Title: Entanglement and nonlocality in microscopic - macroscopic systems

Date: Aug 26, 2008 04:00 PM

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Abstract: Theoretical and experimental results on the Quantum Injected Optical Parametric Amplification (QI-OPA) of optical qubits in the high gain regime (g > 6) are reported. The entanglement of the related Schroedinger Cat-State (SCS) is demonstrated as well as the establishment of Phase-Covariant quantum cloning for a Macrostate consisting of about 106 particles. In addition, the violation of the CHSH inequality is has been realized experimentally. According to the original 1935 definition of the SCS, the overall apparatus establishes for the first time the nonlocal correlations between a microcopic spin (qubit) and a high J angular momentum i.e. a macroscopic multiparticle system close to the classical limit. Applications to Quantum Information will be discussed.

State Non-separability and Violation of Bell's Inequalities by a Microscopic - Macroscopic Schroedinger Cat System

(And: Optical – Mechanical Schroedinger Cat via linear interaction with a Mirror - BEC)

F. De Martini, F. Sciarrino, C.Vitelli, F. Cataliotti

Accademia Nazionale dei Lincei, Roma
Universita' di Roma "La Sapienza", Università di Firenze
Laboratori LENS, Prato (Firenze)

General characters of modern scientific endeavor :

20th Century

REDUCTIONISM = Search for the smallest

21th Century:

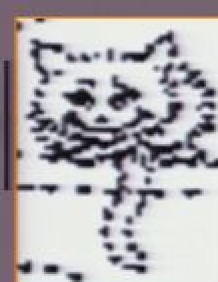
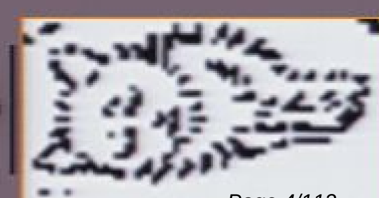
HOLISM = Union of the Microscopic system and of the Macroscopic world

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 interaction
Workshop: "Max Planck and the rise of the new Physics", Accademia dei Lincei

Roma 2000

Schroedinger's Cat

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

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* …

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

) **INTERFERENCE** OF 2 MACROSTATES

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

) **ENTANGLEMENT** MICRO - MACRO

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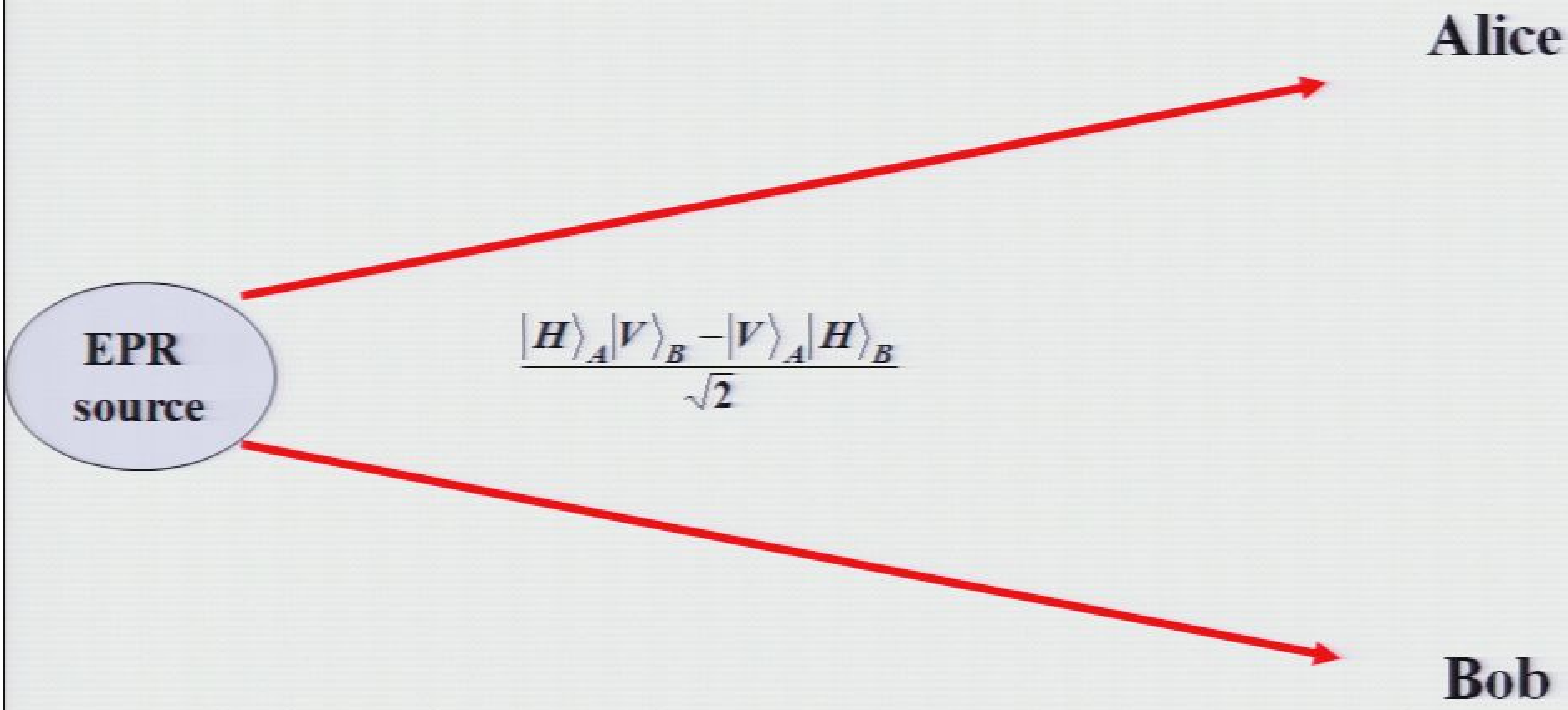
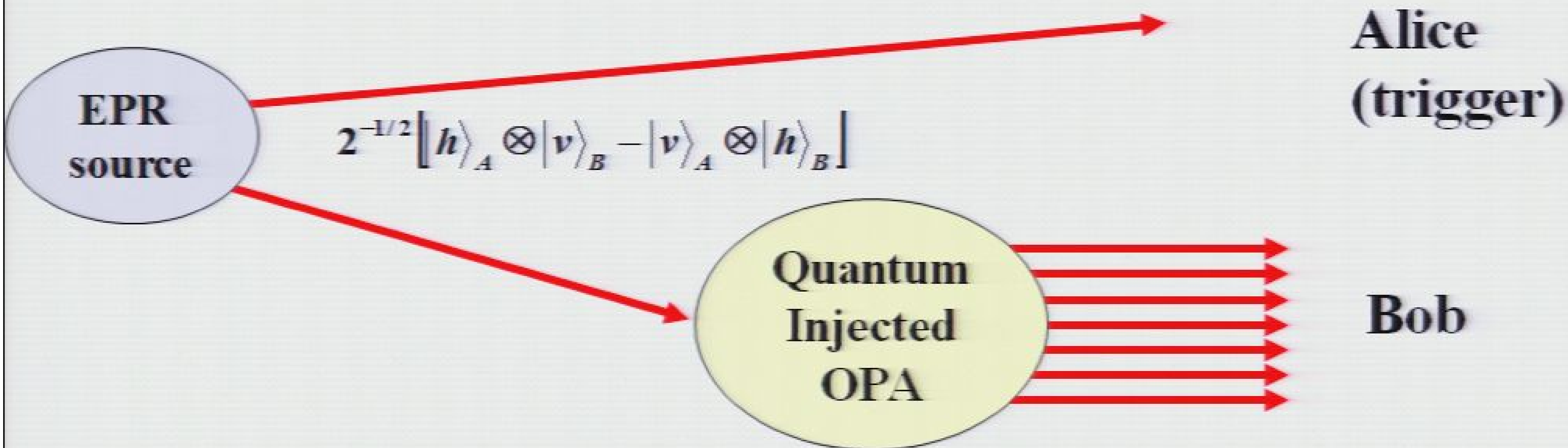
Entanglement between 2 single photons (EPR, 1935)



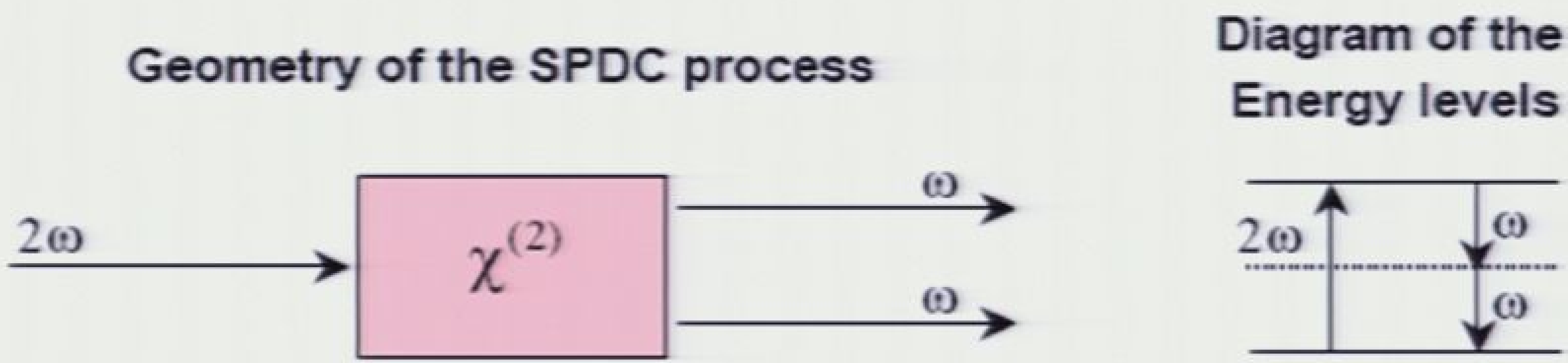
$$\frac{|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B}{\sqrt{2}}$$

Entanglement between a single photon and a mesoscopic field



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

SCHROEDINGER CAT STATE



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

Phase-Matching Conditions:

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

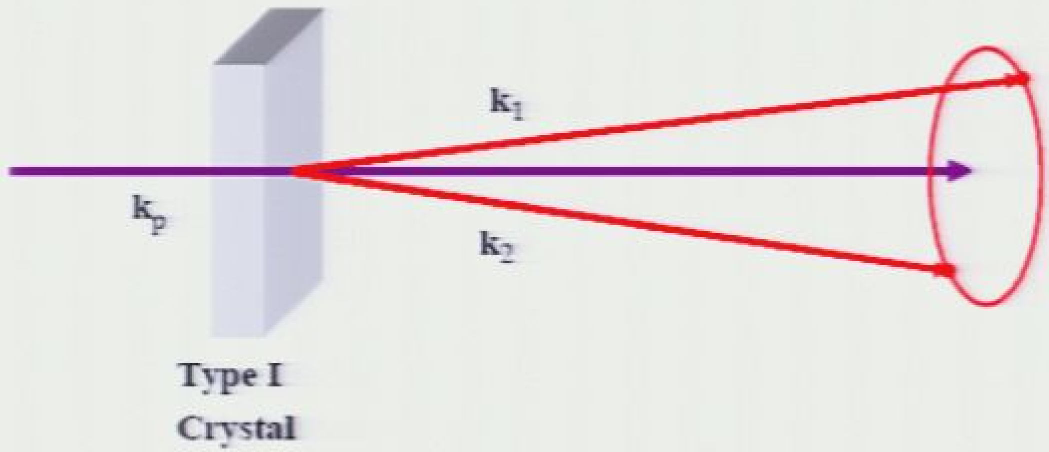
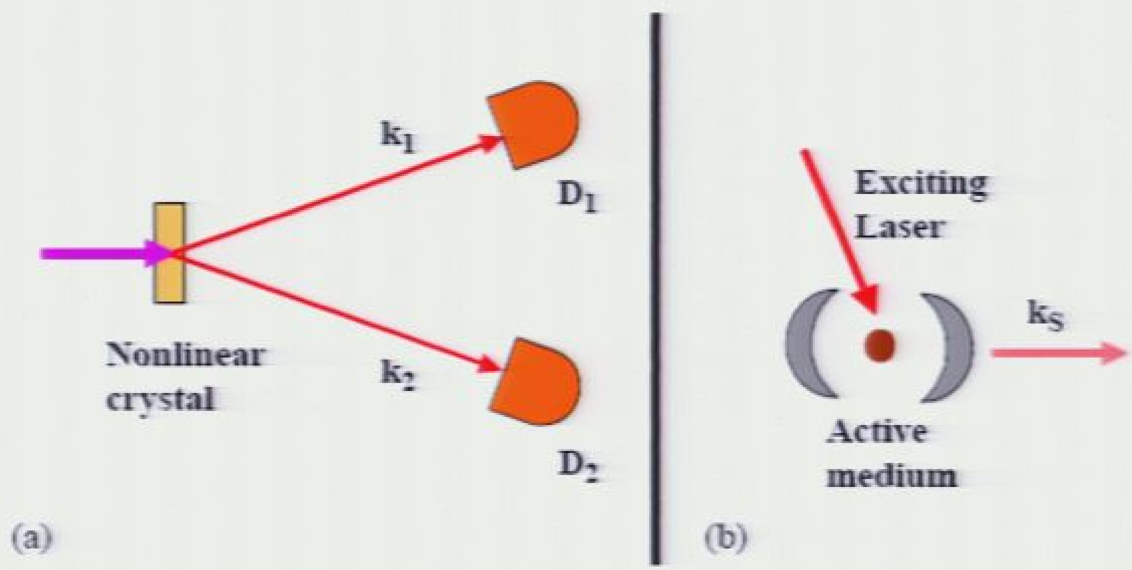


Fig. 10. Type I phase-matched SPDC process.



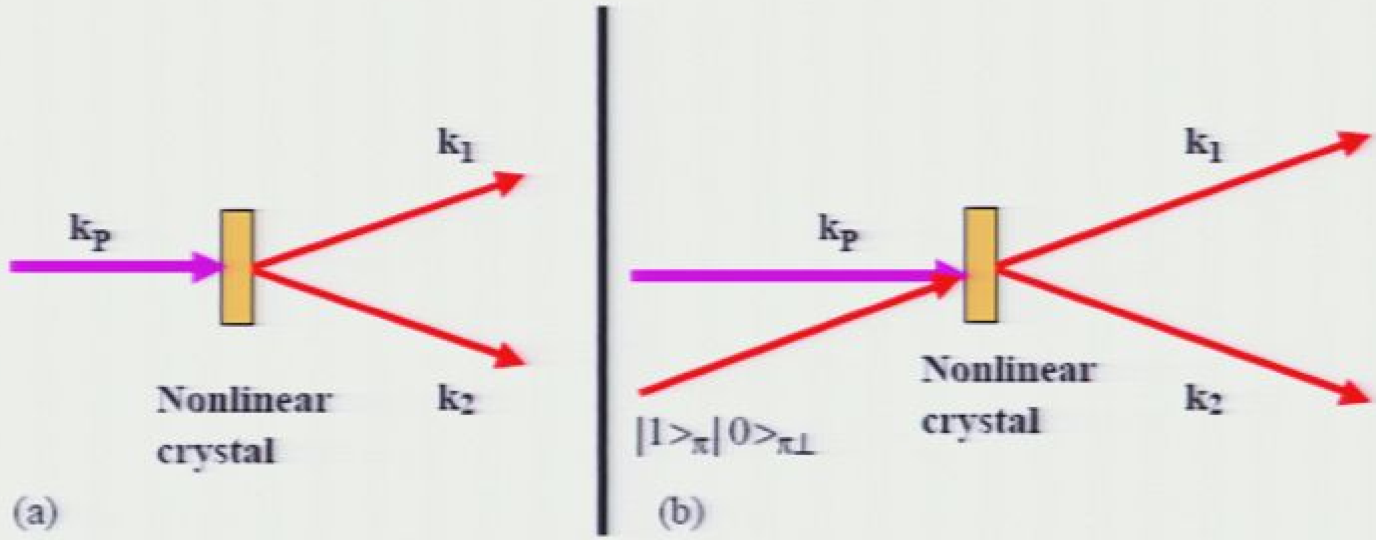


Fig. 20. Optical parametric amplifier working in spontaneous emission regime (a) and stimulated emission regime (b).

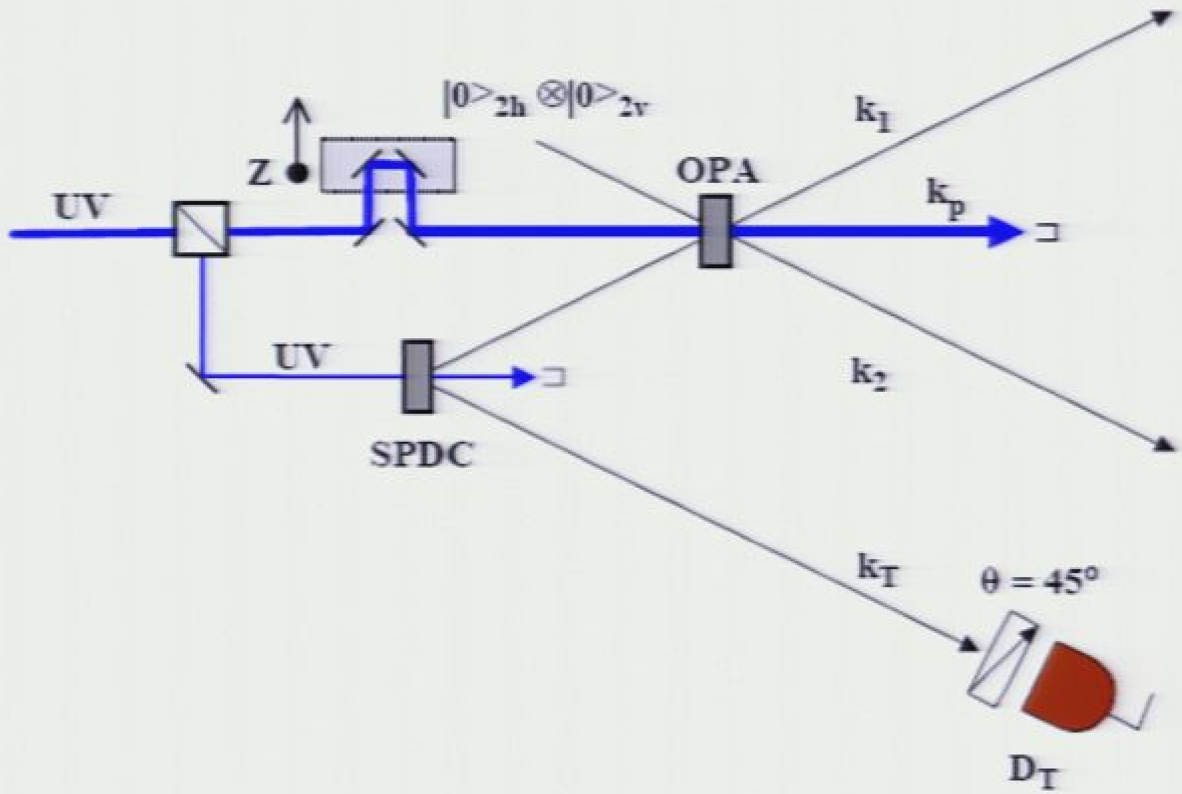


Fig. 21. Schematic diagram of the *quantum injected* optical parametric amplifier (QIOPA) in *entangled configuration*. The injection is provided by an external spontaneous parametric down conversion source of polarization entangled photon states [109].

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

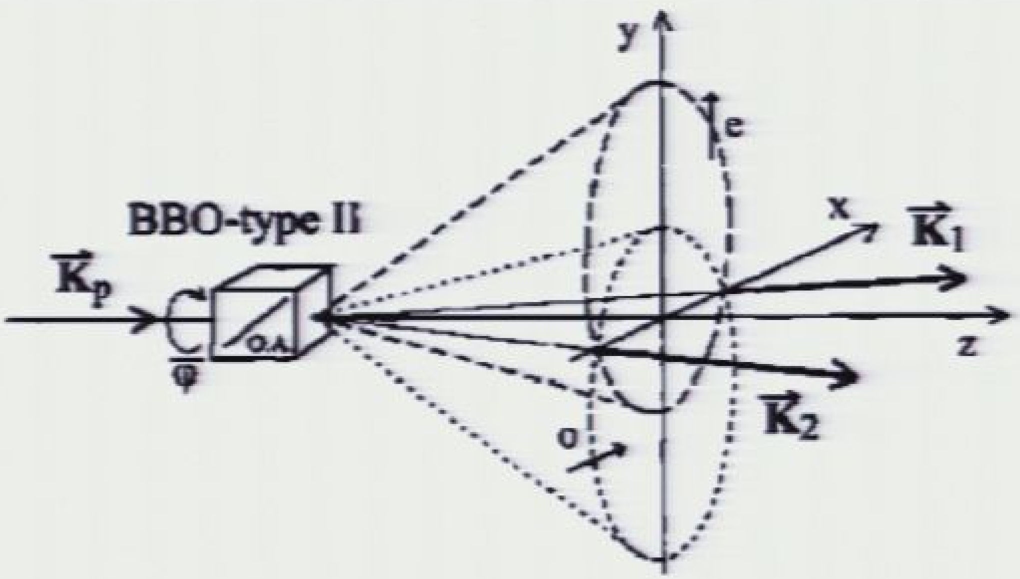


Fig. 13. Generation of polarization entangled states by spontaneous parametric down conversion on modes k_1 and k_2.

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)

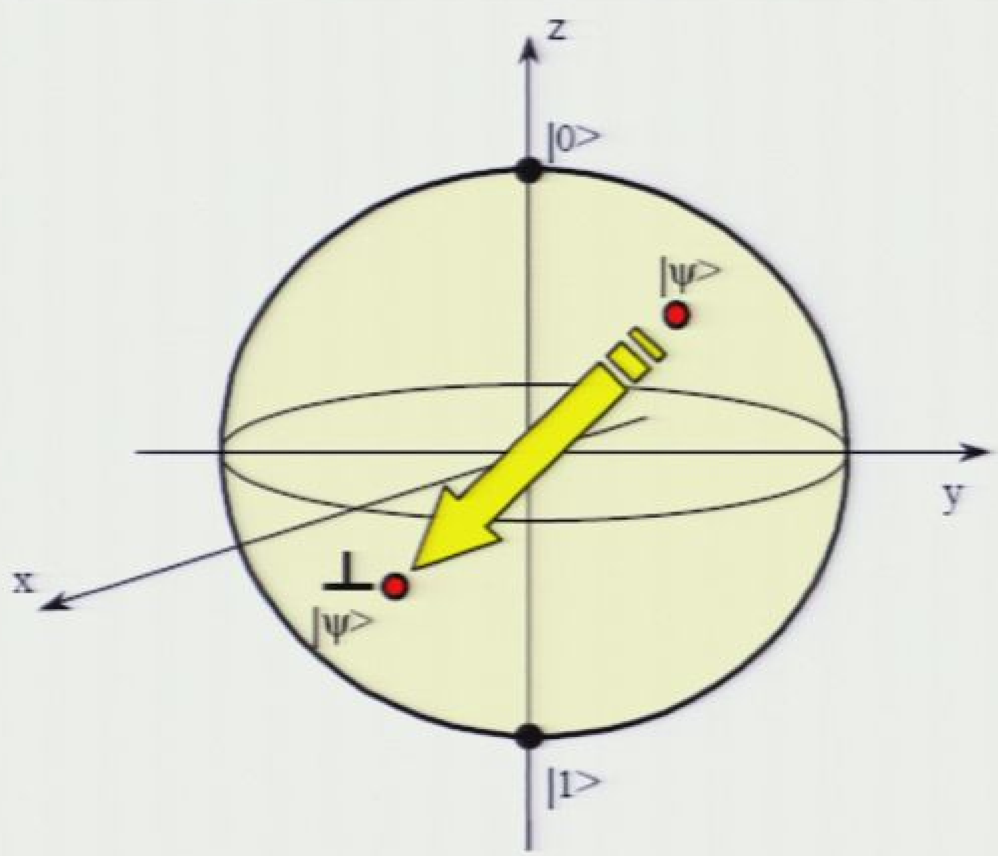


Fig. 29. The universal NOT operation corresponds to the inversion of the sphere, since the states $|\Psi\rangle$ and $|\Psi^{\perp}\rangle$ are antipodes.

Owing to: NON COMPLETELY - POSITIVE MAP

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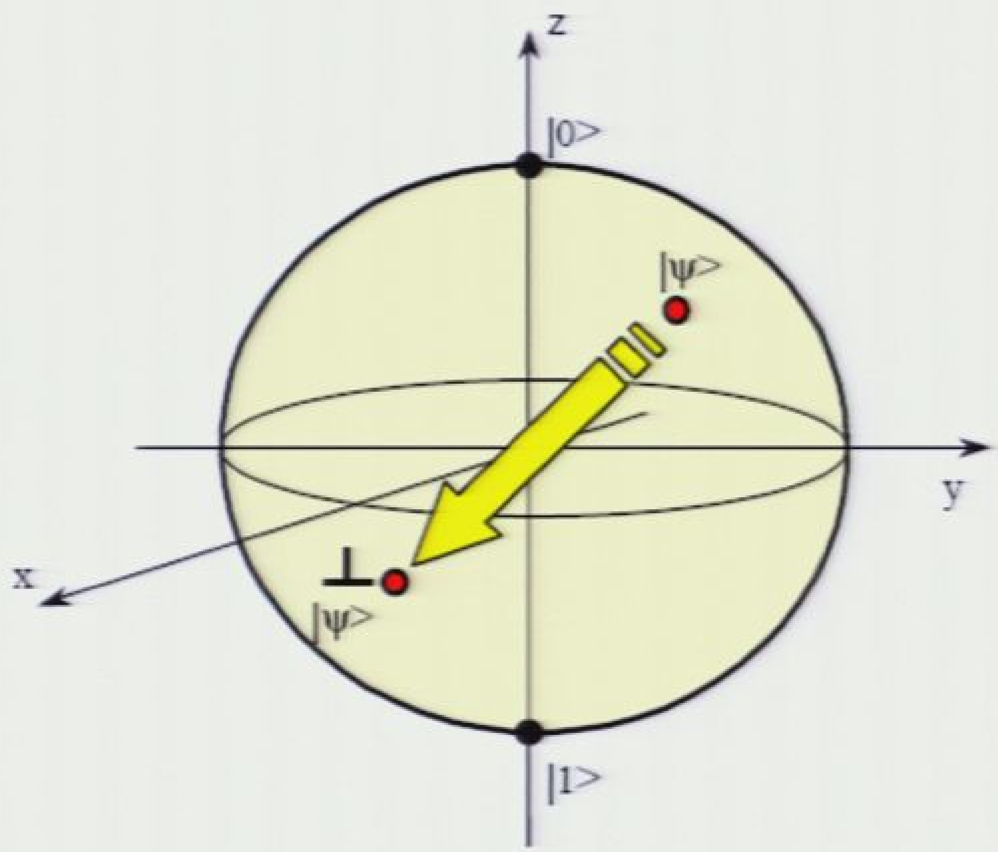

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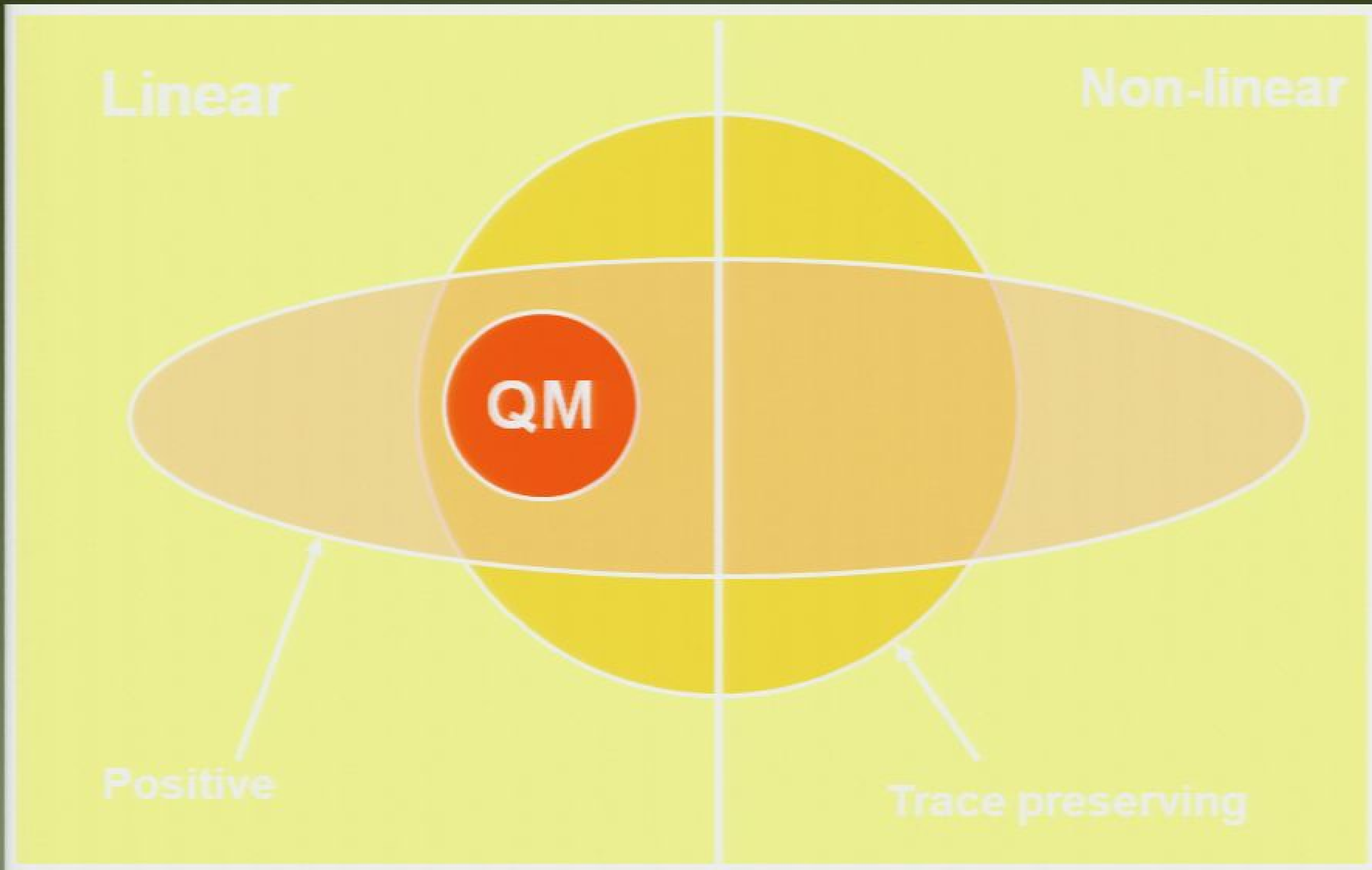

Linear
Non-linear
QM
Positive
Trace preserving

OLUME 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

Francesco De Martini, Daniele Pelliccia, and Fabio Sciarrino

ipartimento di Fisica and Istituto Nazionale per la Fisica della Materia, Università di Roma "La Sapienza," Roma, 00185–Italy

(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

IO CLONING: because QUANTUM MECHANICS IS A LINEAR MAP

IO U-NOT : because QUANTUM MECHANICS IS A CP - MAP

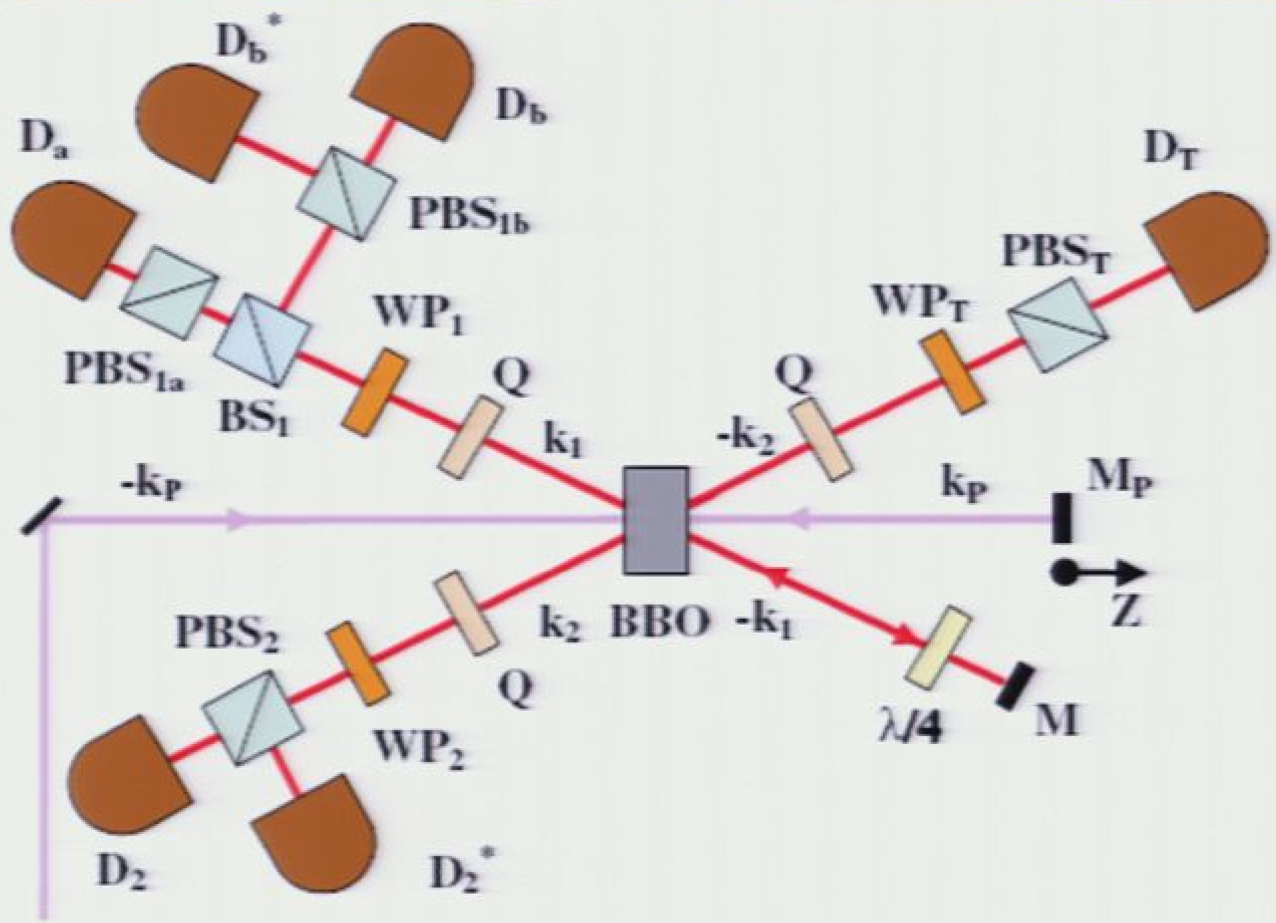
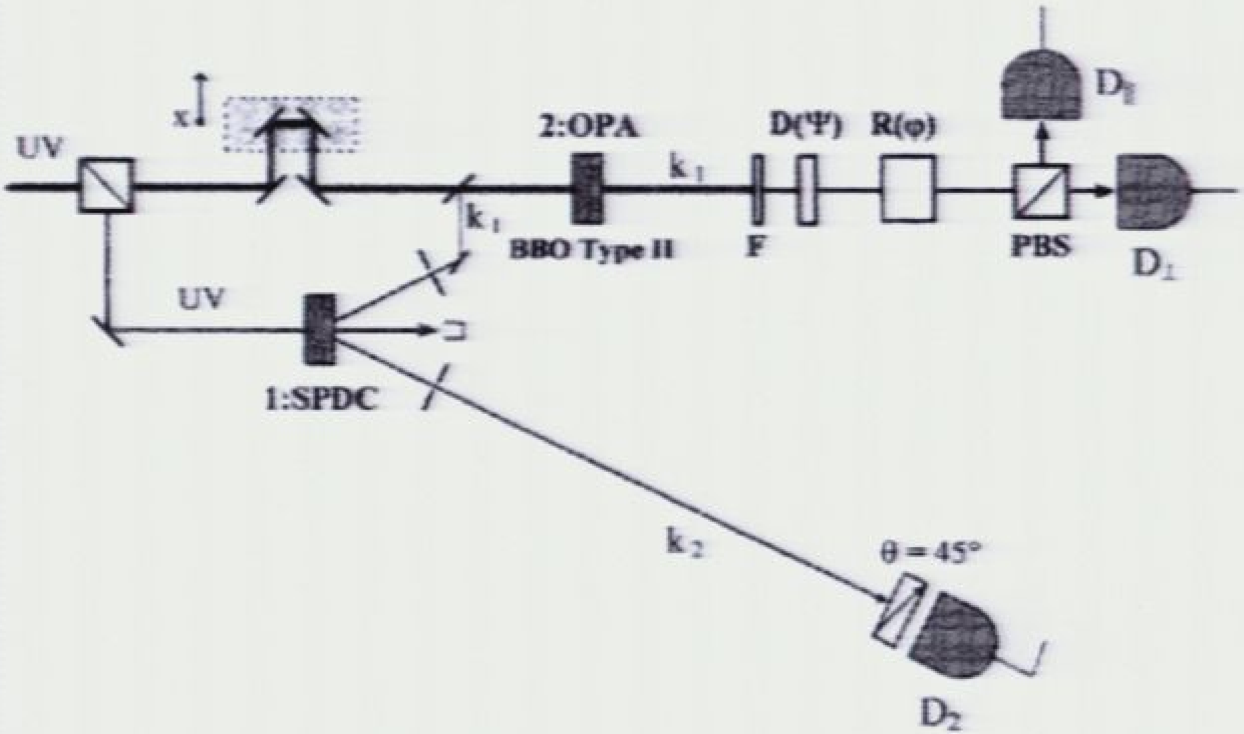


FIG. 1 (color online). Schematic diagram of the universal optimal cloning machine (UOQCM) realized on the cloning (C) channel (mode k_1) of a self-injected OPA and of the Universal NOT (U-NOT) gate realized on the anticloning (AC) channel, k_2.

F. De Martini / Physics Letters A 250 (1998)



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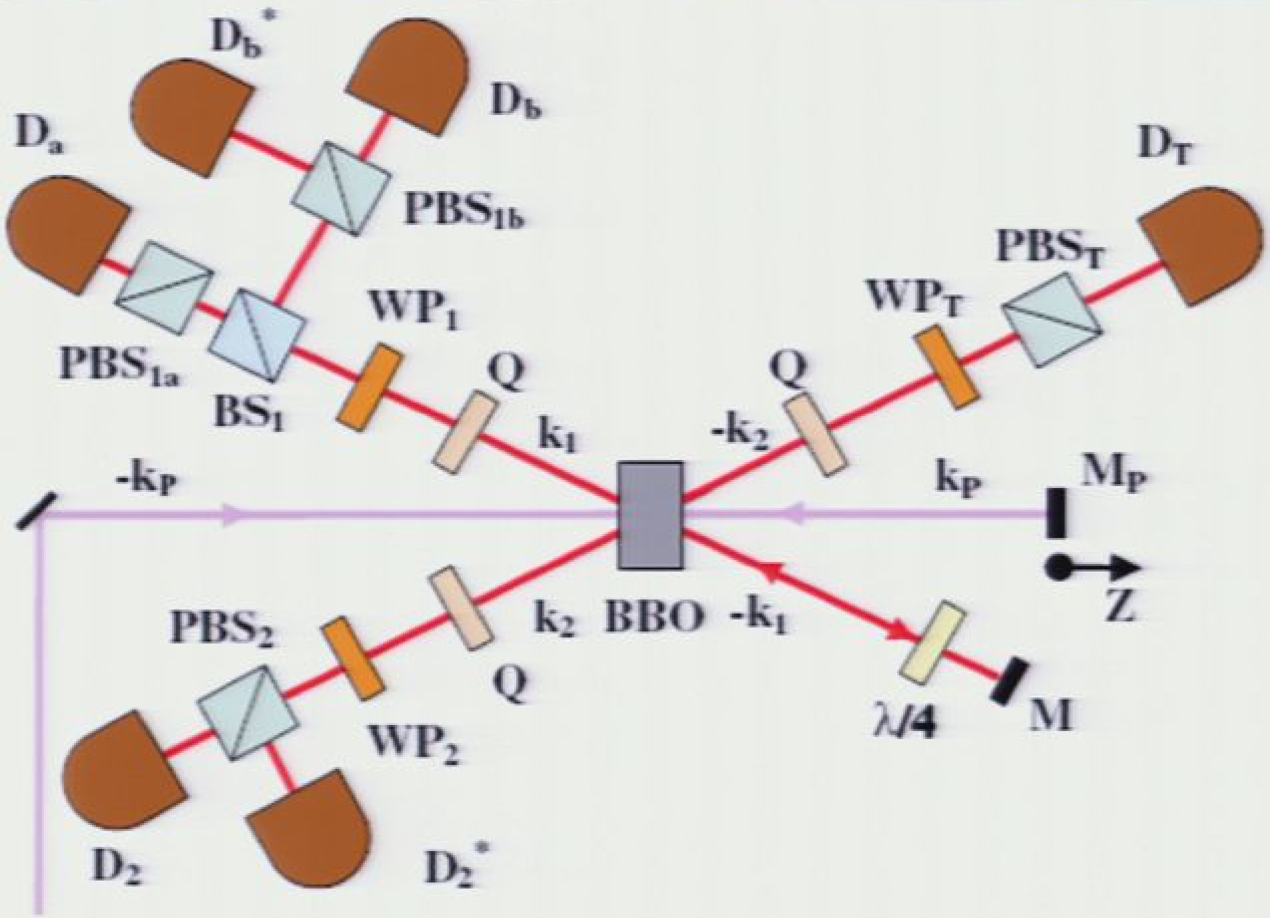
PHASE - COVARIANT QUANTUM CLONING MACHINE



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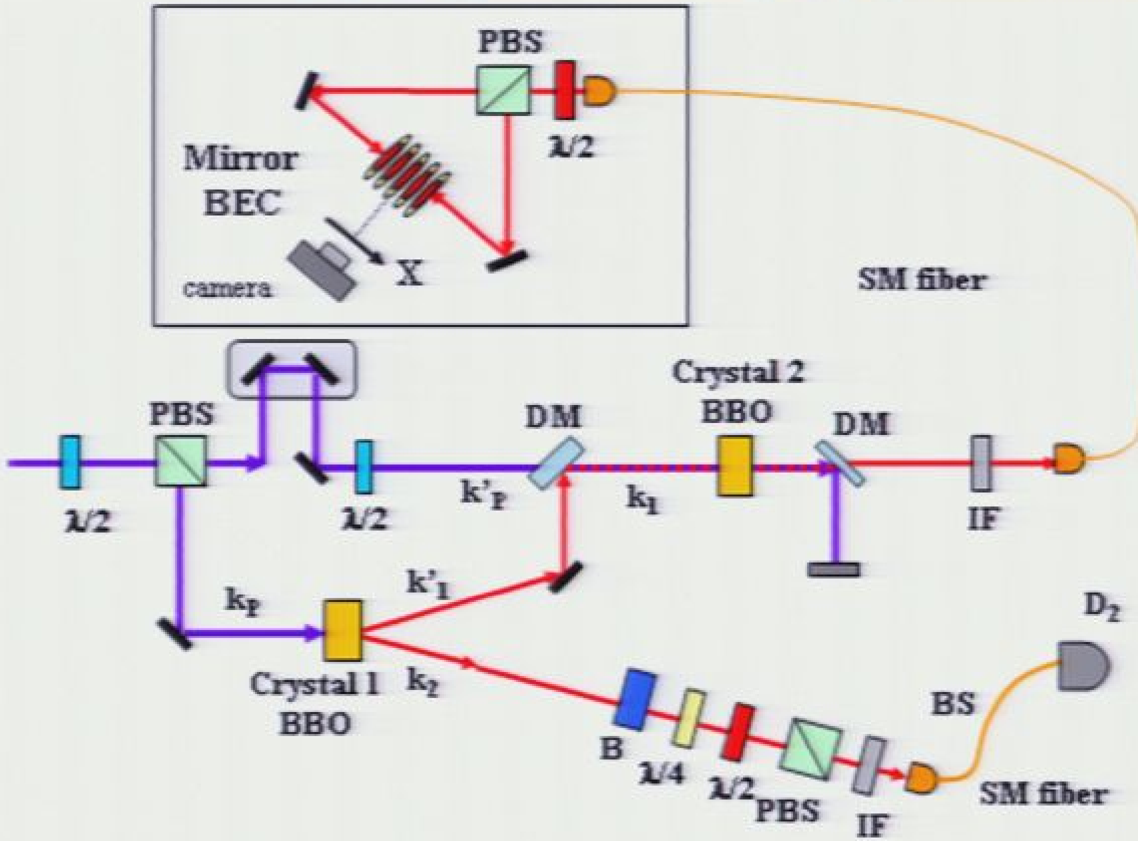


OPTO - MECHANICAL SCHRŐDINGER CAT

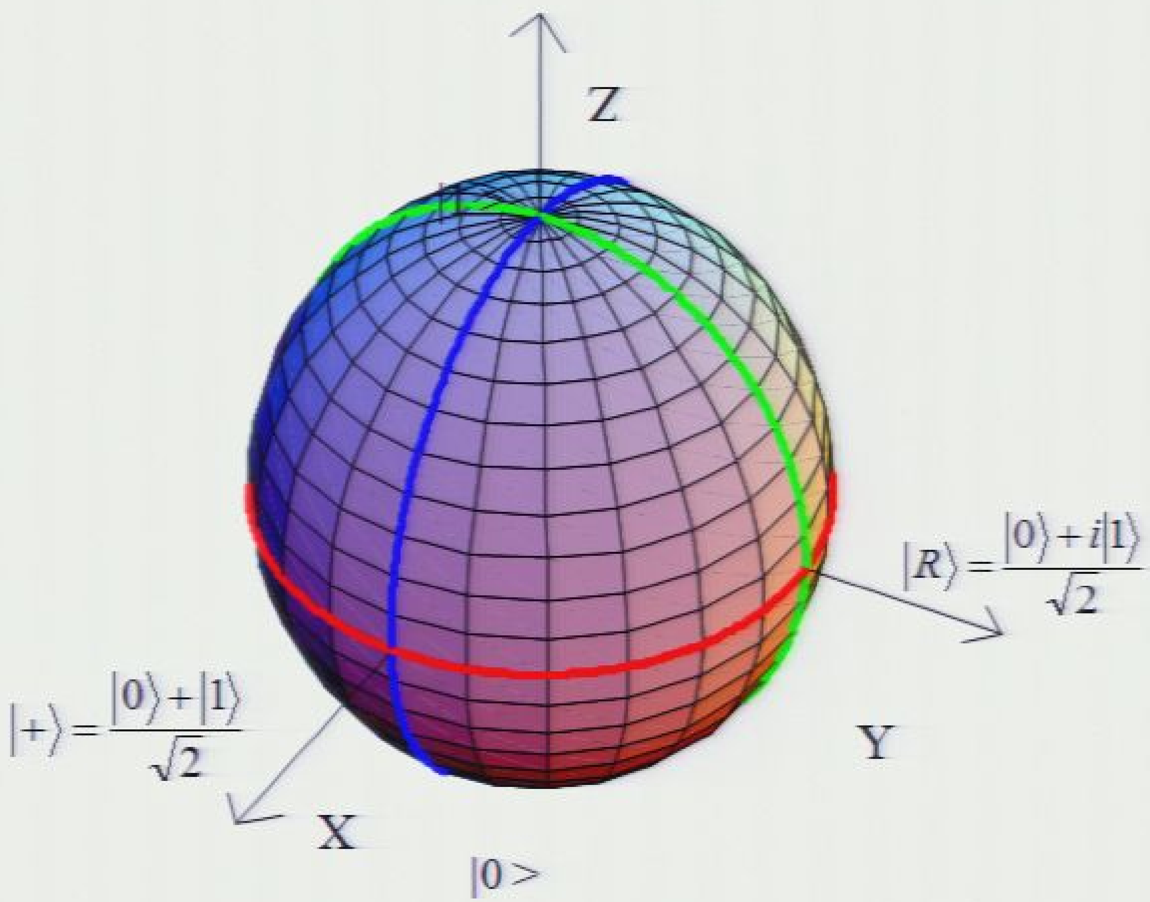
State Non-separability:

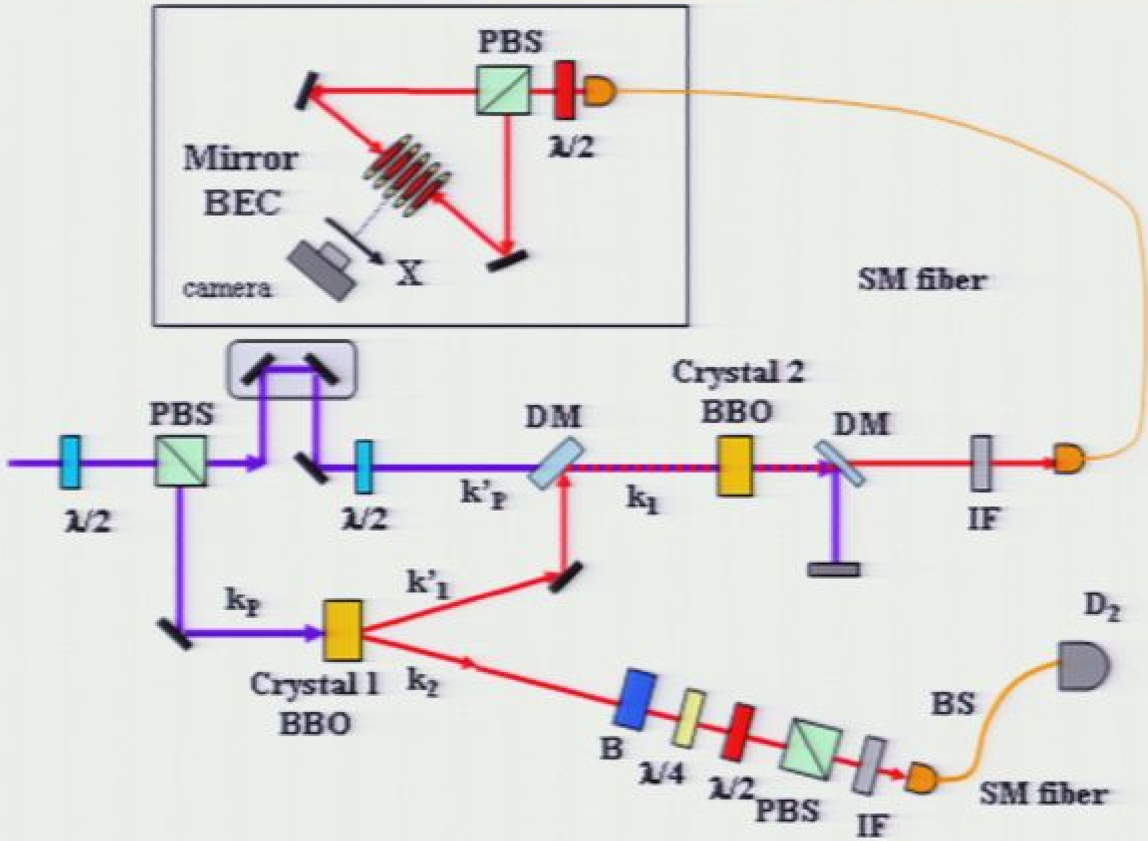
F. De Martini, F Sciarrino, C.Vitelli, Phys.Rev.Lett. **100**, 253601, 2008)

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

On the Bloch sphere:

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





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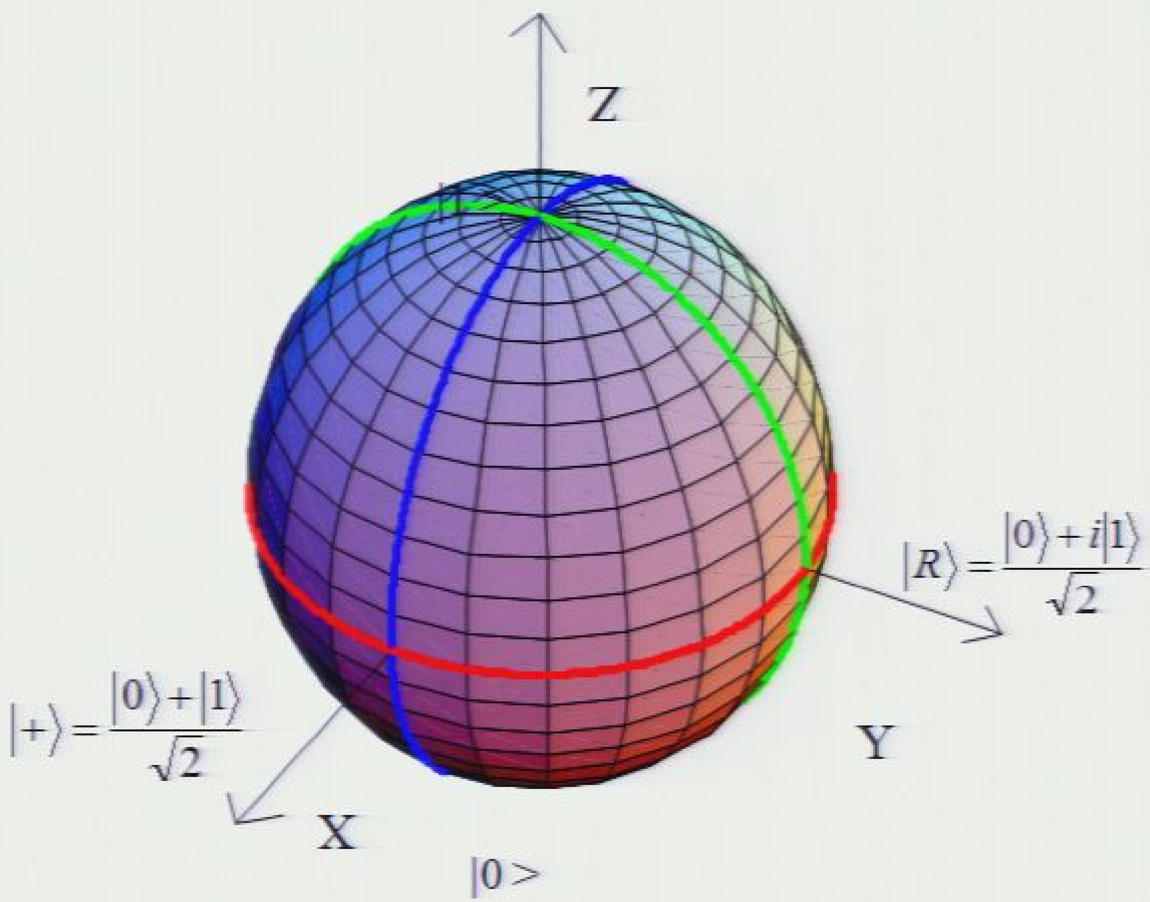

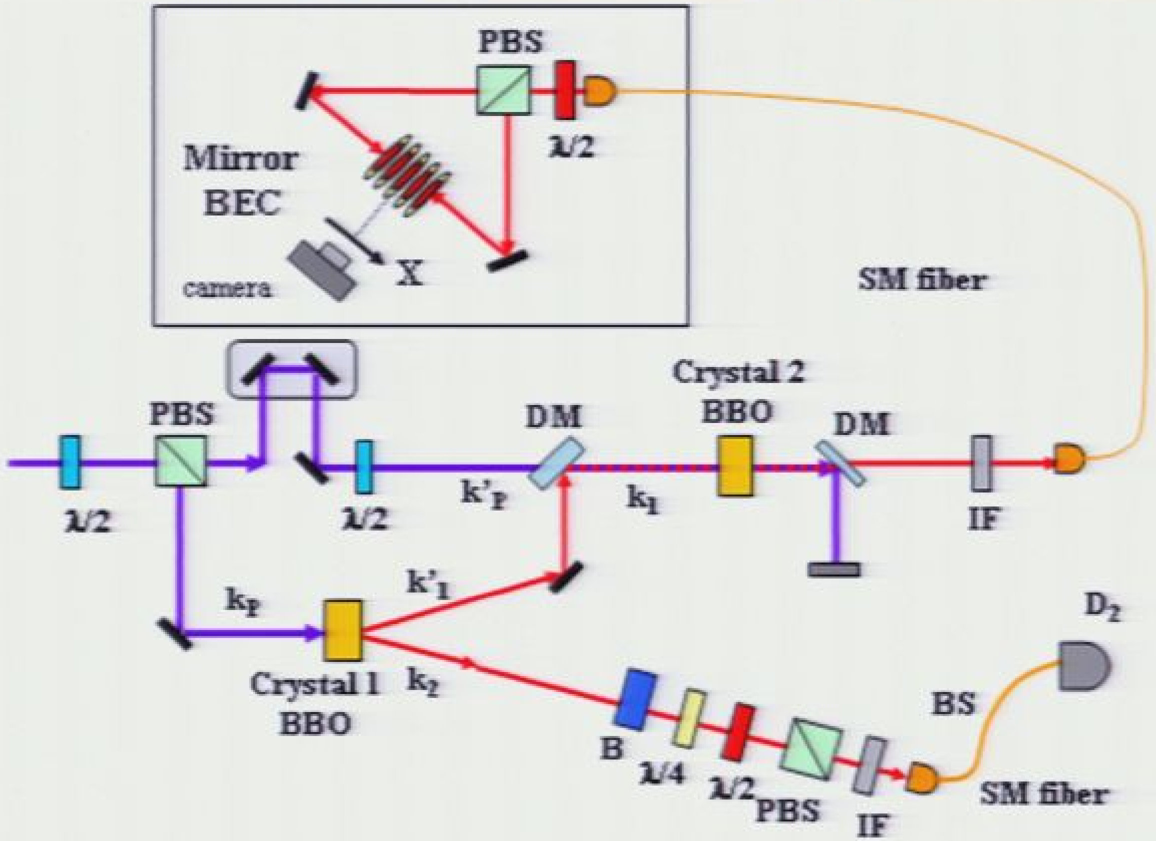

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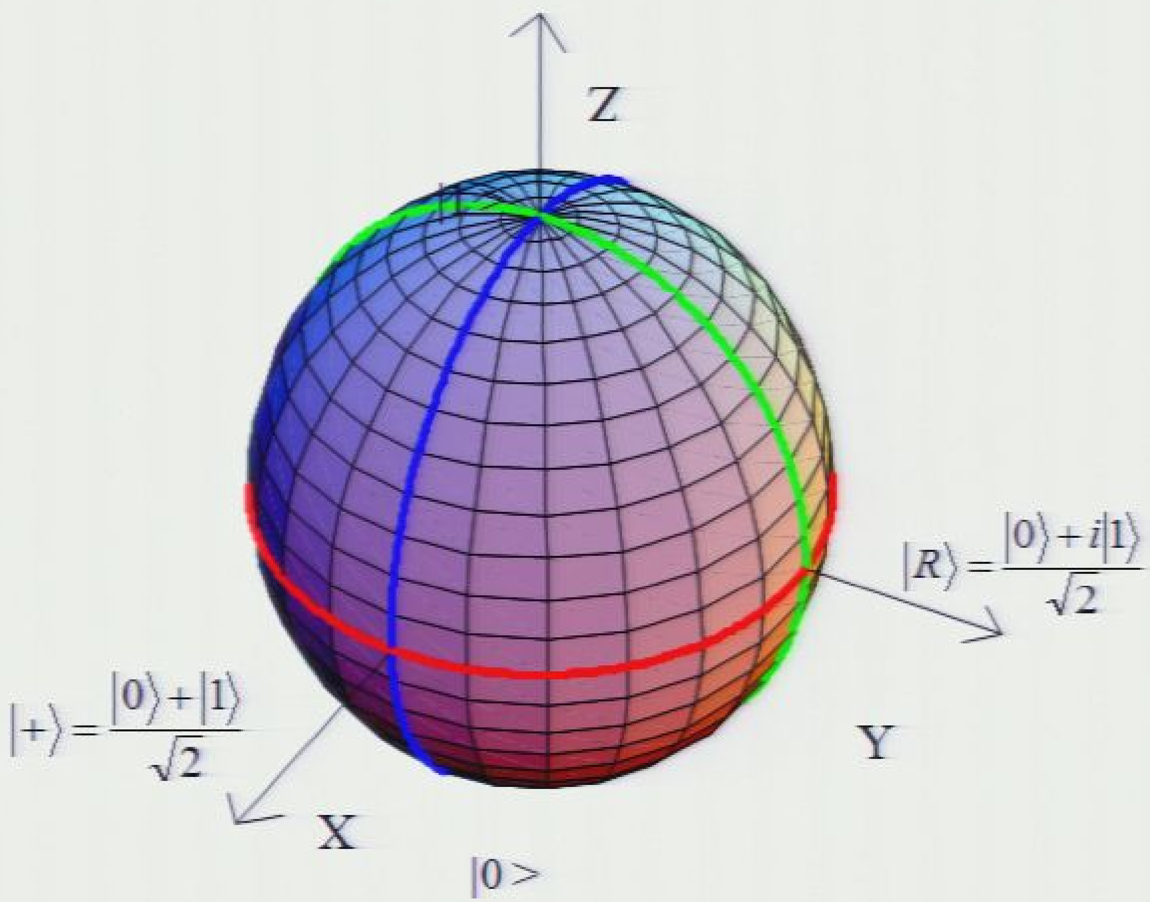
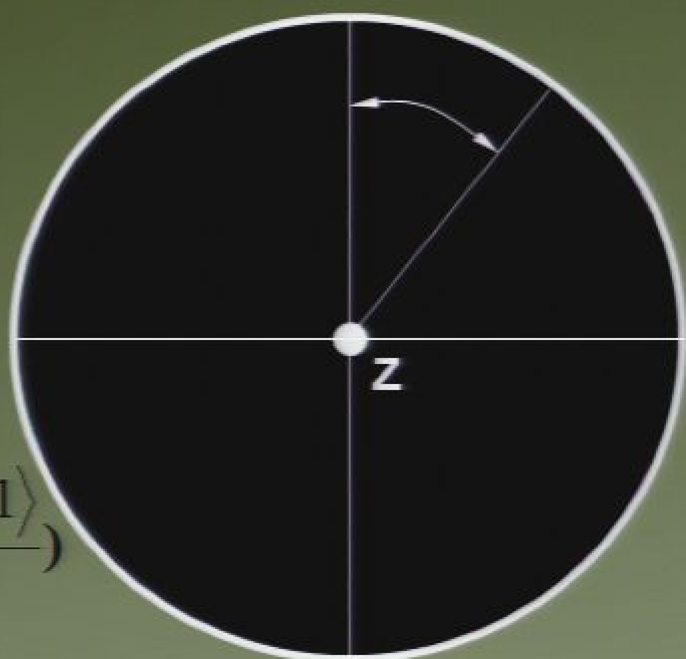


Equatorial z-plane: phase-covariant cloning

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



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

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

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

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

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

Input qubit:

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

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

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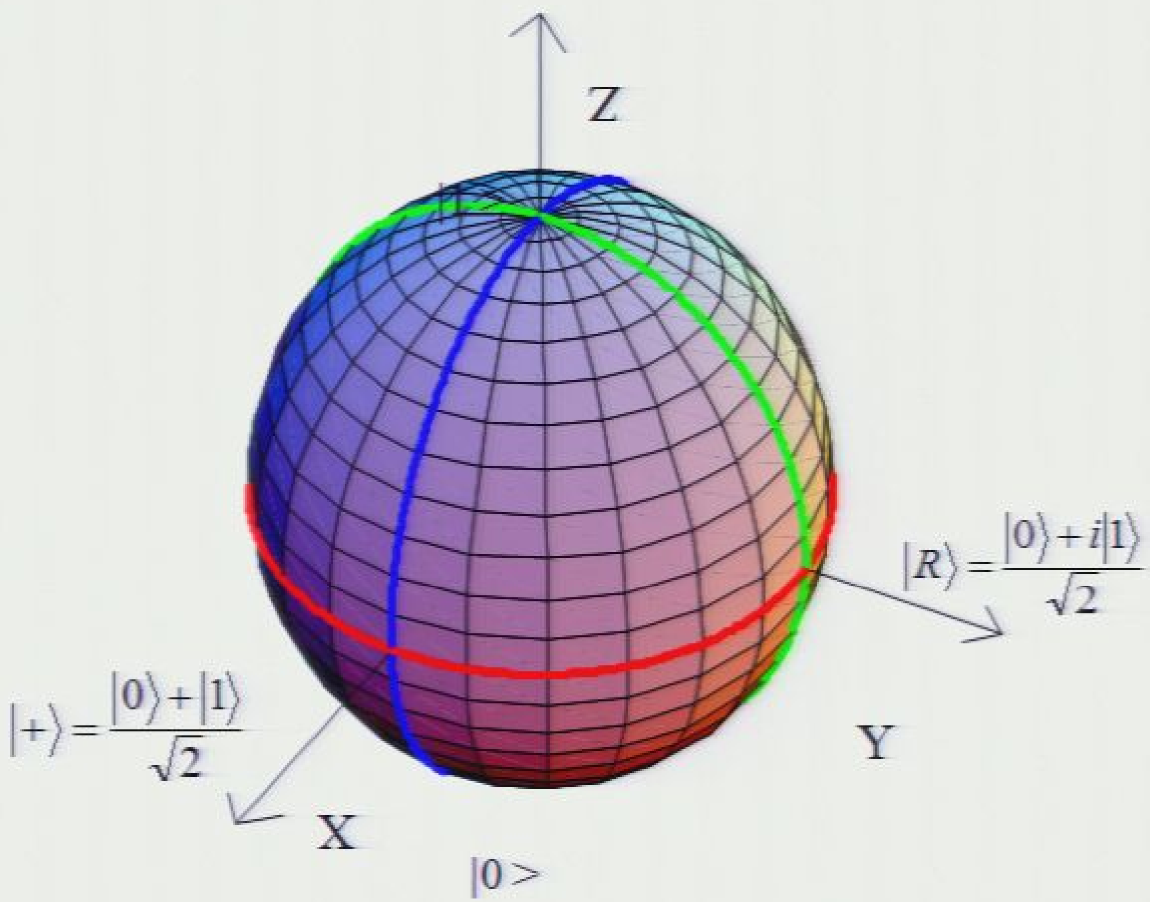

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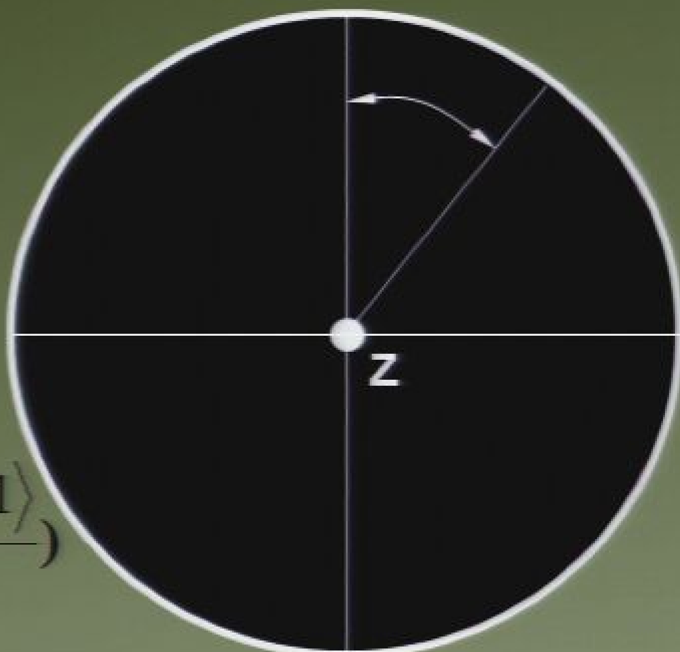

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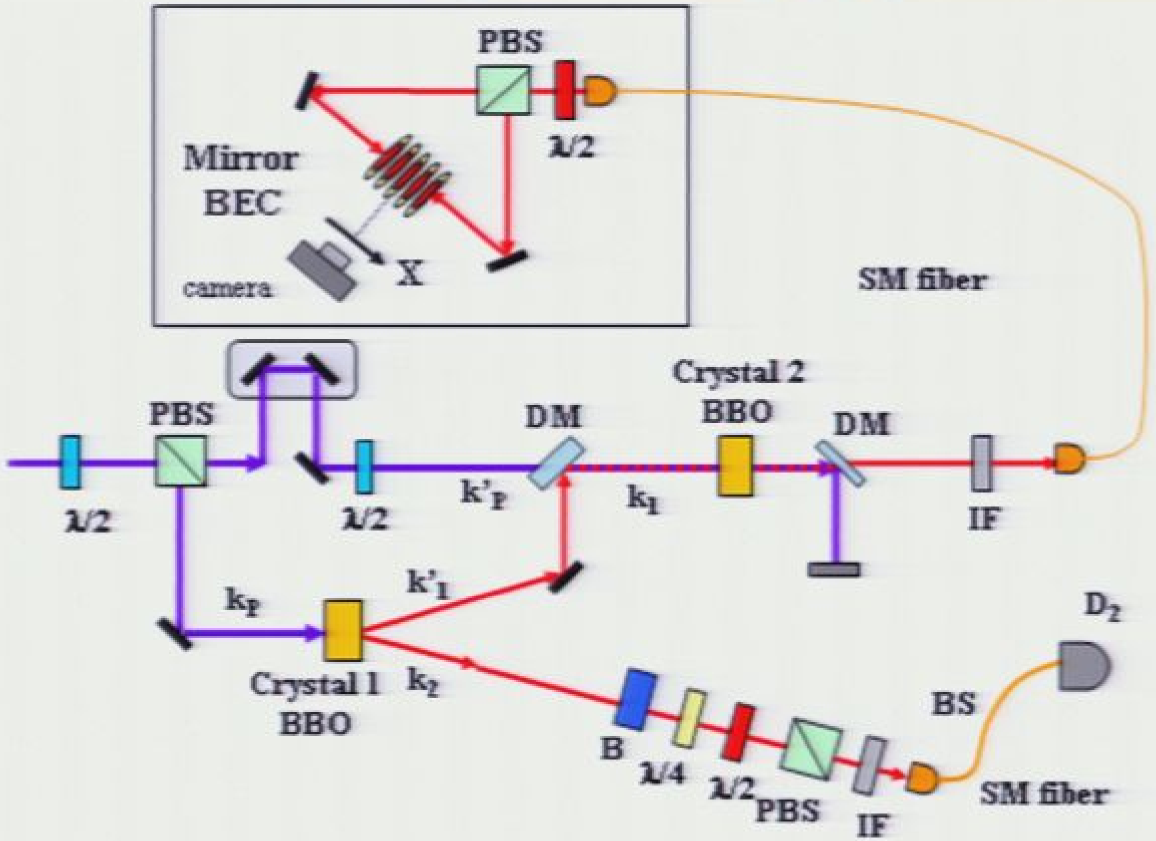

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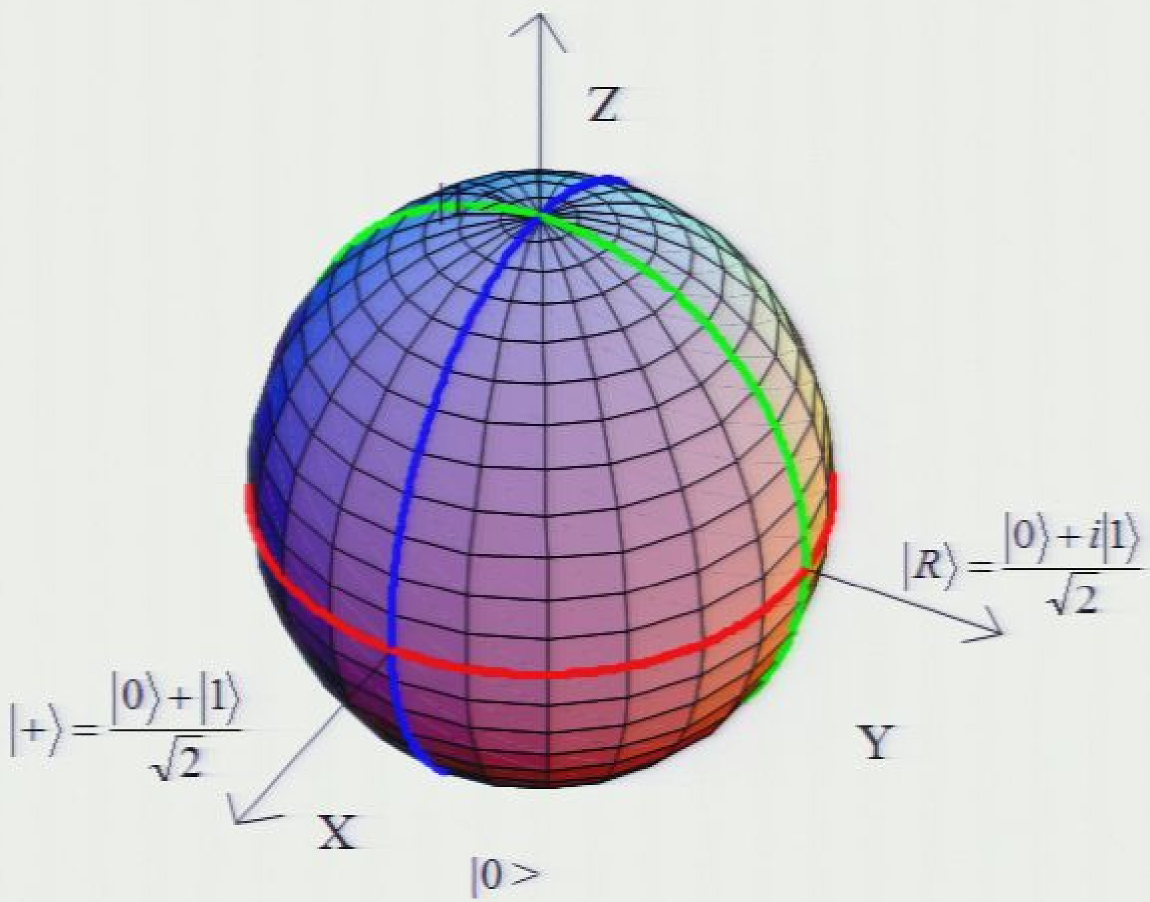

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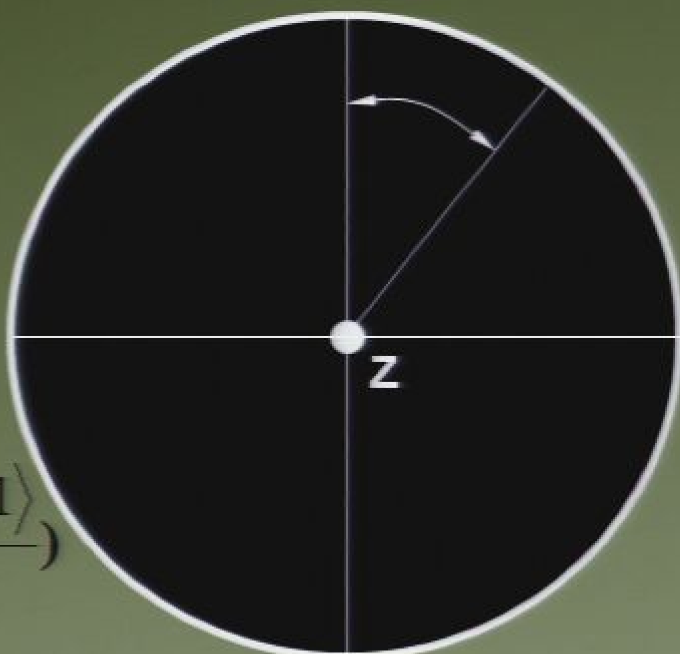

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$$|\mathbf{R}\rangle = (\frac{|0\rangle + i|1\rangle}{\sqrt{2}})$$

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High – gain stimulated Parametric Amplifier (Quantum-injected OPA)

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

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

Optimal
Phase-Covariant
Quantum cloning

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

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

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

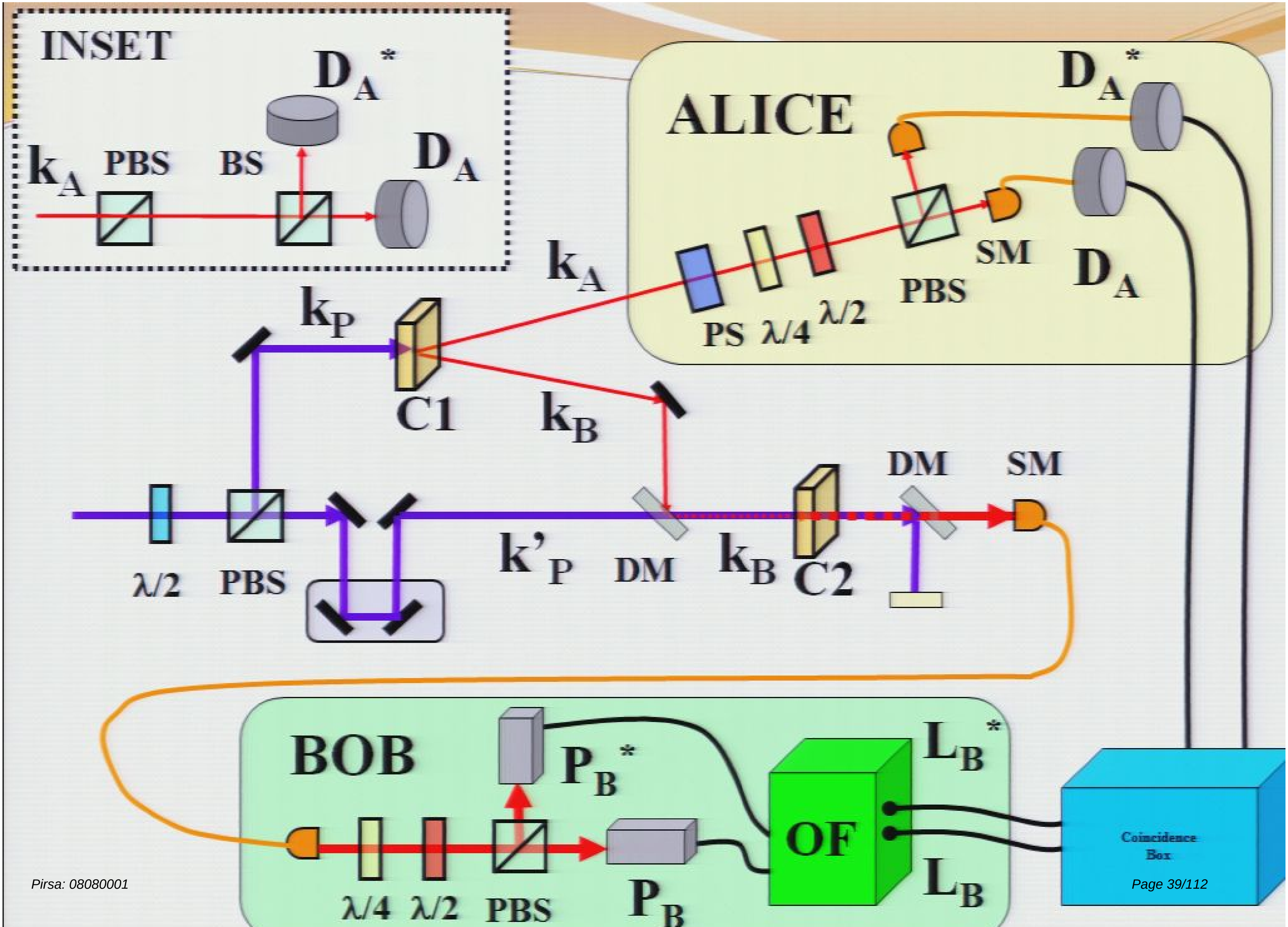
INFORMATION - PRESERVING
transfer of quantum superposition from a Microstate into a Macrostate by a Unitary transformation

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

Bipartite entangled state

Quantum Map Micro-Macro

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



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Coincidence Box

Quantum Map Micro-Macro

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

High – gain stimulated Parametric Amplifier (Quantum-injected OPA)

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

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

Optimal
Phase-Covariant
Quantum cloning

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

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

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

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

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

Bipartite entangled state

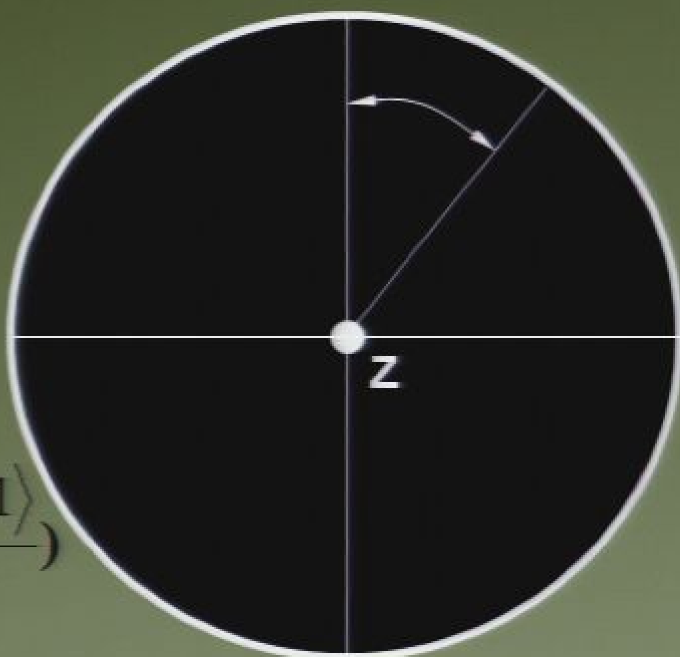
Equatorial z-plane: phase-covariant cloning

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

Input qubit:

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

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



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

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

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

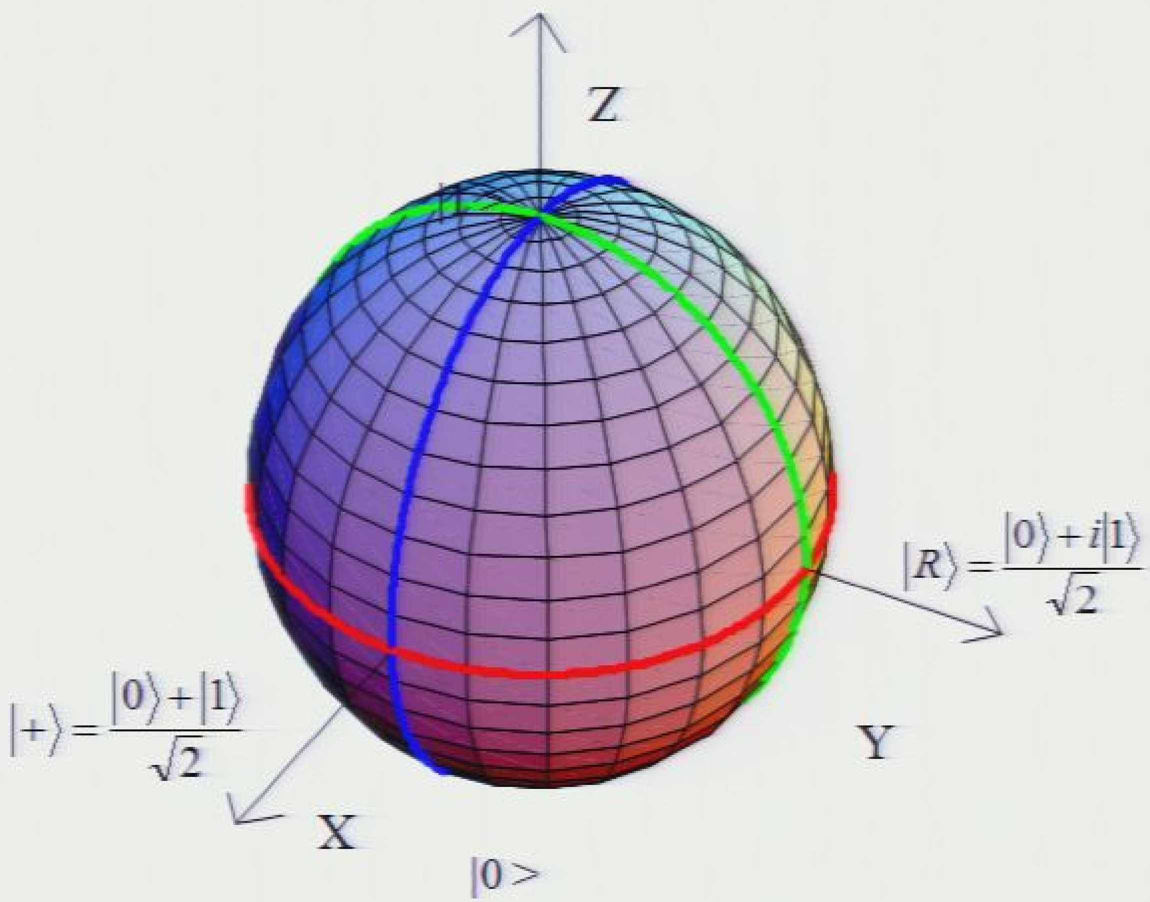
$$|\mathbf{R}\rangle = \left(\frac{|0\rangle + i|1\rangle}{\sqrt{2}}\right)$$

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

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

On the Bloch sphere:

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



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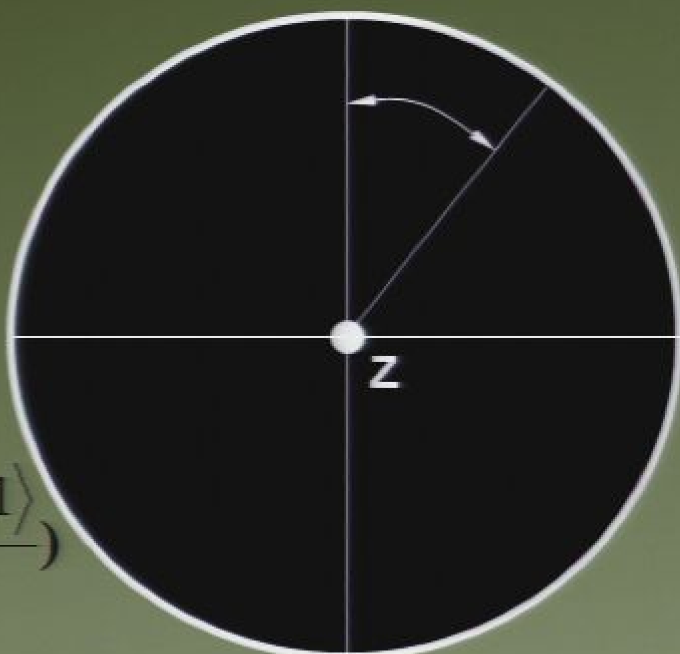

$$\varphi = \frac{3\pi}{2}$$

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

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

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

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

Input qubit:

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

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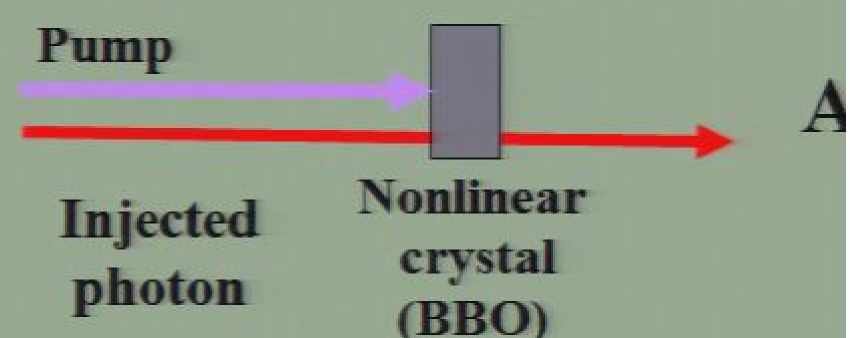
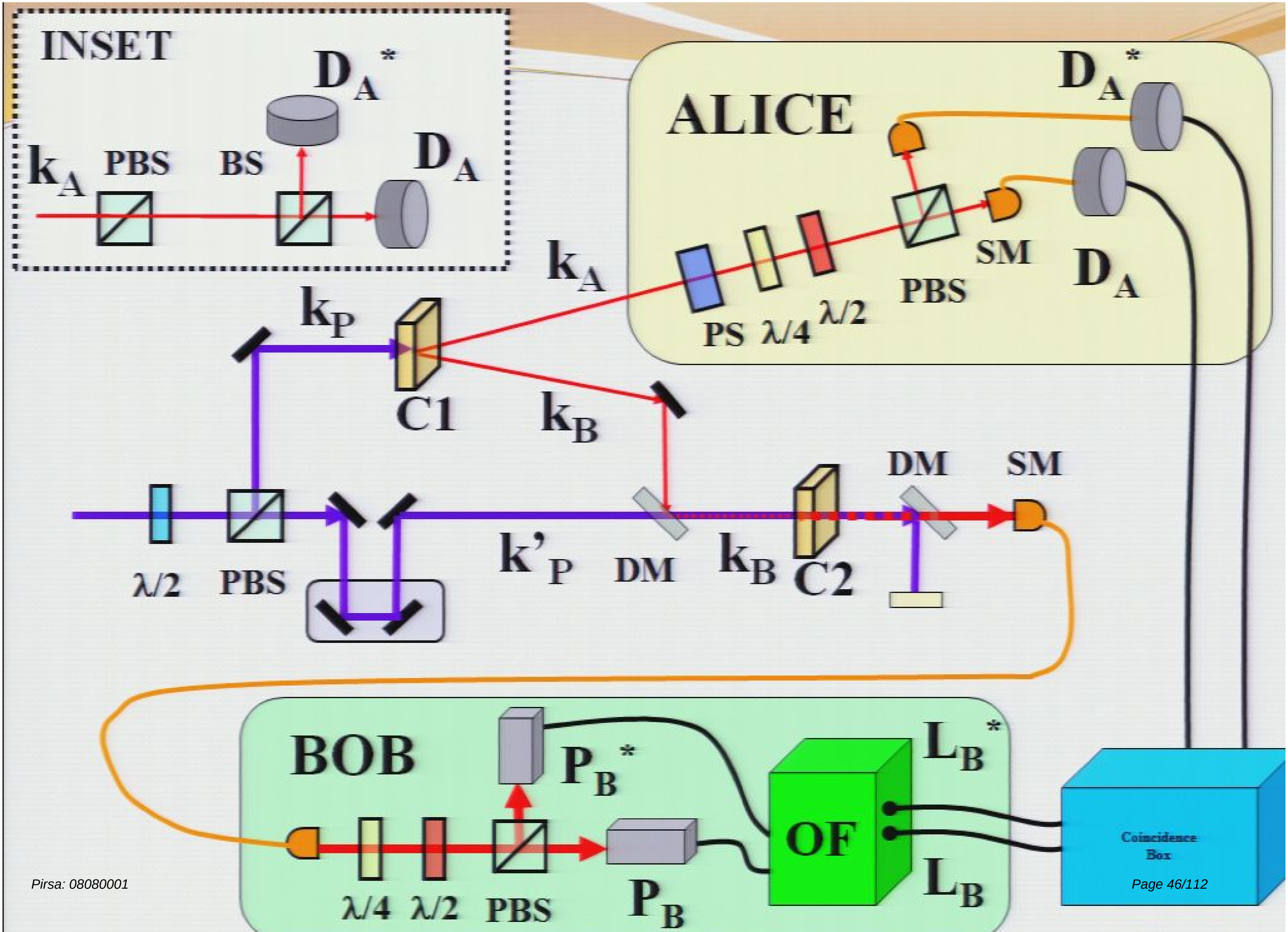


Bipartite entangled state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QI-OPA: Quantum - injected Optical Parametric Amplifier

(NL gain g = 4 ÷ 6.6)

(Phase-covariant cloning - machine)

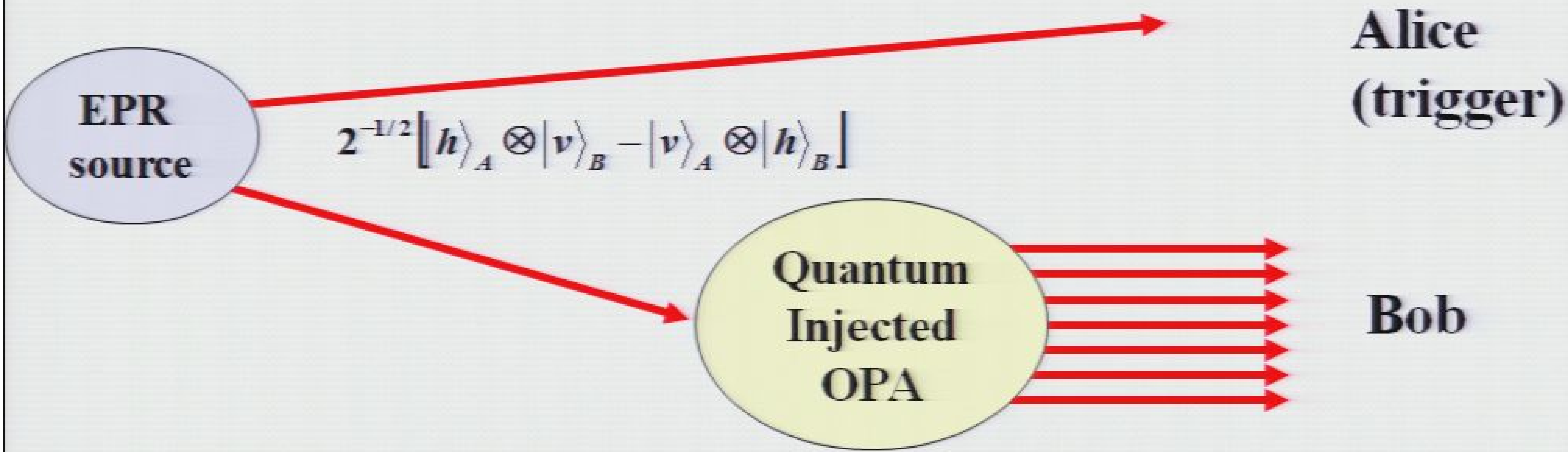
QUANTUM INJECTION BY : ONE - PHOTON: (Spin -½)

(test of state Non-separability)

QUANTUM INJECTION BY : TWO - PHOTONS: (Spin - 1

(Bell's - inequality Violation)

Entanglement between a single photon and a mesoscopic field



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

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

SCHROEDINGER CAT STATE

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

Entanglement Test on a Microscopic-Macroscopic System

Francesco De Martini,[1,2] Fabio Sciarrino,[3,1] and Chiara Vitelli[1]
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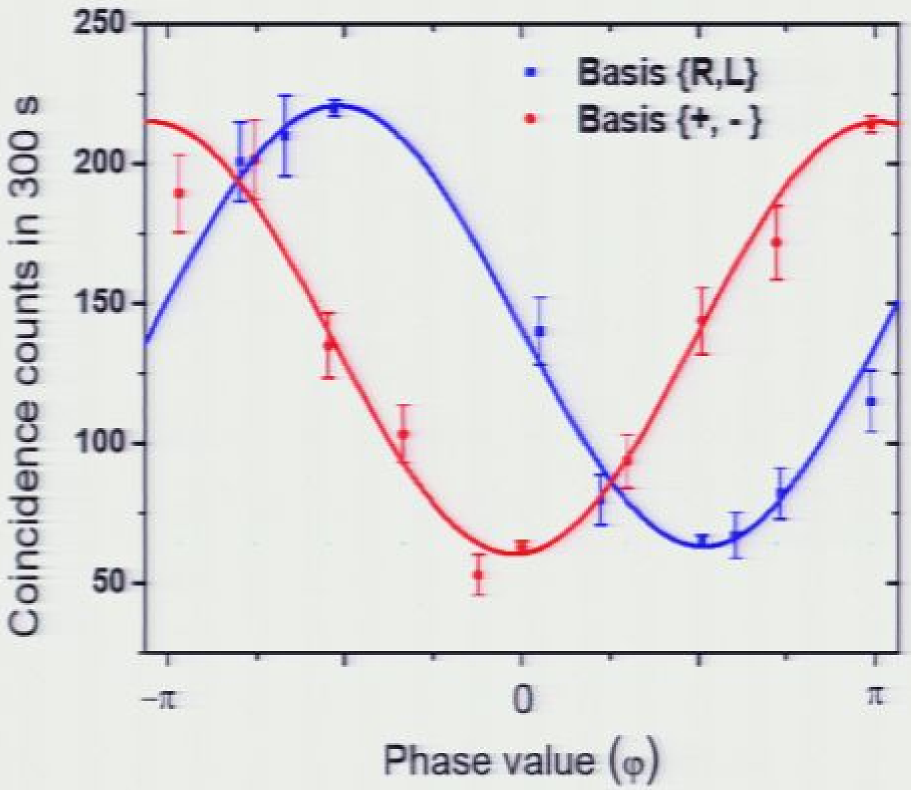
and Consorzio Nazionale Interuniversitario per le Scienze Fisiche della Materia, Roma, 00185 Italy
[2]*Accademia Nazionale dei Lincei, via della Lungara 10, I-00165 Roma, Italy*
[3]*Centro di Studi e Ricerche "Enrico Fermi", Via Panisperna 89/A,Compendio del Viminale, Roma 00184, Italy*
(Received 6 March 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

MICRO-MACRO NON SEPARABILITY TEST

experimental results



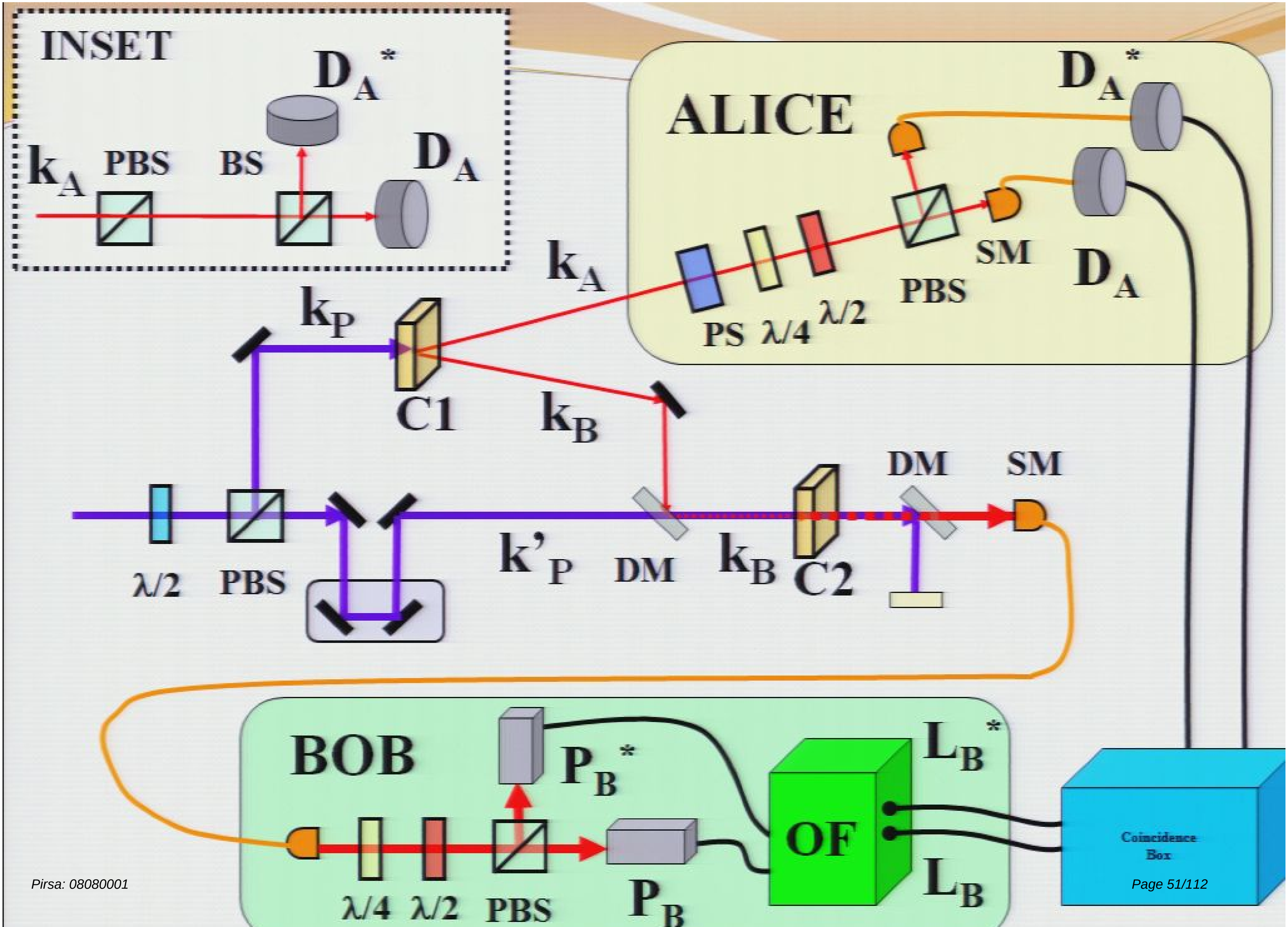
O-Filtering probability 10^{-4}

Necessary-Sufficient
Non-separability Criterion:

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

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

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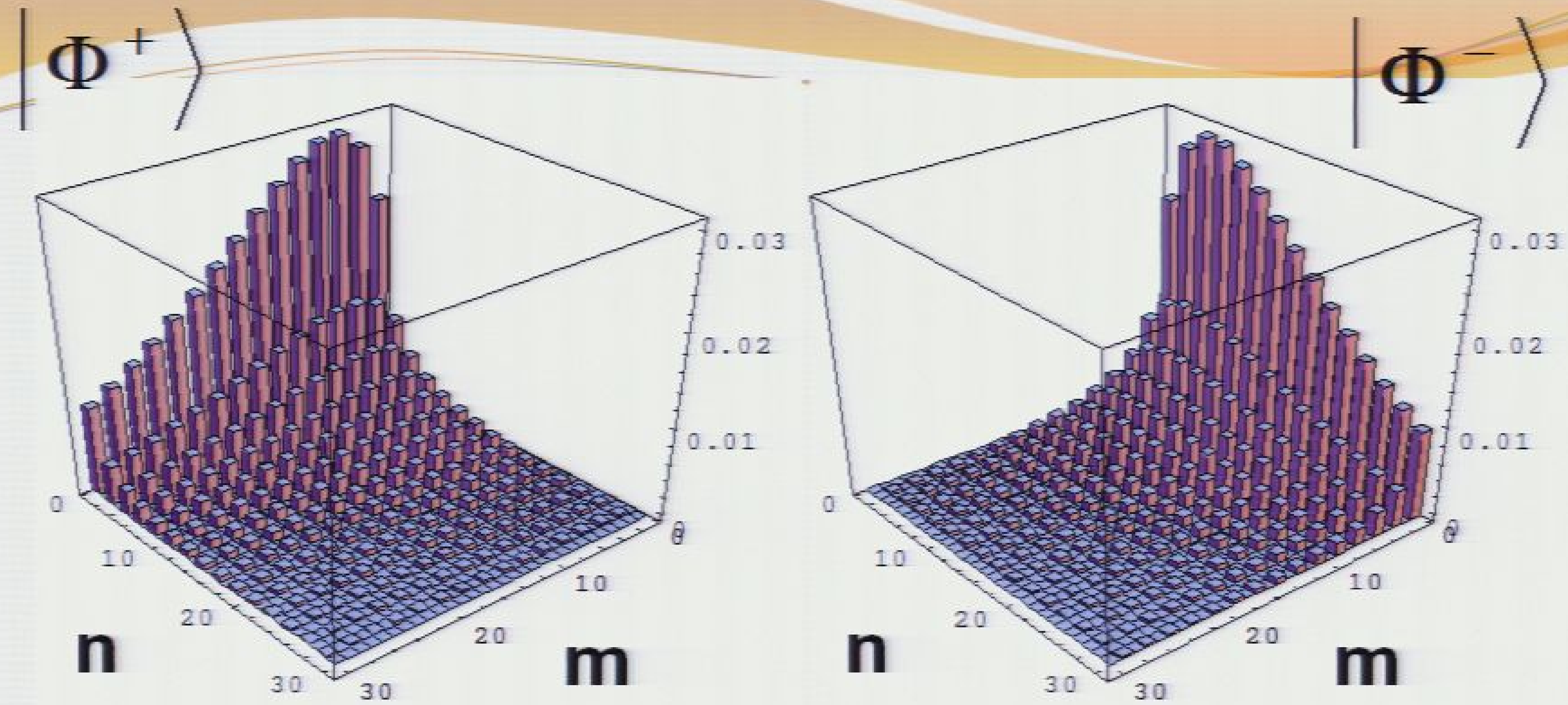
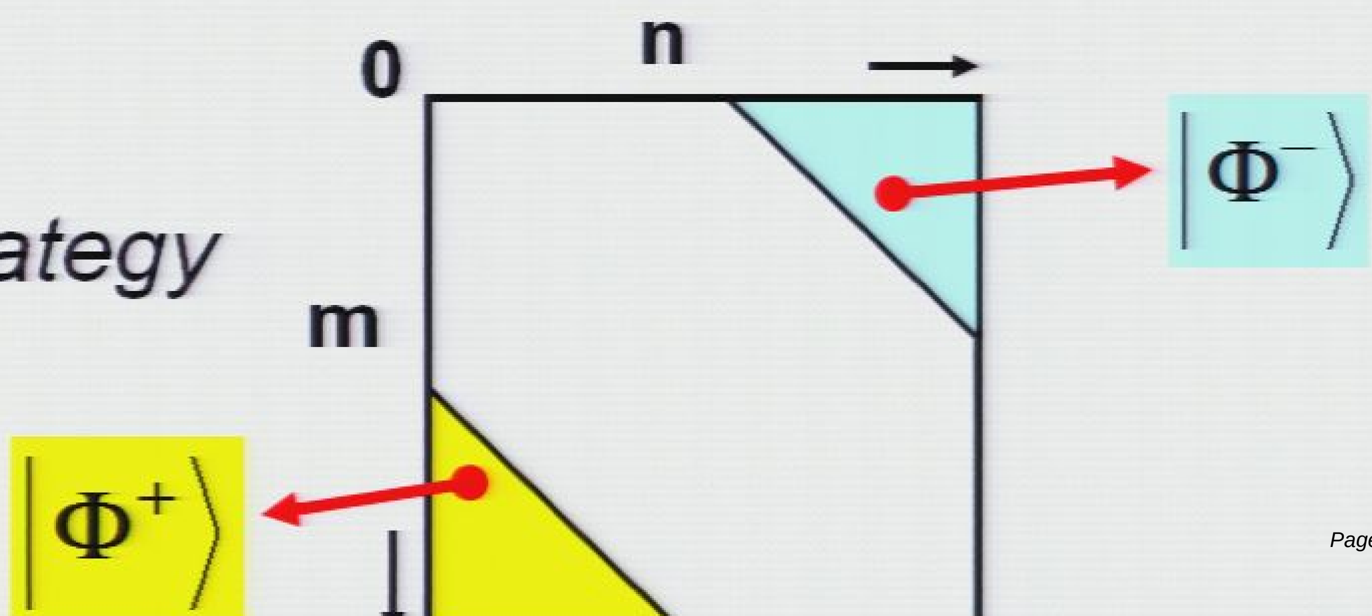
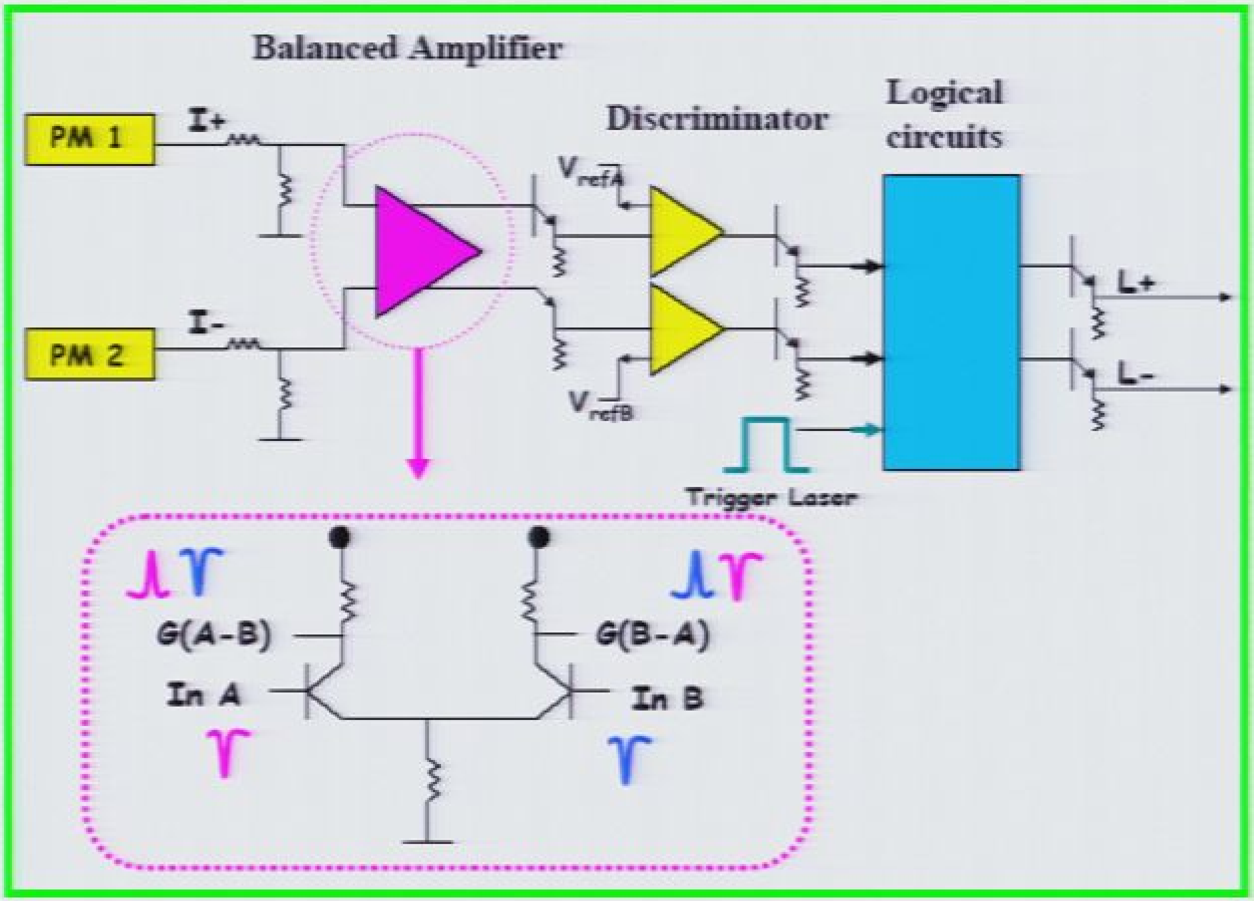
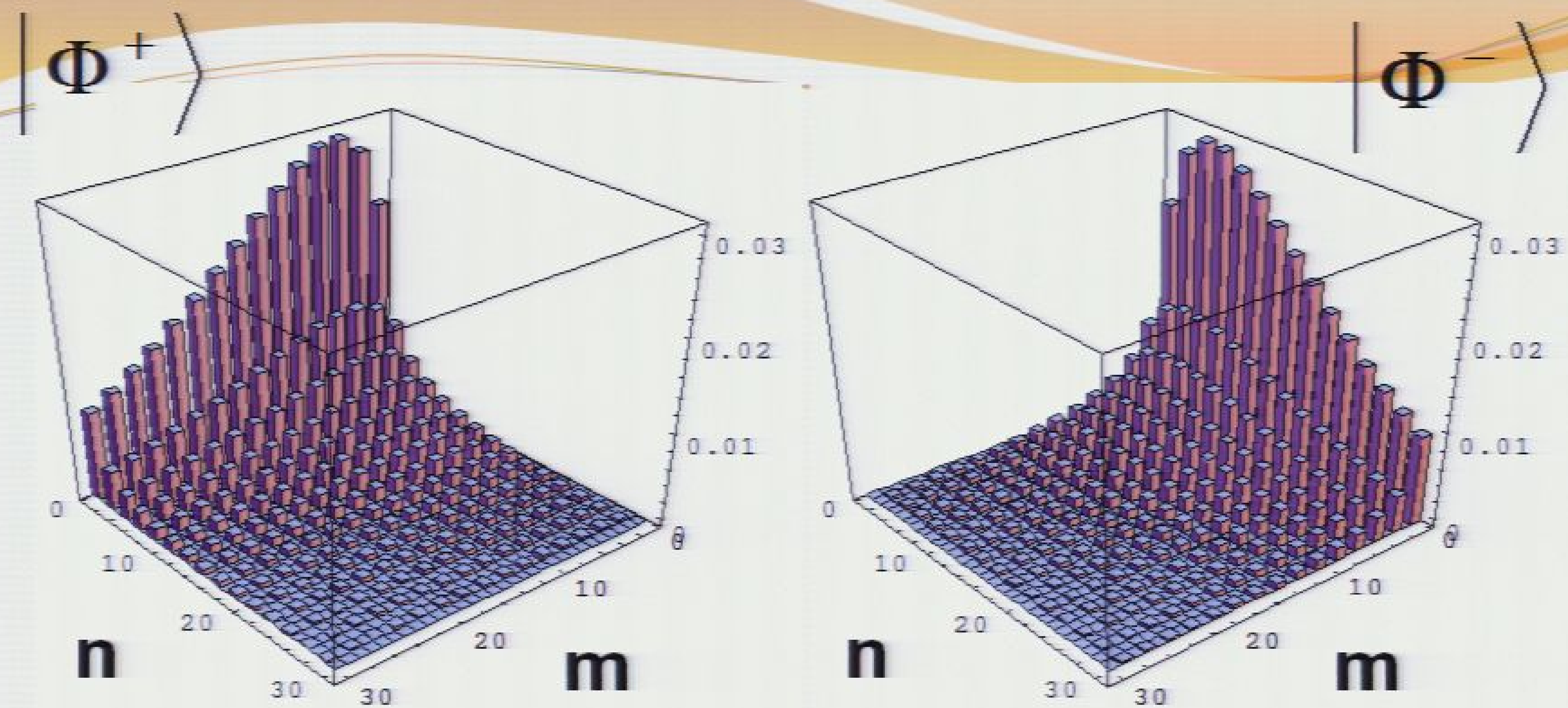


O-Filter :
POVM strategy



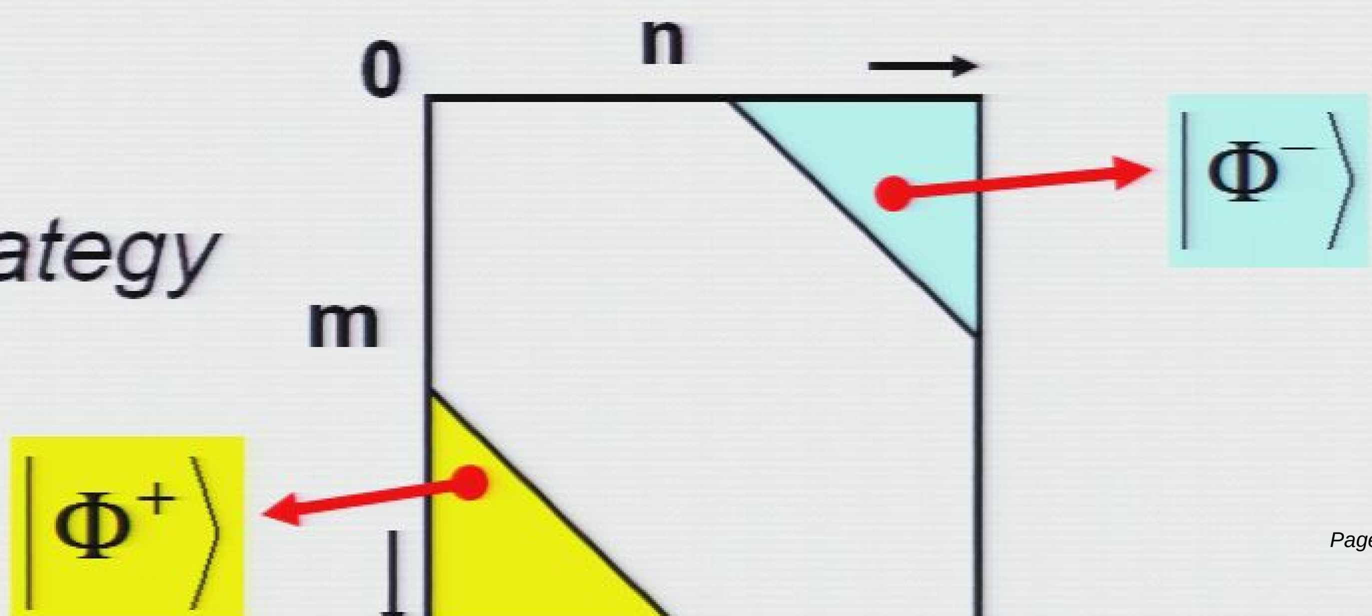


ORTHOGONALITY FILTER (OF)



O-Filter :

POVM strategy

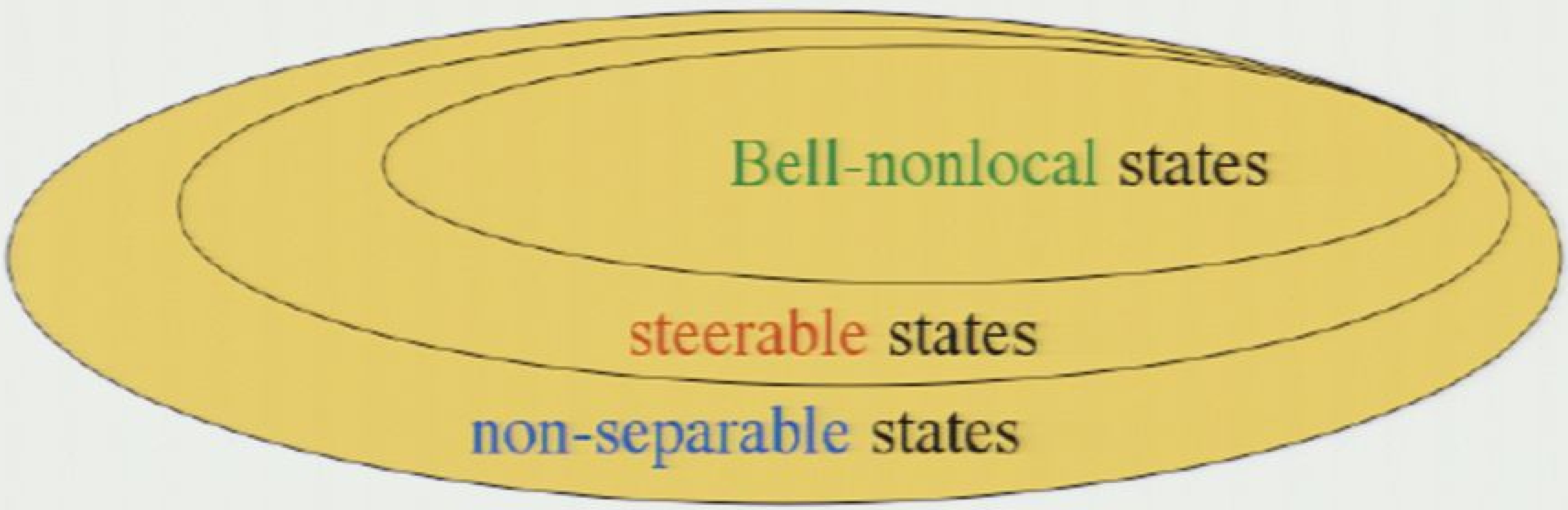


ingle-particle "loss" test for *Multi*-particle entanglement

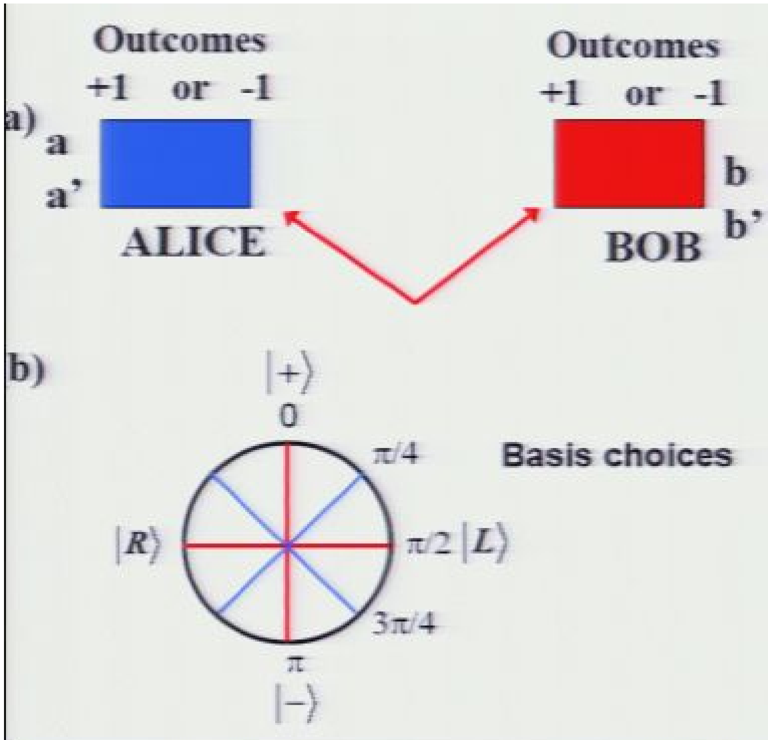
Since entanglement cannot be created or enhanced by *local* operations, e.g. by any loss or filtering mechanism acting on each mode $\mathbf{k_2}$,

Then the realization of entanglement over $\{\mathbf{k_1}, \mathbf{k_2}\}$ at a *single-particle* level implies that entanglement is also realized over these modes in the *multi-particle* regime.

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



Thanks to: H.M.Wiseman



SPIN – 1 INJECTION

Test of CHSH inequalities: choice of observables

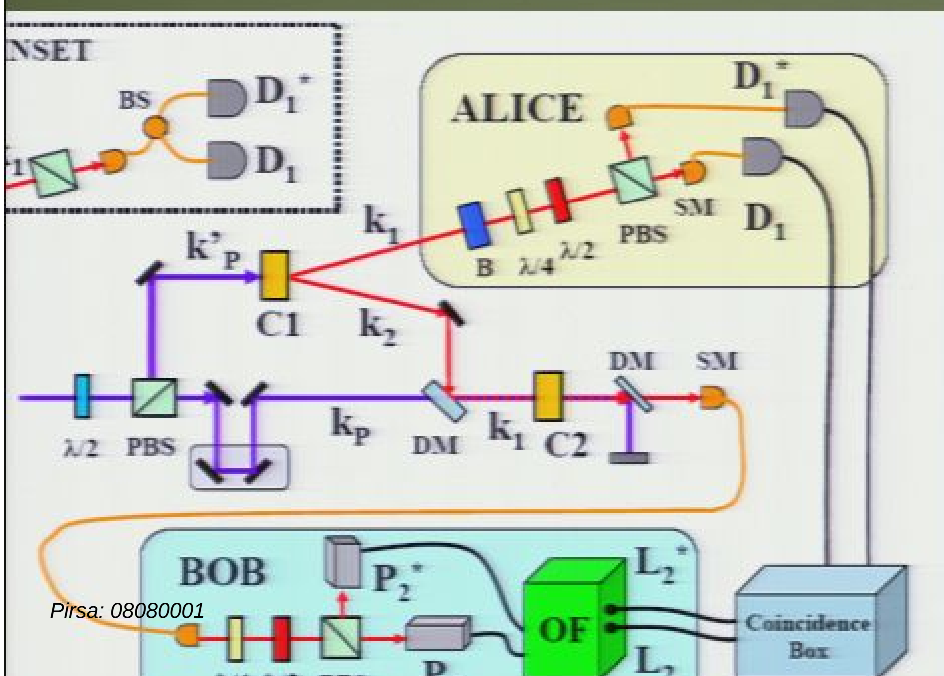
ALICE:

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 $|\Phi^{2\varphi}\rangle$

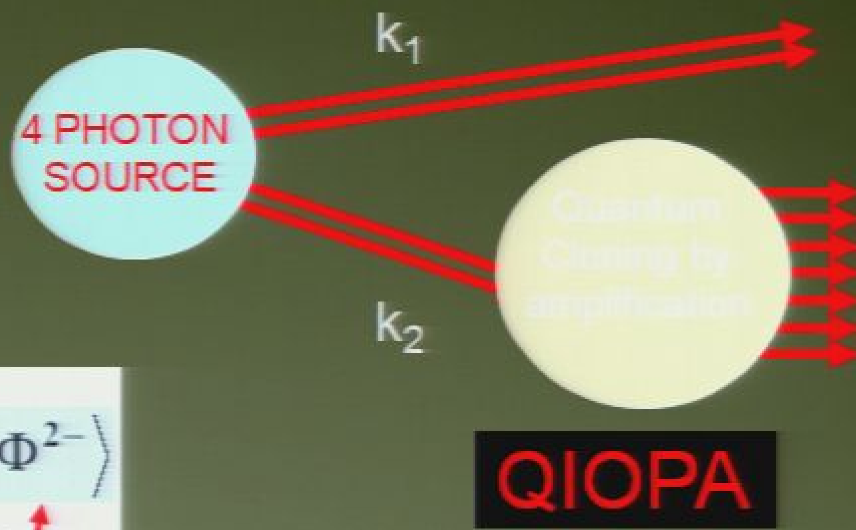
- 1: detection of state $|\Phi^{2\varphi^{\perp}}\rangle$

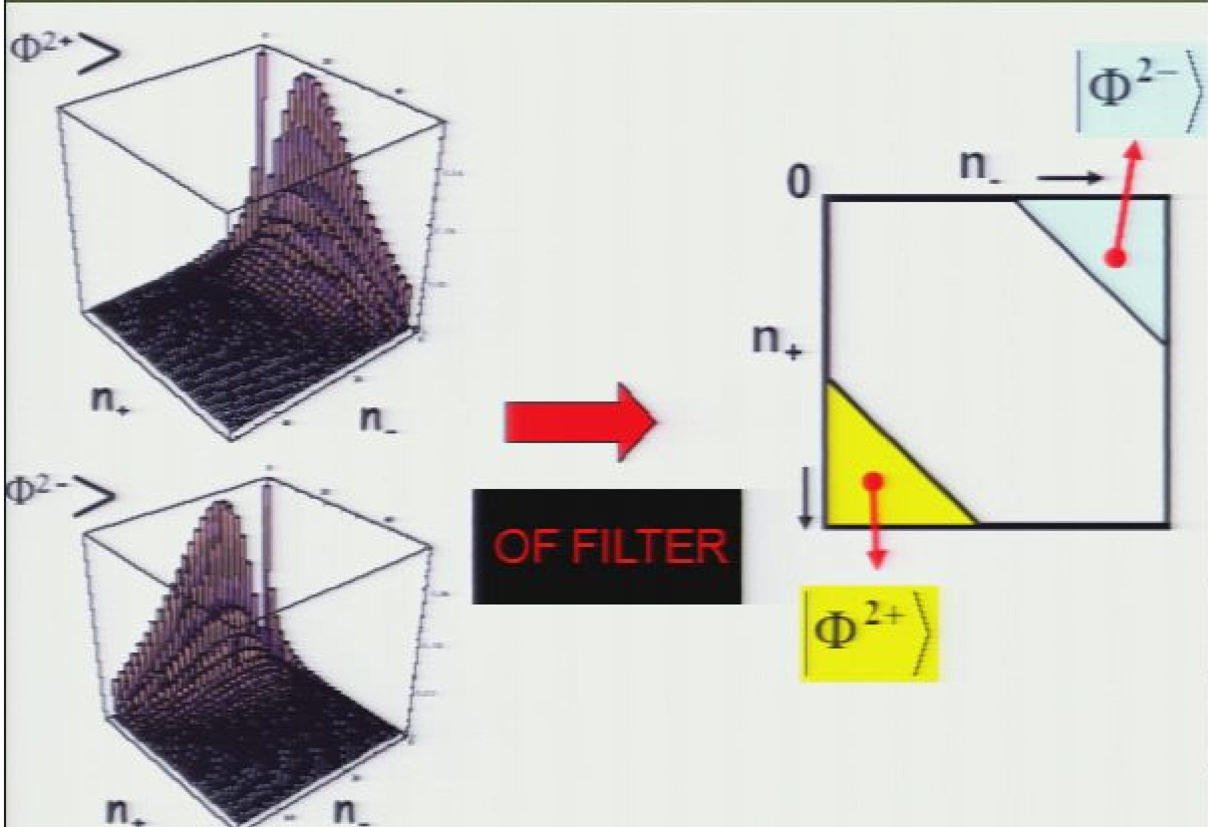
Basis b: $\varphi = 0$

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

Amplification of a spin-1 singlet state

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

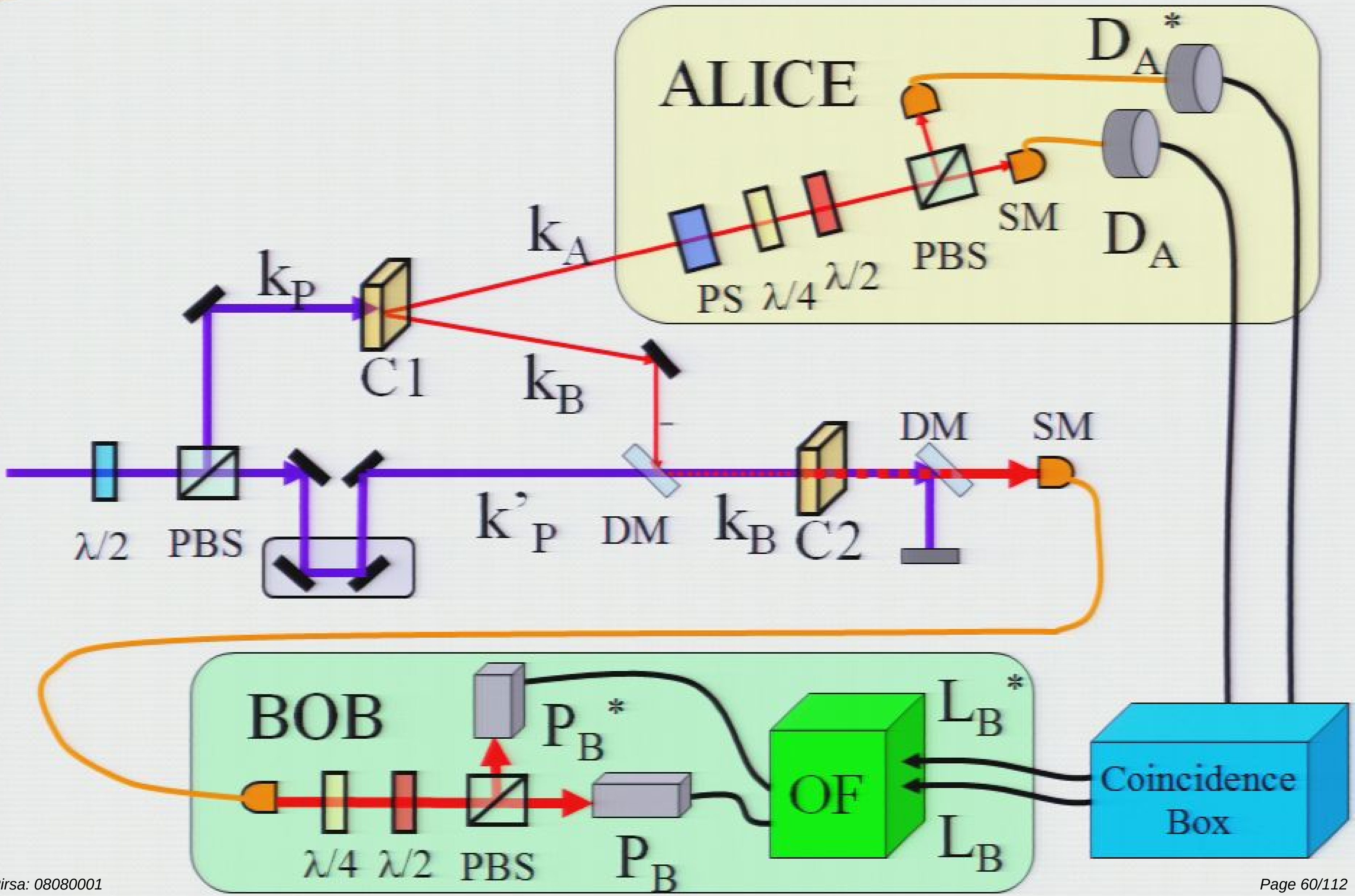




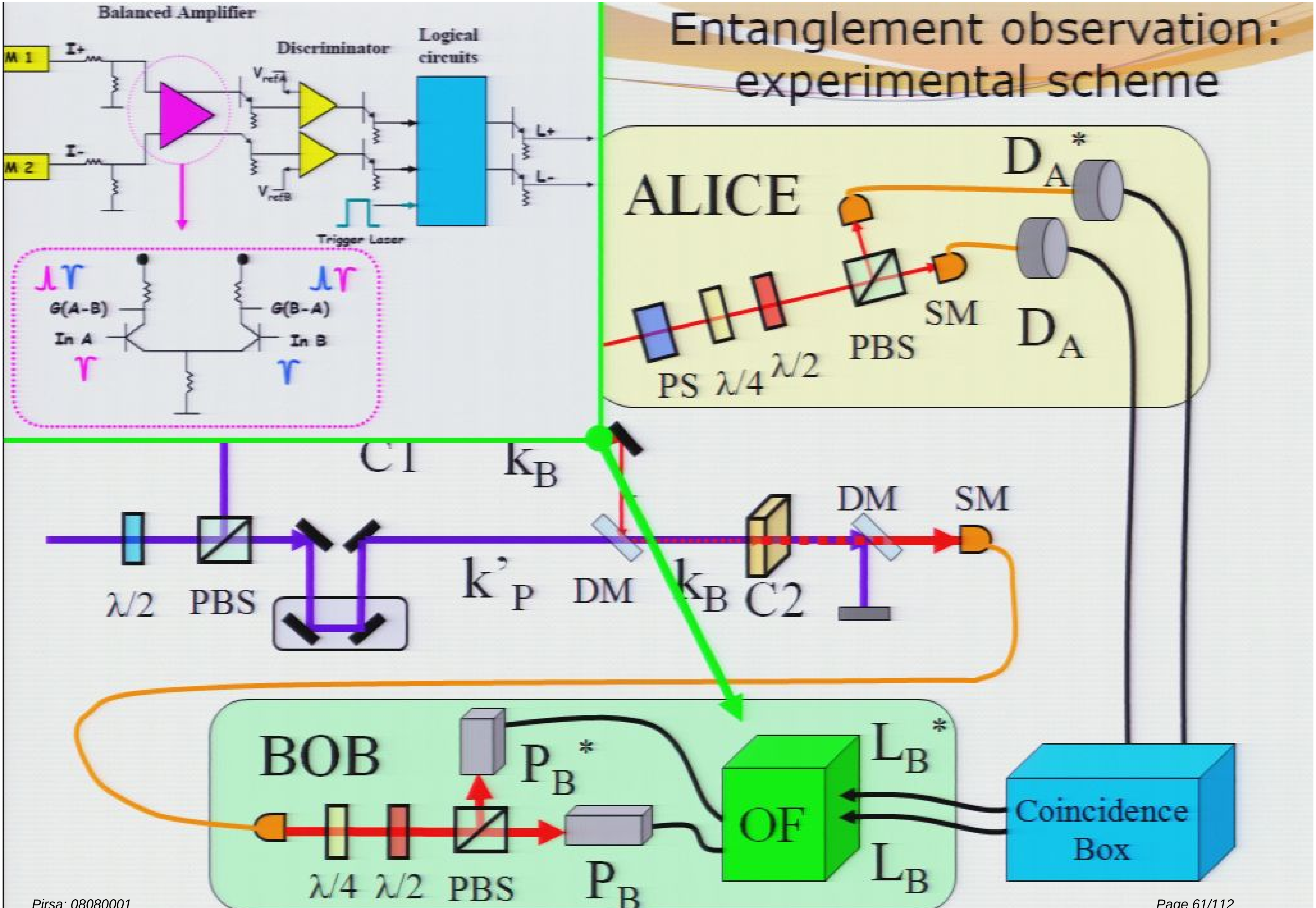
PROBABILISTIC DISCRIMINATION OF OUTPUT WAVEFUNCTION

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

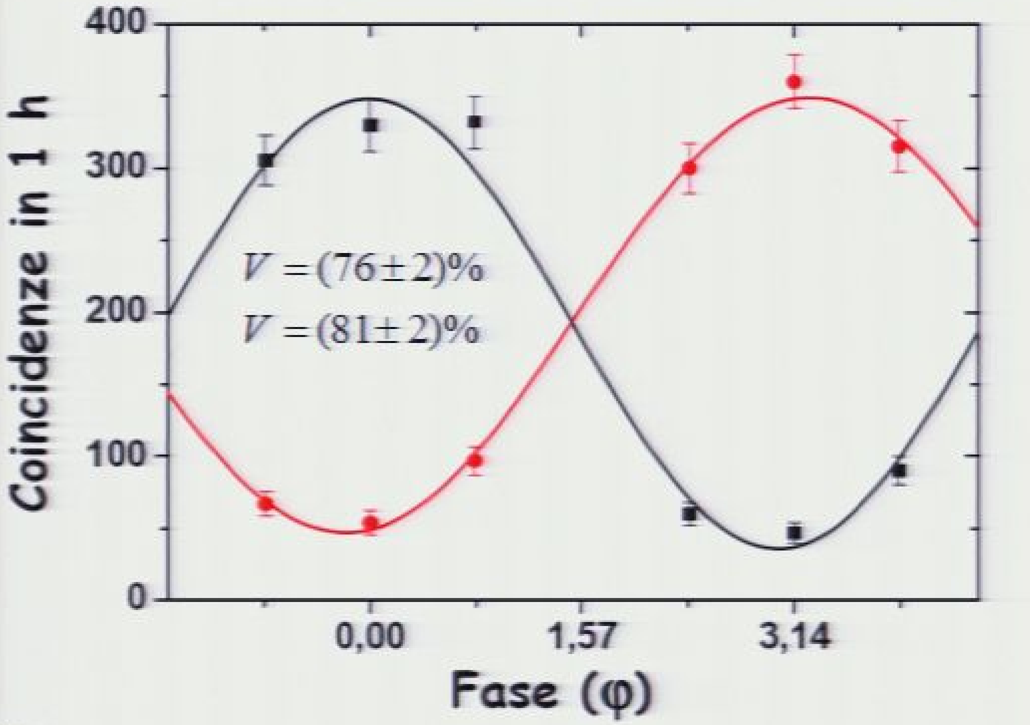
Entanglement observation: experimental scheme

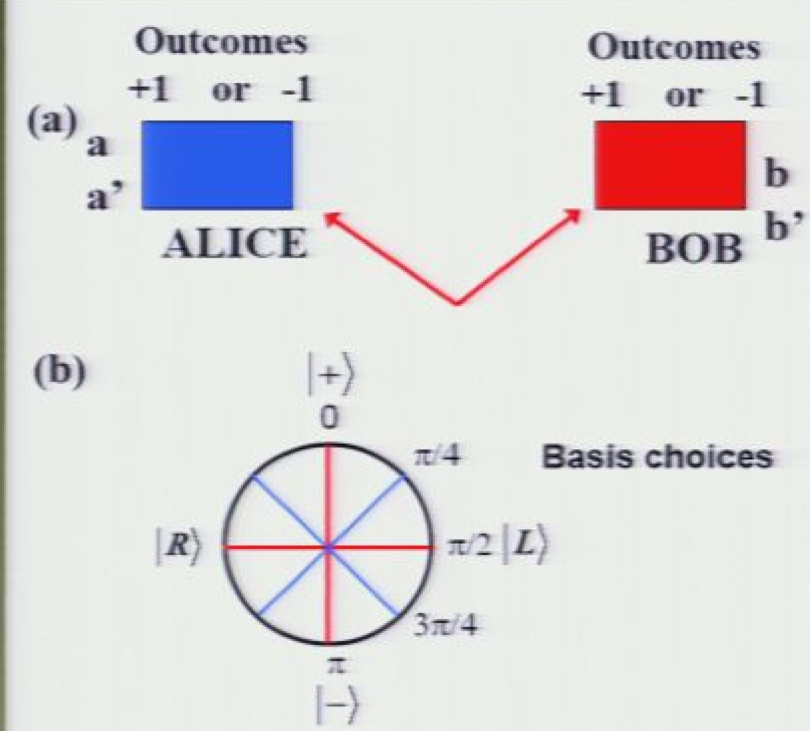


Entanglement observation: experimental scheme



Test of CHSH inequalities: experimental results





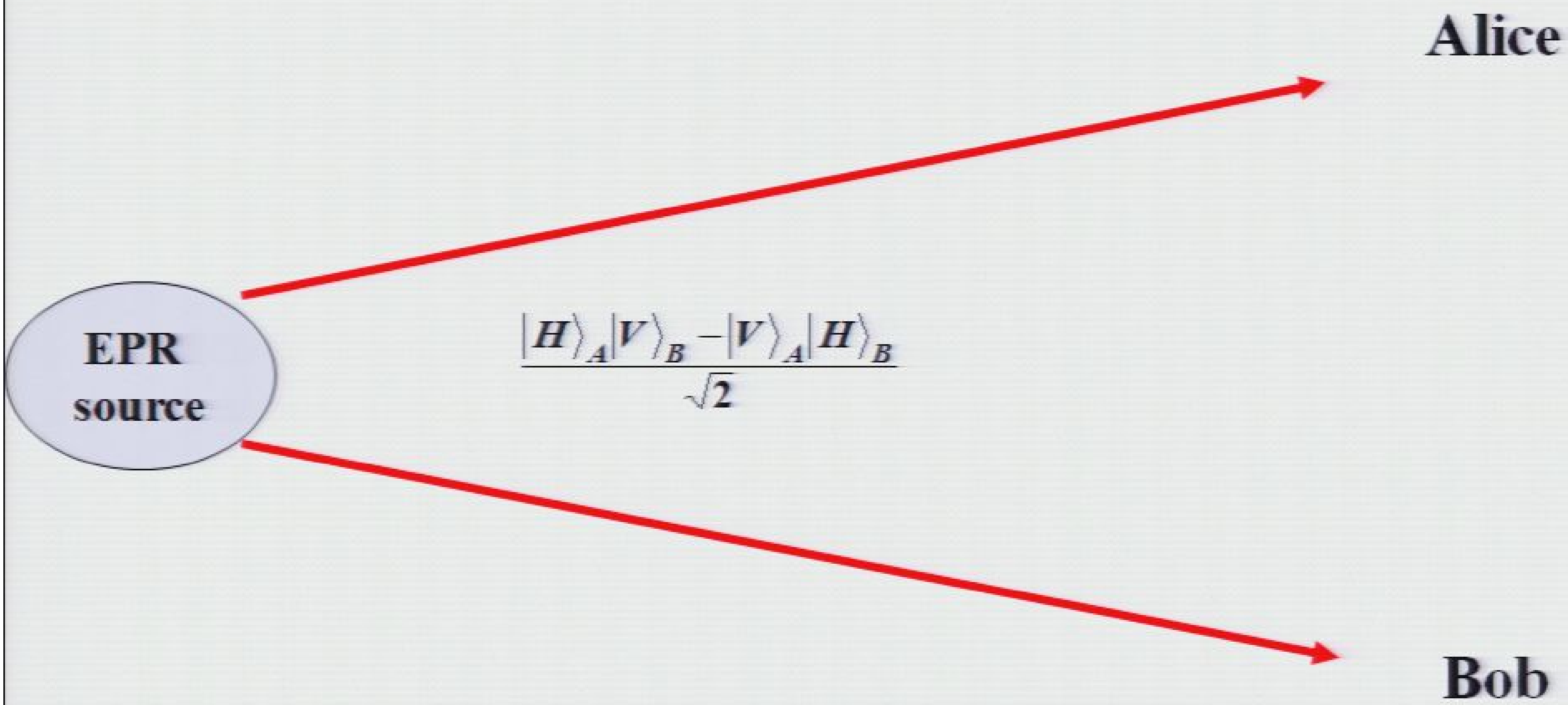
$$S = E(\varphi_1, \varphi_2) + E(\varphi_1', \varphi_2) + E(\varphi_1, \varphi_2') - E(\varphi_1', \varphi_2')$$

For a local realistic theory

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

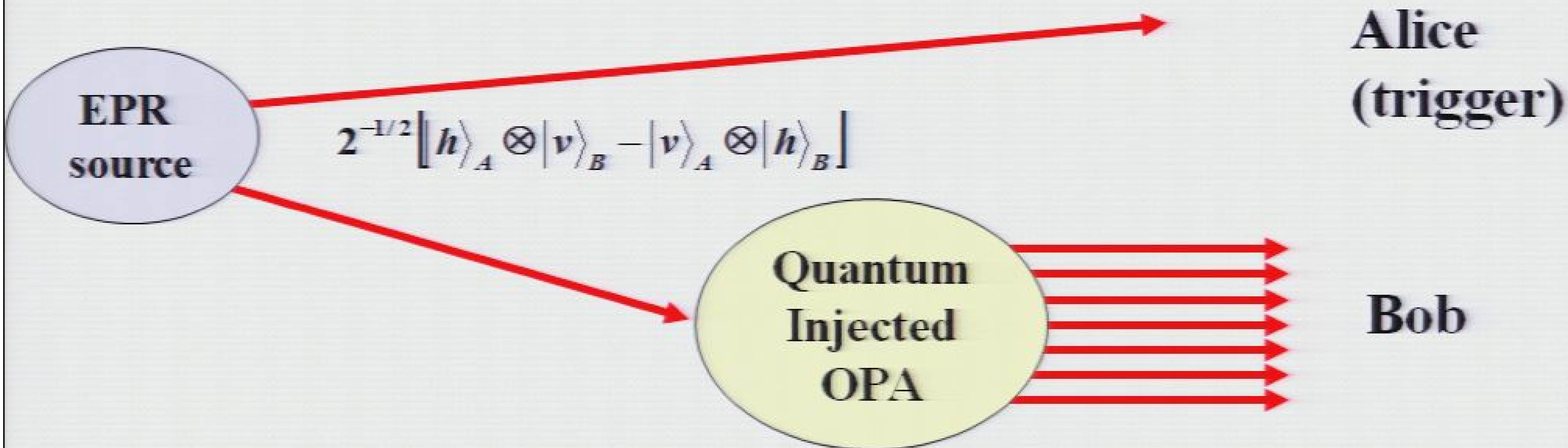
$$S_{exp} = 2.25 \pm 0.05 > S_{CHSH} = 2$$

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)

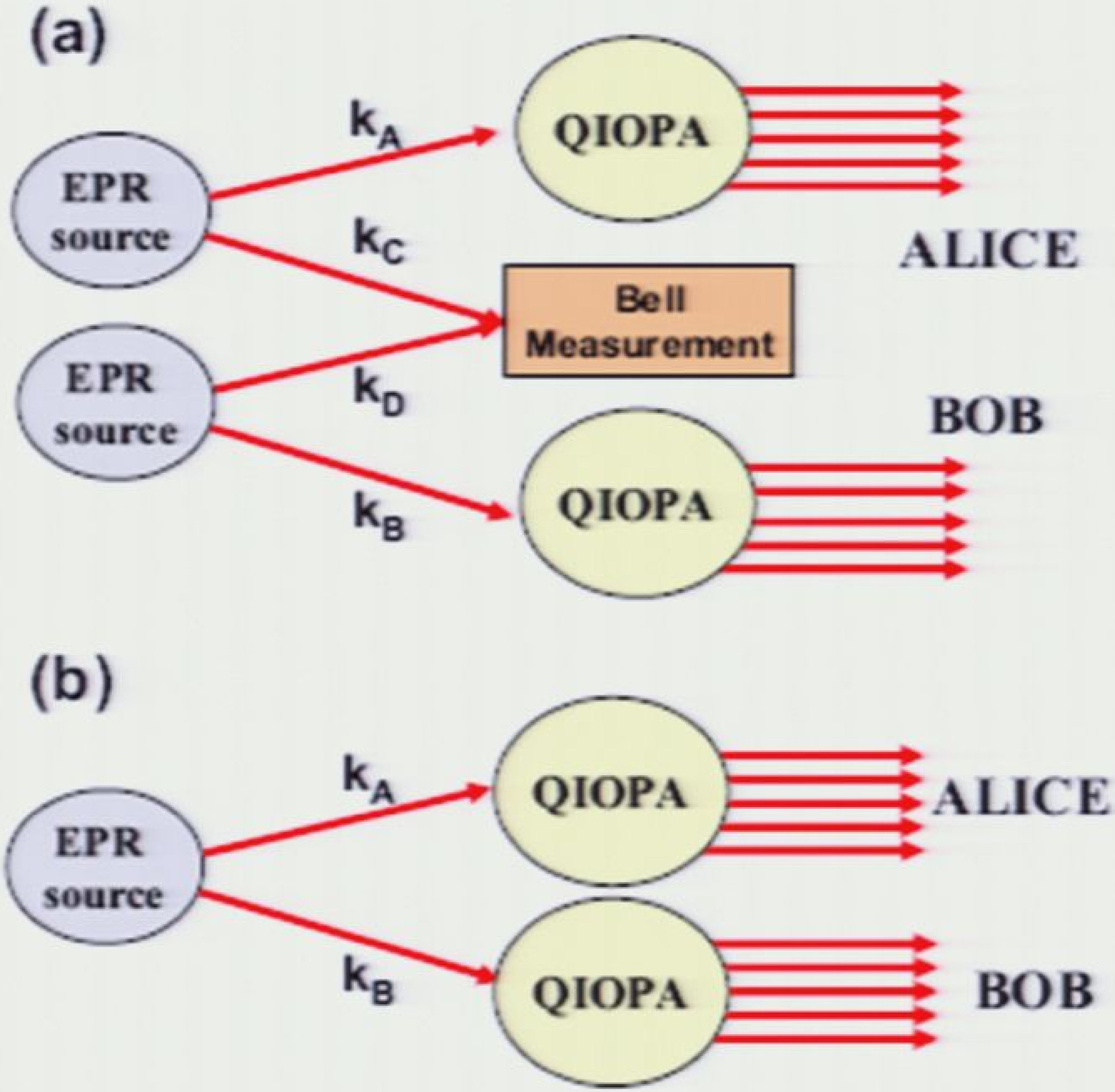


$$2^{-1/2}\left[\left|h\right\rangle_A \otimes \left|v\right\rangle_B - \left|v\right\rangle_A \otimes \left|h\right\rangle_B\right]$$

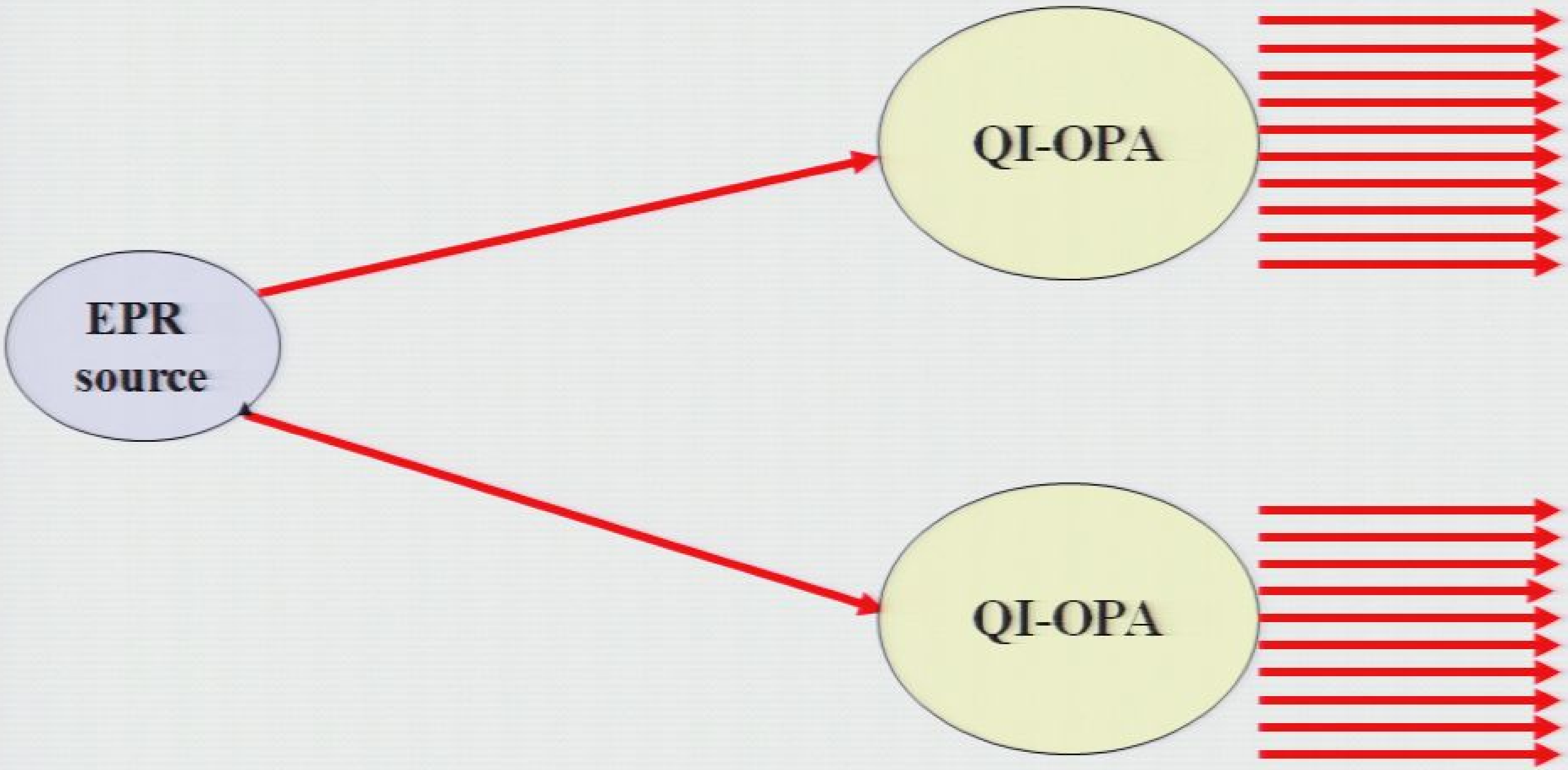
$$\left|\Sigma\right\rangle = 2^{-1/2}\left[\left|h\right\rangle_A \otimes \left|\Phi^V\right\rangle_B - \left|v\right\rangle_A \otimes \left|\Phi^H\right\rangle_B\right]:$$

SCHROEDINGER CAT STATE

MACRO - MACRO ENTANGLEMENT



Entanglement between 2 mesoscopic fields (de-coherence free)



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

$1 \to N$ particle Qubit:

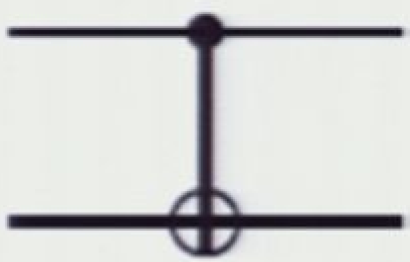
- The 3d order NL polarization is enhanced by a factor: $\xi = N^{3/2}$

Applications to Q. Information:

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

Two qubit gate:

C-NOT



Control qubit

Target qubit

Applications to Q. Information:

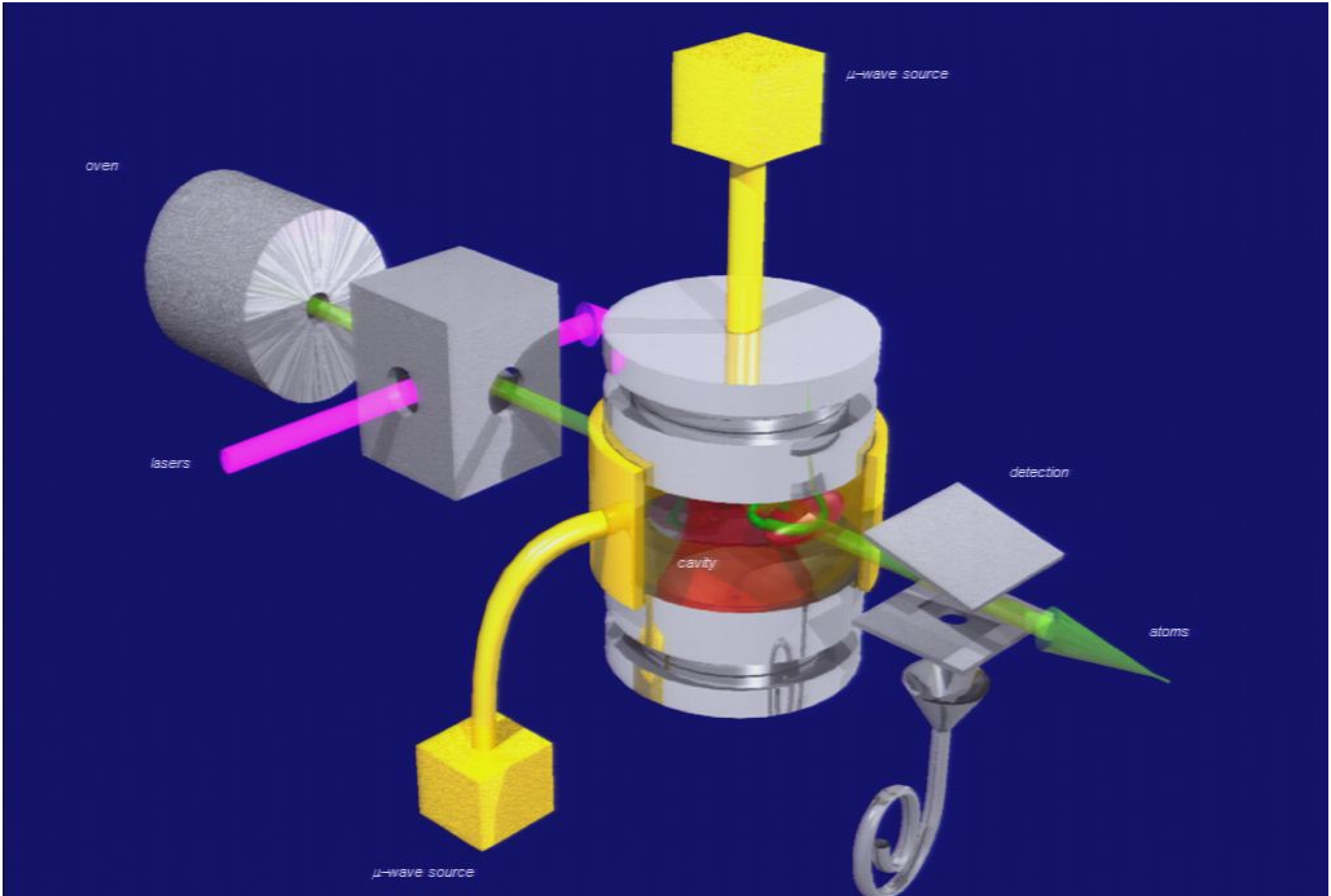
- Enhancement by $\xi \cong 10^{6} \div 10^{10}$ of all photon-photon interactions.
- EXAMPLES:
- A) 2-qubit phase-gates or C-NOT
- B) Superdense Coding (Bennett-Wiesner, 1992)

ATOMIC DECOHERENCE of SCHROEDINGER -CATS

Paolo Maioli, ENS, Paris

May 2003

(3 SLIDES)


μ–wave source
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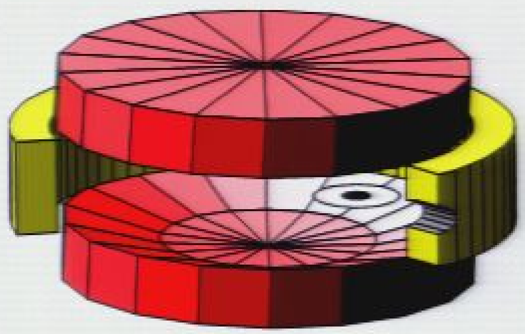
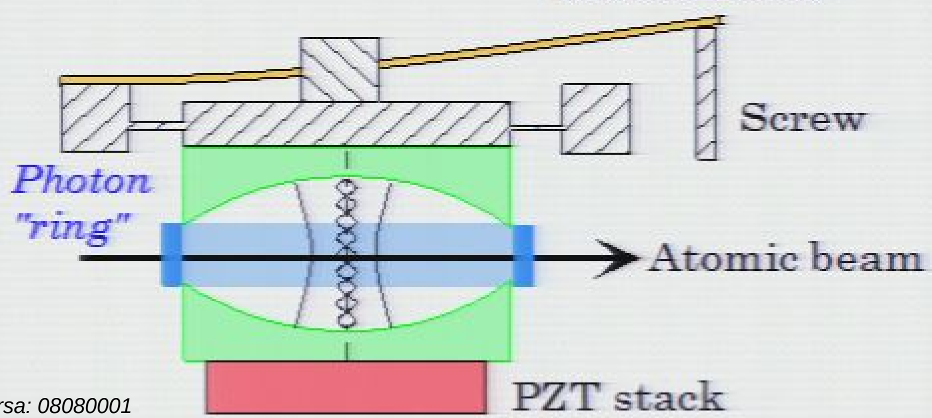
μ–wave source

Superconducting cavity

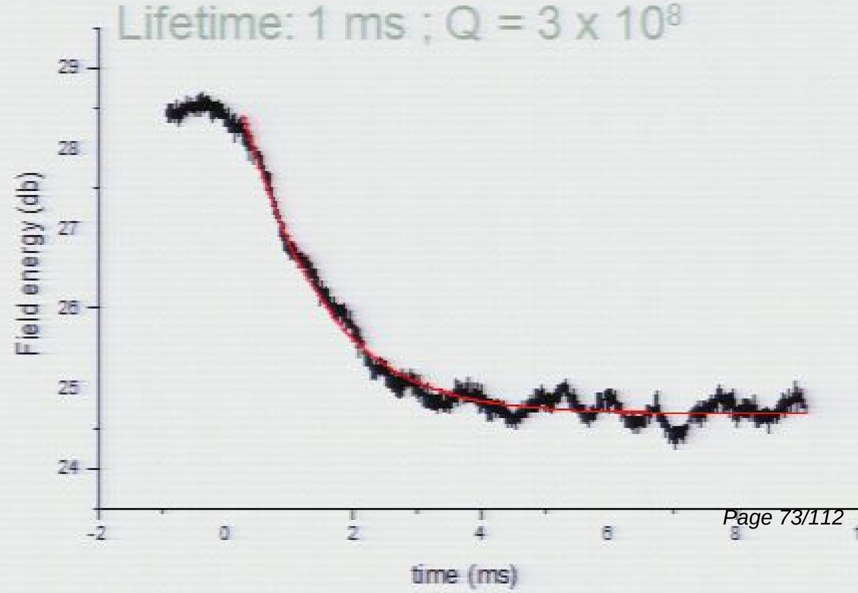


- Open Fabry Perot cavity with a photon "recirculation" ring
- Compatible with a static electric field (circular states stability and Stark tuning)



Polished Niobium mirrors

Lifetime: 1 ms ; Q = 3×10^8



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:

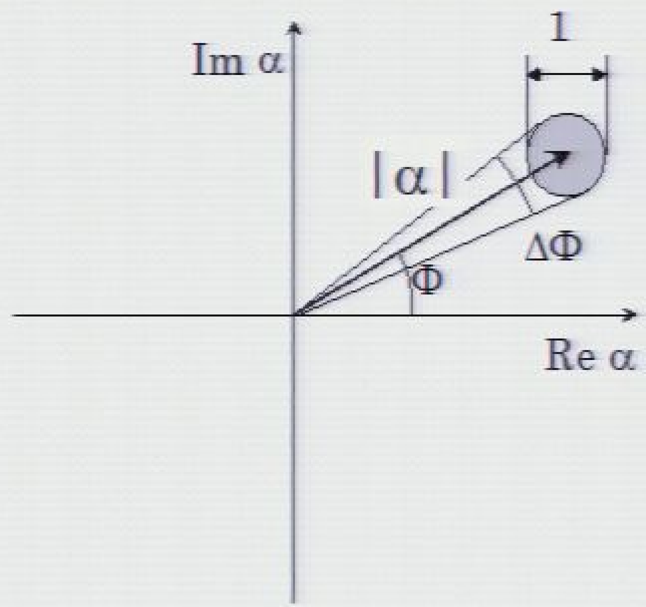
$$\bar{n} = |\alpha|^2$$

Photon number dispersion:

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

A representation:

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

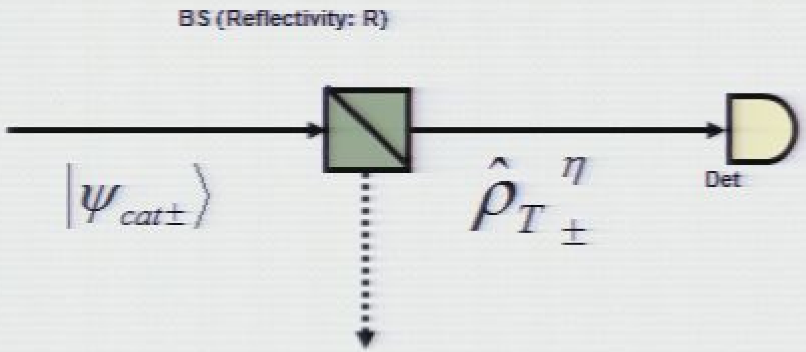


MACROSCOPIC SUPERPOSITION:

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

DECOHERENCE OF MACROSCOPIC SUPERPOSITIONS

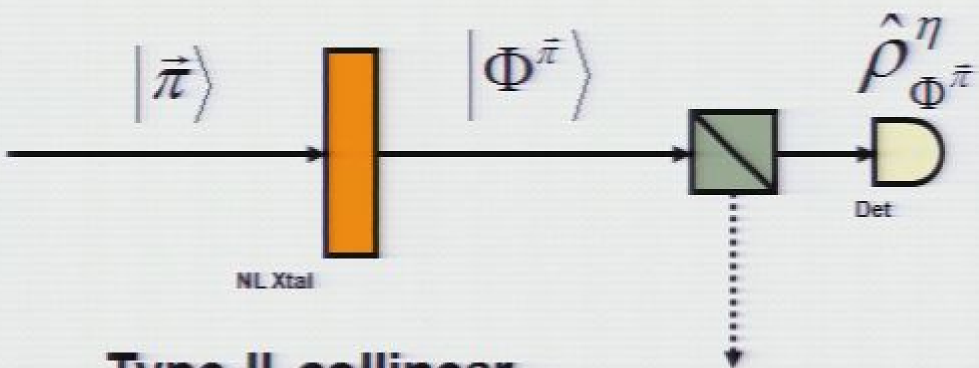
(1) Coherent cat states (R+T=1)



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

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

(2) QIOPA amplified states**BS (R)**



$$\rightarrow \begin{cases} |\vec{\pi}\rangle = \alpha|H\rangle + \beta|V\rangle \\ \downarrow \text{amplification process} \\ |\Phi^{\vec{\pi}}\rangle = \hat{U}|\vec{\pi}\rangle \end{cases}$$

Type-II, collinear

Two possible choices

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

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

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

D. Bures, *Trans. Math. Soc. 1969*
R. Jozsa, *J. Mod. Opt. 1994*
A. Uhlmann, *Rep. Math. Phys. 1986*

where: **STATE FIDELITY**:

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

a) State distinguishability

i.e.

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

→ represents how close two quantum states are

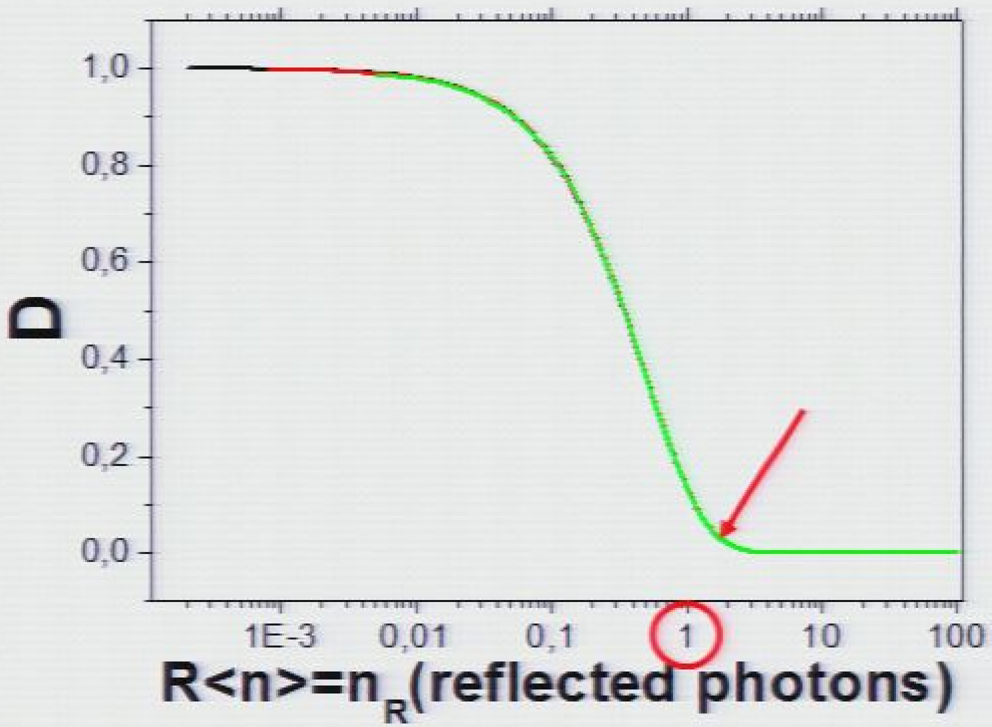
(b) Coherence: state-orthogonality

i.e.

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

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

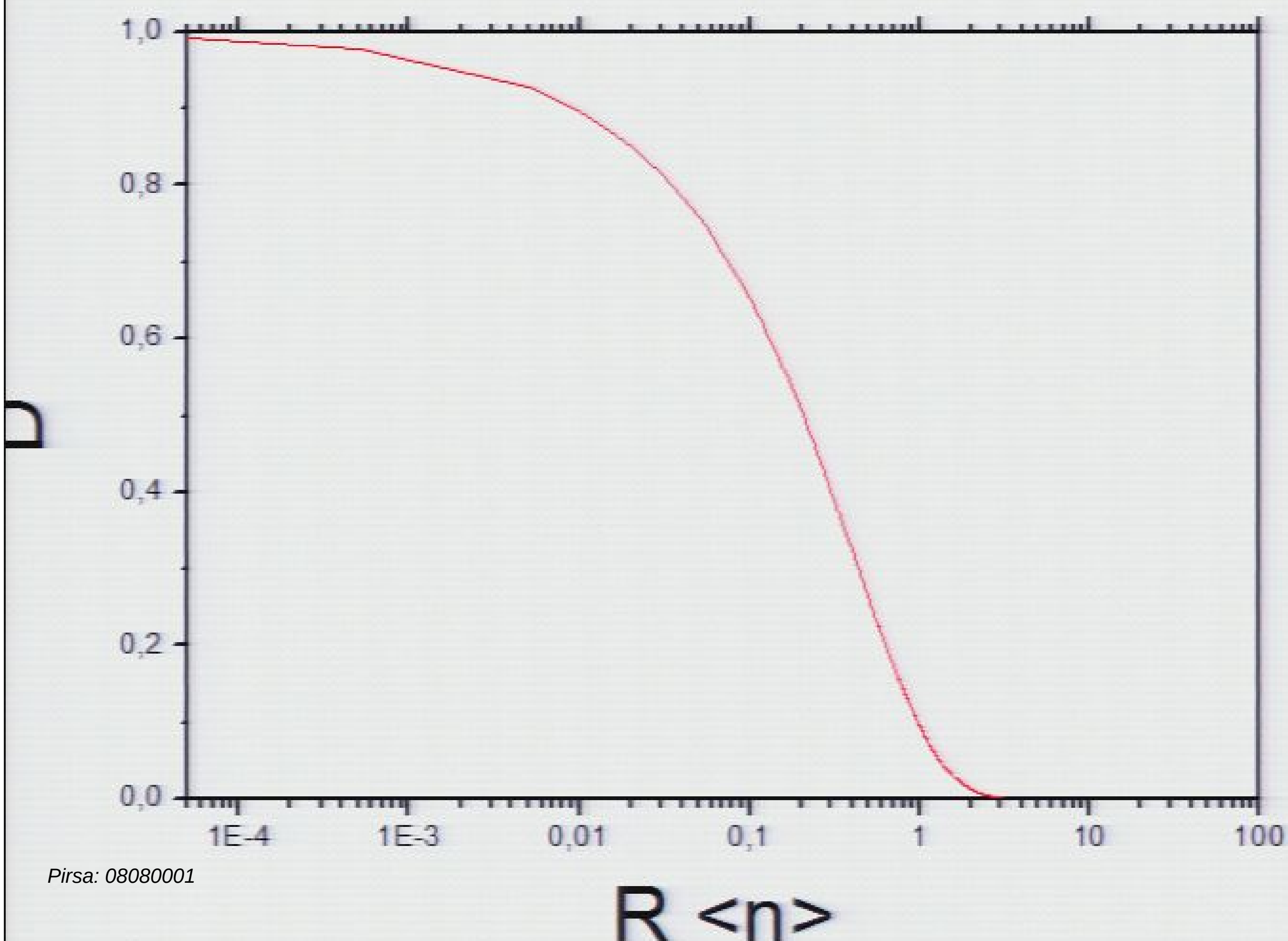
BURES DISTANCE D : $\frac{N}{\sqrt{2}}\left(|\alpha\rangle + |-\alpha\rangle\right) \Leftrightarrow \frac{N}{\sqrt{2}}\left(|\alpha\rangle - |-\alpha\rangle\right)$



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

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

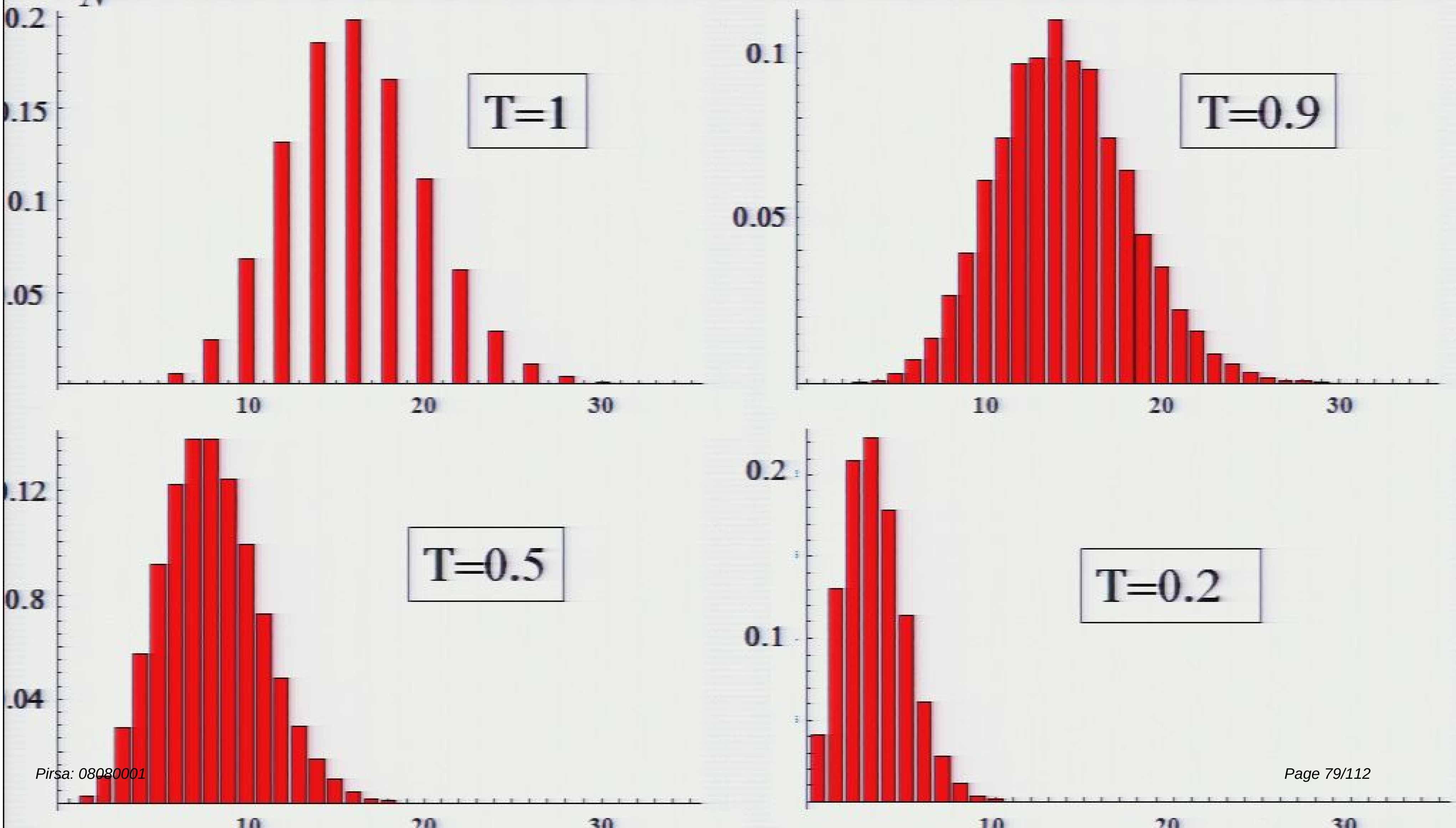
$$D = \sqrt{1 - \sqrt{1 - e^{-4R|\alpha|^2}}}$$

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

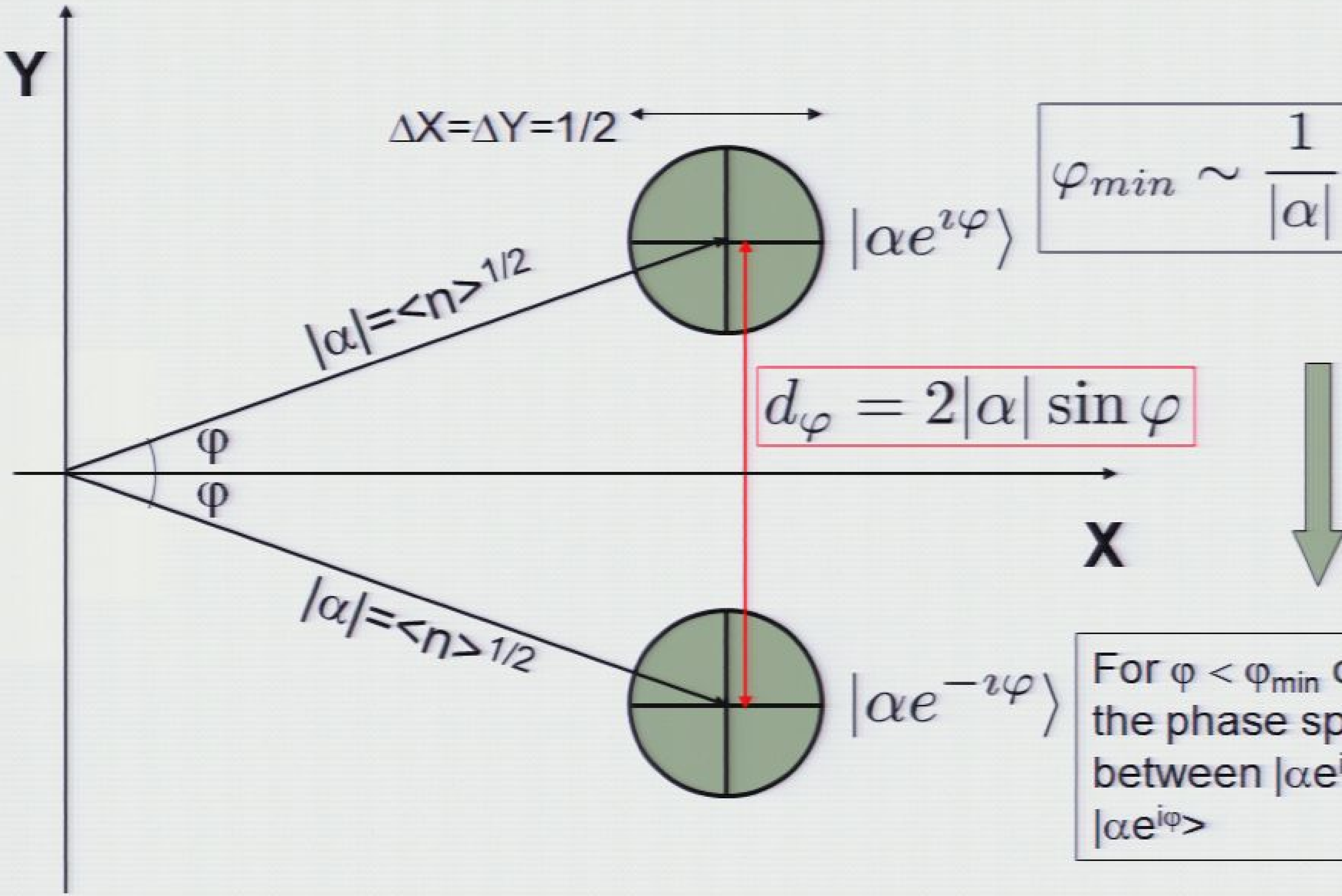
→ for any <n>!

COHERENT - STATE SCHRÖDINGER - CAT

$$\frac{1}{N}\left(|\alpha\rangle + |-\alpha\rangle\right) \;\Rightarrow\; \langle n \rangle = 16$$



COHERENT STATES: PHASE SPACE DISTANCE



$$|\alpha e^{i\varphi}\rangle$$

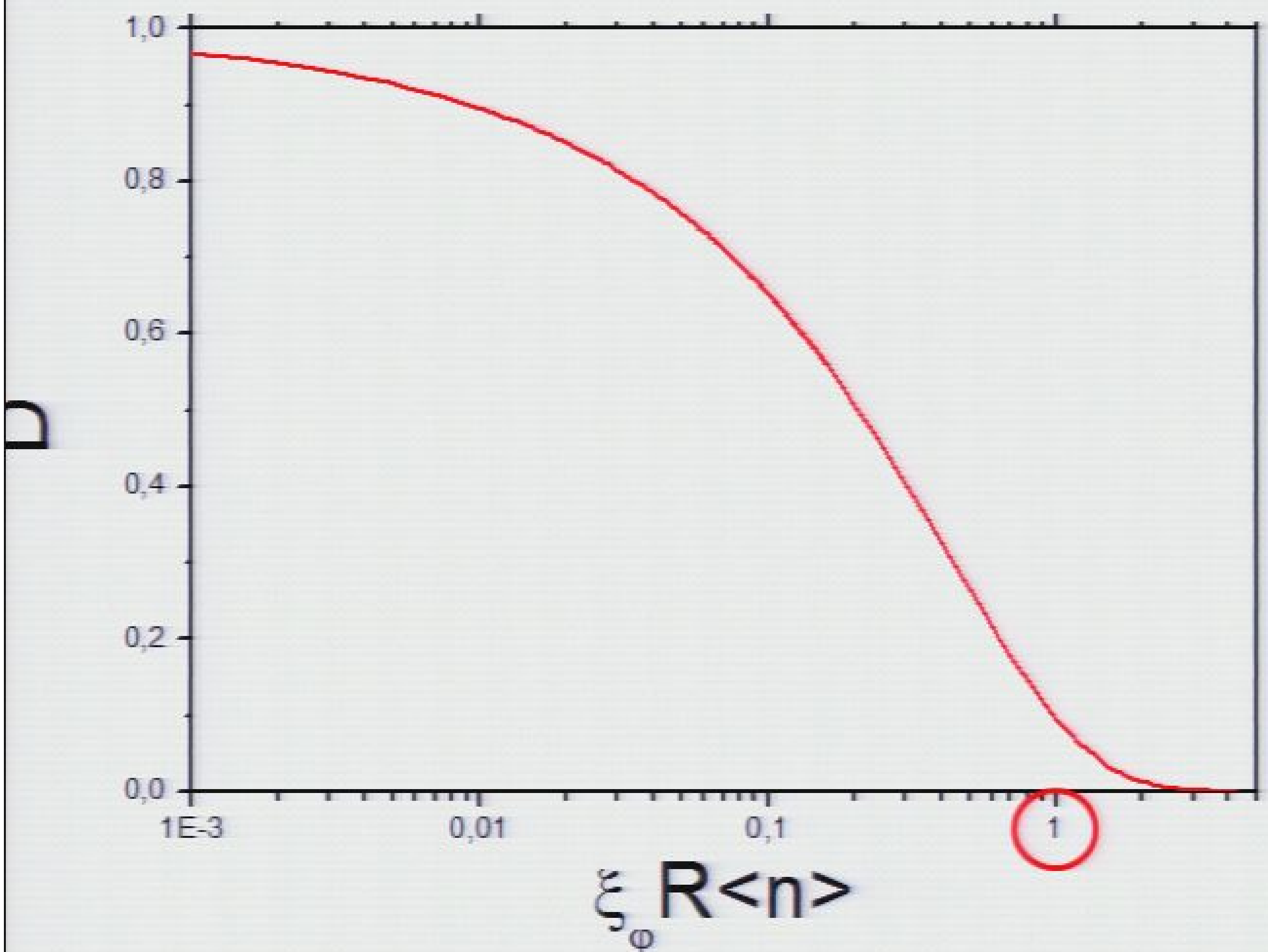
$$\varphi_{min} \sim \frac{1}{|\alpha|} = \frac{1}{\langle n\rangle^{\frac{1}{2}}}$$

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

$$|\alpha e^{-i\varphi}\rangle$$

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

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



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

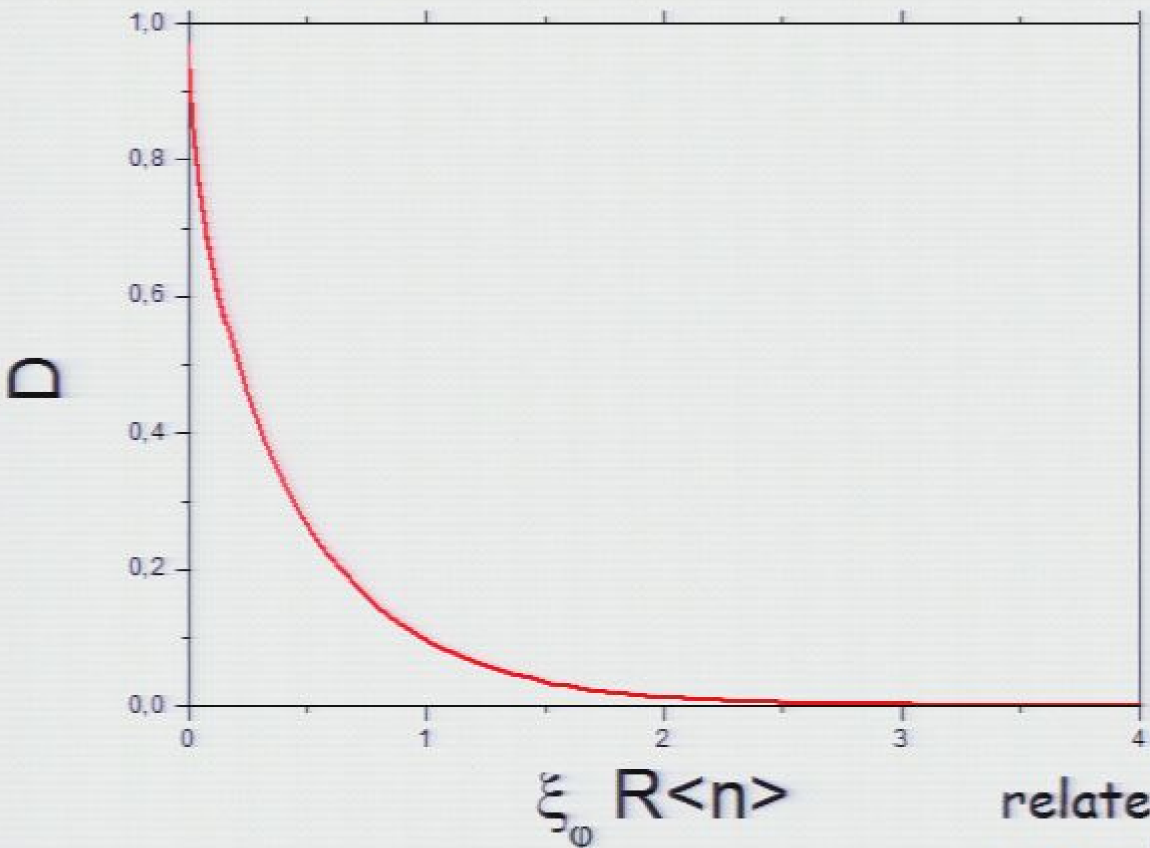
$$(\xi_\varphi)_{min} = \sin^2\frac{1}{|\alpha|} \sim \frac{1}{\langle n\rangle}$$

FOR ANY <n> and φ!

UNIVERSAL FUNCTION FOR COHERENT - STATE MACRO-QUBITS

TRANSMISSION OF QUANTUM SUPERPOSITION OF COHERENT STATES THROUGH A LOSSY CHANNEL

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



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

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 $|\alpha e^{i\varphi}\rangle \Leftrightarrow |\alpha e^{-i\varphi}\rangle$

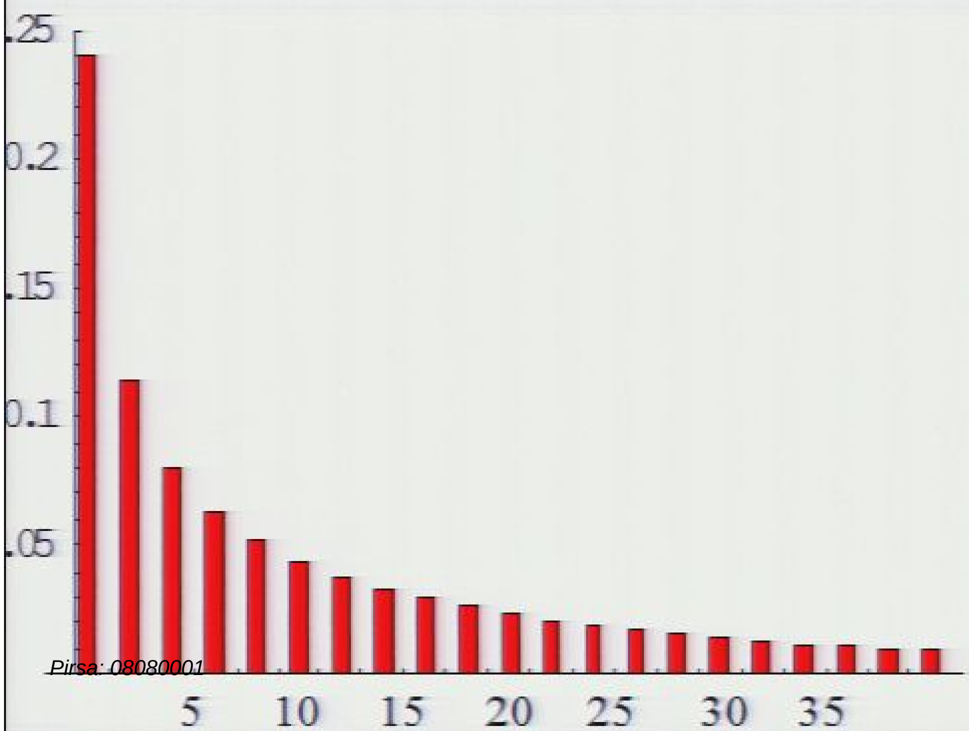
for any <n>!

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

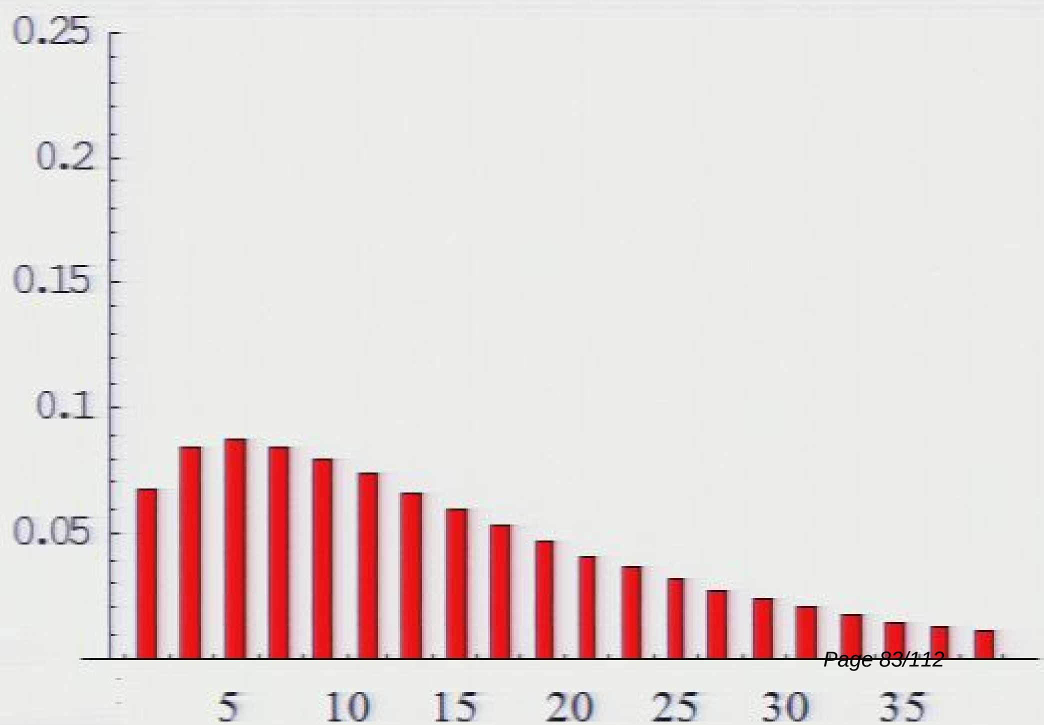
COMPARISON BETWEEN QIOPA SPONTANEOUS AND AMPLIFIED MARGINAL PHOTON DISTRIBUTIONS: SINGLE PHOTON INJECTION

$\langle n \rangle = 16$

QIOPA spontaneous emission distributio (Planck)

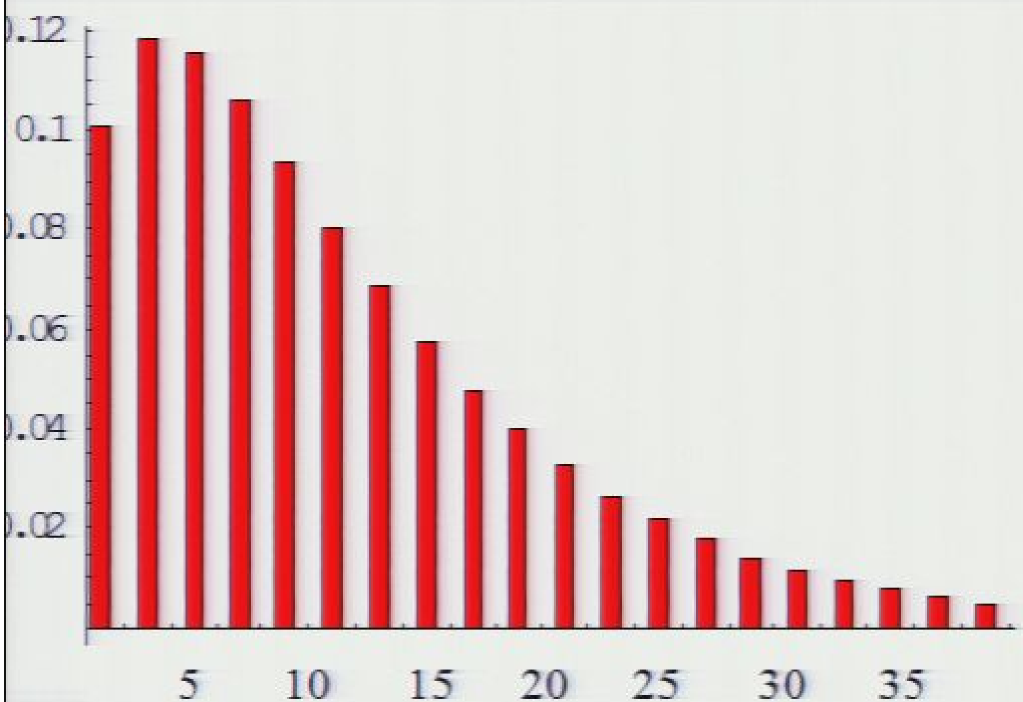


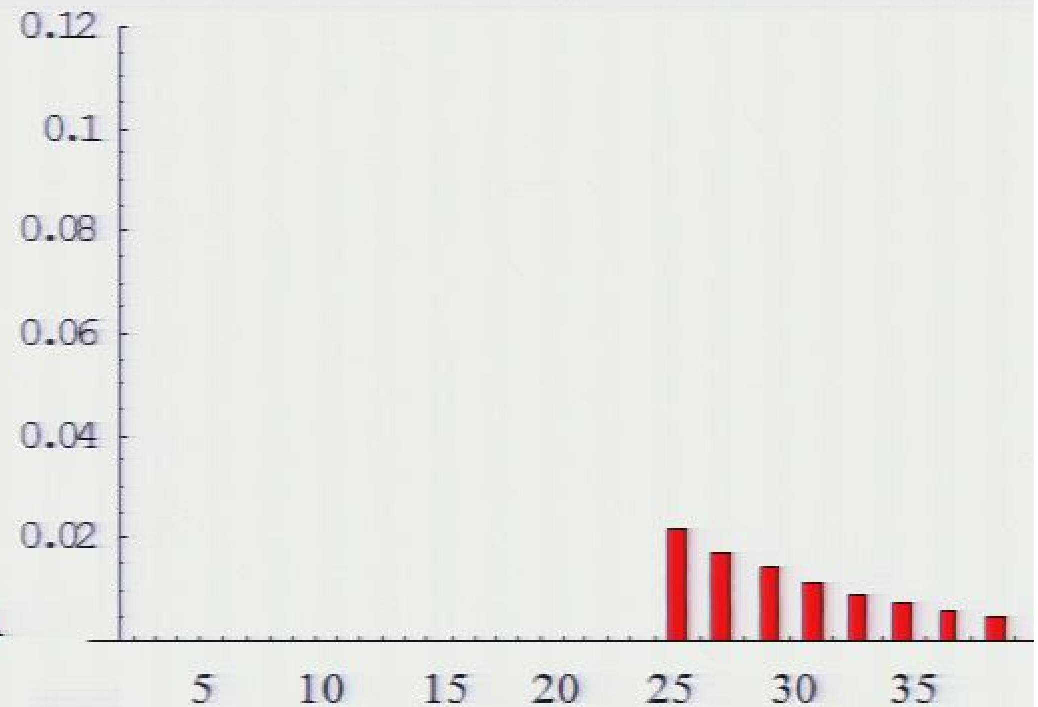
QIOPA $|\Phi^{\phi}\rangle$ equatorial qubits



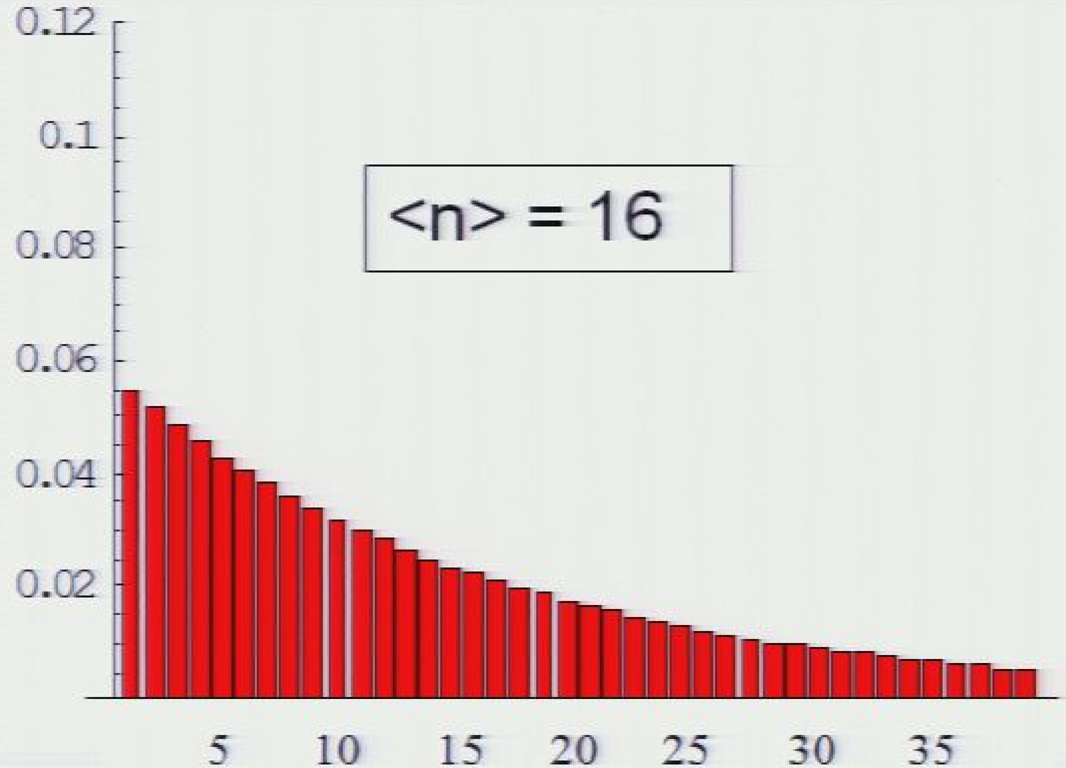
OF - FILTERING OF THE QIOPA GENERATED MACRO STATES

$g = 1.4 \Rightarrow \langle n \rangle = 16$



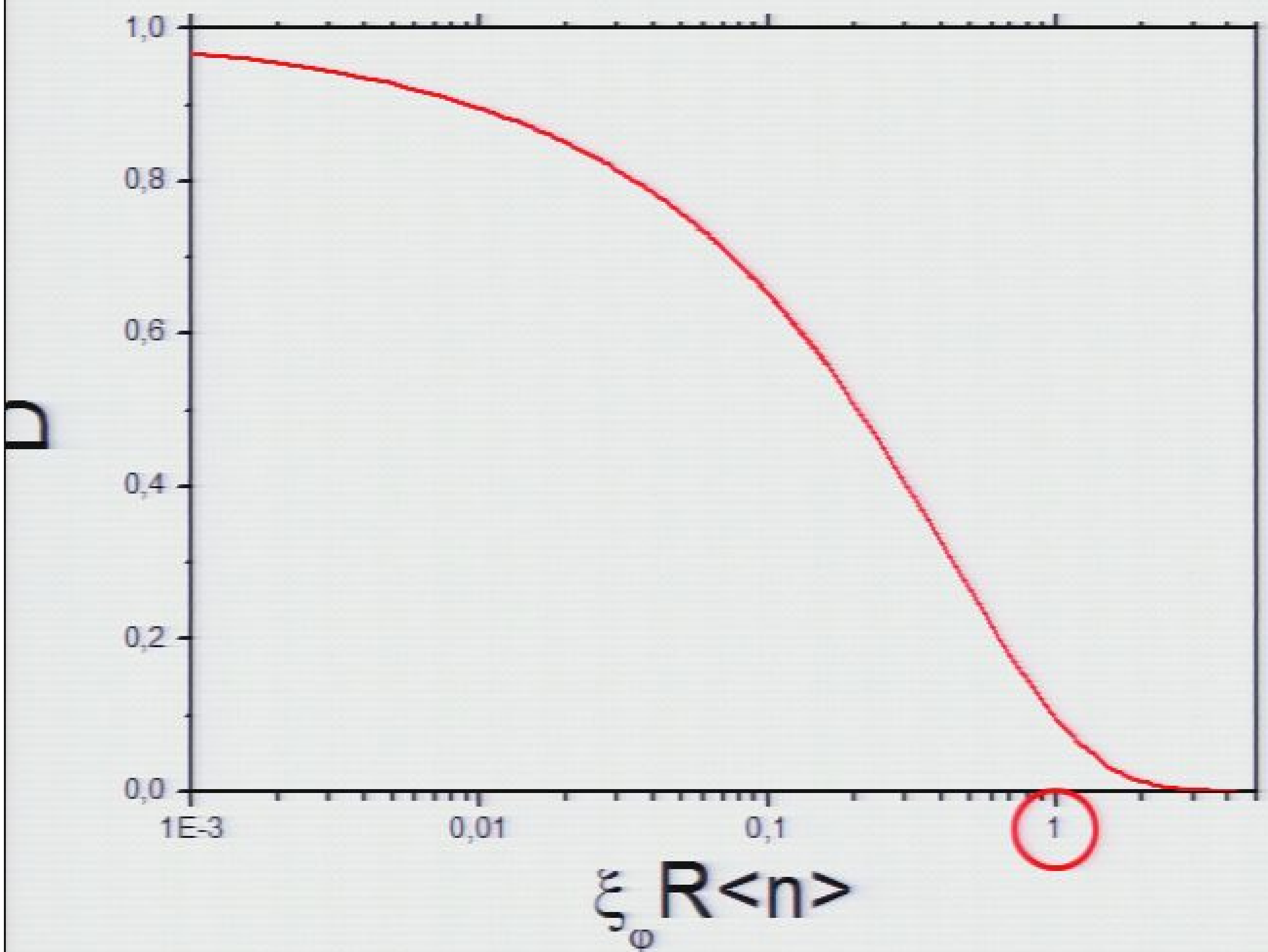


Planckian distribution: QIOPA spontaneous emission



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

φ=π/2



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

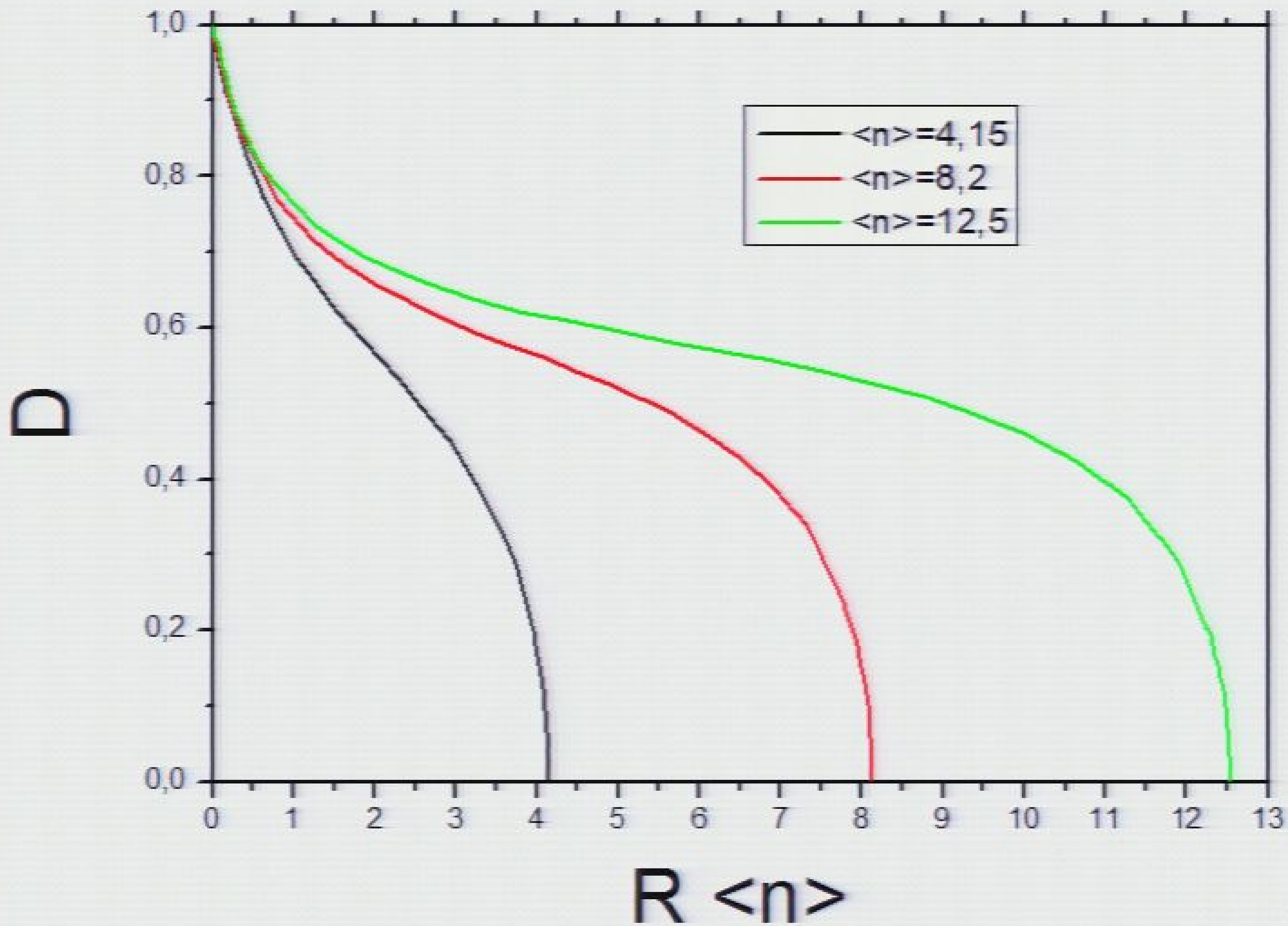
$$(\xi_\varphi)_{min} = \sin^2\frac{1}{|\alpha|} \sim \frac{1}{\langle n\rangle}$$

FOR ANY <n> and φ!

UNIVERSAL FUNCTION FOR COHERENT - STATE MACRO-QUBITS

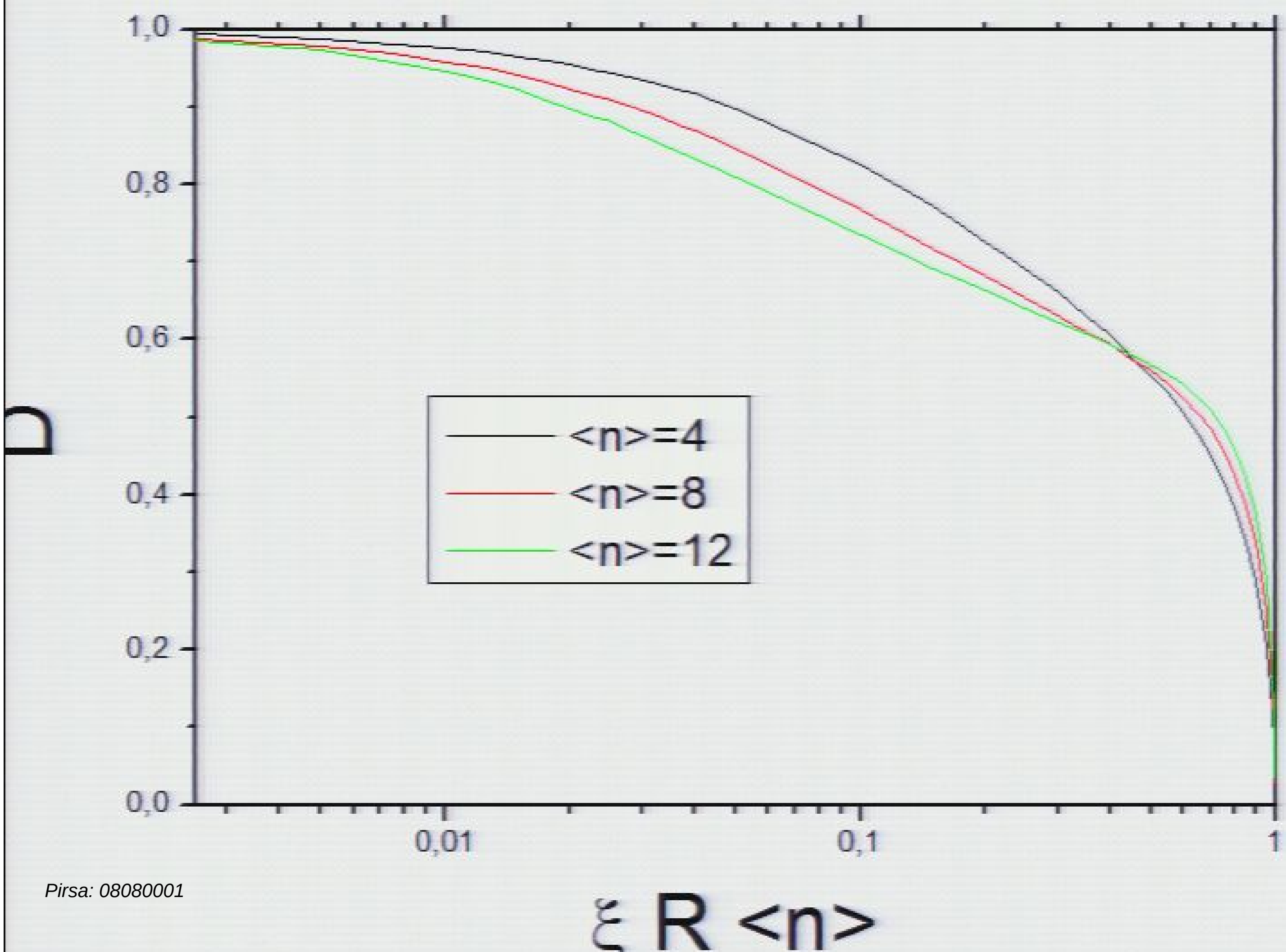
Numerical analysis for QIOPA amplified states

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



EQUATORIAL MACRO – QUBITS :

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

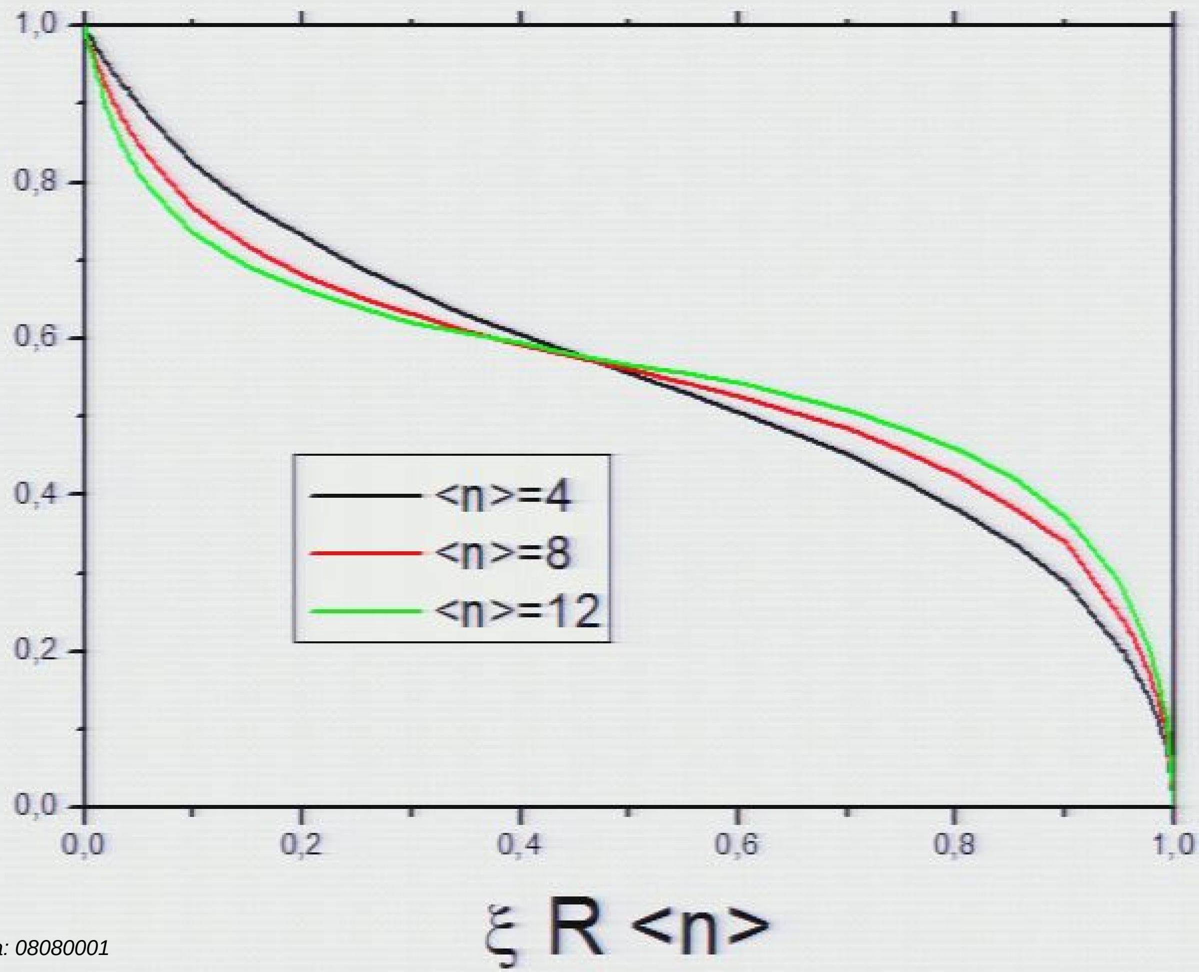


$$\xi = \frac{1}{\langle n \rangle}$$

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

Numerical analysis for QIOPA amplified states

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



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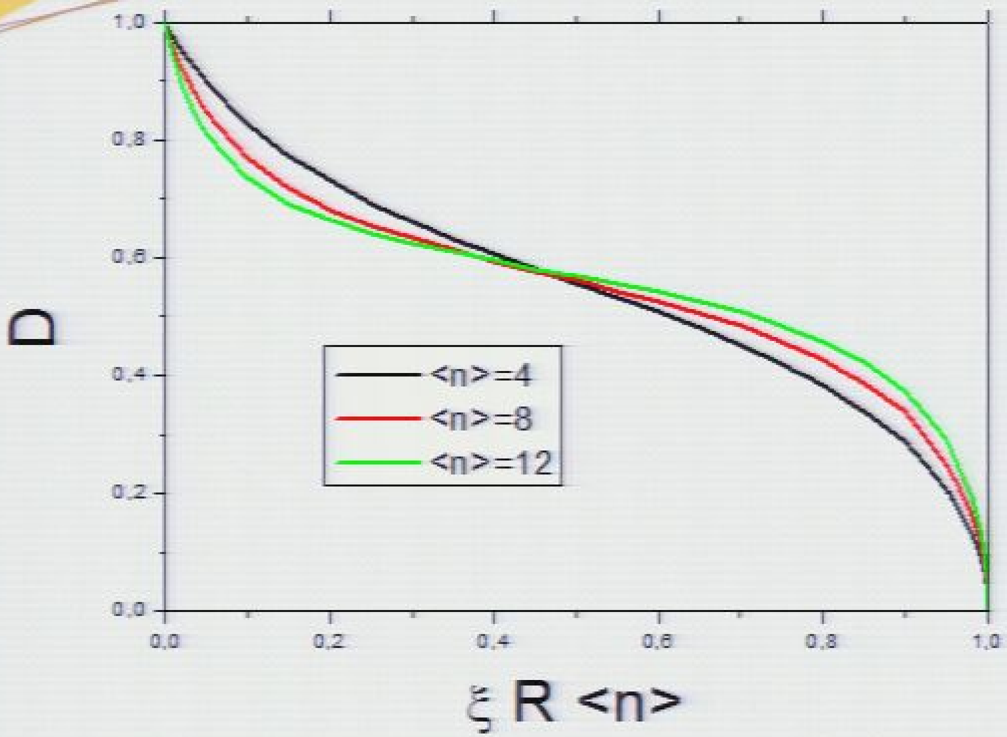
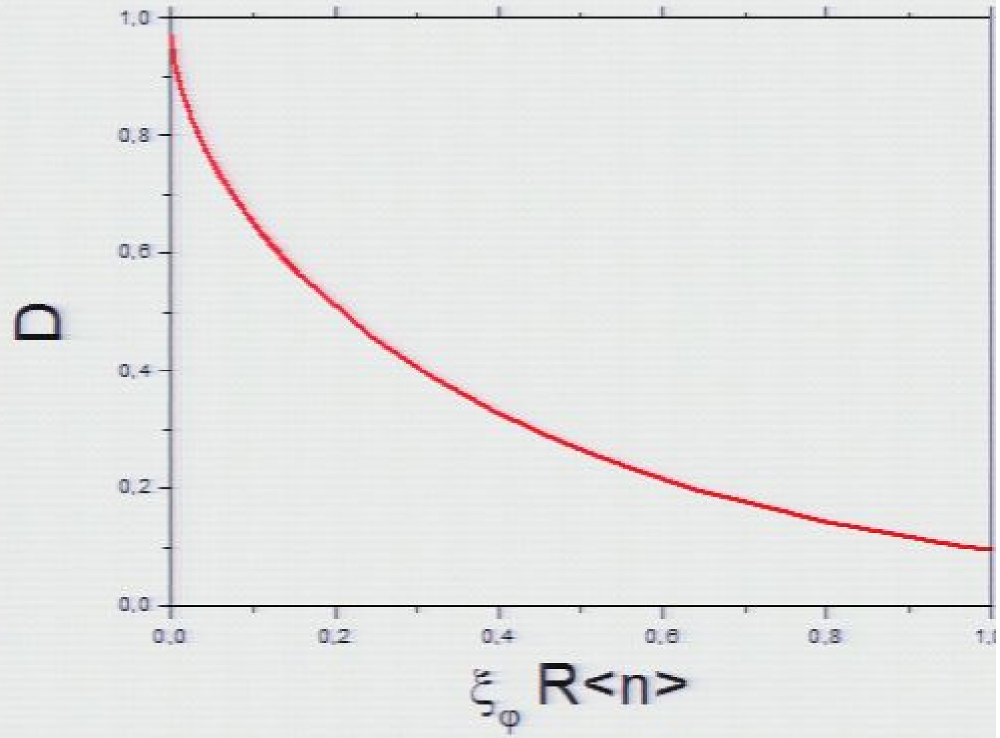
QIOPA equatorial qubits: (R,L) (+,-)

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





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

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

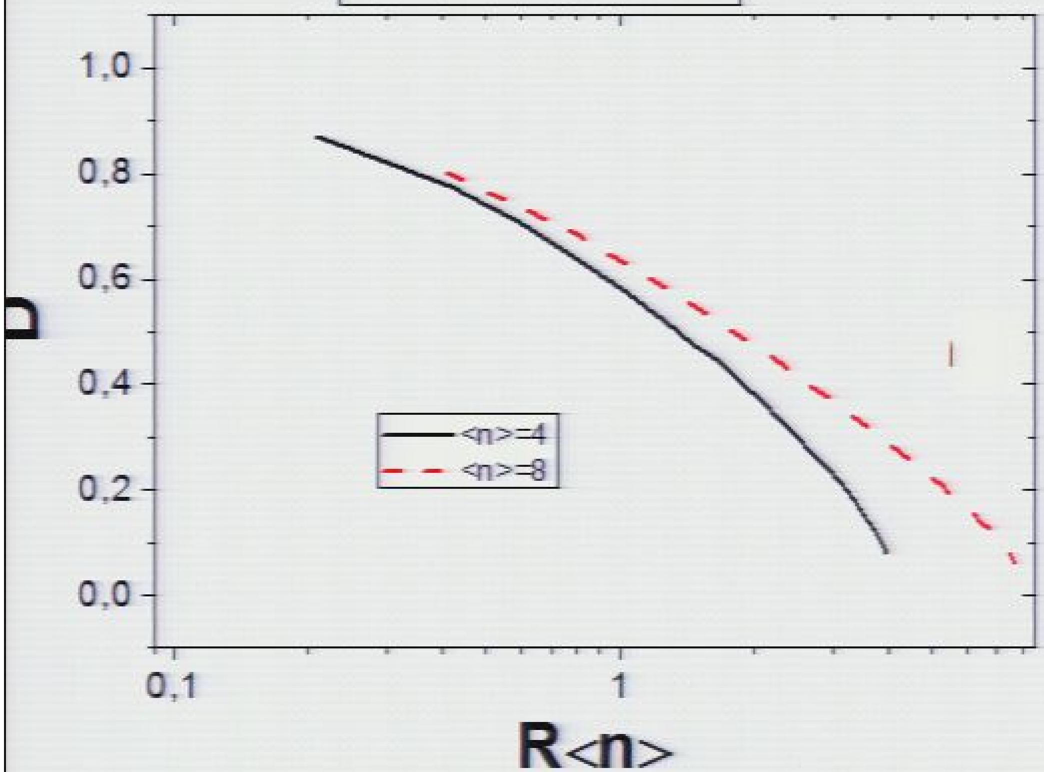
$$(\xi_\varphi)_{min} = \sin^2\frac{1}{|\alpha|} \sim \frac{1}{\langle n\rangle}$$

IOPA Macro-qubits (HV) or Equatorial:

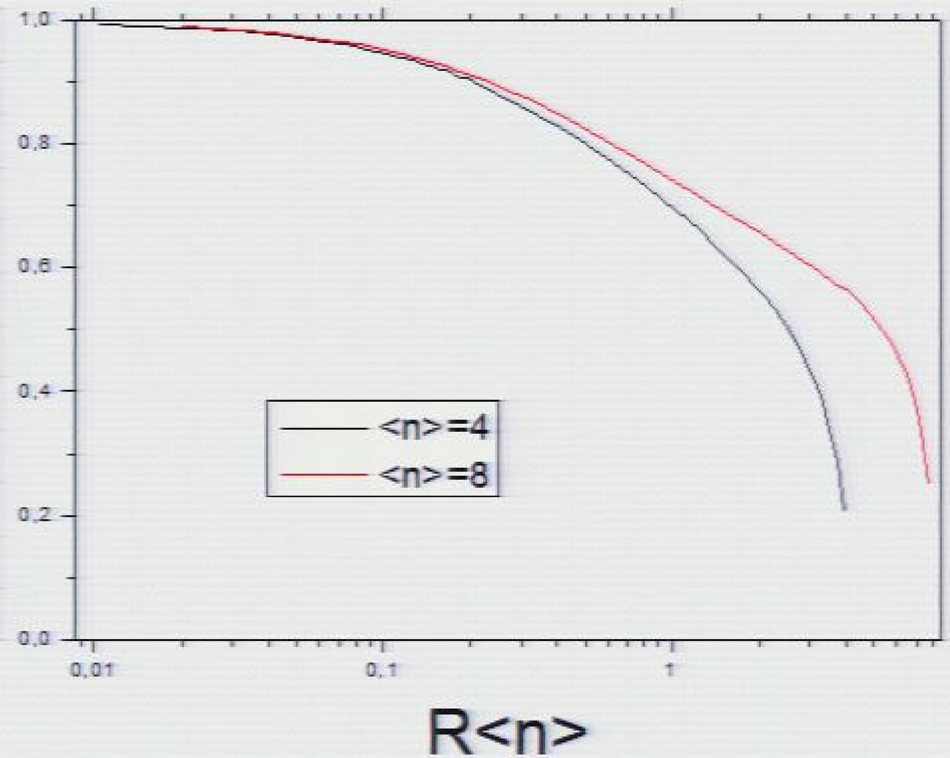
$$\frac{1}{\sqrt{2}}\left(\left|\Phi^{R}\right\rangle+\left|\Phi^{L}\right\rangle\right);\ \frac{1}{\sqrt{2}}\left(\left|\Phi^{+}\right\rangle+\left|\Phi^{-}\right\rangle\right)$$

Numerical analysis for QIOPA amplified states

H,V qubits



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



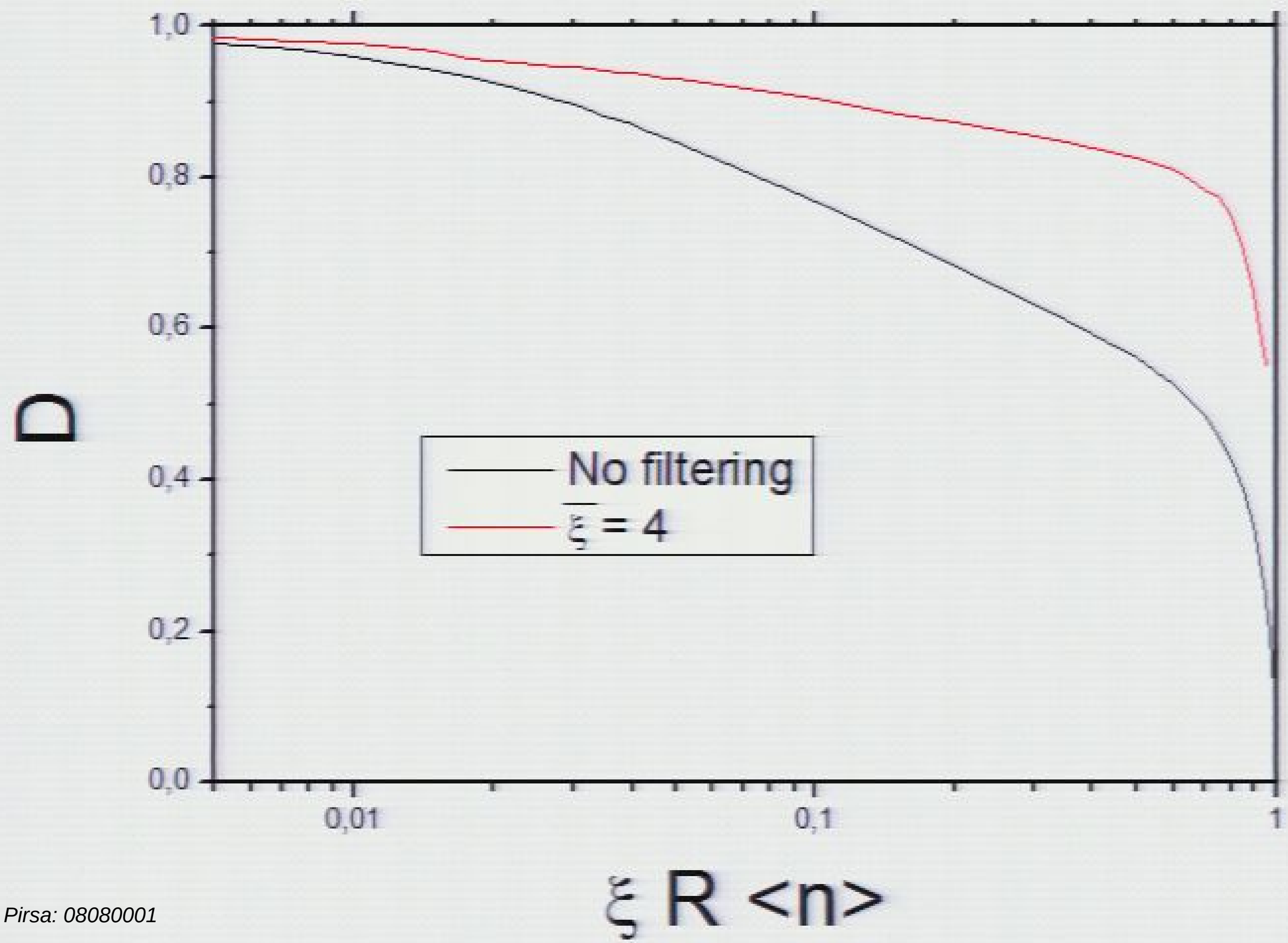
Increased robustness to losses

NOTE THE EFFECT OF PHASE-COVARIANT CLONING!

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

g=1.1

<n>=8



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

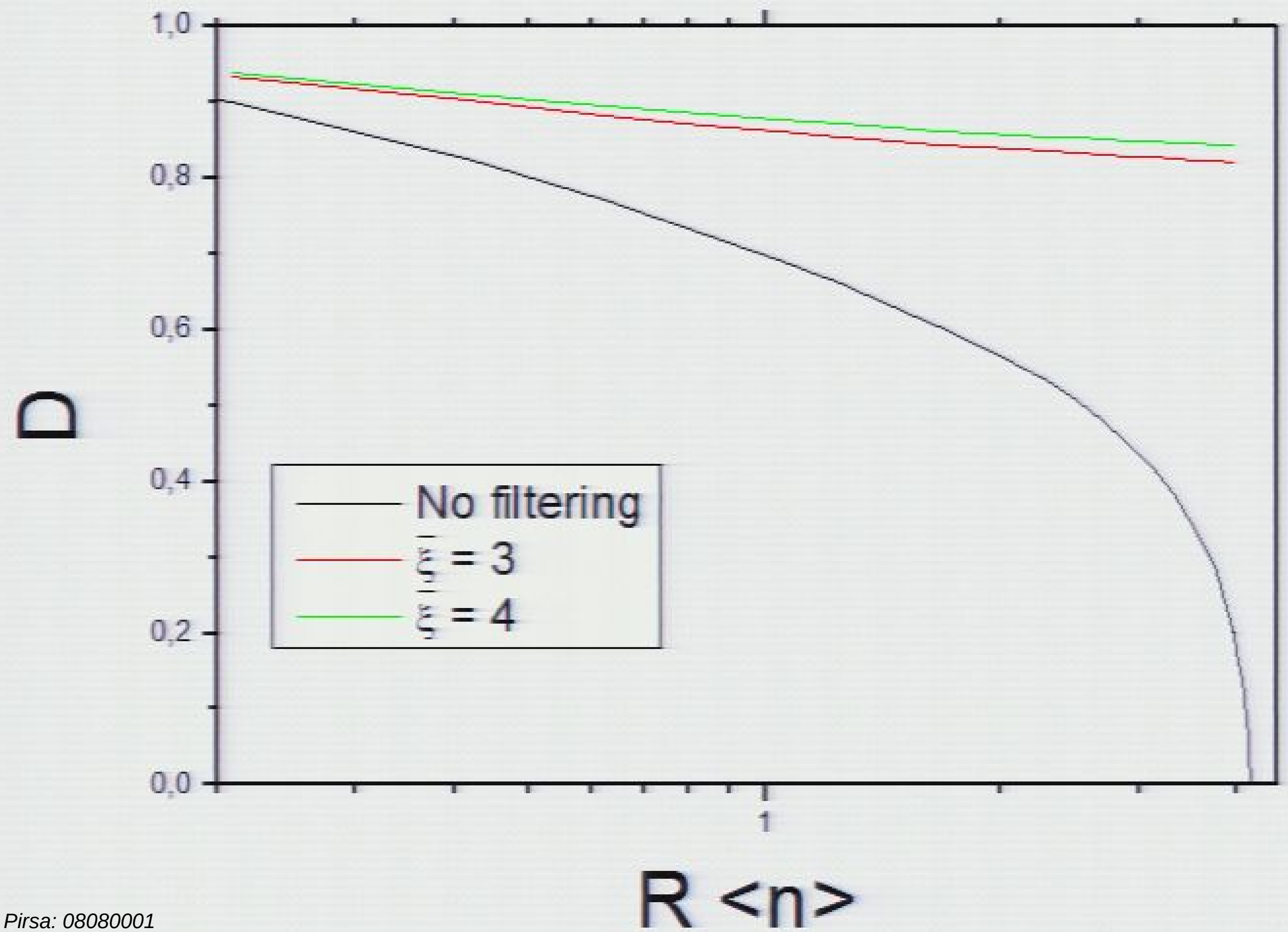
R<n>ξ :reflectivity of the lossy communication channel

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

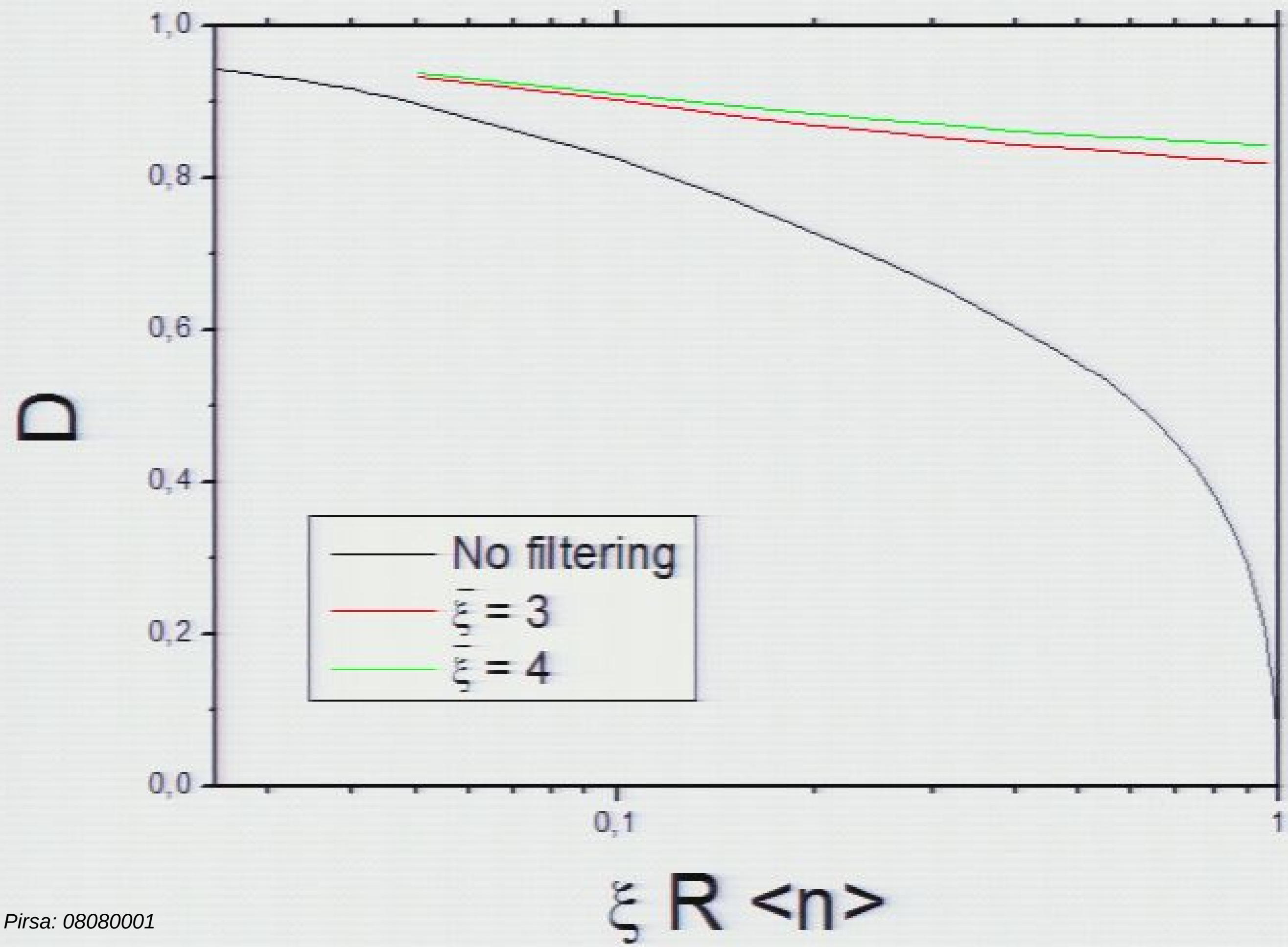
Threshold

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

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

g=0.8

<n>=4



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

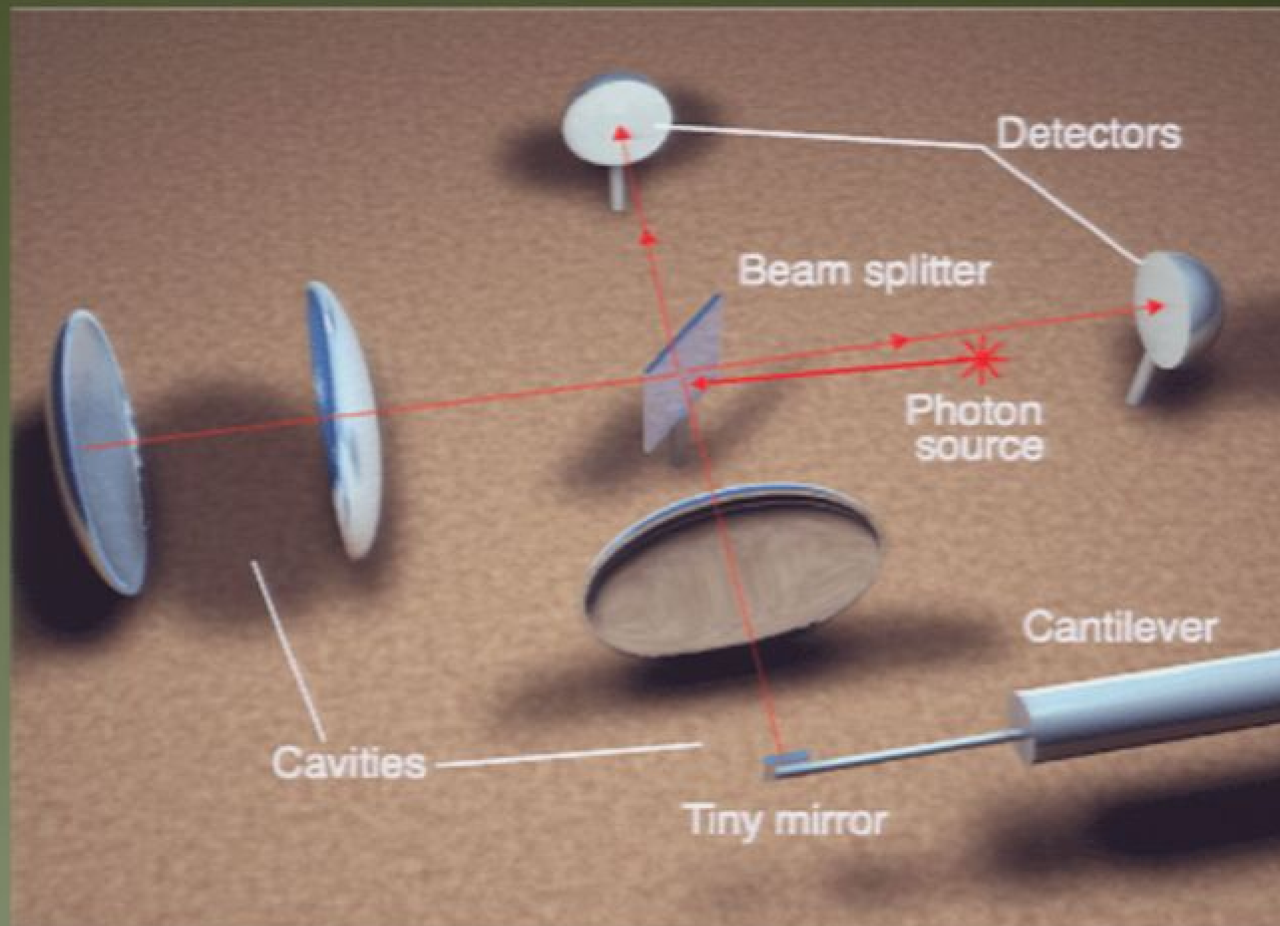
R<n>ξ :reflectivity of the lossy communication channel

Threshold

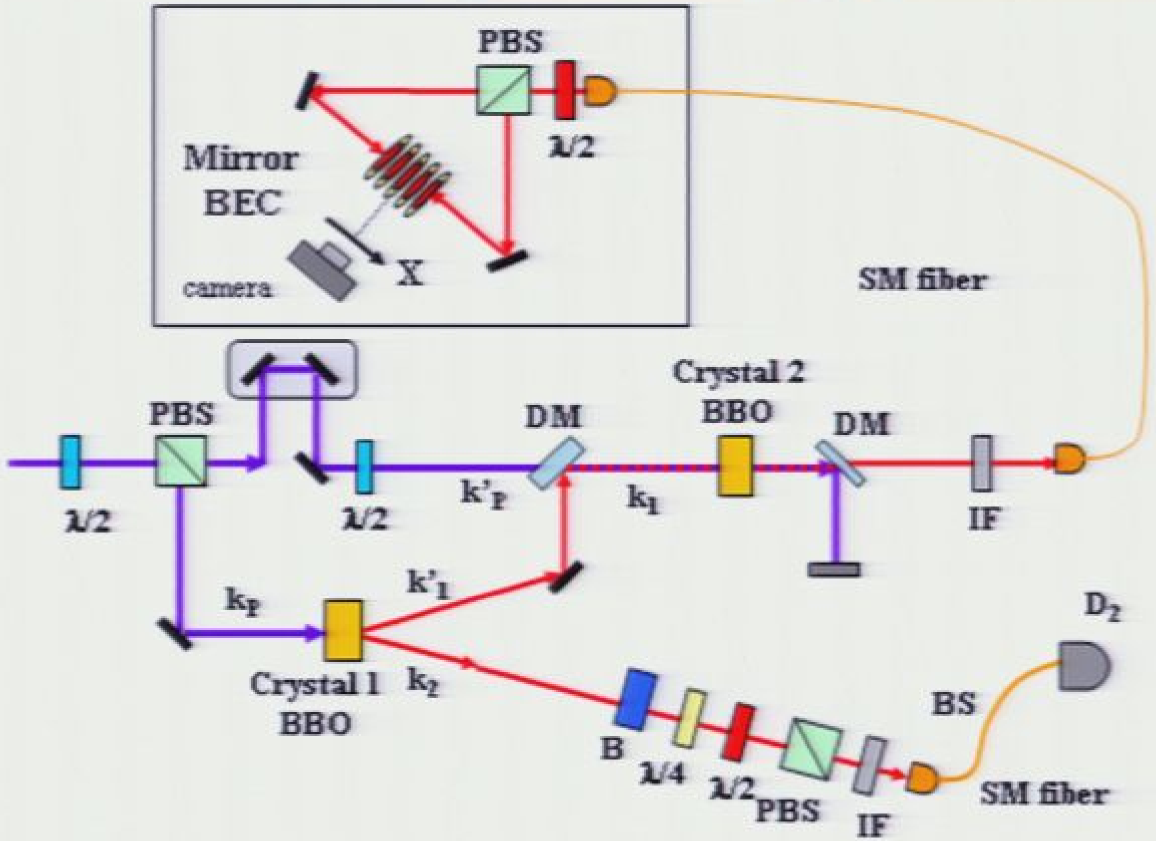
$$\bar{\xi}\langle n \rangle$$

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* **298**, 342 (2002)

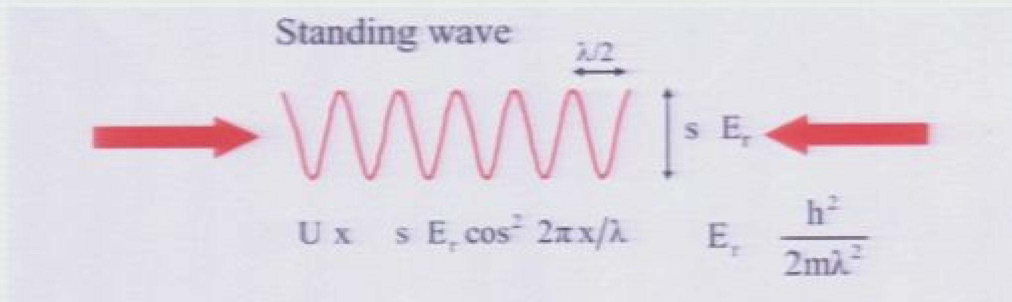


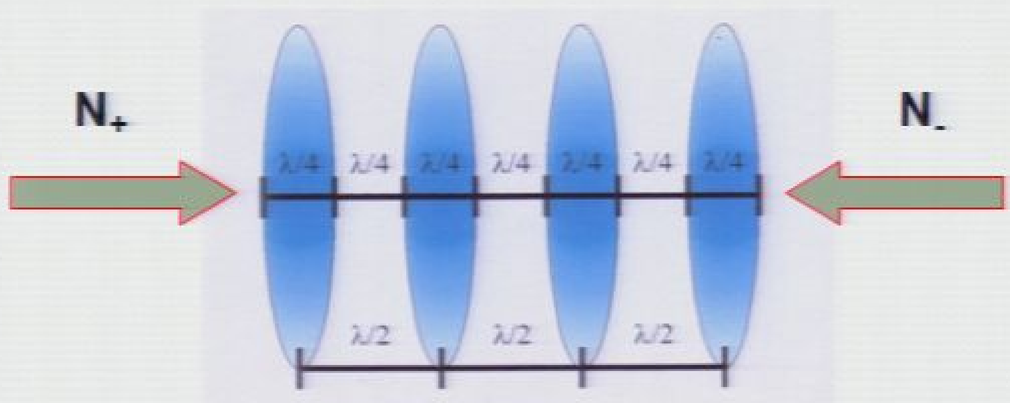
SCHRŐDINGER CAT

State Non-separability:

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

QI-OPA DRIVEN BEC MECHANICAL OSCILLATIONS





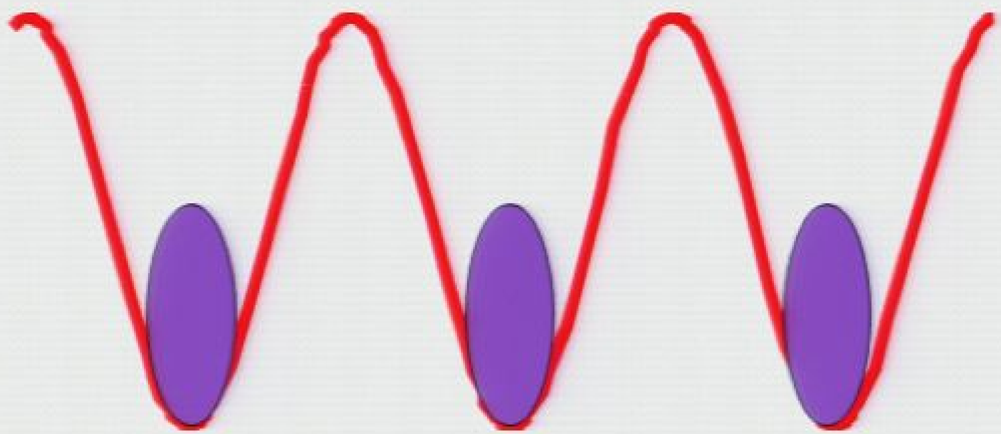
SUPERRADIANT RAYLEIGH SCATTERING → BRAGG SCATTERING:
L.De Sarlo et al (LENS Group) Eur.Phys. J.D. (2004)
L.Fallani et al. (LENS Group) PRA 71, 033612 (2005)

Condensate in a Lattice

The ground state consists of an array of disk shaped condensates each residing in a node of the optical standing wave while tunnelling through the optical barriers keeps phase coherence through the array

Condensate in a Lattice

The ground state consists of an array of disk shaped condensates each residing in a node of the optical standing wave while tunnelling through the optical barriers keeps phase coherence through the array



Condensate in a Lattice

LENS

Università di Firenze

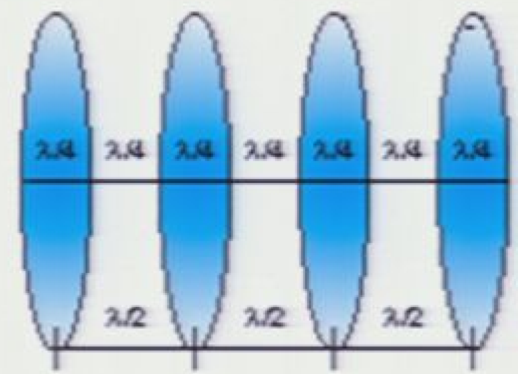
The ground state consists of an array of disk shaped condensates each residing in a node of the optical standing wave while tunnelling through the optical barriers keeps phase coherence through the array

Towards light-matter entanglement

I) Micro-macroscopic photonic entanglement by QIOPA

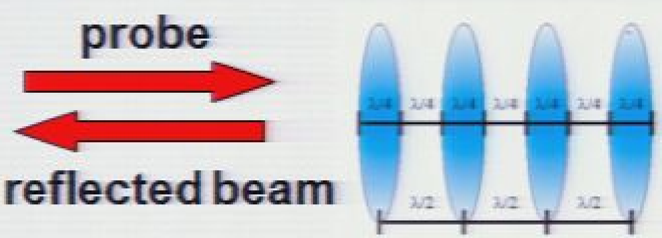
II) BEC mirror

- 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



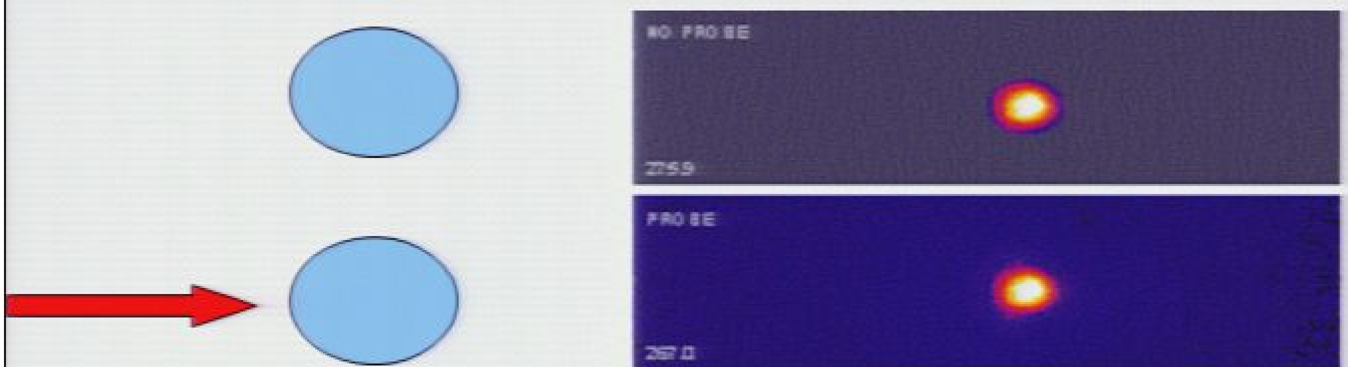
Momentum conservation: $2\hbar k$
light reflection induces a kick on single atom

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

Preliminary results on BEC observed in Florence

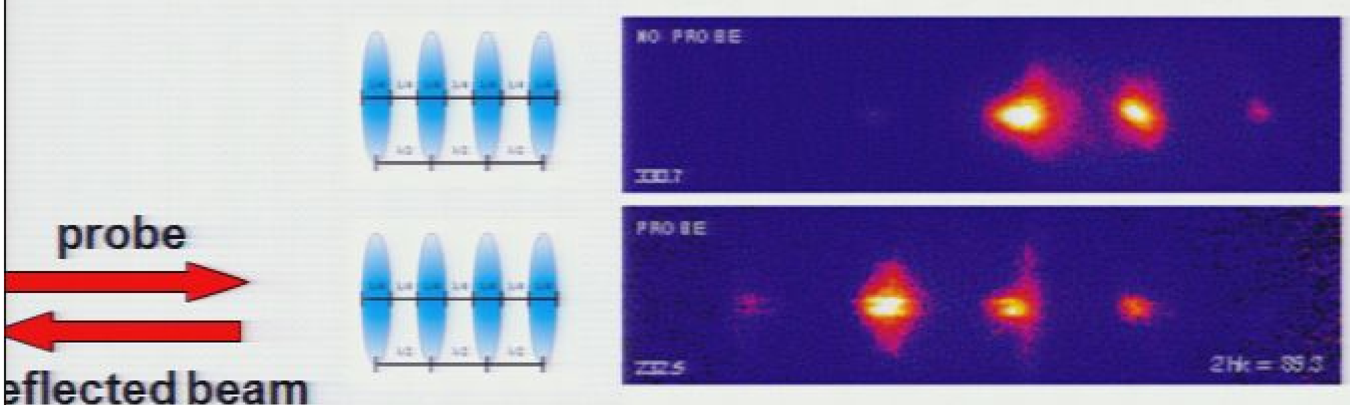
Shadow snapshot of the condensate after expansion: measurement of momentum distribution

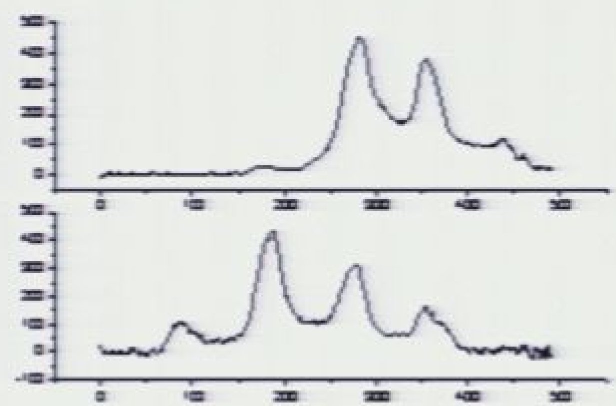
Scattering of radiation by a condensate



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

Scattering of radiation by a Bragg structured condensate

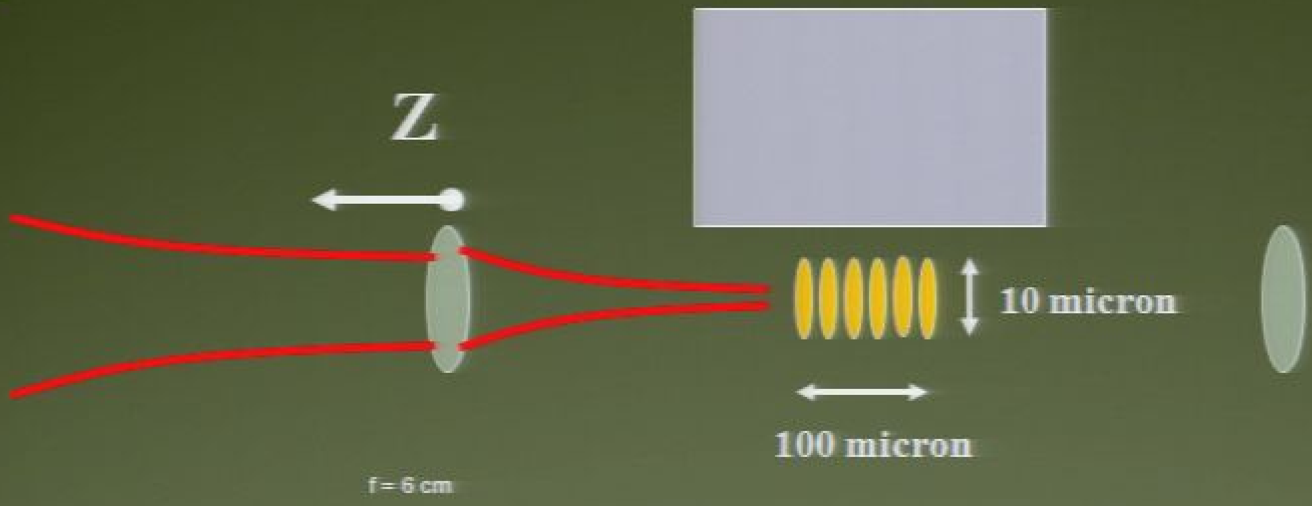




Momentum distribution

Reflected photon per atom ~1.15

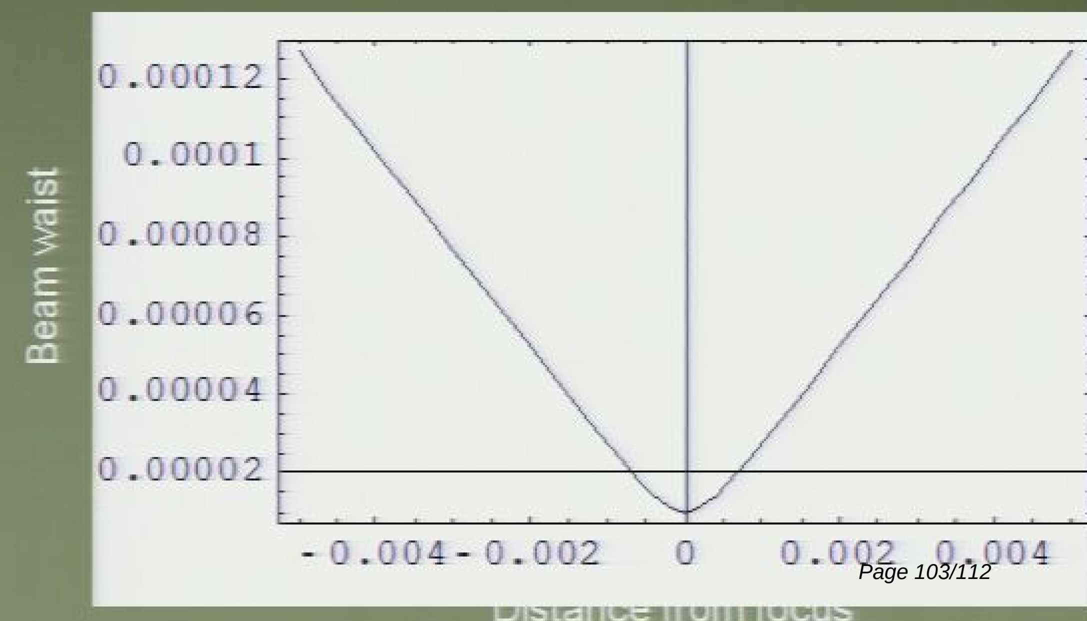
Mode matching: beam - condensate



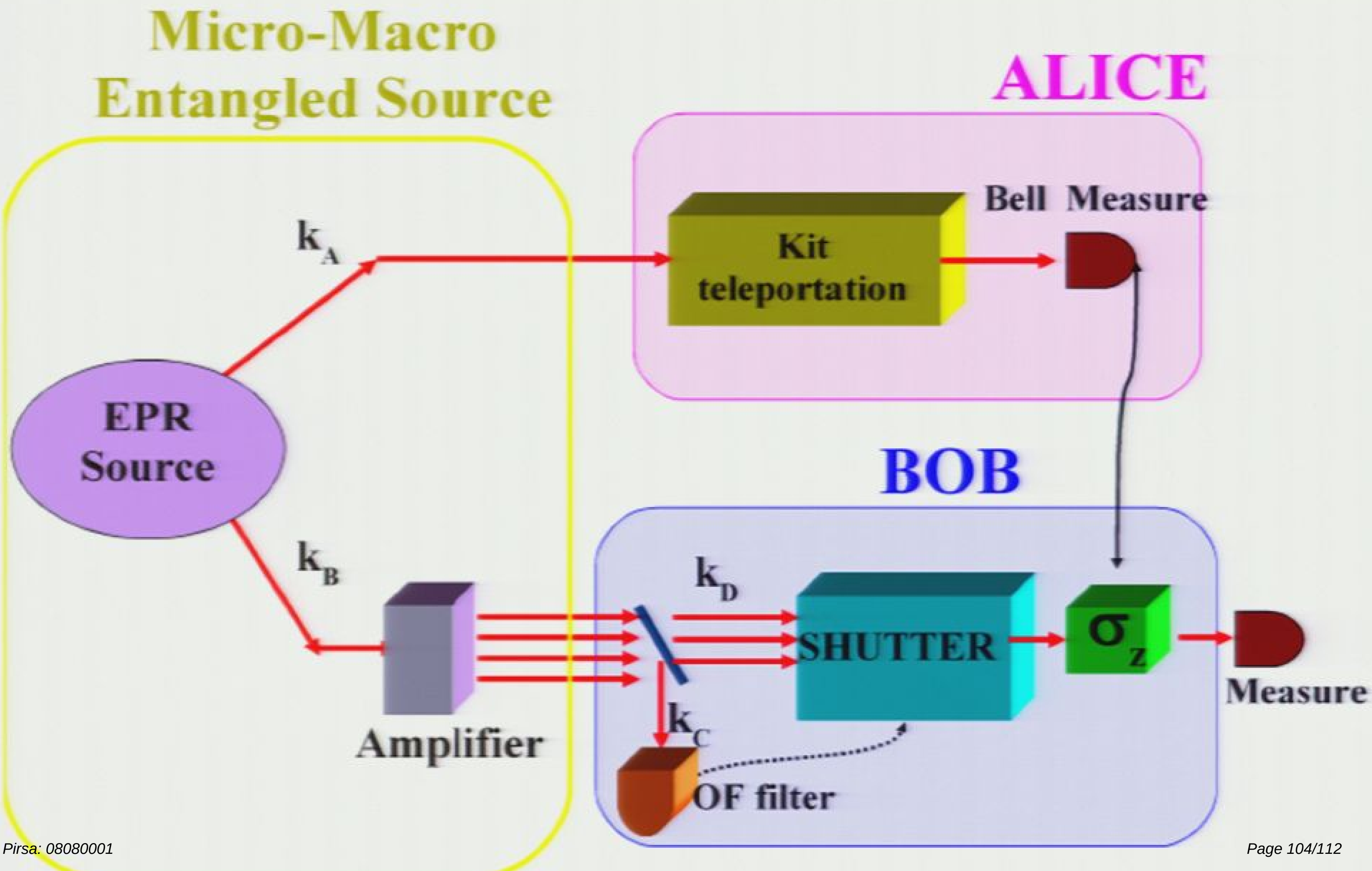
Beam: beam waist 10 micron
Confocal parameter: 400 micron

Focus length equal 6 cm

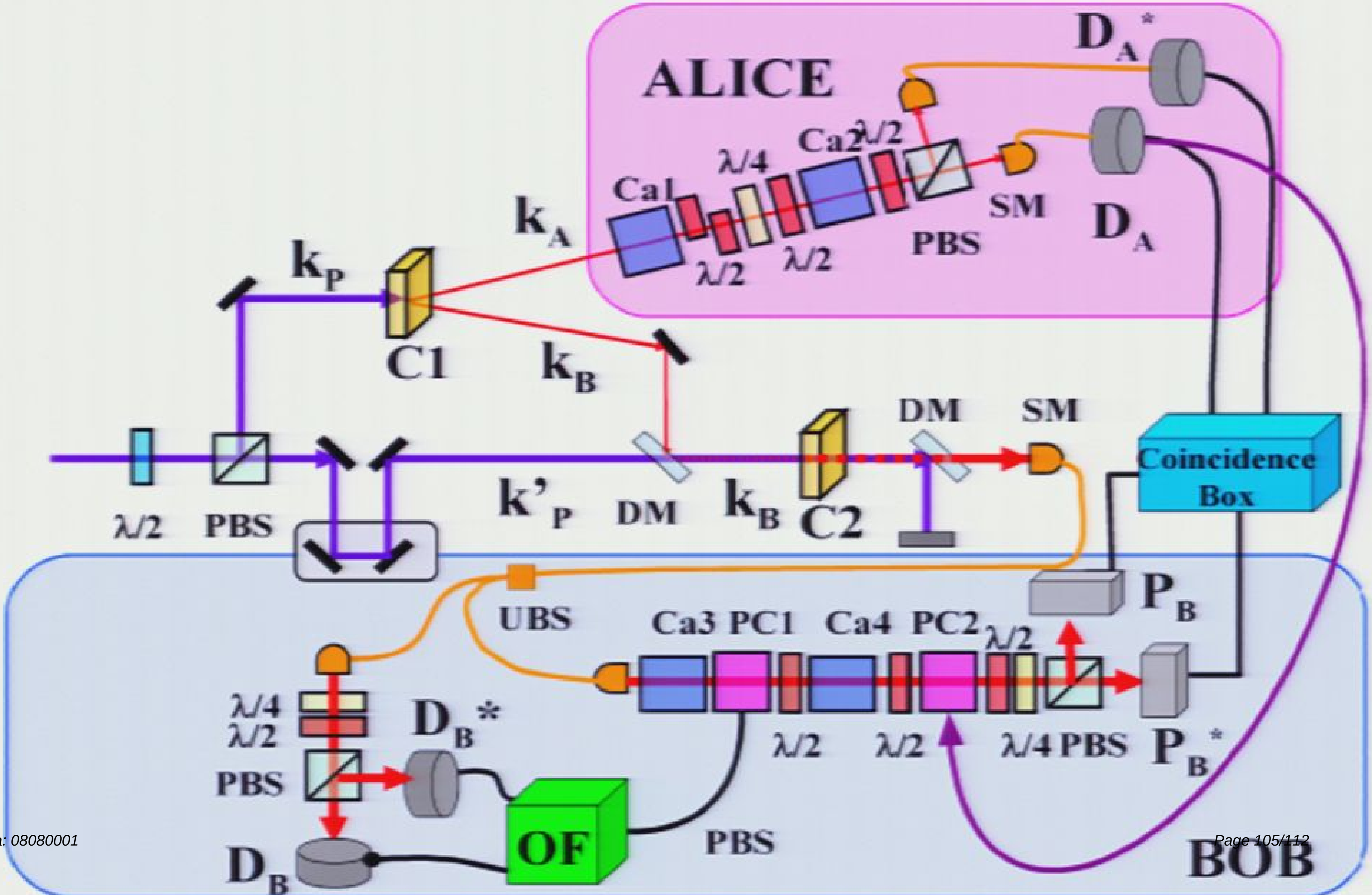
Distance between BEC and microchip
About 50 – 400 micron



MICRO - MACRO QUANTUM TELEPORTATION

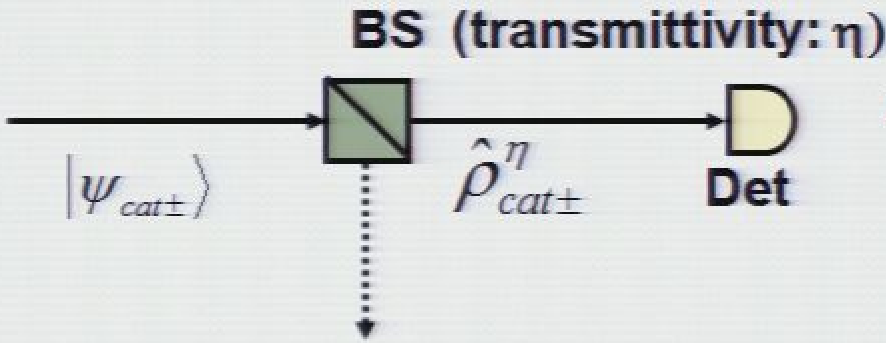


MICRO - MACRO QUANTUM TELEPORTATION



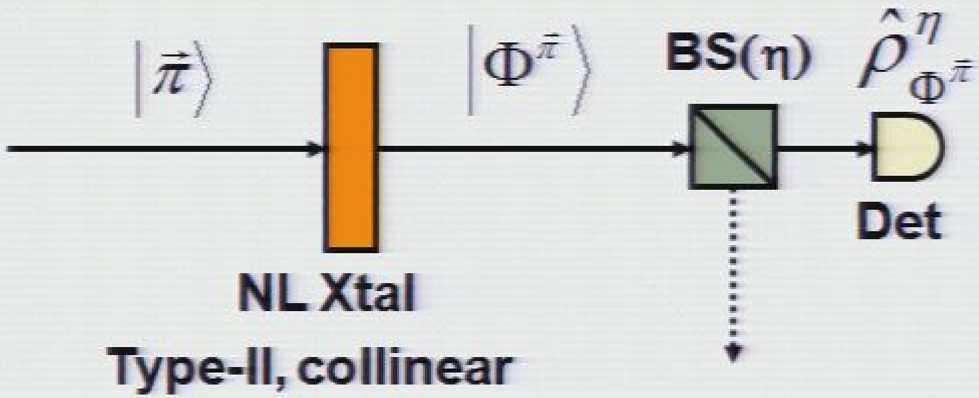
DECOHERENCE OF MACROSCOPIC QUANTUM SUPERPOSITIONS

(1) Coherent cat states



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

(2) QIOPA amplified states



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

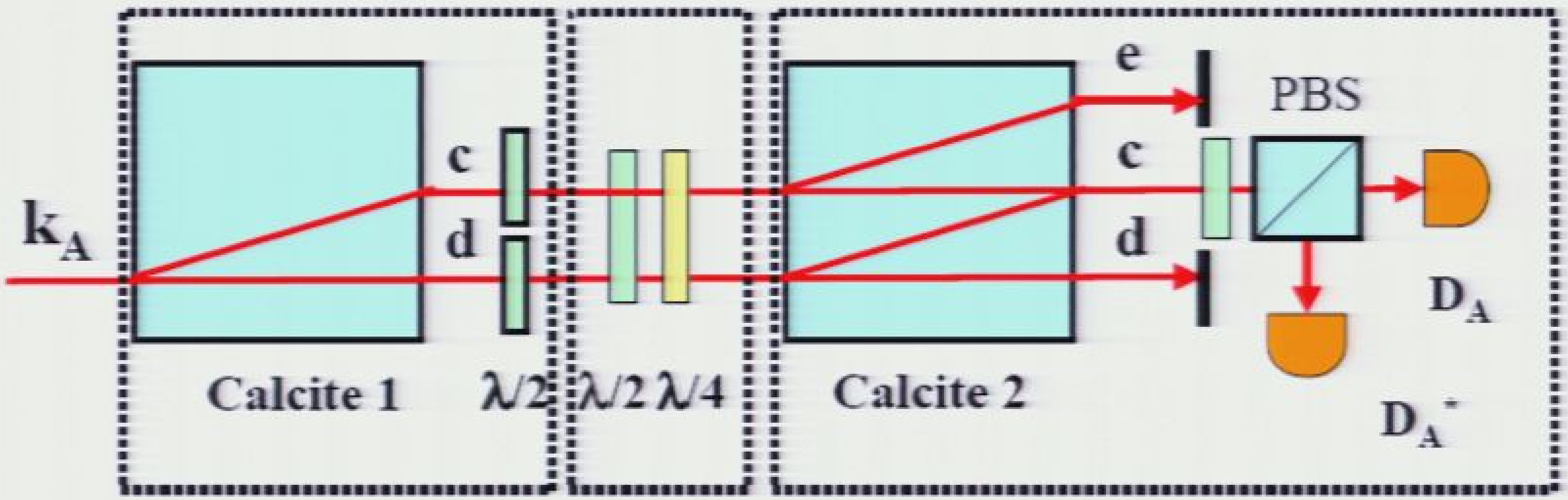
amplification process

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

Two possible choices

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

MICRO MACRO TELEPORTATION: PREPARATION of QUBIT TO BE TELEPORTED



conversion of polarization state into momentum

preparation of the qubit to be teleported

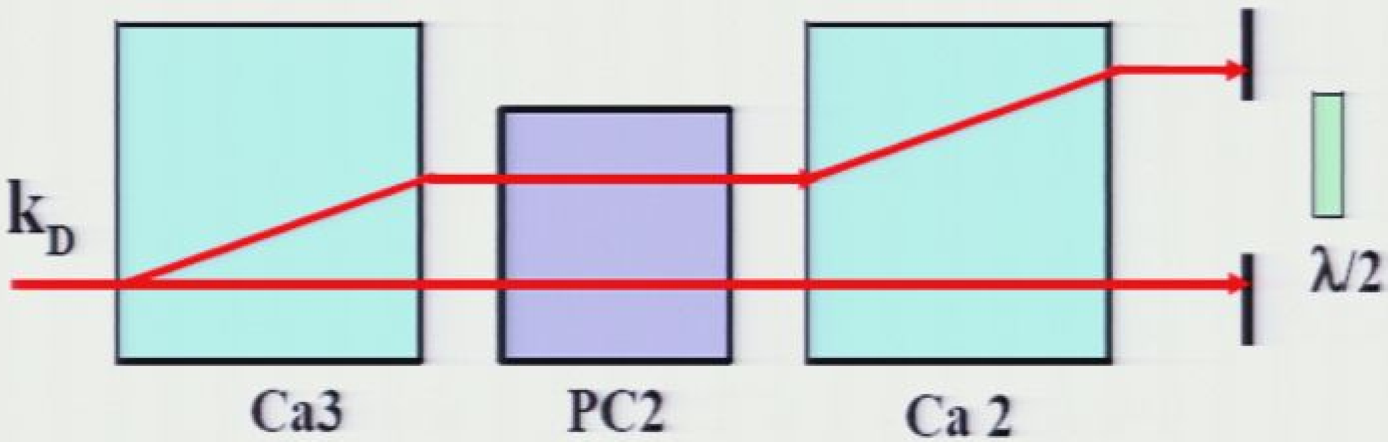
Bell state measurement

D_A: detection of $|\Psi^-\rangle$

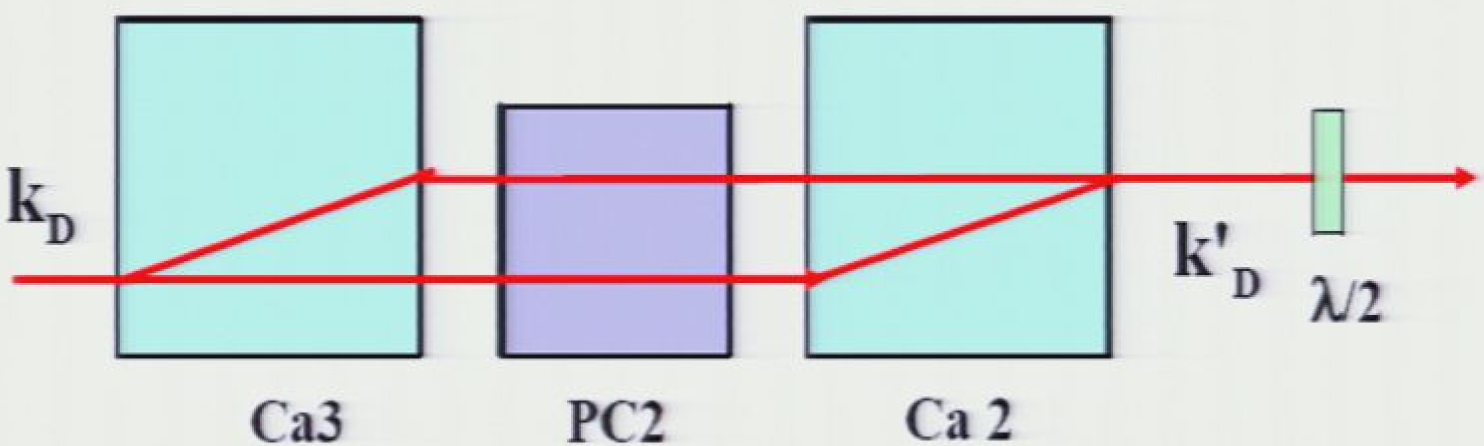
D_A^*: detection of $|\Psi^+\rangle$

MICRO - MACRO TELEPORTATION: FAST OPTICAL SHUTTER FOR OUTPUT SELECTION

(a) SHUTTER OFF

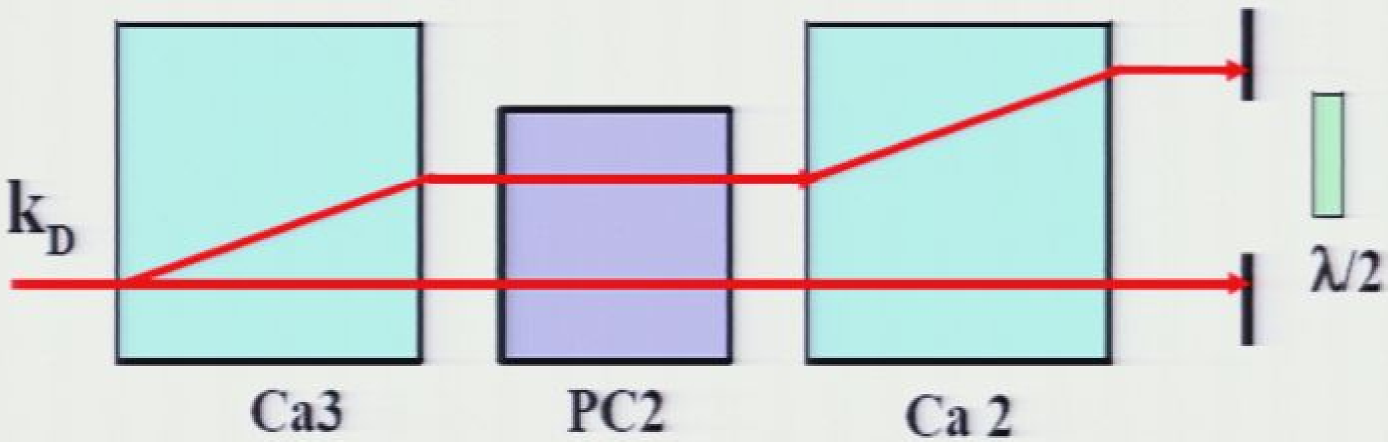


(b) SHUTTER ON

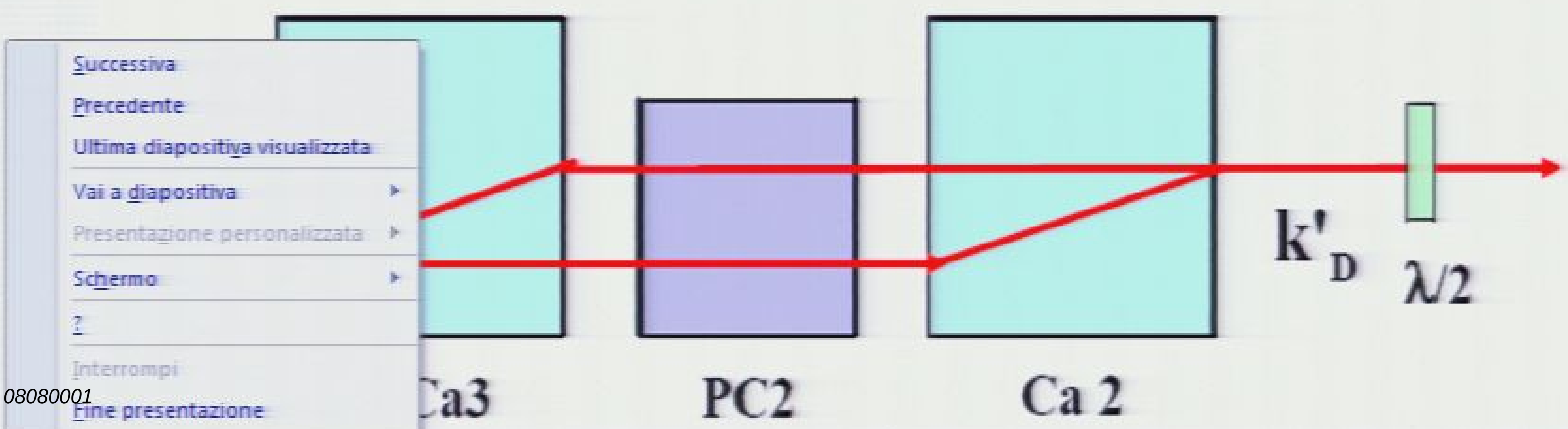


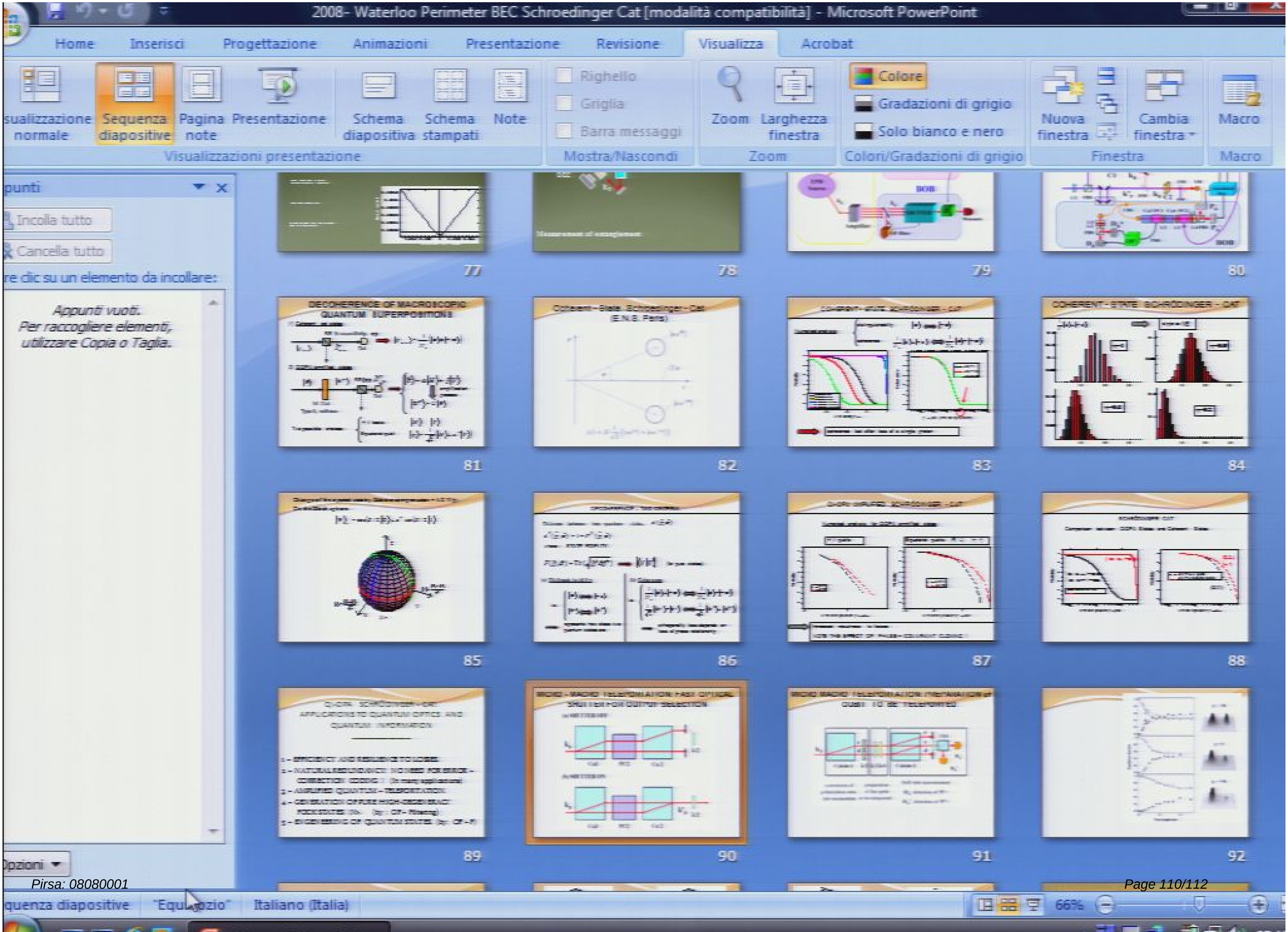
MICRO - MACRO TELEPORTATION: FAST OPTICAL SHUTTER FOR OUTPUT SELECTION

(a) SHUTTER OFF



(b) SHUTTER ON




2008- Waterloo Perimeter BEC Schroedinger Cat [modalità compatibilità] - Microsoft PowerPoint
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Italiano (Italia)
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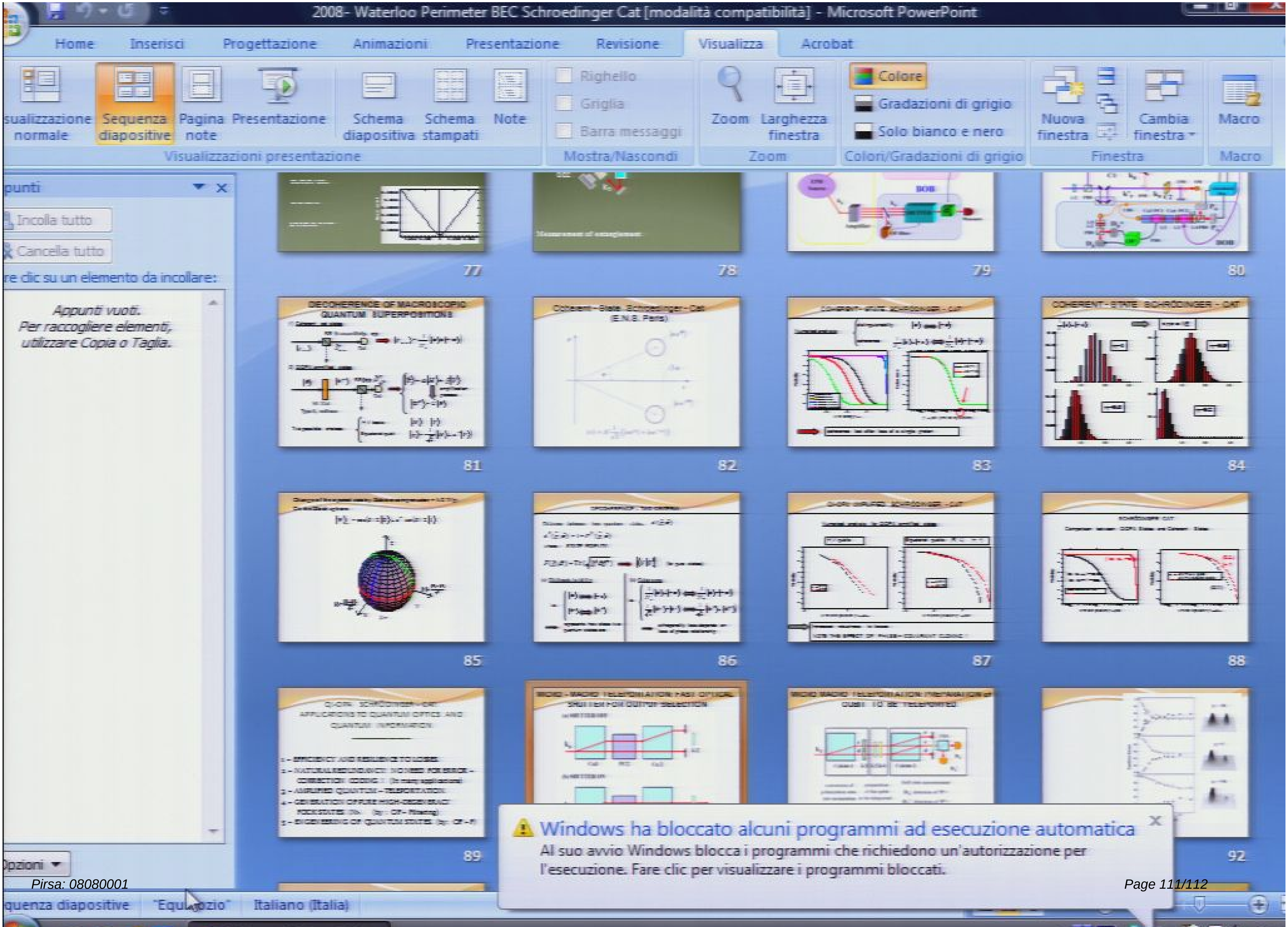
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Revisione
Visualizza
Acrobat
sualizzazione normale
Sequenza diapositive
Pagina note
Presentazione
Schema diapositiva
Schema stampati
Note
Righello
Griglia
Barra messaggi
Zoom
Larghezza finestra
Colore
Gradazioni di grigio
Solo bianco e nero
Nuova finestra
Cambia finestra
Macro
Visualizzazioni presentazione
Mostra/Nascondi
Zoom
Colori/Gradazioni di grigio
Finestra
Macro
punti
Incolla tutto
Cancella tutto
re clic su un elemento da incollare:
Appunti vuoti.
Per raccogliere elementi,
utilizzare Copia o Taglia.
Opzioni
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Windows ha bloccato alcuni programmi ad esecuzione automatica
Al suo avvio Windows blocca i programmi che richiedono un'autorizzazione per l'esecuzione. Fare clic per visualizzare i programmi bloccati.
quenza diapositive
"Equinozio"
Italiano (Italia)

No Signal

VGA-1