Exploring the quantum with atoms and cavities

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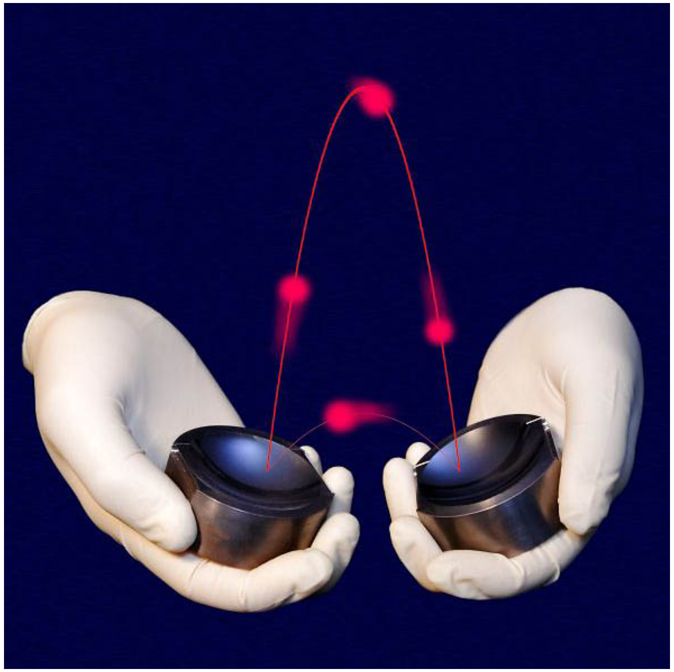
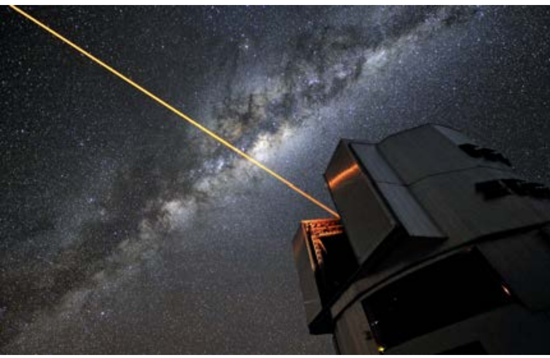


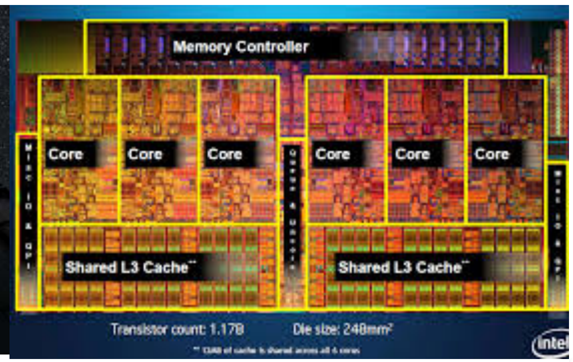
Two radically different paths to explore quantum Nature

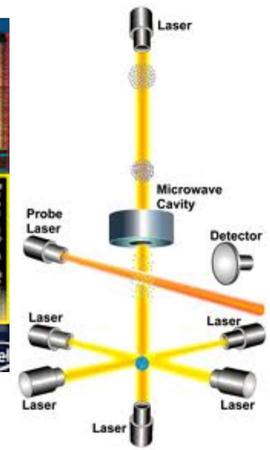
- The hard route
  - Constructing quantum (field) theory from first principles
- The quick and dirty experimental route
  - Look at quantum Nature at work
    - In situations simple enough to bring a direct insight into the most intimate quantum features.
  - No maths, a lot of plumbing, nuts and bolts
    - But some hopefully interesting questions to unveil and discuss
- At some point (« DEA Brossel », 39 years ago), Vincent and I chose to part on these two routes (being much older than me he chosed the had way…)
  - A splitting, which did not hamper a long-term friendship…
    - Happy birthday, Vincent !!

A century of quantum physics

- A detailed understanding of the micro-world and…
  - Countless applications
    - Lasers, solid-state electronics, clocks, MRI…







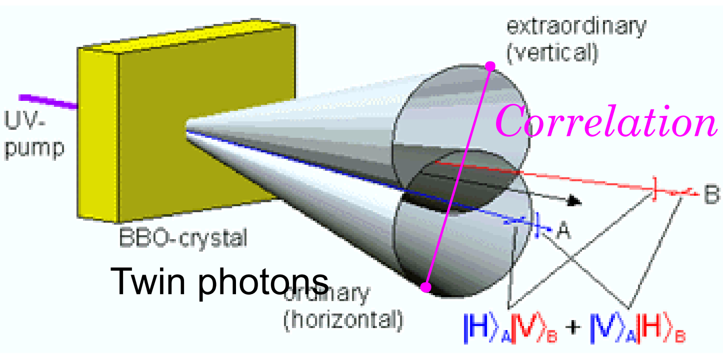
  - A considerable societal and economic impact
    - Large part of GDP results from quantum technologies
      - Also large part of our lifetime expectation!
    - No information society without the quantum
  - An astounding example of the impact of curiosity-driven blue-sky research on the long term
    - Lessons for science support and granting system ?

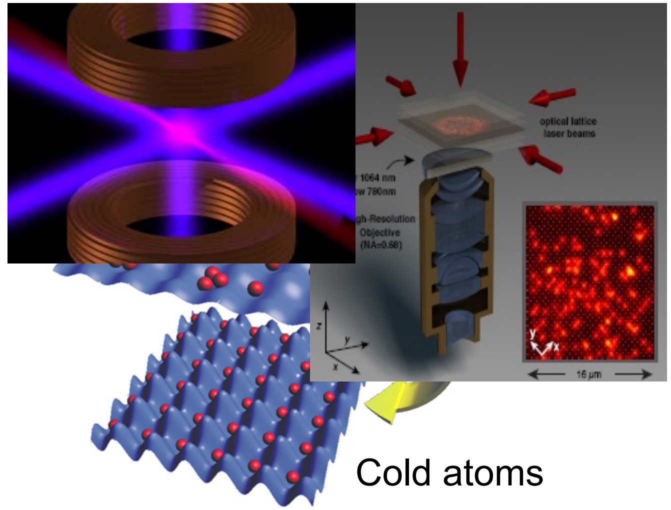
An unprecendented series of sucess…

- …and provided us with extraordinary experimental tools
  - Lasers, computers allow us to manipulate quantum systems
    - Quantum technology makes it possible to explore the quantum.
    - The gedankenexperiments are made real
      - And quantum mechanics passes the test !
        - » What we do observe is precisely what the founding fathers extraordinary wits allowed them to predict
  - Why exploring the quantum 100 years after Bohr?
    - Better confidence in the quantum
    - Better understanding of the interpretation(s)
      - Measurement, state superpositions
    - Exploring the limits of the quantum
      - No quantum behaviors (superpositions aso) at our scale ?
    - Insights into new quantum technologies

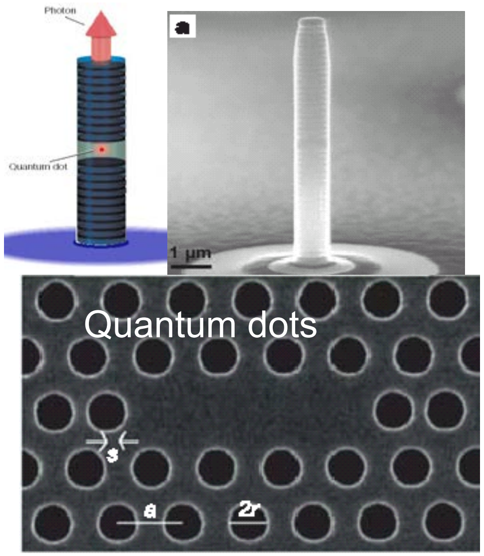
A thriving field worldwide

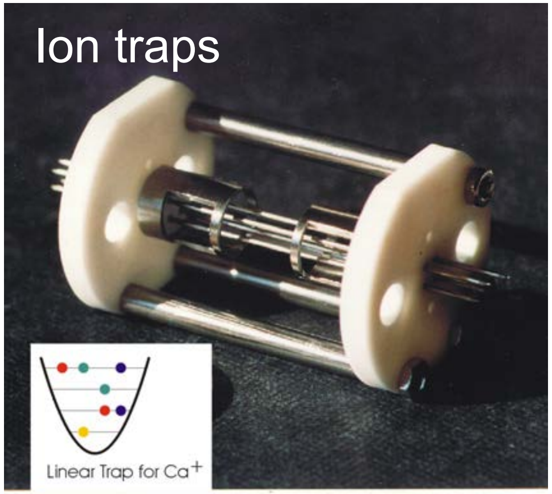
- Many experimental schemes manipulate individual quantum systems

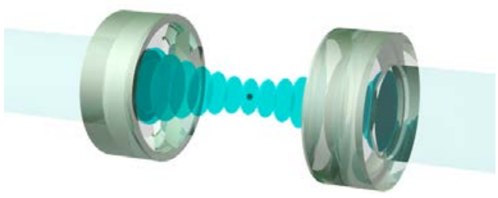




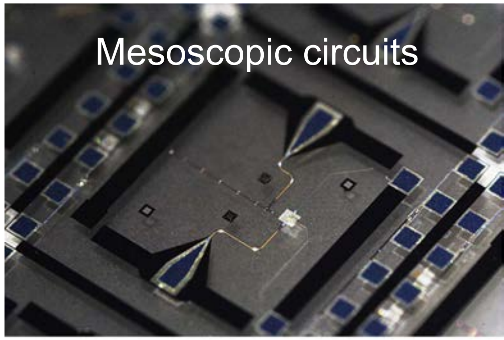
Cold atoms





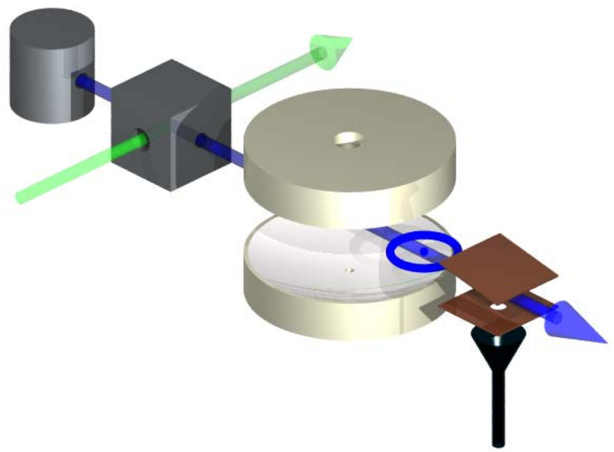


Atoms and cavities



Cavity Quantum Electrodynamics

- A spin and a spring



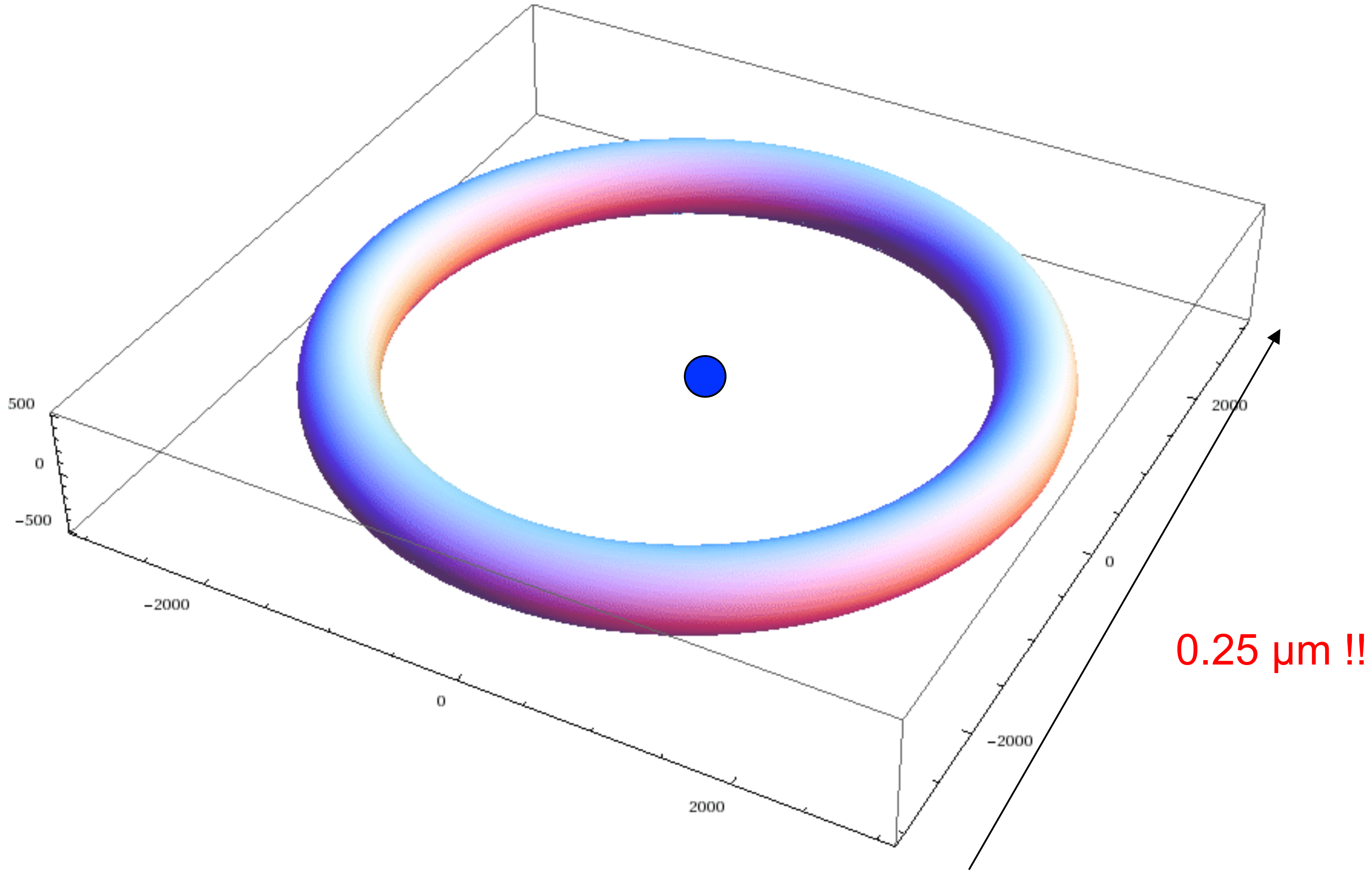
  - Realizes the simplest matter-field system: a single atom coherently coupled to a few photons in a single mode of the radiation field, sustained by a high quality cavity.
  - Direct realization of thought experiments and illustrations of quantum postulates with circular Rydberg atoms and superconducting cavities
    - Measurement
    - Complementarity
    - Macroscopic quantum superpositions (decoherence)

A nearly ideal photon box

- Two mirrors
  - Separation 3 cm
    - Wavelength 6 mm, 51 GHz
  - Superconducting
    - No losses
    - Nearly perfect reflection
  - Photon lifetime T_c= 0.13s !
    - 1 billion bounces
    - 40000km
  - The best mirrors in the world

Circular Rydberg states

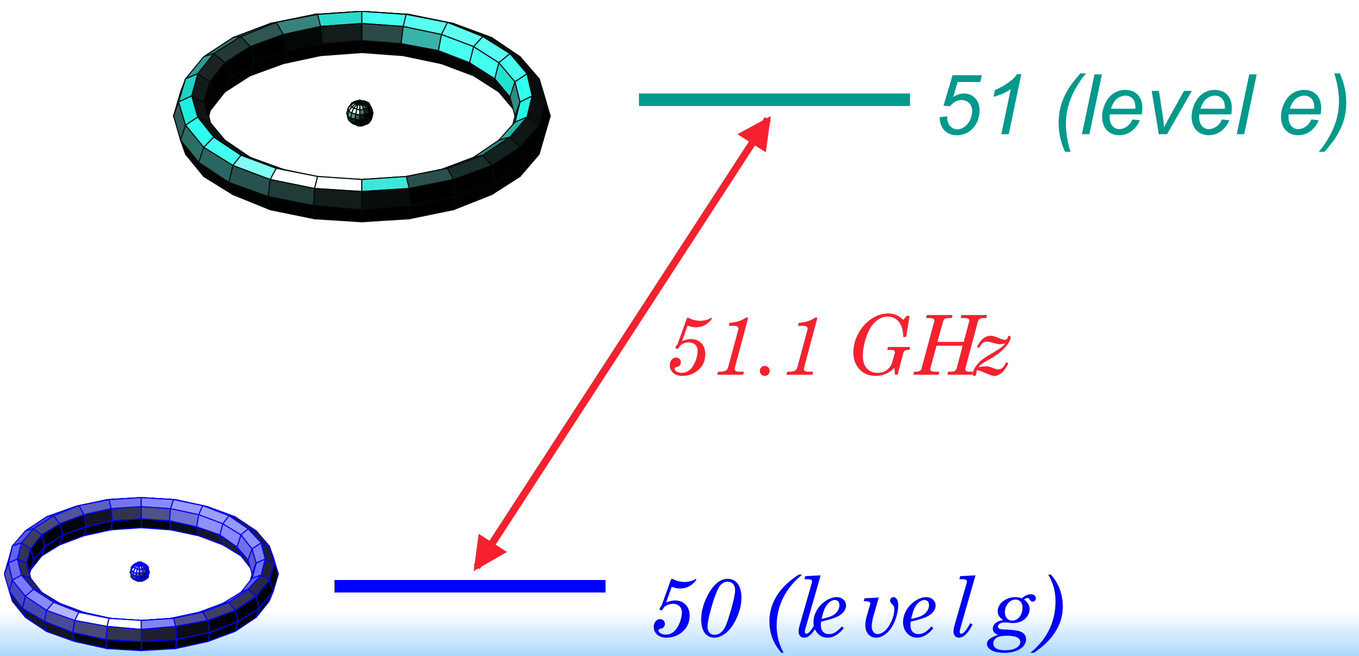
- Giant atoms
  - Highly excited atomic levels



A ground state atom is 2500 times smaller !!

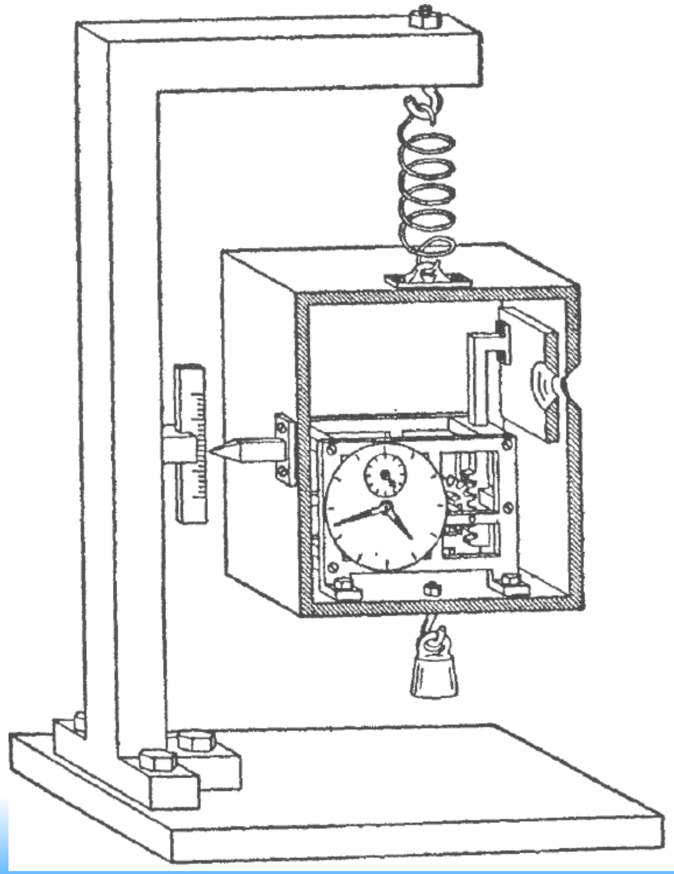
Circular Rydberg states

- Ideal atoms
  - Long lifetime (30ms)
  - Strong coupling to the cavity field
  - Efficient state-selective detection
  - Some technicalities in the preparation stage

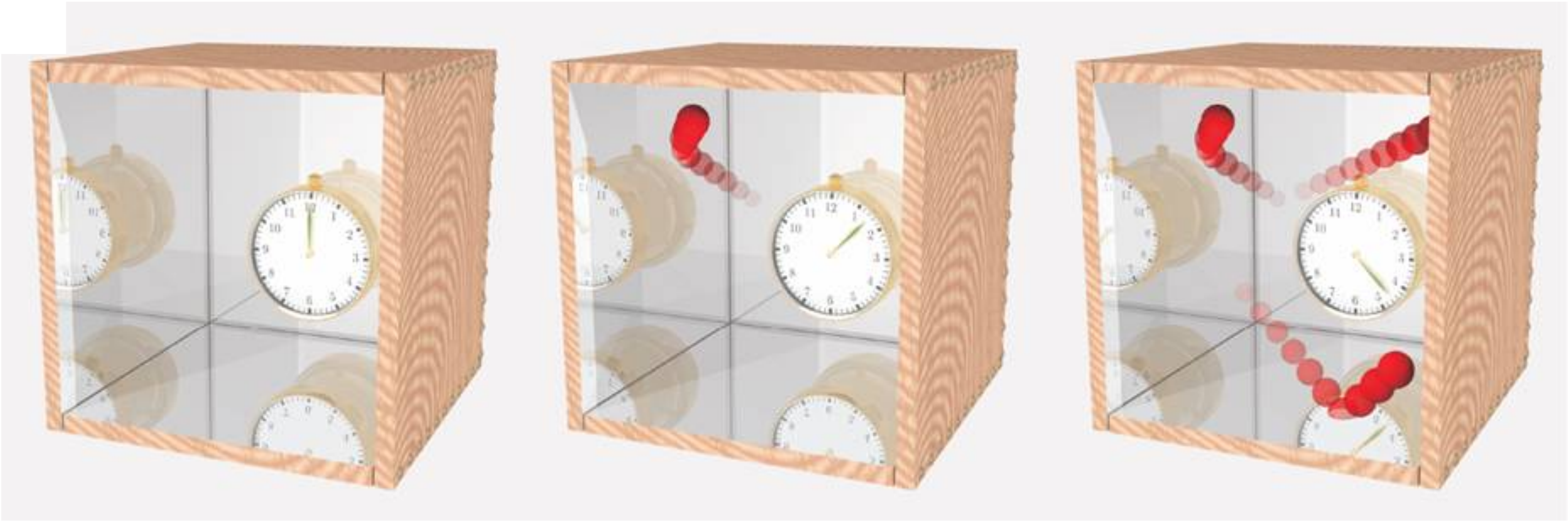


An ideal photon counter ?

- All standard detectors destroy the incoming photons
  - A Quantum Non Demolition photodetector operating at the individual photon level
- A photon ‘box’ able to store a photon for a long time
    - back to Einstein-Bohr’s dream: weighing a photon

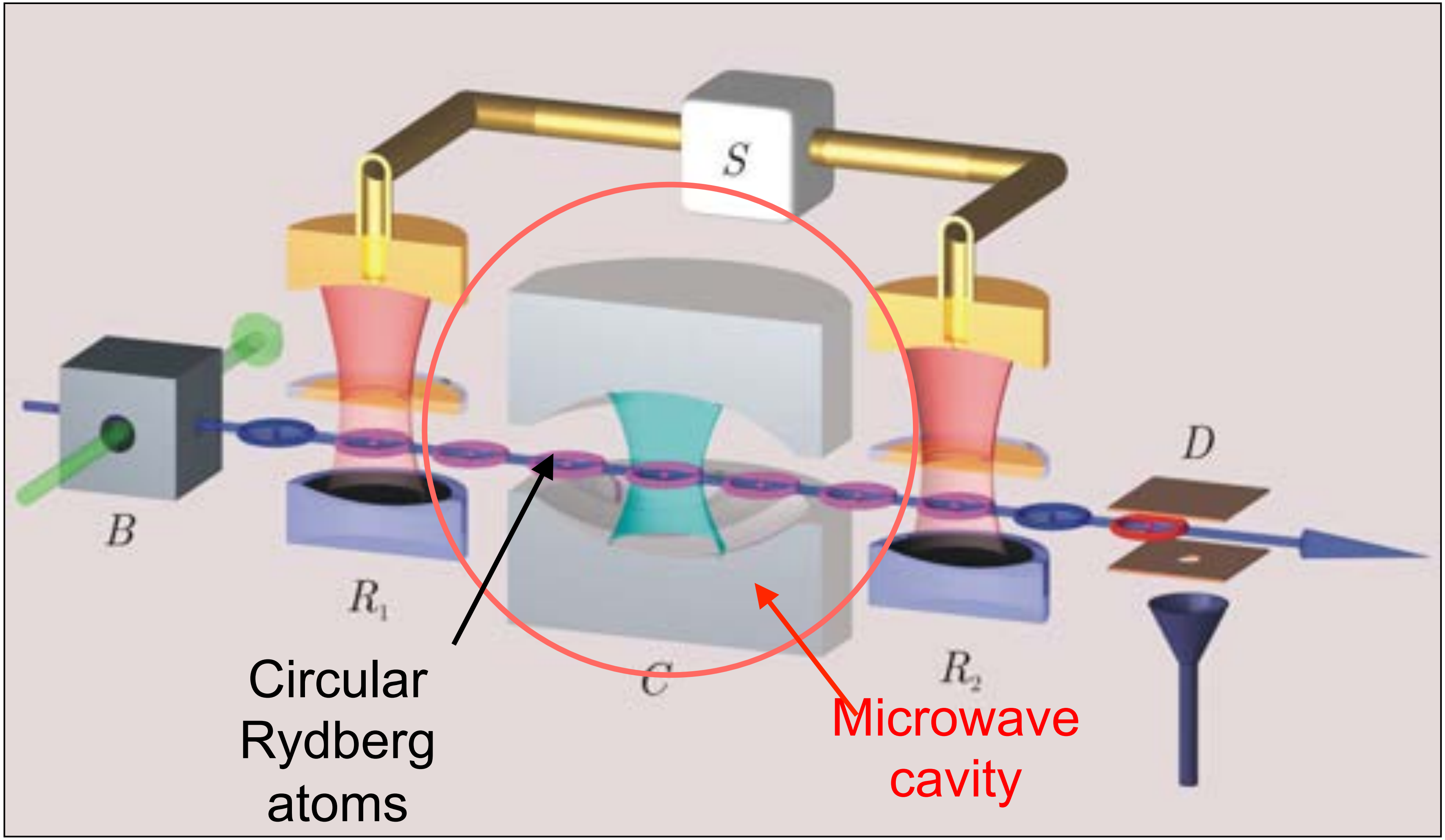


Yet another gedankenexperiment

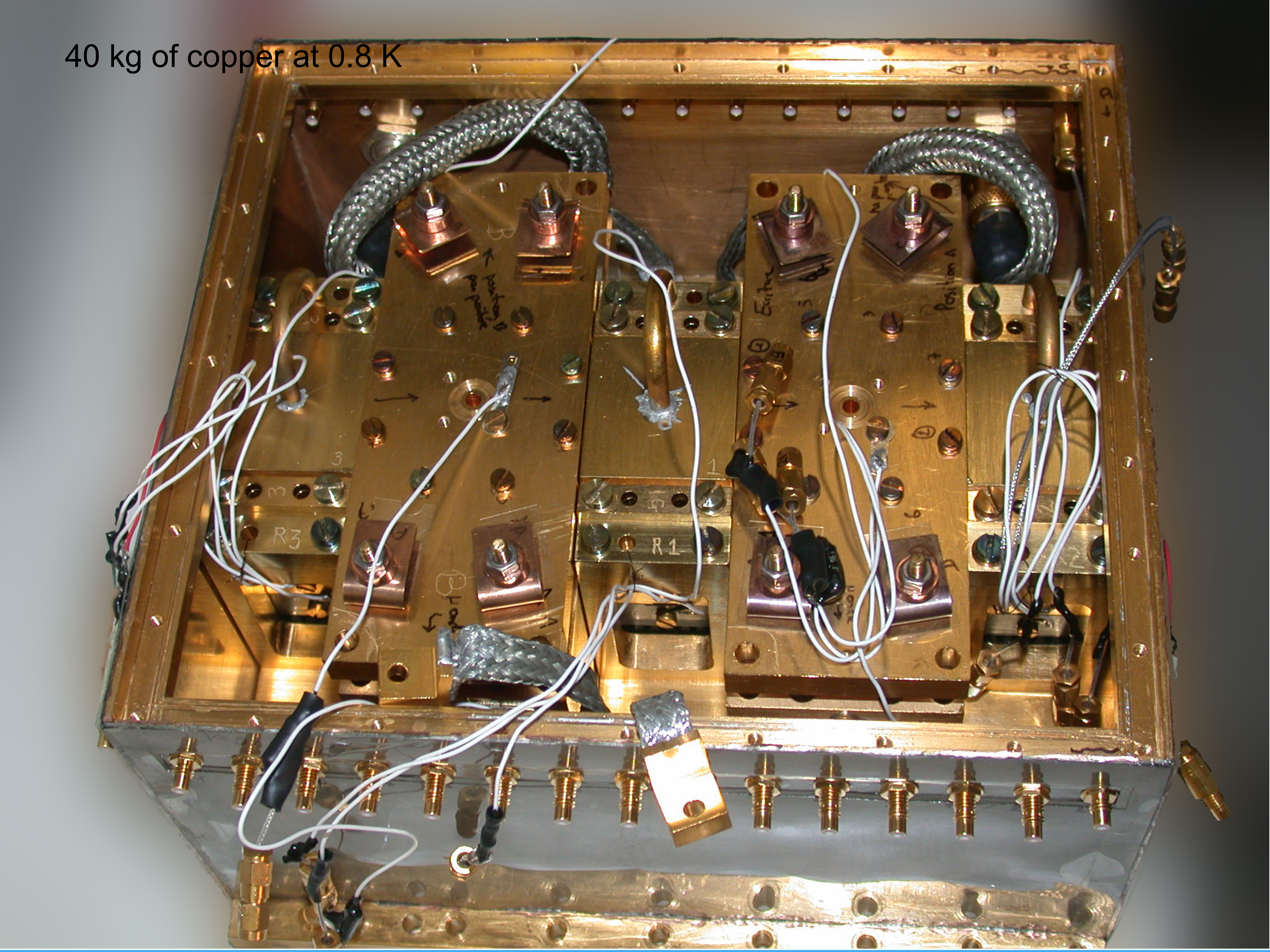


- A clock whose ticking rate is determined by the number of photons in a box
- The final clock hand's position directly measures the photon number
  - Photon box: a superconducting cavity
  - Clock: a single circular Rydberg atom

Experimental set-up



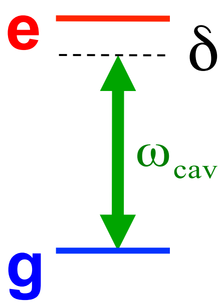
RMP **73**, 565

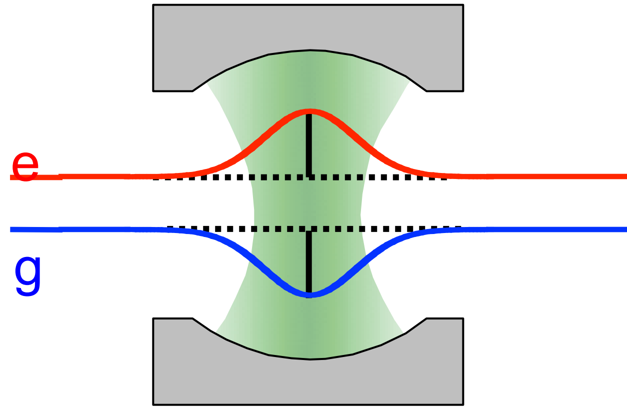


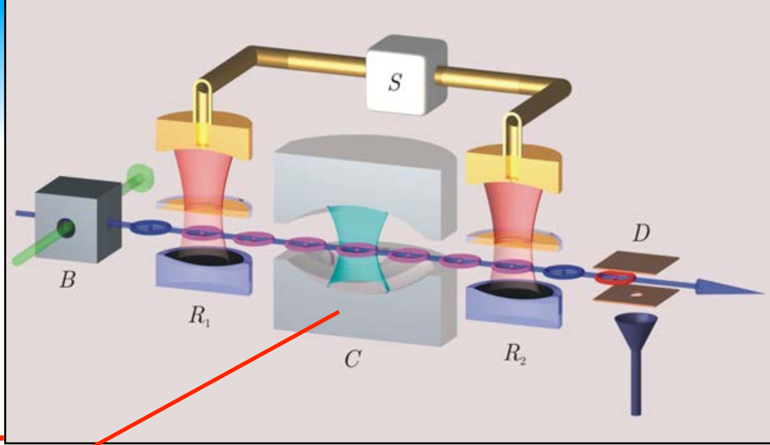
40 kg of copper at 0.8 K

QND measurement

- Quantized light-shifts in the cavity





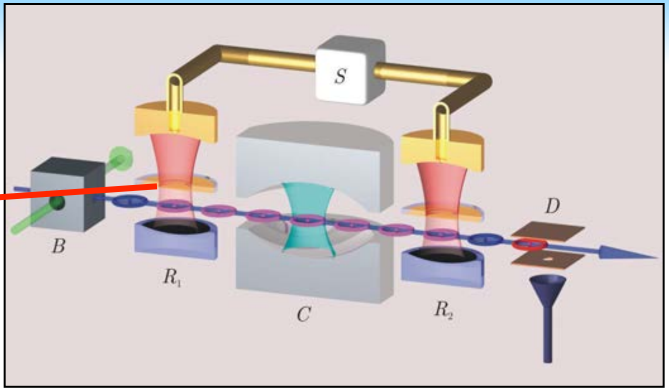


- Atomic clock modified by the interaction with the field
- Modification measured by Ramsey interferometry
  – A state superposition, prepared by a π/2 pulse in R_1, accumulates a phase shift $\phi_0 \left(n + 1/2 \right)$

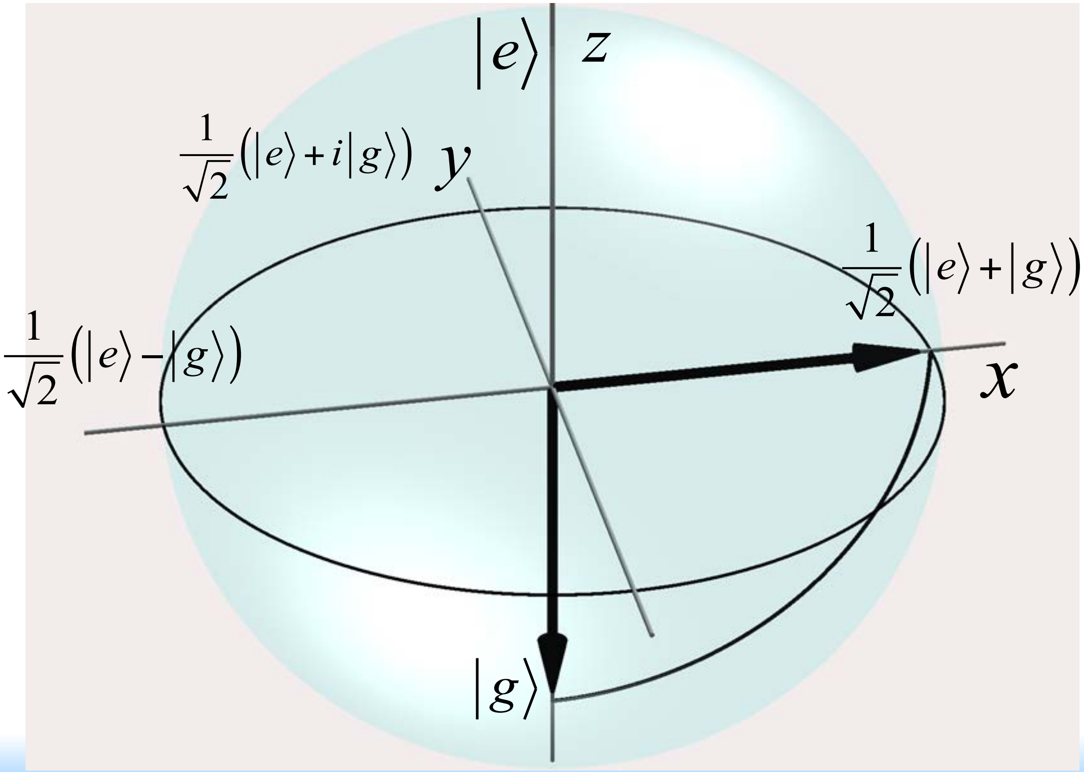
  – Phase shift read out by a second π/2 pulse in R_2 and final atomic state detection in D

Starting the clock

- Create an atomic coherence
  - In R_1 : $|g\rangle \rightarrow \frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)$

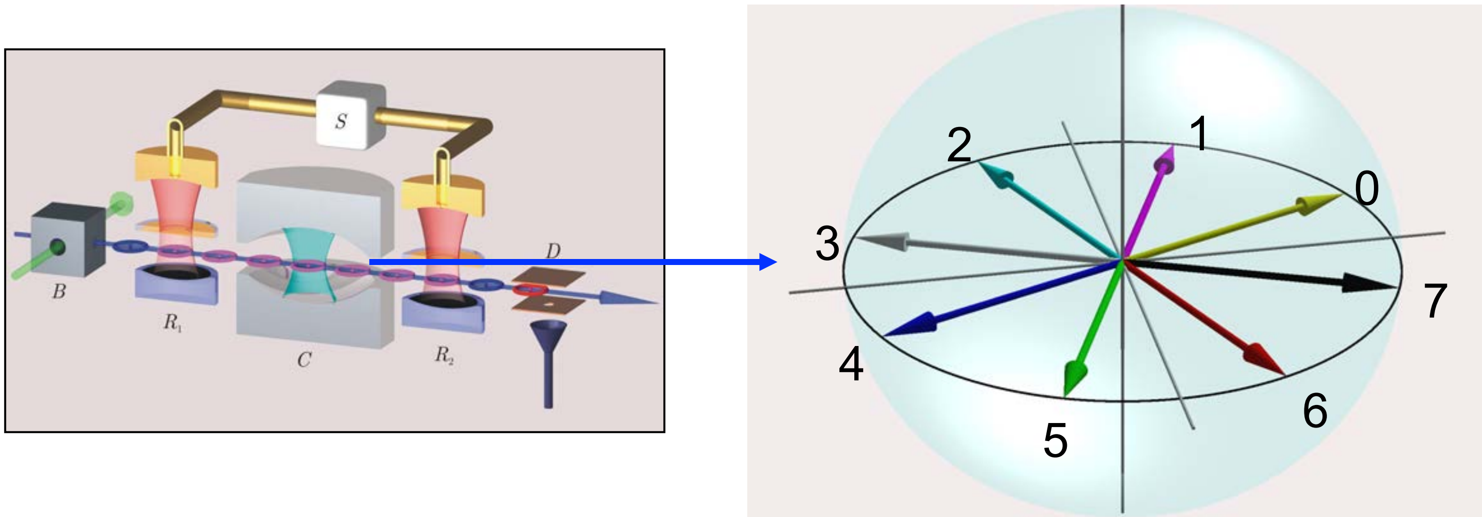


  - A simple geometrical representation: Bloch sphere for the spin ½ representing the two-level atomic transition



Quantized rotation of the atomic spin

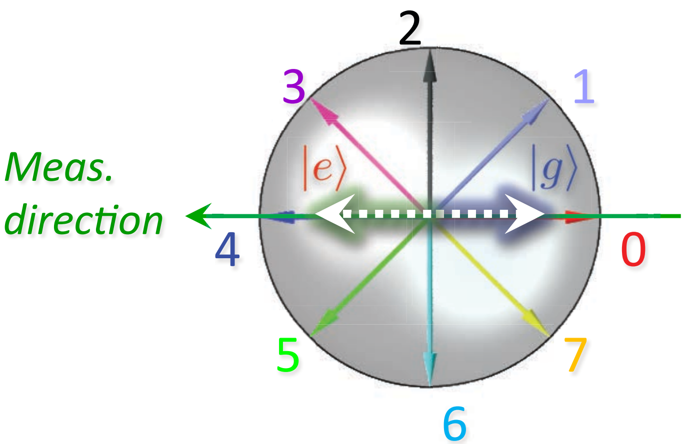
- Photon-number dependent phase shift of the atomic coherence



$$\phi_0 = \frac{\pi}{4}$$

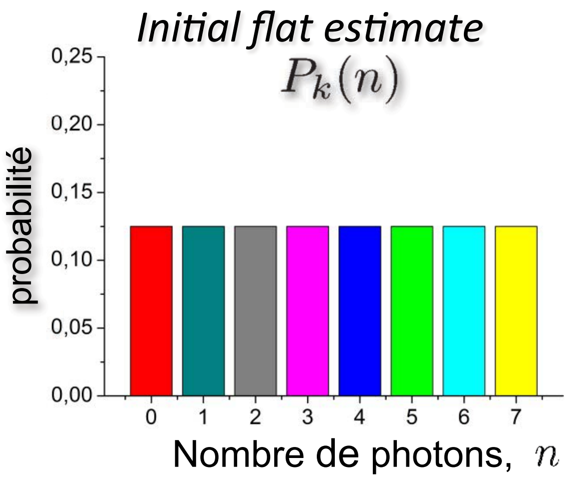
  - The Bloch vector direction reveals the photon number
  - In general non-orthogonal final atomic states correspond to different photon numbers: A single atom does not tell all the story
  - By choosing the phase of the pulse in R_2, measure the component of the spin in any direction of the equatorial plane

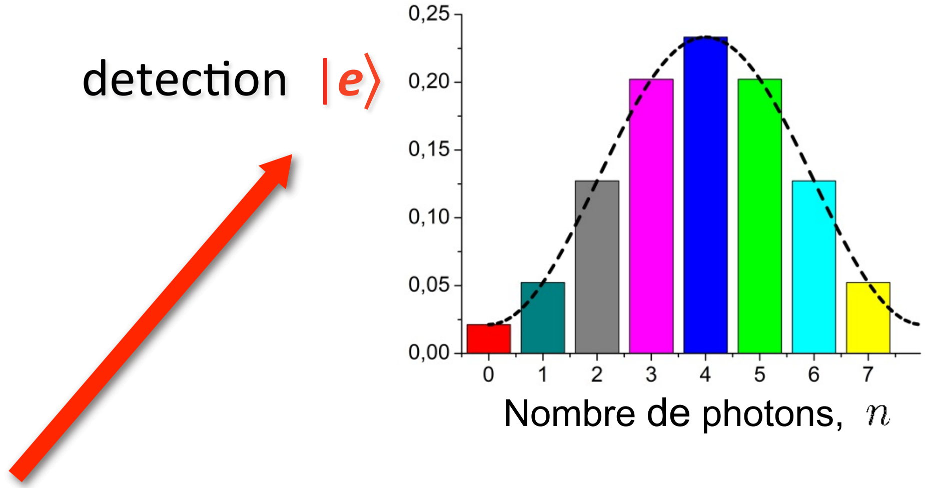
Single atom detection

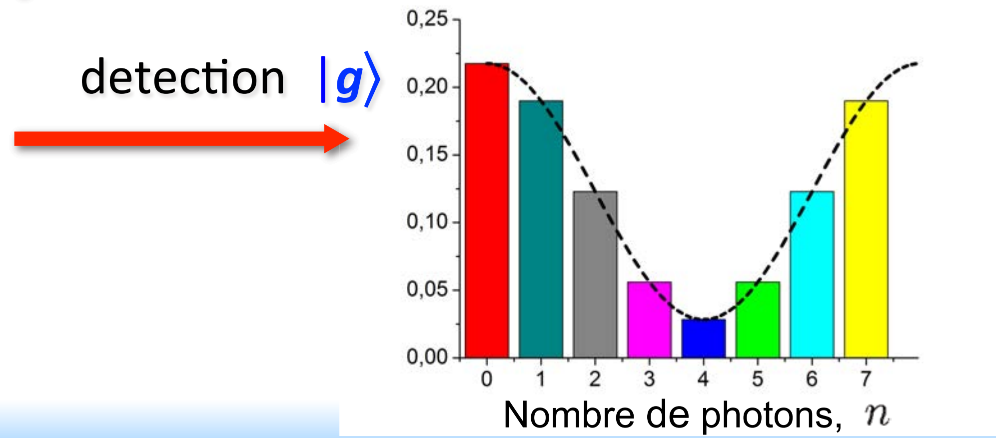


Each detection brings partial information on the photon number

$$P_{k+1}(n) \propto p(e|n)P_k(n)$$







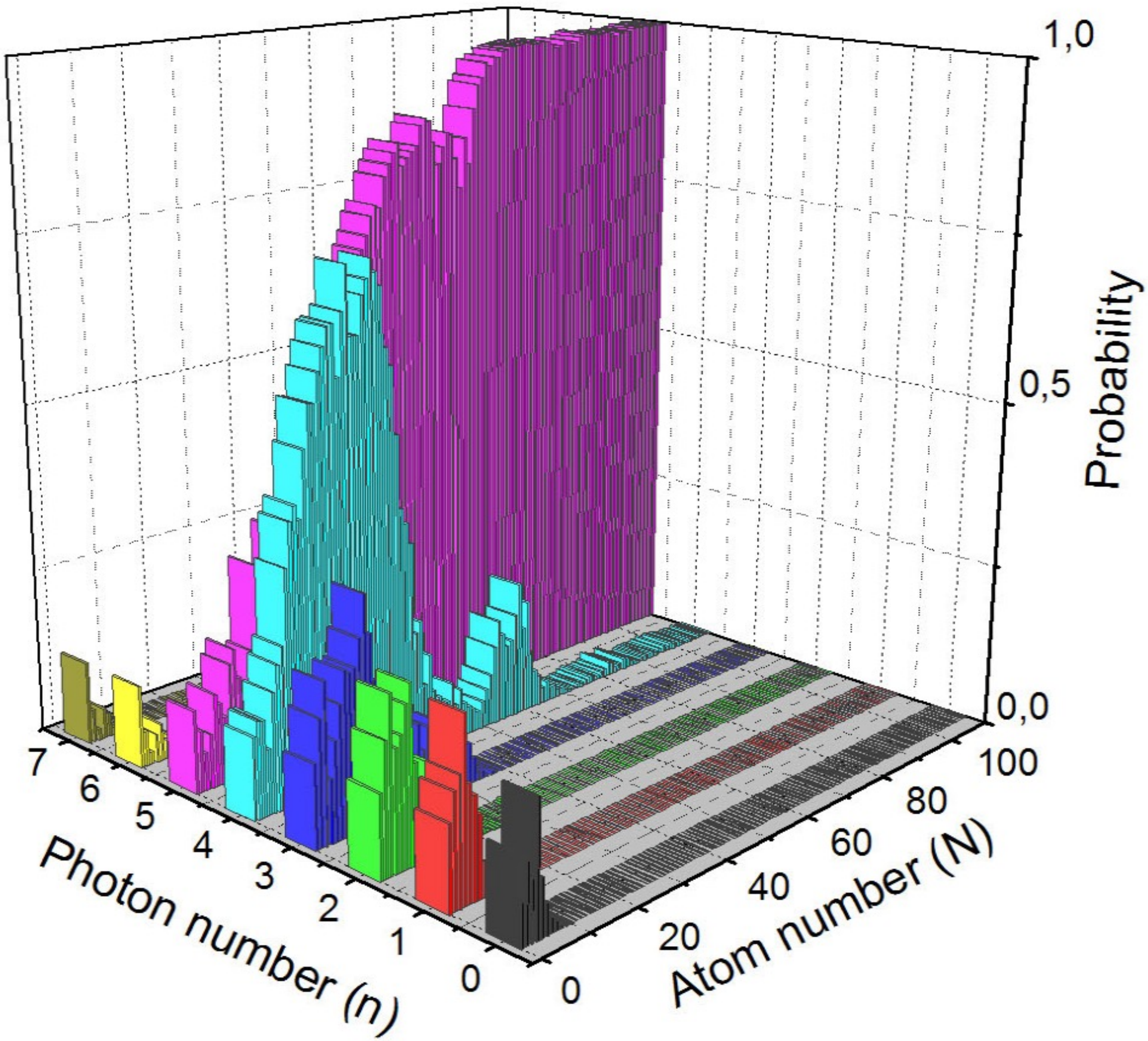
Bayesian inference of the photon number distribution

- Each atom brings partial information on the photon number
  - Recording atomic state changes our inference of the photon number distribution P(n)
    - P(n) multiplied by a sine function after each atomic detection

      (probability to get the atom in the detected state as a function of the photon number
      - Some photon numbers nearly ruled out

- Cumulative decimation of the photon number distribution pins down the photon number
  - Use four settings of the measurement direction chosen randomly
    - Removes any ambiguity and speeds up decimation
  - Requires about n_m^2 atoms to distinguish n_m photon states
    - Statistical noise on the atomic detections

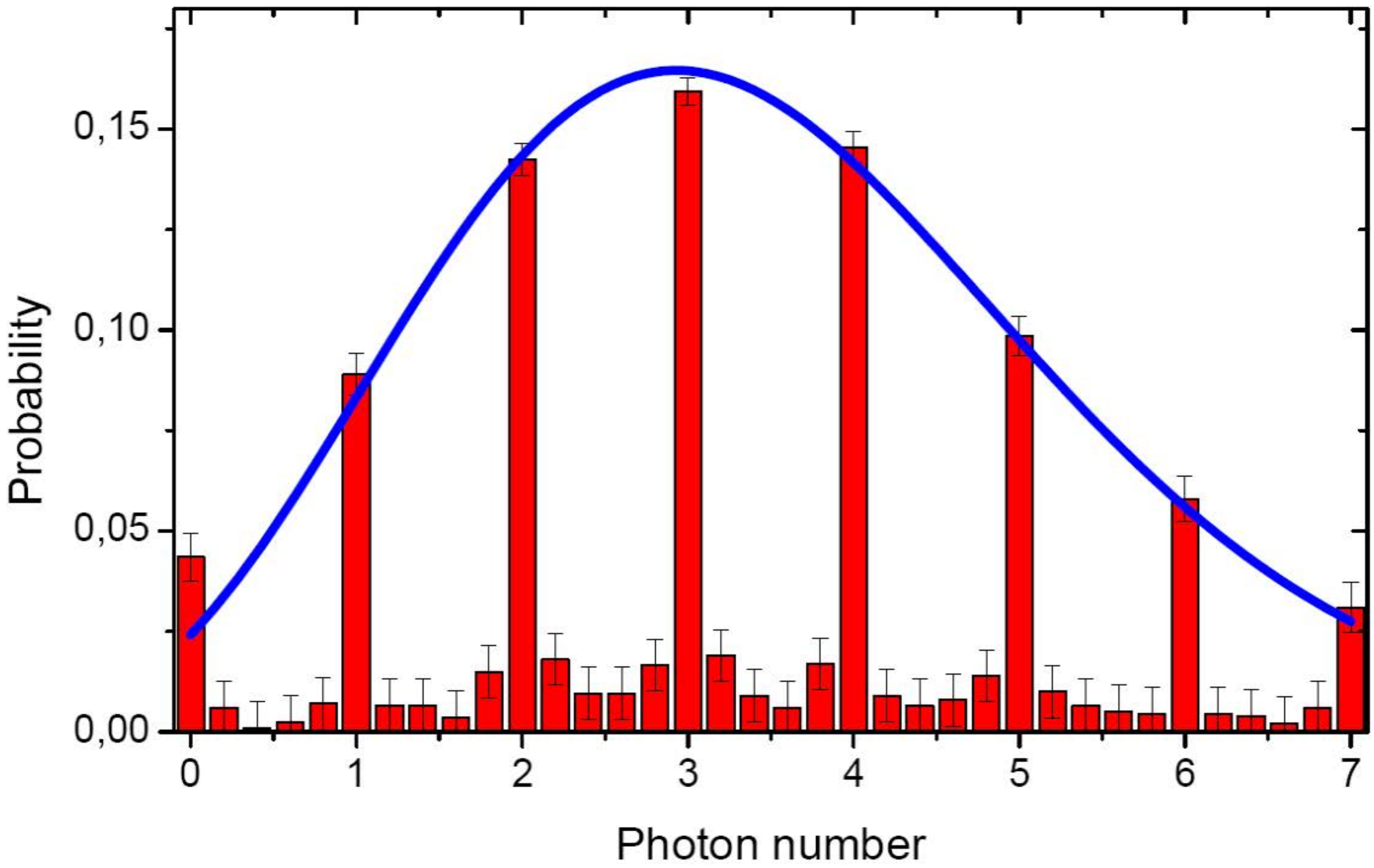
Wave-function collapse in real time



- Evolution of P(n) while detecting 110 atoms in a single sequence
- Initial coherent field with 3.7photons
- Initial inferred distribution flat (no information) but final result independent of initial choice
- Progressive collapse of the field state vector during information acquisition

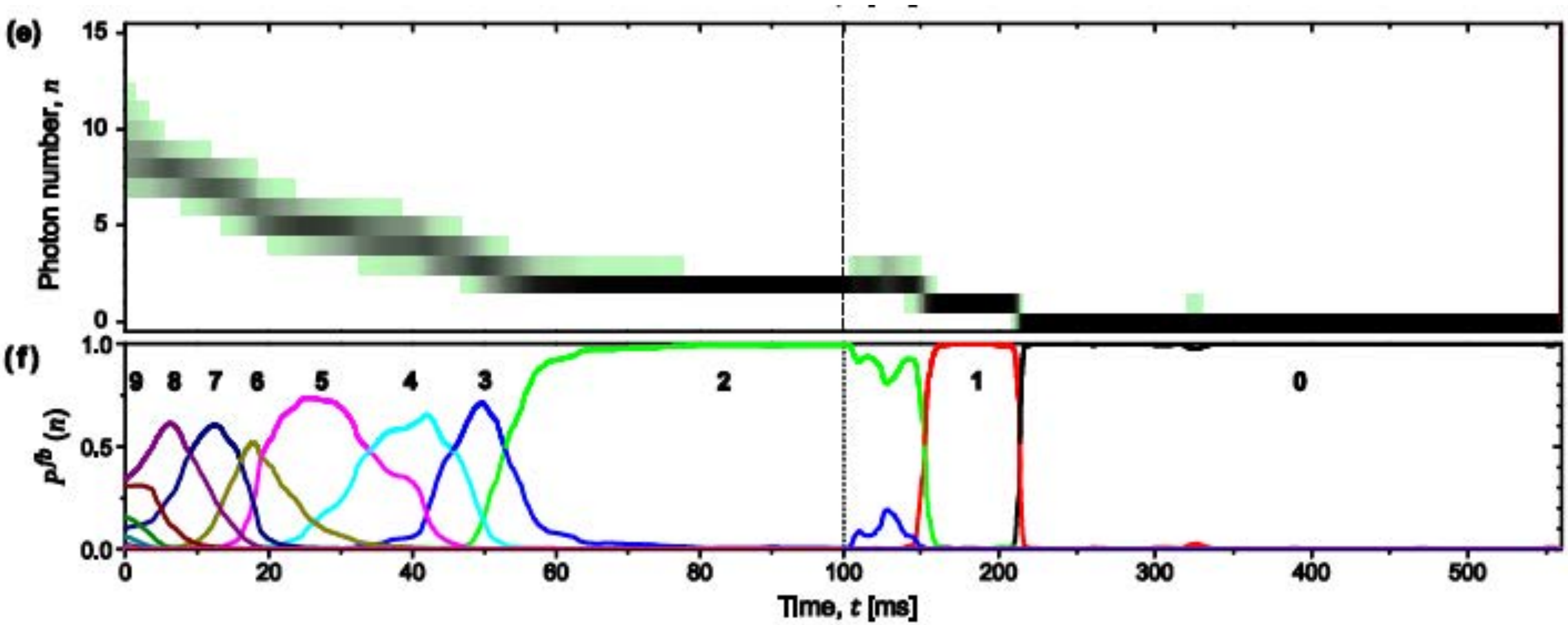
C. Guerlin et al, Nature, **448**, 889

Photon number statistics



Excellent agreement with the expected Poisson distribution

Monitoring the light quantum jumps

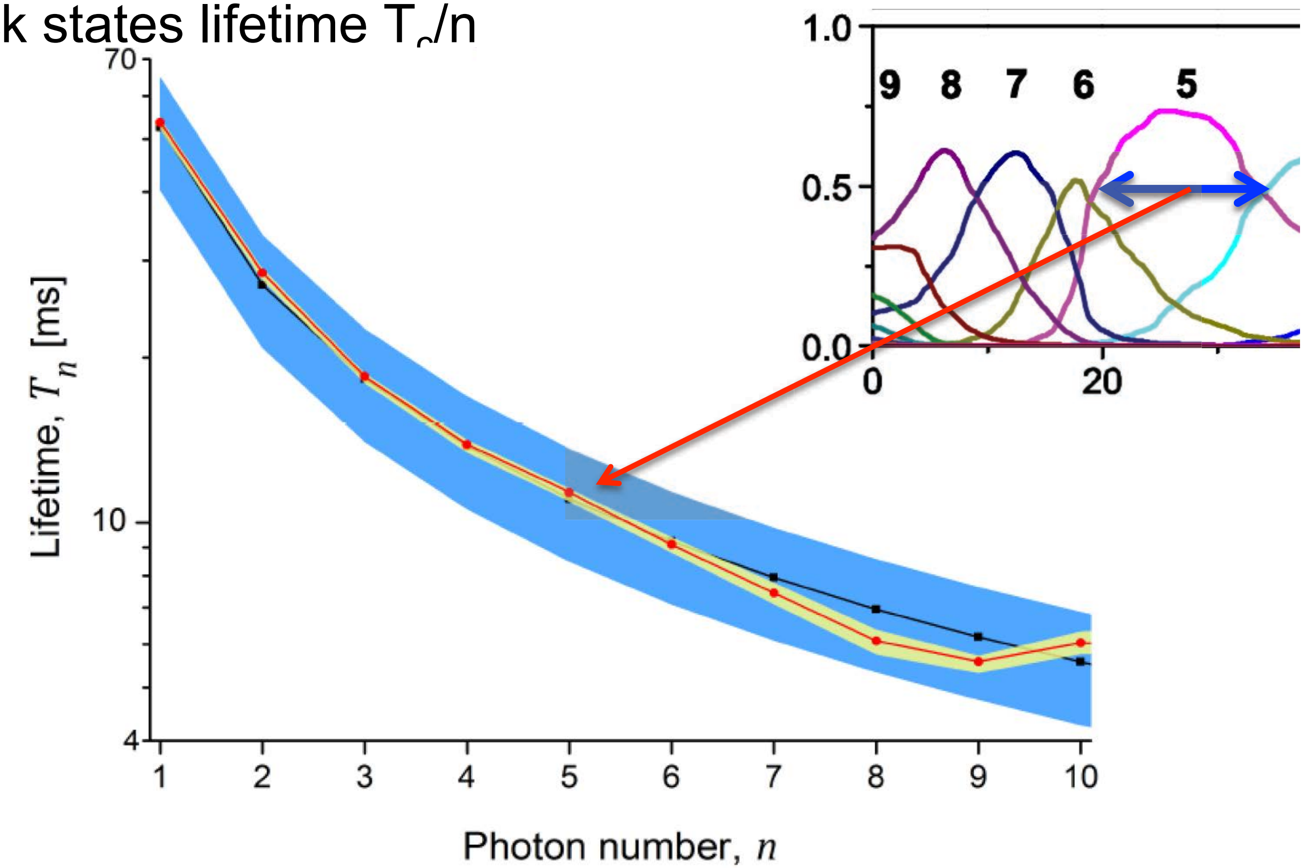


- An improved analyzis method based on the Past Quantum state formalism
  - Allows counting beyond the n=8 periodicity
- Rapid decay of the higher Fock states

T. Rybarczyk et al., PRA 91, 062116

Application: lifetime of the *n* photon Fock state

- Analyze average time between jumps
  - Fock states lifetime T_c/n



  - Quantum states are fragile, all the more so when they get large:
    - decoherence

T. Rybarczyk et al., PRA 91 062116

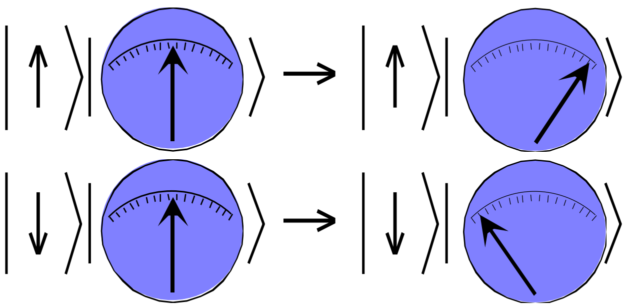
Superpositions in the macro world ?

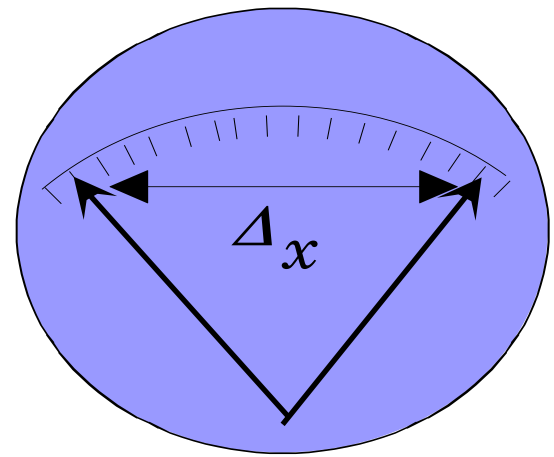
- The Schrödinger cat
  - No quantum superpositions at our scale

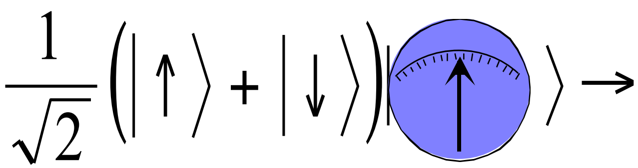
  - We only observe a tiny fraction of all possible quantum states. Why ?

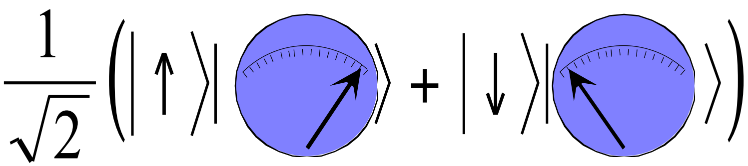
Superposition, measurement and decoherence

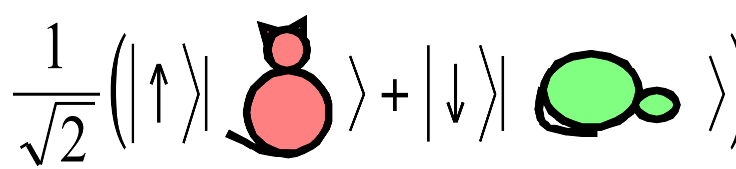
- An essential question for quantum measurement
  - Linearity predicts measurement apparatus in a quantum superposition
    - High AND low







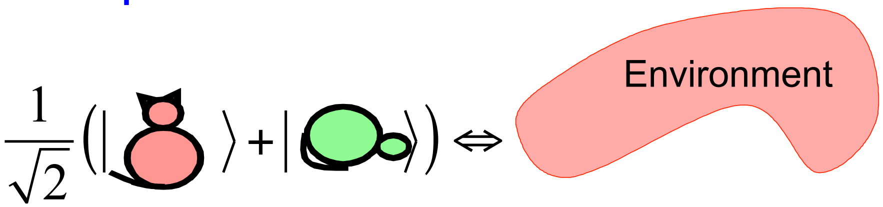




  - Postulates predict a mixture (high OR low)
  - The unlucky cat is a metaphore of measurement

Decoherence and quantum superpositions

- A quantum system is coupled to a complex environment



  - Residual gas
  - Residual radiation
  - Gravity waves !

- Well controlled microsystems
  - Coupling to environment negligible For All Practical Purposes

- Mesoscopic or macroscopic systems
  - This coupling can NEVER be neglected
  - Obviously the case for a measurement apparatus or a cat

Decoherence models

- No general theory

- Simple cases in which quantum relaxation theory can be used to treat explicitly the coupling of a mesoscopic system with an environment

  - Brownian motion (Leggett)
  - Damping of a harmonic oscillator
  - …

- Characteristics valid for all models

  - A few states are nearly stable (pointer states)
  - Their quantum superpositions are utterly unstable

Pointer states

- Stable or nearly stable states in spite of environment coupling
  - Position states for Brownian motion
  - Vacuum for a zero temperature harmonic oscillator
  - Coherent field states
    - A coherent state remains coherent, its energy is damped as the classical field energy
  - All those states are exactly or almost insensitive to decoherence

- Quantum Darwinism
  - Pointer states are those who disseminate most easily copies of themselves into the environment without entanglement

  - All observers of a part of the environment can agree on which pointer state they ‘observe’
    - Quantum objectivity (and realism)

Zurek, RMP, 2003

Mesoscopic quantum superpositions

- Pointer states superpositions
  - Rapidly transformed into a statistical mixture
    - One state OR the other instead of one state AND the other
  - Decoherence time scale
    - Short compared to the classical (energy) damping time
    - Shorter and shorter when the ‘distance’ between state increases.
  - An essential character of mesoscopic systems relaxation:
    - Two (very) distinct time scales
      - Slow one: energy
      - Fast one: decoherence
      - Their ratio is a good measure of the superposed state ‘macroscopicity’

Decoherence and quantum measurement

- Two essential ingredients
  - Measurement result is described by a classical probabilistic alternative
    - Same nature as that of statistical physics
    - God IS playing dice, but He is playing with classical dice
  - Decoherence defines the measured quantity
    - Final state: mixture of pointer states
      - The measured system's state are those correlated to pointer states
      - Without decoherence: entangled state of the system with the meter which can be cast in any joint basis
      - System-meter coupling AND decoherence dynamics both define the measured quantity.

Experimental exploration of decoherence?

- Easy !
  - No quantum superpositions in everyday world…

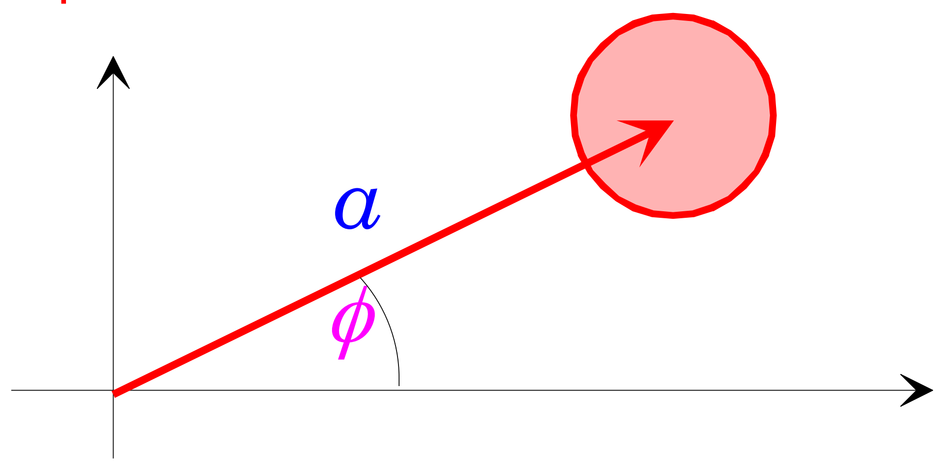
- Not that simple ?
  - Resolve dynamics for a mesoscopic system (two well separated time scales) weakly coupled to its environment.
  - Long relaxation time so that decoherence time is long engouh to be measured
  - Delicate probe of the system's state

- Few appropriate systems. Particularly:
  - Ion in traps
  - CQED

Mesoscopic coherent fields in cavity QED

- A classical amplitude and quantum fluctuations
  - Small field:

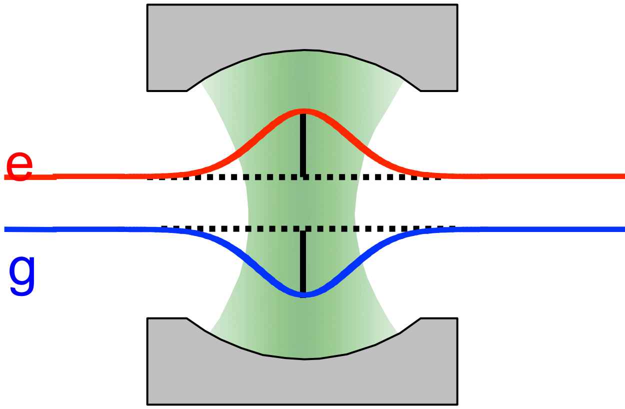
    - A single photon coherent field is quite quantum: fluctuations as large as the amplitude
  - Large field:



    - A large coherent state is nearly classical

Dispersive atom-field interaction

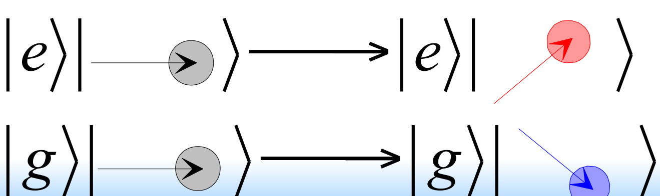
- Non resonant (dispersive) case
  - Two complementary effects
    - Atomic frequency modified by the cavity field (light shifts, proportional to the photon number)



      – Phase of an atomic superposition changed

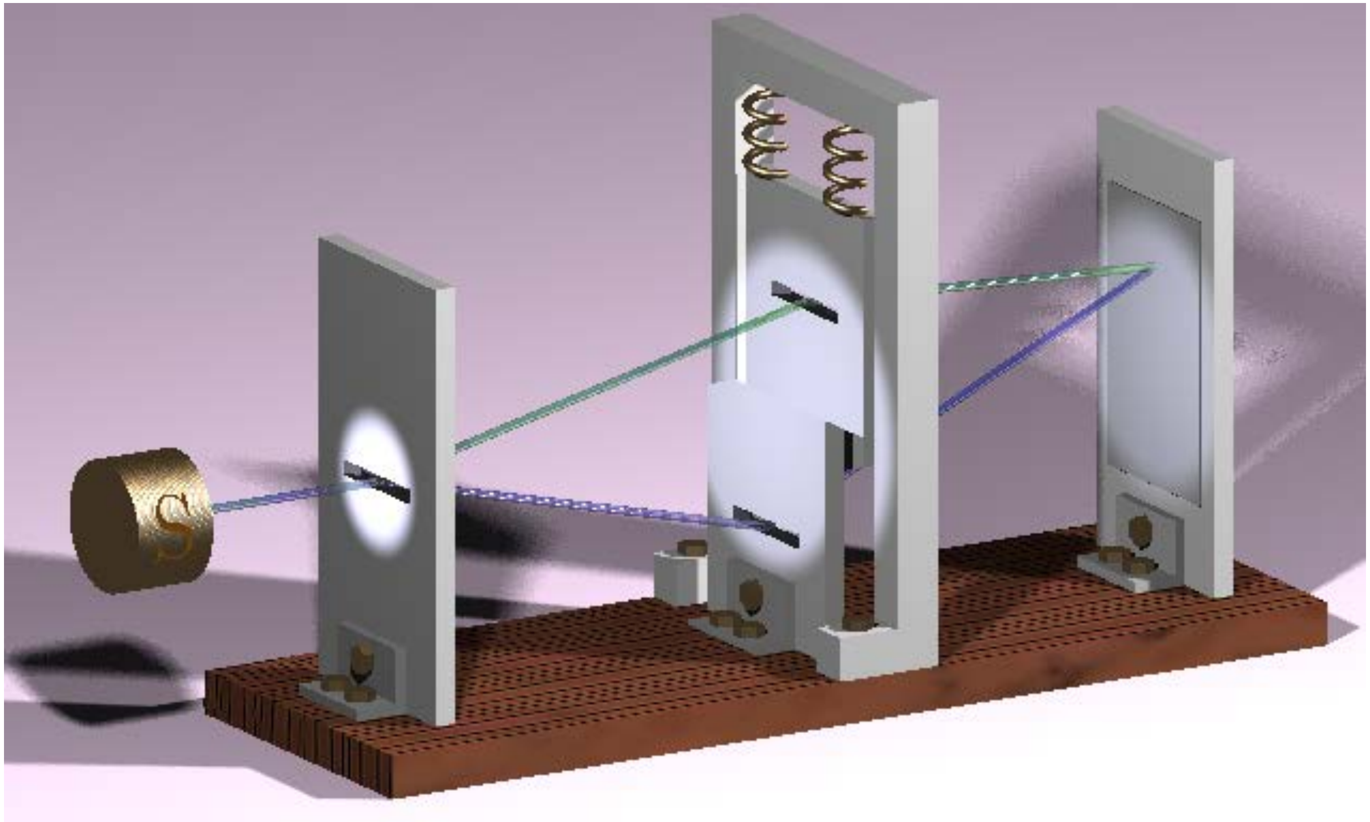
    - Field frequency modified by the presence of the atom (index effect)

      – Classical phase of the field changed (in a way depending upon the atomic state)



Bohr's thought experiment on complemetarity

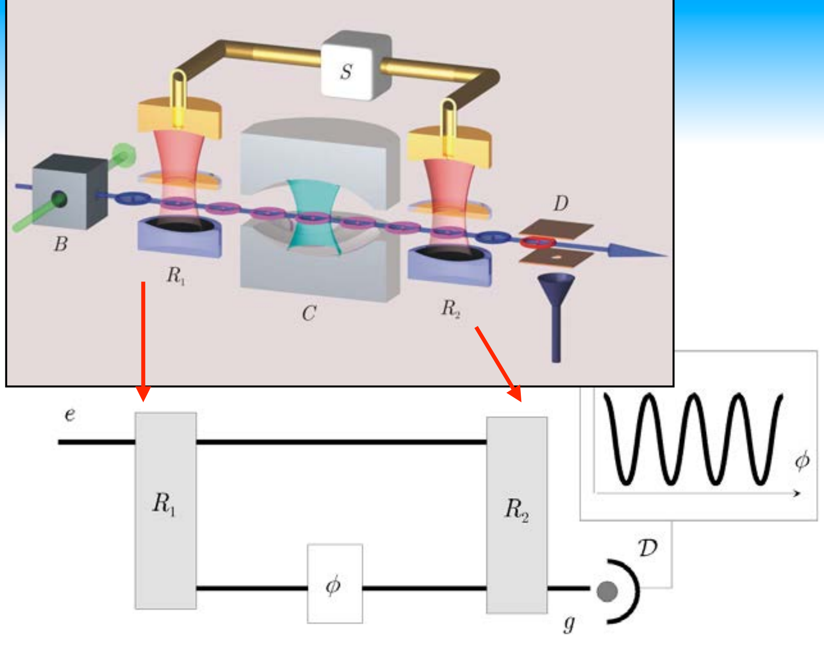
- Complementarity (From Einstein-Bohr at the 1927 Solvay congress)

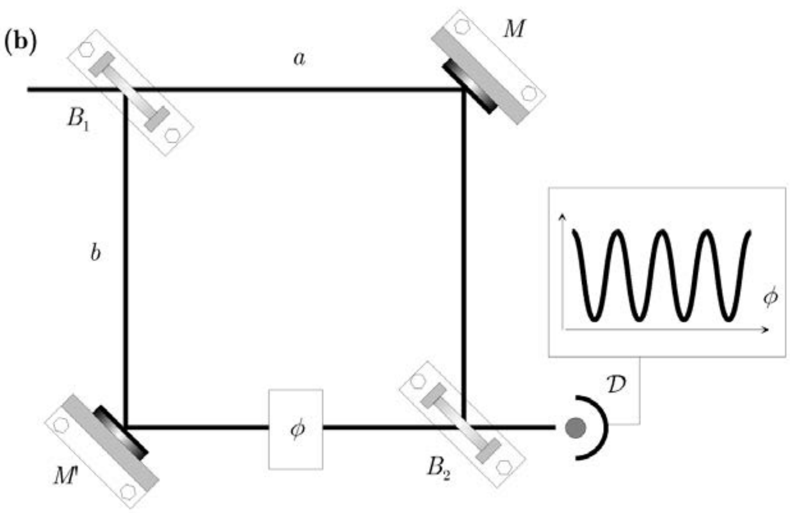


  - Moving slit records the trajectory of the particle in the interferometer

Ramsey interferometer

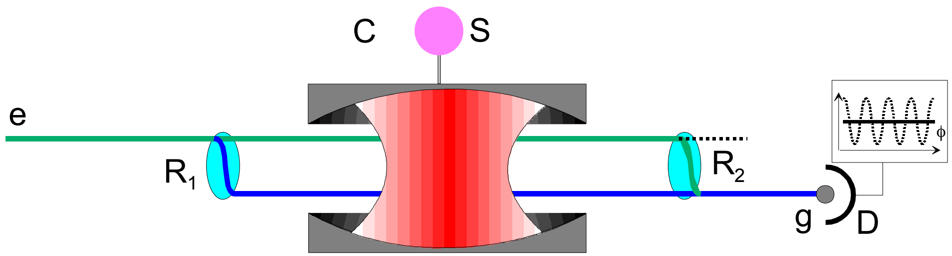
- An atomic version of the Mach-Zehnder interferometer
  - Two classical resonant pulses mix atomic levels
  - Two paths from the initial to the final state
    - Quantum interference
  - Transfer probability sinusoidal function of the phase accumulated by the atom



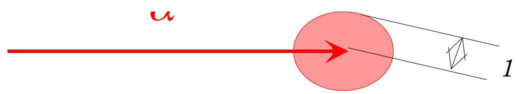


Cavity field as a which path detector

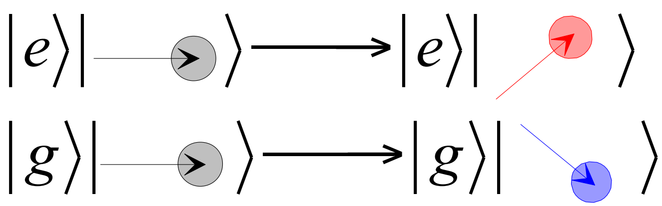
- Insert non-resonant cavity inside the Ramsey interferometer



  – Cavity contains initially a mesoscopic coherent field

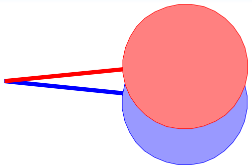


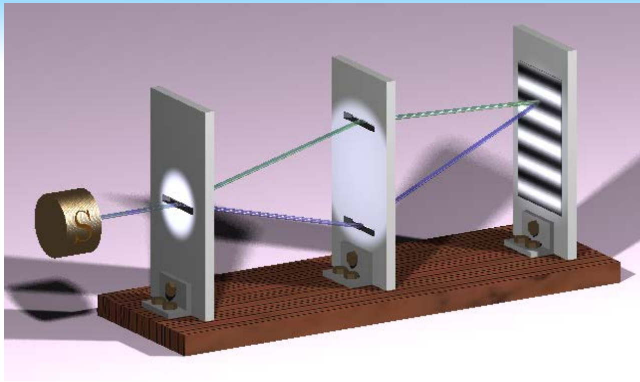
  – The two atomic levels produce opposite phase shifts of the cavity field



- Field amplitude is the ‘needle’ of a ‘meter’ pointing towards atomic state
  – Prototype of a quantum measurement
  – Provides a which-path information and should erase the fringes

Two limiting cases

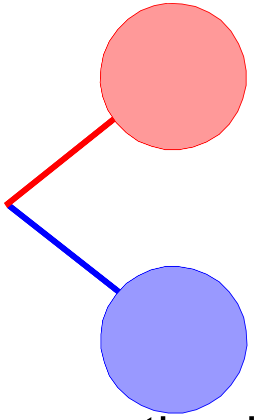


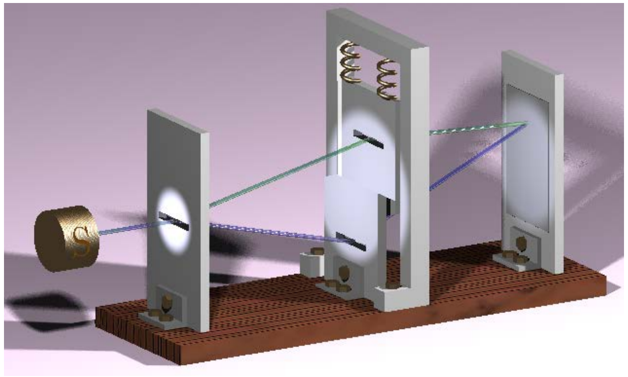


- Small phase shift (large D)

(smaller than quantum phase noise)

  – field phase almost unchanged
  – No which path information
  – Standard Ramsey fringes





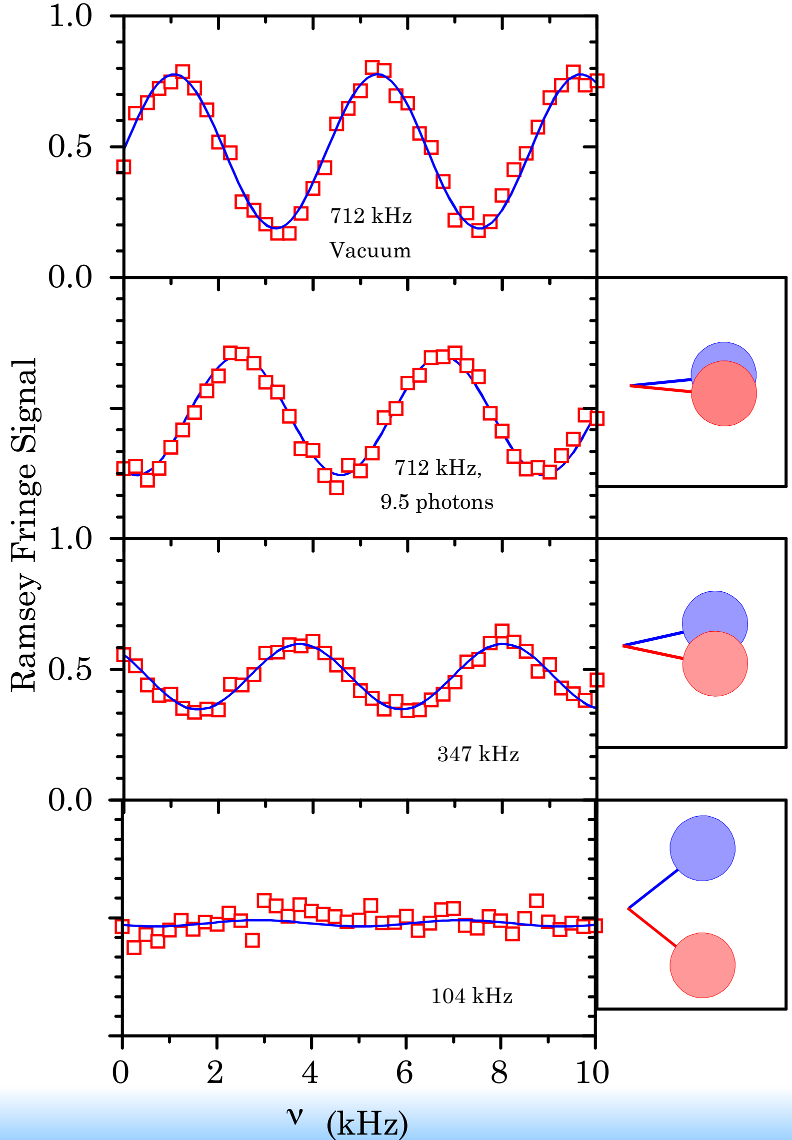
- Large phase shift (small D)

(larger than quantum phase noise)

  – Cavity fields associated to the two paths distinguishable
  – Unambiguous which path information
  – No Ramsey fringes

Fringes and field state

- An illustration of complementarity



Brune et al. PRL 77, 4887

A laboratory version of the Schrödinger cat

Field state after atomic detection

$$\frac{1}{\sqrt{2}}\left(|\nearrow\rangle + |\searrow\rangle\right)$$

A coherent superposition of two "classical" states.

Very similar to the Schrödinger cat

Decoherence transforms this superposition into a statistical mixture

time scale $2T_c/D^2$ where D^2 is the square distance between classical amplitudes (a photon number)

Slow relaxation time scale T_c: possible to study the decoherence dynamics

Decoherence caught in the act

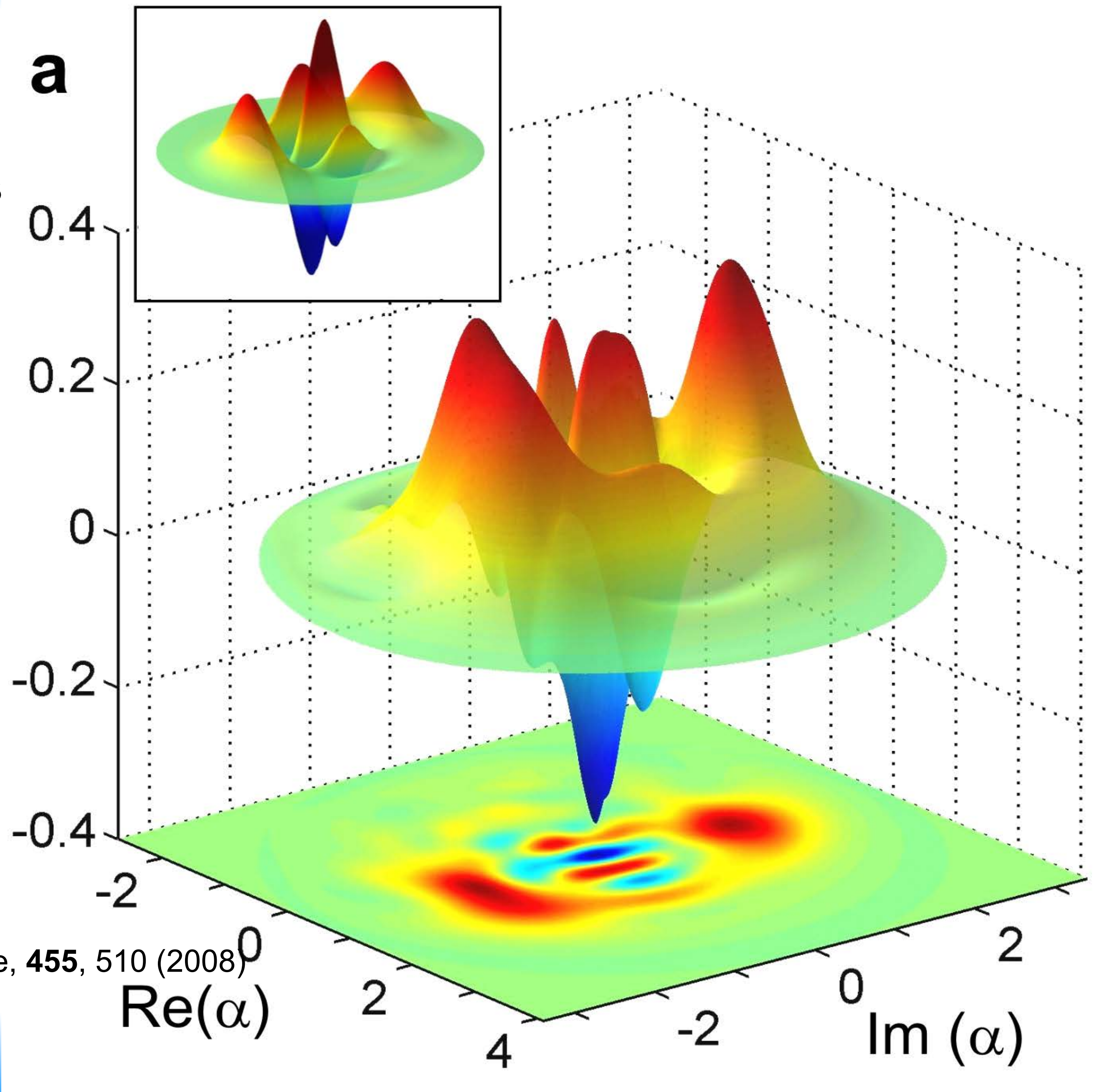
More insight into the quantum nature of a cat

- Prepare a cat by dispersive interaction with a single atom
- Wait…
- … and see : reconstruct the field density matrix
  - Controlled displacements
  - QND photon number measurements
  - MaxEnt reconstruction algorithm
- Plot the cat's Wigner function

The portrait of a cat

- Even cat

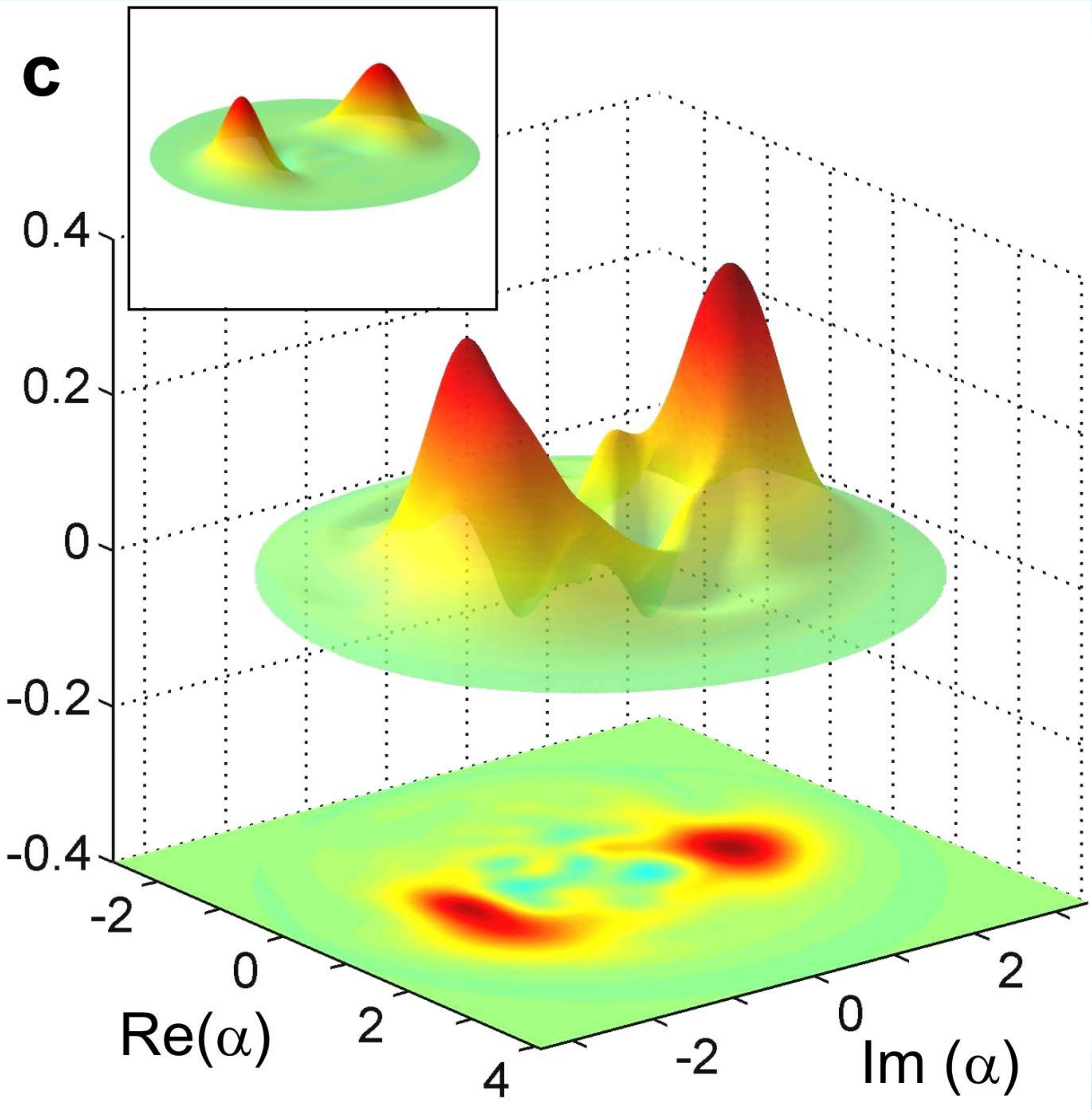
- n=3.5 photons
- ζ=0.37π
- D^2=11.8 photons



S. Deléglise et al, Nature, **455**, 510 (2008)

Schrödinger cat states

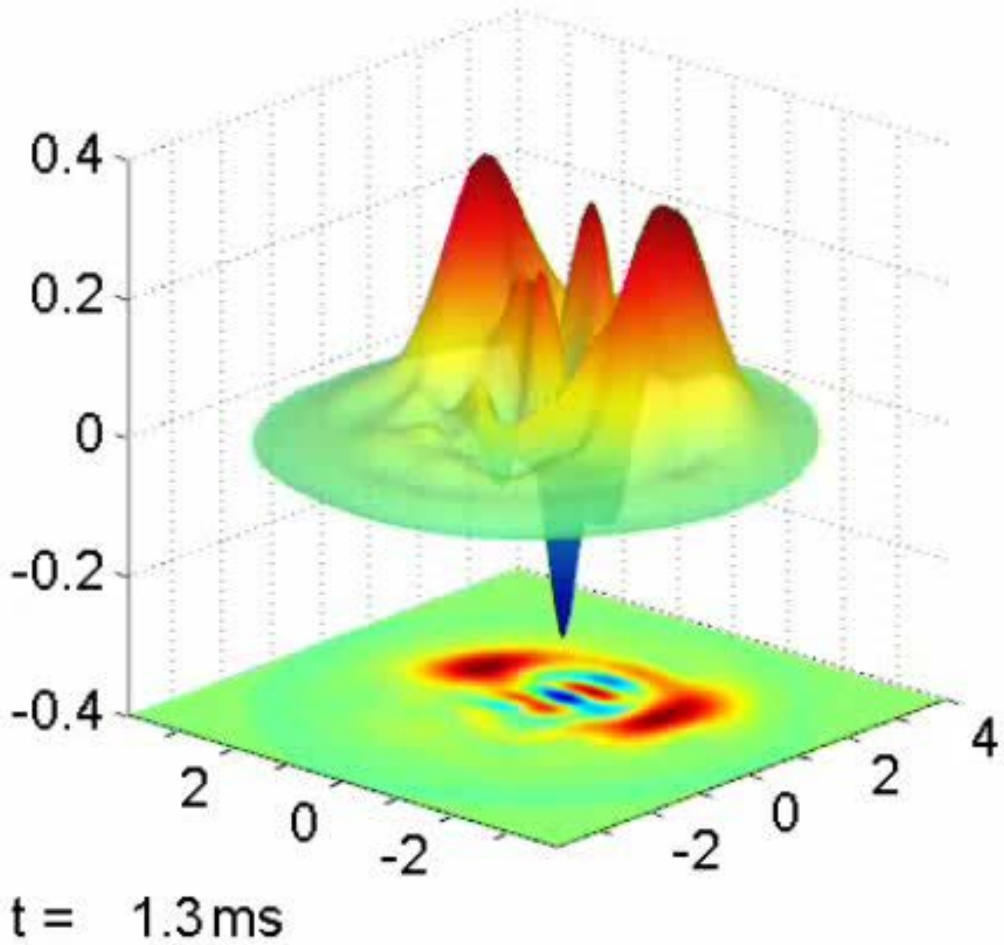
- Statistical mixture



Decoherence of the cat

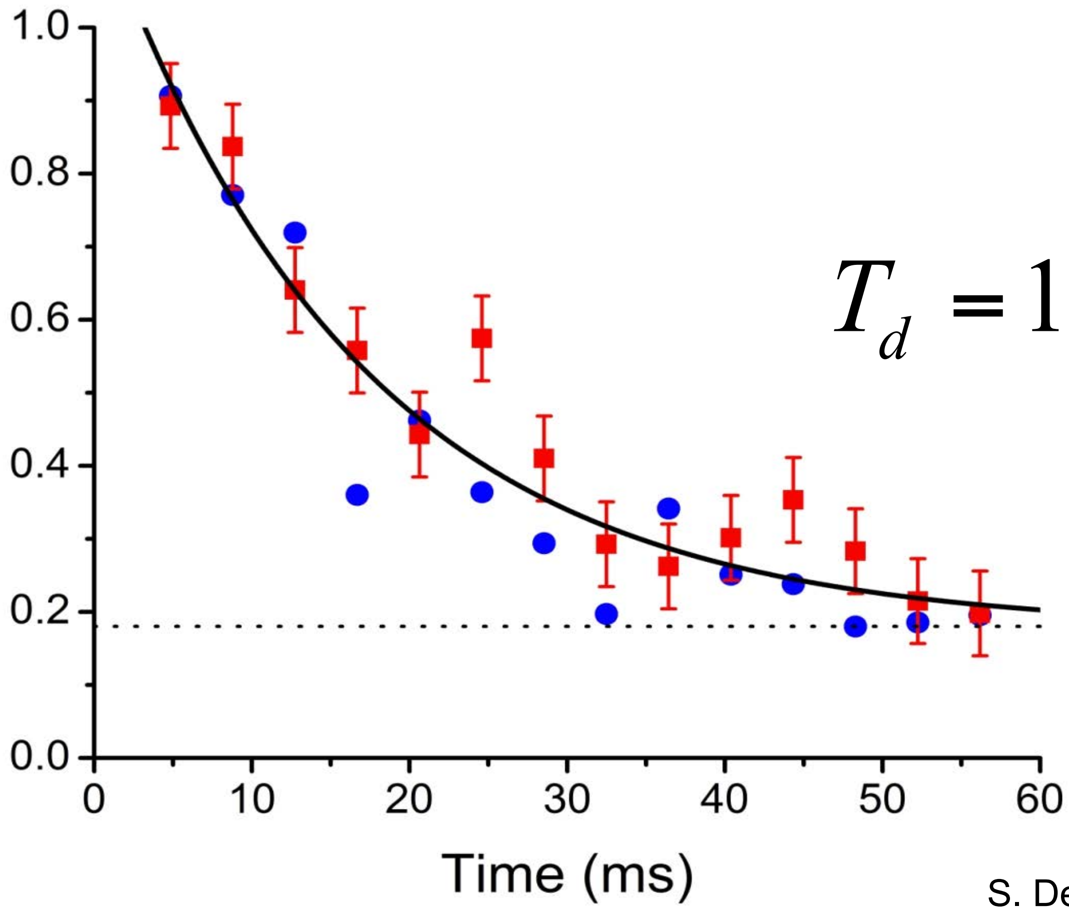
- Time resolved method
  - Data acquisition time: 4 ms
  - Much shorter than the expected decoherence time
    - 19 ms taking residual thermal effects into account
- Monitor cat decoherence in real time

A movie of the cat decoherence



S. Deléglise et al, Nature, **455**, 510 (2008)

Decoherence time



$$T_d = 17 \pm 3 \text{ ms}$$

S. Deléglise et al, Nature, **455**, 510 (2008)

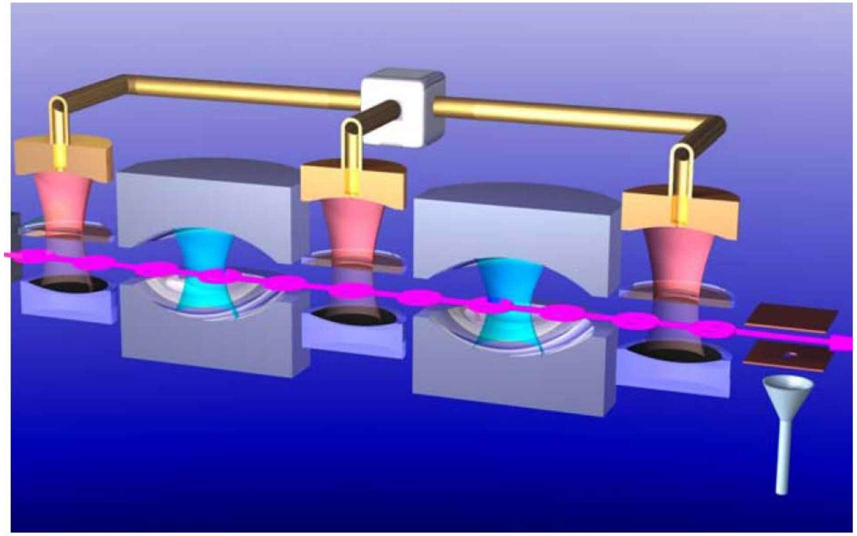
For similar work in circuit QED see Wang et al. PRL **103** 200404

Conclusion: interrelated concepts

- Complementarity, decoherence and entanglement
  - No quantum interference when entanglement with a which path detector
  - No quantum inteference for macroscopic objects
    - Decoherence
    - Results from an unavoidable entanglement with the environment.
  - And quantum superposition is at the heart

Perspectives : A new breed of quantum monster

- Entangling a single atom with two mesoscopic fields



- Dispersive interaction:

no energy exchange but entanglement of the field classical phase with the atomic state (index of refraction)

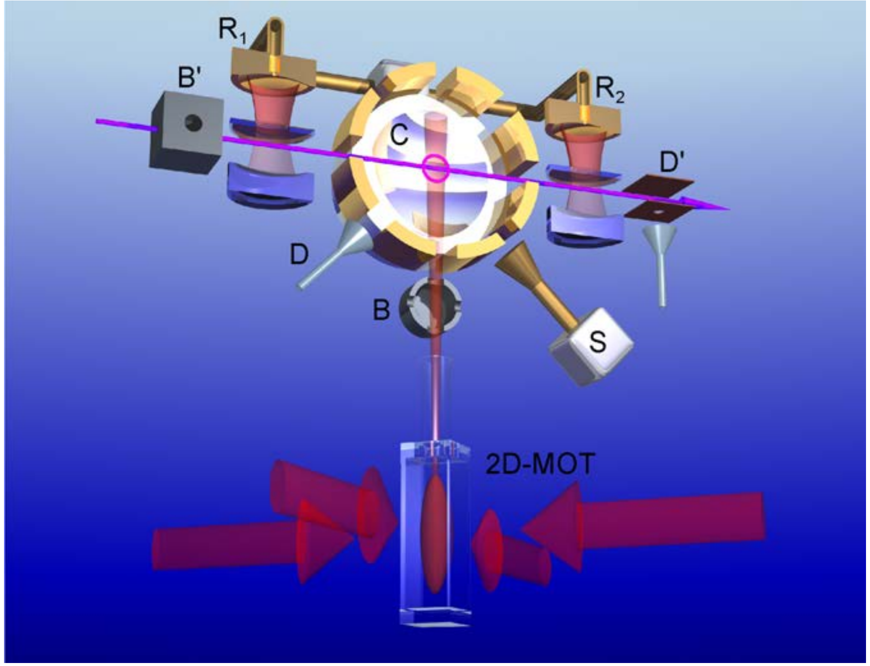
Final two-cavity state $\left|\gamma,\gamma\right\rangle+\left|-\gamma,-\gamma\right\rangle$

P. Milman et al EPJD, **32**, 233

a non local mesoscopic quantum state

Perspectives : Slow atoms in a cavity

- A strong limitation of present experiments
  - Atom-cavity interaction time << both systems lifetime
    - 100 μs << 30ms, 0.13 s
- Achieving long interaction times
  - A set-up with a stationary Rydberg atom in a cavity
  - Circular state preparation and detection in the cavity
  - Interaction time ms range
  - Large cats
  - Quantum Zeno dynamics



J.M. Raimond et al PRL **105**, 213601

A team work

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    - Uni. Bari and INFN
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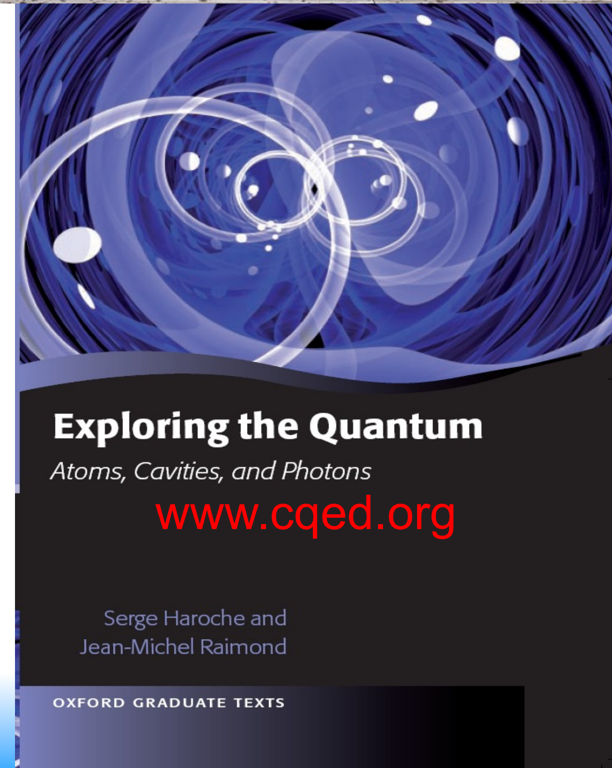
  – CNRS, UMPC, ENS, CdF



www.cqed.org

And, above all

- Happy birthday, Vincent

  – 60 already? I can hardly believe it.