The symbiosis between blue sky research and technology: the example of quantum physics

COLLÈGE DE FRANCE 1530

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Kiev, Mai 2018

LETTRES SCIENCES ECOLE NORMALE SUPERIEURE

Why scientific research?

to satisfy our curiosity about Nature (blue sky research)?

or

to achieve useful tasks and fulfil «societal» needs (applied research)?

Politicians often favor short term «usefulness» and consider long term curiosity as a « luxury »…

The history of science illustrates how short-sighted this is: blue sky research and technology are the two sides of the same coin, which cannot be separated.

Basic research is driven by mere curiosity, as illustrated by the great discoveries about light and matter

Fundamental questions about light (is it a wave or a particle, what is its velocity?)…


Newton

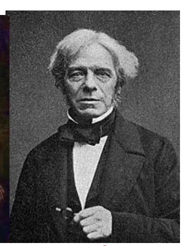

Huygens


Fresnel


Fizeau

…and fundamental questions about matter (how does it carry electricity and exhibit magnetism? How does it interact with light?)…

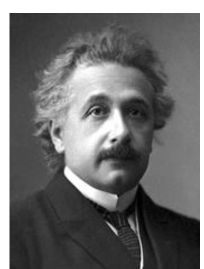

Coulomb

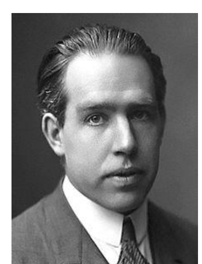

Faraday


Ampère


Maxwell


Planck


Einstein


Bohr

…have led to great discoveries:

Light is an electromagnetic wave propagating at a speed independent of the observer and at the same time an ensemble of particles (photons) carrying energy and momentum.

Matter is made of atoms combining positively charged nuclei with negative electrons occupying discrete energy states and carrying small magnetic moments….

Light and matter obey strange laws with counter-intuitive features (state superposition, entanglement)

Quantum physics and Relativity

The scientists who made these great discoveries had no idea about what they could be useful for…

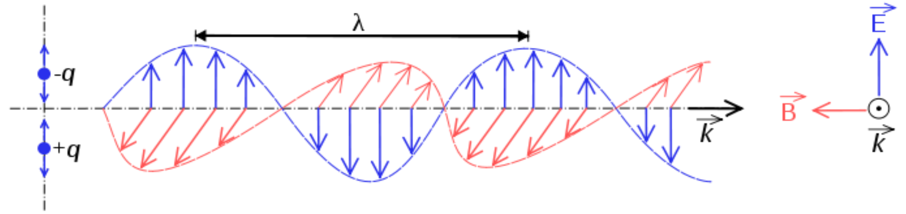
…but, they have led to innovations which have changed our lives, our ways to produce energy, to communicate, to store and process information, to probe matter, to perform medical diagnosis etc…

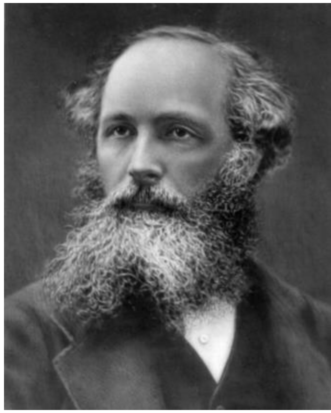
These applications have emerged often serendipitously from the combination of breakthroughs coming from different basic research areas and after a long maturation time

Let us look at a few examples

Electromagnetic wave:

Electric and magnetic fields feeding each other





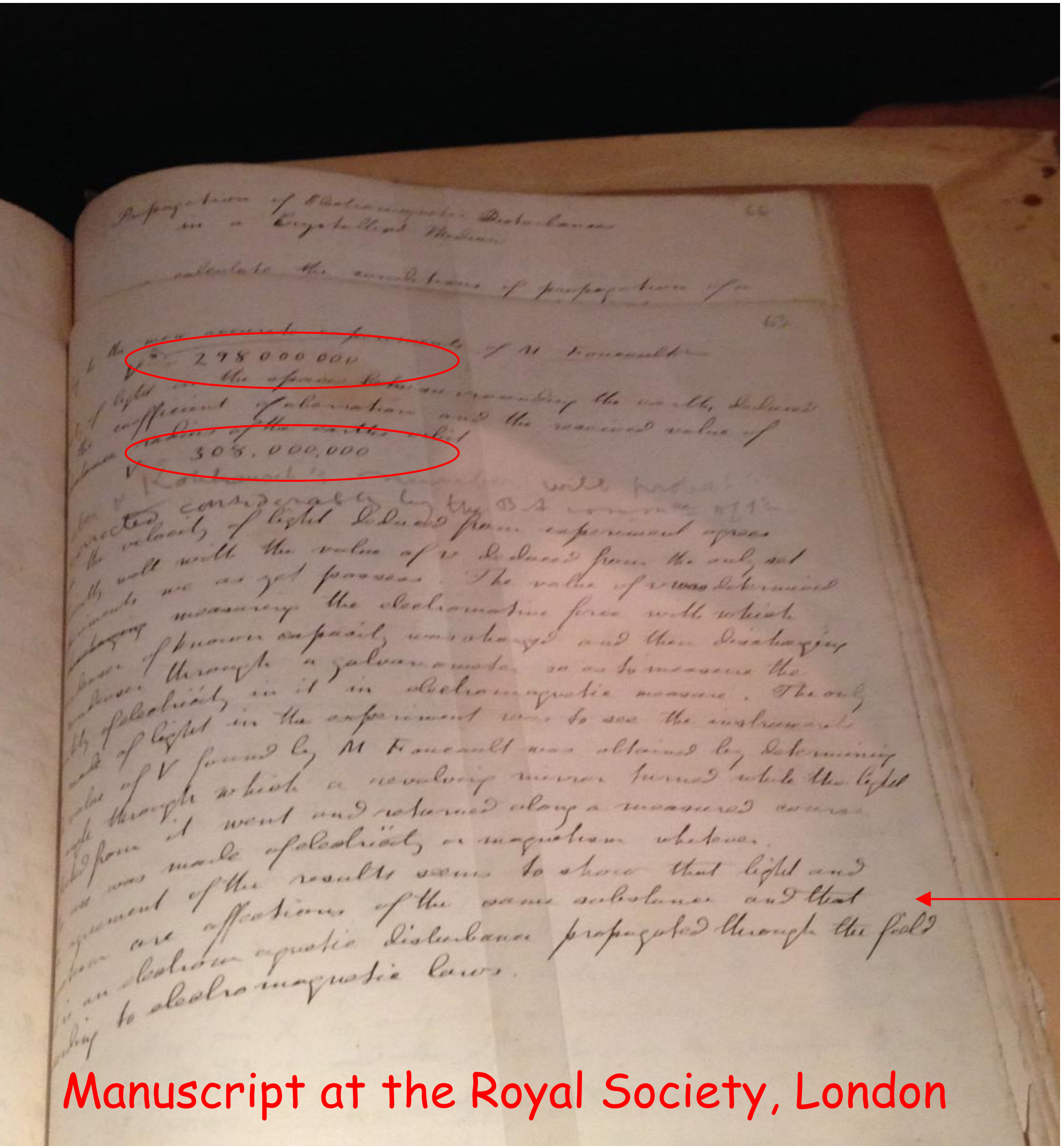
Maxwell

1865

Fizeau

$$c = \frac{1}{\sqrt{\varepsilon\mu}}$$

Coulomb   Ampère

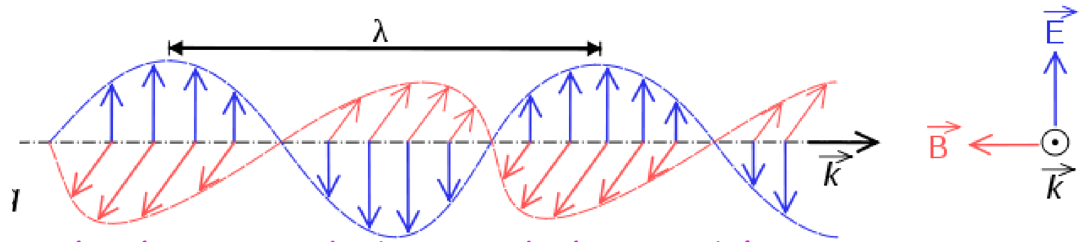


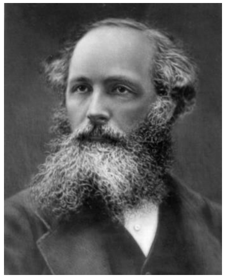
Manuscript at the Royal Society, London

A Blue Sky Discovery:

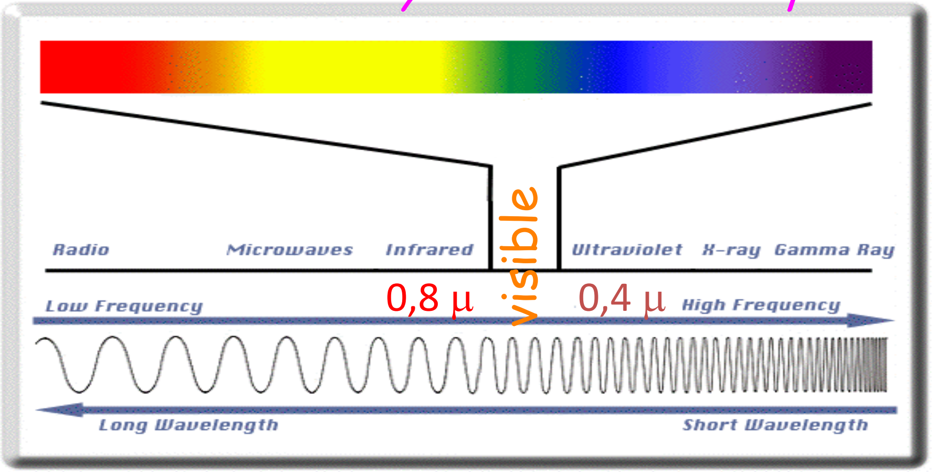
"The agreement of the results seems to show that light and magnetism are affections of the same substance and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws"

Light is an electromagnetic wave (1865)…

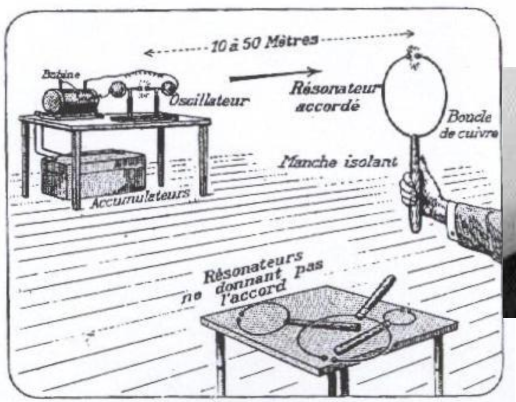




…which extends beyond the visible spectrum



radiowaves (1885)



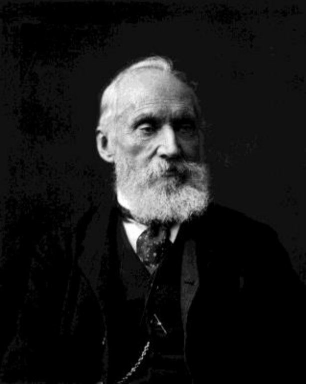
Hertz

Revolutions in technology:
radio-broadcasting,
microwave applications,
X ray medical diagnosis
etc..

…and new questions
leading to Relativity and
Quantum Physics

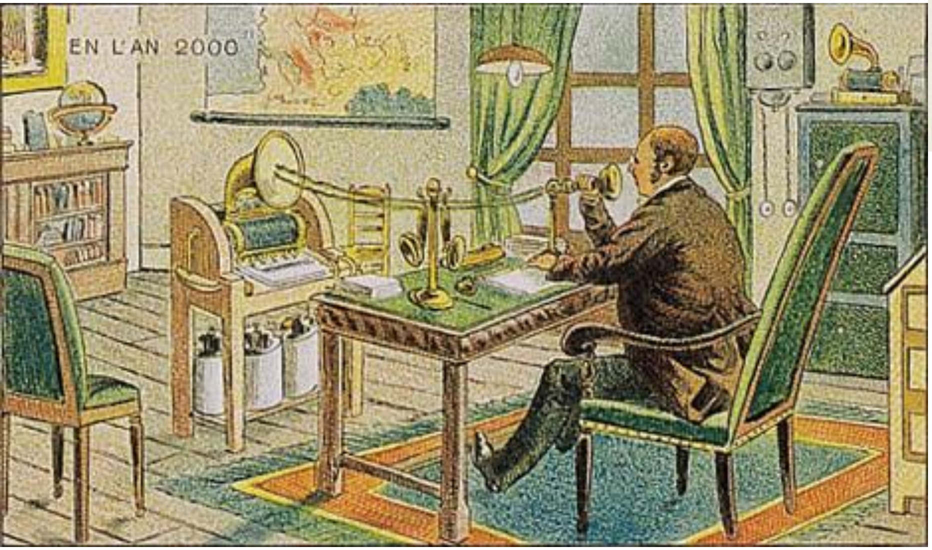
X Rays (1895)

Roentgen

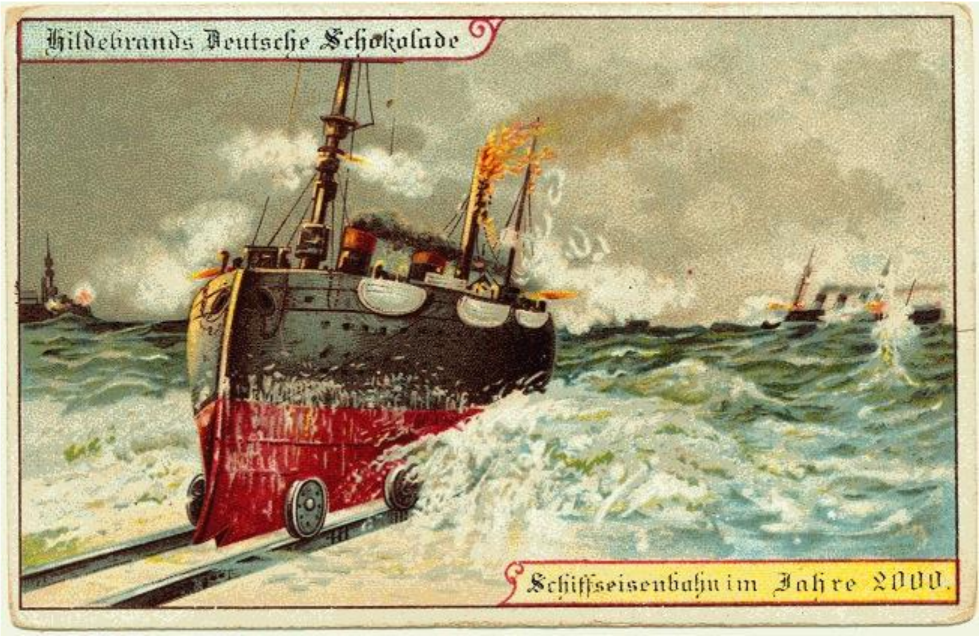


Lord Kelvin

Modern technologies were unimaginable by pre-quantum age 1900 physicists



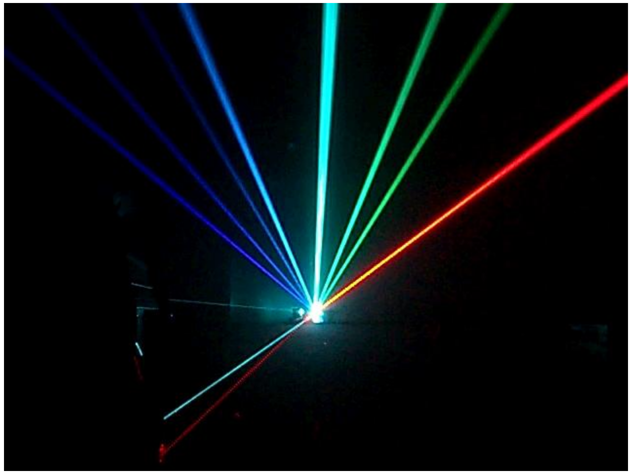
Naive predictions of 20th century technologies made in 1900



Examples of Quantum technologies not anticipated in 1900

Computers

Atomic clocks and GPS

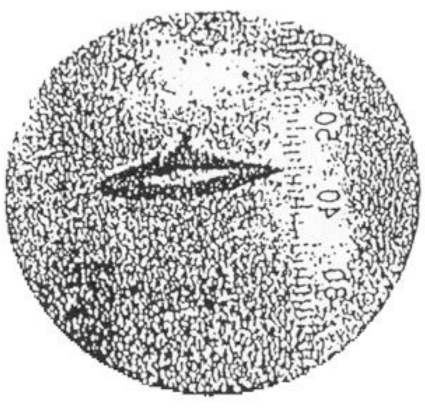


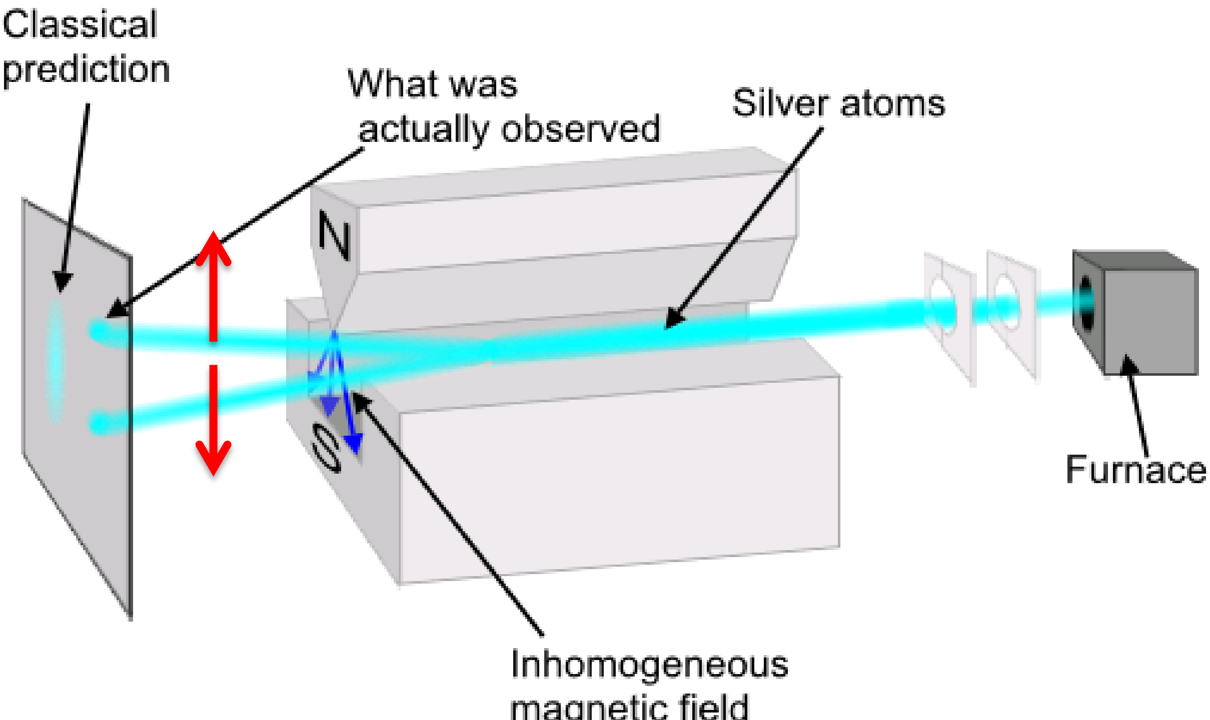
Lasers

MRI scanners

It started with a blue sky discovery: Stern and the electron magnetic moment (1922)

O.Stern



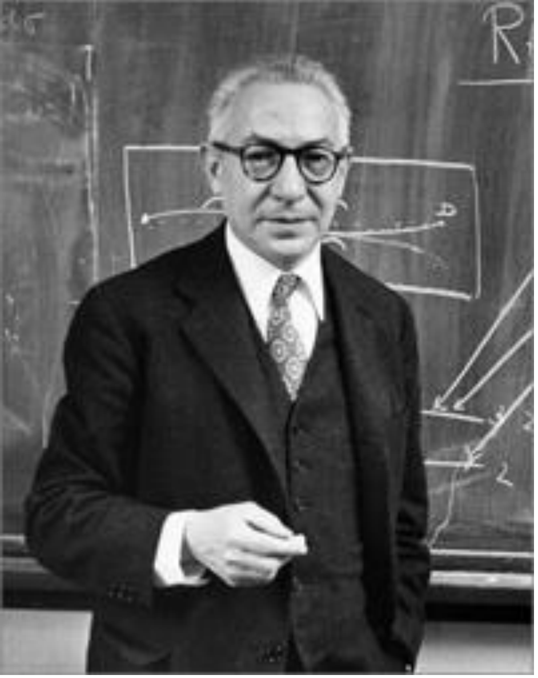


A simple split trace heralding the quantum revolution in technology!

The magnetic moment is quantized

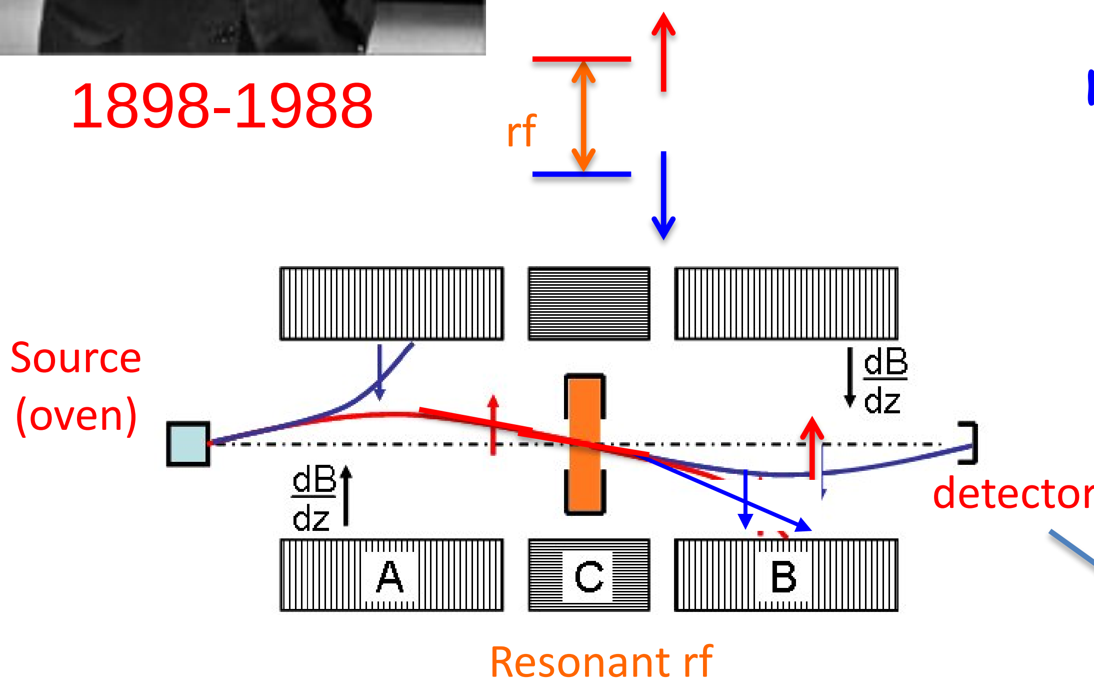
The set-up separates the magnetic moments (spins) pointing up and down

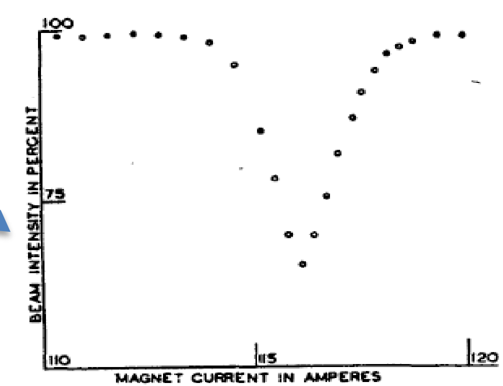
More blue sky science: Isidor Rabi and the rf Molecular Beam method to measure nuclear magnetic moments at Columbia



1898-1988

The resonant rf field flips the magnetic moment in C, changes the molecules trajectories and decreases the detected signal…





Rabi's discoveries opened the way to the MRI, the atomic clocks, the GPS and the laser….

A prescient headline

We're All Radio Stations, Columbia Scientists Report

All Atoms, in Humans or in Steel, Found to Emit and Receive Long Waves

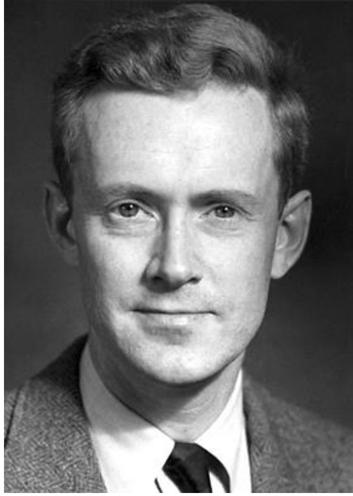
COLUMBUS, Ohio, Dec. 29 (AP).—Every living thing on earth is a radio broadcasting and receiving set unconsciously sending out and receiving long-wave wireless messages.

Professor I. I. Rabi, Dr. P. Kusch and Dr. S. Millman of Columbia University told the American Association for the Advancement of Science today that all

New York Post, December 1939

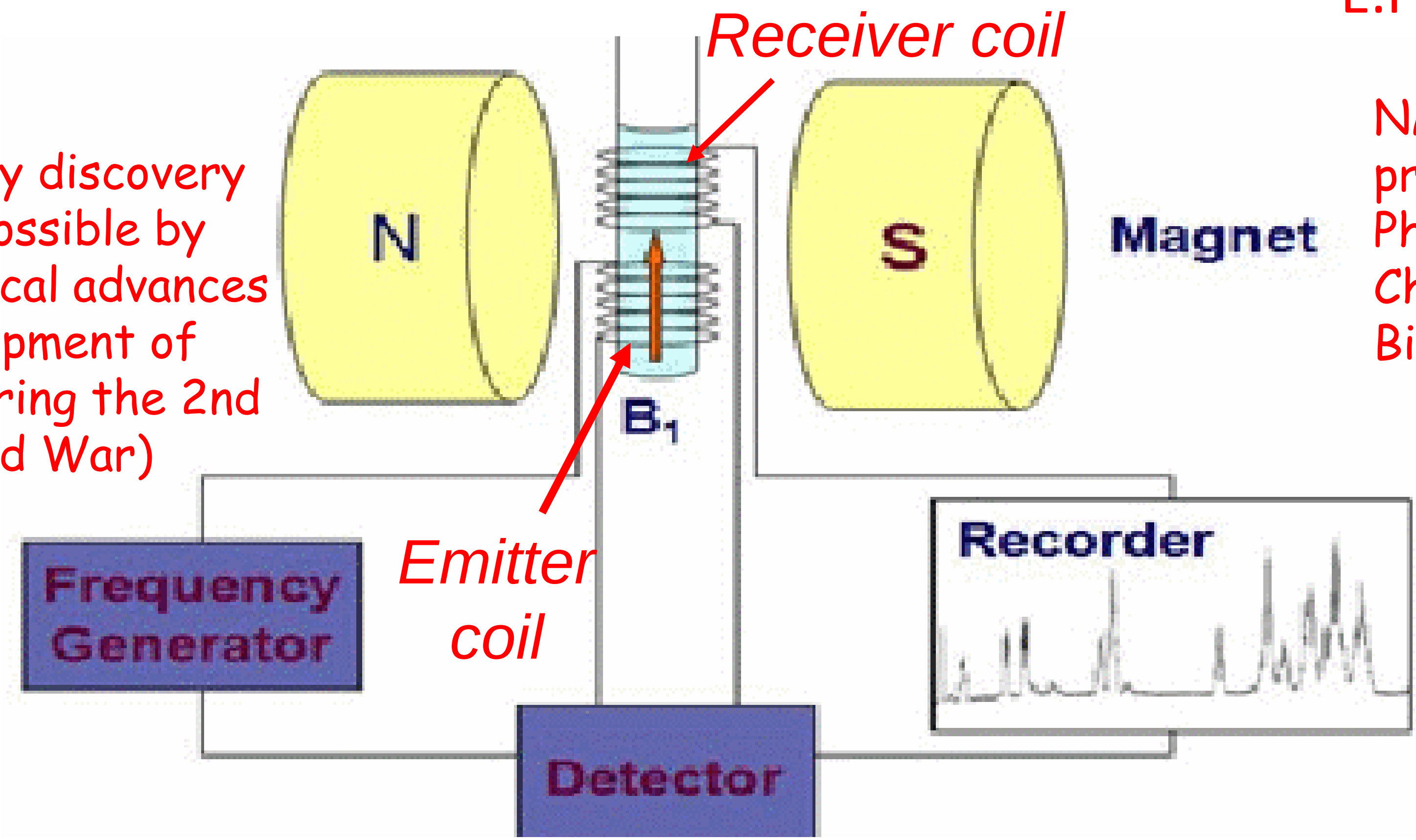
The nuclear magnetic resonance (NMR) 1945

F.Bloch



E.Purcell

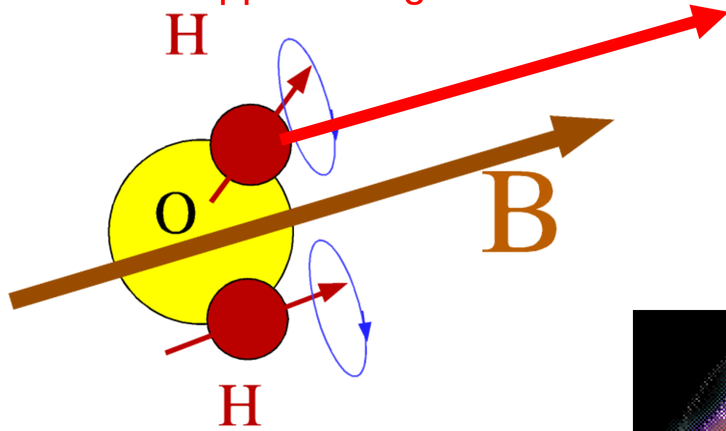
A blue sky discovery made possible by technological advances (development of radars during the 2nd World War)

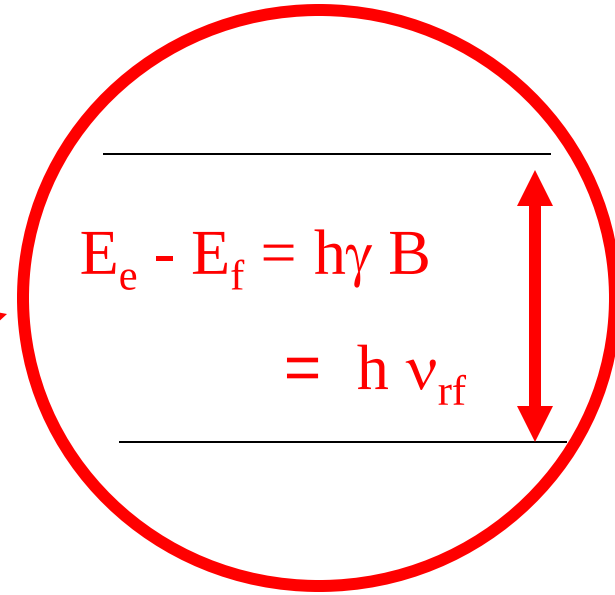


NMR probes in Physics, Chemistry Biology...

An unexpected application: The Magnetic Resonance Imaging (MRI)

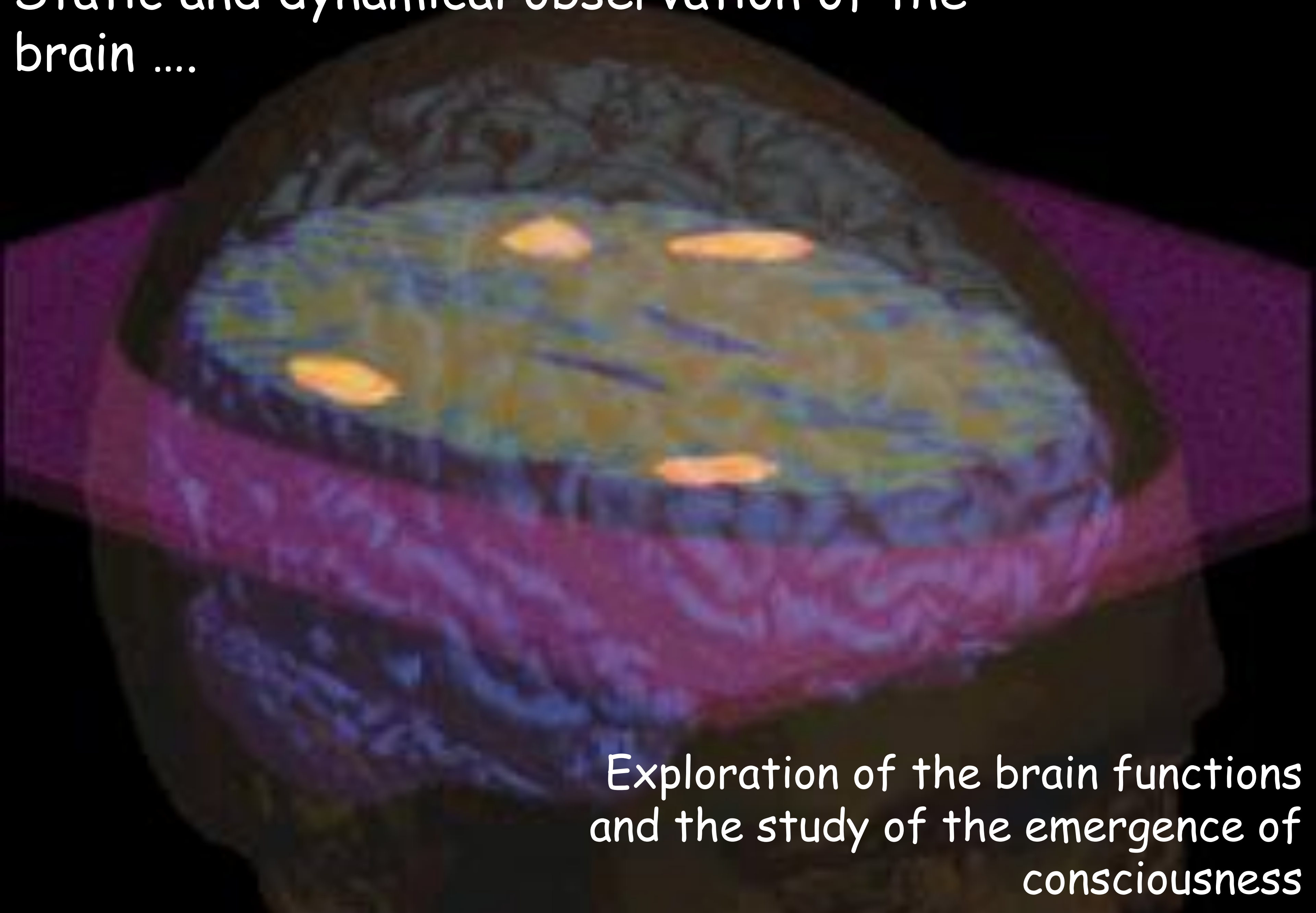
The H atoms have a two-level magnetic structure, with an energy gap proportional to the applied magnetic field





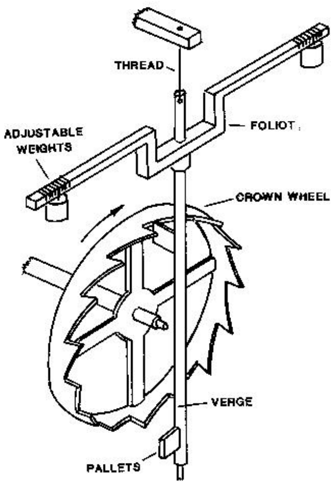
The scattering of radio-waves of variable frequencies in a spatially inhomogeneous magnetic field makes possible the 3D mapping of the body

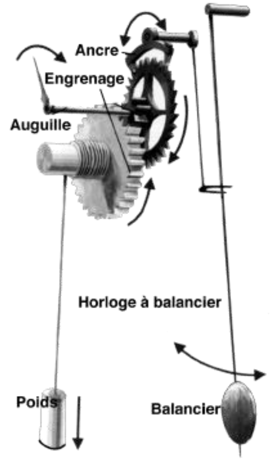
Static and dynamical observation of the brain ....

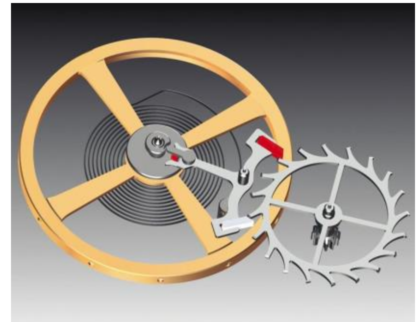


Exploration of the brain functions and the study of the emergence of consciousness

A brief history of the measurement of time







14th century:
Tower clock

17th century:
Pendulum
(Galileo, Huyghens)

18th century
Marine chronomete
and spring watch
(Hook, Harrisson)

1920's
Quartz
clock
(piezoelectric
effect)

Relative uncertainty

14th century	17th century	18th century	1920's
10^{-2}	10^{-4}	10^{-6}	10^{-8}

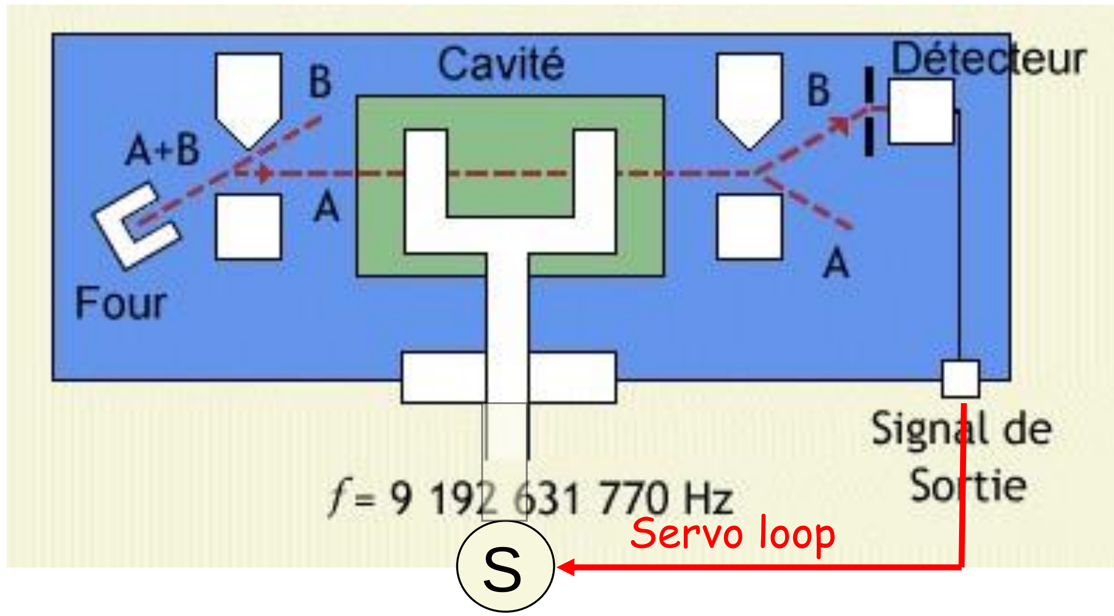
General principle: an oscillator coupled to an escape device which counts periods (the higher the frequency, the better)

nendous progress due to atomic oscillators: The standard atomic clock reaches a 10^{-14} uncertainty and improved clocks sers a 10^{-18} uncertainty (less than 1s over age of Universe!)

The microwave atomic clock operates on an improved Rabi beam machine

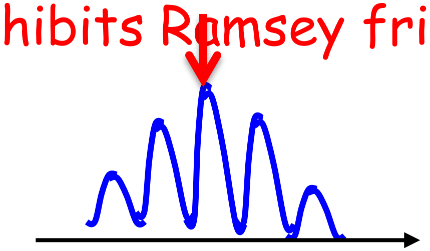
N.Ramsay
(a student of Rabi)

Cesium microwave clock



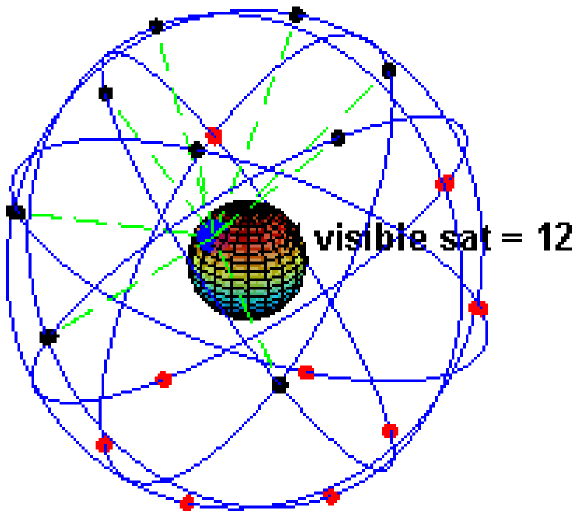
The oscillation of electrons in an atom is much more stable than that of a pendulum, a spring or even a quartz!

Cesium beam probed by a **double microwave pulse**: resonance exhibits Ramsey fringes



Uncertainty about 10^{-14}
(1 second precision over a million years!

A direct application of microwave atomic clocks: the GPS



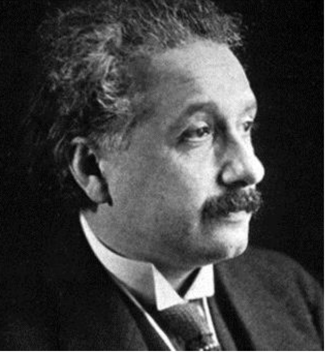
Triangulation with signals received from synchronized atomic clocks embarked on a swarm of satellites circling the Earth

precision of about 1 meter !

The GPS exploits the principles of quantum physics as well as those of Special and General Relativity

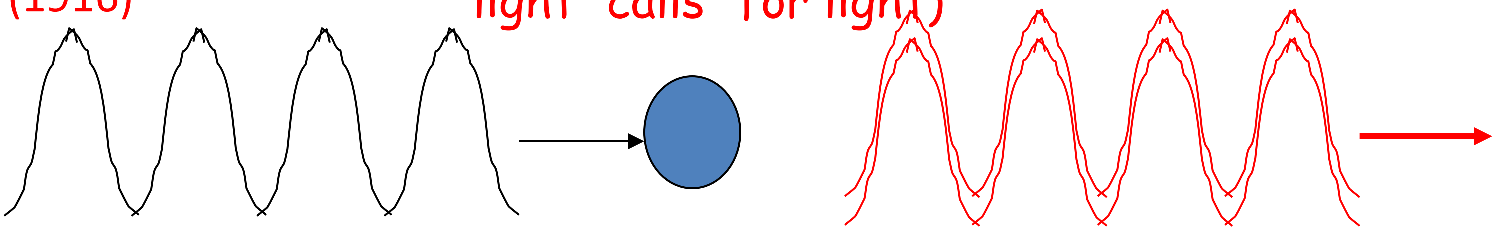
Without relativistic corrections, the GPS would be off by several kilometers and totally useless!

The stimulated emission of light: another blue sky discovery…

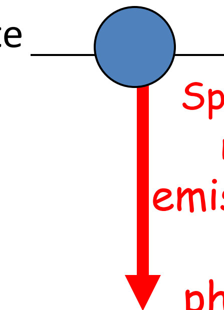


Einstein (1916)

Amplification (stimulated emission: light "calls" for light)



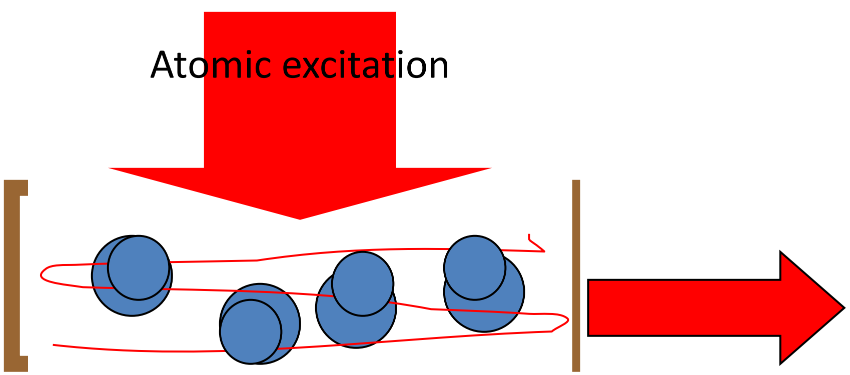
Atom in excited state



Sponta-neous emission of a photon (Bohr-1912)

One photon triggers the emission of a second identical photon and so on…

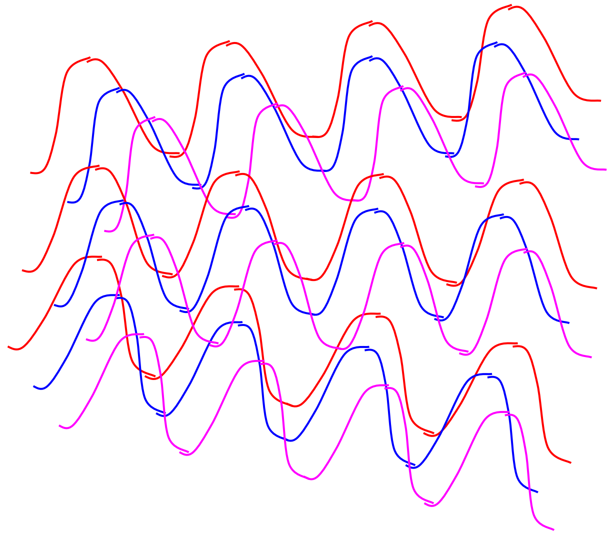
…which has led to the maser, then by extension to the optical domain, to the laser…



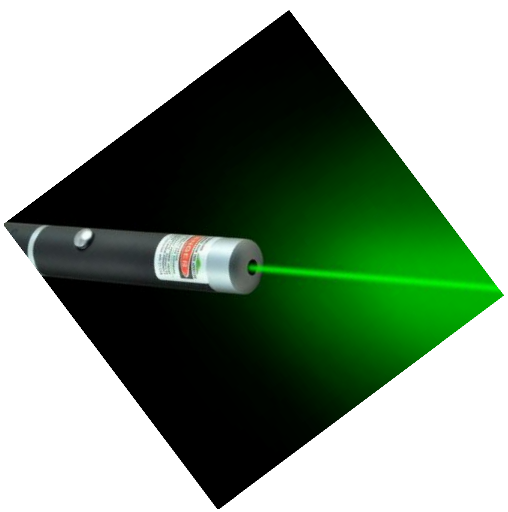
Light between mirrors amplified by excited atoms. Fraction of light escapes through output mirror:

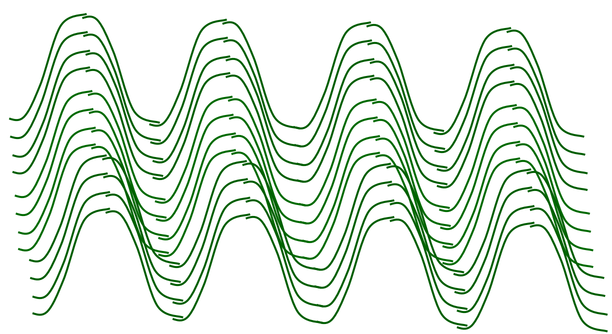
laser beam

Classical versus Laser light



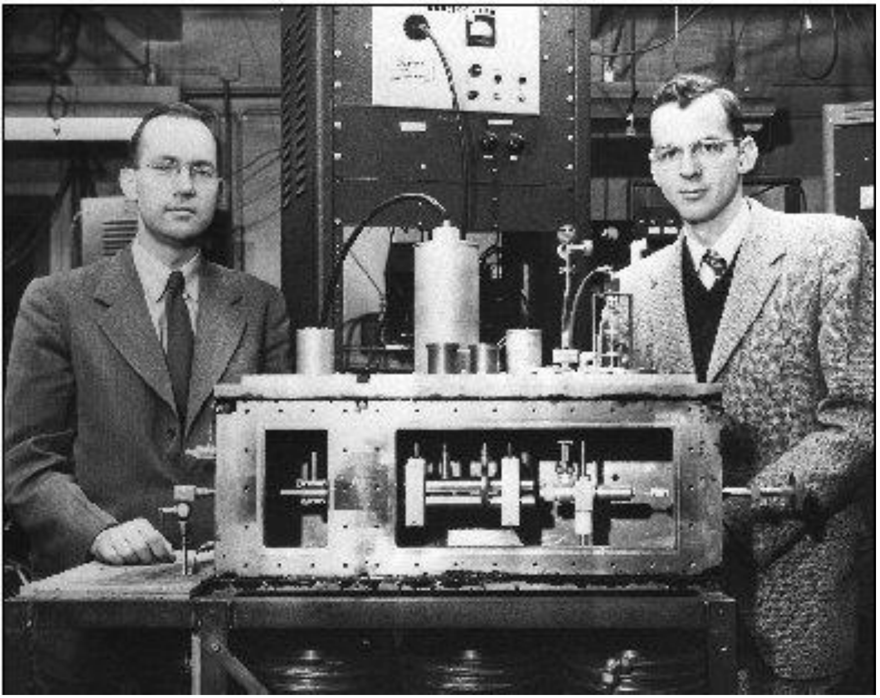
Classical light (Sun, Lamp): atoms emit independently radiations with random phases and dispersion of frequencies and directions





Laser light: atoms emit "in step" radiation with same phase, frequency and direction. This is tamed light

It again started in the microwave domain!



Townes and Gordon at Columbia University (1954) in front of their ammonia beam which produced the first maser emission

The first Maser (Microwave Amplifier by Stimulated Emission of Radiation)

A variant of the Rabi beam machine emitting coherent microwave at frequency of molecular transition

What use for this?

The Laser, Fantastic "tamed" light

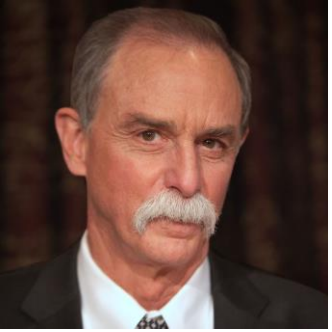
Intense, directive, monochromatic, coherent....

Fusion and evaporation of matter, cooling and trapping of atoms: lasers can achieve the highest temperatures existing inside stars…and produce the coldest objects in the universe (Bose-Einstein condensates or BEC)

Ultra-stable light beams oscillating without skipping a beat over millions of kilometers…or ultra-short light pulses extending over a few nanometers, crossing matter in a few attoseconds (one billionth of a billionth of a second).

A very flexible tool for fundamental research in physics, chemistry and biology and for applications to metrology, medicine, communication etc…

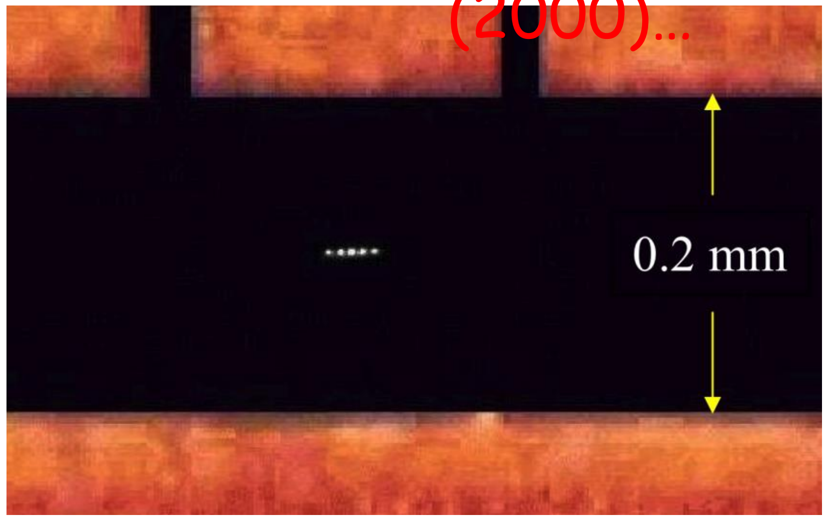
Let us briefly review three domains: manipulation of individual atomic systems for quantum information, ultra precise atomic clocks and gravitational wave detectors



D. Wineland

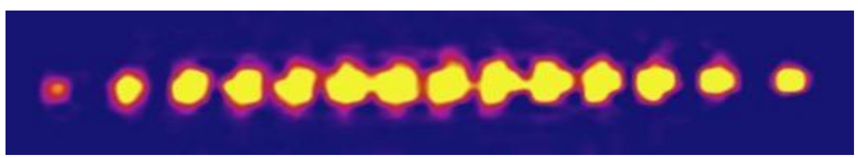
Using lasers to control atoms one by one: five Berrylium ions in the lab of David Wineland (2000)…

Each atom is a 2 level quantum bit (qubit)…

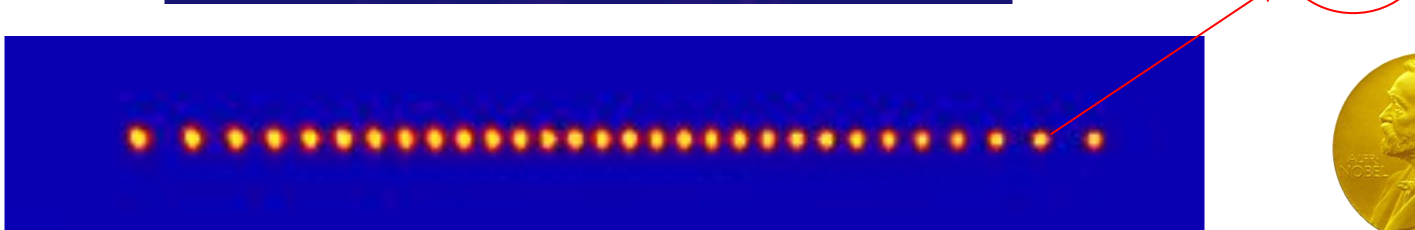


…which evolves as a superposition of 0 and 1 states

… and 14 and 30 Calcium ions in the lab of R. Blatt in Innsbruck (2012-2013)



2^{30} ~ 1 billion states!



2012

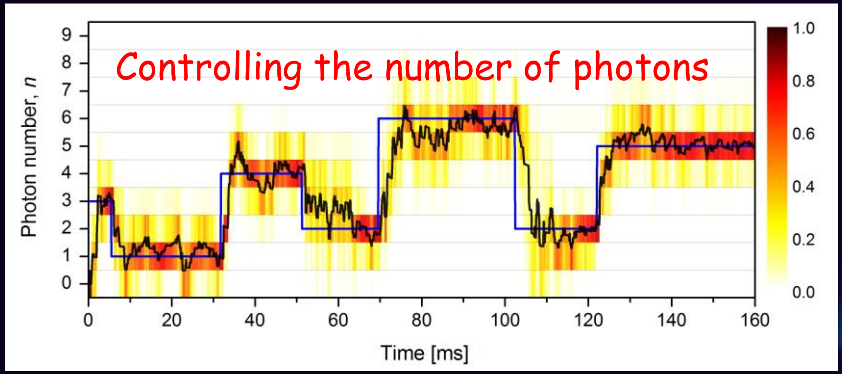
An atomic abacus for quantum information

Cavity Quantum Electrodynamics:

Laser-prepared Rydberg atoms allow us to study the interaction between light and matter at the most fundamental level

ENS-Collège de France, Paris

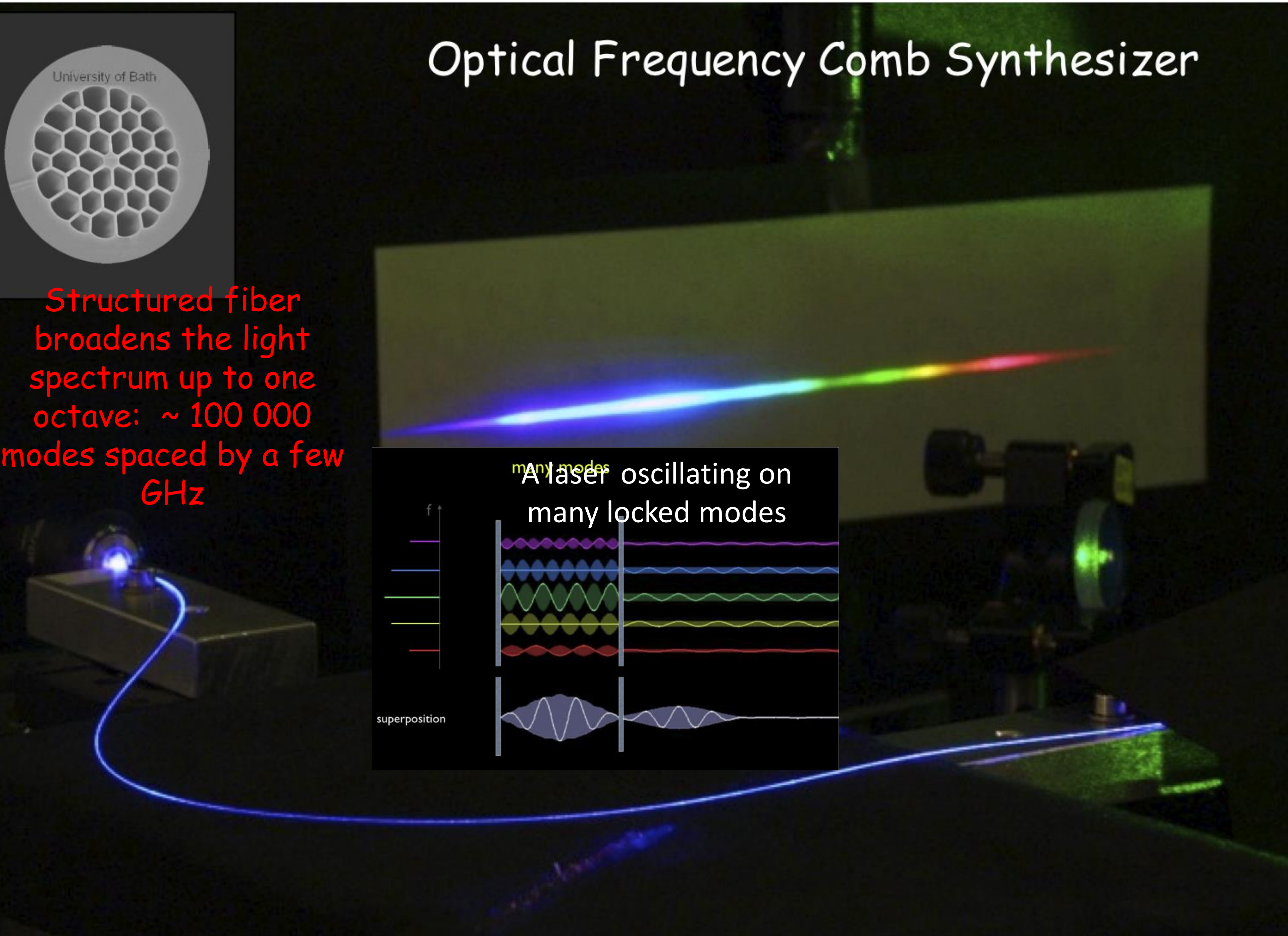
One atom interacts with one (or a few) photon(s) in a box



A sequence of atoms crosses the cavity, couples with its field and carries away information about the trapped light without absorbing the photons

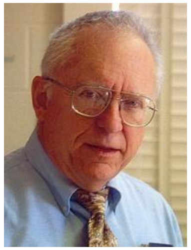
Photons are trapped for more than a tenth of a second!

2012

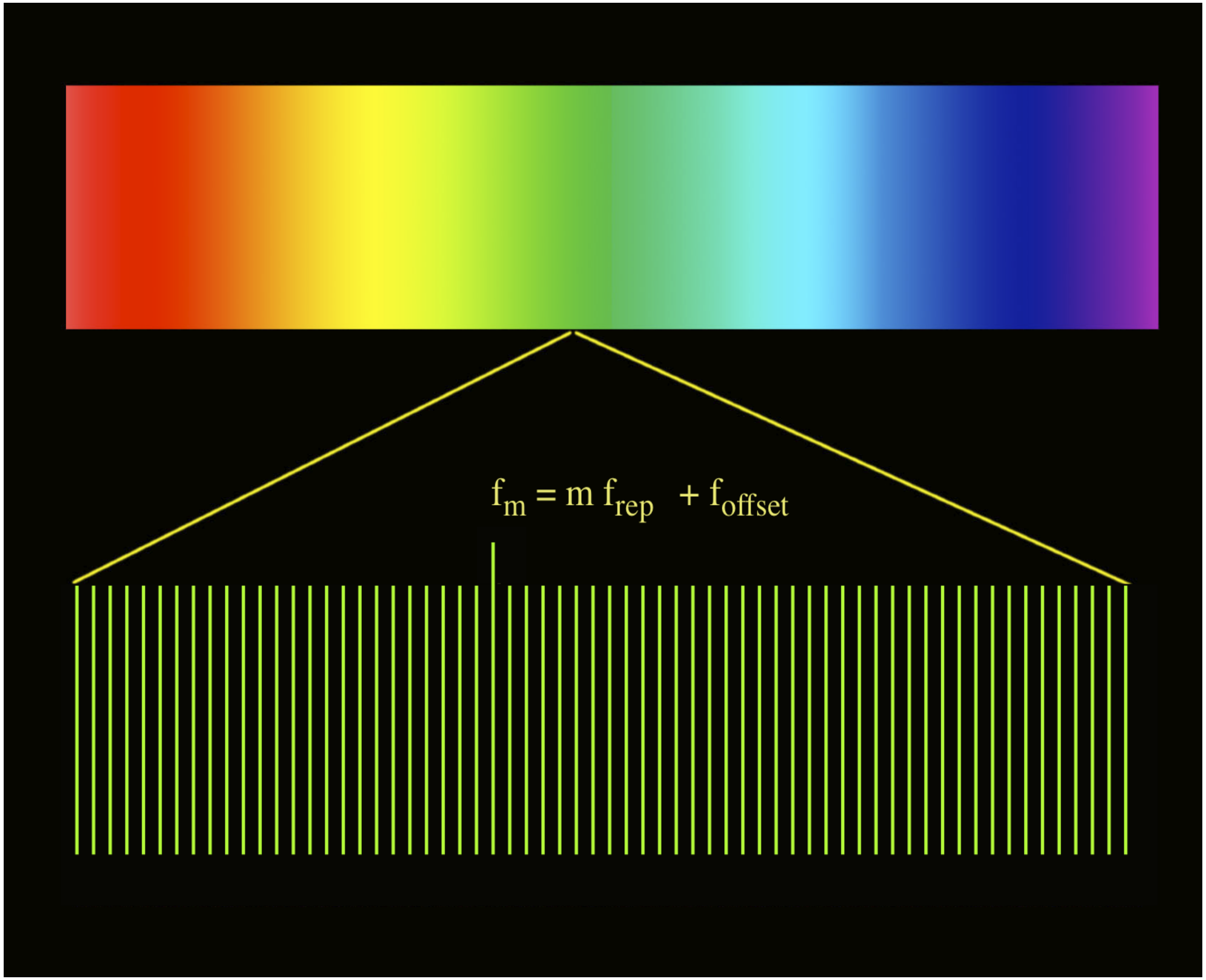

Optical Frequency Comb Synthesizer
University of Bath
Structured fiber broadens the light spectrum up to one octave: ~ 100 000 modes spaced by a few GHz
many modes
A laser oscillating on many locked modes
f
superposition

An ideal escape mecanism for an optical clock: the frequency comb

T.Hänsch

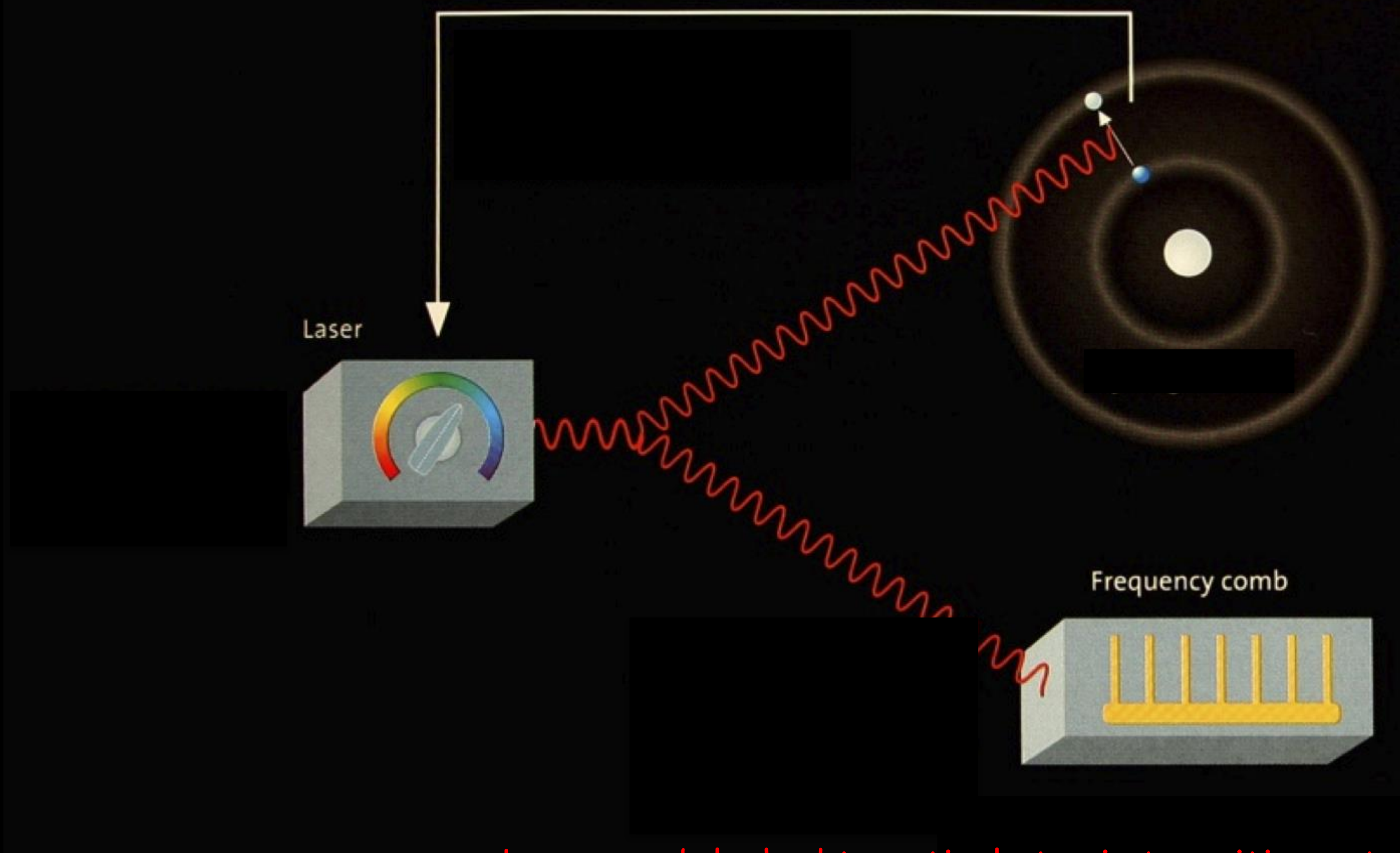


J.Hall



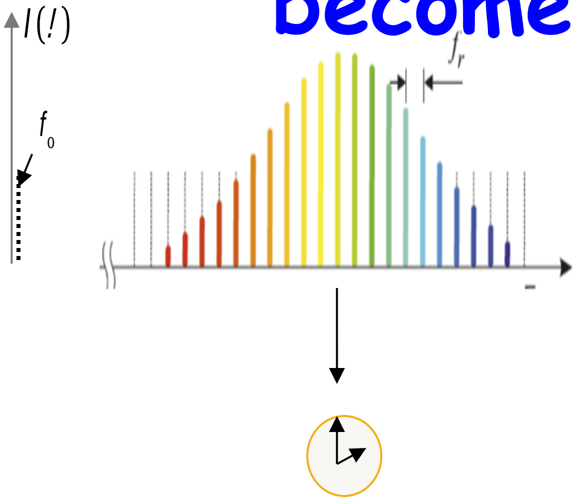
A "ruler" spanning an octave in frequency

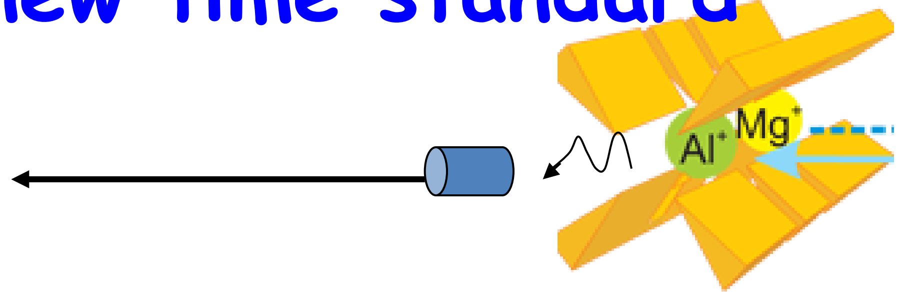
measuring the frequency of an atom with a laser comb



Laser comb locked to optical atomic transition acts as an extremely precise clock escape mecanism

Two kinds of optical clocks competing to become new time standard



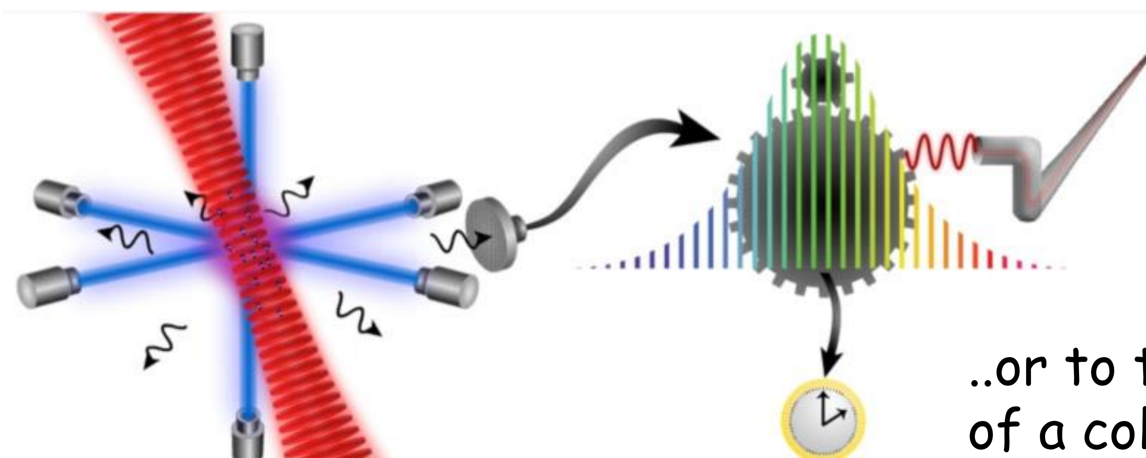


Locking a frequency comb to the optical transition of a single Hg or Al ion in a trap...(NIST...)

Uncertainty

$10^{-17} - 10^{-18}$

~1 s in age of Universe

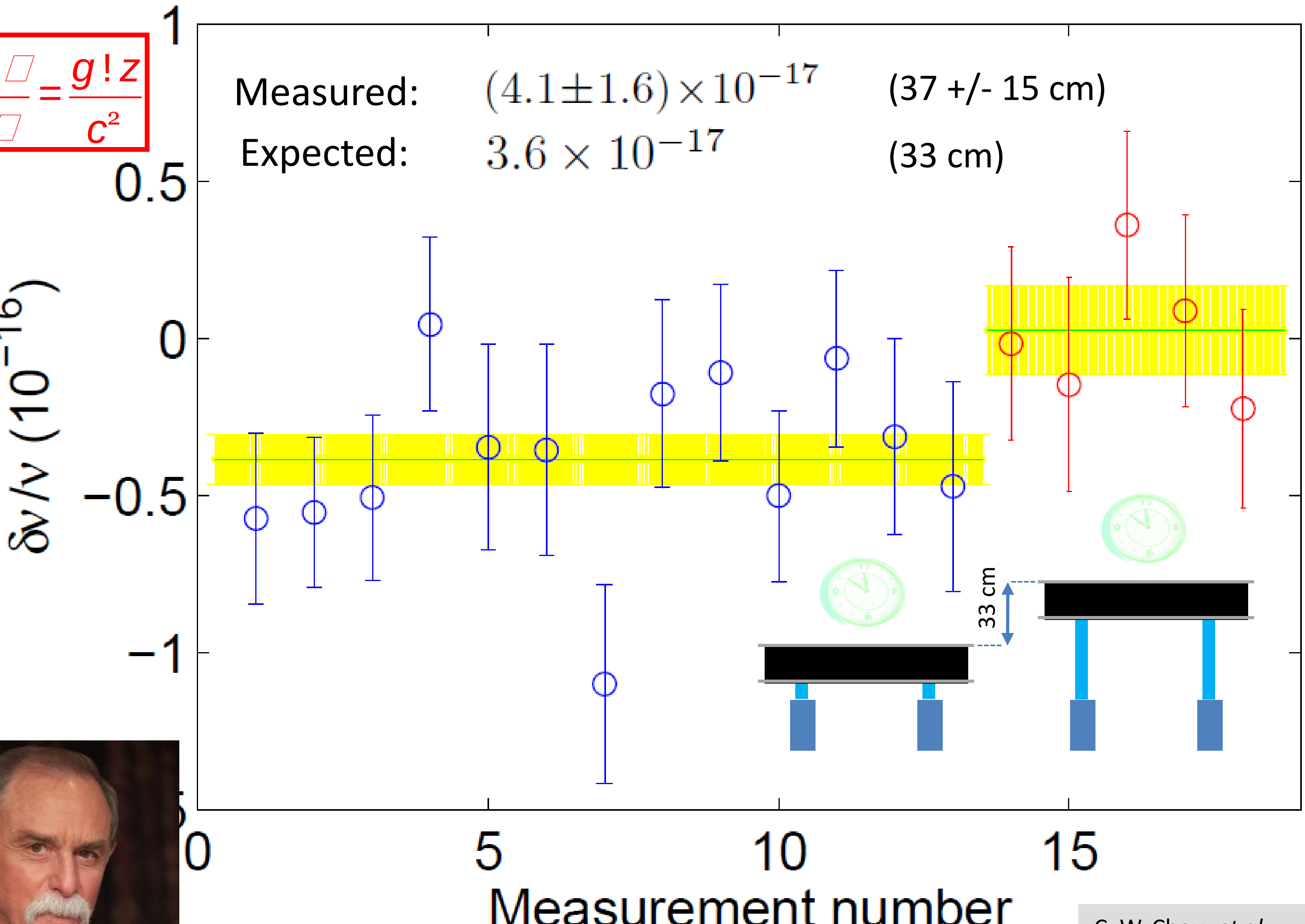


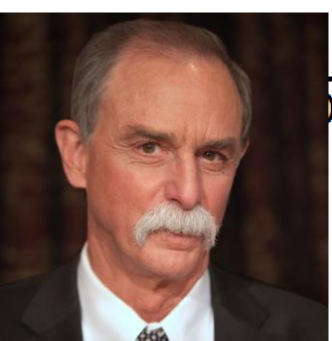
..or to the optical transition of a collection of Sr or Yb neutral atoms at rest in an optical lattice...(NIST, PTB, SYRTE..)

Hänsch, Hall

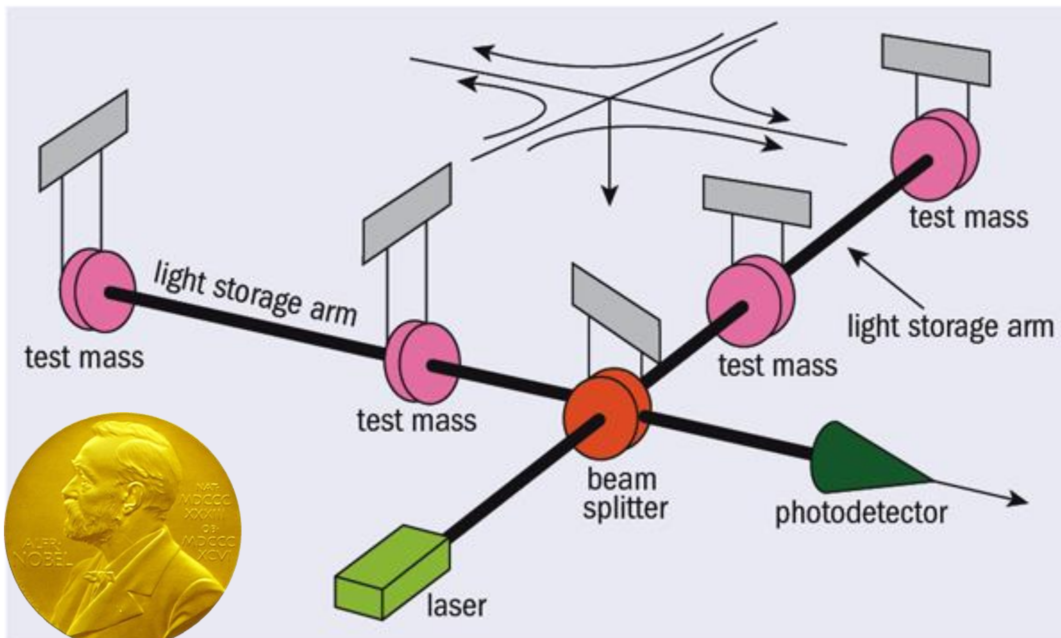
A general relativity test: frequency difference between 2 Al^+ clocks 33 cm apart in altitude!

$$\frac{!\square}{\square} = \frac{g\,!\,z}{c^2}$$

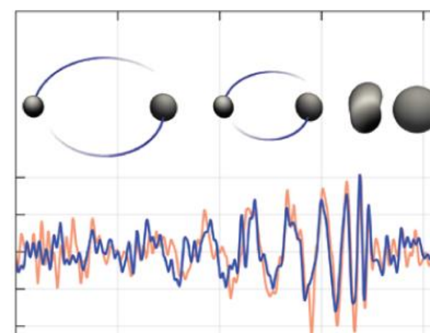




C. W. Chou, *et al.*
Science **329**, 1630 (2010)



Michelson interferometers in which ultrastable laser light is circulating, measuring the variation of length between the two 3 km long arms with the sensitivity of one billionth of an atomic size!



Another use of ultra-stable lasers:
the LIGO/VIRGO gravitational wave antennas (2017 Nobel Prize in Physics)

Detect black holes and neutron star mergers: opens new window to the Universe

The connection between blue sky research and innovation in physics

Observation of Nature

Theoretical Models

Prediction of new effects

Novel technologies

Tools which have revolutionized various fields (physics, chemistry, biology, medecine....)

More precise observations confirming (or falsifying?) the theory.

A virtuous loop!

It is hard to make predictions, especially about the future (Niels Bohr)...

Think about the 1900 postcards predicting XXth century technologies....

What will the « second quantum technology » of the XXIst century be: quantum computers, quantum communication networks, quantum meters, even more precise quantum clocks... or something else quite different and unexpected?

... we can only guess, but we know one thing for sure: without basic research, novel technologies cannot be invented...

...and the past teaches us that wonderful applications often emerge serendipitously from blue sky research...

Novel technologies….

…often come serendipitously from blue sky research…

..which needs two priceless ingredients:

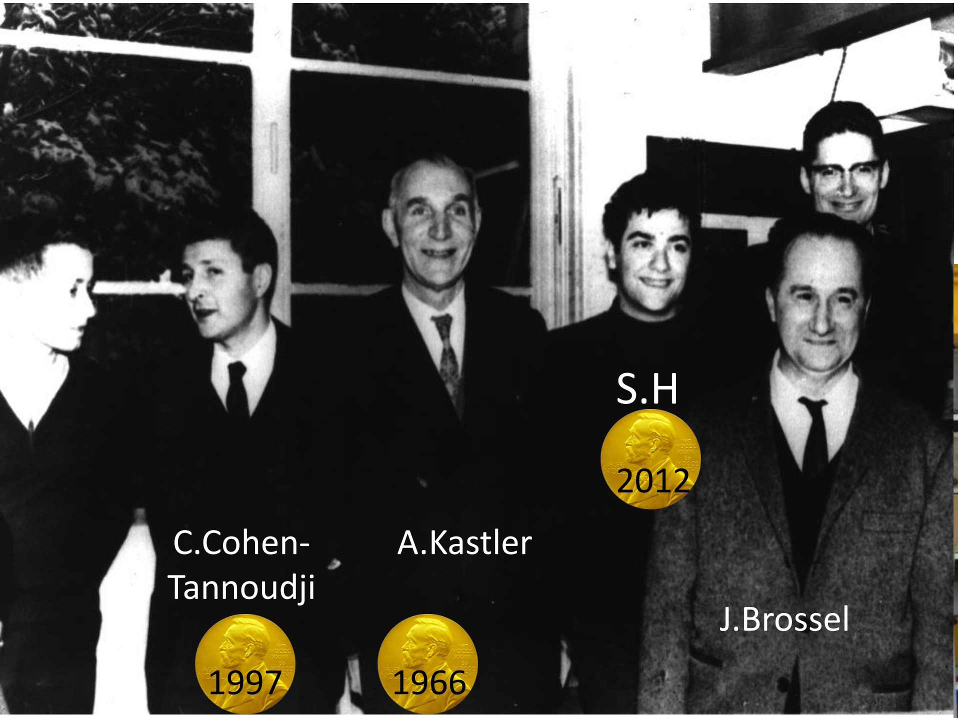
Time & Trust

A few institutions in the world defends these values…

… which, unfortunately, are not always understood by politicians and not really supported by the laws of the global market emphasizing speed and fast marketable results!

To conclude on a positive note:

As illustrated by the Rabi school, it helps to do research in the right environment with outstanding masters, colleagues and students !



A room in the Kastler Brossel lab in 1966
(day of Kastler Nobel Prize announcement)

My own experience

…and the same room in 2012
for another Nobel
announcement