

# Power and Strangeness of the Quantum

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During the XX<sup>th</sup> century, Quantum Physics has disclosed to us the microscopic world of atoms and particles....

....and has given us the keys of modern technologies  
*(nuclear energy, computers, lasers, atomic clocks and GPS, magnetic resonance imaging....)*

The microscopic logic of this theory keeps challenging our classical intuition, even if its strangeness remain generally «veiled» at the macroscopic level.

Recent experiments raise the hopes that it might be possible to harness this microscopic strangeness to achieve in the XXI<sup>st</sup> century new advances at the border between the science of information and physics...

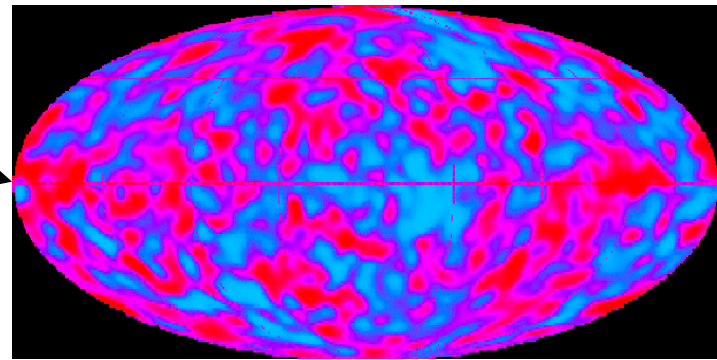
*A second quantum revolution?*

*Quantum physics deals with more than 60 orders of magnitude!*



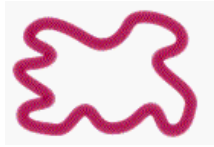
$10^{-35}$  Metre

Super strings  
(elementary  
hypothetical  
pieces  
of the Universe)

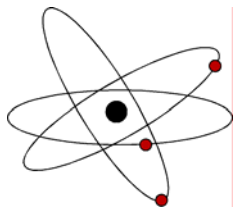
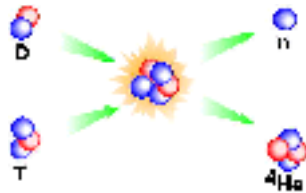


$10^{+26}$  Metres

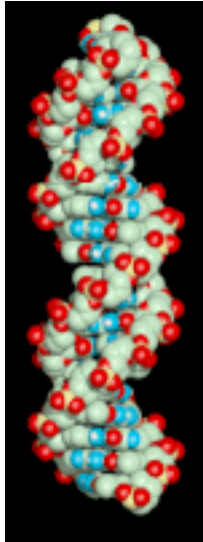
Map of cosmic microwave  
background fluctuations of the  
Universe



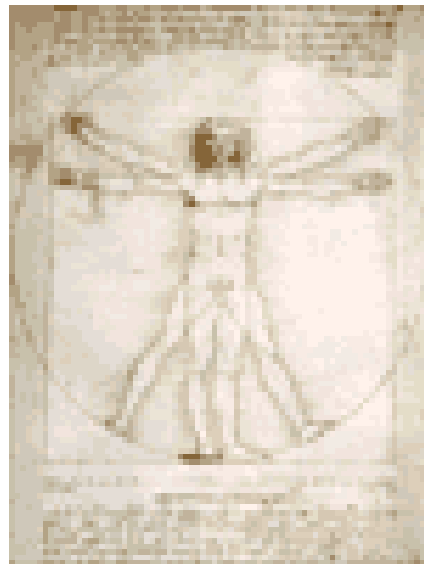
$10^{-35} M$



$10^{-10} M$   
(atoms)



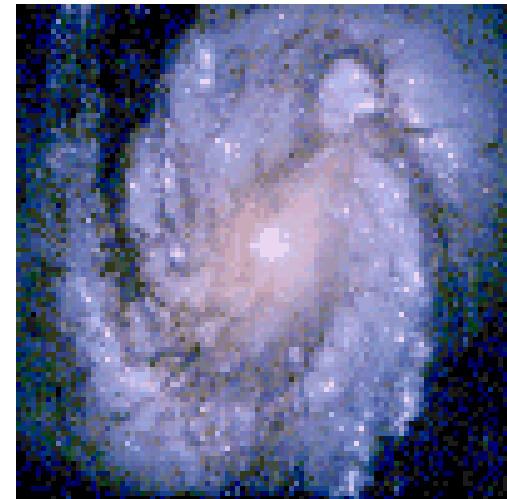
$10^{-8} M$   
(biological  
molecules)



$10^{-3} M -$   
 $10 M$   
(macro-  
world)



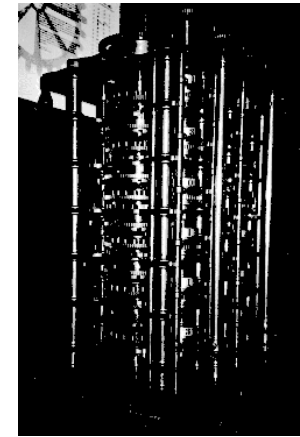
$10^{+8} - 10^{+10} M$   
(planets, stars)



$10^{+20} M$   
(galaxies)

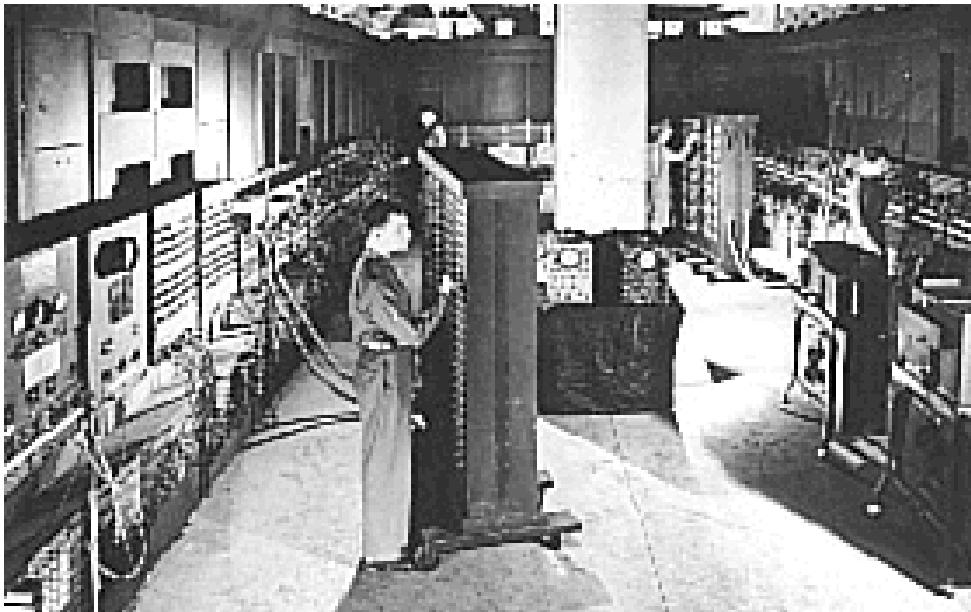
$10^{+26} M$   
Universe

*« Classical » technology has led ....*



*....from Pascal's mechanical calculator (1650)... ...to Babbage's machine (1840)...*

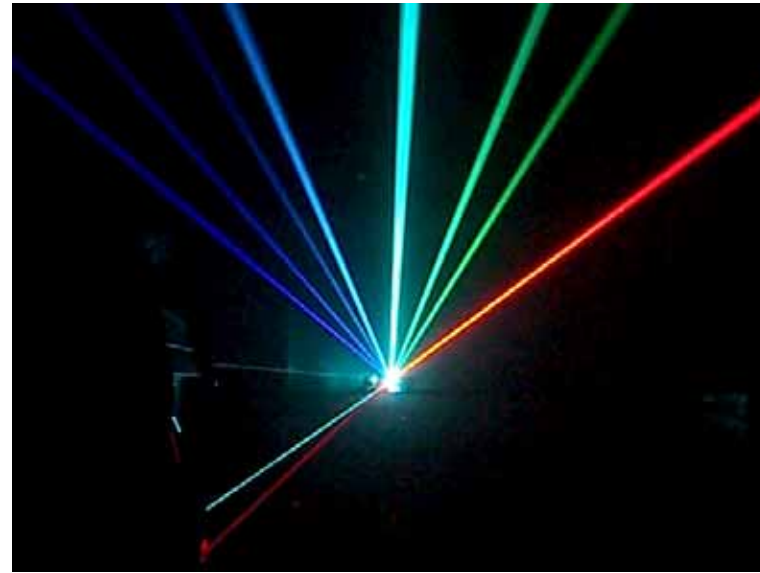
*..and to the huge electrical ENIAC computer (1948)....*



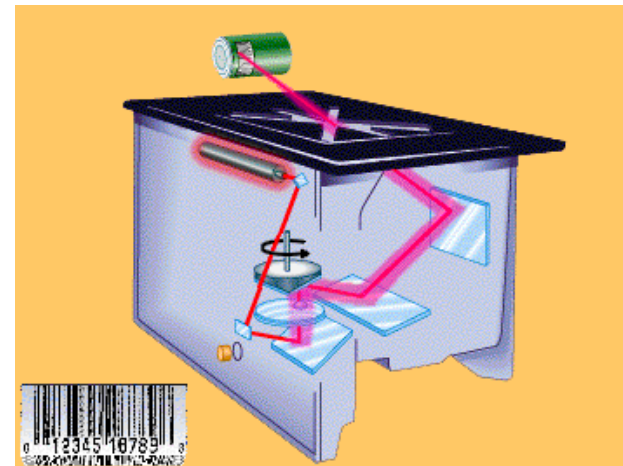
*...reaching a practical limit which could not have been overcome without the « quantum » technology of the transistor and integrated microchip...*



*The laser whose principle can be traced back to Einstein's work on stimulated emission (1917)...*

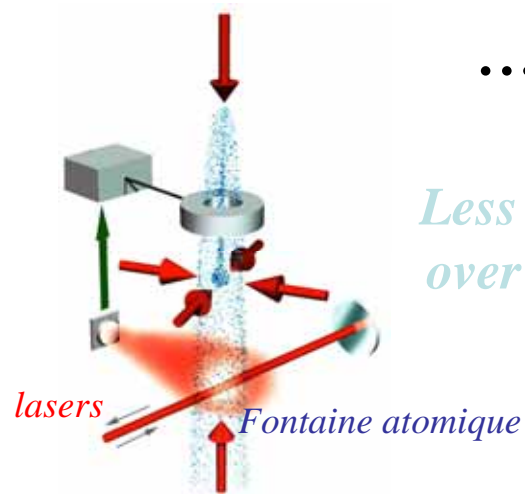


*...has led to a wide range of applications...*



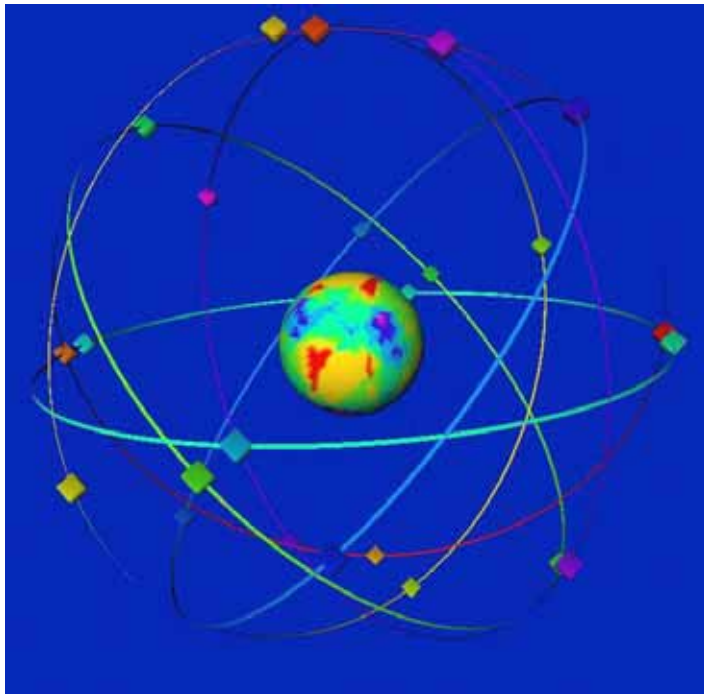
*The precise measurement of time, based on quantum physics principles (atomic clocks)...*

*...has led to important practical applications*



*Less than a second error over ten million years...*

*GPS based on triangulation using satellites carrying atomic clocks*



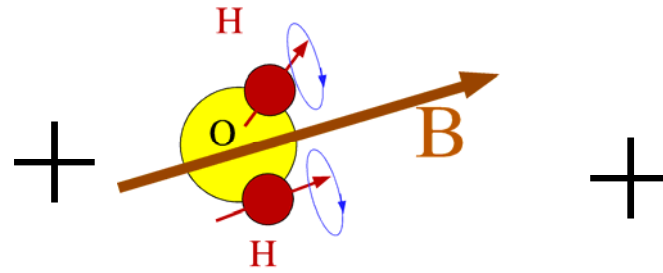
*Position defined everywhere on Earth with a few centimeter precision...*



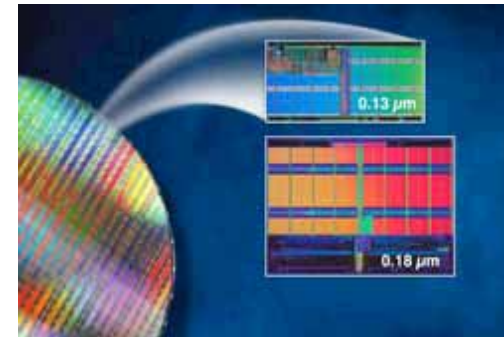
# *The MRI apparatus combines three quantum technologies:*



*Superconducting magnets*



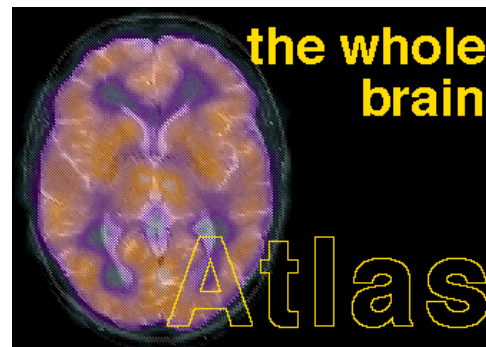
*Magnetic resonance of protons (H) in a magnetic field B*



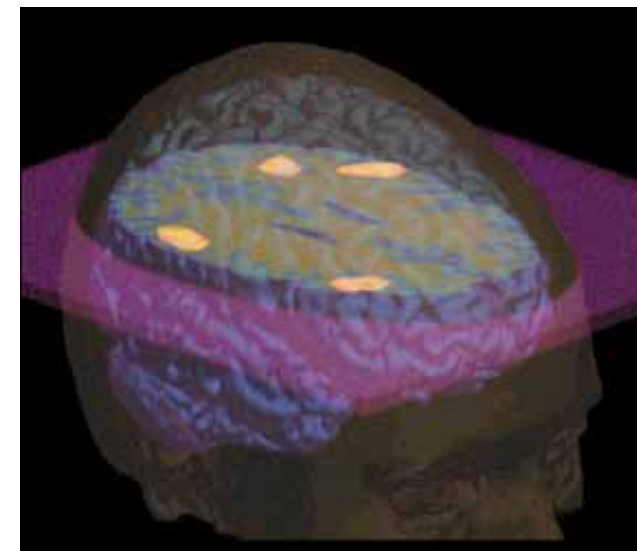
*Integrated transistor microchips for image reconstruction*



*Magnetic resonance imaging (MRI)*

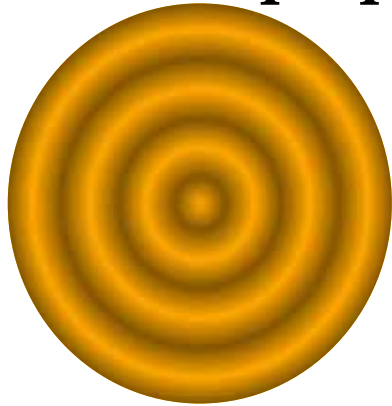


*Static...*



*...or dynamical images (the brain in action..)*

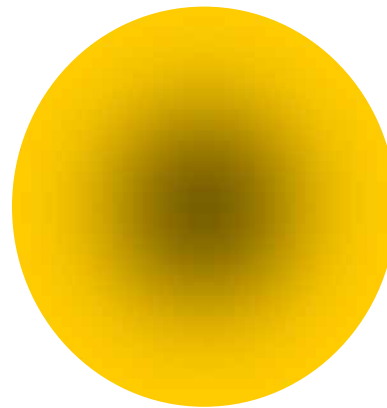
# State superpositions and the wavefunction



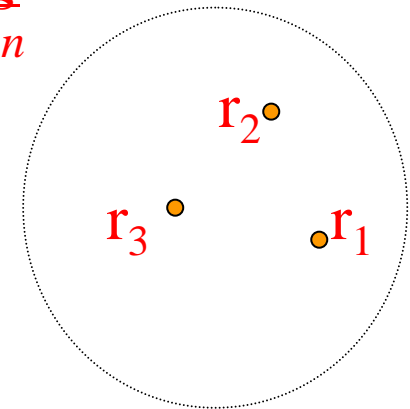
In the H atom, the electron is in a superposition of infinitely many possible positions, inside a spherical volume whose diameter is of the order of 1 Angström

$\Psi(r_1)$   
 $\Psi(r_2)$   
 $\Psi(r_3)$   
.  
.

Wavefunction  $\Psi$  obeying to the Schrödinger equation



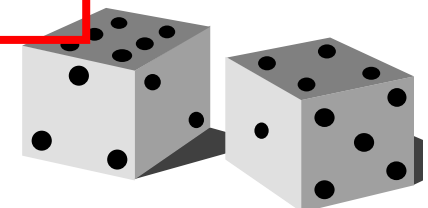
Measuring the electron position



Random result and state collapse

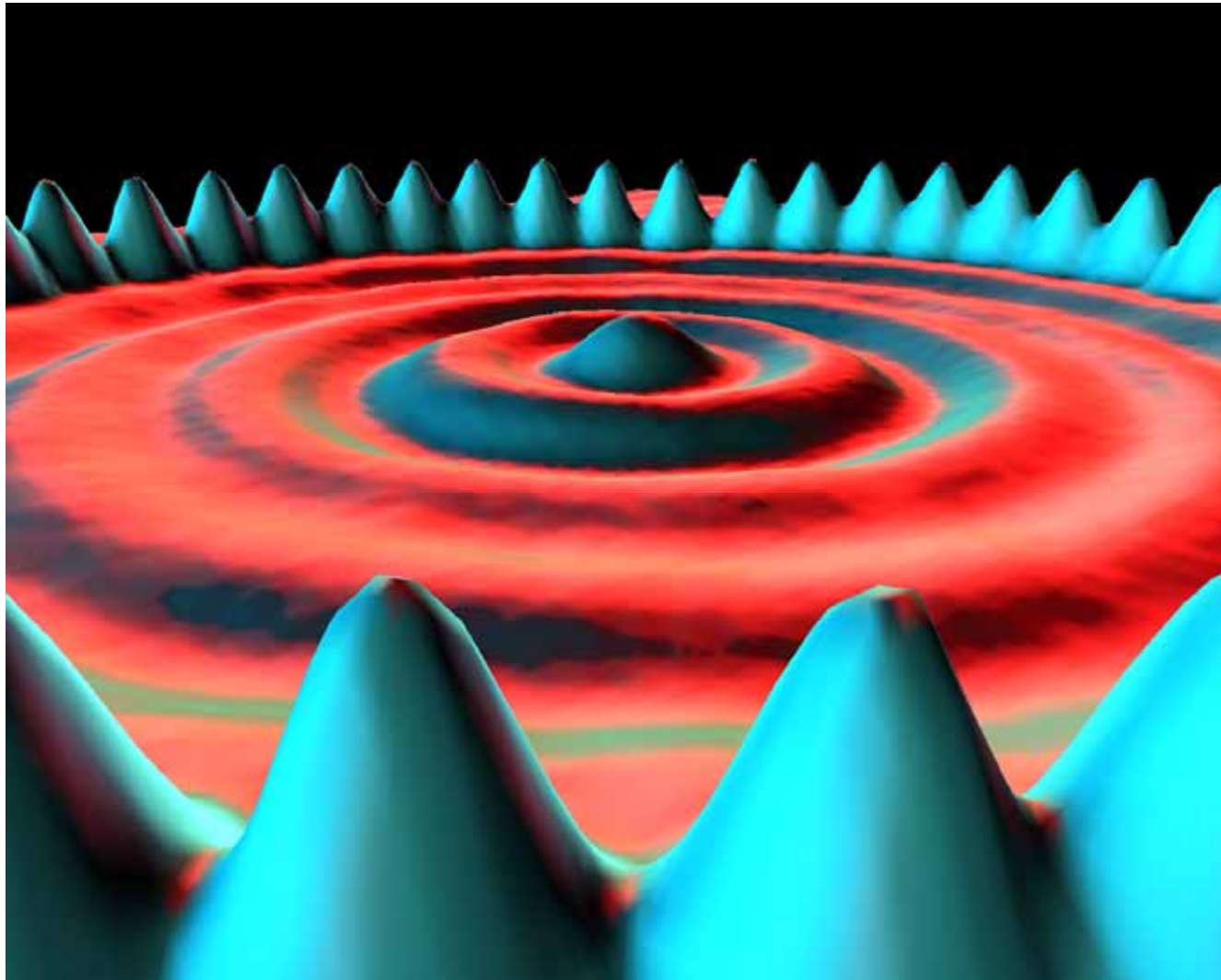
Probability  $P(r) = |\Psi(r)|^2$

God does play dice.... (Einstein did not like this..)





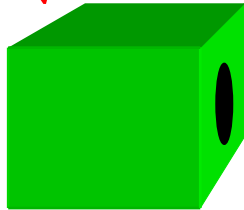
Modern technologies such as scanning tunnelling microscopy allow us to produce real images of wavefunctions (here of electrons confined in an «atomic corral»)



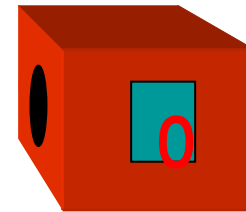
# Quantum theory is statistical...

Preparation of a two-level particle (qubit) in a **quantum state**

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



Measurement of a binary physical observable (polarisation, spin..)



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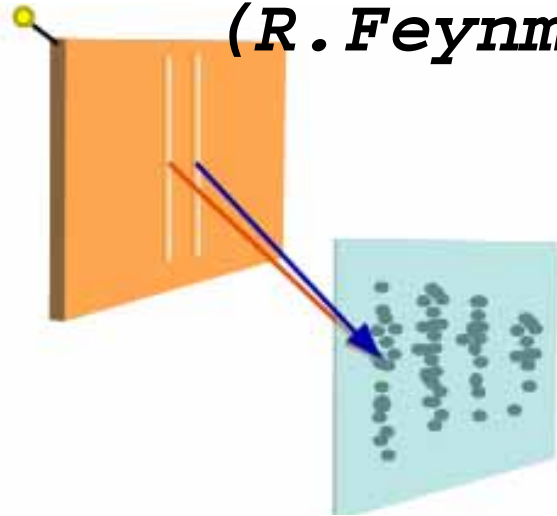
Theory **only** permits to compute **probabilities**

Quantum interference : « the  
essence of quantum strangeness »  
(R. Feynman)

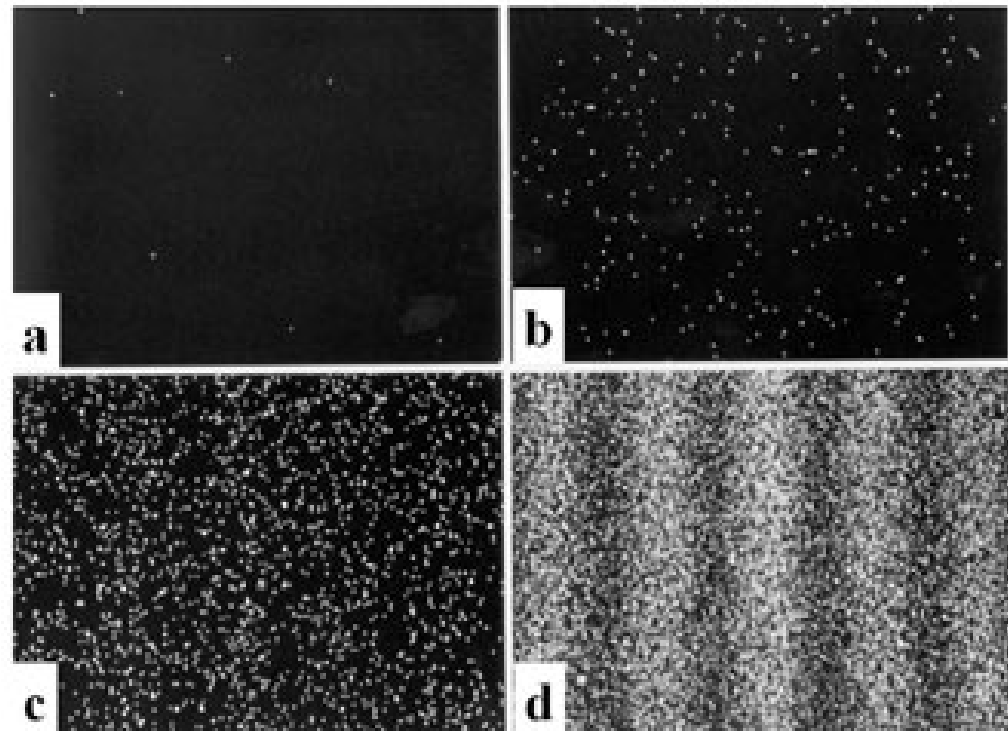


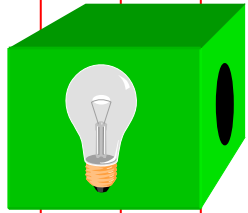
*«Nobody really understands  
quantum physics»*

*Young interferometer with  
photons, electrons, atoms, molecules...  
crossing the set-up one by one*

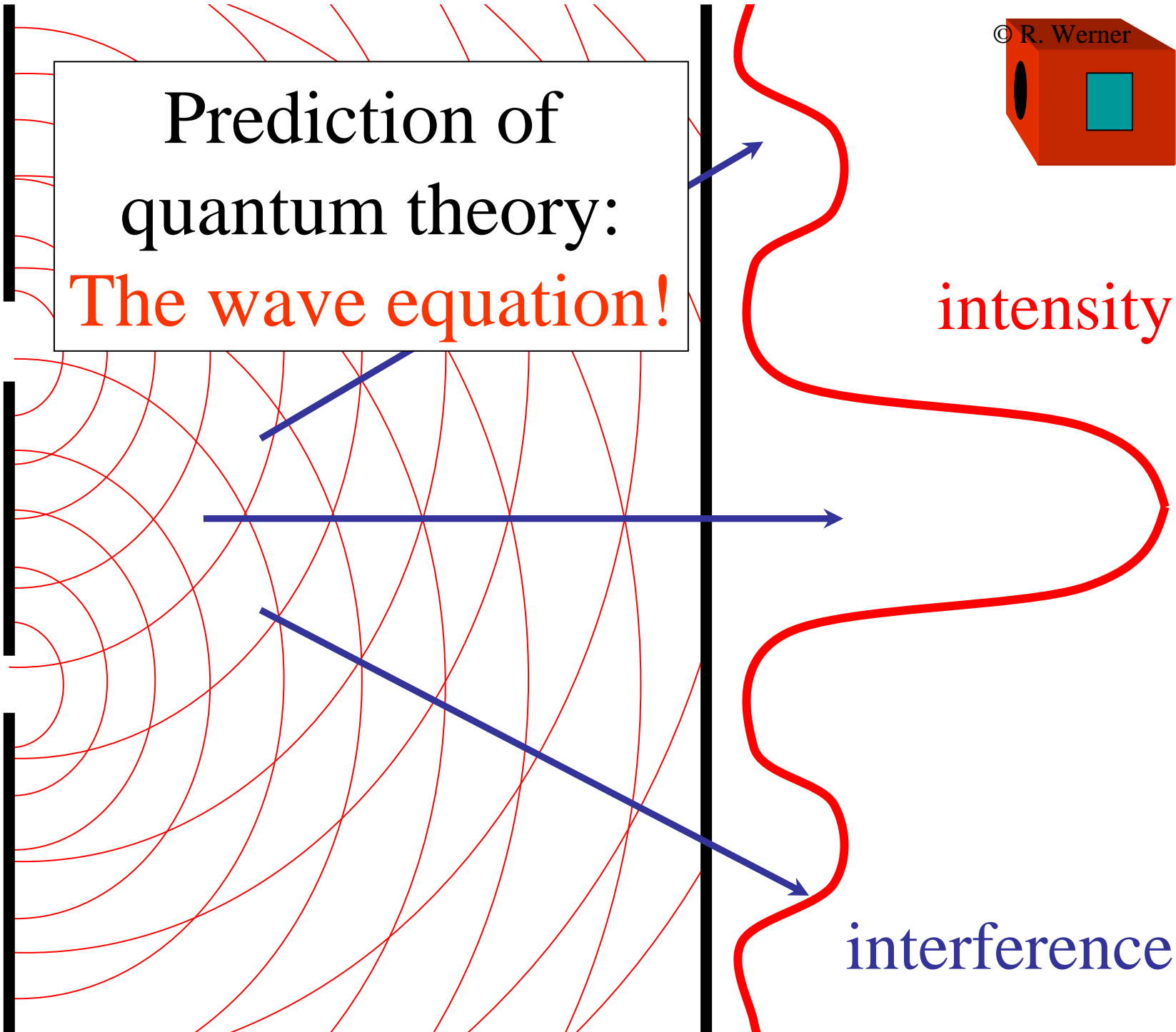
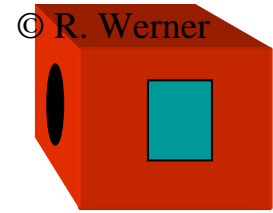


*Interference  
builds up  
progressively, as  
particle are  
detected one at a  
time*  
*quantum logic in  
action*



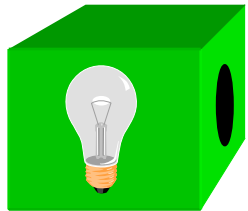


Prediction of quantum theory:  
**The wave equation!**



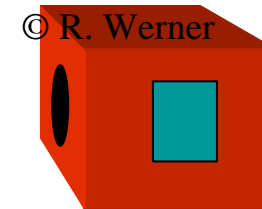
intensity

interference

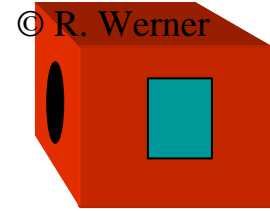
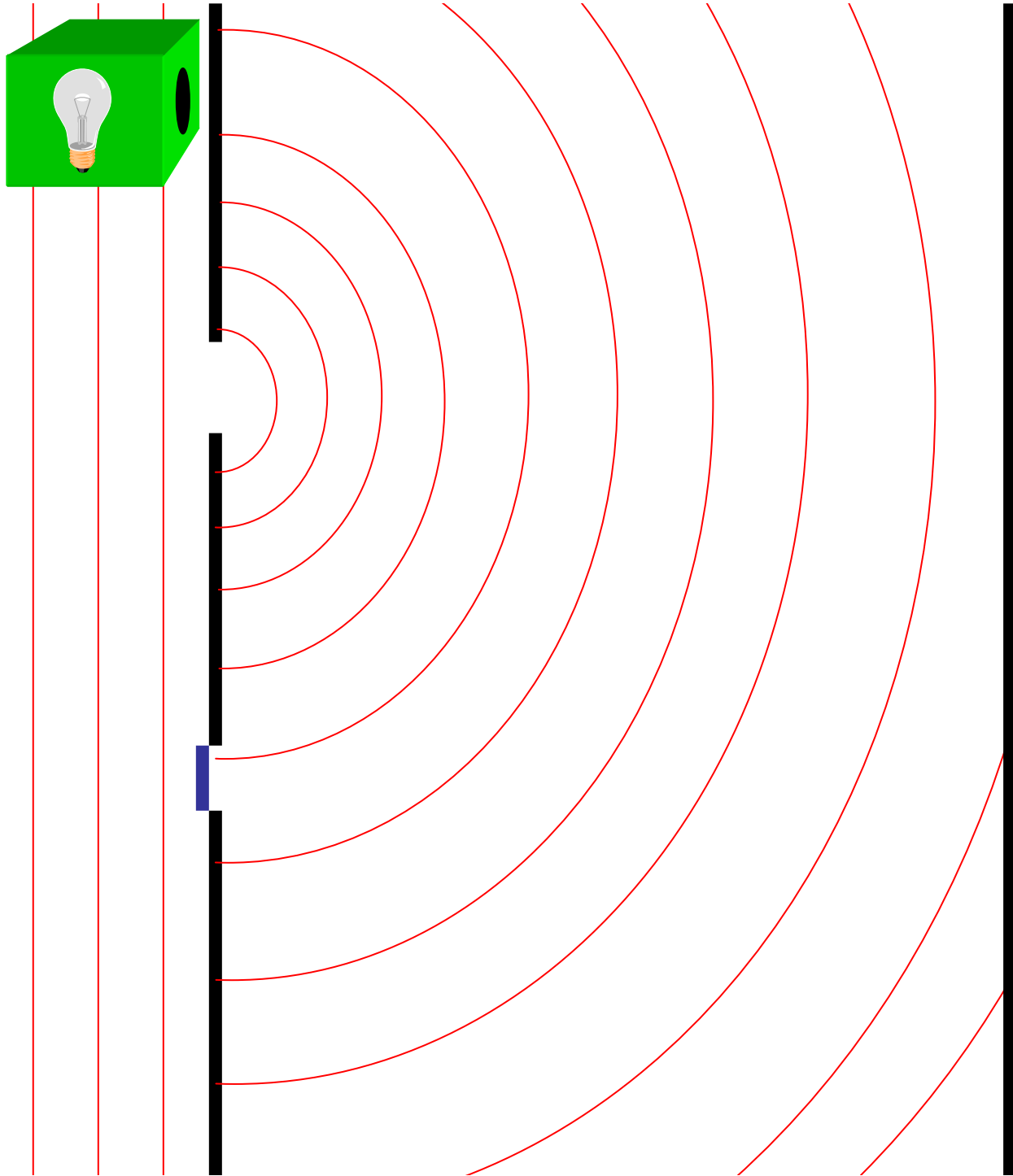


What happened to the  
particle between preparation  
and detection?

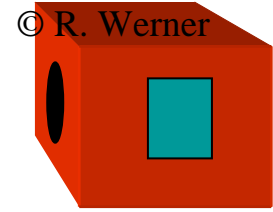
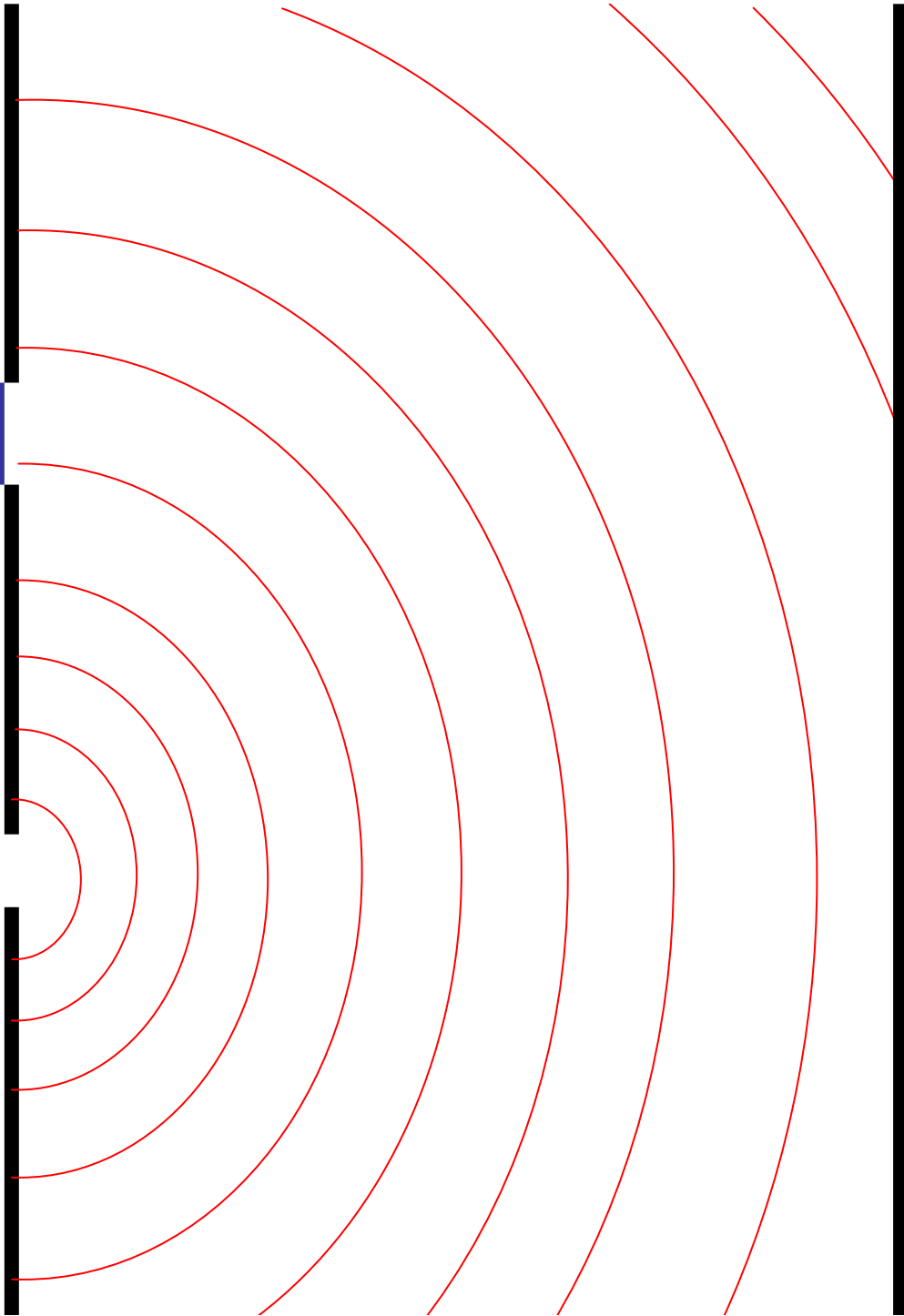
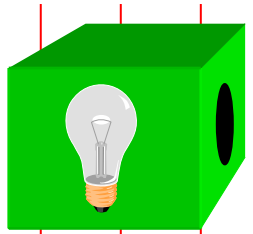
Through which slit did it go?





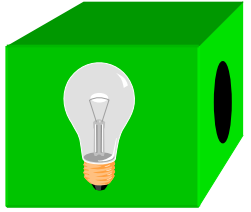


Distribution of particles going through upper slit



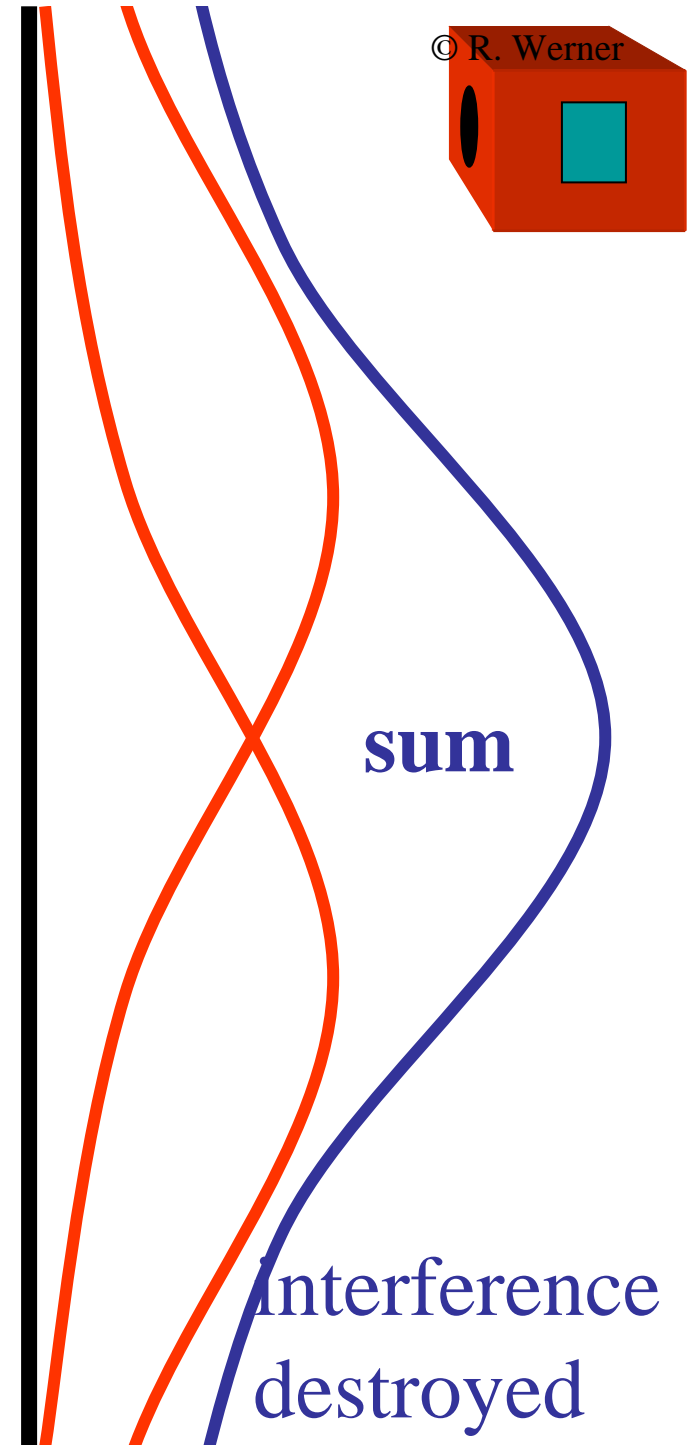
Distribution of particles going through lower slit

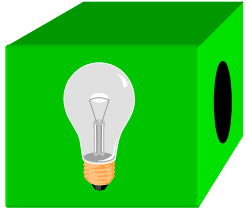




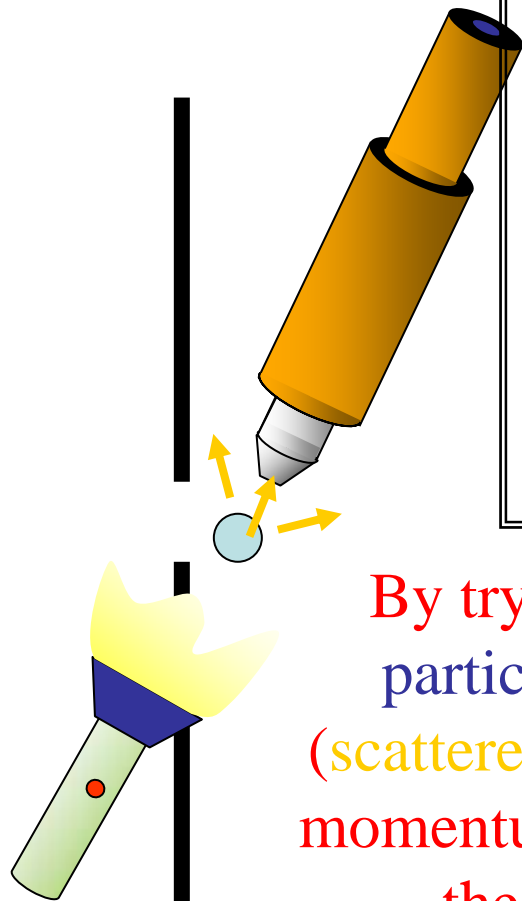
Trying to follow the  
particle path...

...implies a change in  
the set-up (and hence  
changes what  
happens)



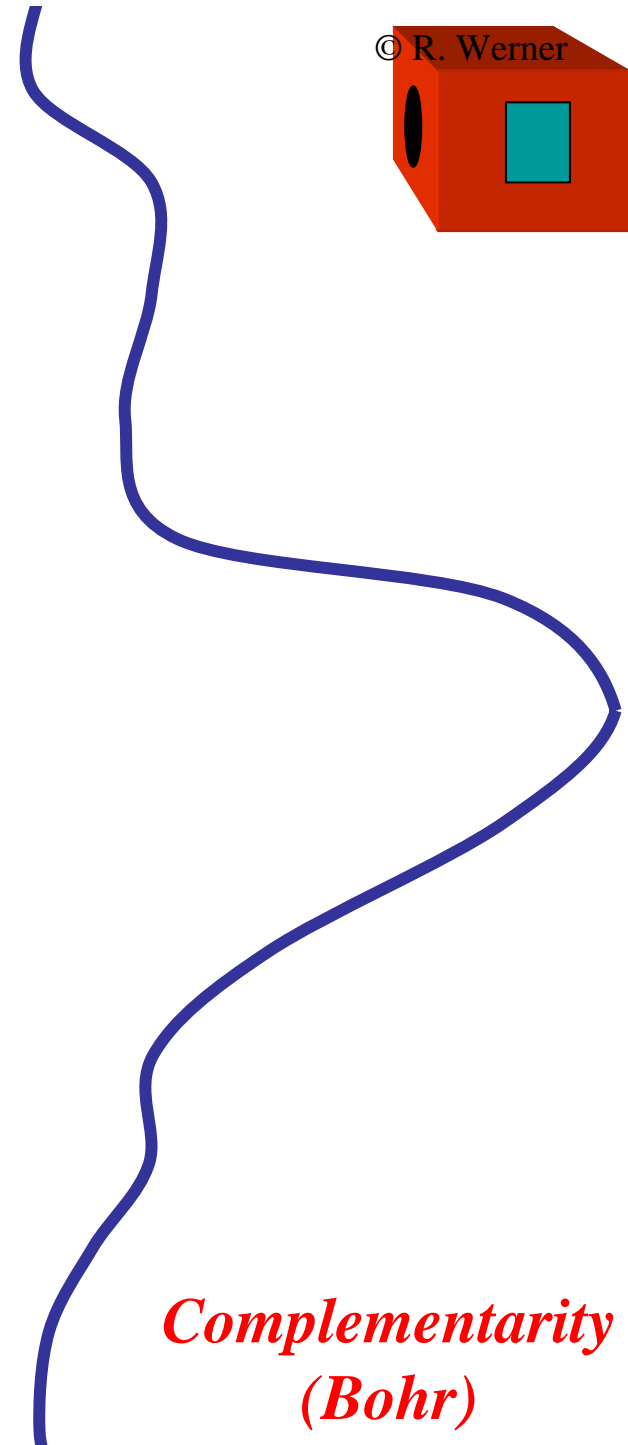
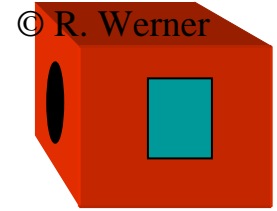


Can we look more subtly?



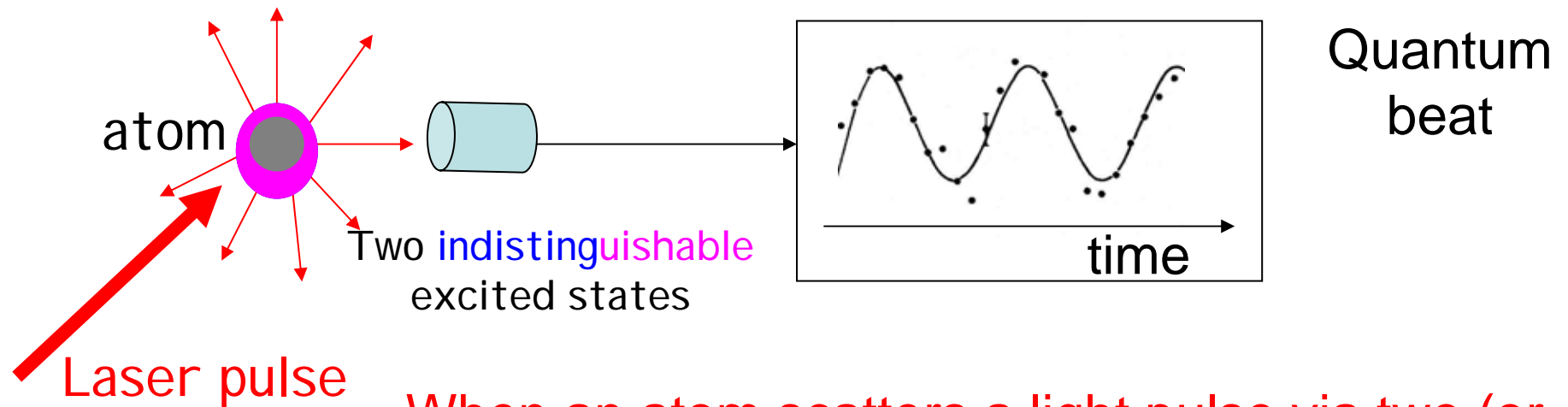
Even looking  
(through a  
microscope)  
influences the  
particle

By trying to localize the  
particle, one perturbs it  
(scattered photons change its  
momentum) and one destroys  
the interferences...



*Complementarity  
(Bohr)*

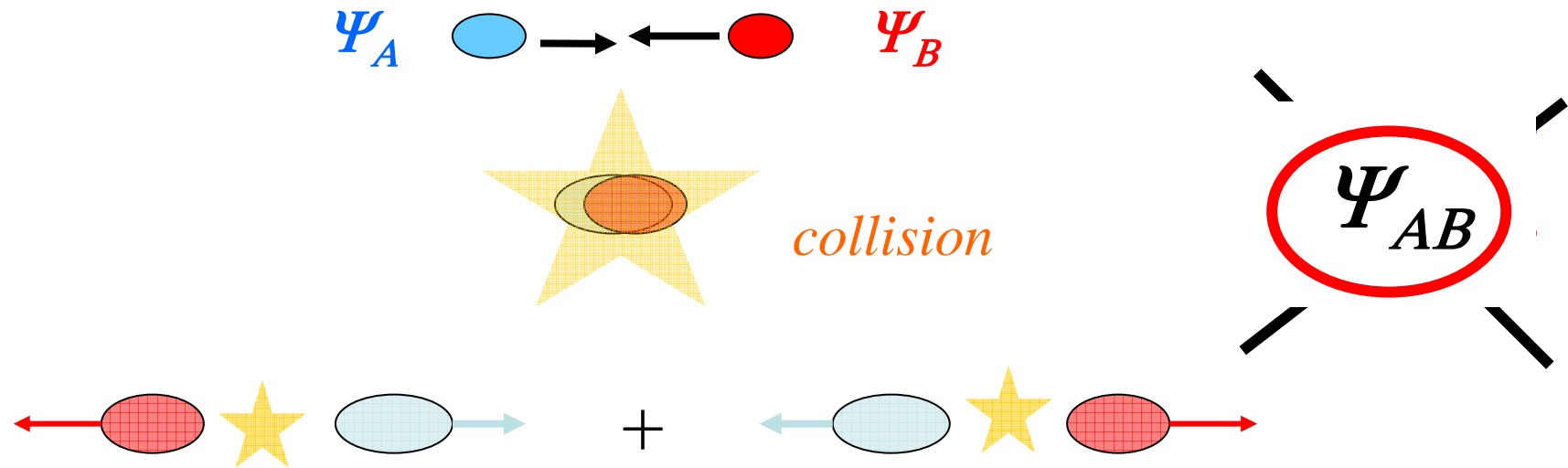
# Quantum interferences are ubiquitous in the microscopic world



When an atom scatters a light pulse via two (or more) indistinguishable excited states, the subsequent fluorescence light exhibits a temporal modulation called «quantum beat» (note analogy with the spatial modulation of the Young double slit set-up).



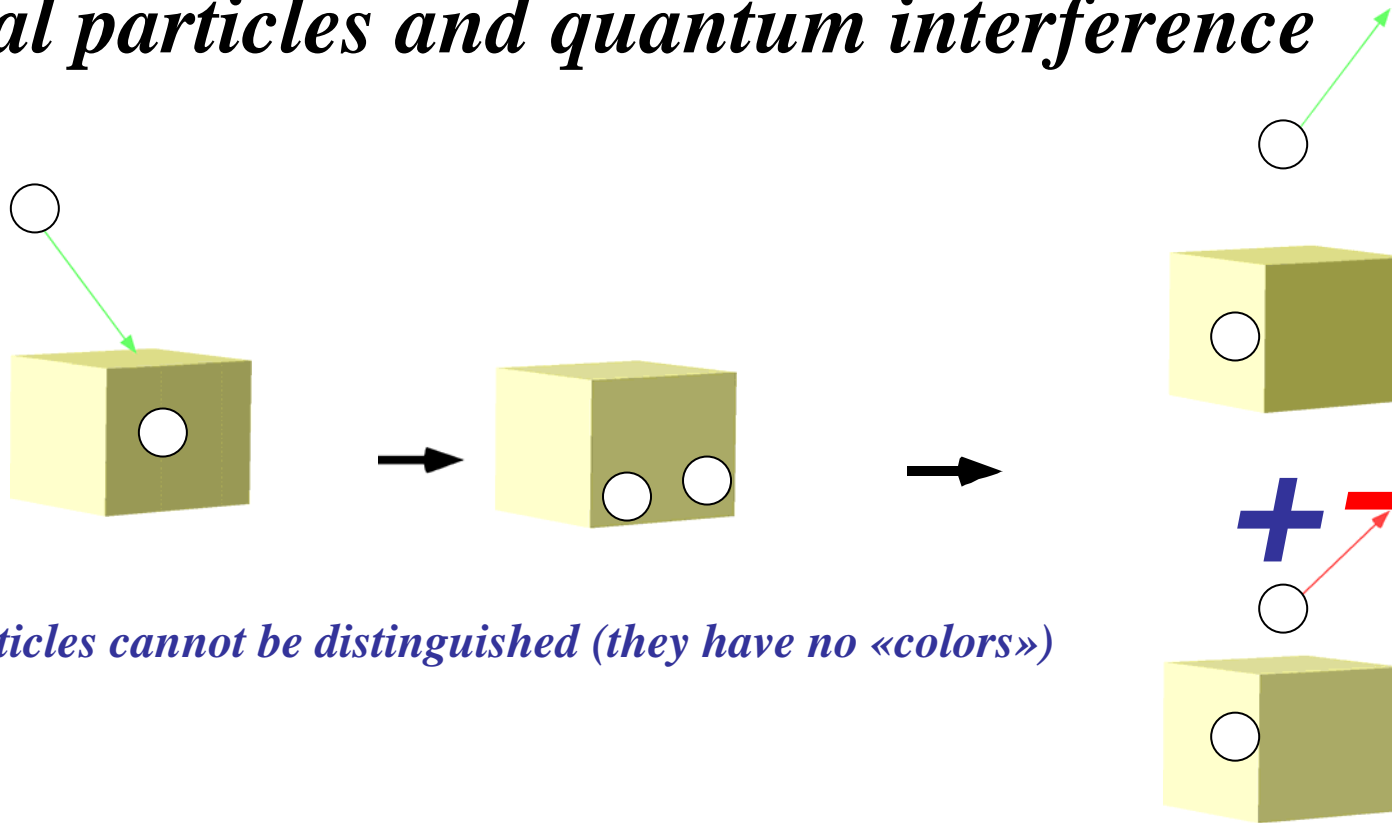
# Superpositions and entanglement of composite systems



$$\Psi_{AB} = \Psi_{left} \Psi_{right} + \Psi_{left} \Psi_{right} \neq \Psi' \Psi'$$

After the collision, there is a wavefunction  $\Psi_{AB}$  of the global system, no longer **wavefunctions for each part**: **there is entanglement**. Measuring one particle changes the global wavefunction and **determines the state of the other at a distance: quantum correlations and non-locality** which Einstein disliked (**EPR paradox**)

# *Identical particles and quantum interference*



*Identical particles cannot be distinguished (they have no «colors»)*

*Fermions: the two amplitudes cancel (sign -): It is impossible to put the two particles in the same state in box: **Pauli exclusion principle***

**1923**

*Bosons: the amplitudes add up (sign + ): Particles have the gregarious tendency to accumulate in box **Bose-Einstein statistics***

**1924**

***Fermions are «individualists» and avoid each other  
(Pauli principle).***

*All particles constituents of matter (electrons, protons, neutrons...)  
are fermions*

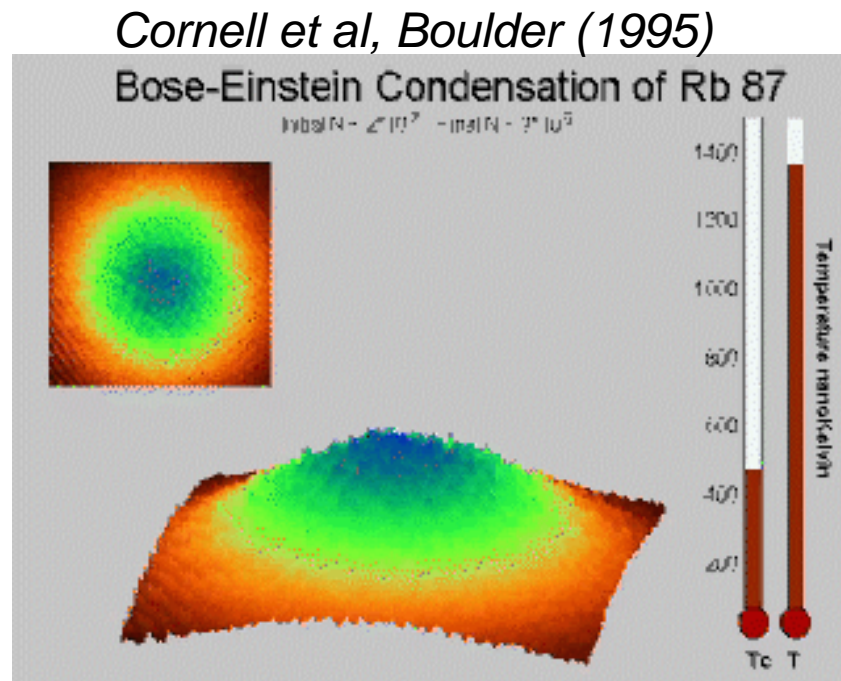
*Explains many « macroscopic » properties which are essential to our  
existence (chemistry, solid states, stability of nuclei.....)*

***Bosons are «gregarious» with a tendency to  
accumulate in the same quantum state***

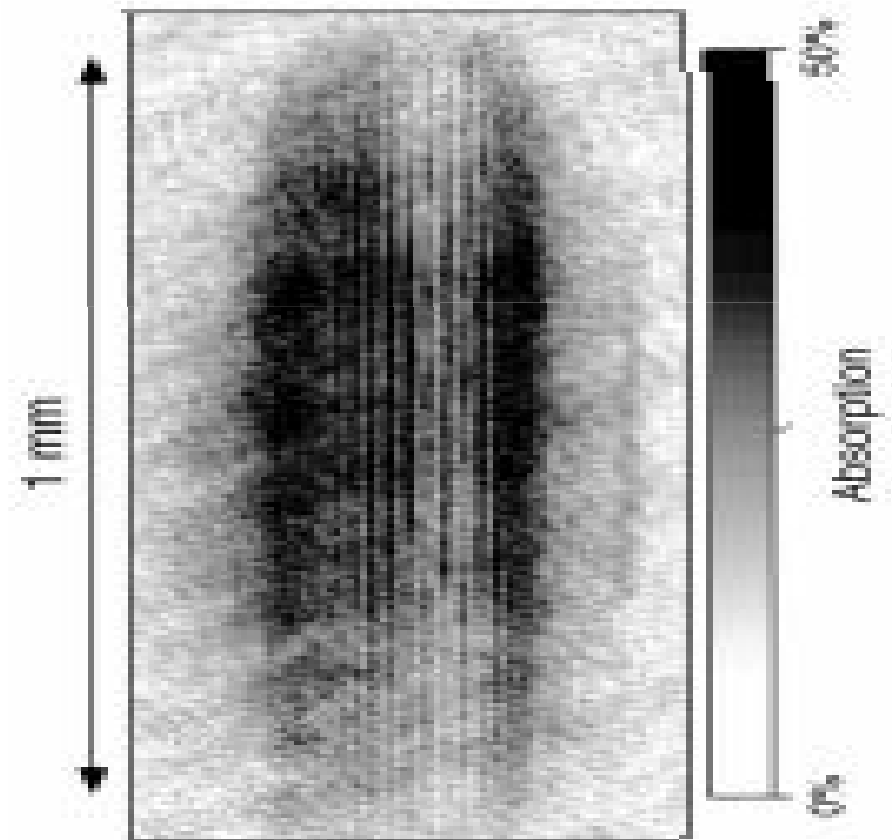
*All particles carrying interactions between the matter constituents  
(photons...) are bosons*

*Explains the properties of light and of laser beams made of photons...*

*Atoms made of an even number of fermions are composite bosons which condense at very low temperature in a quantum state containing a macroscopic number of particles (predicted by Einstein in 1925 and observed in 1995): the coldest objects in Nature ( $10^{-9}$  K)!*



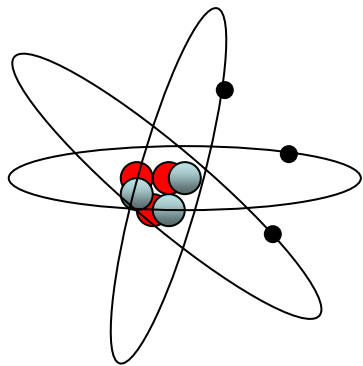
*Ultracold Rubidium atoms in a magnetic trap: evaporative cooling*



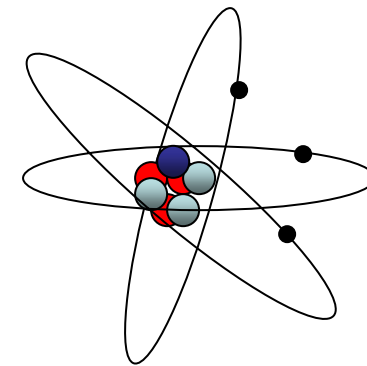
Ketterle et al, MIT

*Condensates are giant matter waves which give rise to interference*

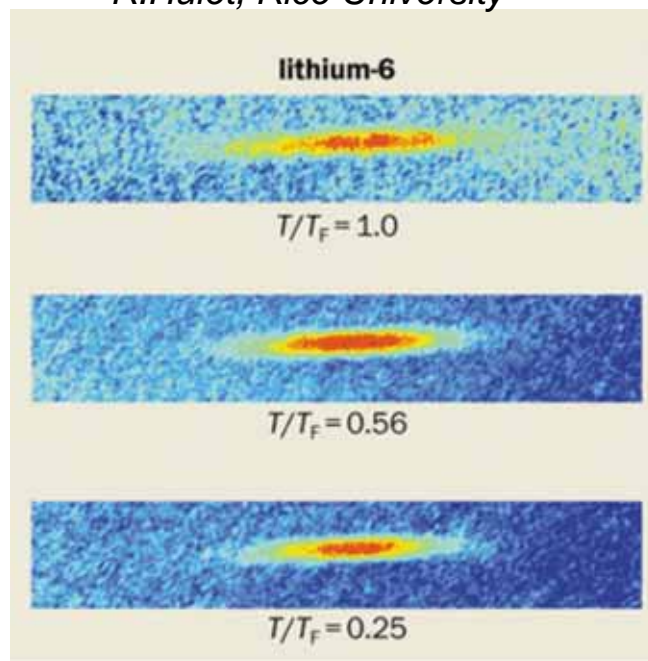
# Direct observation of quantum statistics



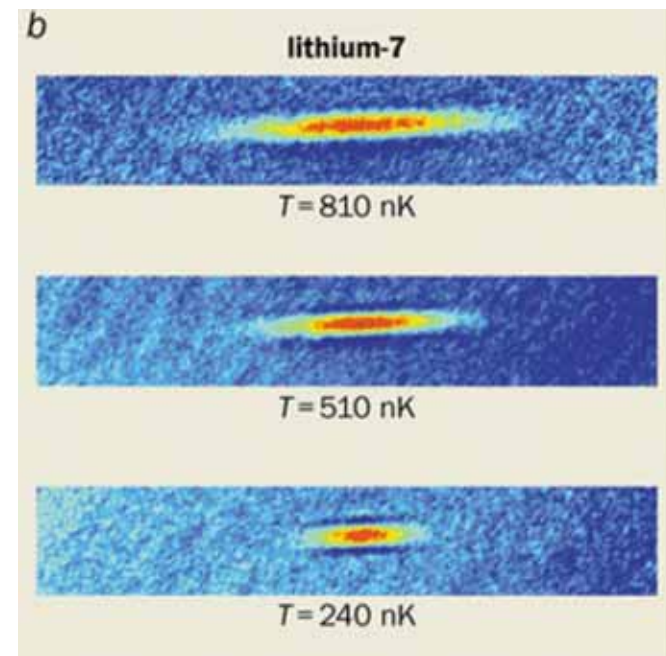
Addition of a  
neutron



*R.Hulet, Rice University*



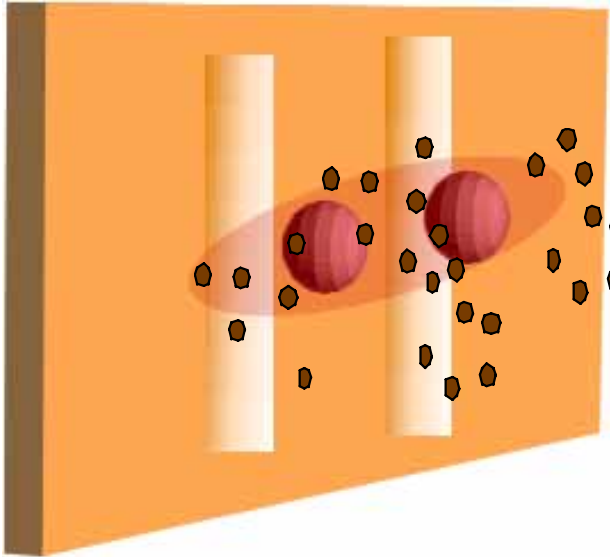
**Fermions**  
**(9 particles)**



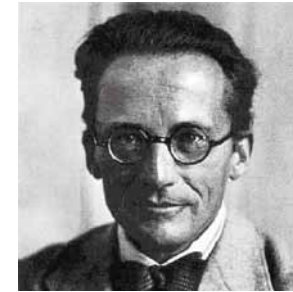
**Bosons**  
**(9+1=10 particles)**



# *Why not superpositions of macroscopic objects?*



## *Schrödinger cat's paradox*



*The environment (molecules, thermal photons..) gets entangled with systems and destroys quantum superpositions*

*(analogous to observation of particle's path in an interferometer)*



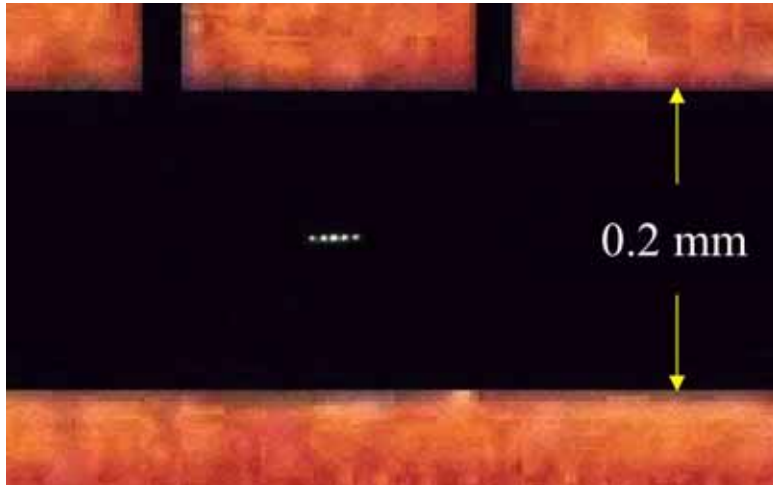
*Decoherence becoming faster and faster as system's size increases*

*Experiments try now to fight decoherence and to observe directly the quantum strangeness in artificial systems made of increasing number of particles...*

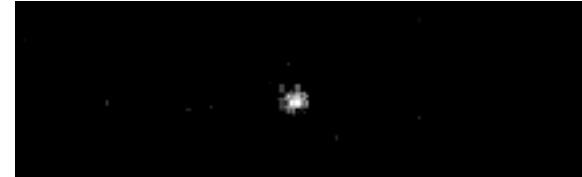
# Seeing isolated trapped atoms

(something Schrödinger thought would be forever impossible..)

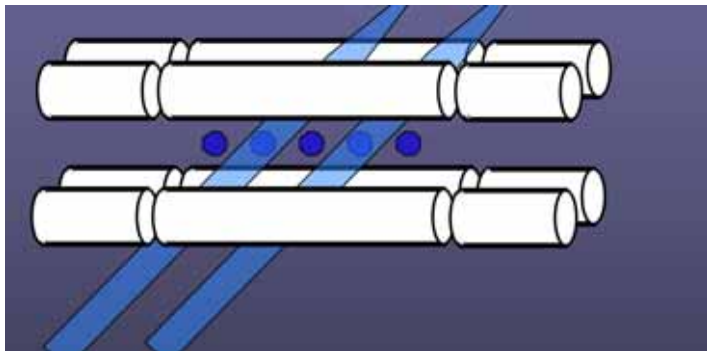
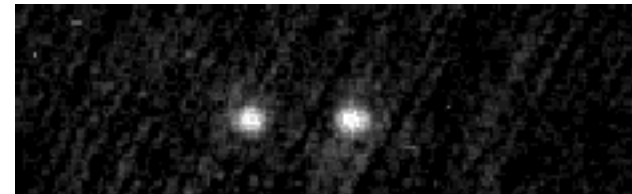
*D. Wineland et al, Boulder*



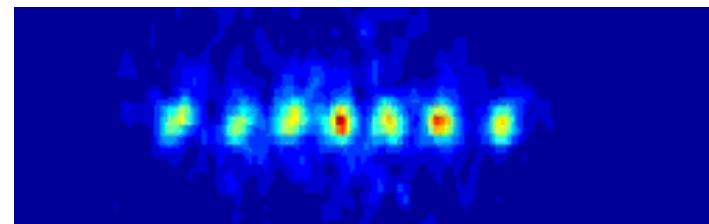
*1 atome*



*2 atomes*



*7 atomes*

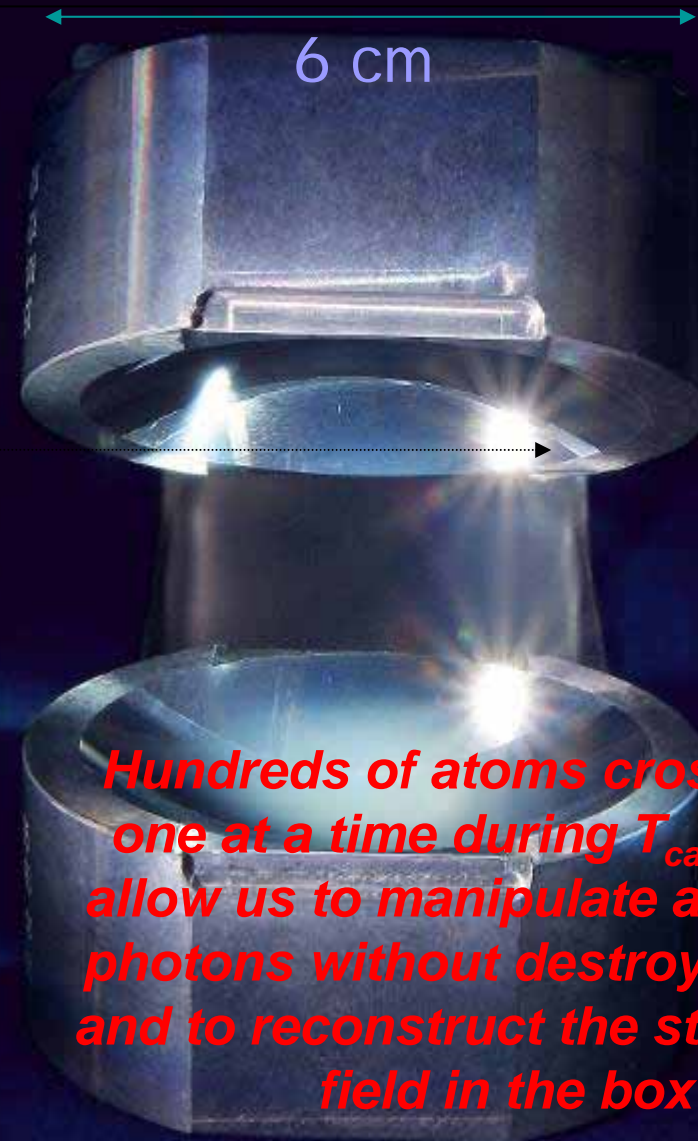


*R. Blatt et al, Innsbruck*

# Seeing microwave photons in a box

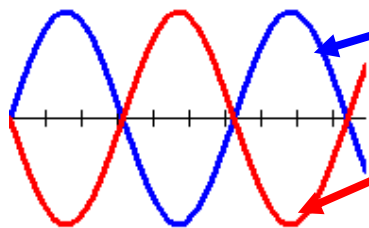
- Superconducting mirrors
- Resonance @  $\nu_{\text{cav}} = 51 \text{ GHz}$
- Lifetime of photons  
 $T_{\text{cav}} = 130 \text{ millisecond}$

- best mirrors ever
- 1.5 billion photon bounces
- Light travels 40 000 km  
(Earth circumference)



Reconstructed «wave function» of a **photonic Schrödinger cat** containing on average 3 photons and prepared by a single atom in a superposition of 2 field components oscillating with opposite phases

These «peaks» correspond to the two «classical» field components



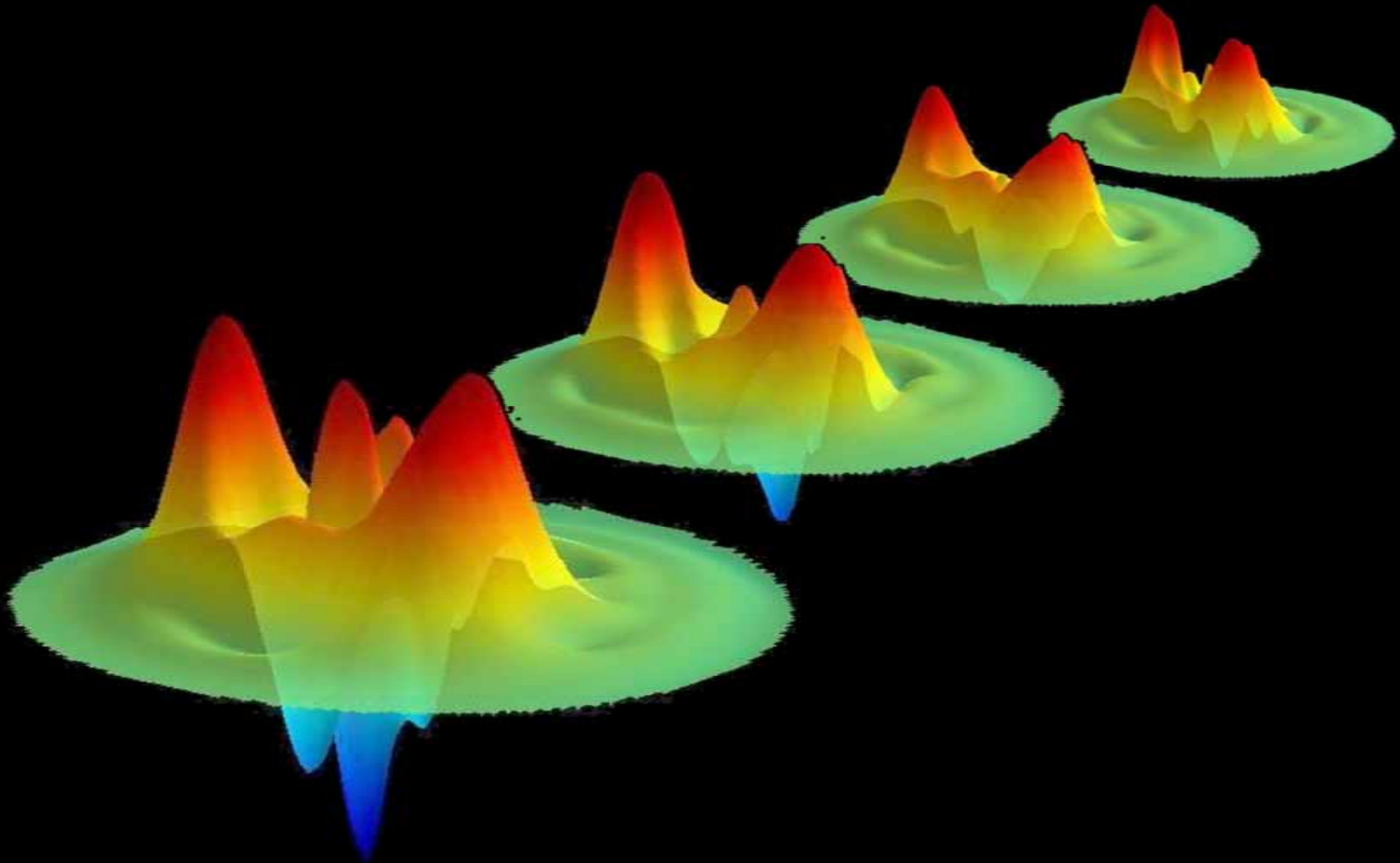
QuickTime™ et un décompresseur sont requis pour visionner cette image.

*S. Deléglise et al, Nature (2008)*

This oscillating feature corresponds to the cat state quantum coherence (responsible for quantum interference effects)

Technically, this wave function is a « Wigner function » in phase space...

# A JOURNEY FROM QUANTUM TO CLASSICAL





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

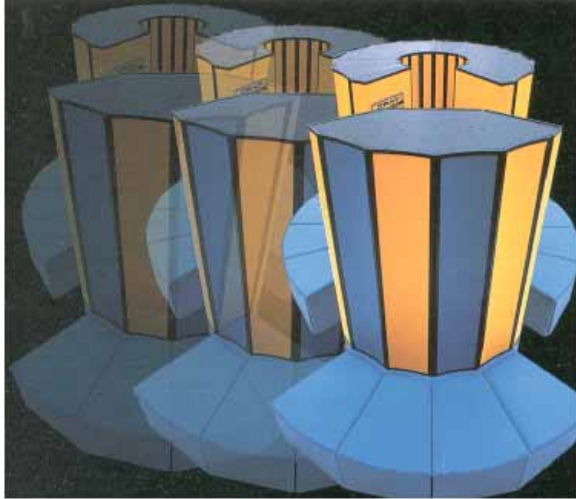
QuickTime™ et un  
décompresseur mpeg4  
sont requis pour visionner cette image.

# The cat's quantumness vanishes

Supplementary  
material on line  
accompanying  
Nature Letter

QuickTime™ et un  
décompresseur mpeg4  
sont requis pour visionner cette image.

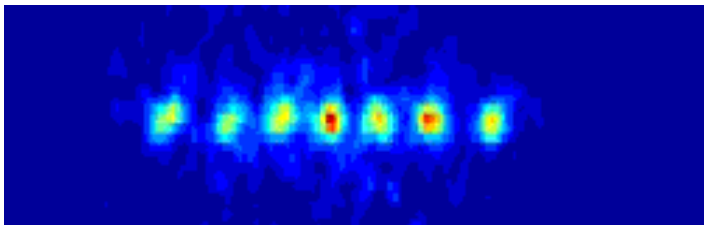
# Could we exploit quantum superpositions and entanglement to compute and communicate?



*A quantum computer would « superpose » a large number of entangled two level « qubits » and perform a kind of parallel computing*

*Some quantum algorithms are much faster than classical ones (e.g. factoring)*

*Very active experimental research on systems made of a few atoms or photons with demos of elementary quantum logic*



*Realizing a large practical quantum computer remains exceedingly difficult because of decoherence and remains an utopy...*

*A simpler (already real) application: **quantum cryptography**. Sharing identical random keys made of 0 and 1 between two partners can be based on entanglement. Quantum physics ensures that it is impossible for a spy to break this secret code without revealing his/her presence.*

# A second quantum revolution or not?

Most probably our increasing ability to juggle with atoms, molecules, photons (and mesoscopic artificial atoms) will lead to applications...Even more probably, these applications will not be the ones we dream about today...

*Don't be obsessed with the quantum computer!  
Just let you be driven by curiosity and have  
fun*