A trip to Quantum Physics

- Schrödinger’s cats, Einstein’s nightmares and quantum technology -

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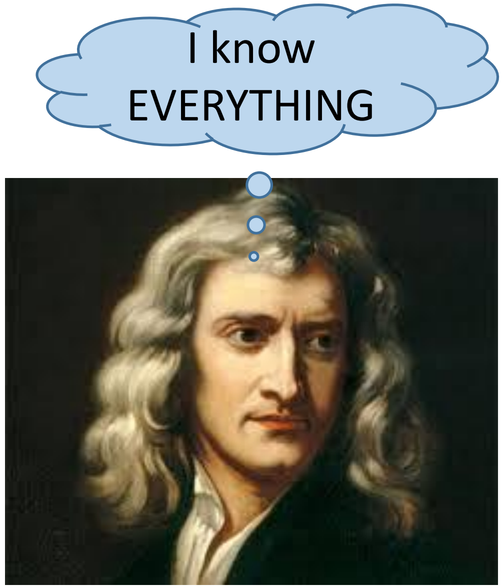
- A bit of history
- Quantum weirdness
- Complexity in quantum systems
- Rise of quantum technology

The first quantum revolution (1905 –1930)

- By the end of the XIX century, classical physics (Newtonian mechanics, Electromagnetism, Statistical Physics…) was well established.



"in this field, almost everything is already discovered, and all that remains is to fill a few unimportant holes."

Johan von Jolly (German physicist at University of Munich) to discourage young **Max Planck** to study physics in 1878.

The first quantum revolution (1905 –1930)

- By the end of the XIX century, classical physics (Newtonian mechanics, Electromagnetism, Statistical Physics…) was well established.

"in this field, almost everything is already discovered, and <u>all that remains</u> is to fill a few <u>unimportant holes</u>."

"Unimportant" holes were:

- The photoelectric effect
- The description of the electron orbits in atoms

The first quantum revolution (1905 –1930)

… until 1905

… an earthquake was about the shake the foundations of Physics

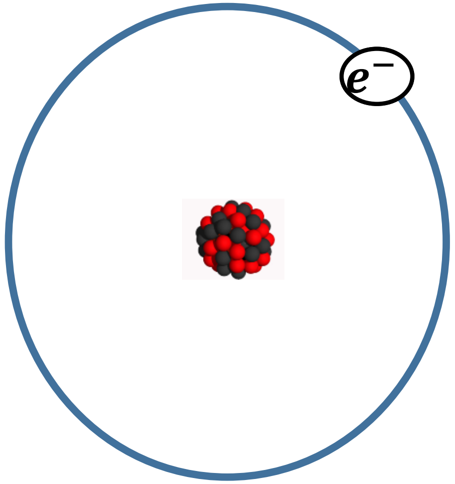
The first quantum revolution (1905 –1930)

Fifth Solvay Conference (Brussels, 1927)

- Those “unimportant holes” led to the development of quantum theory
- The brightest minds of the time were involved in this intellectual endeavour: Einstein, **Max Planck**, Heisenberg, Schroedinger, Dirac, Bohr, Ehrenfest…
- Many of them were shocked about the implications of quantum physics.

Quantum weirdness I: superpositions

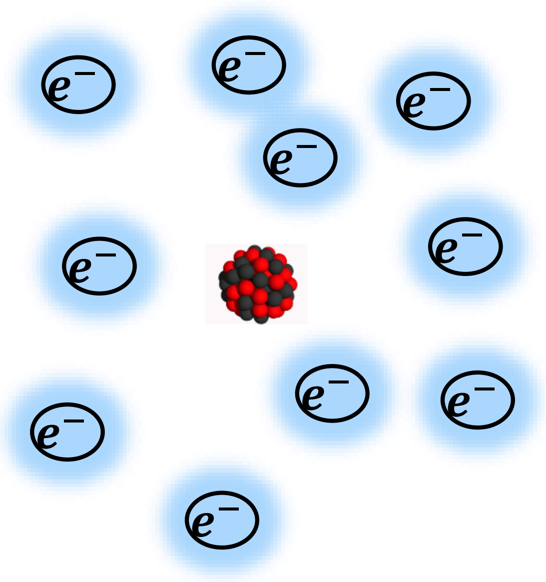
- In classical physics, objects have a well defined position

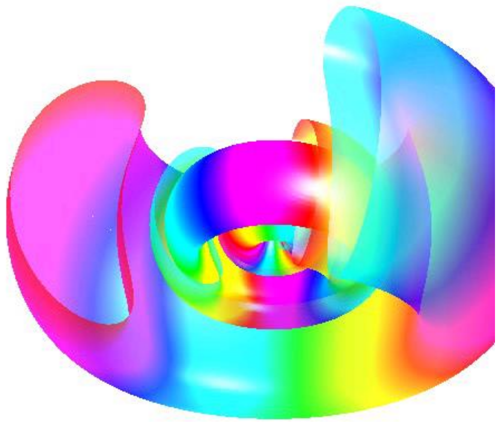


Quantum weirdness I: superpositions

- In quantum physics, a microscopic object can be in a **superposition state**

  … which means, literally, that it can be in ***many places at the same time:***





Mathematically, we describe this state with an object known as wave-function:

- $\Psi(\vec{r})$ = *"probability" wave*
- $|\Psi(\vec{r})|^2$ = set of numbers that allow us to calculate the probability that the particle is at position $\vec{r}$

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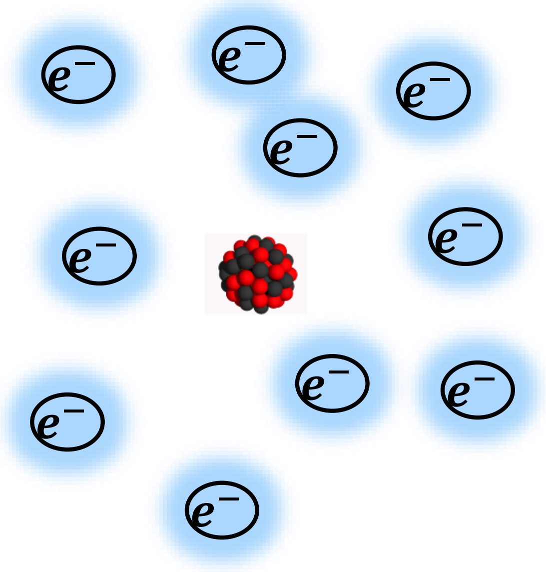
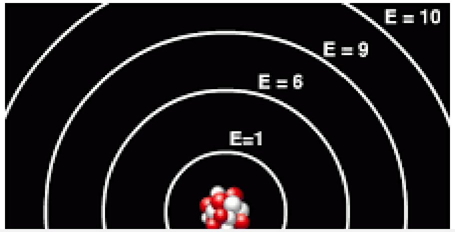


Quantum wave mechanics has been very successful explaining atomic energy levels



$$i\,\hbar\,\frac{\partial \Psi(\vec{r},t)}{\partial t} = \mathrm{H}\,\Psi(\vec{r},t)$$

Quantum weirdness II: measurement

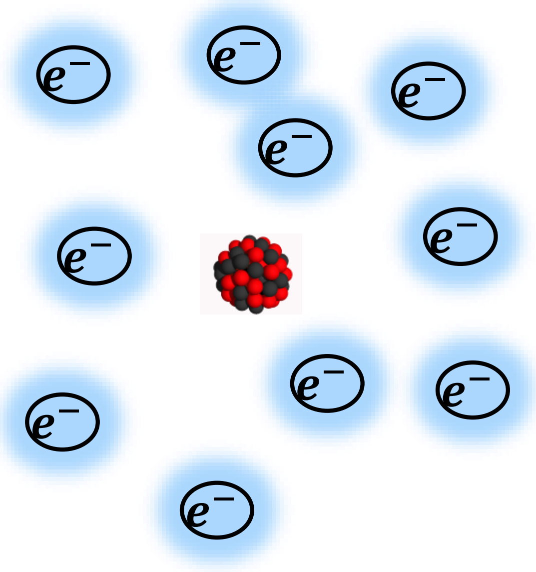
- An object can be in many places at the same time.

OK.

Let's live with that.

- *But quantum physics also predicts that something strange happens when we observe it:*

Wavefunction collapses!



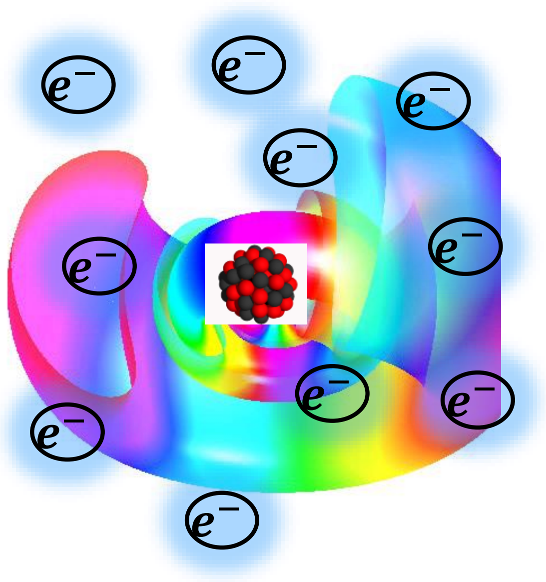
- *The wave-function collapses to a localized state (electron in some well-defined position) after the observation.*

- *Quantum theory only allows us to calculate a probability to find the particle at a given position*

Quantum weirdness II: measurement

Microscopic world (few atoms, few photons)

(Observed system)

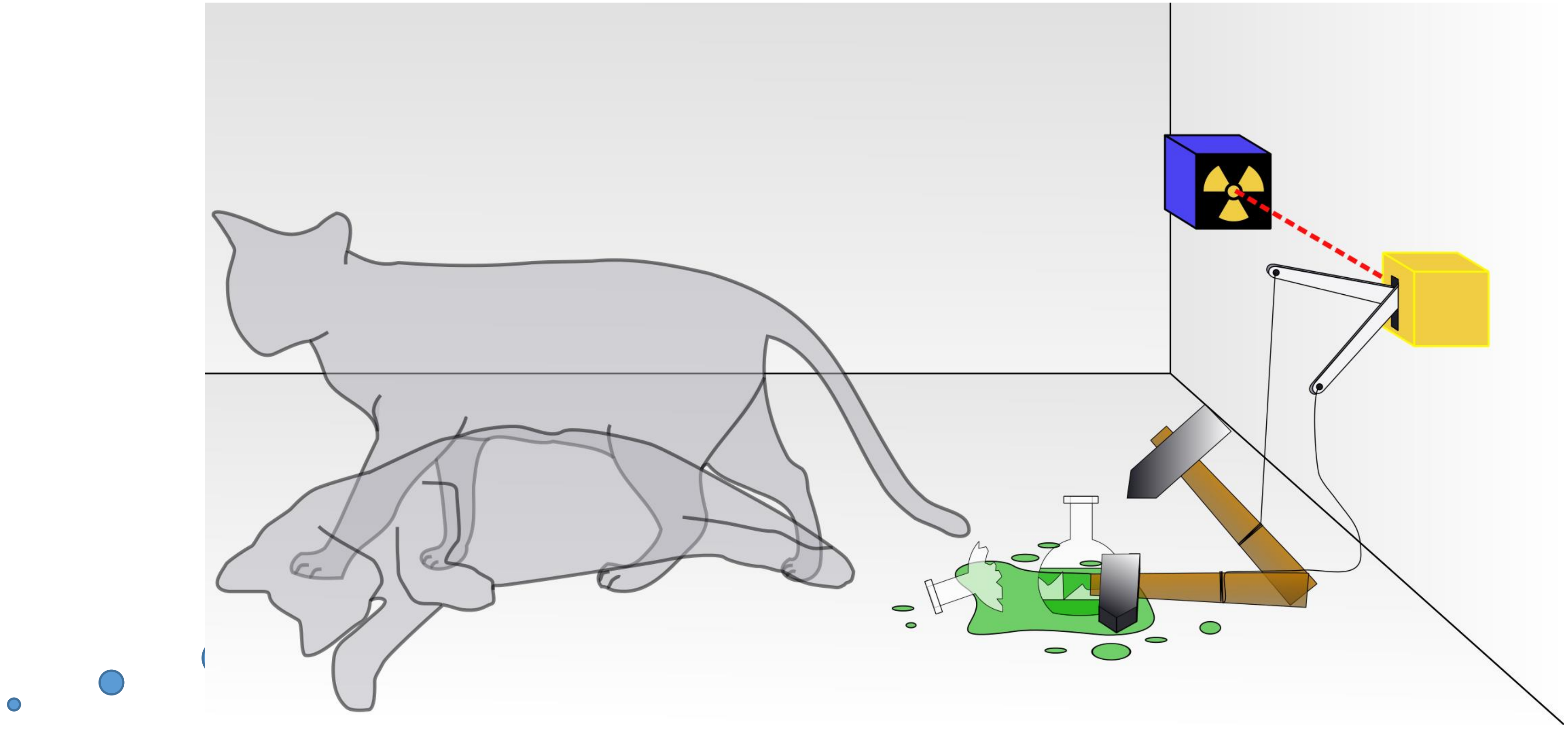


Macroscopic world (large size objects)

(Observer)

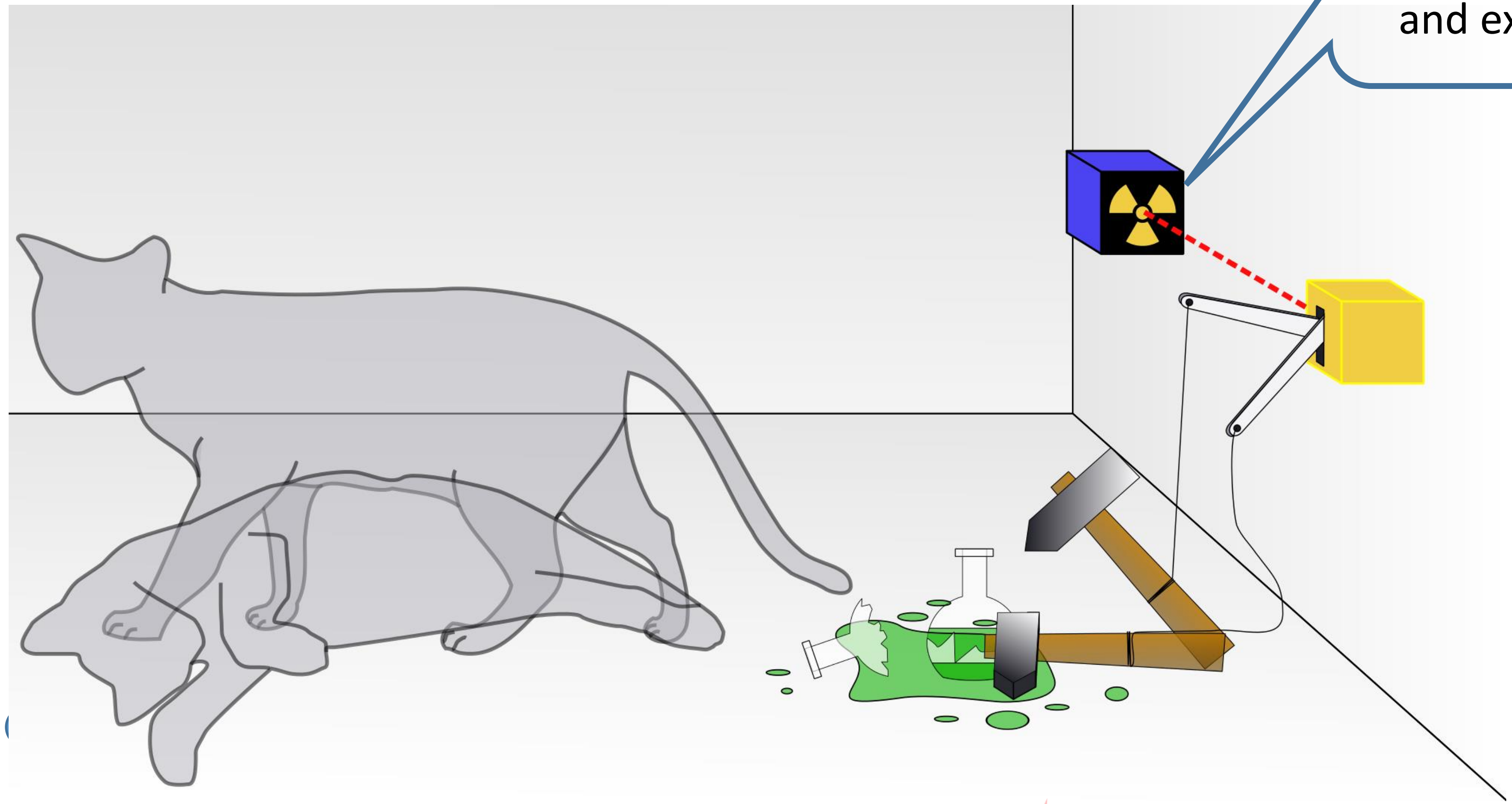
The Schrödinger's cat paradox

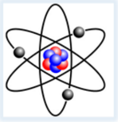
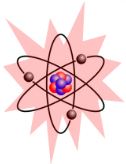
- Could large size objects be also in a quantum superposition?



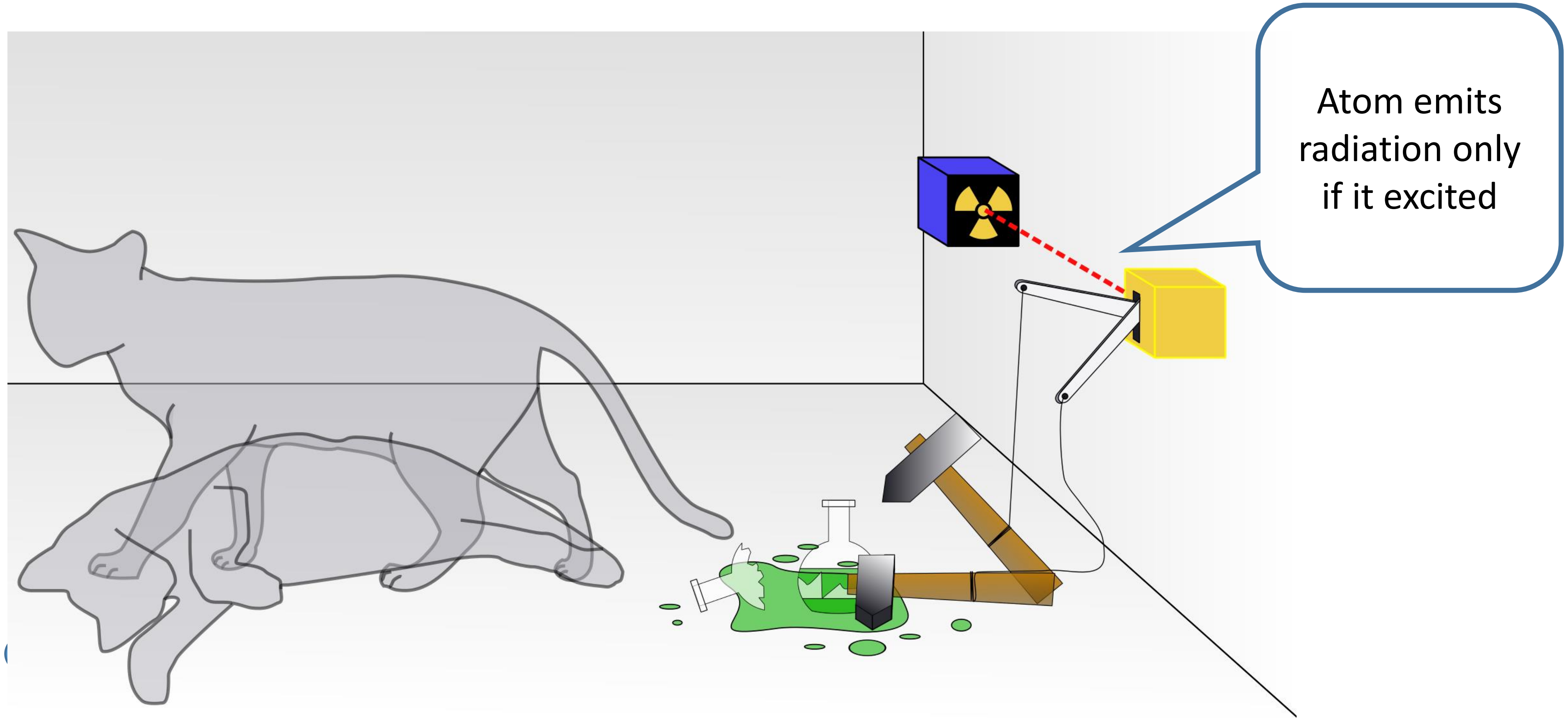
The Schrödinger's cat paradox

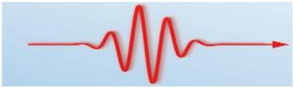
Atom is at the same relaxed and excited



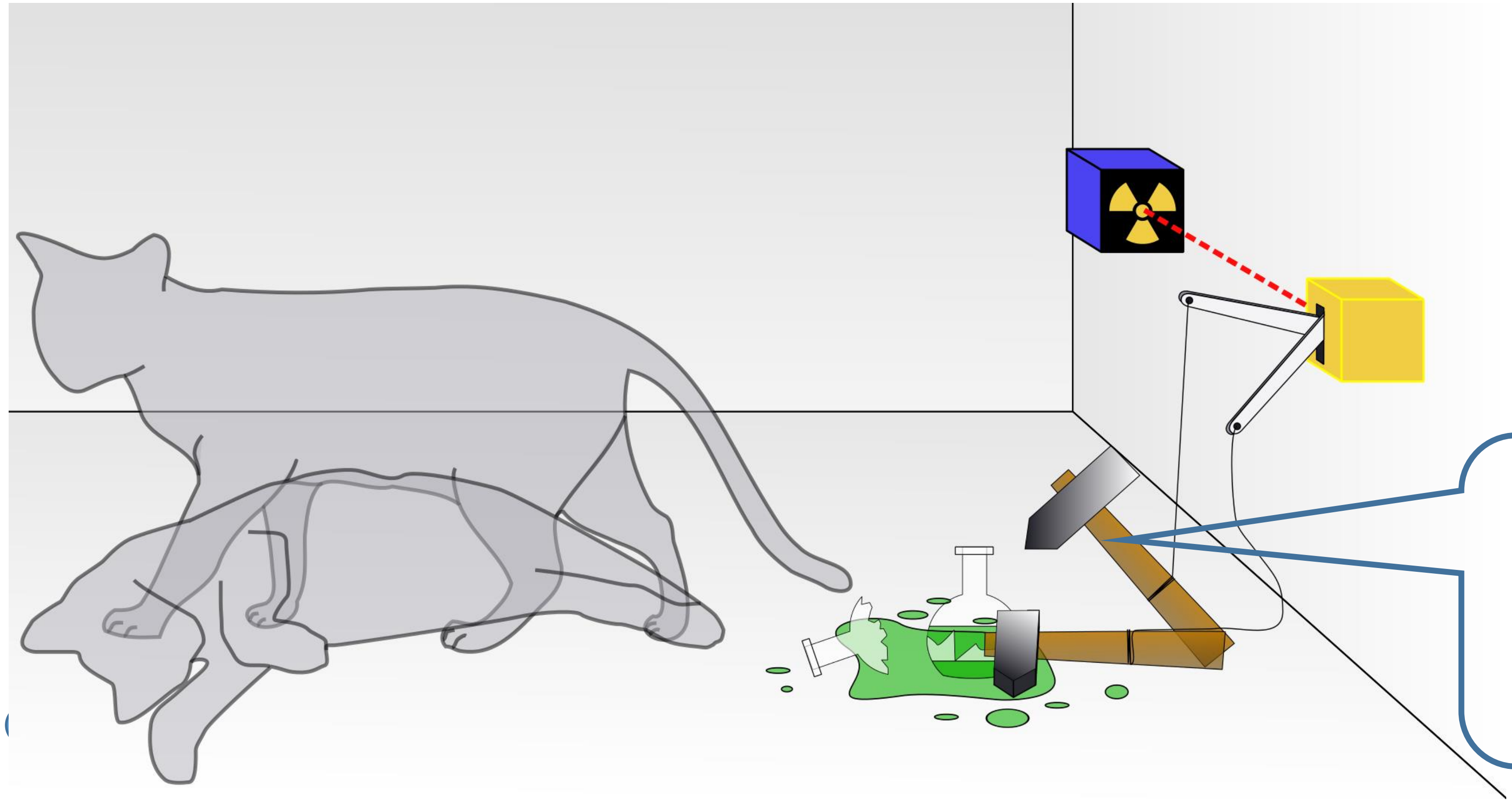
$\Psi =$  $+$ 

The Schrödinger's cat paradox

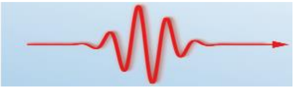


$$\Psi =$$  $$+ (no\ radiation)$$

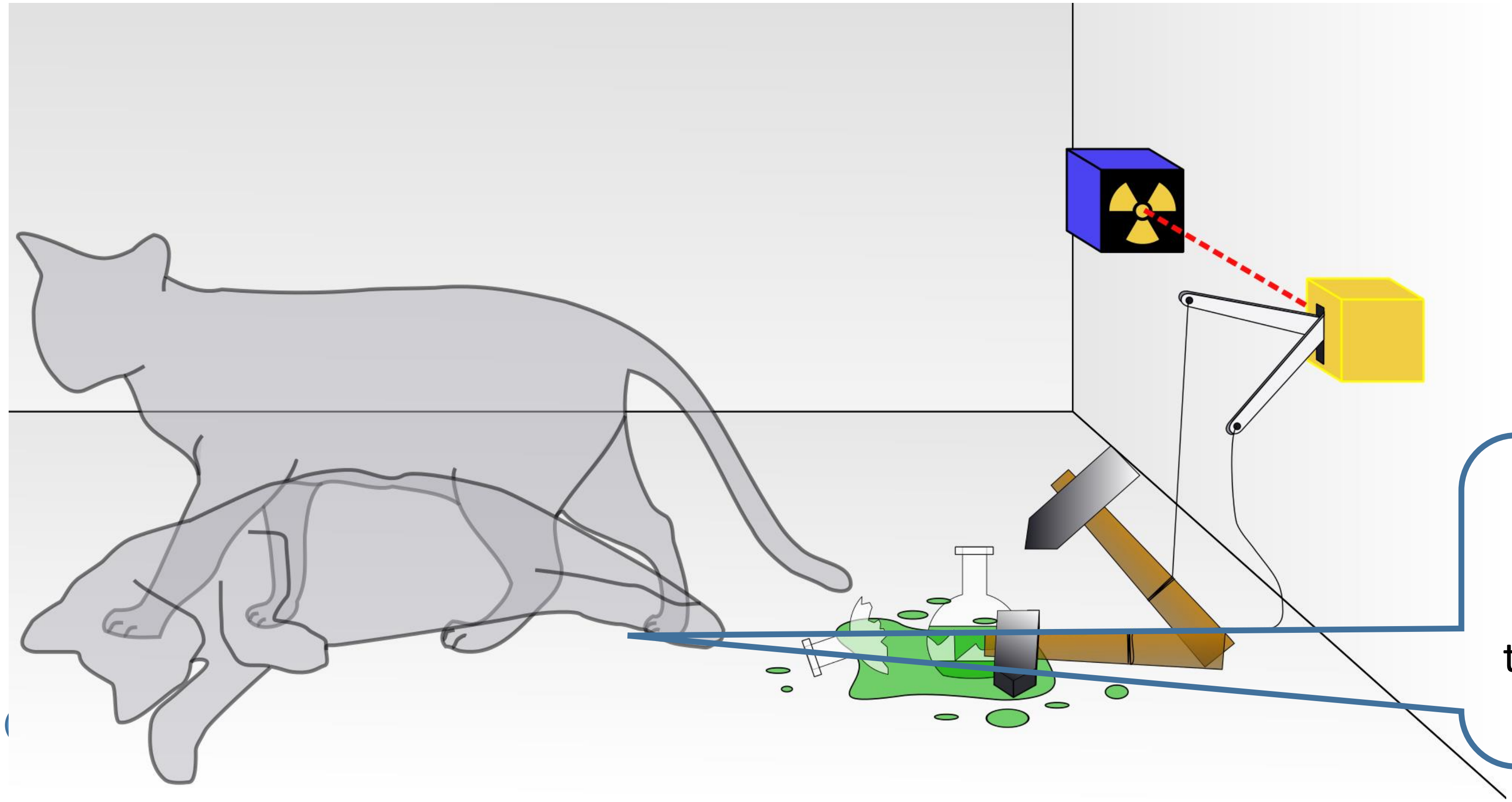
The Schrödinger's cat paradox



Radiation triggers a mechanism that releases poison

$\Psi =$  $+(no\ radiation)$

The Schrödinger's cat paradox



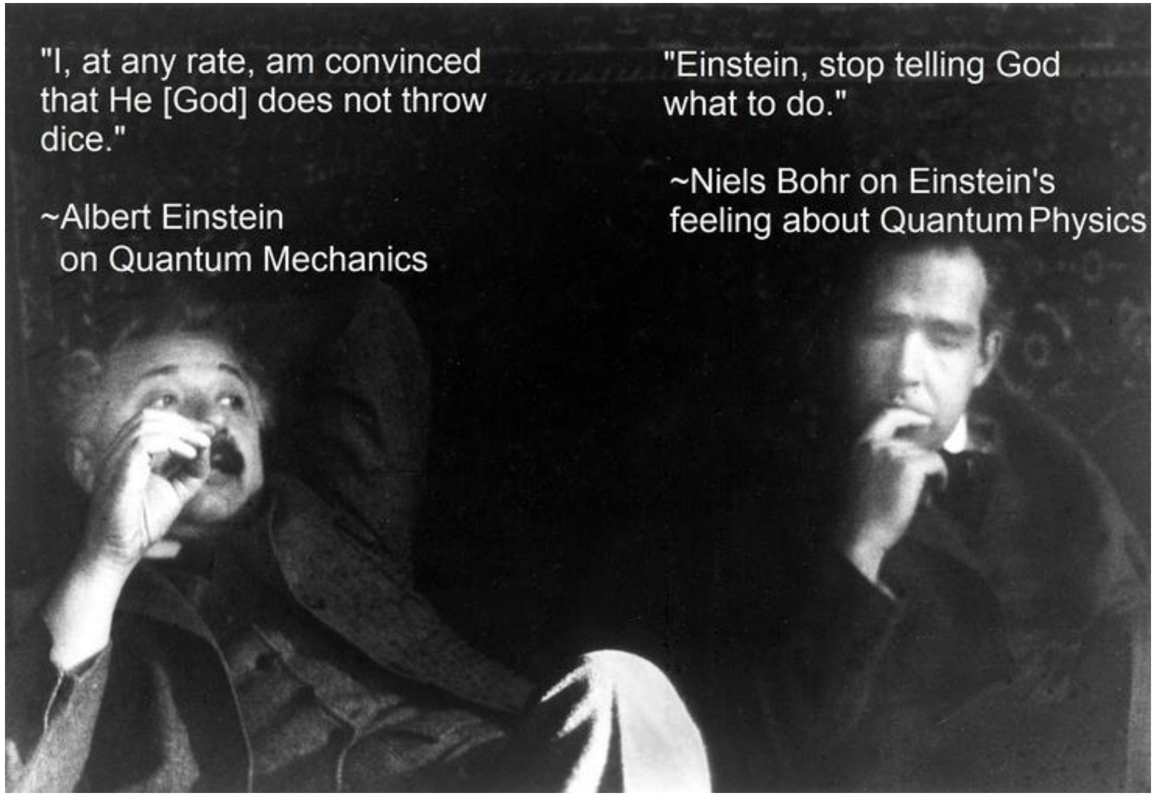
Cat is dead and alive at the same time

$$\Psi = \ DEAD + ALIVE$$

Attitudes towards quantum theory

- Wave function collapse implies a disturbing picture of physical reality.

- Can we be sure about anything? Is probabilities everything we can calculate about microscopic objects?



Attitudes towards quantum theory

- Is it really a problem? Do we ever observe a single microscopic system? Or, equivalently, could a single atom emit so much radiation to kill the cat?

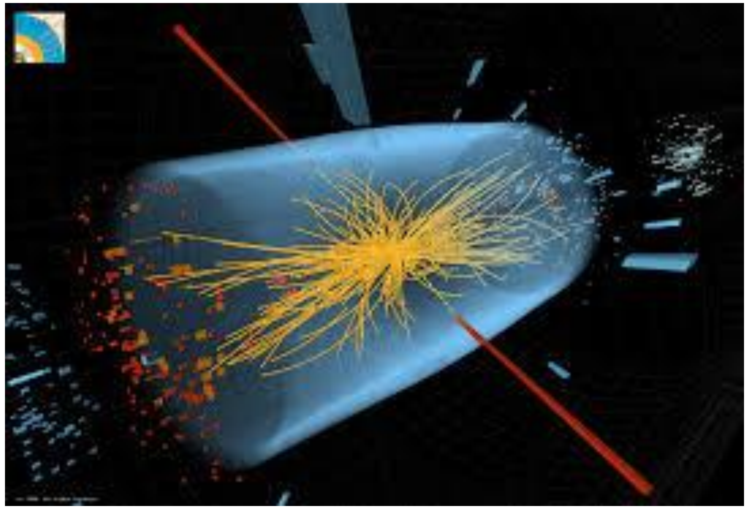
Erwin Schrödinger (1952)

"We never experiment with just one electron or atom [...] In thought-experiments we sometimes assume that we do; this invariably entails ridiculous consequences..."

- *Are there quantum jumps? (II)*, Brit. J. Phil. Sci. 3, 233 (1952)

Attitudes towards quantum theory

- Real experiments deal with measuring many particles at the same time, not a single one.



- Particle accelerators: many collision events

- Solid-state systems (made out of many atoms/electrons)

Quantum measurement: a ~~Gedanken~~ real experiment

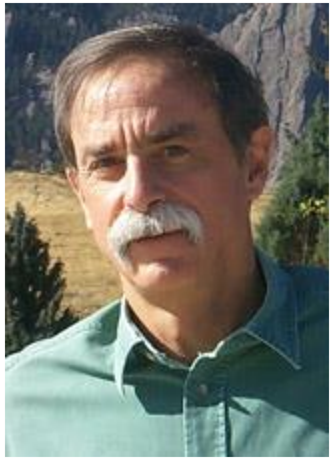
- Relieved?
- We seem to be safe. Wave-function collapse and quantum superpositions are just a convenient assumption in quantum theory, but we will never observe those effects.

Well, really?

- The Nobel Prize in Physics 2012 -

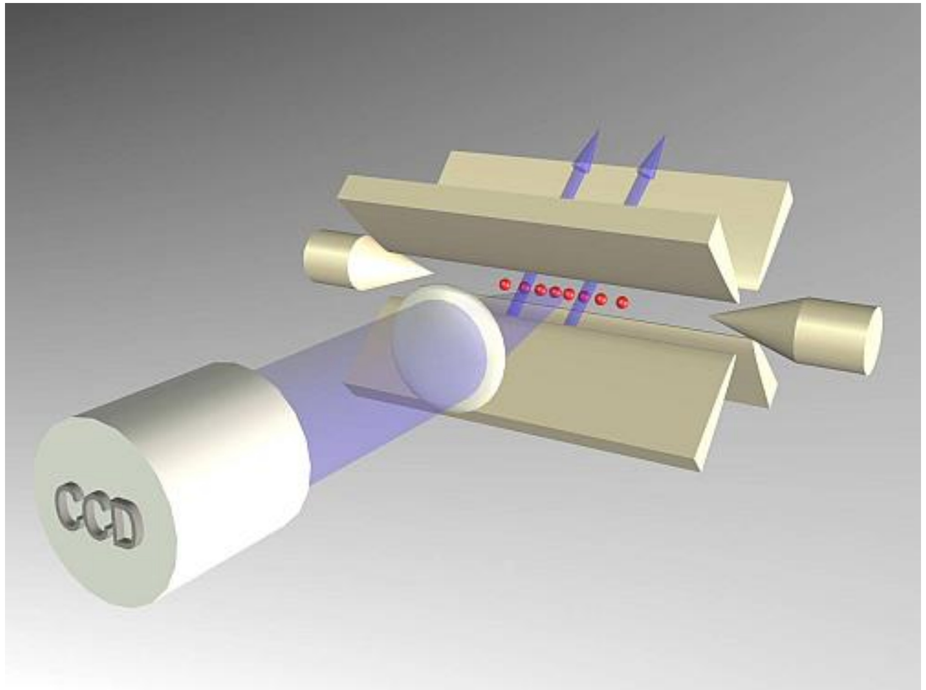
David Wineland and Serge Haroche

"… for ground-breaking experimental methods that **enable measuring** and manipulation of **individual** quantum systems"



Quantum measurement: a ~~Gedanken~~ real experiment

- How does a real quantum measurement work in the lab?

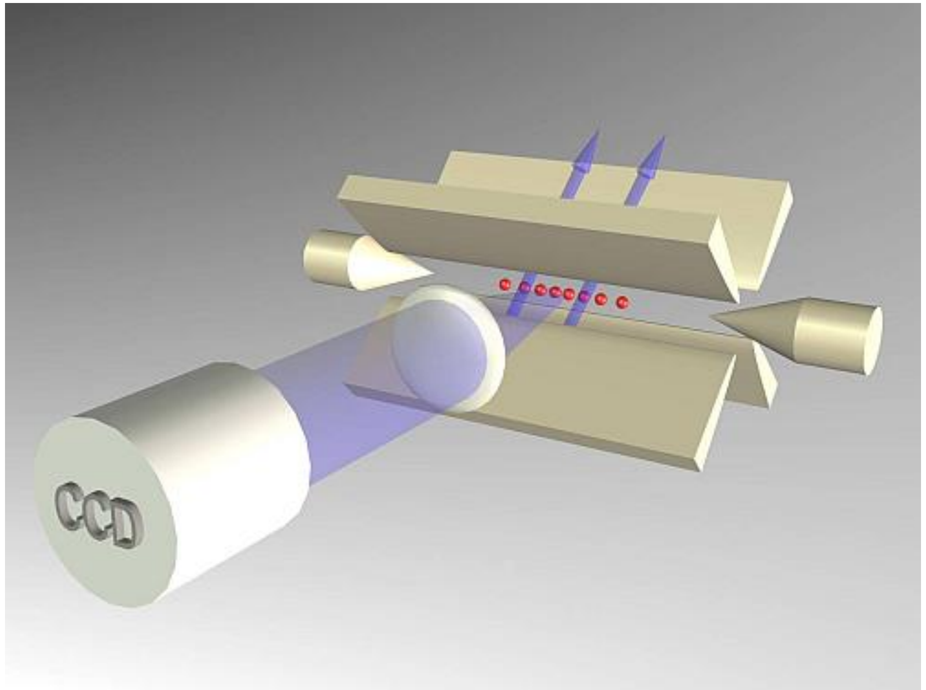


Single Atom:

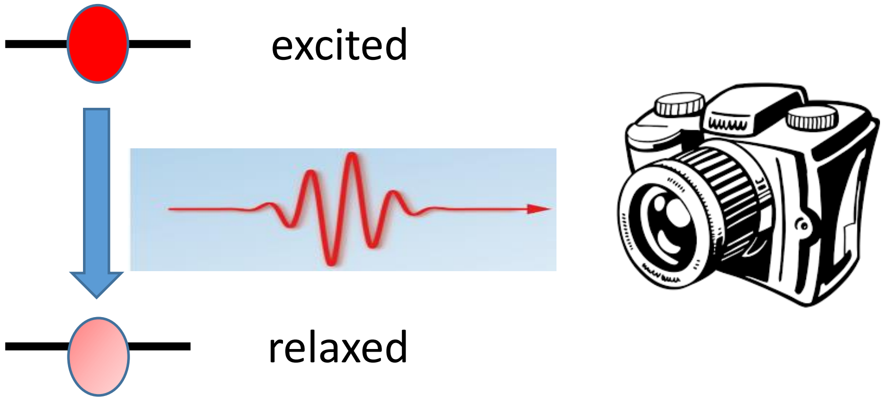
excited

relaxed

Quantum measurement: a ~~Gedanken~~ real experiment

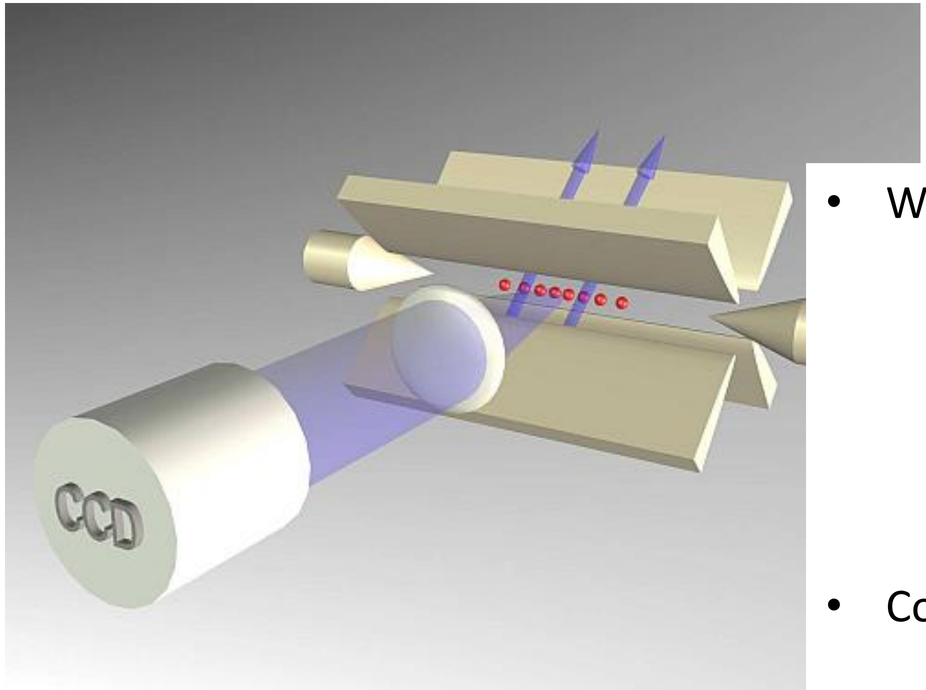


Single Atom



Quantum measurement: a ~~Gedanken~~ real experiment

- Single atom is observed either in a relaxed state or in an excited state !

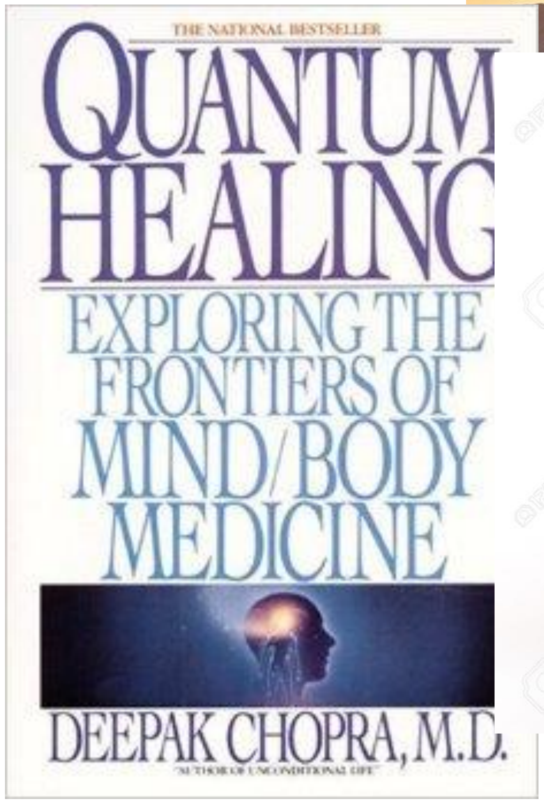


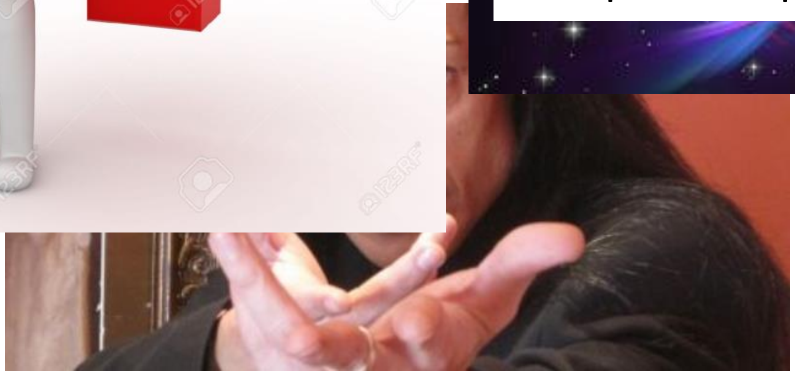
- We do experiment with single atoms…

…. the quantum measurement does not seem to be a "Gedanken Experiment"

- Correct interpretation/explanation still under debate

Pseudoscience warning !

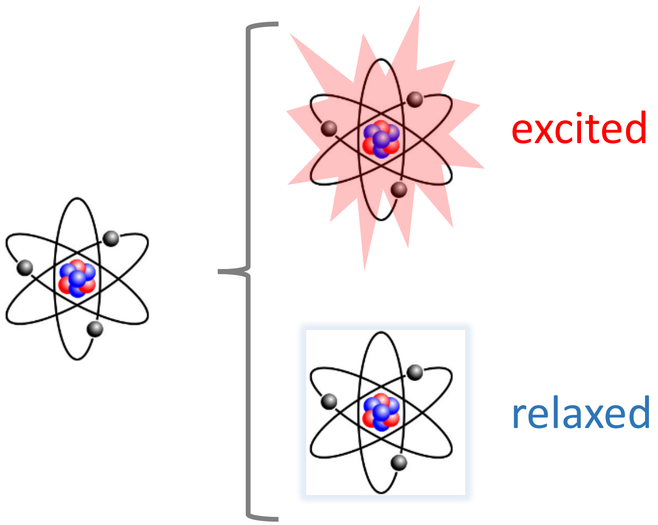




- No scientific basis
- Yes, the observer influences the world, but only if you observe microscopic systems
- We do not create the reality around us, or heal anyone with “quantum powers”

The complexity of quantum systems

- Quantum systems of more with more than one particle become very easily complicated…
- Why? Imagine that we have a single atom. We simplify its description by assuming that it can be in two states (relaxed/excited)

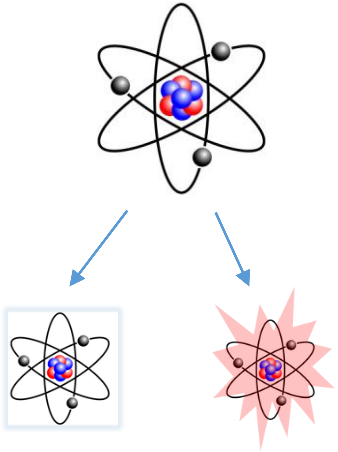


$$\Psi = a\,\psi_{\mathrm{rel}} + b\,\psi_{\mathrm{exc}}$$

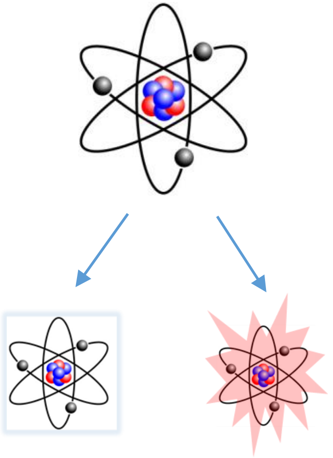
We need **2** numbers to define the state of the atom (how much excited, how much relaxed?)

The complexity of quantum systems

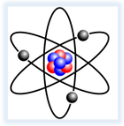
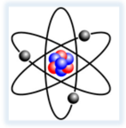
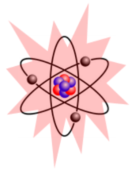
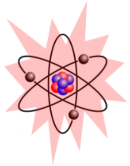
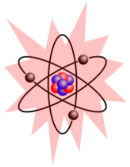
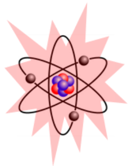
- Now we have two atoms, each of them can be in a different (relaxed or excited) state



Atom 1



Atom 2

Atom 1	**Atom 2**
	
	
	
	

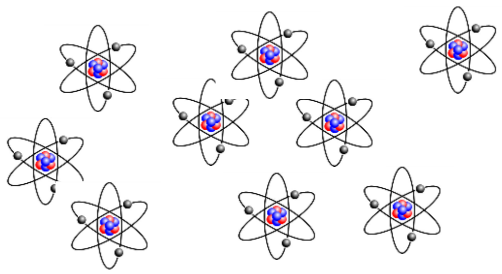
4 combinations

4 numbers to describe a superposition state

$$
\begin{aligned}
\Psi = \; & a\,\psi_{1,\mathrm{rel}}\psi_{2,\mathrm{rel}} \\
& + b\,\psi_{1,\mathrm{rel}}\psi_{2,\mathrm{exc}} \\
& + c\,\psi_{1,\mathrm{exc}}\psi_{2,\mathrm{rel}} \\
& + d\,\psi_{1,\mathrm{exc}}\psi_{2,\mathrm{exc}}
\end{aligned}
$$

The complexity of quantum systems

- Imagine an arbitrary number *N* of atoms:



$$\text{Number of states} = \underbrace{2 \times 2 \times 2 \ \ldots \times 2}_{\text{N times}} = 2^N$$

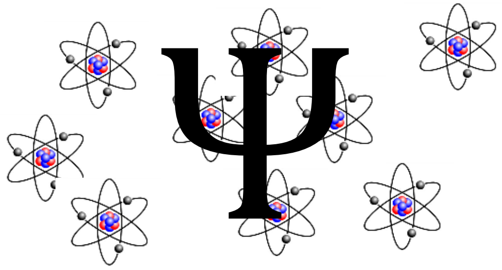
- Still not impressed?

- Take a modest number of atoms: N = 262 (the smallest virus already has N = 180.000 atoms).

The number of states is 2^{262} = the total number of electons/protons/neutrons in the universe !!

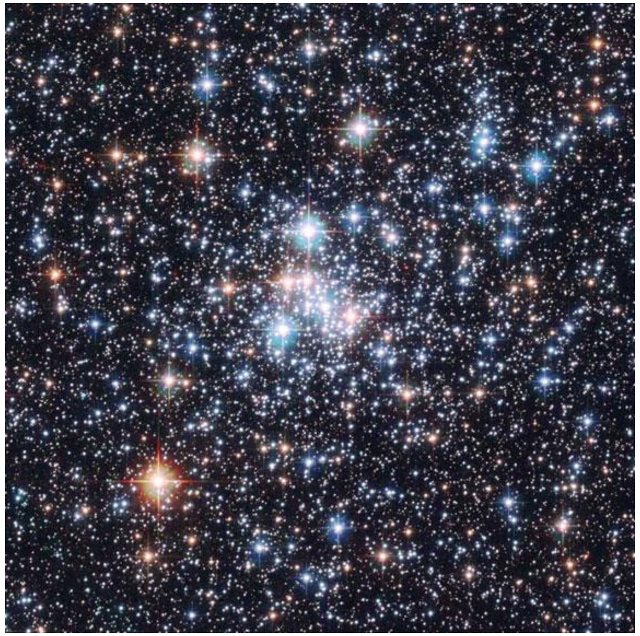
The complexity of quantum systems

- The wavefunction of that small amount of atoms contains so much information …



$$\mathrm{N} = 2^{262}$$

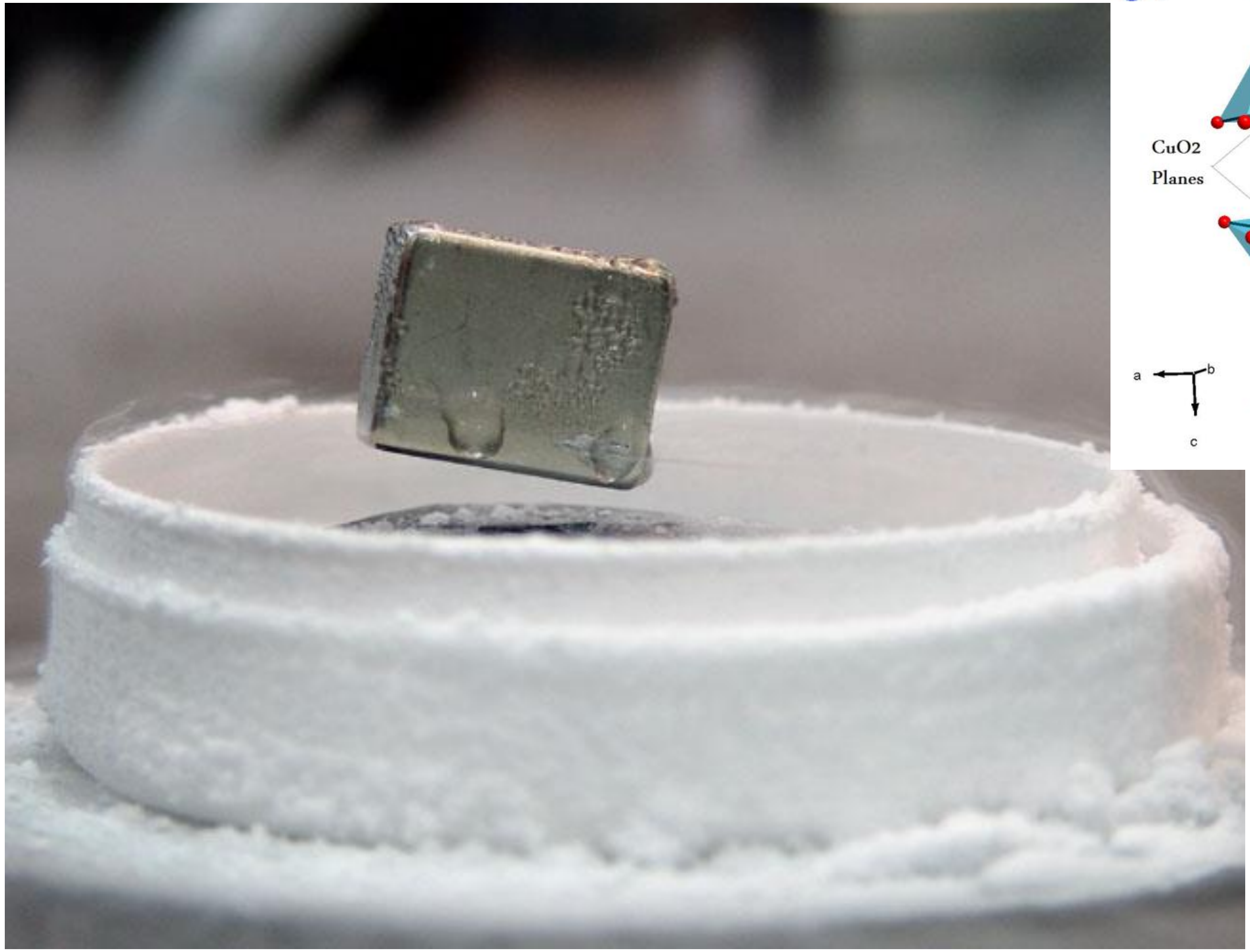
… that the whole observable universe is not big enough to store it !!

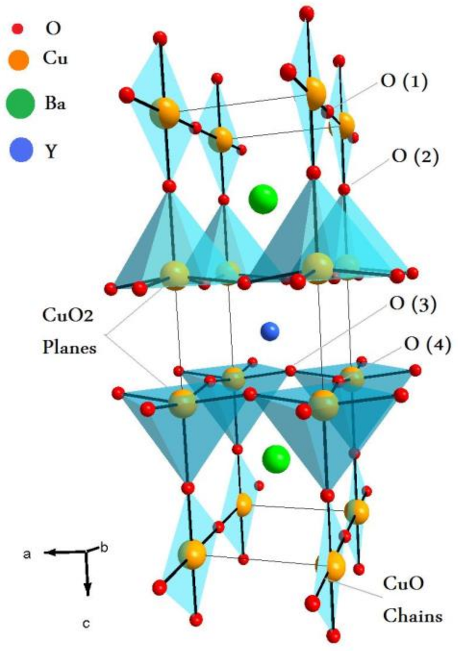


The complexity of quantum systems

- The complexity of quantum systems is the ultimate reason why we still do not understand many quantum phenomena

- E.g. : high-Tc superconductivity





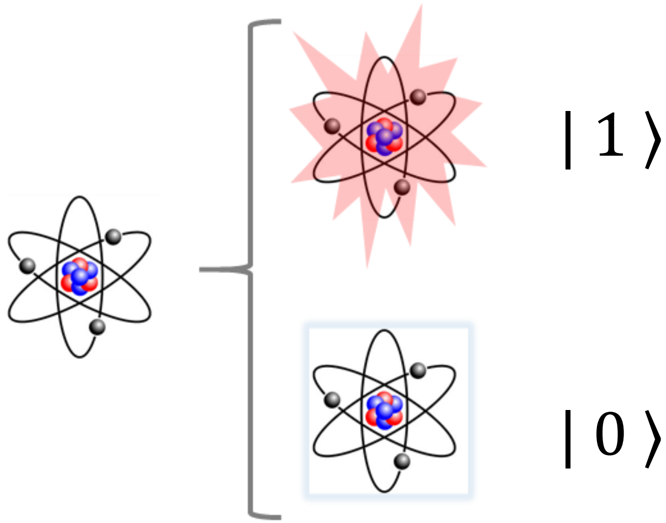
Quantum technology

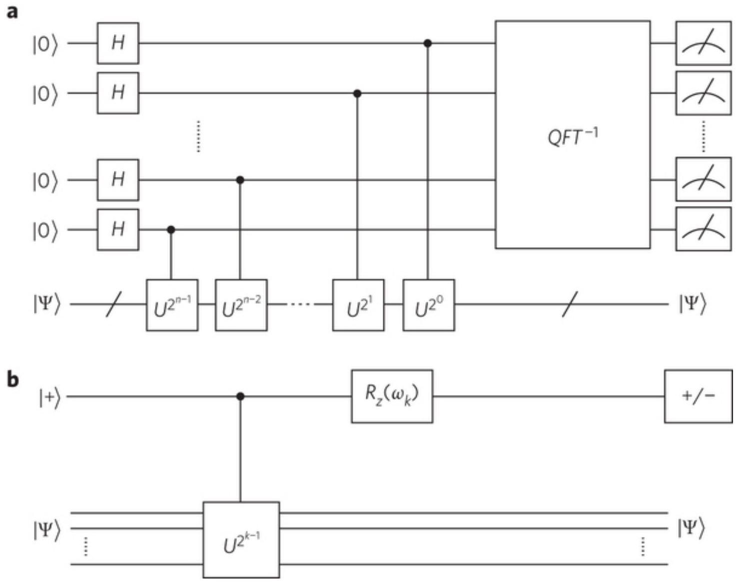
- The enormous amount of “quantum information” contained in systems of many-particles gives us a hint of the computational power of quantum systems
- What if we could use that power to build a “quantum computer”?
- Here we could use atoms as **qubits** to replace the **bits** of a classical computer

Quantum computation

- David Deutch and Richard Josza (1992)

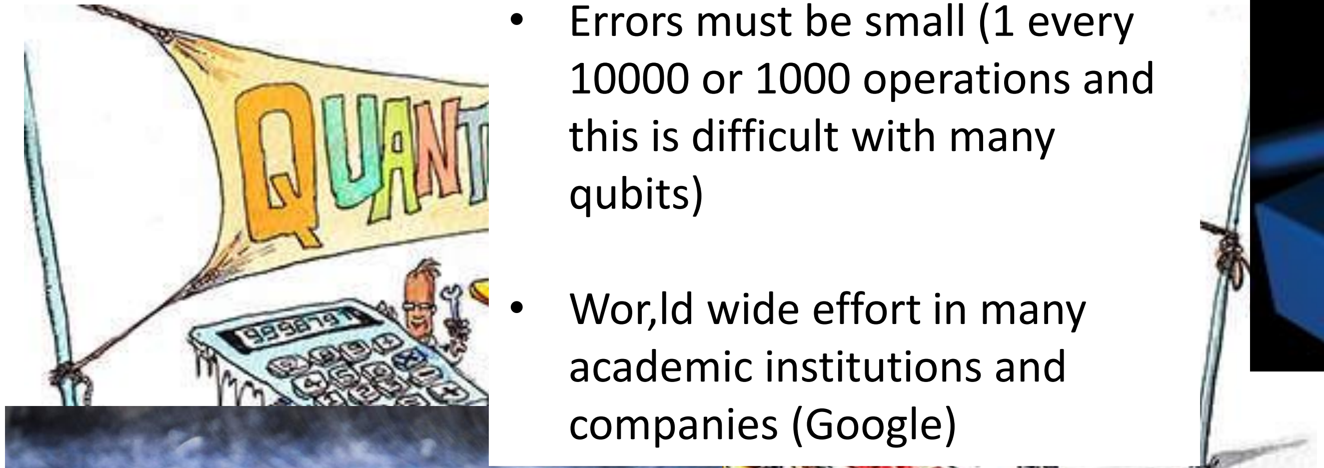
… showed that quantum computers can be used to break codes used in nowadays communications !



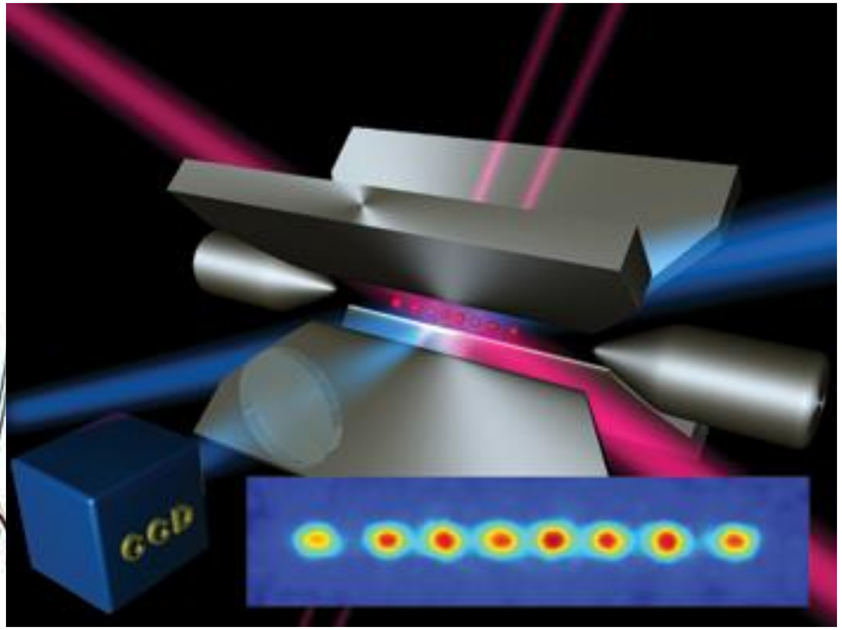


Quantum computation

Quantum computation

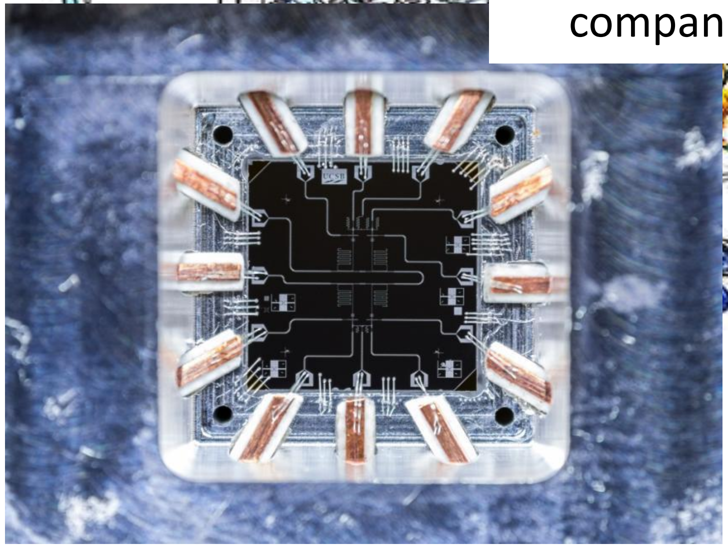


- Errors must be small (1 every 10000 or 1000 operations and this is difficult with many qubits)
- Wor,ld wide effort in many academic institutions and companies (Google)



- Trapped ion quantum computer:

(**Sussex**, Oxford Innsbruck, NIST (EEUU) ..)

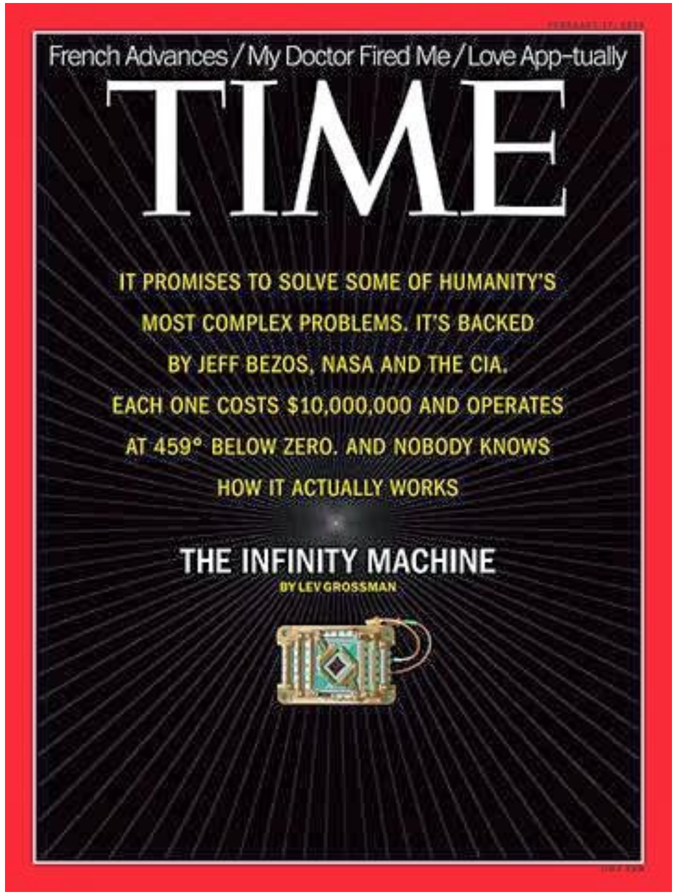


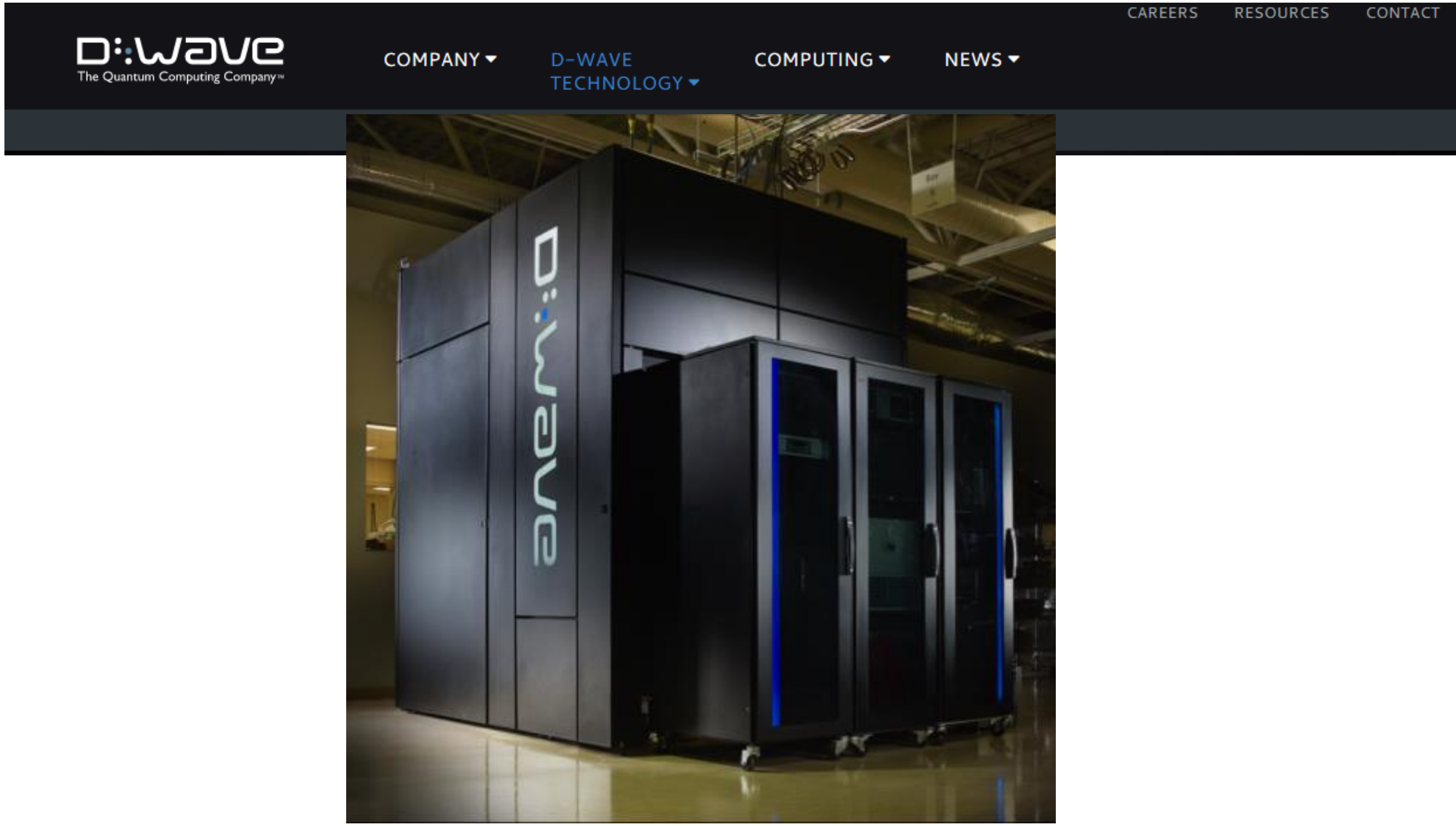
- Superconducting qubit quantum computer:

(UCSB, Google, ETH Zurich, …)

Quantum computation

- Technical progress is slow, but we may expect that a quantum computer may be available in the following years (decades?))
- A company in Canada claims to build quantum computers:





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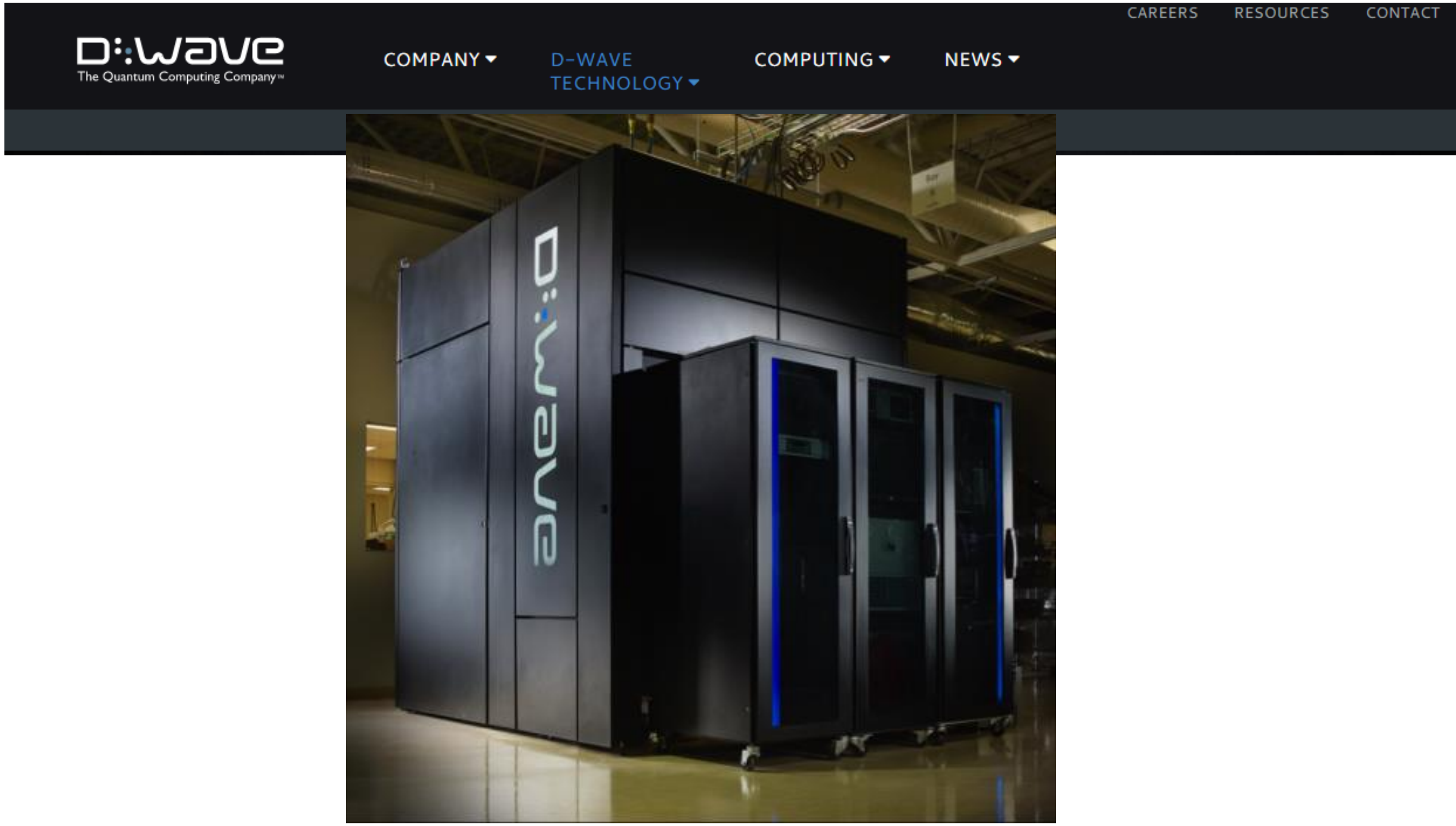
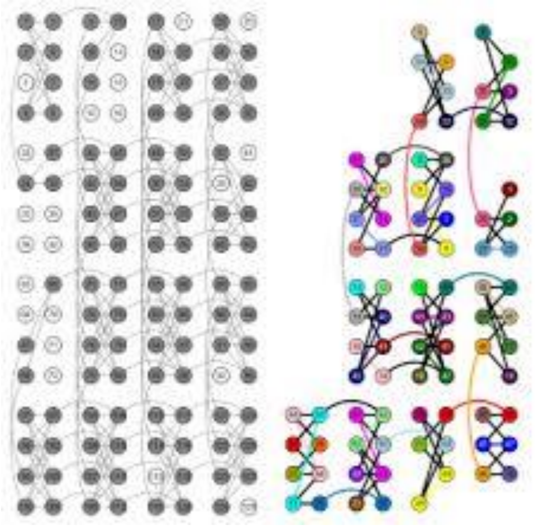


- Large number of qubits (1000)
- Poor connectivity ?



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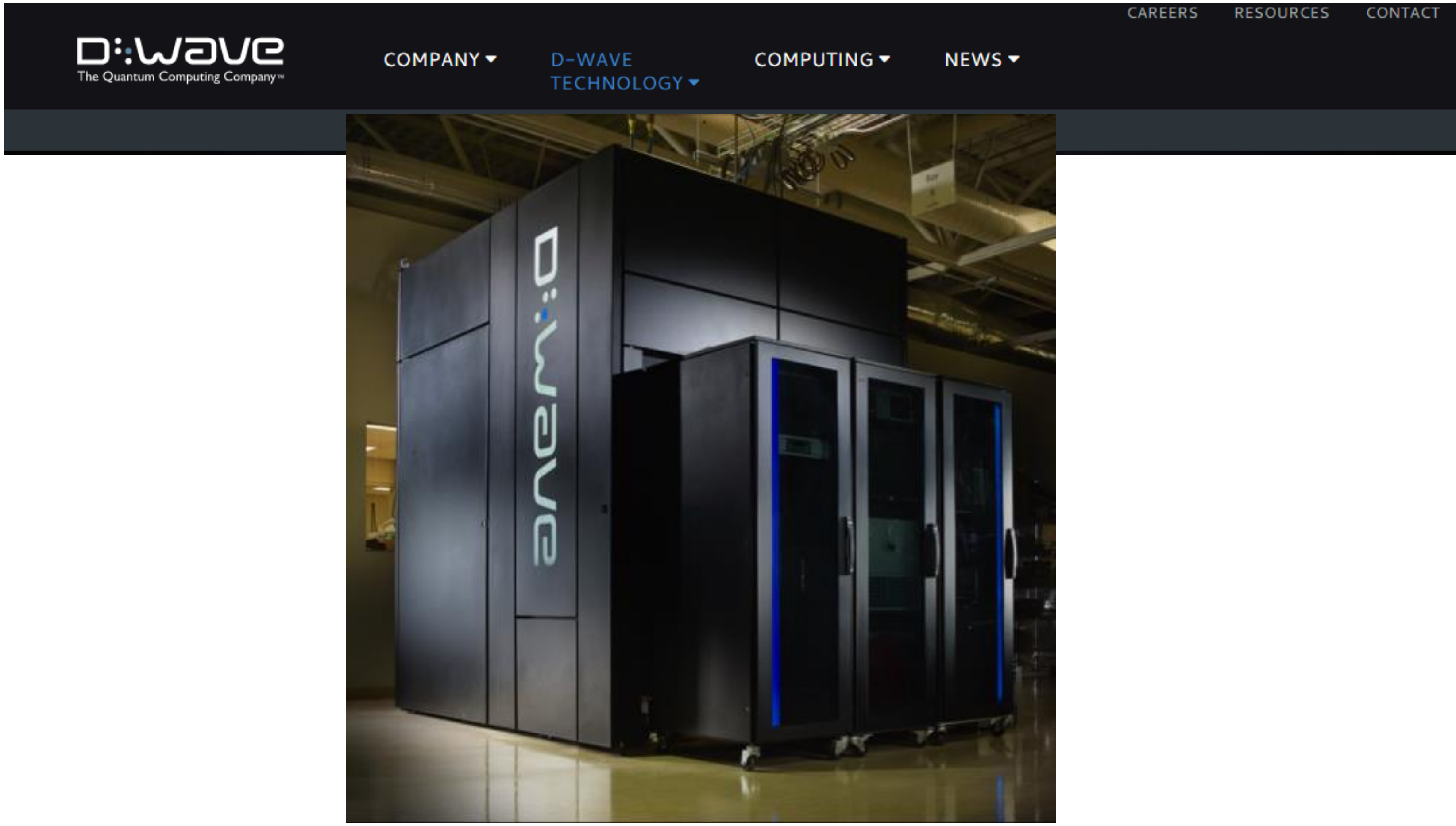


- Large number of qubits (1000)
- Poor connectivity ?
- High temperature/disorder /noise ?
- Interesting device, but still not clear what it can be useful for…

Quantum computation

- Actually we still do not know what are all the possible applications of a quantum computer

Quantum simulation

- Furthermore, we do know even less what are the possible applications of an <u>imperfect</u> quantum computer

- One exciting possibility: Quantum Simulation

. . . trying to find a computer simulation of physics seems to me to be an excellent program to follow out. . . . the real use of it would be with quantum mechanics. . . . Nature isn't classical . . . and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.

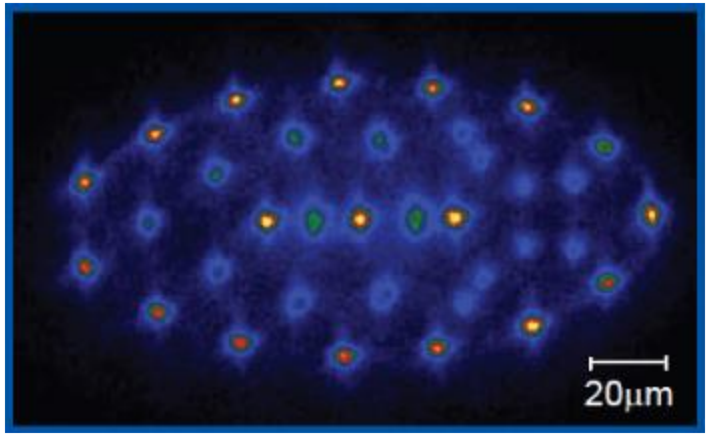
Richard Feynmann
(„Simulating physics with computers" - 1981)

Quantum simulation

- A simulator device is a system that can be used in the design of complicated structures (e.g. airplanes)

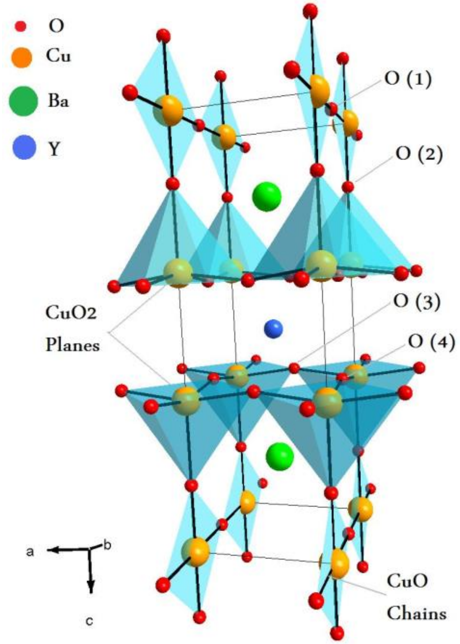
Quantum simulation

- A quantum simulator is a quantum computer of limited functionality that replicates the physics of a complex material (e.g. a complex molecule or a high-Tc superconductor)



System of trapped atoms

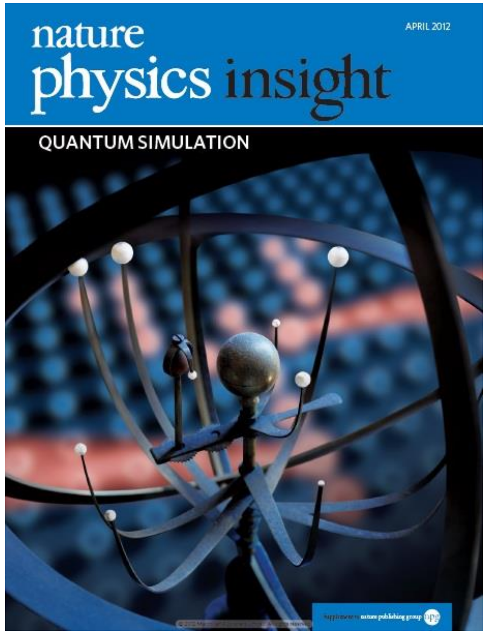
Quantum simulation

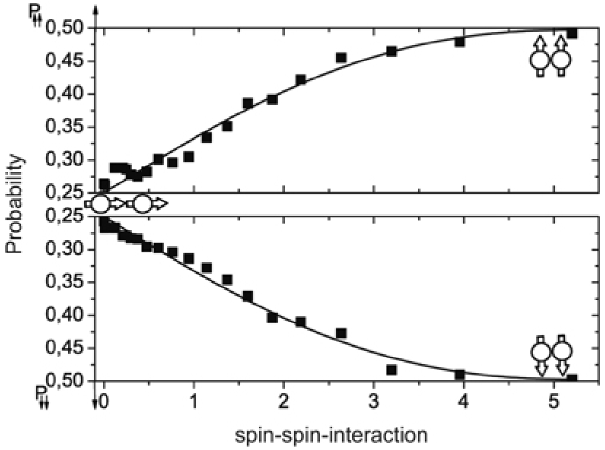


Complex system

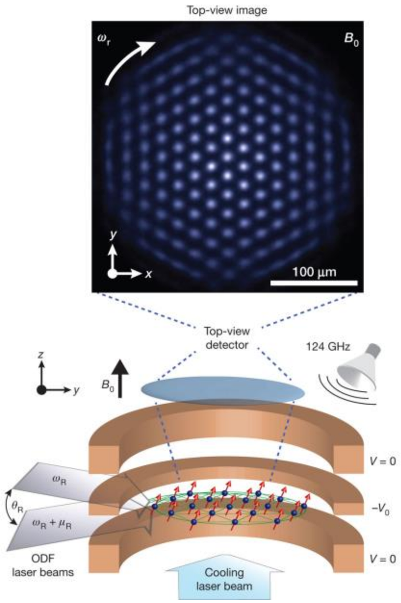
Quantum simulation

- Small prototypes have already been used to test properties of quantum magnets





2-atom synthetic magnet (Max-Planck-Institute, Germany, 2008)
A. Friedenauer et al., Nature Phys. **4**, 757 (2008)



300-atom synthetic magnet (NIST, US 2012)
J. Britton et al., Nature **484**, 489 (2012)

Thank you for your attention !