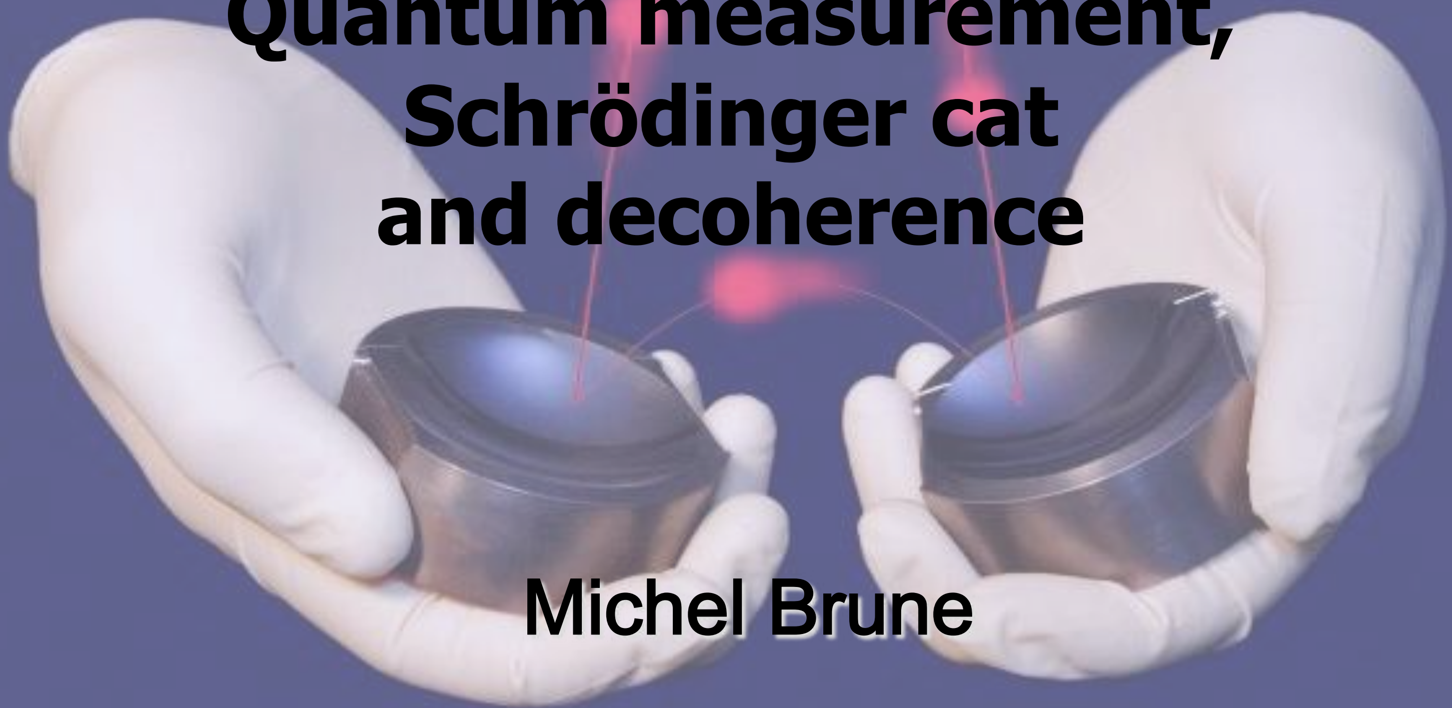
S Paulo Spt 2025

From cavity QED to quantum simulations with Rydberg atoms

Lecture 3

Quantum measurement, Schrödinger cat and decoherence



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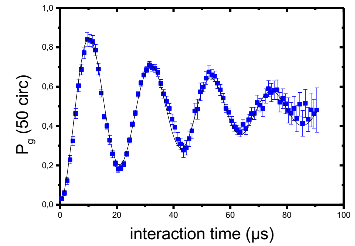
Collège de France, Paris

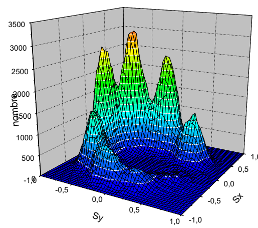
Previous lectures

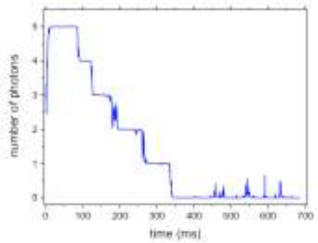
Cavity QED with microwave photons and circular Rydberg atoms:

- L1:Achieving strong coupling between single atoms and single photons



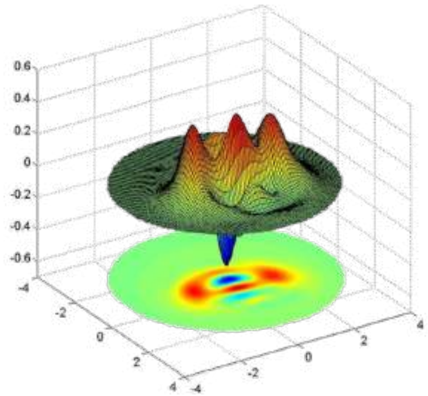
- L2: Performing QND measurement of the field state





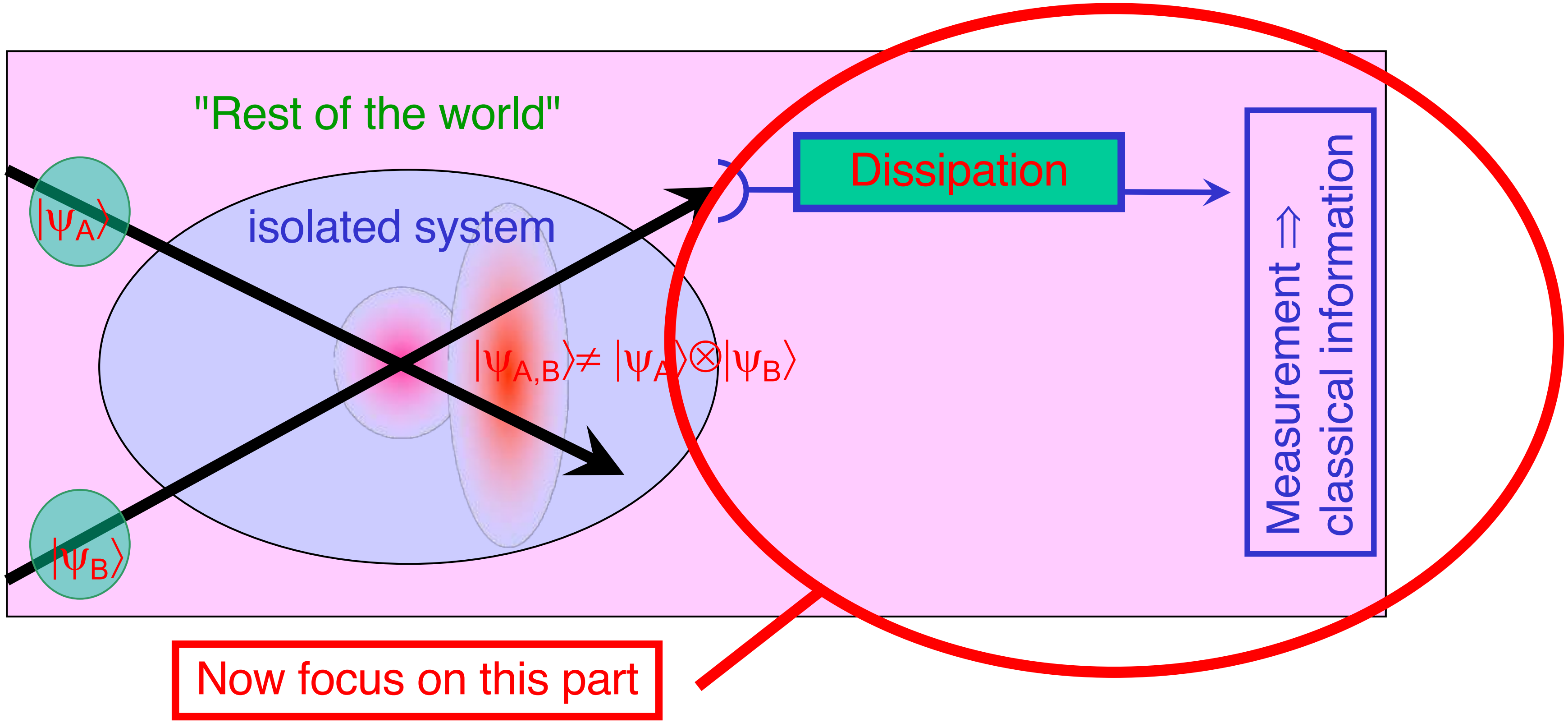
- L3: The same experiment seen from the point of view of the field:

➙Schrödinger cat preparation and monitoring of its decoherence



Lecture 3:
Quantum measurement,
Schrödinger cat and decoherence

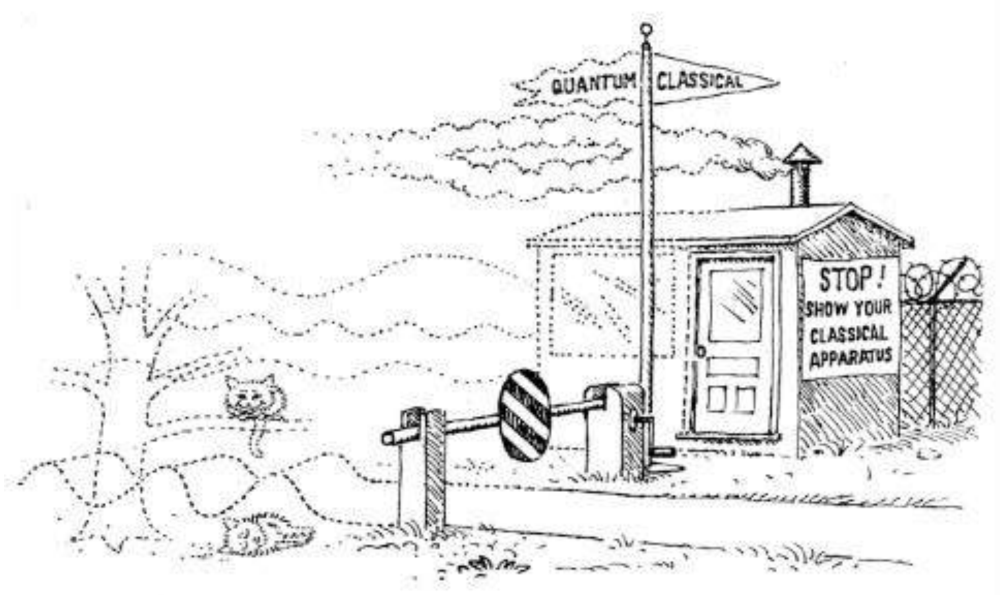
Quantum measurement: basic ingredients



- We have shown how to built an ideal QND meter of the photon number
- This detector is based on a destructive detector of the atom energy.
- Let us now built a more complete, fully quantum, model of detector including the dissipative part

1. The "Schrödinger cat" and the quantum measurement

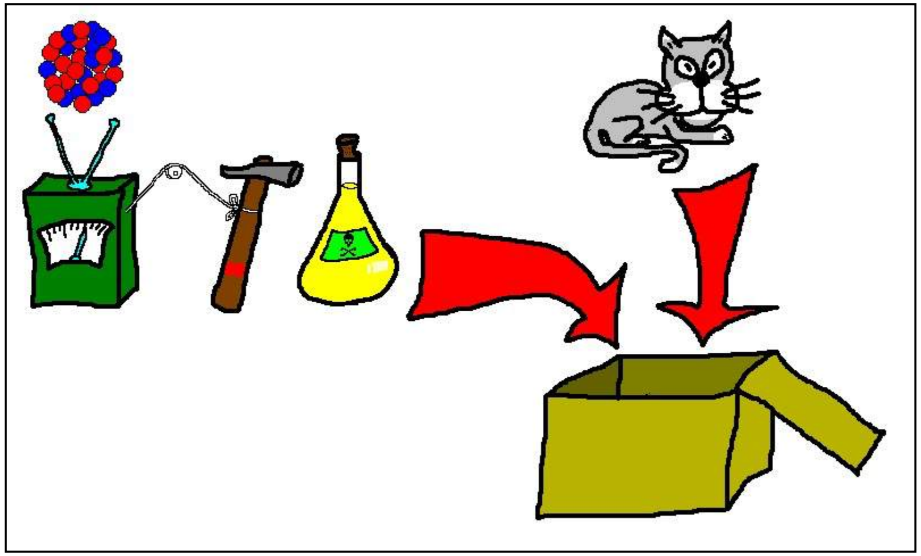
The border separation quantum and classical behavior



Delineating the border between the quantum realm ruled by the Schrödinger equation and the classical realm ruled by Newton's laws is one of the unresolved problems of physics. **Figure 1**

Zurek, Physics Today (1991)

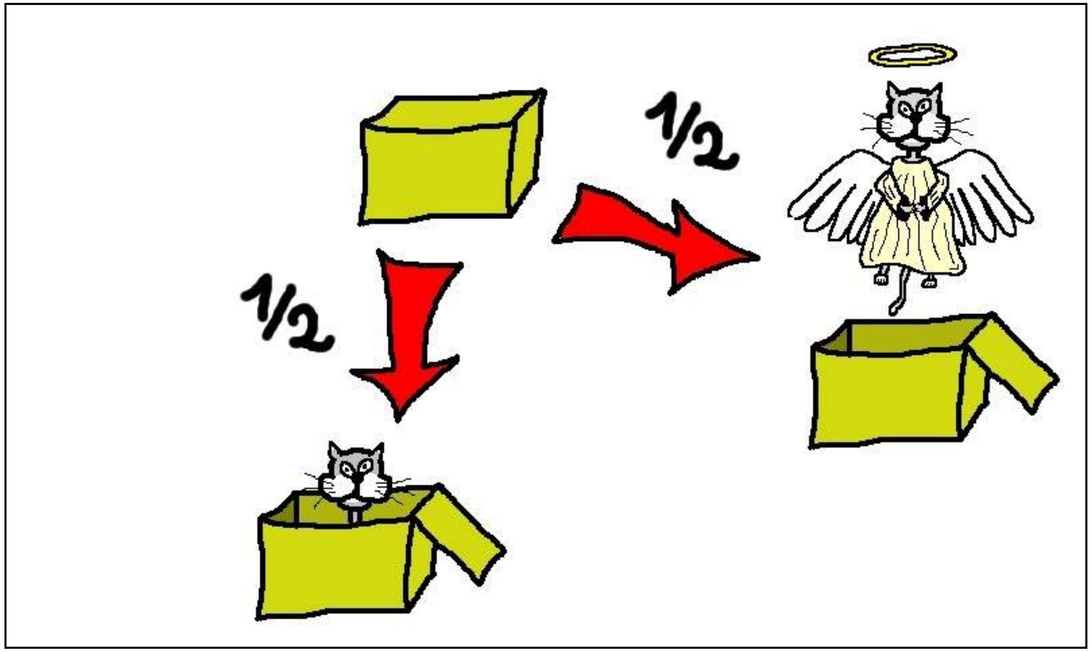
Quantum description of a meter: the "Schrödinger cat" problem



One encloses in a box a cat whose fate is linked to the evolution of a quantum system: one radioactive atom.

The "Schrödinger cat"

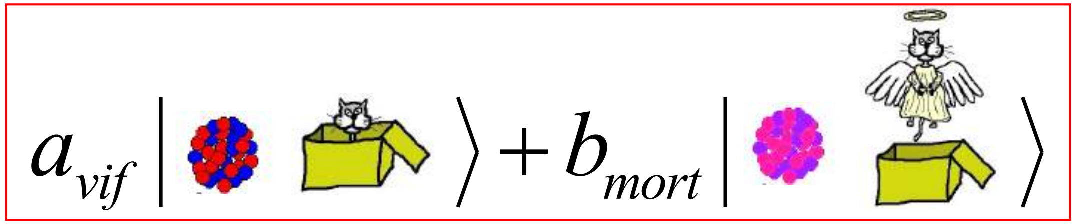
- One closes the box and wait until the atom is desintegrated with a probability 1/2



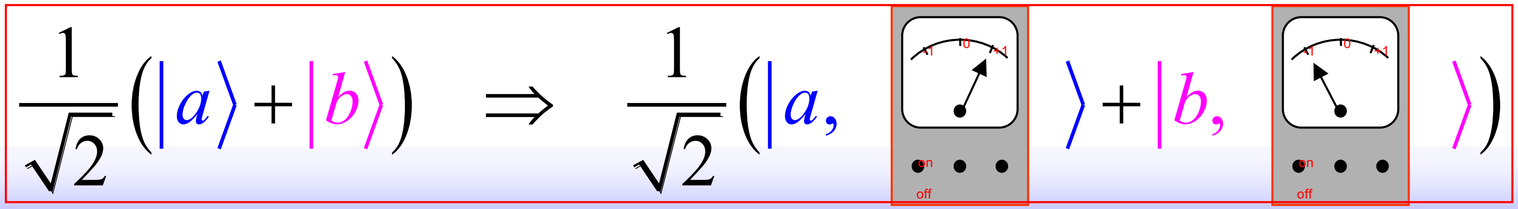
?

- When opening the box is the cat dead, alive or in a superposition of both?

Schrödinger cat and quantum measurement

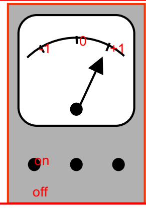


- Before opening the box, the system is isolated and unitary evolution prepares a maximally atom-meter entangled state
- **Does this state "really" exists**?
  - → **a more relevant question**: can one perform experiments demonstrating cat superposition state? Up to which limit?
- That is a fundamental question for the quantum theory of measurement: **how does the unphysical entanglement of SC state vanishes at the macroscopic scale**. That is the problem of the transition between quantum and classical world

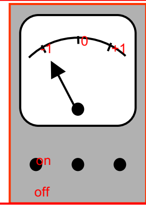


Schrödinger cat and quantum measurement

$$\frac{1}{\sqrt{2}}\left(|e\rangle+|g\rangle\right) \Rightarrow \frac{1}{\sqrt{2}}\Big(|e,$$



$$\rangle + |g,$$



$$\rangle\Big)$$

- Real measurement provide one definite result and not superposition of results: SC states are unphysical ?
- Schrödinger: unitary evolution should "**obviously**" not apply any more at "some scale".
- It seems that the atom-meter space contains to many states for describing reality
- Including dissipation due to the coupling of the meter to the environment will provide a physical mechanism "selecting" the physically acceptable states.

Let's look at this in a real experiment using a meter whose size can be varied continuously from microscopic to macroscopic world.

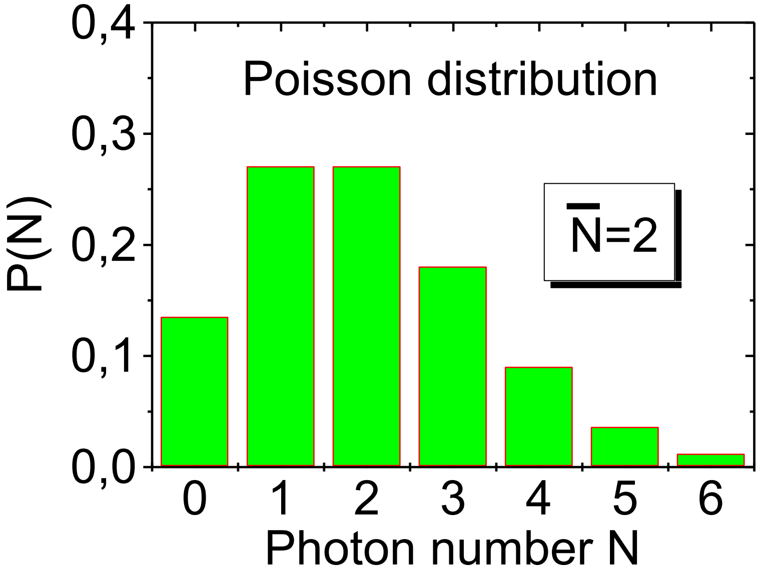
2. A mesoscopic field as atomic state measurement aparatus

A mesoscopic "meter": coherent field states

- Number state: $|N\rangle$
- Quasi-classical state: $|\alpha\rangle = e^{-|\alpha|^2/2}\sum_N \frac{\alpha^N}{\sqrt{N!}}|N\rangle \quad ; \quad \alpha = |\alpha| e^{i\Phi}$

•Photon number distribution

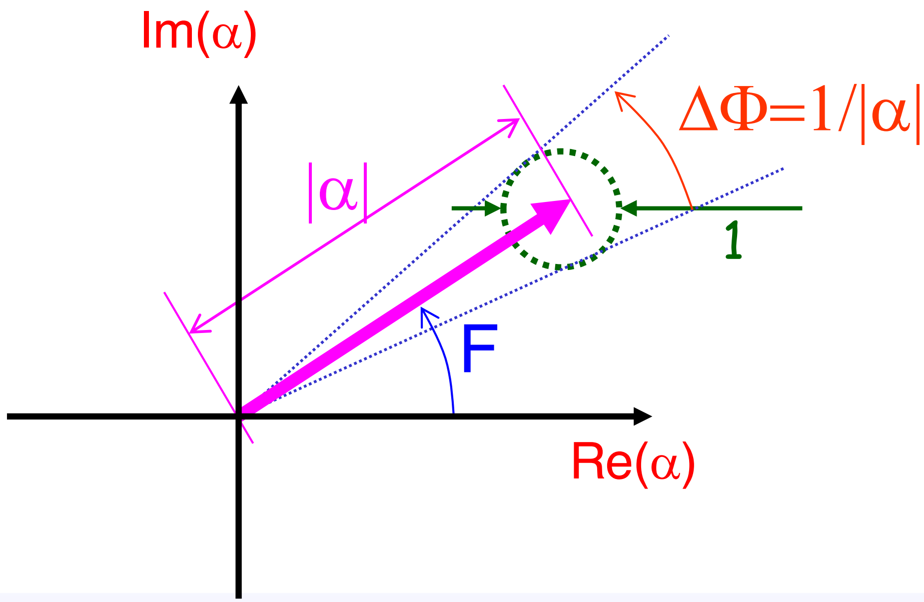
$$P(N) = e^{-\bar{N}} \frac{\bar{N}^N}{N!} \quad ; \quad \bar{N} = |\alpha|^2$$



$\boxed{\Delta N = 1/|\alpha|}$

• Phase space representation

$\boxed{\Delta N \,.\, \Delta\Phi > 1}$



Displacement operator

- Definition: $$\hat{D}(\alpha) = \exp\left(\alpha\hat{a}^\dagger - \alpha^*\hat{a}\right)$$

Where α is a C-number

- Properties

$$|\alpha\rangle \equiv \hat{D}(\alpha)|0\rangle$$

Easily demonstrated using $$\hat{D}(\alpha) = e^{-\frac{1}{2}|\alpha|^2} e^{+\alpha\hat{a}^\dagger} e^{-\alpha^*\hat{a}}$$

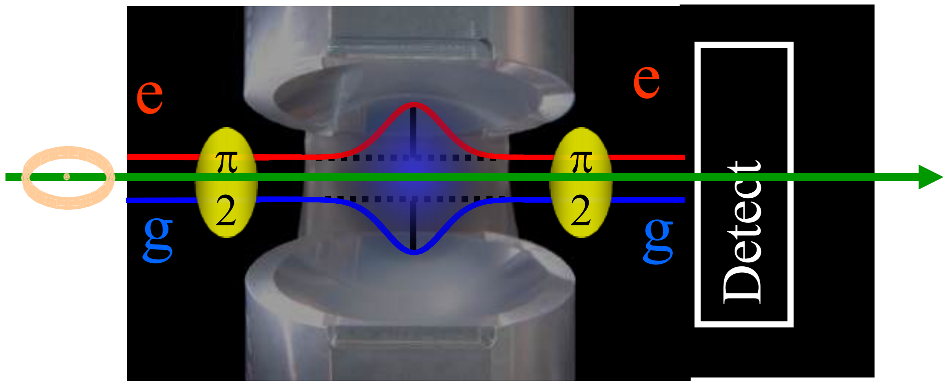
$$\hat{D}^\dagger(\alpha)\hat{a}\hat{D}(\alpha) = \hat{a} + \alpha$$

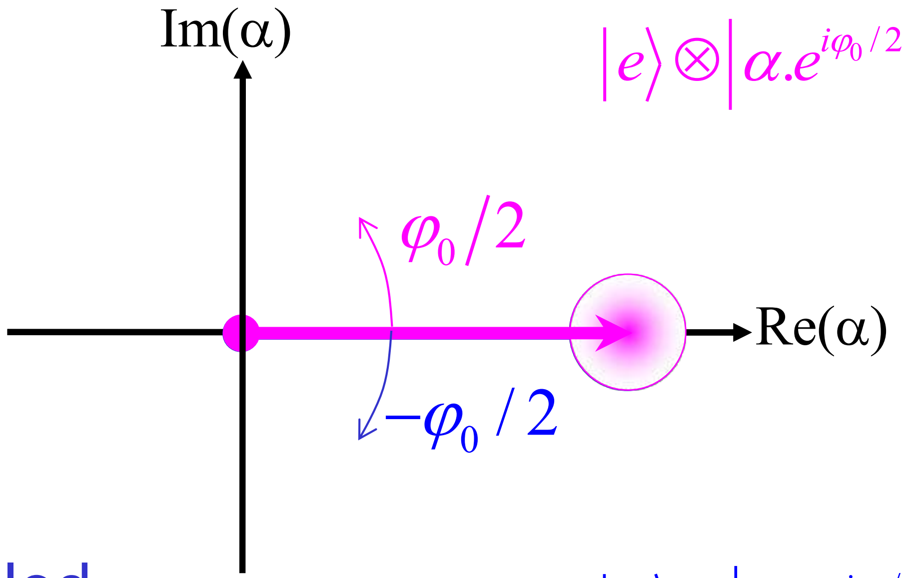
$$\hat{D}(\alpha)\hat{D}(\beta) = e^{(\alpha\beta^* - \alpha^*\beta)/2}\hat{D}(\alpha+\beta)$$

- Coherent states are generated in a cavity by a classical source:

$\hat{D}(\alpha)$ is the corresponding evolution operator

Preparing a phase Schödinger cat state





$|e\rangle \otimes |\alpha . e^{i\varphi_0/2}\rangle$

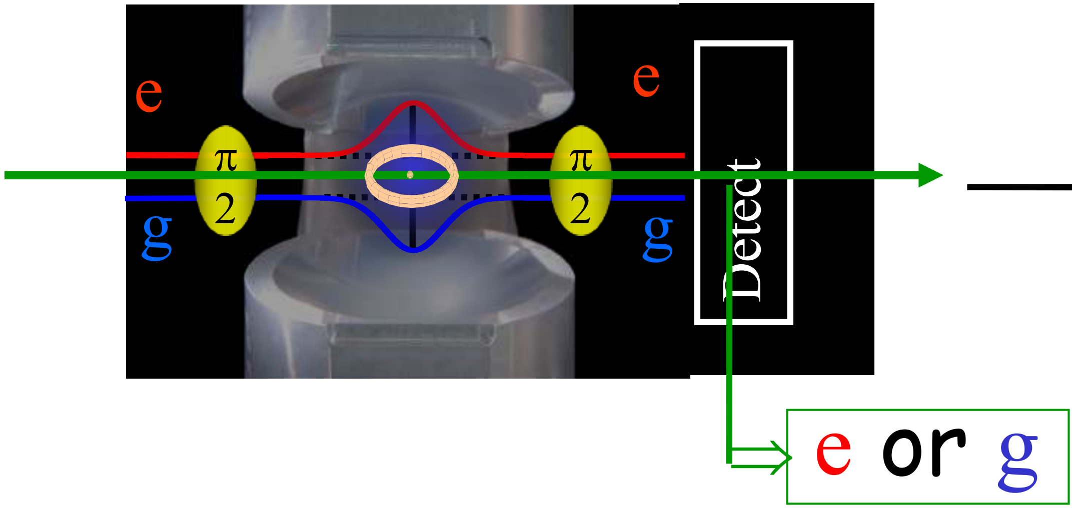
$|g\rangle \otimes |\alpha . e^{-i\varphi_0/2}\rangle$

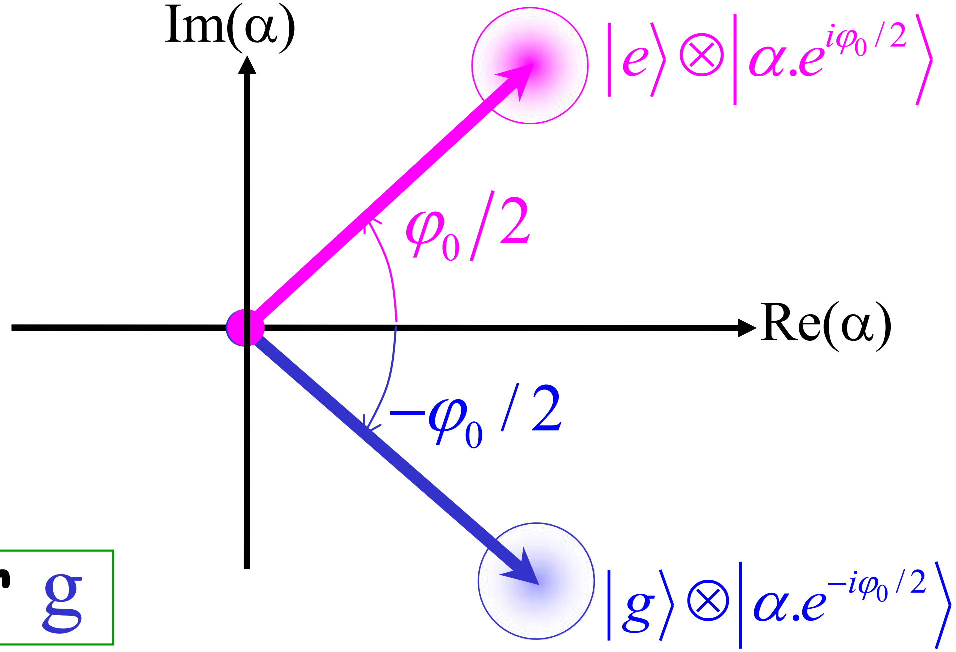
⇒ the field phase is controlled by the atomic energy state

$$\boxed{\frac{1}{\sqrt{2}}\left(|e,\alpha . e^{i\varphi_0/2}\rangle \pm |g,\alpha . e^{-i\varphi_0/2}\rangle\right)}$$

→ Entangled atom-field cat state

Preparing a phase Schödinger cat state





Detection of the atom projects the field on:

$$\frac{1}{\sqrt{2}}\left(\left|e,\alpha.e^{i\varphi_0/2}\right\rangle \pm \left|g,\alpha.e^{-i\varphi_0/2}\right\rangle\right)$$

±: depends on detected state e or g

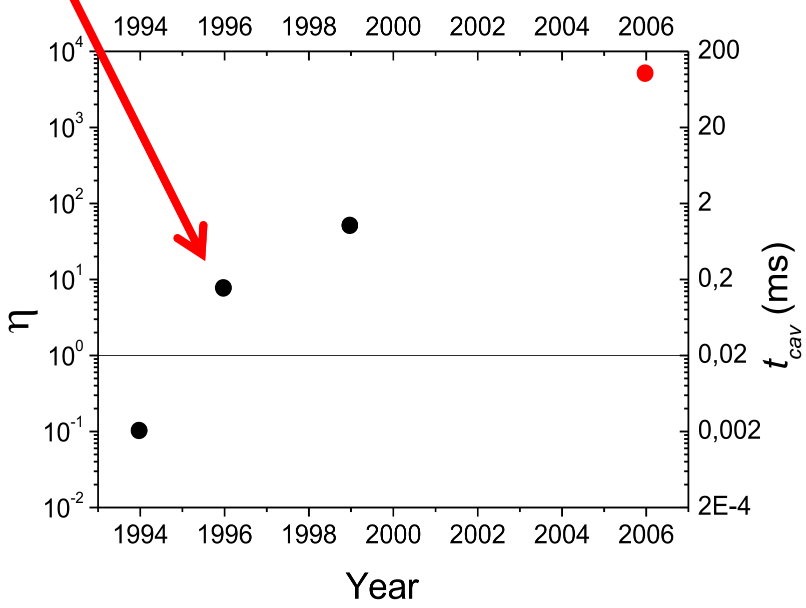
Field changed by a quantum interference process

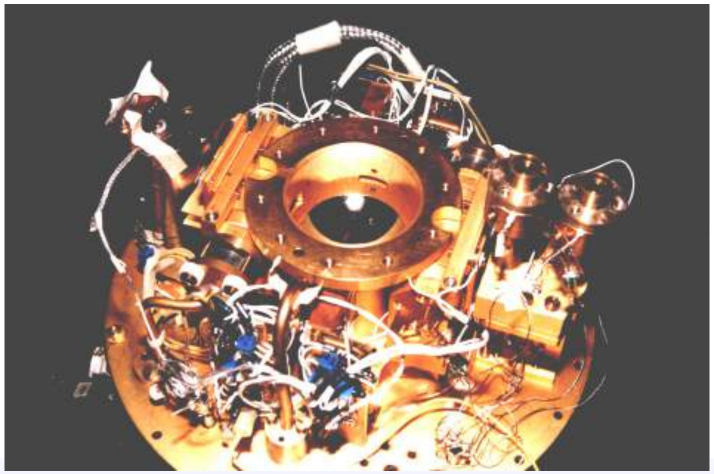
3. Experimental characterization of the cat state

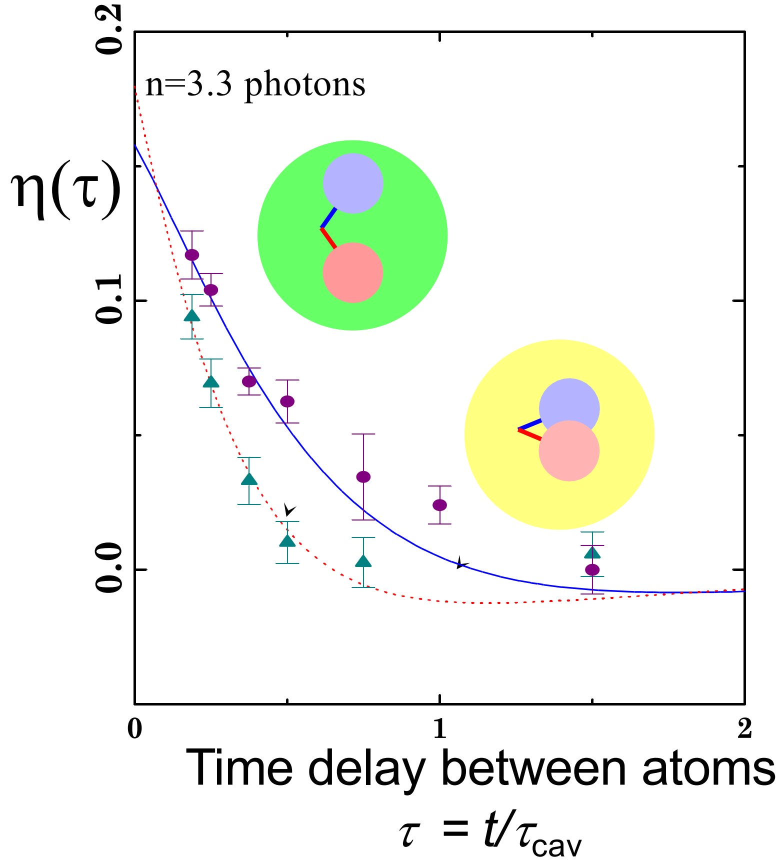
- Full tomography of the quantum state

First cat state generation

Back to 1996



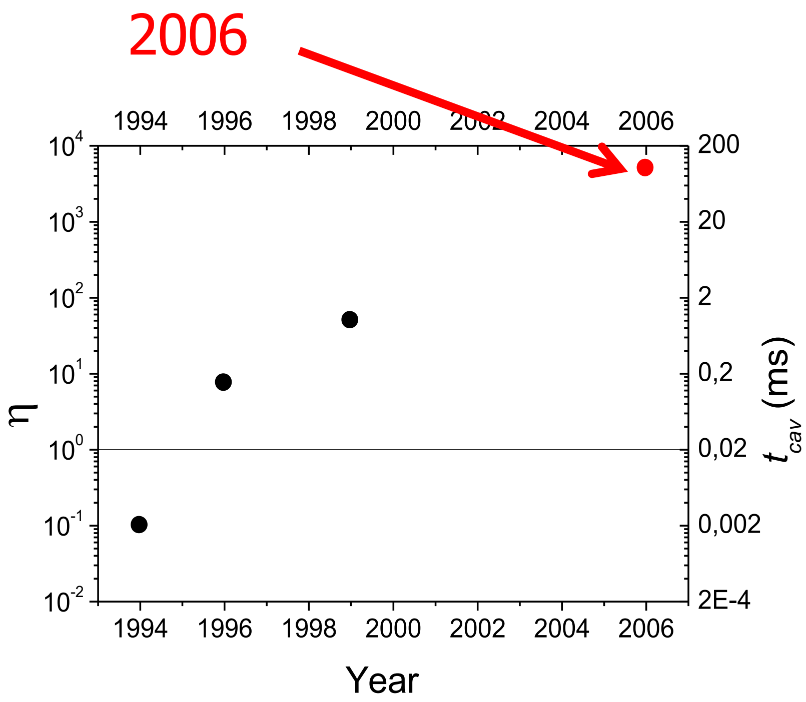


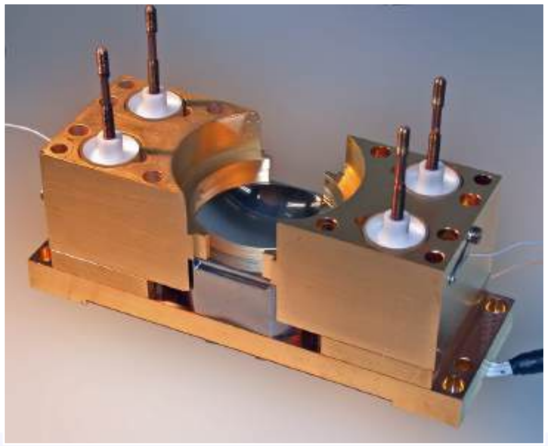


3 photons kitten

Brune et al. Phys. Rev. Lett. 77, 4887 (1996)

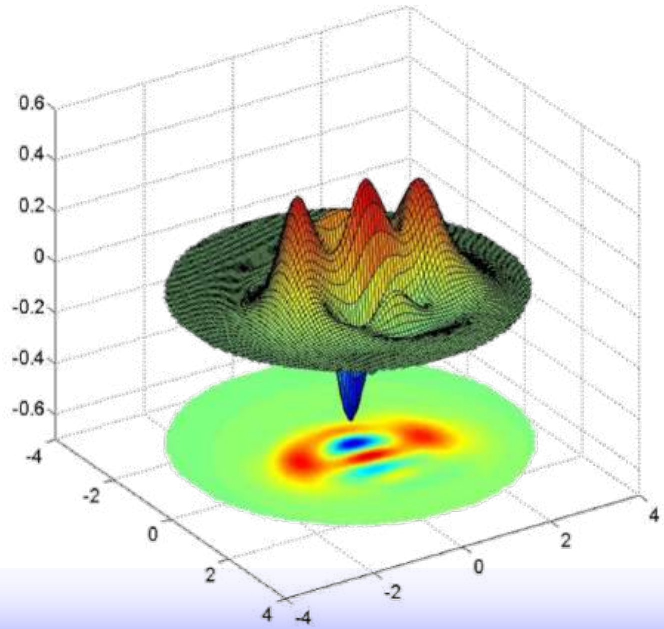
Second cat state generation



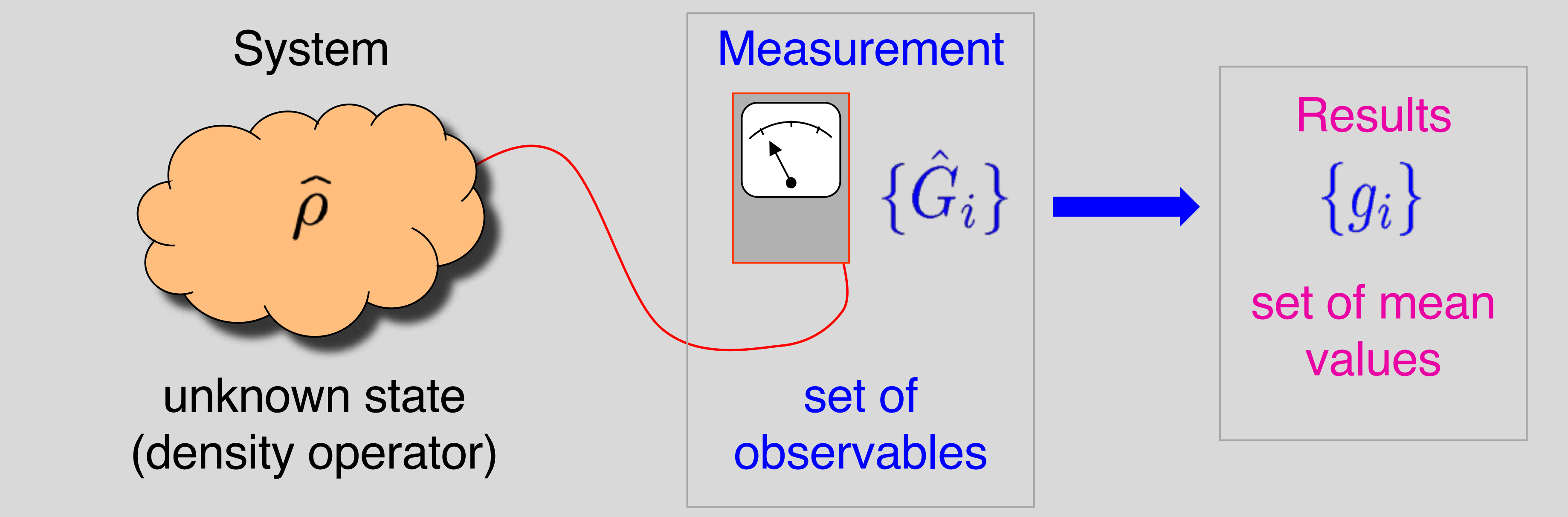


0.1 ms photon lifetime long-enough to

- perform full quantum tomography of the cat state a
- monitor the decoherence of the reconstructed quantum states



Principle of state reconstruction



→ Each measurement sets a constrain to the density operator

$$\boxed{\mathrm{Tr}(\hat{\rho}\,\hat{G}_i) = g_i}$$

Problems to face:

- Having a complete set of observable $\{\hat{G}_i\}$ fully determining $\hat{\rho}$
- Statistical noise on $\{g_i\}$ may lead to unphysical/very noisy density operators

Measuring the field density operator?

General field state description: density operator

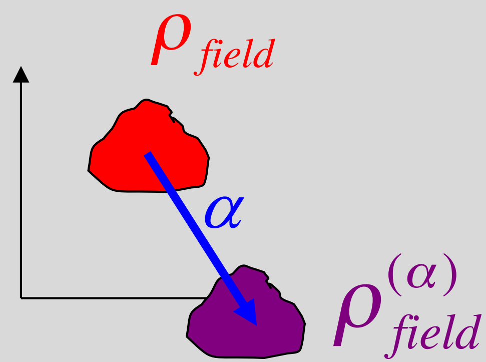
$$\rho_{field} = \begin{bmatrix} \rho_{00} & \rho_{01} & \rho_{02} & . \\ \rho_{10} & \rho_{11} & \rho_{12} & . \\ \rho_{20} & \rho_{21} & \rho_{22} & . \\ . & . & . & . \end{bmatrix}$$

- Previous lectures:

QND counting of photons

⇒ measurement of diagonal elements ρ_{nn}

⇒How to measure the off-diagonal elements of ρ_{field} ?



⇒ by counting photons after applying "displacement"

$$\rho^{(\alpha)}_{field} = \hat{D}(\alpha)\rho_{field}\hat{D}^{+}(\alpha)$$

$$\hat{D}(\alpha) = e^{\alpha a^{+} - \alpha^{*} a} \quad \text{Displacement operator}$$

The displacement operator is the unitary transform corresponding to the coupling to a classical source. It mixes diagonal and off-diagonal matrix elements of ρ_{field}. Measuring the photon number after displacement for a large number of different a gives information about all matrix elements of ρ_{field}.

Choice of reconstruction method

- Various possibilities:
  - Direct fit of ρ_{field} on the measured data $g_i = tr\left[\rho_{field}.\cos\left(\phi\left(\hat{n}\right)+\varphi\right)\right]$
  - Maximum likelihood: find ρ_{field} which maximizes the probability of finding the actually measured results g_i.
  - Maximum entropy principle: find ρ_{field} which fits the measurements and additionally maximizes entropy $S=\rho_{field}\log(\rho_{field})$.

V. Bužek and G. Drobný, *Quantum tomography via the MaxEnt principle*, Journal of Modern Optics **47**, 2823 (2000)

Estimates the state only on the basis of measured information: in case of incomplete set of measurements, gives a "worse estimate" of ρ_{field}.

In practice the two last methods give the same result provided one measures enough data completely determining the state.

State reconstruction: experimental method

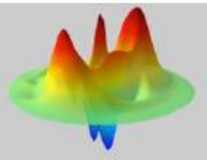
1- prepare the state to be measured $|\psi_{field}\rangle$

2- measure $\hat{G}(\alpha)$ for a large number of different values of α (400 to 600 points).

3- reconstruct ρ_{field} by maximum entropy method

4- Represent the field stae using Wigner function calculated from from ρ_{field}.

What is the Wigner function?



Wigner function representation of the quantum state

- **Definition**

- Position proba. density $$P(x) = Tr(\rho|x\rangle\langle x|) = Tr\big(\rho\,\delta(\hat{x}-x)\big)$$
- Momentum proba. Density $$P(p) = Tr(\rho|p\rangle\langle p|) = Tr\big(\rho\,\delta(\hat{p}-p)\big)$$
- Joint x,p quasi-proba density

$$\boxed{W(x,p) = Tr\big(\rho\,\delta(\hat{x}-x,\hat{p}-p)\big)}$$ "Wigner function"

- Looks like a joined probability **BUT can be negative**.
- Any observable can be expressed as a function of W, which thus **contains all the information on the quantum state**.
- Another equivalent definition:

$$W(x,p) = \frac{1}{\pi\hbar}\int_{-\infty}^{\infty}\langle x-y|\hat{\rho}|x+y\rangle e^{2ipy/\hbar}\,dy.$$

- **Quantum optics version:** field quadratures plays the role of x and p

$$\hat{X} = \frac{1}{\sqrt{2}}(\hat{a}+\hat{a}^{\dagger})$$

$$\hat{P} = \frac{1}{i\sqrt{2}}(\hat{a}-\hat{a}^{\dagger})$$

$$\alpha = x + i\,p$$

Diplacement operator $\hat{D}(\alpha)$

Parity operator $e^{i\pi\hat{a}^{\dagger}\hat{a}}$

$$\boxed{W(\alpha) = \mathrm{Tr}\left[\hat{\rho}\,\hat{D}(-\alpha)e^{i\pi\hat{a}^{\dagger}\hat{a}}\hat{D}(\alpha)\right]}$$

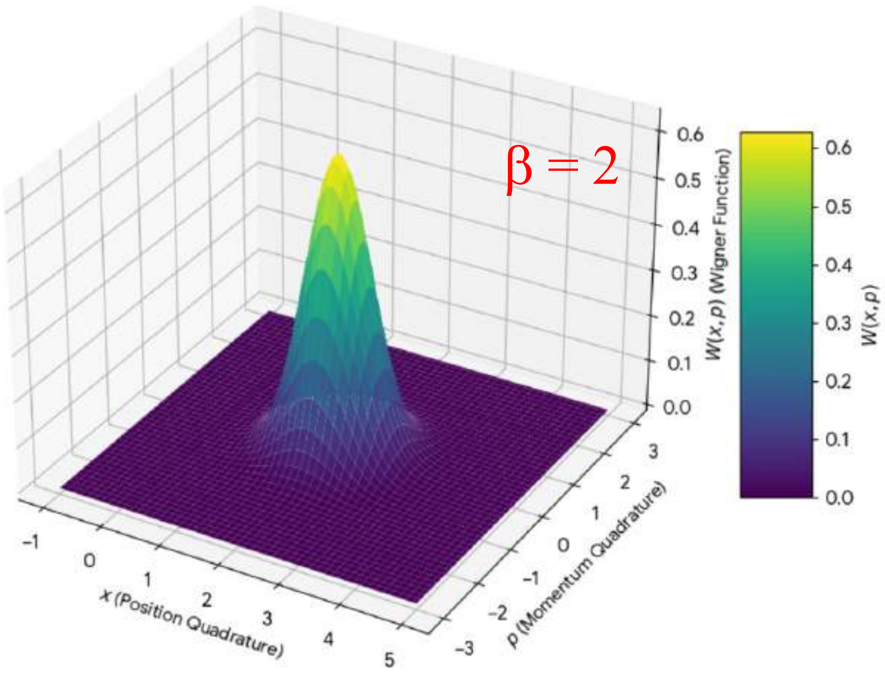
W is an observable

Exemple of Wigner Function

$$\boxed{W(\alpha) = \mathrm{Tr}\left[\hat{\rho}\,\hat{D}(-\alpha)e^{i\pi\hat{a}^\dagger\hat{a}}\hat{D}(\alpha)\right]}$$

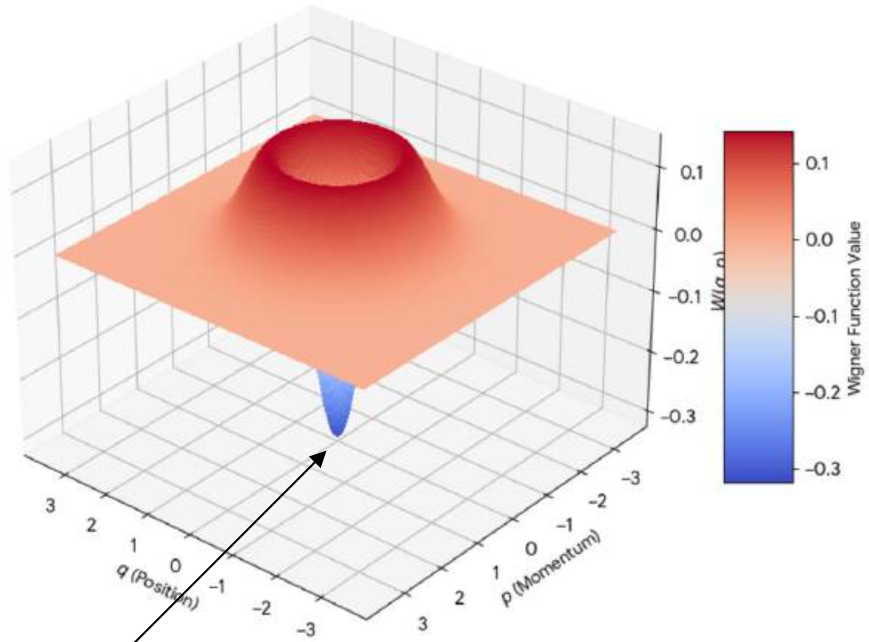
Wigner function for a coherent state $|\beta\rangle$

$$W(\alpha) = \frac{2}{\pi}e^{-2|\alpha-\beta|^2}$$



Gaussian quasi-probability distribution

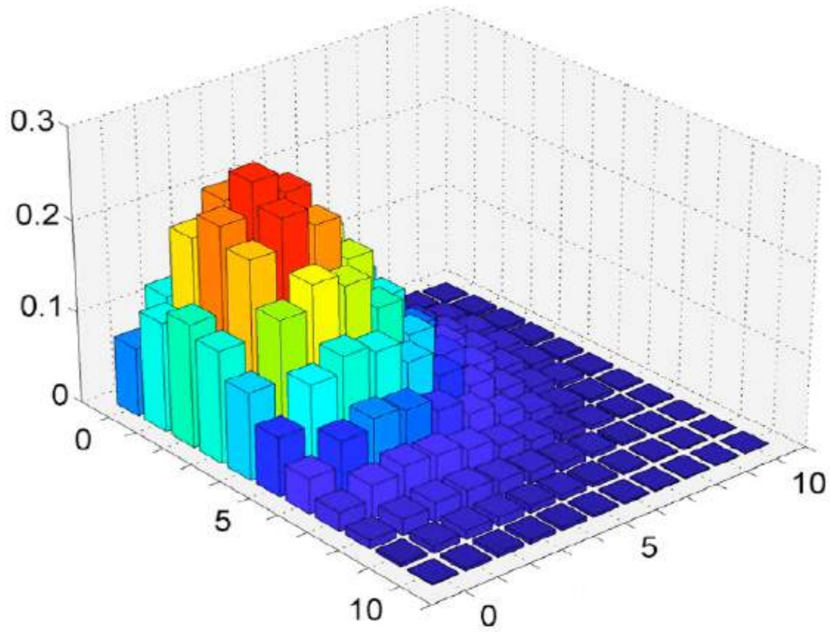
Number state N=1



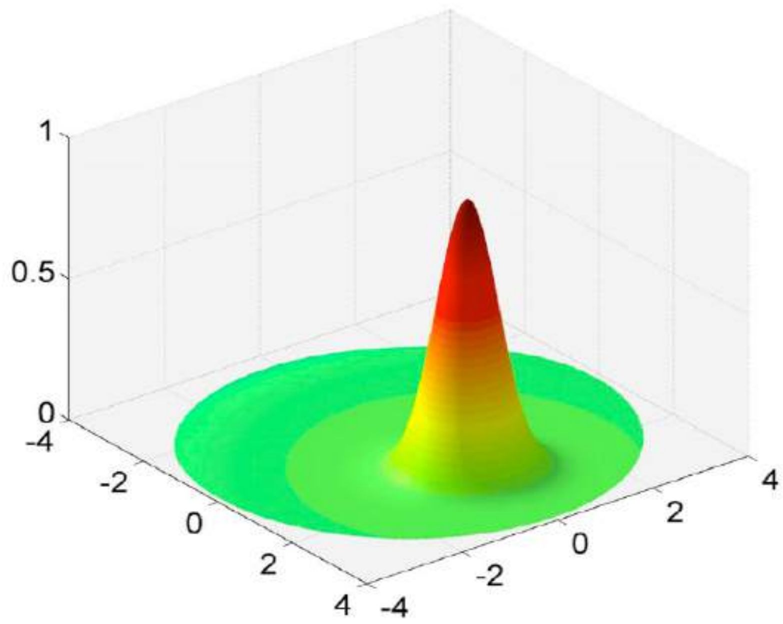
W(α) is negative at some points

reconstruction of a coherent field

- Measurement for 161 values of α (<1 hour measurement)
- 7000 detected atoms in 600 repetition of the experimental sequence for each α.



Density matrix



Wigner function (measurement)

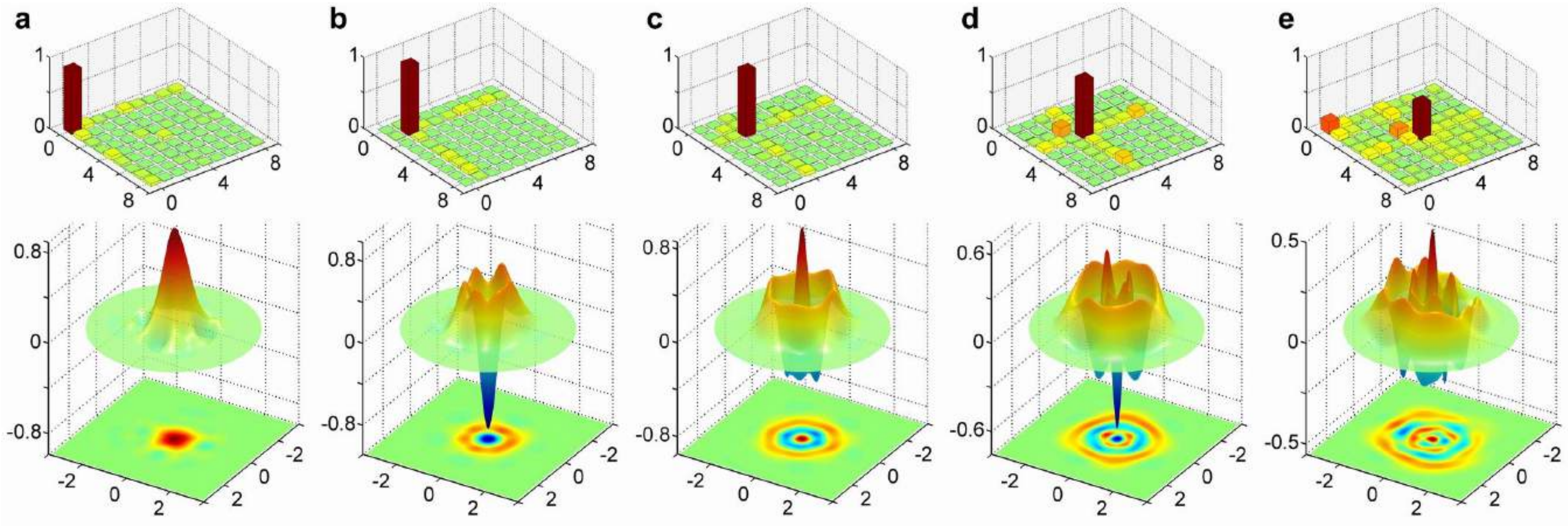
- State fidelity: $F = tr\left(|\beta\rangle\langle\beta|\rho_{field}\right)$

F=98% for β^2= 2.5 photons

Reconstruction of number states

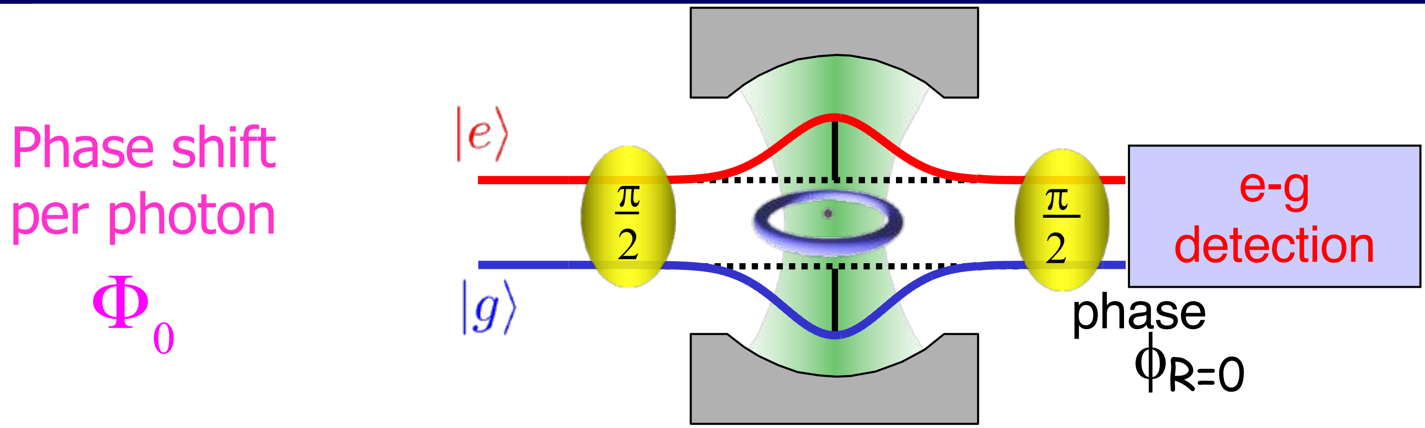
- Prepare a coherent state $\beta^2 = 1.3$ or 5.5 photons.
- Select pure number state by QND measurement of n.

  Phase shift per photon $\phi_0 \approx \pi/2$: measurement of n modulo 4.
- Measurements of $G(\alpha)$ for 2 different values of φ and ~400 values of α.



n=0	1	2	3	4
Fidelity 0.89	0.98	0.92	0.82	0.51

Preparation of the cavity cat state

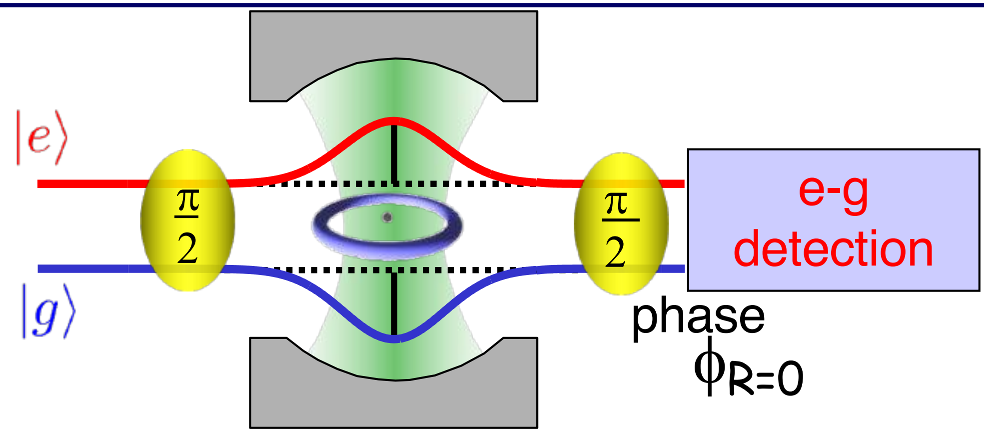


$$\frac{1}{\sqrt{2}}\left(|e\rangle+|g\rangle\right)\otimes|\alpha\rangle \quad \Rightarrow \quad \frac{1}{\sqrt{2}}\left(|e\rangle\otimes\left|\alpha.e^{i\Phi_0/2}\right\rangle+|g\rangle\otimes\left|\alpha.e^{-i\Phi_0/2}\right\rangle\right)$$

Preparation of the cavity cat state

Phase shift per photon

Φ_0



$$\boxed{\frac{1}{\sqrt{2}}\left(|e\rangle+|g\rangle\right)\otimes|\alpha\rangle \Rightarrow \frac{1}{\sqrt{2}}\left(|e\rangle\otimes\left|\alpha.e^{i\Phi_0/2}\right\rangle+|g\rangle\otimes\left|\alpha.e^{-i\Phi_0/2}\right\rangle\right)}$$

- Field state after detection:

$$\Rightarrow \frac{1}{\sqrt{2}}\left(\left|\alpha.e^{i\Phi_0/2}\right\rangle+\left|\alpha.e^{-i\Phi_0/2}\right\rangle\right) \quad \text{if "e" detected}$$

$$+\frac{1}{\sqrt{2}}\left(\left|\alpha.e^{i\Phi_0/2}\right\rangle-\left|\alpha.e^{-i\Phi_0/2}\right\rangle\right) \quad \text{if "g" detected}$$

$$\boxed{\Phi_0 = \pi}$$

e → even cat state

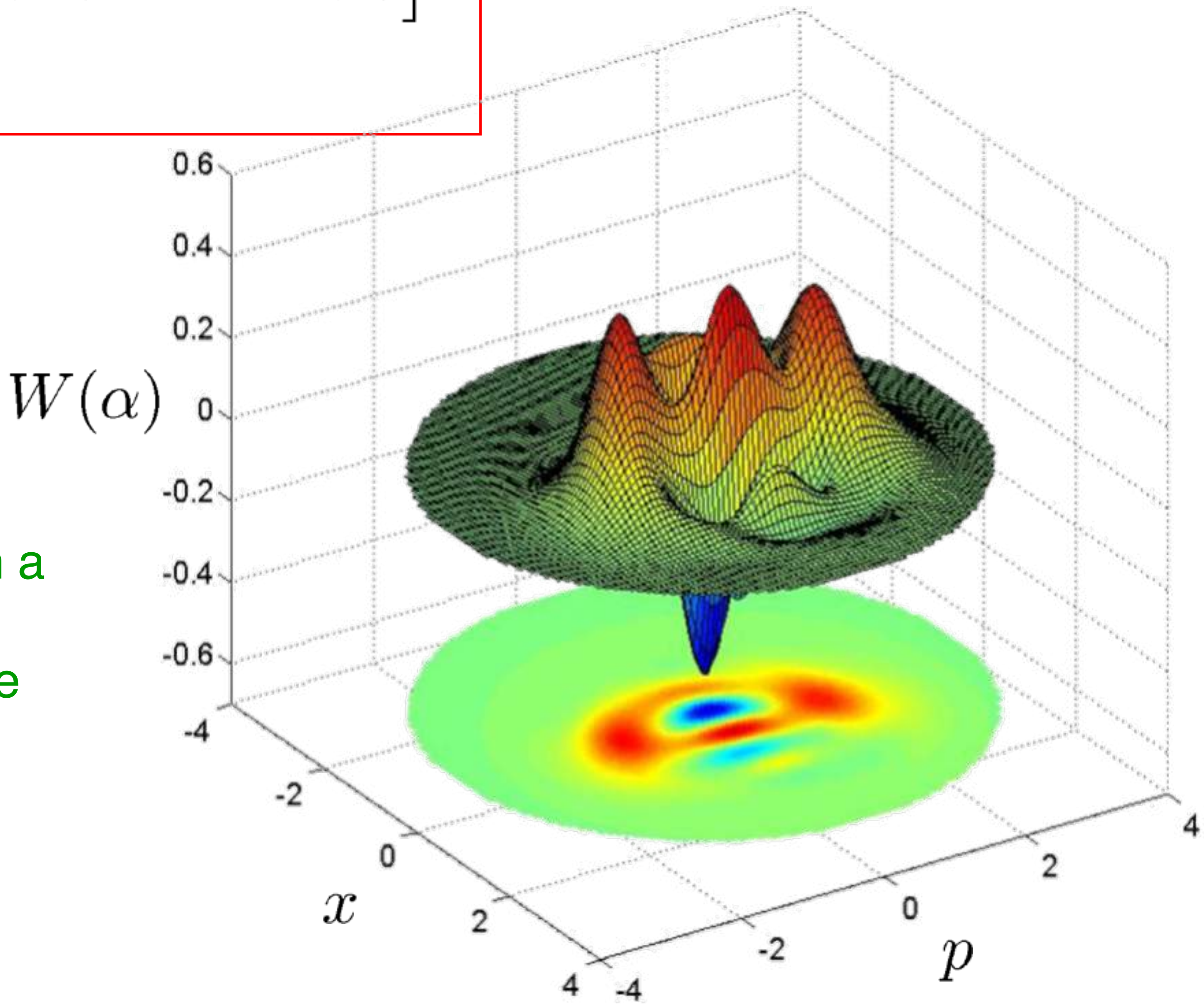
g → odd cat state

Depending on the detected atomic state the cat has a well defined photon number parity.
For π per photon phase shift, one atom measures just the field parity.
Projection on a cat state is the "back-action" of parity measurement.

Reconstructed Wigner function

$$W(\alpha) = \mathrm{Tr}\left[\hat{\rho}_{\mathrm{me}}\, \hat{D}(-\alpha)\, e^{i\pi \hat{a}^\dagger \hat{a}}\, \hat{D}(\alpha)\right]$$

$$\alpha = x + i\,p$$



No a priori knowledge on a prepared state except for the size of the Hilbert space of $N_{\mathrm{Hilbert}} = 9$

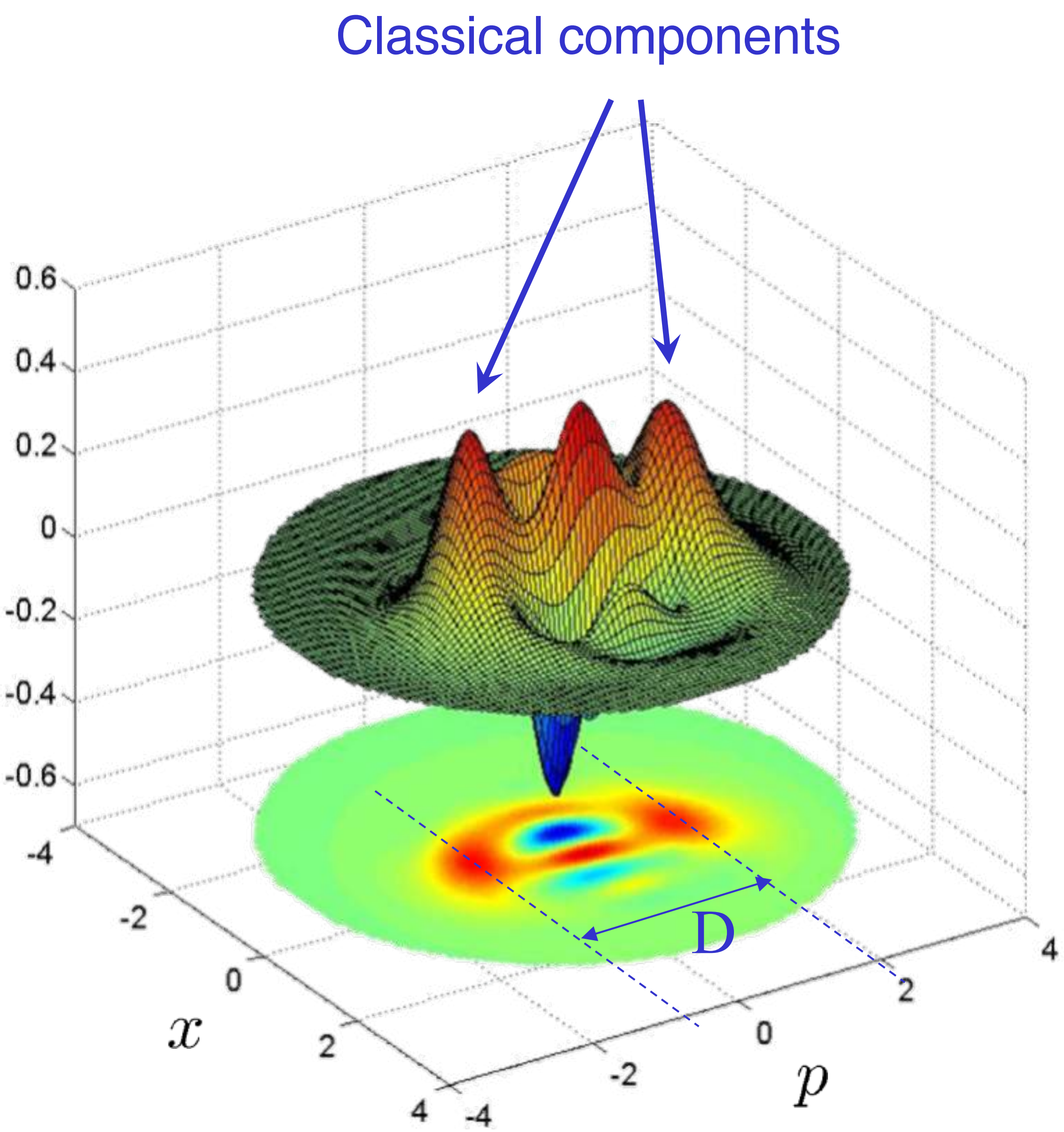
Deleglise et al. Nature **455**, 510 (2008)

Reconstructed Wigner function

≈ 2.1 photons in each classical component
(amplitude of the initial coherent field)

cat size $D^2 \approx 7.5$ photons

coherent components are completely separated
($D > 1$)



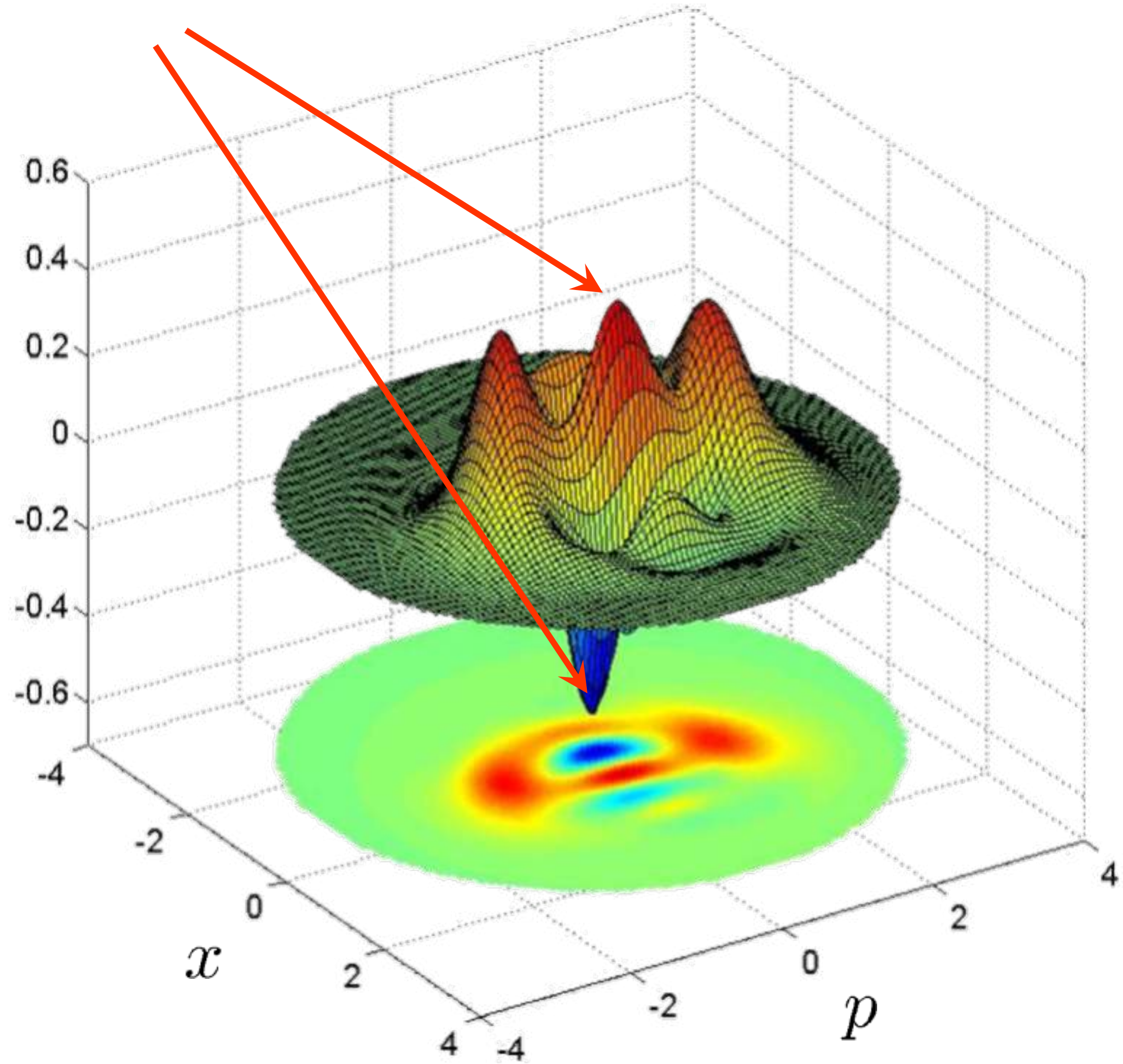
Deleglise et al. Nature **455**, 510 (2008)

Reconstructed Wigner function

Quantum coherence

quantum superposition
of two classical fields
(interference fringes)

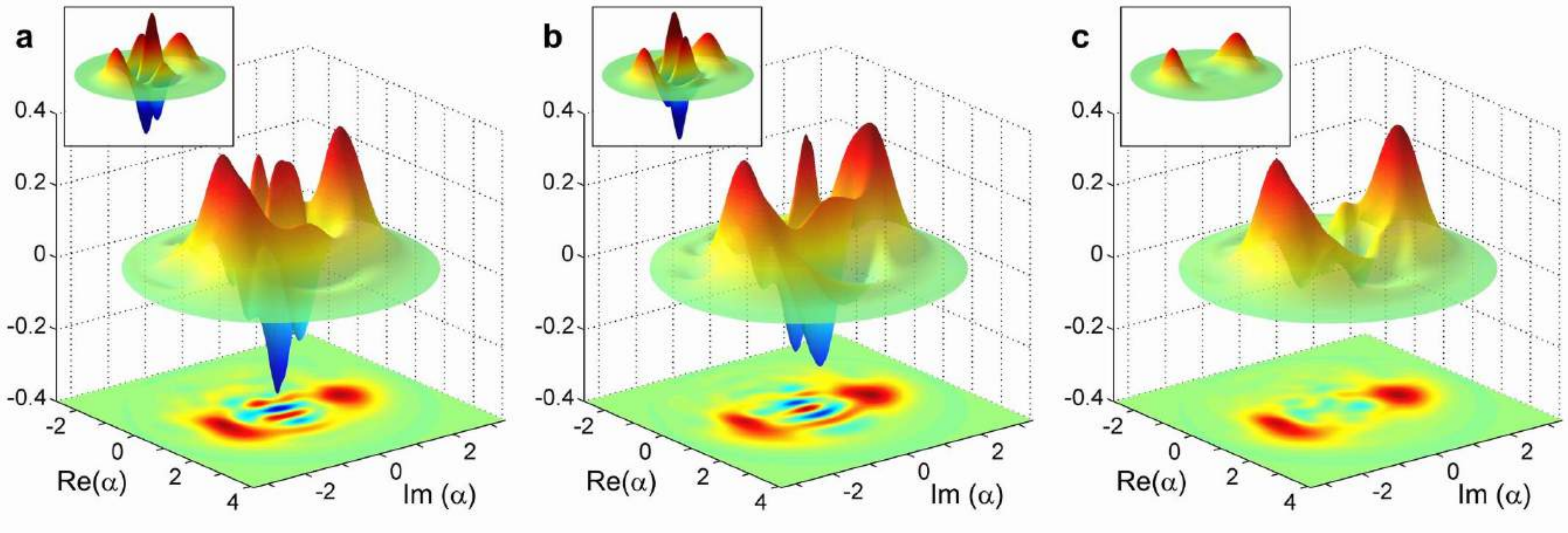
quantum signature of
the prepared state
*(negative values of
Wigner function)*



Deleglise et al. Nature **455**, 510 (2008)

A larger cat for observing decoherence

- Initial coherent field $\beta^2 = 3.5$ photons
- Measurement for 400 values of α.



Even cat

Odd cat

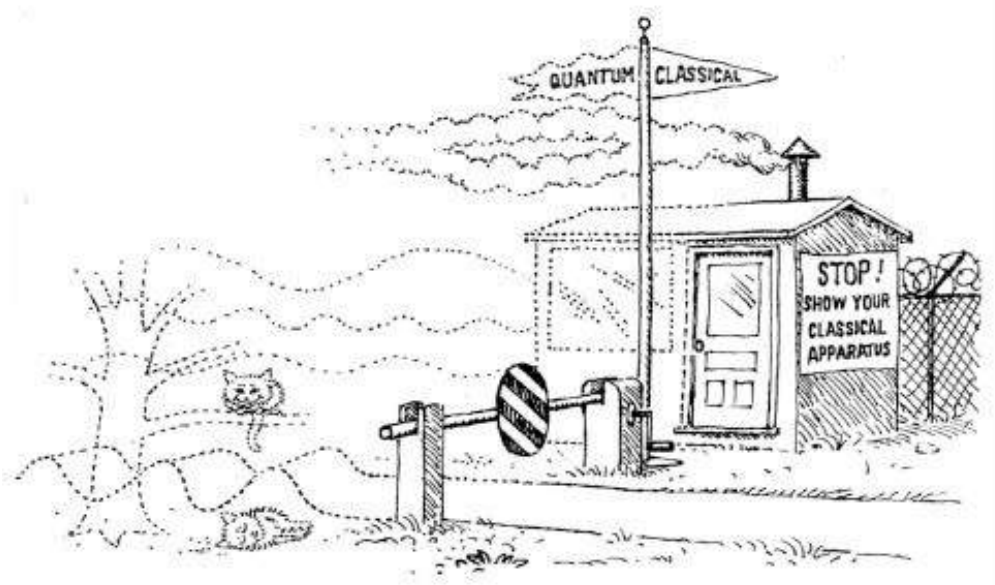
Sum of two WF:
Statistical mixture

State fidelity with respect to the expected
state including phase shift non-lineariry (insets)

$\boxed{F = 0.72}$

Deleglise et al. Nature **455**, 510 (2008)

4. Quantum measurement and cat decoherence



Delineating the border between the quantum realm ruled by the Schrödinger equation and the classical realm ruled by Newton's laws is one of the unresolved problems of physics. **Figure 1**

Zurek, Physics Today (1991)

Going across the border between the classical and the quantum world

The role of the "environment":

- For long atom-cavity interaction time field damping couples the system to the outside world

→ a complete description of the system must take into account the state of the field energy "leaking" in the environment.

- General method for describing the role of the environment:

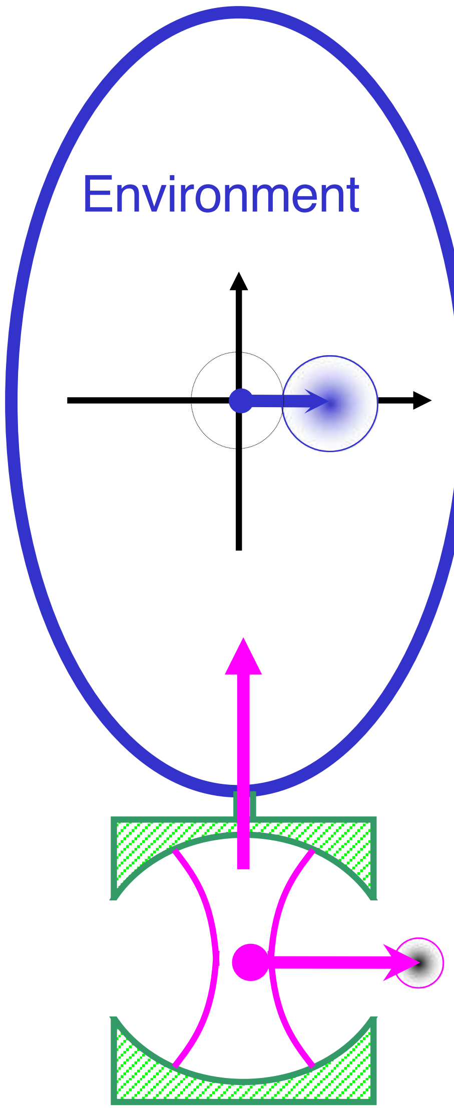
$$\boxed{\frac{d\rho^{field}}{dt} = -\frac{1}{2T_{cav}}\left[a^+a, \rho^{field}\right]_+ + \frac{1}{T_{cav}} a\rho^{field}a^+}$$

master equation of the field density matrix

- Physical result: decoherence

$$\boxed{\tau_{dec} \approx \frac{\tau_{cav}}{\overline{N}}}$$

The origin of decoherence: entanglement with the environment



- Decay of a coherent field:

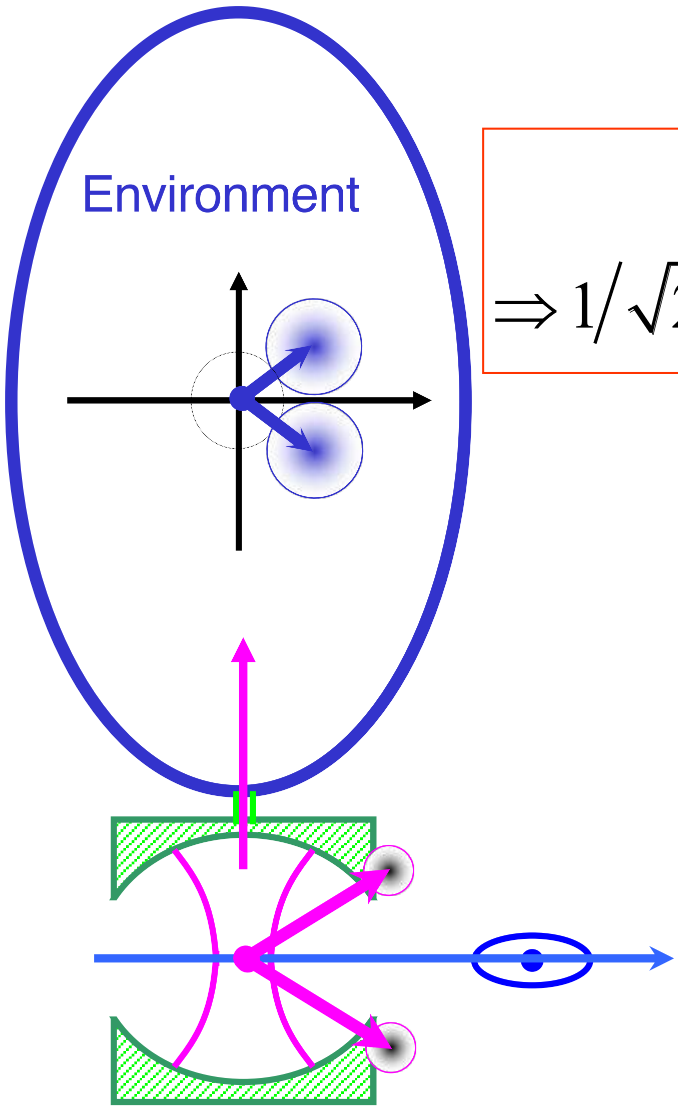
$$|\alpha(0)\rangle \otimes |vacuum\rangle_{env} \rightarrow |\alpha(t)\rangle \otimes |\beta(t)\rangle_{env}$$

$$\alpha(t) = \alpha(0).e^{-t/2\tau_{cav}}$$

- the cavity field remains coherent
- the leaking field has the same phase as α
- no entanglement during decay:

That is **a property defining coherent states**: coherent state are the only one which do not get entangled while decaying

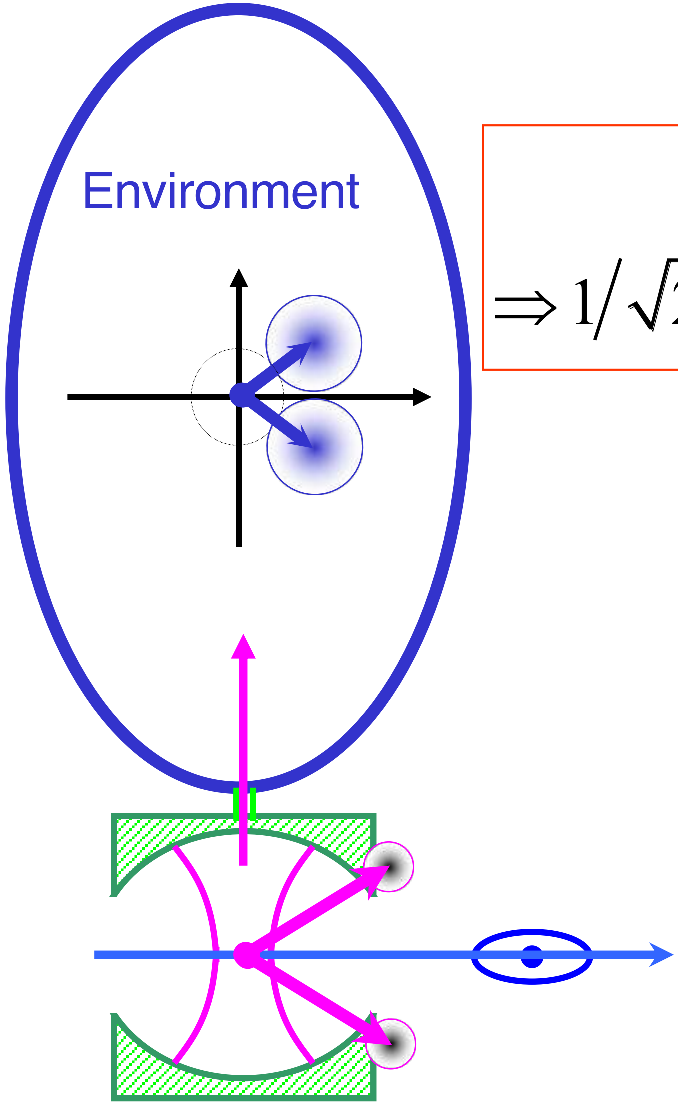
The origin of decoherence: entanglement with the environment



- Decay of a "cat" state:

$$\left|\Psi_{cat}\right\rangle \otimes \left|vacuum\right\rangle_{env}$$
$$\Rightarrow 1/\sqrt{2}\left(\left|\alpha_+(t)\right\rangle \otimes \left|\beta_+(t)\right\rangle_{env} + \left|\alpha_-(t)\right\rangle \otimes \left|\beta_-(t)\right\rangle_{env}\right)$$

The origin of decoherence: entanglement with the environment



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$$\left|\Psi_{cat}\right\rangle \otimes \left|vacuum\right\rangle_{env}$$
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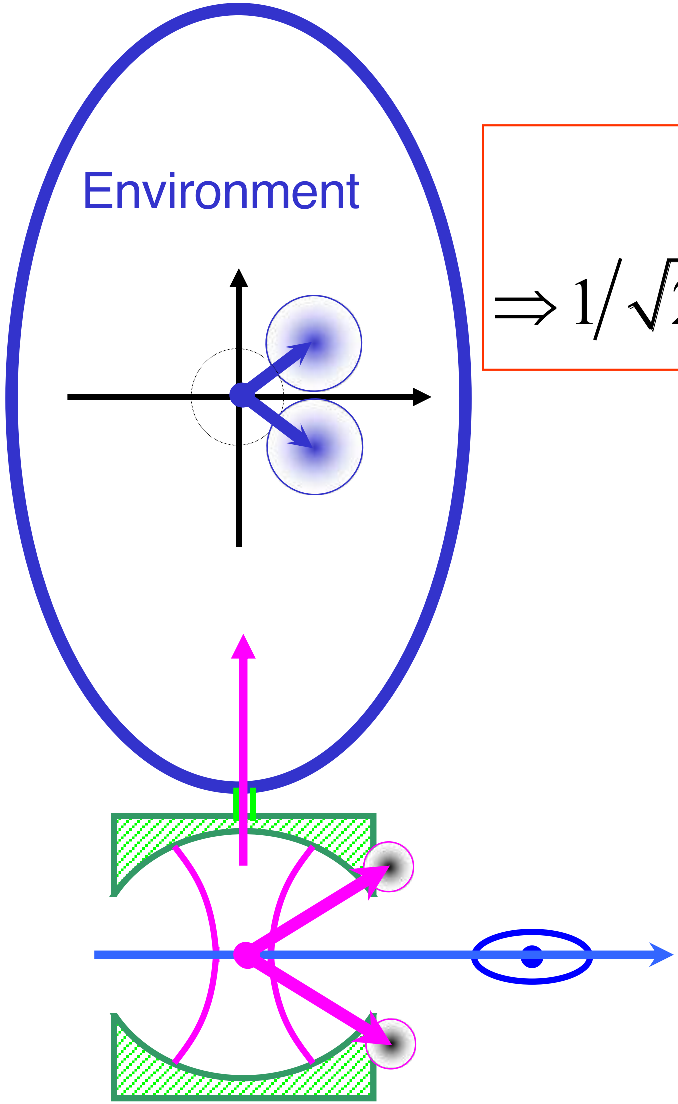
- cavity-environment entanglement: the leaking field "broadcasts" phase information
- trace over the environment

$\Rightarrow$ decoherence (=diagonal field reduced density matrix) as soon as:

$$\boxed{\left\langle \beta_{-}(t) \middle| \beta_{+}(t) \right\rangle_{env} \approx 0}$$

The origin of decoherence: entanglement with the environment



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$$\Rightarrow 1/\sqrt{2}\left(\left|\alpha_+(t)\right\rangle \otimes \left|\beta_+(t)\right\rangle_{env} + \left|\alpha_-(t)\right\rangle \otimes \left|\beta_-(t)\right\rangle_{env}\right)$$

$$\left\langle \beta_+(t) \middle| \beta_-(t) \right\rangle = e^{-|\beta|^2\left(1-e^{2i\Phi_0}\right)}$$

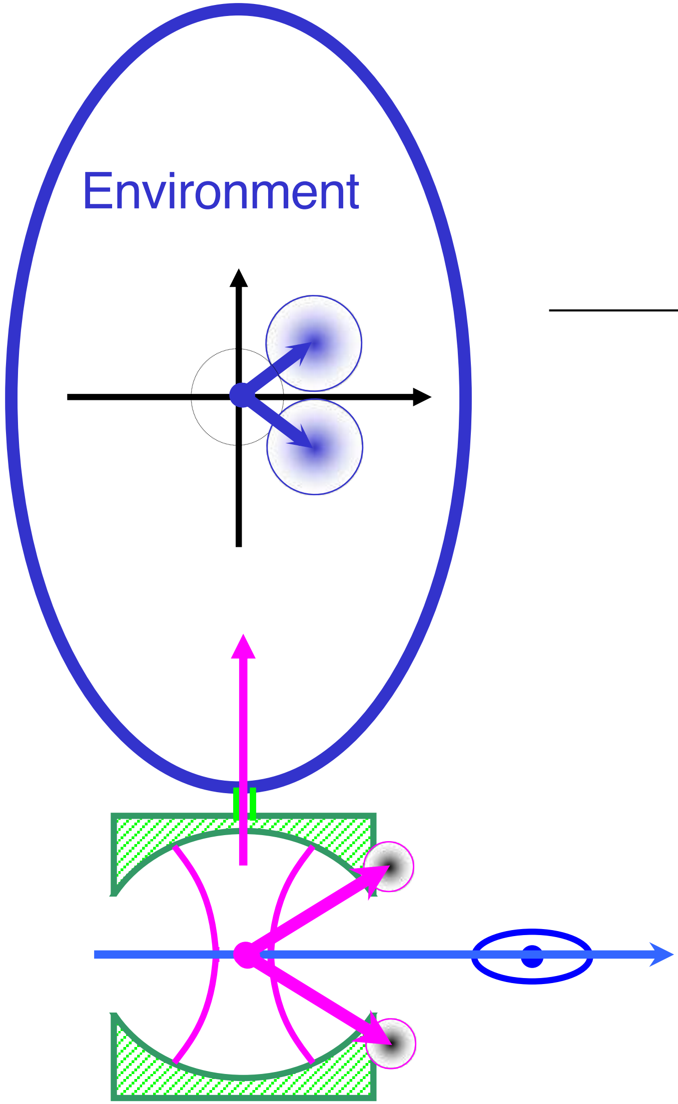
Energy conservation $\quad |\alpha(t)|^2 + |\beta(t)|^2 = |\alpha_0|^2$

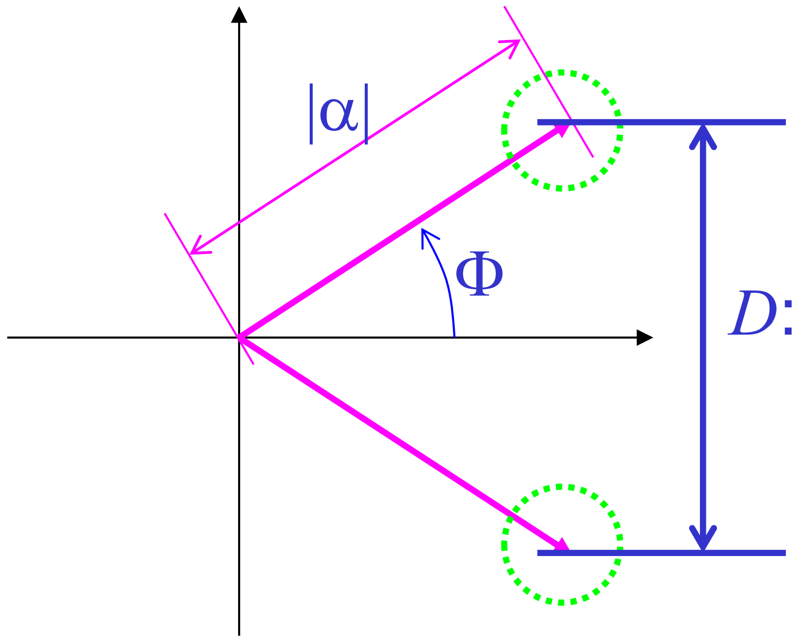
$$\Rightarrow |\beta(t)|^2 = |\alpha_0|^2\left(1-e^{-t/T_{cav}}\right) \approx |\alpha_0|^2 . t/T_{cav}$$

The two states of the environment become orthogonal as soon as

$$|\beta(t)|^2 \approx 1 \Rightarrow t > \frac{T_{cav}}{\bar{N}} \approx T_{dec}$$

The decoherence time





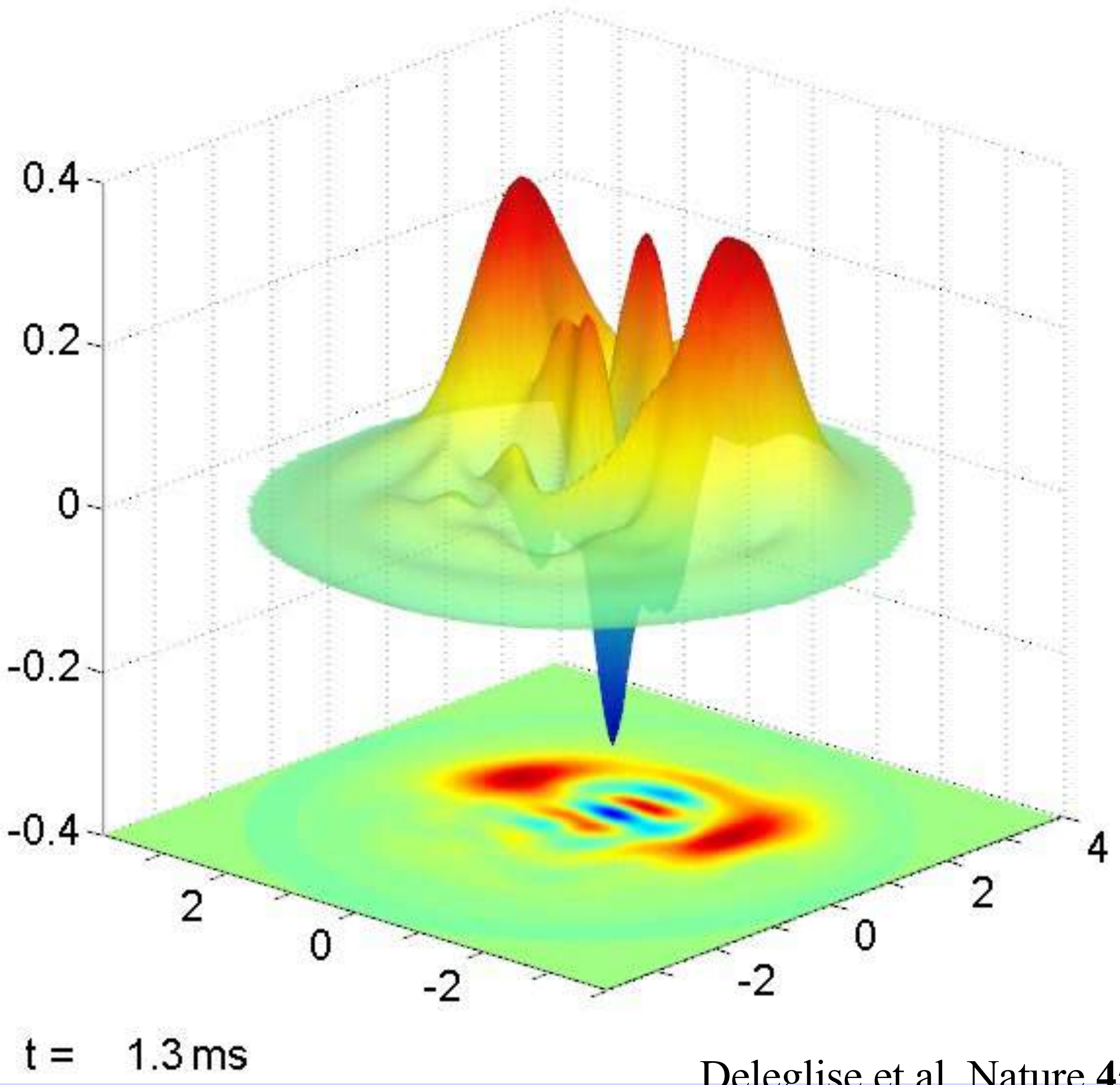
D: "Distance" between the two fields components.

$$T_{decoh} = \frac{2T_{cav}}{D^2} = \frac{T_{cav}}{\bar{N}.2\sin^2(\Phi)}$$

Infinitely short decoherence time for macroscopic fields
→ The Schrödinger cat does not exist for "long" time

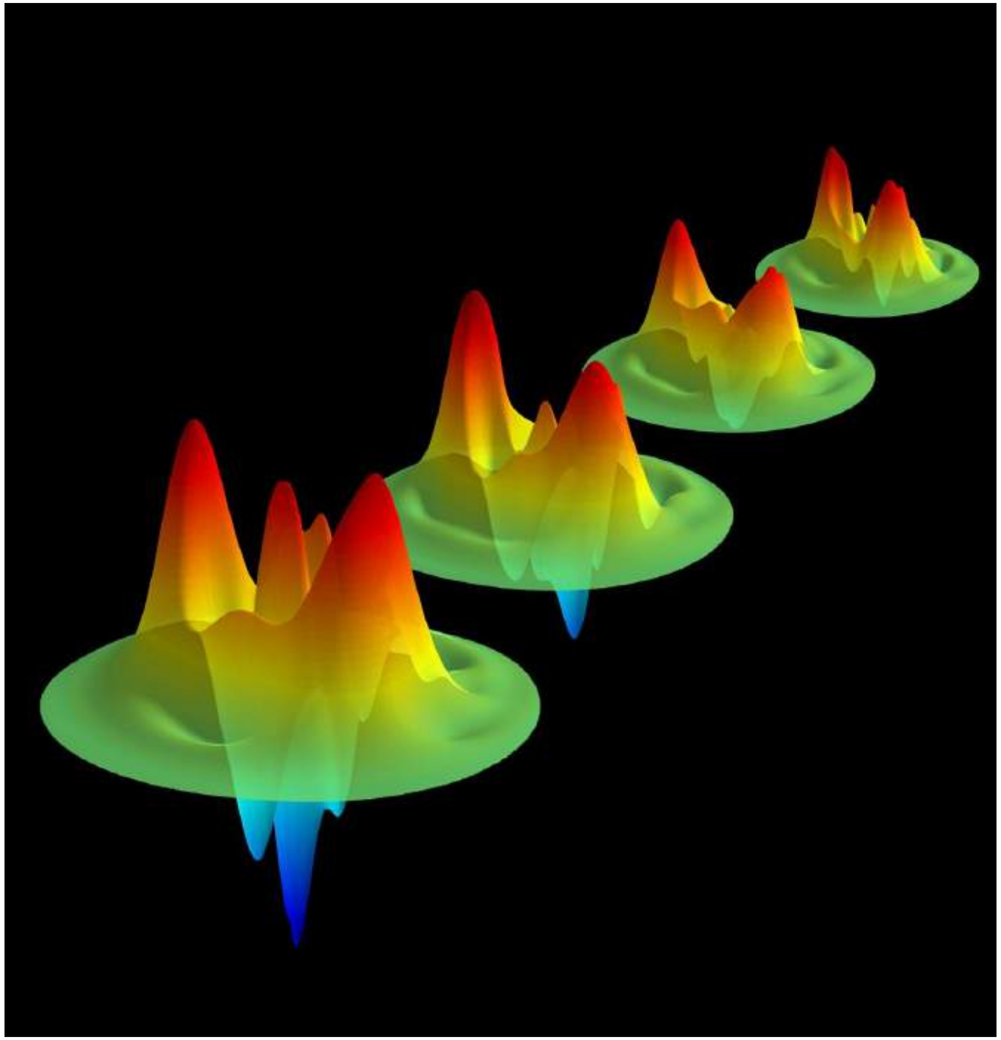
Detailed calculation in
PHYSICA SCRIPTA T78, 29 (1998)

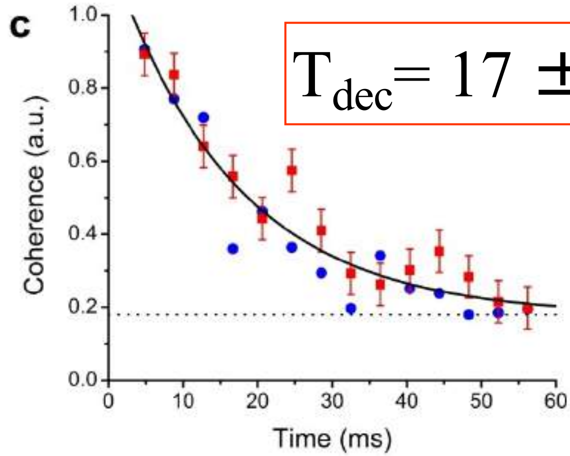
Movie of decoherence



Deleglise et al. Nature **455**, 510 (2008)

Decoherence of a D^2=11.8 photon cat state





T_{dec}= 17 ± 3 ms

$T_{\rm meas} \approx 4\,{\rm ms} < T_{{\rm dec},\,\bar{n}_{\rm th}}$

Theory:

$T_{dec} = 2T_{cav}/D^2 = 22$ ms

+ small blackbody contribution @ 0.8 K

T_{dec}= 19.5 ms

M.S. Kim and V. Bužek, *Schrödinger-cat state at finite temperature*, Phys. Rev. A **46**, 4239 (1992)

Quantum measurement: the role of the environment 1

⇒ Physical origin of decoherence:

leak of information into the environment.

⇒ The experimentalist does not kill the cat when opening the box: the environment “knows” whether the cat is dead or alive well before one opens the box.

⇒ The environment performs continuously unread repeated measurement of the cat state

The “collapse” of the quantum state can be considered as a shortcut to describe this complex physical process

Does it solve “the measurement problem”?

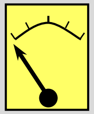
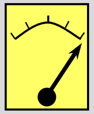
No: if the problem consists in telling how or why nature chooses randomly one classical state.

Yes: once one a priori accepts the statistical nature of quantum theory, dechoherence is the mechanism providing classical probabilities

Quantum measurement: the role of the environment 2

⇒ Definition of "pointer basis" of a meter: (Zurek)

- the pointer state of the meter is a classical state
- once decoherence occurs, the physical state of a meter is described by a diagonal density matrix in the pointer basis:

$|e,$  $\rangle$ $|g,$  $\rangle$

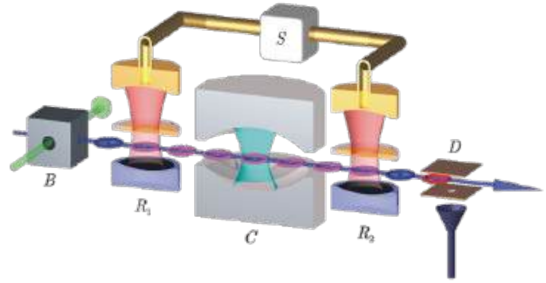
$$\rho_{dec} = \left(\begin{array}{c|c} P_e & 0 \\ \hline 0 & P_g \end{array}\right)$$

⇒ at this level, quantum description only involves classical probabilities and no macroscopic superposition states.

The decoherence approach shows that quantum theory is consistent with classical logic at macroscopic scale: it only provides classical statistics at the macroscopic scale.

Summary

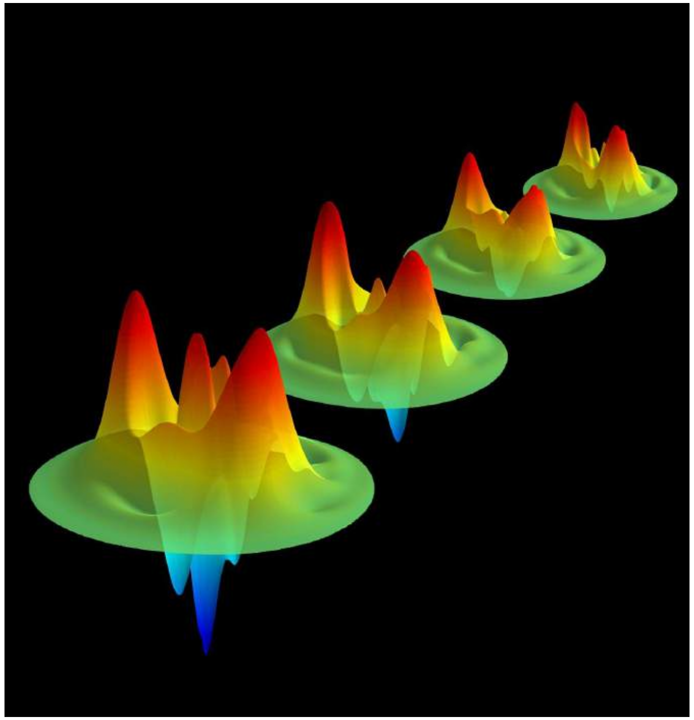
- Generation of cat states in a cavity

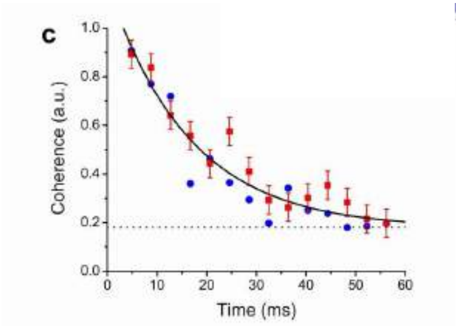


- State measurement (QND) and reconstruction (MaxEnt)

- Wigner function of the cat states

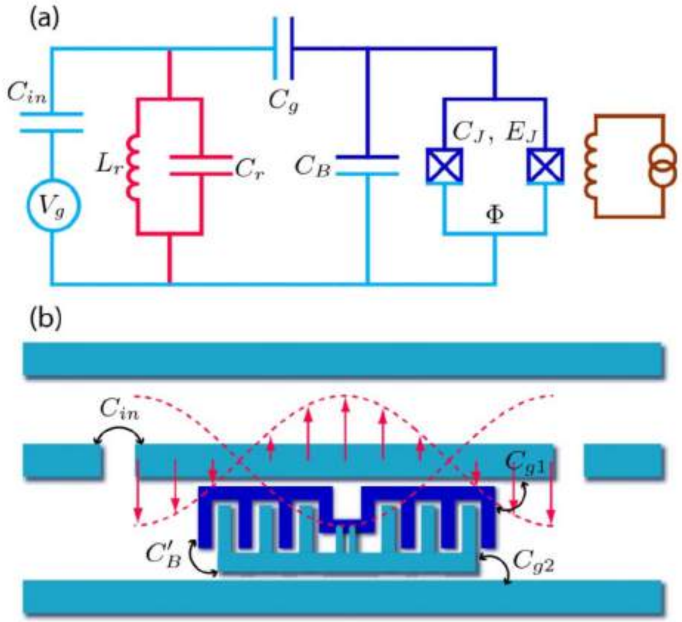
- Time evolution and decoherence of the cats





Continuation of cavity QED

Artificial atoms eventually became as good as real one:
comparable factor of merit T_{coh}/T_{op}



J. Koch et al. PRA 2007

Transmon qubit
+ stripline cavity

Ill. Niklas Elmehed © Nobel Prize Outreach
John Clarke
Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach
Michel H. Devoret
Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach
John M. Martinis
Prize share: 1/3

The Nobel Prize in Physics 2025 was awarded jointly to John Clarke, Michel H. Devoret and John M. Martinis "for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"

A work starting in 1991

Jean-Michel Raimond **Serge Haroche** **Michel Brune**

The LKB-ENS cavity QED team

- Staring, in order of apparition

- Serge Haroche
- Michel Gross
- Claude Fabre
- Philippe Goy
- Pierre Pillet
- Jean-Michel Raimond
- Guy Vitrant
- Yves Kaluzny
- Jun Liang
- Michel Brune
- Valérie Lefèvre-Seguin
- Jean Hare
- Jacques Lepape
- Aephraim Steinberg
- Andre Nussenzveig
- Frédéric Bernardot
- Paul Nussenzveig
- Laurent Collot
- Matthias Weidemuller
- François Treussart
- Abdelamid Maali
- David Weiss
- Vahid Sandoghdar
- Jonathan Knight
- Nicolas Dubreuil
- Peter Domokos
- Ferdinand Schmidt-Kaler
- Jochen Dreyer
- Peter Domokos
- Ferdinand Schmidt-Kaler
- Ed Hagley
- Xavier Maître
- Christoph Wunderlich
- Gilles Nogues
- Vladimir Ilchenko
- Jean-François Roch
- Stefano Osnaghi
- Arno Rauschenbeutel
- Wolf von Klitzing
- Erwan Jahier
- Patrice Bertet
- Alexia Auffèves
- Romain Long
- Sébastien Steiner
- Paolo Maioli
- Philippe Hyafil
- Tristan Meunier
- Perola Milman
- Jack Mozley
- Stefan Kuhr
- Sébastien Gleyzes
- Christine Guerlin
- Thomas Nirrengarten
- Cédric Roux
- Julien Bernu
- Ulrich Busk-Hoff
- Andreas Emmert
- Adrian Lupascu
- Jonas Mlynek
- Igor Dotsenko
- Samuel Deléglise
- Clément Sayrin
- Xingxing Zhou
- Bruno Peaudecerf
- Raul Teixeira
- Sha Liu
- Theo Rybarczyk
- Carla Hermann
- Adrien Signolles
- Adrien Facon
- Stefan Gerlich
- Than Long Nguyen

- Eva Dietsche
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- Frédéric Assémat
- Athur Larrouy
- Valentin Métillon
- Tigrane Cantat-Moltrecht

Collaboration: L davidovich, N. Zaguri, P. Rouchon, A. Sarlette, S Pascazio, K. Mölmer …

Cavity technilogy: CEA Saclay, Pierre Bosland