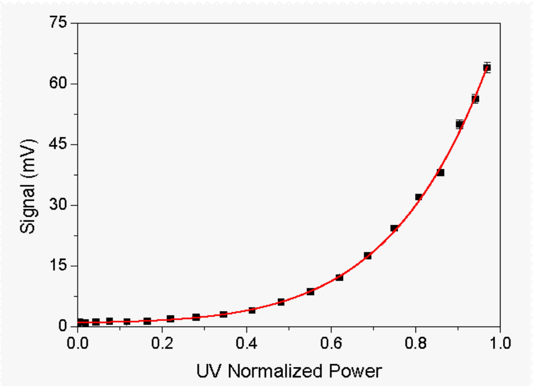


Optimal phase covariant cloning machine

$$H_I = i\hbar\chi\, \hat{a}_V^\dagger \hat{a}_H^\dagger + h.c.$$

Number of generated photons: $\bar{n} = \sinh^2 g$

Number of generated photons: $g = \chi\sqrt{P_{UV}}$



F. De Martini, F. Sciarrino, C. Vitelli *Phys. Rev. Lett.* **100**, 235601 (2008).

Micro versus Macro:

Qubit

$$|\psi\rangle = \alpha|H\rangle + \beta|V\rangle$$

- Can be identified with an high fidelity
- Is quite sensitive to losses
- Sure for cryptographic applications

Macro-Qubit

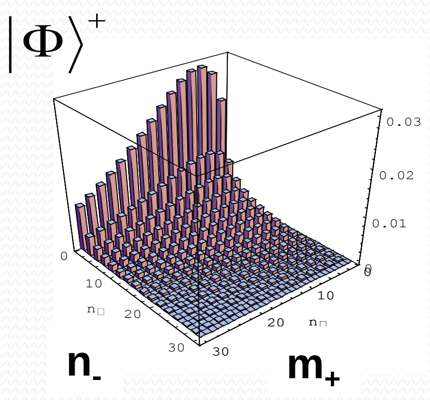
$$|\Psi\rangle = \alpha|\Phi^{H}\rangle + \beta|\Phi^{V}\rangle$$

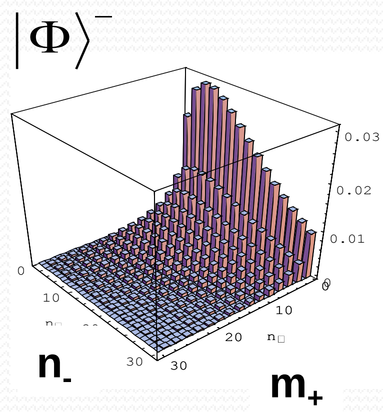
- Quite rubust to losses and decoherence
- Can be identified by a docothomic with a lower fidelity
- Is it sure against eavesdropping?

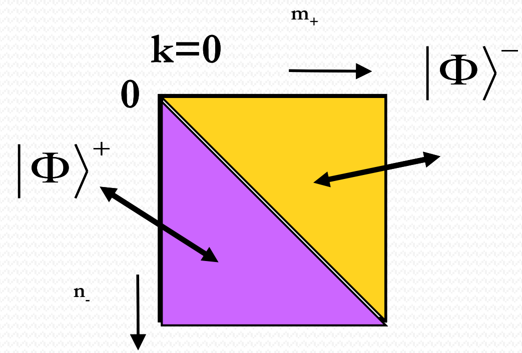
The problem is: how to measure the macro-qubit state?

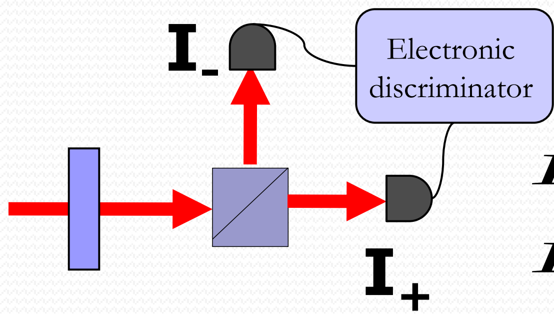
Macro-qubits identification:

Structure of orthogonal macro-qubits: comparing the orthogonally polarized intensity signals we can infer the nature of the macro-state, for each macro-qubit belonging to an equatorial polarization basis.



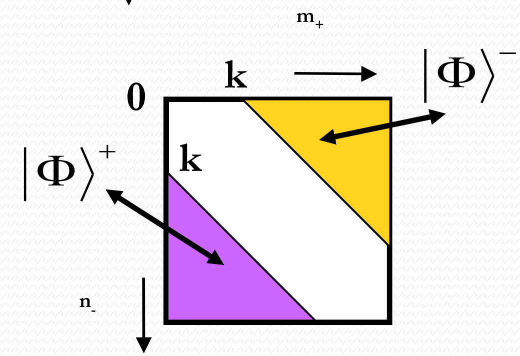






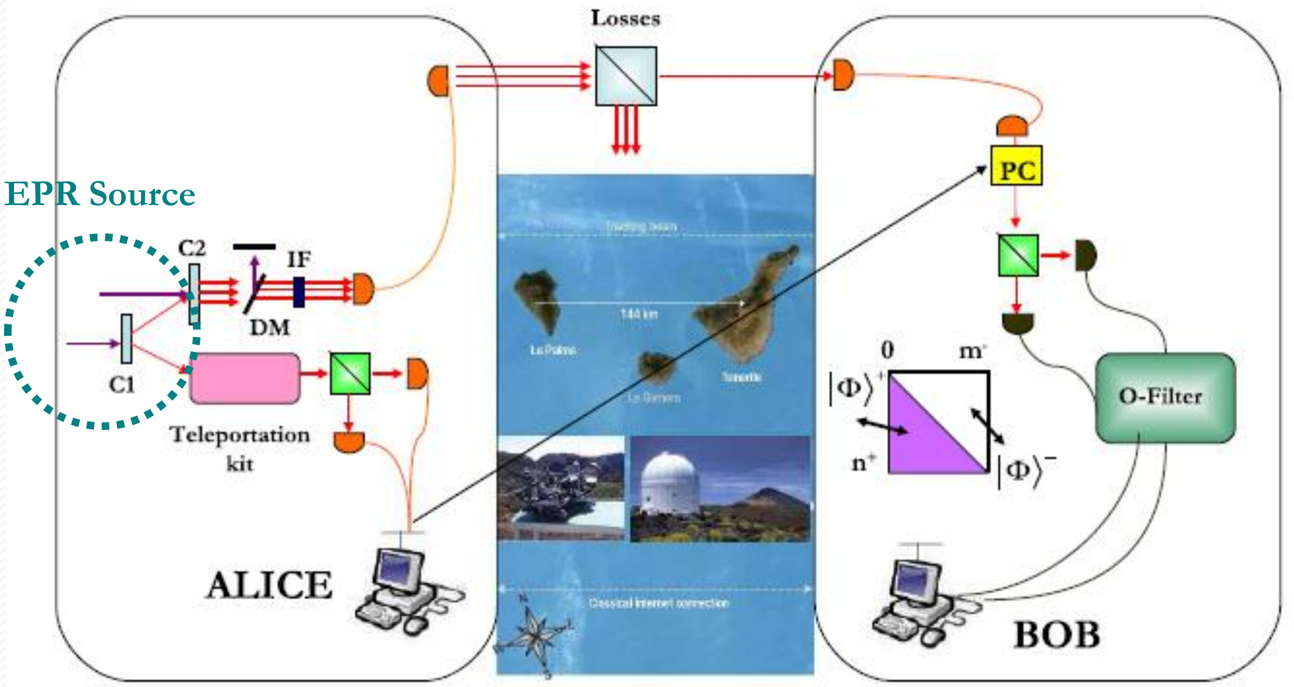
$$I_+ > I_- \Rightarrow k \rightarrow |\Phi^+\rangle$$

$$I_- > I_+ \Rightarrow k \rightarrow |\Phi^-\rangle$$



Micro-Macro Teleportation:

With the present system we could realize the teleportation of a single-photon qubit between the Alice's site and a corresponding photonic macrostate transmitted by a long-range free space link to a Bob's site.



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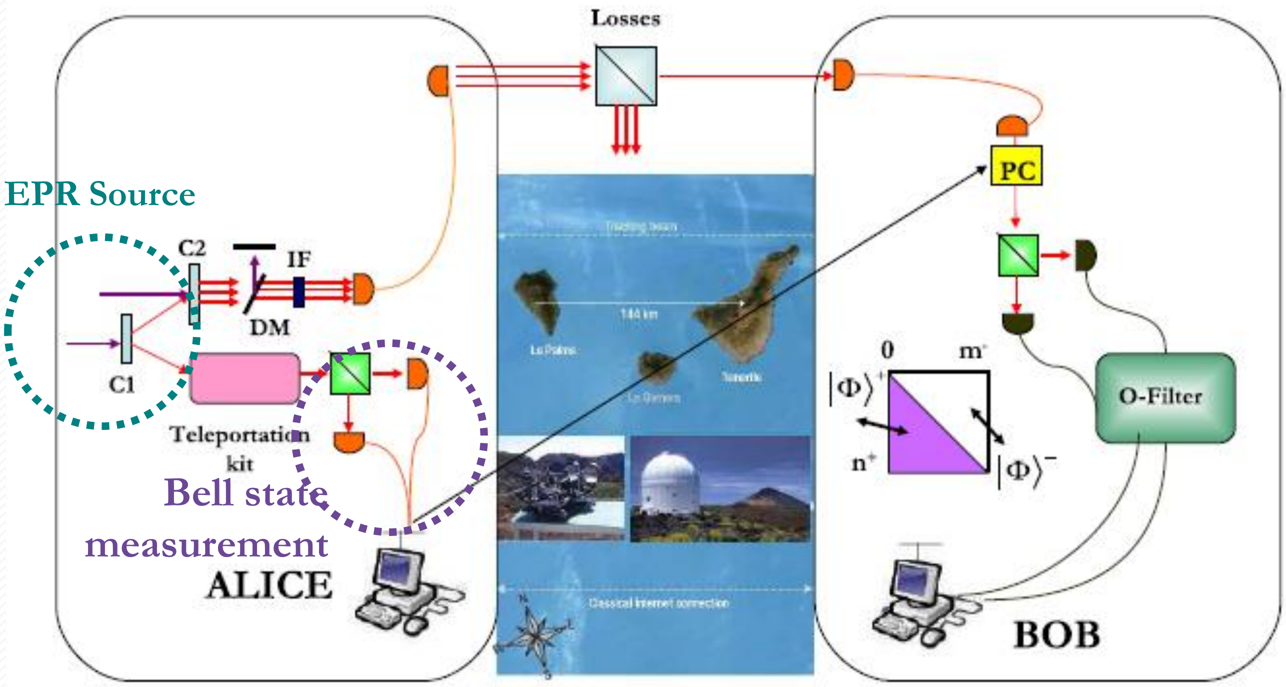

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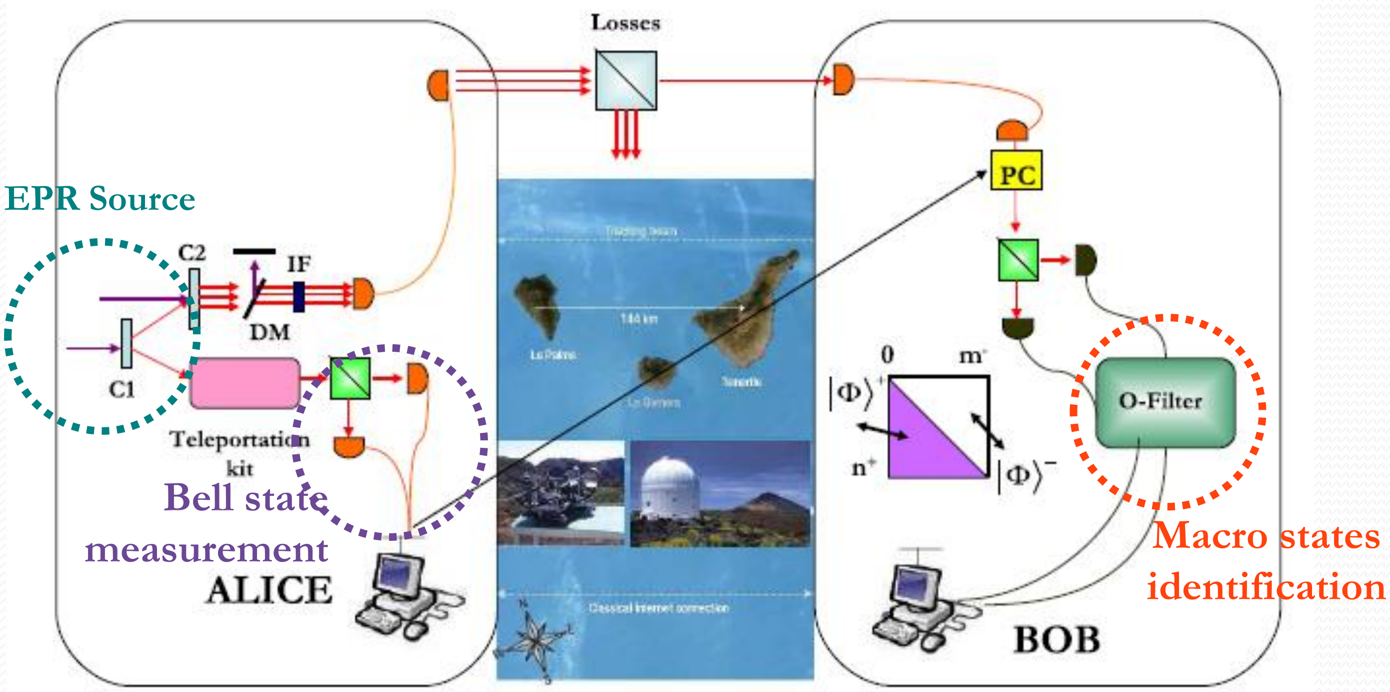


Quantum Teleportation: $F > \frac{3}{4}$

QUANTUM INJECTION : QI-OPA

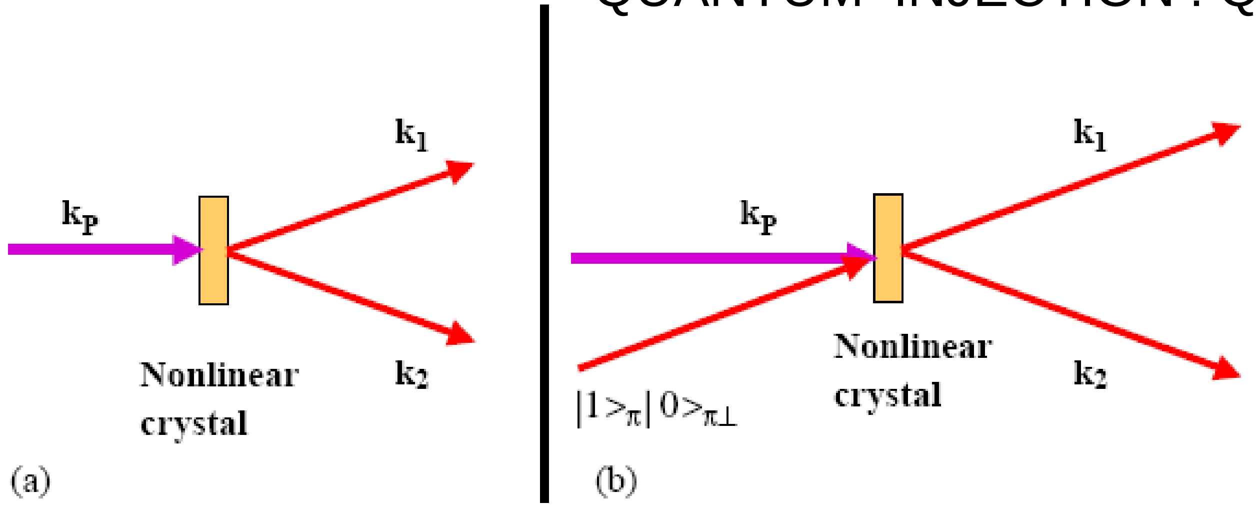


Fig. 20. Optical parametric amplifier working in spontaneous emission regime (a) and stimulated emission regime (b).

High – gain stimulated Parametric Amplifier (Quantum-injected OPA: phase-covariant cloning)

$$\left|\Psi_{in}\right\rangle = \alpha\left|+\right\rangle + \beta\left|-\right\rangle \quad ;\left|\pm\right\rangle = 2^{-1/2}(\left|h\right\rangle \pm \left|v\right\rangle)$$

$$;\left|R/L\right\rangle = 2^{-1/2}(\left|h\right\rangle \pm i\left|v\right\rangle)$$

Optimal
Phase-Covariant
Quantum cloning

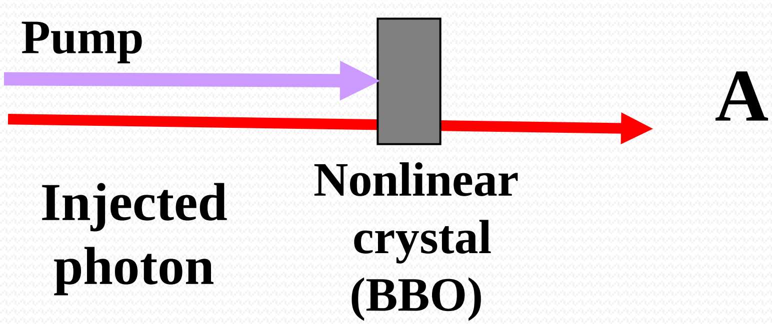
$$\left|\Psi\right\rangle_{out} = \hat{U}_{OPA}\left|\Psi_{in}\right\rangle = \alpha\left|\Psi(+)\right\rangle + \beta\left|\Psi(-)\right\rangle$$

$$\left|+\right\rangle \Rightarrow \left|\Psi(+)\right\rangle; \left|-\right\rangle \Rightarrow \left|\Psi(-)\right\rangle: \; Multi-particle \; (N \approx 10^6)$$

INFORMATION - PRESERVING transfer of quantum superposition from a Microstate into a Macrostate by a Unitary transformation

$$\left|\left\langle \Psi(+)\middle|\Psi(-)\right\rangle\right|^2 = \delta_{+,-} \; : \; Ortho-normal$$

$$\left|\Psi(\pm)\right\rangle = \sum_{i,j=0}^{\infty} \gamma_{ij}\left(\sqrt{(1+2i)!(2j)!}/i!\,j!\right)\left|2i+1\right\rangle_{\pm}\left|2j\right\rangle_{\mp}$$



Bipartite entangled state

COVARIANCE UNDER U $\Rightarrow$ FIDELITY IS INVARIANT UNDER U

$$f_{U|\psi\rangle} = \langle\psi|U^\dagger \, \mathcal{M}\left(U|\psi\rangle\langle\psi|U^\dagger\right) U|\psi\rangle$$

$$= \langle\psi|U^\dagger U \, \mathcal{M}\left(|\psi\rangle\langle\psi|\right) U^\dagger U|\psi\rangle$$

$$= \langle\psi| \, \mathcal{M}\left(|\psi\rangle\langle\psi|\right) |\psi\rangle$$

$$= f_{|\psi\rangle}$$

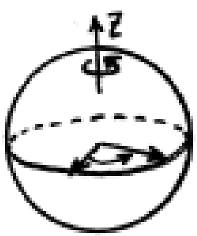
(COVARIANCE)

NON-UNIVERSALLY COVARIANT CLONER

$U \in$ SUBSET OF $SU(2)$ → Abelian Group U(1)

E.G. PHASE-COVARIANT CLONER (D. Bruss et al., PRA, 2000)

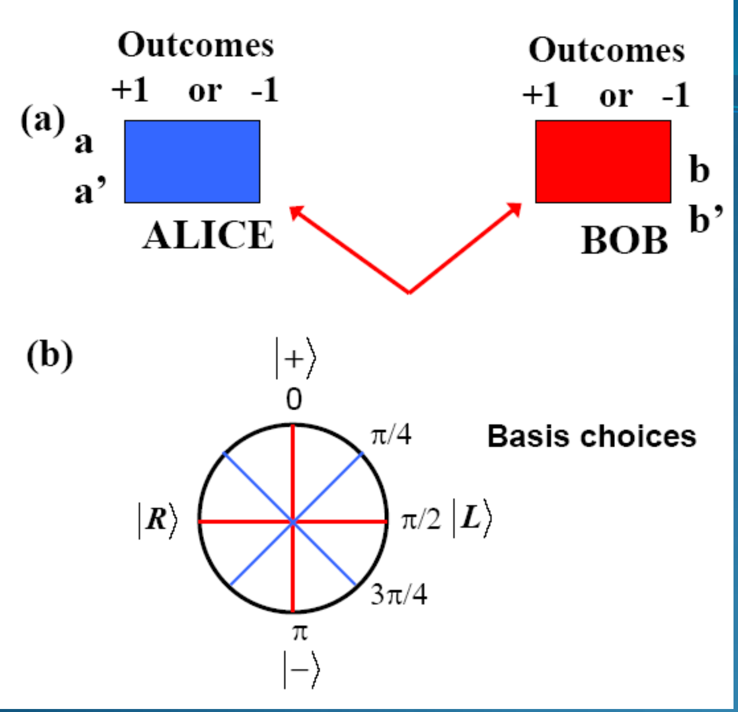
$$U = e^{i\alpha\sigma_z}$$



$$f = \frac{1}{2} + \frac{1}{\sqrt{8}} \simeq 0.854 > \frac{5}{6} \simeq 0.833$$

(UCM)

SPIN – 1 INJECTION



Test of CHSH inequalities: choice of observables

ALICE:

Outcome + 1: detection of state $|2\varphi\rangle$

- 1: detection of state $|2\varphi^{\perp}\rangle$

Basis a: $\varphi = \pi/4$

Basis a': $\varphi = 3\pi/4$

$$\frac{1}{\sqrt{2}}\left(|H\rangle_A + e^{i\phi}|V\rangle_A\right)$$

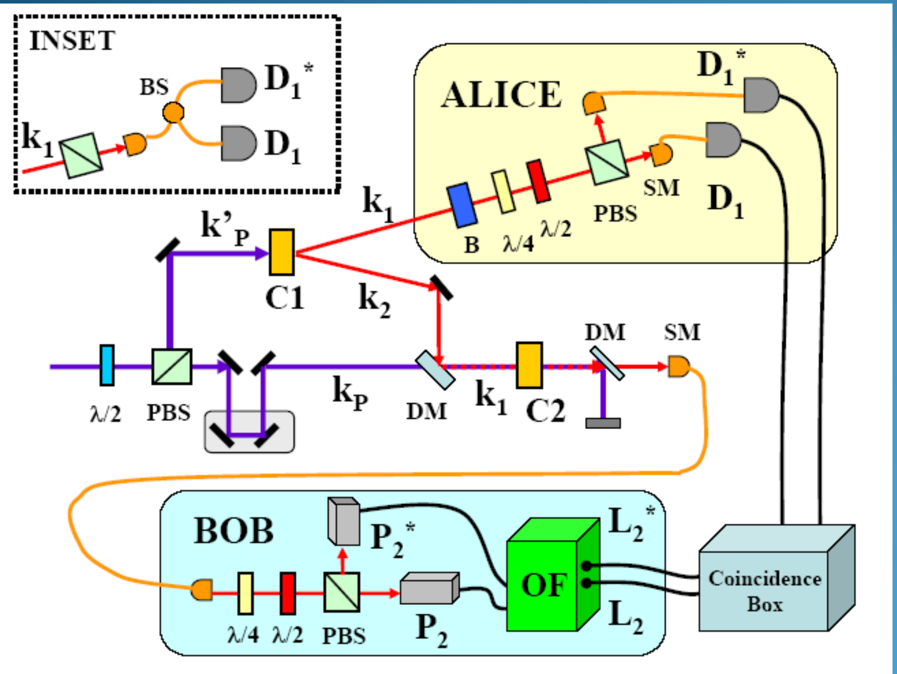
BOB:

Outcome + 1: detection of state $|\Phi^{2\varphi}\rangle$

- 1: detection of state $|\Phi^{2\varphi^{\perp}}\rangle$

Basis b: $\varphi = 0$

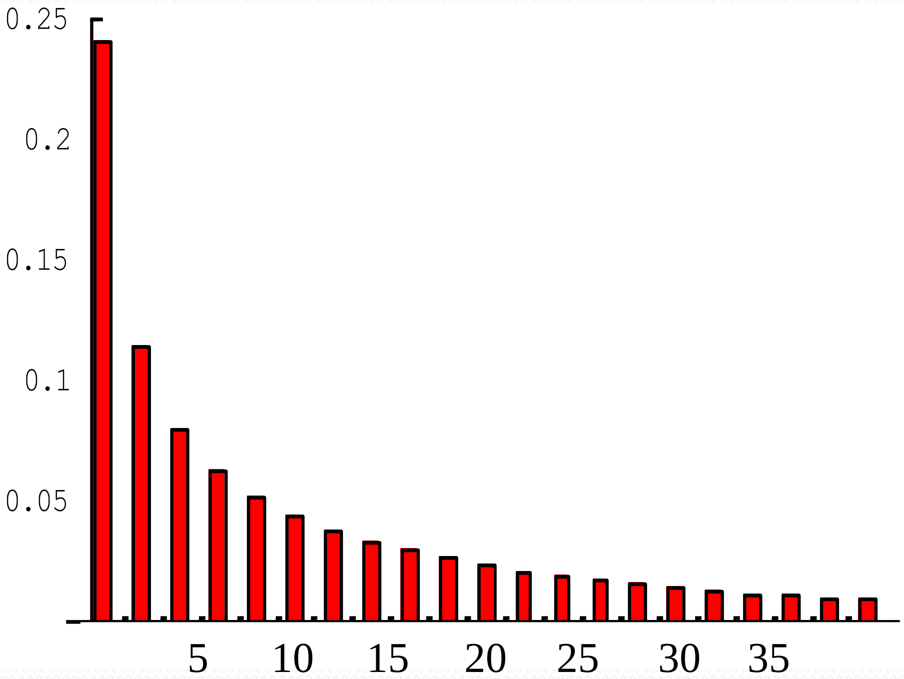
Basis b': $\varphi = \pi/2$



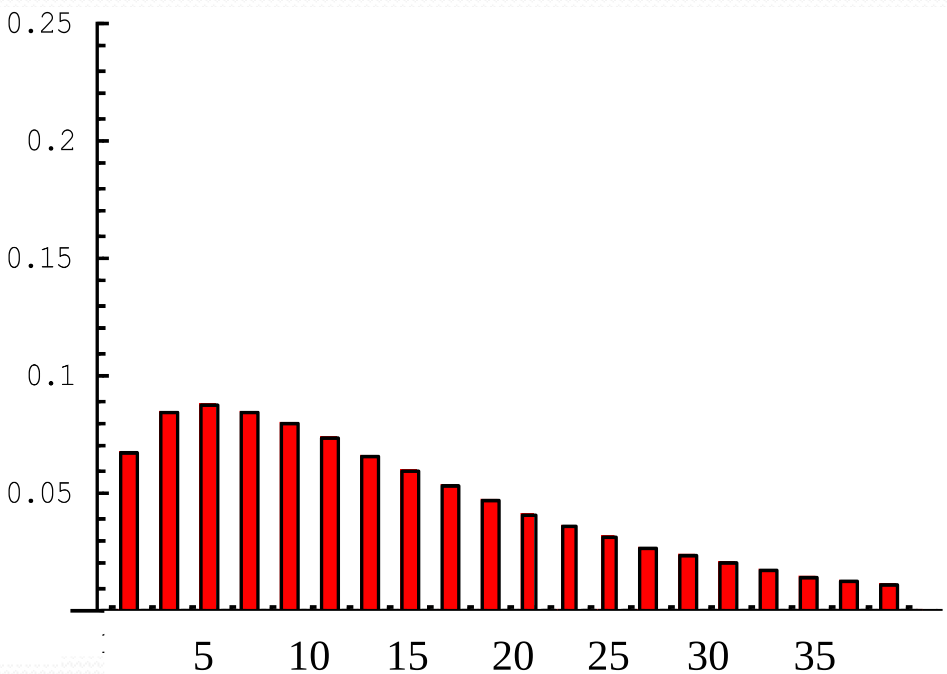
COMPARISON BETWEEN QIOPA SPONTANEOUS AND AMPLIFIED MARGINAL PHOTON DISTRIBUTIONS: SINGLE PHOTON INJECTION

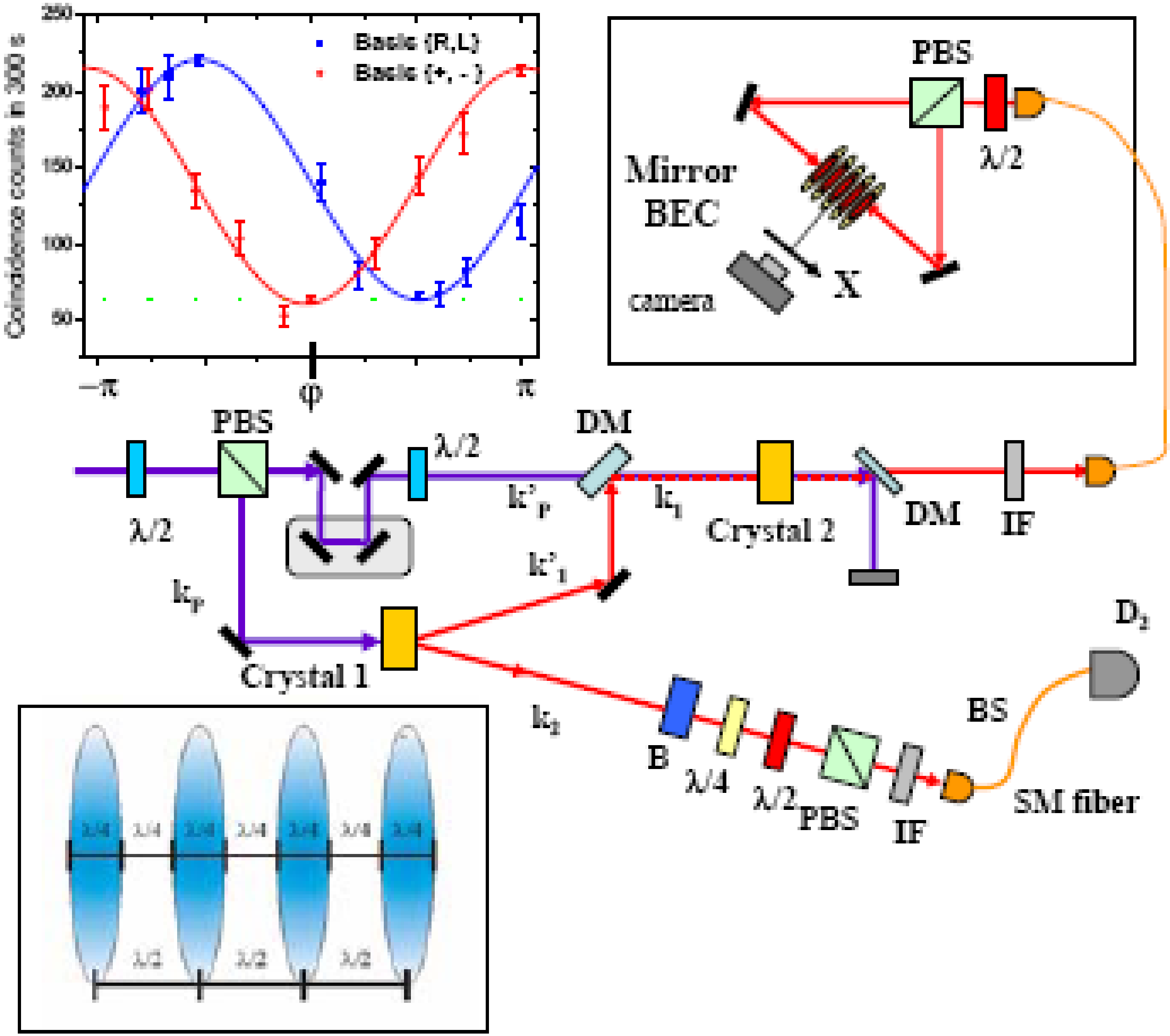
<n> = 16

QIOPA spontaneous emission distributio (Planck)



QIOPA $|\Phi^{\phi}\rangle$ equatorial qubits





250
200
150
100
50
Coincidence counts in 300 s
Basis {R,L}
Basis {+, - }
−π
φ
π
PBS
λ/2
Mirror
BEC
X
camera
λ/2
PBS
DM
k'p
k1
Crystal 2
DM
IF
λ/2
k'1
kp
Crystal 1
D2
k2
BS
B
λ/4
λ/2
PBS
IF
SM fiber
λ/4
λ/2

Applications to Q. Information:

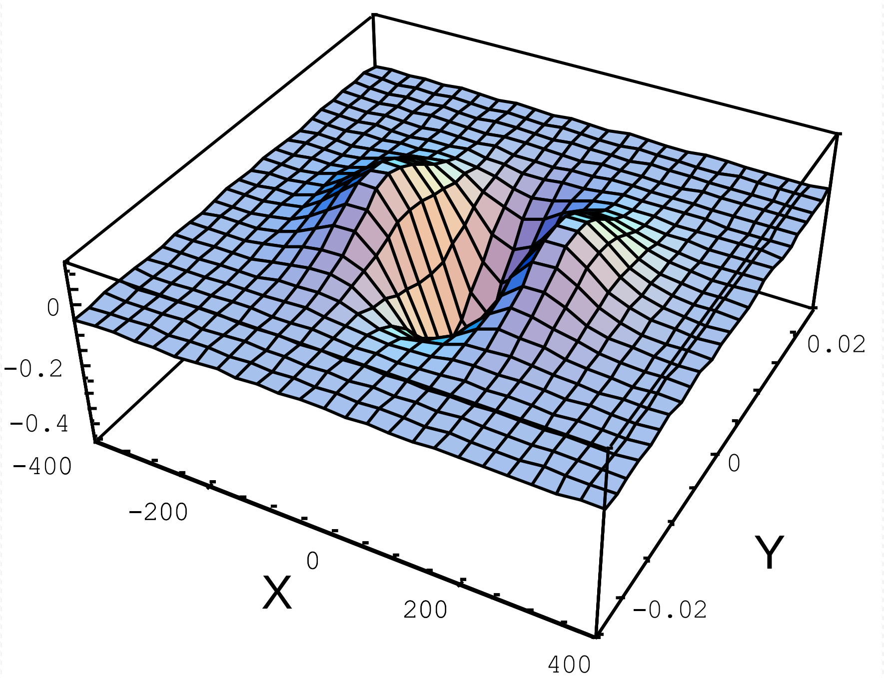
- Enhancement by $\xi \simeq 10^6 \div 10^{10}$ of all photon-photon interactions.
- EXAMPLES:
- A) 2-qubit phase-gates or C-NOT
- B) Superdense Coding (Bennett-Wiesner , 1992)
- C) Efficiency in long range Q. Communication

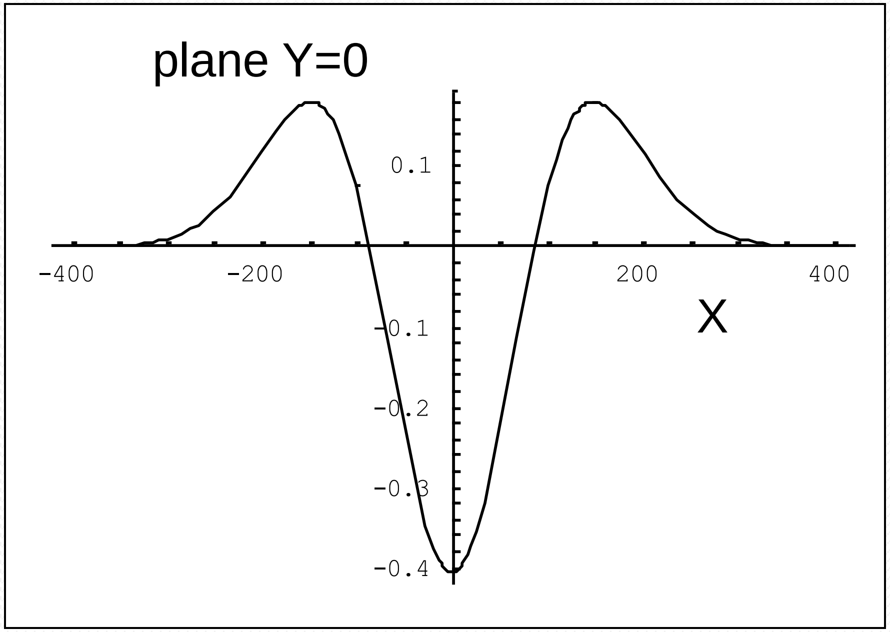
$$|\Psi_{IN}\rangle = |1\rangle_+ |0\rangle_-$$

$$W\{\alpha,\beta\} = -\left(\frac{2}{\pi}\right)^2 \left(1-|\Delta_{AB}|^2\right)\exp\left(-|\Delta|^2\right)$$

$$\begin{cases} |\Delta|^2 = \left[|\gamma_{A+}|^2 + |\gamma_{B-}|^2\right] \\ \Delta_{AB} = \frac{1}{\sqrt{2}}\left(\gamma_{A+}+\gamma_{A+}^*\right) - \frac{i}{\sqrt{2}}\left(\gamma_{B-}+\gamma_{B-}^*\right) \end{cases}$$

$$\begin{cases} X = \gamma_{A+} = (\alpha+\beta^*)e^{-g} \\ Y = \gamma_{B-} = i(\beta-\alpha^*)e^{+g} \end{cases}$$

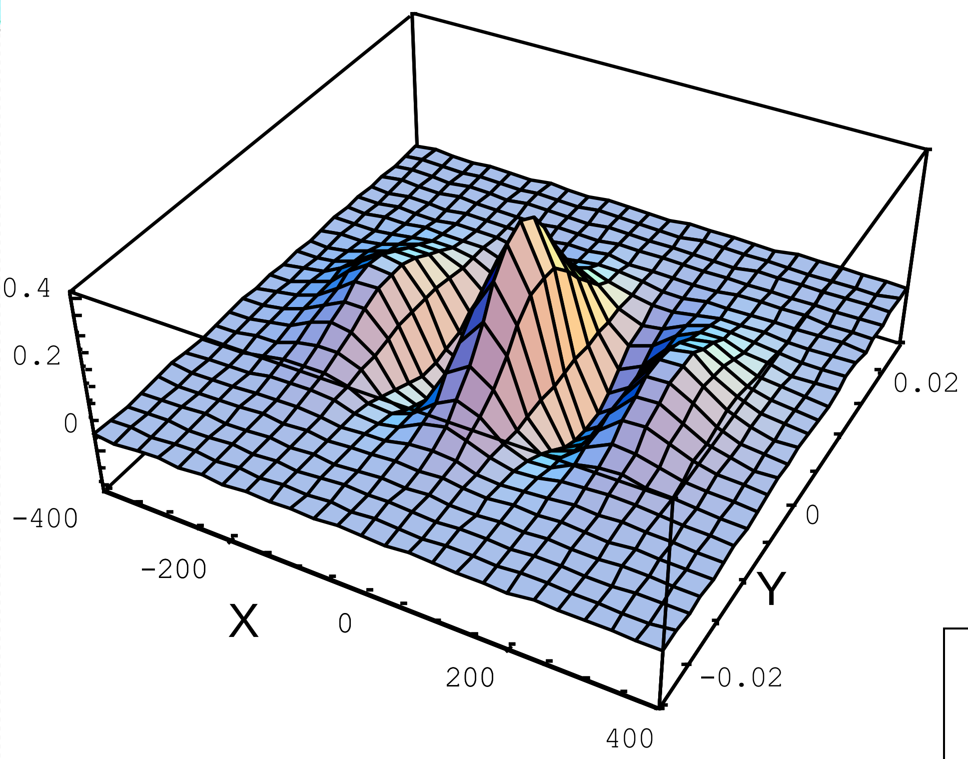




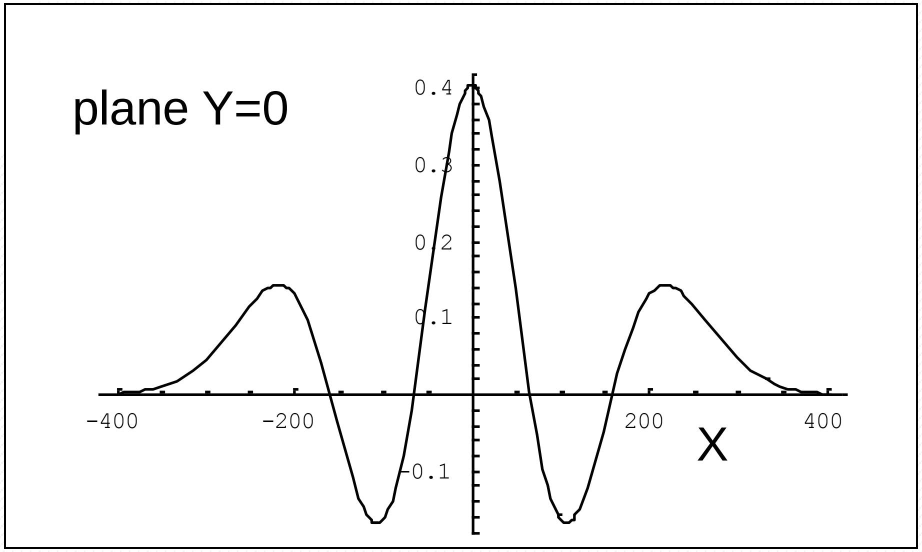
However, not all quantum superpositions are treated equally by decoherence. Interaction with the environment will typically single out a preferred set of states. These *pointer states* remain untouched in spite of the environment, while their superpositions lose phase coherence and decohere. Their name—pointer states—originates from the context of quantum measurements, where they were originally introduced (Zurek, 1981). They are the preferred states of the pointer of the apparatus. They are stable and, hence, retain a faithful record of and remain correlated with the outcome of the measurement in spite of decoherence.

Einselection is this decoherence-imposed selection of the preferred set of pointer states that remain stable in the presence of the environment. As we shall see, einse-

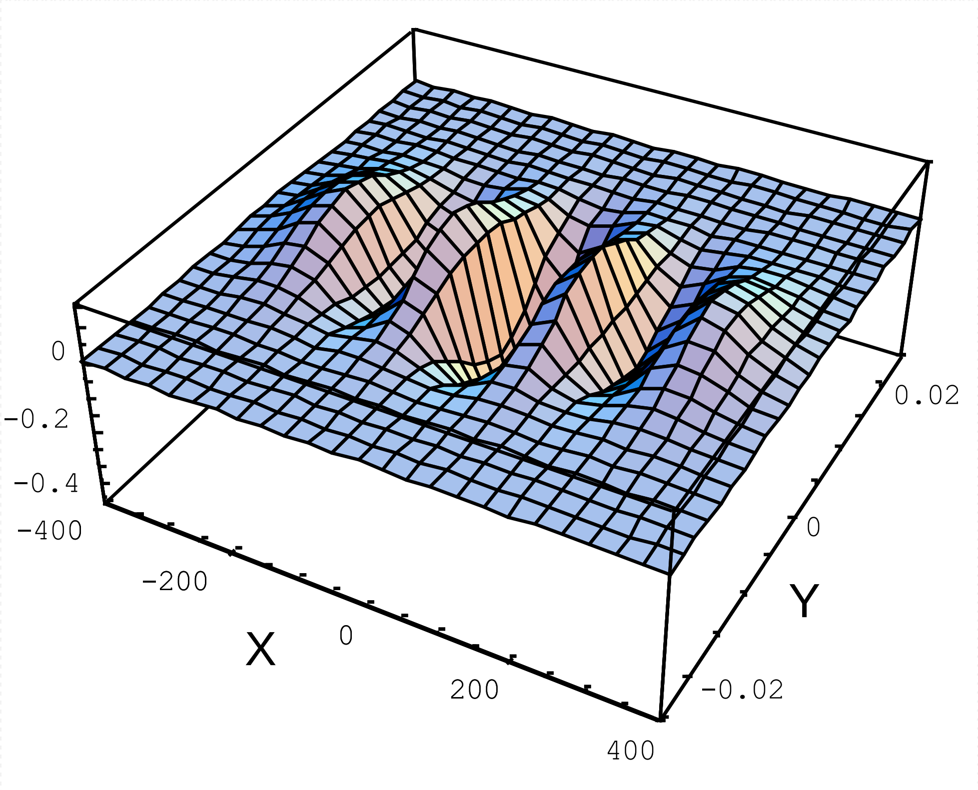
W.H.Zurek, Revs.Mod.Phys. 2003

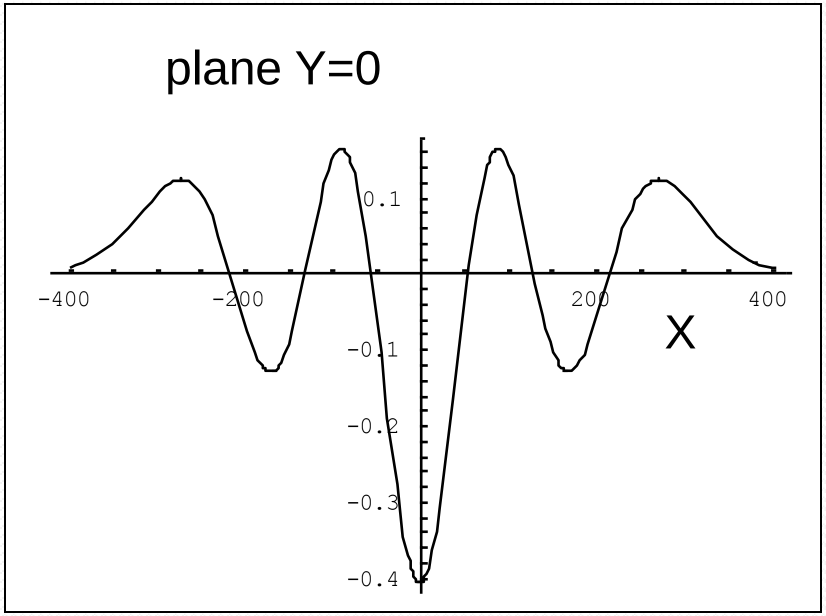


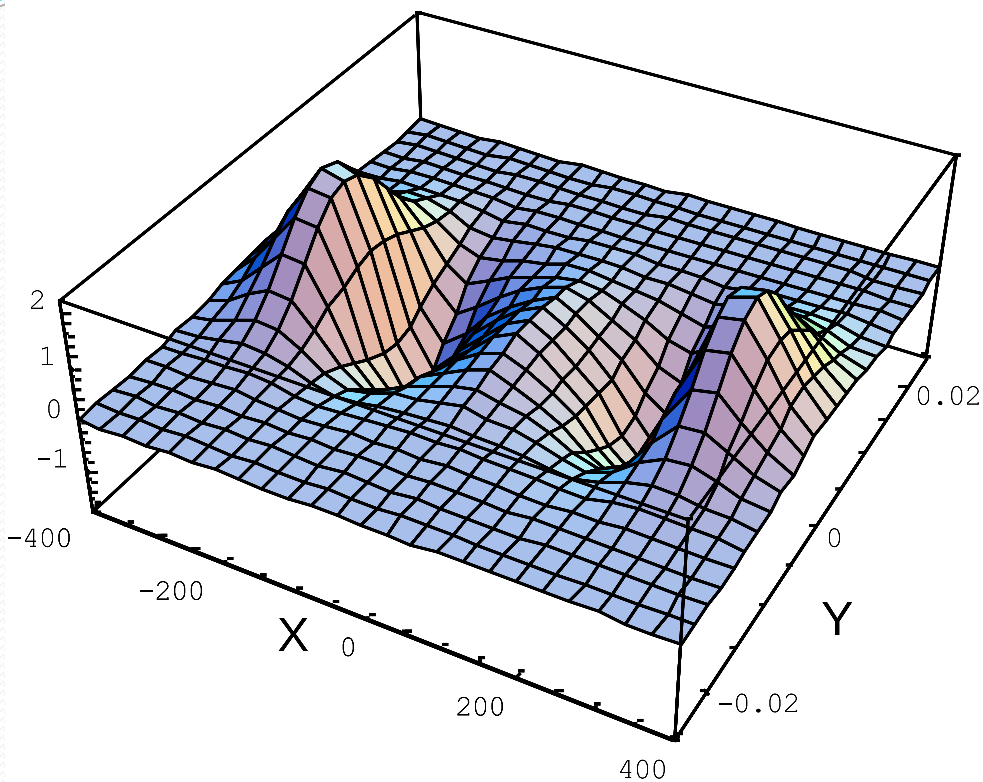
$$|\Psi_{IN}\rangle = |2\rangle_+ |0\rangle_-$$



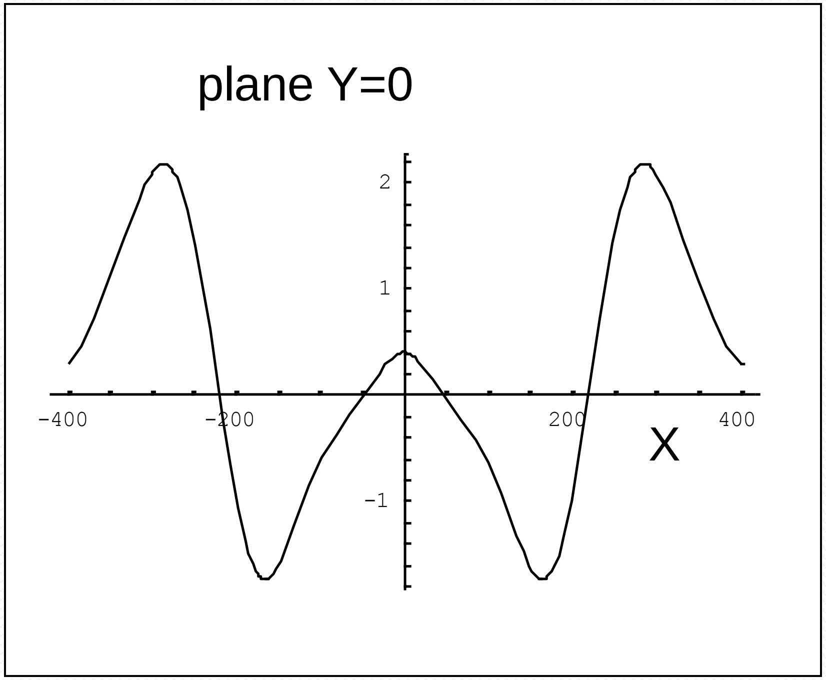
$$\left|\Psi_{IN}\right\rangle = \left|3\right\rangle_{+}\left|0\right\rangle_{-}$$



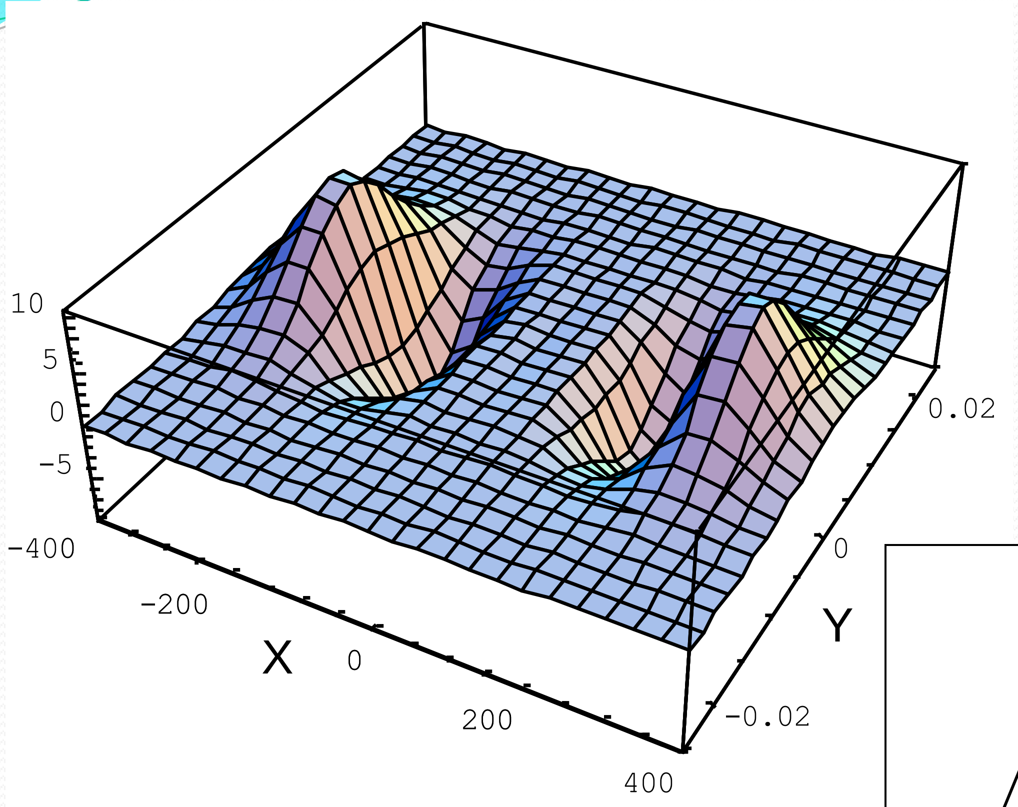




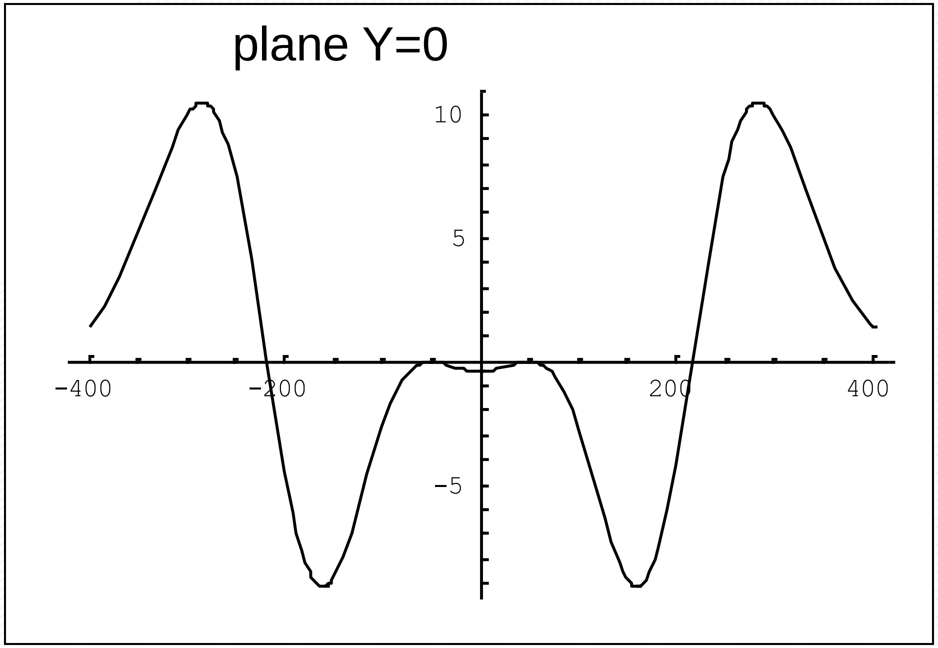
$$\left|\Psi_{IN}\right\rangle = \left|4\right\rangle_{+}\left|0\right\rangle_{-}$$



Wigner functions

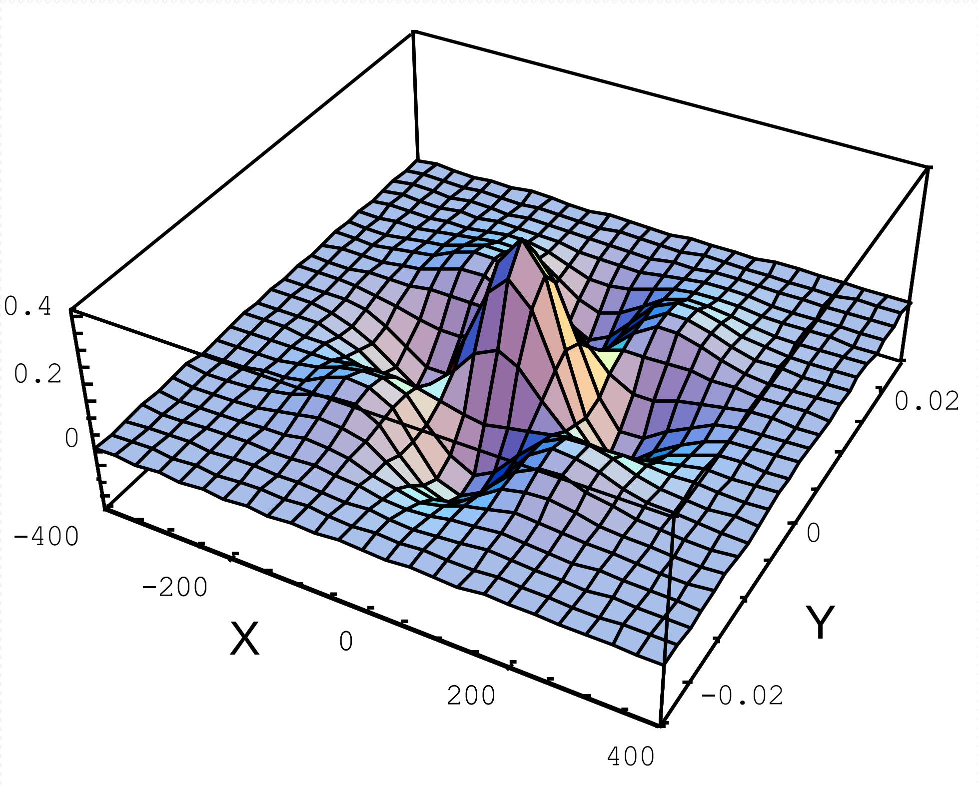


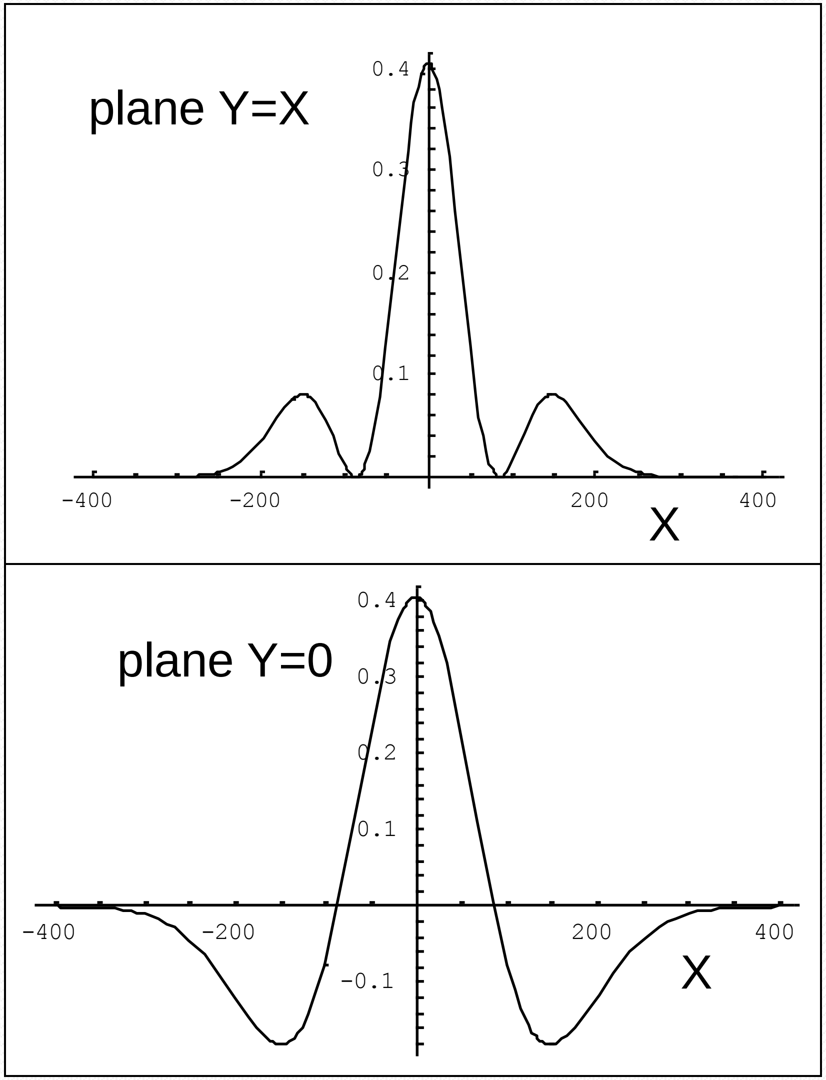
$$\left|\Psi_{IN}\right\rangle = \left|5\right\rangle_{+}\left|0\right\rangle_{-}$$



Wigner functions

$$\left|\Psi_{IN}\right\rangle = \left|1\right\rangle_{+}\left|1\right\rangle_{-}$$





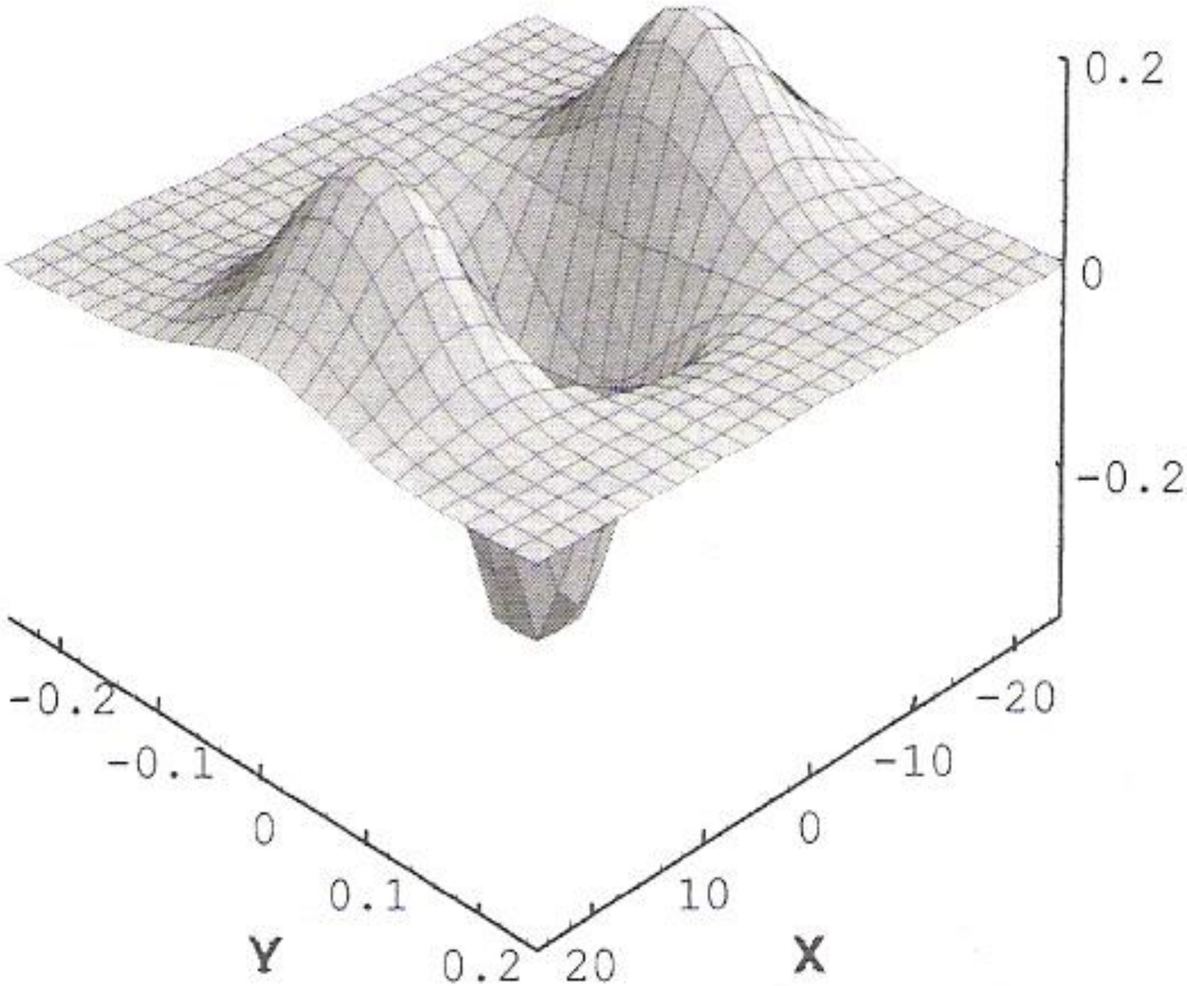
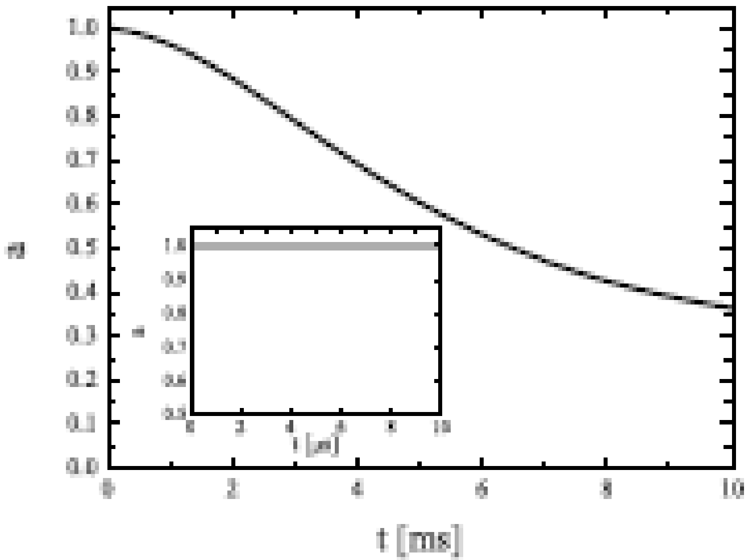
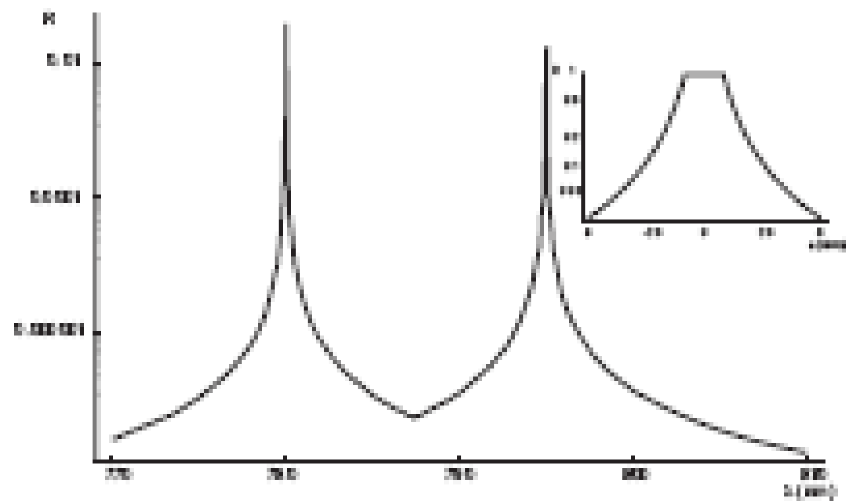
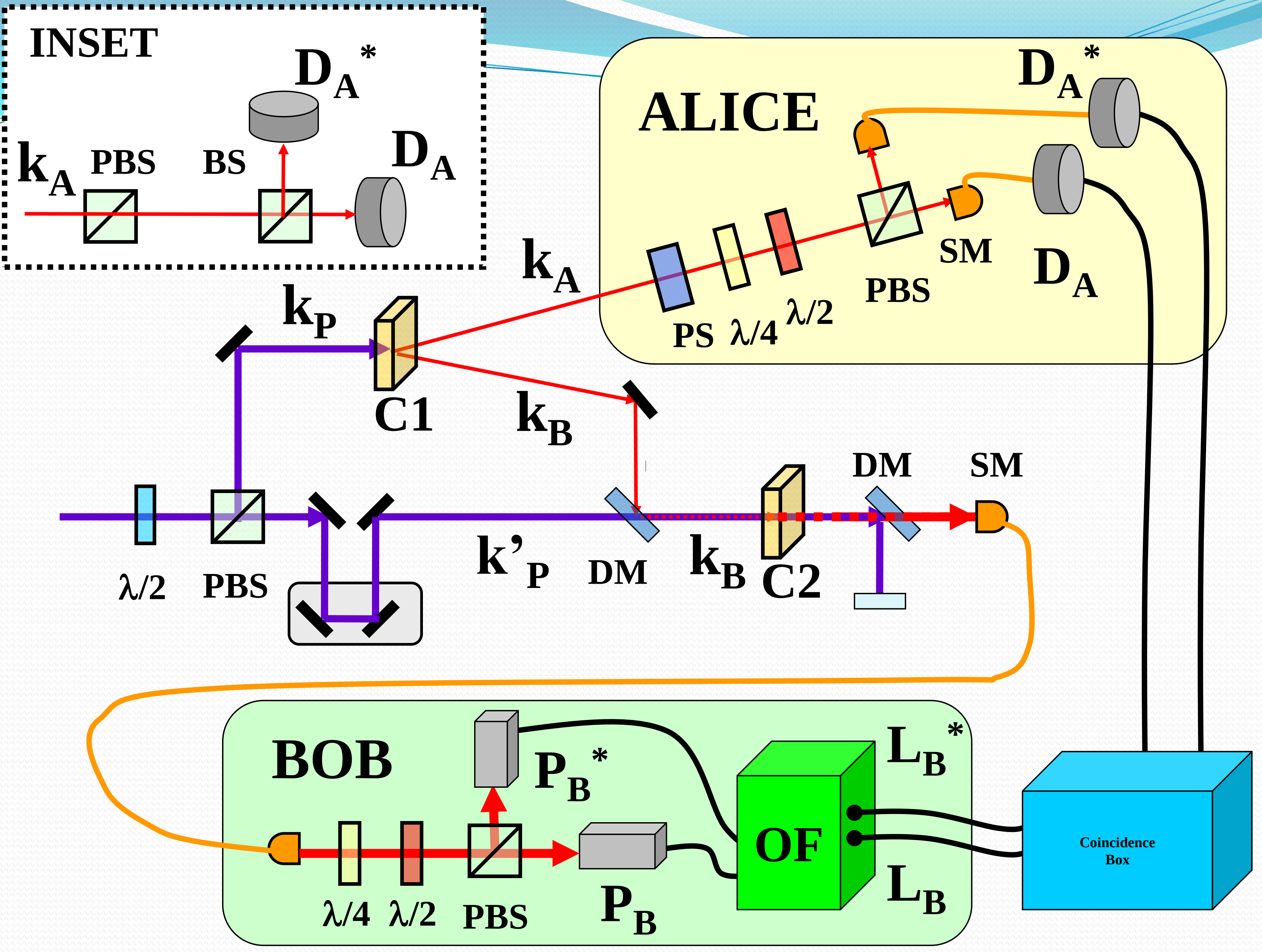


FIG. 2. Tridimensional plot of the Wigner function of the amplified field on mode $\mathbf{k}_2$ at the output of the quantum injected OPA as a function of the squeezed variables: $X = (\alpha + \beta^*)e^{-g}$; $Y = i(\beta - \alpha^*)e^{+g}$, for a parametric gain $g = 2.5$ and $\Delta\Phi = 0$.





OPTICAL REFLECTIVITY by the MIRROR - BEC



INSET
D_A^*
k_A
PBS
BS
D_A
ALICE
D_A^*
D_A
SM
PBS
PS
λ/4
λ/2
k_A
k_P
C1
k_B
λ/2
PBS
k'_P
DM
k_B
C2
DM
SM
BOB
P_B^*
L_B^*
OF
L_B
λ/4
λ/2
PBS
P_B
Coincidence Box


USCITA DI
EMERGENZA

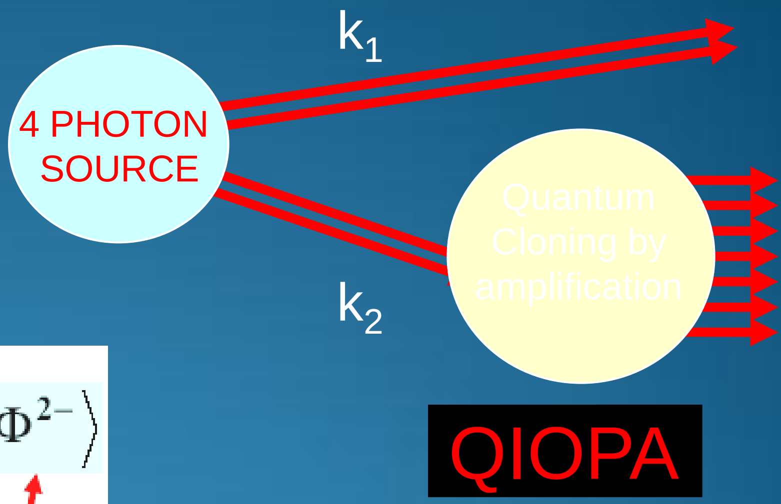
ALLOSTERIC transitions, i.e. conformational changes of proteins conditioned to the binding of a ligand molecule at a specific site, play a key role in bio-molecular processes, e.g. in the regulation of enzyme activity, in motor proteins and ion transport through membranes.

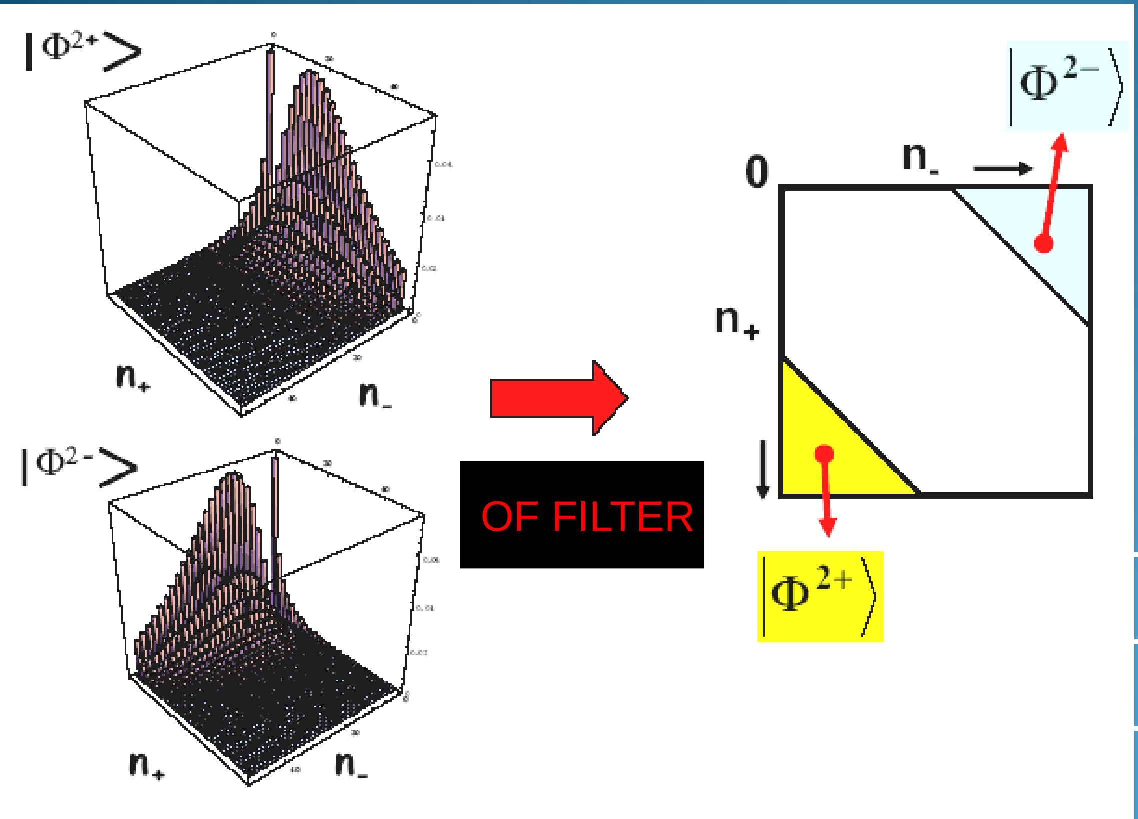
Somewhat related to:

ISOMERIC transformation of retinal in rhodopsin where the conformational change is not brought about by the asdorption of a ligand molecule but by the absorption of a photon.

Amplification of a spin-1 singlet state

Better discrimination with 2-photon amplification than with 1-photon amplification



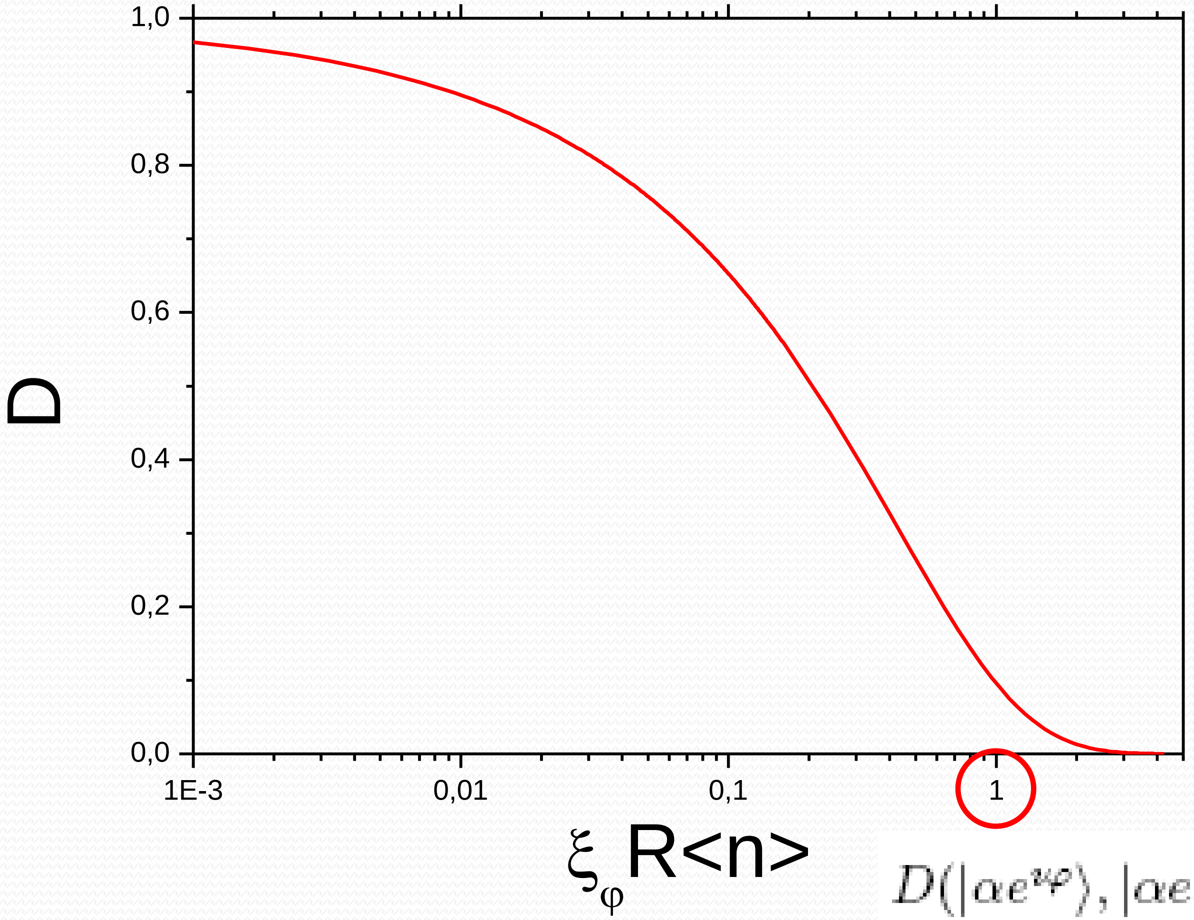


PROBABILISTIC DISCRIMINATION OF OUTPUT WAVEFUNCTION

- $I_+ >> I_-$ $\Rightarrow$ detection of $|\Phi^{2+}\rangle$
- $I_- >> I_+$ $\Rightarrow$ detection of $|\Phi^{2-}\rangle$
- $I_+ \sim I_-$ $\Rightarrow$ data discarded

$$|\varphi\rangle = \mathcal{N}\frac{1}{\sqrt{2}}\left(|\alpha e^{\imath\varphi}\rangle \pm |\alpha e^{-\imath\varphi}\rangle\right) \Rightarrow \mathcal{N}\frac{1}{\sqrt{2}}\left(|\alpha\rangle \pm |-\alpha\rangle\right)$$

$\varphi=\pi/2$



$$\xi_\varphi = \left(\frac{d_\varphi}{d_{\frac{\pi}{2}}}\right)^2 = \sin^2\varphi$$

$$(\xi_\varphi)_{min} = \sin^2\frac{1}{|\alpha|} \sim \frac{1}{\langle n\rangle}$$

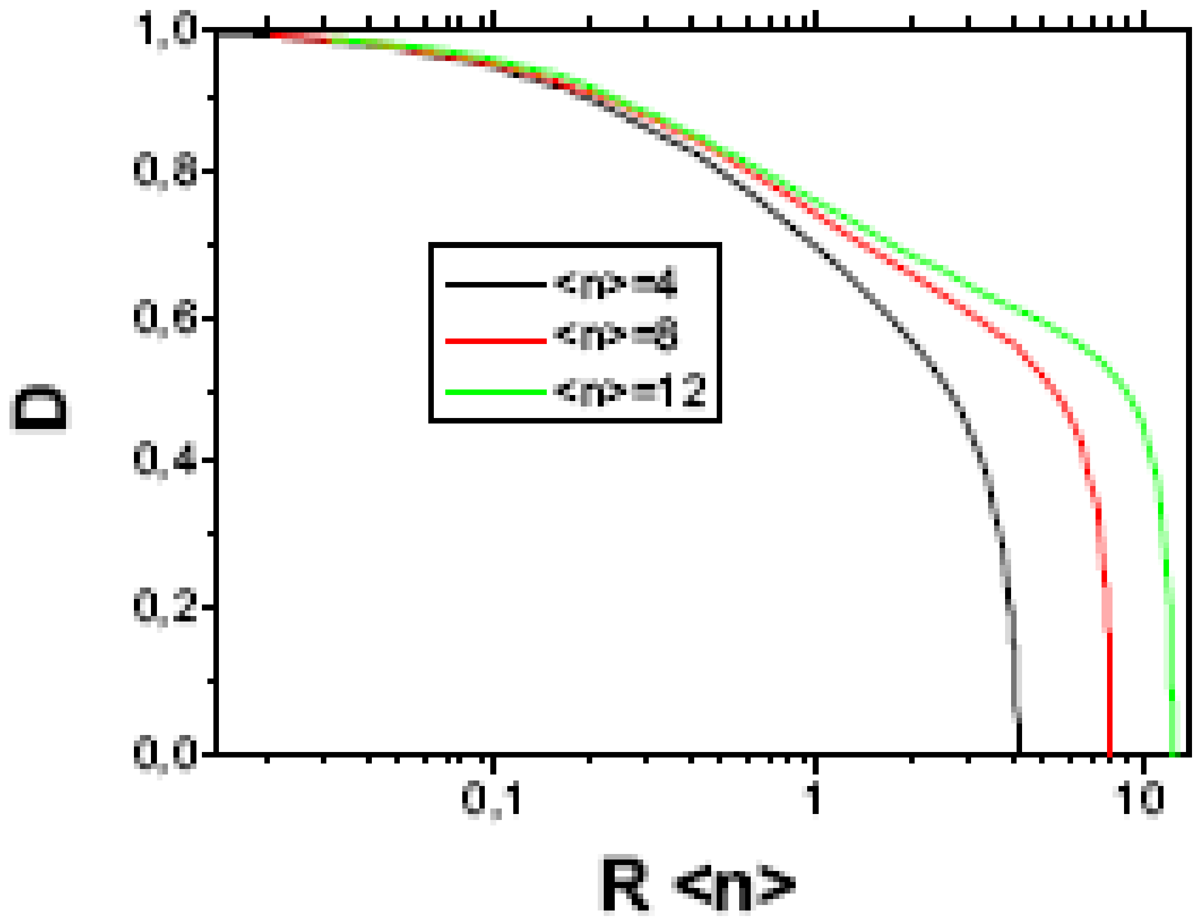
FOR ANY <n> and φ!

$$D(|\alpha e^{\imath\varphi}\rangle, |\alpha e^{-\imath\varphi}\rangle) = \sqrt{1 - e^{-2T|\alpha|^2\sin^2\varphi}}$$

$$D(|\phi_\varphi^+\rangle, |\phi_\varphi^-\rangle) = \sqrt{1 - \sqrt{1 - e^{-4R|\alpha|^2\sin^2\varphi}}}.$$

D: UNIVERSAL FUNCTION FOR COHERENT - STATE MACRO-QUBITS

Decoherence of QI-OPA Macroscopic Quantum Superposition



Equatorial z-plane for Collinear QI-OPA: PHASE - COVARIANT CLONING

$$\varphi = 0; \; |+\rangle_A = \left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right)$$

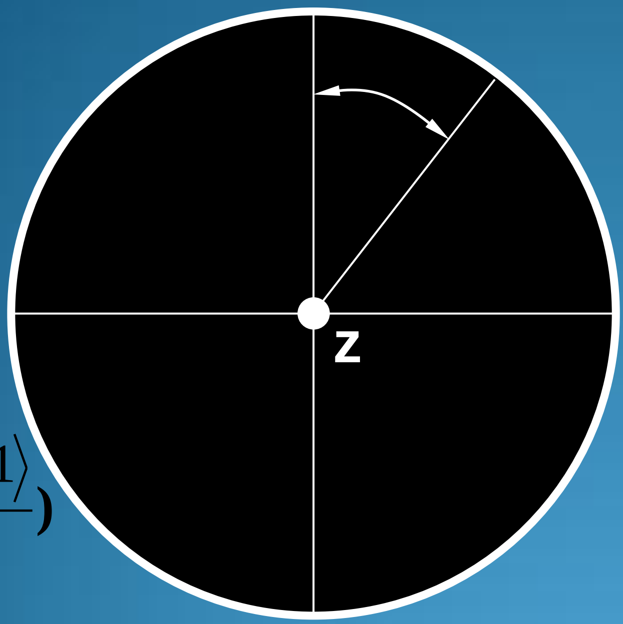
Input qubit:

$$\frac{|0\rangle + e^{i\varphi}|1\rangle}{\sqrt{2}} = \hat{U}_Z \frac{|0\rangle + |1\rangle}{\sqrt{2}}$$

with: $\hat{U}_Z = e^{i\frac{\varphi}{2}\hat{\sigma}Z}$

$$\varphi = \frac{3\pi}{2}$$

$$|\mathbf{L}\rangle = \left(\frac{|0\rangle - i|1\rangle}{\sqrt{2}}\right)$$



$$\varphi = \frac{\pi}{2}$$

$$|\mathbf{R}\rangle = \left(\frac{|0\rangle + i|1\rangle}{\sqrt{2}}\right)$$

$$\varphi = \pi; \; |-\rangle = \left(\frac{|0\rangle - |1\rangle}{\sqrt{2}}\right)$$

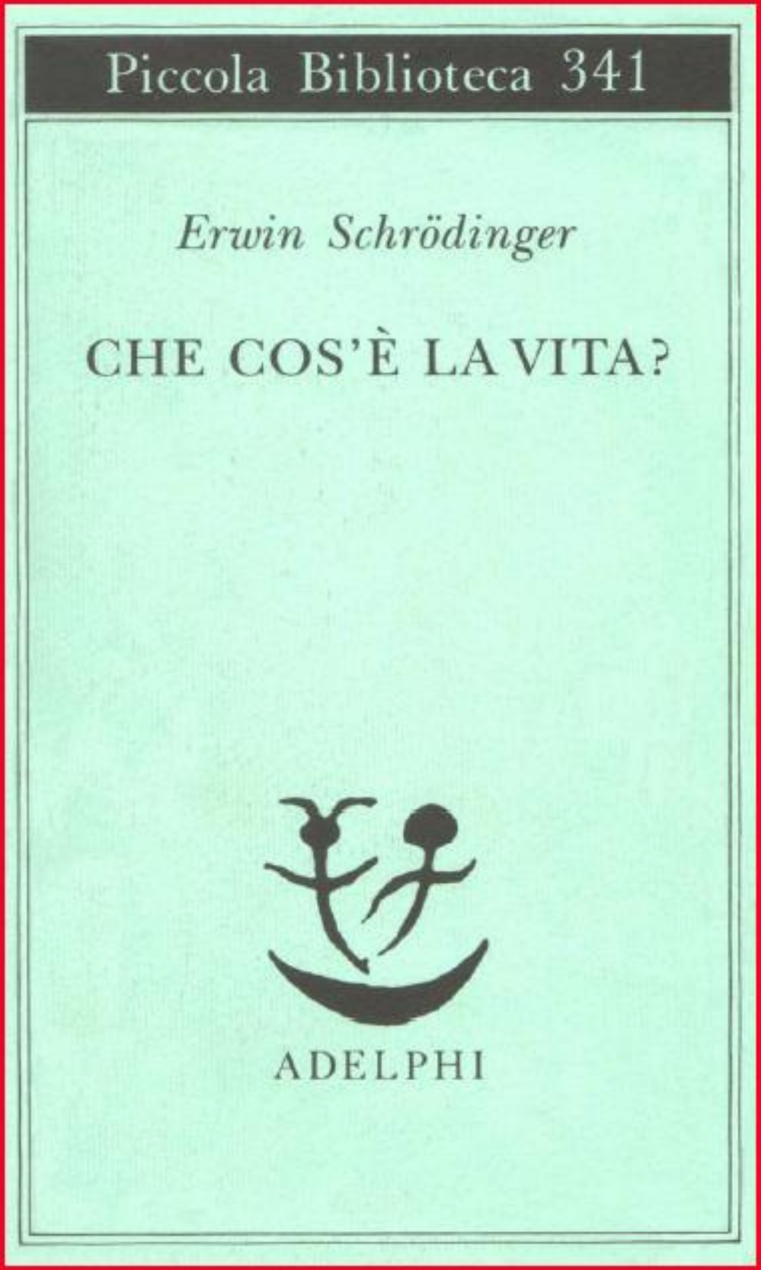
REPLY TO EINSTEIN:

NO quantum-Classical incompatibility

SINCE IN THE QI-OPA CASE
MICRO-WORLD MIRRORED INTO THE MACRO-WORLD
BY THE UNITARY CLONING TRANSFORMATION **U**:

$$2^{-1/2}(|\Phi_1\rangle + |\Phi_2\rangle) = U\left[2^{-1/2}(|\phi_1\rangle + |\phi_2\rangle)\right]$$

MACRO MICRO



E. Schrödinger:
"What is life ?"

Trinity College Lectures
Dublin, 1944

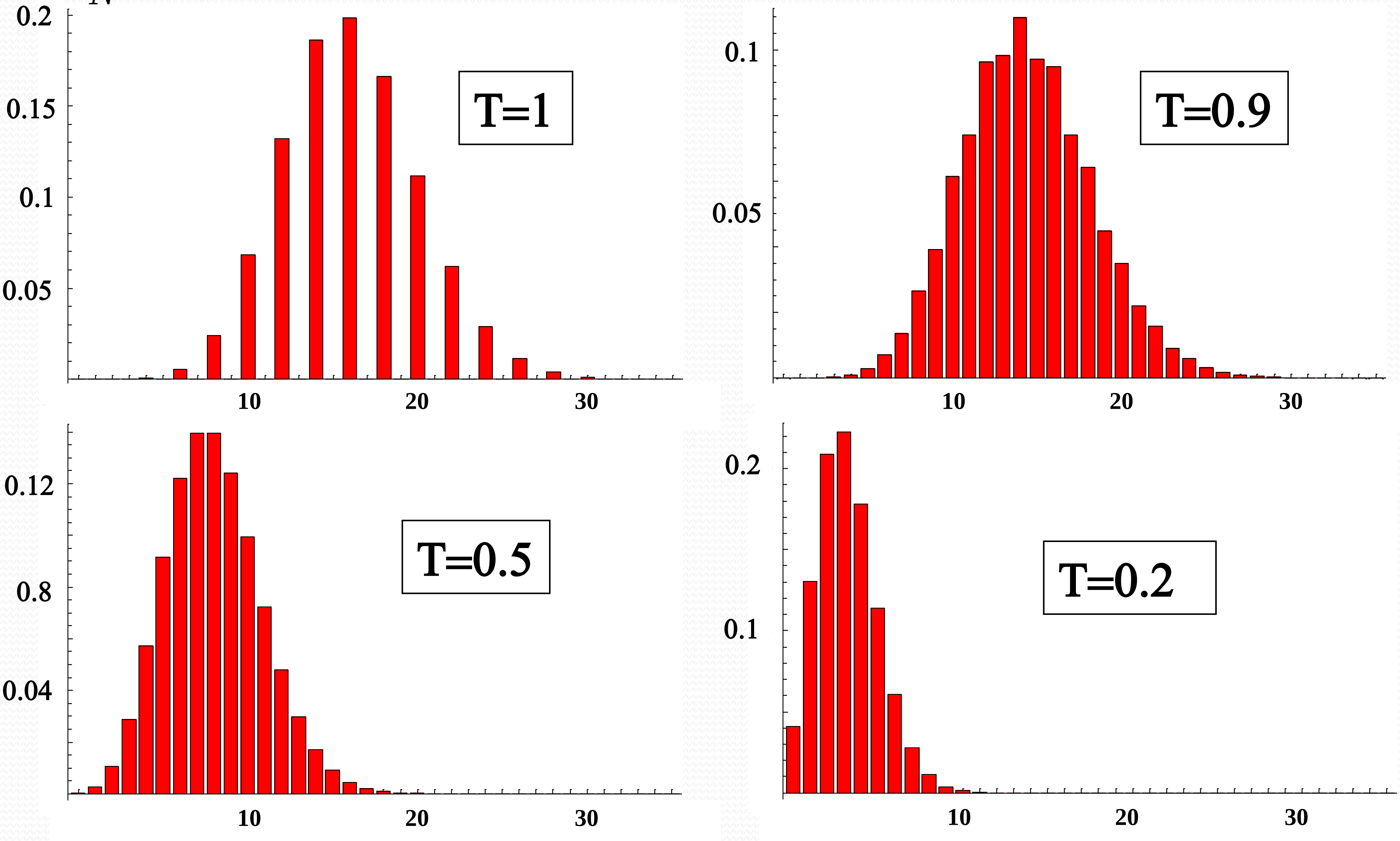
March 1953: Discovery of structure of DNA by:

Rosalind Franklin,
Francis Crick,
James Watson,
Maurice Wilkins

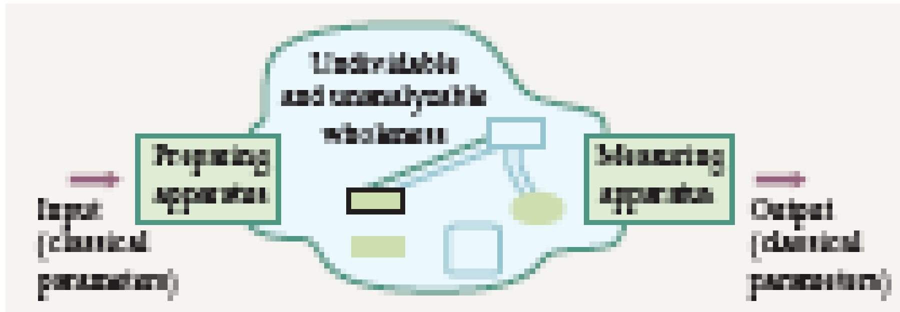
COHERENT - STATE SCHRÖDINGER - CAT

$$\frac{1}{N}\left(|\alpha\rangle + |-\alpha\rangle\right)$$

<n>=16

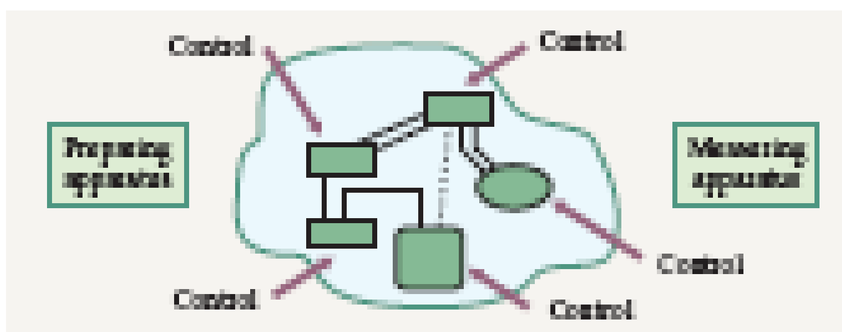


TERMODINAMIC SYSTEM



(Out of control decoherence: e.g. E.N.S. MQS)

QUANTUM COMPUTER



(Control and Error-correction: e.g. QI-OPA MQS, living systems)

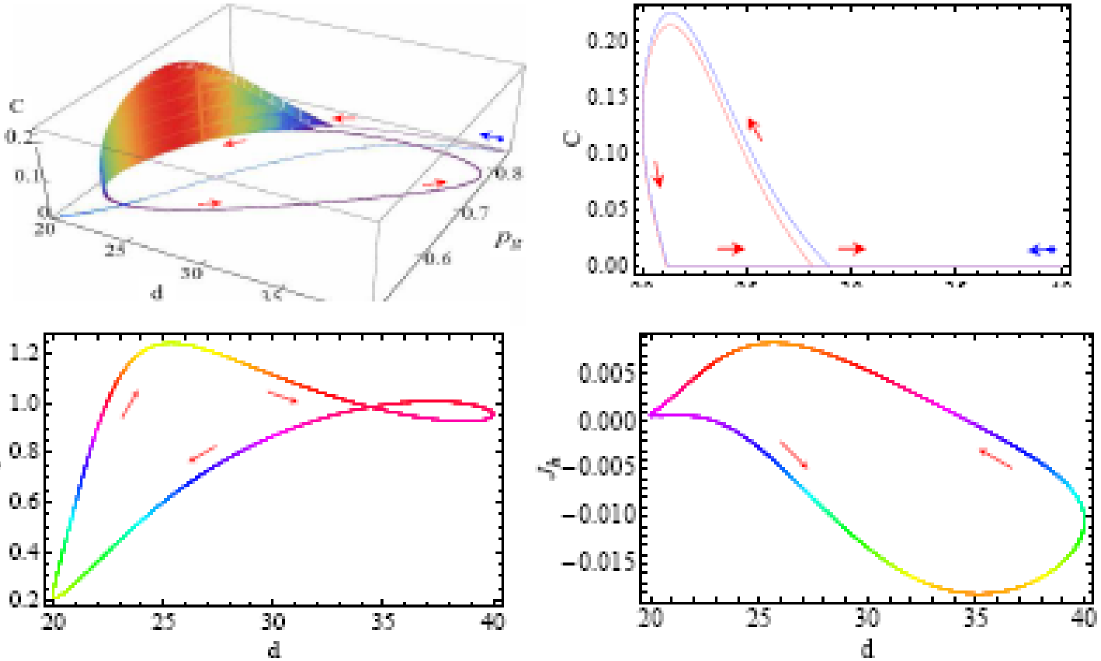


FIG. 3: (Color online) Upper plots: Ground state population p_g and dynamic entanglement C *vs.* the molecular configuration characterized by the relative distance d of spins for the bosonic heat bath with the temperature $T = 1$ and $\kappa = 0.01$. The blue curve (left) represents the thermal equilibrium state at each molecular configuration. The red curve (right) marks the limit cycle. Lower plots: Spectral temperature T_s and heat current J_h *vs.* d on the limit cycle. The blue dot and arrow indicate the starting point and direction of motion. The oscillation parameters are $x_1(0) = -x_2(0) = -20$, $a = 5$, $\tau = 100$, and $B_0 = 1.3$, $B_1 = 2.4$, $\sigma = 120$, $J_0 = 1 \times 10^4$ (see Eq. (5) and the text thereafter).

C: entanglement "concurrence" (W.K.Wootters, PRL 80, 2245 (1998)

Environment-Assisted Quantum Walks in Photosynthetic Energy Transfer

Masoud Mohseni,[1] Patrick Rebentrost,[1] Seth Lloyd,[2] and Alán Aspuru-Guzik[1]

[1]*Department of Chemistry and Chemical Biology, Harvard University, 12 Oxford St., Cambridge, MA 02138*
[2]*Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge MA 02139*

(Dated: May 23, 2008)

Energy transfer within photosynthetic systems can display quantum effects such as delocalized excitonic transport. Recently, direct evidence of long-lived coherence has been experimentally demonstrated for the dynamics of the Fenna-Matthews-Olson (FMO) protein complex [Engel *et al.*, Nature 446, 782 (2007)]. However, the relevance of quantum dynamical processes to the exciton transfer efficiency is to a large extent unknown. Here, we develop a theoretical framework for studying the role of quantum interference effects in energy transfer dynamics of molecular arrays interacting with a thermal bath within the Lindblad formalism. To this end, we generalize continuous-time quantum walks to non-unitary and temperature-dependent dynamics in Liouville space derived from a microscopic Hamiltonian. Different physical effects of coherence and decoherence processes are explored via a universal measure for the energy transfer efficiency and its susceptibility. In particular, we demonstrate that for the FMO complex an effective interplay between free Hamiltonian and thermal fluctuations in the environment leads to a substantial increase in energy transfer efficiency from about 70% to 99%.

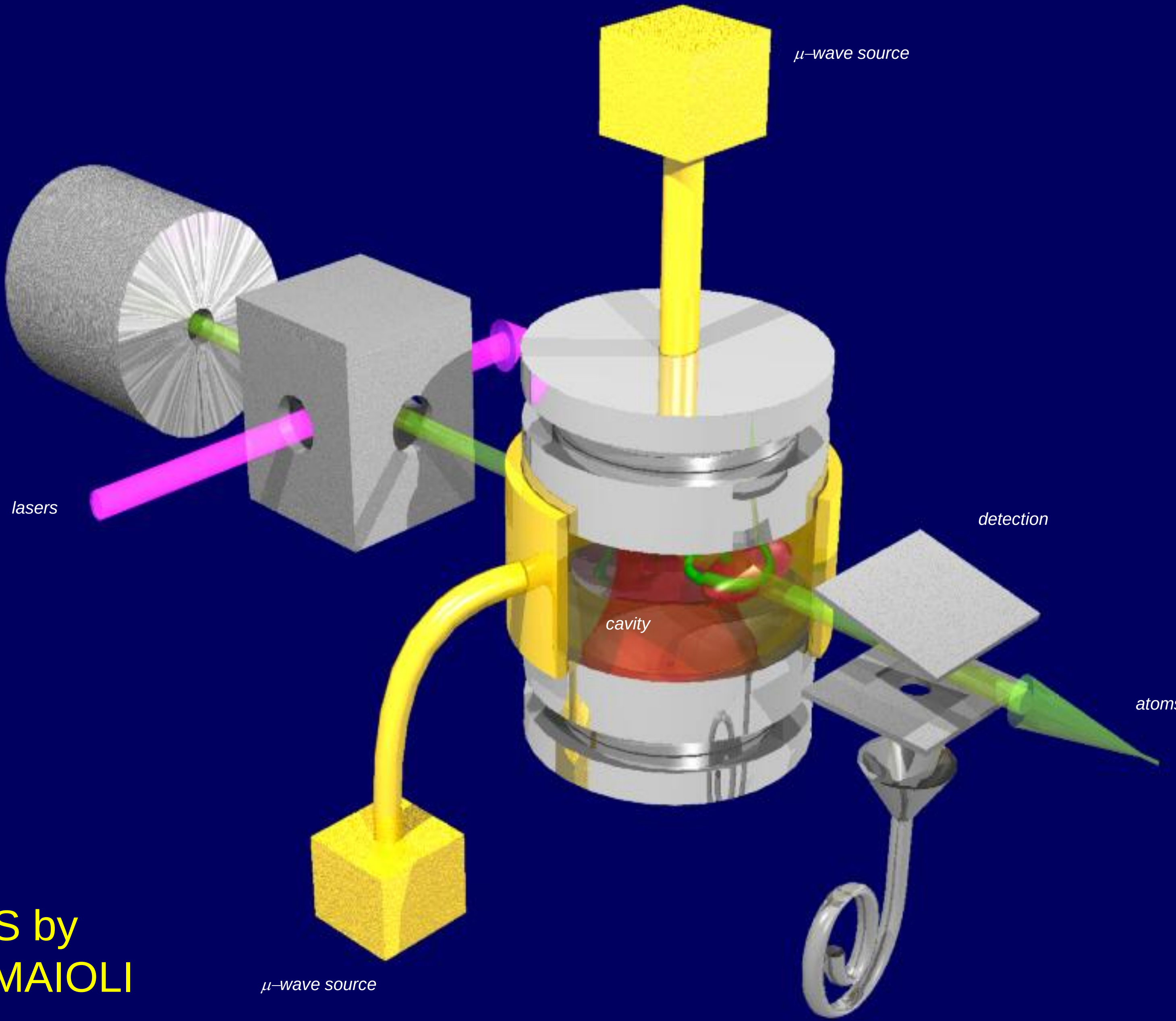
Recent decades have taught us that physics is
a magic window. It shows us the illusion that lies
behind reality - and the reality that lies behind illusion.

Its scope is immensely greater than we once realized.

We are no longher satisfied with insights into particles,
or fields of force, or geometry, or even space and time.

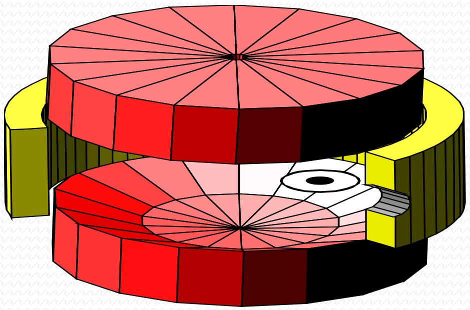
Today we demand of physics some understanding
of existence itself….

J.A.Wheeler, “Law without law” (1980).

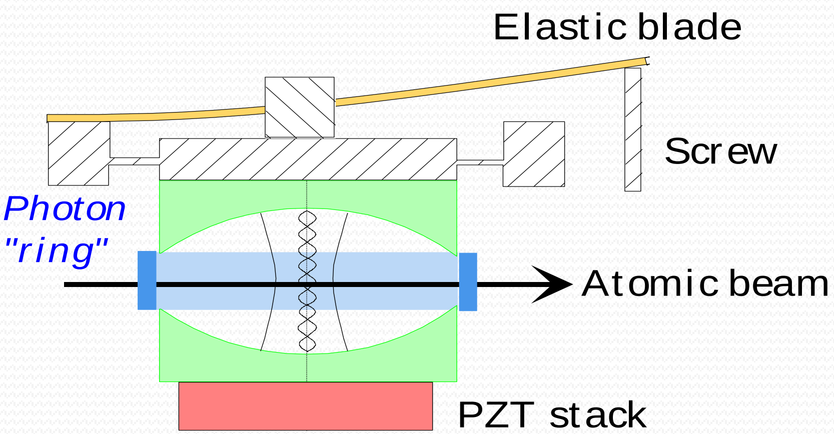


2 SLIDES by
PAOLO MAIOLI
E.N.S. 2004

Superconducting cavity

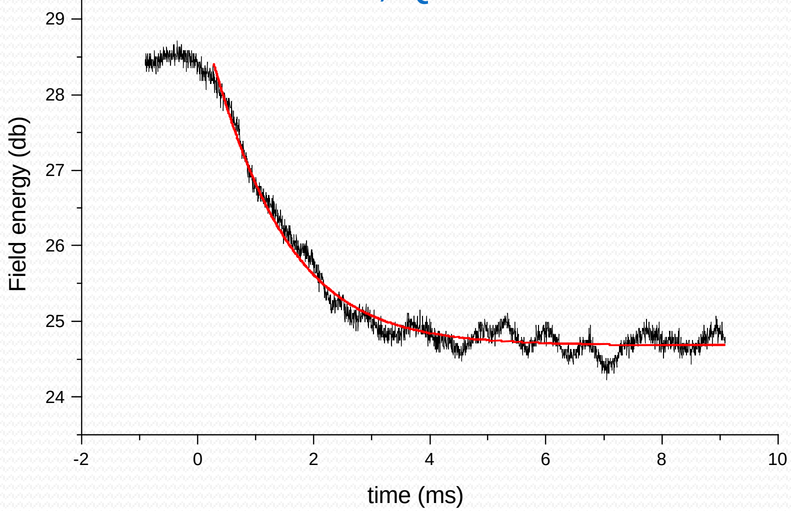


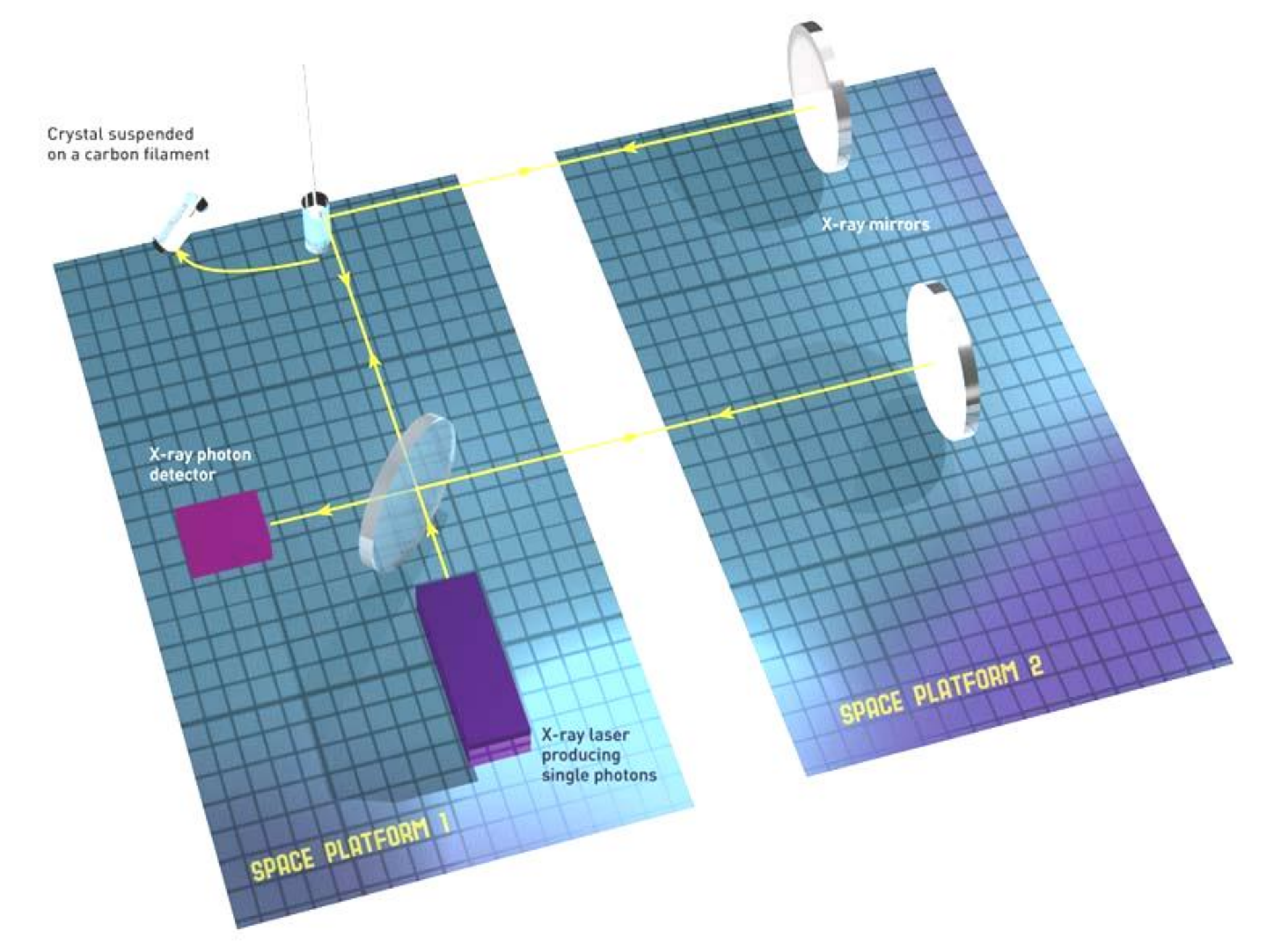
- Open Fabry Perot cavity with a photon "recirculation" ring
- Compatible with a static electric field (circular states stability and Stark tuning)

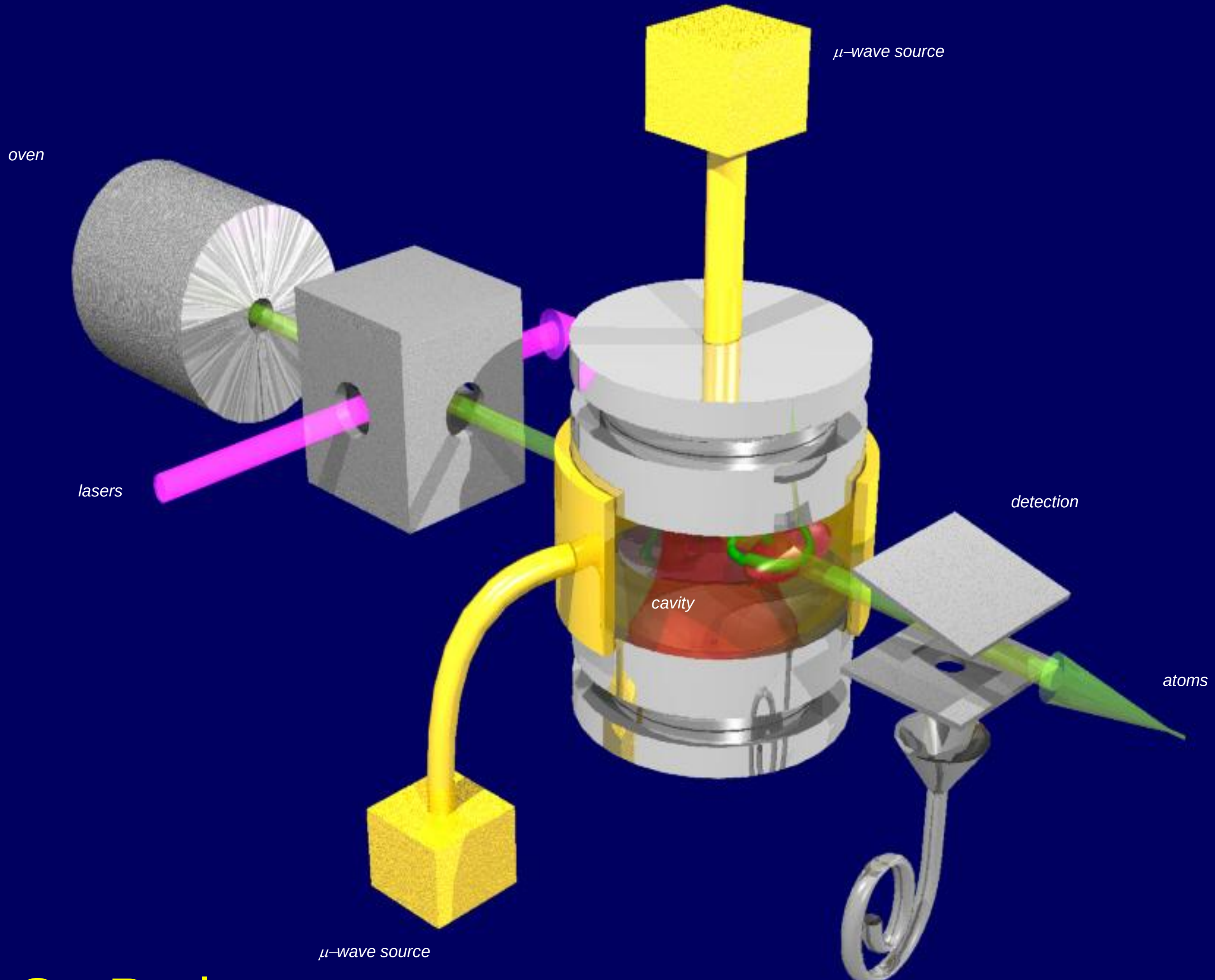


Polished Niobium mirrors

Lifetime: 1 ms ; Q = 3 x 10^8




Crystal suspended
on a carbon filament
X-ray mirrors
X-ray photon
detector
X-ray laser
producing
single photons
SPACE PLATFORM 1
SPACE PLATFORM 2



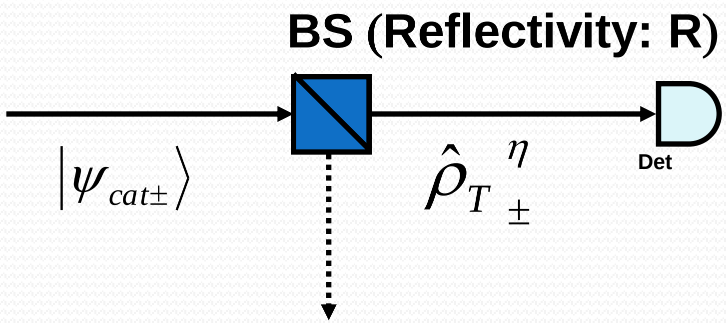
E.N.S.- Paris 2004

O-Filter: “local”Noise Reduction process counteracting the deterimental effects of the quantum no-cloning theorem due the QI-OPA

DECOHERENCE OF MACROSCOPIC SUPERPOSITIONS

(1) Coherent cat states

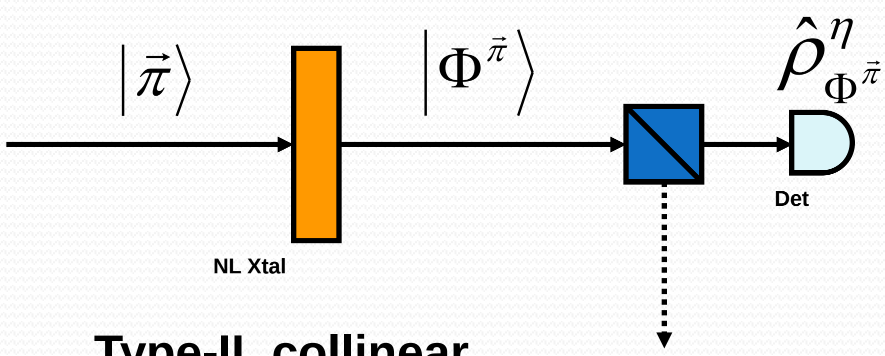
(R+T=1)



$$\left|\Phi_\alpha\right\rangle = N\frac{1}{\sqrt{2}}\left(\left|\alpha\right\rangle \pm \left|-\alpha\right\rangle\right)$$

$$\rho_T \equiv tr_R(\rho_{in})$$

(2) QIOPA amplified states



Type-II, collinear

$$\left|\vec{\pi}\right\rangle = \alpha\left|H\right\rangle + \beta\left|V\right\rangle$$

amplification process

$$\left|\Phi^{\vec{\pi}}\right\rangle = \hat{U}\left|\vec{\pi}\right\rangle$$

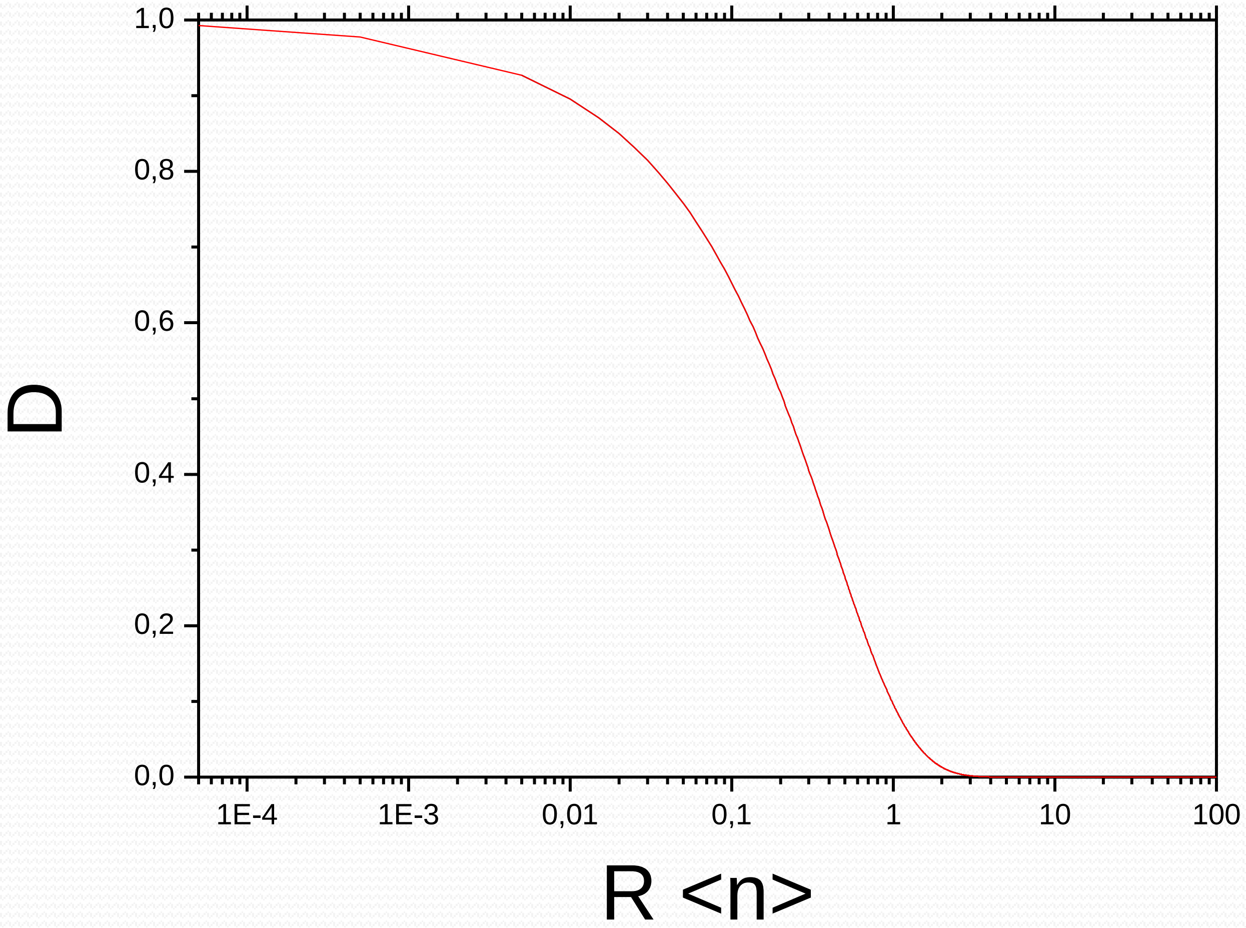
Two possible choices:

- H,V basis: $\left|H\right\rangle \left|V\right\rangle$
- equatorial qubit: $\left|\varphi\right\rangle = \frac{1}{\sqrt{2}}\left(\left|H\right\rangle + e^{i\varphi}\left|V\right\rangle\right)$

QUANTUM SUPERPOSITION OF COHERENT STATES THROUGH A LOSSY CHANNEL: analytical solution

Quantum superposition of coherent states:

$$|\psi\rangle = \frac{N}{\sqrt{2}}\left(|\alpha\rangle \pm |-\alpha\rangle\right)$$

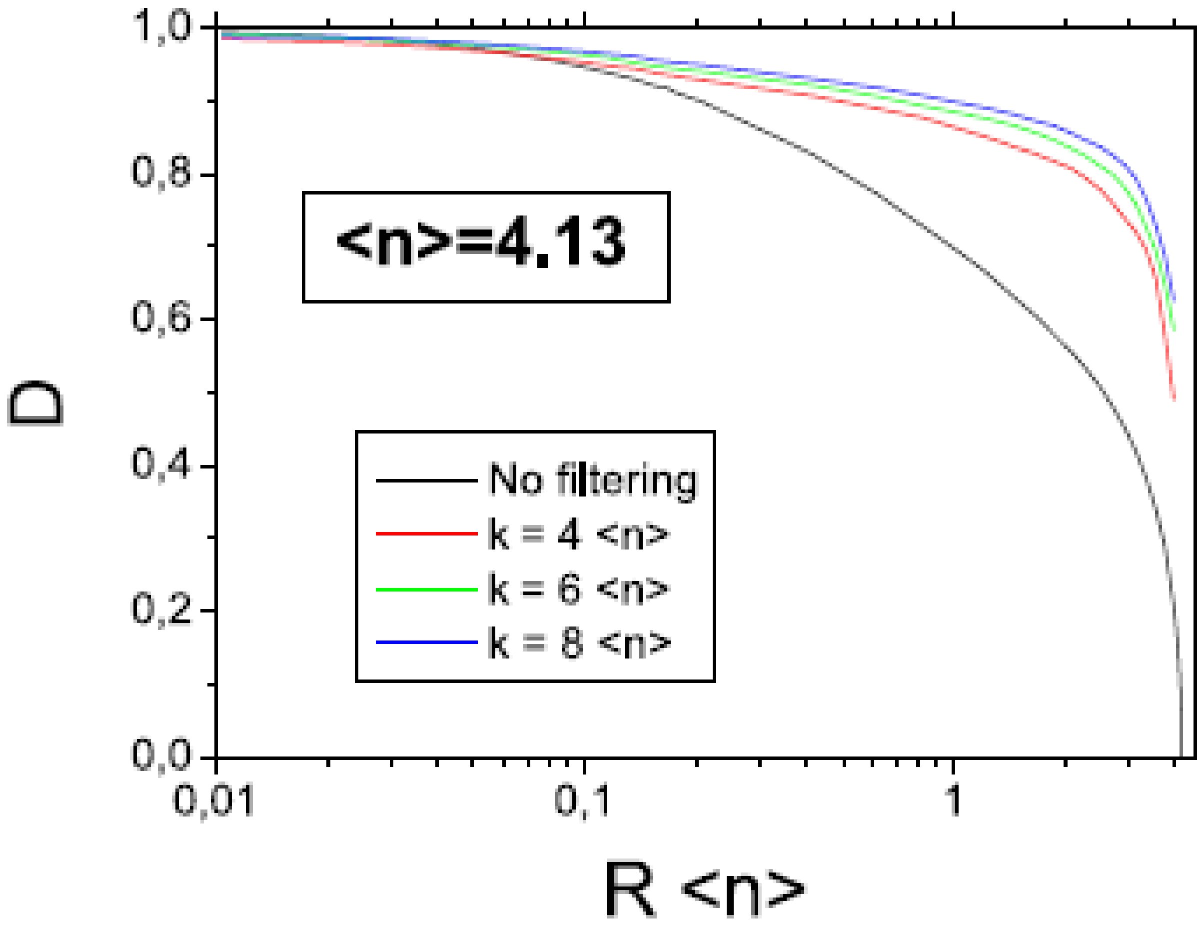


Bures distance:

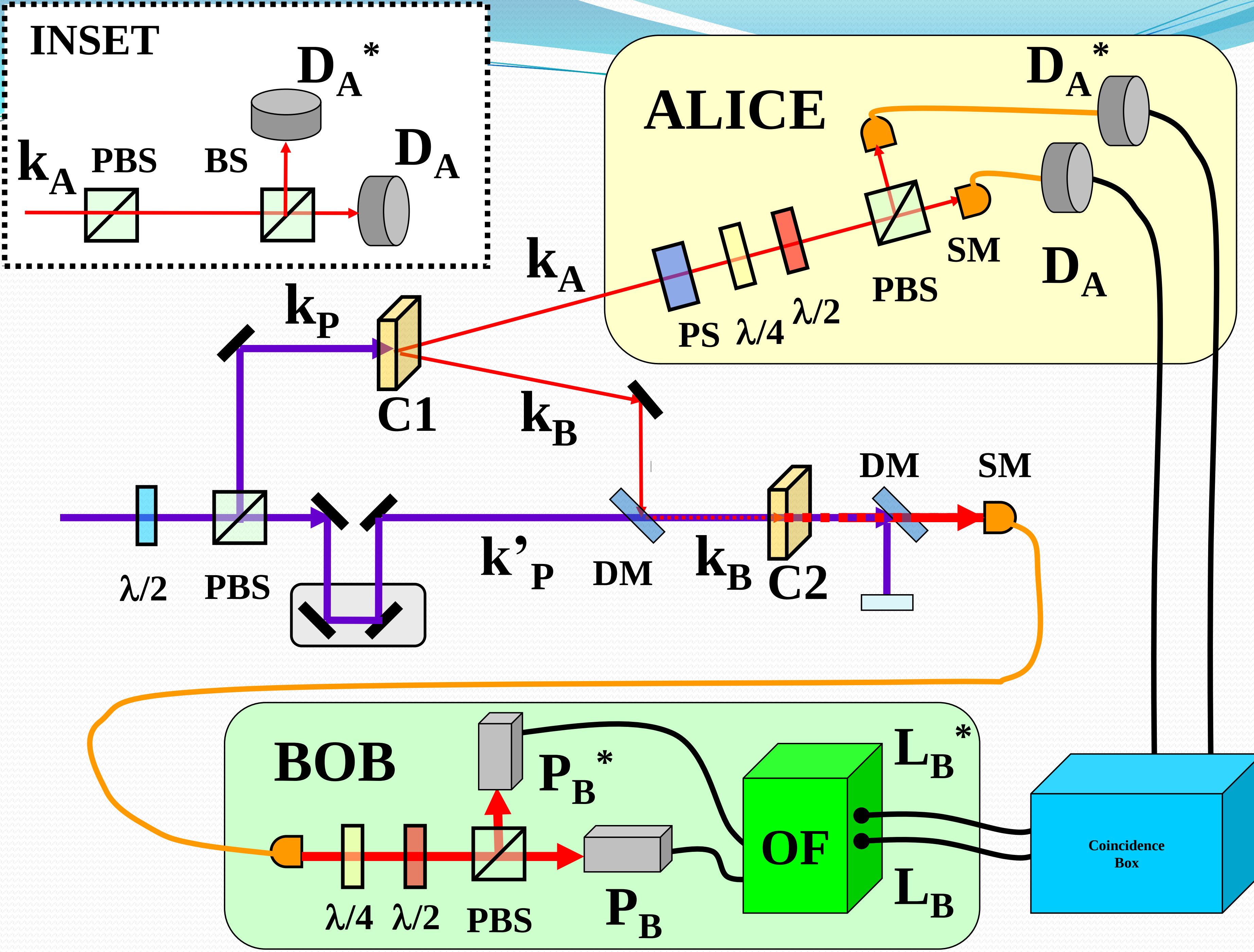
$$D = \sqrt{1-\sqrt{1-e^{-4R|\alpha|^2}}}$$

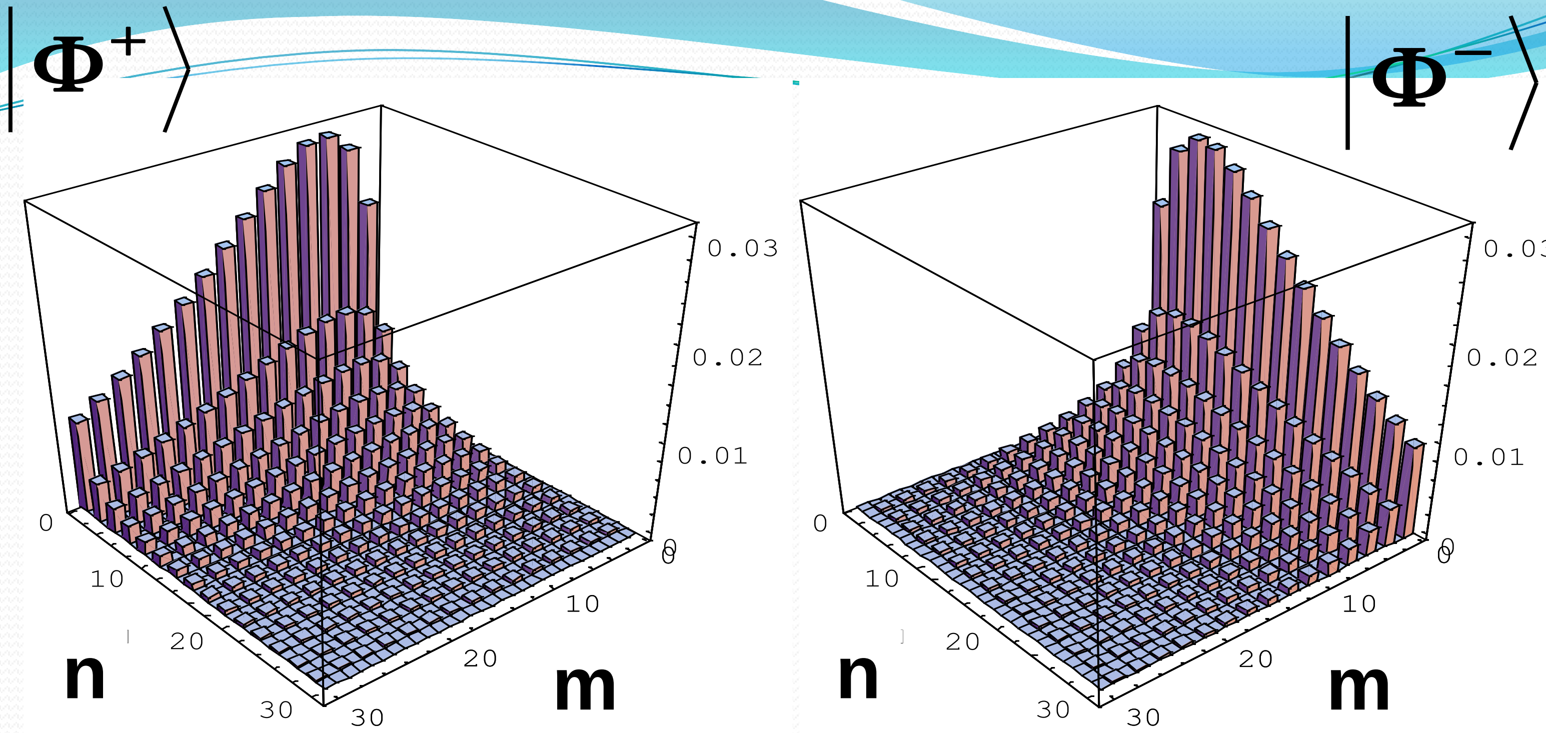
Depends **only** on the number of reflected (**lost**) photons: R<n>

→ for any <n>!



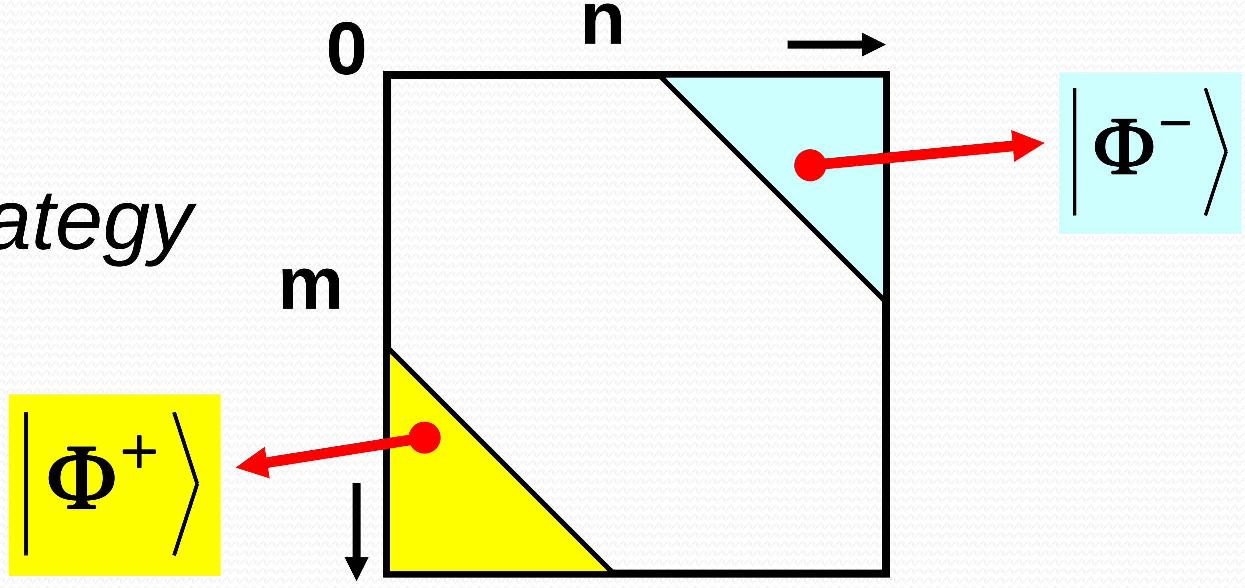
<n>=4.13
No filtering
k = 4 <n>
k = 6 <n>
k = 8 <n>
D
R <n>
1,0
0,8
0,6
0,4
0,2
0,0
0,01
0,1
1


INSET
D_A^*
k_A
PBS
BS
D_A
ALICE
D_A^*
k_A
D_A
SM
PBS
PS
λ/4
λ/2
k_P
C1
k_B
DM
SM
λ/2
PBS
k'$_P$
DM
k_B
C2
BOB
P_B^*
L_B^*
OF
L_B
λ/4
λ/2
PBS
P_B
Coincidence
Box



O-Filter :

POVM strategy



THE LOSSY CHANNEL

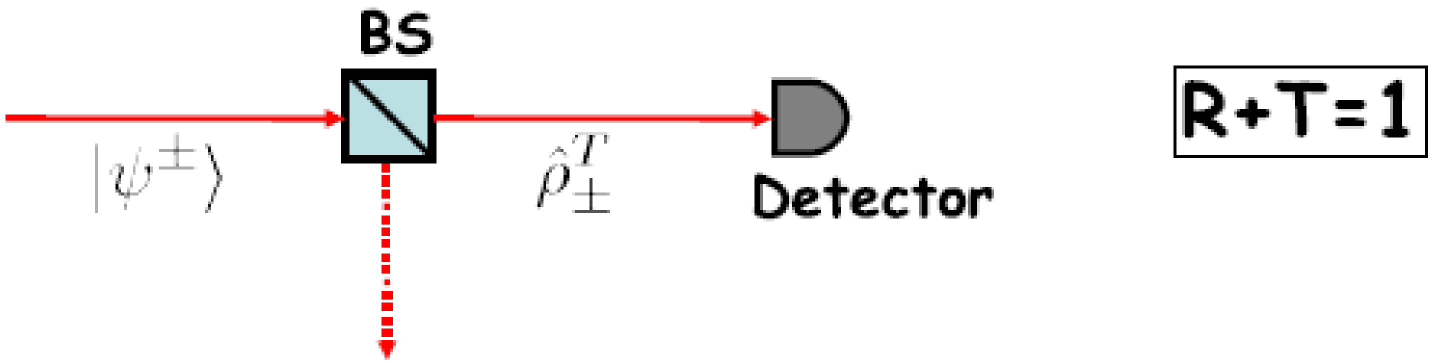
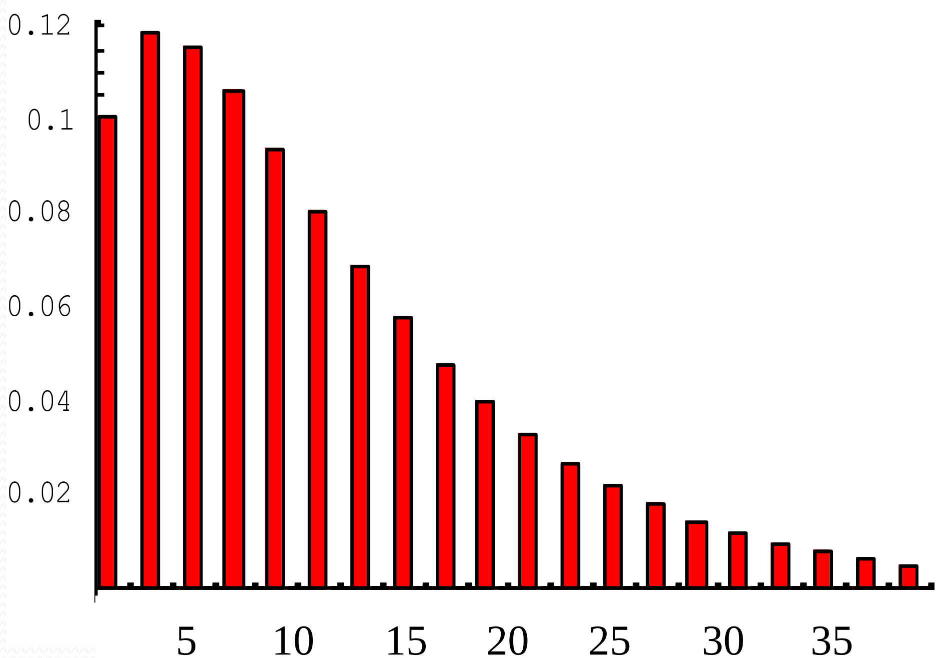
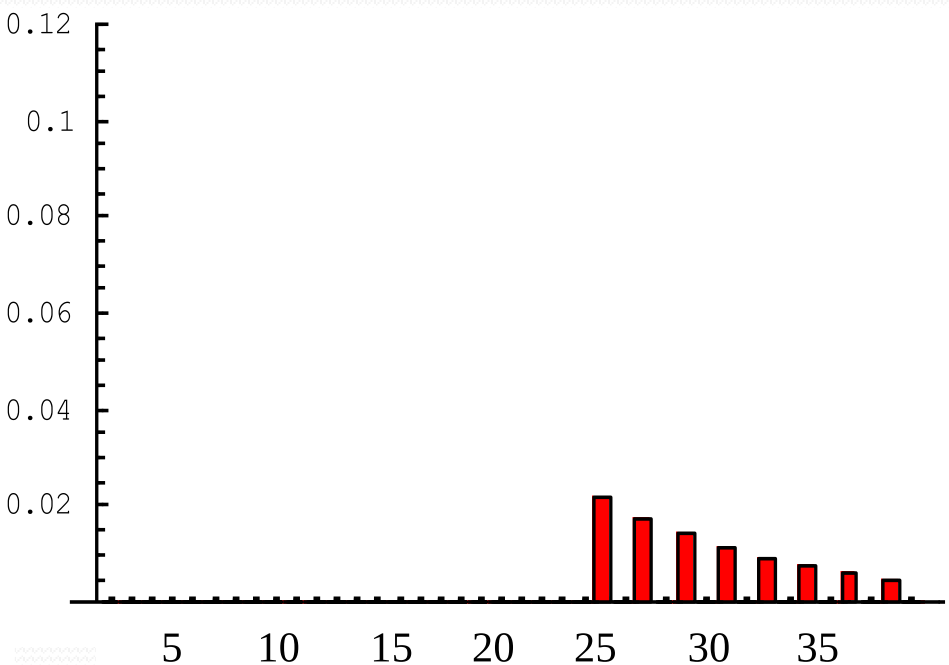


FIG. 1: Schematization of the decoherence model by a linear beam-splitter of transmittivity T.

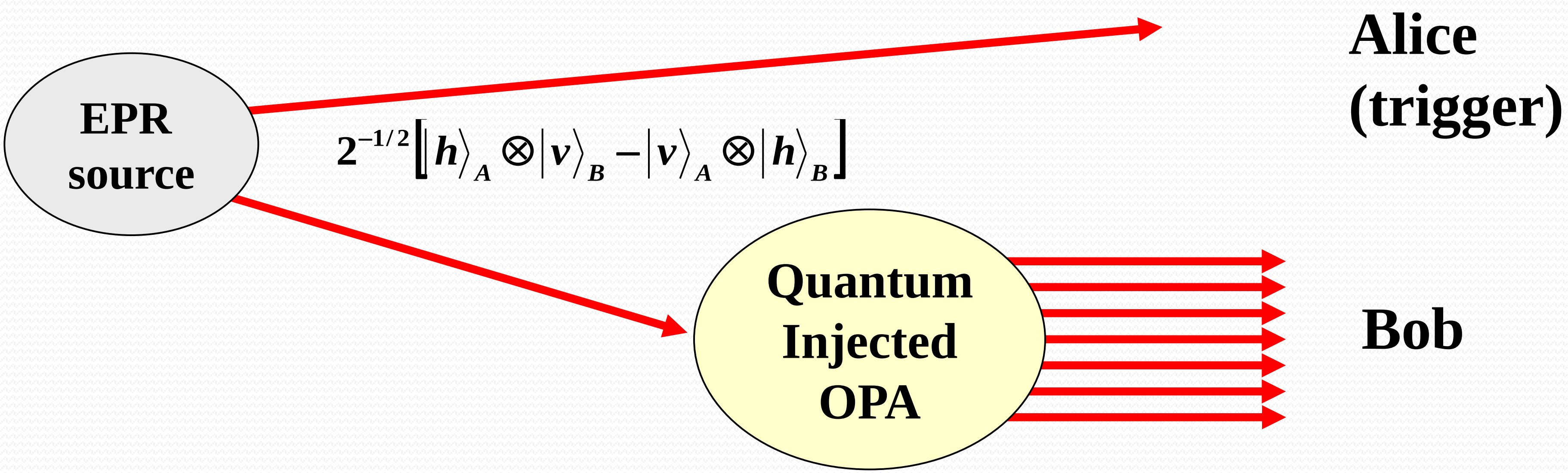
OF - FILTERING OF THE QIOPA GENERATED MACRO STATES

g = 1.4 → <n> = 16





Entanglement between a single photon and a mesoscopic field



$$|\Sigma\rangle = 2^{-1/2}\left[|h\rangle_A \otimes \left|\Phi^V\right\rangle_B - |v\rangle_A \otimes \left|\Phi^H\right\rangle_B\right]:$$

SCHROEDINGER CAT STATE

Phase – Covariant Quantum Cloning (collinear output modes)

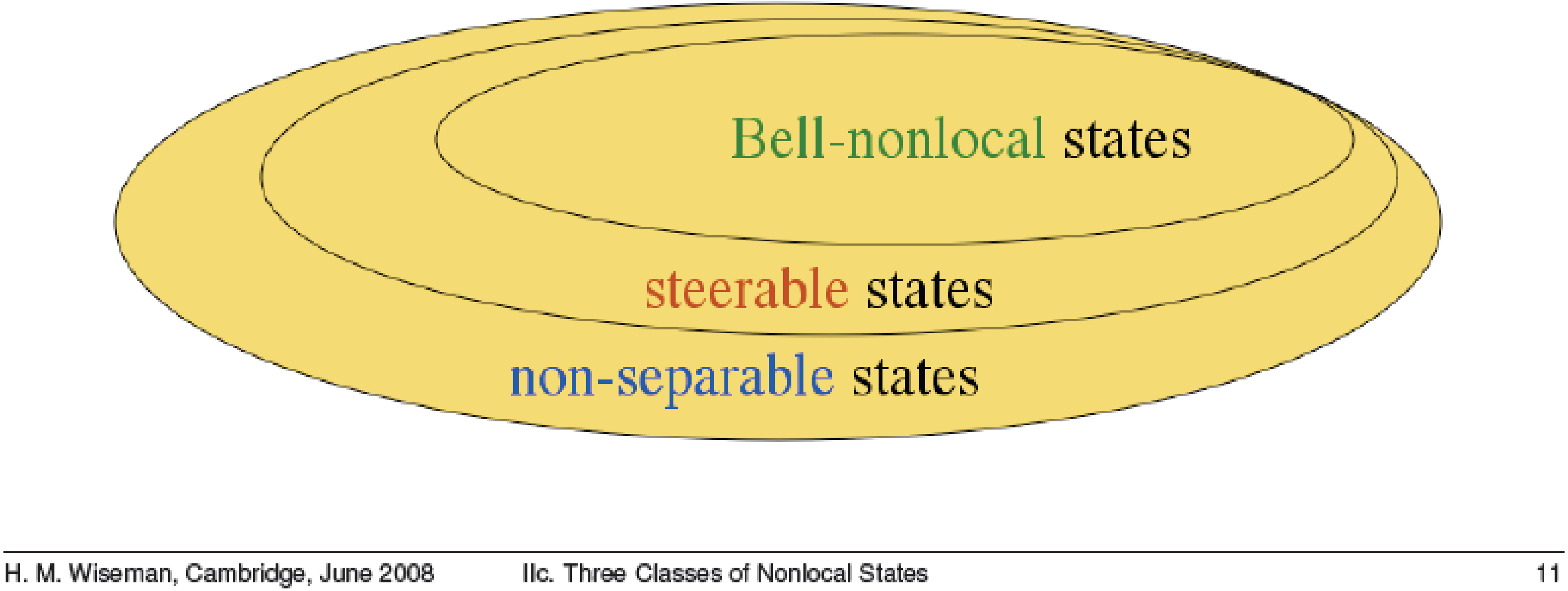
Quantum – Injected OPA Squeezing Hamiltonian:

$$\boldsymbol{H}_{\boldsymbol{int}} = i\hbar\chi\{\hat{a}_{\perp}\hat{a}_{=}\} + \text{h.c.} =$$

$$= i\tfrac{1}{2}\hbar\chi\{\hat{a}_{+}^{2} - \hat{a}_{-}^{2}\} + \text{h.c.} = \tfrac{1}{2}\hbar\chi\{\hat{a}_{R}^{2} - \hat{a}_{L}^{2}\} + \text{h.c.}$$

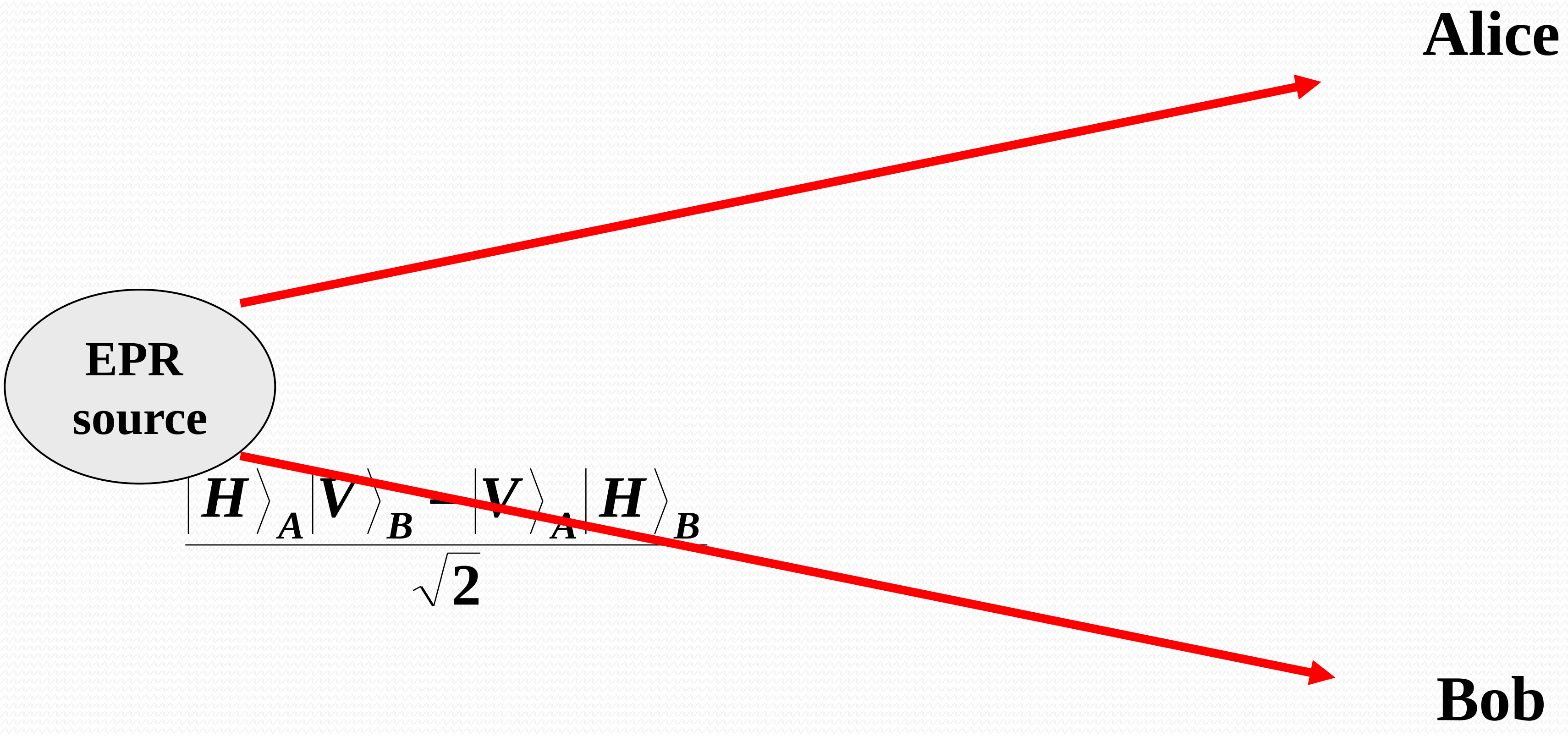
Amplifies equally well qubits SU(1,1) transformed.

$\hat{a}_{\pm} = 2^{-1/2}\{\hat{a}_{\perp} \pm \hat{a}_{=}\}$; $\hat{a}_{R/L} = 2^{-1/2}\{\hat{a}_{\perp} \pm i\,\hat{a}_{=}\}$



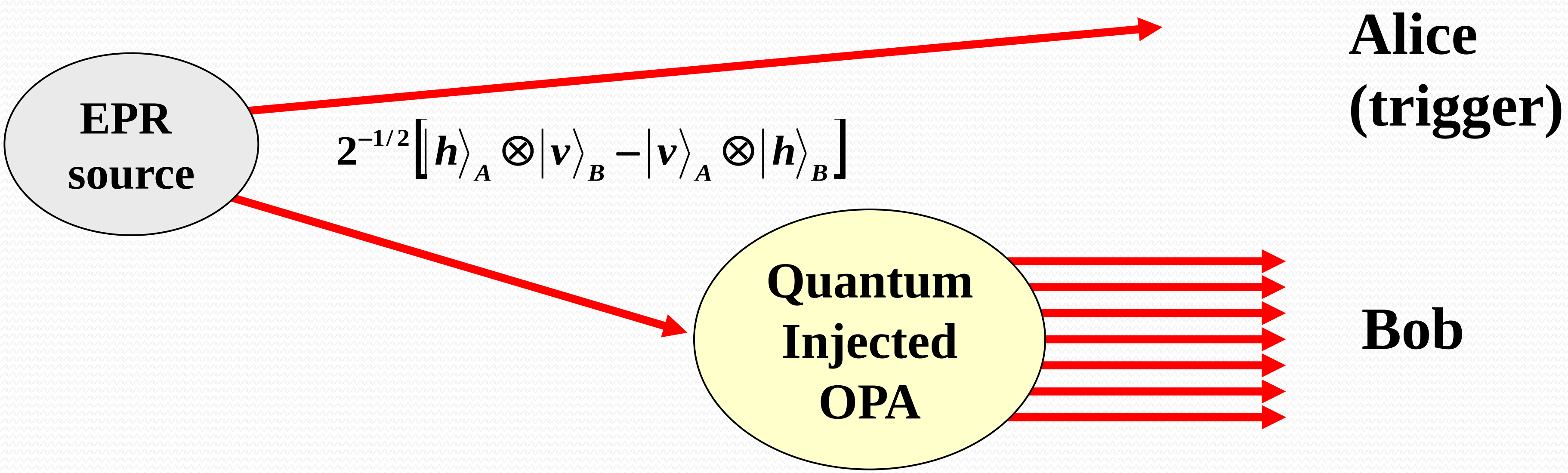
Thanks to: H.M.Wiseman

Entanglement between 2 single photons (EPR, 1935)



$$\frac{|H\rangle_A |V\rangle_B - |V\rangle_A |H\rangle_B}{\sqrt{2}}$$

Entanglement between a single photon and a mesoscopic field (1998-2008)

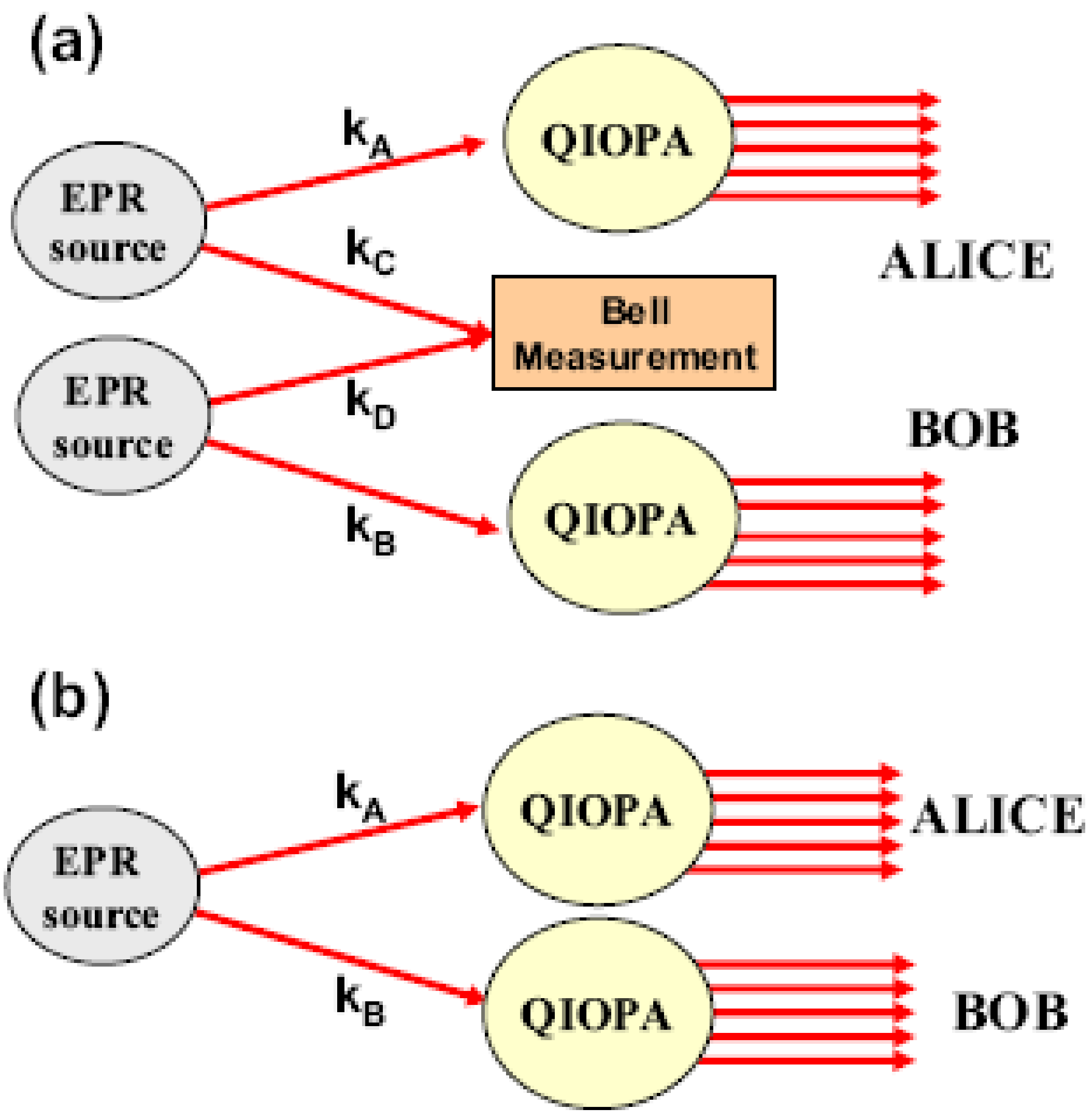


$$2^{-1/2}\left[|h\rangle_A \otimes |v\rangle_B - |v\rangle_A \otimes |h\rangle_B\right]$$

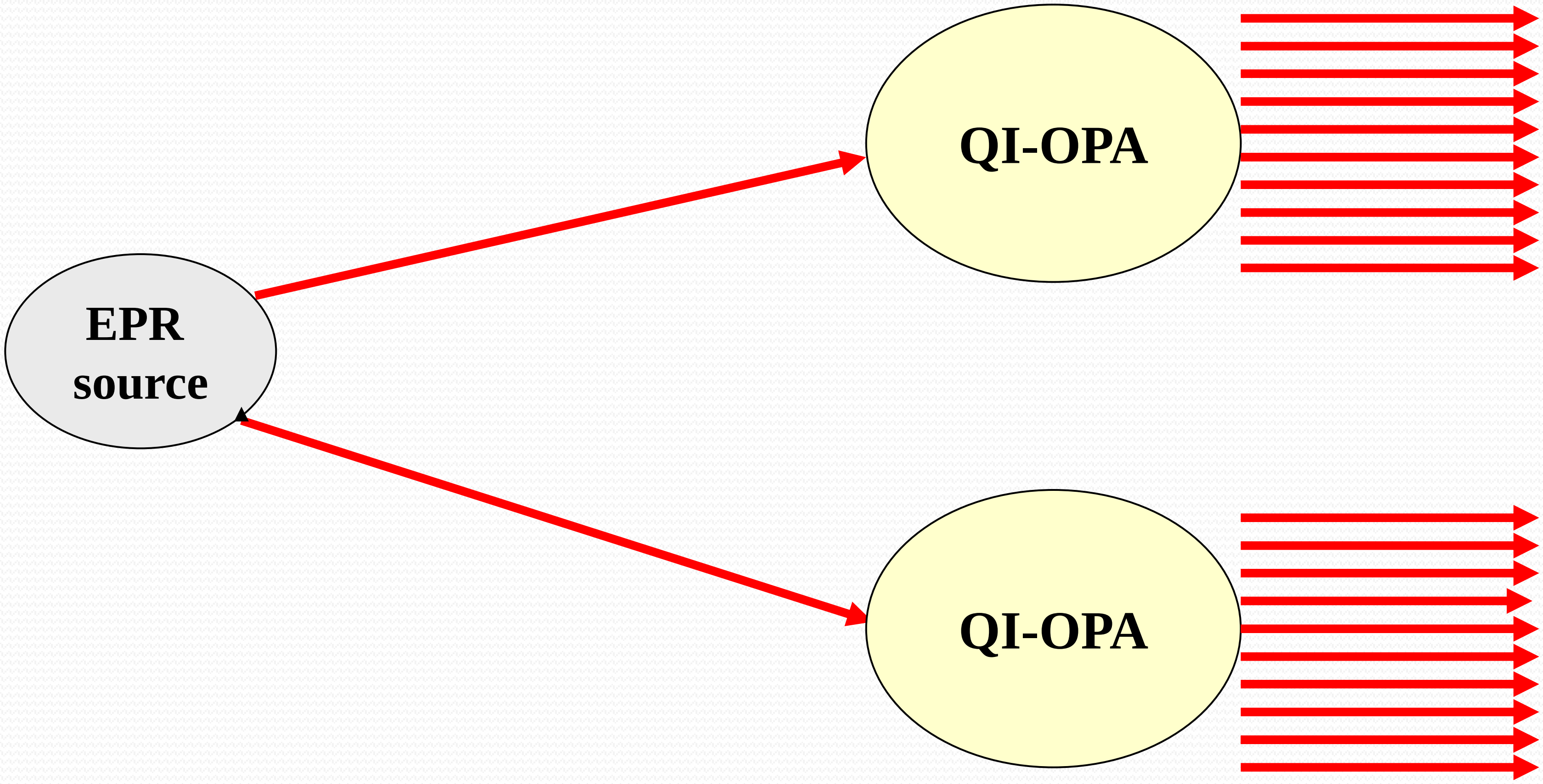
$$|\Sigma\rangle = 2^{-1/2}\left[|h\rangle_A \otimes \left|\Phi^V\right\rangle_B - |v\rangle_A \otimes \left|\Phi^H\right\rangle_B\right]:$$

SCHROEDINGER CAT STATE

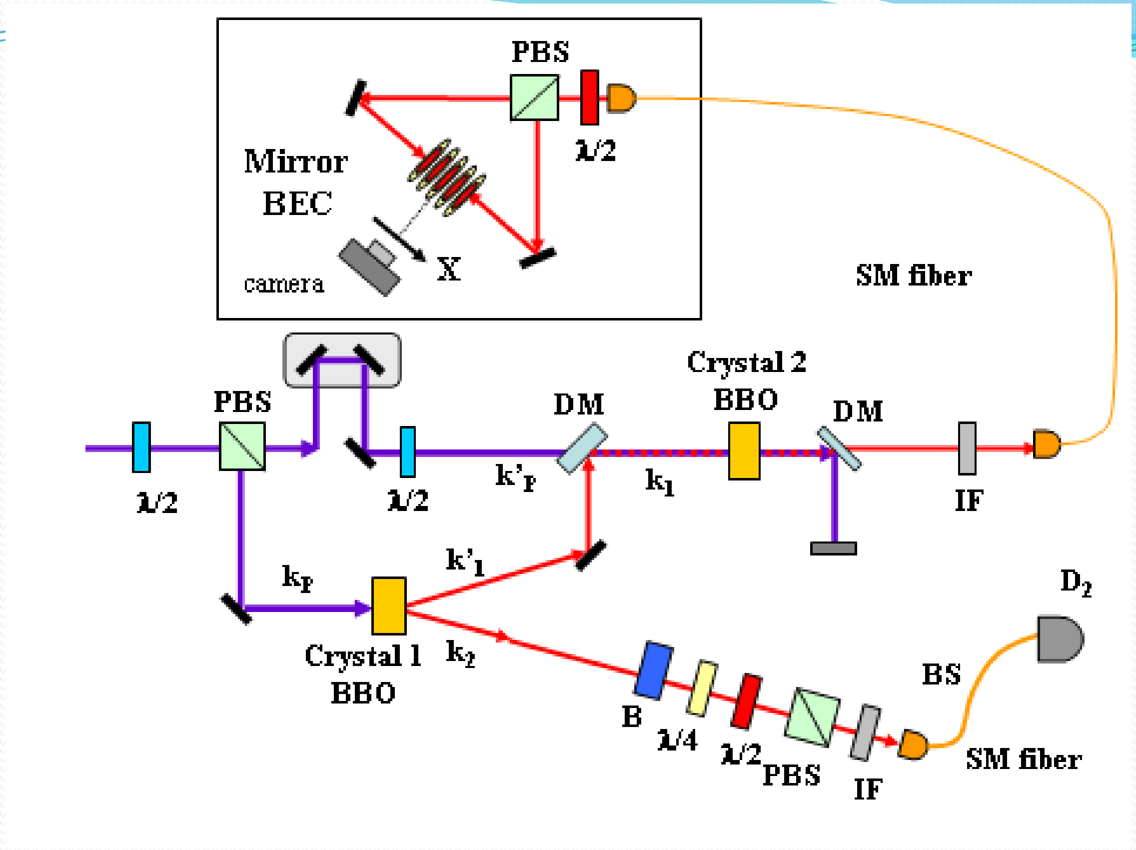
MACRO - MACRO ENTANGLEMENT



Entanglement between 2 mesoscopic fields
MACRO - MACRO CONTEXTUALITY



$$\left|\boldsymbol{\Sigma}\right\rangle = \frac{\left|\boldsymbol{\Theta}\right\rangle_A \otimes \left|\boldsymbol{\Phi}\right\rangle_B - \left|\boldsymbol{\Theta}_\perp\right\rangle_A \otimes \left|\boldsymbol{\Phi}_\perp\right\rangle_B}{\sqrt{2}} \quad : (Macroscopic\ Bell - State)$$

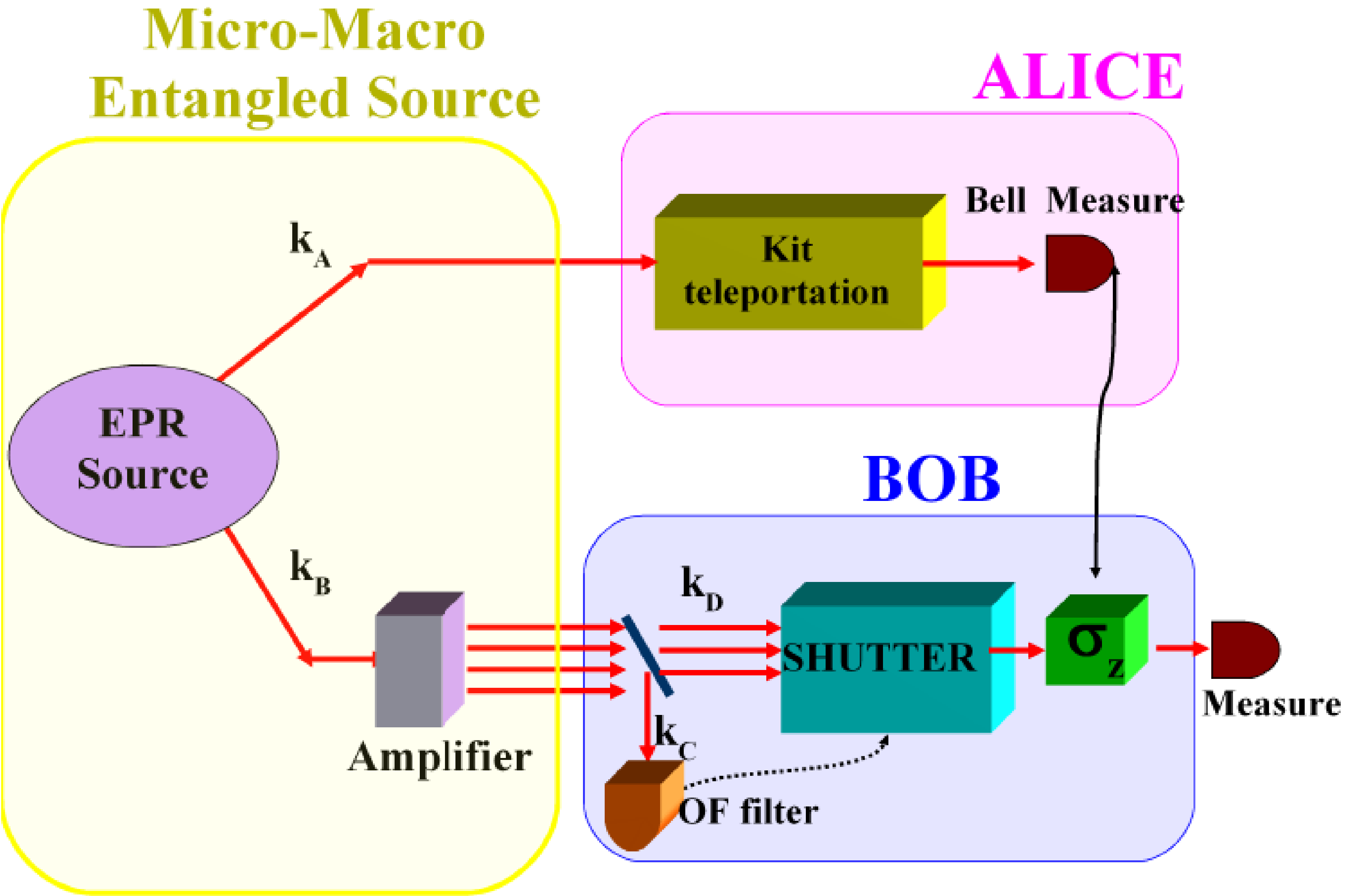


SCHRŐDINGER CAT

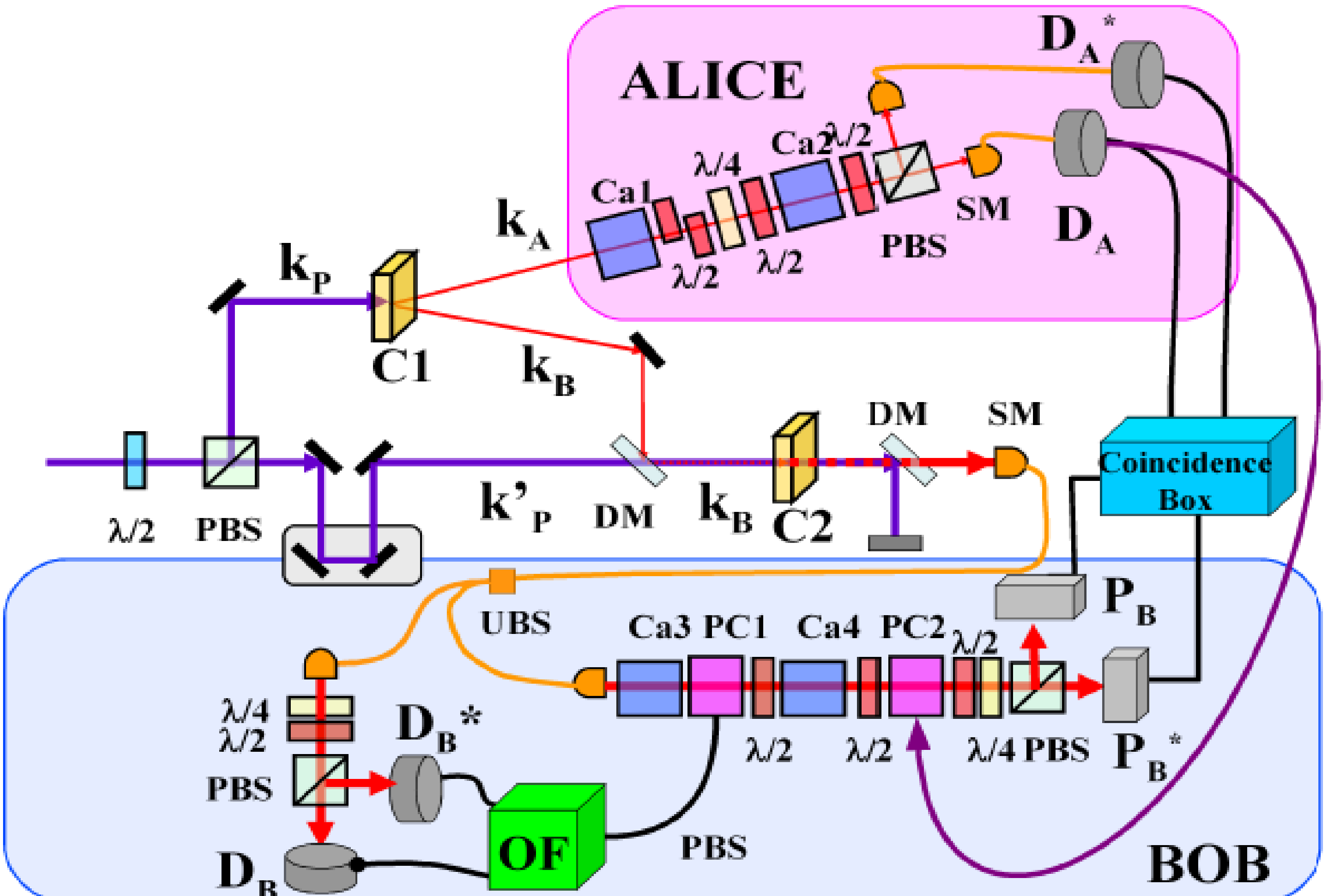
State Non-separability:

F. De Martini, F Sciarrino, C.Vitelli, Phys.Rev.Lett. **100**, 253601, 2008)

MICRO - MACRO QUANTUM TELEPORTATION

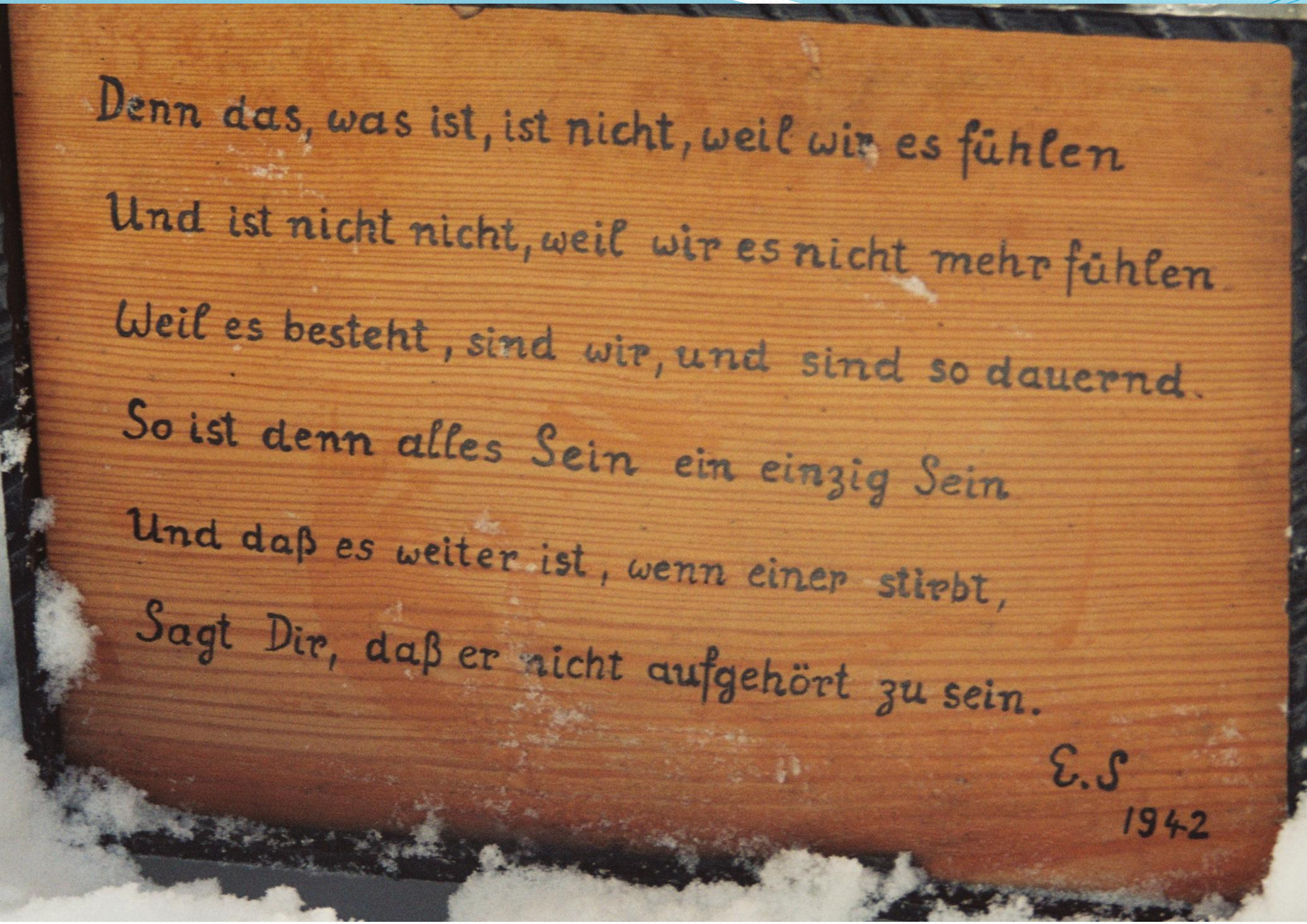


MICRO - MACRO QUANTUM TELEPORTATION




$i\hbar\dot{\psi} = H\psi$
Erwin Schrödinger
*12 VIII 1887 + 4 I 1961
Annemarie Schrödinger
*31 XII 1896 + 3 X 1965
R I P
Denn das, was ist, ist nicht, weil wir es fühlen
Und ist nicht nicht, weil wir es nicht mehr fühlen.
Weil es besteht, sind wir, und sind so dauernd.
So ist denn alles Sein ein einzig Sein
Und daß es weiter ist, wenn einer stirbt,
Sagt Dir, daß er nicht aufgehört zu sein.
E.S.


$i\hbar\dot{\psi}=H\psi$

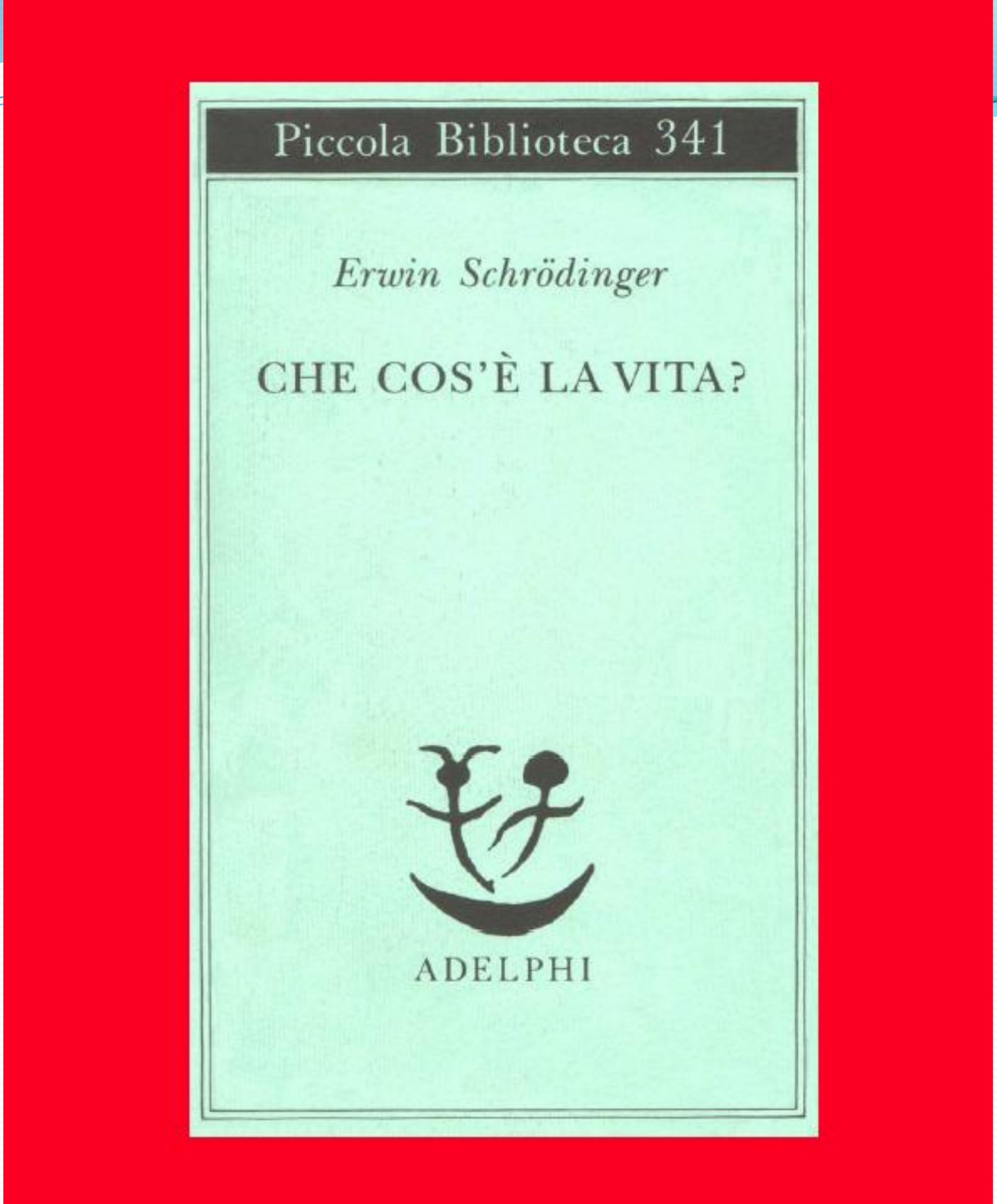

Denn das, was ist, ist nicht, weil wir es fühlen
Und ist nicht nicht, weil wir es nicht mehr fühlen
Weil es besteht, sind wir, und sind so dauernd.
So ist denn alles Sein ein einzig Sein
Und daß es weiter ist, wenn einer stirbt,
Sagt Dir, daß er nicht aufgehört zu sein.
E.S
1942

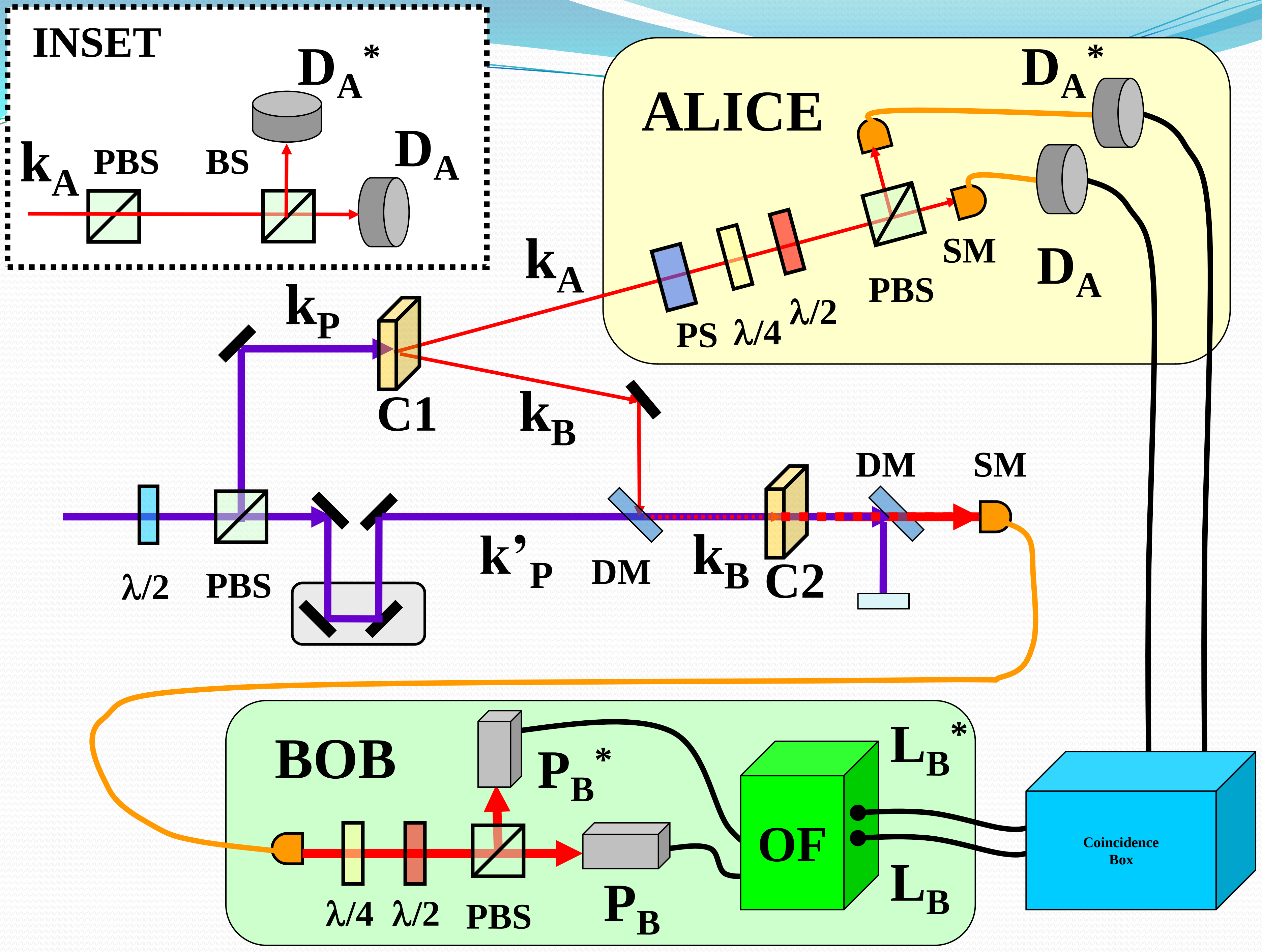
Denn das, was ist, ist nicht, weil wir es fühlen.
Und ist nicht nicht, weil es nicht mehr fühlen.
Weil es besteht, sind wir, und sind so dauernd.
So ist denn alles Sein ein einzig Sein.
Und daß es weiter ist, wenn einer stirbt,
Sagt Dir, daß er nicht aufgehört zu sein.

Erwin Schroedinger 1942

Non è che ciò che è sia in quanto noi lo percepiamo.
E non è che ciò che non è non sia, perché noi non lo percepiamo più.
Ed è poiché ciò che è sussiste, che noi siamo, anzi: siamo per sempre.
Tutto l’Essere è un unico Essere.
E che l’Essere continui ad essere quando uno muore
Ti dice che egli non ha cessato di essere.

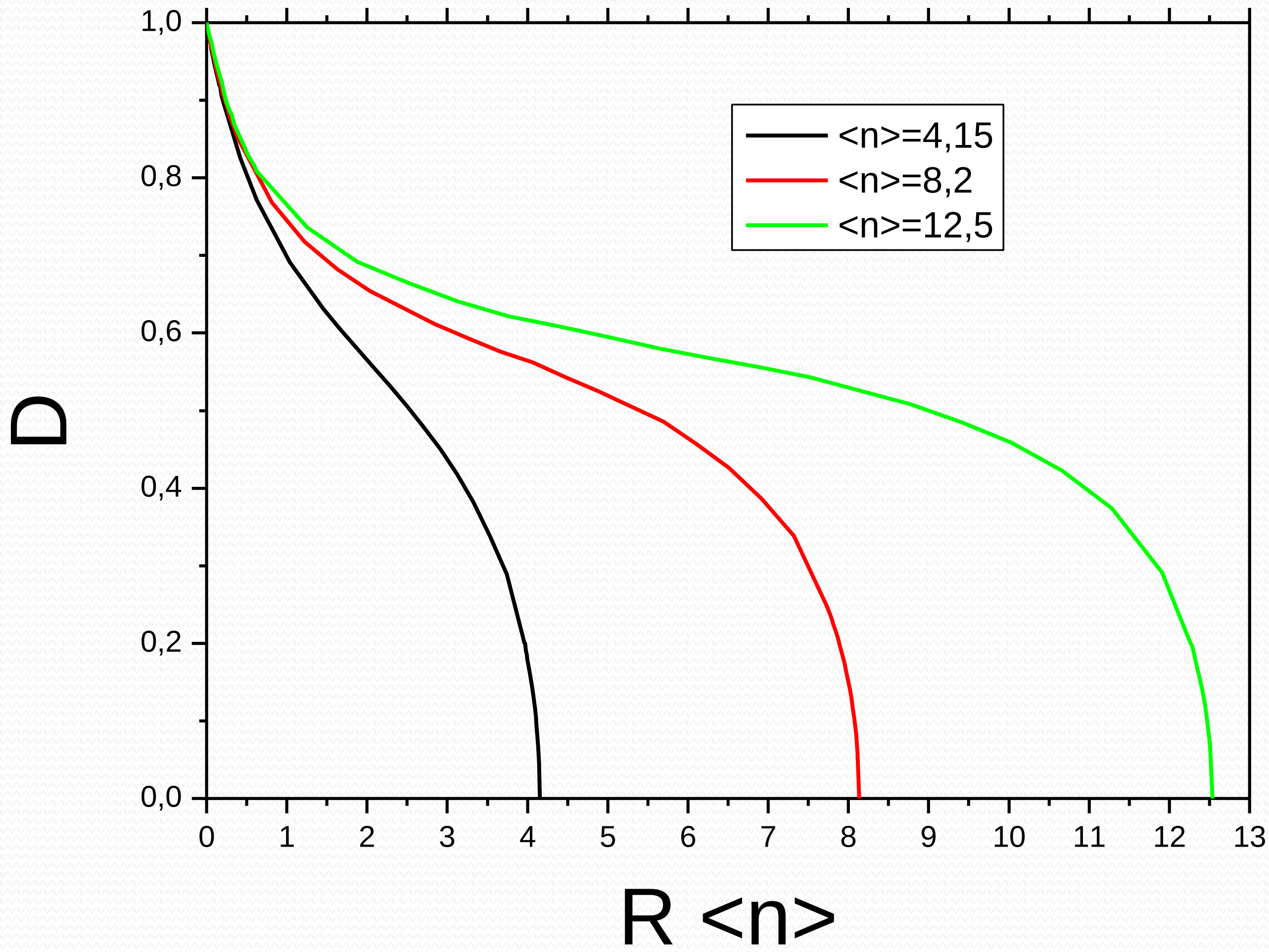
(*traduzione di Bruno Bertotti*)


Piccola Biblioteca 341
Erwin Schrödinger
CHE COS'È LA VITA?
ADELPHI


INSET
D_A*
k_A
PBS
BS
D_A
ALICE
D_A*
D_A
SM
PBS
PS
λ/4
λ/2
k_A
k_P
C1
k_B
λ/2
PBS
k'_P
DM
k_B
C2
DM
SM
BOB
P_B*
L_B*
OF
L_B
λ/4
λ/2
PBS
P_B
Coincidence
Box

Numerical analysis for QIOPA amplified states

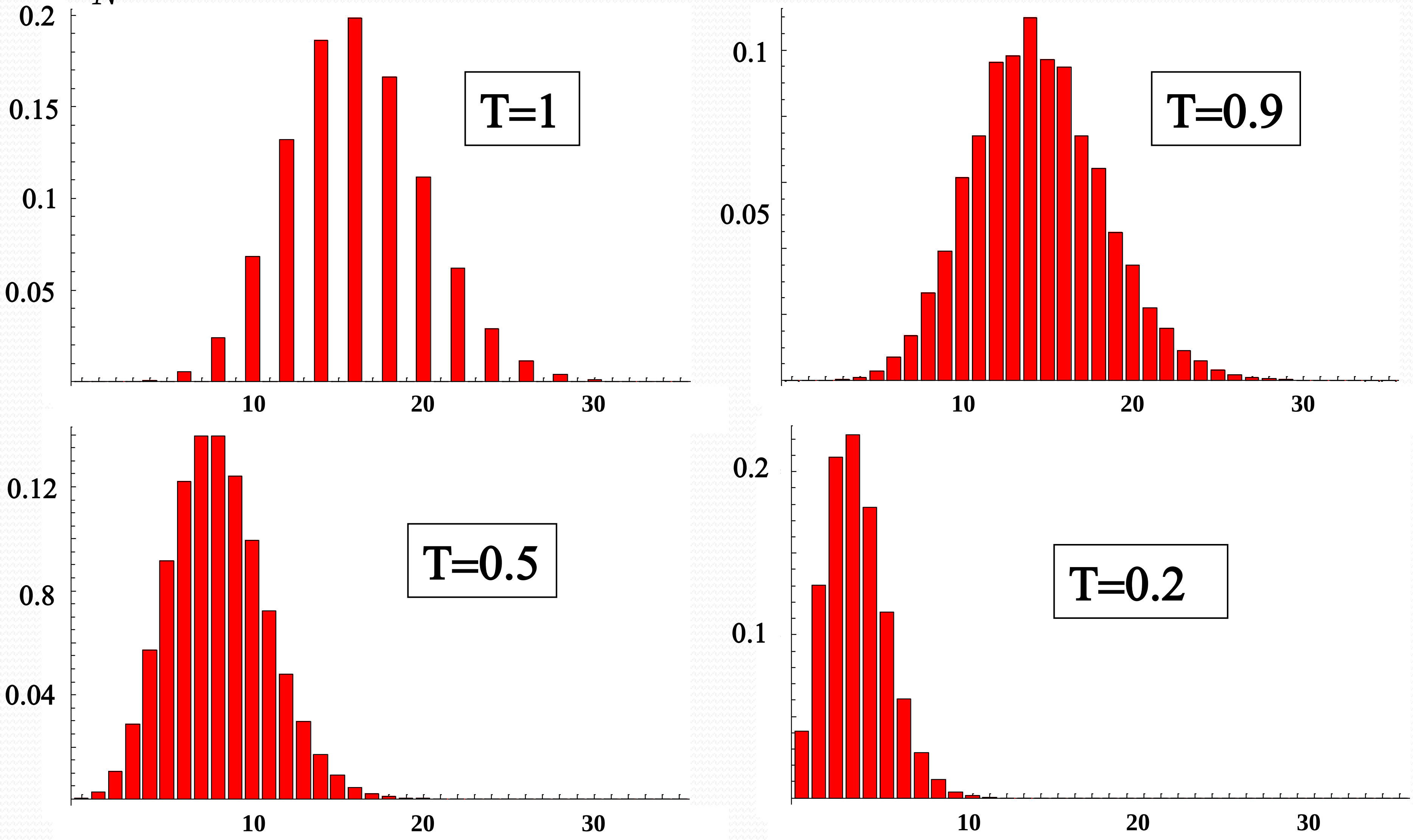
Equatorial qubits: (R,L) (+,-)



COHERENT - STATE SCHRÖDINGER - CAT

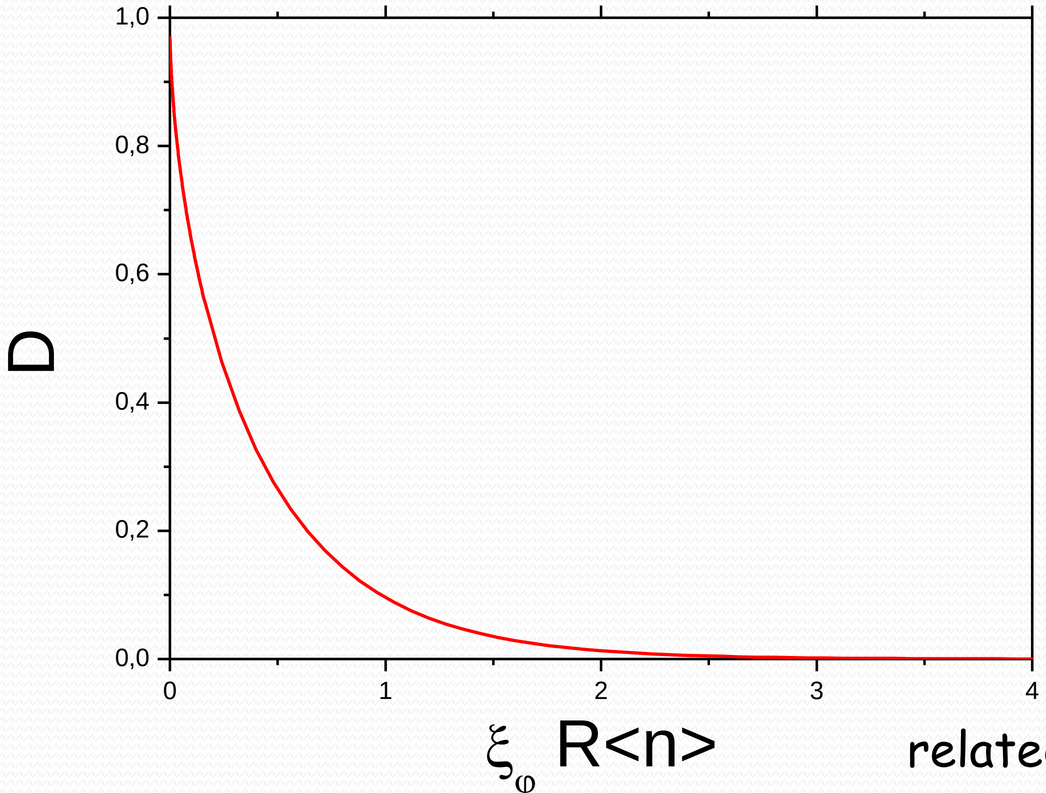
$$\frac{1}{N}\left(|\alpha\rangle + |-\alpha\rangle\right)$$

<n>=16



TRANSMISSION OF QUANTUM SUPERPOSITION OF COHERENT STATES THROUGH A LOSSY CHANNEL

Quantum superposition of coherent states: $|\varphi\rangle = \mathcal{N}\frac{1}{\sqrt{2}}\left(|\alpha e^{\imath\varphi}\rangle \pm |\alpha e^{-\imath\varphi}\rangle\right)$



$$D = \sqrt{1-\sqrt{1-e^{-4R|\alpha|^2\sin^2\varphi}}}$$

Depends only on the number of reflected photons scaled by the factor:

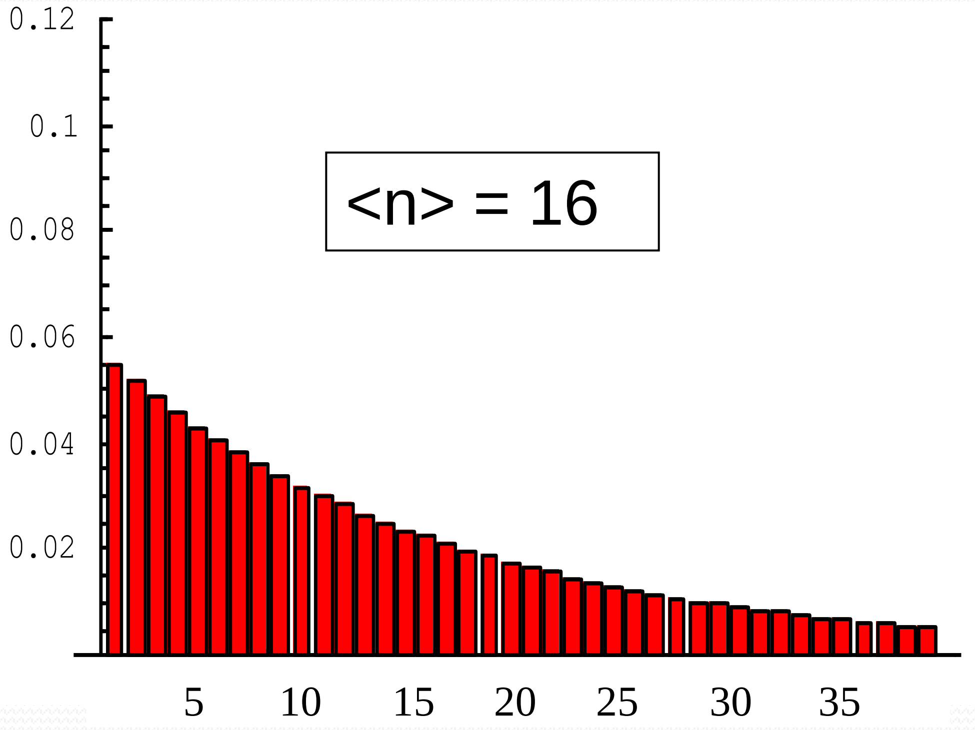
$$\xi_\varphi = \left(\frac{d_\varphi}{d_{\frac{\pi}{2}}}\right)^2 = \sin^2\varphi$$

related to the distance in the phase space between $|\alpha e^{i\varphi}\rangle \Leftrightarrow |\alpha e^{-i\varphi}\rangle$

➡ **for any <n>!**

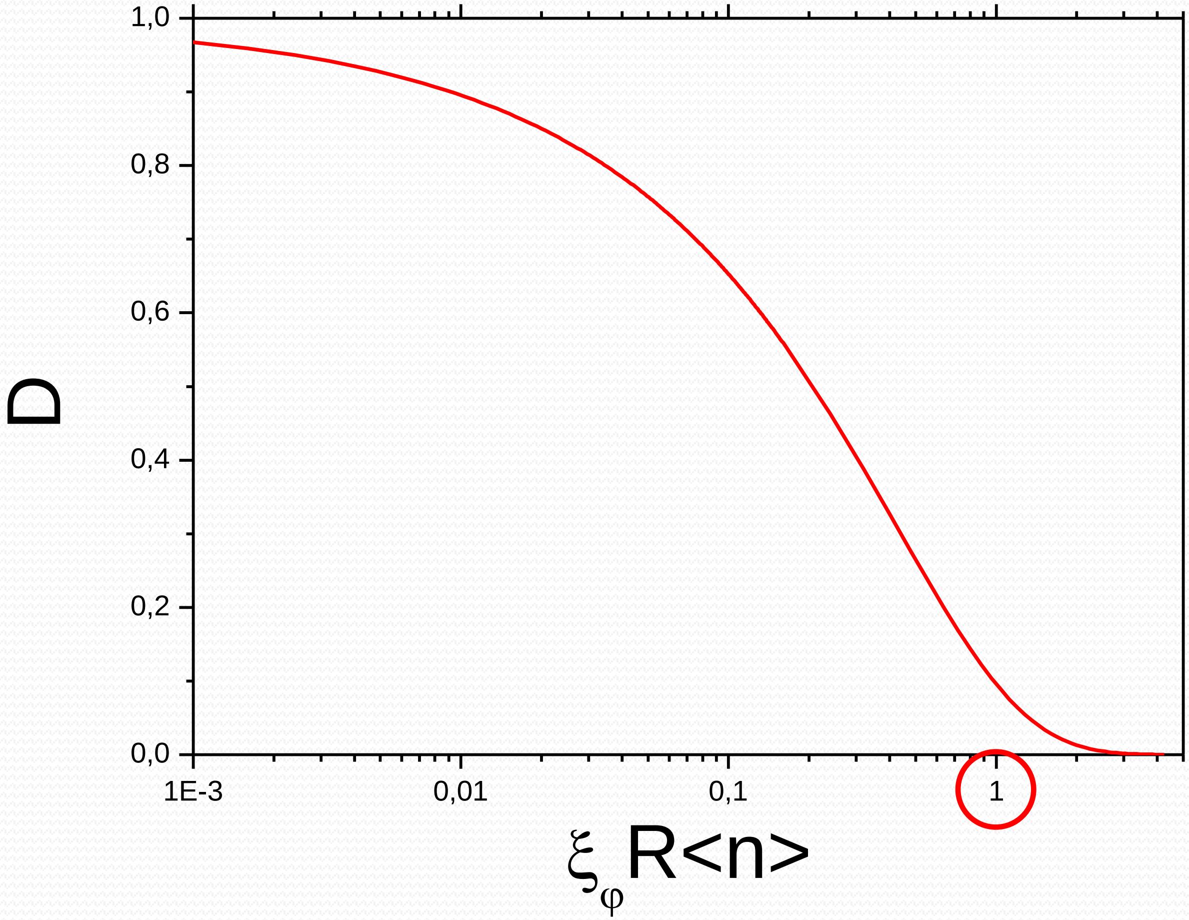
Minimum distance : $(\xi_\varphi)_{min} = \sin^2\frac{1}{|\alpha|} \sim \frac{1}{\langle n\rangle}$

Planckian distribution: QIOPA spontaneous emission



$$|\varphi\rangle = \mathcal{N}\frac{1}{\sqrt{2}}\left(|\alpha e^{\imath\varphi}\rangle \pm |\alpha e^{-\imath\varphi}\rangle\right) \Rightarrow \mathcal{N}\frac{1}{\sqrt{2}}\left(|\alpha\rangle \pm |-\alpha\rangle\right)$$

φ=π/2



$$\xi_\varphi = \left(\frac{d_\varphi}{d_{\frac{\pi}{2}}}\right)^2 = \sin^2\varphi$$

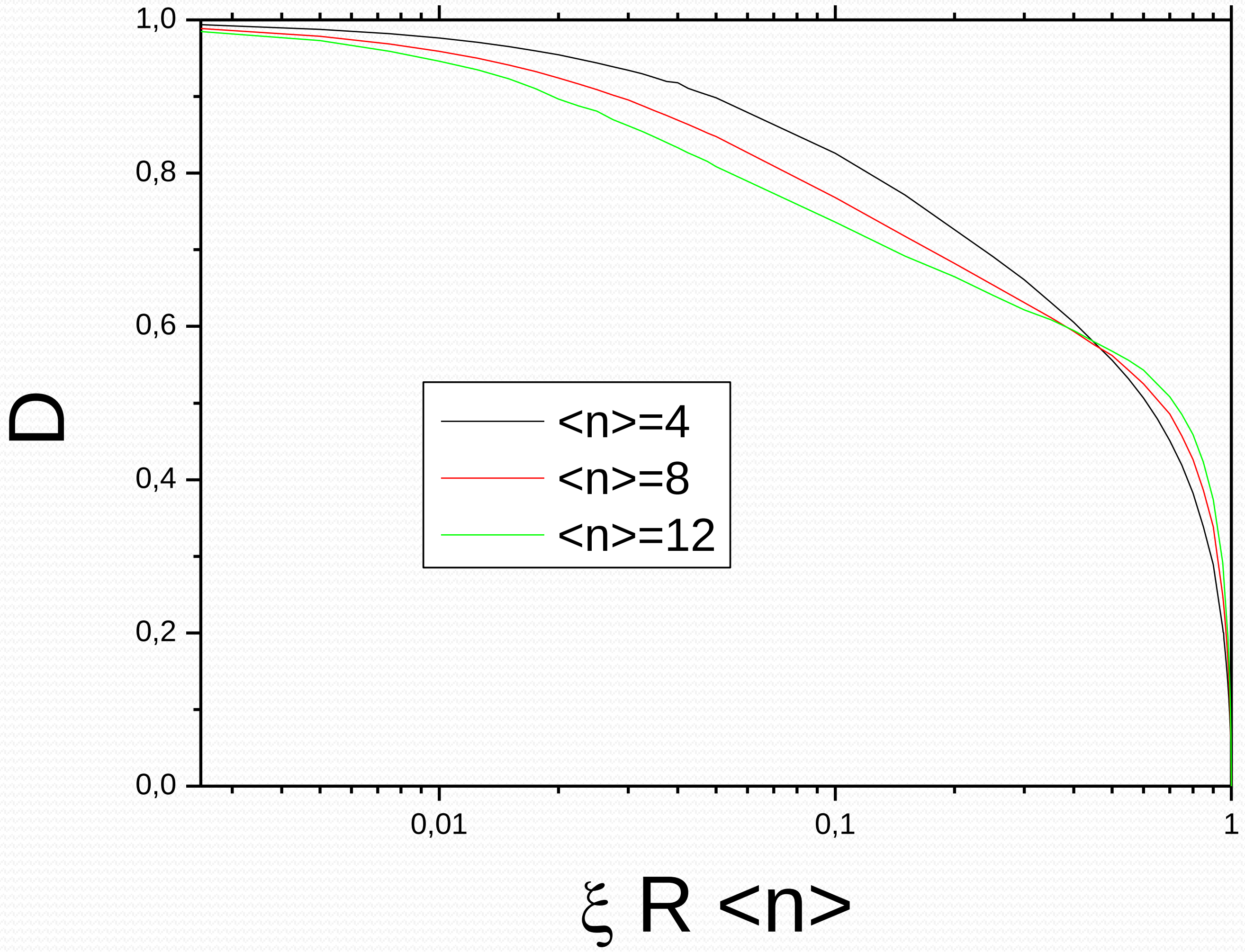
$$(\xi_\varphi)_{min} = \sin^2\frac{1}{|\alpha|} \sim \frac{1}{\langle n\rangle}$$

FOR ANY <n> and φ!

UNIVERSAL FUNCTION FOR COHERENT - STATE MACRO-QUBITS

EQUATORIAL MACRO – QUBITS :

$$\frac{1}{\sqrt{2}}\left(\left|\Phi^{R}\right\rangle+\left|\Phi^{L}\right\rangle\right) \quad or: \quad \frac{1}{\sqrt{2}}\left(\left|\Phi^{+}\right\rangle+\left|\Phi^{-}\right\rangle\right)$$

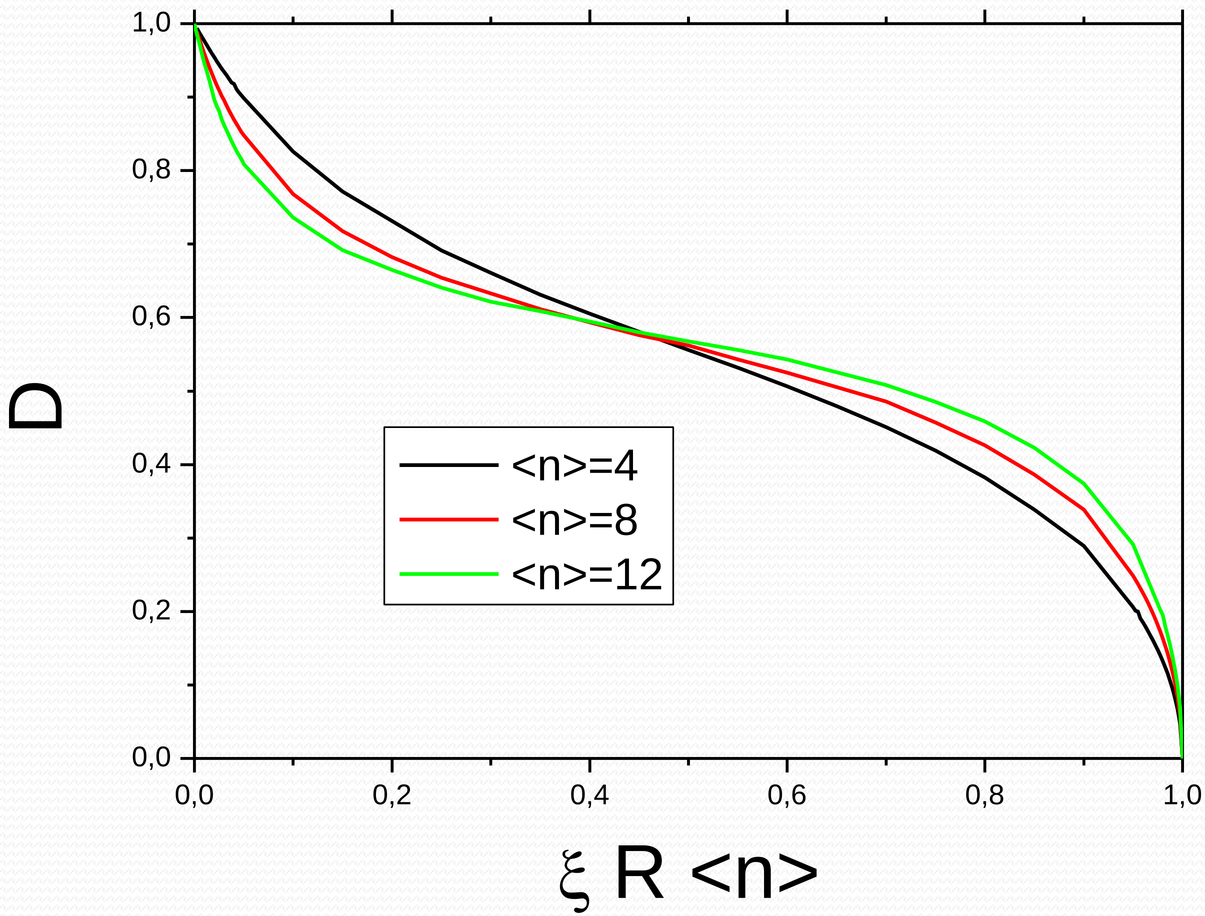


$$\xi = \frac{1}{\langle n \rangle}$$

R<n>ξ :reflectivity of the lossy communication channel

Numerical analysis for QIOPA amplified states

Equatorial qubits: (R,L) (+,-)

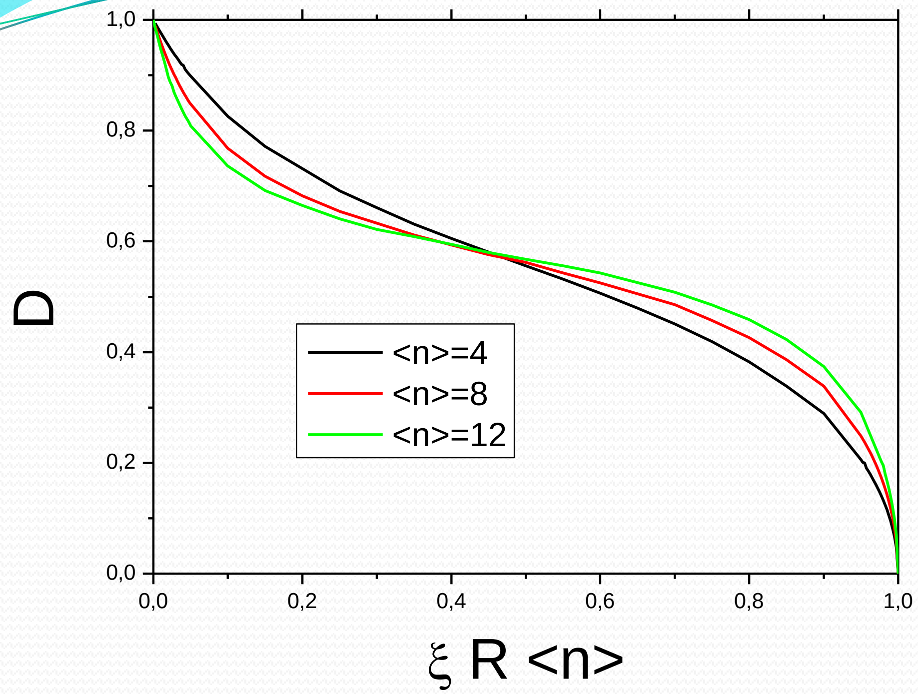


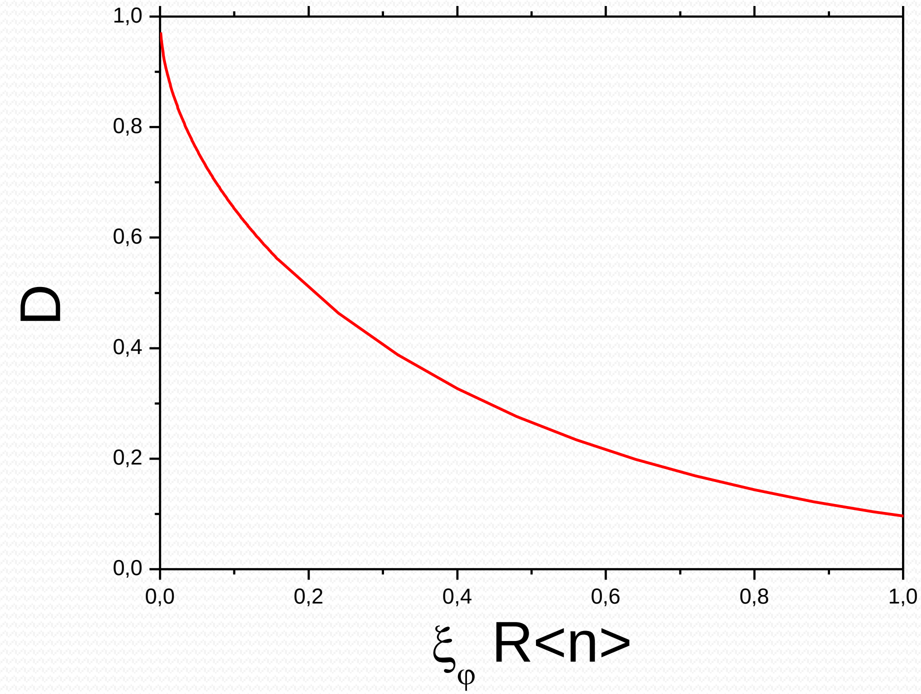
$$\xi = \frac{1}{\langle n \rangle}$$

R<n>ξ :reflectivity of the lossy communication channel

QIOPA equatorial qubits: (R,L) (+,-)

$$|\varphi\rangle = \mathcal{N}\frac{1}{\sqrt{2}}\left(|\alpha e^{\imath\varphi}\rangle \pm |\alpha e^{-\imath\varphi}\rangle\right)$$





$$\xi = \frac{1}{\langle n\rangle}$$

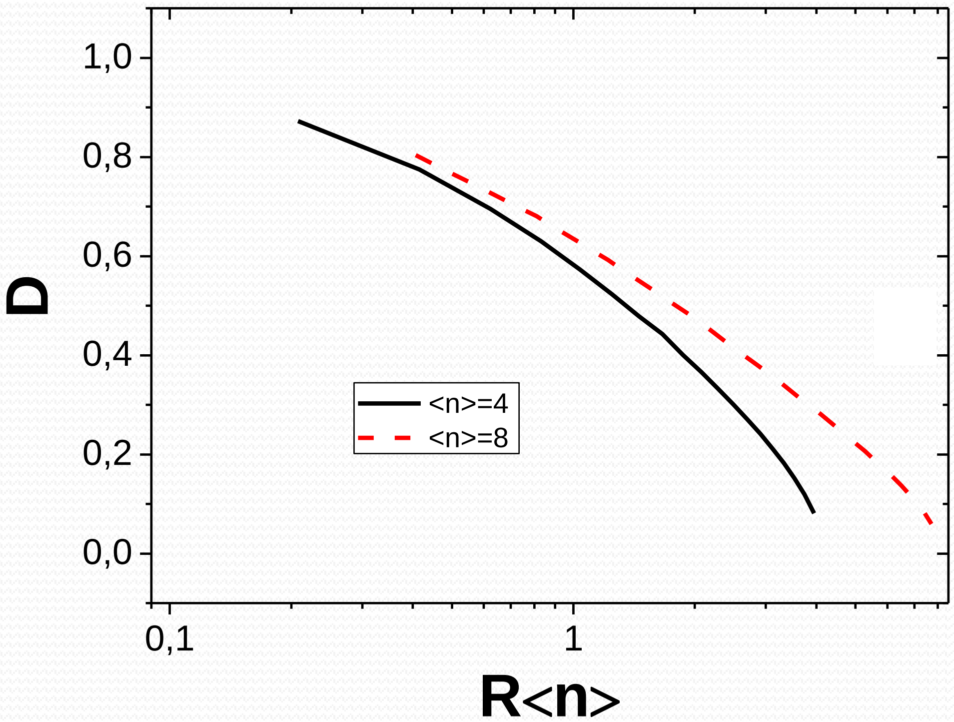
$$\xi_\varphi = \left(\frac{d_\varphi}{d_{\frac{\pi}{2}}}\right)^2 = \sin^2\varphi$$

$$(\xi_\varphi)_{min} = \sin^2\frac{1}{|\alpha|} \sim \frac{1}{\langle n\rangle}$$

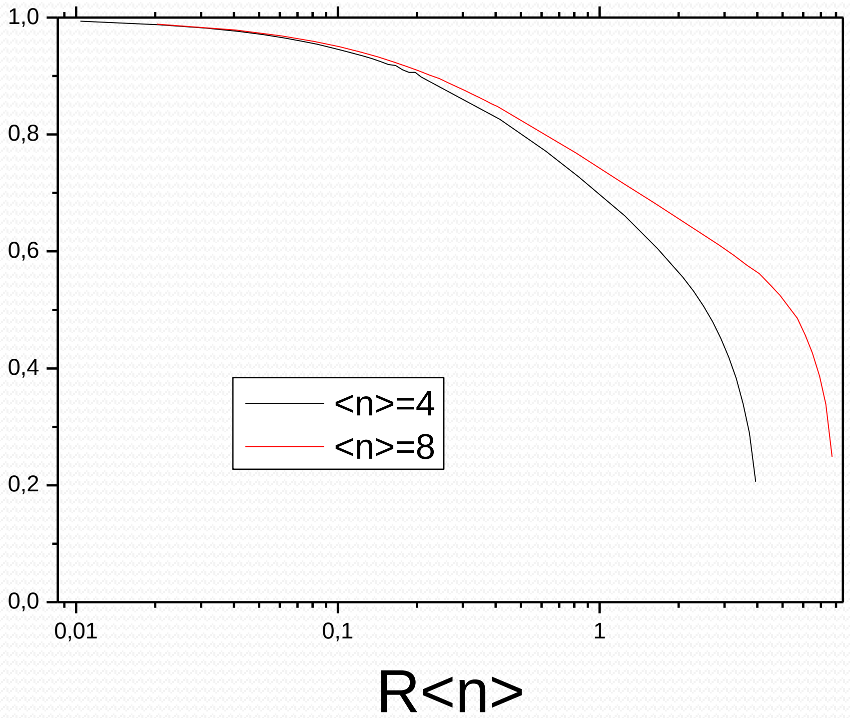
$$\frac{1}{\sqrt{2}}\left(\left|\Phi^{R}\right\rangle+\left|\Phi^{L}\right\rangle\right);\frac{1}{\sqrt{2}}\left(\left|\Phi^{+}\right\rangle+\left|\Phi^{-}\right\rangle\right)$$

Numerical analysis for QIOPA amplified states

H,V qubits



Equatorial qubits: (R,L) (+,-)



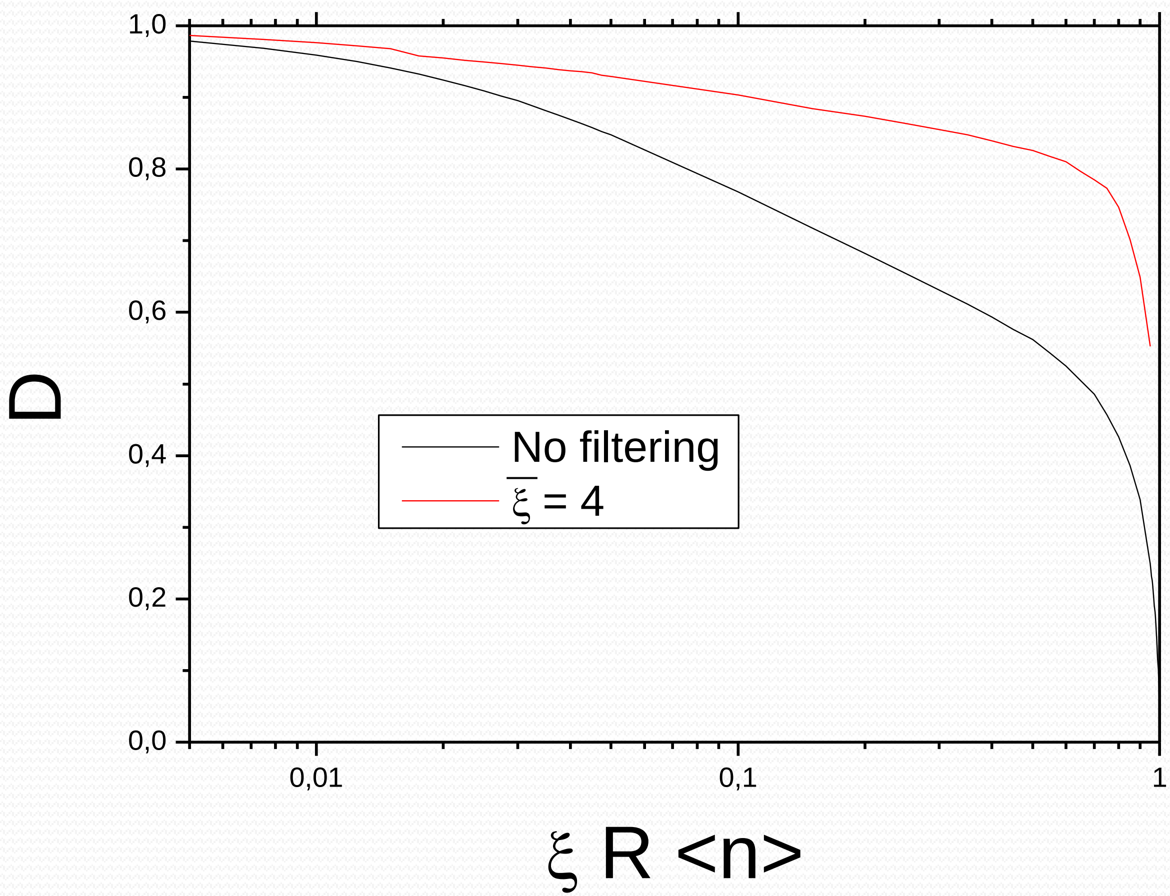
Increased robustness to losses

NOTE THE EFFECT OF PHASE-COVARIANT CLONING!

Equatorial qubits: (R,L) (+,-)

g=1.1

<n>=8



$$\xi = \frac{1}{\langle n \rangle}$$

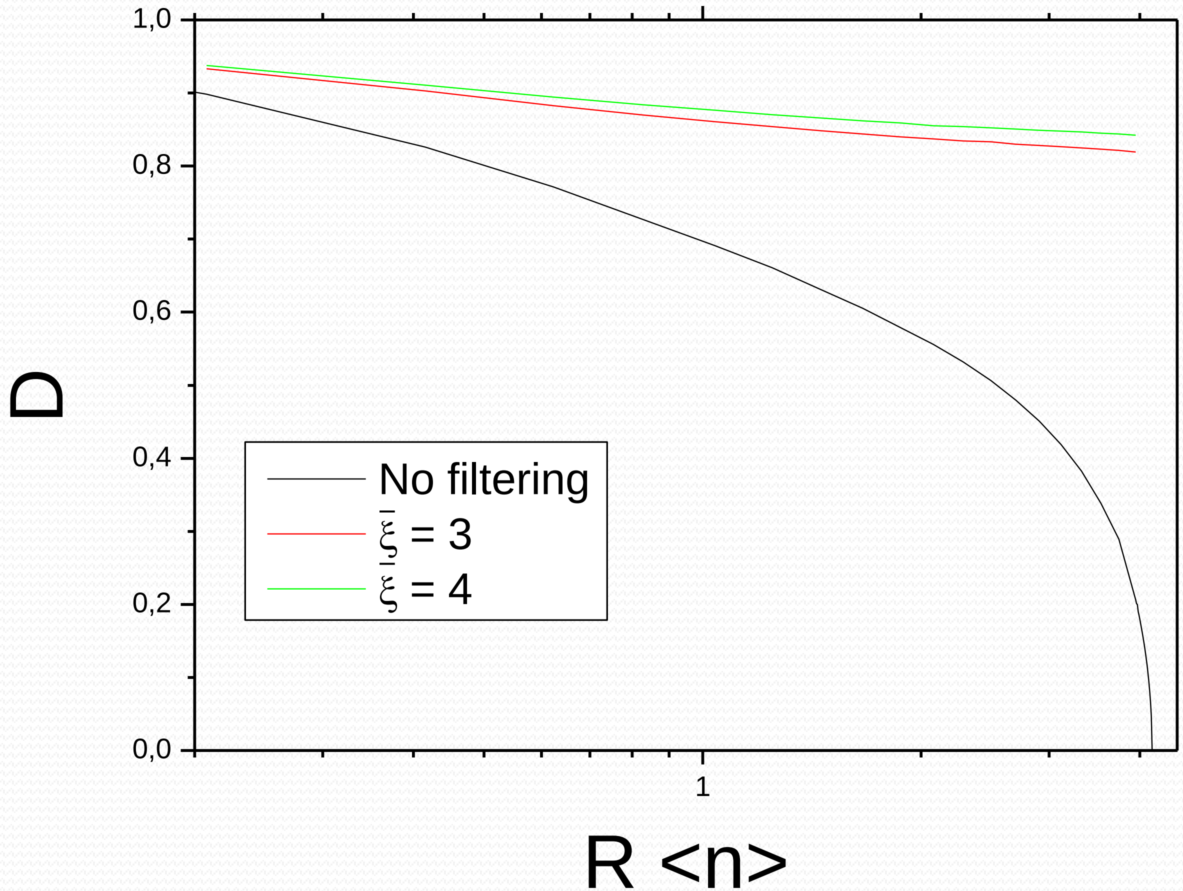
R<n>ξ :reflectivity of the lossy communication channel

Threshold

$$\bar{\xi}\langle n \rangle_T = \bar{\xi} T \langle n \rangle$$

DISTANCE ENHANCEMENT: DISTRIBUTIONS DISCRIMINATION THROUGH O-FILTER

Equatorial qubits: (R,L) (+,-)



g=0.8

<n>=4

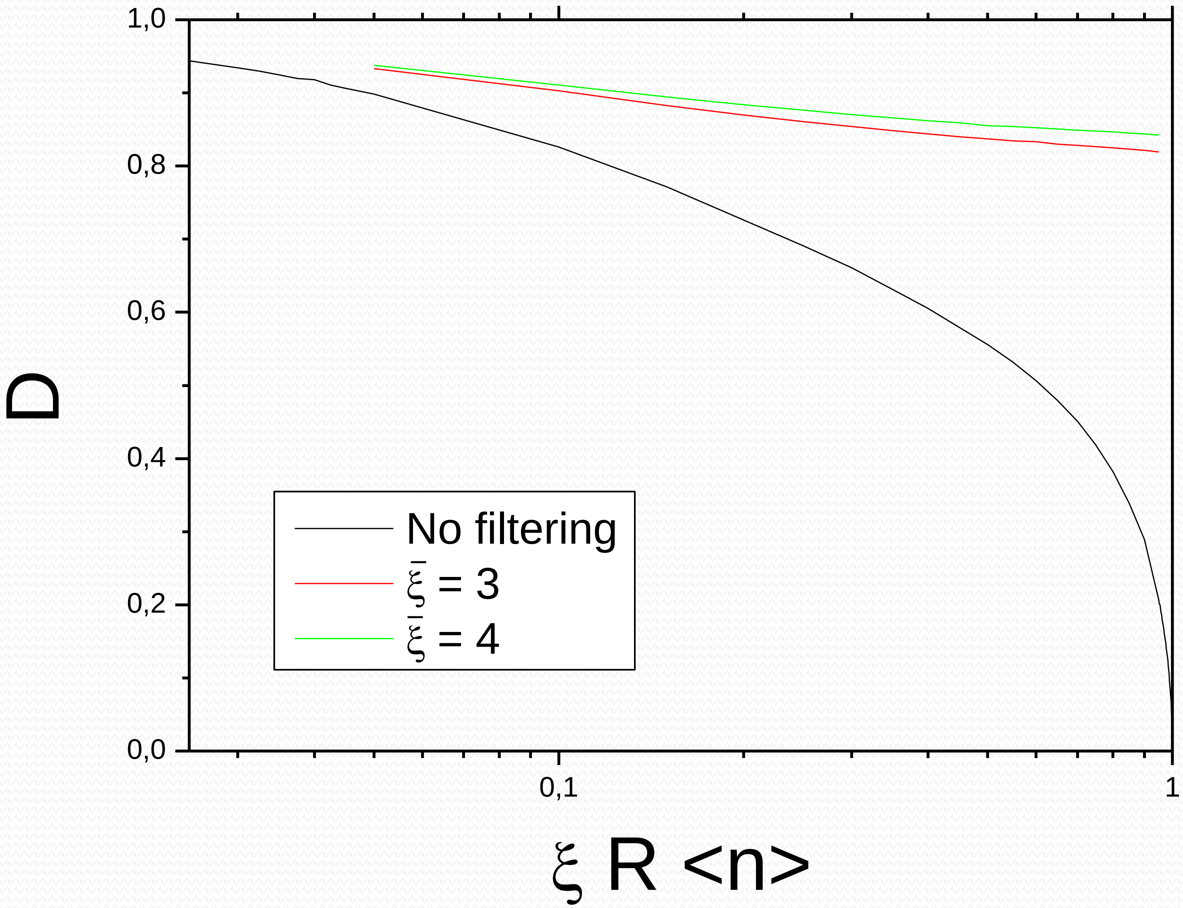
Threshold

$\bar{\xi}\langle n\rangle$

Equatorial qubits: (R,L) (+,-)

g=0.8

<n>=4



$$\xi = \frac{1}{\langle n \rangle}$$

R<n>ξ :reflectivity of the lossy communication channel

Threshold

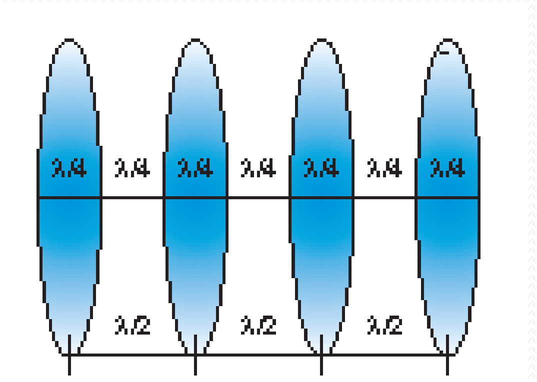
$$\bar{\xi}\langle n \rangle$$

Towards light-matter entanglement

I) Micro-macroscopic photonic entanglement by QIOPA

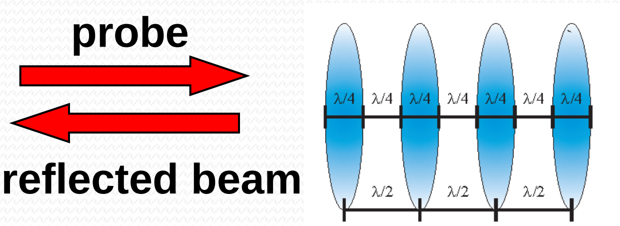
II) BEC mirror

- BEC condensate with 10^5 atoms
- Optical lattices induces a Bragg structure on the BEC
- High reflectivity on bandwidth of GHz



Alternating slabs of condensate and vacuum.

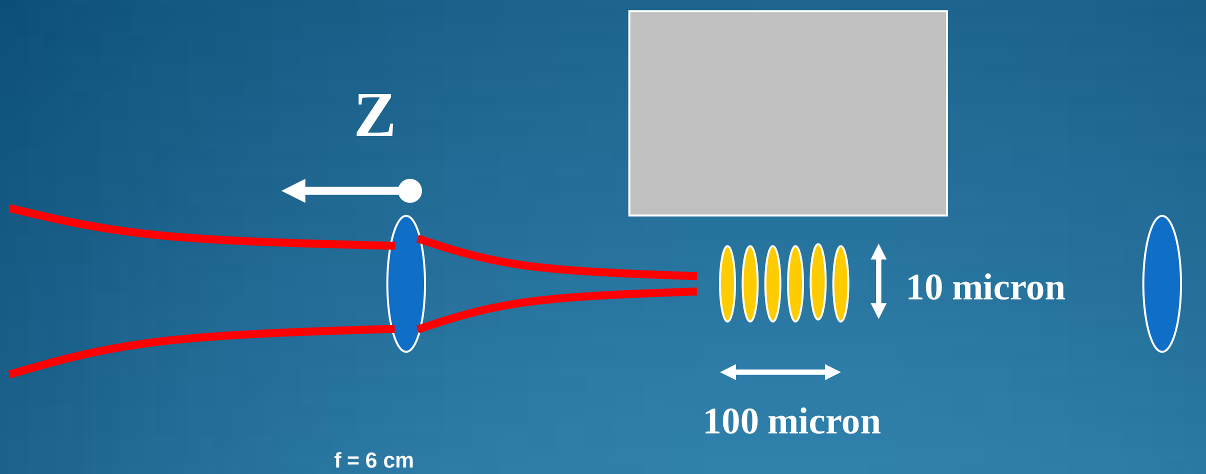
III) Light-matter entanglement by photon scattering



Momentum conservation: $2\hbar k$
light reflection induces a kick on single atom

F. Cataliotti and F. De Martini, submitted to PRL

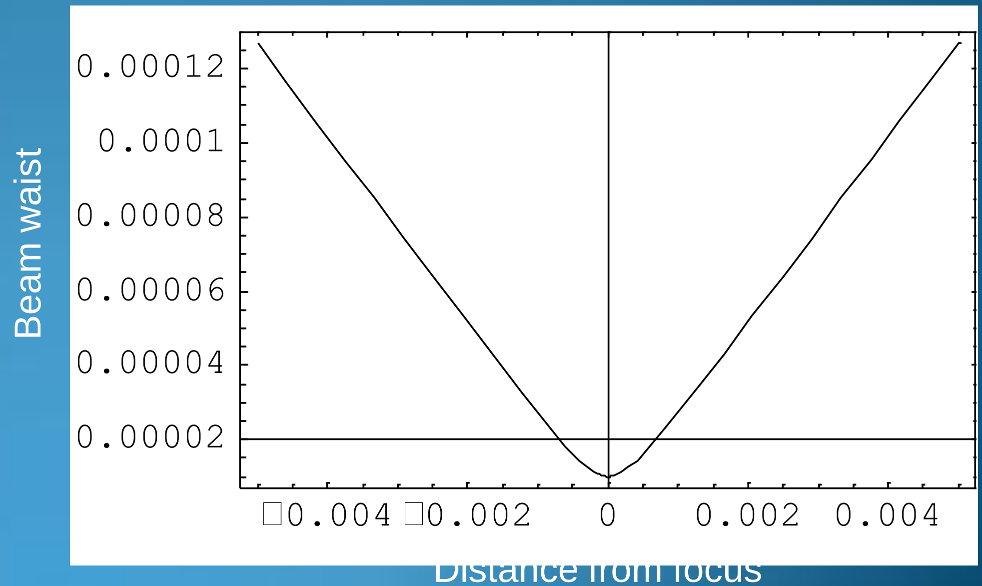
Mode matching: beam - condensate



Beam: beam waist 10 micron
Confocal parameter: 400 micron

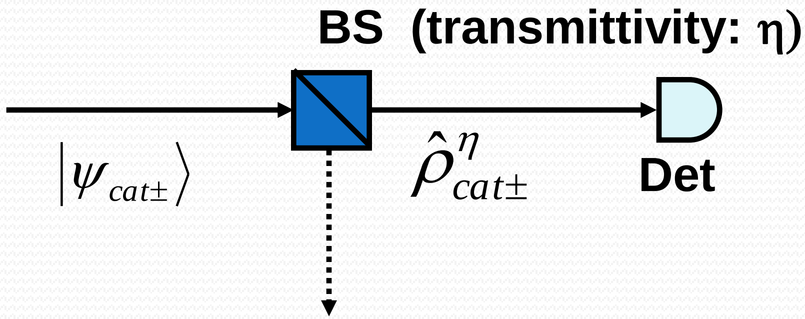
Focus length equal 6 cm

Distance between BEC and microchip
About 50 – 400 micron



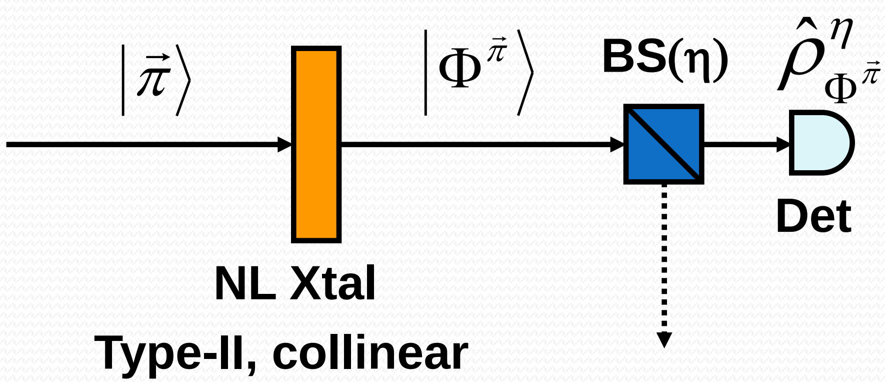
DECOHERENCE OF MACROSCOPIC QUANTUM SUPERPOSITIONS

(1) Coherent cat states



$$|\psi_{cat\pm}\rangle = \frac{1}{N_{\pm}}\left(|\alpha\rangle \pm |-\alpha\rangle\right)$$

(2) QIOPA amplified states



$$|\vec{\pi}\rangle = \alpha|H\rangle + \beta|V\rangle$$

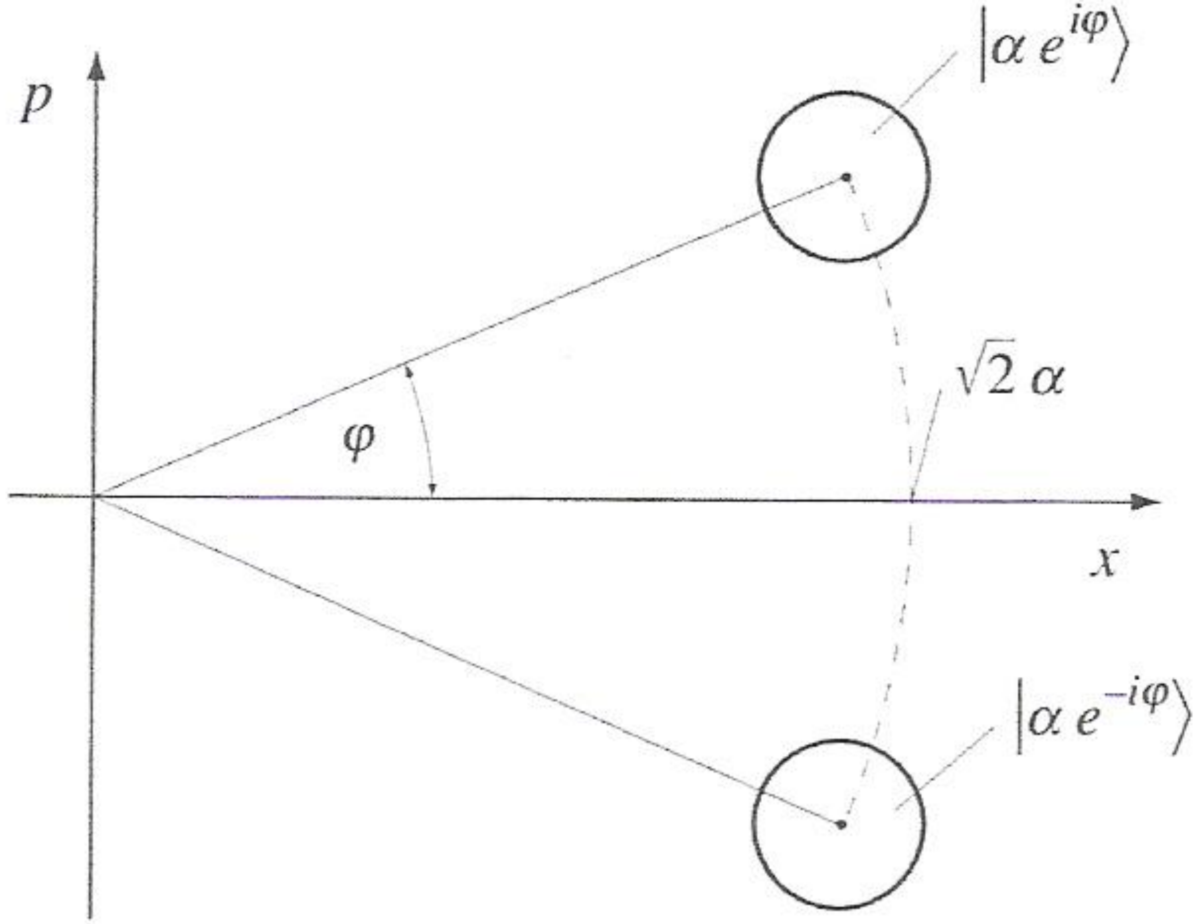
amplification process

$$|\Phi^{\vec{\pi}}\rangle = \hat{U}|\vec{\pi}\rangle$$

Two possible choices:

- H,V basis: $|H\rangle$ $|V\rangle$
- Equatorial qubit: $|\varphi\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle + e^{i\varphi}|V\rangle\right)$

Coherent - State Schroedinger - Cat (E.N.S. Paris)



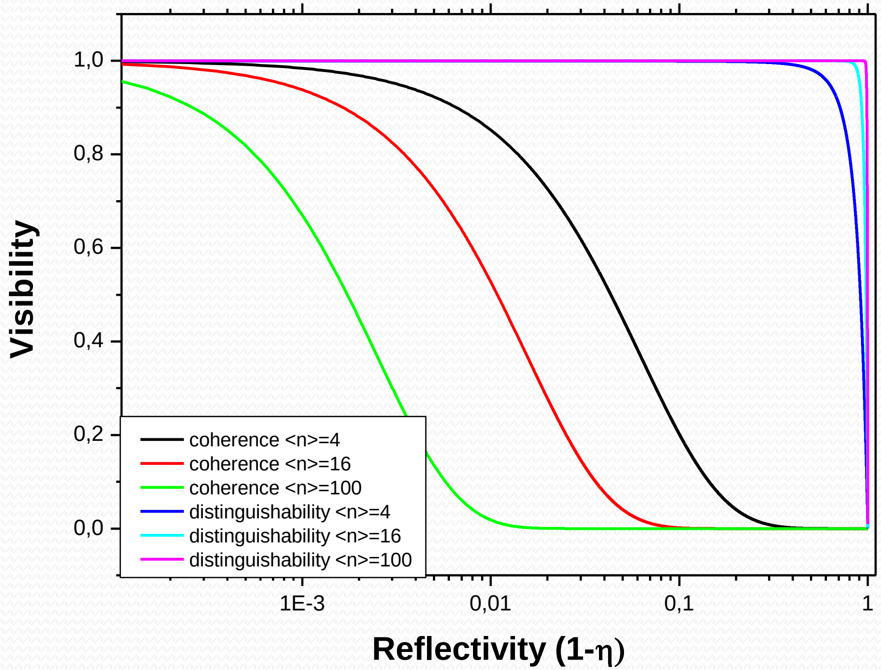
$$|\psi\rangle = \mathcal{N}\frac{1}{\sqrt{2}}\left(|\alpha e^{i\varphi}\rangle + |\alpha e^{-i\varphi}\rangle\right)$$

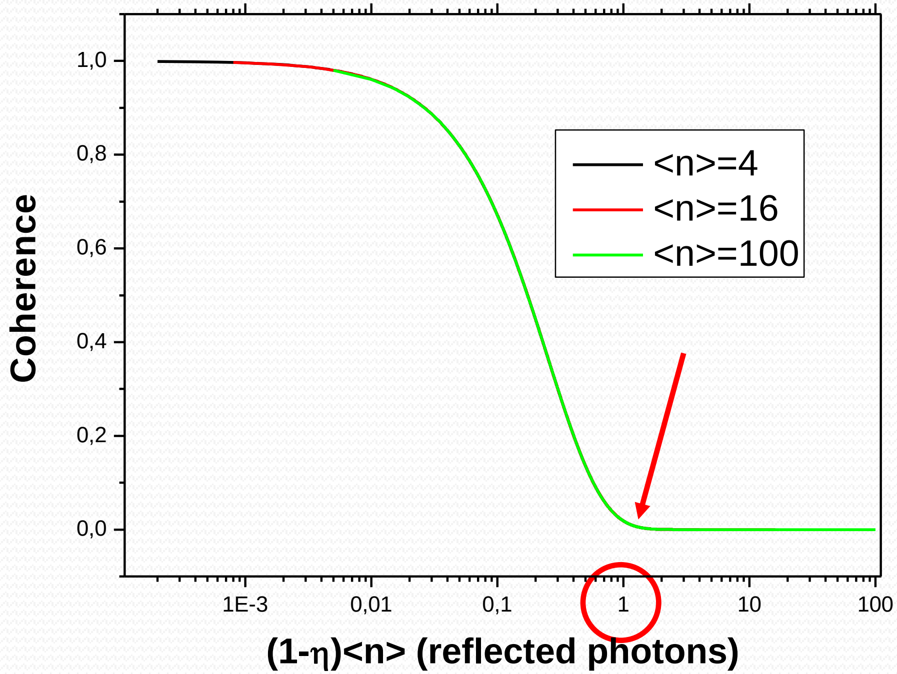
COHERENT - STATE SCHRÖDINGER - CAT

Numerical analysis:

distinguishability: $|\alpha\rangle \Leftrightarrow |-\alpha\rangle$

coherence: $\frac{1}{N_+}\left(|\alpha\rangle + |-\alpha\rangle\right) \Leftrightarrow \frac{1}{N_-}\left(|\alpha\rangle - |-\alpha\rangle\right)$



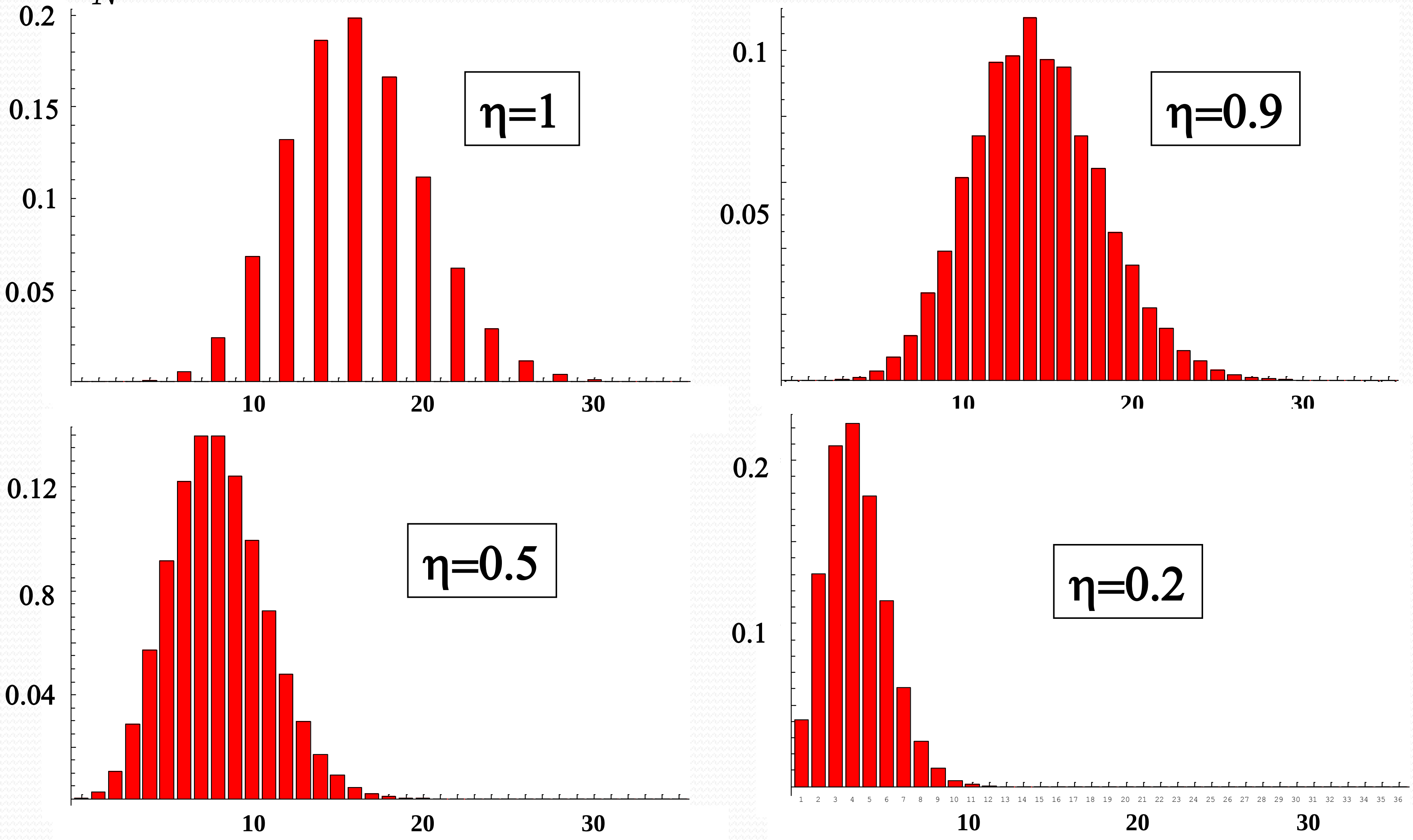


coherence lost after loss of a single photon

COHERENT - STATE SCHRÖDINGER - CAT

$$\frac{1}{N}\left(|\alpha\rangle + |-\alpha\rangle\right)$$

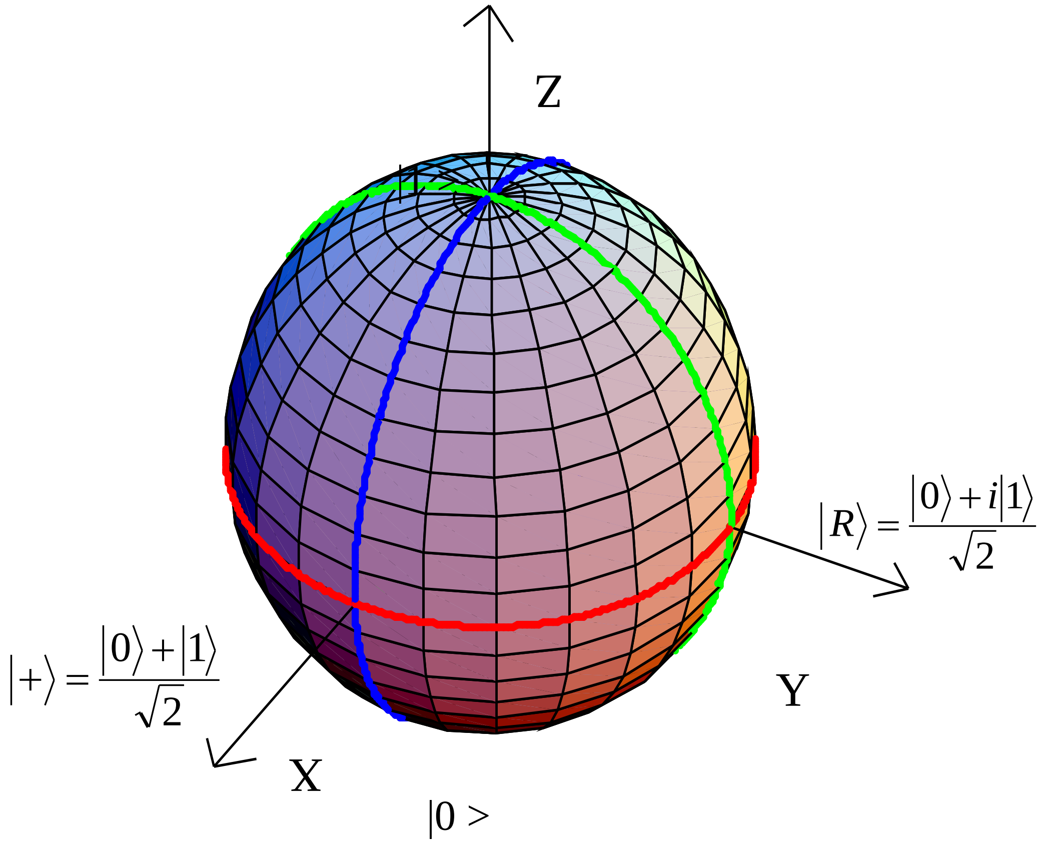
<n>=16



Change of the injected state by Babinet compensator + λ/2 Wp.

On the Bloch sphere:

$$|\Psi\rangle_{in} = \cos(\theta/2)|0\rangle + e^{i\varphi}\sin(\theta/2)|1\rangle$$



DECOHERENCE : TWO CRITERIA

Distance between two quantum states: $d(\hat{\rho},\hat{\sigma})$

$$d^2(\hat{\rho},\hat{\sigma}) = 1 - F^2(\hat{\rho},\hat{\sigma})$$

where : **STATE FIDELITY**:

$$F(\hat{\rho},\hat{\sigma}) = \mathrm{Tr}\left(\sqrt{\hat{\rho}^{\frac{1}{2}}\hat{\sigma}\hat{\rho}^{\frac{1}{2}}}\right) \Rightarrow \left|\langle\psi|\varphi\rangle\right|$$

(for pure states)

(a) Distinguishability

i.e.

$$\begin{cases} |\alpha\rangle \Leftrightarrow |-\alpha\rangle \\ |\Phi^R\rangle \Leftrightarrow |\Phi^L\rangle \end{cases}$$

→ represents how close two quantum states are

(b) Coherence

i.e.

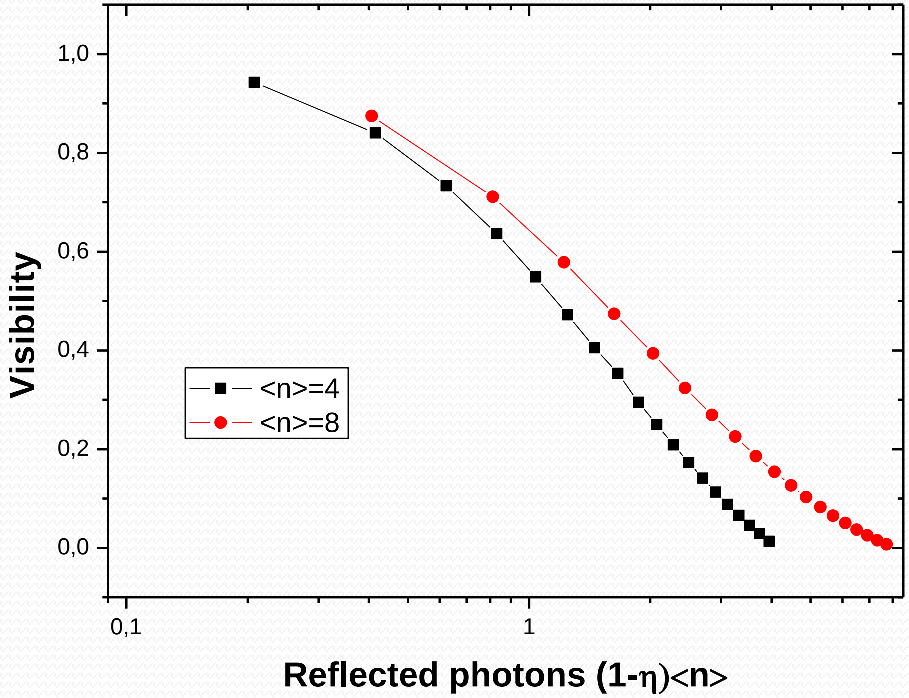
$$\begin{cases} \frac{1}{N_+}\left(|\alpha\rangle + |-\alpha\rangle\right) \Leftrightarrow \frac{1}{N_-}\left(|\alpha\rangle - |-\alpha\rangle\right) \\ \frac{1}{\sqrt{2}}\left(|\Phi^R\rangle - |\Phi^L\rangle\right) \Leftrightarrow \frac{1}{\sqrt{2}}\left(|\Phi^R\rangle + |\Phi^L\rangle\right) \end{cases}$$

→ orthogonality loss depends on loss of phase relationship

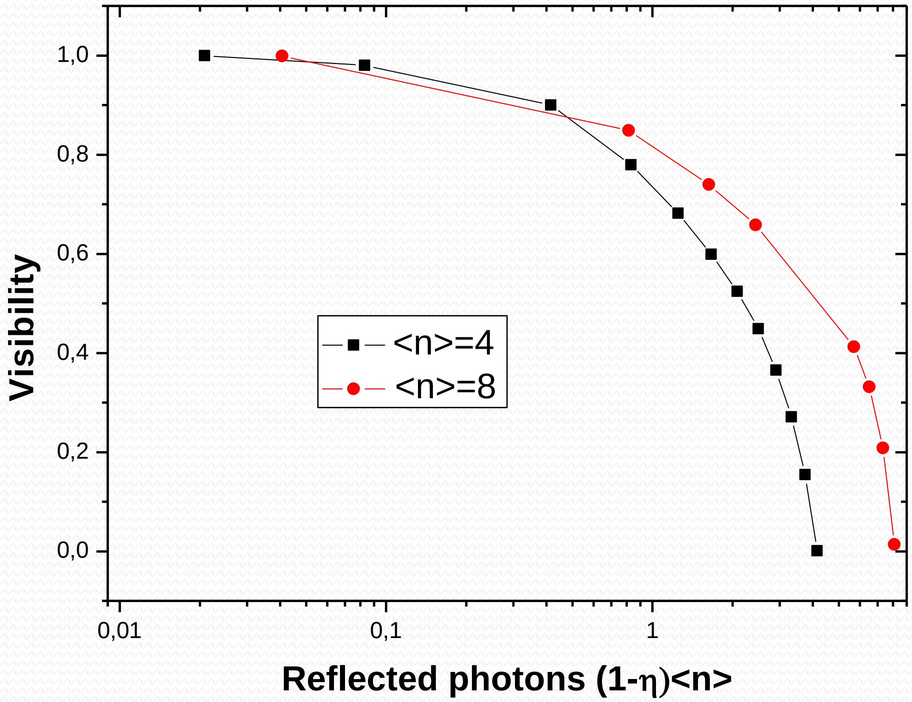
QI-OPA AMPLIFIED SCHRÖDINGER - CAT

Numerical analysis for QIOPA amplified states

H,V qubits



Equatorial qubits: (R, L)   (+, -)

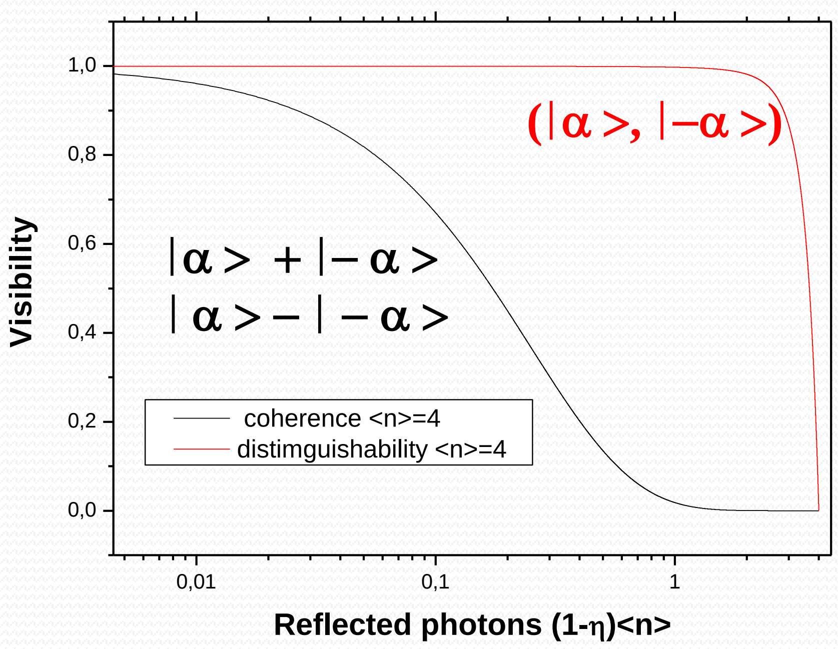


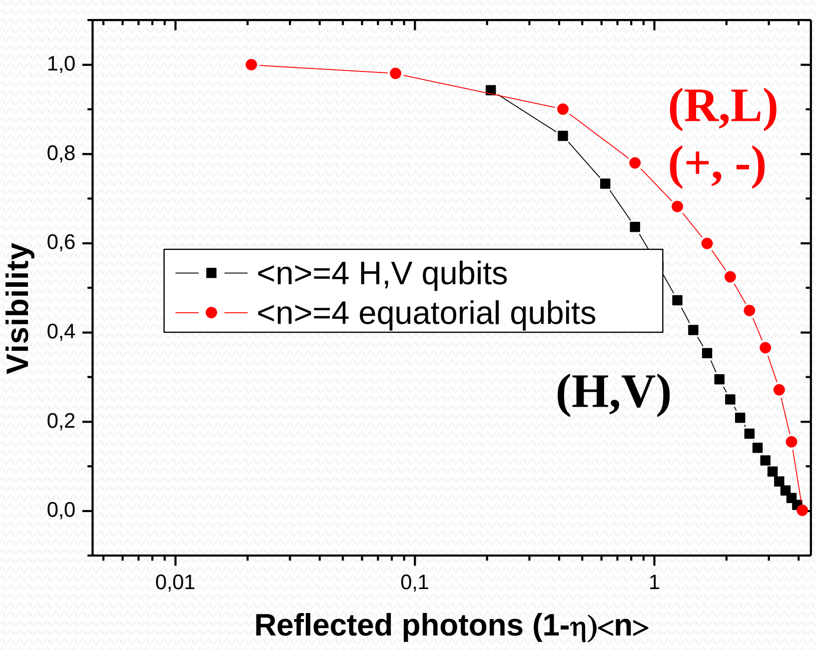
Increased robustness to losses

NOTE THE EFFECT OF PHASE – COVARIANT CLONING !

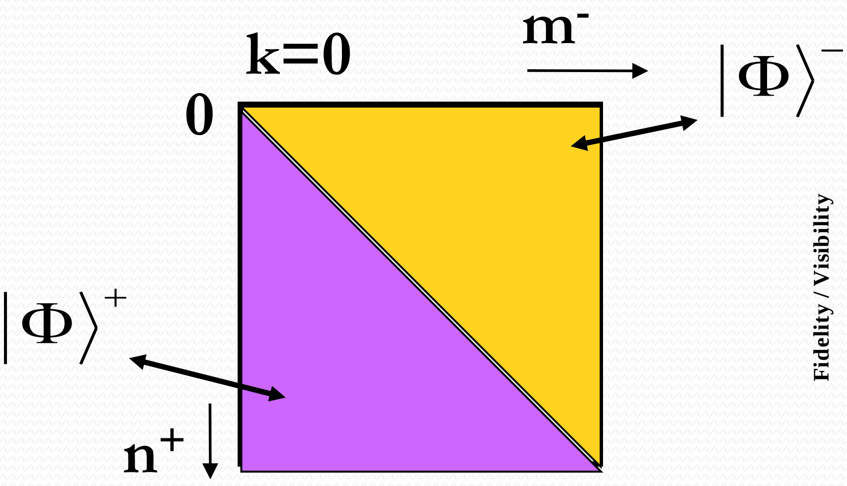
SCHRÖDINGER CAT

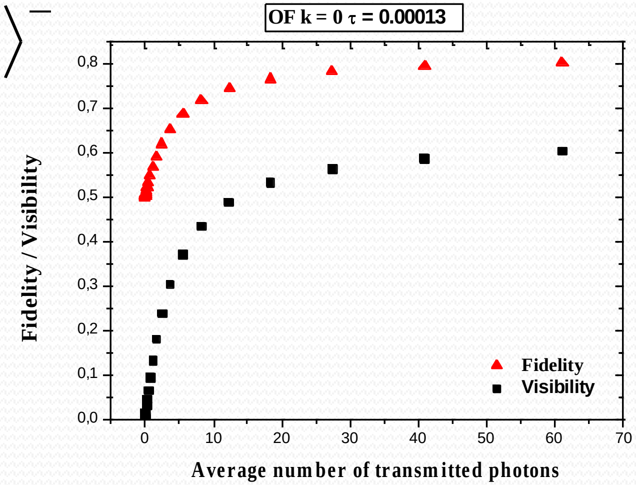
Comparison between QIOPA States and Coherent States:

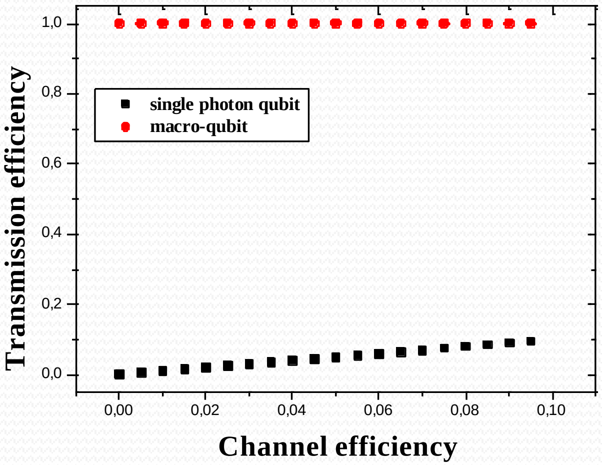




Macro qubits transmission: identification of orthogonal states







OPTIMAL UNIVERSAL QUANTUM CLONING MACHINES

optimal fidelity

$$\mathscr{F}_{N\to M}(|\phi\rangle, \rho_{out}) = \frac{NM + M + N}{MN + 2M} = \frac{N + 1 + \beta}{N + 2} \tag{85}$$

with $\beta \equiv N/M \leqslant 1$ [159,160,163]. As we can see $\mathscr{F}_{N\to M}(|\phi\rangle, \rho_{out})$ is larger than the one obtained by the N estimation approach and reduces to that result for $\beta \to 0$, i.e. for an infinite number of copies: $M \to \infty$. Of course the zero-cloning $N = M$ condition is expressed by $\beta = 1$ and $\mathscr{F}_{N\to N} = 1$. The extra positive term β in the above expression accounts for the excess of quantum information which, originally stored in N states, is optimally redistributed by entanglement among the $M - N$ remaining blank qubits encoded by UOQCM [158]. Precisely, the entanglement is established by the cloning process between the blank qubits and the machine itself which may be modelled as a “ancilla” information system.

OPTIMAL UNIVERSAL-NOT GATE (Nature, 419, 2002)
OPTIMAL UNIVERSAL QUANTUM ENTANGLER, (PRA 70, 2004)
OPTIMAL QUANTUM REVERSION (PRA 73, 2006)

Fundamental quantum constraint:

LINEARITY

(Quantum Cloning is a non-linear map !)

VOLUME 92, NUMBER 6 PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2004

Contextual, Optimal, and Universal Realization of the Quantum Cloning Machine and of the NOT Gate

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(Received 21 July 2003; revised manuscript received 25 November 2003; published 10 February 2004)

A simultaneous realization of the universal optimal quantum cloning machine and of the universal-NOT gate by a quantum injected optical parametric amplification, is reported. The two processes, forbidden in their exact form for fundamental quantum limitations, are found universal and optimal, and the measured fidelity $F < 1$ is found close to the limit values evaluated by quantum theory. This work may enlighten the yet little explored interconnections of fundamental axiomatic properties within the deep structure of quantum mechanics.

DOI: 10.1103/PhysRevLett.92.067901 PACS numbers: 03.67.Mn, 03.65.Ta, 03.67.Lx, 42.50.Dv

NO CLONING and

NO BROADCASTING : because QUANTUM MECHANICS IS A **LINEAR** MAP

NO U-NOT GATE : because QUANTUM MECHANICS IS A **CP**- MAP

(No Broadcasting: H.Barnum, C.M.Caves, C.Fuchs et al. PRL 76, 2818, 1996)

Realizable Quantum CP-Maps

- **A (realizable) *completely-positive* map (*CP-map*) $\Lambda(\rho)$ preserves positivity for:**

- **(a) any local state in the Hilbert space *H***
- **(b) when tensor-multiplied with the "identical map" *I* acting on *any* Hilbert space *K*, the extended map $\Lambda(\rho) \otimes I$ is positive for *any* state in the entangled space $H \otimes K$ for *any* extension of *K*.**

- **A (non realizable) *positive* map (*P-map*) only satisfies (a): examples: *partial-transpose* of ρ or "*spin-flip*" *(U-NOT)*.**

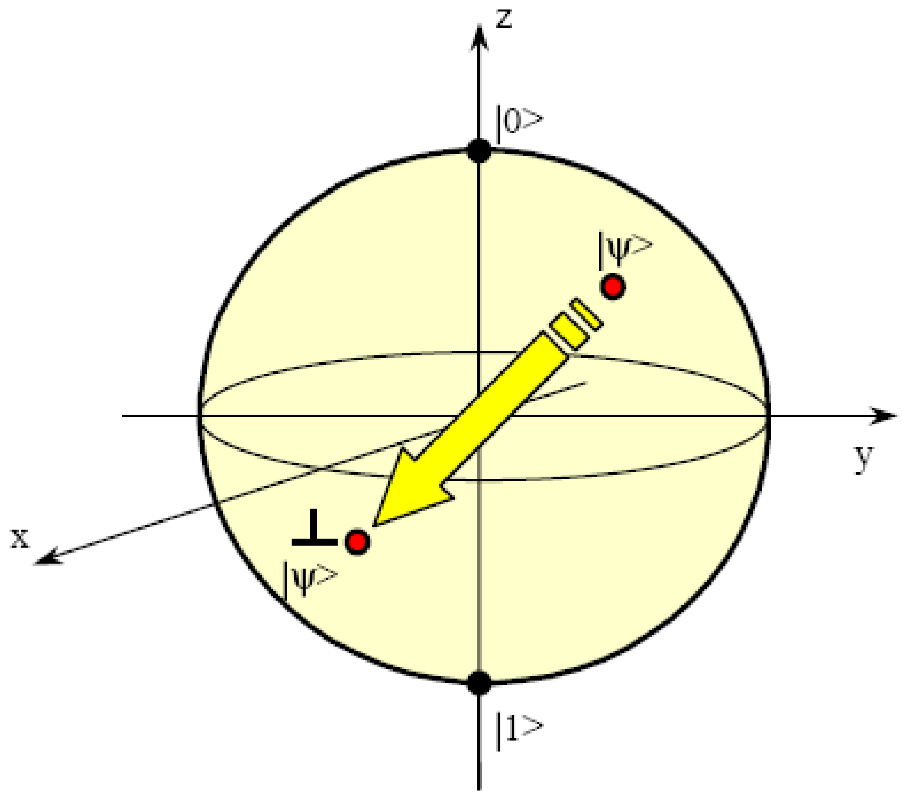
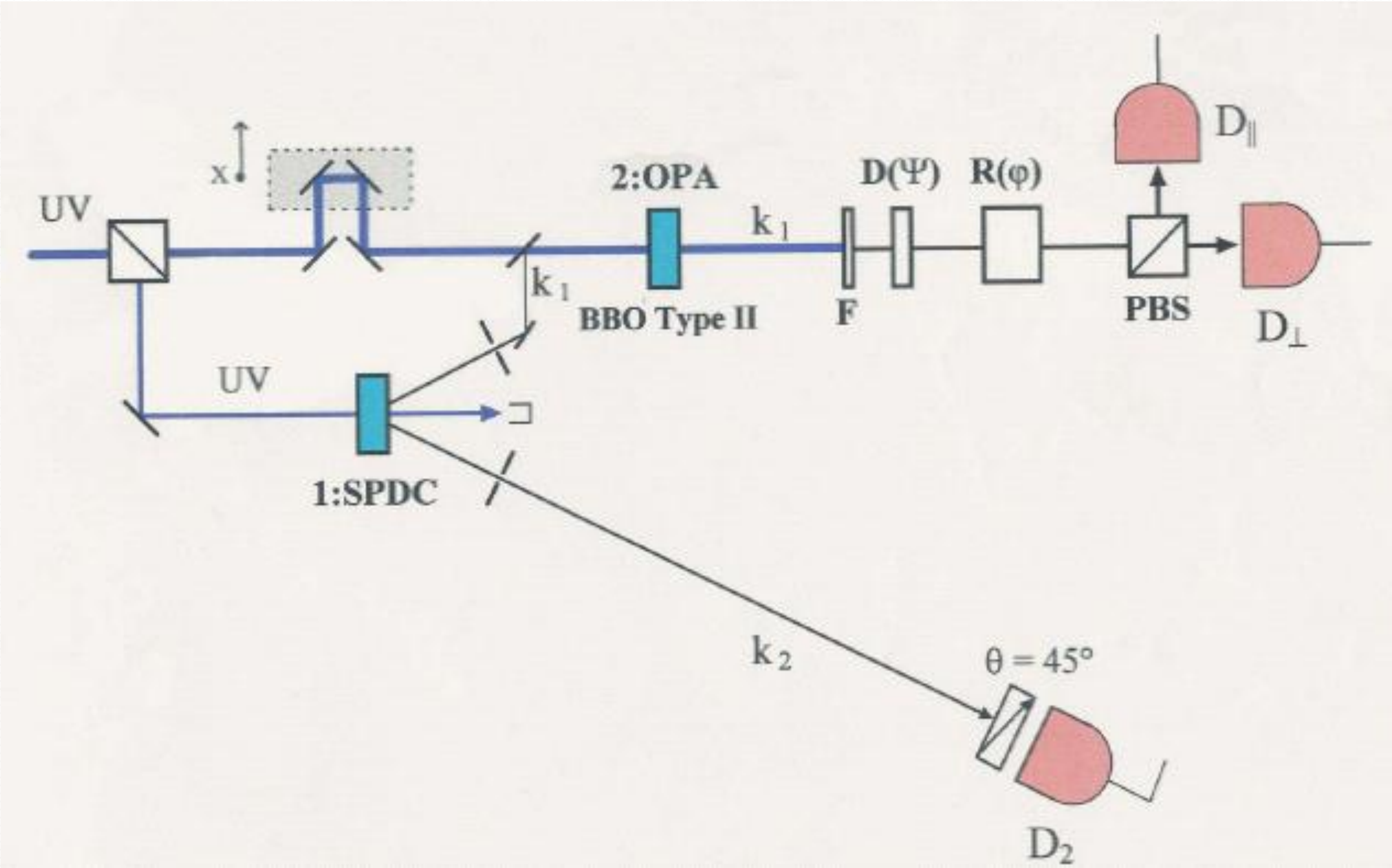


Fig. 29. The universal NOT operation corresponds to the inversion of the sphere, since the states $|\Psi\rangle$ and $|\Psi^{\perp}\rangle$ are antipodes.

Owing to**: NON COMPLETELY - POSITIVE MAP** (CP-MAP)

F.De Martini, S. Buzek et al. NATURE 419, 2002

NL gain: g = 6.5 $\rightarrow$ M $\cong$ 4 $\sinh^2 g$ = 350.000



F.De Martini, Phys.Letters A 250, 15 (1998).

QI-OPA SCHRÖDINGER - CAT: APPLICATIONS TO QUANTUM OPTICS AND QUANTUM INFORMATION

____

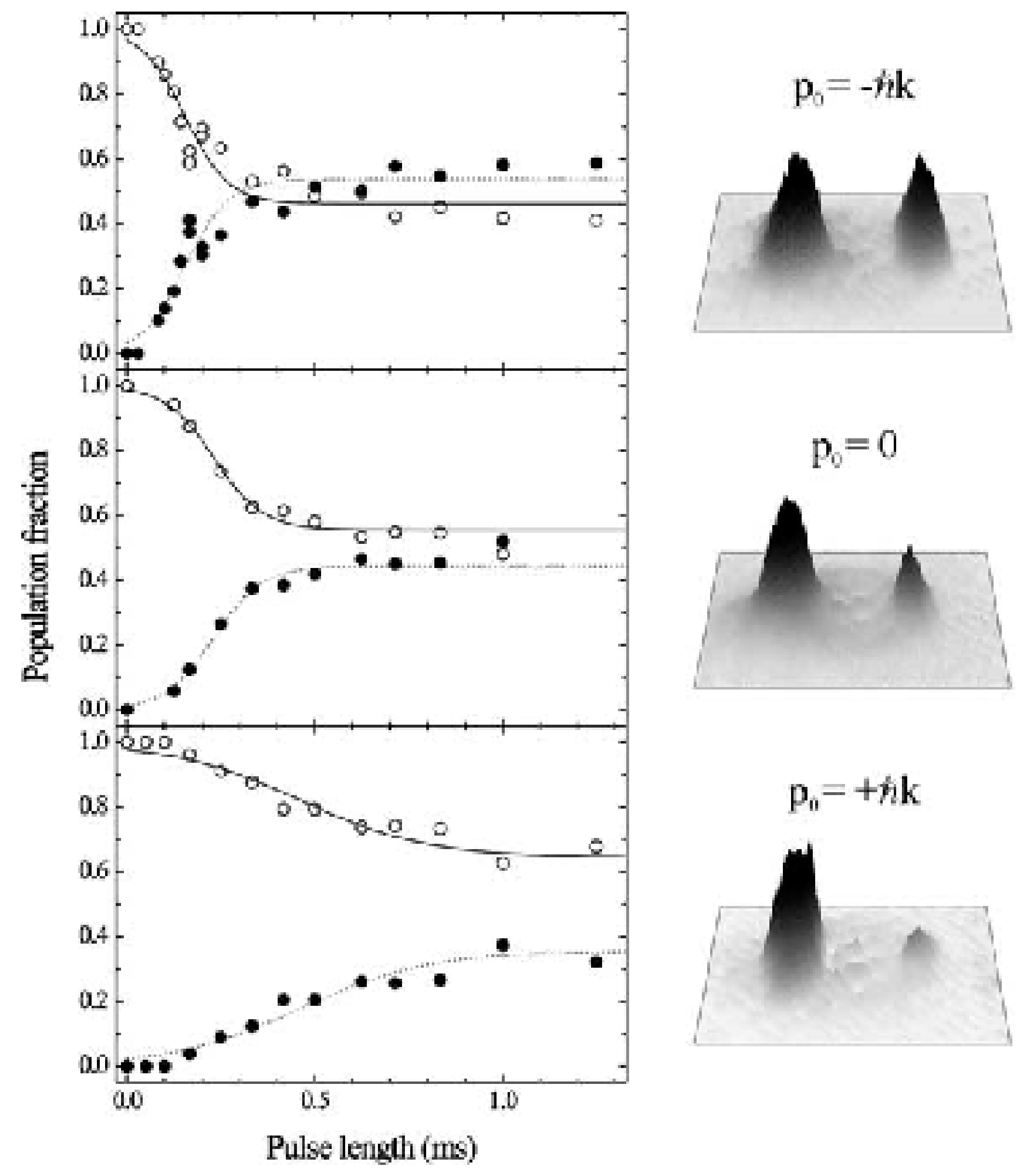
1 – EFFICIENCY AND RESILIENCE TO LOSSES.

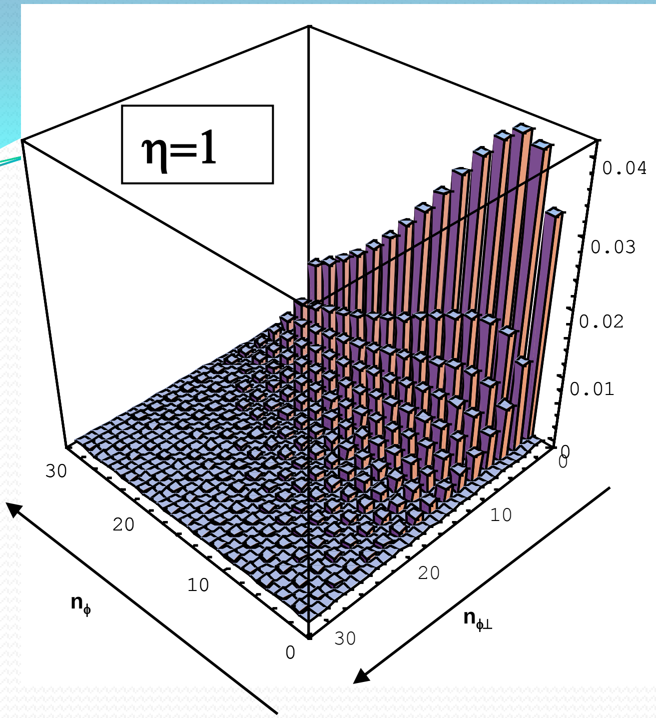
2 – NATURAL REDUNDANCY: NO NEED FOR ERROR – CORRECTION CODING ! (In many applications)

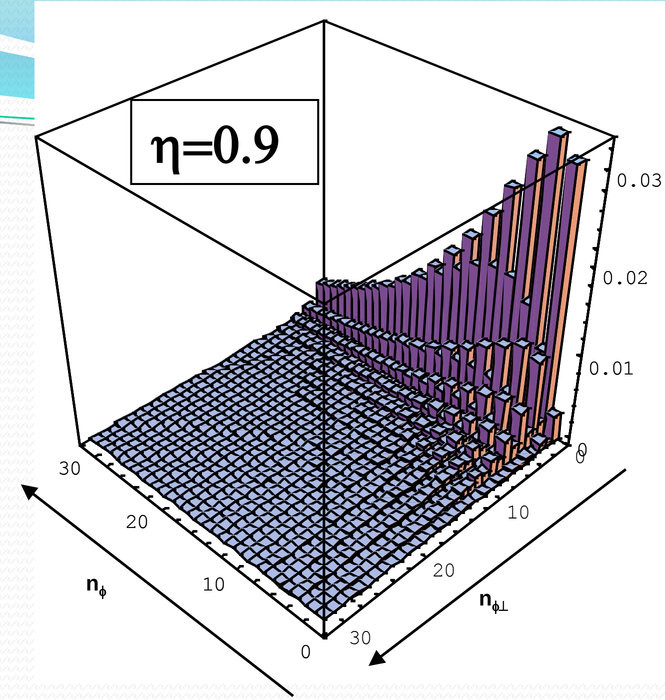
3 – AMPLIFIED QUANTUM – TELEPORTATION.

4 – GENERATION OF PURE HIGH-DEGENERACY FOCK STATES |N>. (by : OF – Filtering)

5 – ENGENEERING OF QUANTUM STATES. (by: OF – F)


Population fraction
Pulse length (ms)
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
$p_0 = -\hbar k$
$p_0 = 0$
$p_0 = +\hbar k$

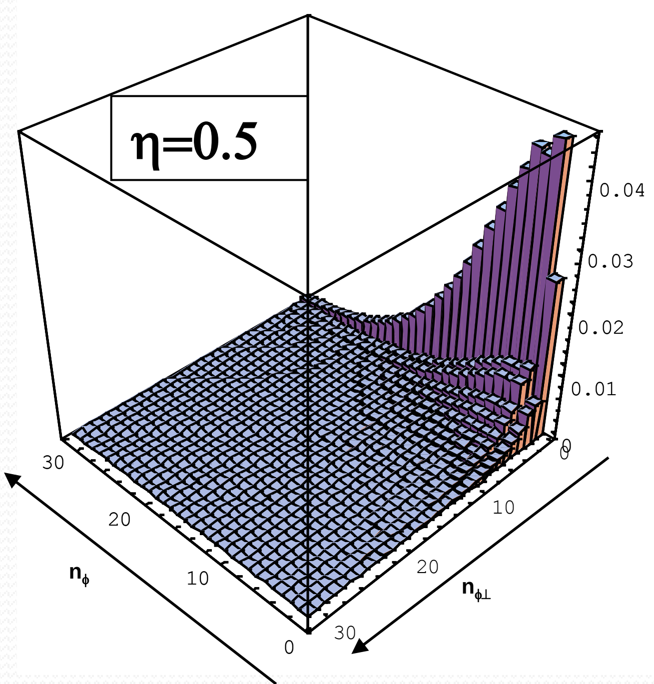


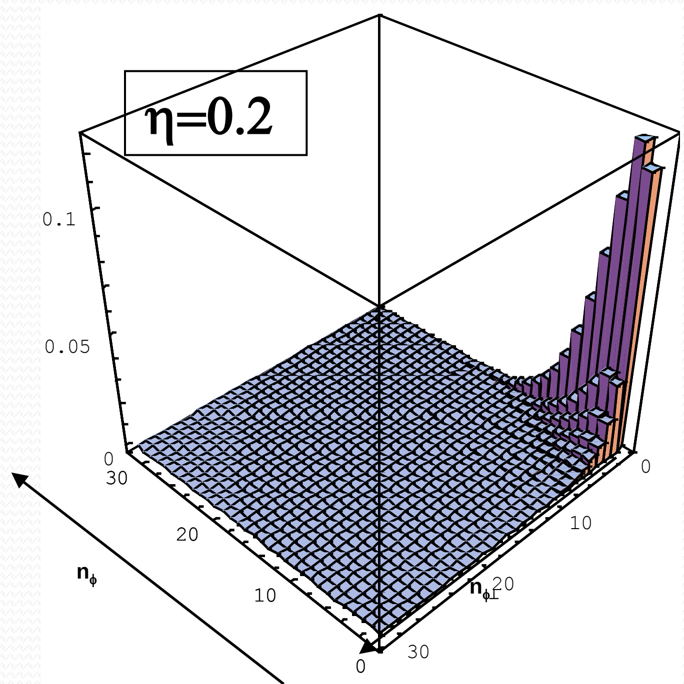


EQUATORIAL QUBIT

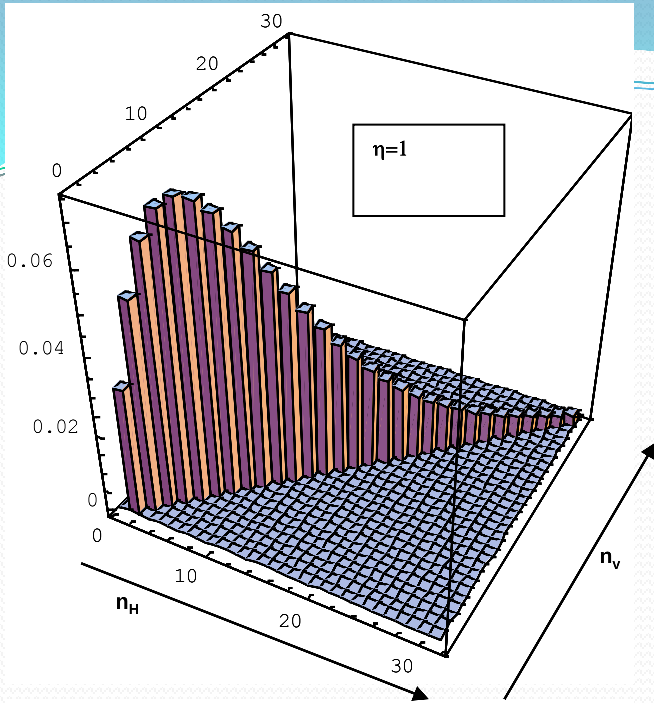
g=1.5

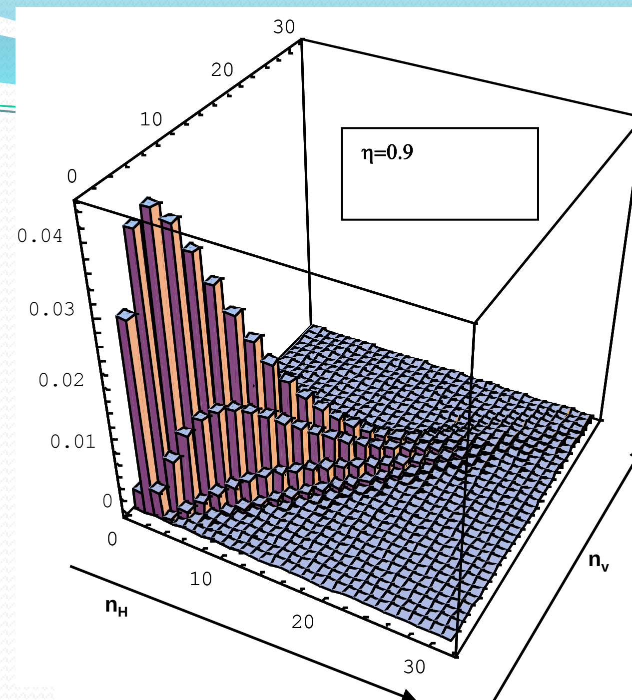
<n>~19





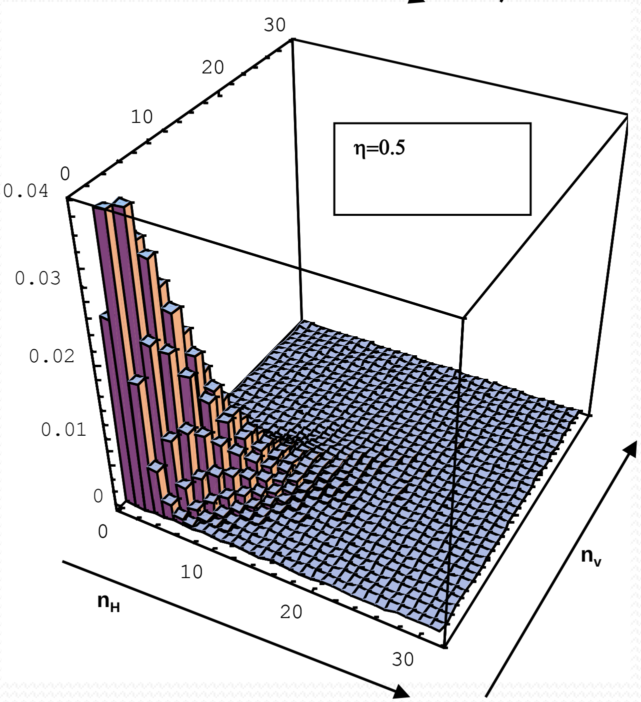
H,V QUBITS

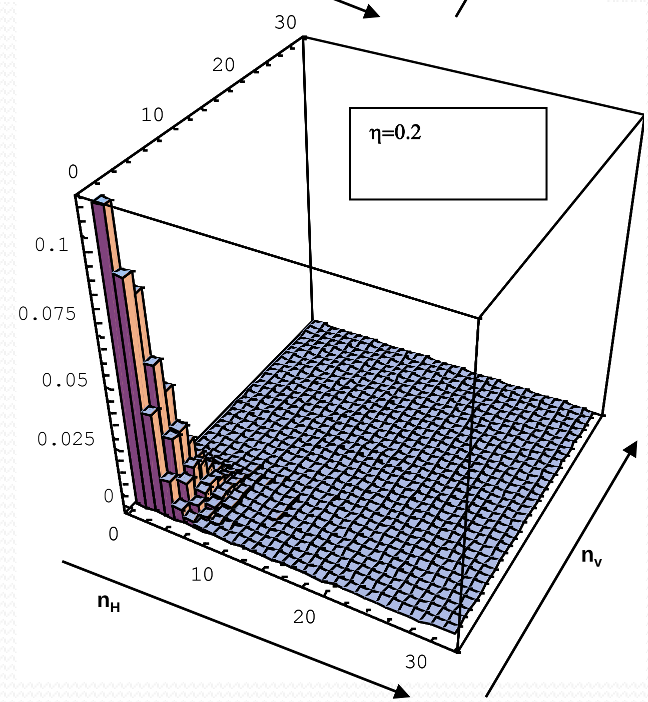




g=1.5

<n>~19





Universal Optimal Quantum Cloning Machine (UOQCM)

$\rho_i = \rho_{j \neq i}$: symmetric cloning

"Fidelity" F independent of $|\phi\rangle_{in}$:"universality"

$$F_{N \to M}^{CLONING} = \frac{N+1+\beta}{N+2}; \quad \beta = \frac{N}{M}$$

$$F_{N \to M}^{ESTIMATION} = \frac{N+1}{N+2}$$

F.De Martini, F.Sciarrino, Phys.Rev.Lett. 92,067901 (2004).
F.De Martini, V.Buzek, F.Sciarrino, C.Sias, NATURE, 419,815 (2002).
D.Pelliccia, F.Sciarrino, F.De Martini, Phys.Rev.A 68, 042306 (2003).

Wigner Function

Evaluated as the 8-dimensional Fourier transform of the symmetrically-ordered characteristic function in terms of the complex phase-space variables $\tilde{\alpha},\tilde{\beta}$: $\{\tilde{\alpha}_j, \tilde{\alpha}_j^*, \tilde{\beta}_j, \tilde{\beta}_j^*\}$ (*):

$$W\{\tilde{\alpha},\tilde{\beta}\} = W_A\{\tilde{\alpha}\}\, W_B\{\tilde{\beta}\} \times [1 - |e^{i\Phi}\Delta_A\{\tilde{\alpha}\} + \Delta_B\{\tilde{\beta}\}|^2]$$

$W_A\{\tilde{\alpha}\} = (2/\pi^2)\exp(-[|\gamma_{A+}|^2 + |\gamma_{A-}|^2])$; $H_I = i\hbar g\,[A^\dagger - e^{i\Phi}B^\dagger] + h.c.$

A): for: $\Delta_A\{\tilde{\alpha}\} = 2^{-1/2}(\gamma_{A+} - i\,\gamma_{A-})$ and:

$\gamma_{A+} \equiv (\tilde{\alpha}_1 + \tilde{\alpha}_2^*)e^{-g}$; $\gamma_{A-} \equiv i(\tilde{\alpha}_1 - \tilde{\alpha}_2^*)e^{+g}$ ["squeezed-variables"]

B): for: $\Delta_B\{\tilde{\beta}\}$ (same as above, with $A \to B$, $\tilde{\alpha} \to \tilde{\beta}$)

(*) F.De Martini, PRL 81,2842 (1998).

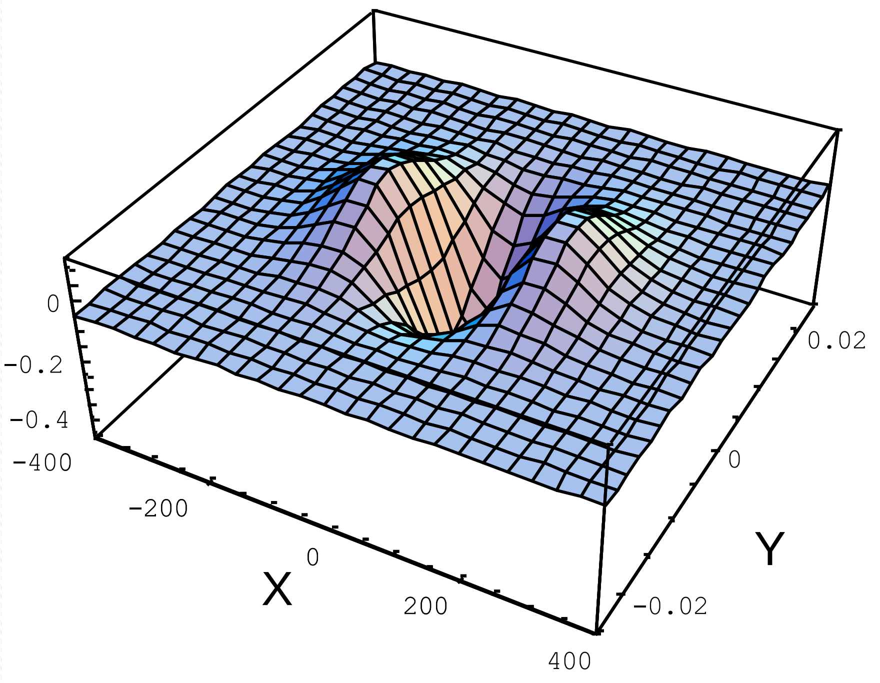
Wigner functions

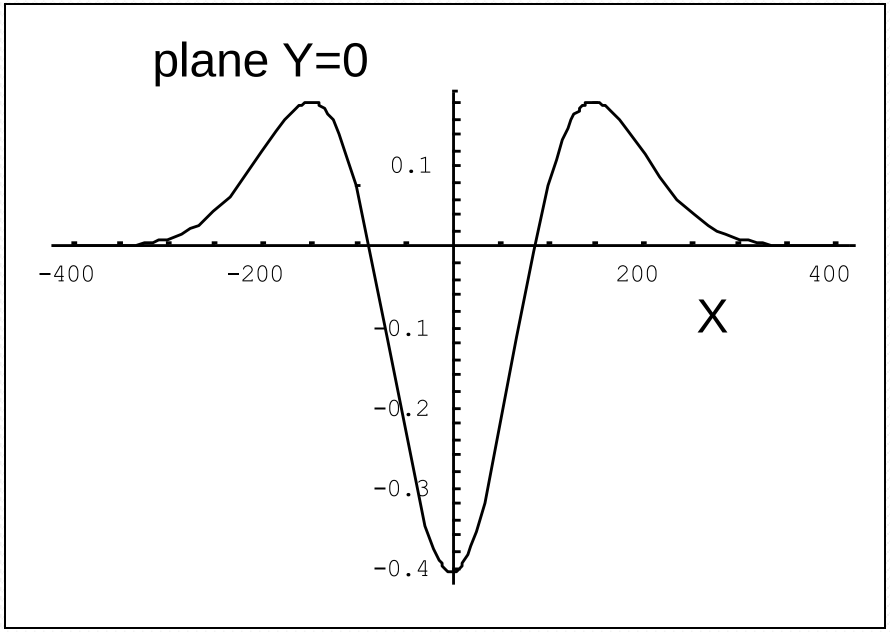
$$\left|\Psi_{IN}\right\rangle = \left|1\right\rangle_{+}\left|0\right\rangle_{-}$$

$$W\{\alpha,\beta\} = -\left(\frac{2}{\pi}\right)^2\left(1-\left|\Delta_{AB}\right|^2\right)\exp\left(-\left|\Delta\right|^2\right)$$

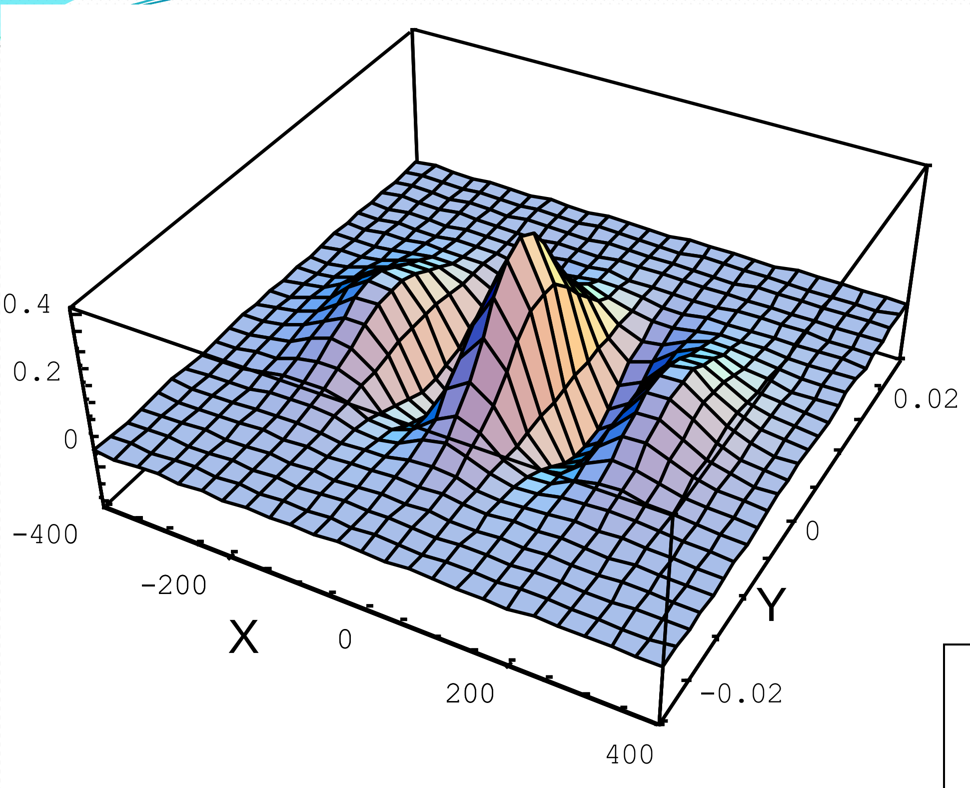
$$\begin{cases} \left|\Delta\right|^2 = \left[\left|\gamma_{A+}\right|^2 + \left|\gamma_{B-}\right|^2\right] \\ \Delta_{AB} = \frac{1}{\sqrt{2}}\left(\gamma_{A+}+\gamma^*_{A+}\right) - \frac{i}{\sqrt{2}}\left(\gamma_{B-}+\gamma^*_{B-}\right) \end{cases}$$

$$\begin{cases} X = \gamma_{A+} = (\alpha+\beta^*)e^{-g} \\ Y = \gamma_{B-} = i(\beta-\alpha^*)e^{+g} \end{cases}$$

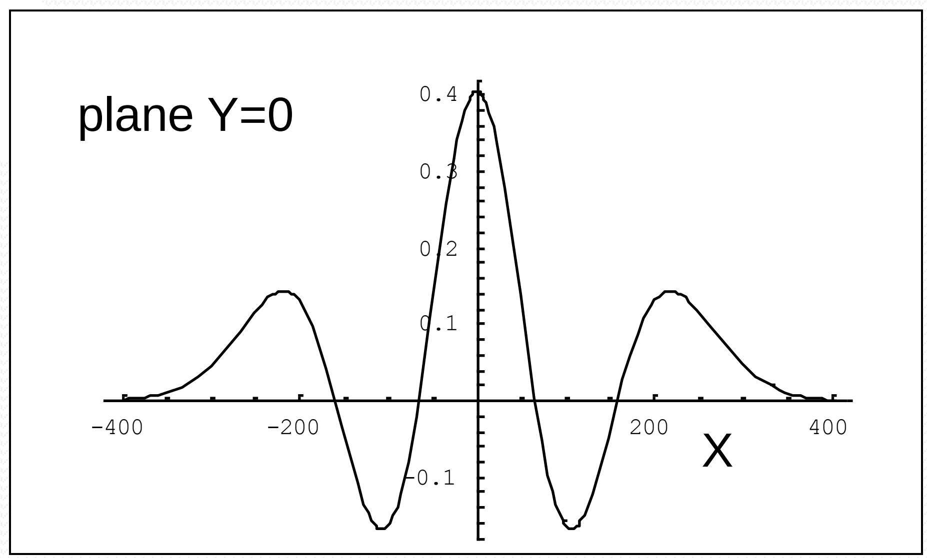




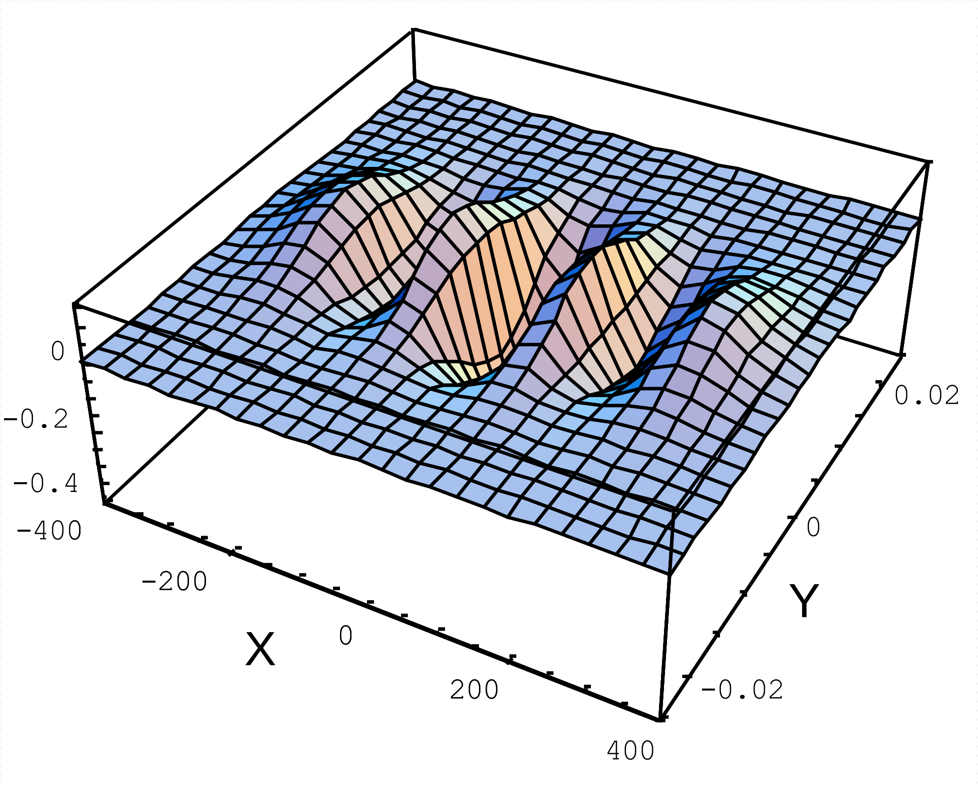
Wigner functions

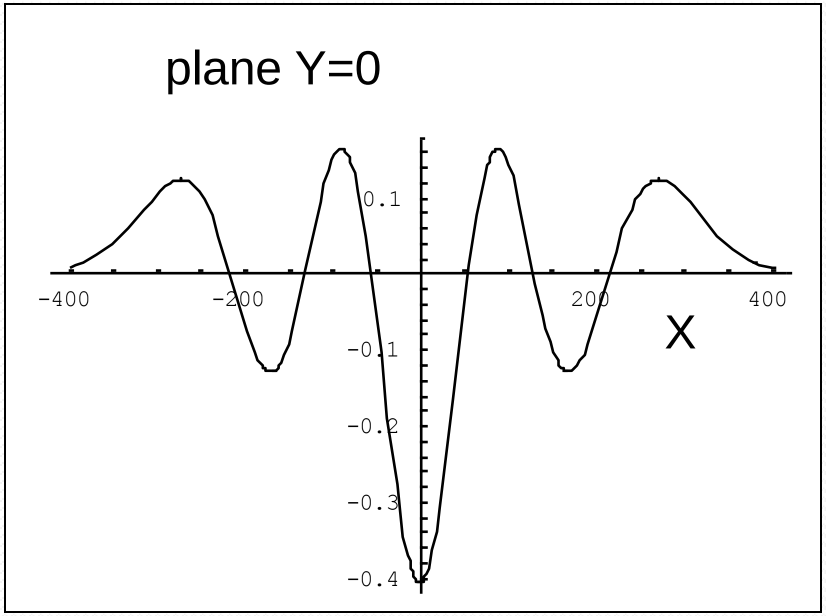


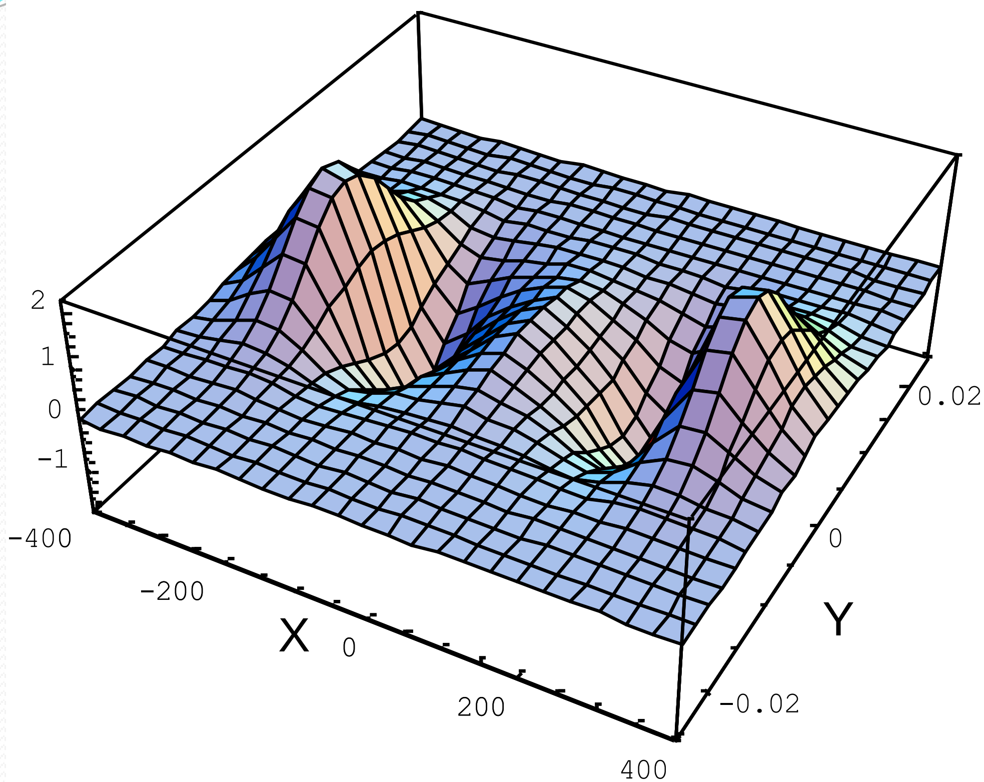
$$|\Psi_{IN}\rangle = |2\rangle_{+}|0\rangle_{-}$$



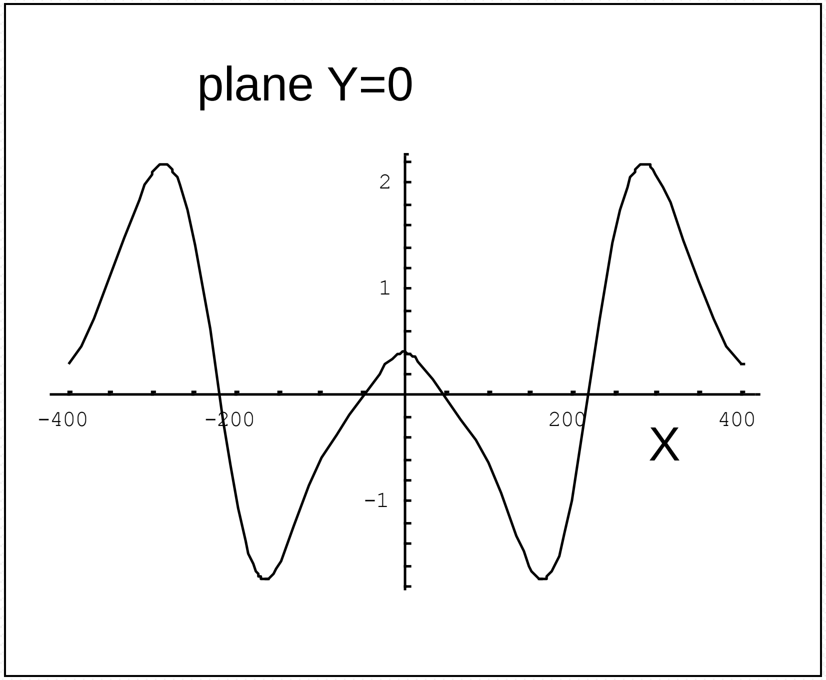
$$|\Psi_{IN}\rangle = |3\rangle_+ |0\rangle_-$$

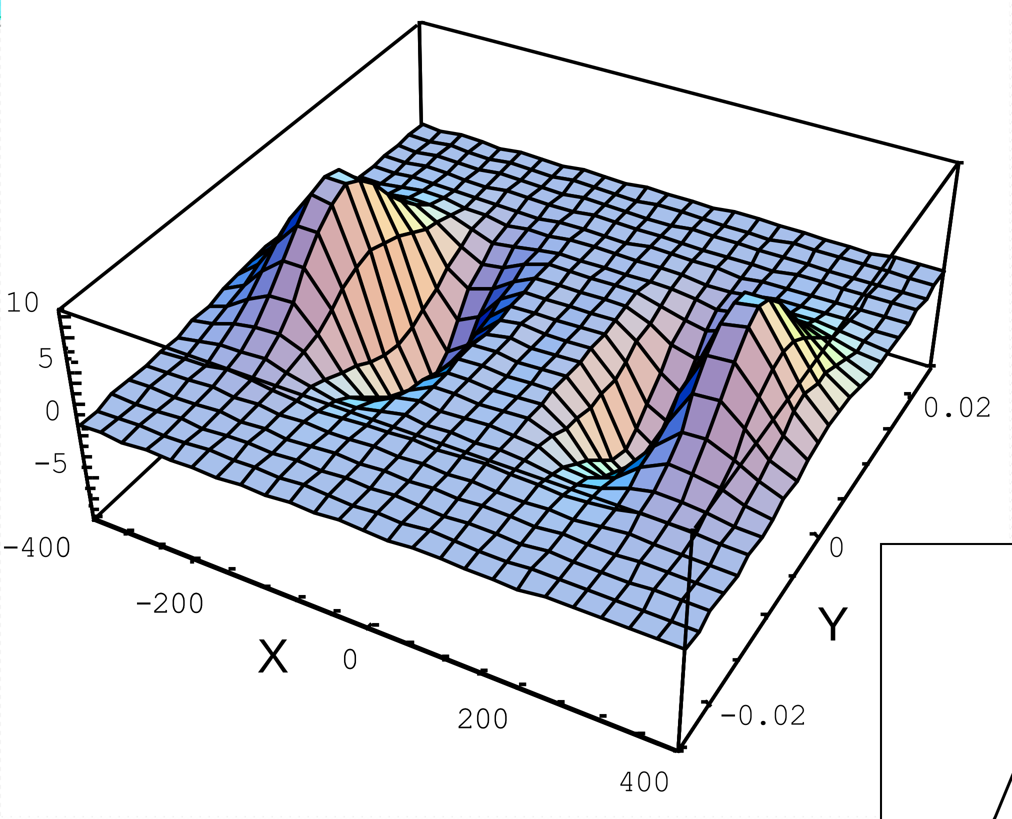




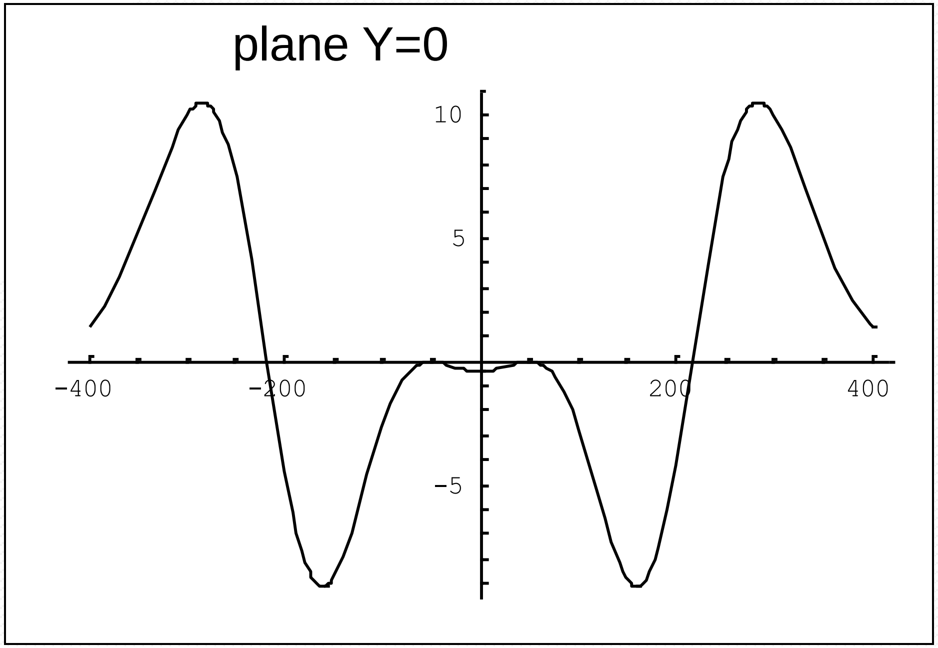


$$\left|\Psi_{IN}\right\rangle = \left|4\right\rangle_{+}\left|0\right\rangle_{-}$$

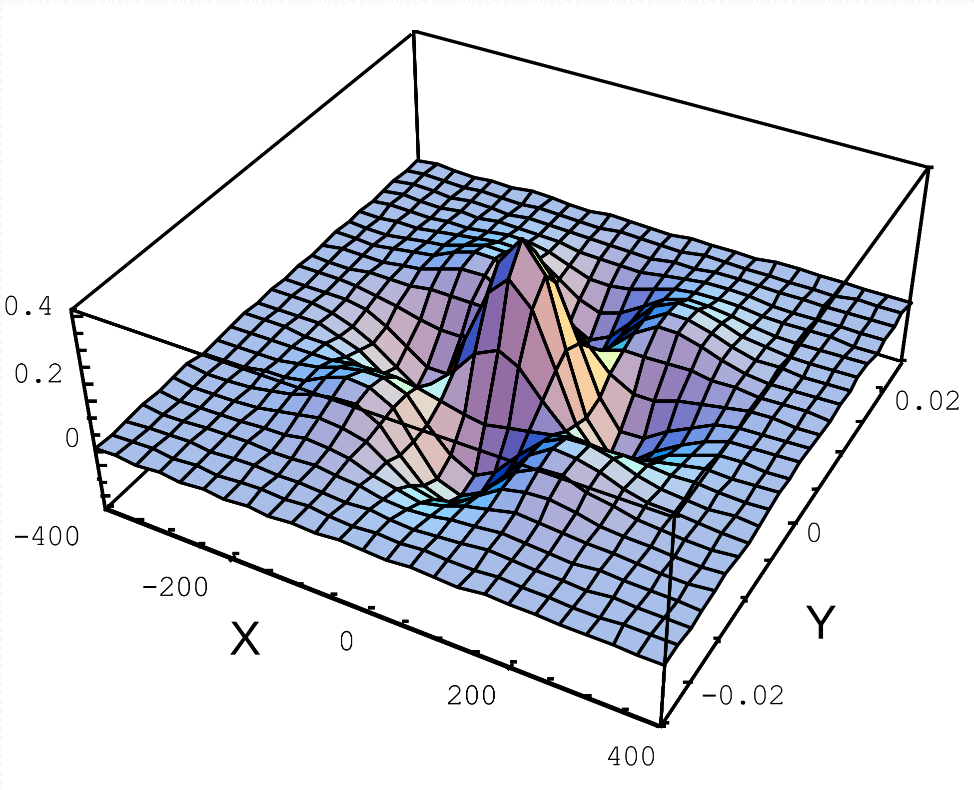


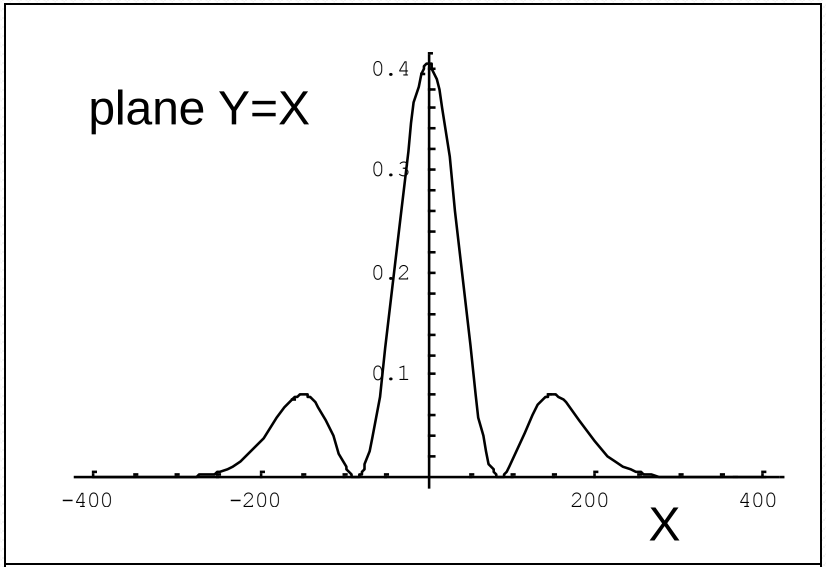


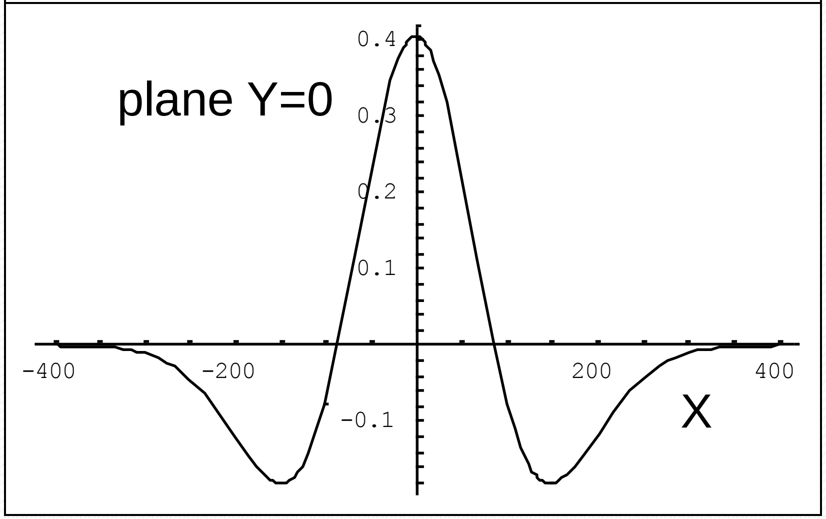
$$|\Psi_{IN}\rangle = |5\rangle_+ |0\rangle_-$$



$$\left|\Psi_{IN}\right\rangle = \left|1\right\rangle_{+}\left|1\right\rangle_{-}$$







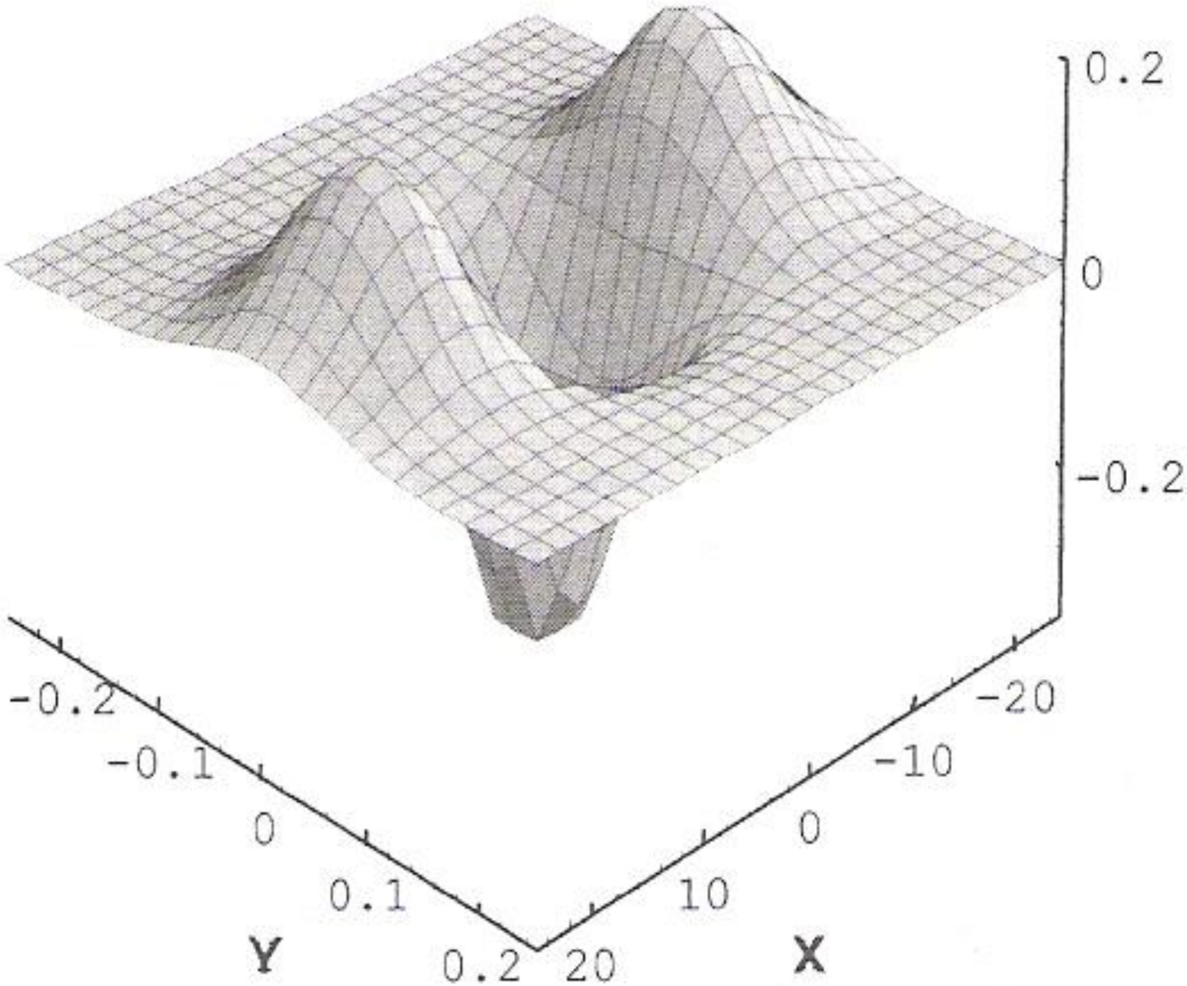
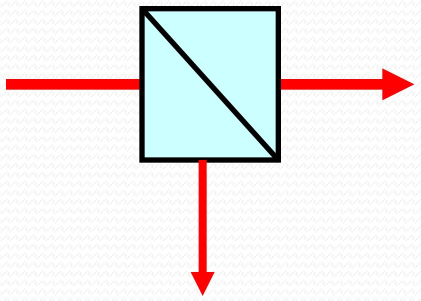


FIG. 2. Tridimensional plot of the Wigner function of the amplified field on mode $\mathbf{k}_2$ at the output of the quantum injected OPA as a function of the squeezed variables: $X = (\alpha + \beta^*)e^{-g}$; $Y = i(\beta - \alpha^*)e^{+g}$, for a parametric gain $g = 2.5$ and $\Delta\Phi = 0$.

QIOPA DECOHERENCE: decrease of the fringe patterns "visibility" V vs stray reflectivity $R_H = |r|^2$ on cloning mode

$$\text{Output } M-\text{qubit}:$$

$$|\phi\rangle_M = \frac{|H\rangle + |V\rangle}{\sqrt{2}}$$

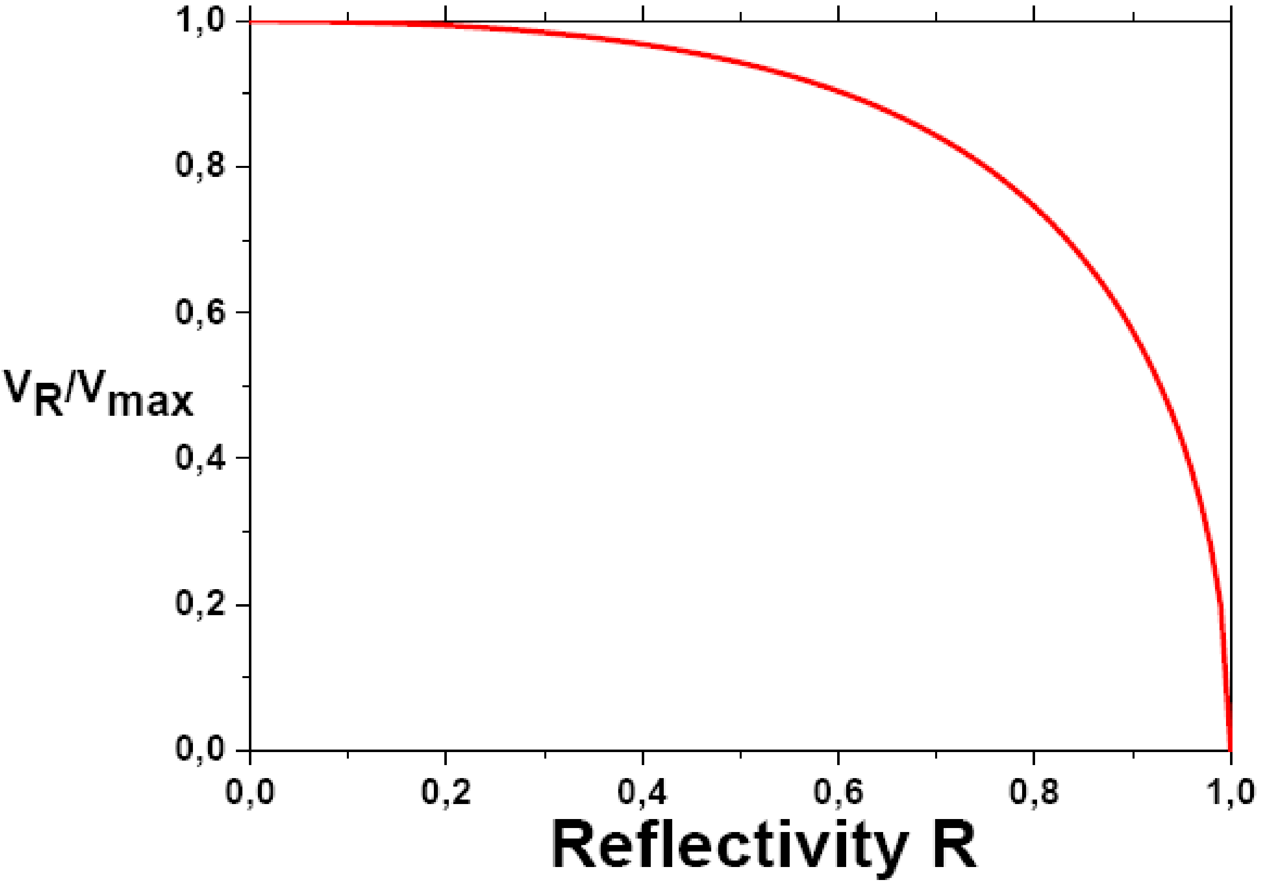


Polarization dependent Reflectivity

$R_V = |r|^2 = 0$, $T_V = |t|^2 = 1$

$V_{max} = (1+2\Gamma^2)^{-1}$

(on cloning mode)



NOTE: High resilience to losses !

$\mathbf{V_R/V_{max}=50\%}$ for an average loss of **90%** of M output particles.

QI-OPA OUTPUT STATE

$$|\Psi\rangle = U_{AB}|\Psi\rangle_{in} \equiv \exp(-igH_I)|\Psi>_{in} =$$

$$=\Sigma_{m:(0\rightarrow M-N)}(-1)^m P_{MN}(m)\times|M-m\rangle_{1h}\otimes|m\rangle_{1v}\otimes|m\rangle_{2h}\otimes|M-N-m\rangle_{2v}$$

$$|\Psi\rangle_{in} = (\alpha|\Phi^\alpha\rangle_{in} + \beta|\Phi^\beta\rangle_{in})$$

$$|\Psi\rangle = (\alpha|\Phi^\alpha\rangle_{out} + \beta|\Phi^\beta\rangle_{out})$$

SCHROEDINGER CAT STATE !
(Massive Qubit)

S-CAT state: $|\Psi\circledast = (\alpha\, |\Phi^{\alpha}\circledast_{out} + \beta\, |\Phi^{\beta}\circledast_{out})$

:

$$|\Phi^{\alpha}\circledast_{out} = C^{-3} \sum_{i,j=0}^{\infty} \Gamma^{i+j} (-1)^{j} \sqrt{i+1}\, |i+1, j, j, i\rangle$$

$$|\Phi^{\beta}\circledast_{out} = C^{-3} \sum_{i,j=0}^{\infty} \Gamma^{i+j} (-1)^{j} \sqrt{j+1}\, |i, j+1, j, i\rangle$$

$$< \Phi^{\alpha} \,|\Phi^{\beta}\circledast_{out} = 0 \;; \qquad < \Phi^{\alpha} \,|\, \Phi^{\alpha}\circledast_{out} = < \Phi^{\beta} \,|\Phi^{\beta}\circledast_{out} = 1$$

$$|a,b,c,d\rangle \equiv |a\rangle_{1h} \otimes |b\rangle_{1v} \otimes |c\rangle_{2h} \otimes |d\rangle_{2v}$$

C=coshg, Γ=tanhg,

"…..A cat is penned up in a steel chamber, along with the following diabolical devices……

…… It is typical in these cases that an indeter-minacy originally restricted to the atomic domain becomes transformed into macroscopic indeterminacy, which can be *resolved* by direct observation. That prevent us from naively accepting as valid a "blurred model" for

representing reality….."

Erwin Schroedinger, Naturwissenschaften 23, 807, 1935
"The present situation in quantum mechanics"

Wigner Function

Evaluated as the 8-dimensional Fourier transform of the symmetrically-ordered characteristic function in terms of the complex phase-space variables: $\{\tilde{\alpha}, \tilde{\beta}\} = \{\tilde{\alpha}_j, \tilde{\alpha}_j^*, \tilde{\beta}_j, \tilde{\beta}_j^*\}$ (*):

$$\mathbf{W}\{\tilde{\alpha}, \tilde{\beta}\} = \mathbf{W}_A\{\tilde{\alpha}\}\, \mathbf{W}_B\{\tilde{\beta}\} \times [1 - |e^{i\Phi}\Delta_A\{\tilde{\alpha}\} + \Delta_B\{\tilde{\beta}\}|^2]$$

$\mathbf{W}_A\{\tilde{\alpha}\} = (2/\pi^2)\exp(-[|\gamma_{A+}|^2 + |\gamma_{A-}|^2])$; $H_I = i\hbar g\,[A^\dagger - e^{i\Phi}B^\dagger] + h.c.$

A): for: $\Delta_A\{\tilde{\alpha}\} = 2^{-1/2}(\gamma_{A+} - i\,\gamma_{A-})$ and:

$\gamma_{A+} \equiv (\tilde{\alpha}_1 + \tilde{\alpha}_2^*)e^{-g}$; $\gamma_{A-} \equiv i(\tilde{\alpha}_1 - \tilde{\alpha}_2^*)e^{+g}$ [“squeezed-variables”]

B): for: $\Delta_B\{\tilde{\beta}\}$ (same as above, with $A \to B$, $\tilde{\alpha} \to \tilde{\beta}$)

(*) F.De Martini, PRL 81,2842 (1998).

QI-OPA: realization of the Quantum Map

$$\left|\Psi_{in}\right\rangle = \alpha\left|+\right\rangle + \beta\left|-\right\rangle \quad ;\left|\pm\right\rangle = 2^{-1/2}(\left|h\right\rangle \pm \left|v\right\rangle)$$

$$;\left|R/L\right\rangle = 2^{-1/2}(\left|h\right\rangle \pm i\left|v\right\rangle)$$

$$\left|\Psi\right\rangle_{out} = \hat{U}_{OPA}\left|\Psi_{in}\right\rangle = \alpha\left|\Psi(+)\right\rangle + \beta\left|\Psi(-)\right\rangle$$

Coherent states

Classical states

states generated by a classical source

$$|\alpha\rangle = D(\alpha)|0\rangle$$

D(α): displacement operator

$$D(\alpha) = e^{\alpha a^\dagger - \alpha^* a}$$

As a function of Fock states:

$$|\alpha\rangle = e^{-|\alpha|^2/2} \sum_n \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

Average photon number:

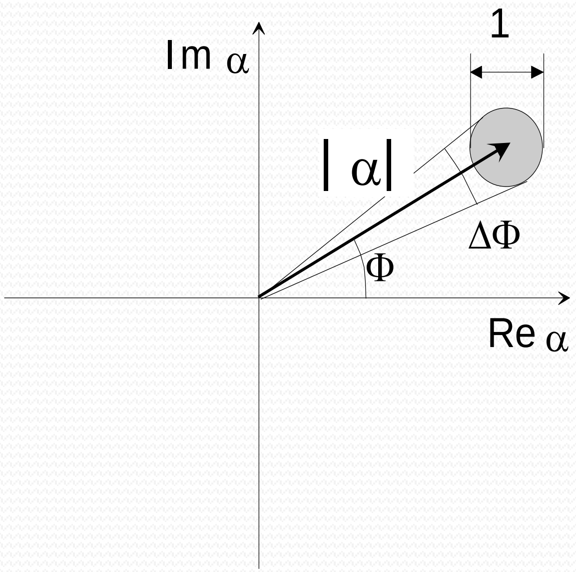
$$\bar{n} = |\alpha|^2$$

Photon number dispersion:

$$\Delta n = \sqrt{\bar{n}}$$

A representation:

- phase space
- coherent state = complex classical amplitude plus quantum fluctuations



MACROSCOPIC SUPERPOSITION:

$$|\Phi_\alpha\rangle = N \frac{1}{\sqrt{2}} \left(|\alpha\rangle \pm |-\alpha\rangle \right)$$

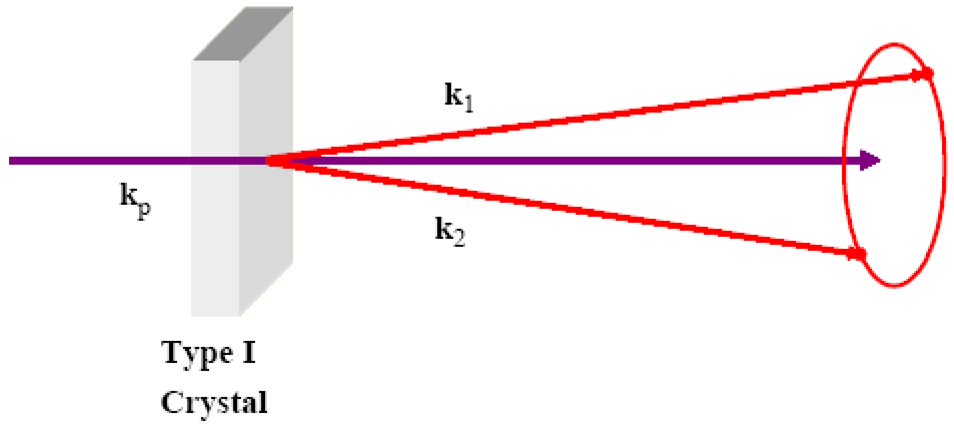
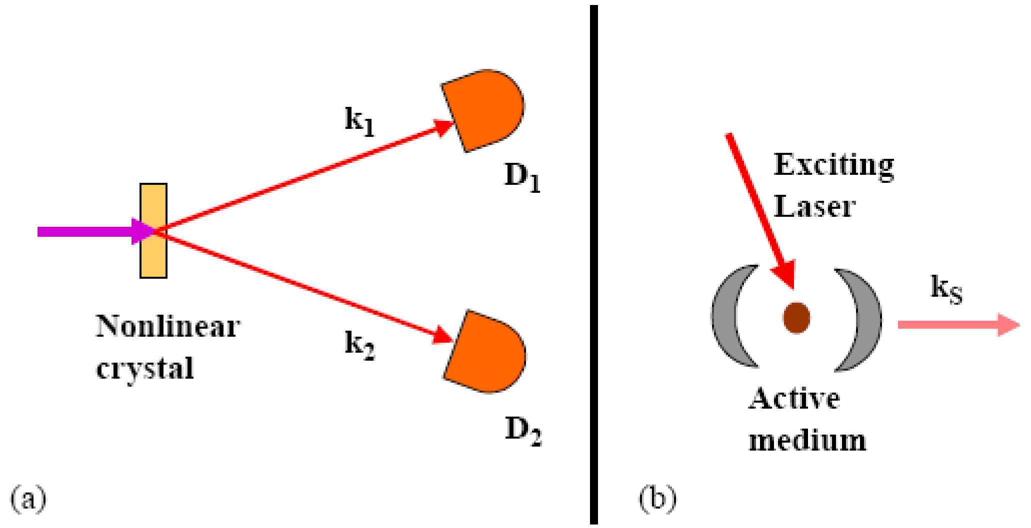


Fig. 10. Type I phase-matched SPDC process.



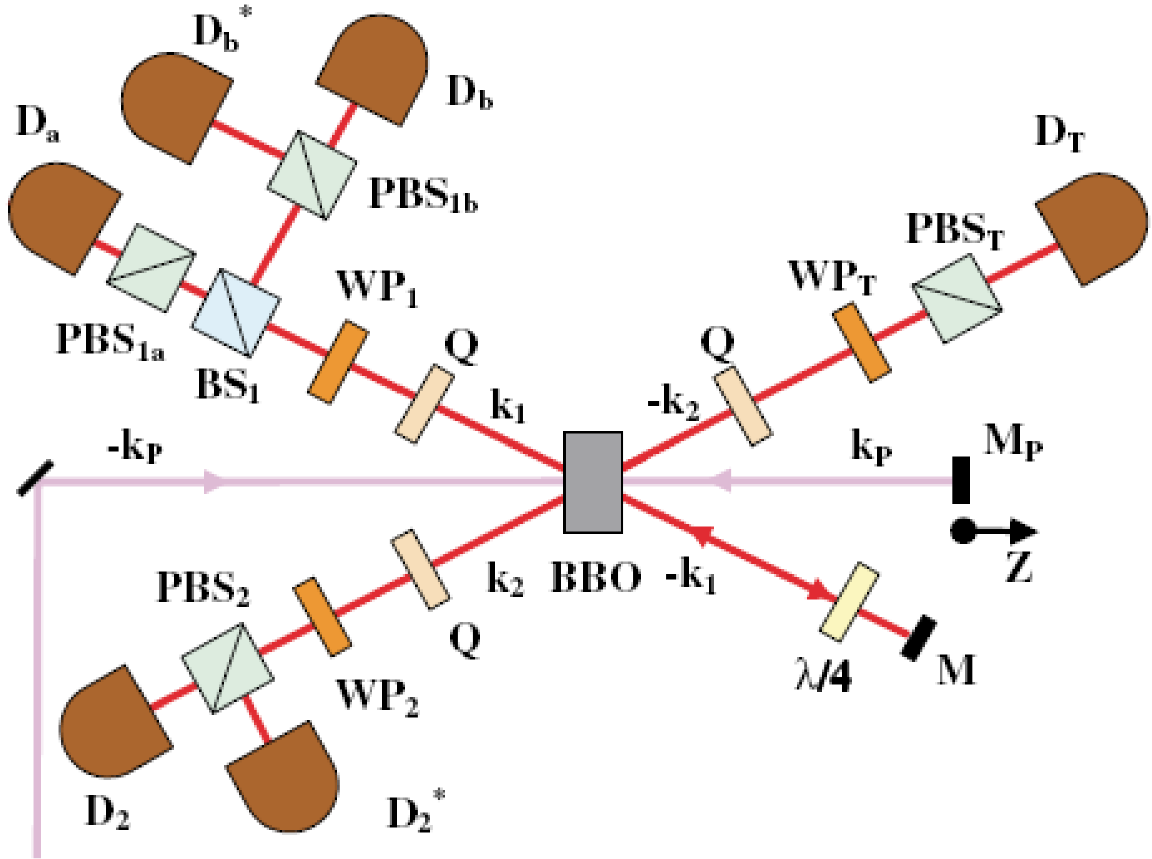
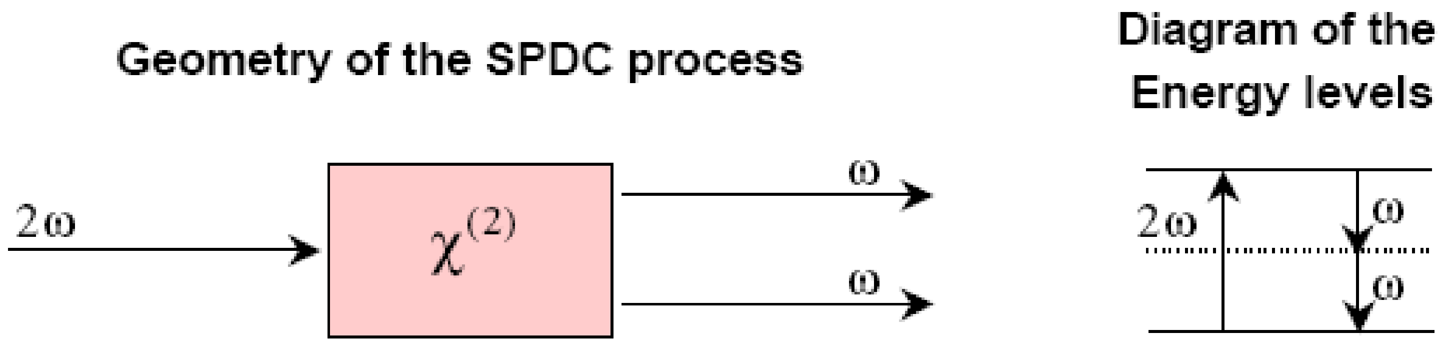


FIG. 1 (color online). Schematic diagram of the universal optimal cloning machine (UOQCM) realized on the cloning (C) channel (mode k_1) of a self-injected OPA and of the Universal NOT (U-NOT) gate realized on the anticloning (AC) channel, k_2.



. Schematic representation of the spontaneous parametric down-conversion (SPDC) process.

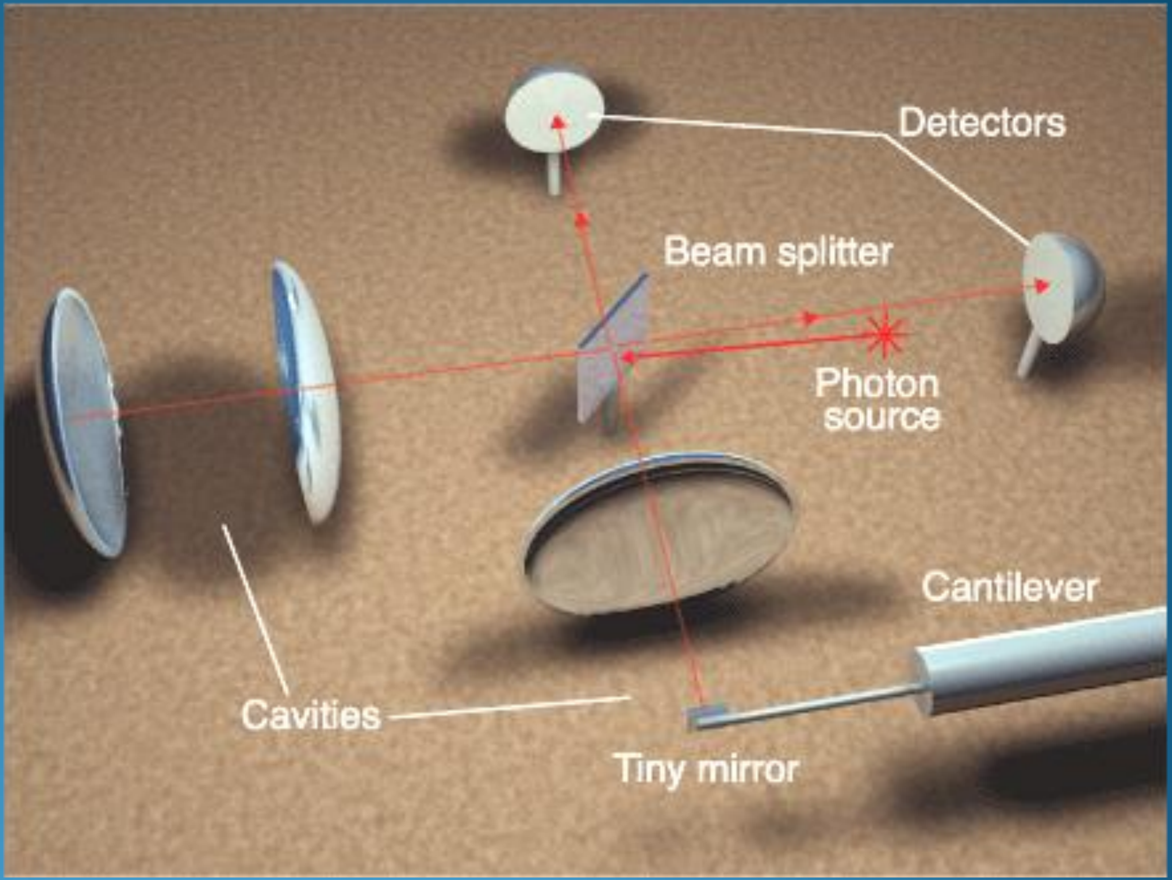
Phase-Matching Conditions:

$$\nu_P = \nu_1 + \nu_2,$$
$$\vec{k}_P = \vec{k}_1 + \vec{k}_2,$$

O-Filter: “local”Noise Reduction process counteracting the deterimental effects of the quantum no-cloning theorem due to QI-OPA

Penrose's cat (2003)

Mirror: 10 micrometers wide



W. Marshall, C. Simon, R. Penrose, and D. Bouwmeester, *Phys. Rev. Lett.* **91**, 130401 (2003)
C. Seife, "Quantum Experiment Asks 'How Big Is Big?'" *Science* **29**8, 342 (2002)

General characters of modern scientific endeavor :

20th Century

REDUCTIONISM = Search for the smallest

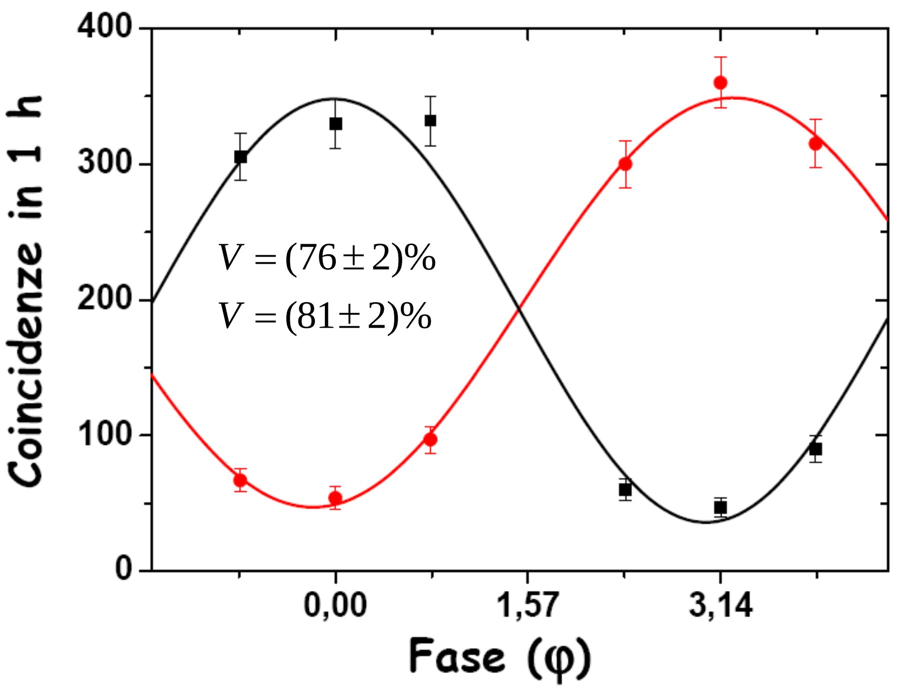
21th Century:

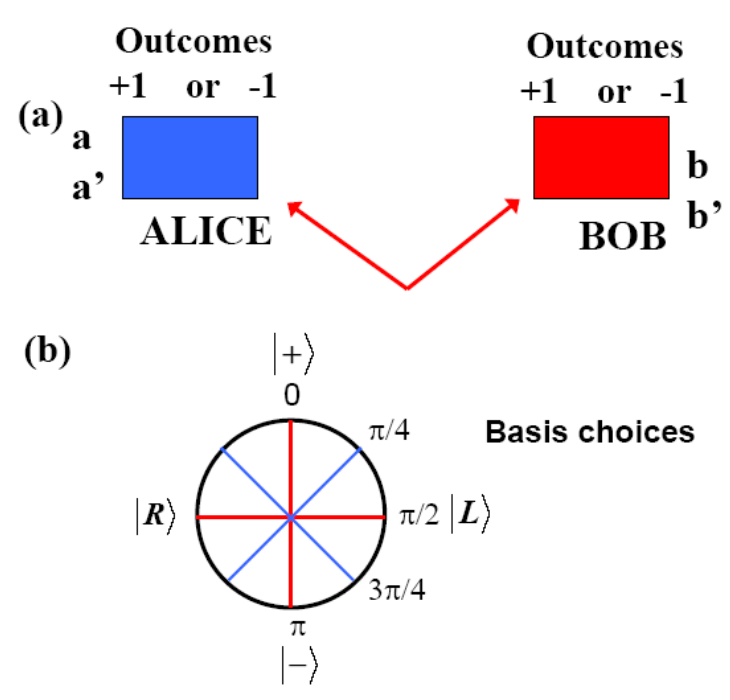
HOLISM = Union of the Microscopic system and of the Macroscopic world

Elementary particles -Physical vacuum ;
Micro - Macroscopic particle entanglement ;
Schroedinger – Cat ;
Mathematical, Physical, Biological Complexity)

Tsung-Dao Lee, Nobel Prize 1957 for parity nonconservation in weak interactions
Workshop: "Max Planck and the rise of the new Physics" , Accademia dei Lincei, Roma 2000.

Test of CHSH inequalities: experimental results



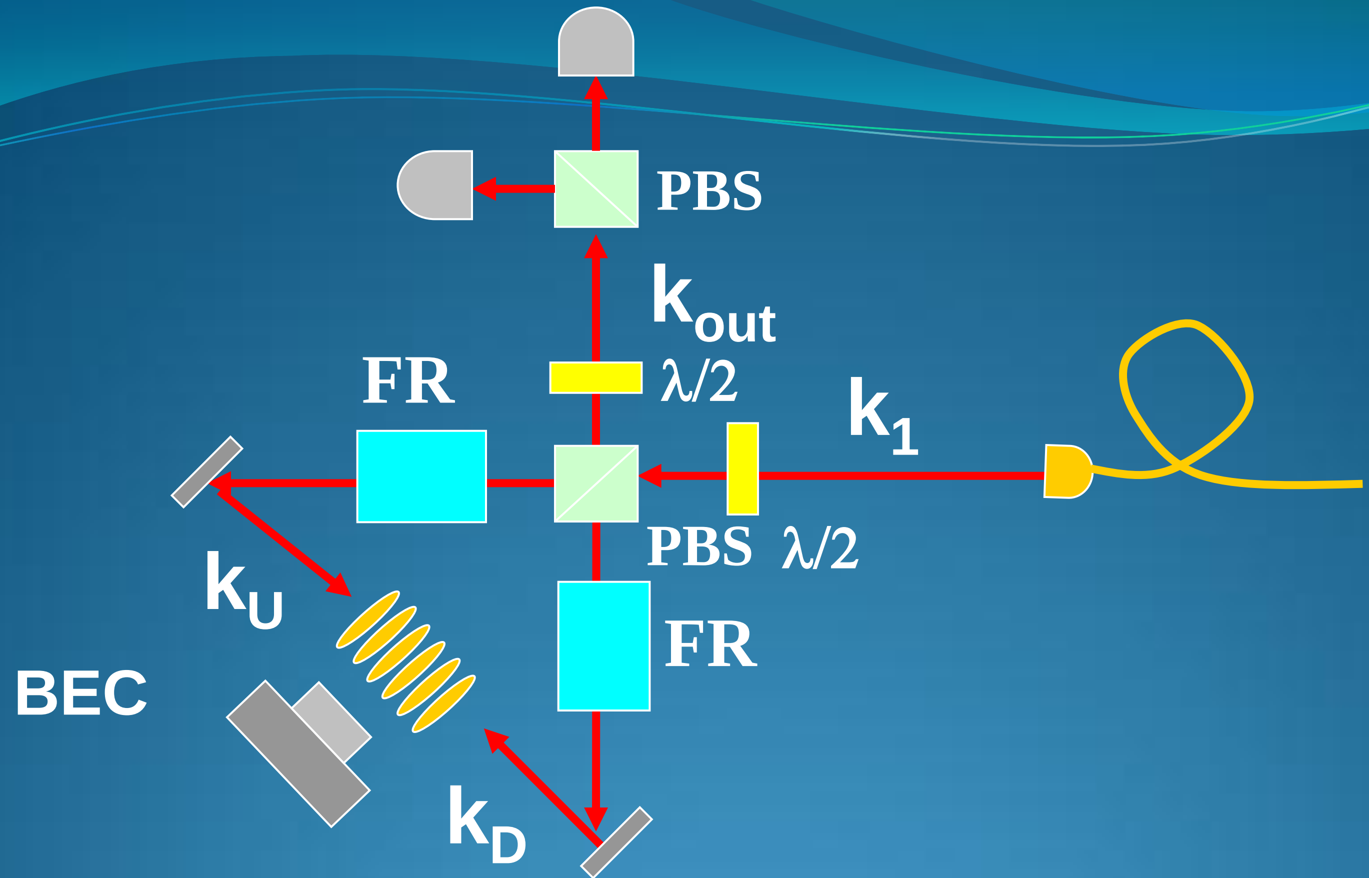


$$S = E(\varphi_1, \varphi_2) + E(\varphi_1', \varphi_2) + E(\varphi_1, \varphi_2') - E(\varphi_1', \varphi_2')$$

For a local realistic theory

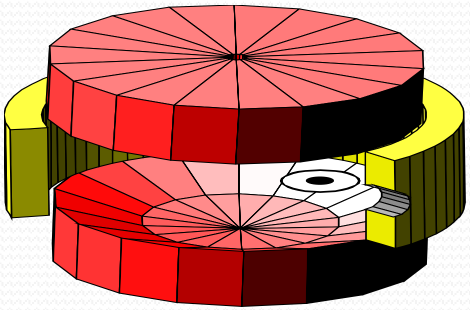
$$|S| \leq S_{CHSH} = 2$$

$$S_{\exp} = 2.25 \pm 0.05 > S_{CHSH} = 2$$



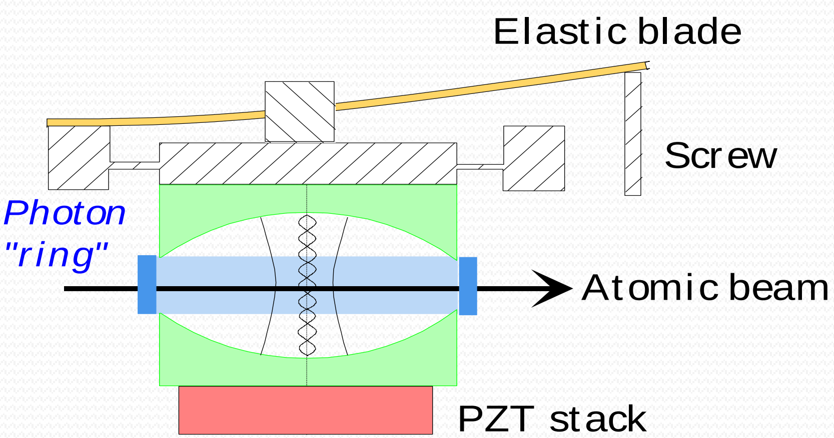
Measurement of entanglement

Superconducting cavity

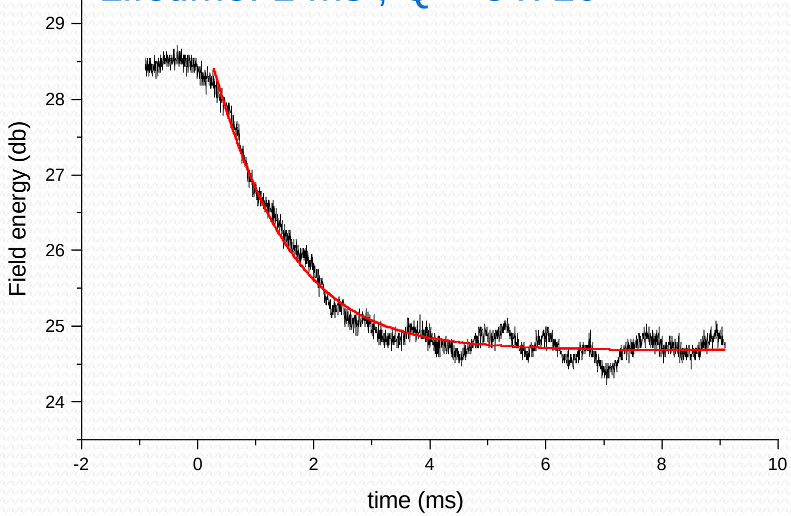


Polished Niobium mirrors

- Open Fabry Perot cavity with a photon "recirculation" ring
- Compatible with a static electric field (circular states stability and Stark tuning)



Lifetime: 1 ms ; Q = 3 x 10^8



Efficient Long Range Communication by Quantum Injected Optical Parametric Amplification

PSATS – QUEST 2010

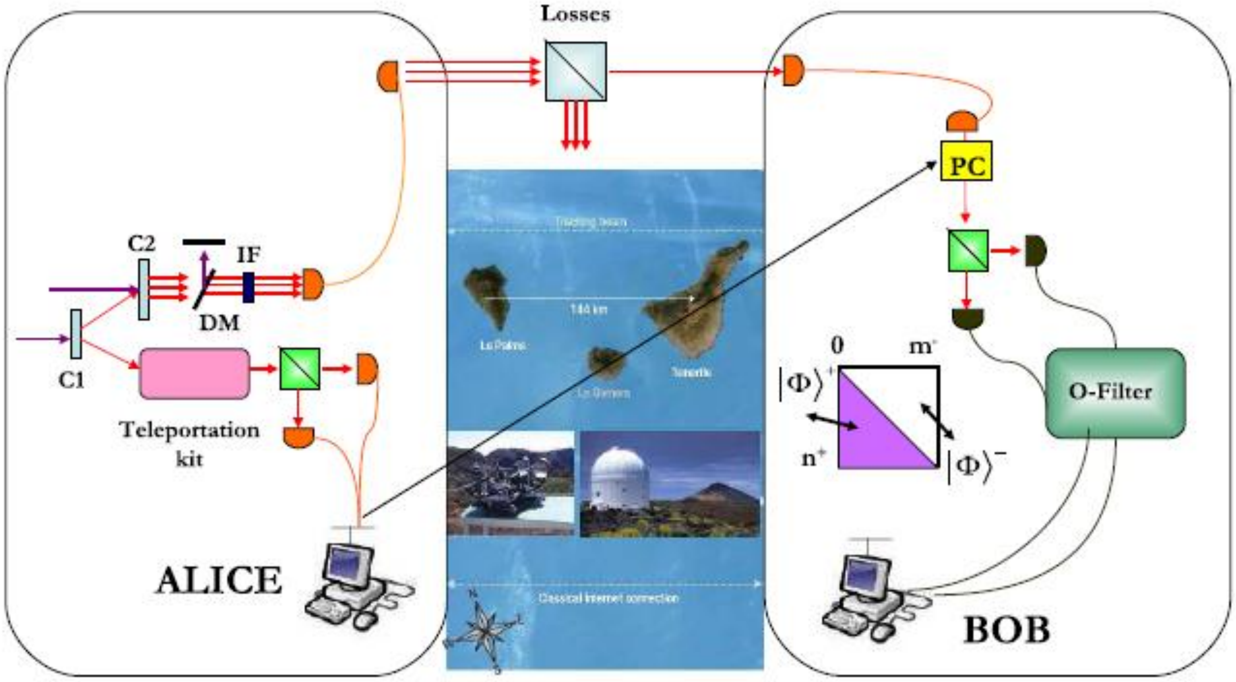
Chiara Vitelli, Lorenzo Toffoli,

Fabio Sciarrino, Francesco De Martini

Invited by: Rupert Ursin, Wien

Micro-Macro Teleportation:

With the present system we could realize the teleportation of a single-photon qubit between the Alice's site and a corresponding photonic macrostate transmitted by a long-range free space link to a Bob's site.



Outline

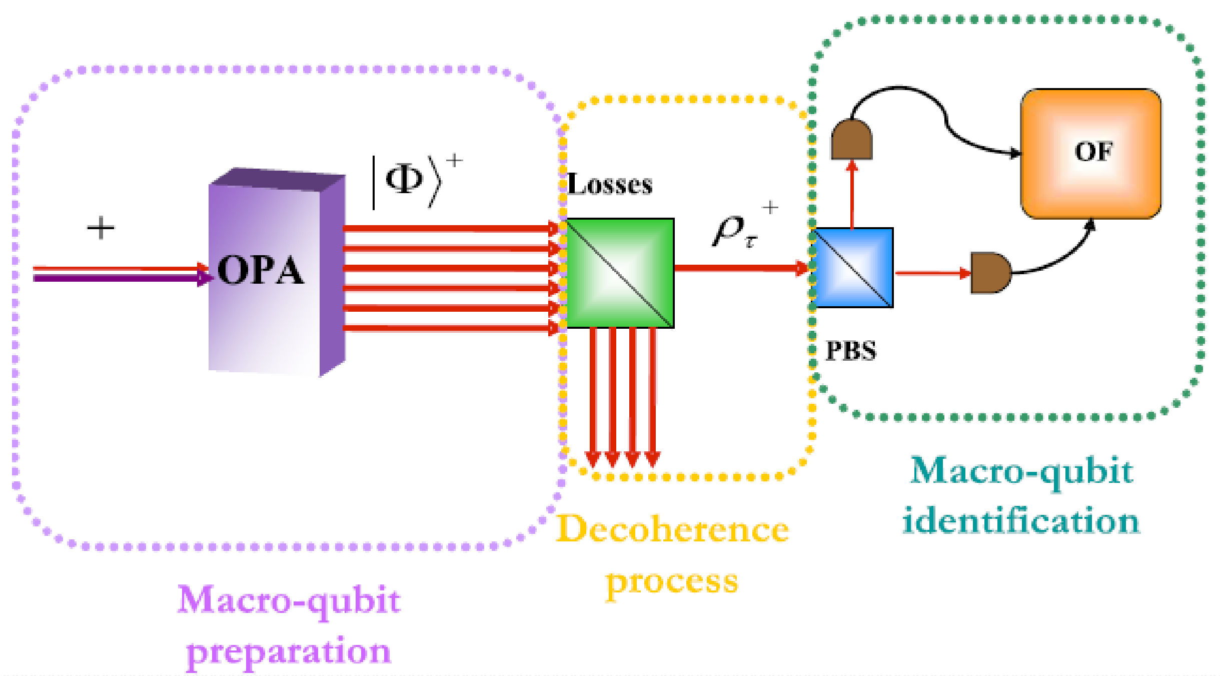
- Free-space optical communications over long distances are associated with severe losses.

- In order to enhance the transmission Efficiency we propose the use of macro quantum states of light consisting in thousand of photons and obtained through an optical parametric amplification process.

  → We address the problem of the discrimination of such macro states, in connection with the transmission fidelity after the propagation over a lossy channel

  → We consider the realization of a Micro-Macro Teleportation experiment as a possible application for this quantum resource

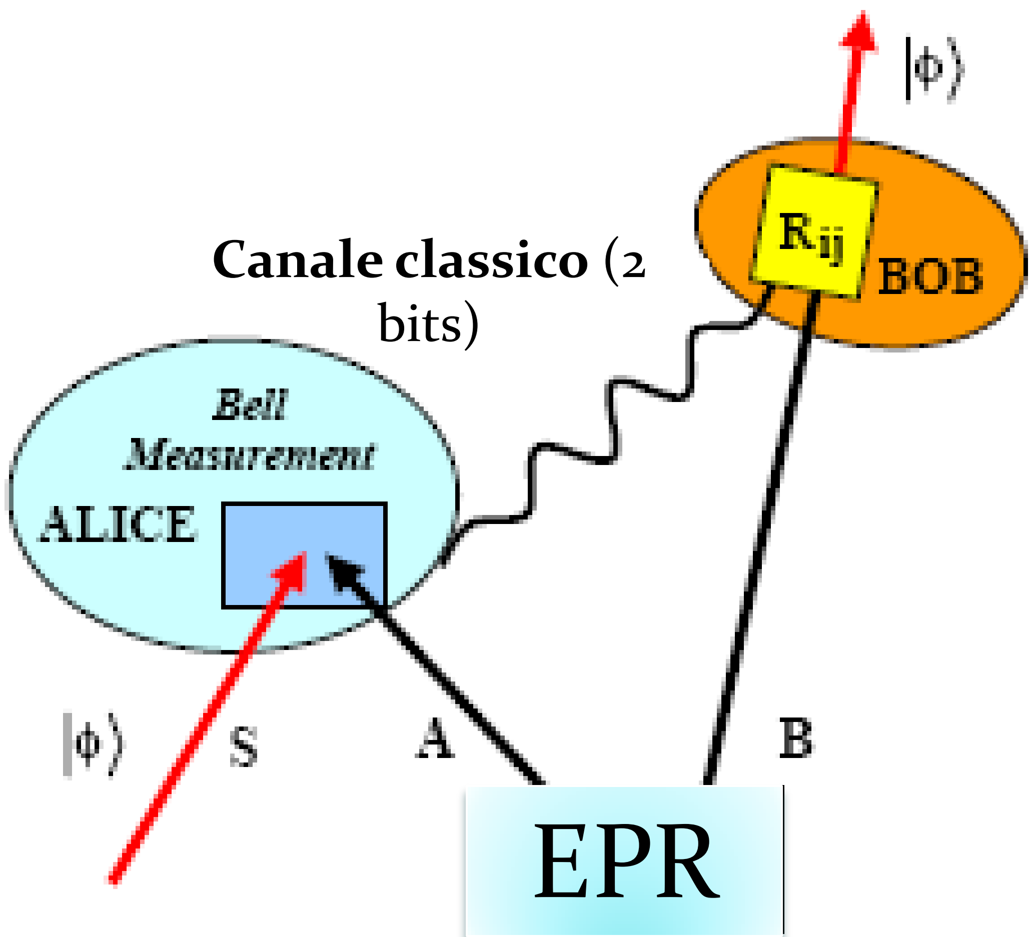
Macro qubit transmission:



Beam splitter decoherence model:

$$b_\pm = \sqrt{\tau}\, c_\pm + i\sqrt{1-\tau}\, d_\pm$$

$$|\Phi^+\rangle\langle\Phi^+| \longrightarrow \rho_\tau^+ = Tr_d(\rho_{tot})$$


|φ⟩
Rij
BOB
Canale classico (2 bits)
Bell Measurement
ALICE
|φ⟩
S
A
B
EPR