

# The Laser and Quantum Physics



COLLÈGE  
DE FRANCE  
— 1530 —

Serge Haroche  
Académie des Sciences,  
February 5<sup>th</sup> 2025



The laser is a direct offspring and a powerful enabler of quantum physics

I will talk about the lineage of discoveries which have led to the birth of this fantastic source of light, recall some of the breakthroughs it has made possible over the last sixty five years and discuss the promises it holds for further discoveries in basic science

# Breakthroughs prior to the Heisenberg-Schrödinger 1925 discoveries

1905



Light is made of wave and particles (photons)

1913



Atomic electrons have quantized angular momentum and discrete energy levels. They move by quantum jumps between levels while emitting or absorbing photons, conserving energy in the process.

1916



**Stimulated emission:** an excited atom irradiated by photons resonant with a transition towards a lower energy state emits photons identical to the impinging ones.

1924

Bose



Photons in a field mode are indistinguishable particles. A variety of atoms (bosons) behave like photons and at very low temperatures condensate in same state

De Broglie



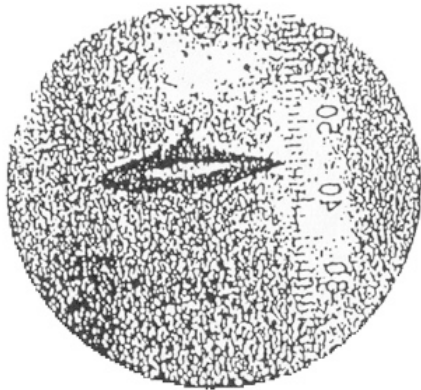
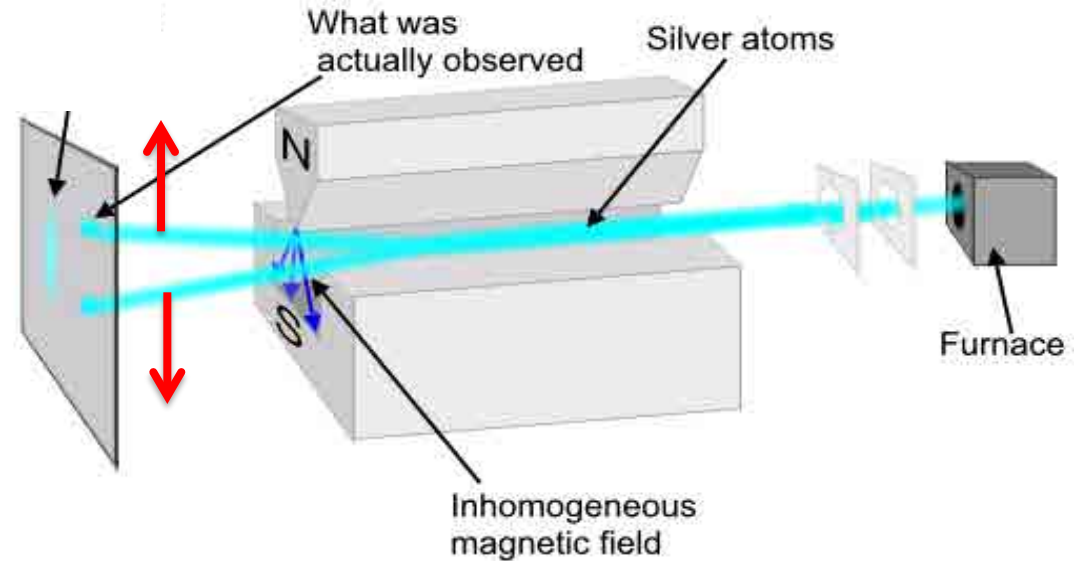
Wave-particle duality is extended to matter. It explains the similar gregarious properties of photons and bosonic atoms

**Einstein to Langevin: «the veil hiding the mysteries of the quantum world starts to be lifted»**

# Discovery of two-level systems: the spin (1922)



Classical



The set-up separates the magnetic moments (spins) pointing up and down and shows spatial quantization and the existence of two-level systems. (the future qubits)

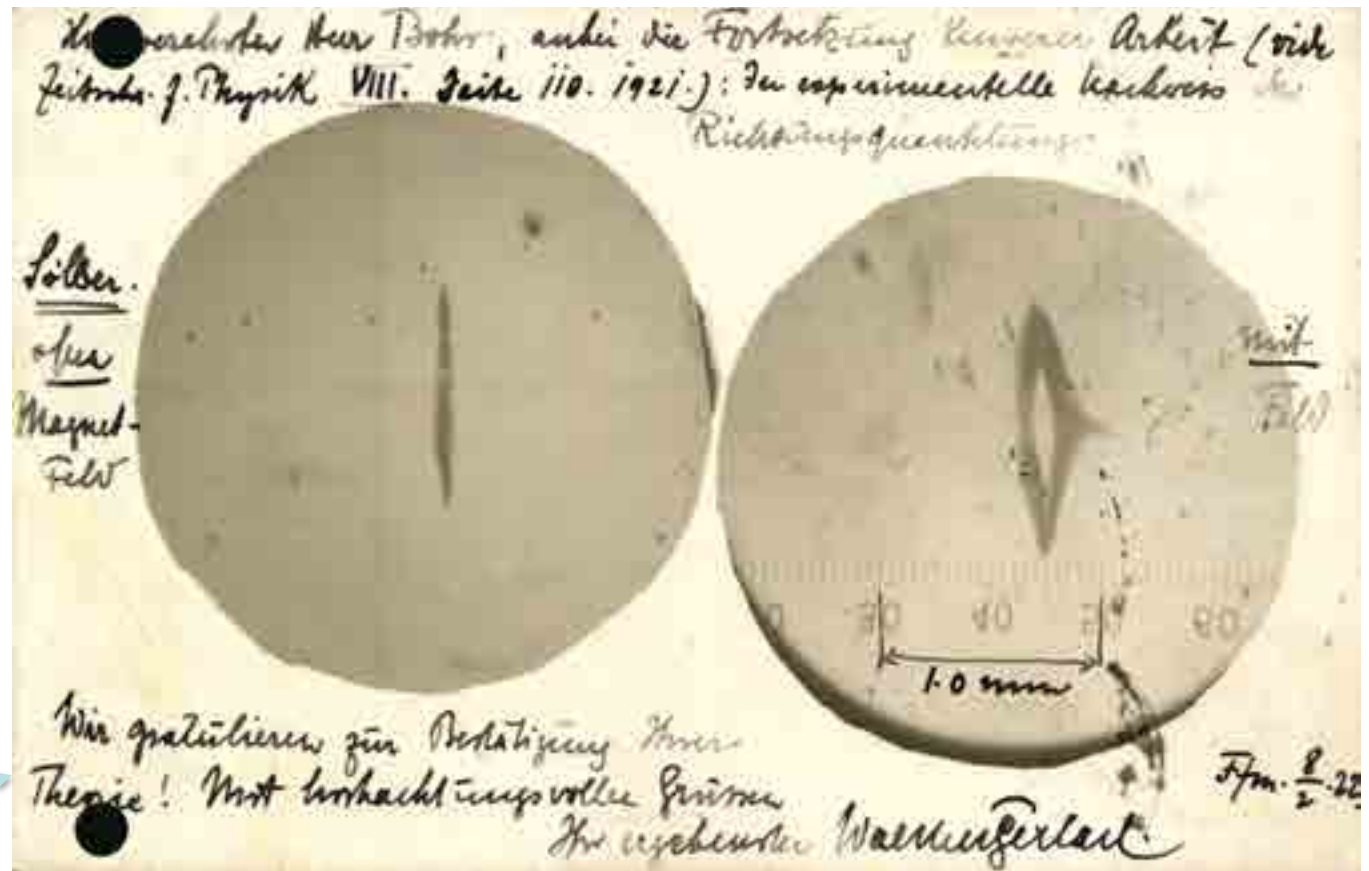
# Walther Gerlach to Niels Bohr on February 13 1922



By permission of N.Bohr archives, Copenhagen



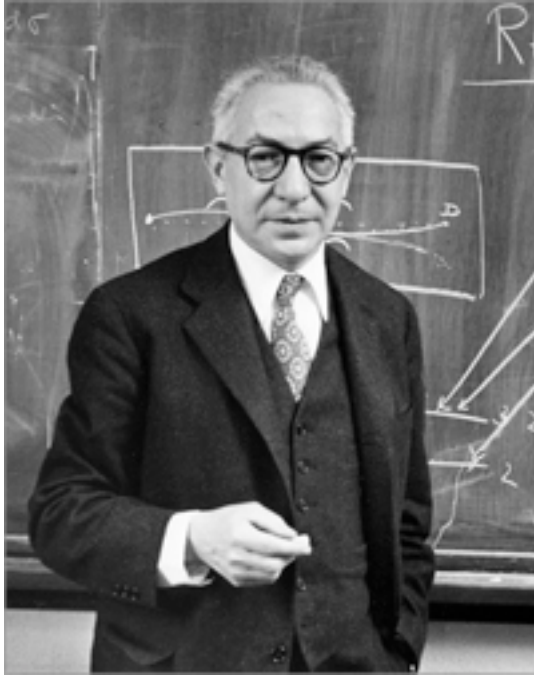
« We congratulate you for the confirmation of your theory »



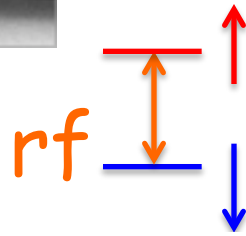
A simple split trace on a glass plate announces the XX<sup>th</sup> century quantum revolution in technology and the qubit in the twenty first century !



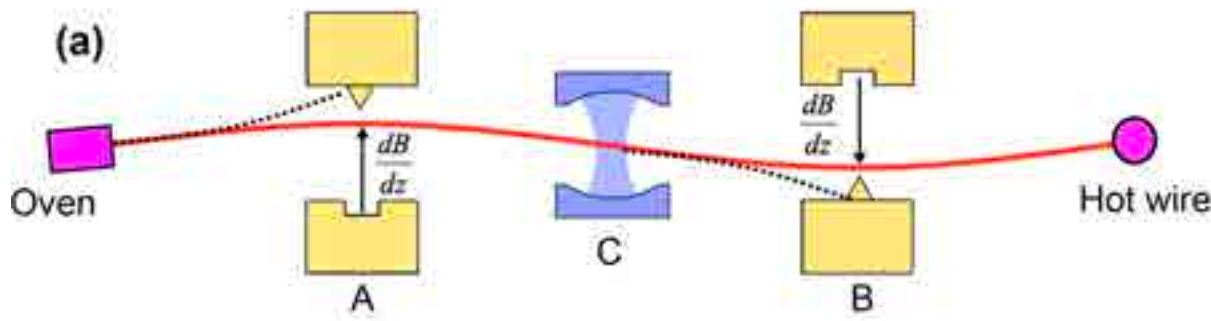
# More blue sky science: Isidor Rabi and the rf Molecular Beam method to measure nuclear magnetic moments at Columbia



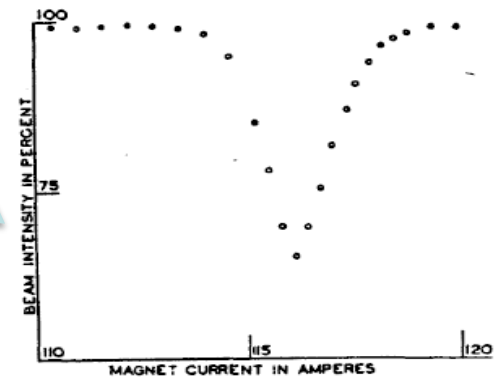
1898-1988



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



Rabi's magnetic resonance announced the NMR, the MRI, the atomic clocks, the GPS, the optical pumping, the maser 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. 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

# Exploiting the quantum properties of atomic spins and two-level systems (Stern's and Rabi's legacy)

1946



F. Bloch E. Purcell

NMR in bulk materials



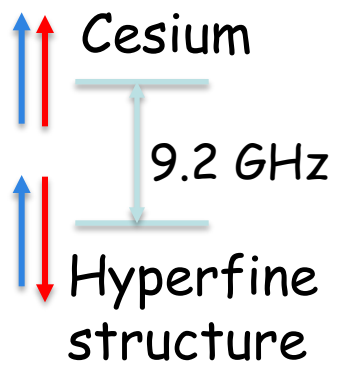
Magnetic Resonance Imaging (MRI)



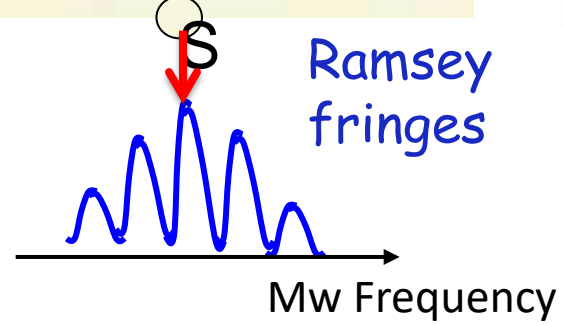
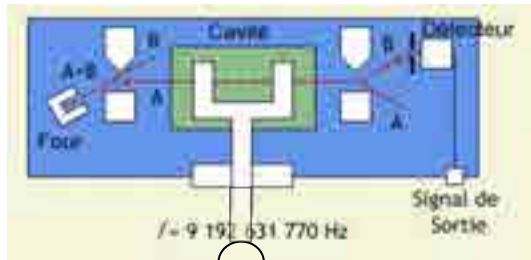
1950



N. Ramsey



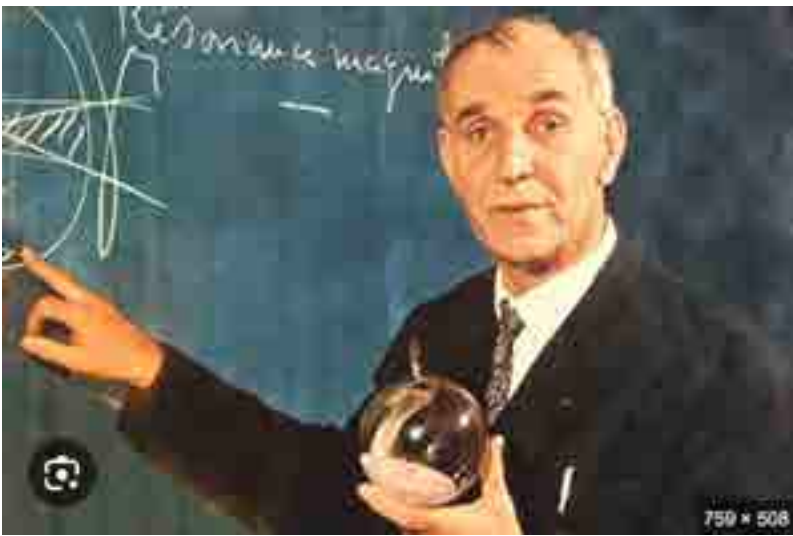
The atomic microwave clock



the GPS



# Another pre-laser invention: Manipulating atoms with light by Optical Pumping



A. Kastler

Light can change the distribution of population between atomic energy states: possibility of cooling matter with light (« effet lumineux frigorifique »)

1952



J. Brosse

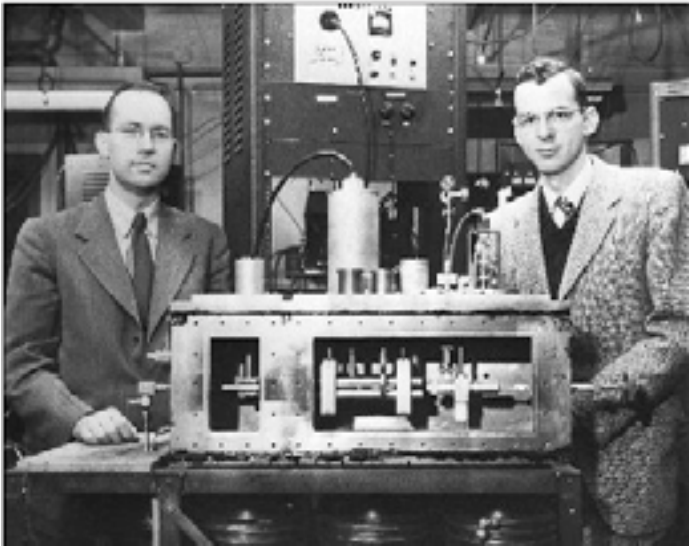


C. Cohen-Tannoudji

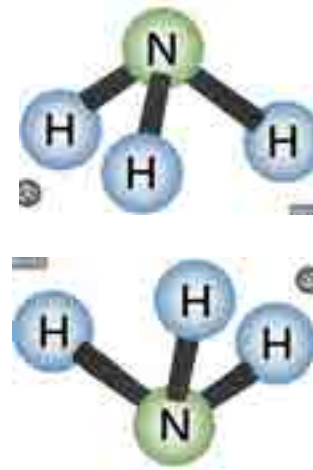
Discovery of light shifts in optical pumping experiments announcing the tailoring of the energy landscape of atoms moving in spatially varying light fields and the Quantum non-demolition counting of photons

1960

# Exploiting stimulated emission in two-level system: from the Maser to the Laser

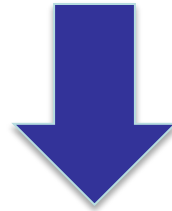


C. Townes and J. Gordon  
at Columbia U (1954)



Another two level  
system: Ammonia  
molecule

Microwave  
Amplification  
by  
Stimulated  
Emission of  
Radiation



T. Maiman  
(1960)

The « optical maser »  
or **Laser**



# 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)

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 « miraculous » tool for fundamental research in physics,  
chemistry and biology and for applications to metrology,  
medicine, communication (a multibillion dollar market...)

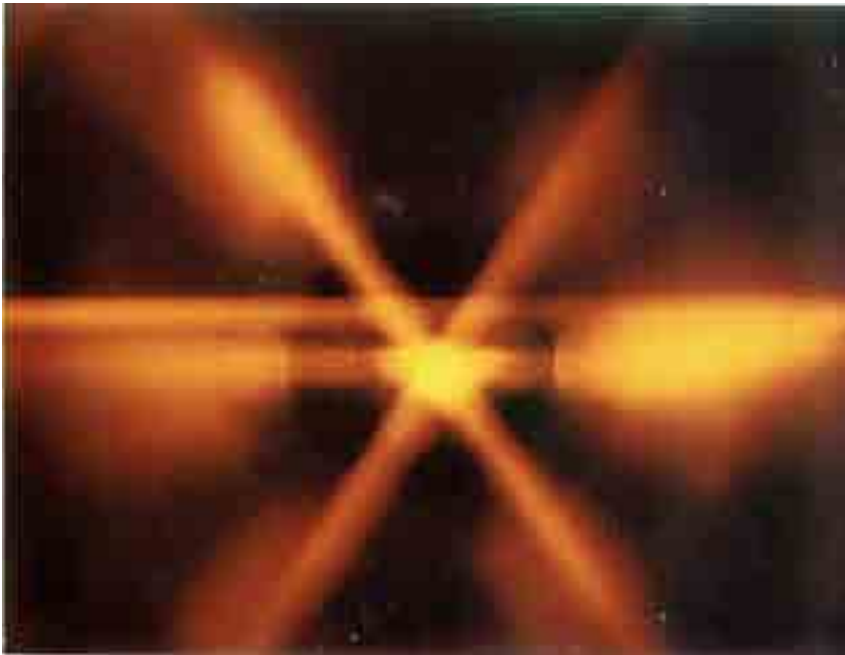
# 65 years of Atomic, Molecular & Optical Physics

The laser has made tremendous progresses possible and has led to quantitative and qualitative revolutions in basic research

More than ten order of magnitude improvement in many fields  
(a factor of ten every five years!)

	1960	2025
Temperatures and kinetic energies of atoms:	1-300K	$10^{-9}$ K (cold atoms)
Precision (spectroscopy and clocks):	$10^{-8}$	$10^{-19}$ - $10^{-20}$
Sensitivity of measurements:	$10^{13}$ atoms	1 atom/ 1 photon
Speed and time resolution:	$10^{-9}$ s	Attosecond ( $10^{-18}$ s)
Sensitivity to length variation $\Delta h/h$	$10^{-8}$ - $10^{-9}$ (Interferometric definition of meter)	$10^{-21}$ - $10^{-22}$ (LIGO/VIRGO)

# Laser cooling of atoms



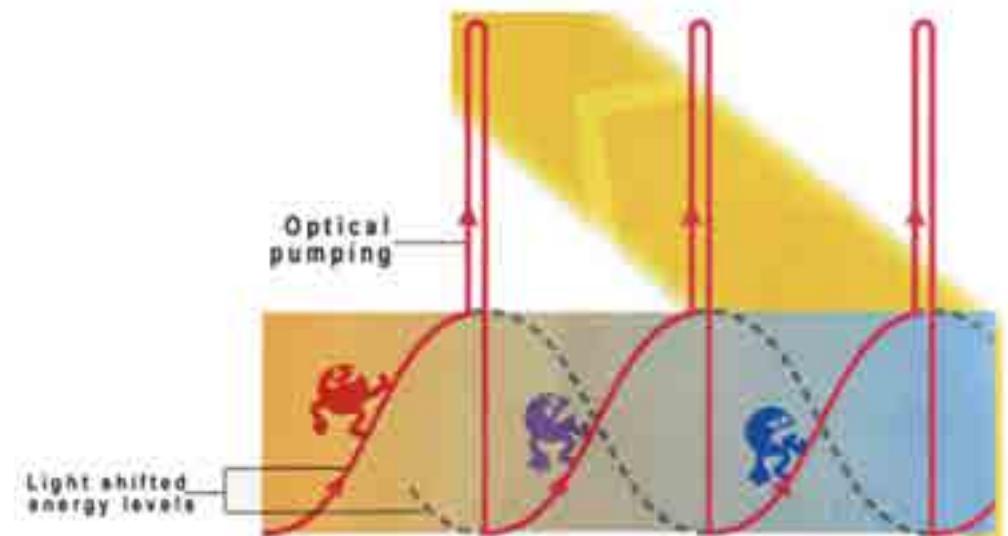
Courtesy of W.Phillips

Optical molasses:  
atoms at about  
 $1 \mu\text{K}$  fluoresce at  
intersection of  
laser beams

Ultra-cold  
atoms: BEC and  
degenerate  
Fermi gases

**Sisyphus cooling:** atoms keep  
climbing energy barriers under  
combined effect of light-shifts  
and optical pumping

C.Cohen-Tannoudji & J.Dalibard



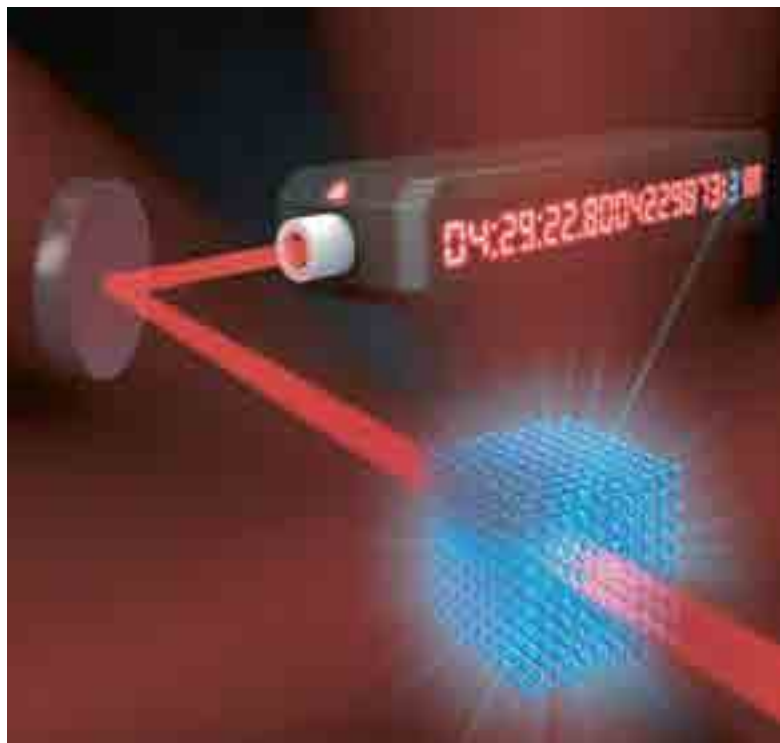
Poster of Swedish Academy of Sciences

# Optical atomic clock at 429 THz ( $4,2 \times 10^{14}$ Hz)

Uncertainty  $10^{-19}$  (1/20<sup>th</sup> of a second  
over age of the Universe!)

100000 times more precise than  
GPS microwave clocks!

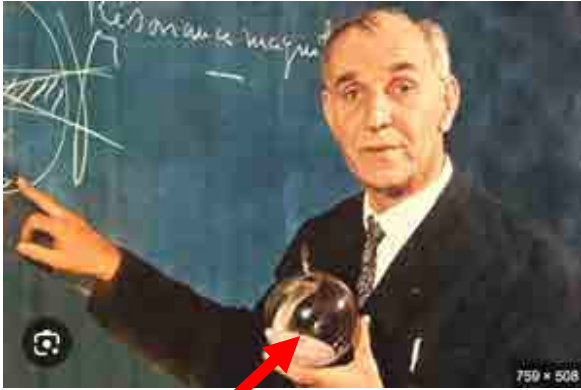
Sensitive to general relativity space-  
time curvature over 1mm altitude  
difference!



Courtesy J.Ye

4 laser systems involved:





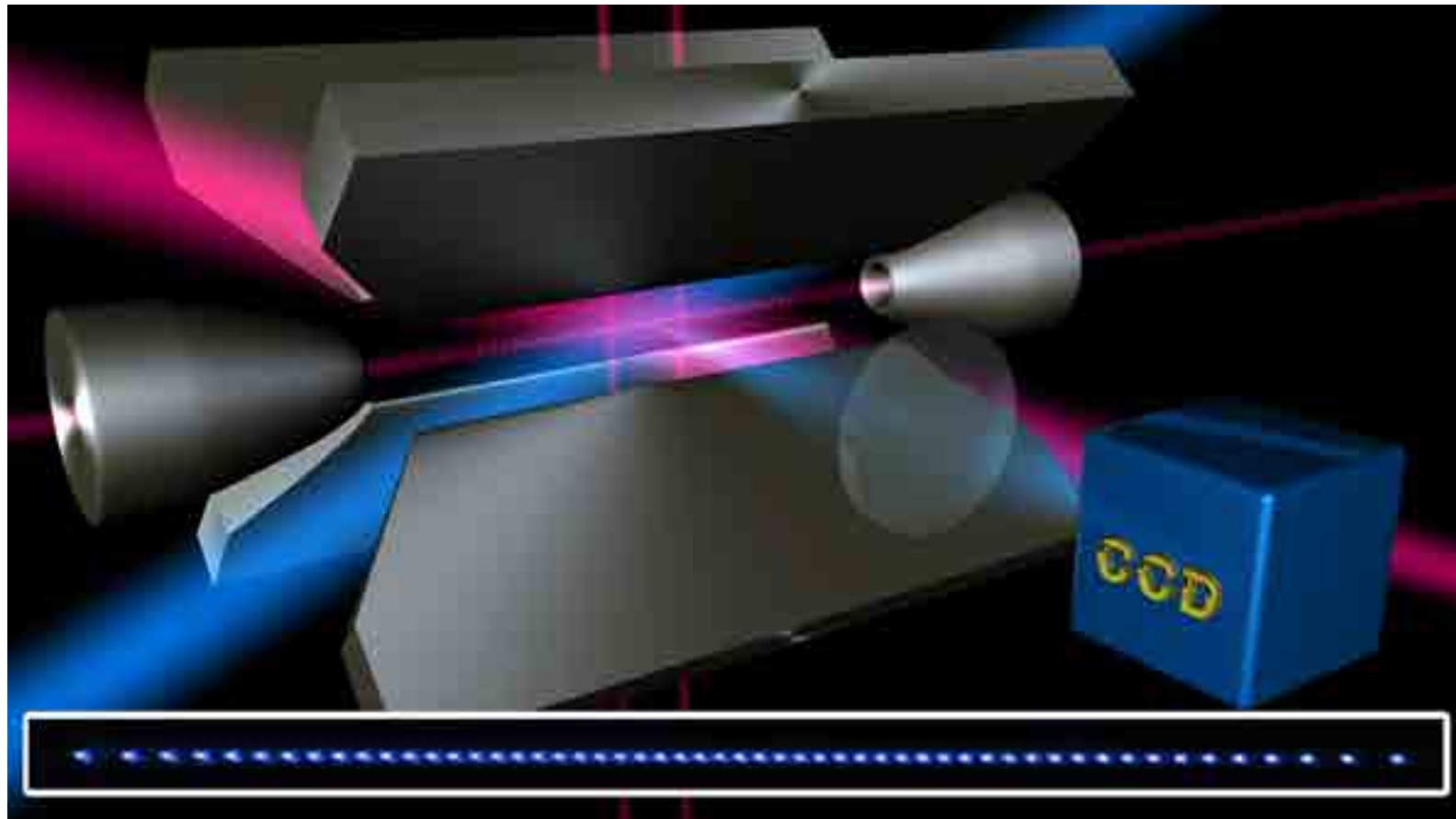
# Non-destructive single atoms and molecules manipulation with lasers

Fluorescence induced by laser optical pumping on individual ions or neutral atoms trapped by field gradients (akin to Stern-Gerlach)

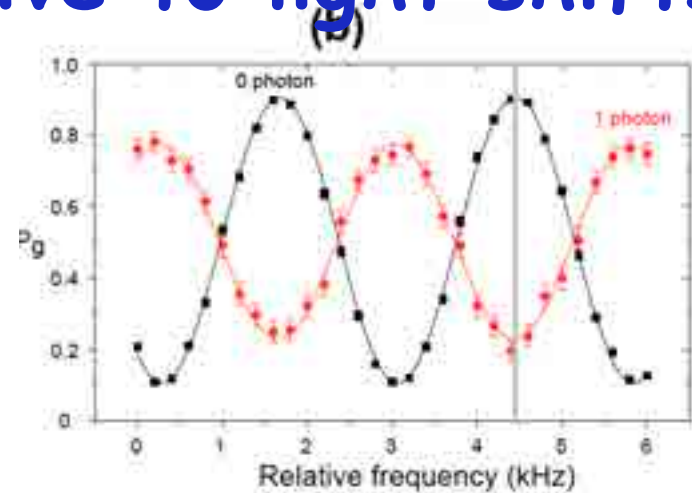
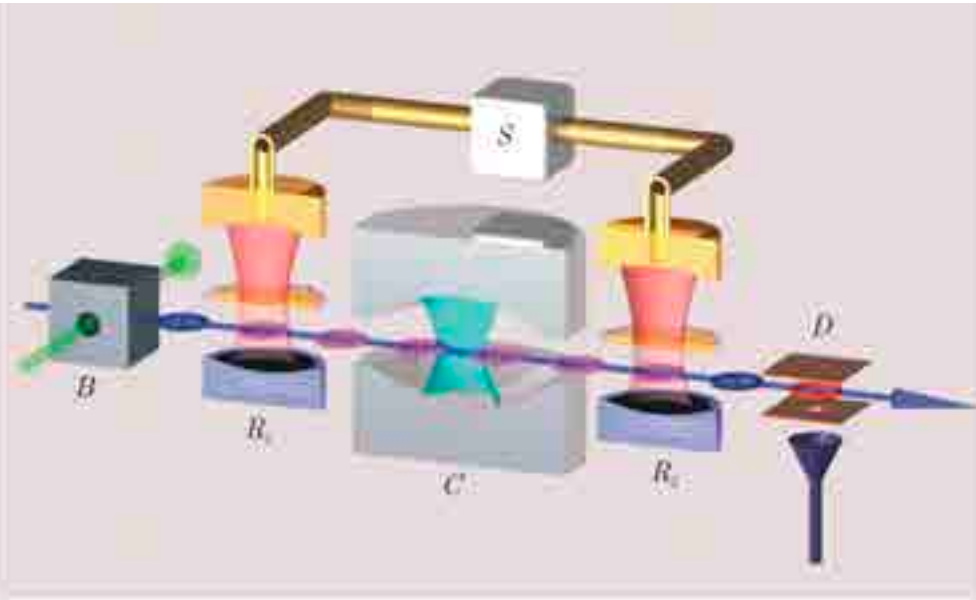
$10^{13}$  Hg atoms  
in OP cell

54 Ca atoms in  
linear ion-trap  
(courtesy of  
R.Blatt)

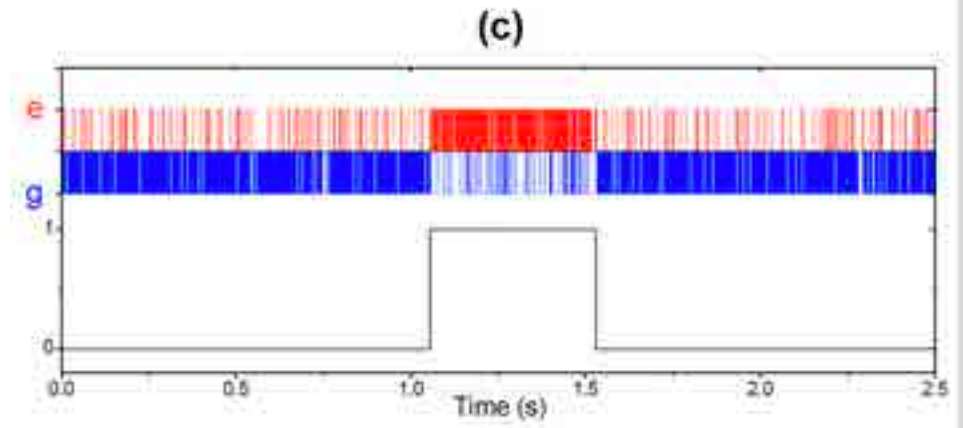
Demonstration  
of elementary  
steps of  
Quantum  
Computing



# Quantum Non Demolition counting of photons trapped in a cavity by a Rydberg microwave clock extremely sensitive to light shifts



One photon fringe shift



Birth, life and death of a photon

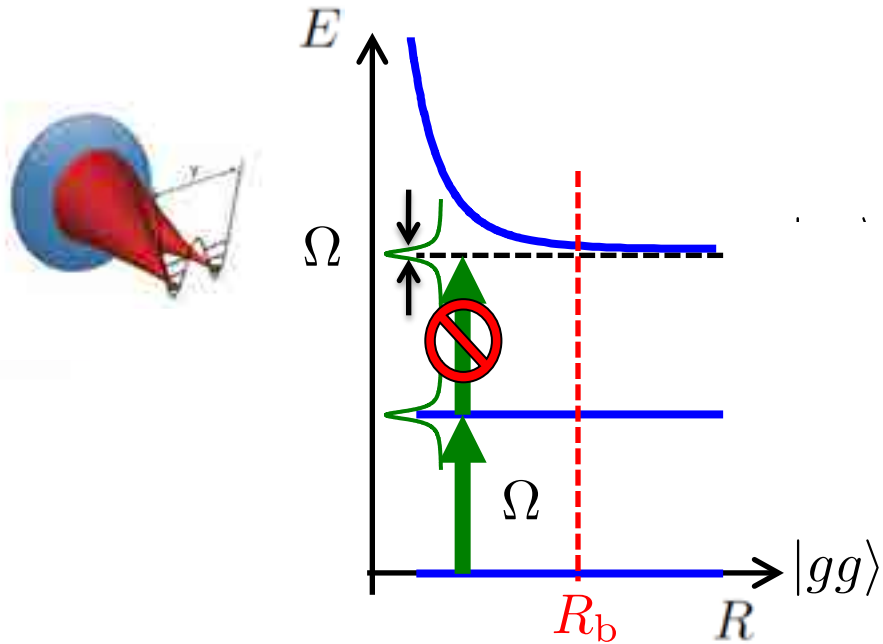
A Ramsey interferometer set-up

Cavity QED experiments  
at LKB

(J.-M. Raimond, Brune, SH  
et al)

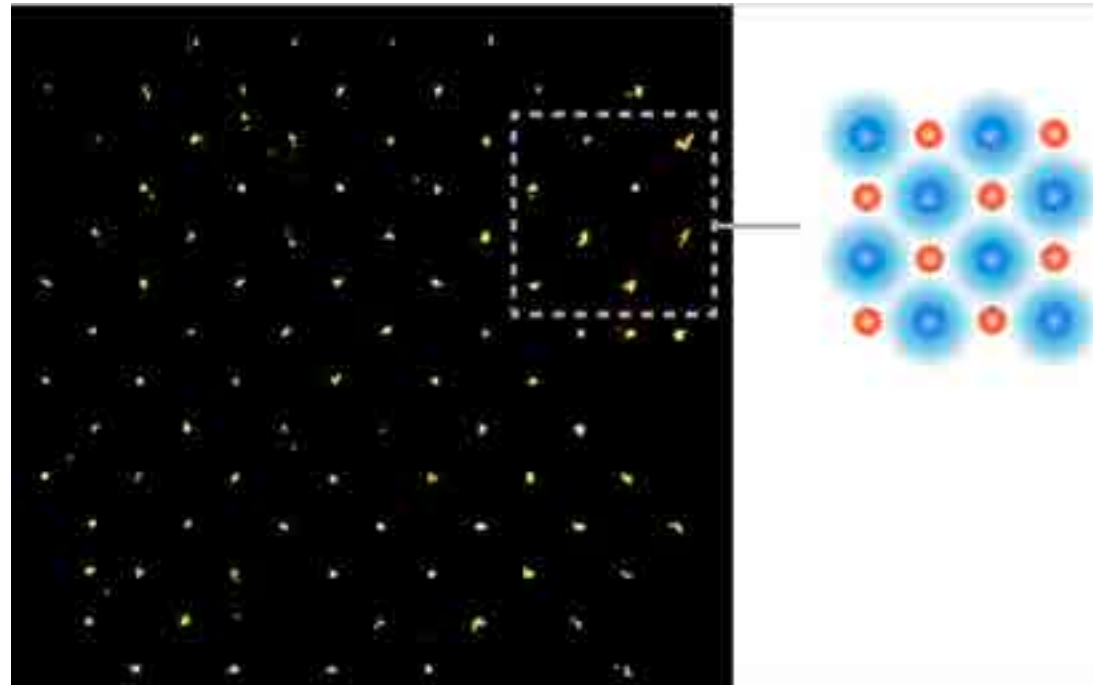


# Rydberg atom quantum simulators



Quantum simulation of antiferromagnetic materials and of other many-body condensed matter systems.

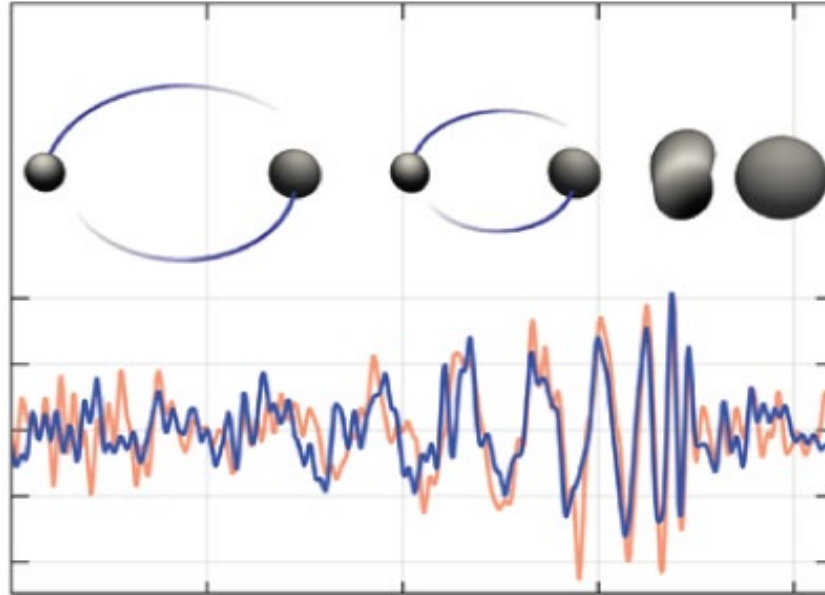
Rydberg atoms interact at tens of  $\mu\text{m}$  distances in optical tweezer arrays via **dipole blockade** effect



A.Browaeys et al, Nature

# Gravitational wave detection (2015)

The  
coalescence  
of two black  
holes 1,3  
Billion light-  
years away...

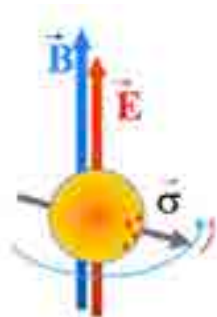


...has produced  
a gravitational  
wave detected  
by the two  
antennas of  
LIGO  
(VIRGO joined  
in 2016)

*A tour de force detecting a displacement of mirrors (separated by 4km) of less than ten billionth of an atomic diameter ( $10^{-21}$  sensitivity to relative displacements)*



# Searching for new physics with ultra-precise Laser spectroscopy: looking for electron edm



Looking for Ramsey fringe shift when huge E field is parallel vs anti-parallel to B field on electron in heavy polar molecule  
(ACME-Harvard, Imperial College- London, JILA-Boulder)

Is the electron exactly spherical?

$edm \leq 10^{-36} \text{ e.cm}$  (standard model)

$edm \approx 10^{-31} - 10^{-32} \text{ e.cm}$  (supersymmetric T violation)

Precision of present experiment:

$edm \approx 4 \cdot 10^{-30} \text{ e.cm}$

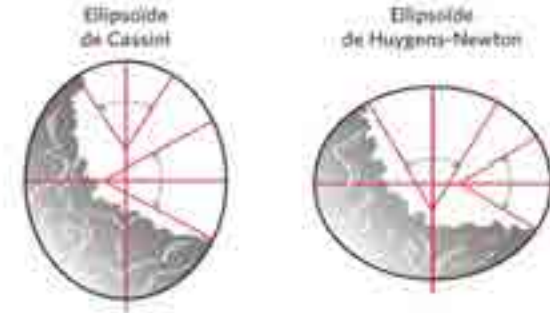
sensitive to defect of sphericity  $\frac{\delta R}{R} \approx 10^{-17}$

If electron had size of Earth,  
 $\delta R$  would be 0.1 nm !

Finding electron asymmetry at level of  $10^{-31} - 10^{-32} \text{ e.cm}$  could be evidence of new particles (dark matter?) with important implications for quantum physics and cosmology.

# The passion for precision in blue sky science

*« Is the electron perfectly round? »  
reminds a question raised by Maupertuis in 1736  
at the French Academy of sciences:  
« is the Earth exactly spherical? »*



Maupertuis

The Maupertuis and La Condamine expeditions to Lapland and Peru demonstrated that the Earth is oblate by measuring two arcs of meridian at different latitudes, confirming Newton and Huygens theories.



La Condamine

$$\frac{\delta R_{\text{Earth}}}{R_{\text{Earth}}} \approx 3.10^{-3}$$

The scientific method has not changed, but the precision and the amount of knowledge have tremendously increased!

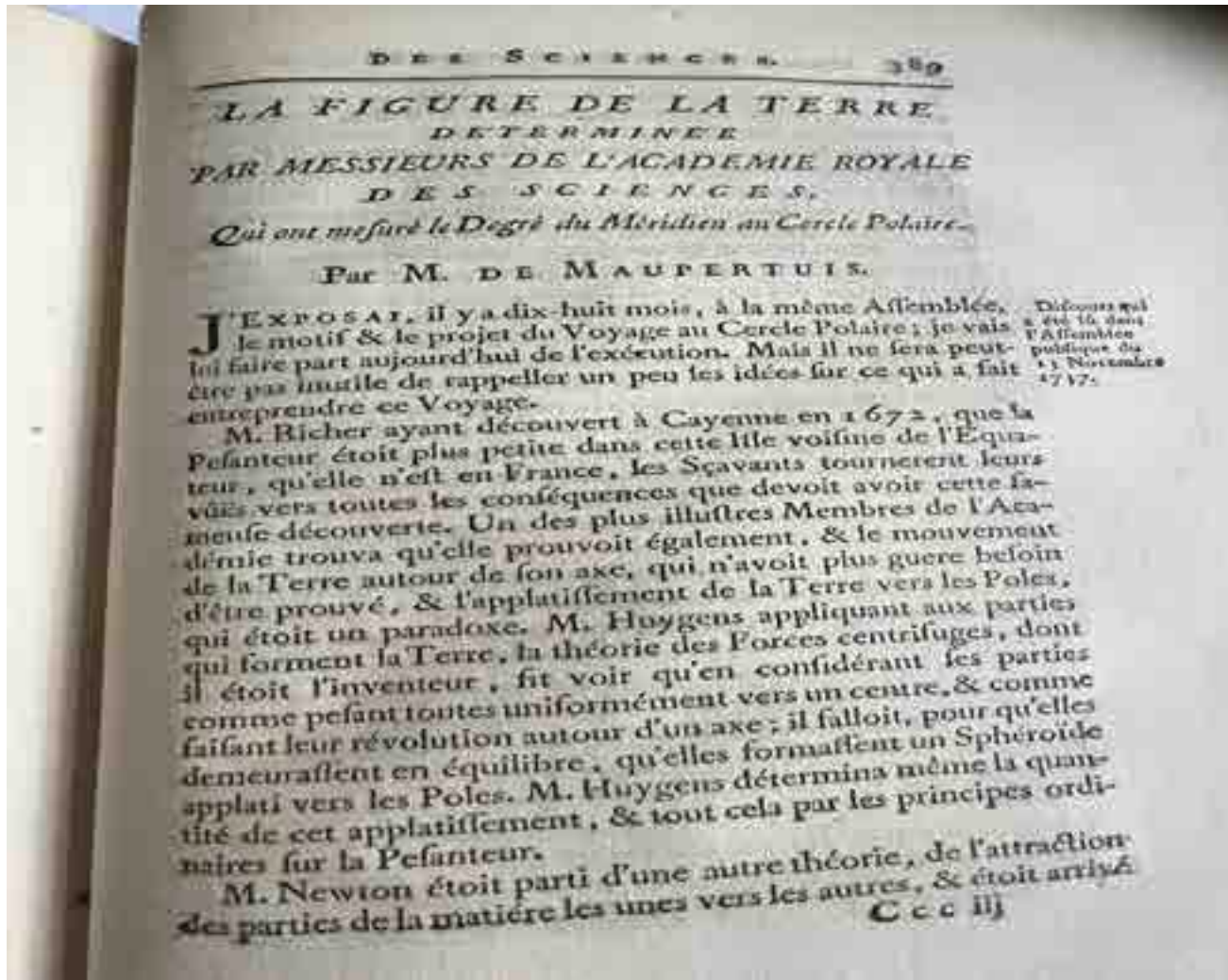
Research has always taken time and money...

It was then more adventurous and more dangerous...

# THE FIGURE OF THE EARTH

DETERMINED

BY THE GENTLEMEN OF THE ROYAL ACADEMY OF SCIENCES  
Who have measured the Degree of the Meridian at the Polar circle  
By M. de MAUPERTUIS



LA FIGURE DE LA TERRE  
DETERMINÉE  
PAR MESSIEURS DE L'ACADEMIE ROYALE  
DES SCIENCES.

Qui ont mesuré le Degré du Méridien au Cercle Polaire.

Par M. DE MAUPERTUIS.

J'EXPOSAI, il ya dix-huit mois, à la même Assemblée, le motif & le projet du Voyage au Cercle Polaire; je vais lui faire part aujourd'hui de l'exécution. Mais il ne sera peut-être pas inutile de rappeler un peu les idées sur ce qui a fait entreprendre ce Voyage.

Discours qui a été lu dans l'Assemblée publique du 11 Novembre 1747.

M. Richer ayant découvert à Cayenne en 1672, que la Pesanteur étoit plus petite dans cette Ile voisine de l'Equateur, qu'elle n'est en France, les Sçavants tournerent leurs vûes vers toutes les conséquences que devoit avoir cette fameuse découverte. Un des plus illustres Membres de l'Académie trouva qu'elle prouvoit également, & le mouvement de la Terre autour de son axe, qui n'avoit plus guere besoin d'être prouvé, & l'applatissement de la Terre vers les Poles, qui étoit un paradoxe. M. Huygens appliquant aux parties qui forment la Terre, la théorie des Forces centrifuges, dont il étoit l'inventeur, fit voir qu'en considérant les parties comme pesant toutes uniformément vers un centre, & comme faisant leur révolution autour d'un axe; il falloit, pour qu'elles demeurassent en équilibre, qu'elles formassent un Sphéroïde applati vers les Poles. M. Huygens détermina même la quantité de cet applatissement, & tout cela par les principes ordinaires sur la Pesanteur.

M. Newton étoit parti d'une autre théorie, de l'attraction des parties de la matière les unes vers les autres, & étoit arrivé

When the measurement of the Meridian that crosses France was completed, it was surprising to see that the degrees towards the North had been found to be smaller than those towards the South; *this was absolutely the opposite of what would follow from the flattening of the Earth* (according to Huygens and Newton).

To correctly determine the figure of the Earth, it was necessary to compare two degrees of the Meridian as different in latitude as possible, because (...) the difference between neighboring degrees is too small and could be confused with the errors of observations, whereas if they are at great distances from each other, *this difference, repeated as many times as there are intermediate degrees, will be too considerable a sum to escape observers.*

# Curiosity

Testing theory by observation

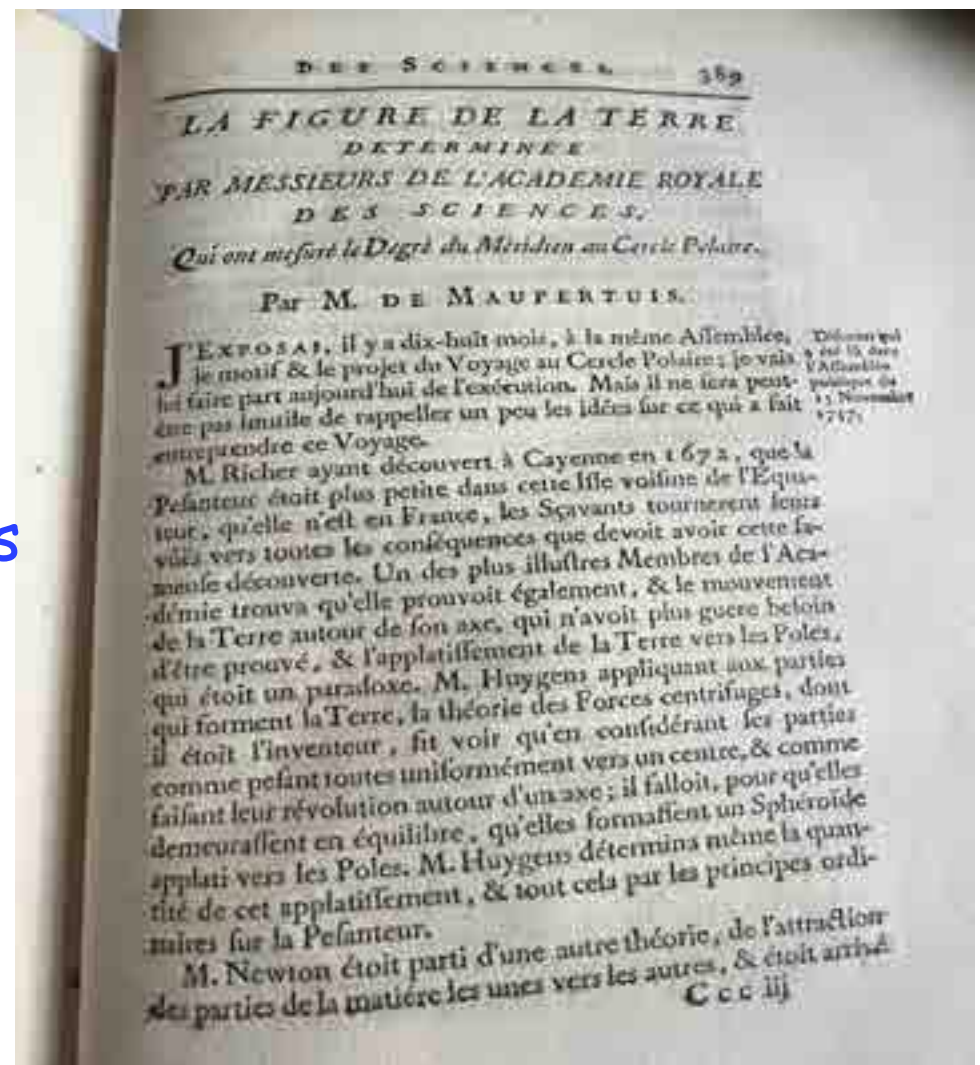
Need to justify utility

Time, trust and money

Use of latest optical technologies  
(sextants sensitive to star  
aberration)

Large teams and international  
collaborations (Celsius, Bradley)

Systematic accuracy evaluation



3 centuries later, lasers make possible geodesical surveys of Earth which confirm Maupertuis results, with much higher precision

Maupertuis'  
Tomb  
(Saint Roch  
Church, Paris)



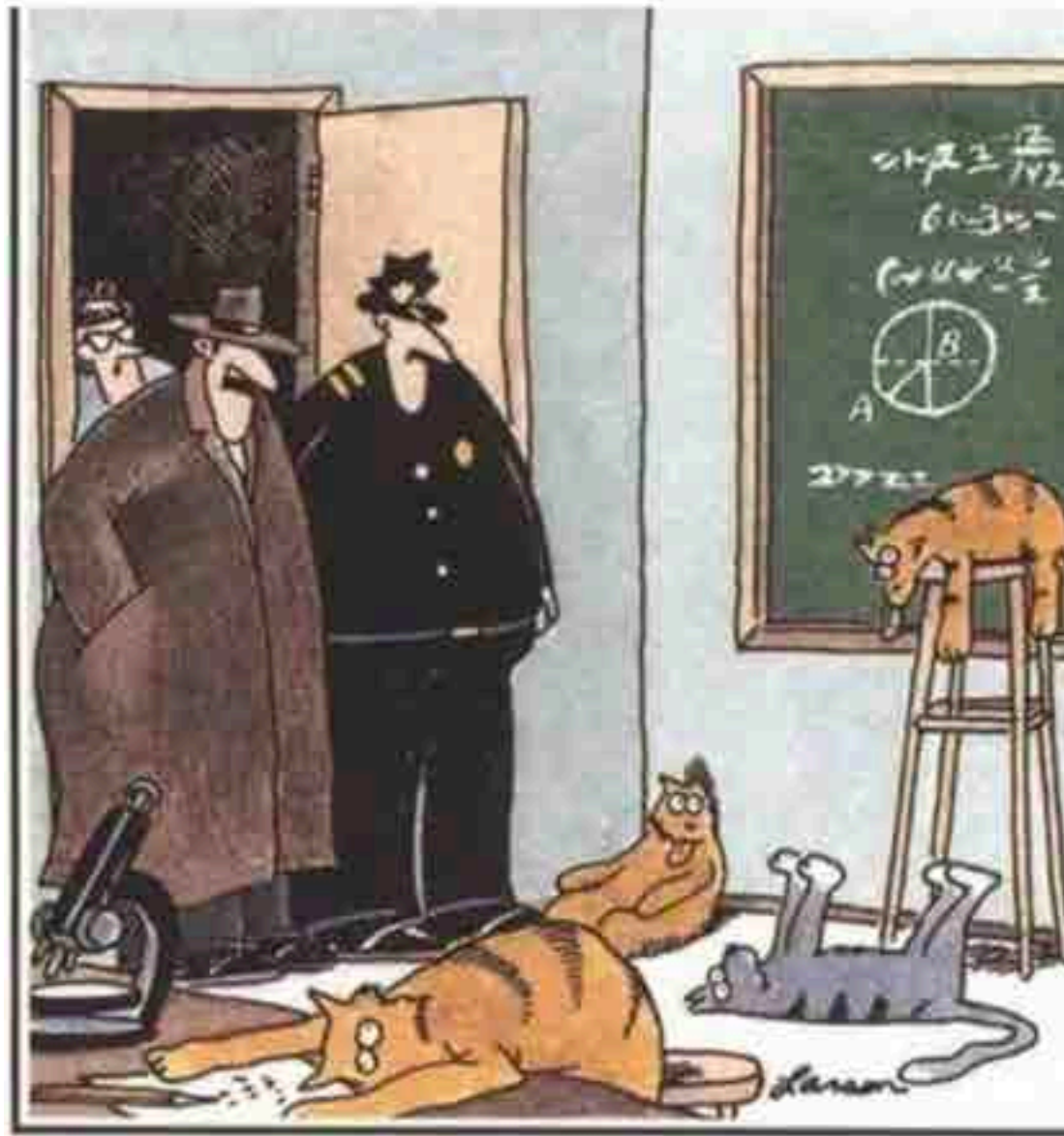
Voltaire

« Vous avez confirmé dans ces lieux pleins d'ennui  
Ce que Newton connut sans sortir de chez lui ».

"You have confirmed in these boring places  
What Newton knew without leaving home"



About the dangers of scientific curiosity and the fate of cats in quantum physics



The far side Gallery

Larson cartoon

"Notice all the computations, theoretical scribblings, and lab equipment, Norm. Yes, curiosity killed these cats."