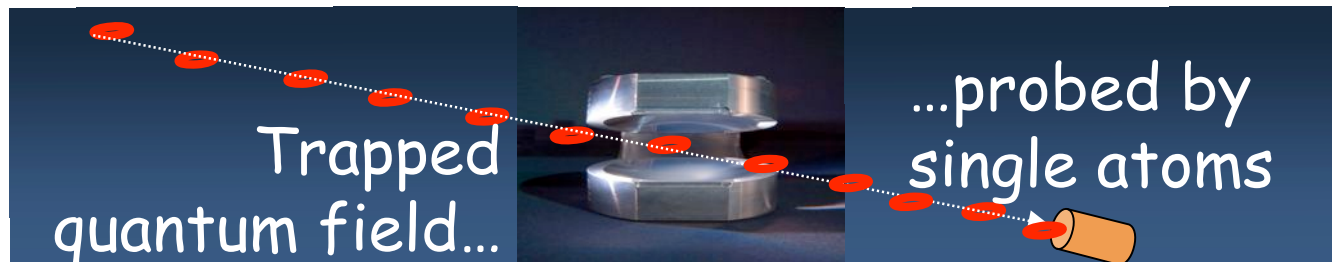


Fundamental tests in Cavity Quantum Electrodynamics

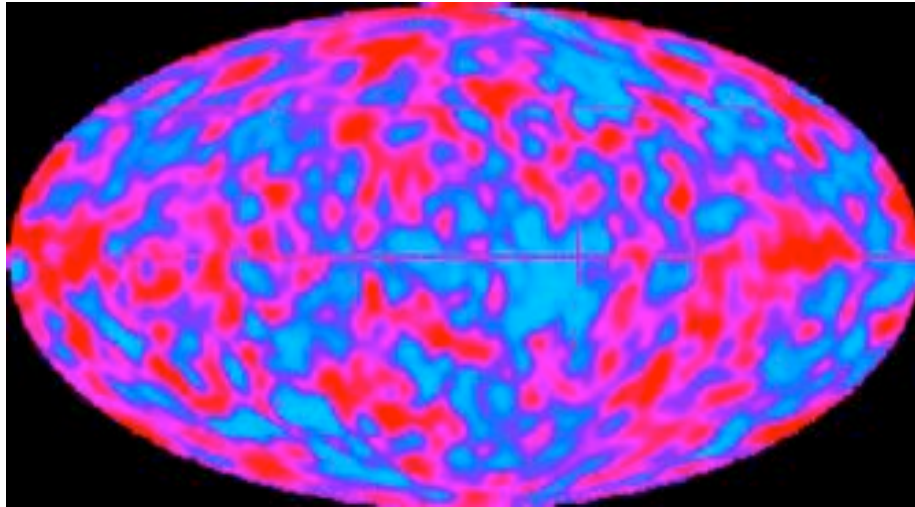
Serge Haroche,
ENS and Collège de France, Paris
CERN Colloquium, May 27 2010



A « photon box » as an ideal laboratory to demonstrate effects which can lead to applications...

*Fundamental tests of quantum measurement theory
&
exploration of the quantum-classical boundary*

The photon is an ubiquitous and elusive particle



COBE satellite map of the cosmic blackbody background

It has no mass....

*....and flies at maximum velocity
(the speed of light!)*

*It carries (almost) all
information about the Universe....*

*....but it is destroyed while
delivering its message*

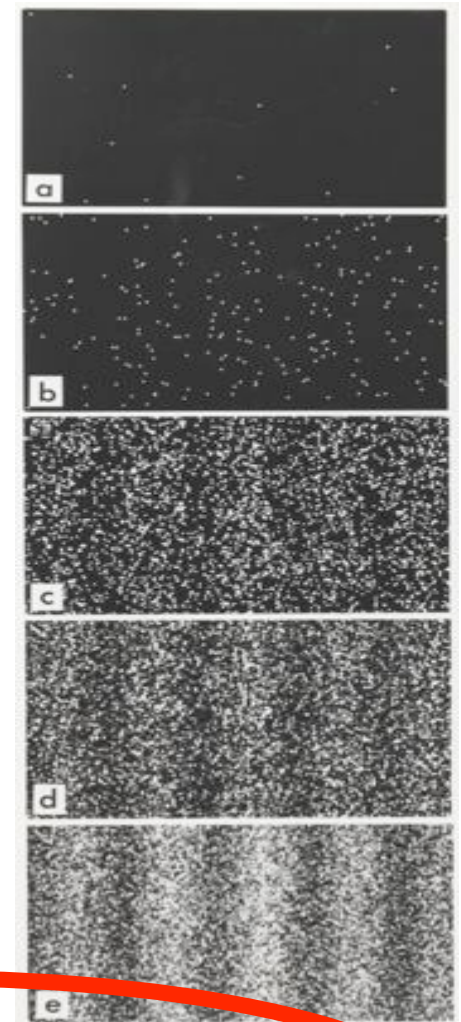
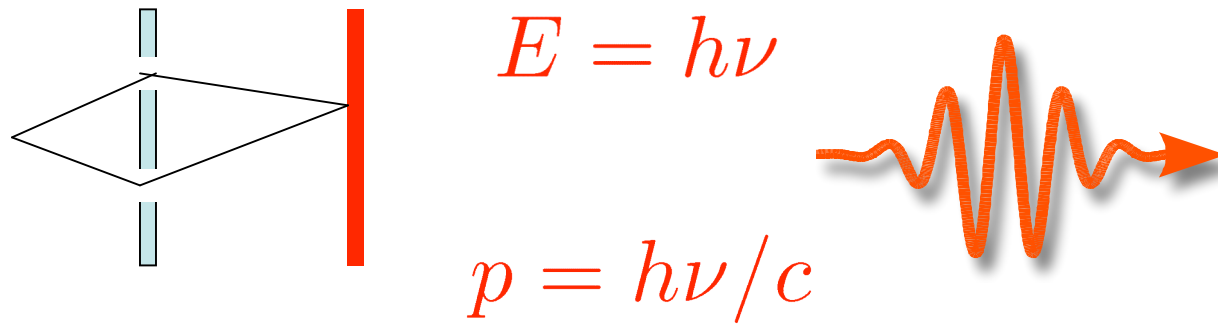
In free space, it is eternal....

...but it is very fragile and does not survive long in captivity

We observe photons under very unusual conditions, trapping them during a perceptible time and detecting them repeatedly without destroying them.

A new way to « look »

Photons are intrinsically quantum



*Young double-slit experiment with photons:
Fringes are revealed after detecting many photons
arriving one by one on the screen...*

*“I am a particle, look at the discrete spots and I am
a wave, look at the interference fringes.”*

Atoms and photons →
confined in a box

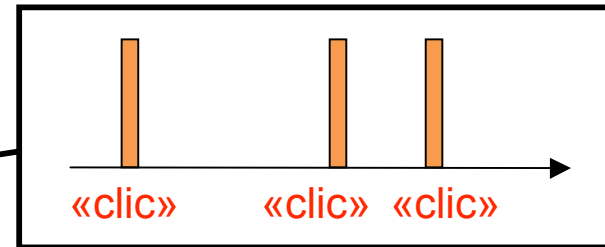
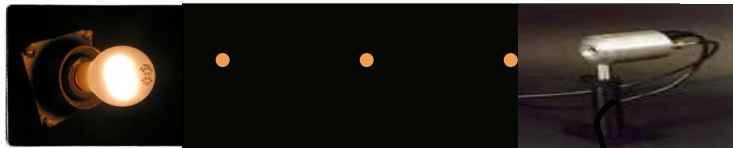
Cavity Quantum Electrodynamics

Ambigram of Douglas Hofstadter

LIGHT IS A

WAVE!

Usual photon detection : « chronicle of a foretold death »



$$|1\rangle \xrightarrow{\text{clic}} |0\rangle$$

*A clic projects the field onto the vacuum:
the photon dies upon delivering its message*

**This is not what textbooks of Quantum Physics tell us
about ideal projective measurements!**

A Quantum Non-Demolition (QND) measurement should instead realize:

$$|1\rangle \xrightarrow{\text{clic}} |1\rangle \xrightarrow{\text{clic}} |1\rangle \xrightarrow{\text{clic}} \dots \xrightarrow{\text{clic}} |1\rangle \quad ?$$

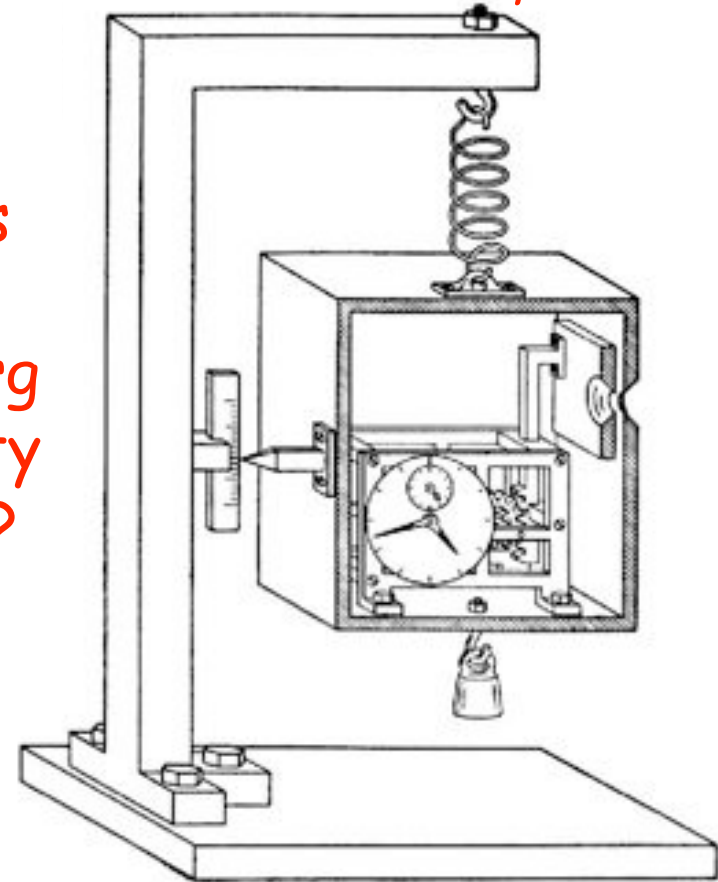
**We need a non-demolition detector at single photon level...
and a very good box to keep the photons alive long enough**

Light in a box as a testing ground for quantum physics: in Cavity QED, thought experiments become real



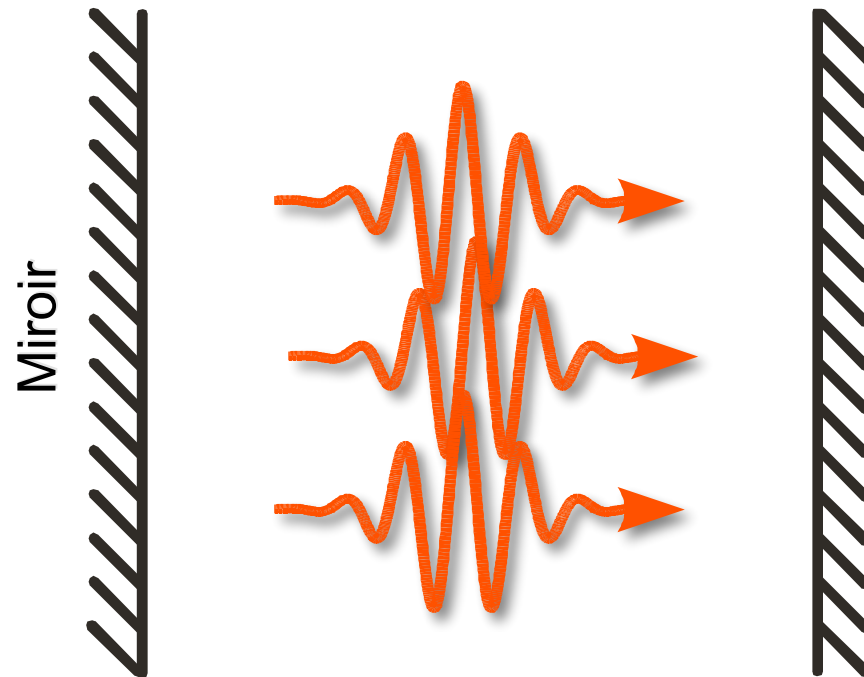
By weighing a photon, one could detect it without destroying it and measure its escape time

Does this violate Heisenberg uncertainty relations?



Trapping a photon

Fabry-Pérot resonator



Requirements: quasi perfect reflection on mirrors
(no absorption, transmission, scattering)

Cavity Quantum Electrodynamics:

a stage to witness the interaction between light and matter at the most fundamental level

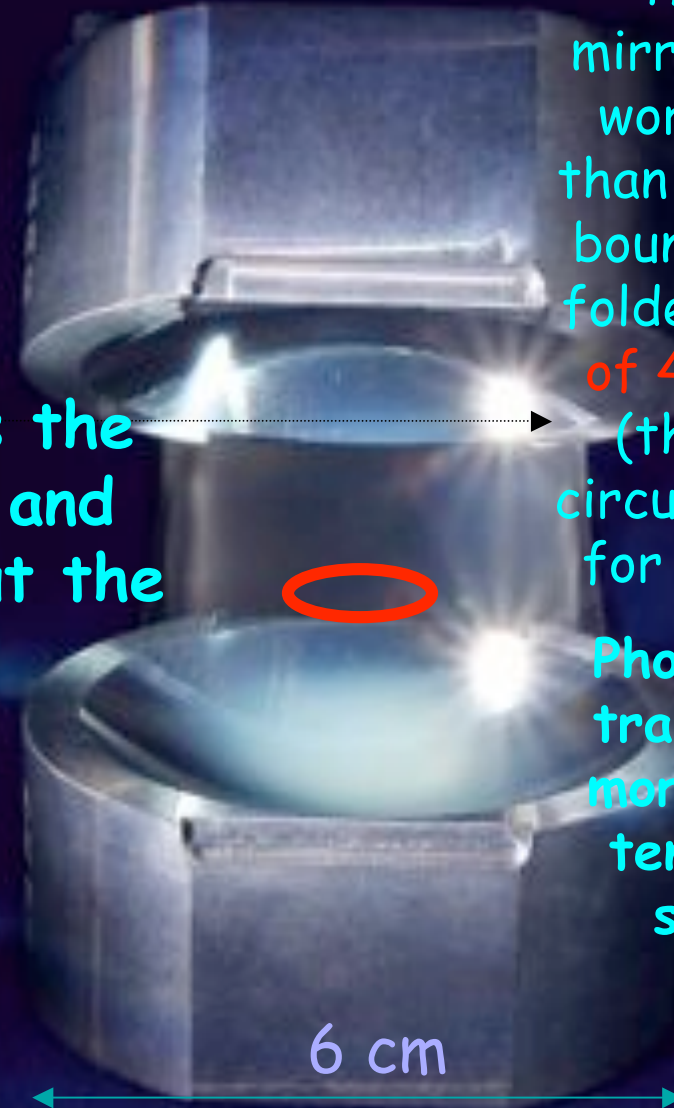
One **atom** interacts with one (or a few) photon(s) in a box

A sequence of atoms crosses the cavity, couples with its field and carries away information about the trapped light

Photons bouncing on mirrors pass many many times on the **atom**: the cavity enhances tremendously the light-matter coupling

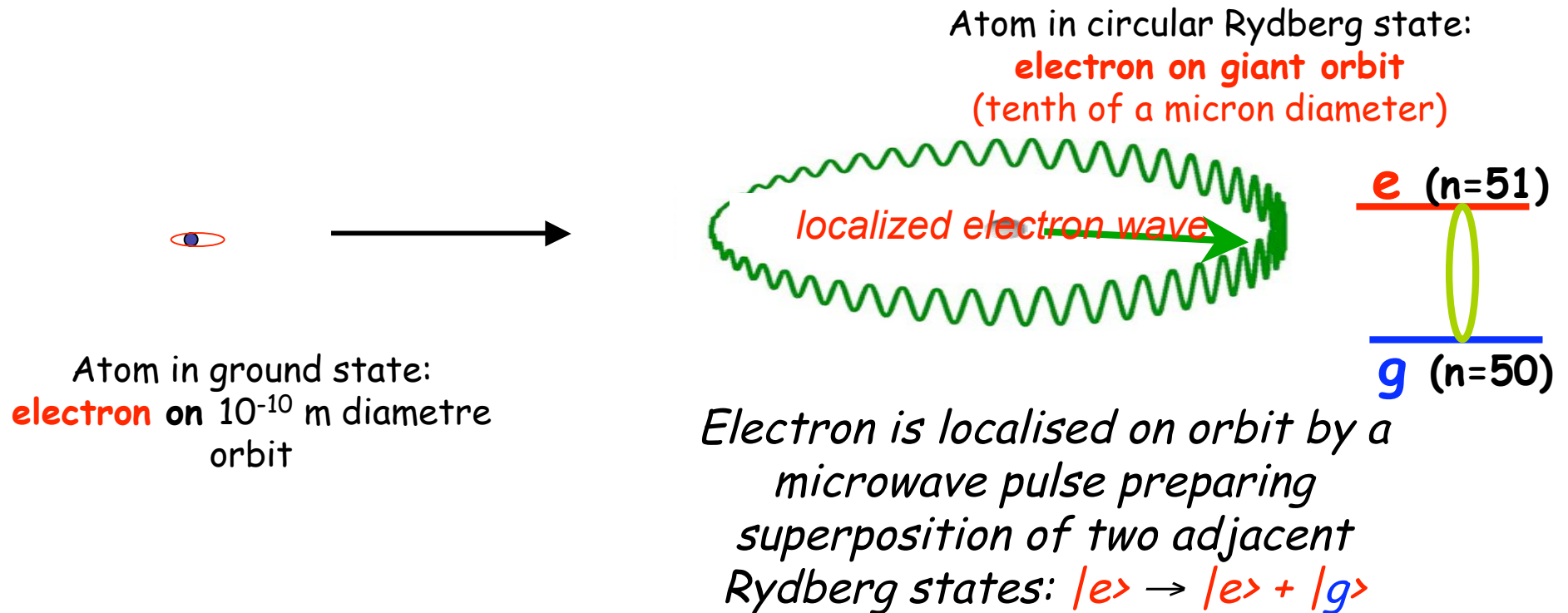
The best mirrors in the world: more than **one billion** bounces and a folded journey of **40.000km** (the earth circumference) for the light!

Photons are trapped for more than a tenth of a second!



6 cm

An extremely sensitive detector: the circular Rydberg atom



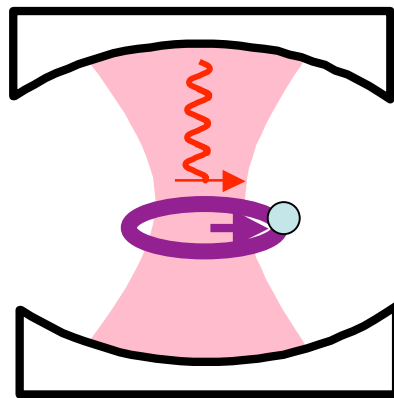
The localized wave packet **paquet** revolves around nucleus at the transition frequency (51 GHz) between the two states like a clock's hand on a dial.

When atom interacts with non-resonant photons, this frequency is slightly modified, which results in clock delay.

How Light delays the Rydberg atomic clock

The cavity has a frequency $\nu = \nu_{at} + \delta$ slightly different from the rotation frequency of the atomic dipole: the photons cannot be absorbed and the atomic clock is '*transparent*'...

...but the electric field associated to the photons perturbs the rotation of the atomic '*hand*'...



$$E_{\text{photon}} \approx \sqrt{\frac{h\nu}{\epsilon_0 V_{\text{boîte}}}} \approx 10^{-3} \text{ V / m}$$

$$E_{\text{atome}} \approx \frac{q}{4\pi\epsilon_0 r_{at}^2} \approx 10^5 \text{ V / m}$$

The electric field of a photon, about a hundred million times smaller than the Coulomb field seen by the Rydberg electron, slightly modifies the atomic clock frequency

$$\left[\frac{\Delta\nu_{at}}{\nu_{at}} \right]_{\text{par photon}} = 4.10^{-13} \frac{\nu_{at}}{\delta} \longrightarrow \left[\frac{\Delta\nu_{at}}{\nu_{at}} \right]_{\text{par photon}} = 4.10^{-7} \text{ pour } \delta = 10^{-6} \nu_{at} = 50 \text{ kHz}$$

A single photon may delay the clock by about 1 second/month

$$\left[\Delta\nu_{at} \right]_{\text{par photon}} = 4.10^{-7} \nu_{at} = 20 \text{ kHz} \longrightarrow \left[\Delta\Phi_{at} \right]_{\text{par photon}} = 2\pi \Delta\nu_{at} \cdot t_{\text{transit}} = \pi$$

During an atom's transit time across the cavity (30 μs), the hand makes 1.5 million turns and one photon shifts its phase by half a turn.

A smaller phase-shift per photon is achieved by increasing δ

How light delays the Rydberg atomic clock: a light shift effect

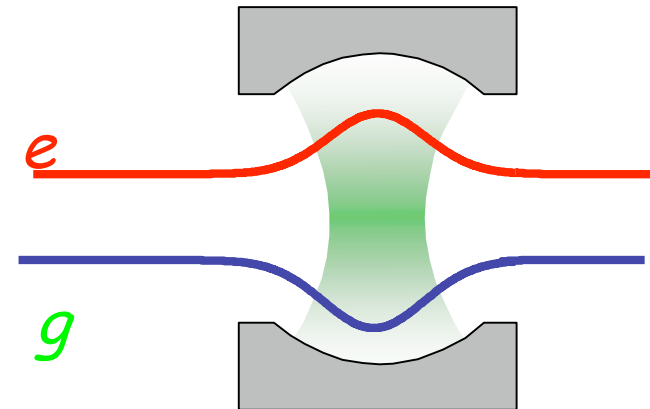
Important parameters: vacuum Rabi frequency $\Omega(z)$, atom-cavity detuning δ

Non-resonant atom ($\delta \neq 0$)
experiences *light-shifts with
opposite signs* in levels e and g as
it crosses C

To lowest order in Ω/δ , the shifts
are *proportional to the photon
number N* and the interaction with
the cavity field produces a phase
shift of atomic dipole:

$$\Delta\Phi(N) = N \int \frac{\Omega^2(z)}{2\delta} \frac{dz}{v} + \dots = N\varphi_0 + \dots$$

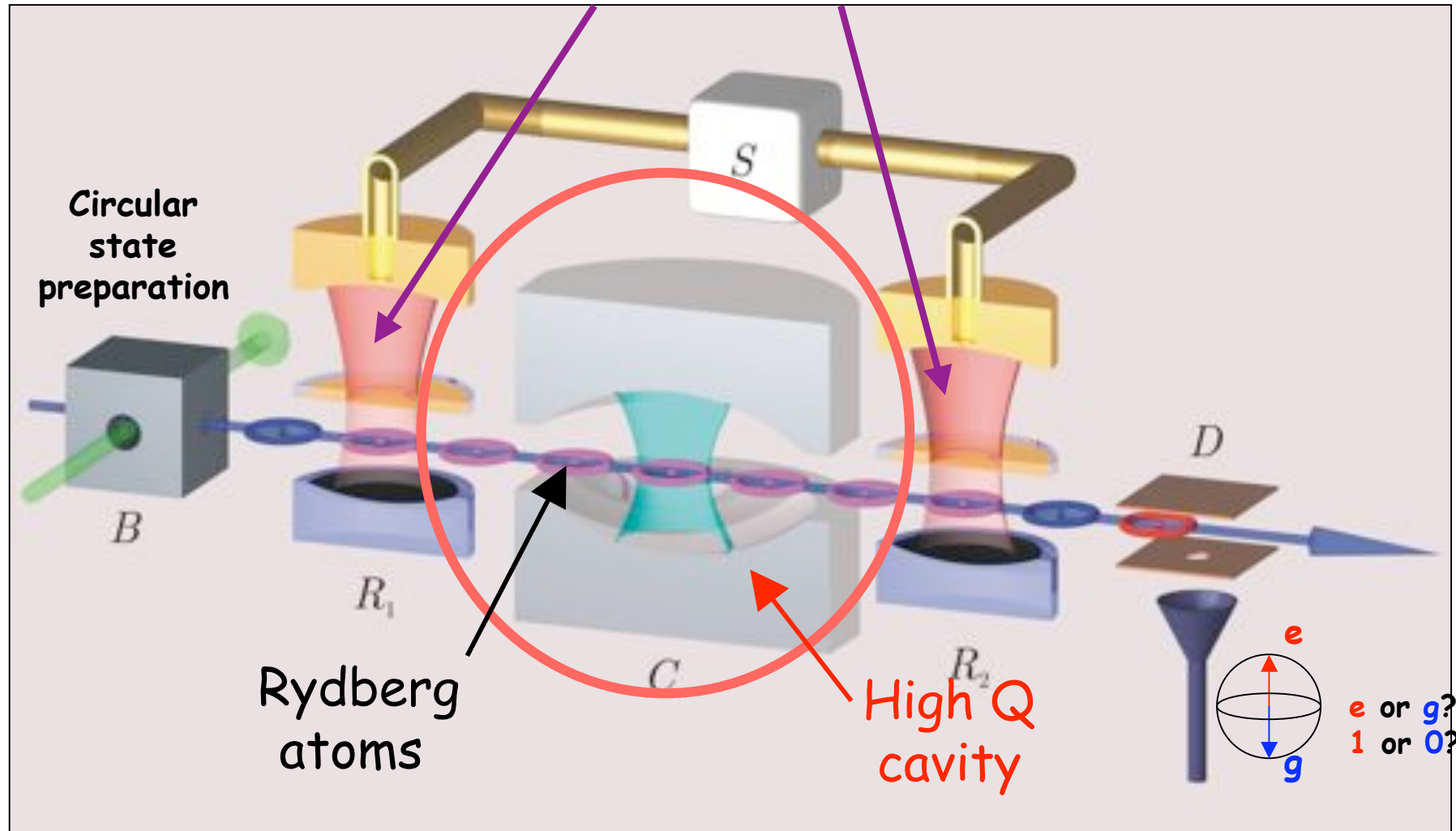
Measuring this phase shift amounts
to a QND photon counting



*Adiabatic evolution
prevents atom from
absorbing or
emitting photons
even for $\delta \sim \Omega$*

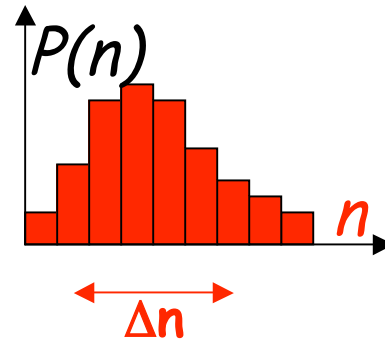
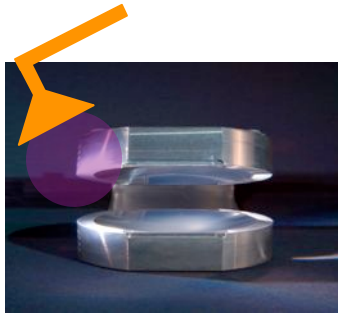
An artist's view of set-up...

Classical pulses
(Ramsey interferometer)



An atomic clock delayed by photons trapped inside

QND measurement of arbitrary photon numbers: progressive collapse of field state



A coherent field
(Glauber state)
has uncertain photon
number:

$$\Delta n \Delta \phi \geq 1/2$$

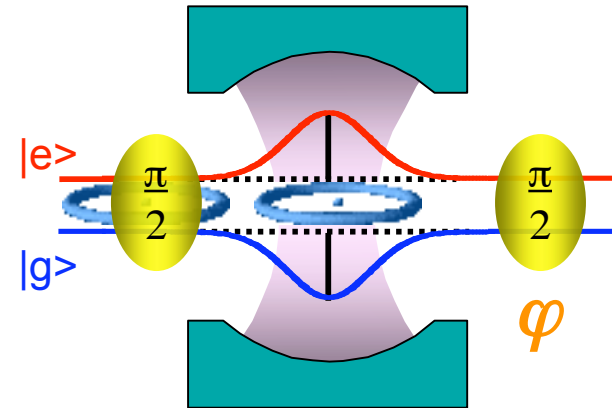
Heisenberg relation

A small coherent state with Poissonian uncertainty and $0 \leq n \leq 7$ is initially injected in the cavity and its photon number is progressively pinned-down by QND atoms

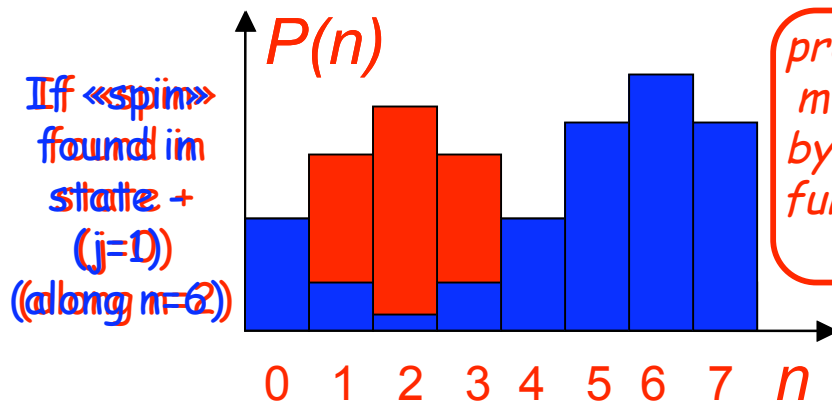
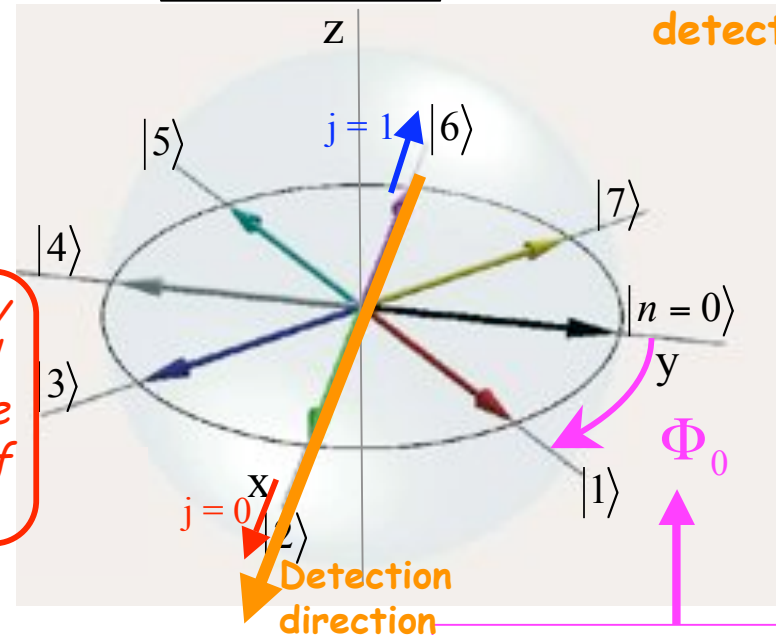
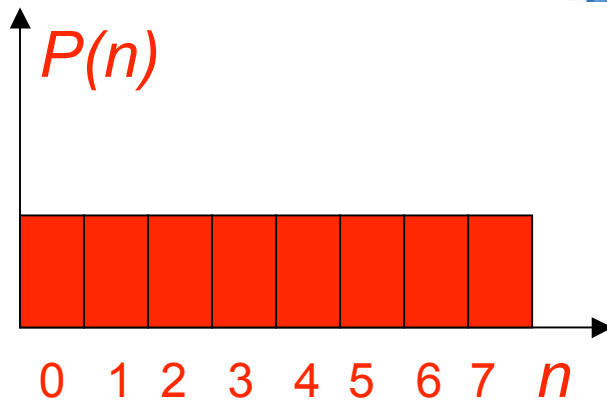
Experiment illustrates on light quanta the three postulates of measurement: state collapse, statistics of results, repeatability.

Counting photon numbers: 1st atom effect on inferred photon distribution

Chose $\Phi_0 = \pi/4$



2nd Ramsey pulse maps a direction in equatorial plane back into e/g « axis » before detection



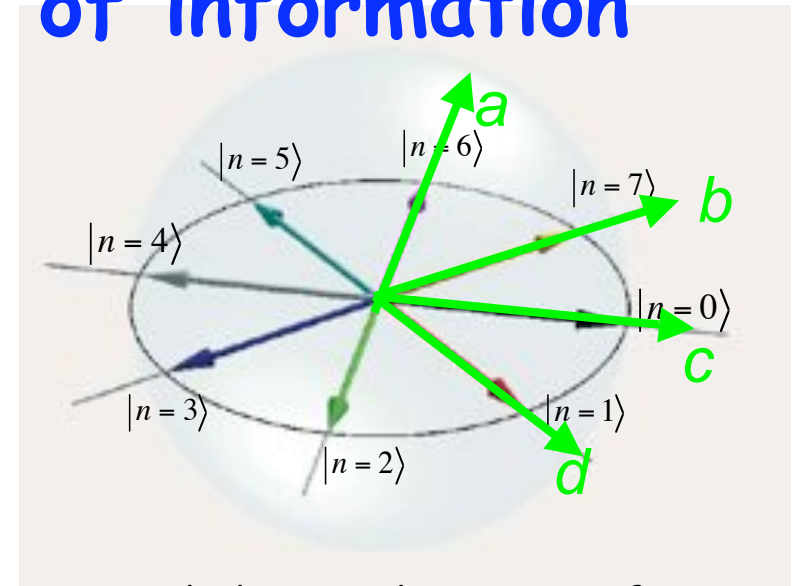
probability multiplied by a cosine function of n

If «spin» found in state + (j=1) (along n=2)

phase shift per photon

Random decimation of photon number
projection postulate (or Bayes law)

A step-by-step acquisition of information



To pin down photon number, send a sequence of atoms one by one...

...and change direction of spin detection to decimate ***different*** numbers

$$P^{(N)}(n) = \frac{P^{(0)}(n)}{2Z} \prod_{k=1}^N [1 + \cos(n\Phi_0 - \phi(k) - j(k)\pi)] / 2$$

↓ ↓
a/b/c/d 0/1

Spin reading

000101101010001011001...

Direction

abdcadbcbadcaabcbacd b...

$$P^{(N)}(n) \longrightarrow \delta(n - n_0)$$

Progressive collapse!

Progressive collapse as n is pinned down to one value

Which number will win the race?

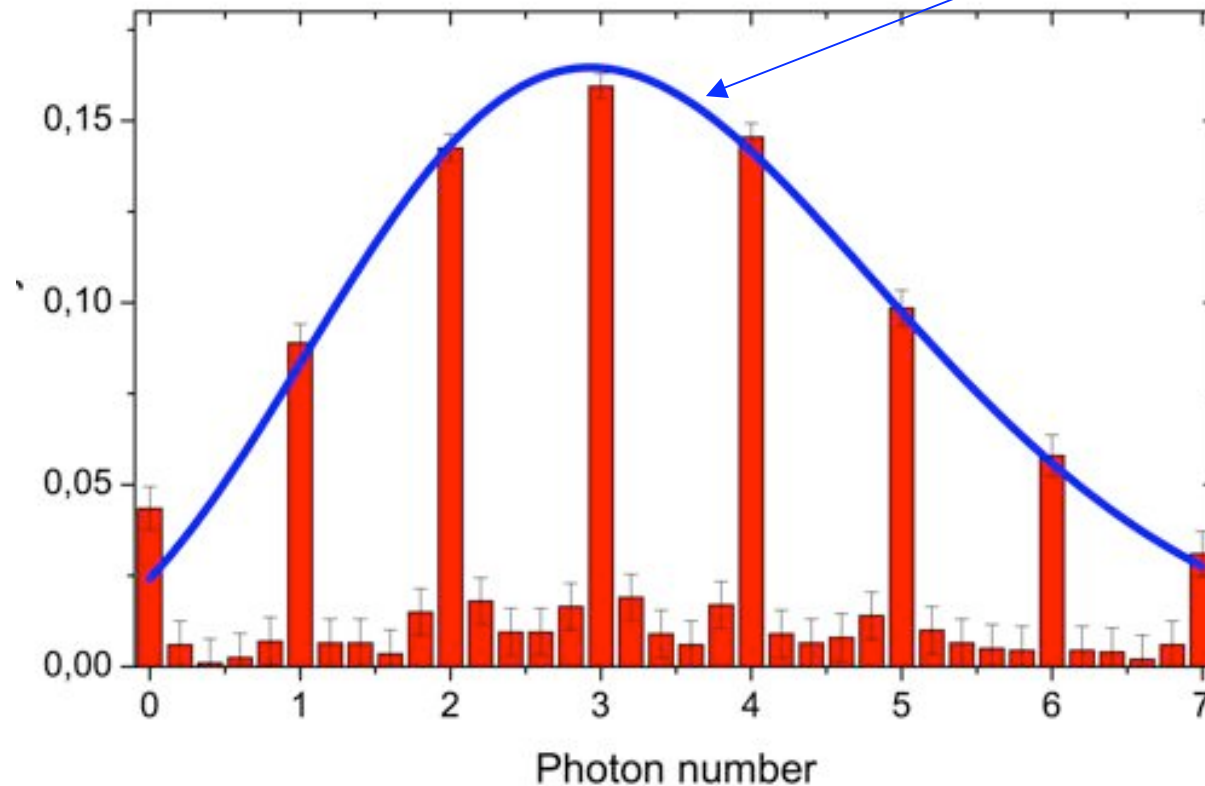
Bayes law in action...

$n = 7 \ 6 \ 5 \ 4 \ 3 \ 2 \ 1 \ 0$



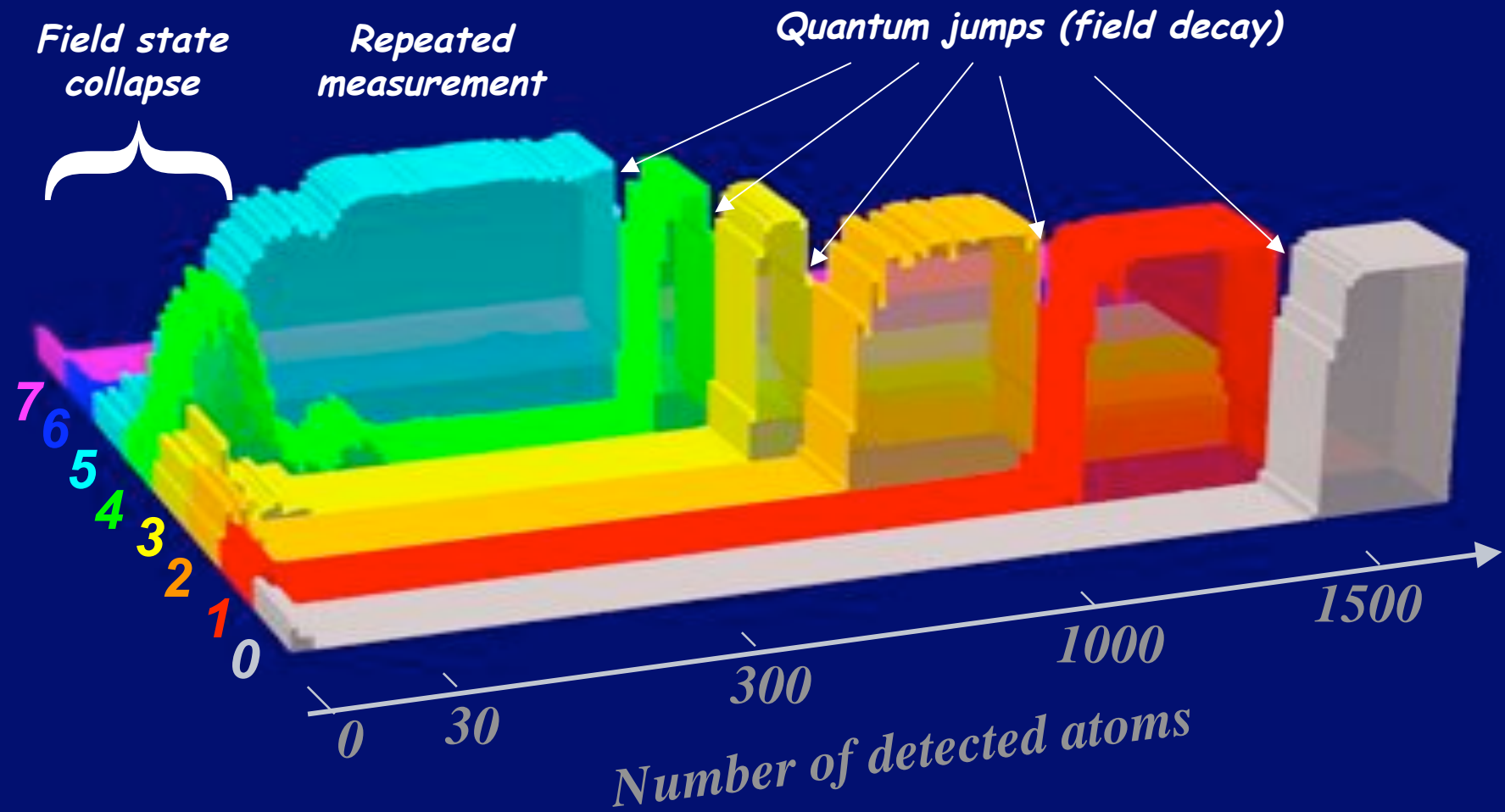
Statistical analysis of 2000 sequences: histogram of the Fock states obtained after collapse

*Coherent field with
 $\langle n \rangle = 3.43$*



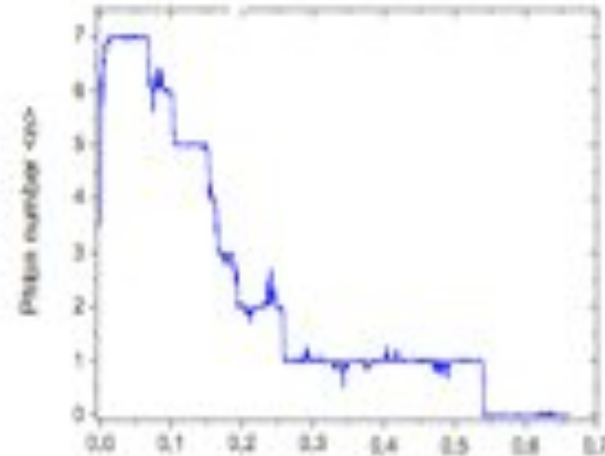
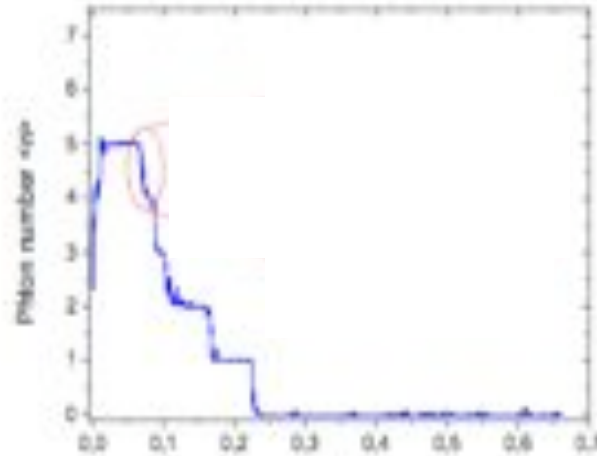
Illustrates quantum measurement postulate about statistics

Evolution of the photon number probability distribution in a single measuring sequence over a long time interval



Single realization of field trajectory: real Monte Carlo

Photon number trajectories



$$\Delta E_n = n\hbar\Delta\nu_{cav} = \frac{n\hbar}{T_{cav}}$$

$$\Delta T_n = \frac{T_{cav}}{n}$$

$$\Delta E_n \Delta T_n = \hbar$$

*Heisenberg
uncertainty
relations*

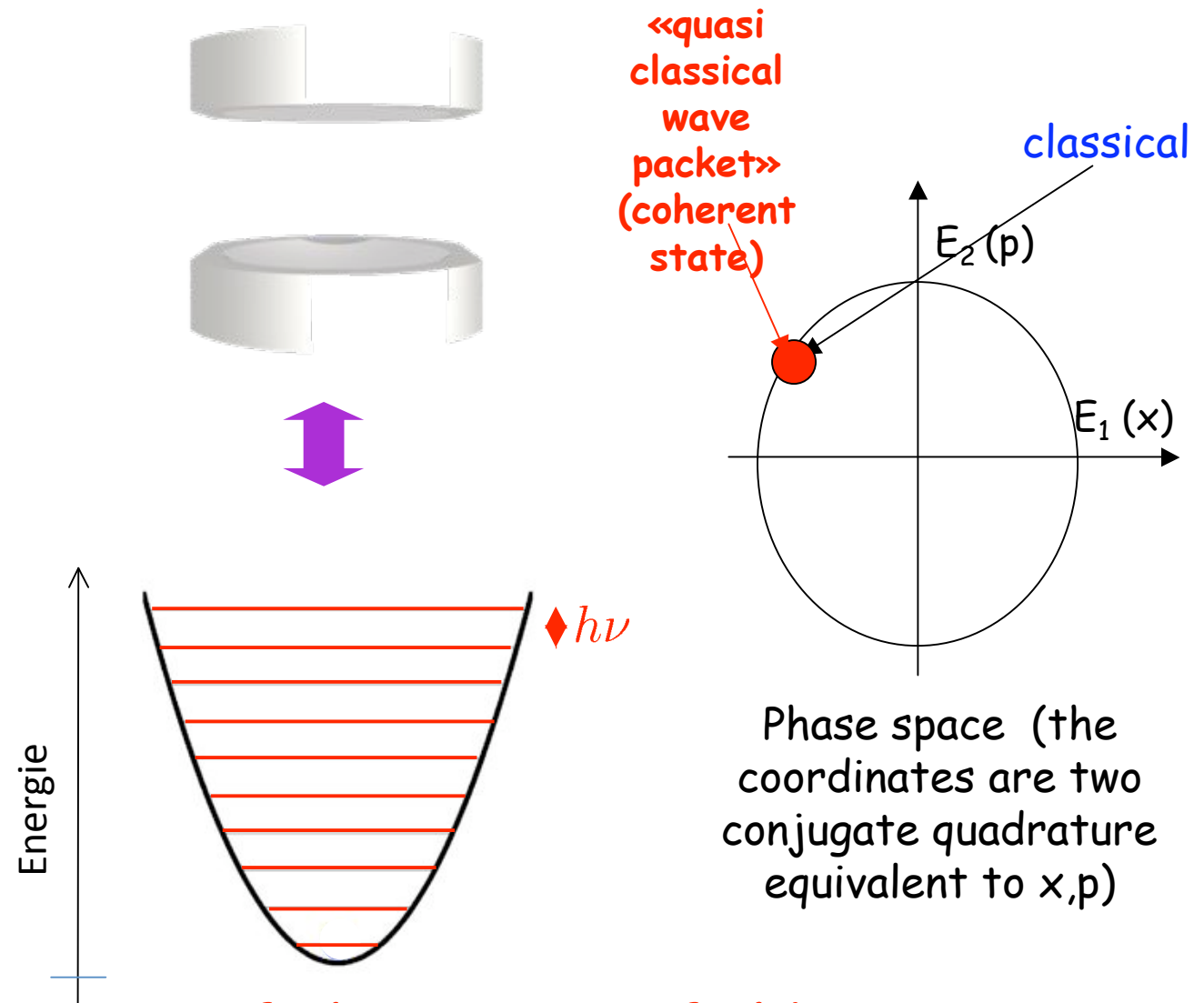
An inherently random process (durations of steps widely fluctuate and only their statistics can be predicted - see Brune, Bernu, Deléglise, Sayrin, Guerlin, Dotsenko, Raimond & Haroche, Phys.Rev.Lett. 101, 240402 (2008))

The field's state contains much more information than the distribution of the photon number...

Preparing and reconstructing non-classical states of the field and recording their time-evolution: a study of decoherence and the quantum-classical boundary



A field mode is a harmonic oscillator



A complete description of the quantum field state is given by its Wigner function in phase space

Description of a field state by density operator and Wigner function

Pure state

$$|\Psi\rangle = \sum_n C_n |n\rangle \quad ; \quad \text{état cohérent} \quad |\beta\rangle = e^{-|\beta|^2/2} \sum_n \frac{\beta^n}{\sqrt{n!}} |n\rangle \quad (\text{Poisson})$$

Statistical mixture and density operator:

$$\rho = \sum_i p_i |\psi_i\rangle \langle \psi_i| \quad (\sum_i p_i = 1) \quad ; \quad \rho = \sum_{n,n'} \rho_{n,n'} |n\rangle \langle n'| = \iint dx dx' \rho_{xx'} |x\rangle \langle x'|$$

Pure states are special cases $\rightarrow \rho$ is a projector: all p_i 's are zero save 1

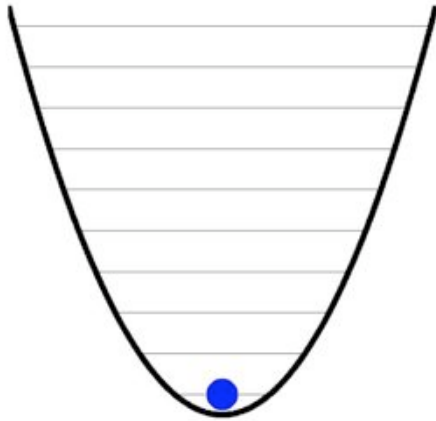
Wigner function in phase space:

$$W(x, p) = \frac{1}{\pi} \int \rho_{x+\frac{u}{2}, x-\frac{u}{2}} e^{-2ipu} du$$

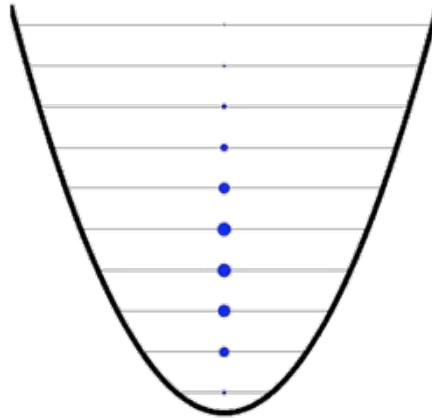
Density operator ρ and real Wigner function $W(\alpha=x+ip)$ are transformed into each other by an invertible mathematical formula: they contain the same amount of information, defining fully the state of the field.

Some pure states

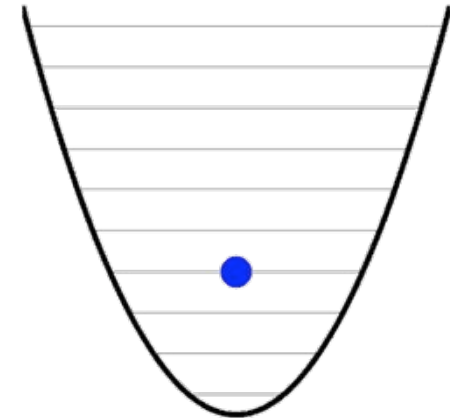
Vacuum



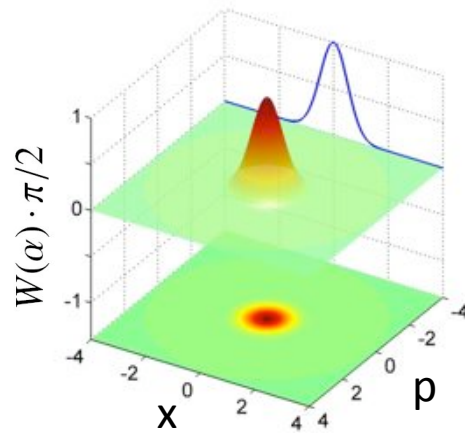
Coherent state



Fock state (number state)



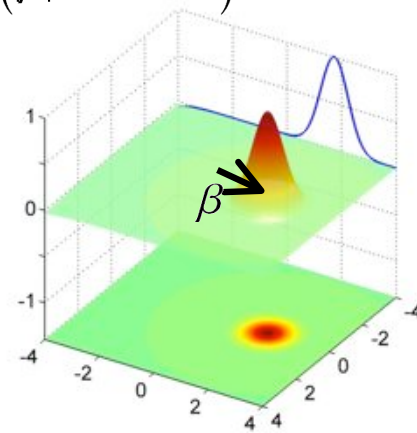
$|0\rangle$



$$\alpha = x + ip$$

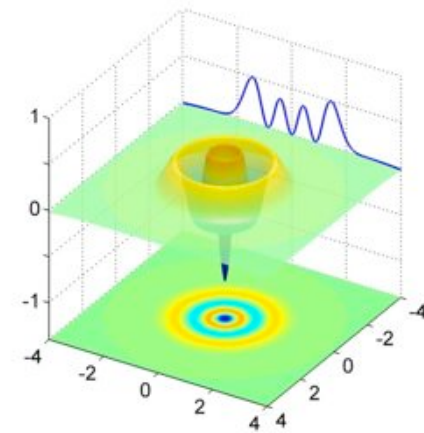
$$|\beta\rangle = e^{-|\beta|^2/2} \sum_n \frac{\beta^n}{\sqrt{n!}} |n\rangle$$

$(|\beta|^2 = \bar{n} = 3)$



Translated vacuum

$|n\rangle$ ($n=3$)



Schrödinger cat state

Schrödinger Cat

$$|\Psi\rangle = \frac{1}{\sqrt{2}} [|\beta\rangle + |-\beta\rangle]$$

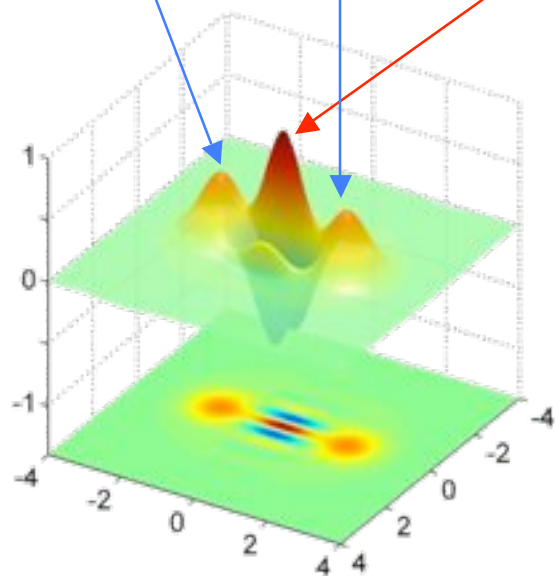
$$\rho_{\text{chat}} = \frac{(|\beta\rangle + |-\beta\rangle)(\langle\beta| + \langle-\beta|)}{2}$$

$$= \frac{|\beta\rangle\langle\beta| + |-\beta\rangle\langle-\beta| + |\beta\rangle\langle-\beta| + |-\beta\rangle\langle\beta|}{2}$$

\neq

Statistical mixture

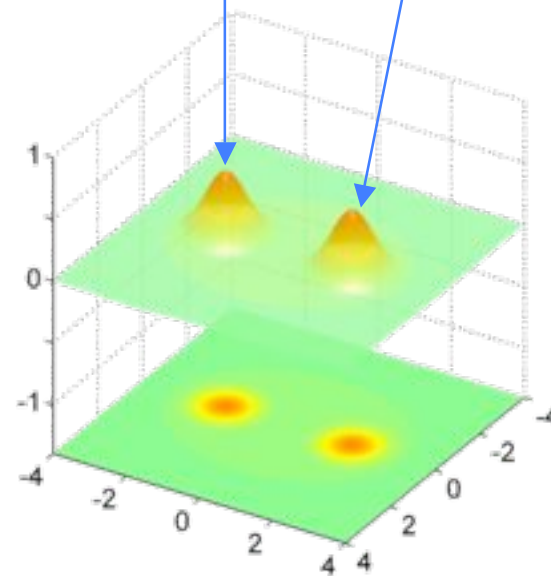
$$\rho_{\text{mélange}} = \frac{|\beta\rangle\langle\beta| + |-\beta\rangle\langle-\beta|}{2}$$



Quantum state



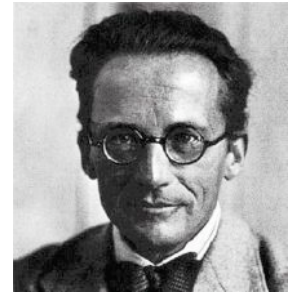
decoherence



Classical state

**Non-classical states are characterized by oscillating (non-Gaussian) Wigner functions, which assume negative values (quantum interferences).
Decoherence very quickly washes out the quantum features**

Schrödinger cat story: A large system coupled to a single atom ends up in a strange superposition...



$$a_{\text{vivant}} | \text{atom} \text{ cat in box} \rangle + b_{\text{mort}} | \text{atom} \text{ cat out of box} \rangle$$



**Our version:
a coherent
field coupled
to a single
atom
collapses into
a superposition
of two fields
with opposite
phases**

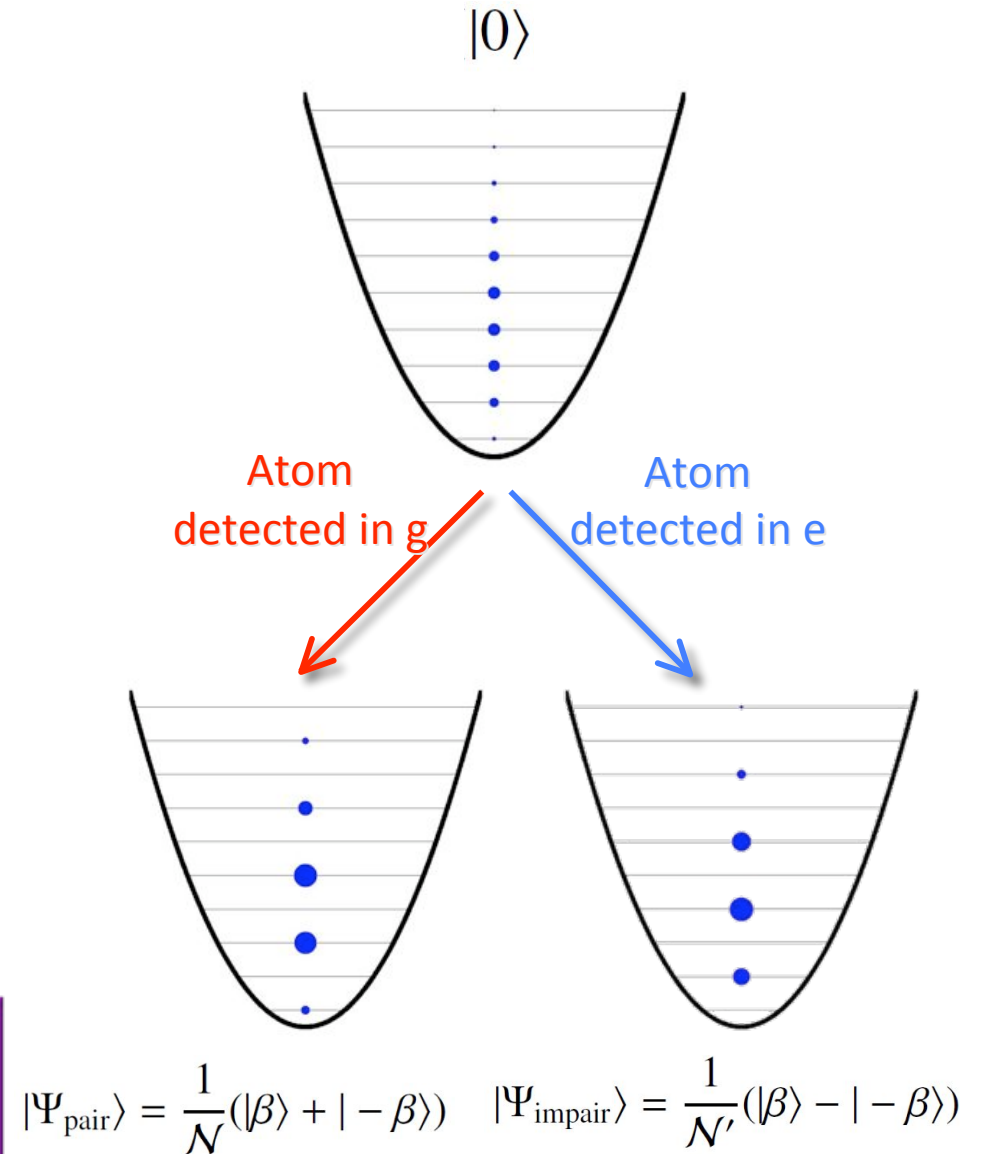
Preparing the Schrödinger cat state

$$|\beta\rangle = \underbrace{\frac{1}{2}[|\beta\rangle + |-\beta\rangle]}_{\sum_{n \text{ pair}} C_n |n\rangle} + \underbrace{\frac{1}{2}[|\beta\rangle - |-\beta\rangle]}_{\sum_{n \text{ impair}} C_n |n\rangle}$$

Even photon numbers Odd photon numbers

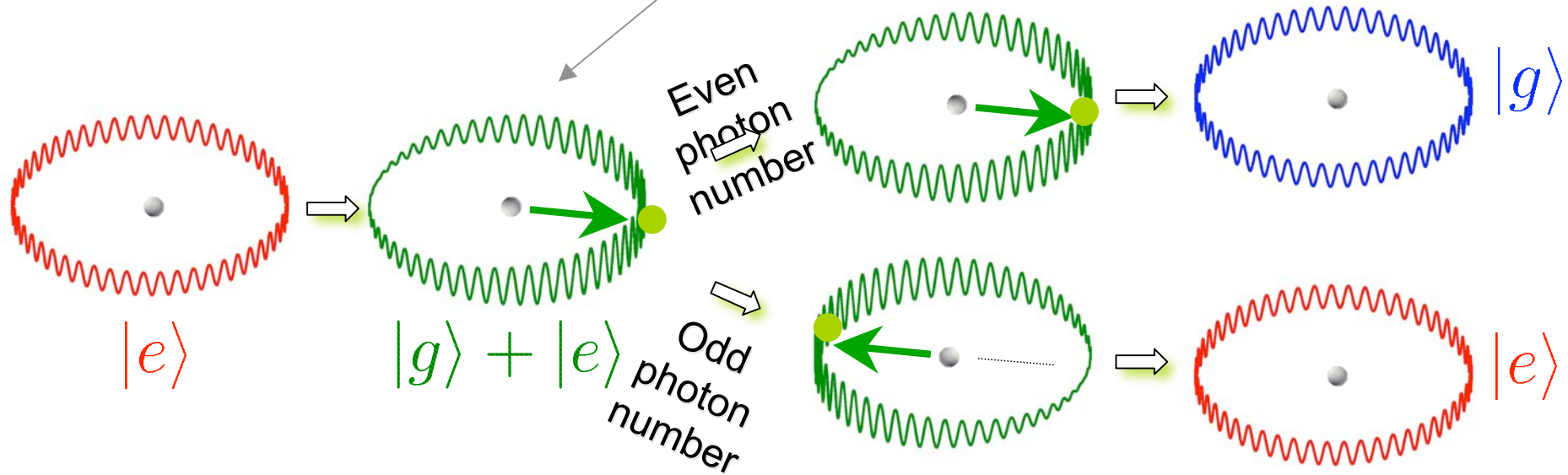
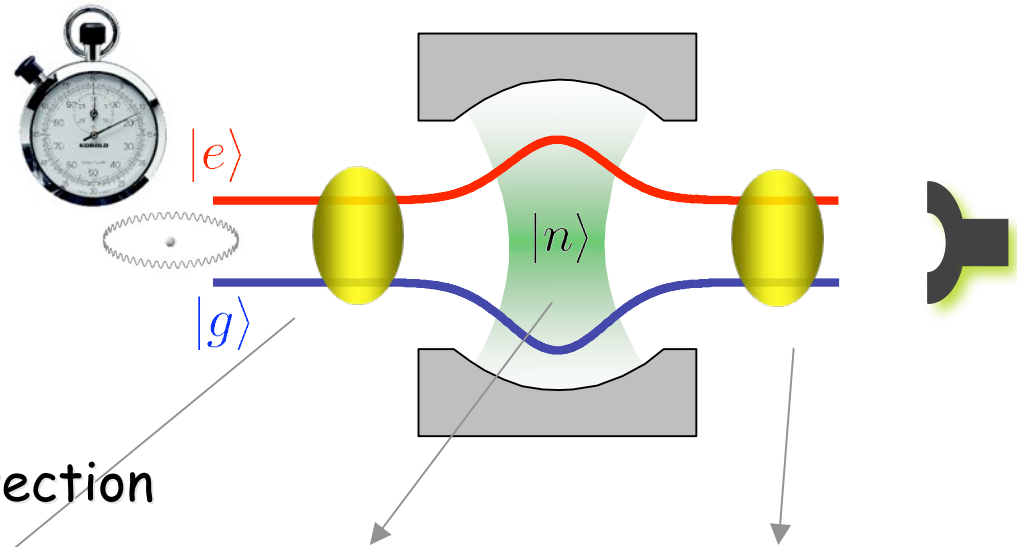
1. Injecting a coherent field by coupling to a classical source
2. Measuring the photon number parity by sending an atom with $\varphi_0 = \pi$

⇒ The Schrödinger cat state is produced by the back action of a parity measurement on the field's phase



Measuring the field's parity (n modulo 2)

1. Triggering the clock:
First microwave pulse
2. Phase-shifting the clock:
interaction with the cavity field
3. Reading the clock:
Second microwave pulse and detection of atomic state



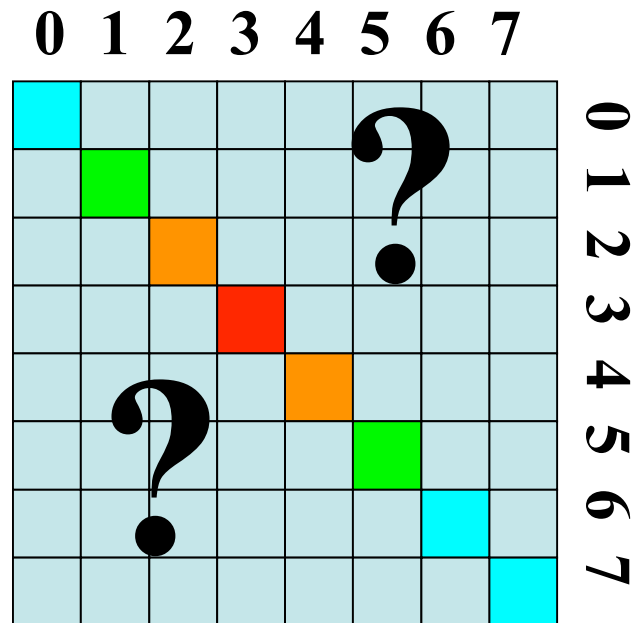
Atomic state phase shift per photon $\phi_0 = \pi$ number parity

Once the “cat” has been prepared, its quantum state is scanned with subsequent atoms carrying away an “imprint” of the field out of the cavity...



S. Deléglise, I. Dotsenko, C. Sayrin, J. Bernu, M. Brune, J-M. Raimond & S. Haroche, Nature, 455, 510 (2008)

QND photon counting and field state reconstruction



Repeated QND photon counting on copies of field determines the diagonal ρ_{nn} elements of the field density operator in Fock state basis, but leaves the off-diagonal coherences $\rho_{nn'}$ unknown

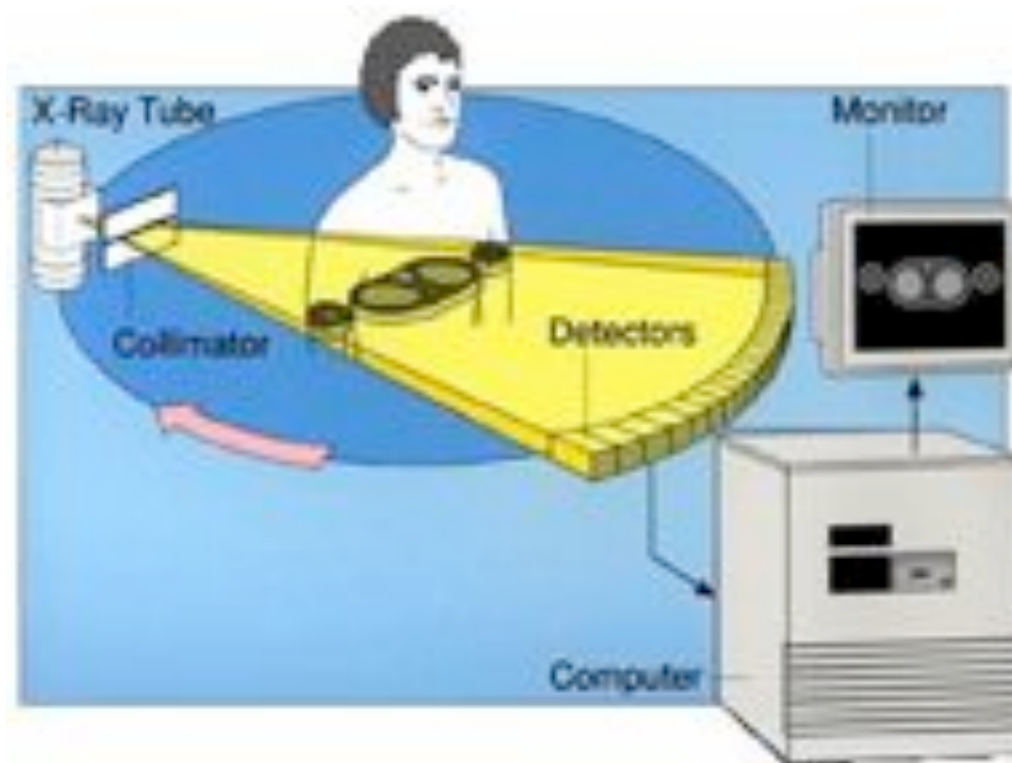
Recipe to determine the off-diagonal elements and completely reconstruct ρ :

translate the field in phase space by homodyning it with coherent fields of different complex amplitudes and count (on many copies) the photon number in the translated fields

Tomography of trapped light

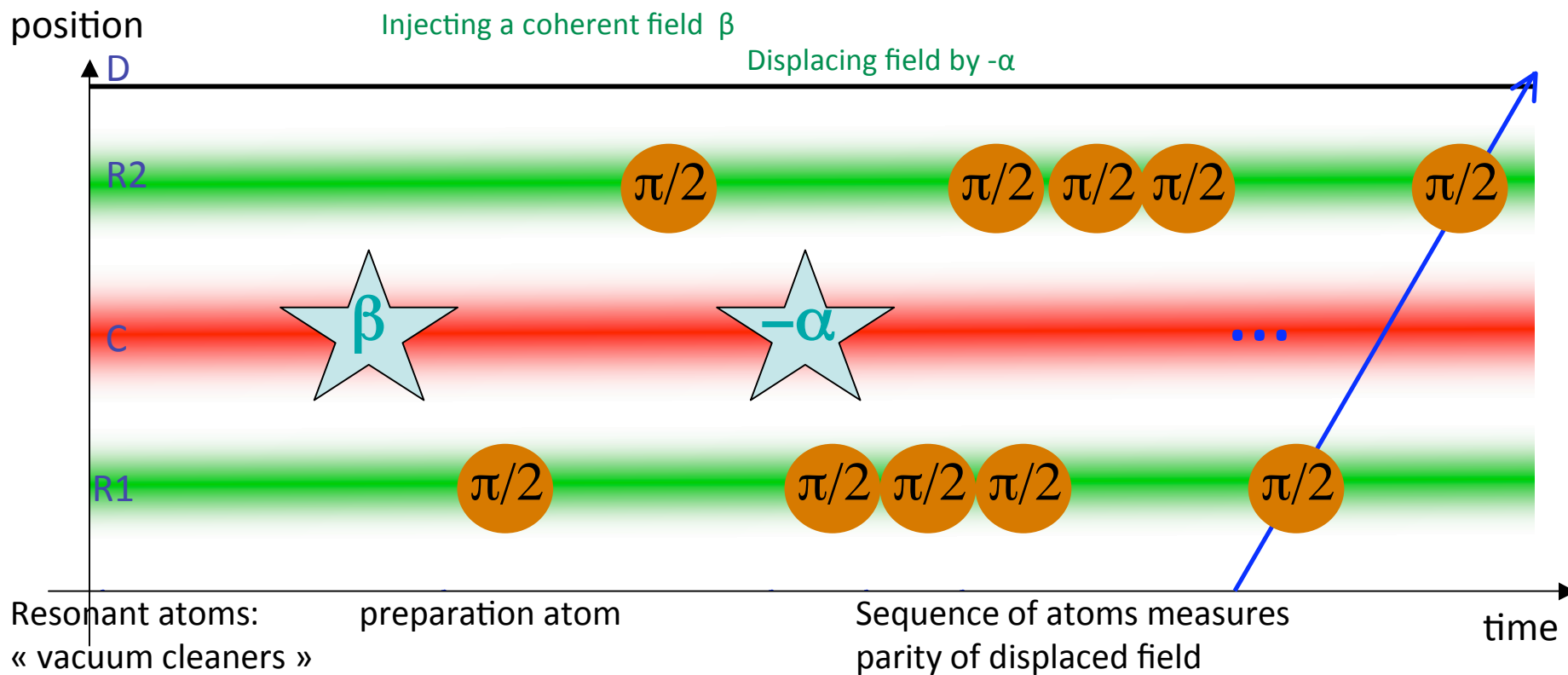
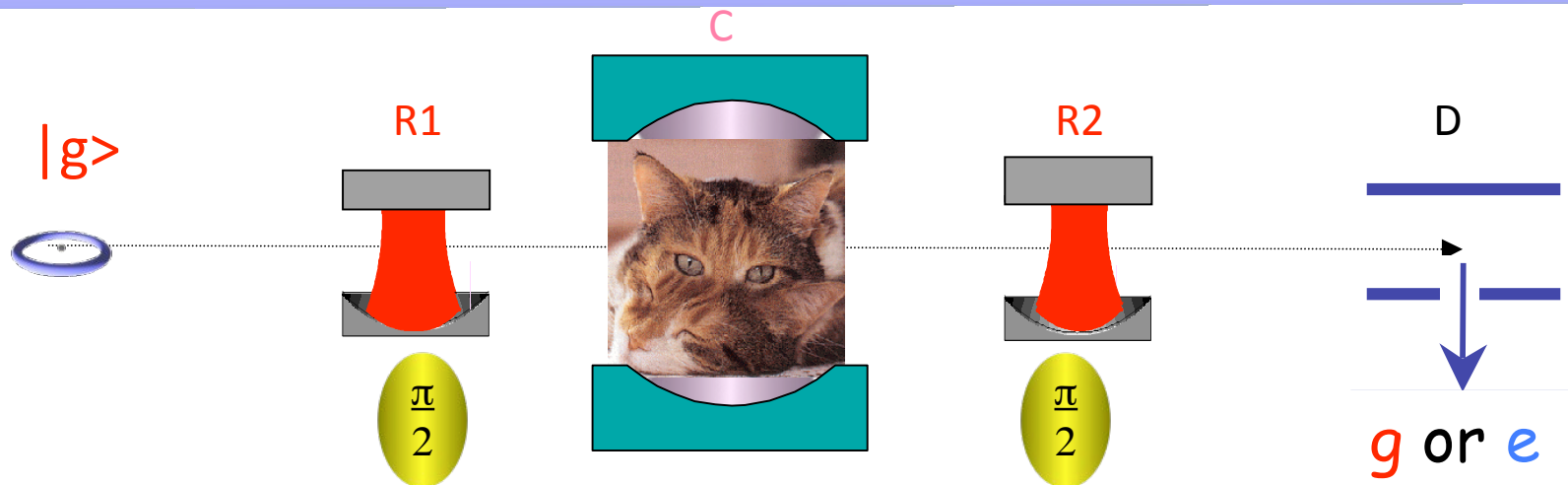
State reconstruction is analogous to CAT(*) SCAN medical tomography

(*): **CAT** is here acronym of
Computer
Assisted
Tomography
(not Schrödinger
CAT!)



Mixing with coherent fields of different complex amplitudes is equivalent to rotating the direction of observation in X ray cat scans. By a mathematical transform, a computer fully reconstructs the quantum state.

Preparing and reconstructing a « cat »

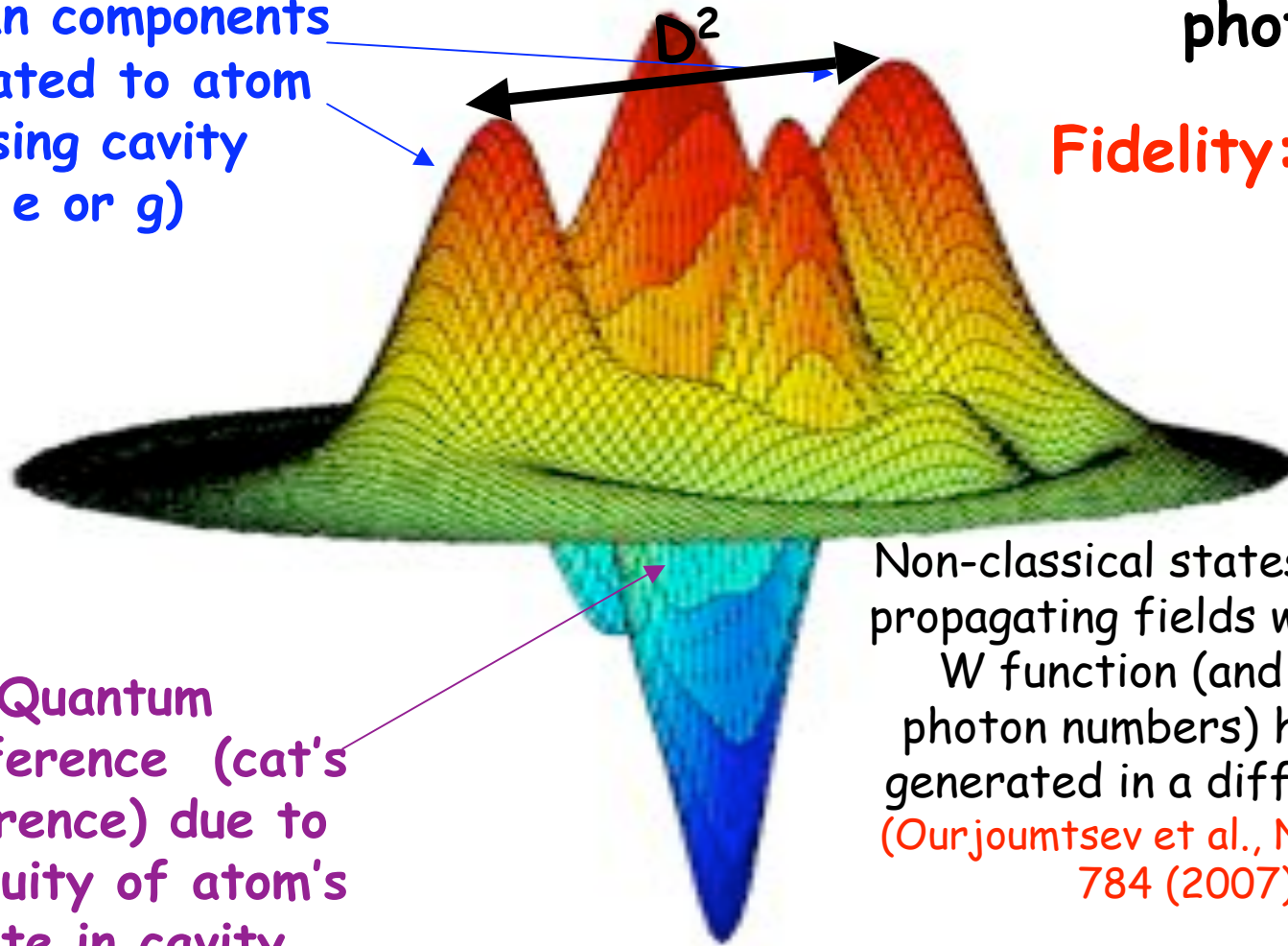


Reconstructed Wigner function of cat $|\beta\rangle + |-\beta\rangle$

$D^2 = 8$
photons

Gaussian components
(correlated to atom
crossing cavity
in e or g)

Fidelity: 0.72



Quantum
interference (cat's
coherence) due to
ambiguity of atom's
state in cavity

Non-classical states of freely
propagating fields with similar
W function (and smaller
photon numbers) have been
generated in a different way
(Ourjountsev et al., Nature 448,
784 (2007))

Similar W-functions reconstructions of synthesised superpositions of Fock
states by J. Martinis et al (SBU) in Circuit QED

Decoherence in action

The random **loss** of a single photon changes cat state parity.
On average, state turns into a statistical mixture: this is

decoherence

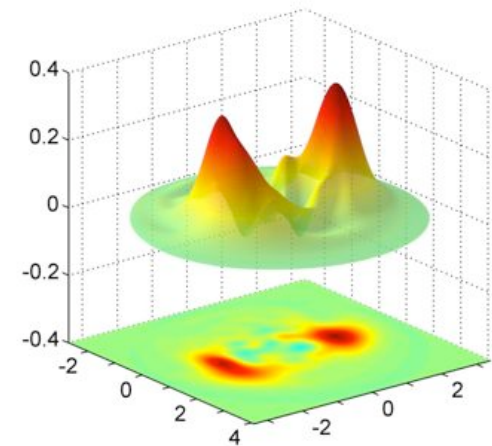
$$|\Psi_{\text{even}}\rangle = \frac{1}{\sqrt{2}} [|\beta\rangle + |-\beta\rangle] \quad + \quad |\Psi_{\text{odd}}\rangle = \frac{1}{\sqrt{2}} [|\beta\rangle - |-\beta\rangle]$$

Statistical mixture

$$\rho_{\text{mixture}} = \frac{1}{2} [|\beta\rangle\langle\beta| + |-\beta\rangle\langle-\beta|]$$

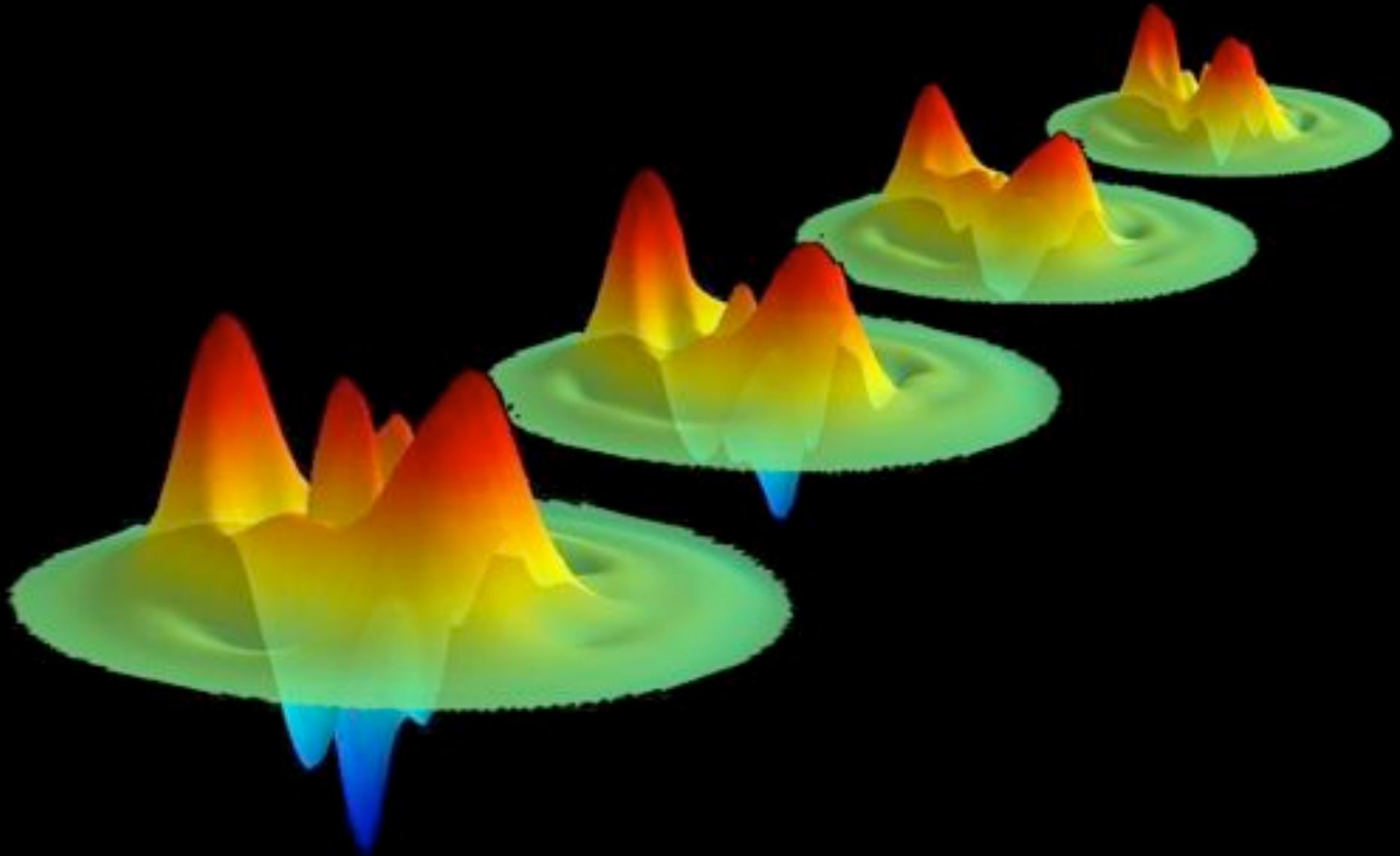
No more interferences on Wigner function

$$T_{\text{dec}} = \frac{2T_{\text{cav}}}{D_{\text{cat}}^2}$$

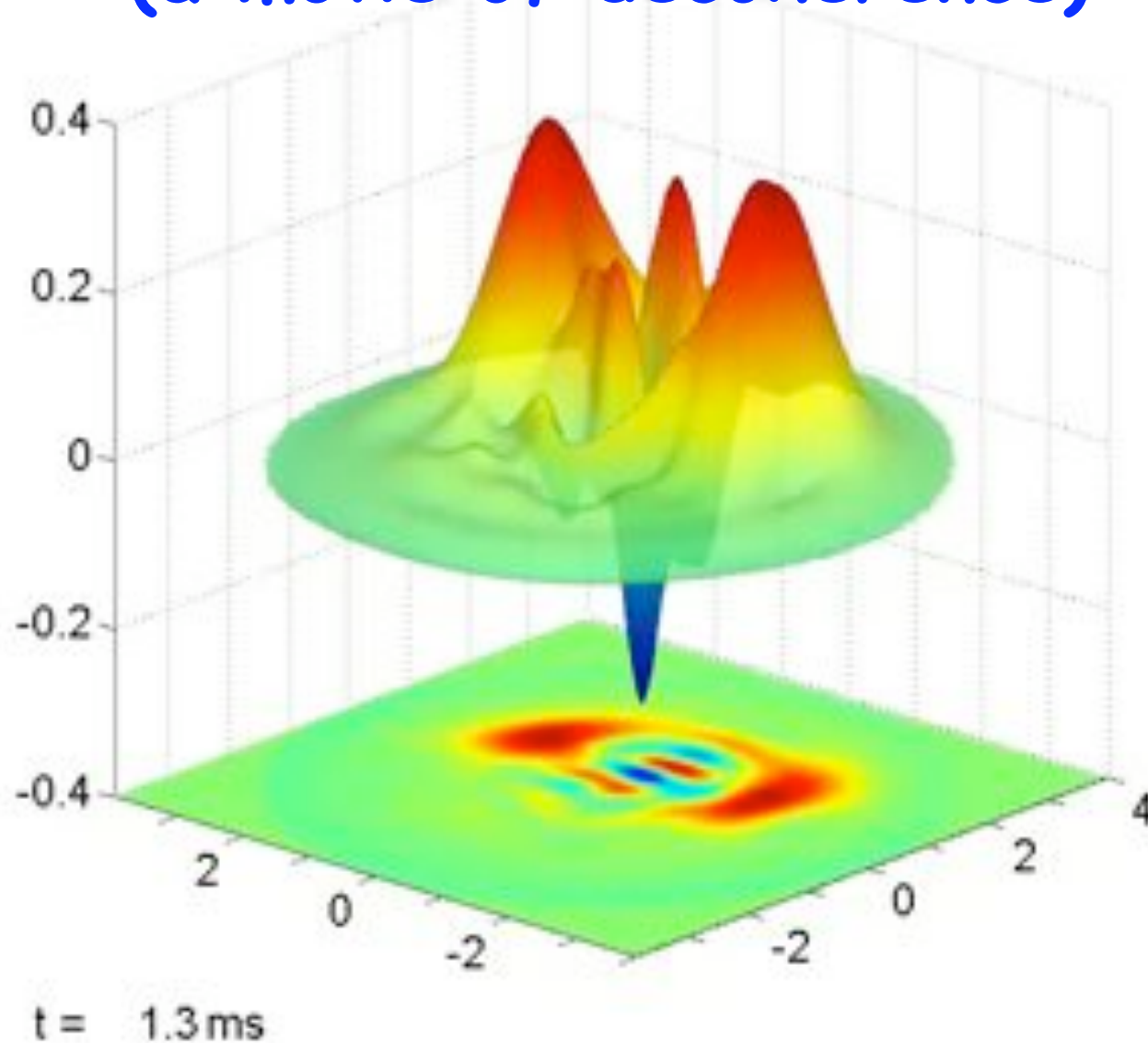


Coupling to environment destroys quantum interferences at a rate becoming larger and larger when « size » of system increases

A JOURNEY FROM QUANTUM TO CLASSICAL

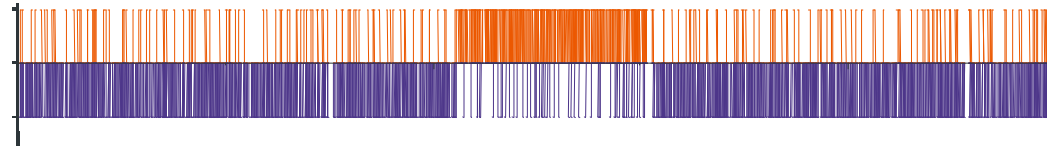


Fifty milliseconds in the life of a Schrödinger cat (a movie of decoherence)



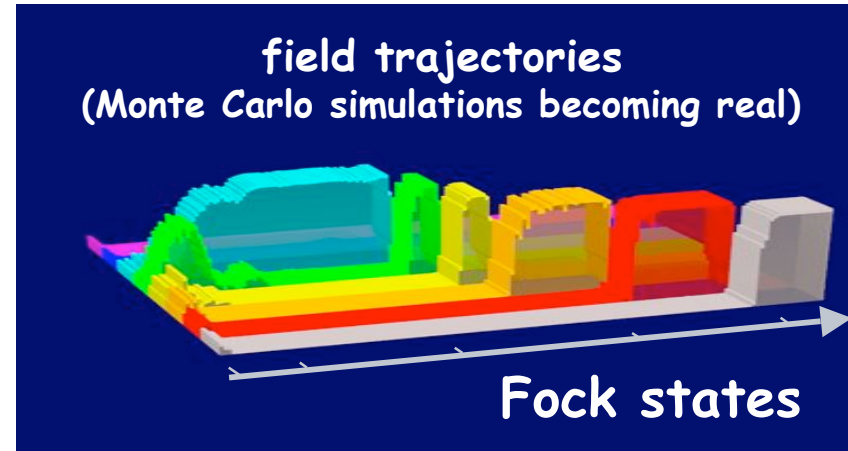
Conclusion and perspectives

Field quantum jumps

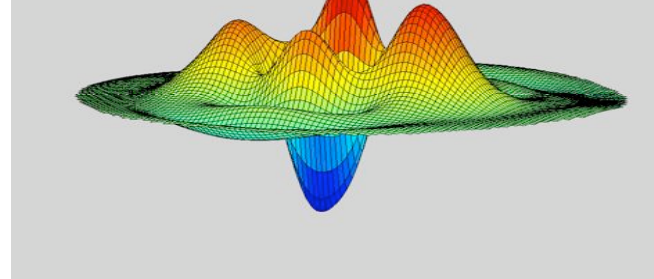


Trapping the light fantastic

Super-mirrors
make new ways
to look possible:
trapped photons
become like
trapped atoms

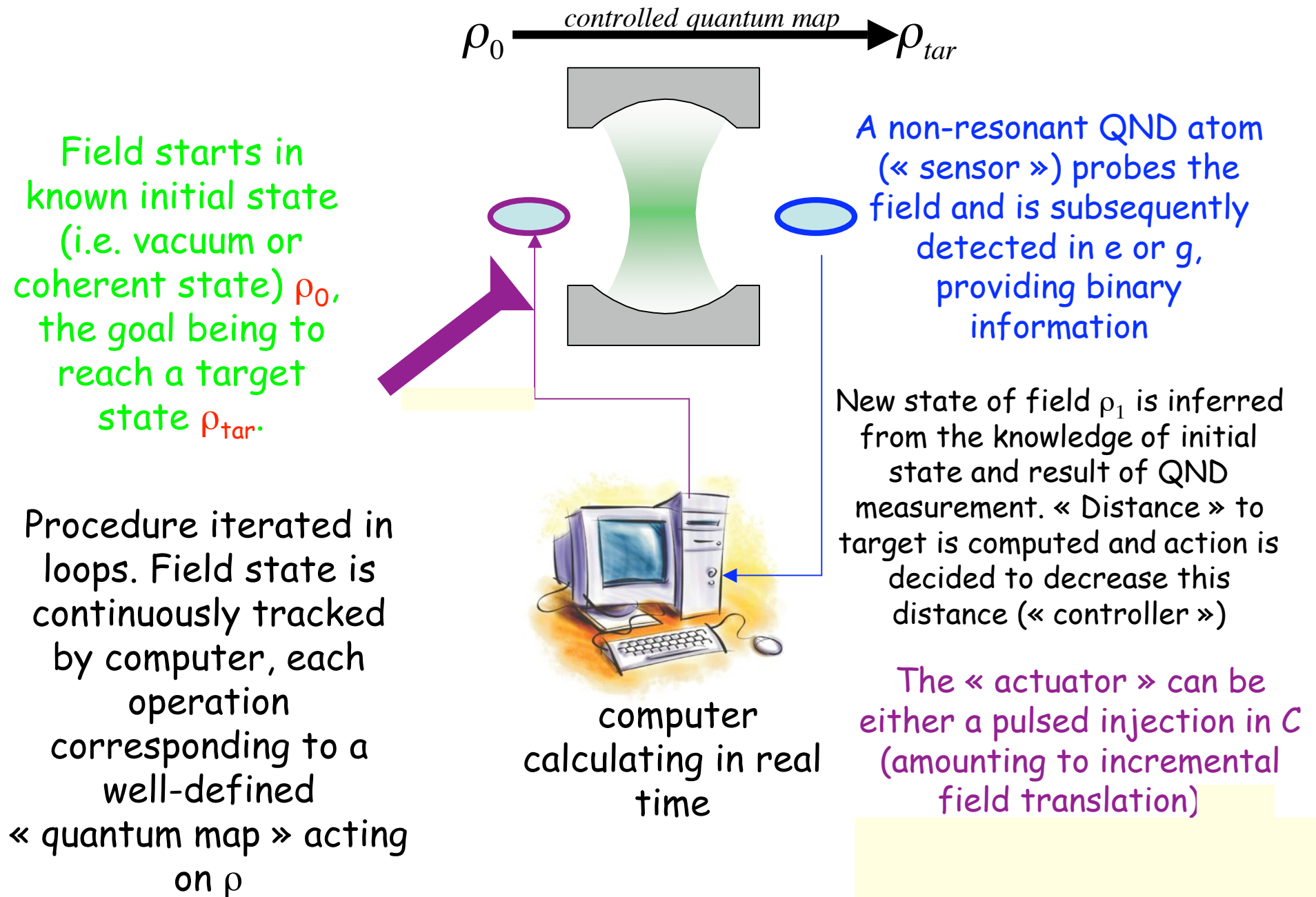


Preparing and reconstructing cats
and other non-classical states

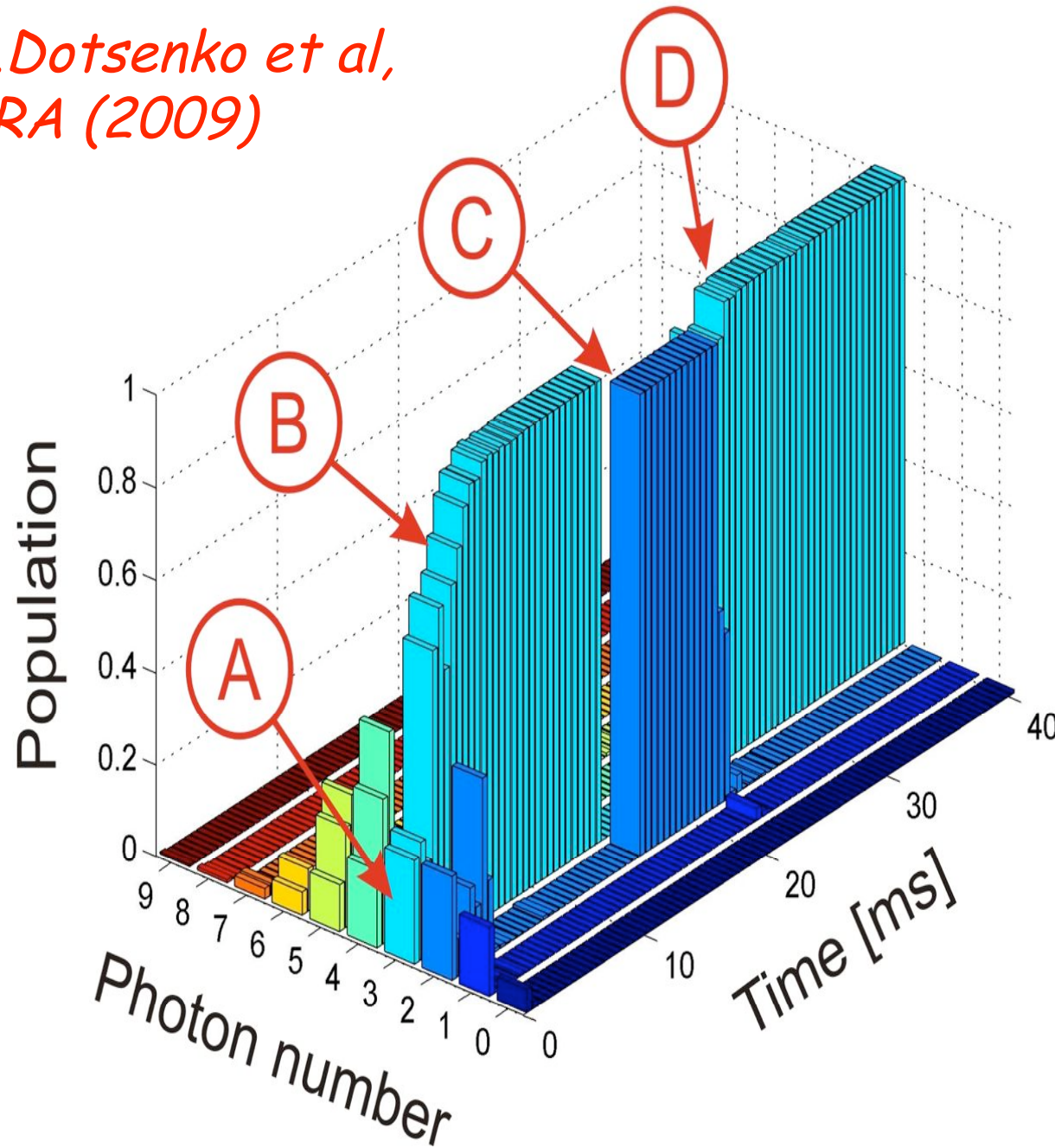


Soon, channelling field towards
desired state by quantum feedback..

The principle of quantum feedback



*I.Dotsenko et al,
PRA (2009)*

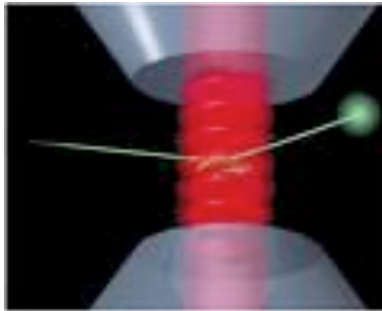


Example of field actuator

A simulation:

An initial coherent field (A) is steered by a few feedback loops towards the $n=3$ Fock state (B), then undergoes a quantum jump towards $n=2$ (C) before being brought back to $n=3$ by feedback correction (D)

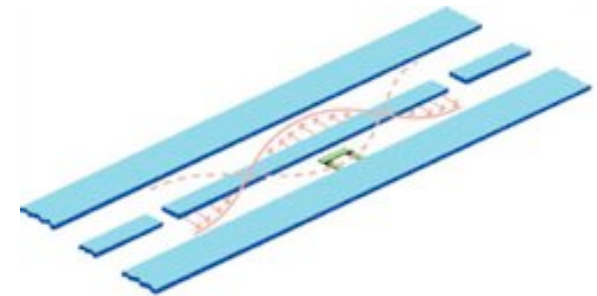
The ideas of Cavity QED are applied in many devices with real or artificial atoms and various kinds of cavities ...



Cold atoms in optical cavities



Quantum dots in semiconductors



Circuit QED with Josephson junctions coupled to coaxial lines



Atoms or quantum dots coupled to optical microresonators



Quantum optomechanics



Emis

The Paris CQED group



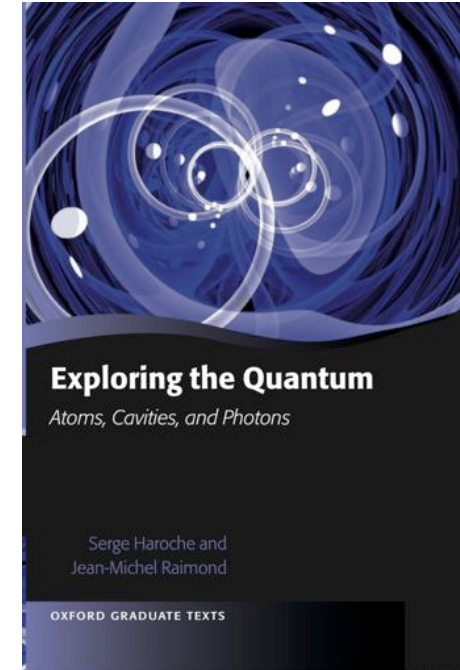
F.Schmidt-Kaler,
 E.Hagley,
 C.Wunderlich,
 P.Milman,
 A. Qarry,
 F.Bernardot,
 P.Nussenzweig,
 A.Maali,
 J.Dreyer,
 X.Maître,
 G.Nogues
 A.Rauschenbeutel
 P.Bertet,
 S.Osnaghi,
 A.Auffeves,
 T.Meunier,
 P.Maioli,
 P.Hyafil,
 J.Mosley,
 U.Busk Hoff
 T.Nierengarten
 C.Roux
 A.Emmert
 A.Lipascu
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 S.Deléglise*
 C.Sayrin
 Z.Xing-Xing
 B.Peaudecerf



Exploring the Quantum
Atoms, cavities and Photons
 S.Haroche and J-M.Raimond
 Oxford University Press



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Photo credit: M.Lebidinsky, CNRS