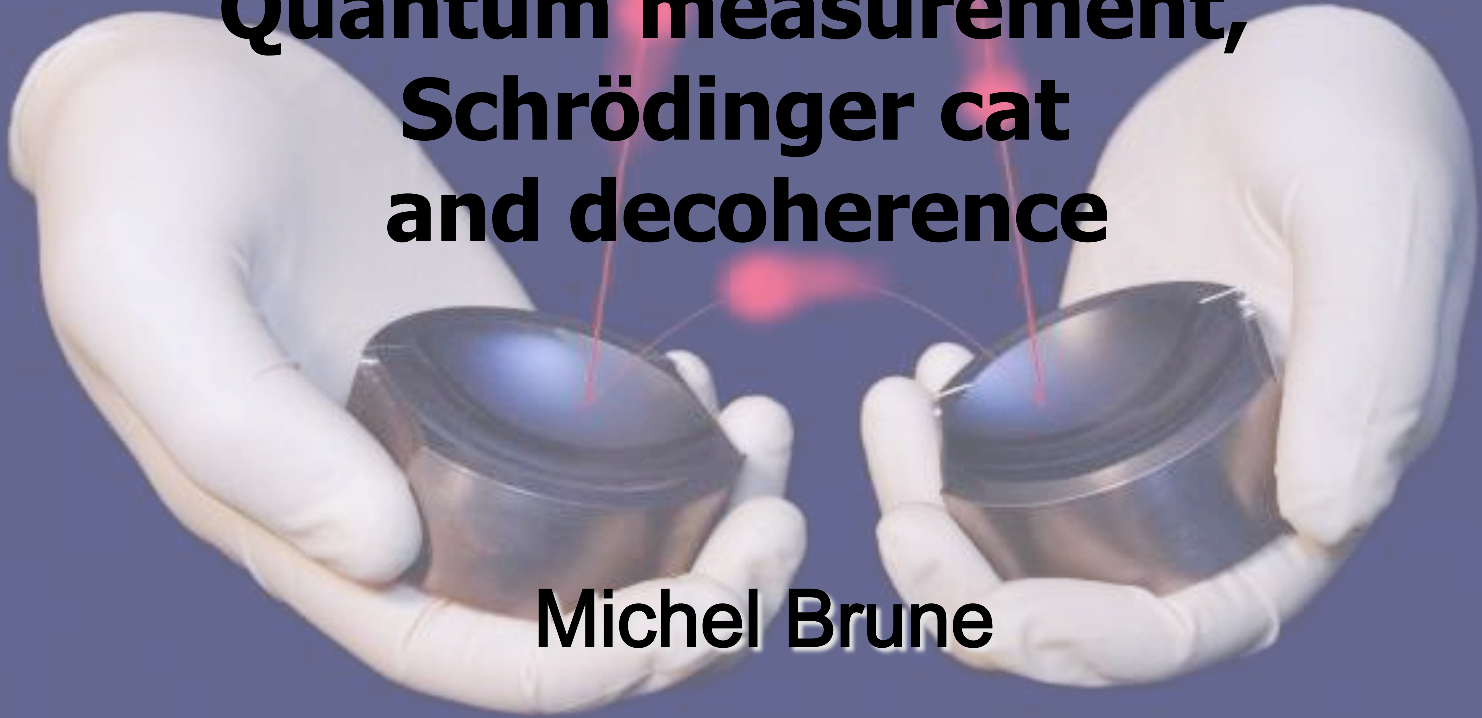
From cavity QED to quantum simulations with Rydberg atoms

Lecture 4

Quantum measurement, Schrödinger cat and decoherence



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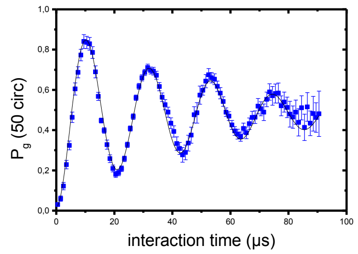
Collège de France, Paris

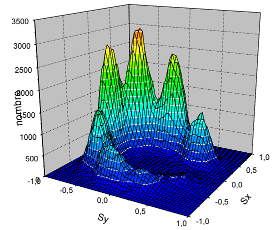
Previous lectures

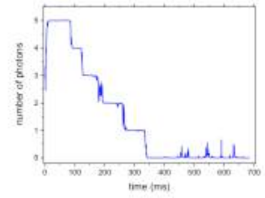
Cavity QED with microwave photons and circular Rydberg atoms:

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

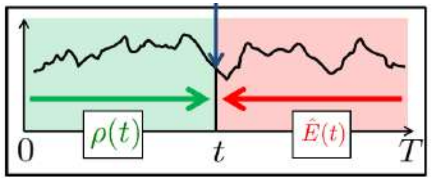


- L2: Performing QND measurement of the field state



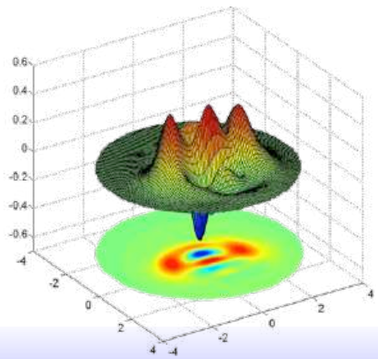


- L3: application to quantum feedback and past quantum state analysis of a quantum trajectory



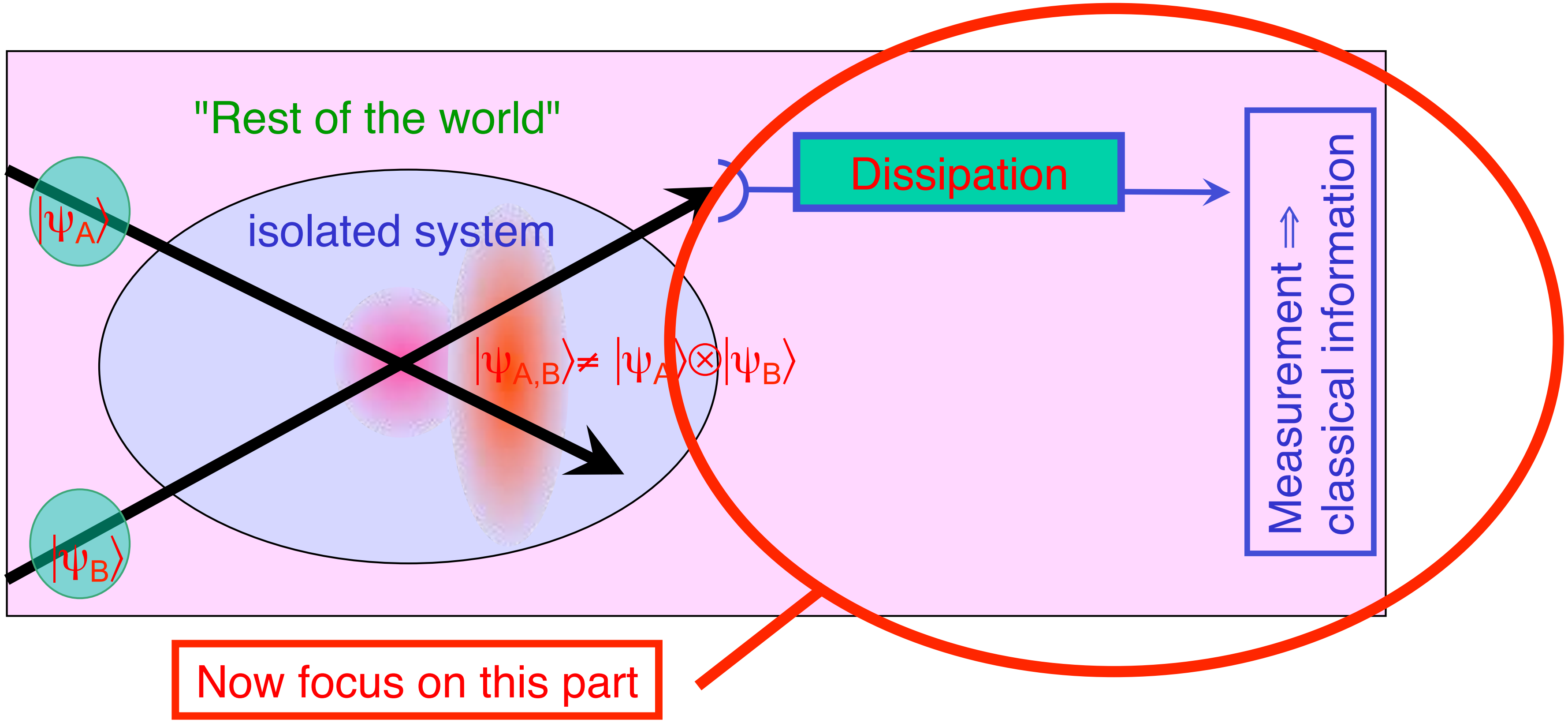
- L4: The same experiment seen from the point of view of the field:

➞Schrödinger cat preparation and monitoring of its decoherence



Lecture 4:
Quantum measurement,
Schrödinger cat and decoherence

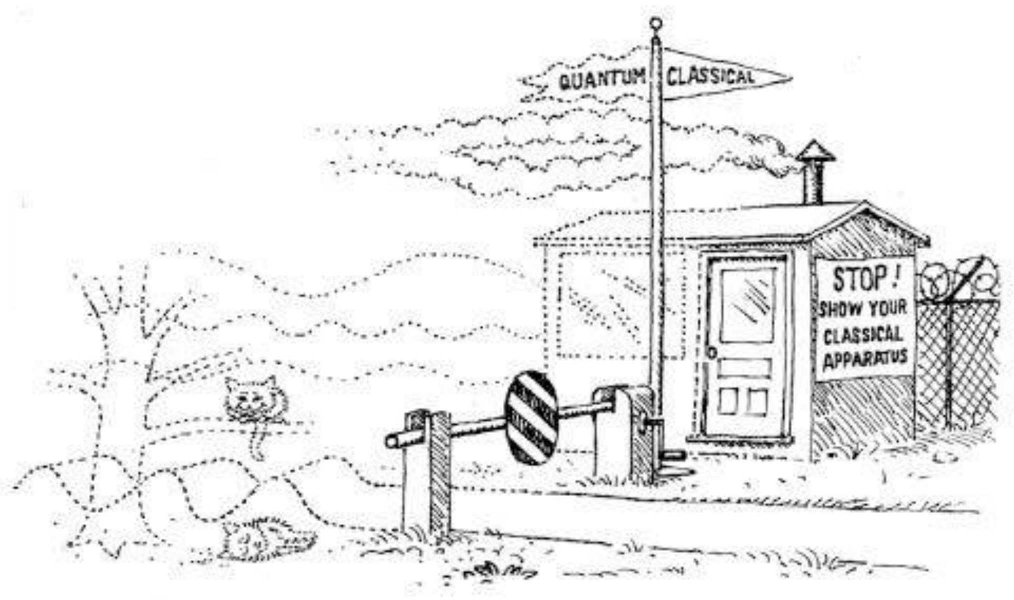
Quantum measurement: basic ingredients



- 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

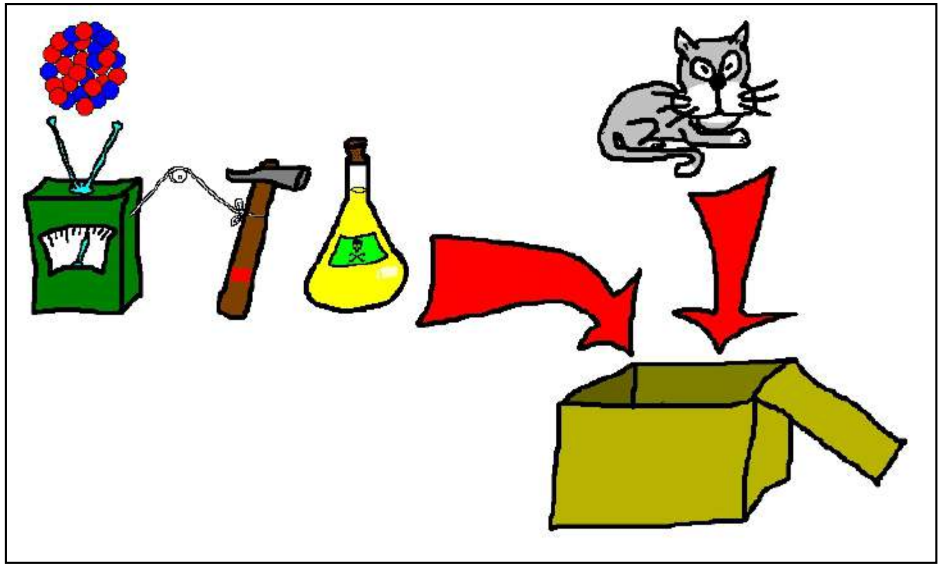
The border separation quantum and classical behavior



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)

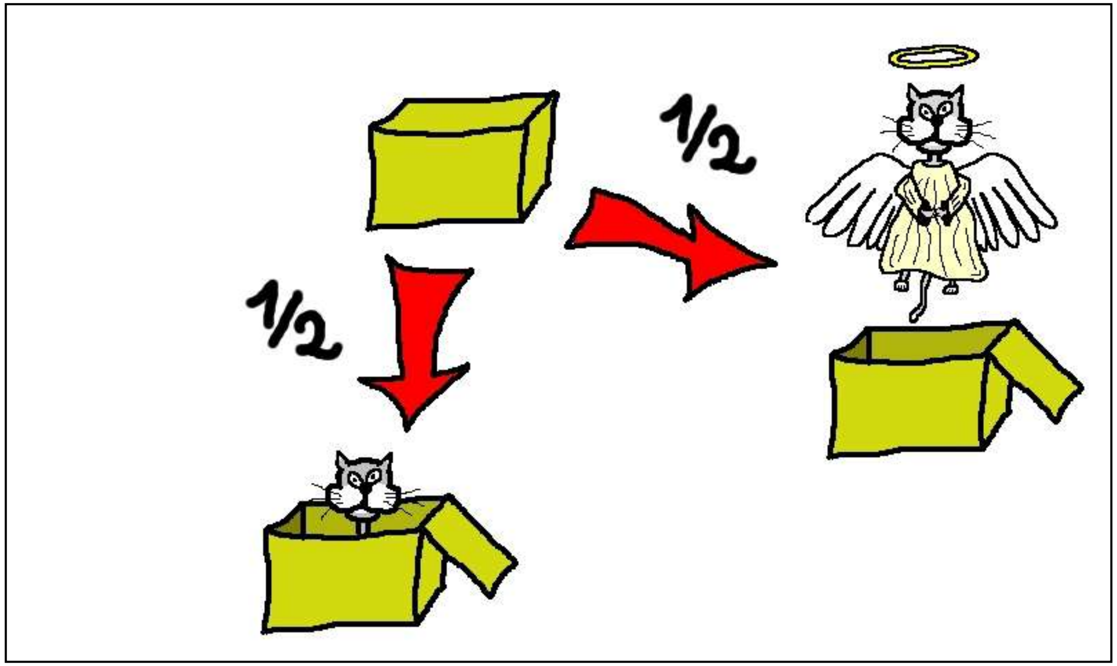
Quantum description of a meter: the "Schrödinger cat" problem



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

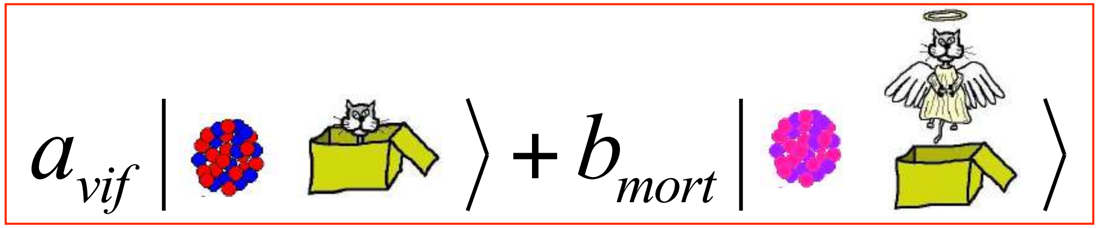
The "Schrödinger cat"

- 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?

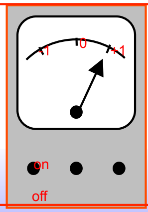
Schrödinger cat and quantum measurement

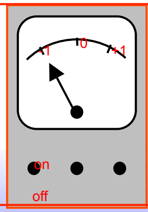


- Before opening the box, the system is isolated and unitary evolution prepares a maximally atom-meter entangled state
- Does this state "really" exists?

  → 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

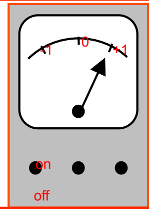
$$\frac{1}{\sqrt{2}}\left(|a\rangle + |b\rangle\right) \Rightarrow \frac{1}{\sqrt{2}}\left(|a,\right.$$


$$\rangle + |b,$$


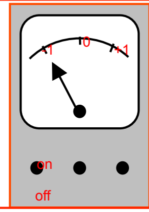
$$\left.\rangle\right)$$

Schrödinger cat and quantum measurement

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



$$\rangle + |g,$$



$$\left.\rangle\right)$$

- 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.

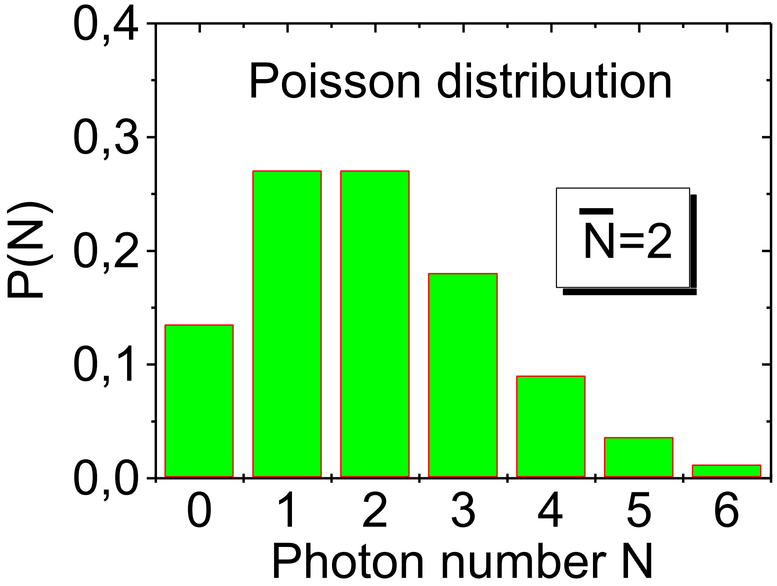
2. A mesoscopic field as atomic state measurement aparatus

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

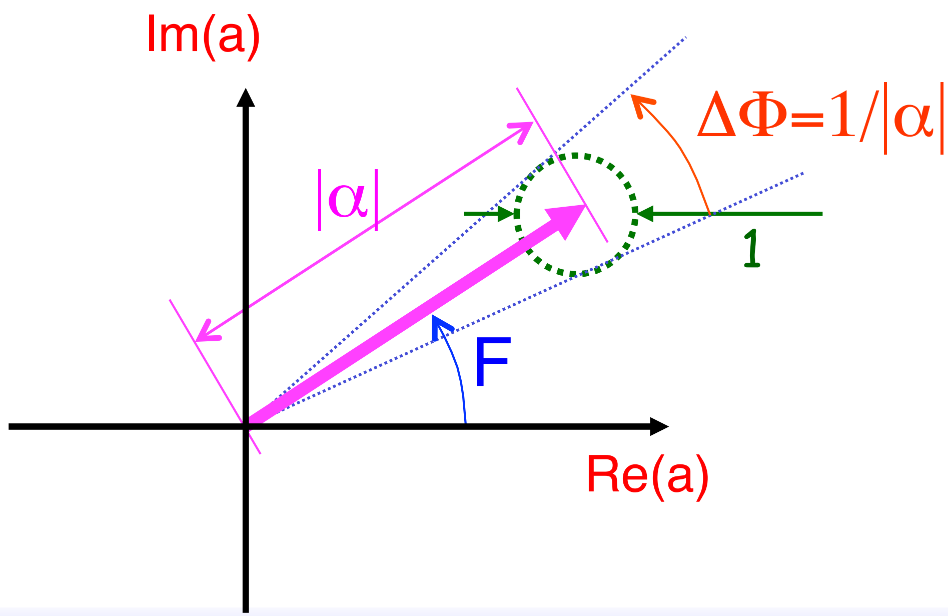
$$P(N) = e^{-\bar{N}} \frac{\bar{N}^N}{N!} \quad ; \quad \bar{N} = |\alpha|^2$$



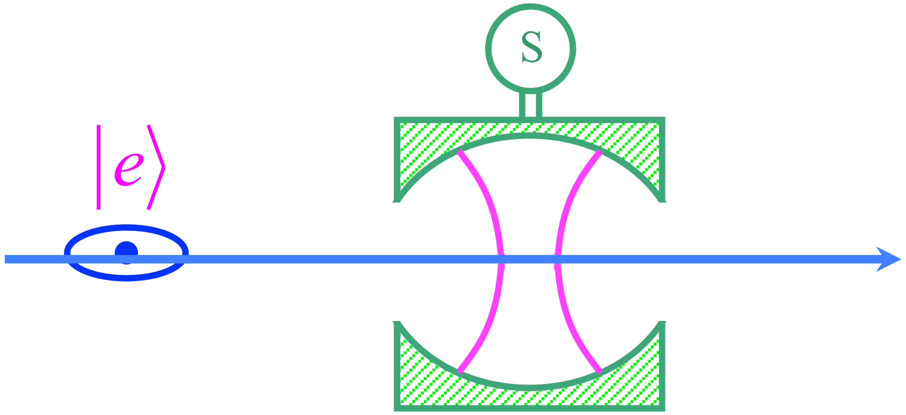
$\Delta N = 1/|\alpha|$

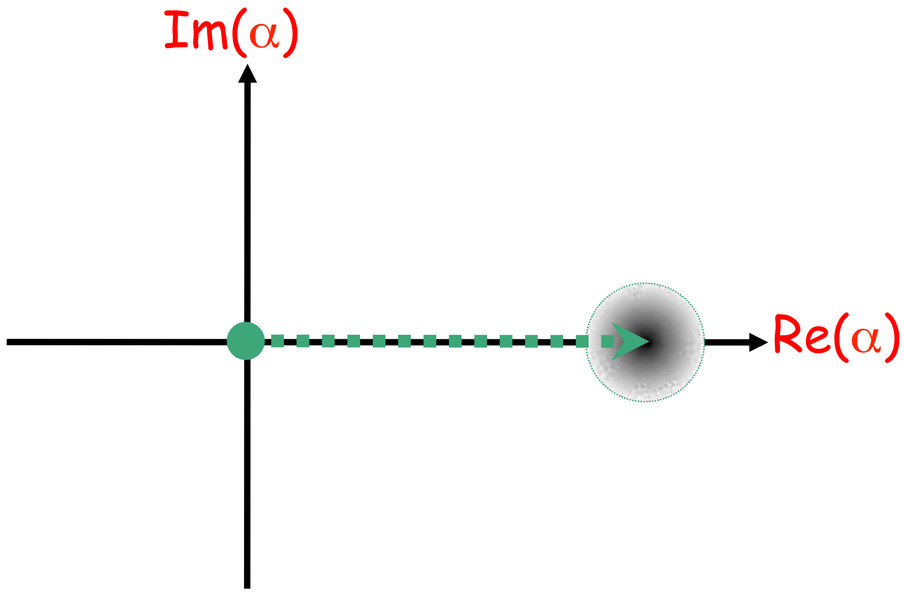
• Phase space representation

$\Delta N \,.\, \Delta\Phi > 1$



QND detection of atoms using non-resonant interaction with a coherent field





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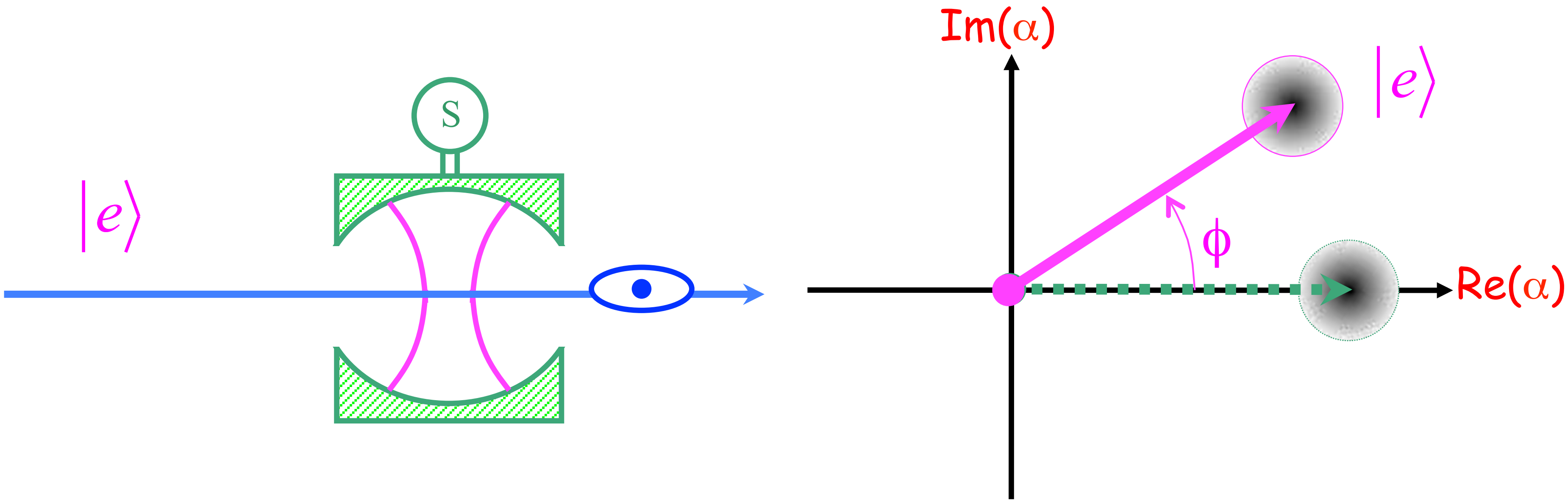
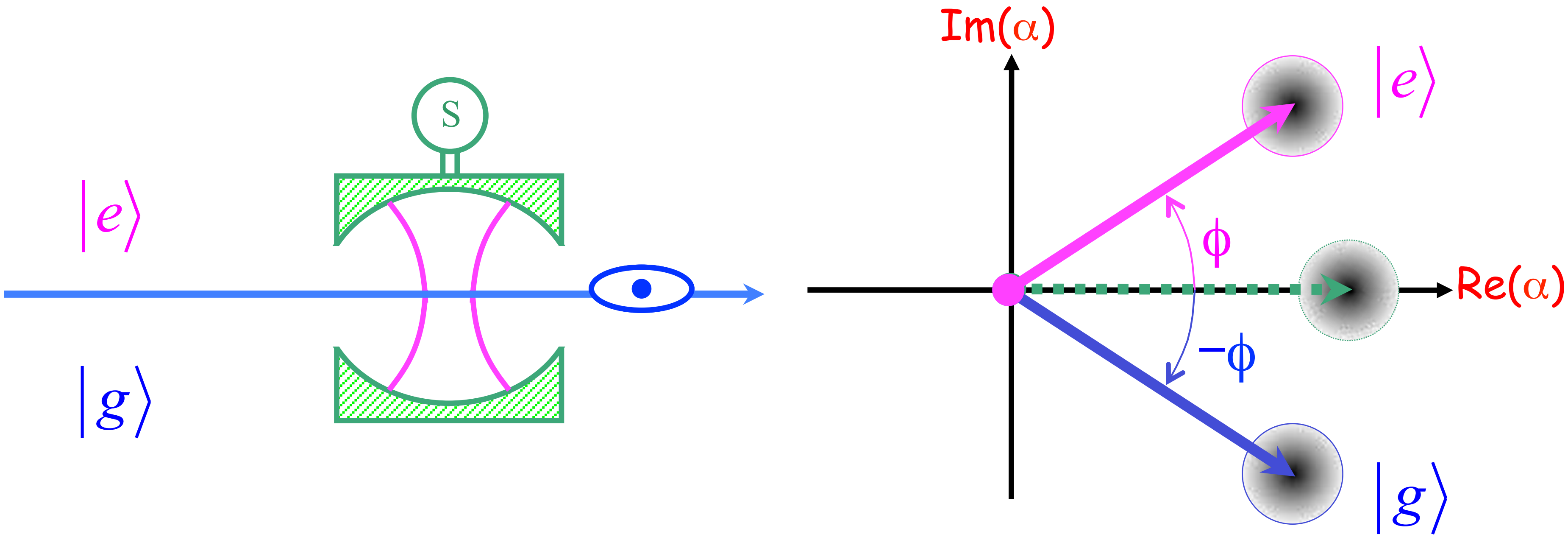


$$|e\rangle \otimes |\alpha\rangle \rightarrow |e\rangle \otimes \left|\alpha . e^{i\Phi_0}\right\rangle$$

QND detection of atoms using non-resonant interaction with a coherent field



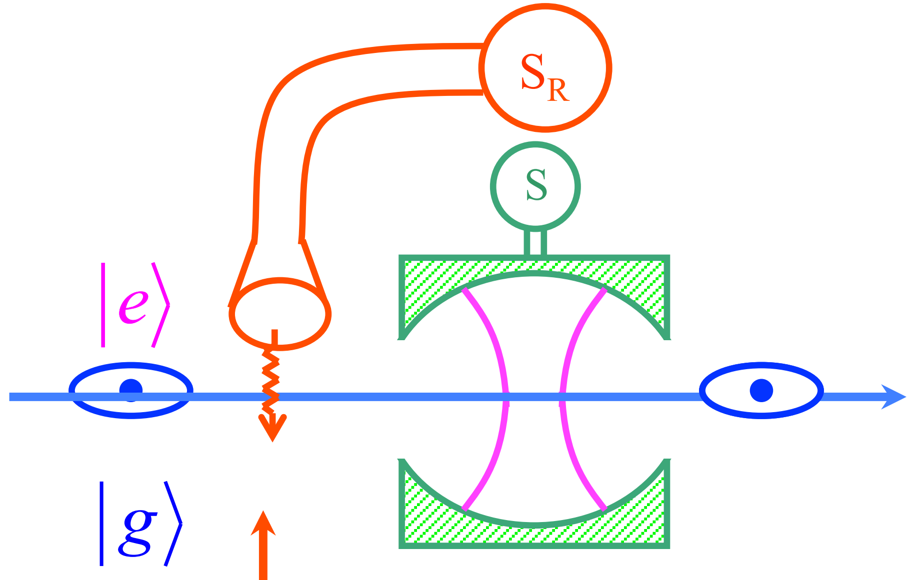
$$|e\rangle \otimes |\alpha\rangle \rightarrow |e\rangle \otimes |\alpha . e^{i\Phi_0}\rangle$$

$$|g\rangle \otimes |\alpha\rangle \rightarrow |g\rangle \otimes |\alpha . e^{-i\Phi_0}\rangle$$

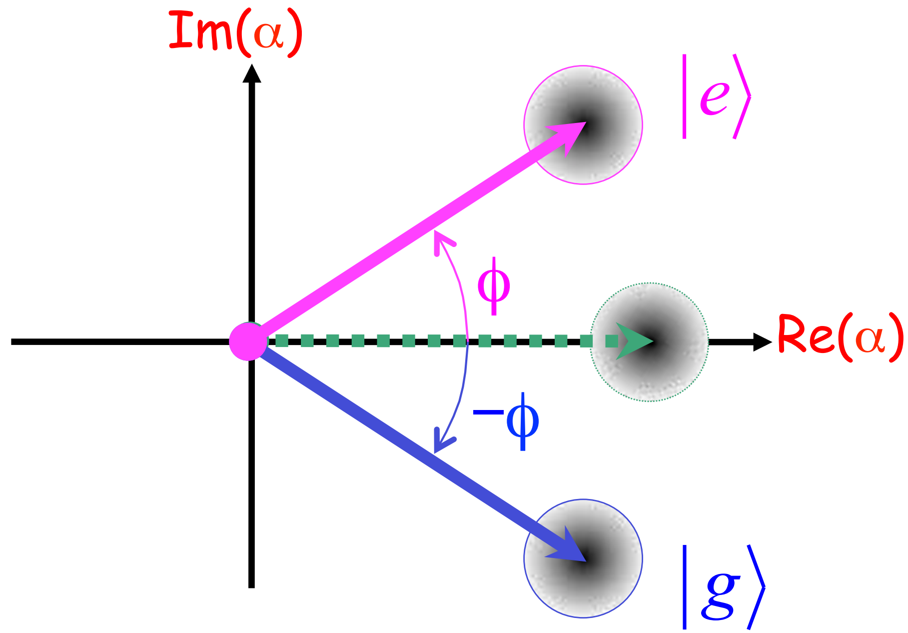
a single atom controls the phase of the field

➙The field phase "points" on the atomic state

QND detection of atoms using non-resonant interaction with a coherent field



π/2 pulse R_1



$$|e\rangle \otimes |\alpha\rangle \rightarrow |e\rangle \otimes |\alpha.e^{i\Phi_0}\rangle$$

$$|g\rangle \otimes |\alpha\rangle \rightarrow |g\rangle \otimes |\alpha.e^{-i\Phi_0}\rangle$$

a single atom controls the phase of the field

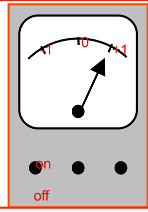
$$\frac{1}{\sqrt{2}}\left(|e\rangle + |g\rangle\right) \otimes |\alpha\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|e\rangle \otimes |\alpha.e^{i\Phi_0}\rangle + |g\rangle \otimes |\alpha.e^{-i\Phi_0}\rangle\right)$$

→ The field phase "points" on the atomic state

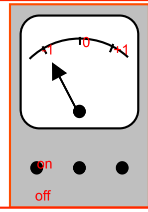
Atom-meter entanglement

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

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



$$\Big\rangle+\Big|g,$$



$$\Big\rangle\Big)$$

This is a "Schrödinger cat state"

Let us now consider the effect of coupling of the cavity to the “environment”

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:

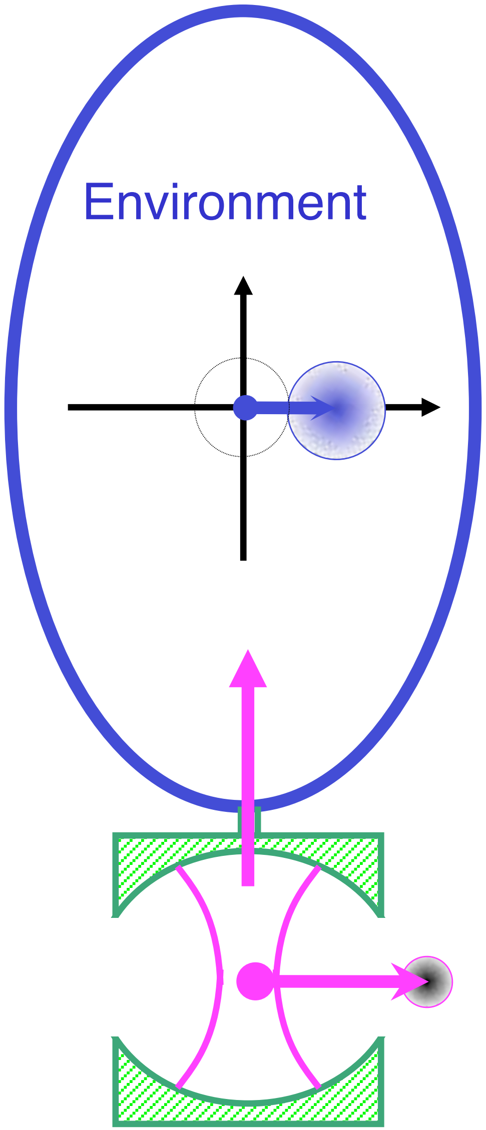
$$\frac{d\rho^{field}}{dt} = -\frac{1}{2T_{cav}}\left[a^{+}a,\rho^{field}\right]_{+} + \frac{1}{T_{cav}}a\rho^{field}a^{+}$$

master equation of the field density matrix

- Physical result: decoherence

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

The origin of decoherence: entanglement with the environment



- Decay of a coherent field:

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

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

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

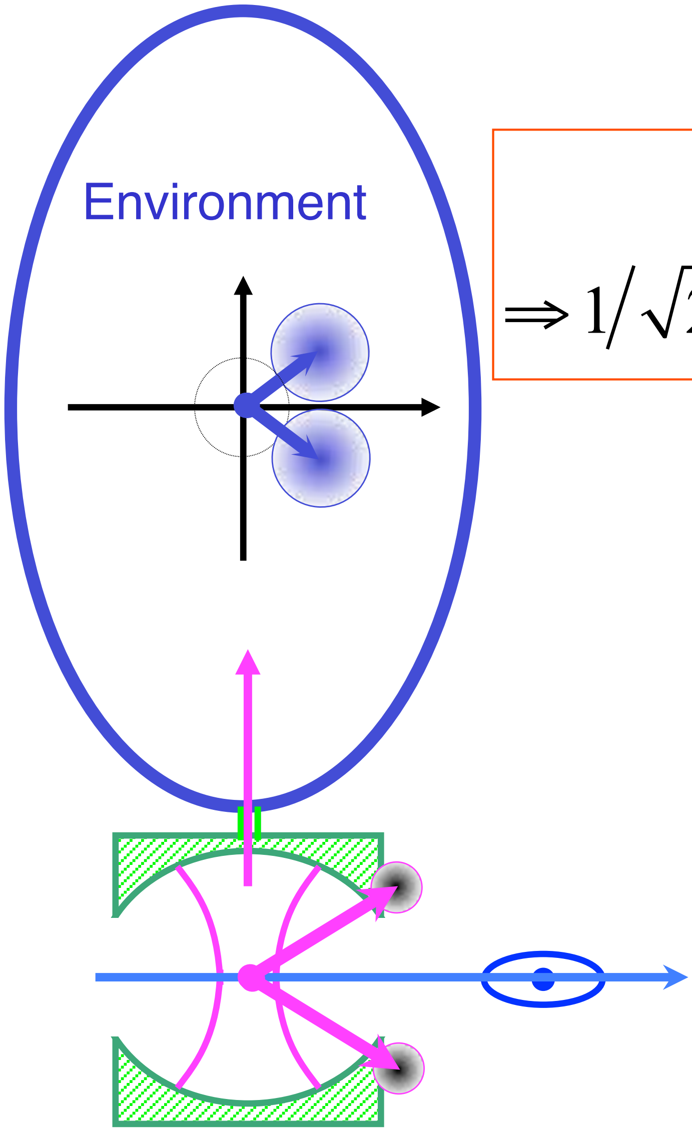
That is a property defining coherent states: coherent state are the only one which do not get entangled while decaying

The origin of decoherence: entanglement with the environment

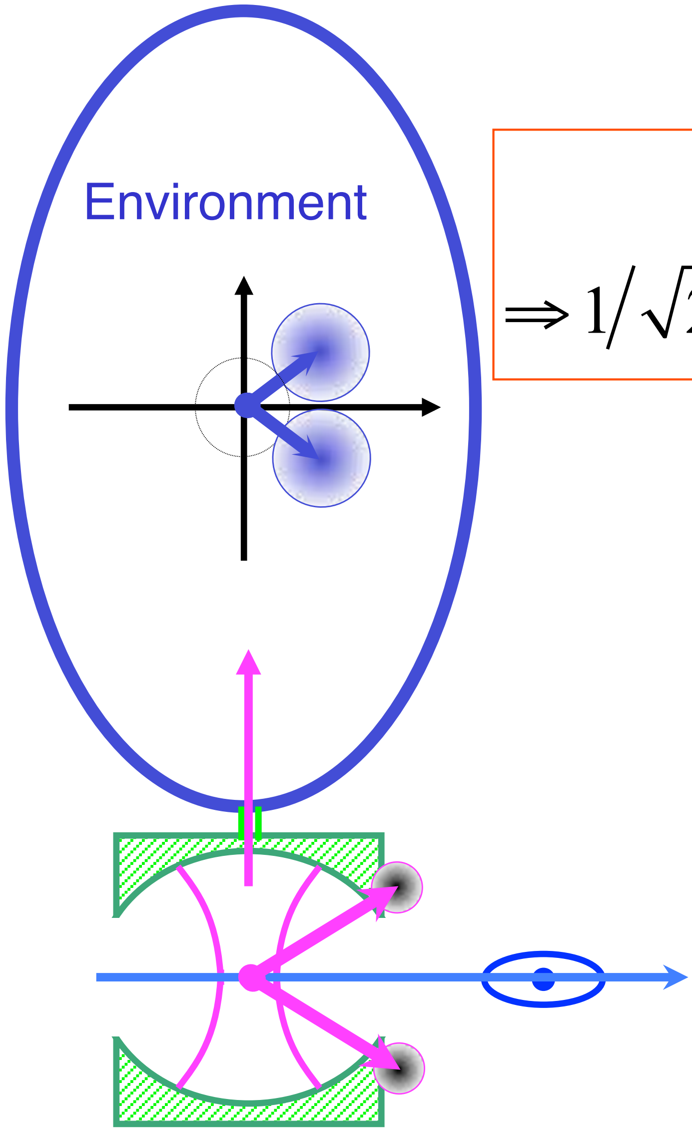
- Decay of a "cat" state:

$$|\Psi_{cat}\rangle \otimes |vacuum\rangle_{env}$$

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



The origin of decoherence: entanglement with the environment



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$$\left|\Psi_{cat}\right\rangle \otimes \left|vacuum\right\rangle_{env}$$

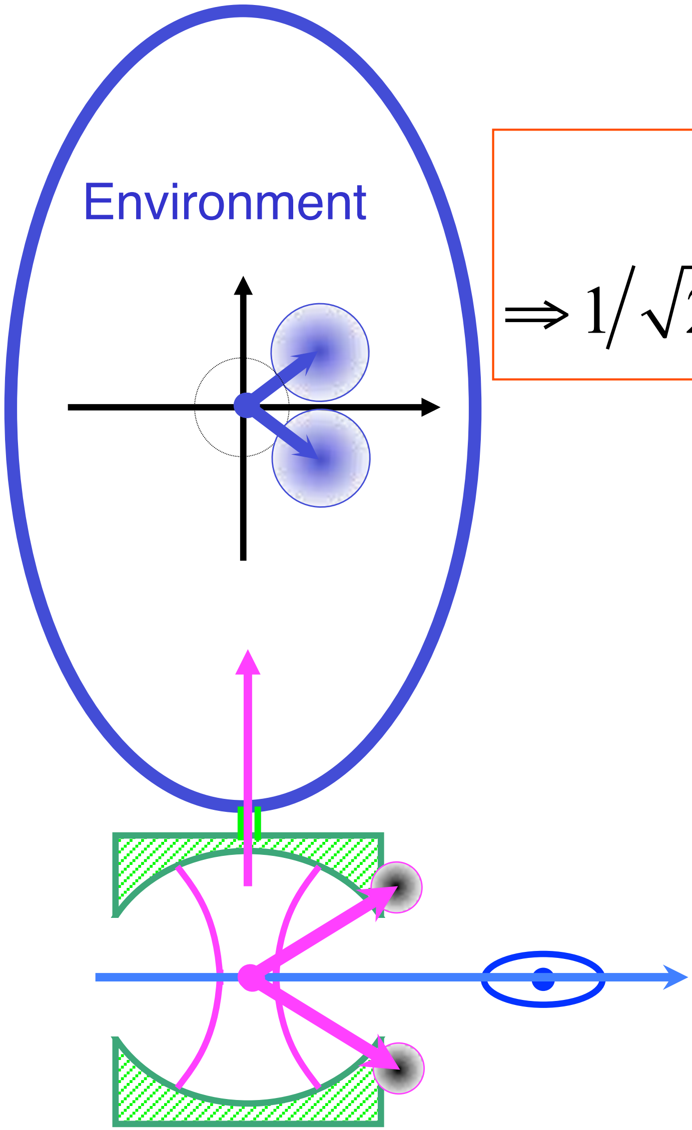
$$\Rightarrow 1/\sqrt{2}\left(\left|\alpha_{+}(t)\right\rangle \otimes \left|\beta_{+}(t)\right\rangle_{env} + \left|\alpha_{-}(t)\right\rangle \otimes \left|\beta_{-}(t)\right\rangle_{env}\right)$$

- cavity-environment entanglement: the leaking field "broadcasts" phase information
- trace over the environment

⇒ decoherence (=diagonal field reduced density matrix) as soon as:

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

The origin of decoherence: entanglement with the environment



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

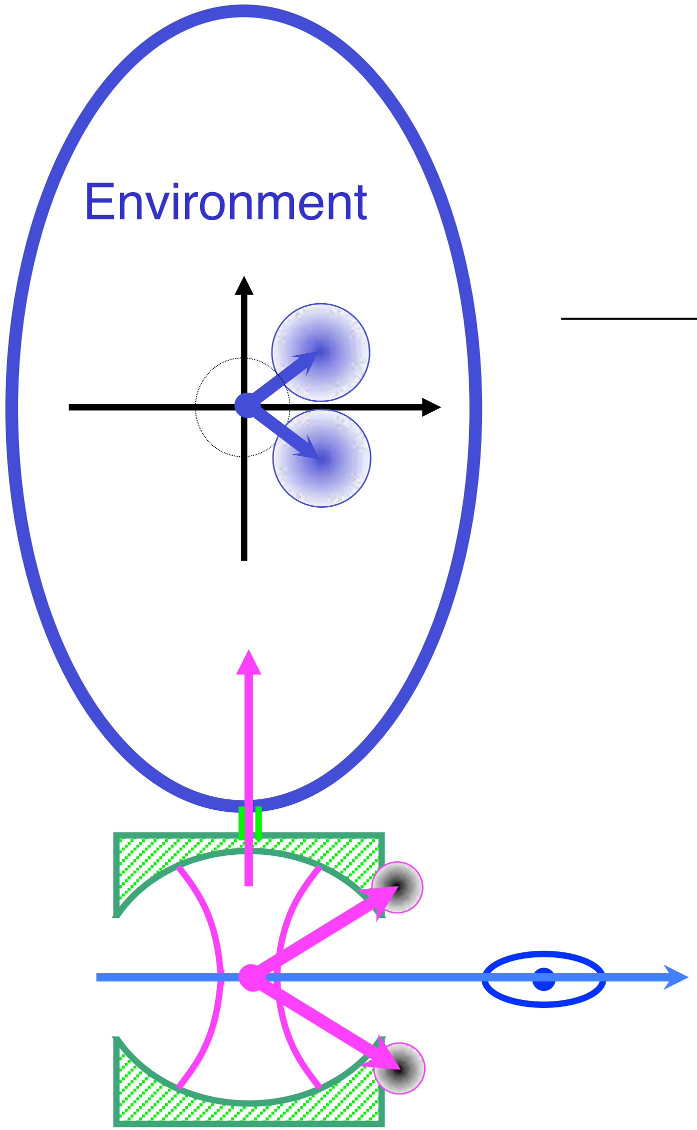
$$\left|\alpha(t)\right|^2 + \left|\beta(t)\right|^2 = \left|\alpha_0\right|^2$$

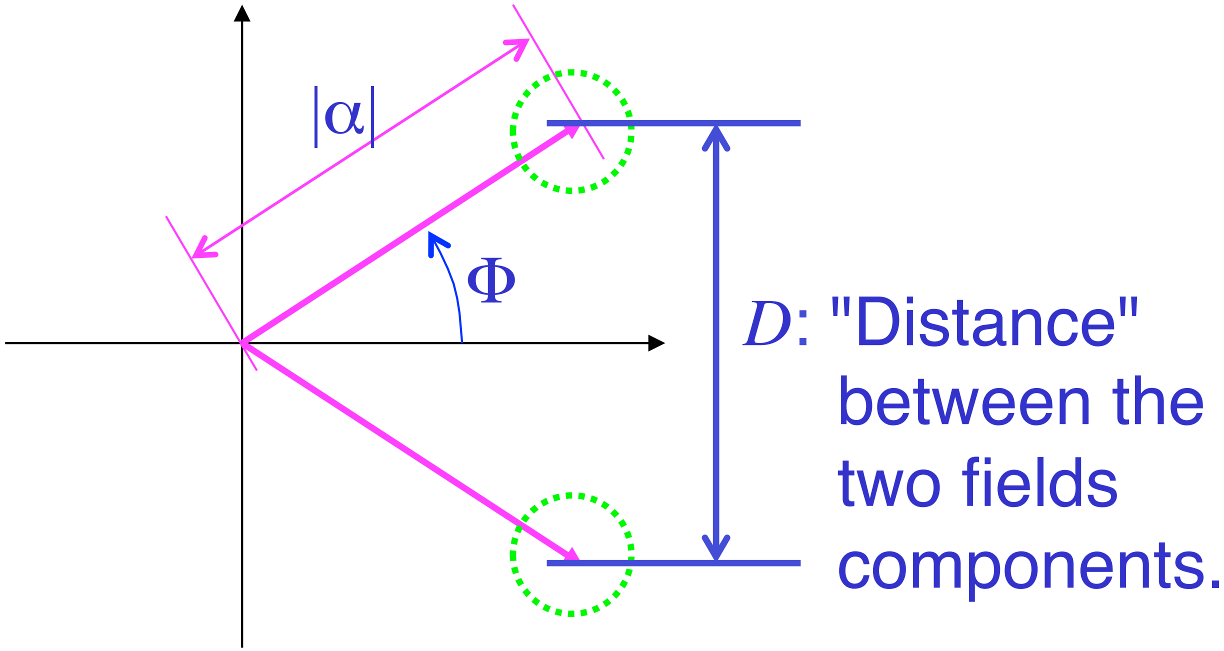
$$\Rightarrow \left|\beta(t)\right|^2 = \left|\alpha_0\right|^2\left(1-e^{-t/T_{cav}}\right) \approx \left|\alpha_0\right|^2 .t/T_{cav}$$

The two states of the environment become orthogonal as soon as

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

The decoherence time





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

Infinitely short decoherence time for macroscopic fields

→ The Schrödinger cat does not exist for "long" time

Detailed calculation in
PHYSICA SCRIPTA T78, 29 (1998)

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 solves "the measurement problem"?

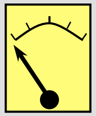
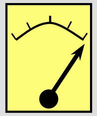
No: if the problem consists in telling how or why nature chooses randomly one classical state.

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:

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

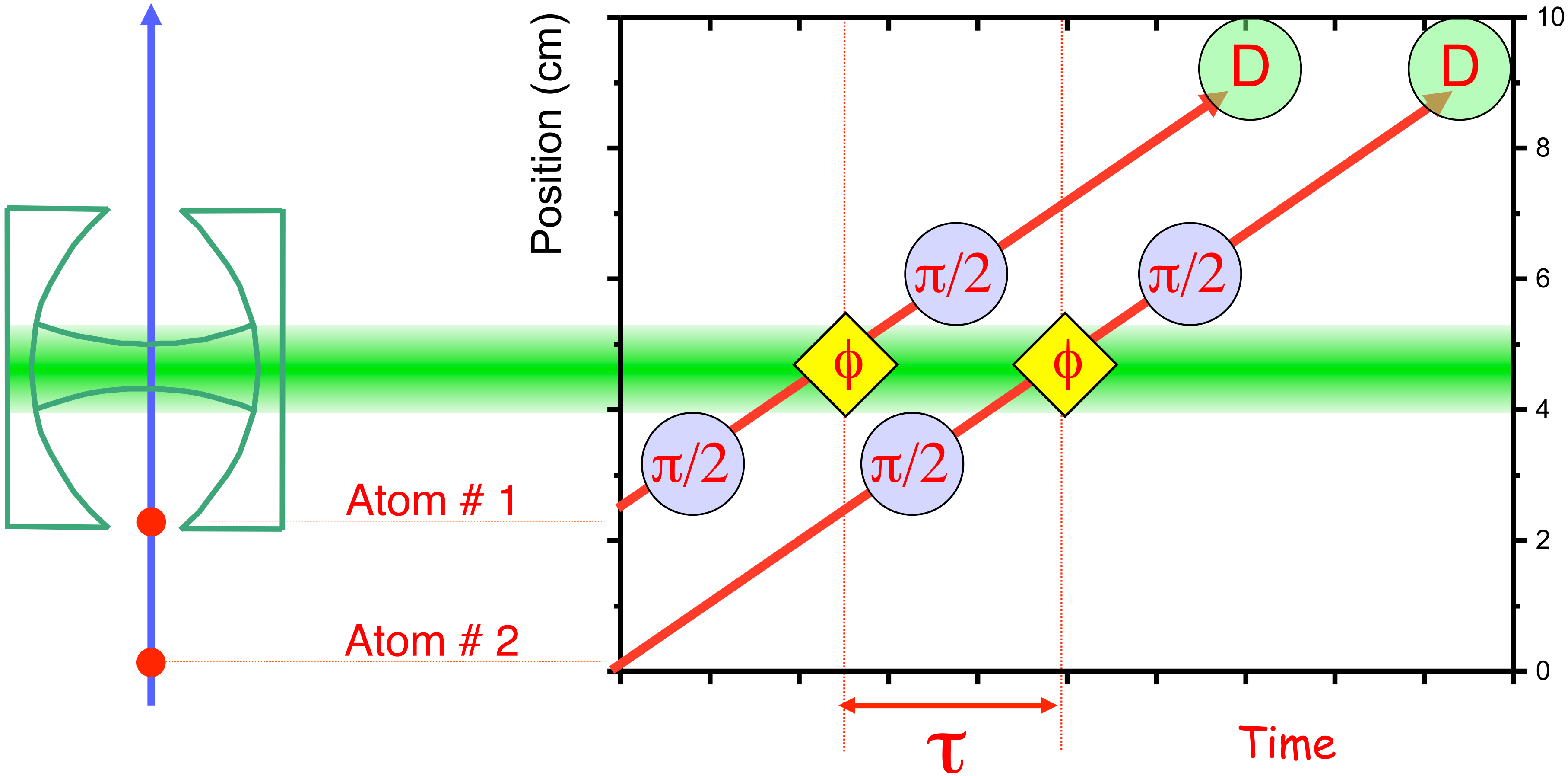
$$\rho_{dec} = \begin{pmatrix} P_e & 0 \\ 0 & P_g \end{pmatrix}$$

⇒ 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.

3. Observing decoherence experimentally

Probing the coherence of the cat state

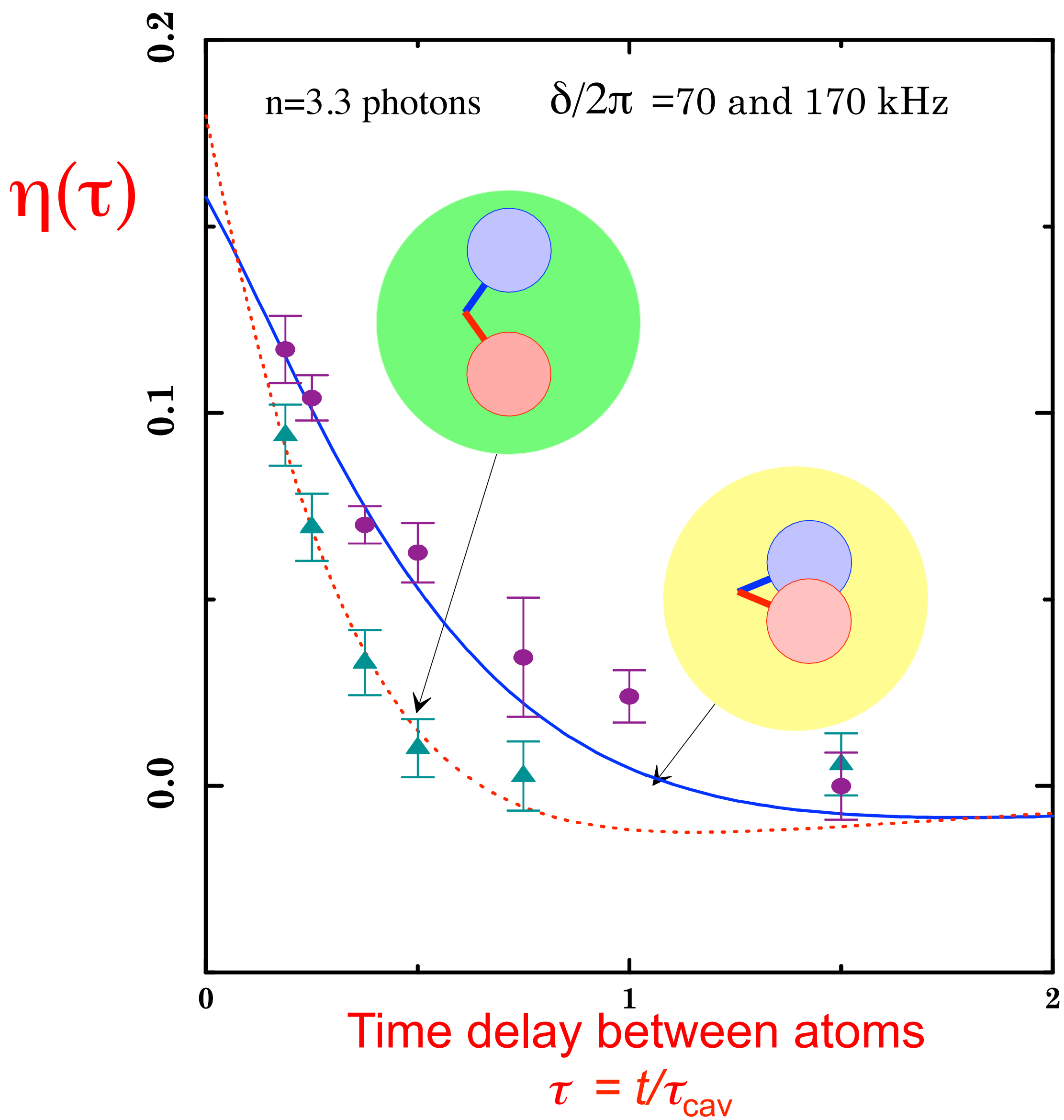


- Non resonant phase shift in C

"cat" state coherence

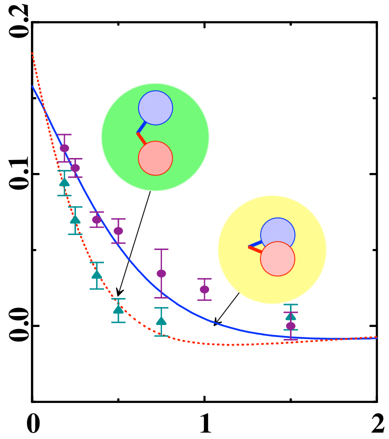
Interference term in two atom correlation

Decoherence signal



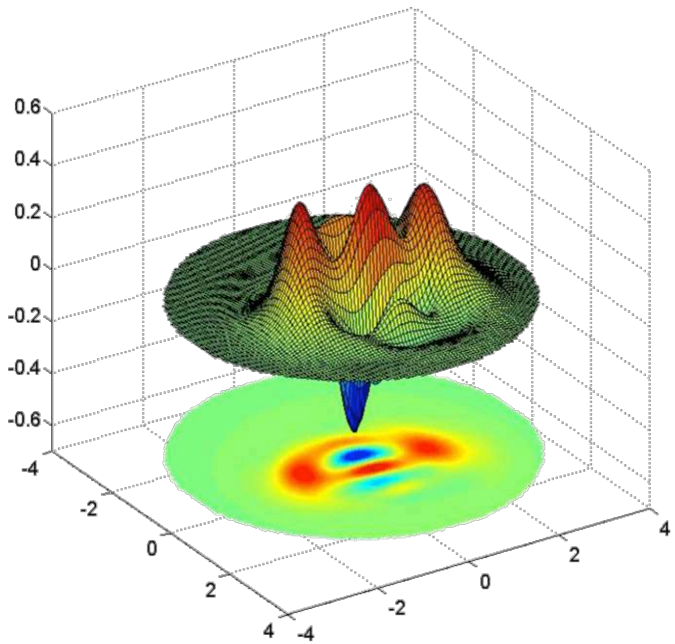
Brune et al. Phys. Rev. Lett. 77, 4887 (1996)

4. Full tomography of the field state

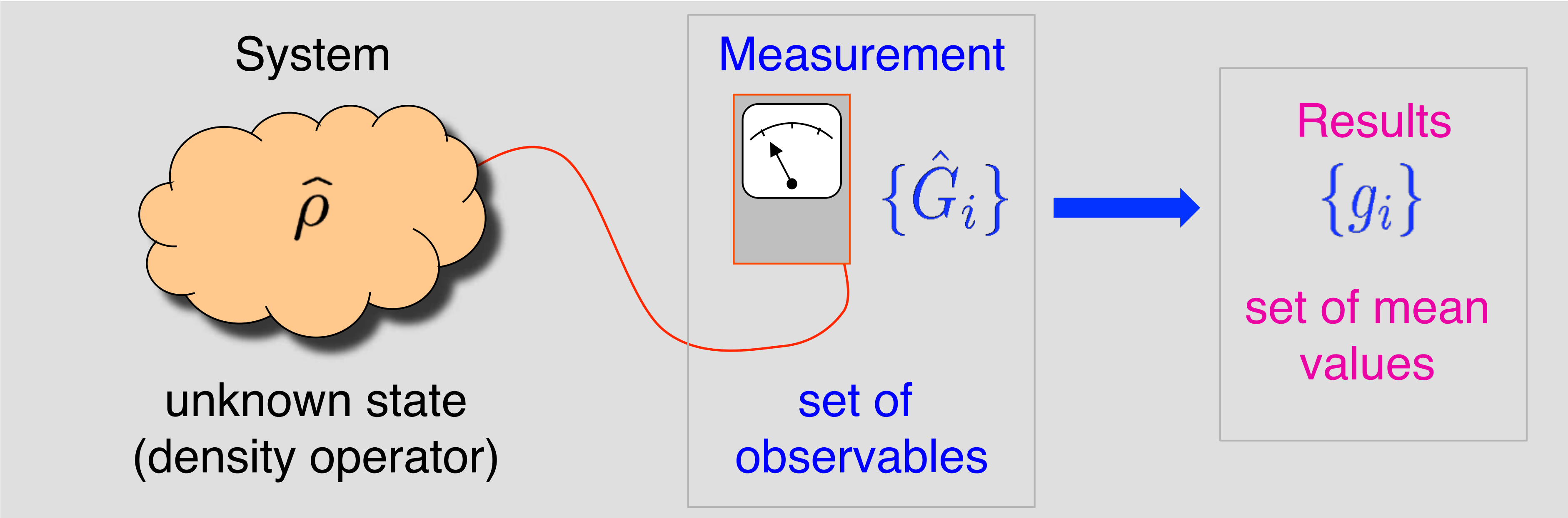


This correlation signal is a very partial information on the field state

One can reconstruct the full density matrix of the cavity field



Principle of stet reconstruction



→ Each measurement sets a constrain to the density operator

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

Problems to face:

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

Measuring the field density operator?

General field state description: density operator

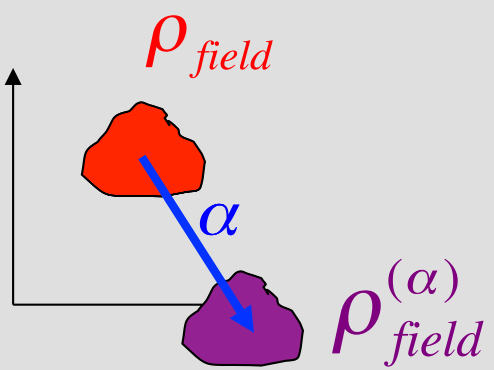
$$\rho_{field} = \begin{bmatrix} \rho_{00} & \rho_{01} & \rho_{02} & . \\ \rho_{10} & \rho_{11} & \rho_{12} & . \\ \rho_{20} & \rho_{21} & \rho_{22} & . \\ . & . & . & . \end{bmatrix}$$

- Previous lectures:

QND counting of photons

$\Rightarrow$ measurement of diagonal elements ρ_{nn}

$\Rightarrow$How to measure the off-diagonal elements of ρ_{field} ?



$\Rightarrow$ 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 $|\psi_{field}\rangle$

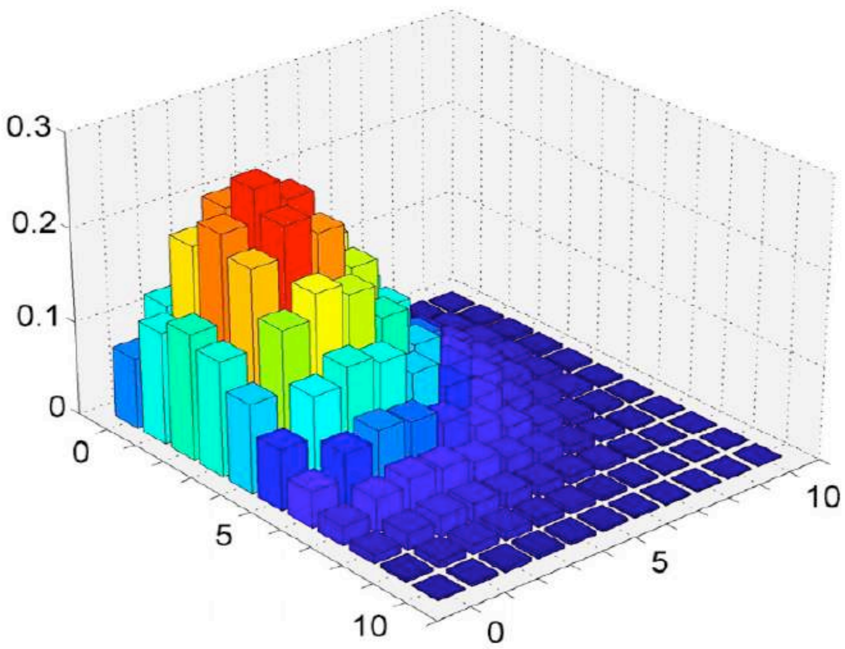
2- measure $\hat{G}(\alpha)$ for a large number of different values of α (400 to 600 points).

3- reconstruct ρ_{field} by maximum entropy method

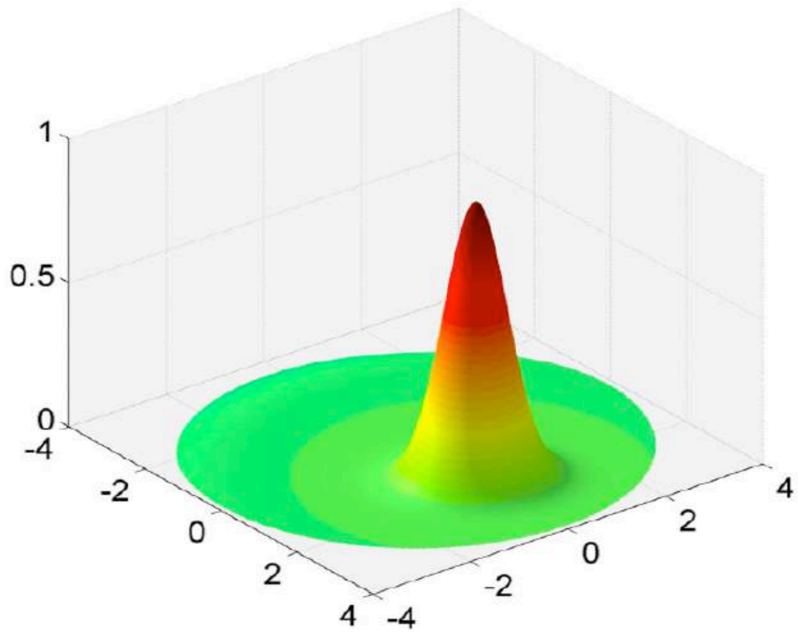
4- calculate Wigner function from ρ_{field}.

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



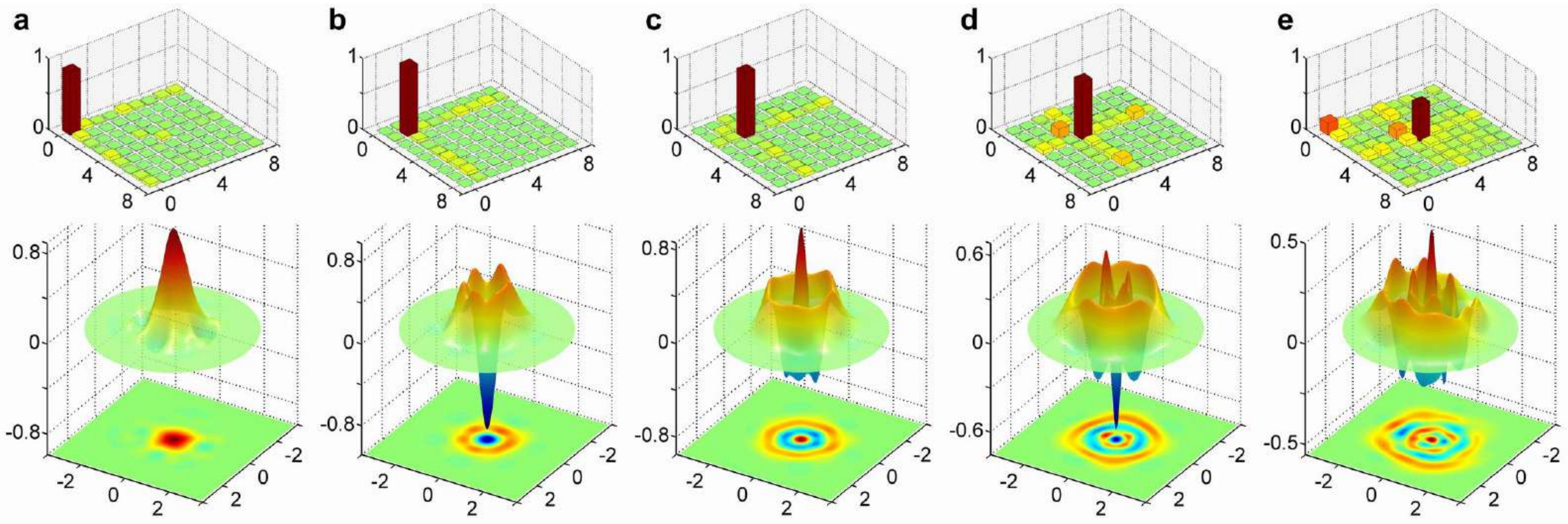
Wigner function (measurement)

- 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

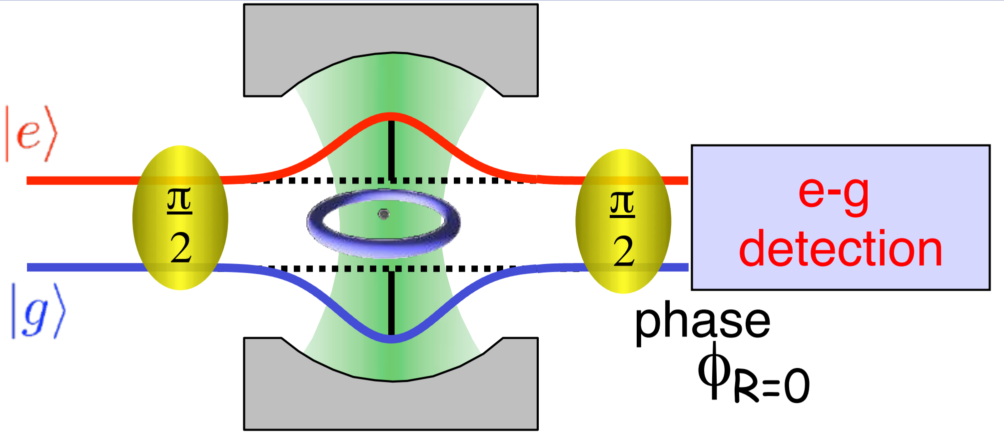
5. Schrödinger cat states reconstruction

- state preparation
- a movie of decoherence

Preparation of the cavity cat state

Phase shift per photon

Φ_0

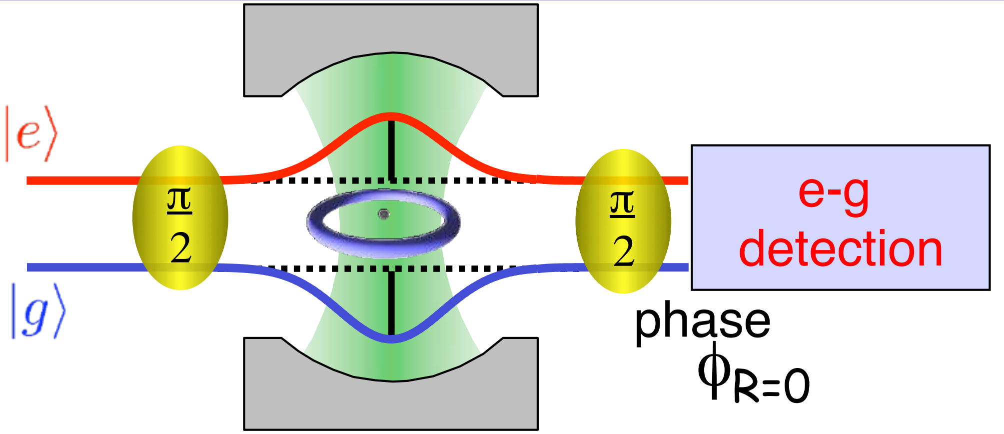


$$\frac{1}{\sqrt{2}}\left(|e\rangle+|g\rangle\right)\otimes|\alpha\rangle \;\Rightarrow\; \frac{1}{\sqrt{2}}\left(|e\rangle\otimes\left|\alpha.e^{i\Phi_0/2}\right\rangle+|g\rangle\otimes\left|\alpha.e^{-i\Phi_0/2}\right\rangle\right)$$

Preparation of the cavity cat state

Phase shift per photon

Φ_0



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

- Field state after detection:

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

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

$$\Phi_0 = \pi$$

e → even cat state

g → odd cat state

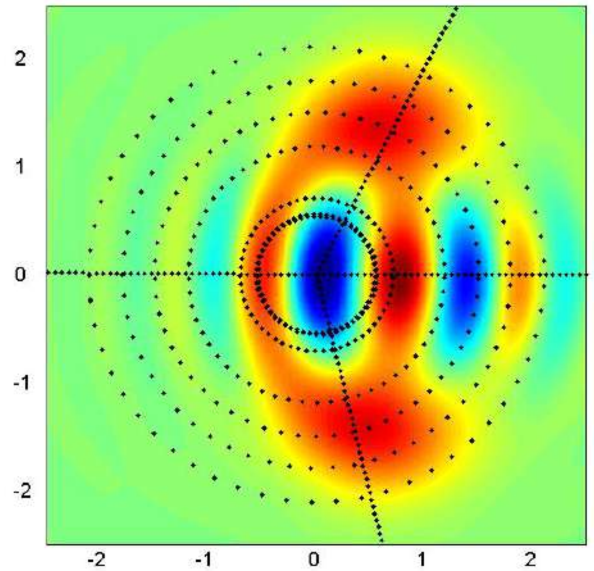
Depending on the detected atomic state the cat has a well defined photon number parity.

For π per photon phase shift, one atom measures just the field parity.

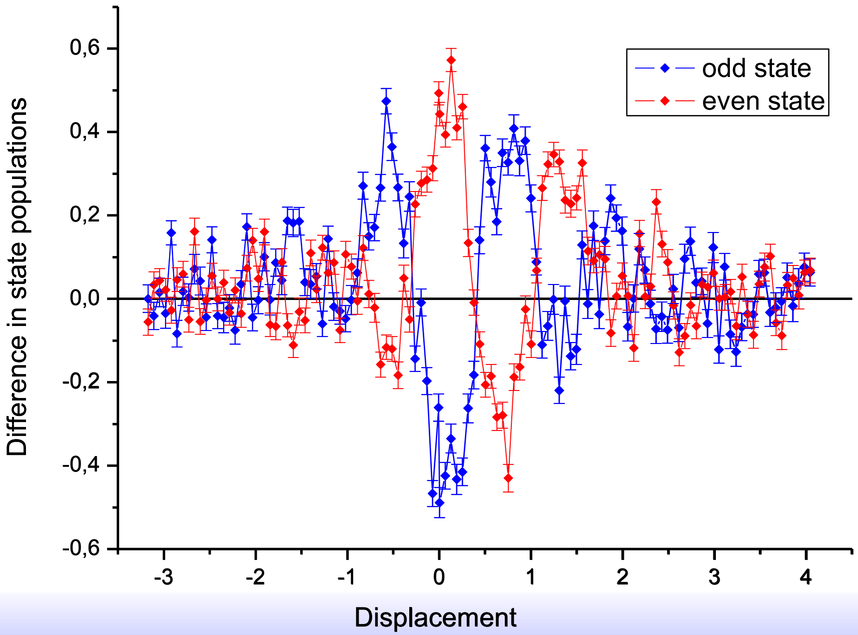
Projection on a cat state is the "back-action" of parity measurement.

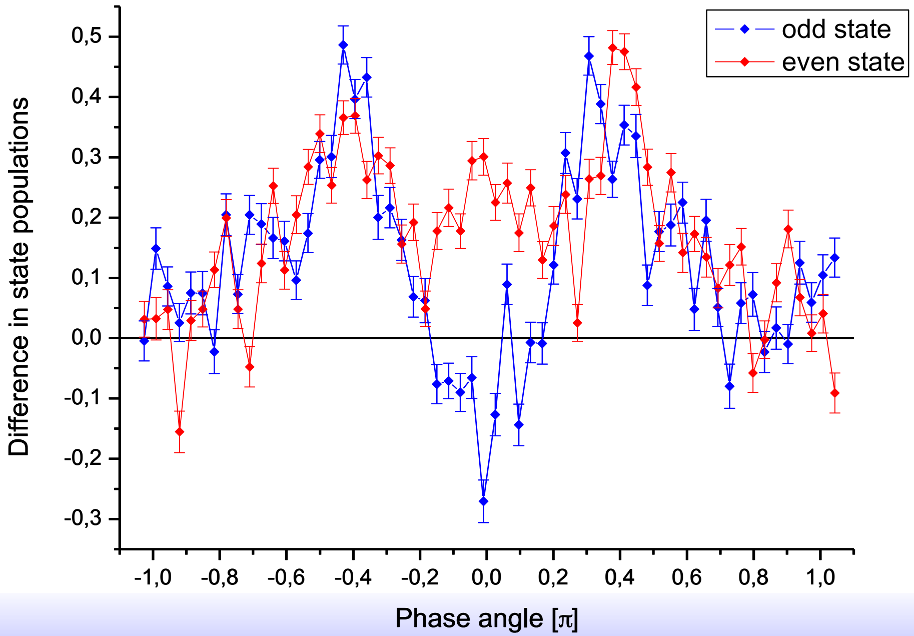
Measured raw data

- We perform measurements at about 600 points in the phase space (about 10 scans)
- ≈ 100 state preparations for each point
- ≈ 12 probe atoms for each state preparation



measured raw data

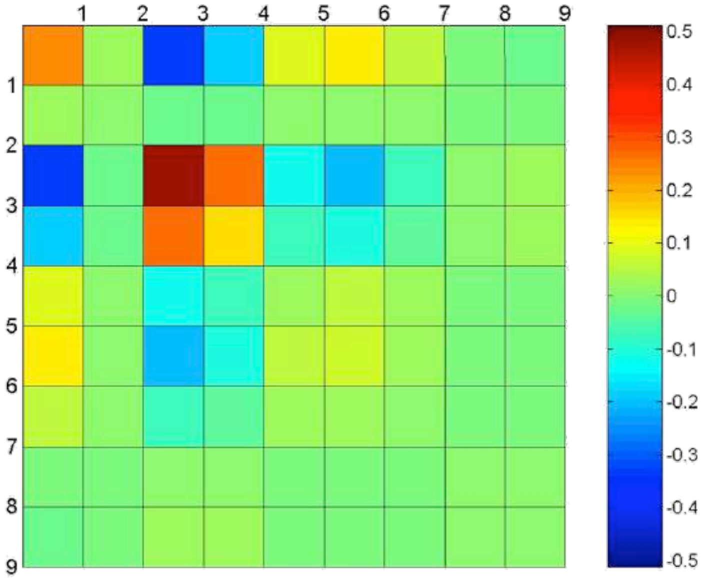




Reconstructed density matrix (real part)

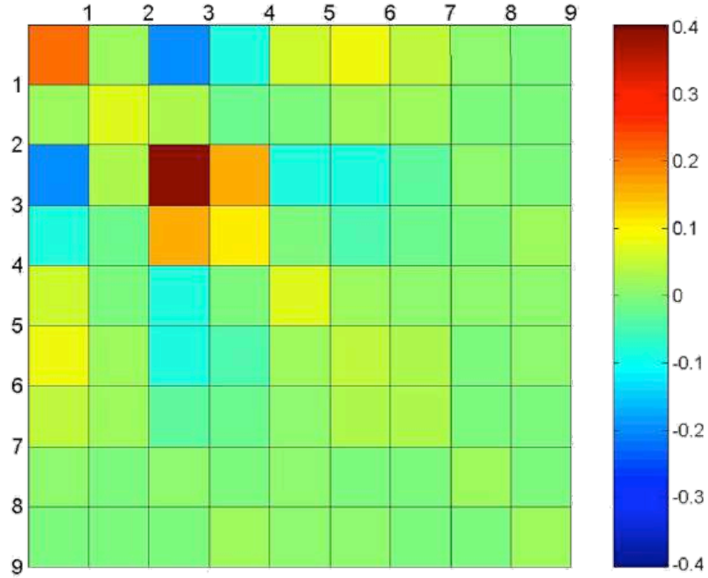
Even (odd) cat has even (odd) photon number statistics

expectation
(even cat)



($\bar{n}_{inj} \approx 2.1$ photons)

reconstruction
(even cat)



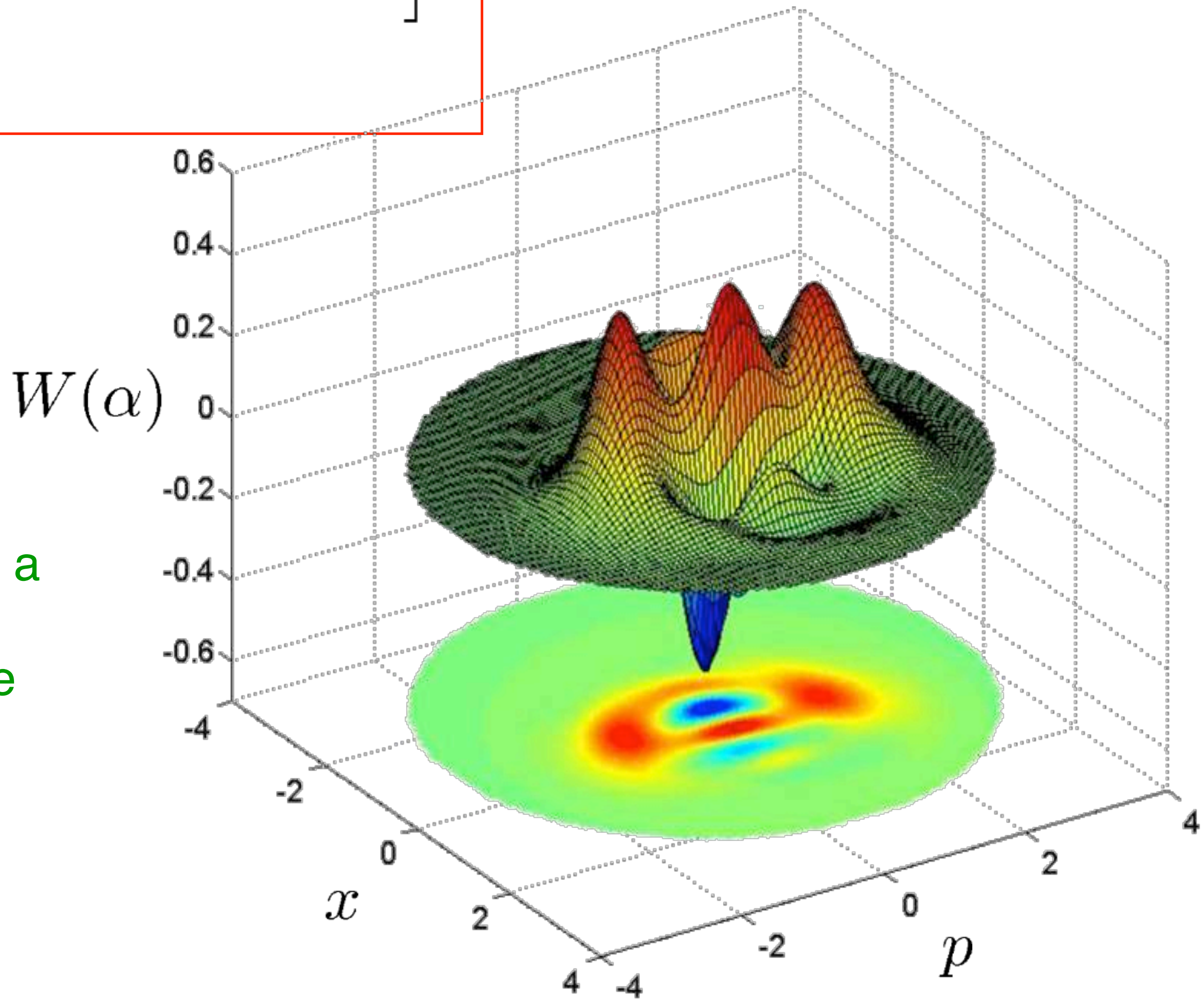
($\langle n \rangle = 2.2$ photons)

Fidelity of the preparation and reconstruction - 66%
(71% for the odd state)

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)

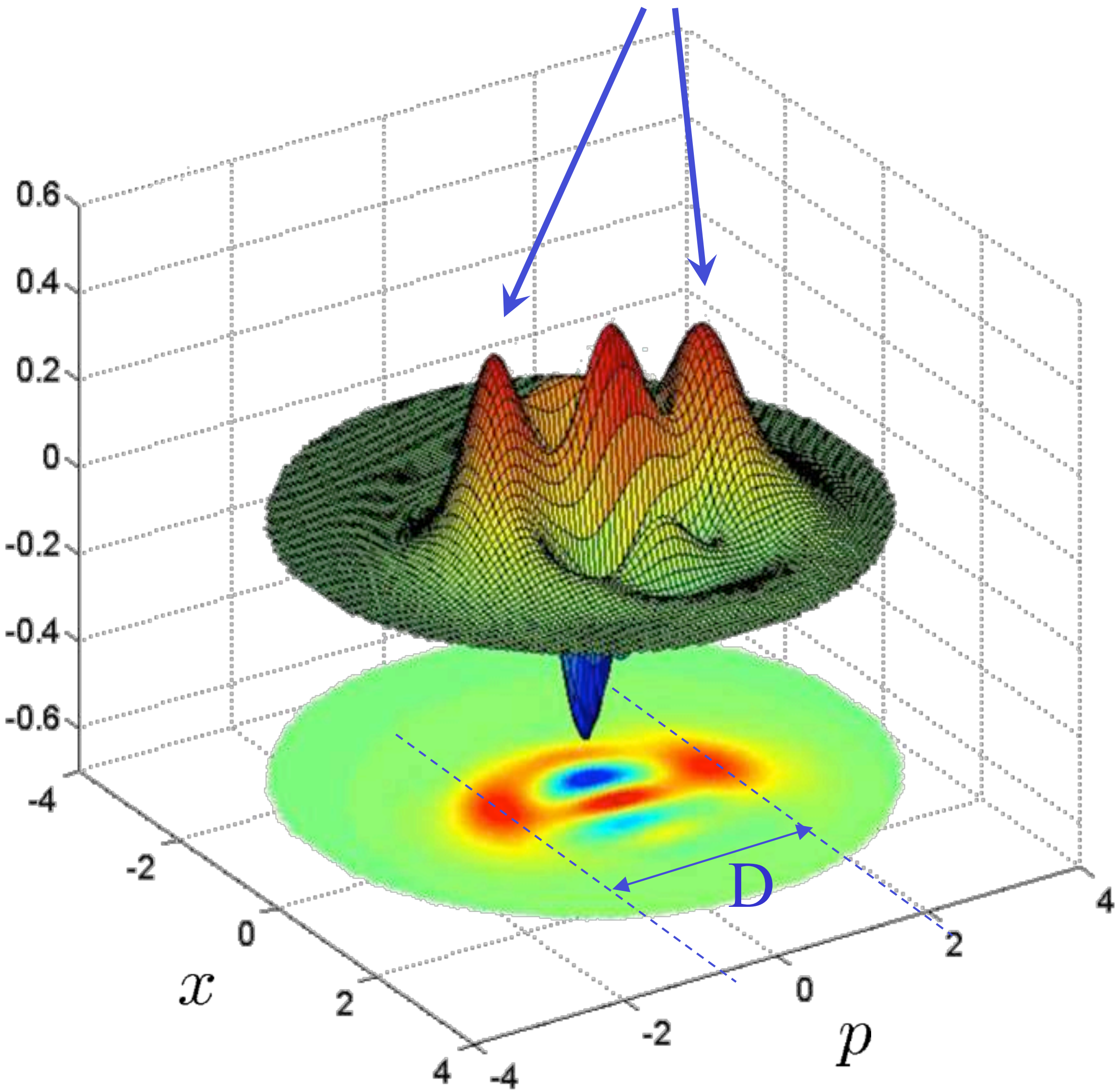
Reconstructed Wigner function

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

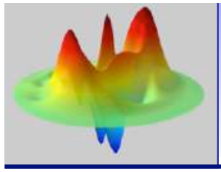
cat size $D^2 \approx 7.5$ photons

coherent components are completely separated
(D > 1)

Classical components



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

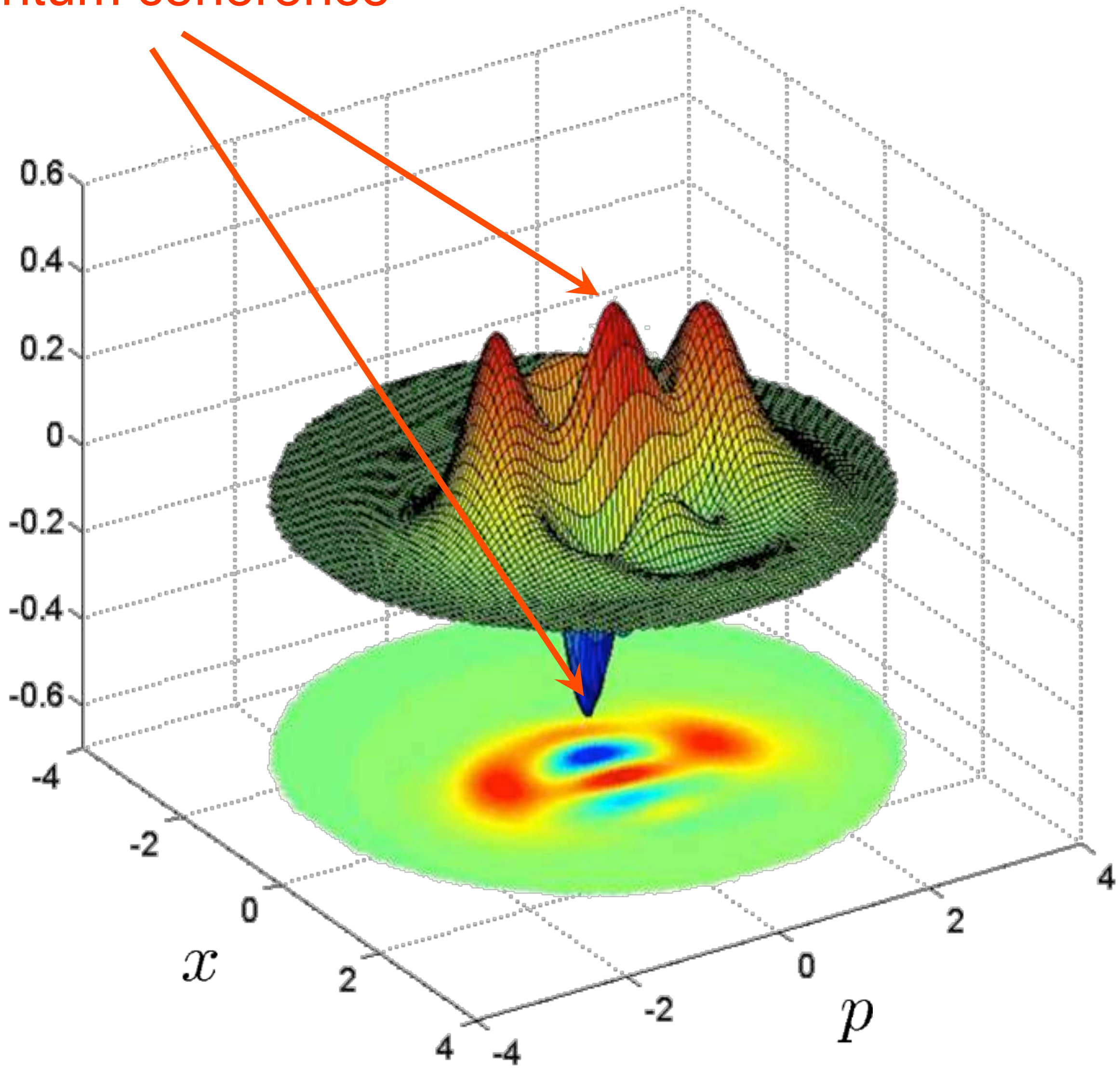


Reconstructed Wigner function

Quantum coherence

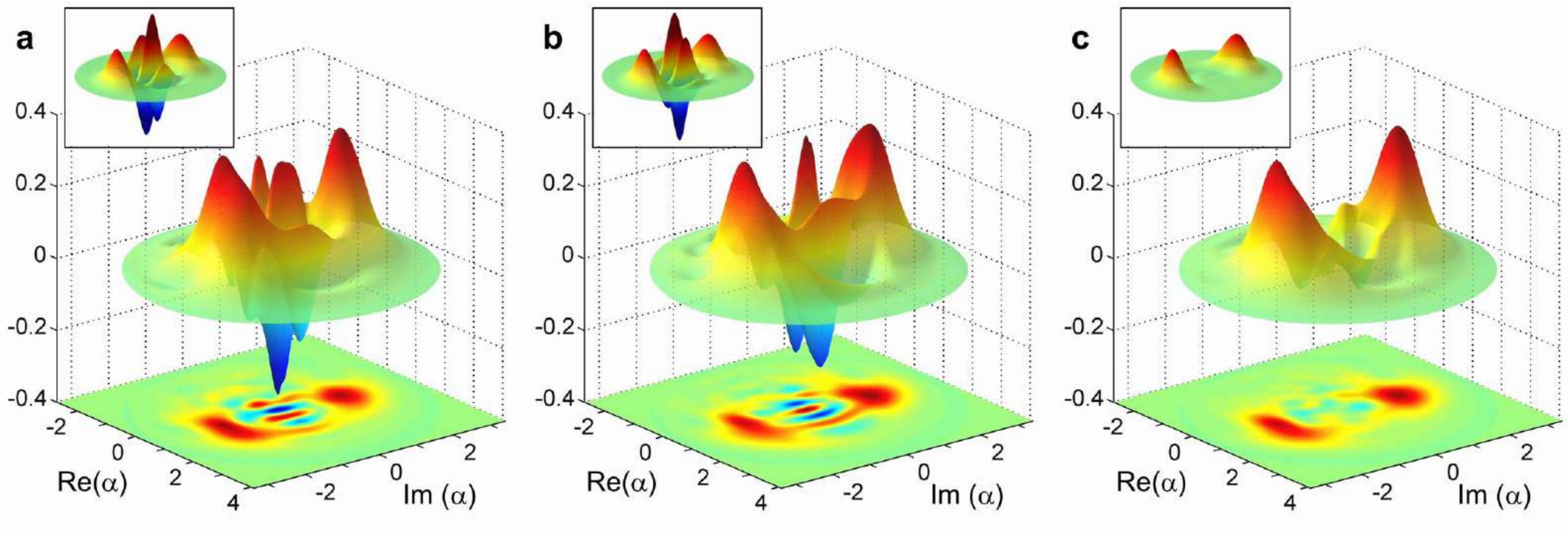
quantum superposition of two classical fields *(interference fringes)*

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



A larger cat for observing decoherence

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



Even cat

Odd cat

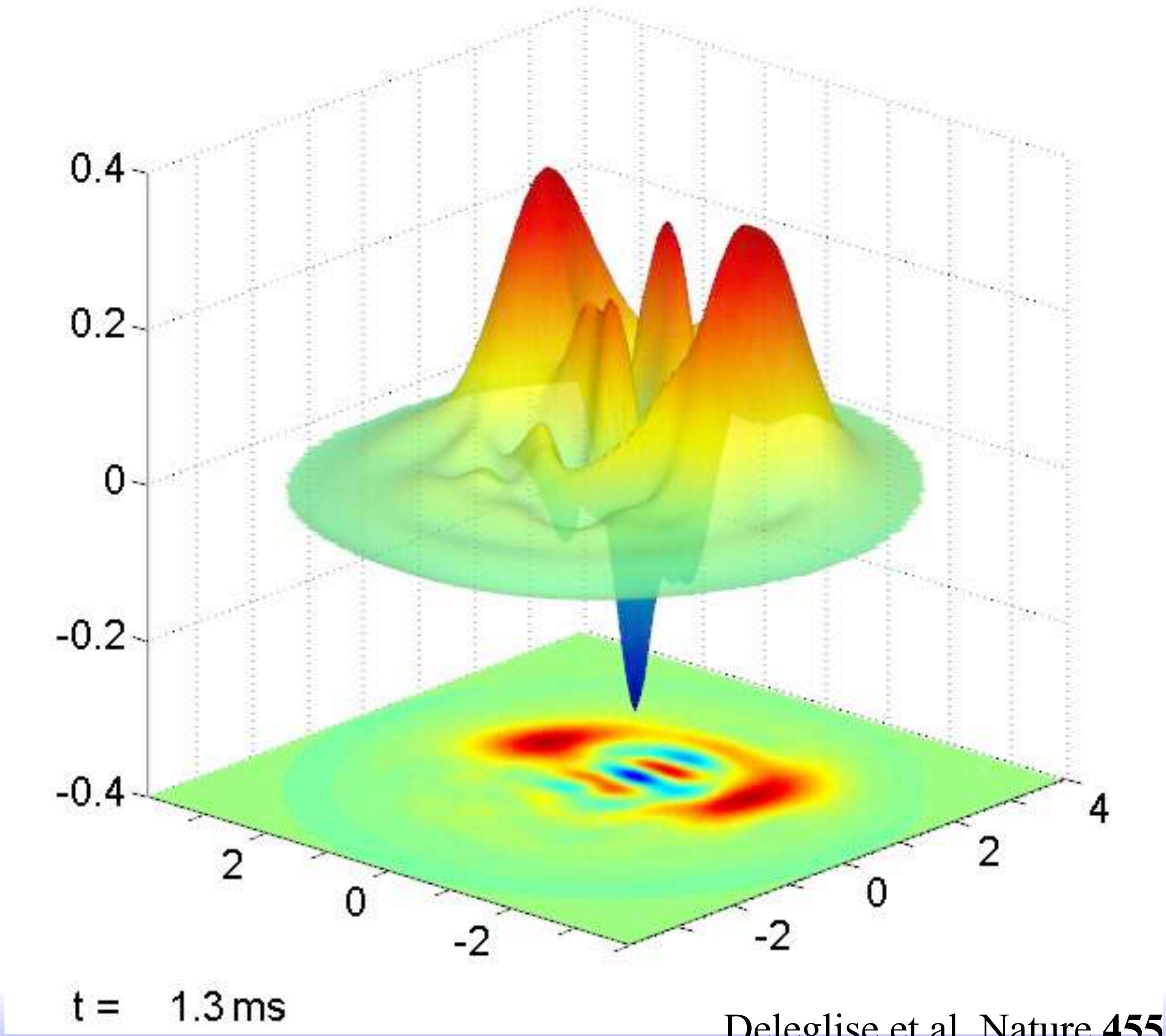
Sum of two WF:
Statistical mixture

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

$F = 0.72$

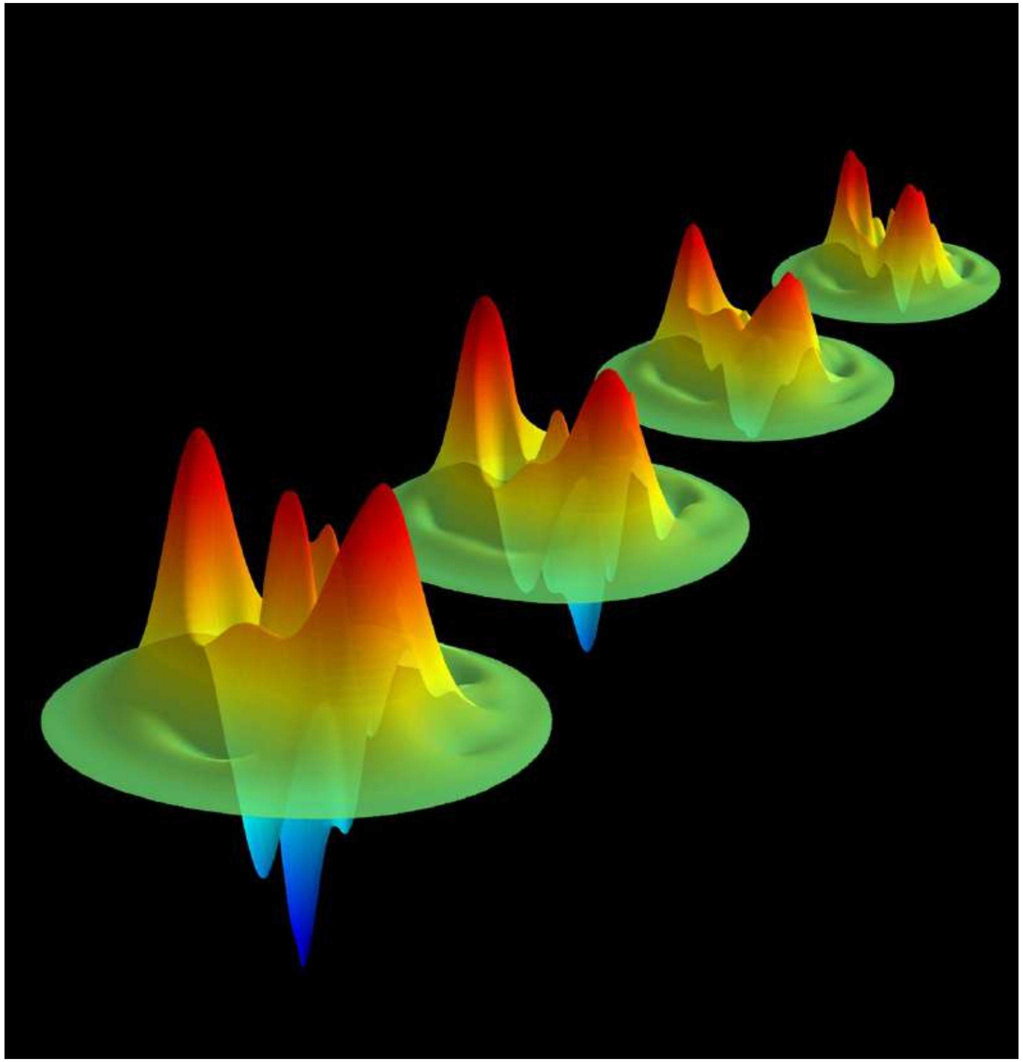
Deleglise et al. Nature **455**, 510 (2008)

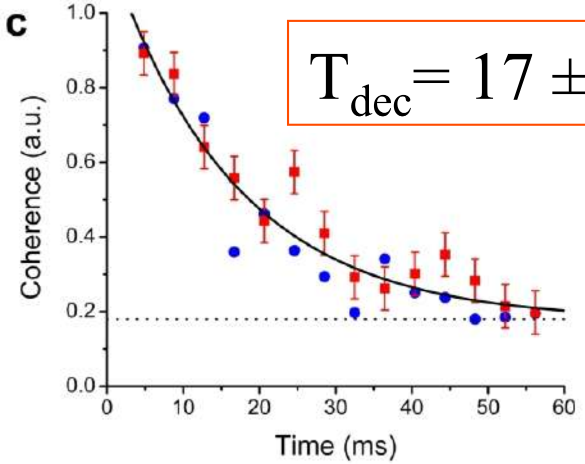
Movie of decoherence



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

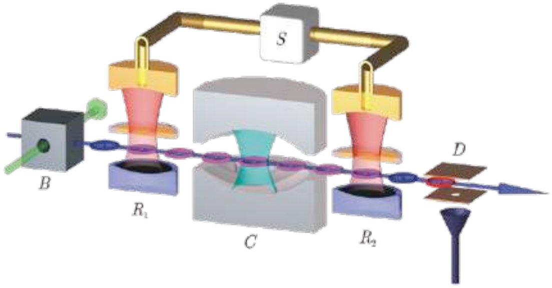
+ small blackbody contribution @ 0.8 K

T_{dec}= 19.5 ms

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

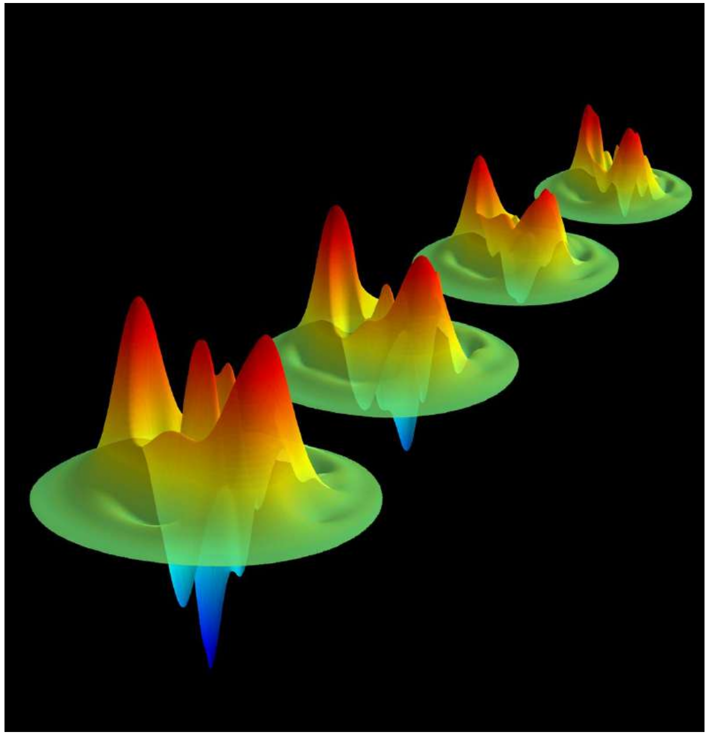
Summary

- Generation of cat states in a cavity

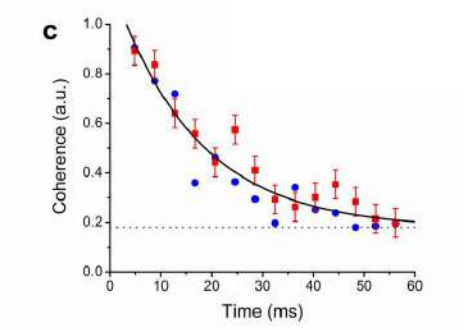


- State measurement (QND) and reconstruction (MaxEnt)

- Wigner function of the cat states

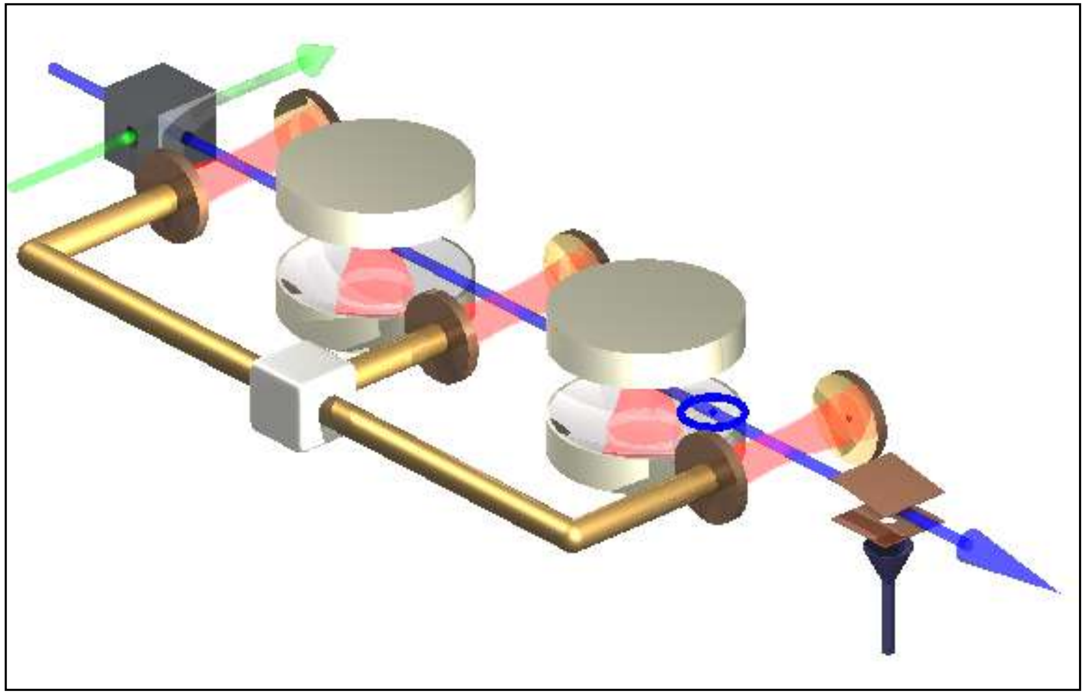


- Time evolution and decoherence of the cats

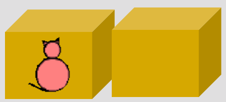
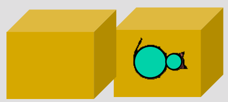


Perspectives

CQED with two cavities

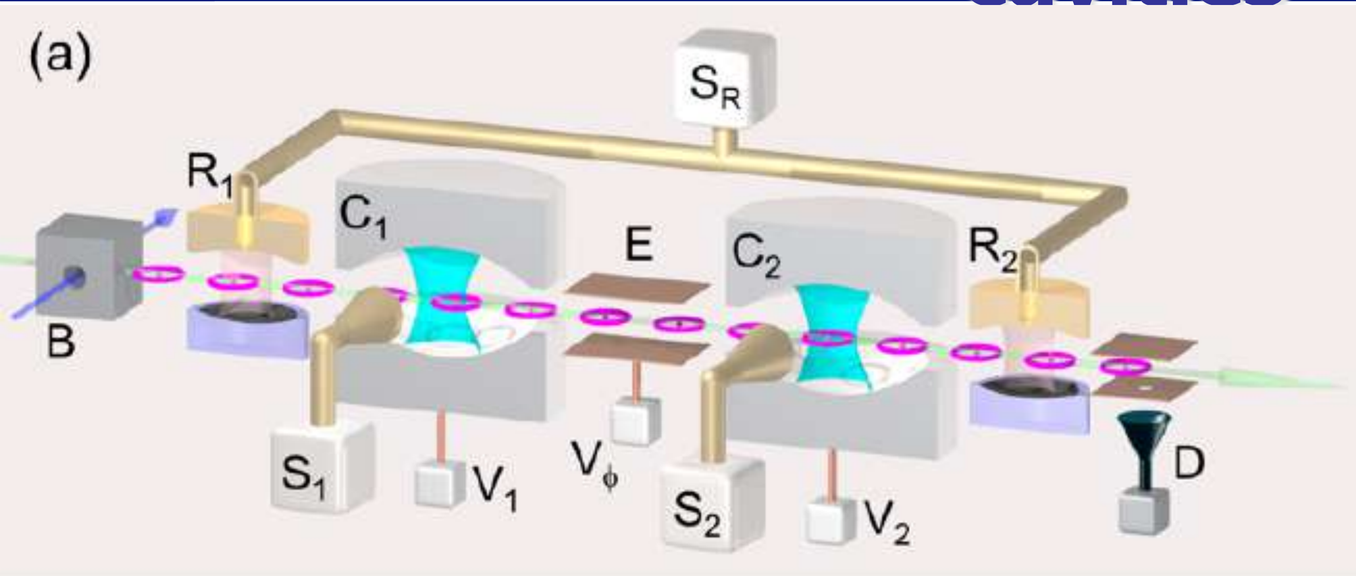


$$\frac{1}{\sqrt{2}}\left(|\alpha\rangle|0\rangle+|0\rangle|-\alpha\rangle\right)$$

$\frac{1}{\sqrt{2}}\Big(\Big|$  $\Big\rangle+\Big|$  $\Big\rangle\Big)$

→ alive-here-and-dead-there state

Exploring non-local states with two cavities



- Full state reconstruction by "quantum trajectory tomography

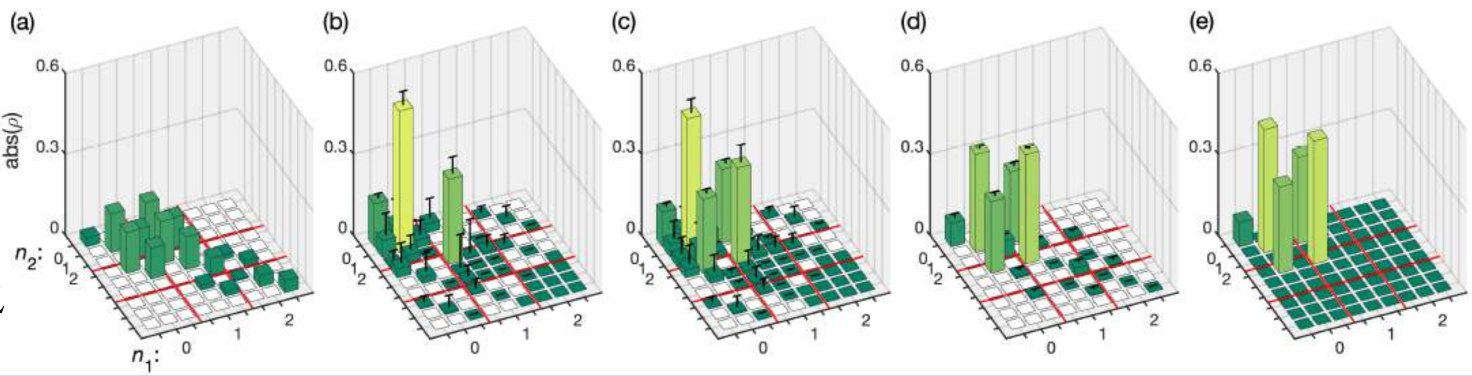
Method proposed by P. Rouchon

P. Six et al., Phys. Rev. A 93, 012109 (2016)

Quantum state tomography with non-instantaneous measurements, imperfections, and decoherence.

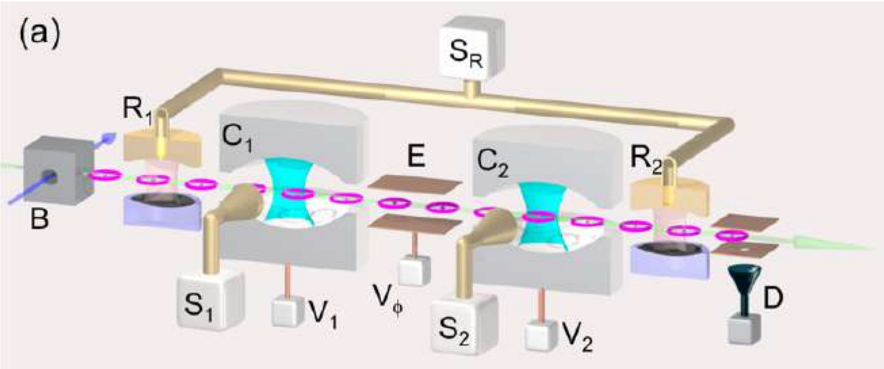
$$\frac{1}{\sqrt{2}}\left(\left\langle 1,0\right| + \left|0,1\right\rangle\right)$$

V. Métillon et al., accepted PRL
arXiv:1904.04681



A two-cavity experiment: exploring quantum thermodynamics

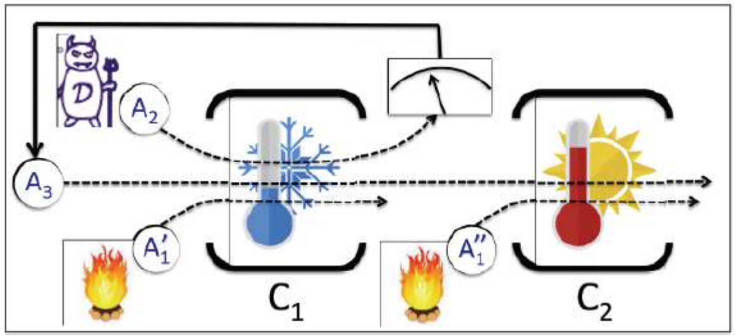
- Fast atoms crossing two microwave high-Q cavities



- Projects

Quantum thermodynamics

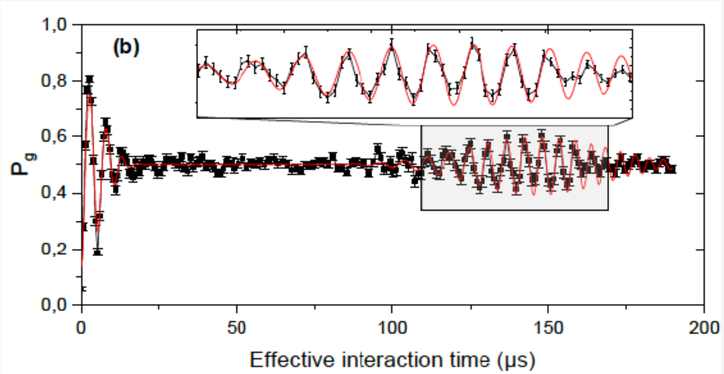
(ANR with A. Auffeves and P. Sénellart)



Heat going from cold to hot using information!
Exp. In progress

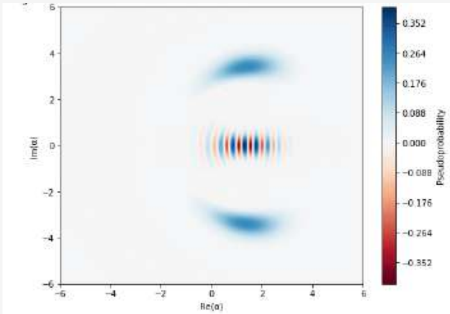
- People: Igor Dostenko, collab. A. Auffeves

Slow atoms cavity QED set-up



Collapse and revival of Rabi oscillation

Preparatio n of a 44 photons cat state

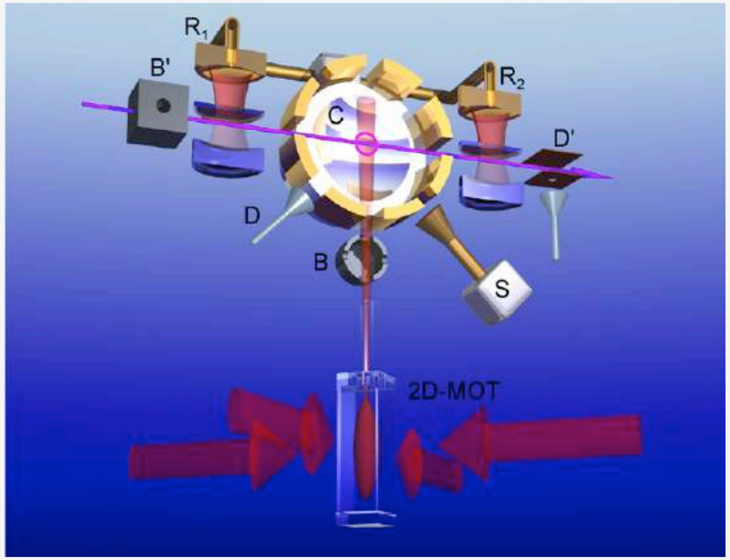


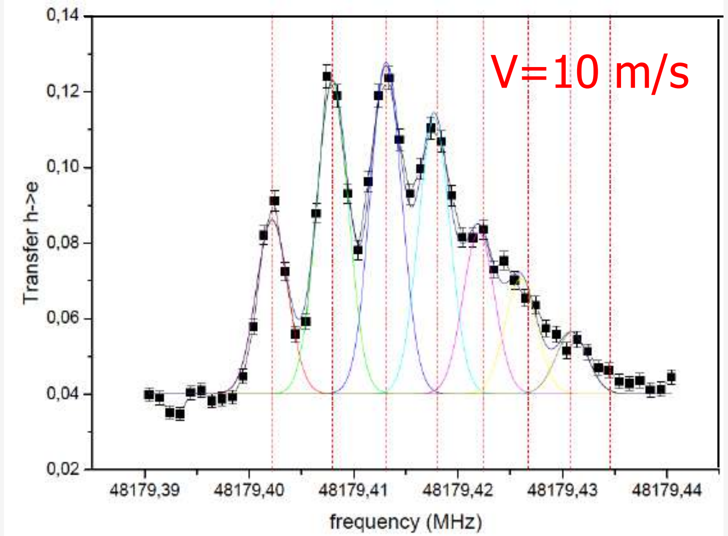
- parspectives:
  - Large cats, metrology of decoherence
  - Quantum Zeno dynamics

J.M. Raimond et al PRL **105**, 213601 (2010)

  - Reservoir engineering

A. Sarlette, A. et al. PRL **107**, 010402 (2011)



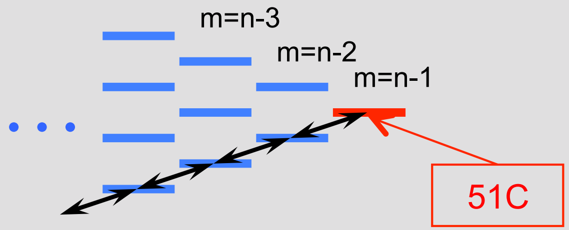


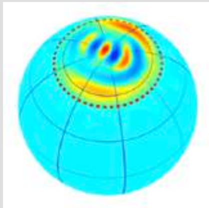
Dressed states spectroscopy

Another direction: Rydberg atoms without cavities

Engineering quantum state of the Rydberg electron motion

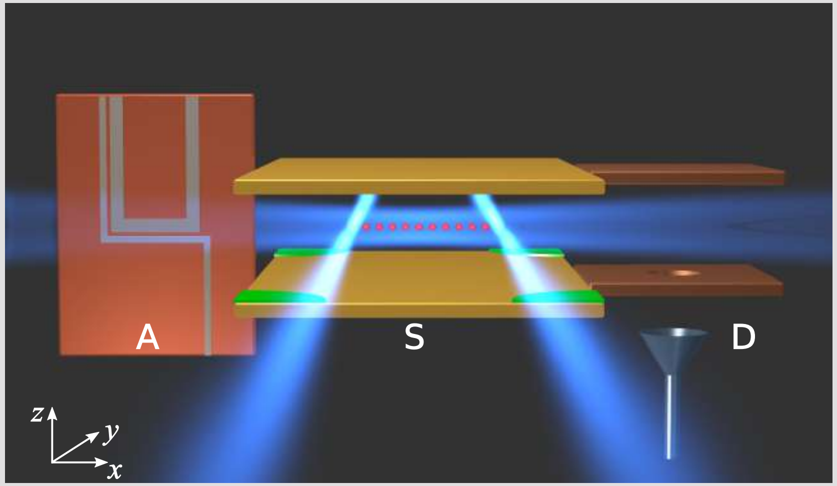
$|n,l,m\rangle$: n^2 levels with same n

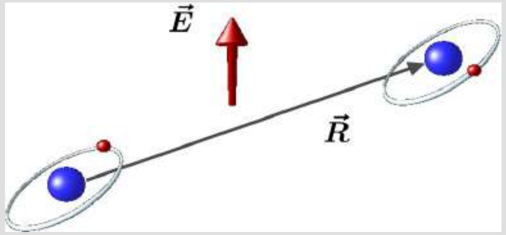




One Rydberg atom
→ use multi-level structure of for quantum metrology

→ more about this in the coloquium





Trapped Rydberg atoms with dipole interactions
→ quantum simulations with circular atoms

→ topic of lecture 5

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
- Dorian Grosso
- 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