Science and Technology
of Materials, Interfaces, and Processing

AVS e-Talk Series: Quantum Science Challenges & Opportunities
Presented by: Philippe Bouyer

General Information

- Welcome to the AVS e-Talk on Quantum Science Challenges & Opportunities.
- Please place your phones on mute.
- Upon registering you were able to submit a question to be answered by the Philippe Bouyer. These questions were reviewed by Philippe and he will do his best to answer as many as possible during the 15-minute Q&A session at the end of the e-Talk.
- This is a one-hour presentation with no scheduled breaks.

ENJOY THE e-TALK!

AVS Upcoming Events

AVS Webinar Schedule

https://www.avs.org/Education-Outreach/Short-Courses/Short-Courses-Schedule

Phase Change Memory Technology:
Overview and Process Challenges
for Current and Future Implementation

Presented by:

Eric Joseph,
IBM T.J. Watson Research Center

Yu Zhu,
Jiangsu Advanced Memory Technnology Corp., Ltd.

September 25, 2019

1:00 p.m.-5:00 p.m. (EDT)

AVS Short Course Schedule

https://www.avs.org/Education-Outreach/Short-Courses/Short-Courses-Schedule

AVS Southern California Chapter

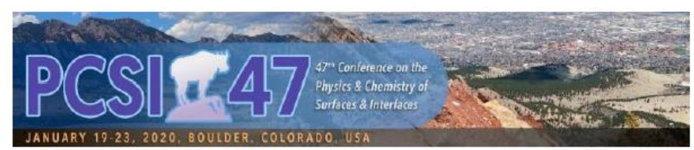
September 30 – October 2, 2019, Buena Park, CA

AVS 66 National Short Course Program

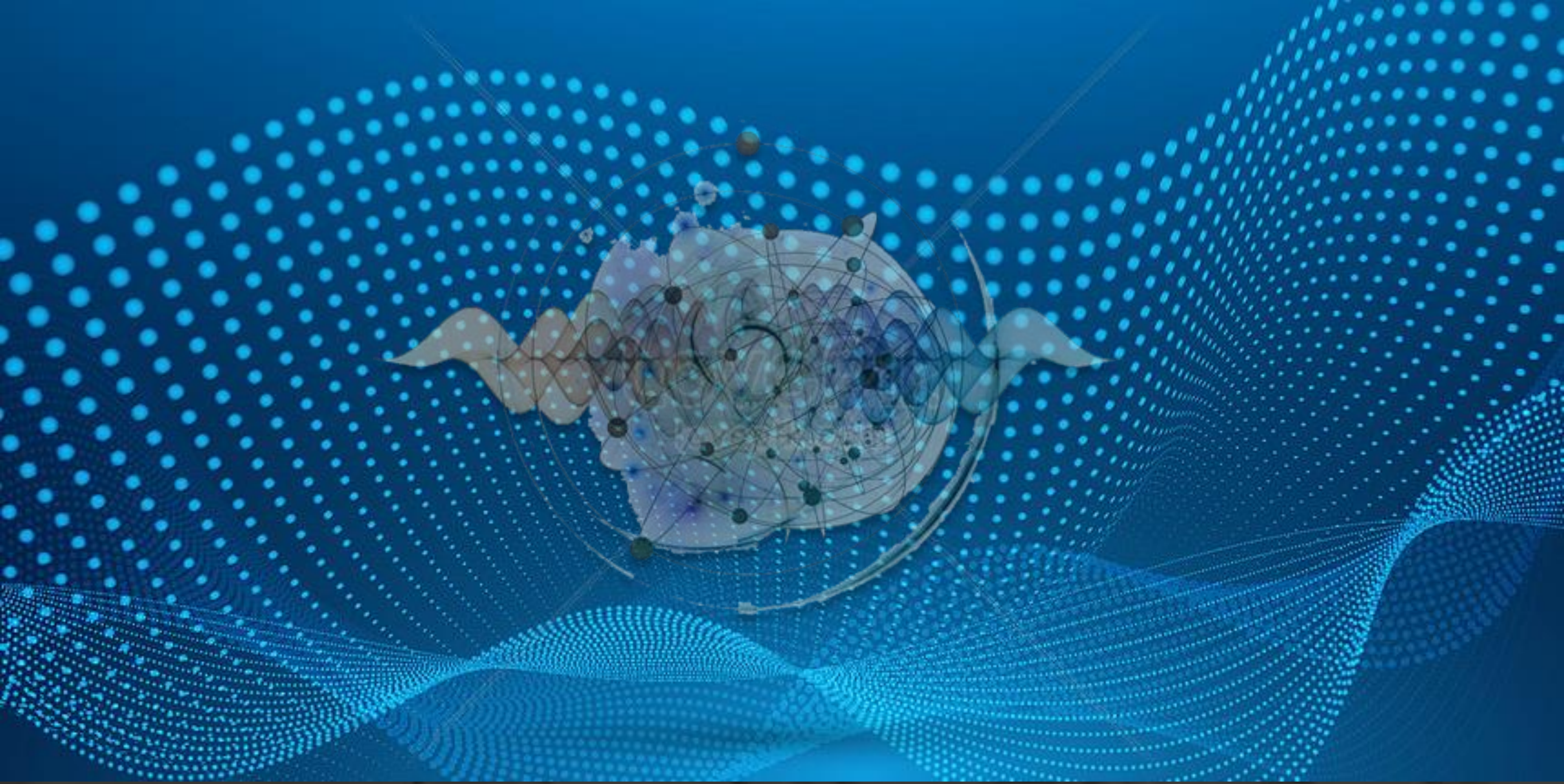
October 21-24, 2019, Columbus, OH

REGISTER HERE!

Technical Meetings



AVS Website: www.avs.org
Questions: Contact Heather Korff, heather@avs.org, 530-896-0477

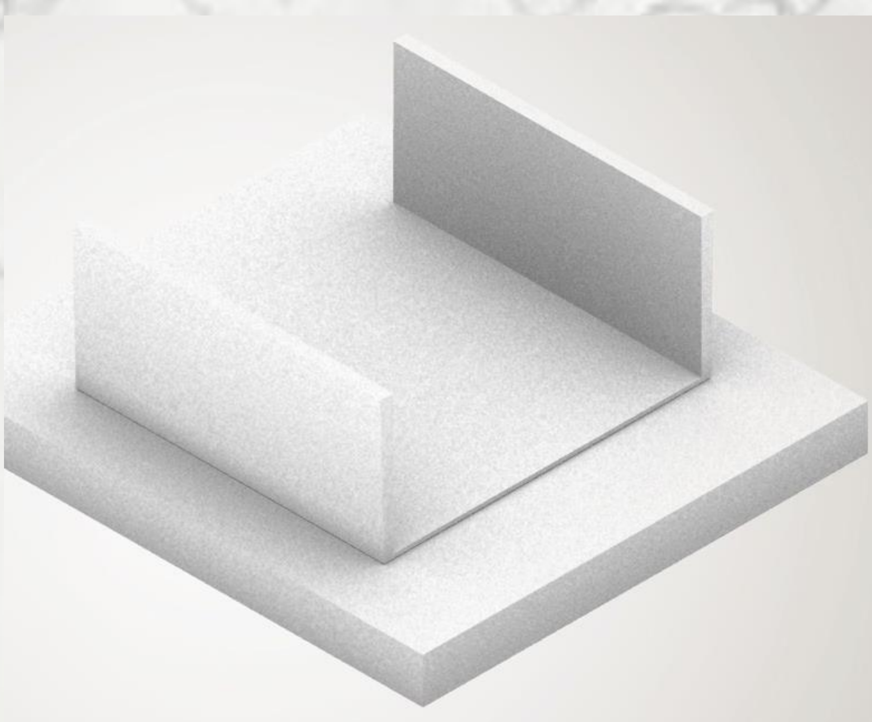


Quantum Science

Philippe Bouyer – CNRS, IOGS, Univ. Bordeaux – AIP/AVS Quantum Science

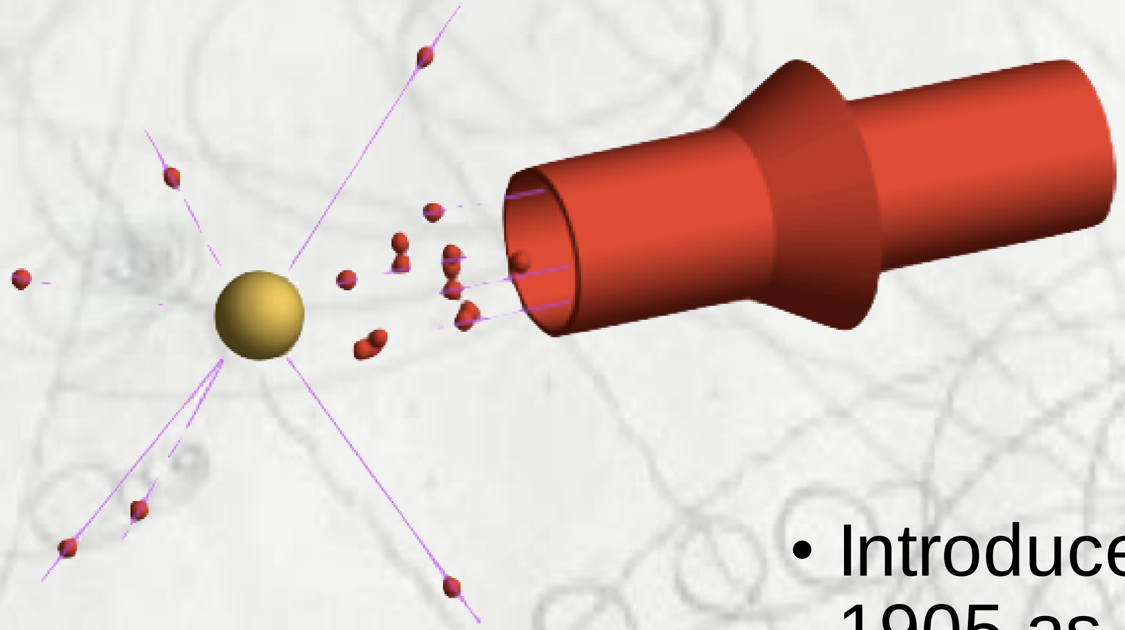
What is it ?

- First (in the beginning of the last century) came the ideas that energy can be quantized …

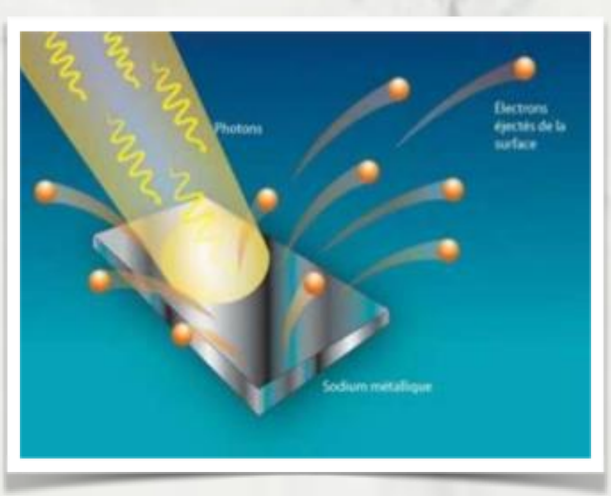


Max Planck : Energy can only be a multiple of an elementary unit

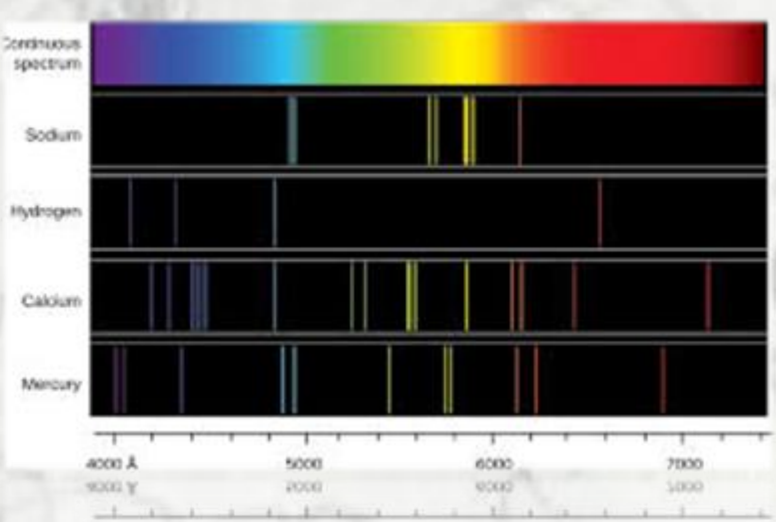
The photon : a quantum of energy



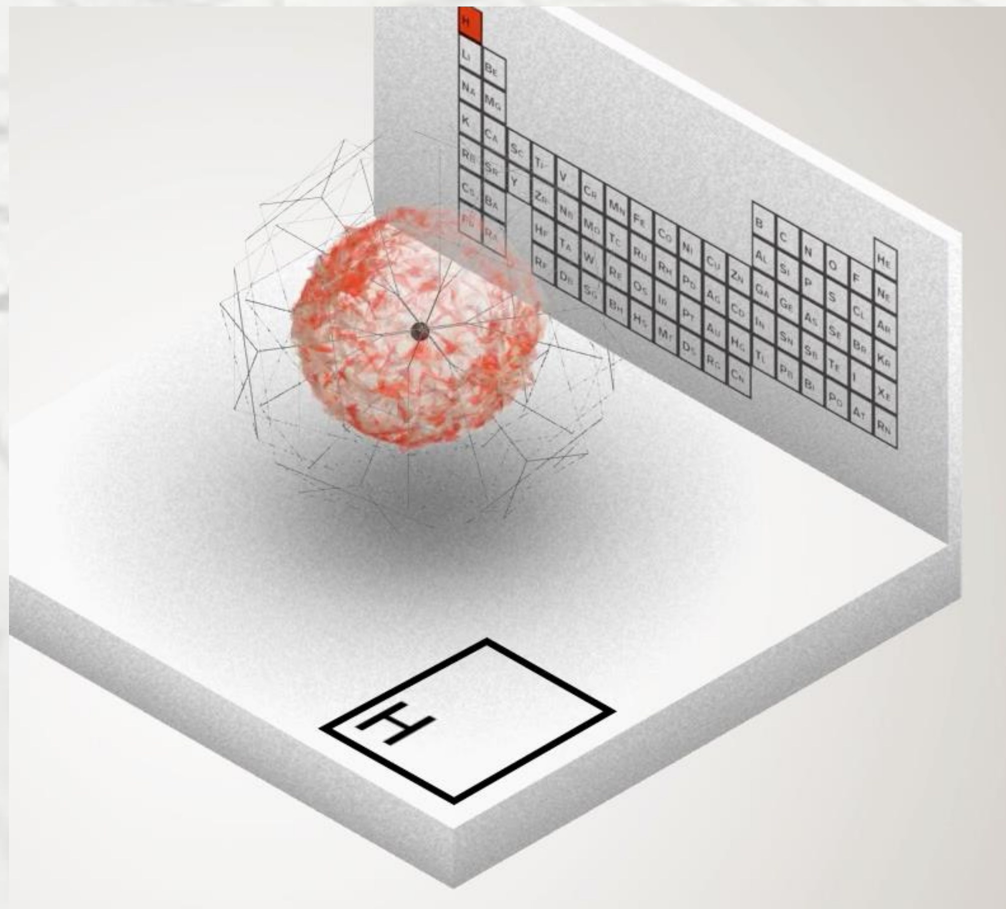
- Introduced by A. Einstein in 1905 as a quantum of light to explain the photoelectric effect.
- Baptised photon in 1926 by Frithiof Wolfers in a note at the Académie des Sciences.



Atomic physics



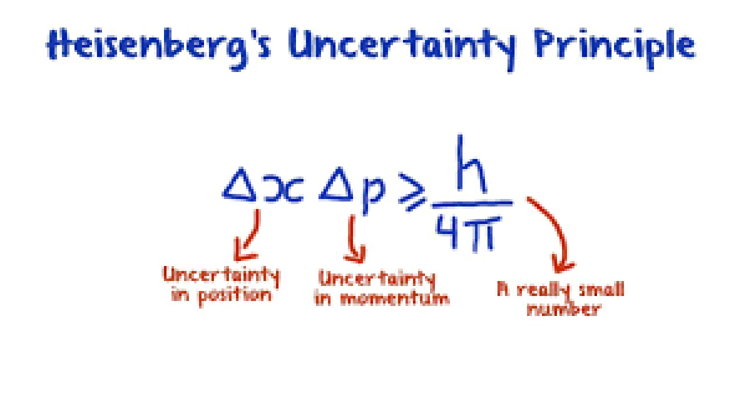
- Quantum science lead to atomic physics, spectroscopy lines …



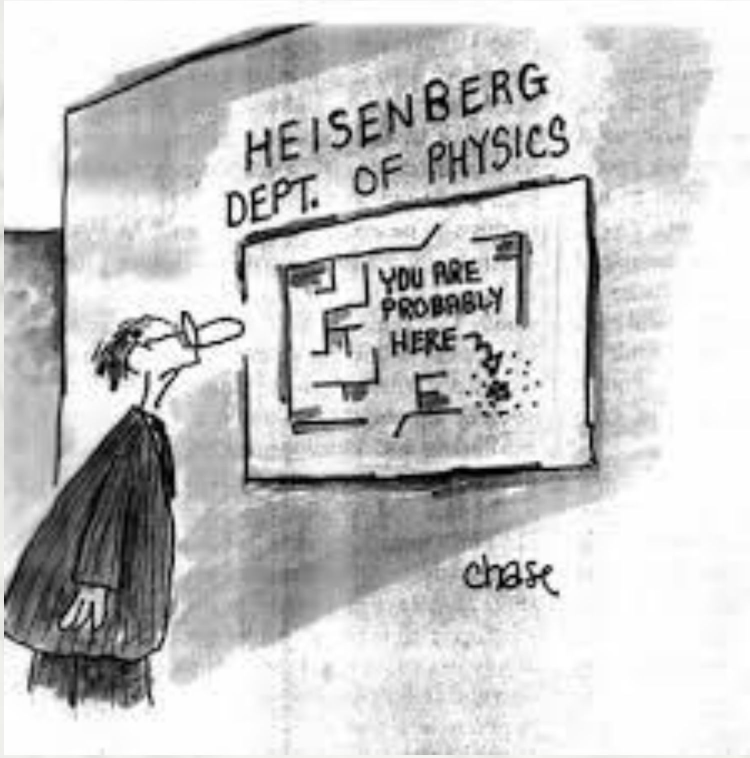
Niels Bohr: Electrons in an atom are trapped in a quantized box around the nucleus.

The laser

Quantum physics …



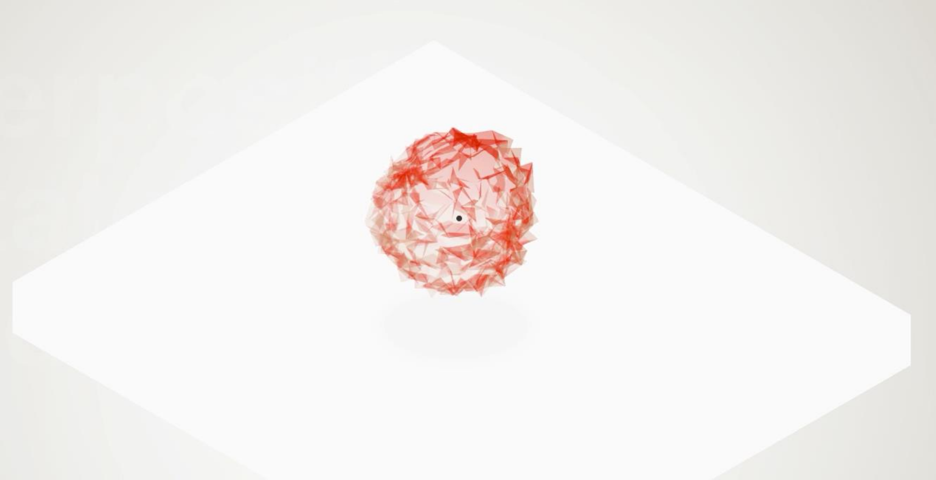
Heisenberg : we are unable to precisely locate the particle given its conjugate momentum

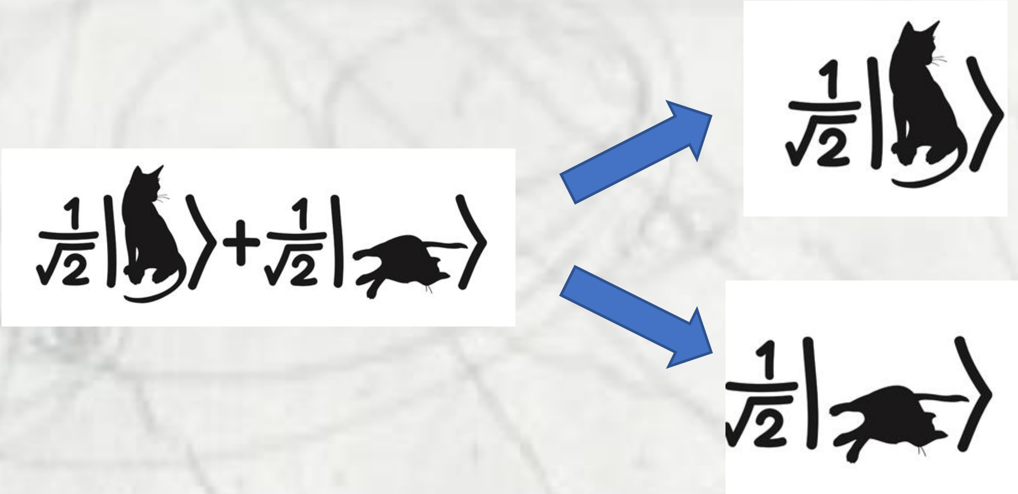


… is probabilistic

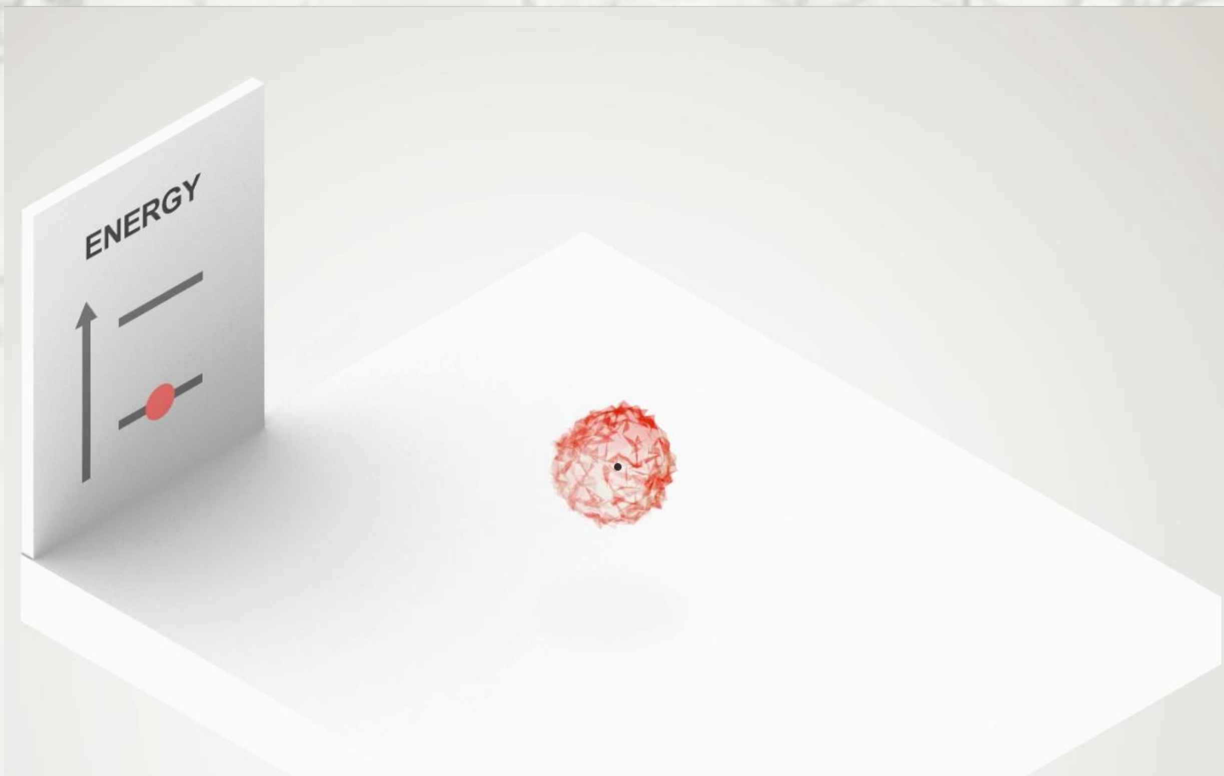
Schödinger : the cat is dead and alive

Systems do not have definite properties …



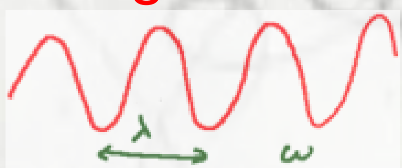


… until we watch them

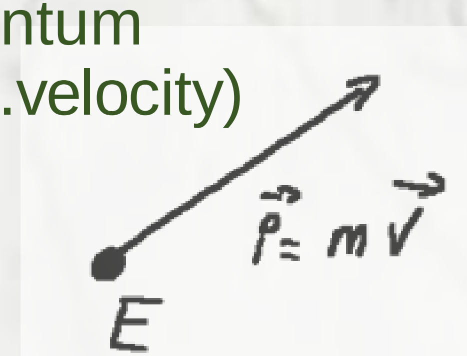


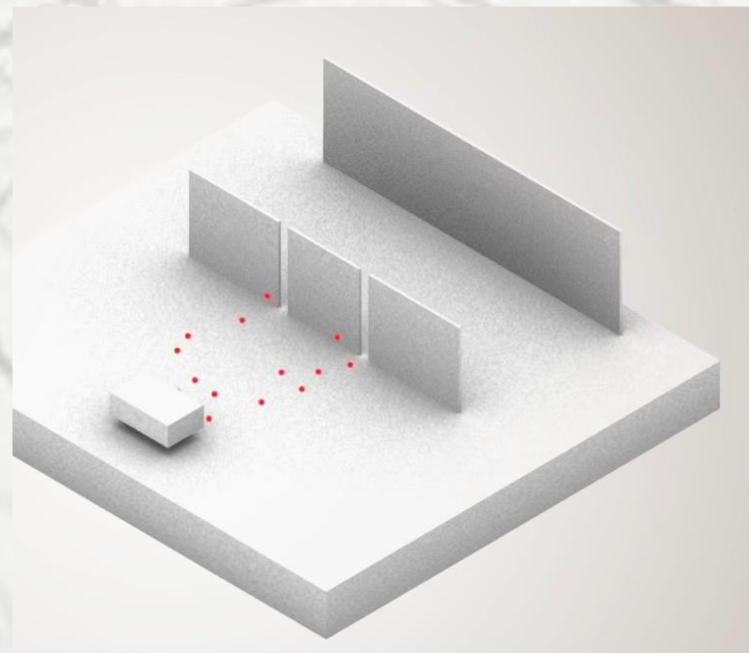
Wave particle duality

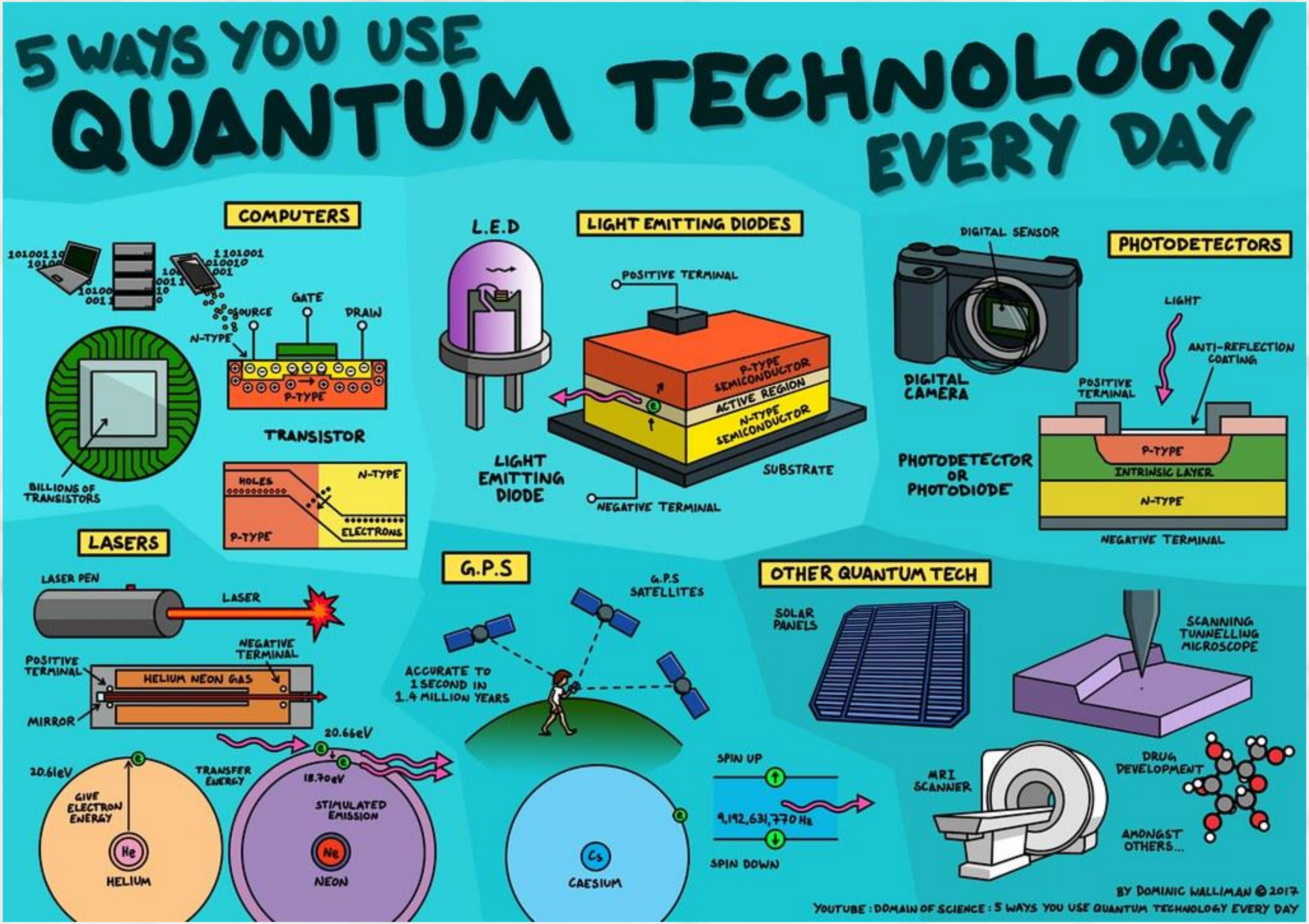
- Light is
  - A wave described by frequency and wavelength



  - A particle described by energy and momentum (mass.velocity)






5 WAYS YOU USE QUANTUM TECHNOLOGY EVERY DAY
COMPUTERS
SOURCE
GATE
DRAIN
N-TYPE
P-TYPE
TRANSISTOR
BILLIONS OF TRANSISTORS
HOLES
N-TYPE
P-TYPE
ELECTRONS
L.E.D
LIGHT EMITTING DIODES
POSITIVE TERMINAL
P-TYPE SEMICONDUCTOR
ACTIVE REGION
N-TYPE SEMICONDUCTOR
LIGHT EMITTING DIODE
SUBSTRATE
NEGATIVE TERMINAL
DIGITAL SENSOR
PHOTODETECTORS
DIGITAL CAMERA
LIGHT
ANTI-REFLECTION COATING
POSITIVE TERMINAL
P-TYPE
INTRINSIC LAYER
N-TYPE
PHOTODETECTOR OR PHOTODIODE
NEGATIVE TERMINAL
LASERS
LASER PEN
LASER
POSITIVE TERMINAL
NEGATIVE TERMINAL
HELIUM NEON GAS
MIRROR
20.61eV
GIVE ELECTRON ENERGY
He
HELIUM
TRANSFER ENERGY
20.66eV
18.70eV
STIMULATED EMISSION
Ne
NEON
G.P.S
G.P.S SATELLITES
ACCURATE TO 1 SECOND IN 1.4 MILLION YEARS
Cs
CAESIUM
SPIN UP
9,192,631,770 Hz
SPIN DOWN
OTHER QUANTUM TECH
SOLAR PANELS
SCANNING TUNNELLING MICROSCOPE
MRI SCANNER
DRUG DEVELOPMENT
AMONGST OTHERS...
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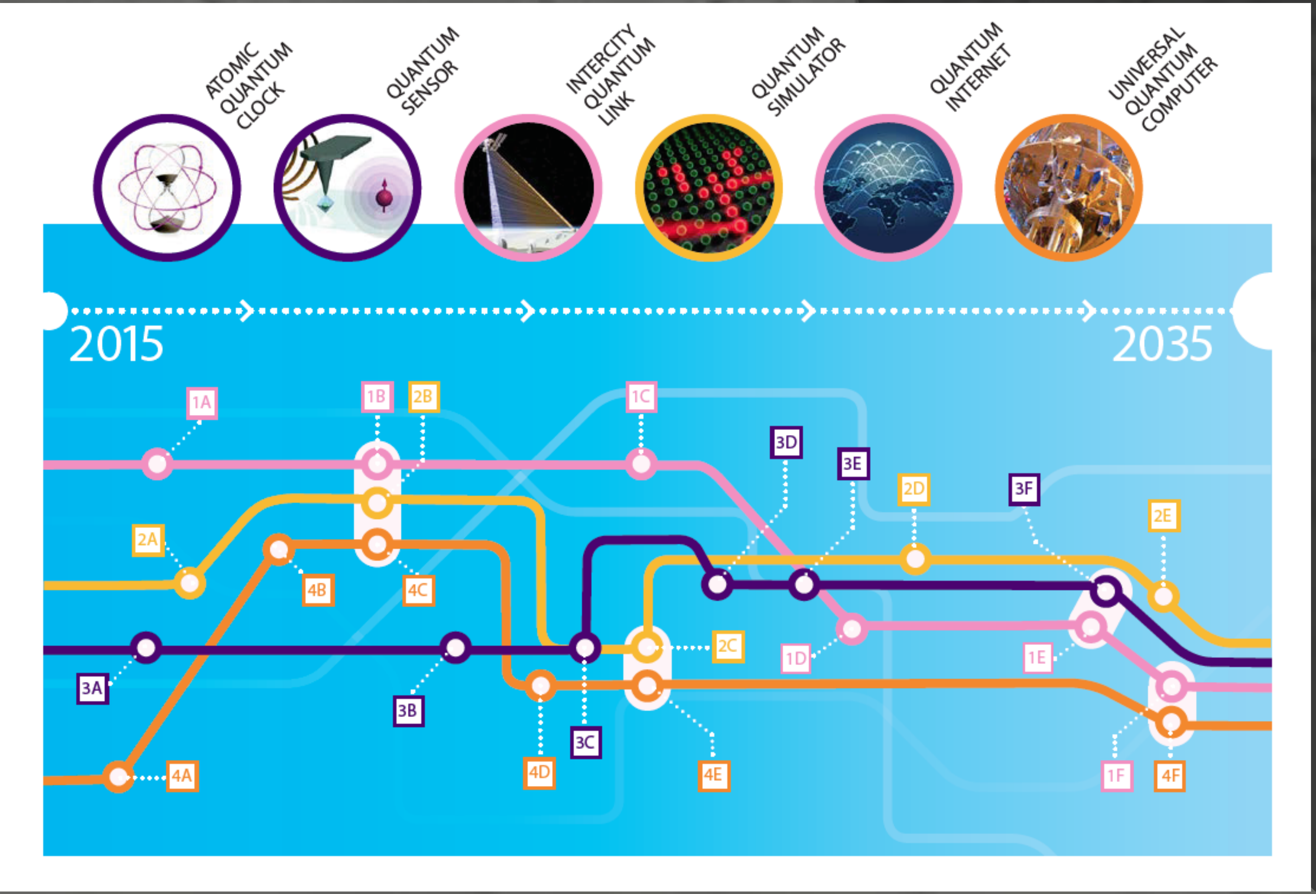
YOUTUBE : DOMAIN OF SCIENCE : 5 WAYS YOU USE QUANTUM TECHNOLOGY EVERY DAY

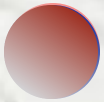
The second quantum revolution

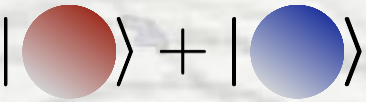
Superposition
Entanglement
Matter-waves



Two possible states
Polarisation

One photon

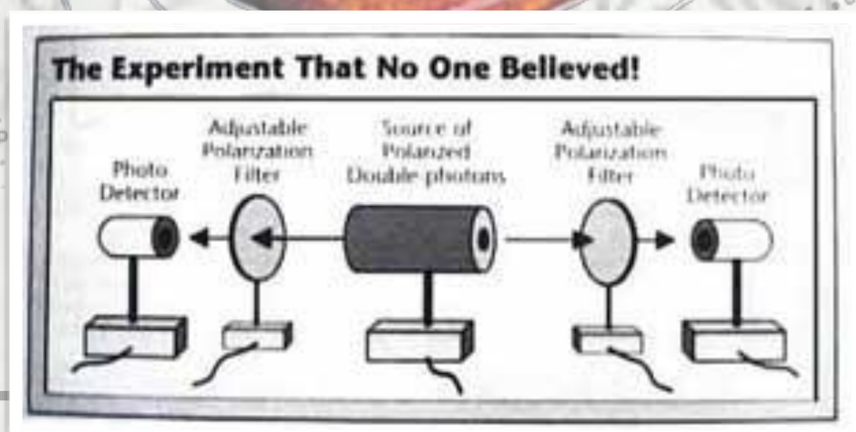




Coherent superposition

One of the biggest mystery of Quantum Mechanics (Feyman)

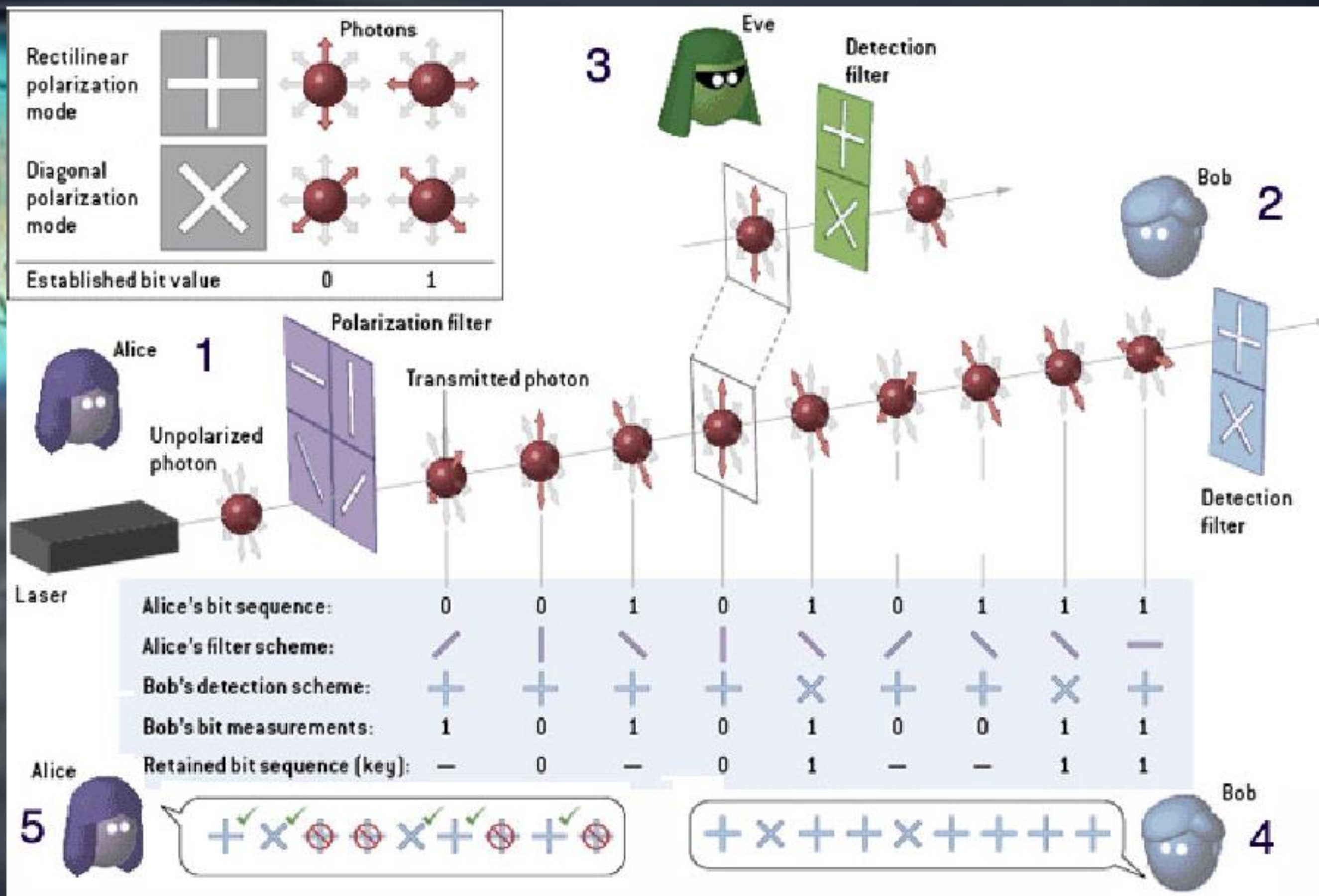
Two states
photons
Entangled



Entanglement and non locality

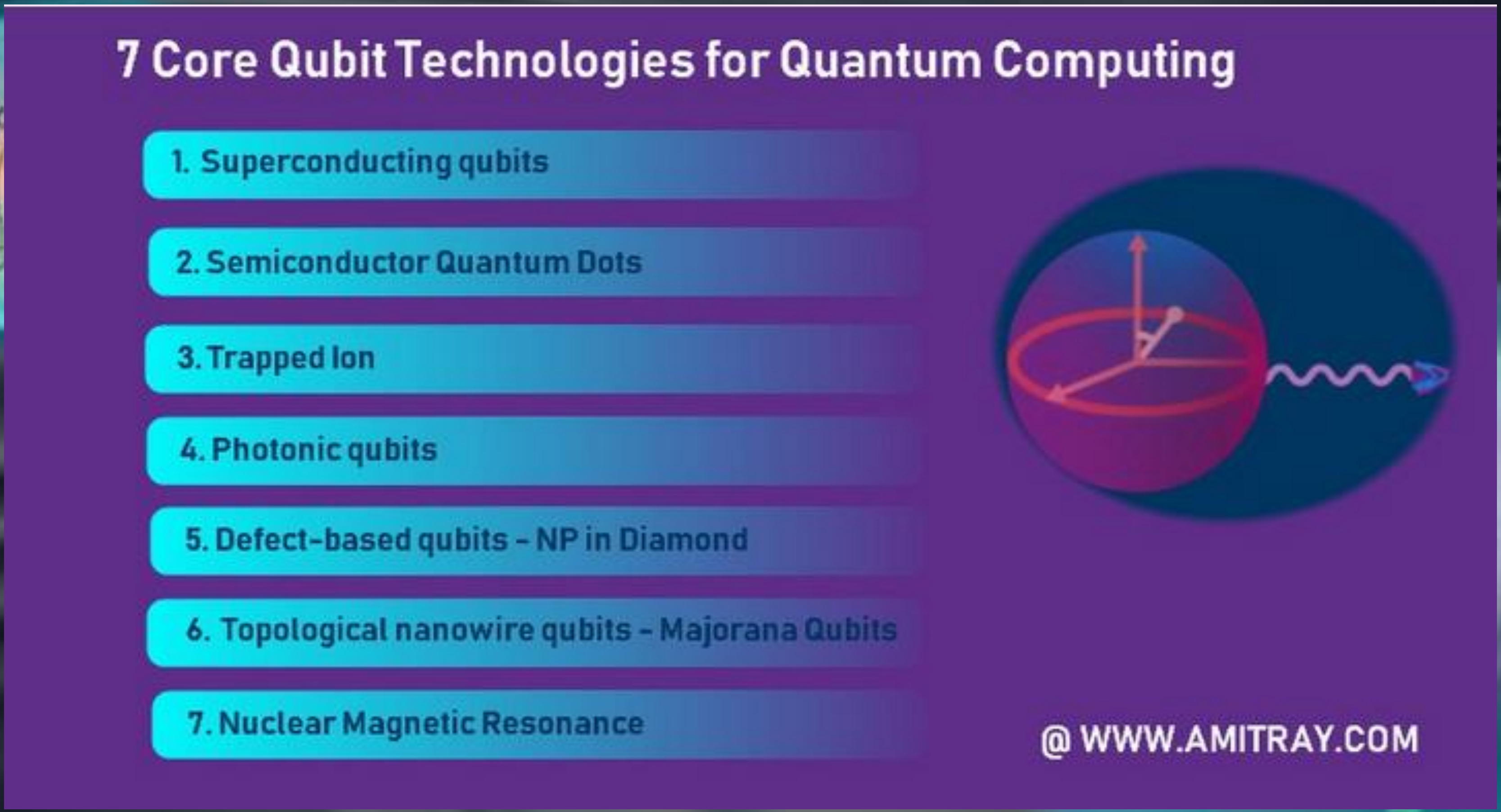
Demonstrated in the 1980 (Aspect)

Quantum key distribution



https://www.semanticscholar.org/paper/Is-Quantum-State-in-BB-84-Protocol-Really-1-)-Lee-Kim/1d0e2facfd2c79db6f100c4b2c8a81153475a940

Quantum computers



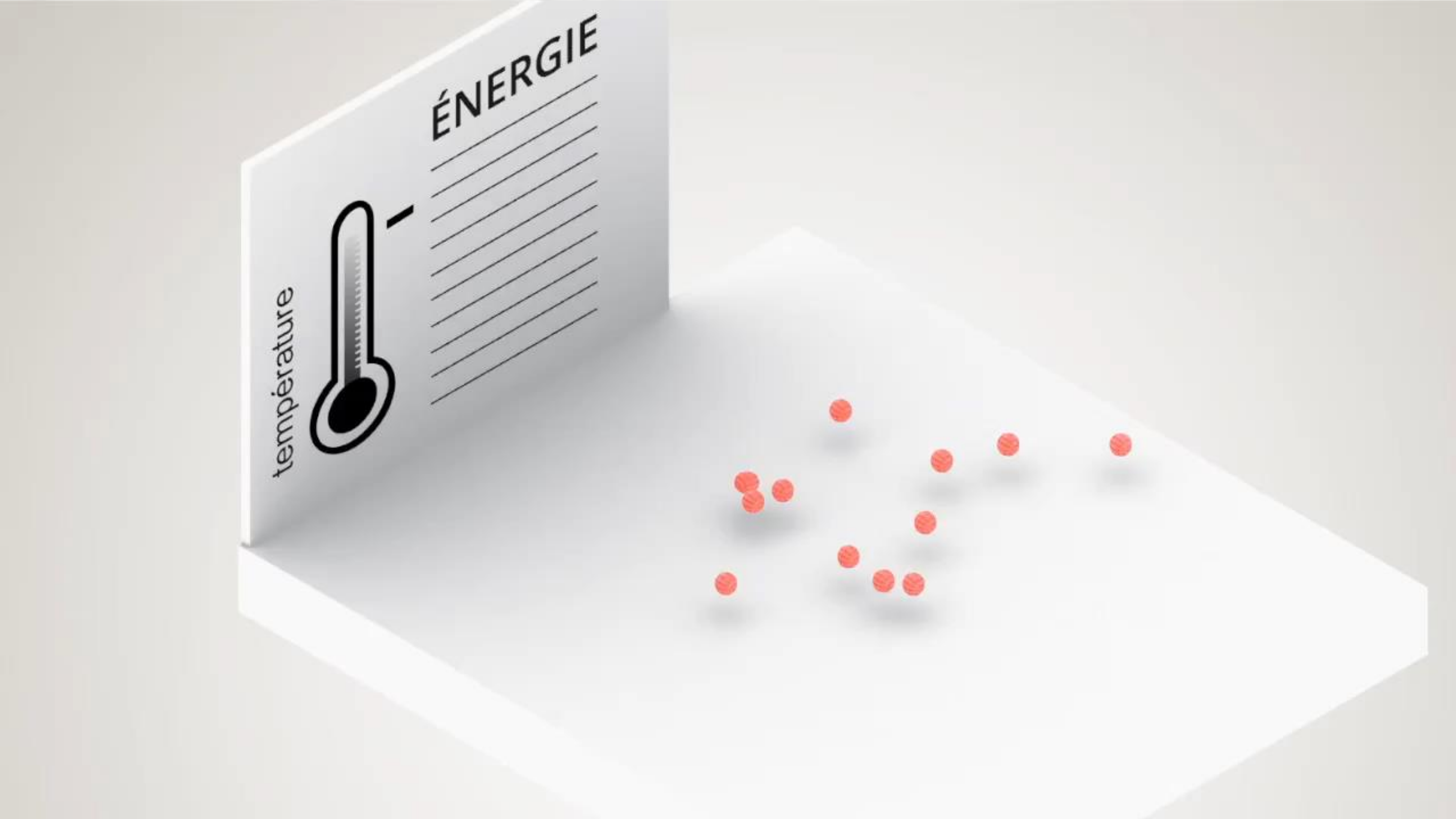
Matter-waves

- **Louis de Broglie extended to any particle the concept of coexistence of waves and particles discovered by Albert Einstein in 1905 in the case of light and photons.**
  - **introduced the *de Broglie wavelength*, matter analog of the photonic wavelength.**

$$\lambda_{opt} \Rightarrow \lambda_{dB} = \frac{h}{m\, v_{at}}$$

  - **wavelength increases when the particle is light and slow**
  - **wave behaviour properties increases when the wavelength is larger**

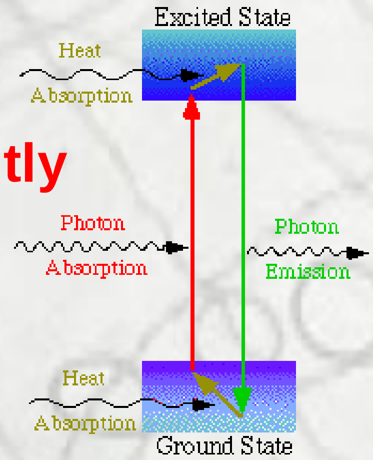
	Mass (kg)	Velocity (m/s)	Wavelength (m)
Man through a door (1 m)	70	1	10^{-35}
Red blood cell in a capillary (100 µm)	10^{-16}	0,1	10^{-15}
Atom through a slit (100 nm)	10^{-27} - 10^{-25}	500	10^{-9} - 10^{-11}

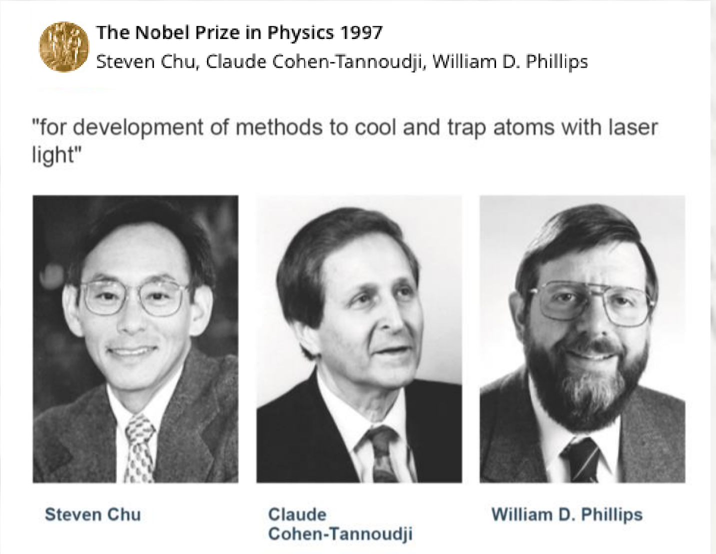


Atoms have different kinetic energy and move randomly independently

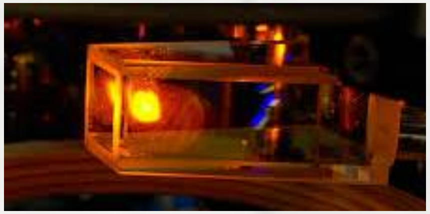
Colling matter to 0 K

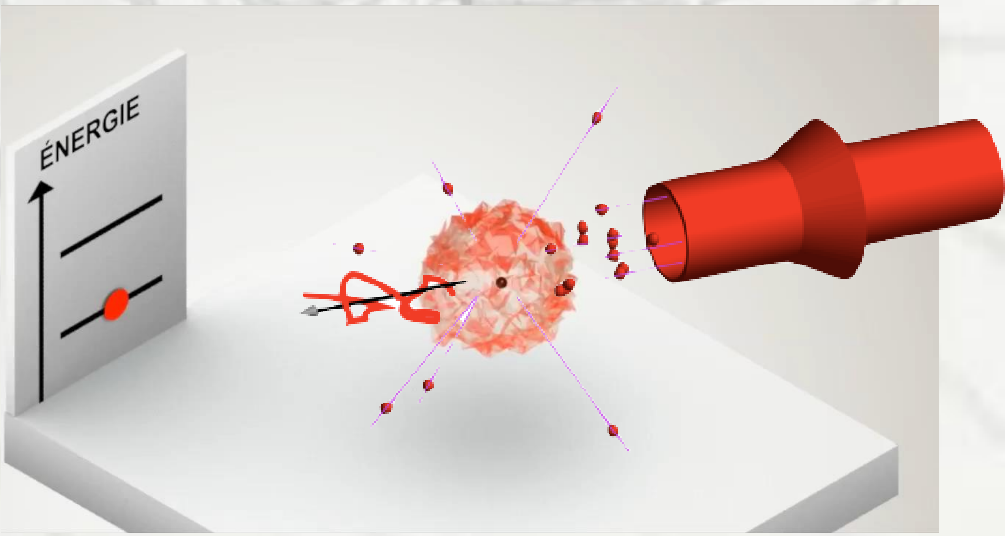
Atom absorbs a photon with slightly less energy



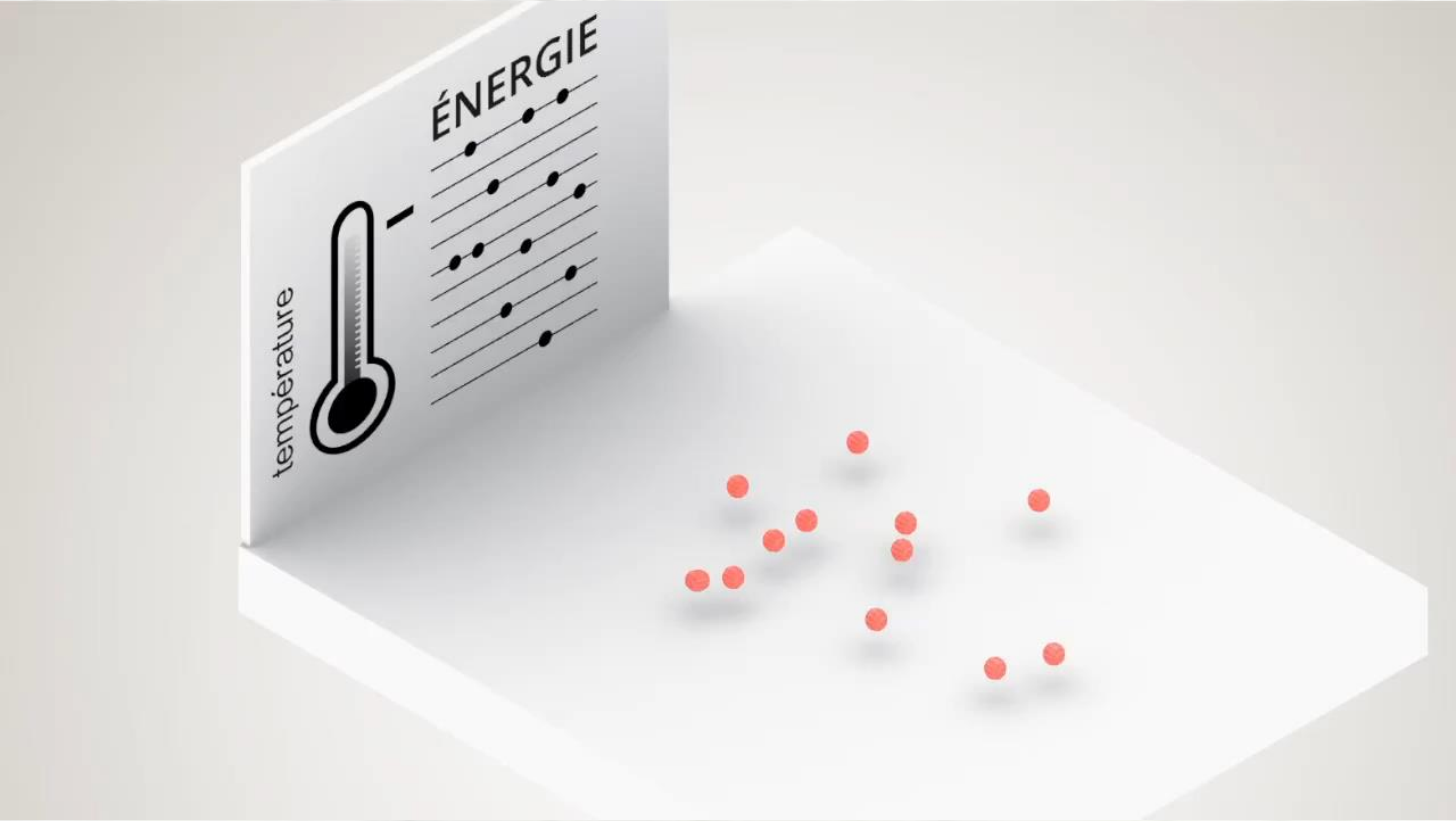


But has to release the photon with more energy

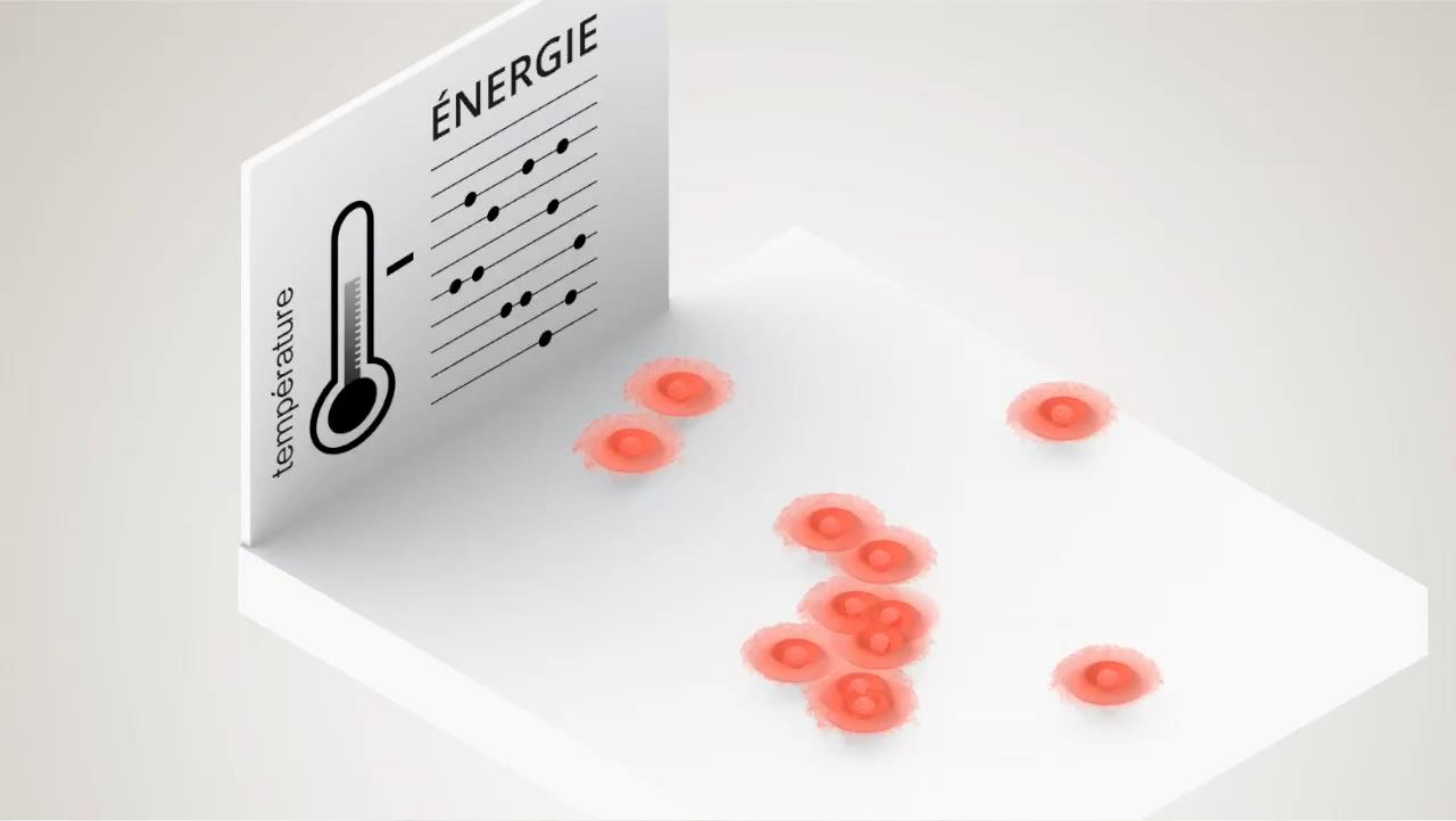




As a results, it has to loose kinetic energy.



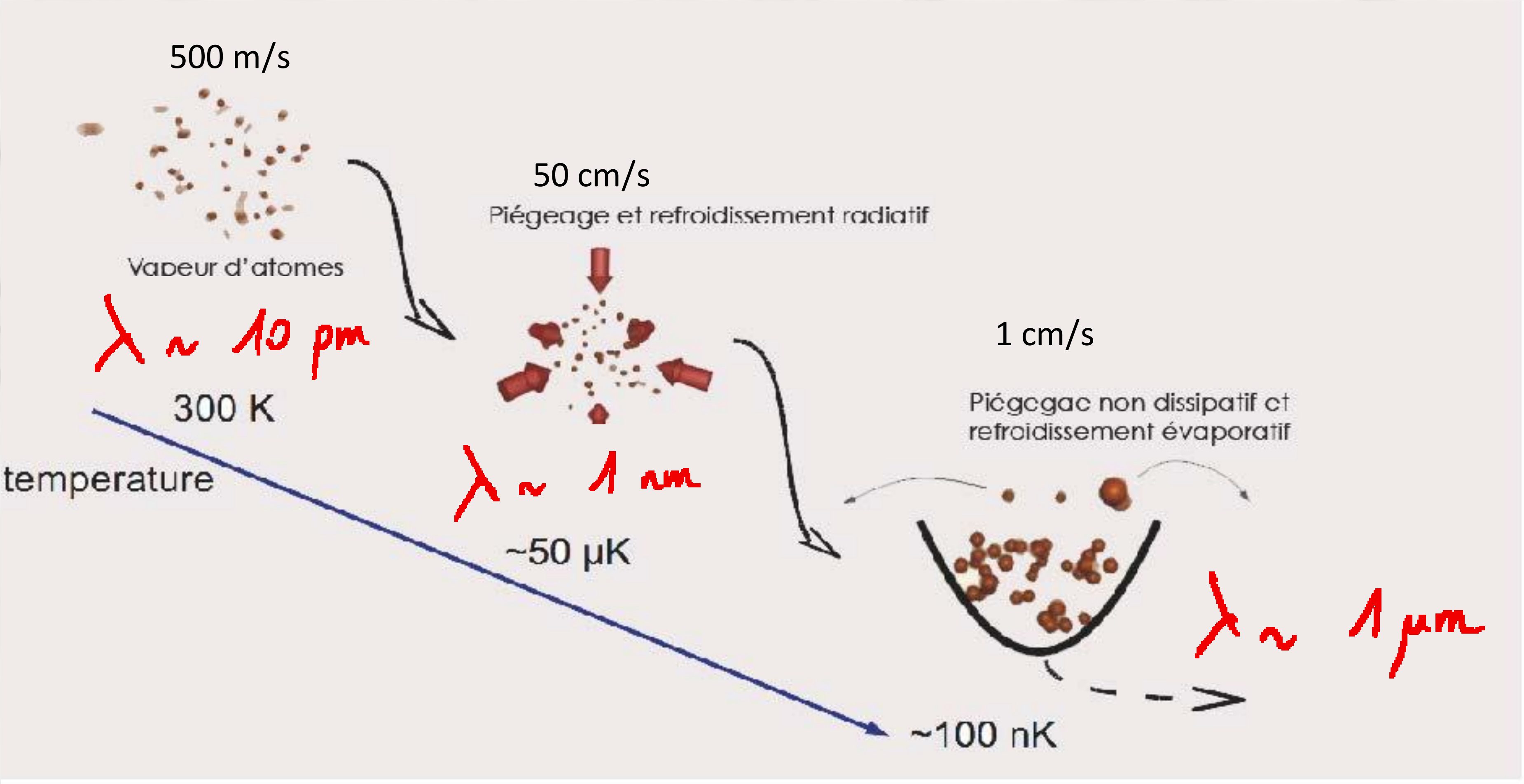
When we cool the atoms down, they slow down and their energy decreases



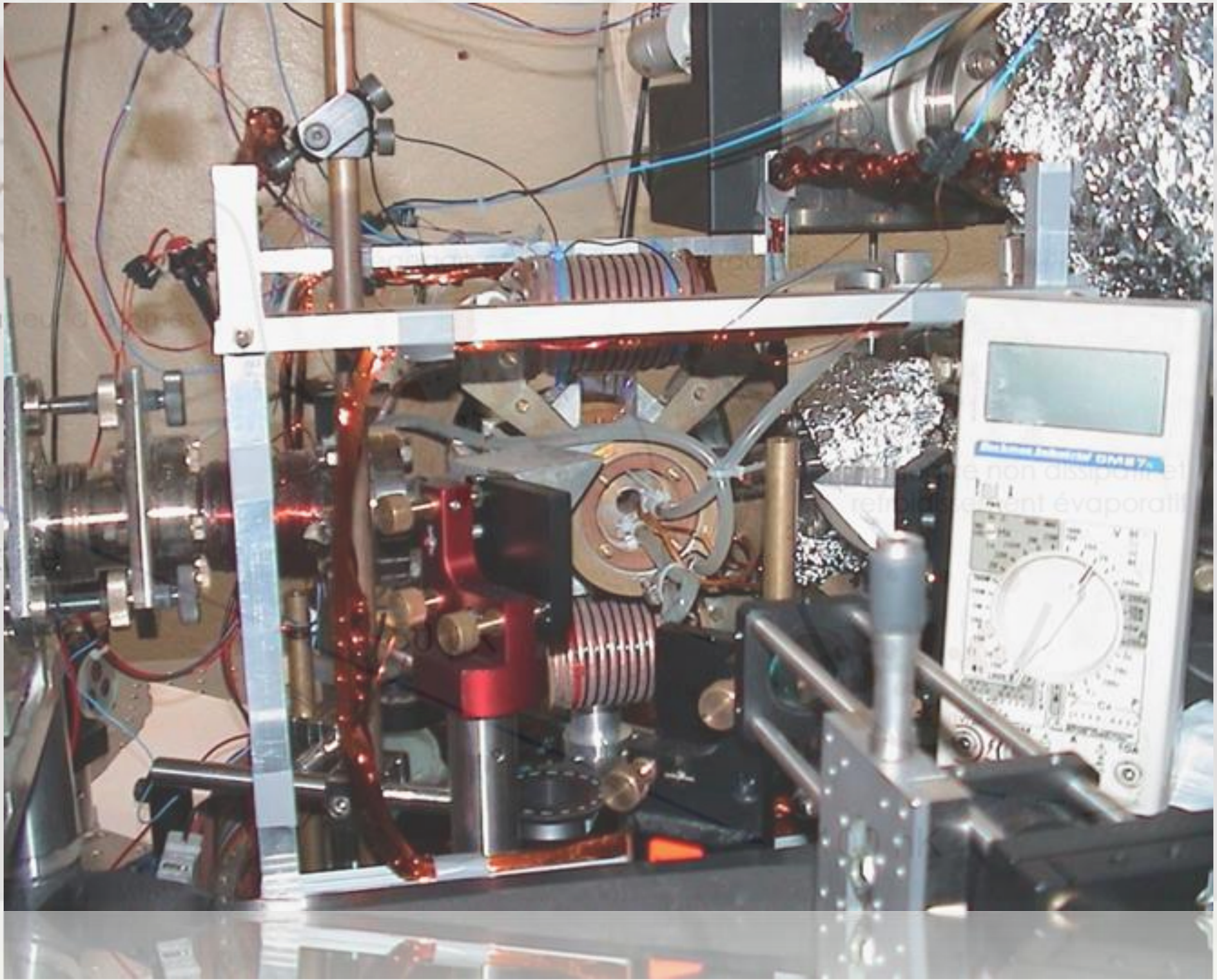
At wery low temperature, the atoms become « fussy » like a wave. When this wave is too large, all the atoms fall into the same wave.

How to “create” and engineer matter waves

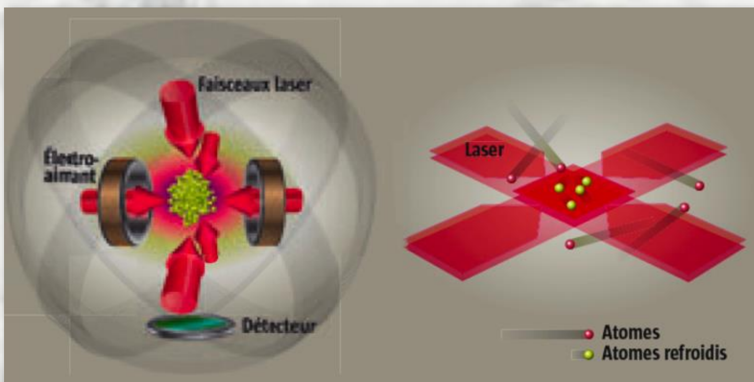
Ultra cold atoms are the ideal matter wave source

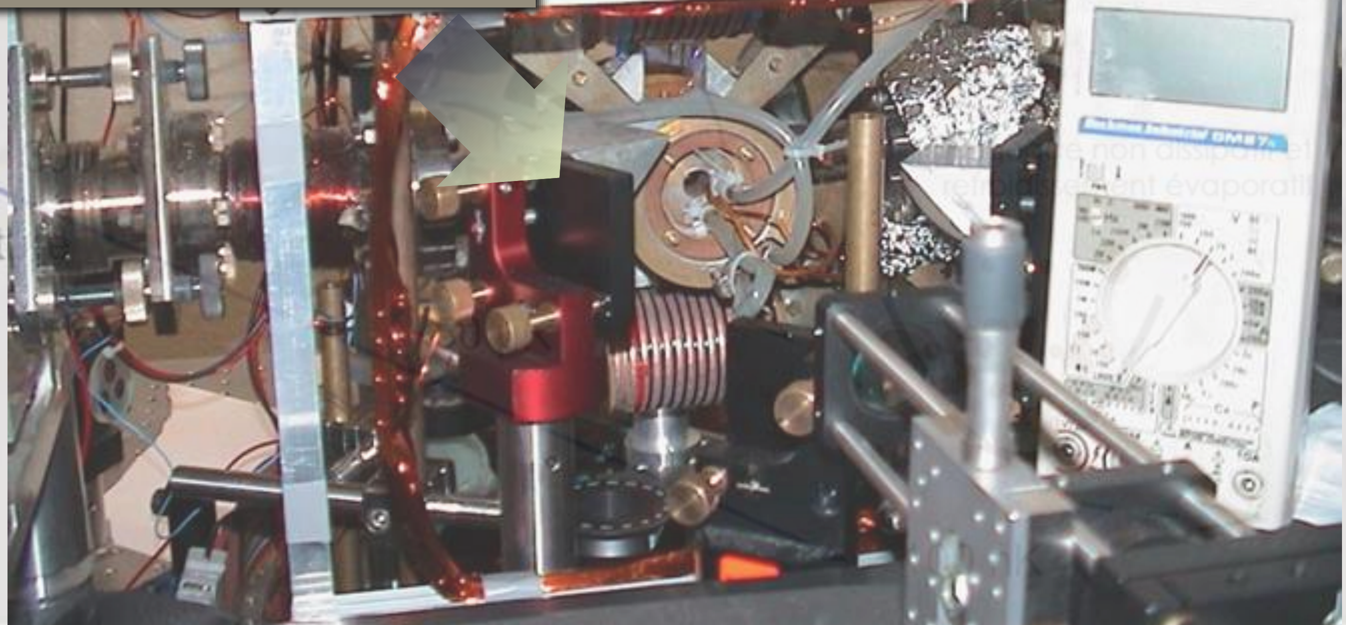


Cooling atoms towards absolute zero

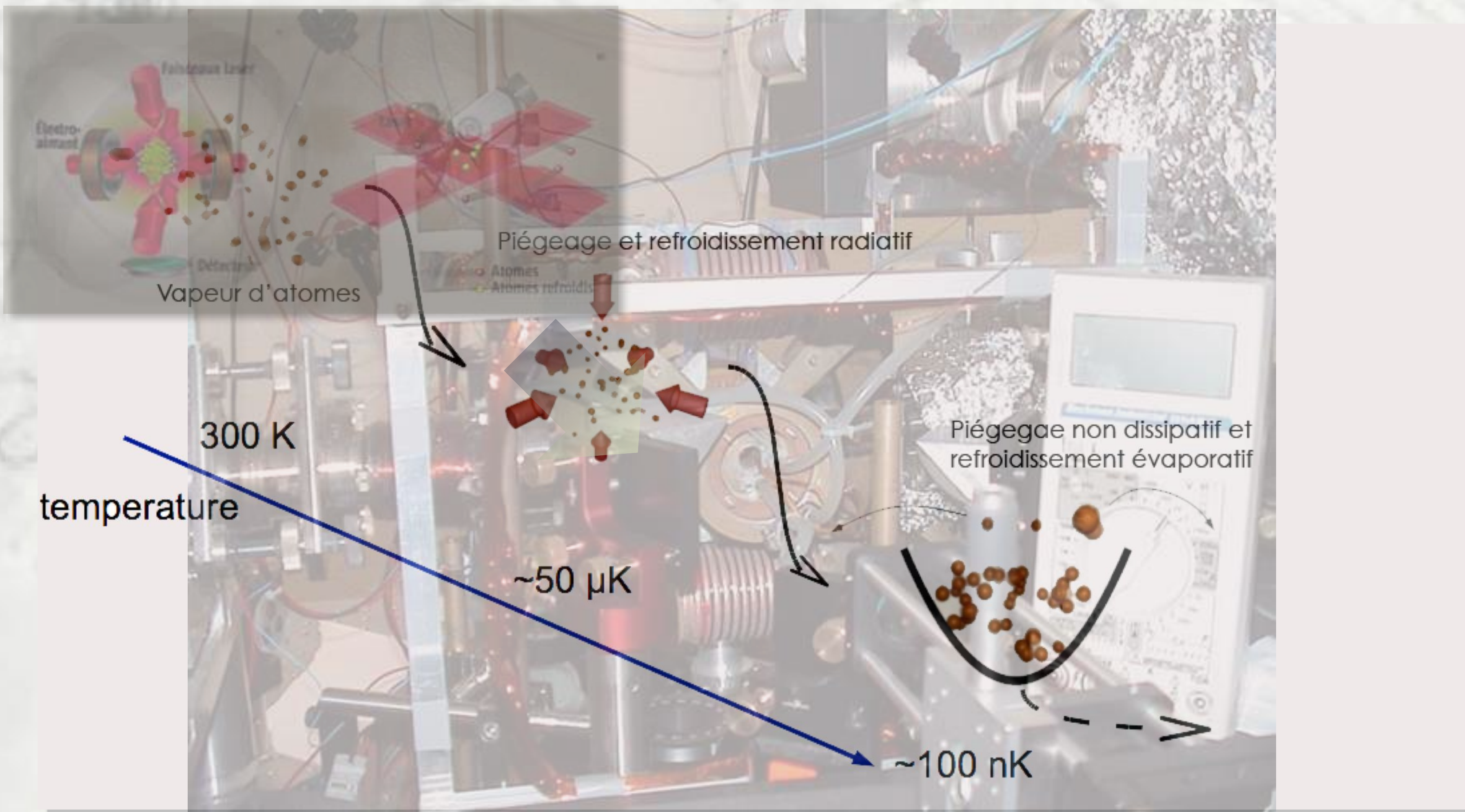


Laser cooling

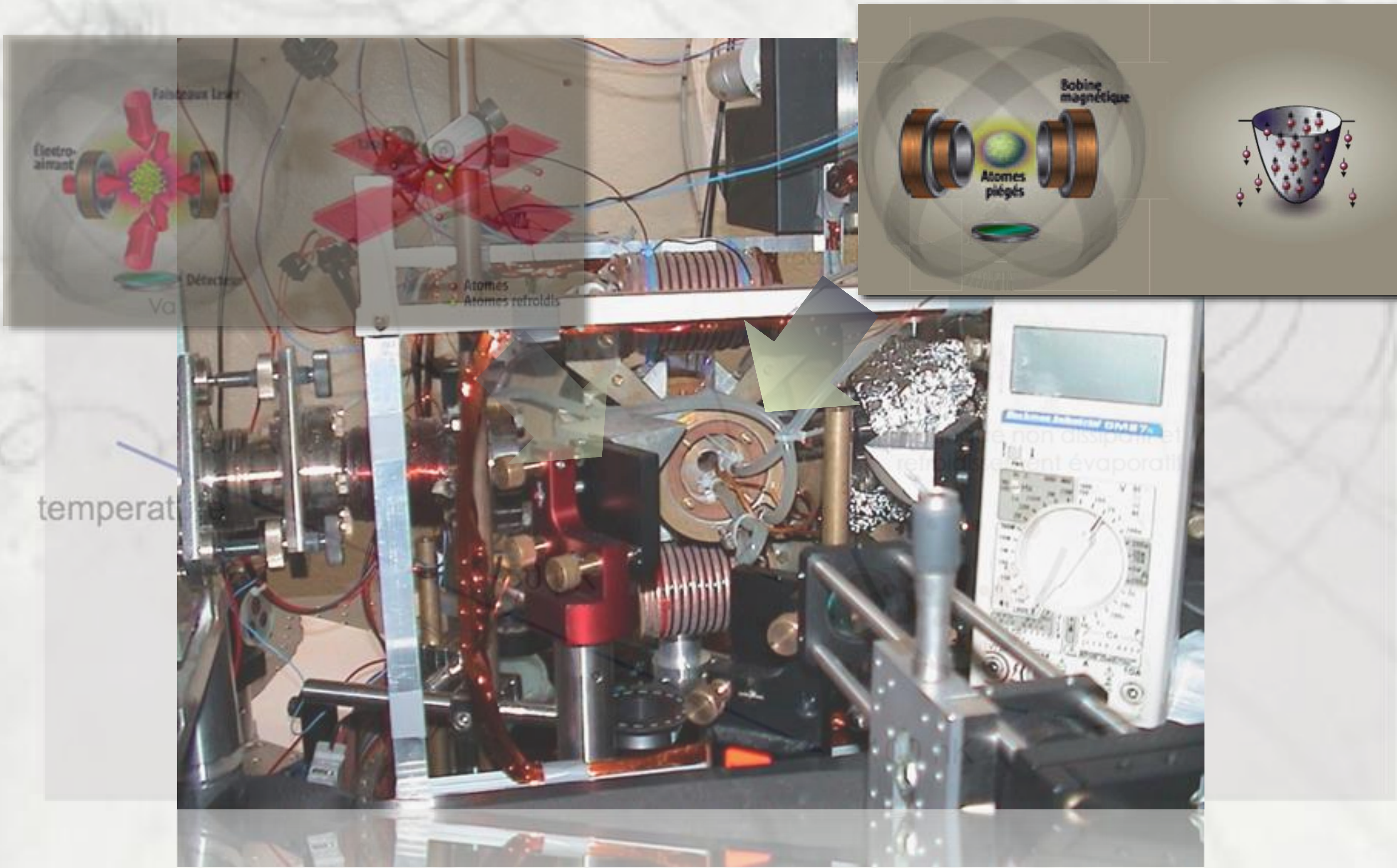




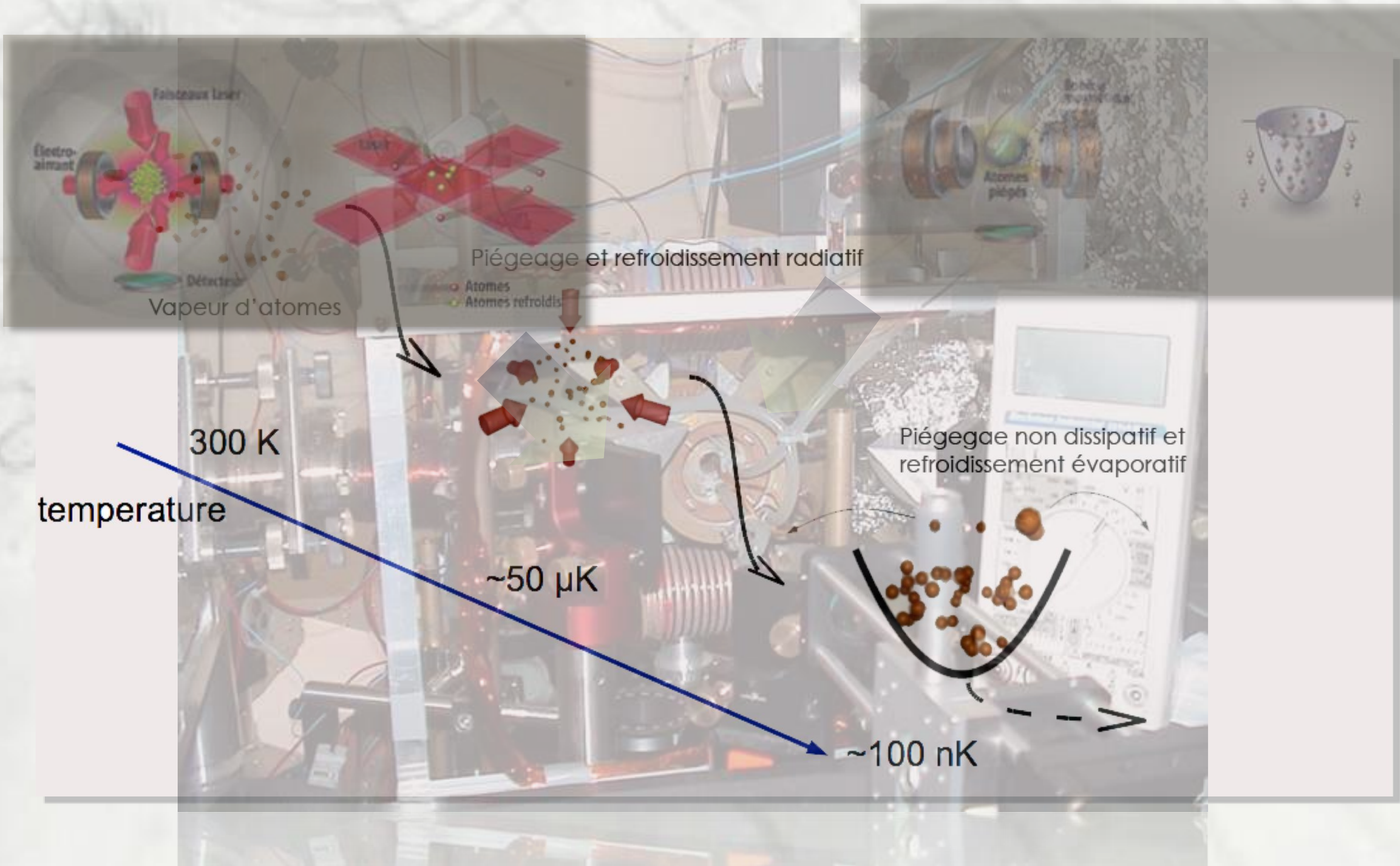
Laser cooling



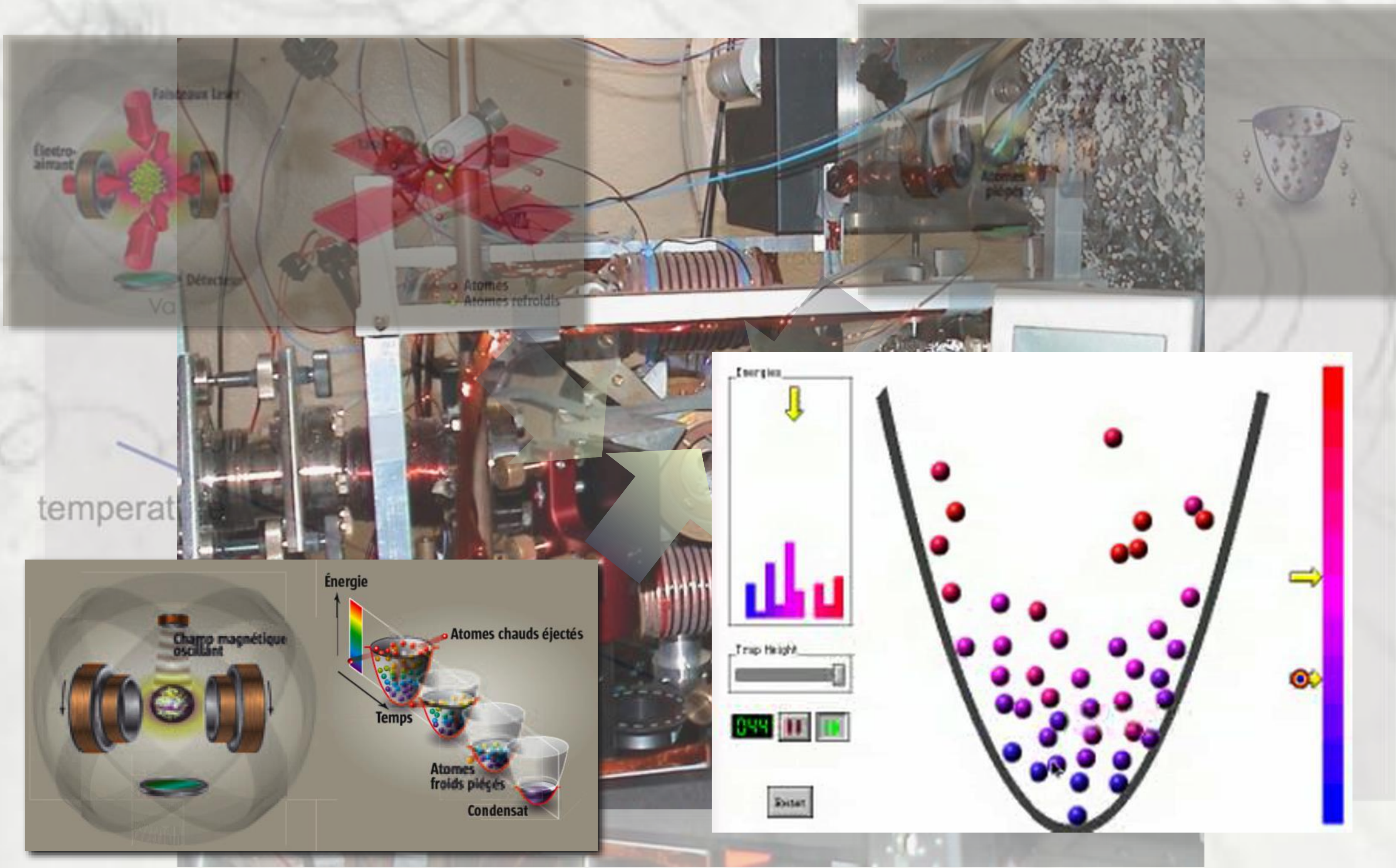
Cooling by evaporation



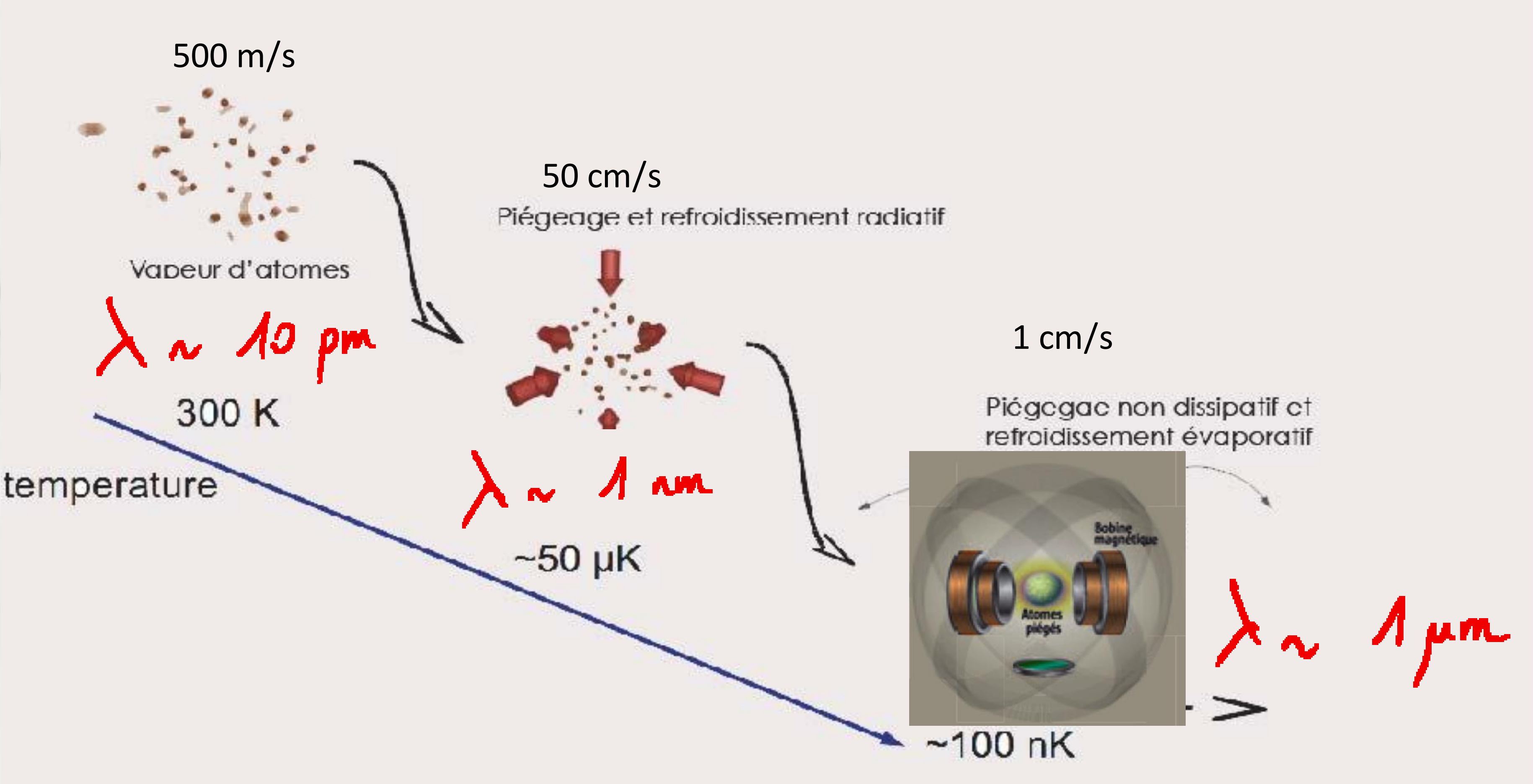
Cooling by evaporation



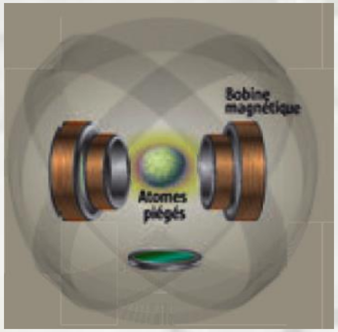
Bose-Einstein Condensation

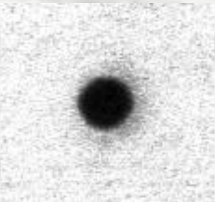


Bose-Einstein Condensation



Monitoring and imaging matter waves



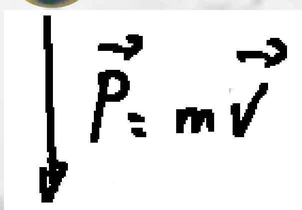


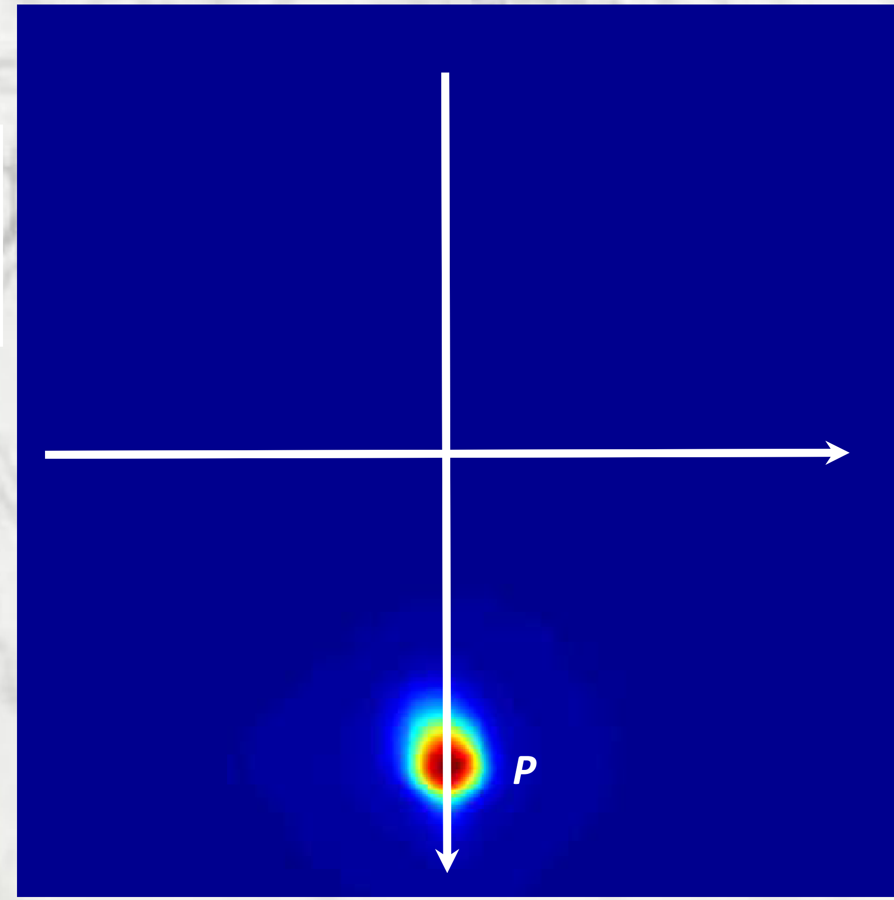
Cooled and trapped atoms can be directly observed with a camera

Monitoring and imaging matter waves

Cooled and trapped atoms can be directly observed with a camera

Monitoring and imaging matter waves

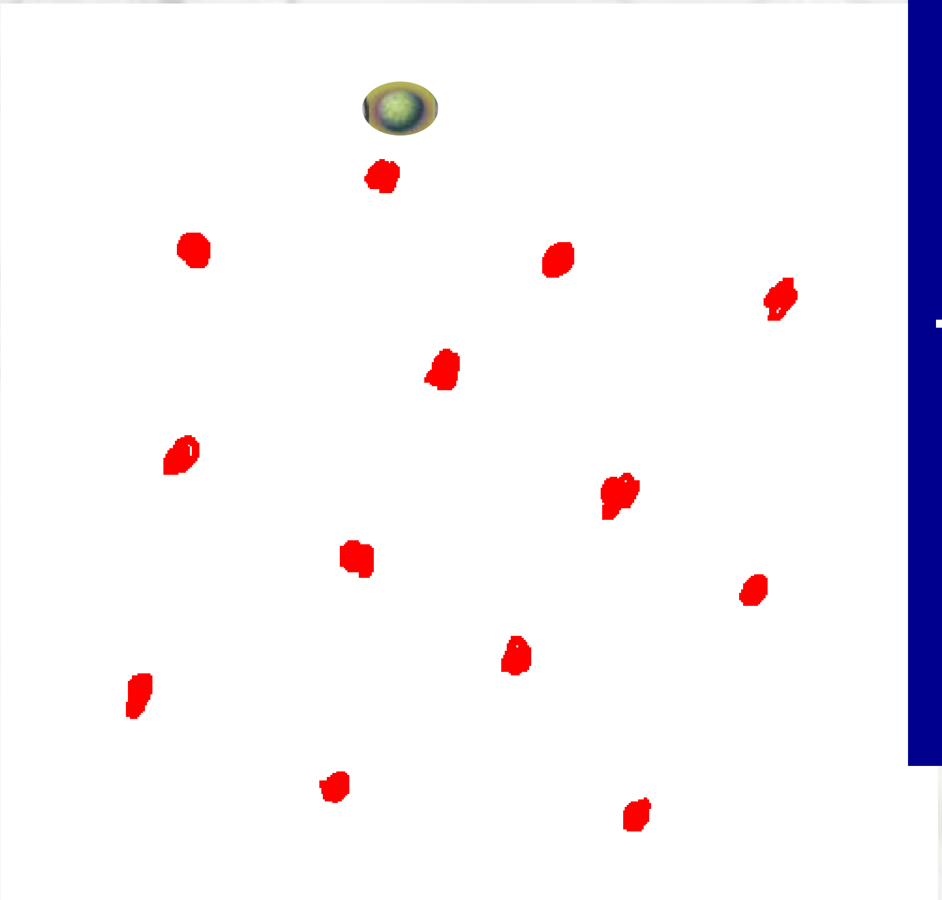


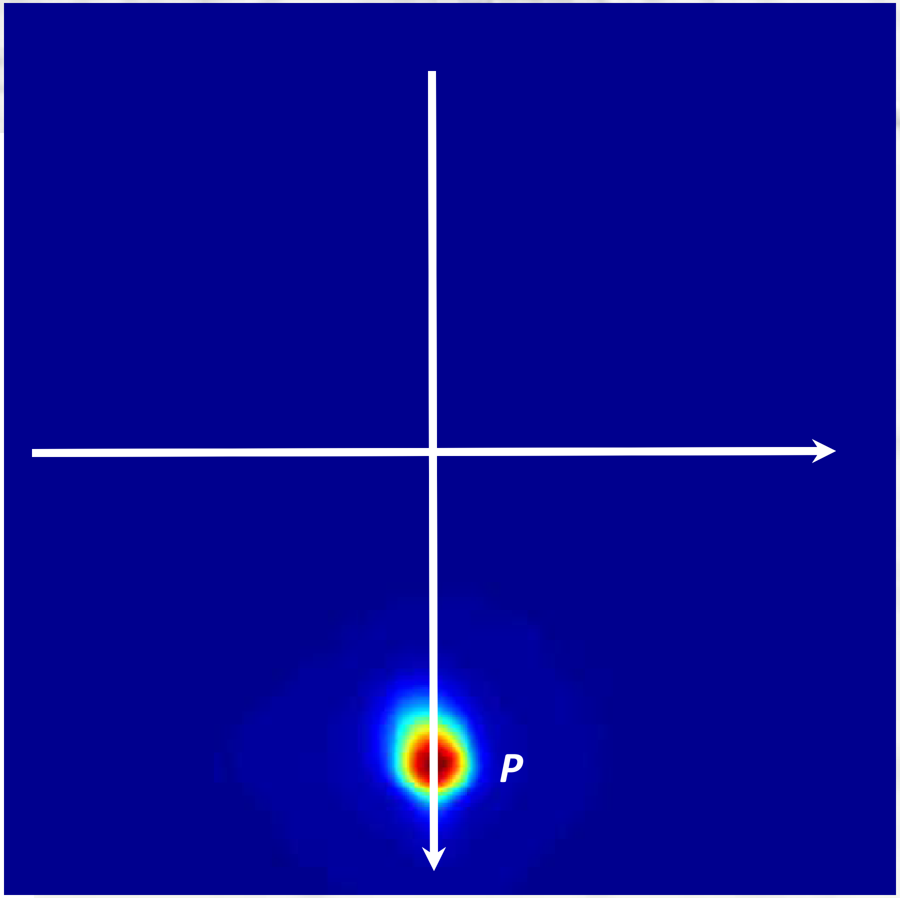


When imaging atoms after they are ejected from the trap, we directly monitor the velocity and the velocity distribution (*time of flight*).

A "quantum simulator" for conductivity

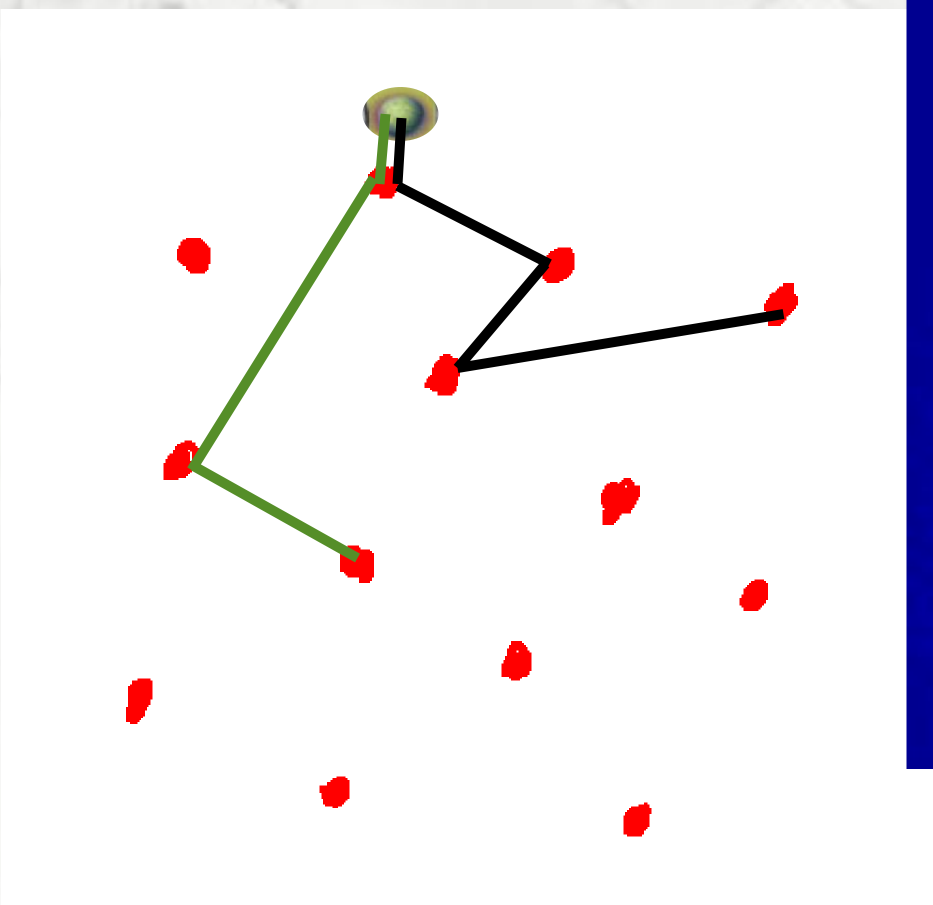
Adding arbitrarily placed *obstacles* that will deflect the atoms.

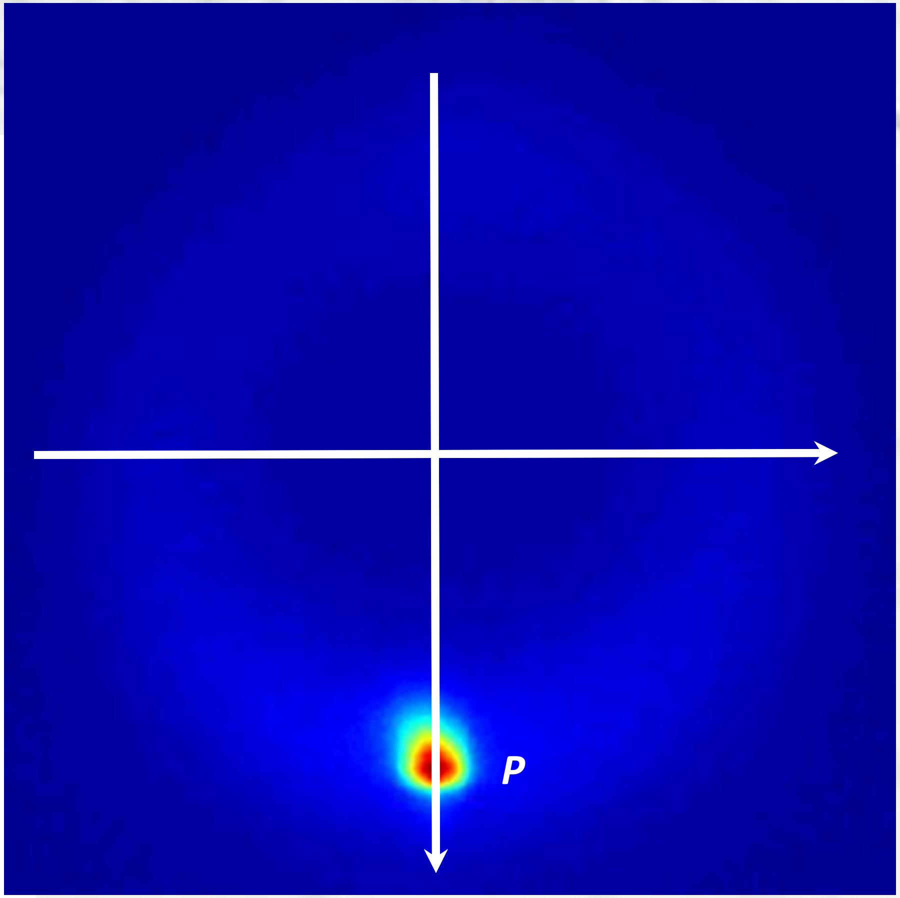




A "quantum simulator" for conductivity

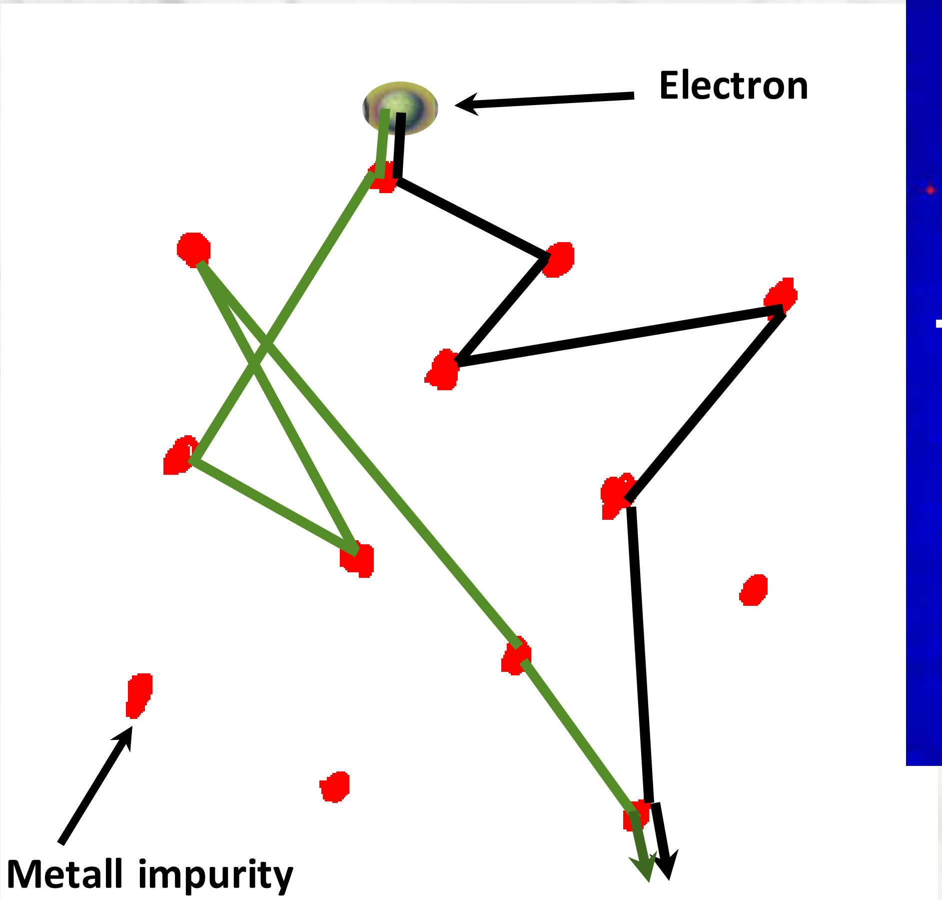
The atoms will have a random walk because of scattering

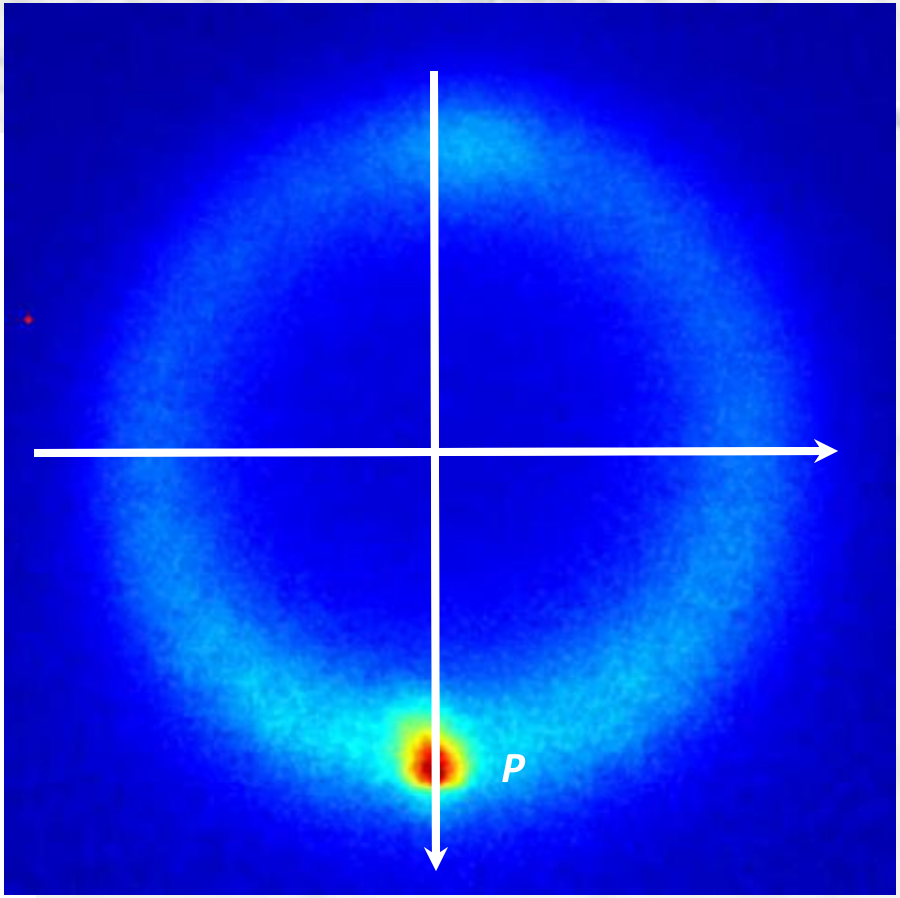




A “quantum simulator” for conductivity

We observe a transport phenomenon mimicking conventional electrical conductivity





A "quantum simulator" for conductivity

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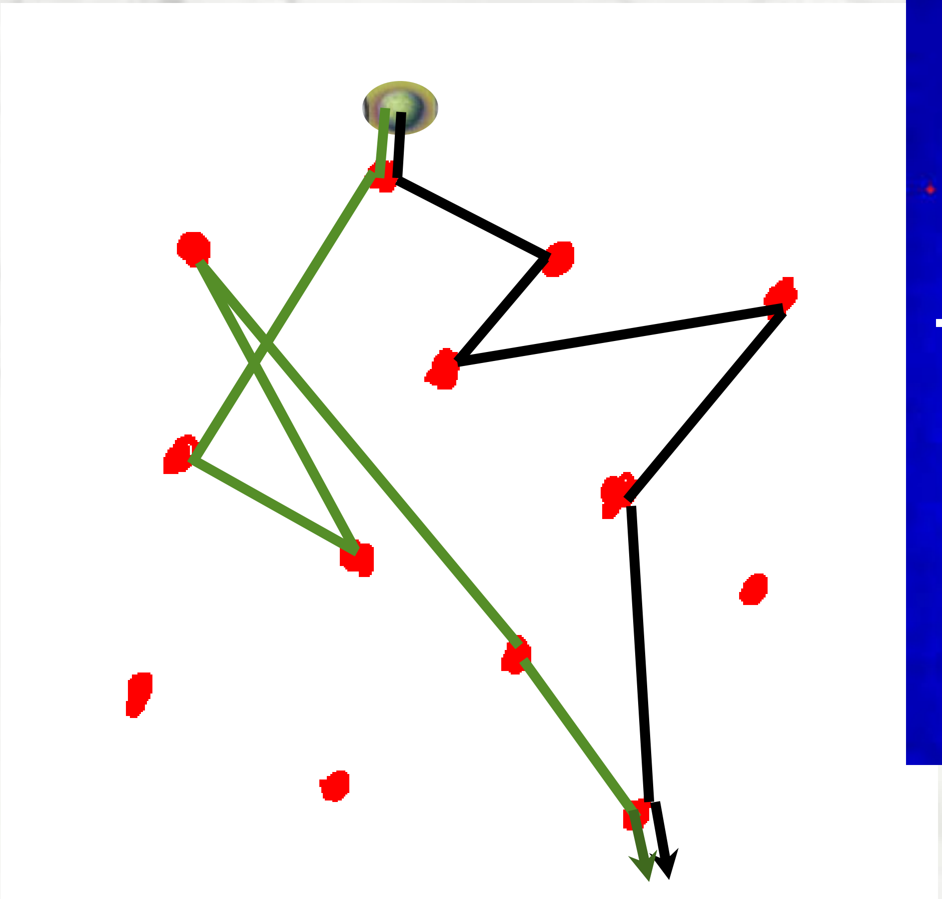
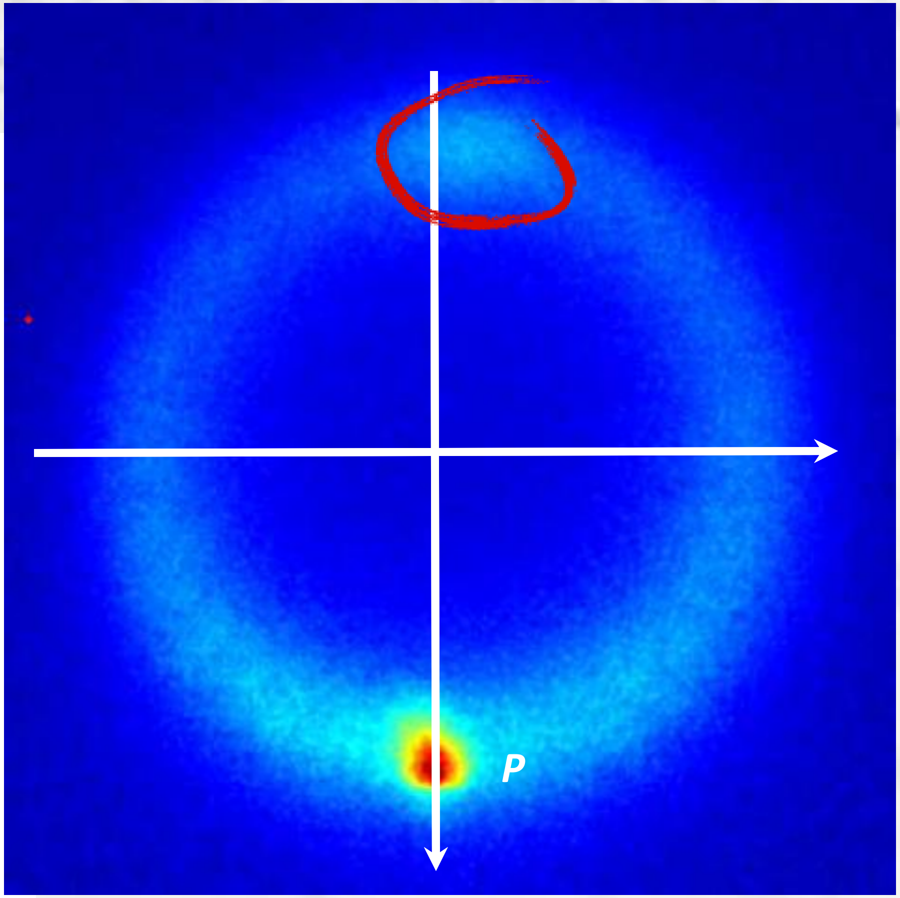
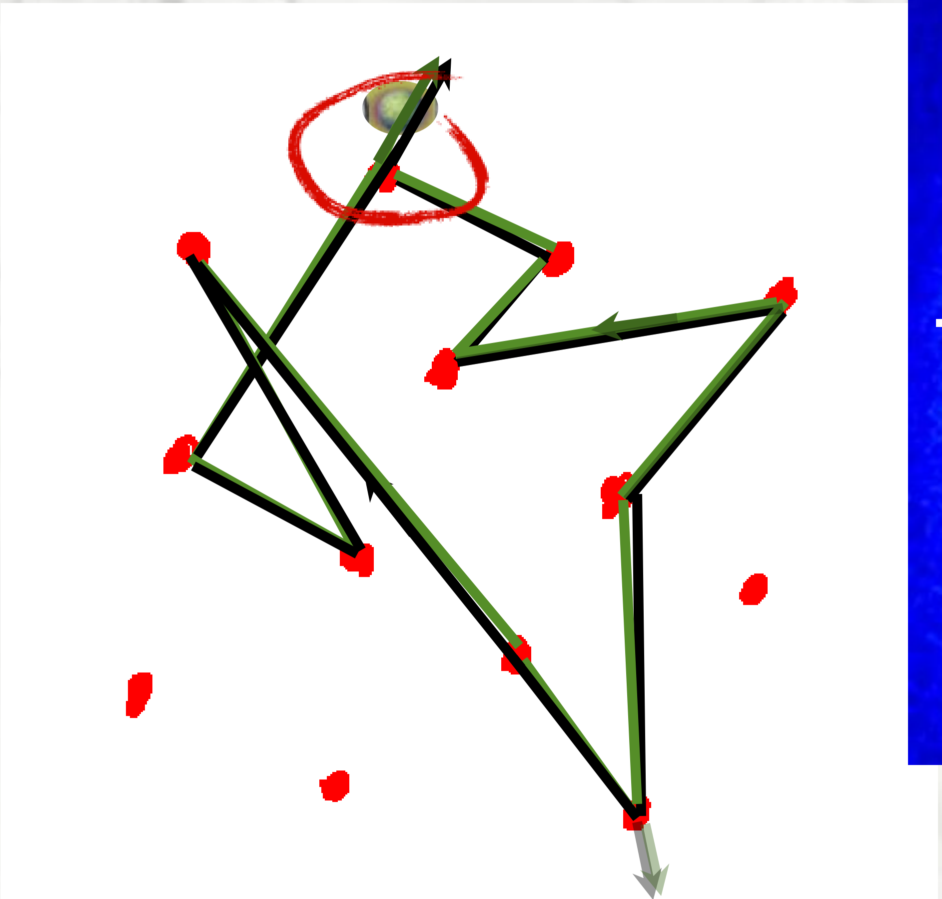
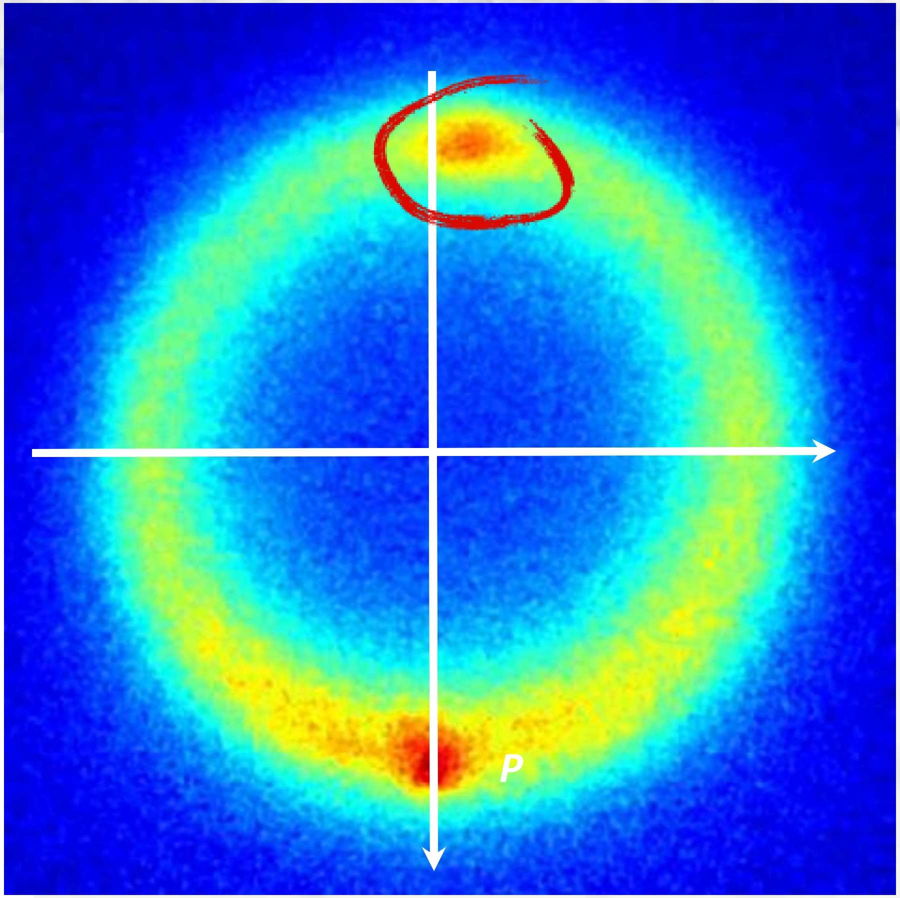




A "quantum simulator" for conductivity

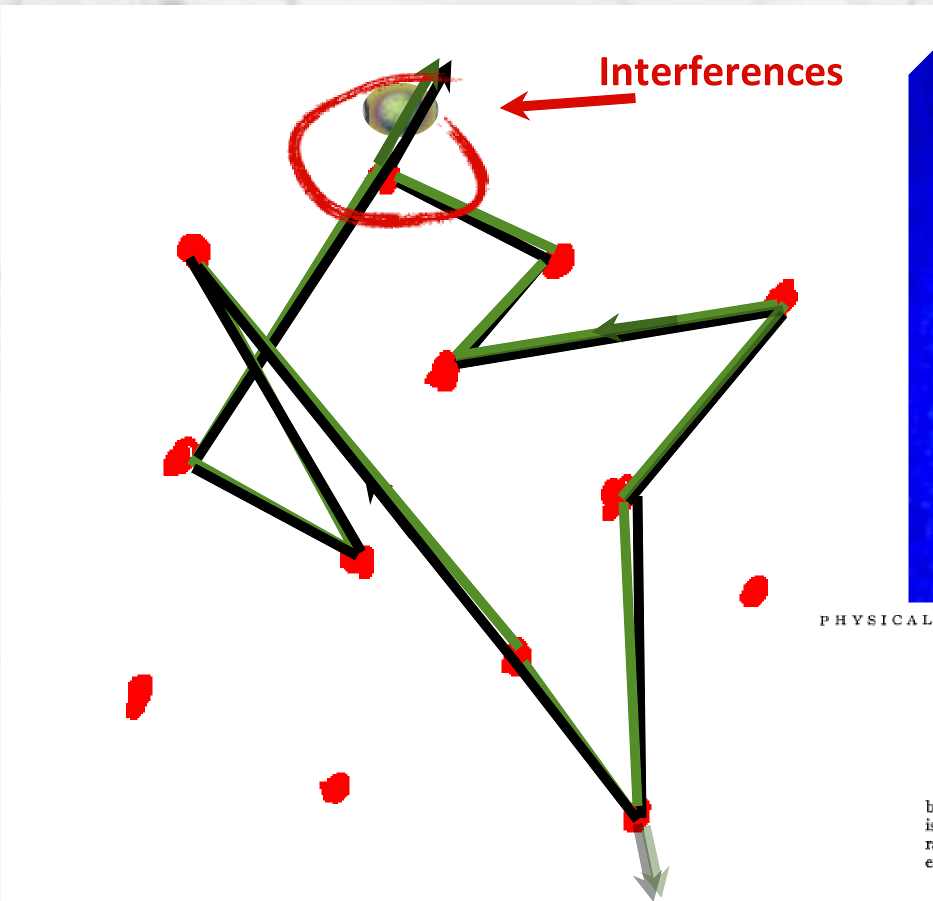
Observation of enhanced retroreflection

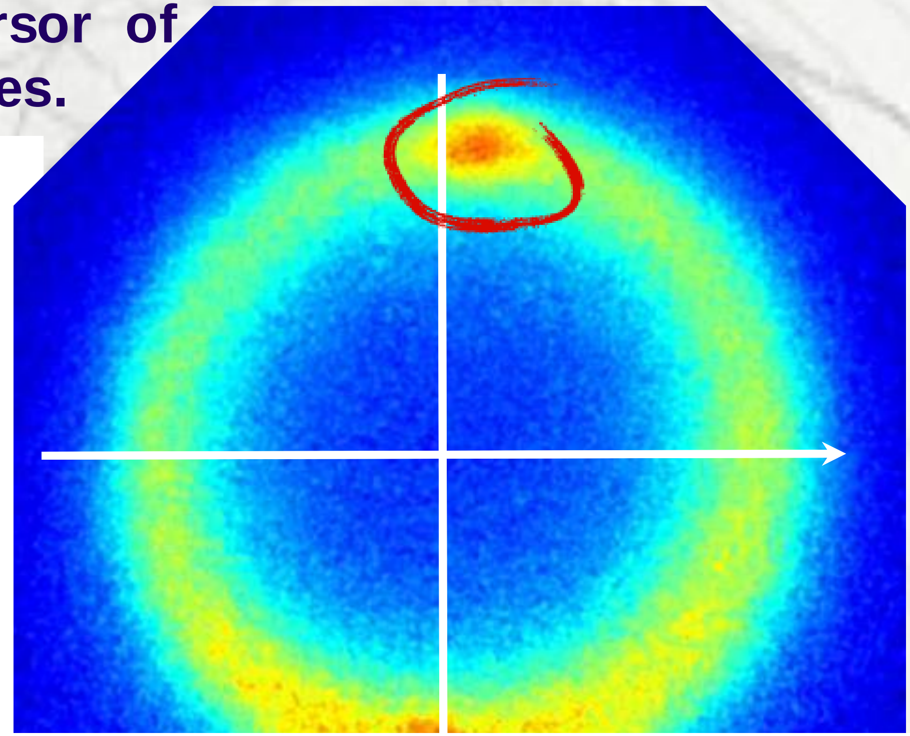




A "quantum simulator" for conductivity

Observation of interference phenomena called weak localisation, precursor of specific insulating electronic states.





PHYSICAL REVIEW VOLUME 109, NUMBER 5 MARCH 1, 1958

Absence of Diffusion in Certain Random Lattices

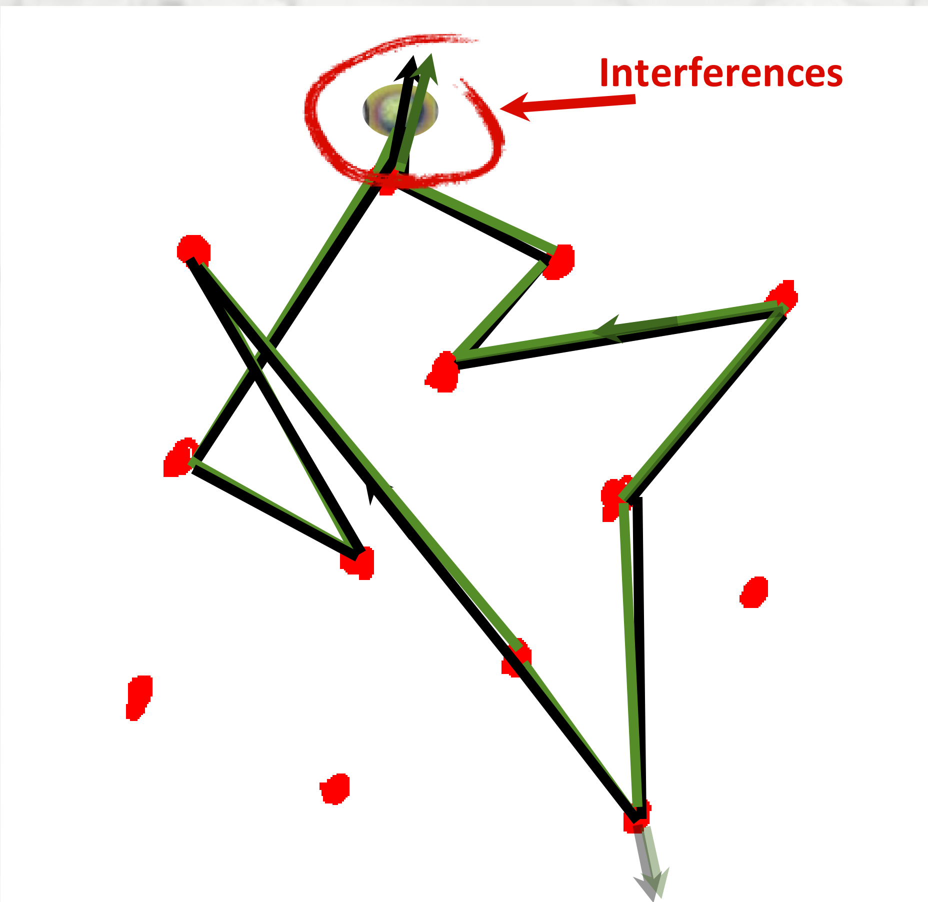
P. W. Anderson
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received October 10, 1957)

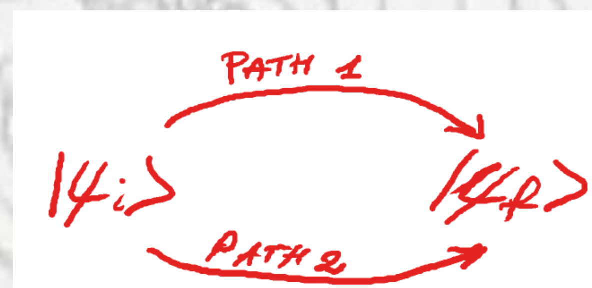
This paper presents a simple model for such processes as spin diffusion or conduction in the "impurity band." These processes involve transport in a lattice which is in some sense random, and in them diffusion is expected to take place via quantum jumps between localized sites. In this simple model the essential randomness is introduced by requiring the energy to vary randomly from site to site. It is shown that at low enough densities no diffusion at all can take place, and the criteria for transport to occur are given.

Controlling and using matter wave interferences

This interferences are the *signature of matter wave coherence*

⇨ **Quantum mechanics : matter wave propagation is affected by interferences between paths**





PATH 1 : $|\mathcal{A}_I|^2 = |\langle\psi_f|\psi_i\rangle_I|^2$

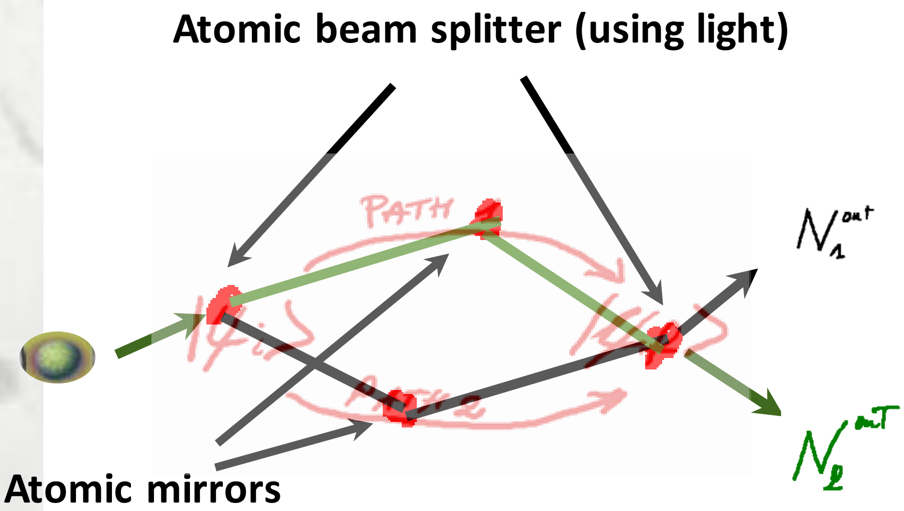
PATH 2 : $|\mathcal{A}_{II}|^2 = |\langle\psi_f|\psi_i\rangle_{II}|^2$

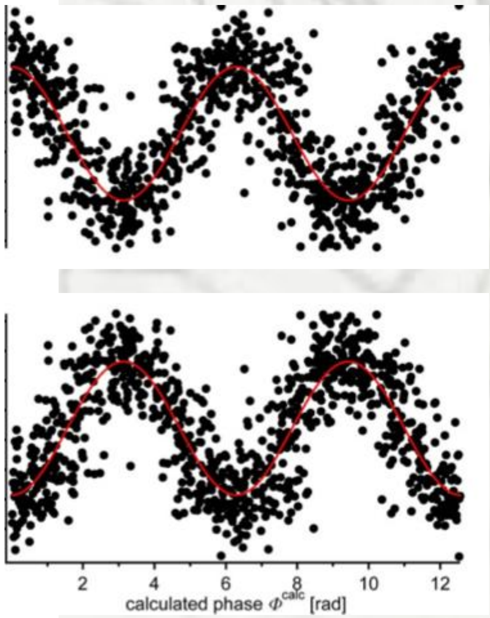
2 PATHS : $|\mathcal{A}|^2 = |\mathcal{A}_I + \mathcal{A}_{II}|^2$

$$= |\mathcal{A}_I|^2 + |\mathcal{A}_{II}|^2 + 2\,\mathrm{Re}\,\mathcal{A}_I\mathcal{A}_{II}^* .$$

Building an atom interferometer

If we control the paths, we can create an *atom (or matter wave) interferometer*





$$N_1^{out} = 1 - N_2^{out} = 1 + \cos\left[\phi_{path\,2} - \phi_{path\,1}\right]$$

At the output of the interferometer, the number of atoms is modulated. The modulation depends on the paths difference.

Building an atom interferometer

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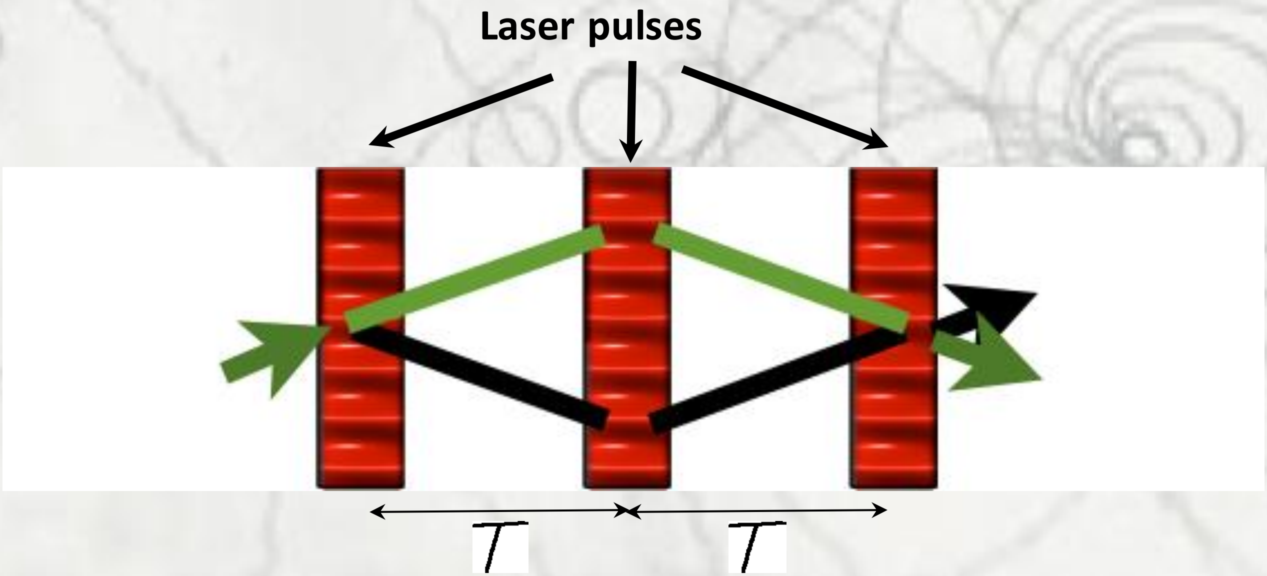
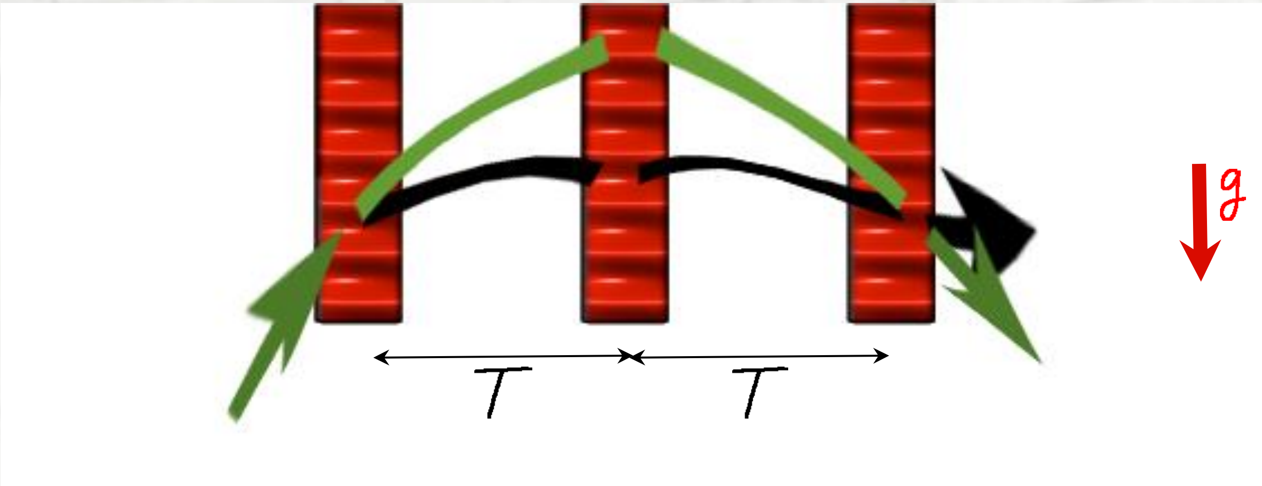


Building an atom interferometer

If we control the paths, we can create an *atom (or matter wave) interferometer*



The phase shift in the interferometer will depend on the acceleration experiences by the atoms

$$\Delta\phi \sim \frac{2\pi}{\lambda_{laser}} g T^2$$

Gravity meter (example)

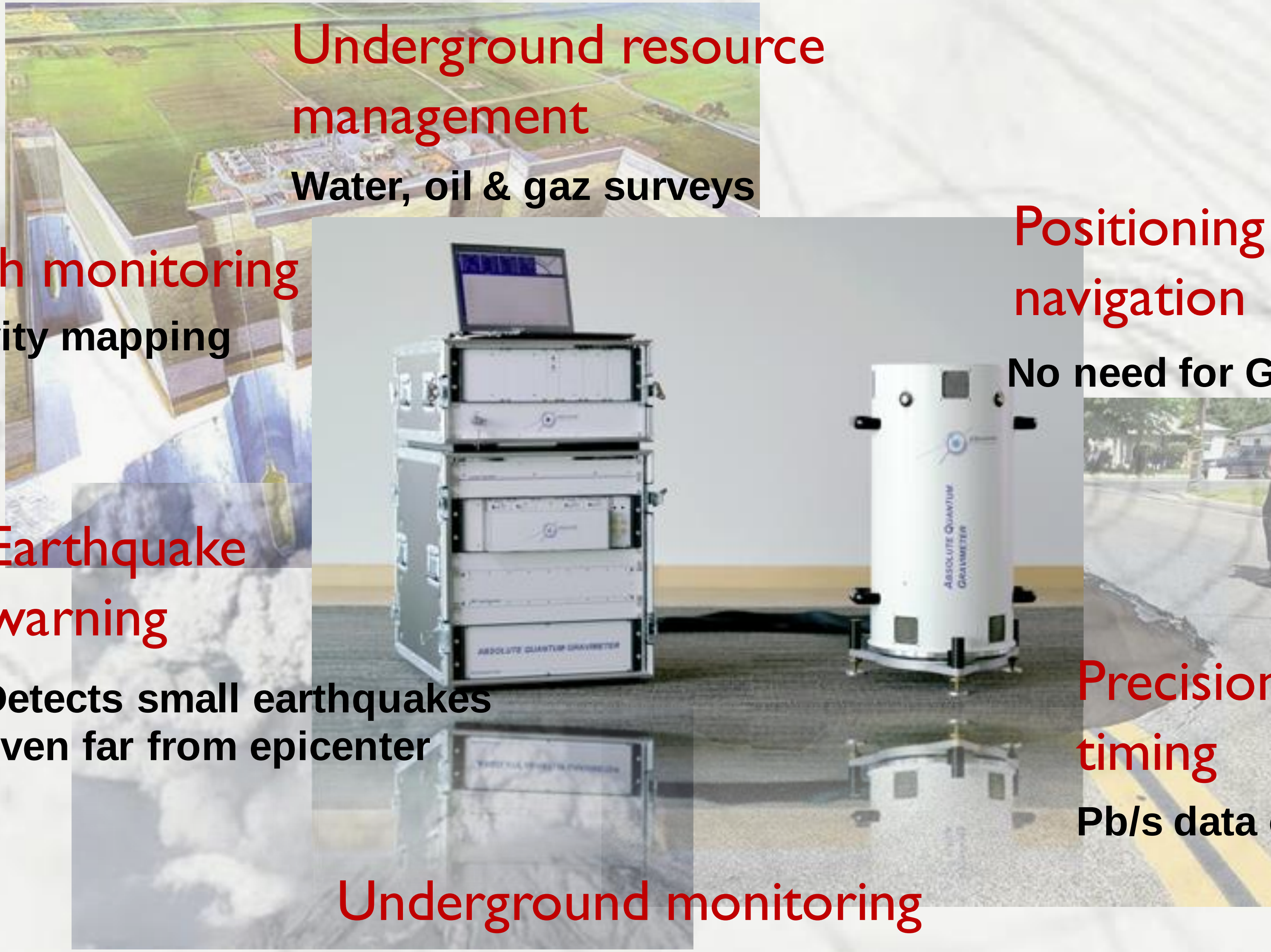
$$\Delta g_{\mathrm{min}} \sim \frac{\lambda_{\mathrm{laser}}}{6 \times \sqrt{N_{\mathrm{at}}}} \frac{1}{T^2} \sim 10^{-8} \mathrm{m.}\, s^2 \sim 1 \mu \mathrm{Gal}$$

Height variations < 1cm, density variations (water/rock/cavity) at 100 m

Sensitive

Exact

Long term stable



Underground resource management

Water, oil & gaz surveys

Earth monitoring

Gravity mapping

Positioning and navigation

No need for GPS

Earthquake warning

Detects small earthquakes even far from epicenter

Precision timing

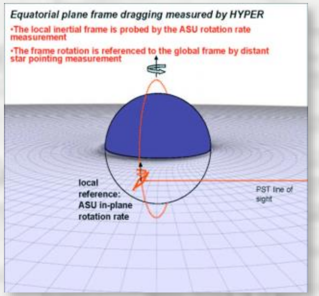
Pb/s data control

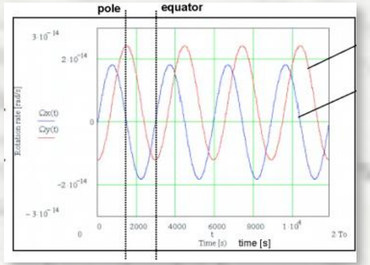
Underground monitoring

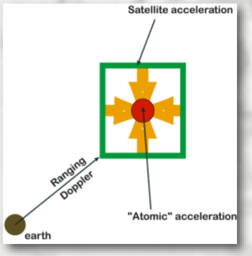
Cavities, galeries

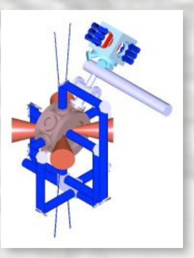
Applications of quantum sensing

- Gravimetry
  - Geodesy/gradiometry
  - Oil/mineral/resource management
  - Gravity anomaly detection
- Low cost, compact, navigation grade IMU
  - Autonomous vehicle navigation
  - Gravity compensated IMU (grav grad/gyro)
  - GPS-free high accuracy navigation
- Gravitational physics
  - Equivalence Principle
  - Gravity-wave detection
  - Post-Newtonian gravity, tests of GR
  - Tests of the inverse square law
  - Dark matter/energy signatures?
- Beyond Standard model
  - Charge neutrality
  - h/m, tests of QED









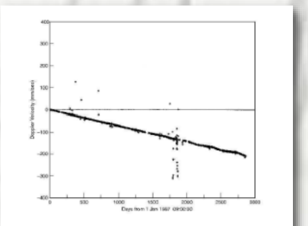
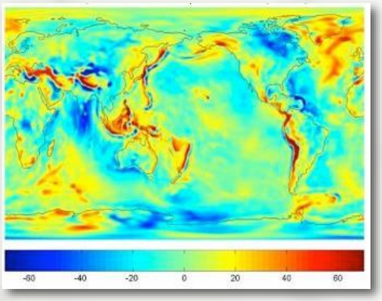
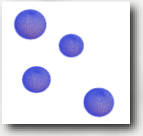
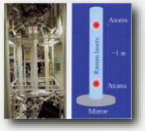
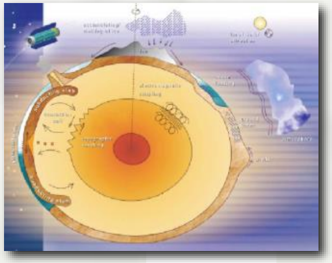


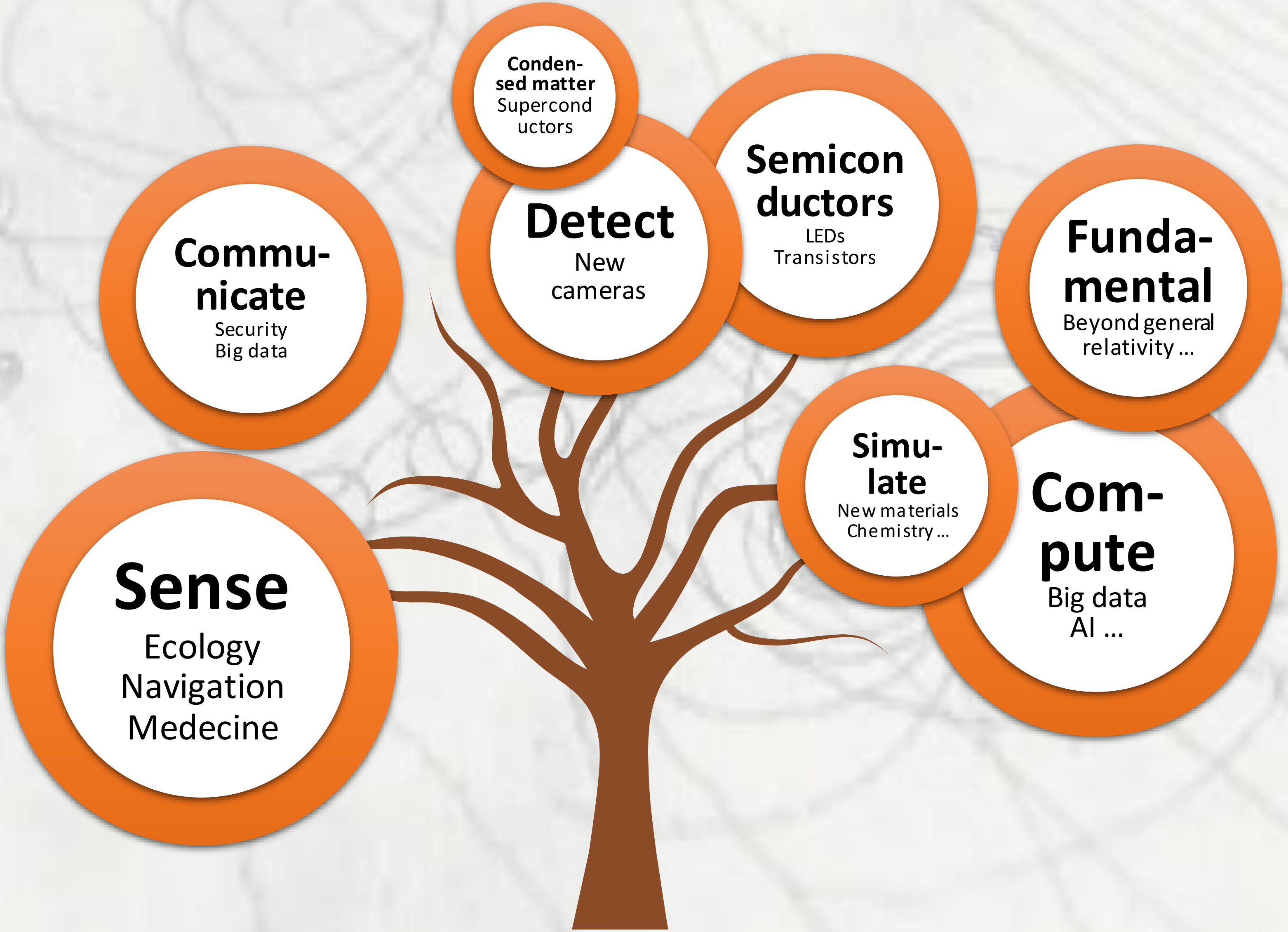
FIG. 8: CHASMP two-way Doppler residuals (observed Doppler velocity minus model Doppler velocity) for Pioneer 10 vs. time. 1 Hz is equal to 65 mm/s range change per second. The model is fully-relativistic. The solar system's gravitational field is represented by the Sun and its planetary systems [49].











The quantum tree