Reflections on blue sky research

Serge Haroche,
Collège de France, Paris

2015 is the International Year of Light

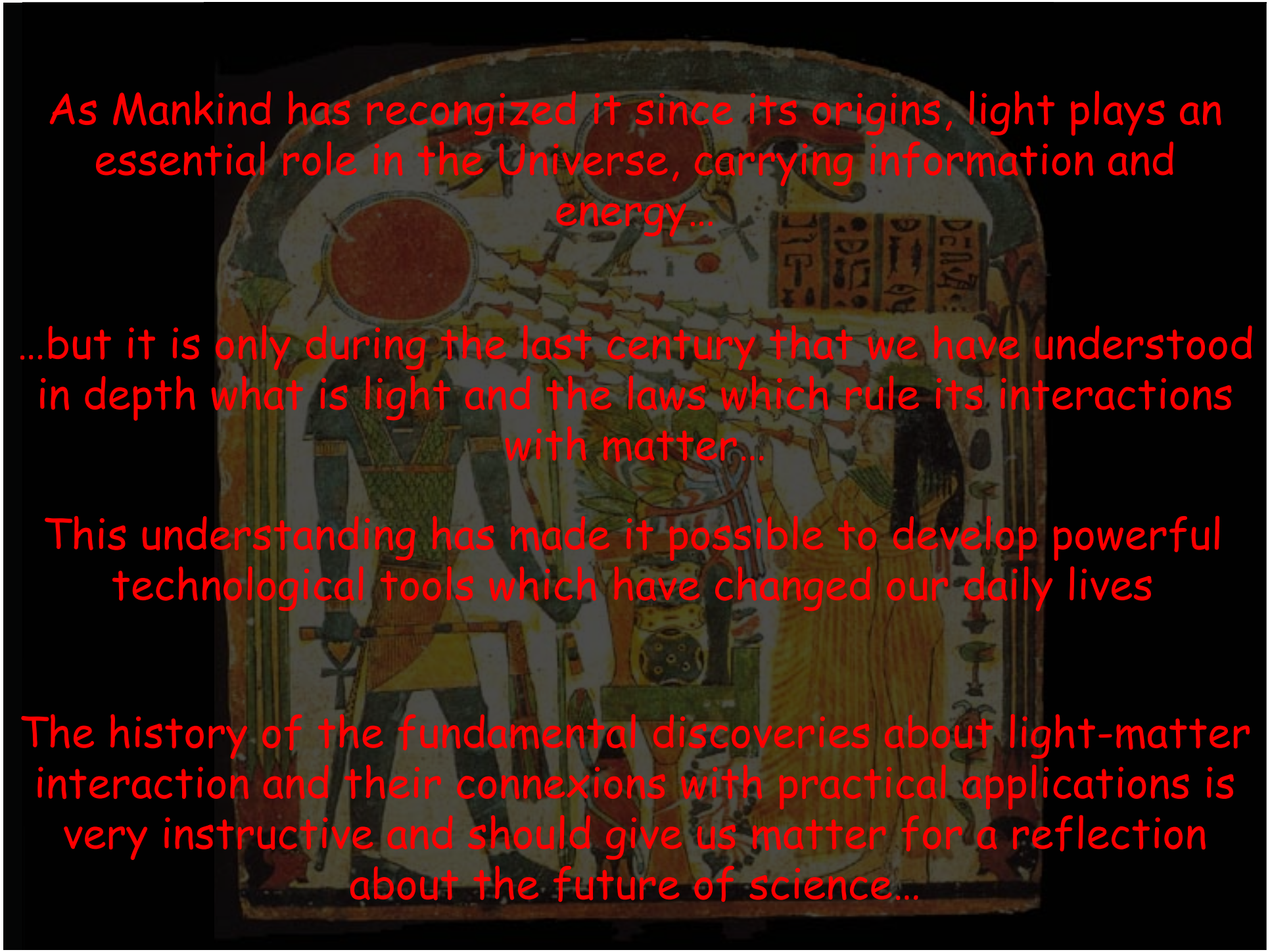
To review the history of the concept of light through the centuries provides an ideal opportunity to reflect about blue sky research and its connexions with innovations

Understanding light under its different forms and controlling it has led to fundamental discoveries in physics and to very powerful technologies which have revolutionized our lives

Almost all information we get from the world around us comes from light …

… it also carries the energy which makes life possible on Earth

« What is Light? » is a question which has fascinated Mankind since ancient times



As Mankind has recongized it since its origins, light plays an essential role in the Universe, carrying information and energy…

…but it is only during the last century that we have understood in depth what is light and the laws which rule its interactions with matter…

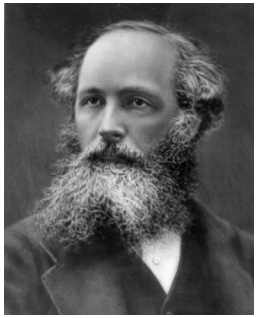
This understanding has made it possible to develop powerful technological tools which have changed our daily lives

The history of the fundamental discoveries about light-matter interaction and their connexions with practical applications is very instructive and should give us matter for a reflection about the future of science…

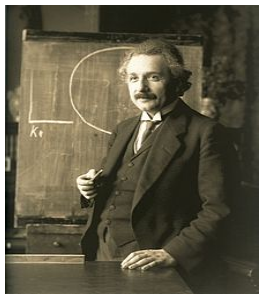
Why celebrating light this year?

1000 years ago, in 1015: Alhazen and the first theory of Optics

200 years ago, in 1815: Fresnel and the wave theory of light: "light is a transversal wave"



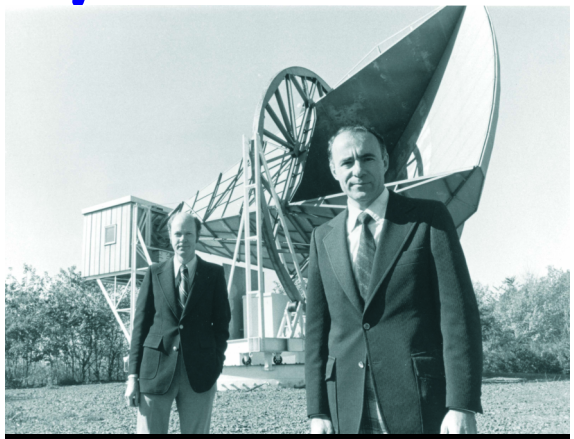
150 years ago, in 1865: Maxwell and the electromagnetic theory

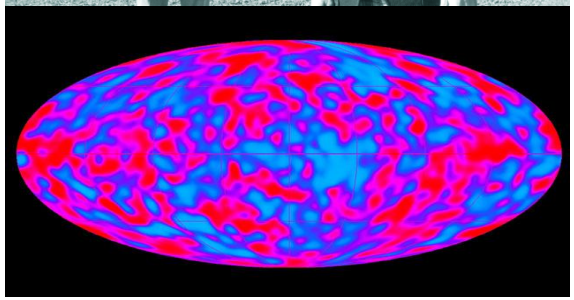


100 years ago, in 1915: General Relativity, the ultimate achievement of Einstein's reflections about light

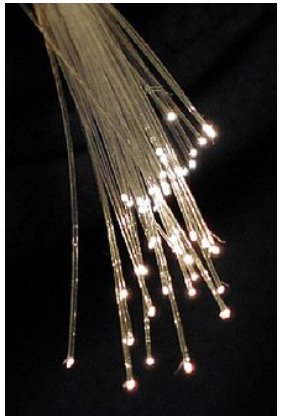
50 years ago:

1965: Penzias and Wilson discover the cosmological radiation background

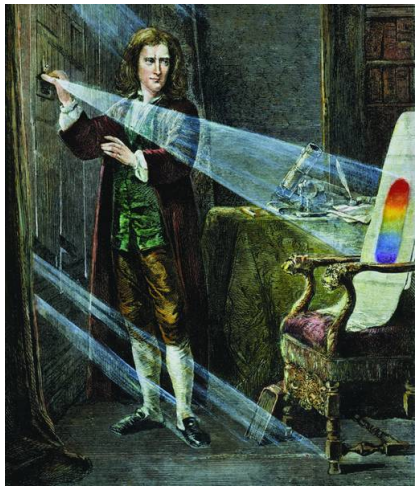




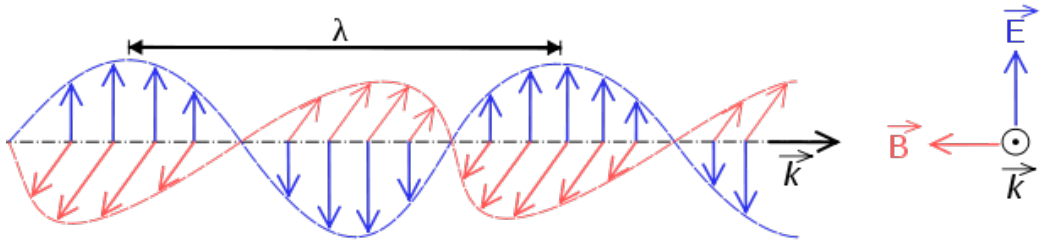
1965: First laser technologies. C.Kao introduces optical fibers for telecoms



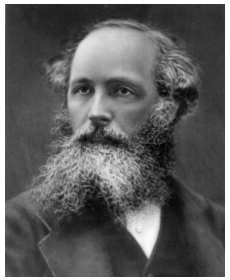
Light is a wave, but a wave of what?



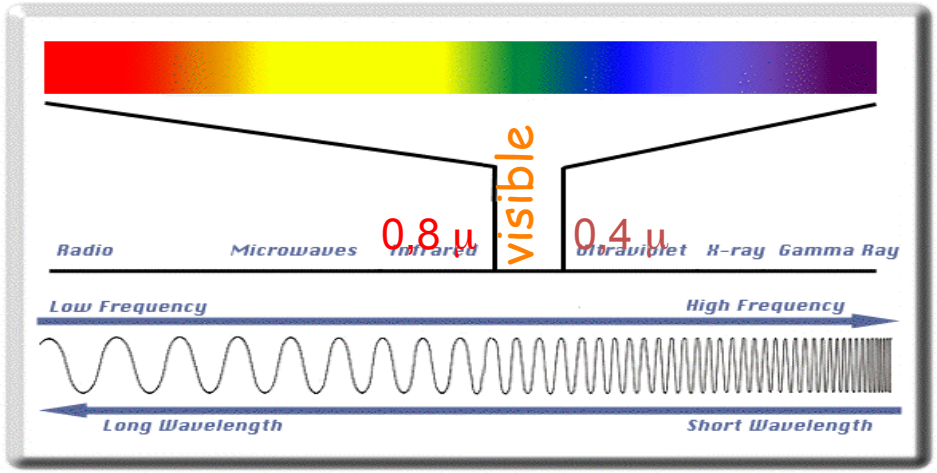
Newton and the spectral decomposition of light



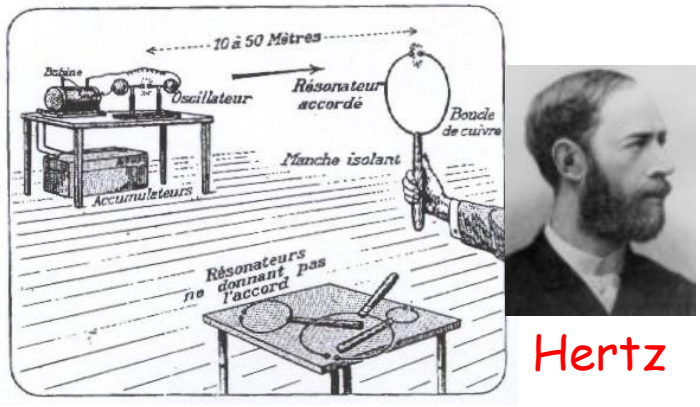
Electromagnetic wave extending beyond the visible



Maxwell (1865)



Radiowaves (1885)



Hertz

The light, visible or invisible, is an essential source of scientific information

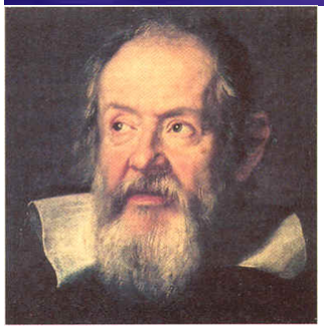
X Rays (1895)

Roentgen

Maxwell tells us that light flies at c= 300.000 km/s…
…but in which reference frame?

Can we catch up with light?

What would it be like if we could?



A hint had been given by Galileo: the laws of mechanics are the same in all frames in uniform translation with respect to each other: this is the relativity of motion.

1905

Einstein genial intuition: this invariance must also apply to electromagnetism (and to all laws of physics)

Hence, there is no preferred frame for light and c must be the same for all observers, whatever their velocity with respect to each other: one cannot catch up with light!

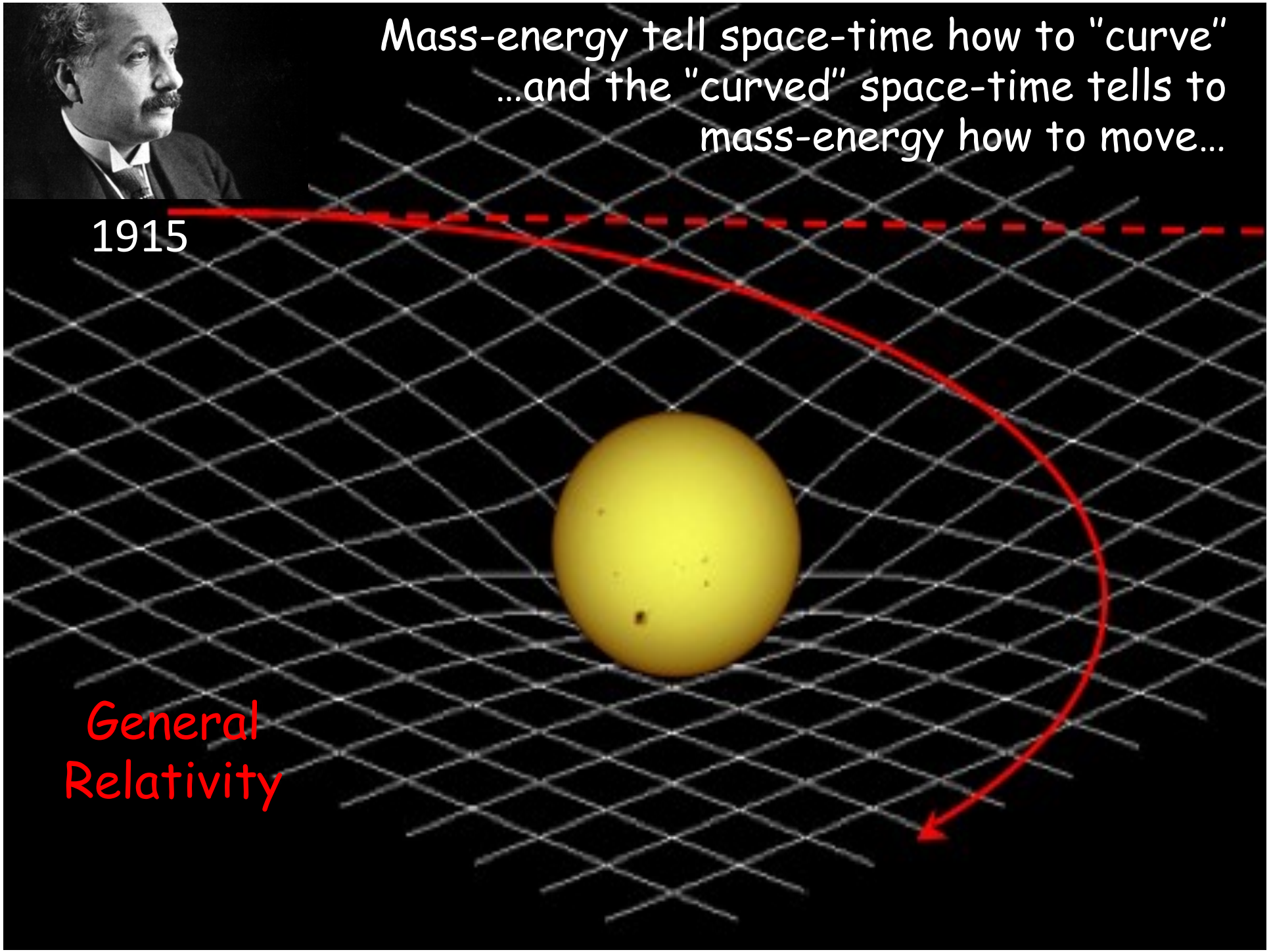
But then, time (like space) cannot be described with the same "coordinate" in two frames with relative velocity: relativity of space-time and special relativity theory!

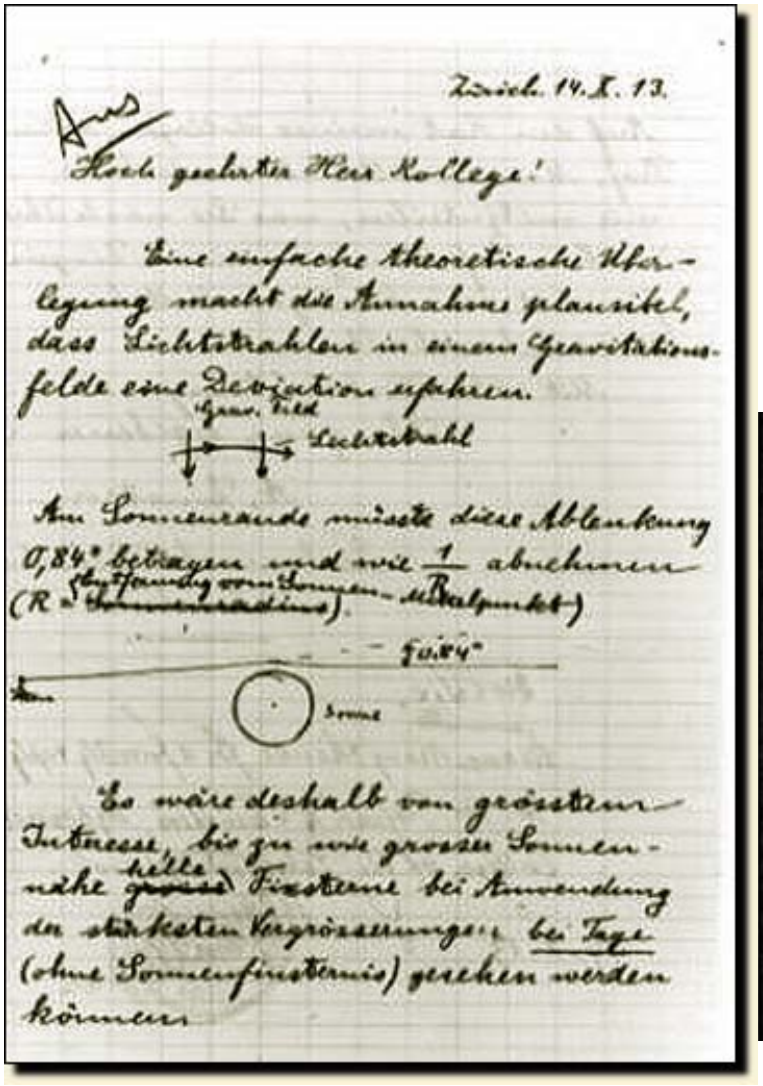
Which led Einstein to the most well-known equation in Science:

$E = mc^2$

Space and time are intimately linked…

…as well as mass and energy


Mass-energy tell space-time how to "curve"
…and the "curved" space-time tells to
mass-energy how to move…
1915
General
Relativity



Zürich, 14. X. 13.

Hochgeehrter Herr Kollege!

Eine einfache theoretische Überlegung macht die Annahme plausibel, dass Lichtstrahlen in einem Gravitationsfelde eine Deviation erfahren.

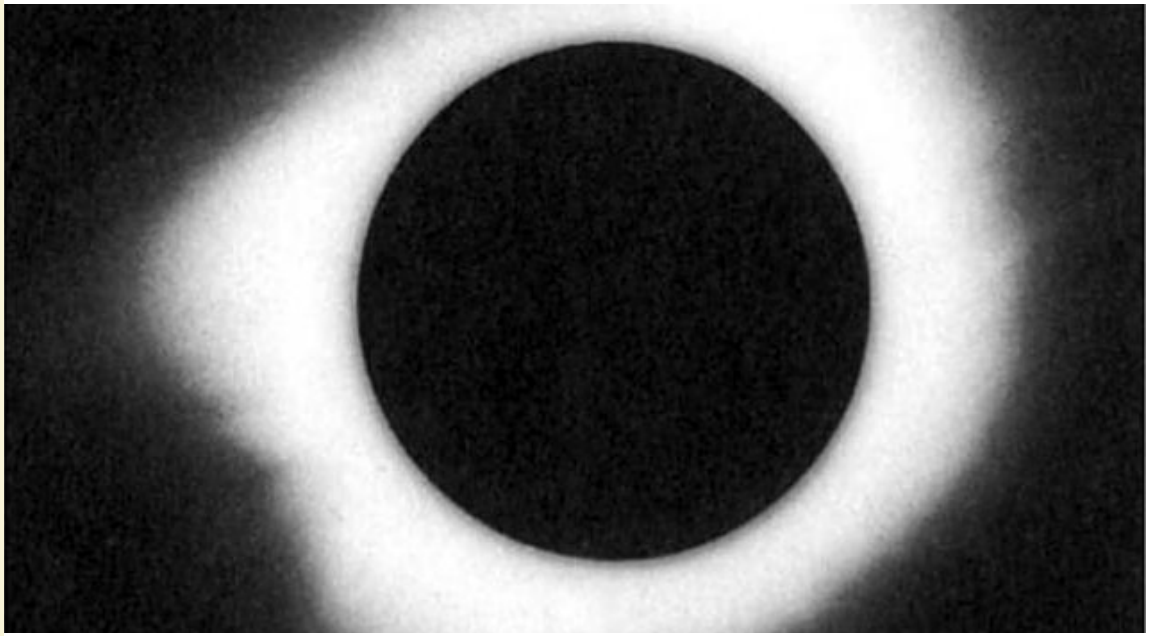
Grav. Feld — Lichtstrahl

Am Sonnenrande müsste diese Ablenkung 0,84" betragen und wie $\frac{1}{\text{Entfernung vom Sonnen-Mittelpunkt}}$ abnehmen (R = Sonnenradius).

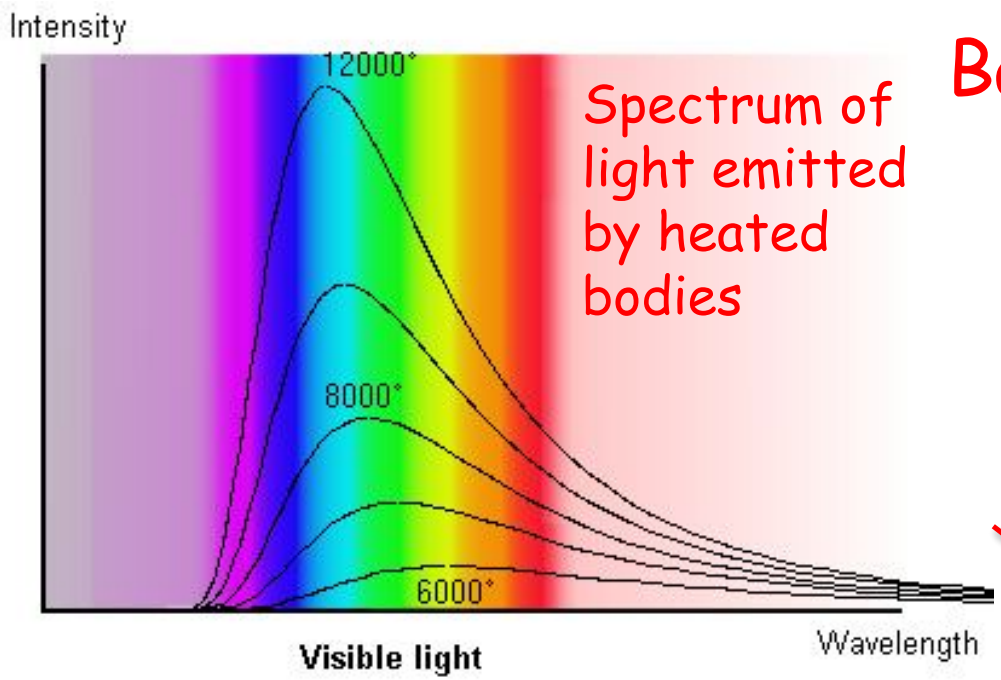
0,84" — Sonne

Es wäre deshalb von grösstem Interesse, bis zu wie grosser Sonnennähe helle Fixsterne bei Anwendung der stärksten Vergrösserungen bei Tage (ohne Sonnenfinsternis) gesehen werden können.

Einstein's letter describing the deflection of light rays grazing the sun



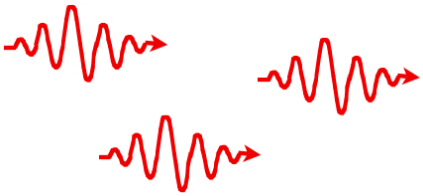
The 1919 eclipse during which the effect was observed



Spectrum of light emitted by heated bodies

Back to 1905….

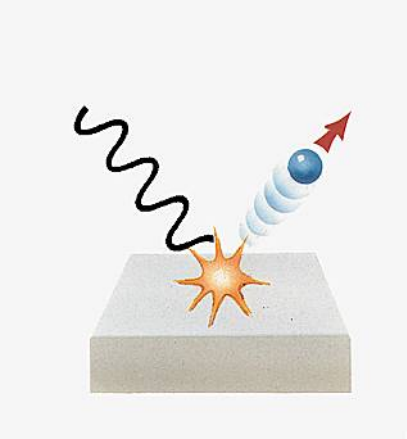
Birth of quantum physics



The photon

$$E = h\nu$$

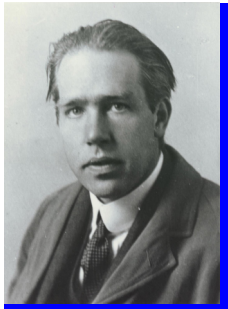
$$p = \frac{h\nu}{c} = \frac{h}{\lambda}$$



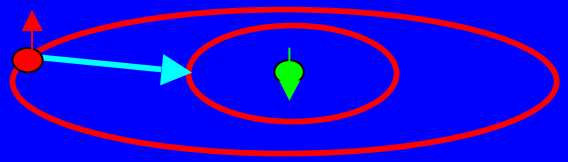
Photoelectric effect

h: Planck constant

The quantum atom…



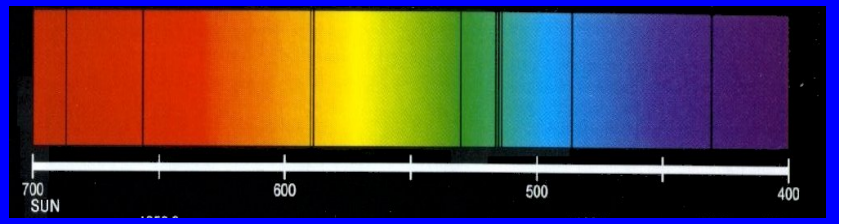
Bohr
(1913)



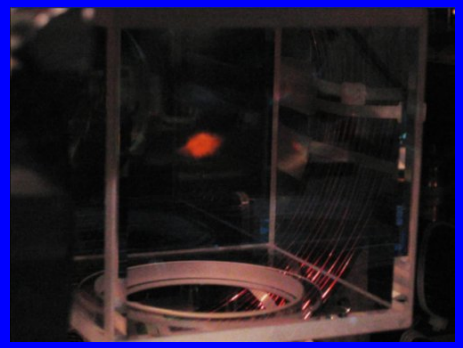
The electron jumps between quantized orbits by emitting or absorbing a photon of frequency ν such that

$$E_2 - E_1 = h\nu$$

…explains another mystery about light: the discreteness of the atomic spectra



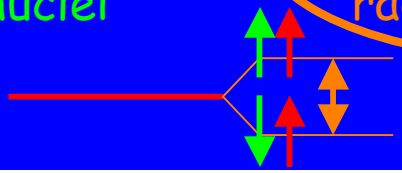
Resonant interaction with visible light….

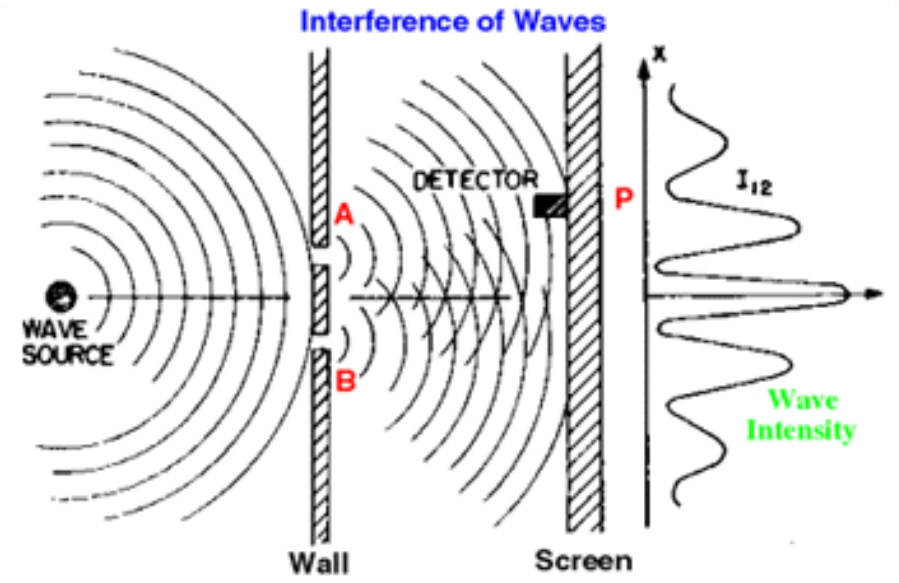


Laser cooling and trapping of atoms

Magnetism of electrons & nuclei

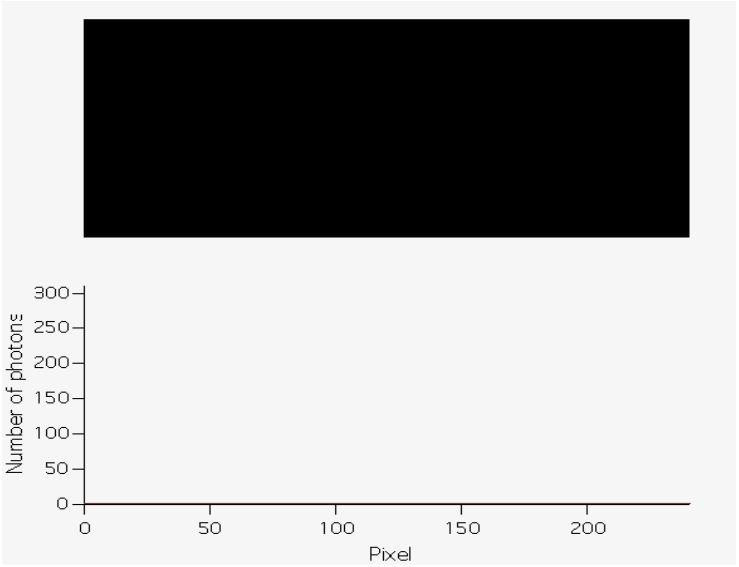
..and resonant interaction with radio-waves…





Wave-particle dualism and Young double slit experiment:
each photon goes through the two slits
("state superposition")

Randomness of each detection:
« God plays dice»
(Einstein)

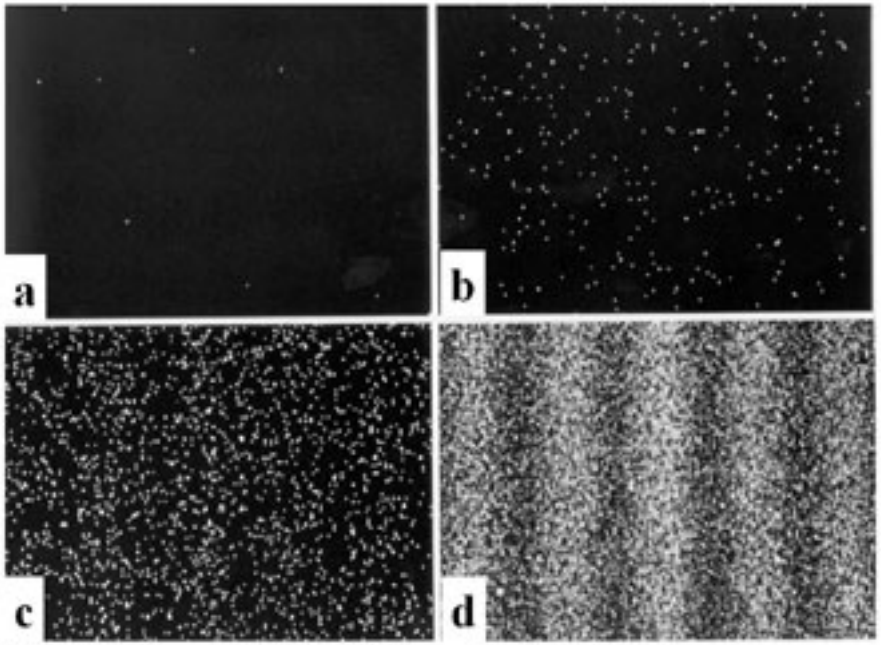


De Broglie

Wave-particle dualism for matter too:

$$p = mv = \frac{h}{\lambda} \quad \Rightarrow \lambda = \frac{h}{mv}$$

Particles (electrons, atoms, molecules…) also have a wave character



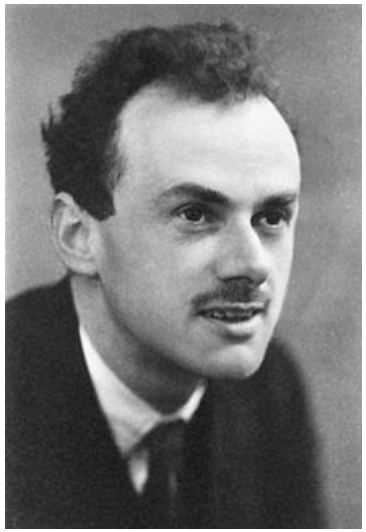
Single-electron Build-up of Interference Pattern

Schrödinger
(1926)

The wave equation

$$H\Psi = i\hbar \frac{\partial \Psi}{\partial t}$$

$\psi(r,t)$: *probability amplitude*

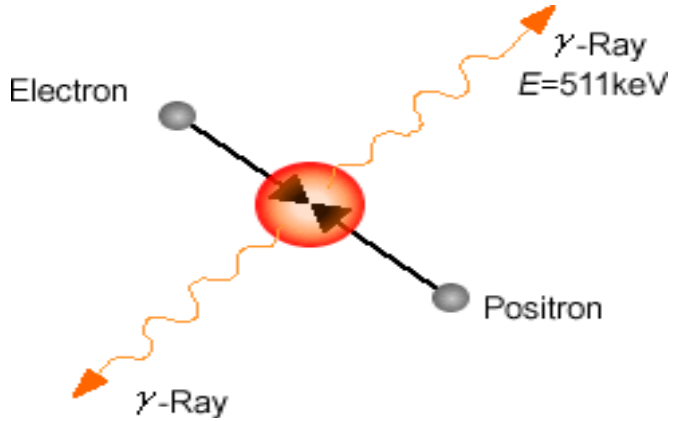


Paul Dirac
(1928)

Marrying quantum physics and relativity

$$i\hbar\gamma^{\mu}\partial_{\mu}\psi = mc\psi$$

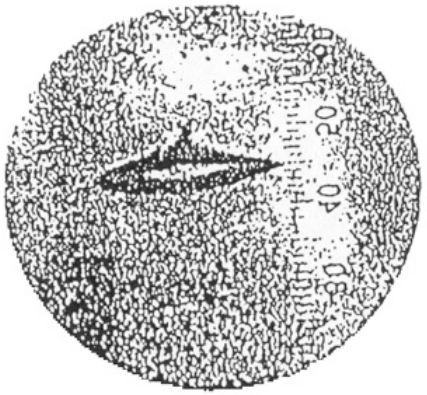
Predicts antimatter!



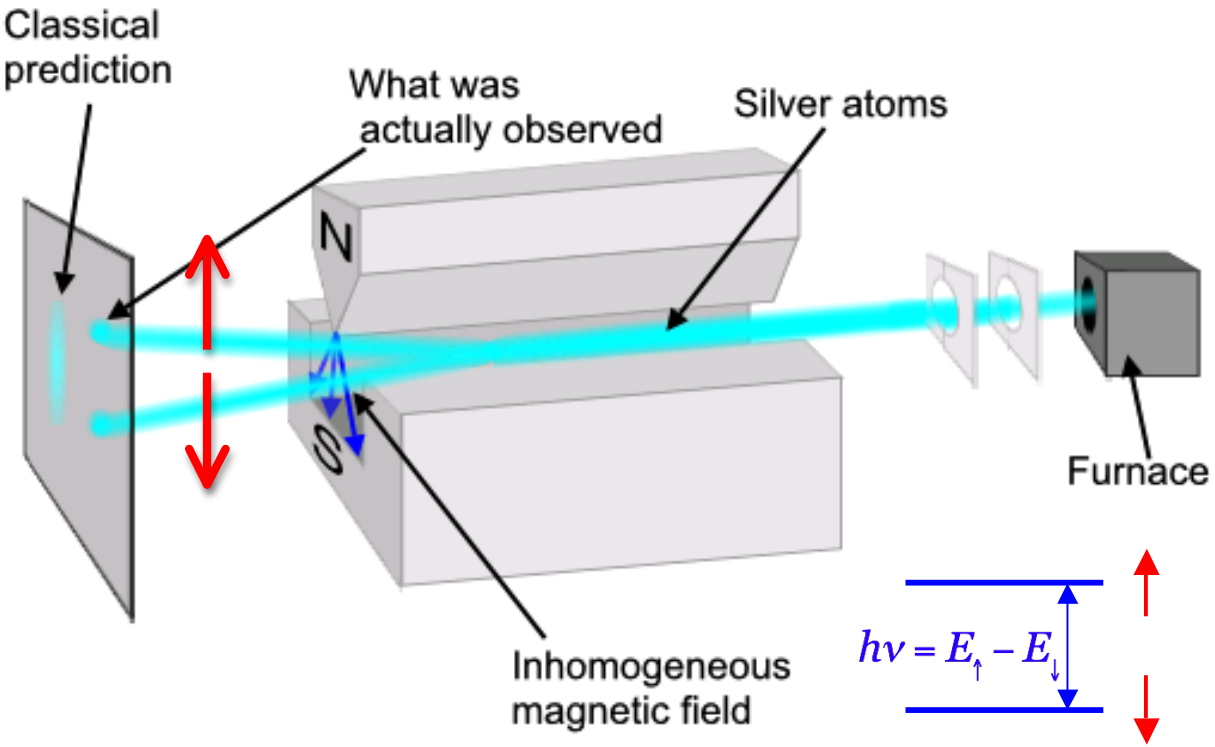

The path from blue sky research…
…to innovations
…is often unpredictible

O.Stern

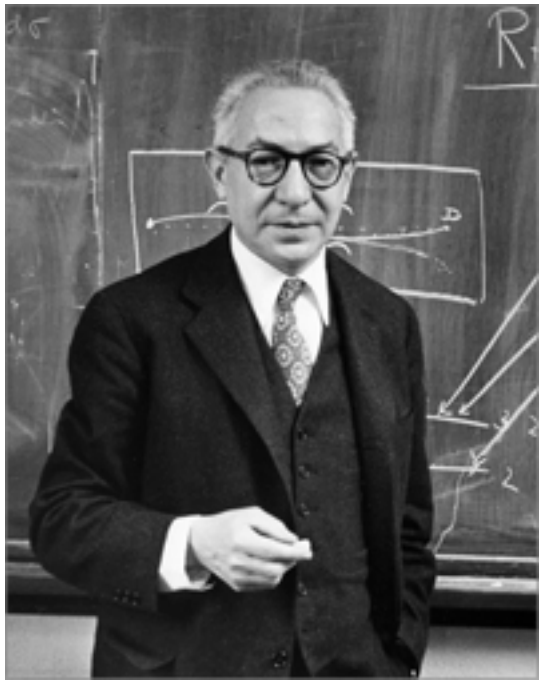
O.Stern discovers the electron magnetic moment (1922)



A simple split trace heralding revolutions in technology!



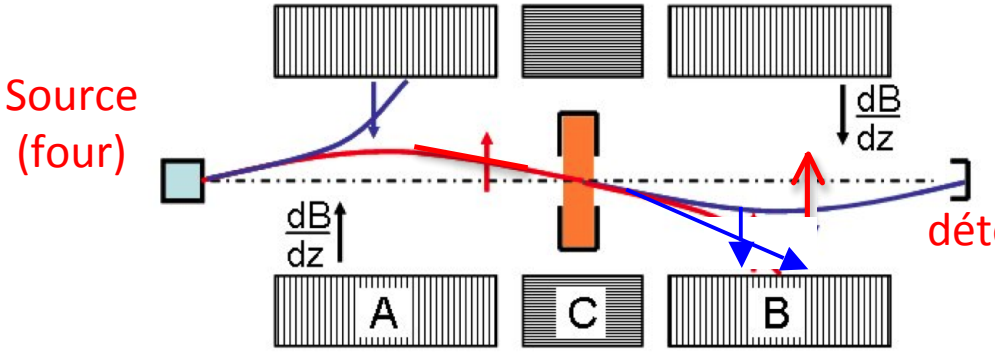
The set-up separates the spins pointing up and down:

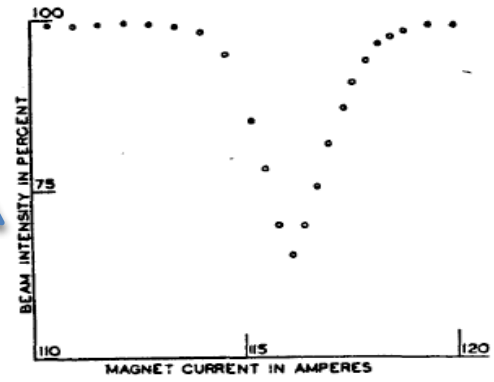


1898-1988

Isidor Rabi and the Molecular Beam method to measure nuclear magnetic moments at Columbia

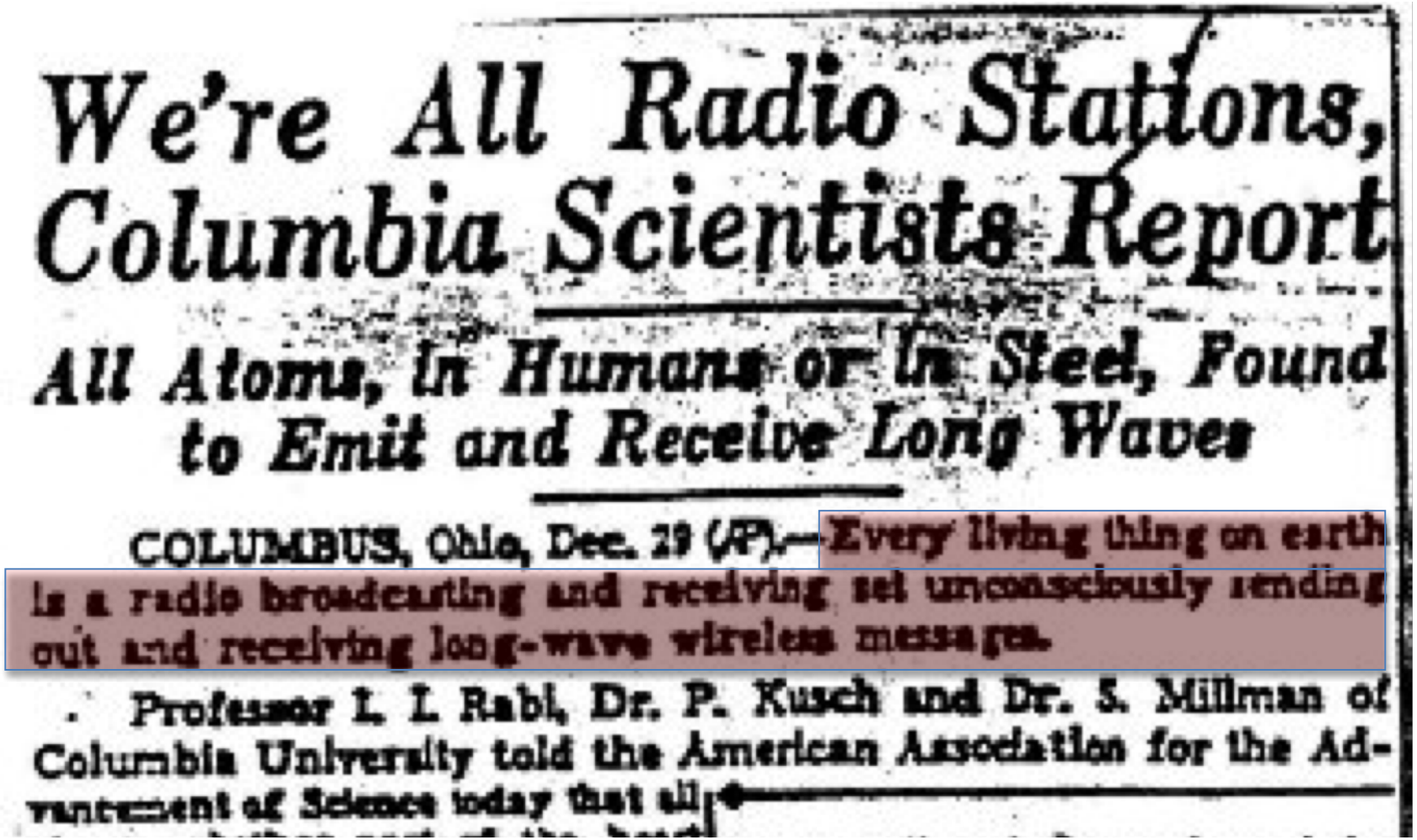
The resonant radio-wave flips the magnetic moment in C, changes the molecules trajectories and decreases the detected signal…





The discoveries of Rabi and his students opened the way to the MRI, the GPS and the laser….

A prescient headline



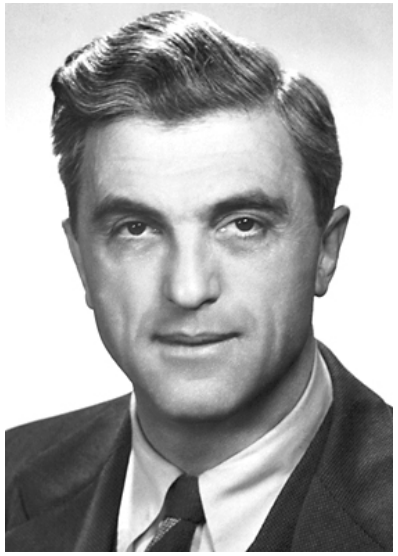
We're All Radio Stations, Columbia Scientists Report

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.

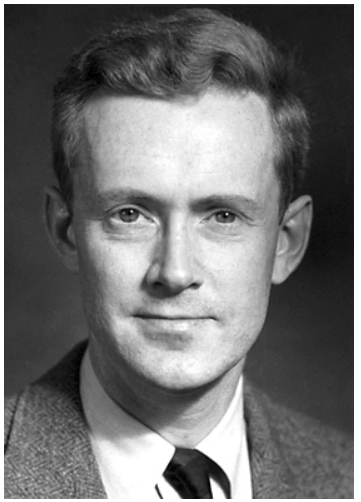
Professor I. I. Rabi, Dr. P. Kusch and Dr. S. Millman of Columbia University told the American Association for the Advancement of Science today that all

New York Post, December 1939

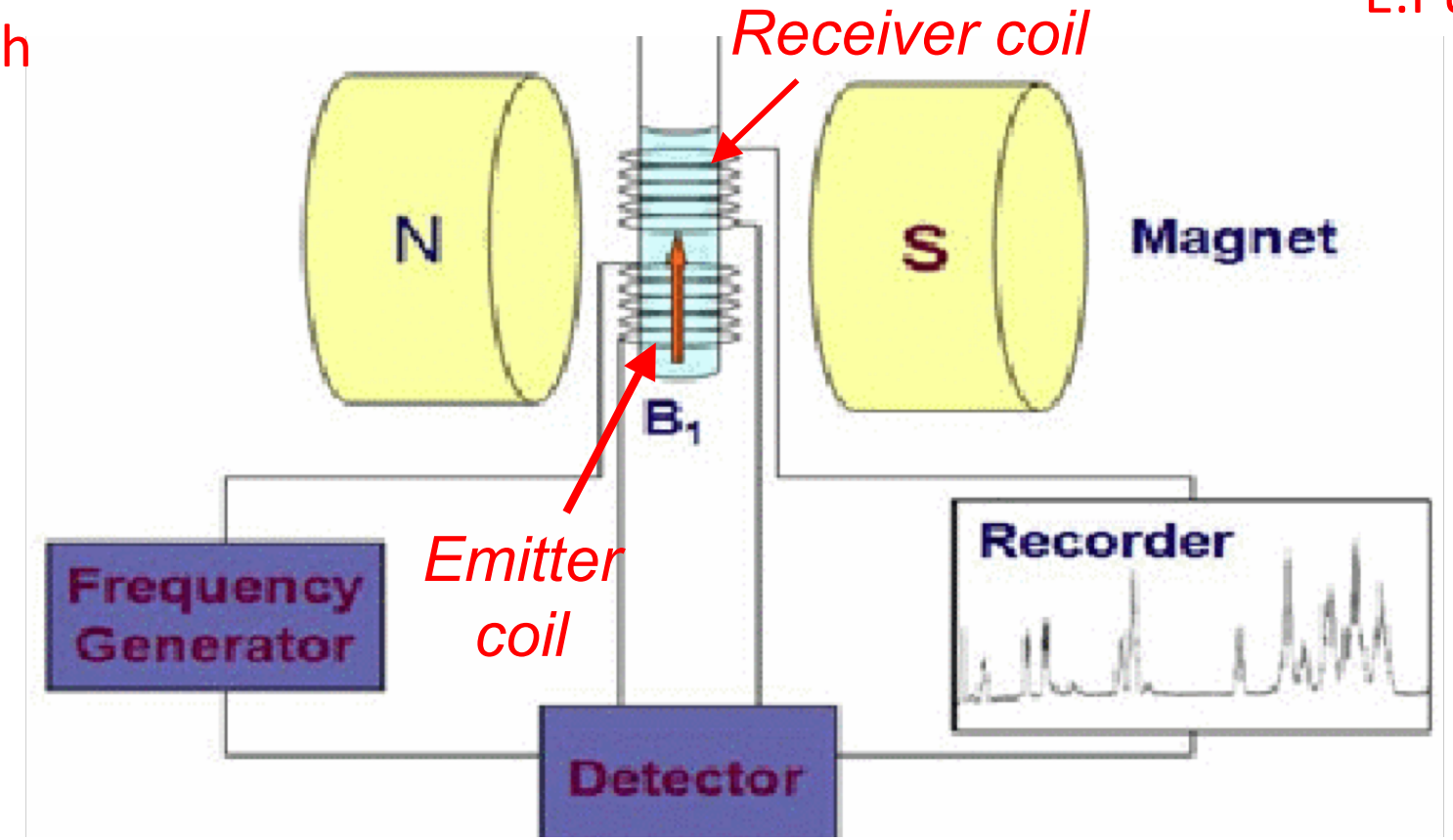


F.Bloch

The nuclear magnetic resonance (NMR) 1945

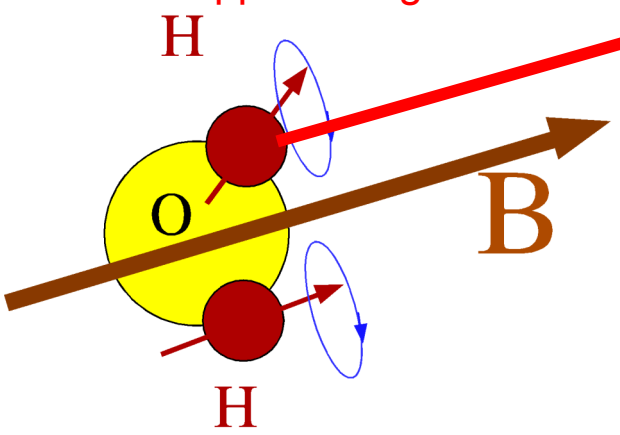


E.Purcell



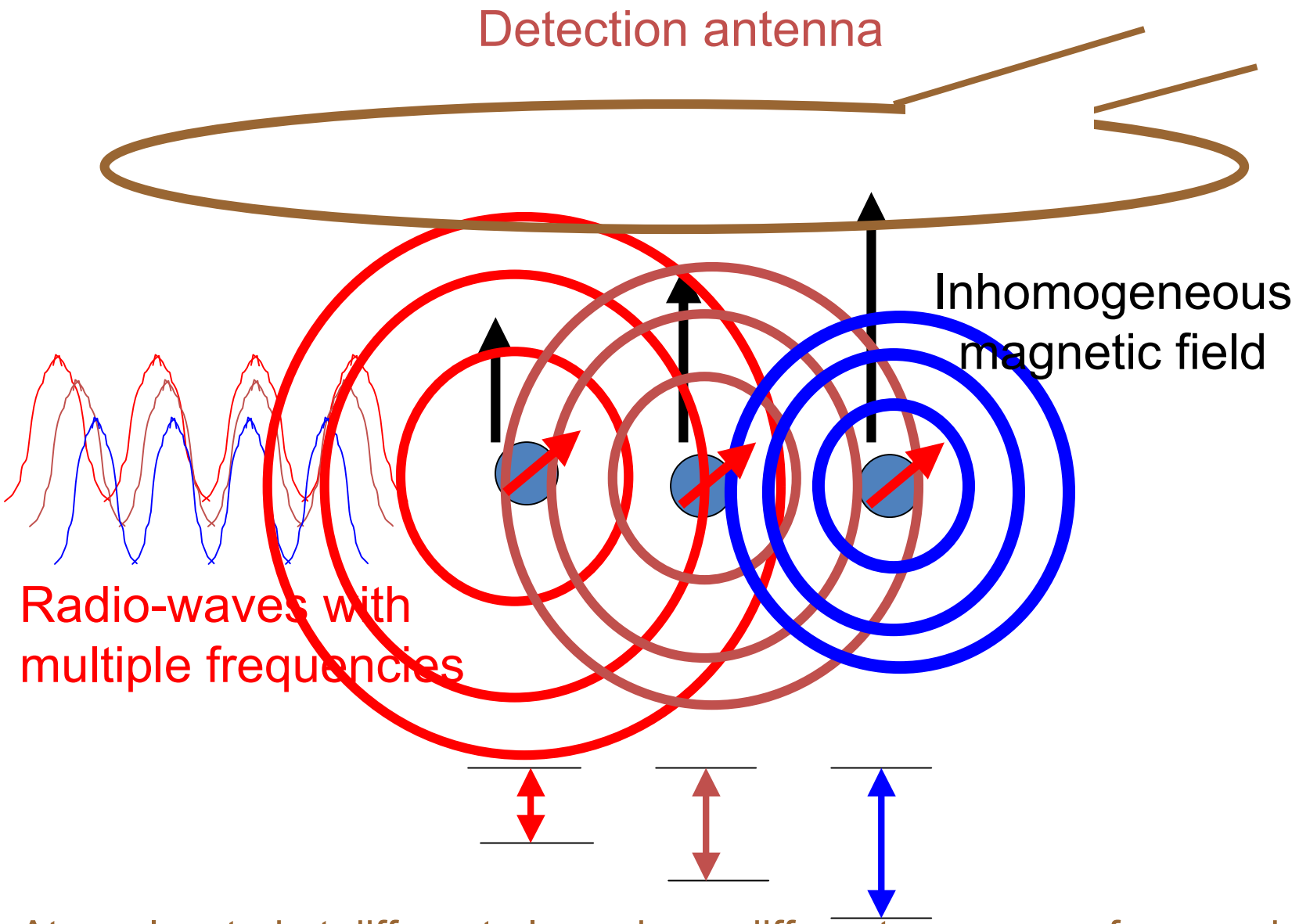
An unexpected application: The Magnetic Resonance Imaging (MRI)

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

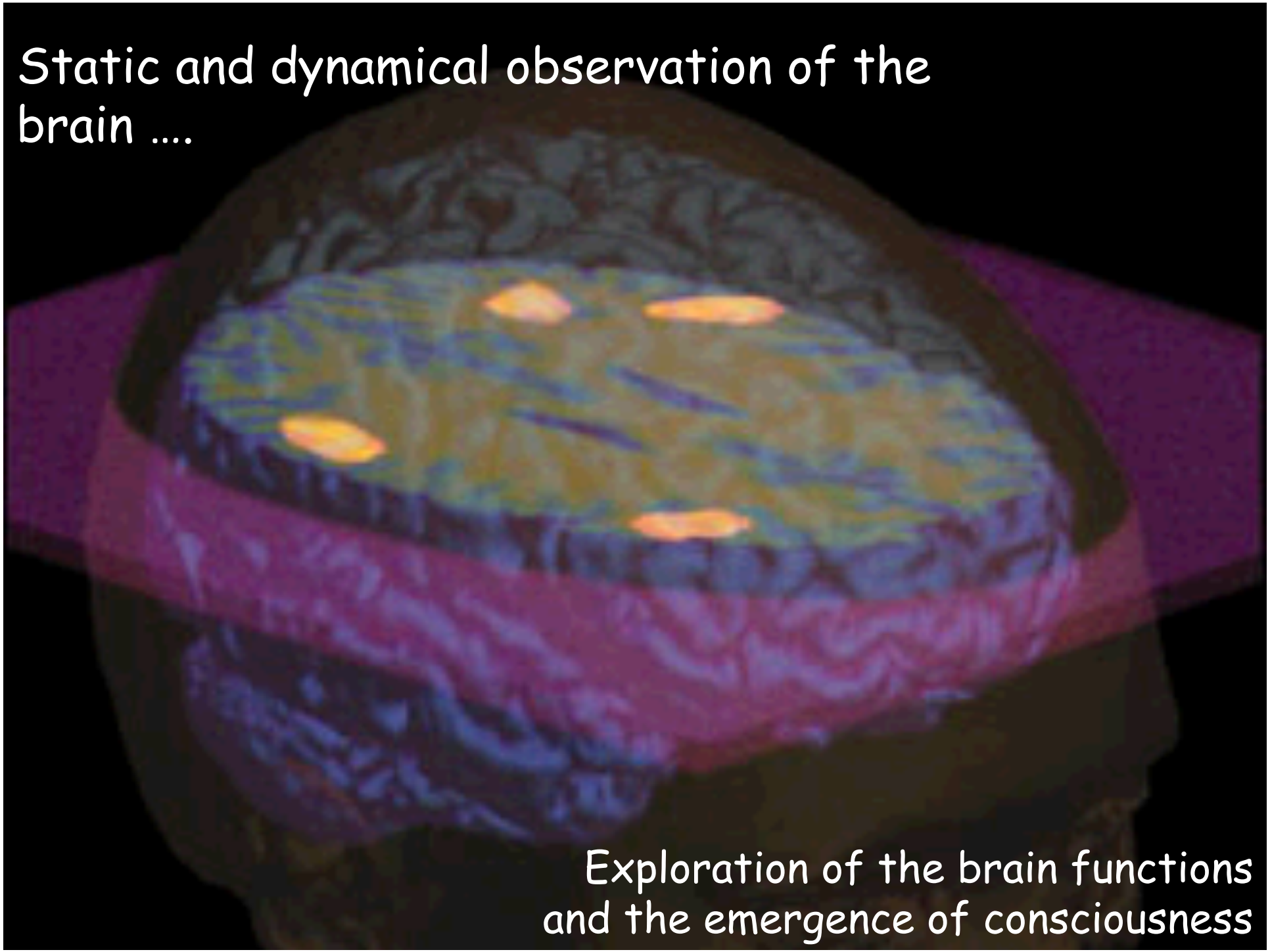


$$E_e - E_f = h\gamma B = h\nu_{rf}$$

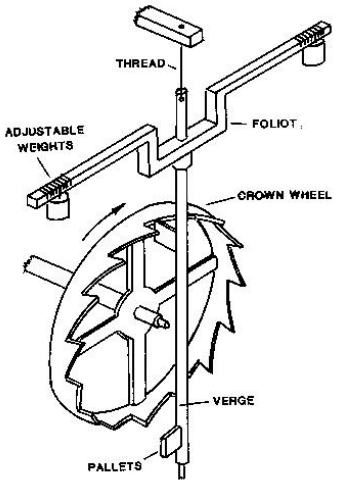
The scattering of radio-waves of variable frequencies in a spatially inhomogeneous magnetic field makes possible the 3D mapping of the body



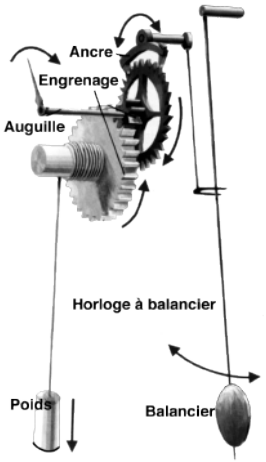
Atoms located at different places have different resonance frequencies and scatter towards the antenna rf fields at different wavelengths. The intensity of each scattered ‘’color’’ provides information about the atomic density at each point.


Static and dynamical observation of the brain ….
Exploration of the brain functions and the emergence of consciousness

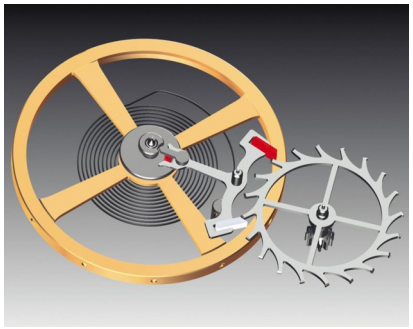
A brief history of the measurement of time



14th century:
tower clocks



17th century:
Pendulum clocks
(Galileo, Huyghens)



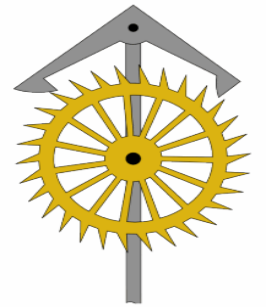
18th century

Spring clocks/marin chronometre
(Harrisson)

1920's

Quartz cocks
(piezo-electricity)

Uncertainty			
10^{-2}	10^{-4}	10^{-6}	10^{-8} ~1s/year



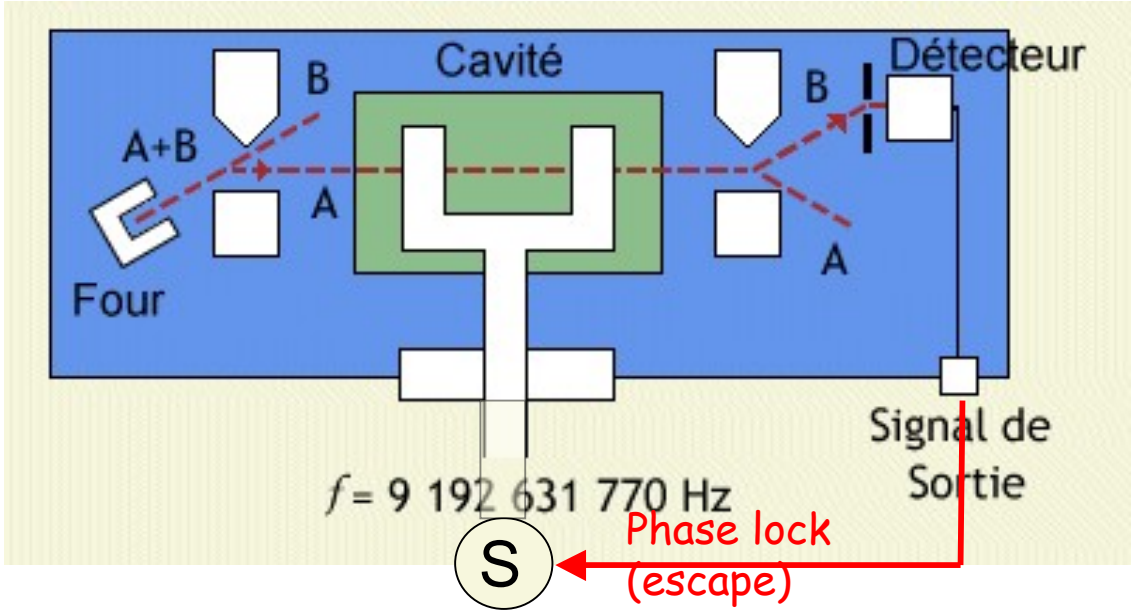
Principle: Oscillator coupled to an escape mecanism which counts periods (and provides energy)

Much less improvement in precision during the 6 centuries before the 1950's than since!

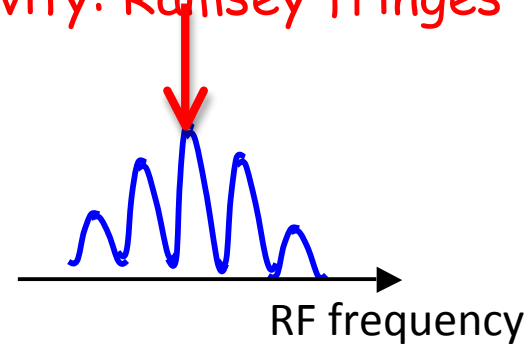
Atomic clocks (proposed by Rabi in 1944)

N.Ramsay

The oscillation of electrons in atoms is much faster and much more stable that that of a pendulum, a spring or a quartz crystal!

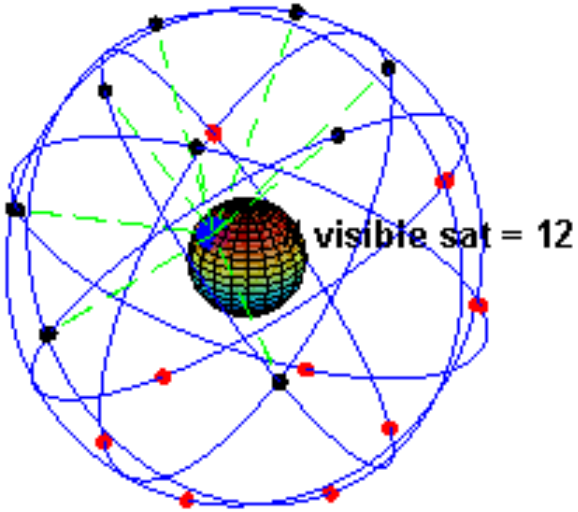


Cesium atomic beam with a double cavity: Ramsey fringes



10^{-14} uncertainty:
one second precision over a million years

The Global Positioning System

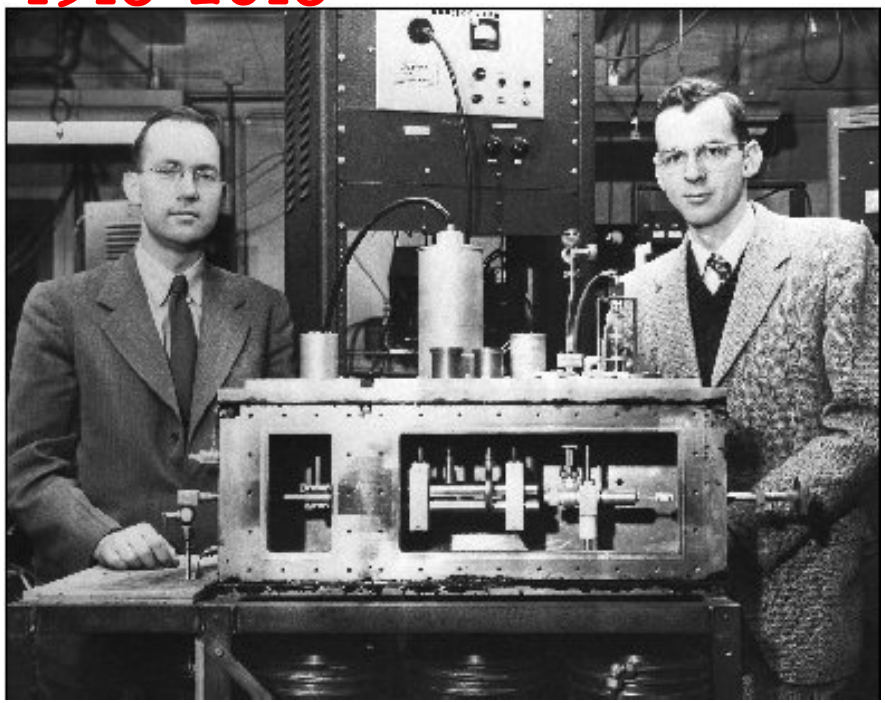


Triangulation with signals received by synchronized Cs clocks orbiting the Earth in satellites

A metre precision!

Without relativistic corrections (special and general relativity), the GPS would be off by kilometers!

1915-2015

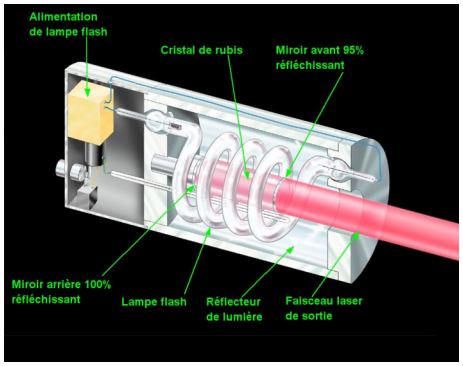


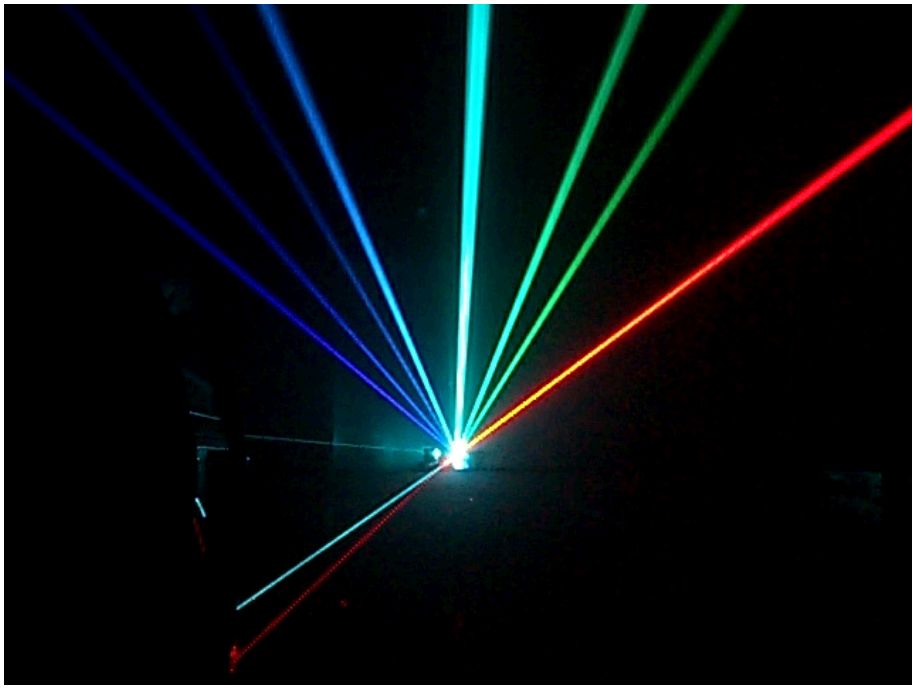
Townes and Gordon in
Columbia (1954)
in front of their ammonia
beam which produced the
first maser

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

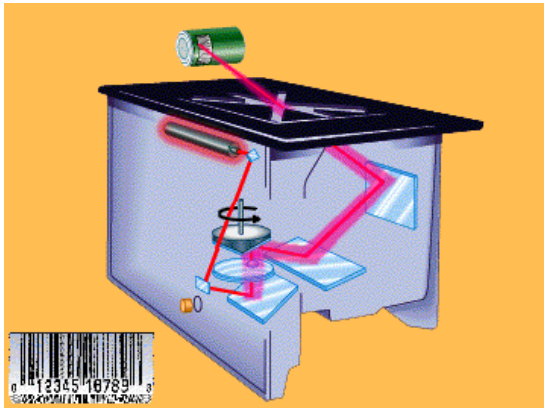
Then came the Laser (1960)

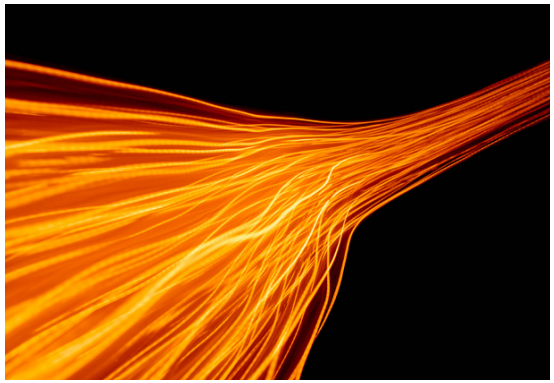
(Light Amplifier by Stimulated Emission of Radiation)

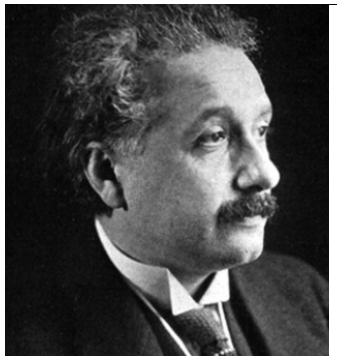




…and all its applications …

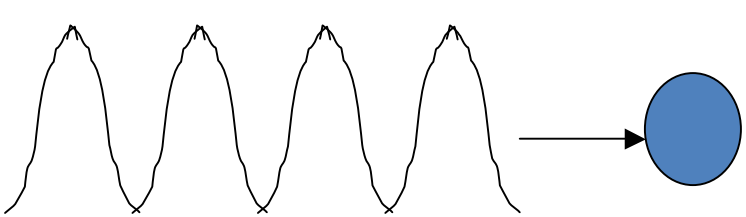


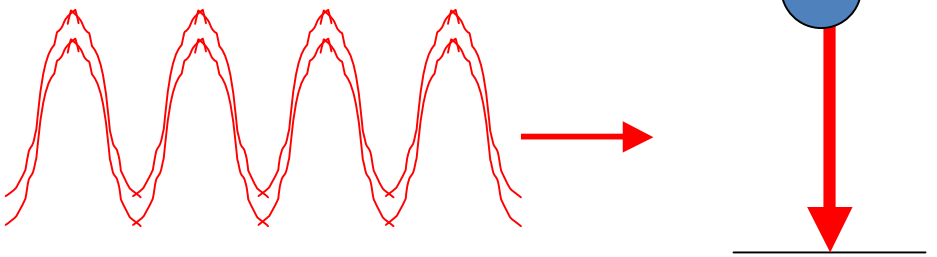




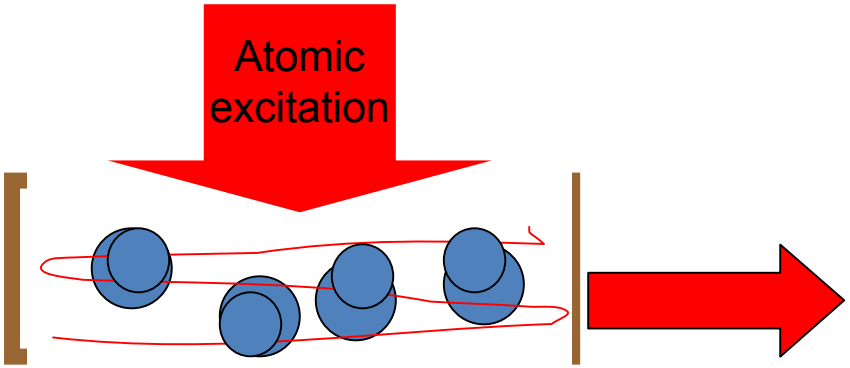
Stimulated emission: another of Einstein's ideas (1916)

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





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

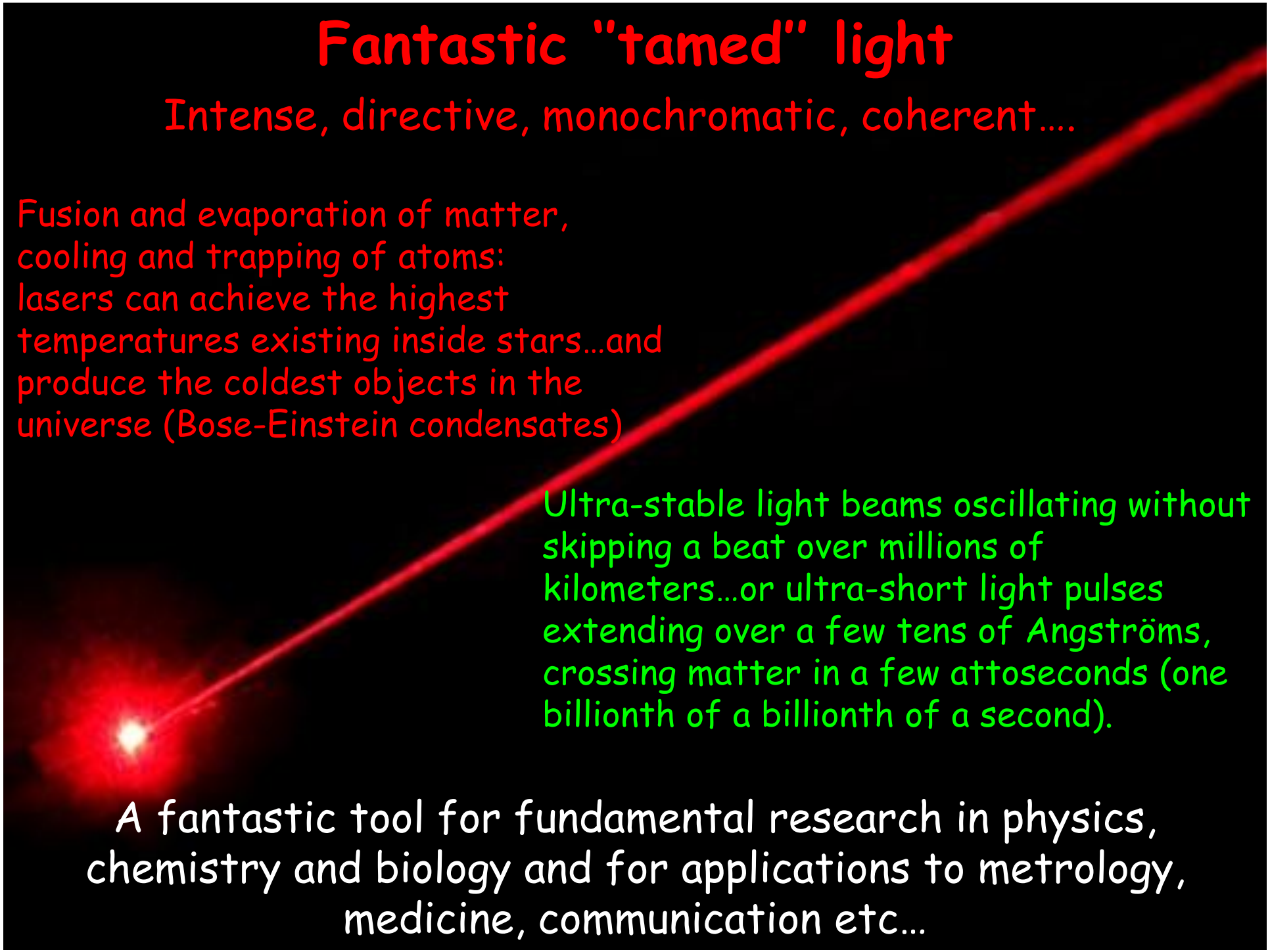


The light going back and forth between the mirrors is amplified by the excited atoms. The radiation noise is amplified to the point of self-oscillation and a fraction of the light escapes through the partly transmitting output mirror: this is the laser beam

Fantastic "tamed" light

Intense, directive, monochromatic, coherent….

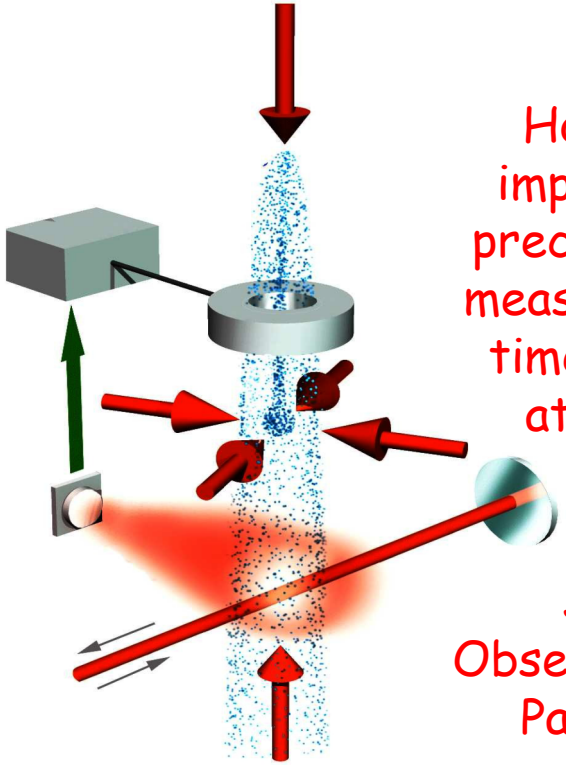
Fusion and evaporation of matter,
cooling and trapping of atoms:
lasers can achieve the highest
temperatures existing inside stars…and
produce the coldest objects in the
universe (Bose-Einstein condensates)



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

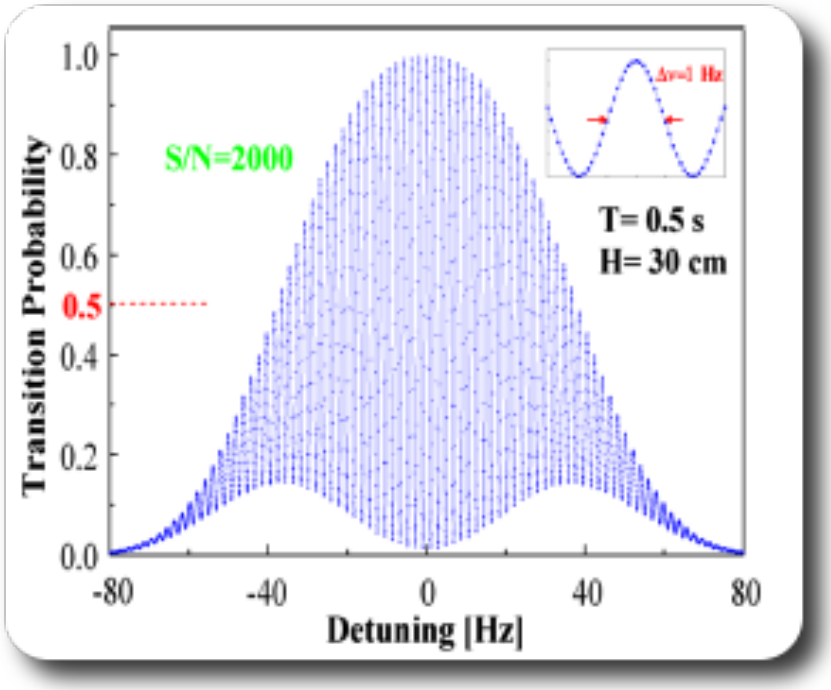
A fantastic tool for fundamental research in physics, chemistry and biology and for applications to metrology, medicine, communication etc…

The microwave fountain clock



How lasers improved the precision in the measurement of time: the cold atom clock

Syrte-Observatoire de Paris-ENS



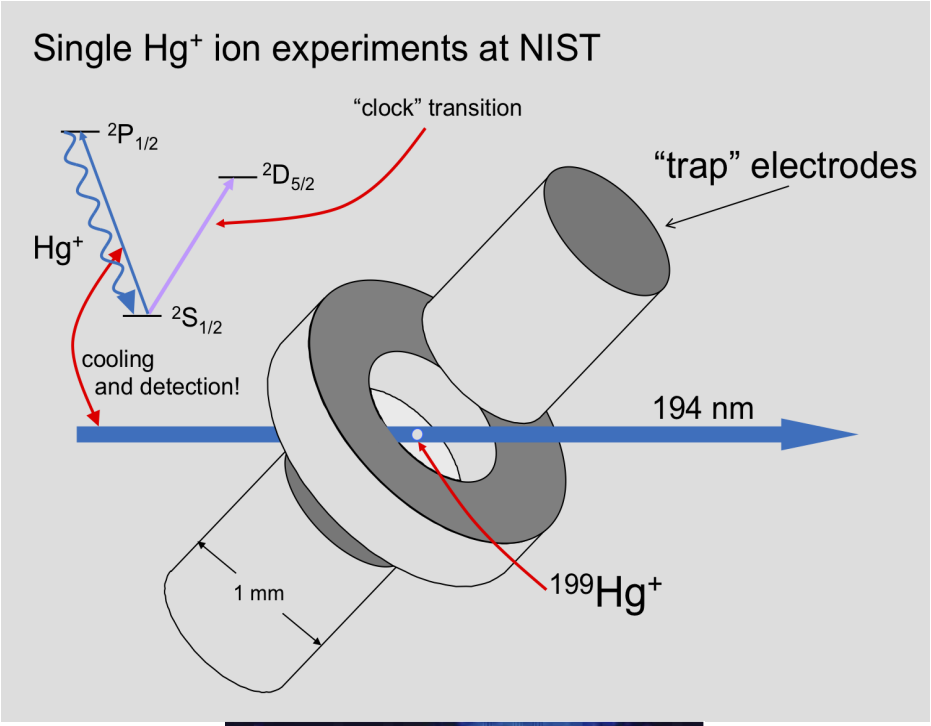
Ramsey fringes are a hundred time narrower

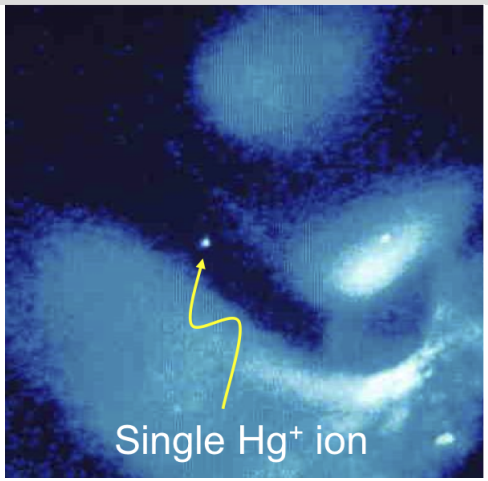
Slow atoms cross the rf zone two times (going up, then down). Atoms are prepared and detected by laser beams.

Uncertainty over a day: 10^{-16}

One second over 100 million years!

Cold ions and neutral atoms optical clocks





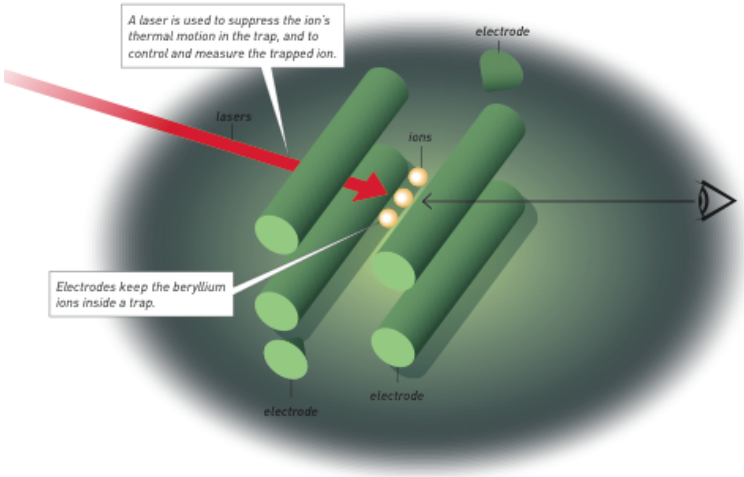
The oscillator is either a single trapped ion, or an ensemble of a few thousand ultra-cold atoms, manipulated and interrogated by laser beams. The clock frequency corresponds to an optical transition, excited by an ultra-stable laser locked to the transition.

The frequency, downconverted and counted by an optical escape mecanism called a "frequency comb", is 10^4 times larger than that of the microwave Cs clock. Hence a further improvement in precision:

10^{-18} :
one second over the age
of the Universe
(14 billion years!)

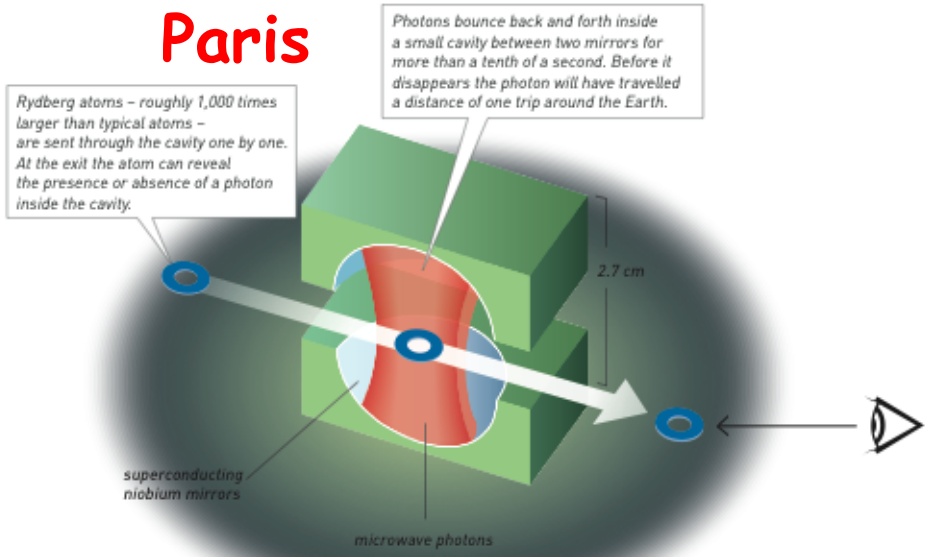
Controlling quantum particles

Boulder



Trapped ions

Paris

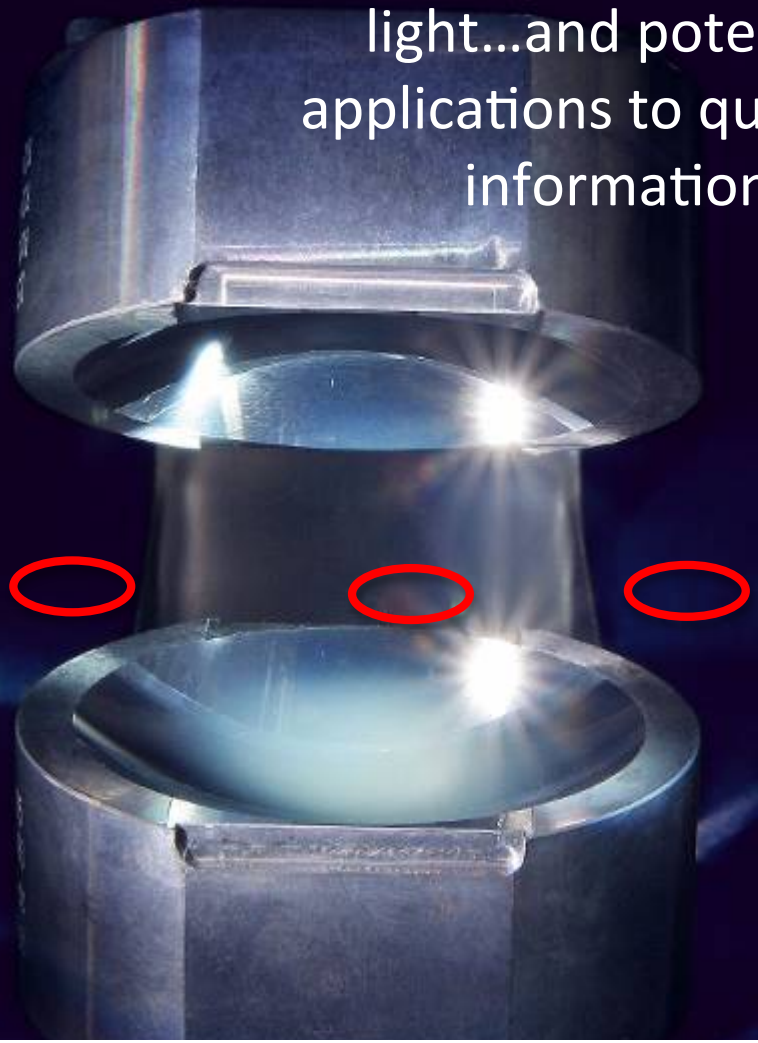


Trapped photons

The two sides of a coin: manipulating non-destructively single atoms with photons or single photons with atoms

Cavity QED :
photons trapped in a box made of ultra-highly reflecting mirrors interact with atoms crossing the box one at a time

Non-destructive manipulations of photons, tests of quantum physics, Schrödinger cats of light…and potential applications to quantum information



Why is it important to be able to manipulate single quantum particles?

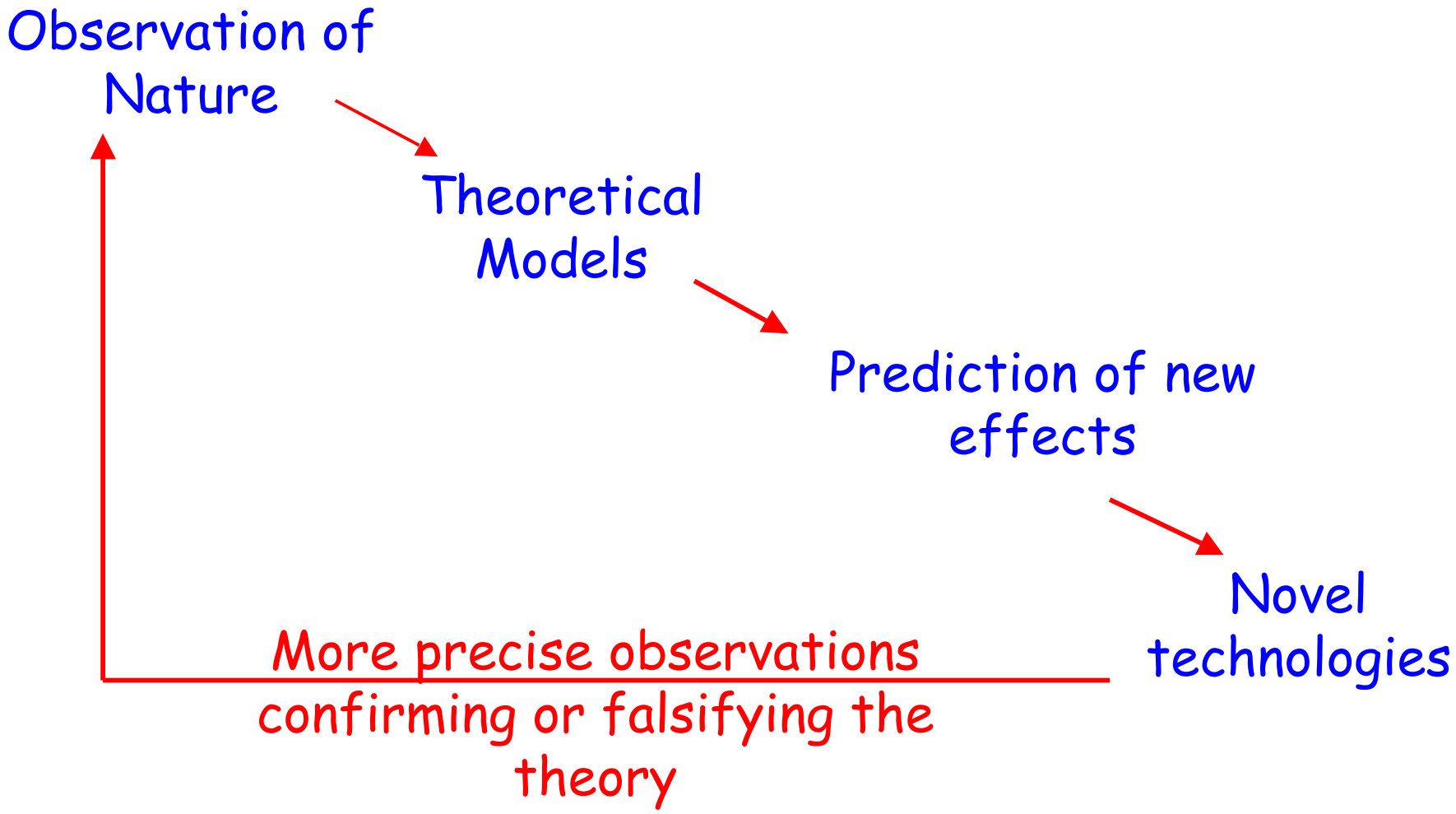
Curiosity: is it possible? How does Nature behaves at this level?

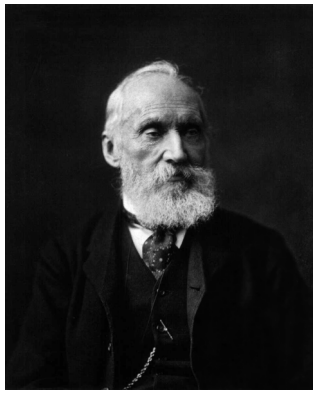
We never experiment with single electrons, atoms or small molecules…In thought experiments we assume that we do. It always results in ridiculous consequences… **» (Schrödinger 1952)**

Small systems react faster and pack more information per unit volume, leading to more powerful devices (Moore's law)

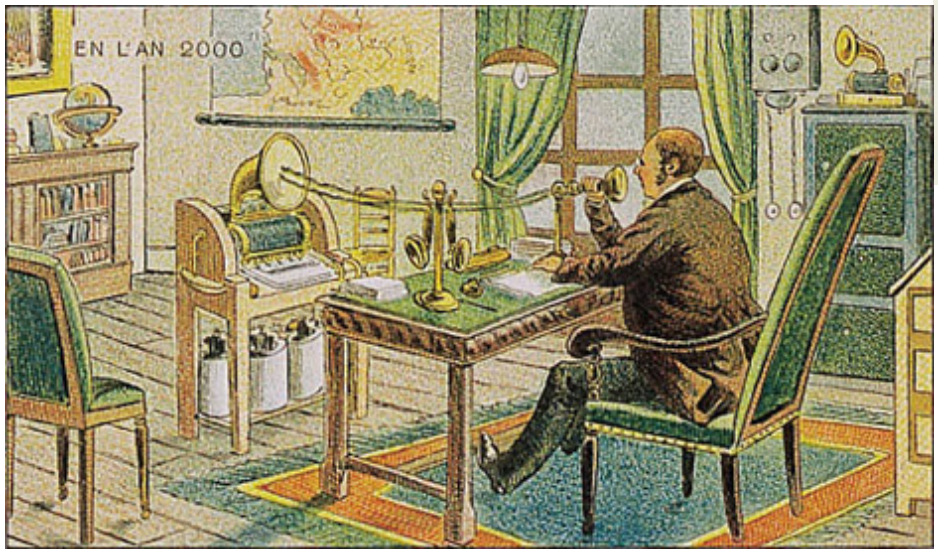
Quantum physics makes a wide range of new states accessible for possible applications

The permanent dialogue between blue sky research and innovation

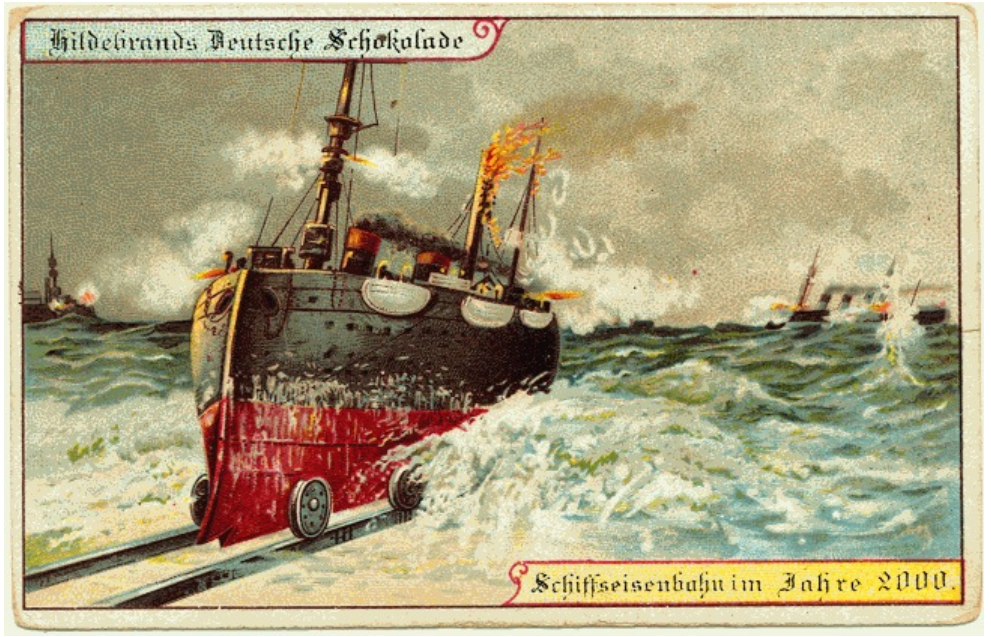




The modern technologies were unimaginable in 1900, even by the best scientists (here Lord Kelvin)

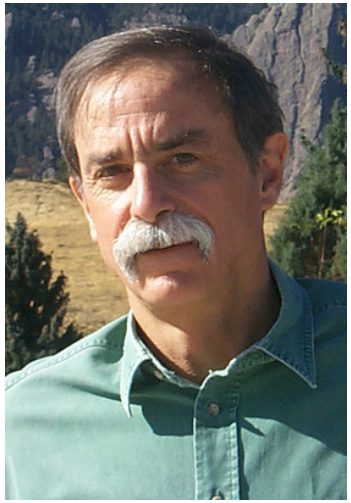


Naive predictions made during the Paris World Fair of 1900 about what life would be like in the year 2000



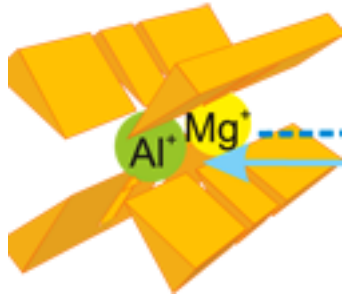
More powerful computers and/or simulators (quantum logic)?

More secrete communications (quantum cryptography)?



D.Wineland

More precise measurements? (quantum metrology for atomic clocks)



It is hard to make predictions, especially about the future…

(Attributed to Niels Bohr)

Think about the 1900 postcards predicting XXth century technologies….

… but one thing is sure: without basic research, novel technologies cannot be invented…

…and the past teaches us that wonderful applications always emerge serendipitously from blue sky research…

Novel technologies….

…often come serendipitously from blue sky research…

..which needs two priceless ingredients:

Time & Trust

Research is fully successful where and when these two ingredients are present!

It is not favored by the laws of the global market which emphasize speed and fast obtained marketable results!