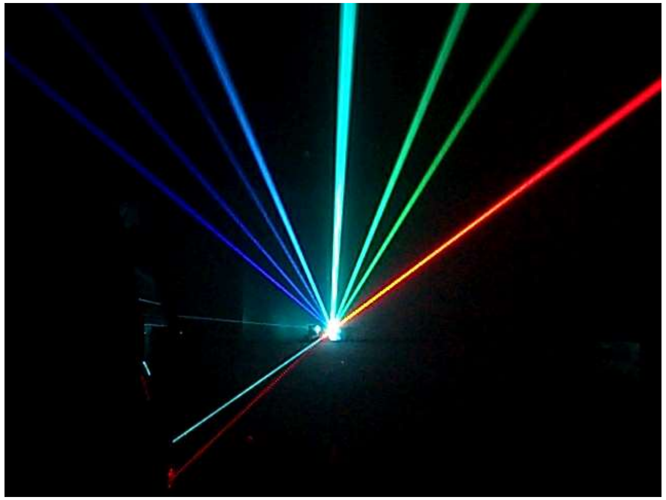
The Laser revolution in basic science

COLLÈGE DE FRANCE 1530

Serge Haroche
Jicable'23, Lyon
June 18th 2023

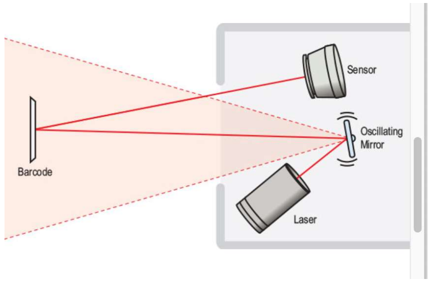
LETTRES SCIENCES ECOLE NORMALE SUPERIEURE

The laser, a fantastic tool applied in many technologies...



...has led to breakthroughs in basic science (atomic physics, metrology, quantum information, chemistry, biology, astronomy....)

Some practical applications of lasers

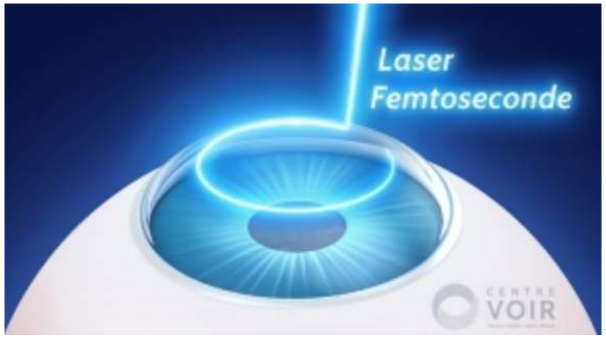


Wikipedia
Code 128

Scanning barcodes

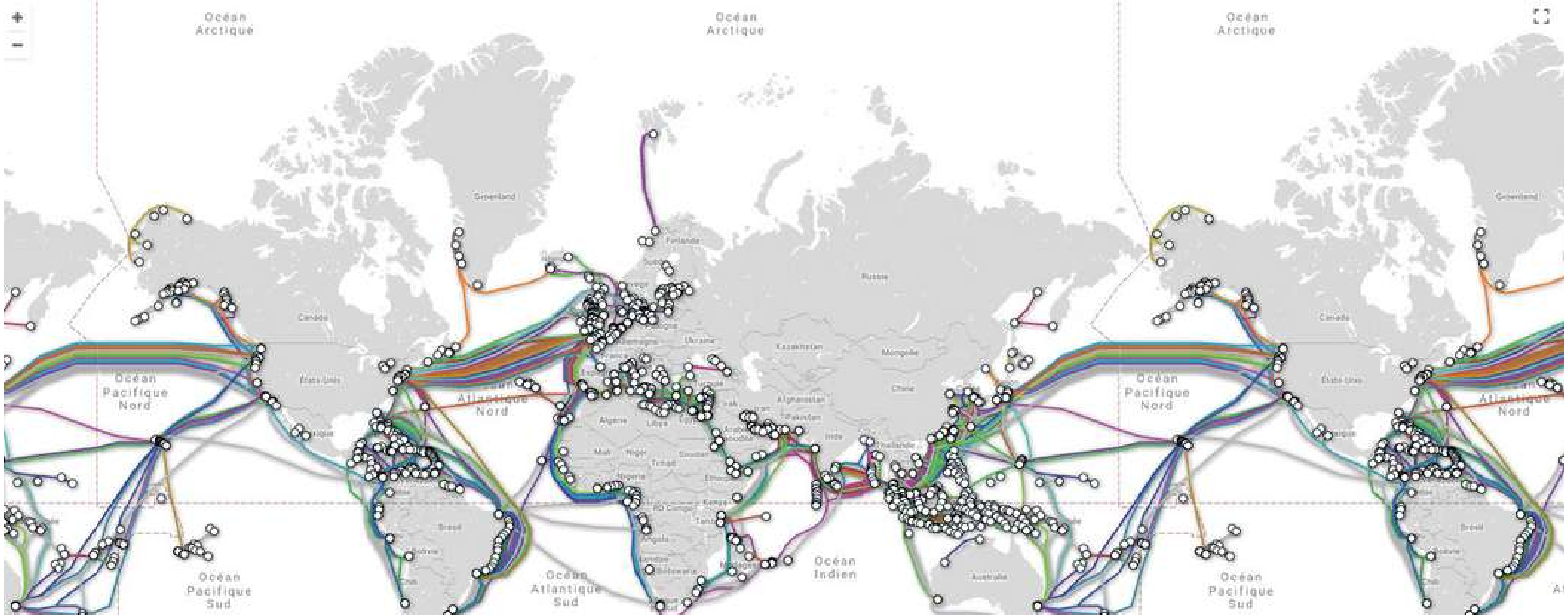
Reading CD's and DVD's

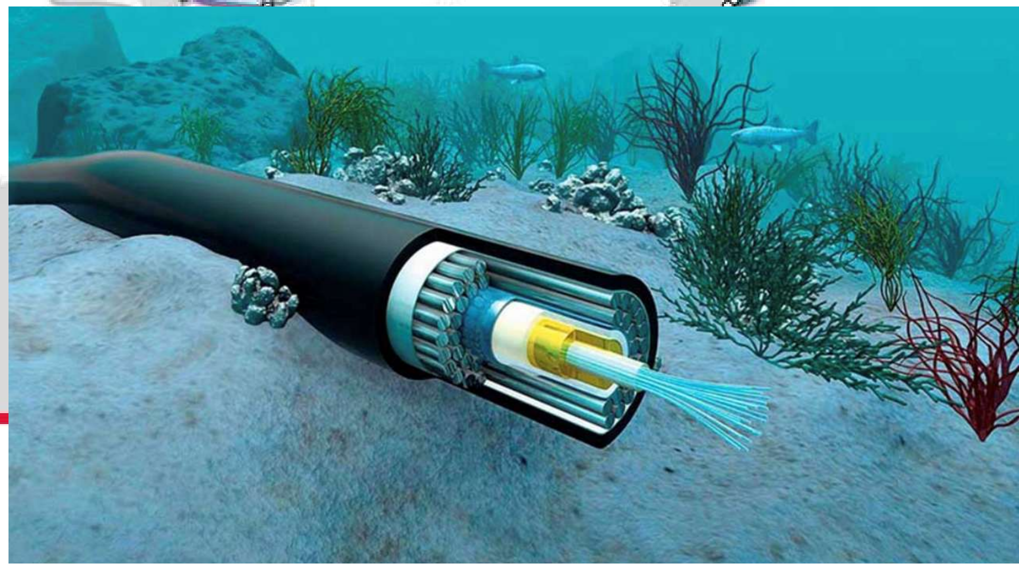
LIDAR technology



Eye surgery....

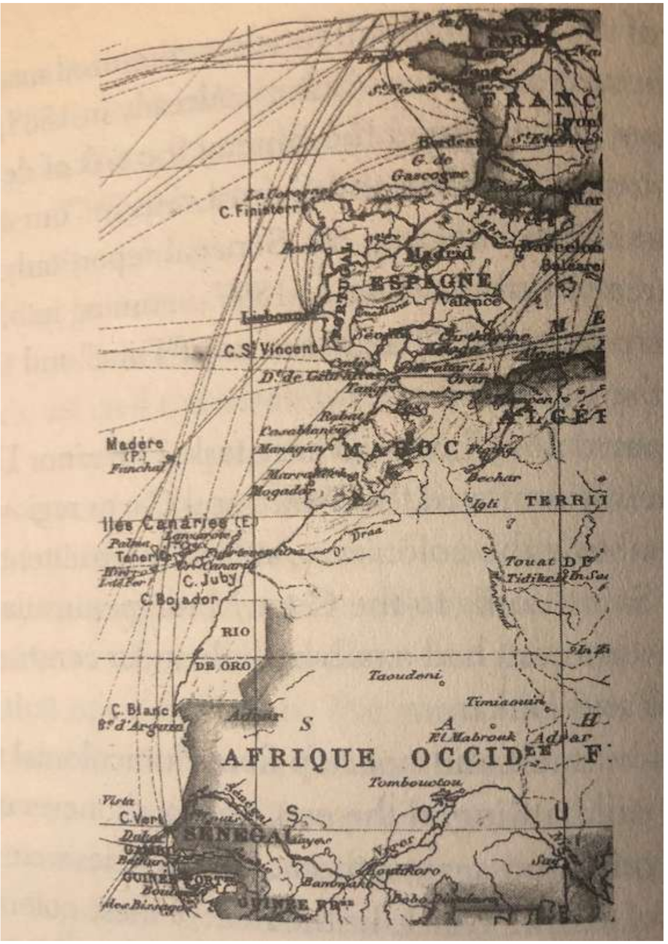
Internet optical fiber cable network





What is the (far-fetched…) connection between electric cable networks and the laser?

Electrical intercontinental cables have been estabished in the 19th century for time synchronization and longitude measurements.



This practical developpment has raised questions which have played an important role in the emergence at the turn of the twentieth century of modern physics (relativity and quantum mechanics)

The laser is an offsprings of these scientific revolutions. Its development has been applied to time and space measurement, to navigation and many other domains…which the pionners of telegraphic cable networks could not even have dreamed about….

Peter Galison: « Einstein's clocks, Poincaré's maps »

The laser in basic science

How it was invented after a fundamental discovery

How it revolutionizes measurement of space and time

How it makes possible the manipulation of single atoms for quantum information processing

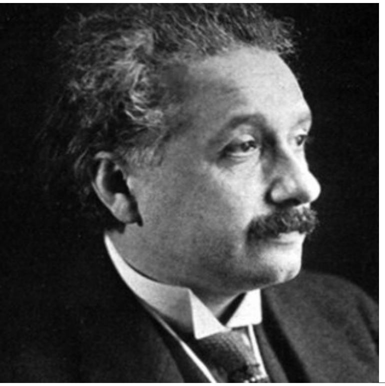
How it achieves cooling matter at extremely low temperatures

How it generates extremely high light intensities and extremely short light pulses useful in chemistry

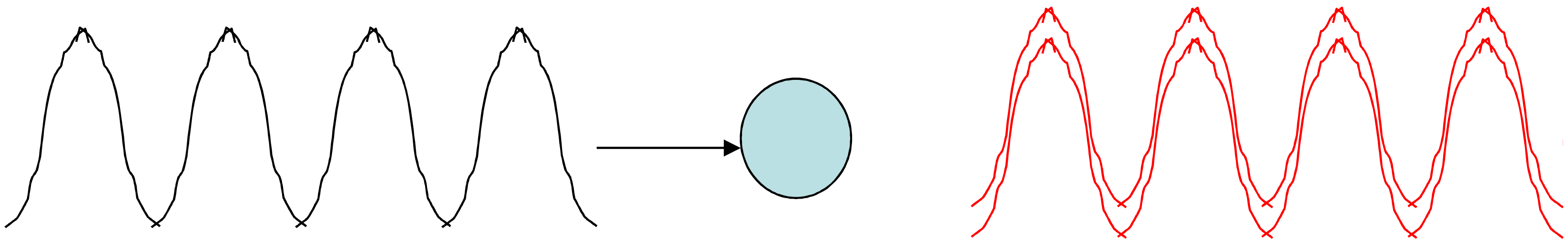
How it opens the way to gravitational astronomy…

… and what else to expect

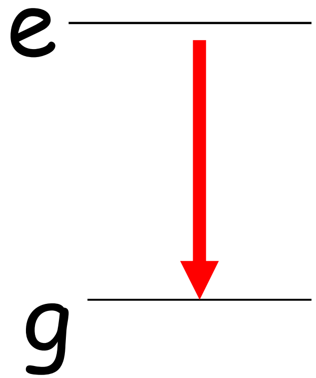
Stimulated emission of light: one of Einstein's bright ideas (1916)



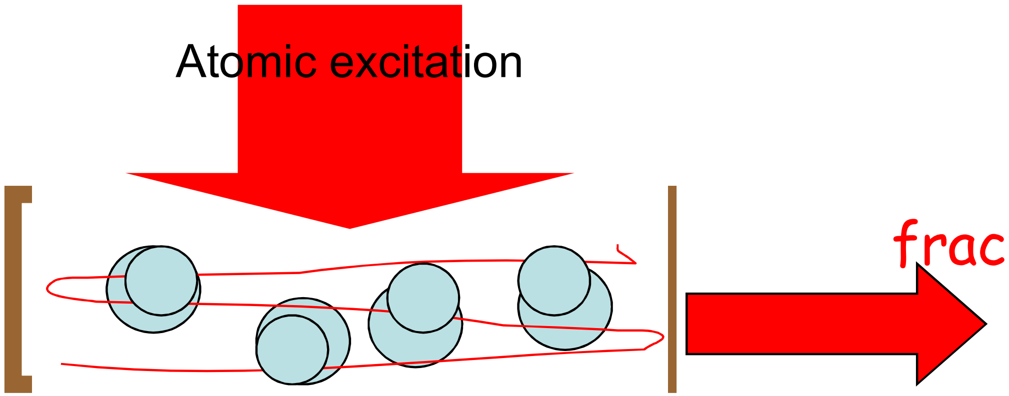
Excited atoms amplify light



Atomic energy levels



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



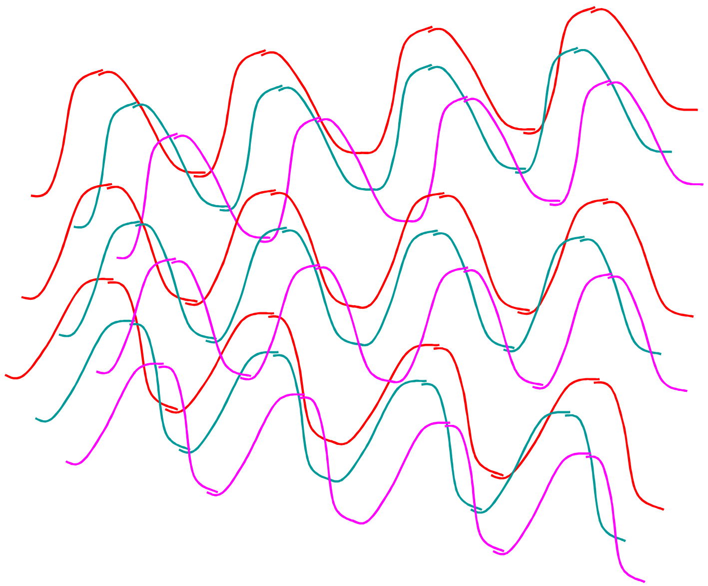
Light between mirrors amplified by excited atoms to the point of self-oscillation and a fraction of light escapes through output mirror:

laser beam

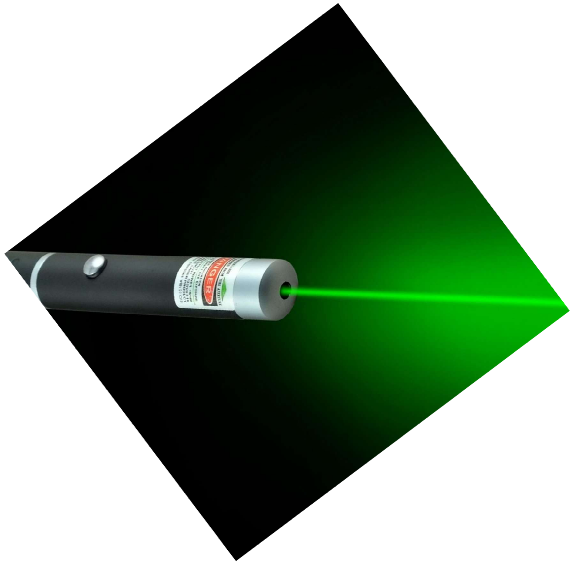
(photons "in step")

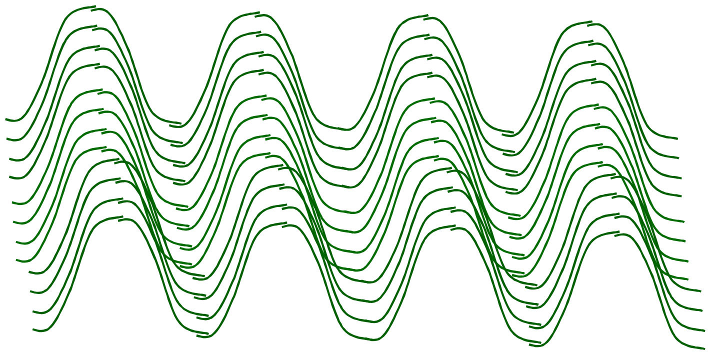
Fifty years between discovery and application!

Classical versus Laser light



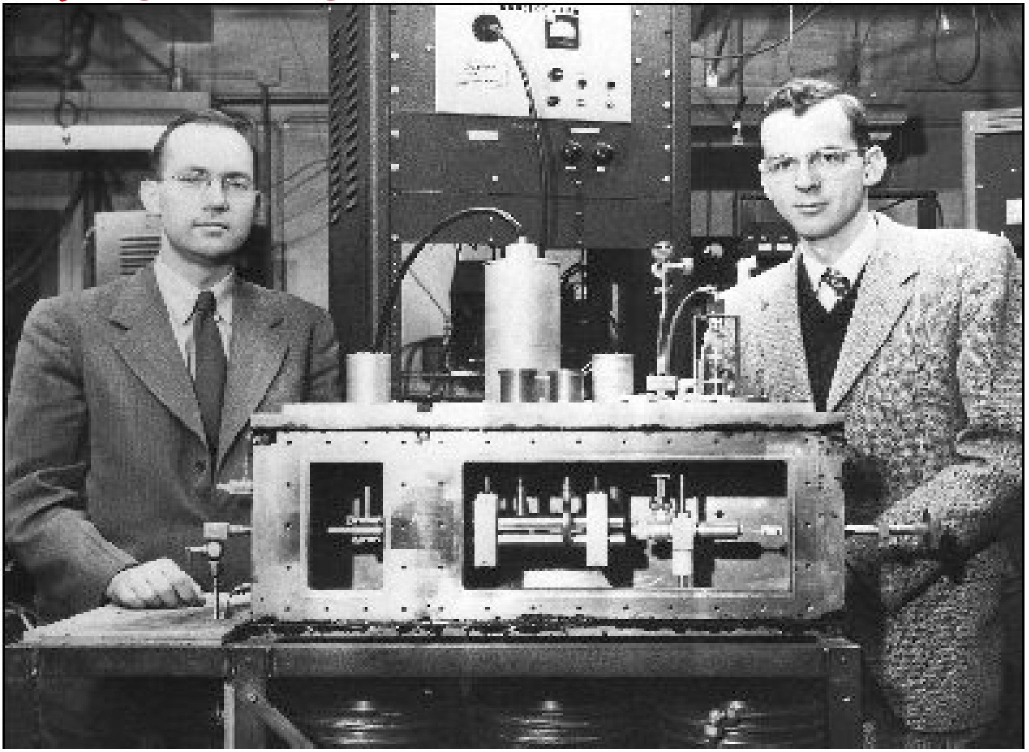
Classical light (Sun, Lamp): atoms emit independently radiations with random phases and dispersion of frequencies and directions





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

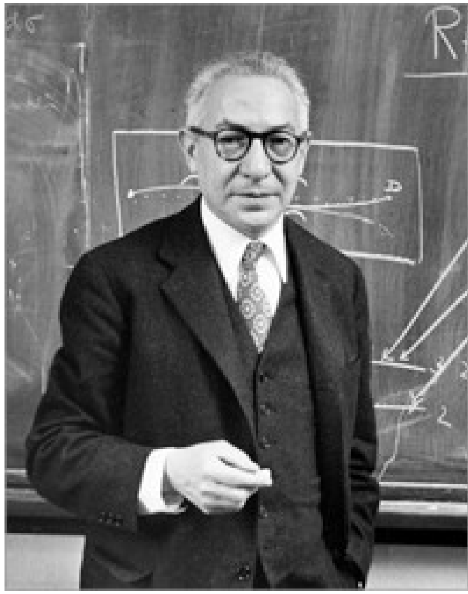
1915-2015



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

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

The Maser, atomic clocks and NMR are inventions originating from I.Rabi's **molecular beam method**



1898-1988

The "optical maser" (1958)

Charles
Townes
(1915-2015)

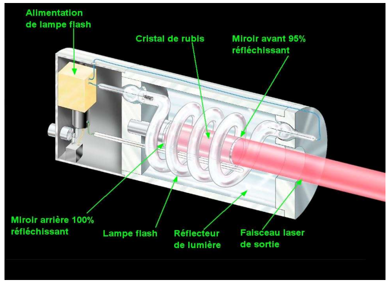
How to
« pump »
atoms
efficiently in
excited state?
What kind of
cavity?

Arthur
Schawlow
(1921-1999)

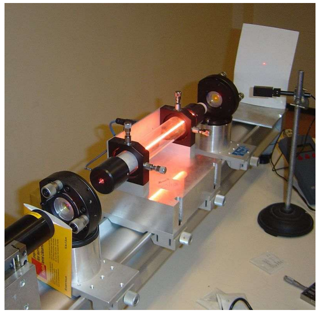
The first lasers (1960)

Theodor
Maiman
(1927-2007)

Ruby laser



Gas laser



Ali
Javan
(1926-2016)

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…

60 years of Atomic, Molecular & Optical Physics

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

A ten order of magnitude (or more) improvement in many fields (a factor of ten every five years!)

	1960	2020's
Precision (spectroscopy and clocks):	10^{-8}	10^{-18}
Sensitivity of measurements:	10^{10} atoms	1 atom/ 1 photon
Temperatures and kinetic energies of atoms:	1-300K	10^{-10} K (cold atoms)
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)

Progresses of metrology due to laser

Before lasers the meter was related to the wavelength of a Krypton classical lamp

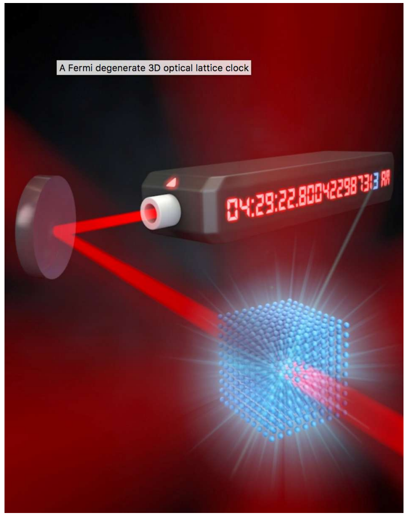
1960

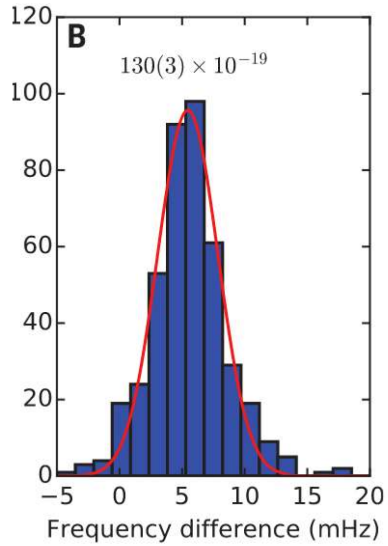
$$\frac{\Delta\lambda}{\lambda} = 10^{-8}$$

1 meter = 1,650,763.73 λ_K

2020's

The second will be (soon?) related to the period of an atomic optical transition. Knowing the velocity of light, the meter will be defined with a ten order of magnitude improved precision



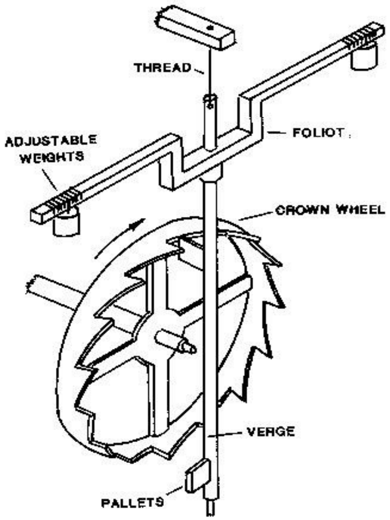


1 sec = 429 228 004 229 873.13 periods of Sr transition

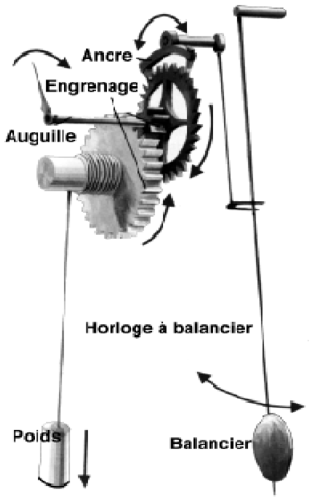
$$\frac{\Delta\nu}{\nu} = 10^{-18}$$

1 m: distance traveled by light during 1/ 299 792 458 sec

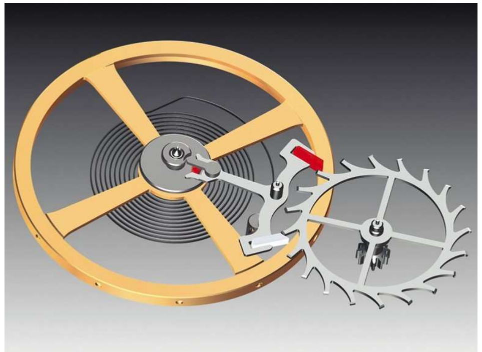
A brief history of the measurement of time



14th century:
Tower clock



17th century:
Pendulum (Galileo, Huyghens)



18th century
Marine chronomete and spring watch (Harrisson)

1920's
Quartz clock (piezoelectric effect)

Relative uncertainty			
10^{-2}	10^{-4}	10^{-6}	10^{-8} 1s/year

General principle: an oscillator coupled to an escape device which counts periods. The higher the frequency, the more precise the clock

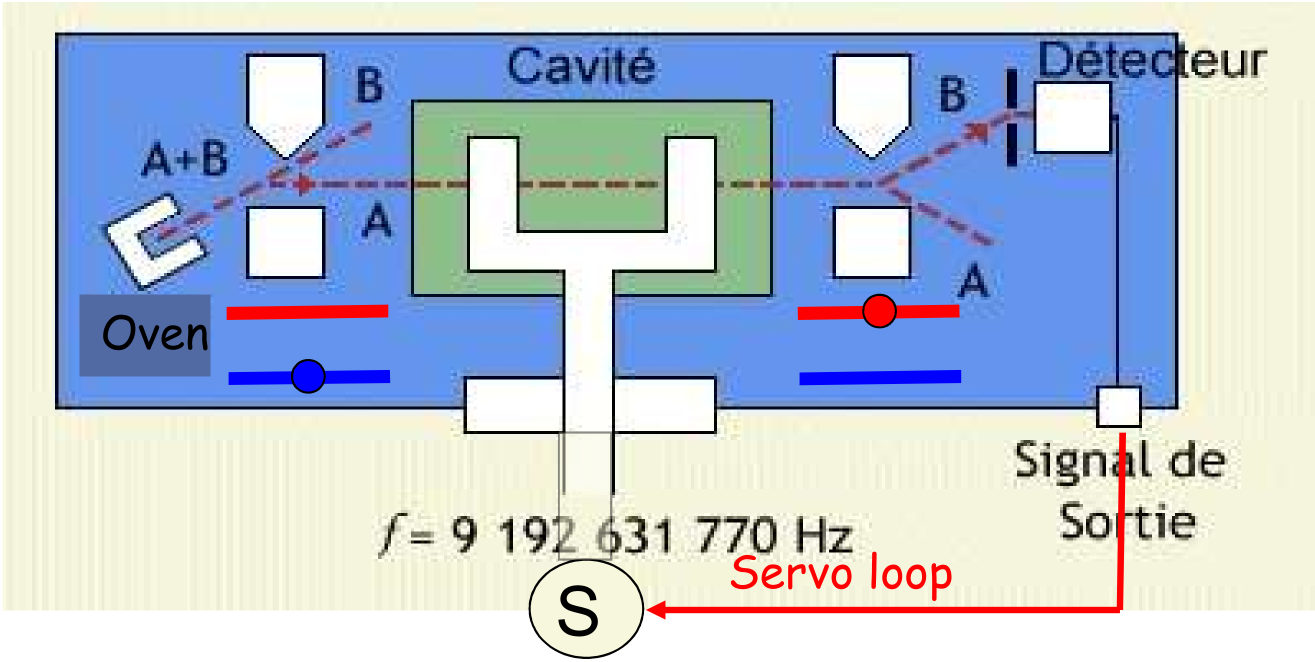
On a log scale, much less improvement in the 6 centuries preceding the 1950's than during the last sixty years with advent of atomic clocks counting atomic transition frequencies!

The microwave atomic clock operates, like the maser, on an atomic beam machine

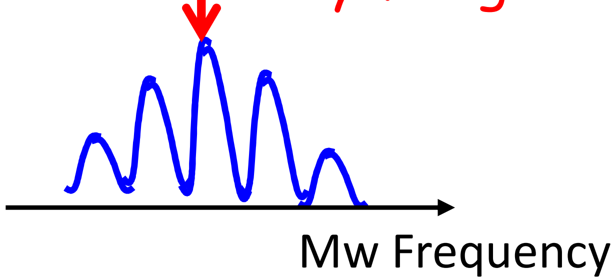
N.Ramsay
(a student of Rabi)

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!



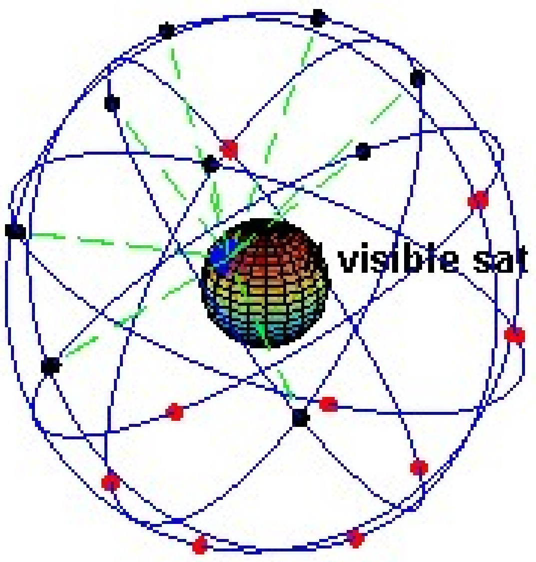
Cesium beam probed by a **double microwave pulse**: resonance exhibits Ramsey fringes



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

The GPS

The GPS

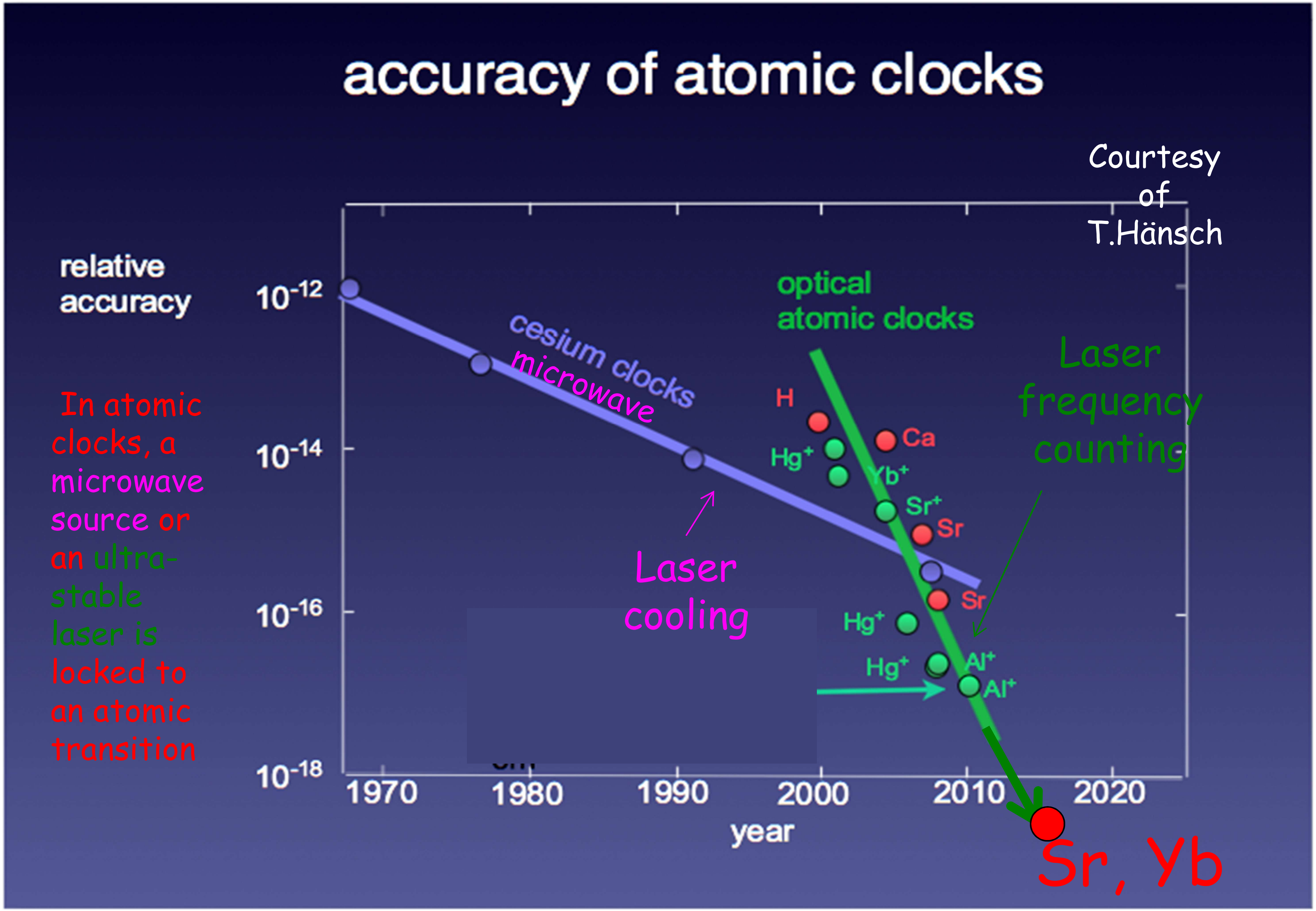


Triangulation with signals received from synchronized microwave atomic clocks embarked in satellites. Nanosecond per day and meter precision!

$$\frac{\Delta\nu}{\nu} = 10^{-14}$$

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

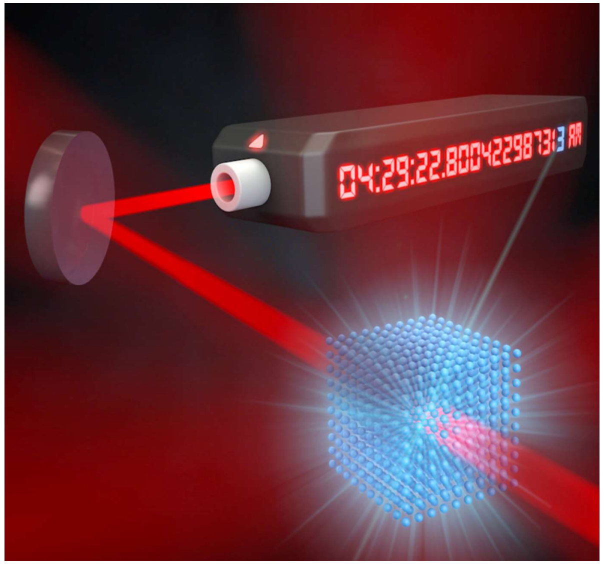
The present GPS has improved by eleven orders of magnitude the clock synchronization precision of the cable telegraph pionners… and further improvements are still to come with optical clocks…



The best clocks of 2020's are 10^{11} times more precise than the best quartz clocks of the 1950's: **10^{-14} s per day instead of 10^{-3} s**

Strontium Optical clock (oscillating at ≈ 4. 10^{14}Hz)

JILA
(Boulder
-2017)



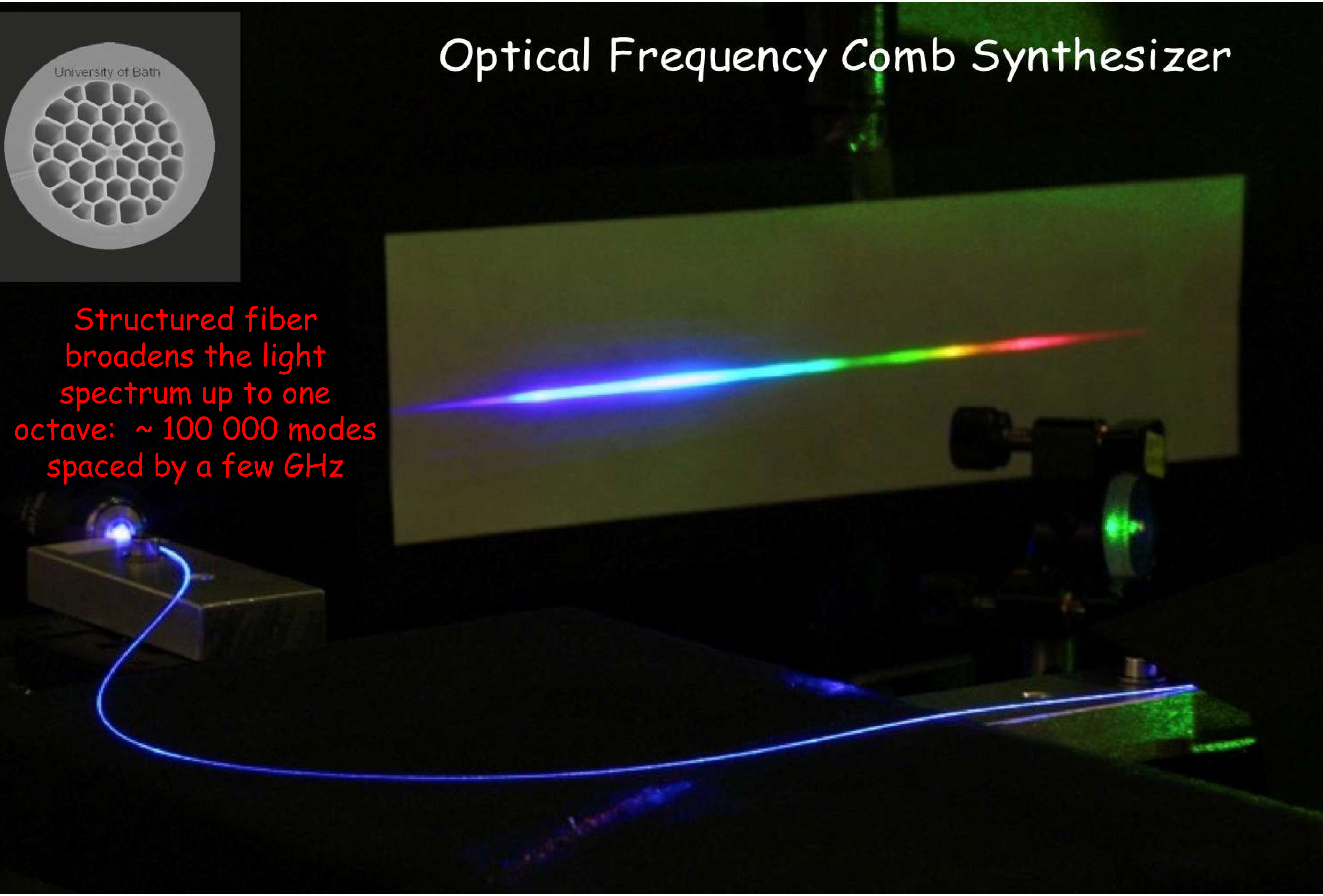
Accuracy
3.5 10^{-19}

Less than a tenth of a second uncertainty since the Big Bang!

Ultrastable laser locked on an optical transition of strontium observed on a 3D array of cold atoms: different lasers are used to cool and trap the atoms and to lock on the transition frequency.

Optical frequencies counted by ***frequency comb laser***

Optical Frequency Comb Synthesizer



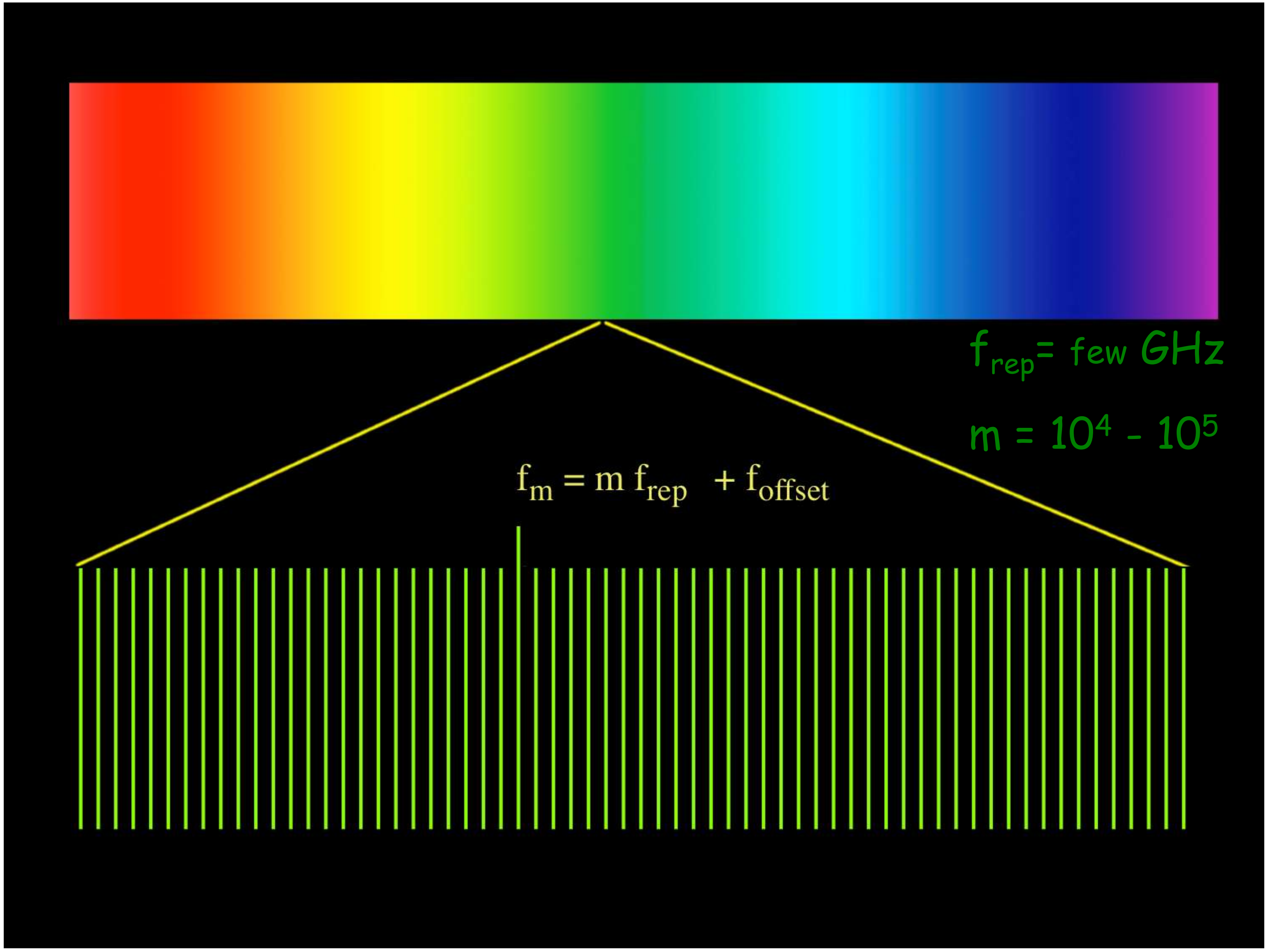
Structured fiber broadens the light spectrum up to one octave: ~ 100 000 modes spaced by a few GHz

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

T.Hänsch

J.Hall

2005



A "ruler" spanning an octave in frequency measuring the frequency of an atom with a laser comb

An optical clock

Sr

Al^+

Stable laser locked to atom is a[redacted] optical clock and the comb bridg[redacted] gap with the microwave domain (escape mechanism)

Lock Microwave to comb interval

60 years of Atomic, Molecular & Optical Physics

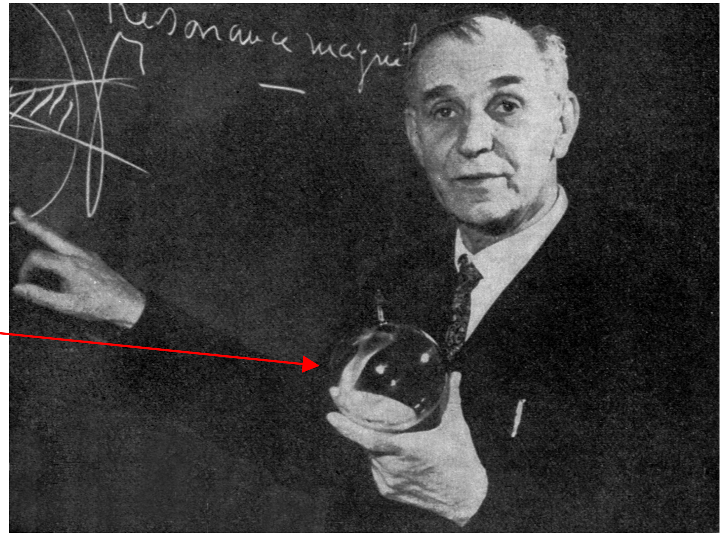
The laser has made tremendous progresses possible and has led to quantitative and qualitative revolutions in basic research

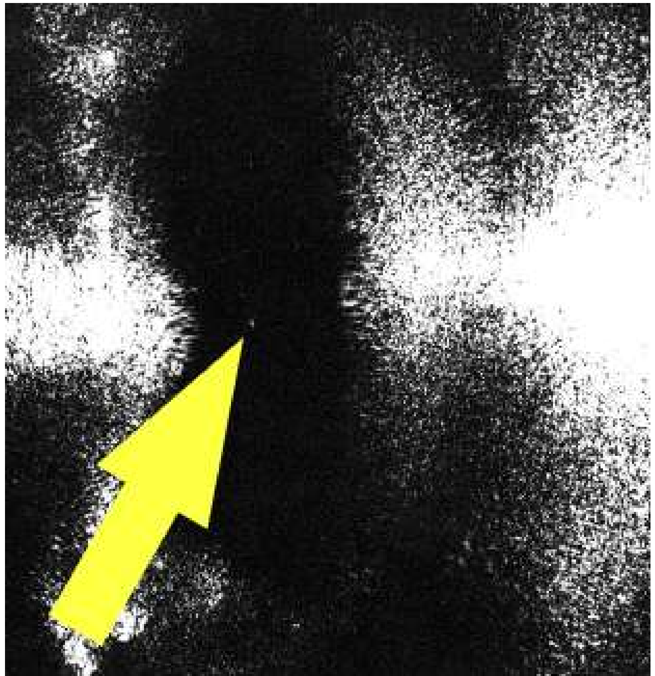
A ten order of magnitude (or more) improvement in many fields (a factor of ten every five years!)

	1960	2019
Precision (spectroscopy and clocks):	10^{-8} (1s/year)	10^{-18} (1s/age of Universe)
Sensitivity of measurements:	10^{10} atoms in cell	1 atom/ 1 photon
Temperatures and kinetic energies of atoms:	1-300K	10^{-10} K (cold atoms)
Speed and time resolution:	Nanosecond (10^{-9}s)	Attosecond (10^{-18}s)
Relative sensitivity to length variation $\Delta h/h$	10^{-8} - 10^{-9} (Interferometric definition of meter)	10^{-21} - 10^{-22} (LIGO/VIRGO)

Detection sensitivity in spectroscopy

Optical Pumping experiment of the 1960's: cell containing ~ 10^{10} atoms





P.Toschek

First observation of a single Ba^+ ion in a Paul trap (P.Toschek group, 1978)

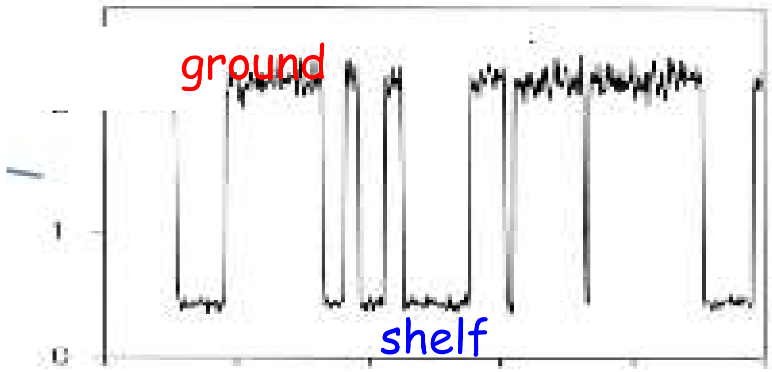
Ten orders of magnitude again!

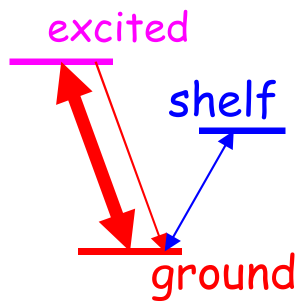
Single atom physics and quantum information

Quantum jumps of a trapped ion:

intensity of ion's fluorescence

(Toschek-Wineland (1985)



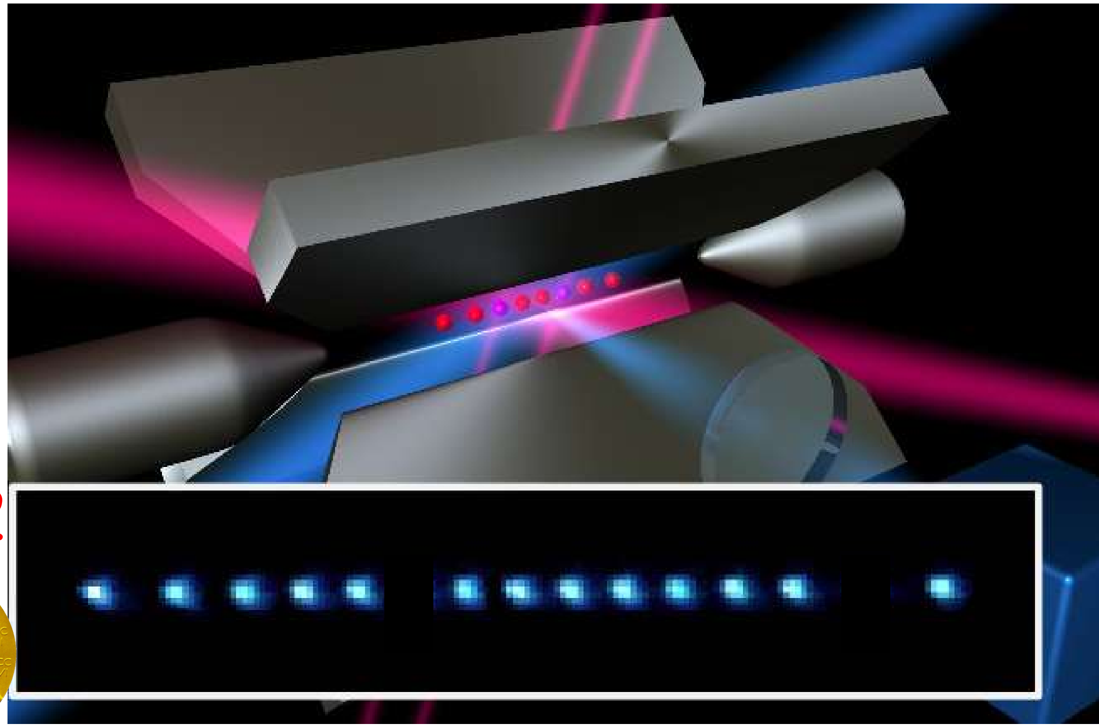


Fluorescence from a string of trapped ions behaving as quantum bits (Blatt, Wineland.....)

Similar experiments manipulate trapped photons (my research group)

Photons and atoms as qubits for quantum information

2012



60 years of Atomic, Molecular & Optical Physics

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

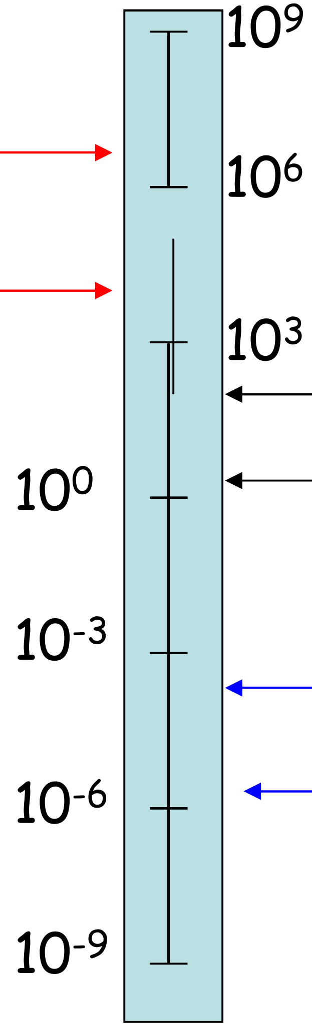
A ten order of magnitude (or more) improvement in many fields (a factor of ten every five years!)

	1960	2019
Precision (spectroscopy and clocks):	10^{-8} (1s/year)	10^{-18} (1s/age of Universe)
Sensitivity of measurements:	10^{10} atoms in cell	1 atom/ 1 photon
Temperatures and kinetic energies of atoms:	1-300K	10^{-10} K (cold atoms)
Speed and time resolution:	Nanosecond (10^{-9}s)	Attosecond (10^{-18}s)
Relative sensitivity to length variation $\Delta h/h$	10^{-8} - 10^{-9} (Interferometric definition of meter)	10^{-21} - 10^{-22} (LIGO/VIRGO)

Going towards T=0K

1997

S.Chu, W.Phillips,
C.Cohen-Tannoudji



Inside stars

Sun surface

Room temperature
(atomic velocity ~ 500 m/s)

Cosmologic background

Cryogenic
methods
(liquid He)

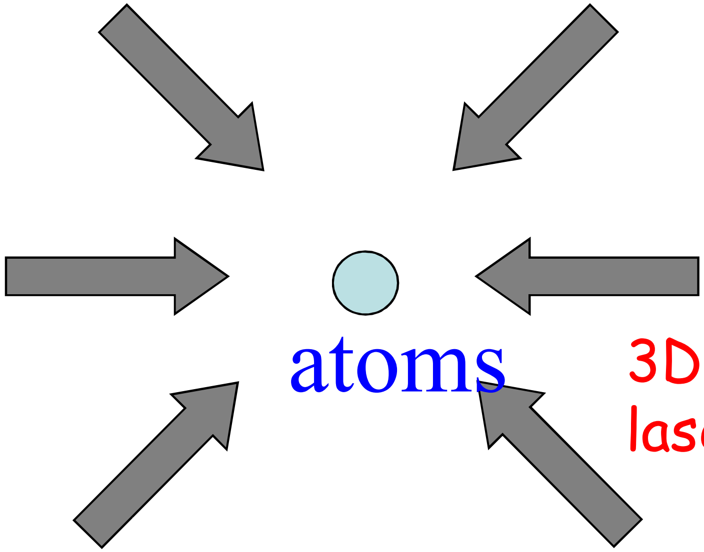
"Doppler" Laser cooling
(v ~ 1m/s) in 1985

SubDoppler cooling
(v ~ 10 cm/s) in 1988

Evaporative cooling and
Bose Einstein condensates
(v ~ 1mm/s) in 1995

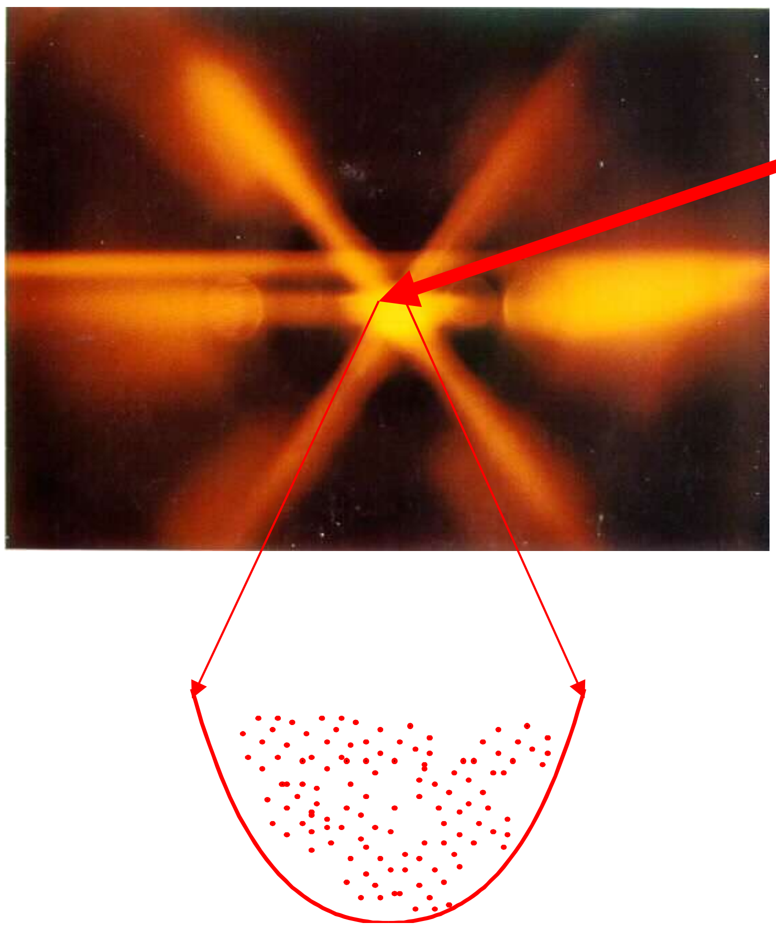
Eleven orders of magnitude gained towards low temperatures and 5 to 6 orders towards low atomic velocities since 1960-70

Optical molasses and magnetic trap



3D cooling with six laser beams

One billion atoms at a few, microKelvins, flying in random direction at a few tens of cm/s like in a viscous medium, scattering laser photons

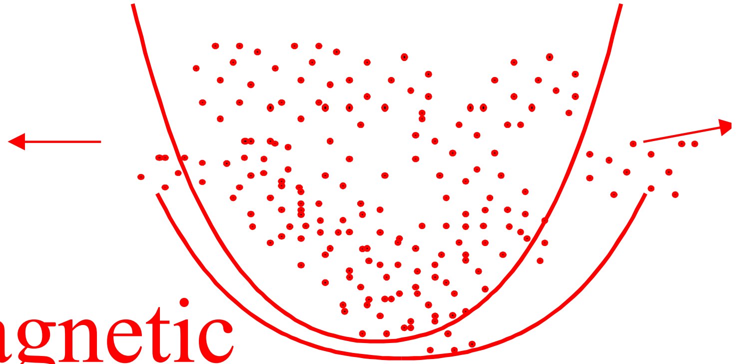


One turns the light off and switch on a configuration of magnetic fields which trap the cold atoms as if they were in a kind of magnetic bottle with non-material walls

Is it possible to cool even more?

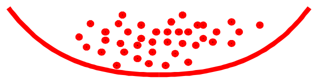
How to reach the condensation threshold ?

Cooling by evaporation: one lowers the trapping walls to let the fastest atoms escape

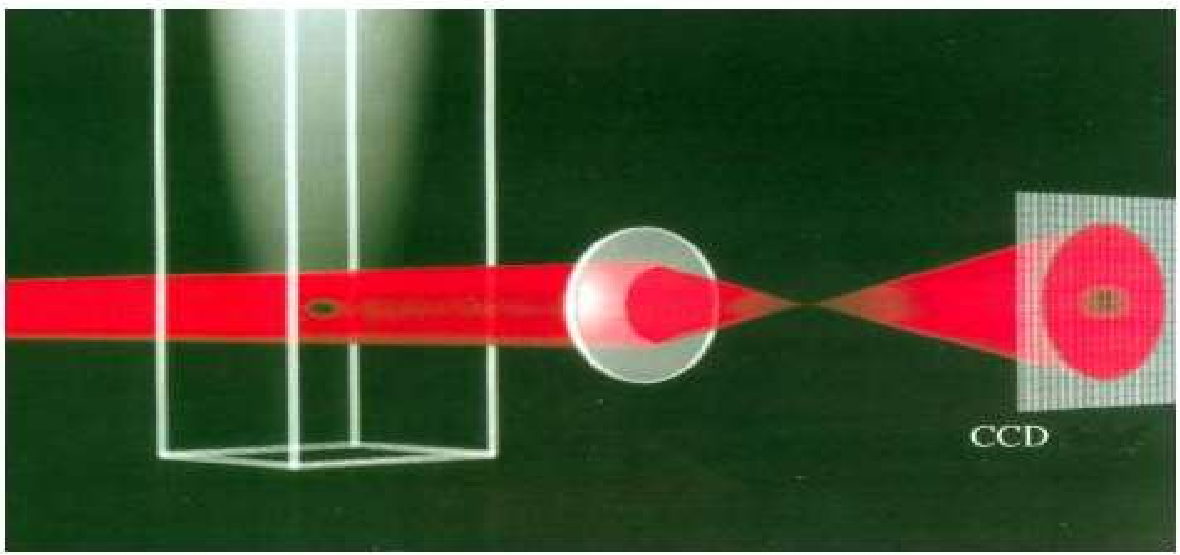


Magnetic trap

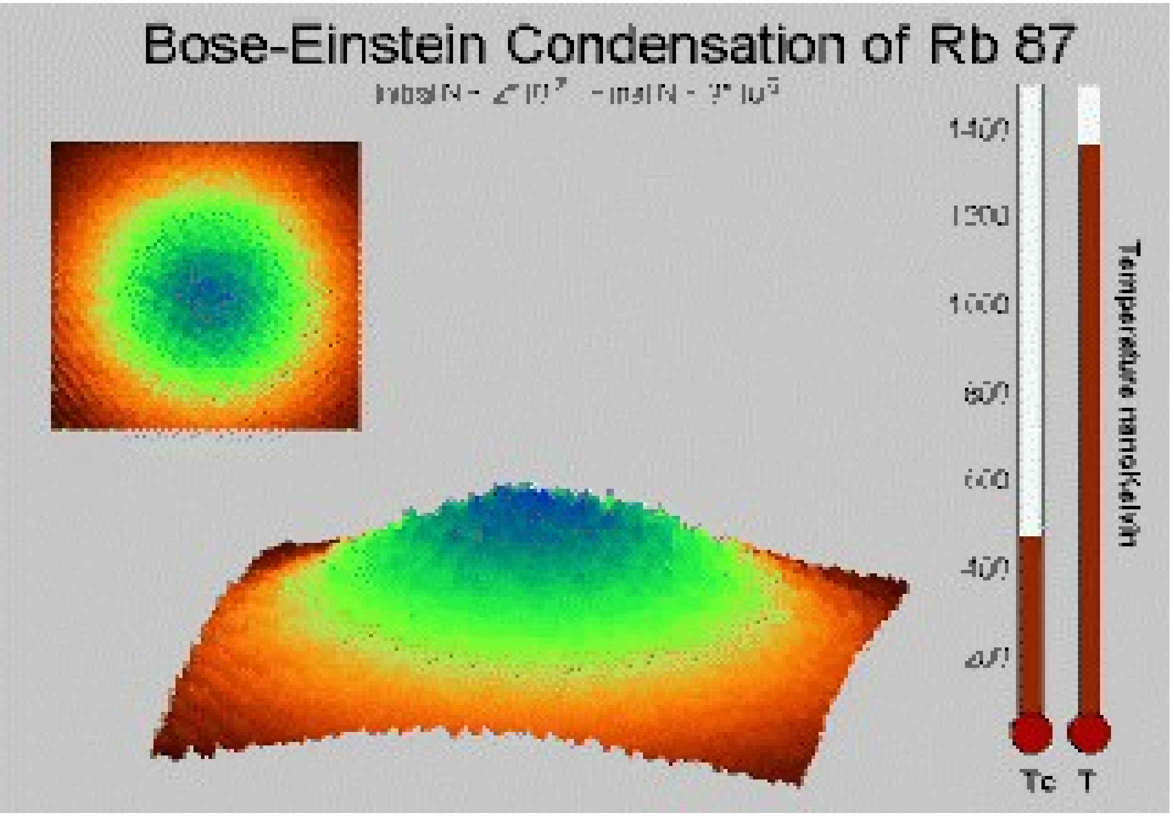
Interatomic distance becomes smaller than the de Broglie wavelength: Bose-Einstein condensation



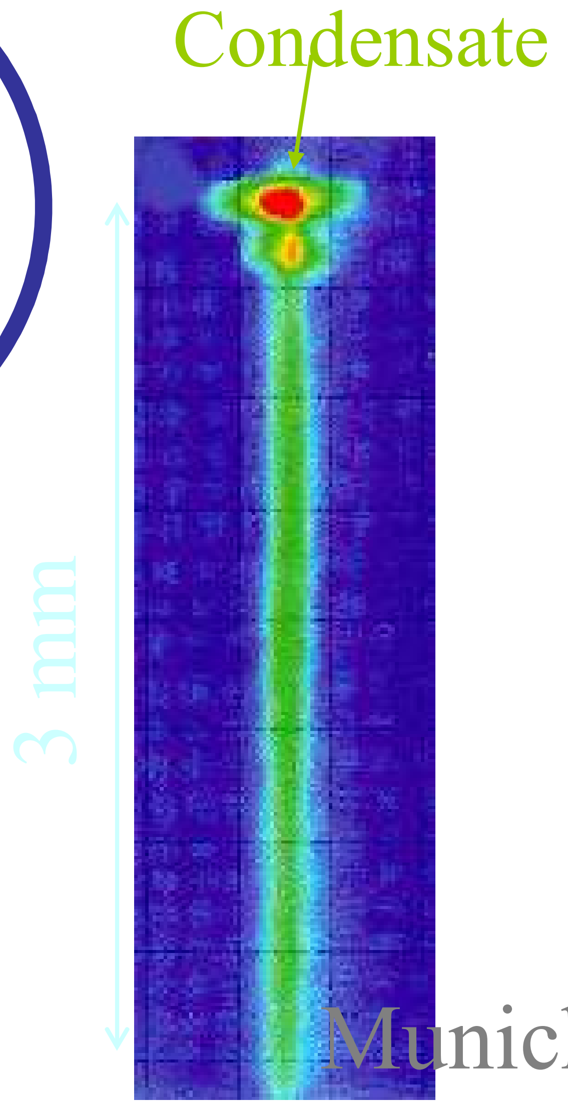
Imaging the atoms with laser light (shadow of the atomic cloud on a screen)



Film of Bose-Einstein condensation



The coldest objects in the Universe



Cornel,
Weiman,
Ketterle

2001

And image of an atom- laser

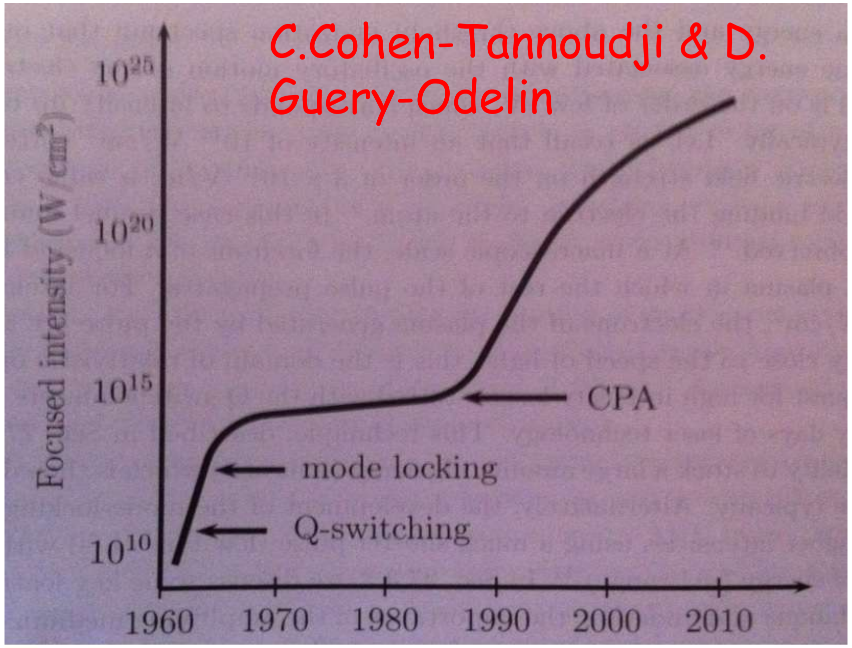
60 years of Atomic, Molecular & Optical Physics

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

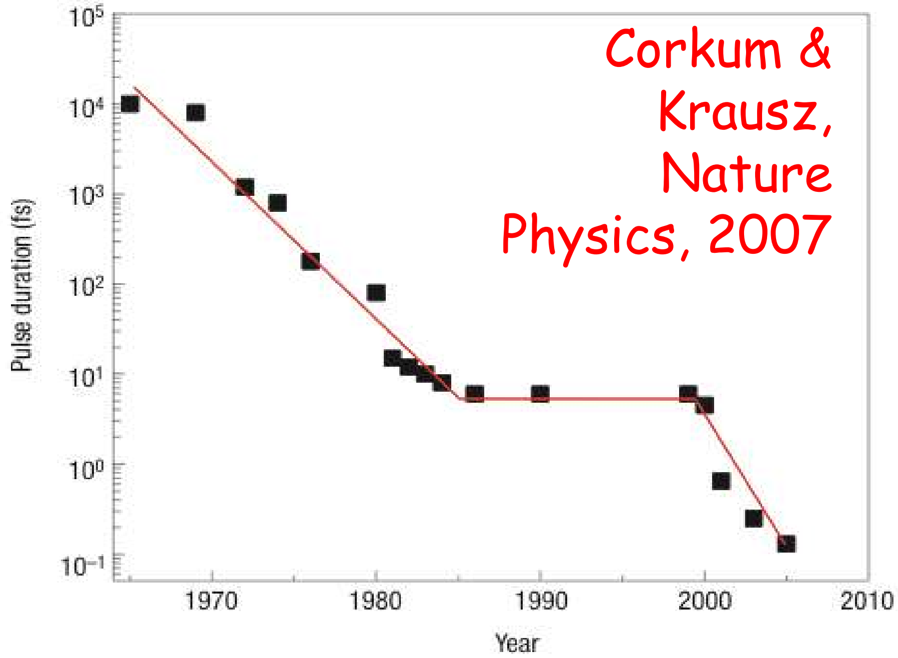
A ten order of magnitude (or more) improvement in many fields (a factor of ten every five years!)

	1960	2019
Precision (spectroscopy and clocks):	10^{-8} (1s/year)	10^{-18} (1s/age of Universe)
Sensitivity of measurements:	10^{10} atoms in cell	1 atom/ 1 photon
Temperatures and kinetic energies of atoms:	1-300K	10^{-10} K (cold atoms)
Speed and time resolution:	Nanosecond (10^{-9}s)	Attosecond (10^{-18}s)
Relative sensitivity to length variation $\Delta h/h$	10^{-8} -10^{-9} (Interferometric definition of meter)	10^{-21} -10^{-22} (LIGO/VIRGO)

High light power and ultra-short light pulses progresses over last fifty years



Evolution of peak laser power (W/cm^2)



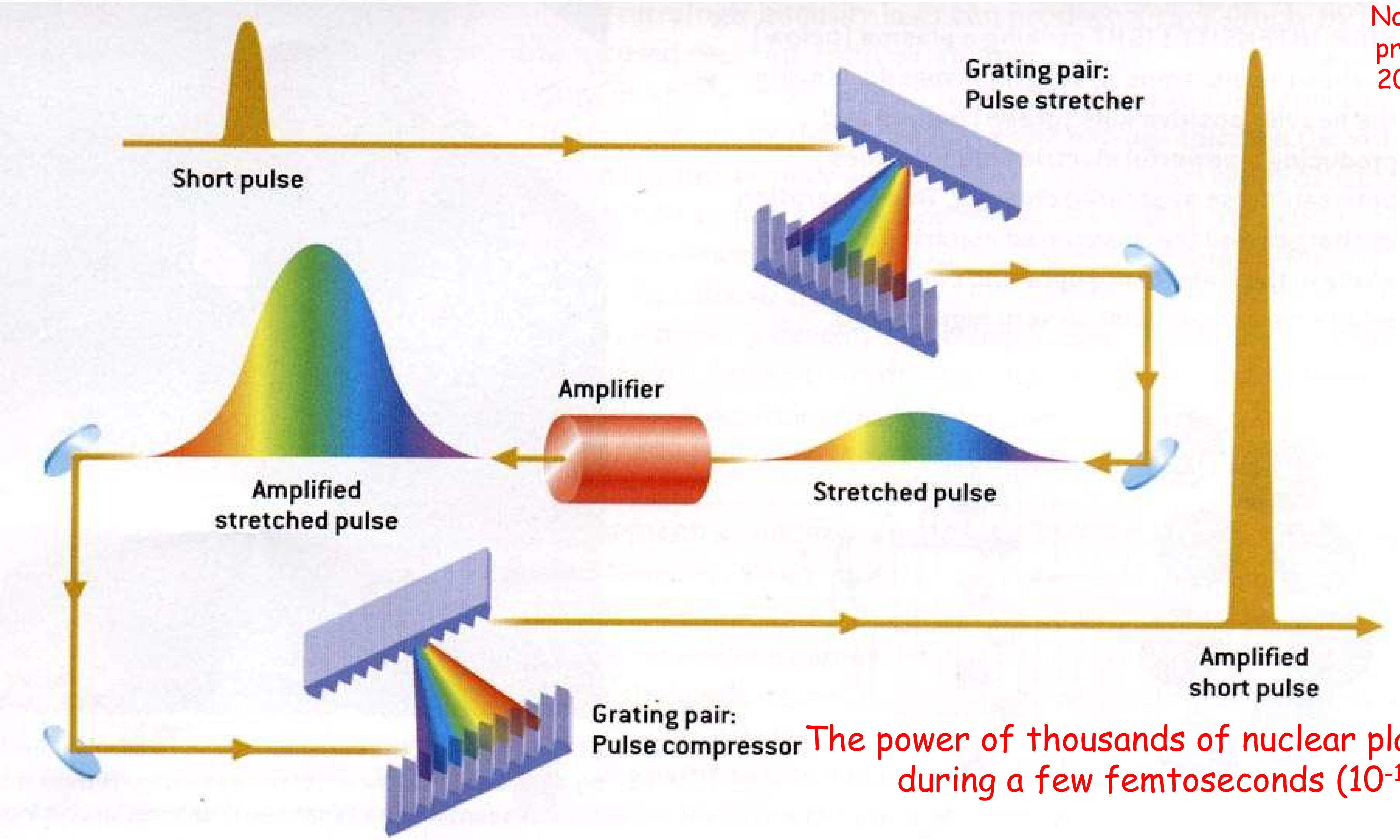
Evolution of pulse duration (femtoseconds)

Short laser pulses generate ultra-short X ray pulses in the attosecond range by non linear optical effects in gases

Chirped Pulse Amplification (CPA)

Strickland et Mourou, Opt.Comm.56, 219 (1985)

Nobel prize 2018



The power of thousands of nuclear plants during a few femtoseconds (10^{-15} s)!

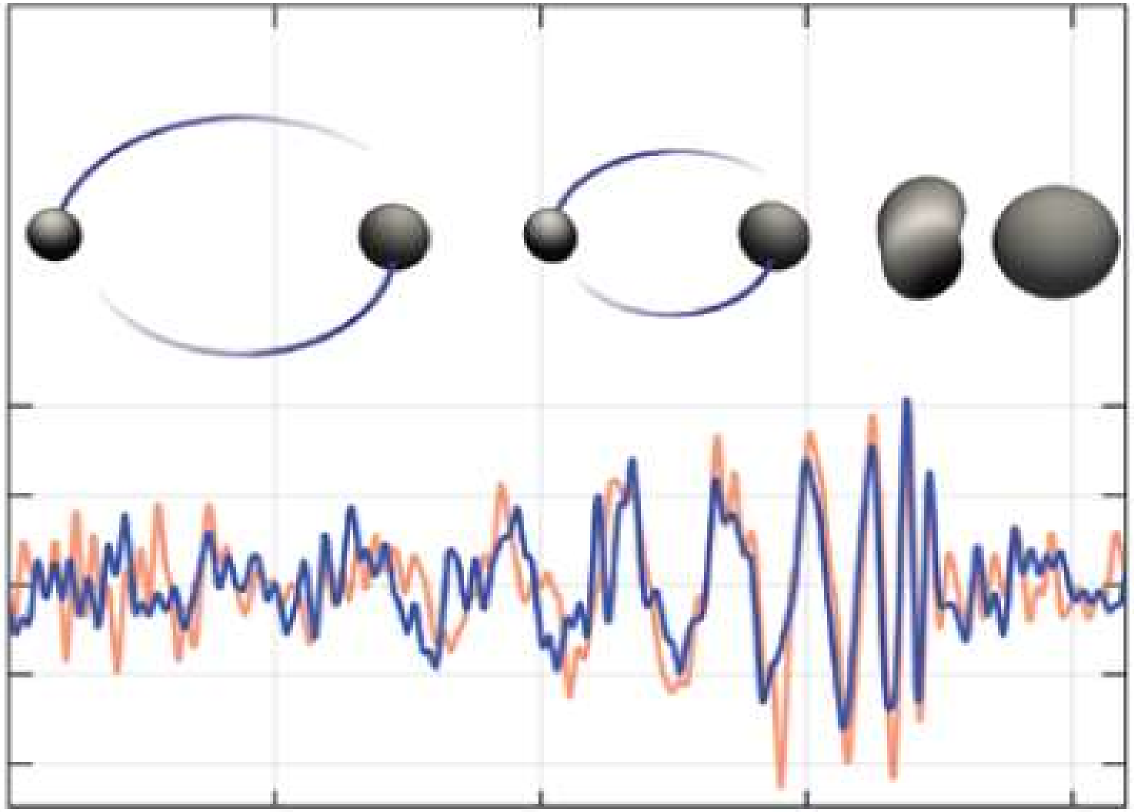
60 years of Atomic, Molecular & Optical Physics

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

A ten order of magnitude (or more) improvement in many fields (a factor of ten every five years!)

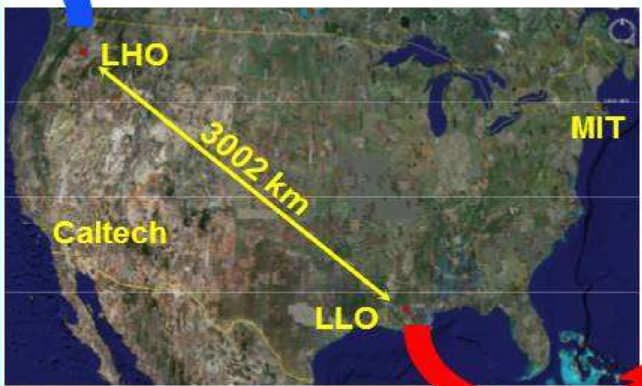
	1960	2019
Precision (spectroscopy and clocks):	10^{-8} (1s/year)	10^{-18} (1s/age of Universe)
Sensitivity of measurements:	10^{10} atoms in cell	1 atom/ 1 photon
Temperatures and kinetic energies of atoms:	1-300K	10^{-10} K (cold atoms)
Speed and time resolution:	Nanosecond (10^{-9}s)	Attosecond (10^{-18}s)
Relative sensitivity to length variation $\Delta h/h$	10^{-8} - 10^{-9} (Interferometric definition of meter)	10^{-21} - 10^{-22} (LIGO/VIRGO)

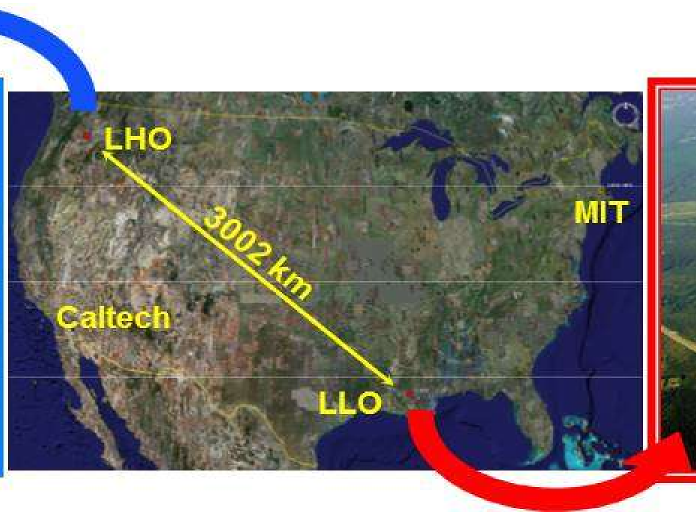
The coalescence of two black holes 1,3 Billion light-years away…

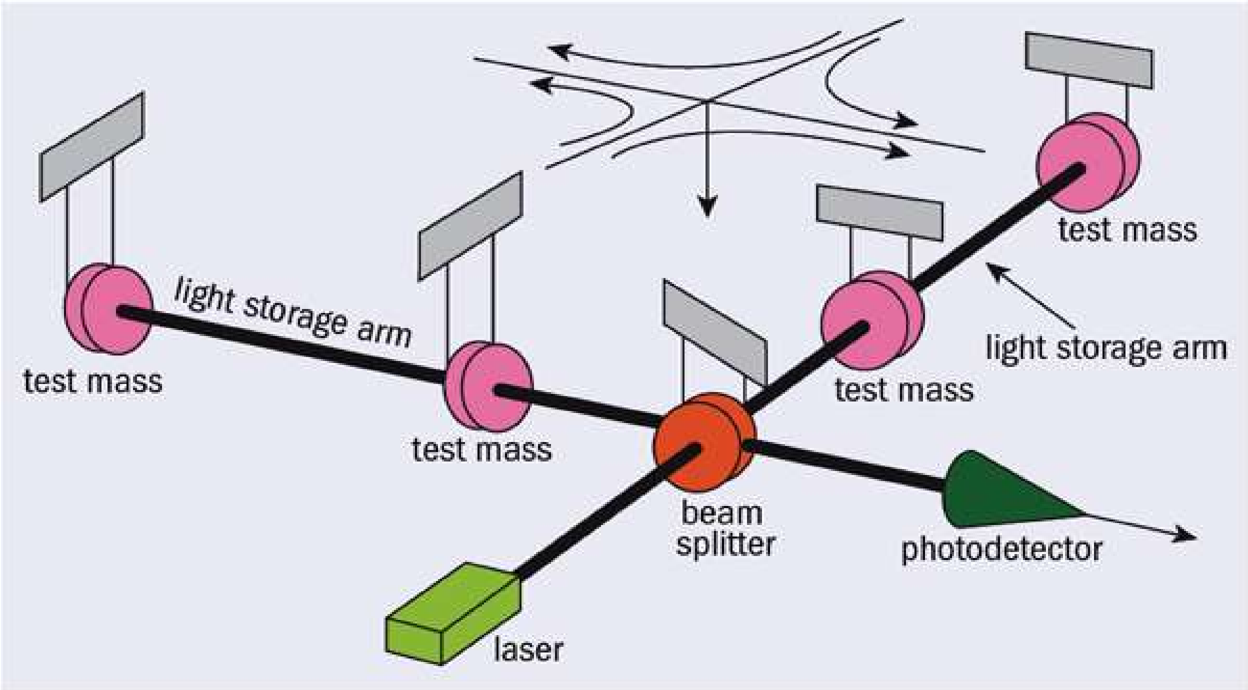


…has produced a tiny gravitational wave detected by the two antennas of LIGO

A tour de force detecting a displacement of mirrors (separated by 4km) of less than a billionth of an atomic diameter!



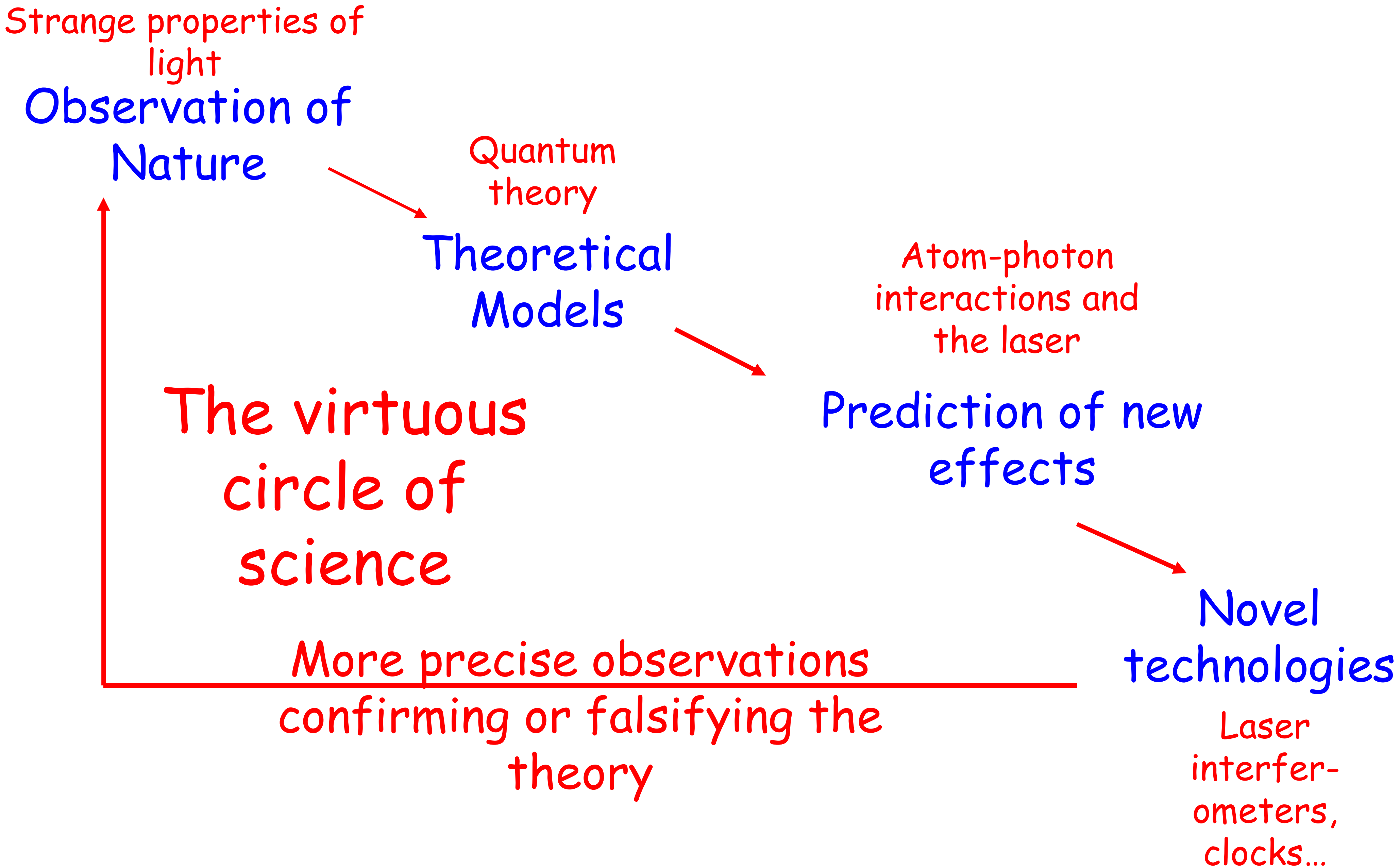




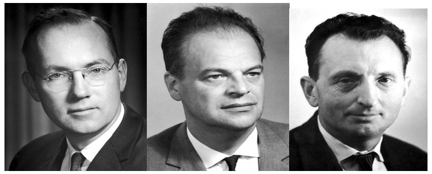
Two Michelson interferometers fed by an ultrastable laser measure the relative change of the length of the two arms when the gravitational wave alters the curvature of space-time…

2017 Opens a new window into the Universe: Gravitational wave astronomy

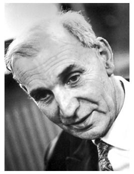
The permanent dialogue between blue sky research and innovation



40 Physics & Chemistry Nobel laureates in 60 years related to lasers and their applications…

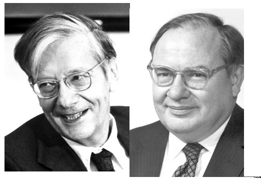


1964 (the Laser)



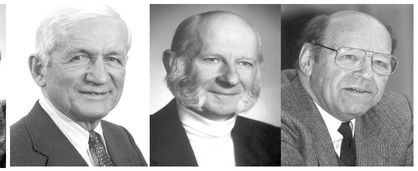
1966 (Optical pumping)

1971 (Holography)



1981 (Laser spectroscopy)

1986 (Lasers in chemistry)

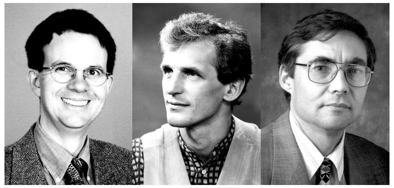


1989: (atomic clocks & ion traps)

1997: (Laser cooling of atoms)

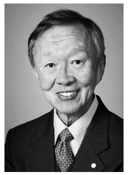
1999: (ultra-short laser pulse chemistry)

2000: (Layered Heterostructures and laser diodes)



2001: (Bose Einstein Condensation)

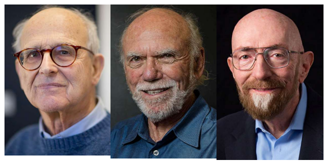
2005: (Quantum optics and frequency combs for optical clocks)



2009: (Optical fibers for laser beams)

2012: (Control of single quantum particles)

2014: Super-resolved fluorescence microscopy

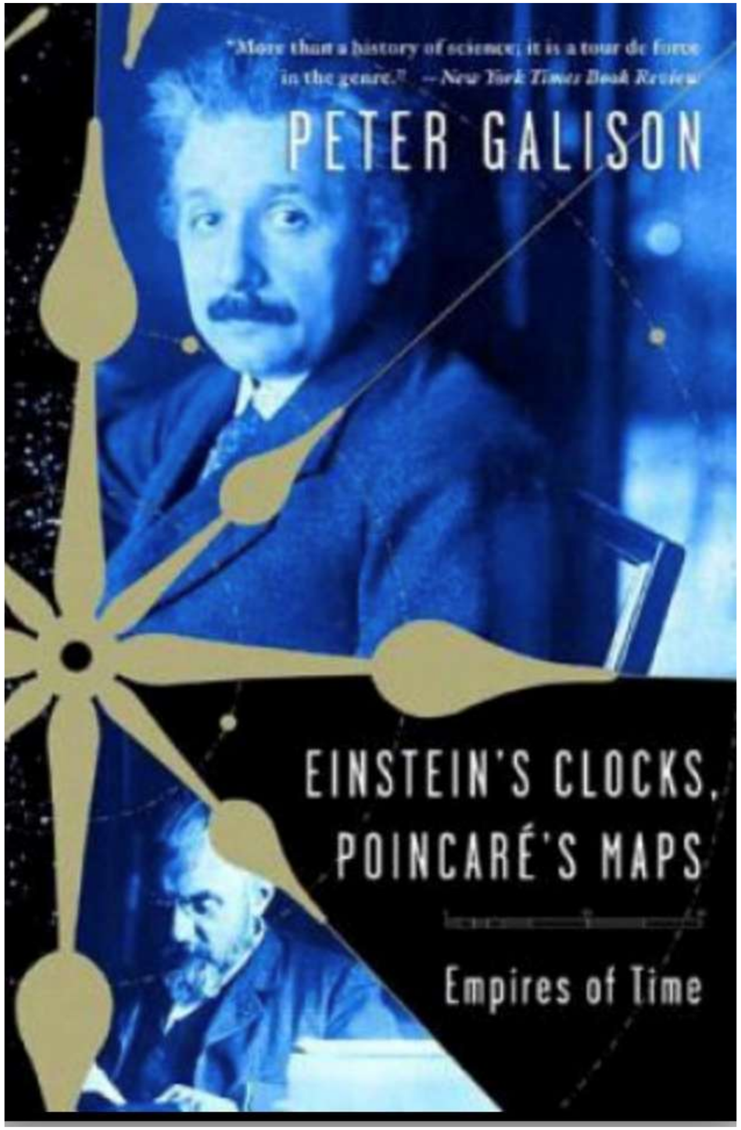


2017: detection of gravitational waves by the LIGO/VIRGO collaboration

2018: Optical tweezers and ultra intense and ultra short light pulses

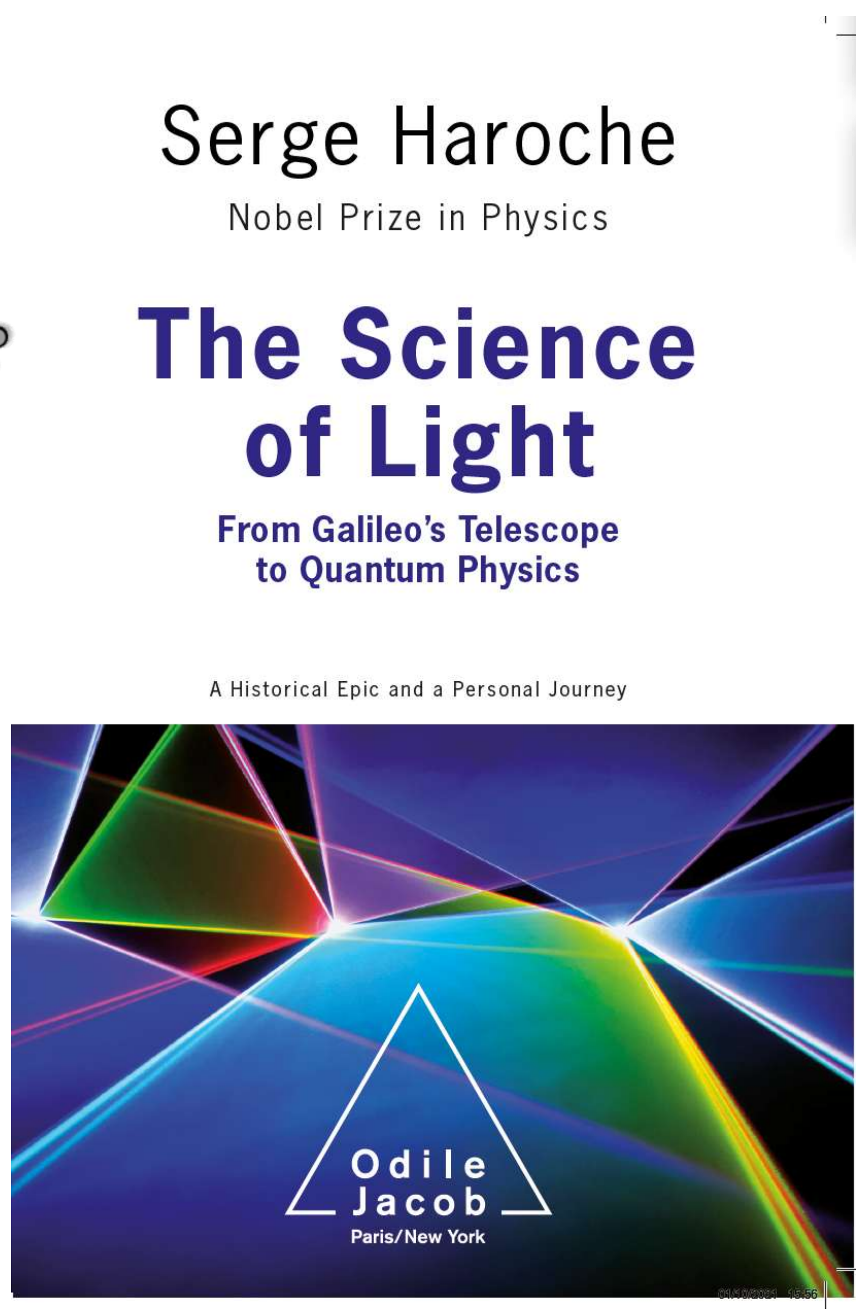
2022: Entanglement and quantum non-locality

…. and more to come…



How telegraphic cable networks have influenced the physics revolution

Thank you!



More about lasers and basic science