"Enrico Fermi" Chair
2021/2022

Lectures at Sapienza Università di Roma,
January-May 2022

A History of the Science of Light

From Galileo's telescope to the laser and the quantum information technologies

Serge Haroche,
Ecole Normale Supérieure and
Collège de France, Paris

Lecture 12. April 21th 2022

Lecture 12:

A passion for precision: the measurement of time

The progresses of high resolution spectroscopy in the microwave and optical domains have been correlated during the last 60 years with the advances of time metrology. Clocks have gained nine to ten orders of magnitude in precision, notably due to the development of the direct measurement of optical frequencies made possible by the invention of laser frequency combs. We analyse in this lecture these spectacular achievements and consider possible applications of this metrology of extreme precision.

Outline of lecture

A reminder about Hydrogen spectroscopy as a test bench to demonstrate high precision spectroscopy methods

A brief history of time measurement from pendulums to atomic clocks

The frequency comb revolution

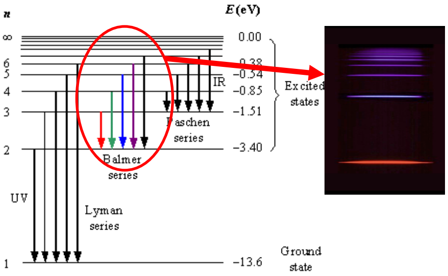
Trapped ions optical clocks

Neutral atoms optical clocks and applications

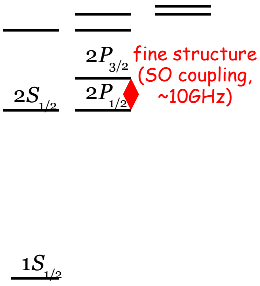
A test bench on precise measurements: a reminder about Hydrogen

The simplest of atoms has served as a test bench for high resolution laser spectroscopy, by using more and more precise methods. The comparison with theory gave new values of fundamental constants and made possible precise tests of Quantum Electrodynamics. Theodor Hänsch (Stanford, then Max Planck Institute in Garching, Germany) has been for over 50 years a pioneer in this domain of research.

These diagrams do not take into account the hyperfine structure (magnetic coupling between electron and proton)- The Lamb shift is not to scale.

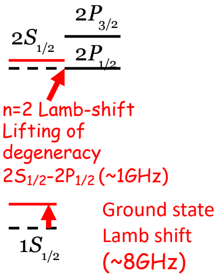


Bohr-Schrödinger (non relativistic theory)



fine structure (SO coupling, ~10GHz)

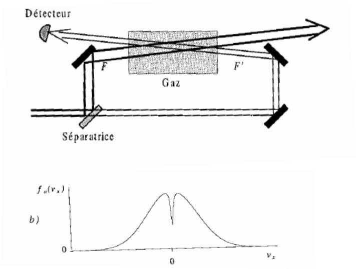
Dirac (relativity and spin)



n=2 Lamb-shift
Lifting of degeneracy
$2S_{1/2}$-$2P_{1/2}$ (~1GHz)

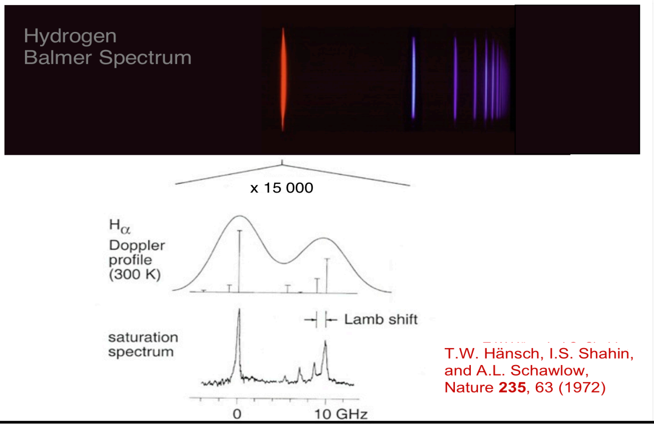
Ground state Lamb shift (~8GHz)

Quantum Electrodynamics



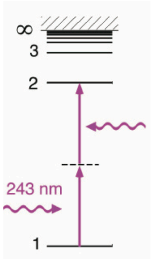
First spectrum of the Balmer α line of H with a pulsed laser by Doppler-free saturation spectroscopy: the fine structure is resolved as well as the n=2 Lamb shift

(1972)



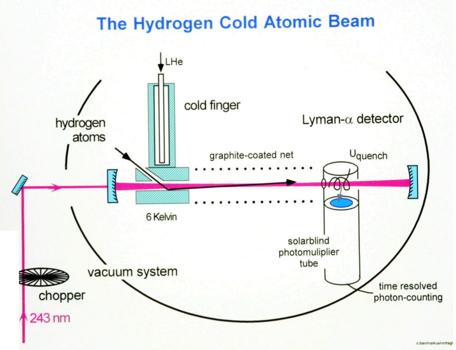
T.W. Hänsch, I.S. Shahin, and A.L. Schawlow, Nature **235**, 63 (1972)

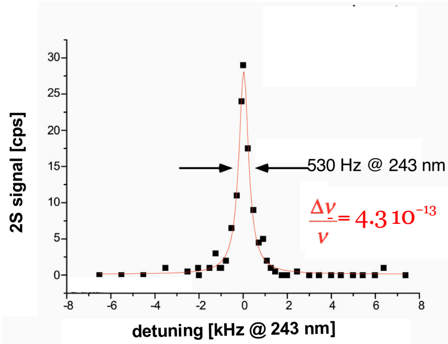
Doppler free two-photon spectroscopy of the H 1S-2S transition



(natural line width: 1.3 Hz)

T.Hänsch group
Garching, 2015



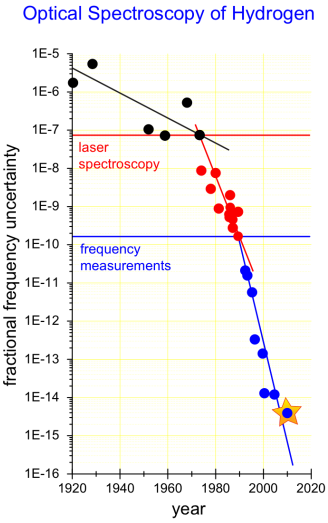


$\frac{\Delta\nu}{\nu} = 4.3\,10^{-13}$

Elimination of first order Doppler effect. No recoil shift. Correction of second order Doppler by extrapolating line at low atomic velocity. An improvement by about a factor of 1 million in line width since the first spectrum of 1972.

Progresses of H spectroscopy

C.G.Parthey et al, PRL 107, 203001 (2011)



Frequency of 1S-2S line of H:
2 466 061 413 187 035 ± 10 Hz

$$\frac{\Delta\nu}{\nu} = 4.2\times10^{-15}$$

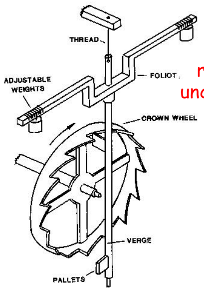
Rydberg constant:
R= 10 973 731, 568527 (73) m^{-1}

$$\frac{\Delta R}{R} = 6\,10^{-12}$$

1S Lamb-shift :
8 172,876(29)MHz

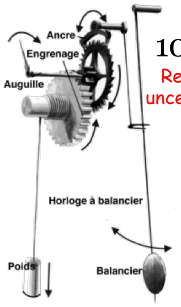
To reach these precisions, it is not enough to detect narrow optical lines: one must be able to count directly the optical frequencies, which has constituted a revolution in time measurements.

A brief history of time measurement from the pendulum to atomic clocks



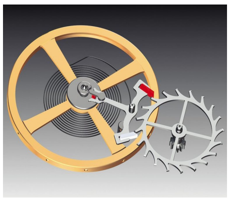
10^{-2} relative uncertainty

14th century:
torsion pendulum with foliot in church tower clocks



10^{-4} Relative uncertainty

17th century:
Pendulum clock
(Galileo, Huygens)

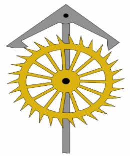


10^{-6} Relative uncertainty

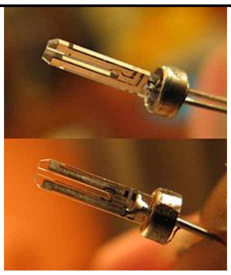
18th century:

Marine chronometer with oscillating spring (Hook, Harrisson)

Navigation
(measurement of longitudes)



Principle: a mechanical oscillator is coupled to an escape mechanism which provides the energy compensating the friction losses and count the number of periods.



Quartz crystal cut in the form of a fork vibrating at 2^{15} Hz

Quartz clocks (~1920)

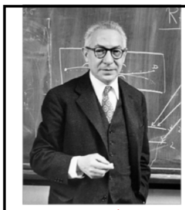
Marrying mechanical and electrical oscillators

Clocks based on the piezo-electric effect discovered in 1880 by P.and J. Curie: The mechanical vibrations of a crystal and the strain they produce induce the apparition of oscillating charges at the crystal surface, which couple the mechanical vibration to the oscillation of an electrical circuit. This circuit plays the role of the escape mechanism of mechanical clocks. A frequency divider circuit makes it possible to count a number of period multiple of 2 displayed on an analogic or digital dial.

Uncertainty ~10^{-8}-10^{-9}

In 6 centuries, the uncertainty has decreased from one quarter of an hour per day (foliot tower clocks) to a hundred of microseconds per day (best quartz clocks).

Limitations of clocks based on “man-made oscillators”: there is no absolute frequency reference and drifts due to the perturbation by environment and wear of the oscillator parts are unavoidable….



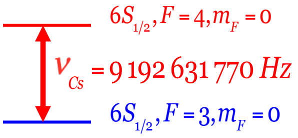
I.Rabi

The Cesium atomic clock

Principle of atomic clock suggested in 1944 by Rabi. It uses the Ramsey method of separated oscillatory fields

N.Ramsey

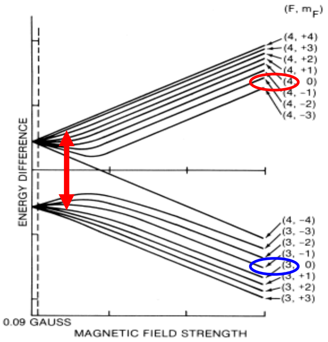
hyperfine transition in Cesium ground state



$6S_{1/2}, F=4, m_F=0$

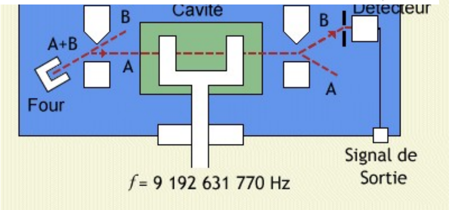
$\nu_{Cs} = 9\,192\,631\,770\ Hz$

$6S_{1/2}, F=3, m_F=0$



Zeeman effect of 6S state in Cs

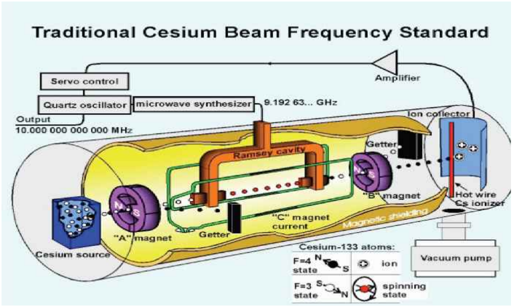
“Magic” field in which the frequency of the 0 → 0 transition is (almost) insensitive to field. Initial and final states are selected by Stern-Gerlach magnets (the F=3, m_F=0 state is a high field seeker and F=4, m_F =0 a low field seeker-see Zeeman energy diagram on right). The resonance is detected by the Ramsey method. The rf frequency is locked to the central Ramsey fringe.



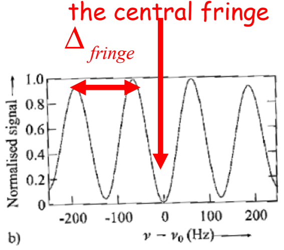
Clock is locked to a « natural atomic oscillator » whose frequency is fixed by the laws of quantum physics

Thermal Cesium beam clock

The
GPS
clocks



Locking of the rf frequency to
the central fringe



$$\Delta_{fringe} = 1 / T_{Ramsey}$$

Relative uncertainty of the clock frequency:

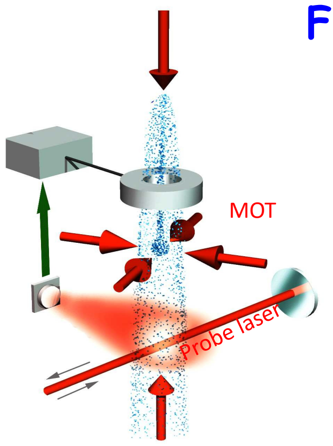
$$\sigma_A = \frac{\delta\nu_{clock}}{\nu} \approx \frac{\Delta_{fringe}}{\nu_{Cs}} \times \frac{1}{S_{ignal} / N_{oise}} = \frac{1}{\nu_{Cs} T_{Ramsey}} \times \frac{1}{S / N}$$

The signal to noise ratio S/N is mainly due to the quantum projection noise: the detection of atoms in F=3 or F=4 is ruled by a quantum probability distribution, the signal fluctuating around its average by an amount proportional to the square root of the number of detected atoms, i.e. to $\sqrt{\tau}$ (τ : total time of measurement). Typically, S/N ~ $3\text{x}10^3\ \sqrt{\tau}$/s and T_{Ramsey} ~10^{-2} s, hence:

$$\sigma_A = \frac{\delta\nu_{clock}}{\nu} \approx 3 \times 10^{-12} / \sqrt{\tau}$$

The relative clock uncertainty (Allan variance in technical terms) varies as $\tau^{-1/2}$ until τ ~10^5 to 10^6s. Beyond this duration, σ_A reaches a bottom and starts increasing at longer times (uncertainty related to long term drifts of environment). The ultimate stability is ~10^{-14} per day i.e. 10^5 times better than a quartz oscillator!

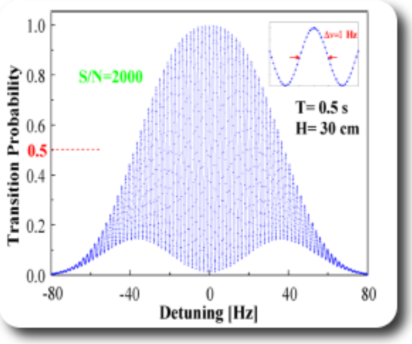
Fountain Cesium clock (SYRTE/NIST/PTB)



A great improvement
of lasers for
microwave atomic
clocks: cold atoms

Syrte-
Observatoire de
Paris-ENS

Cesium atoms cross the rf zone twice (while going up and then down). The preparation and detection of atomic states is optical; atoms are laser pumped in F=3 and they are detected in state F=4 by their fluorescence when they cross an horizontal probe laser beam at bottom tuned to absorb light from the F=4 state



By using atoms cooled and trapped in a MOT and launched upward by a laser push, T_{Ramsey} is increased by two orders of magnitude (~0.5s instead of 10^{-2}s).

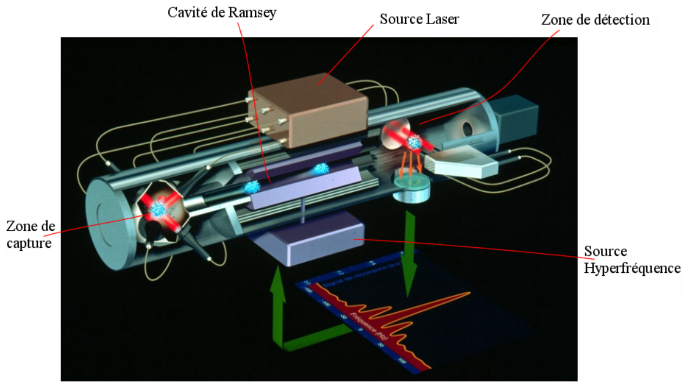
$$\sigma_A \approx 5 \times 10^{-14} / \sqrt{\tau}$$

Stability about 10^{-16} per day
(10 ps per day)

The PHARAO clock project (CNES)

Projet d' **H**orloge **A**tomique par **R**efroidissement d' **A**tomes en **O**rbite

(To be sent to the ISS)



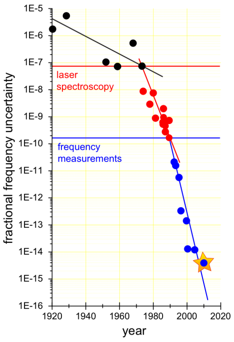
Atoms move in zero gravity with a speed of a few cm/s

T_{Ramsey}~ 10s

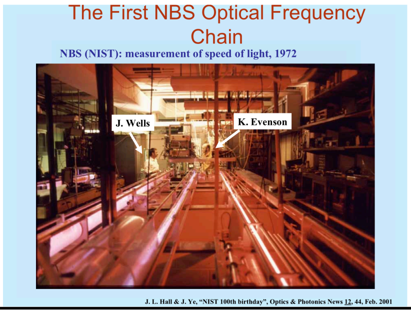
$$\textit{Expected stability (one day average)}: \ 10^{-16} - 10^{-17}$$

The Frequency Comb revolution

Optical Spectroscopy of Hydrogen



The progress in Hydrogen spectroscopy



The First NBS Optical Frequency Chain

NBS (NIST): measurement of speed of light, 1972

J. L. Hall & J. Ye, "NIST 100th birthday", Optics & Photonics News 12, 44, Feb. 2001

Cesium atomic clocks (Rubidium or Hydrogen clocks as well) operate on hyperfine transitions in the radiofrequency domain at a few GHz. Until the years 2000, the measurement of the frequencies of optical transitions (like the 1S-2S transition in Hydrogen) relied on the operation of complex "frequency chains" bridging the gap between the microwaves and the optical domain. These chains used devices performing harmonic generation and measuring the beat notes between sources of increasing frequencies by exploiting non-linear optical effects (see Lecture 10 describing the precise determination of the speed of light in 1972).

The development at the end of the 1990's by T. Hänsch and J.Hall of the ***frequency combs*** has greatly simplified bridging the gap between microwave and optical domains, made possible the direct measurement of the latter with an improved precision and, most importantly, has opened the way to novel atomic clocks directly counting the period of optical transitions. These clocks, in full development today, are up to five order of magnitude more precise than the standard microwave clocks, promising new fundamental progresses and possible applications.

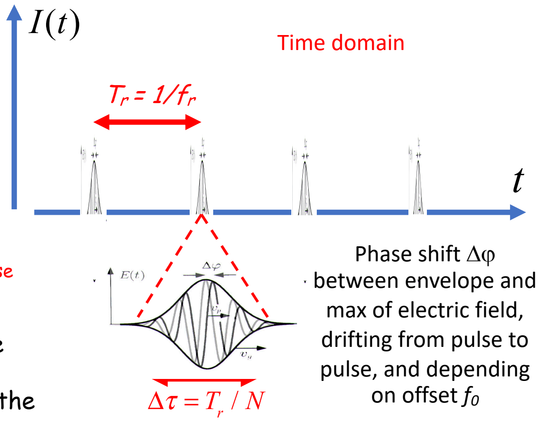
Frequency combs (T.Hänsch-J.Hall)

Lasers emitting over a wide spectral bandwidth (e.g. Titane sapphire laser) can oscillate on hundreds of thousands of phase-locked modes with spectrum forming a comb of regularly spaced frequencies. Interference between modes results in a periodic train of pulses, separated by a time interval T_r, each lasting a few femto-seconds, i.e. extending over a few optical periods. The frequency spacing f_r between the modes is equal to $1/T_r$. .

$f_p = f_o + p f_r$

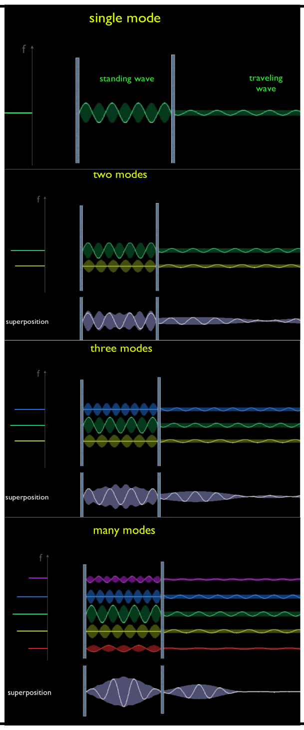
offset

Mode spacing and pulse repetition frequency



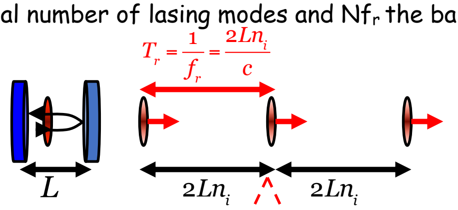
Phase shift Δφ between envelope and max of electric field, drifting from pulse to pulse, and depending on offset f_0

Questions: What is the mode locking mechanism? How can it be extended over an optical octave (from ν to 2ν)? On which parameters of the laser do f_r and f_0 depend? How to calibrate the comb (measurement of f_0 and f_r)? How to use the FC for spectroscopy? How to use it as an escape mechanism in an optical atomic clock?



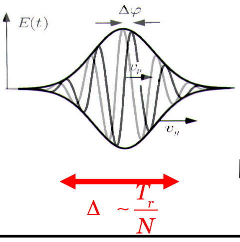
Beating between modes: Fourier analysis

Time evolution: a wave packet, superposition of phase locked modes makes round trips between the mirrors. The frequency mode spacing is $f_r = c/2Ln_i$ and the round trip time is $T_r = 1/f_r$ (n_i = n(I) is the intensity dependent average refractive index of the laser medium between the cavity mirrors). After each rebound on output mirror a fraction of light escapes, forming a train of pulses separated from each other by time interval T_r. Each pulse lasts a time $Tr/N = 1/Nf_r$ where N is the total number of lasing modes and Nf_r the bandwidth of laser emission.



General properties of Fourier transforms

Phase shift between carrier and pulse envelope drifting from one pulse to next



Δφ is related to the difference between the phase and the group velocity of light and depends upon offset f_0.

The frequency offset f_0 and the phase shift drift of the frequency comb

The phase shift drift is related to the fact that in general the mode frequency spacing is not an exact divider of the frequency of each mode. The comb frequencies are thus expressed as multiples of f_r plus a non-integer number f_0.

Consider for simplicity that the broad band laser spectrum is flat (all modes with same amplitude E_0). The field of the phase-locked superposition is a geometric series:

$$E(t) = \sum_{p=0}^{N-1} E_0 e^{2i\pi(f_0+pf_r)t} = E_0 e^{2i\pi f_0 t} \times \sum_{p=0}^{N-1} e^{2ip\pi f_r t}$$

$$= E_0 e^{2i\pi f_0 t} \frac{e^{2iN\pi f_r t}-1}{e^{2i\pi f_r t}-1} = E_0 e^{2i\pi f_0 t} e^{i(N-1)\pi f_r t} \frac{\sin N\pi f_r t}{\sin \pi f_r t}$$

The light field is non-zero when the $\sin(\pi f_r t)$ denominator is equal to zero, hence, for all k integers:

$$\pi f_r t = k\pi \to t = k/f_r = kT_r$$

The laser output is a sequence of pulses separated by $T_r=1/f_r$. The field phase is shifted from pulse to pulse by:

$$\Delta\varphi = 2\pi f_0 T_r = 2\pi f_0 / f_r$$

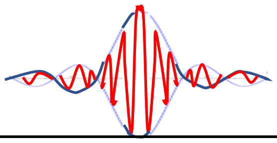
To suppress this phase drift, the frequency comb can be adjusted so that f_0 is an integer multiple of f_r and all modes are harmonics of the fundamental frequency f_r. The comb parameters f_0 and f_r vary with the length L of the cavity and with the light intensity I via the non-linear medium index $n_i(I)$. L and I can be tuned independently to fix f_0 as multiple of f_r.

The time variation of the kth pulse then writes:

$$E_0 e^{i\omega_c \tau} \frac{\sin N\pi f_r \tau}{\pi f_r \tau} \; ;$$

$$\tau = t - kT_r \text{ and } \omega_c / 2\pi = f_0 + (N-1) f_r / 2$$

Frequency $\omega_c/2\pi$ of carrier is the average of the N modes frequencies

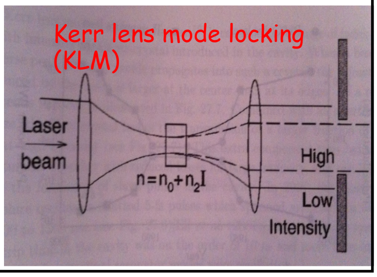


Mechanisms of Mode-Locking

The laser operation depends on non-linear optical effects. When several modes compete to extract energy from a large spectral band inverted medium, these non-linear effects favor regimes in which the modes cooperate to increase by positive interference the peak intensity of the field.

Active mode locking: insert in cavity an electro-optical crystal which modulates the medium transmission at a frequency f equal to the mode spacing of the laser. Initially the modes of the laser oscillate independently, with random phases. The modulation acting on a mode of frequency ν generates side bands at frequencies ν+f and ν-f, very close to those of adjacent modes. Nearly degenerate oscillators (one mode and the side band of the adjacent one) are coupled because they interact with the same amplifying medium. Being very close in frequency, they have a tendency to lock in phase and to beat in unison. This locking extends, via side band generation, to many adjacent modes. This synchronization mechanism was first observed by Huygens: two pendulums of nearly same frequency and suspended to the same wall lock in phase after a few osciliations. Analyzed in the time domain, the modulation of the light transmission acts as a gate which periodically opens and favors the transmission of pulses of light synchroneous with the round trip time between the mirrors.

Passive mode locking: insert in cavity a saturable medium which absorbs in proportion more low intensity than high intensity one. Natural fluctuations of the phase between modes, corresponding to a temporary increase of the light intensity, will be preferably amplified, leading to a natural mode locking favoring the propagation of bursts of light making round trips between the mirrors. A particular case is the Kerr mode locking (KLM) effect already mentioned in lecture 9: a crystal with intensity dependent index acts as a lens focalizing intense light more than low intensity beams. A diaphragm placed behind the crystal will block a fraction of low intensity light but let all the intense light go through, thus favoring mode cooperation and the build up of a train of intense pulses.


Kerr lens mode locking (KLM)

"White light" frequency combs

Phase-modulation of a laser pulse crossing a dielectric medium

The glass non-linearity varies very rapidly with the pulse intensity, resulting in a fast time change of the refractive index during the pulse propagation: This produces a phase-modulation spreading the light spectrum. The non-linearities are dramatically increased when light propagates along a microstructured glass fiber whose section looks like a bee-hive. The non linearities generate by mode beating supplementary modes whose combinations of frequencies are also multiple of f_r. Hundreds thousands of modes are phase locked together.

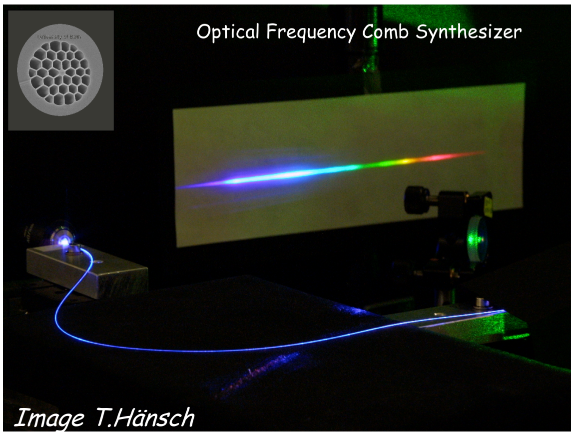


Image T.Hänsch

The spread spectrum extends over more than one octave and looks (at low resolution) like the spectrum of the white light of the sun

Comb calibration: measurement of f_r and f_0

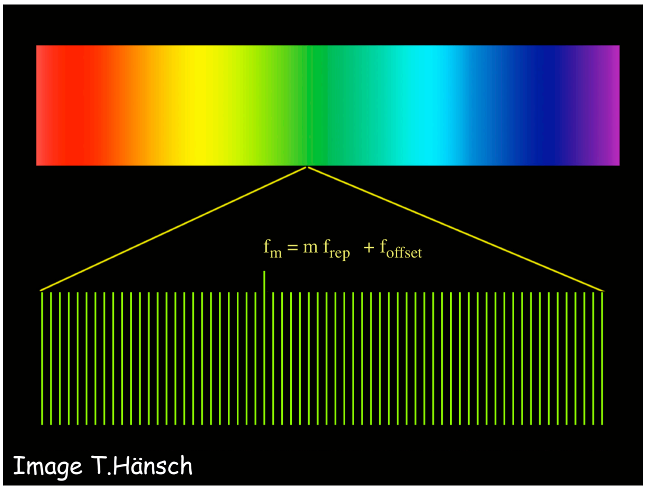
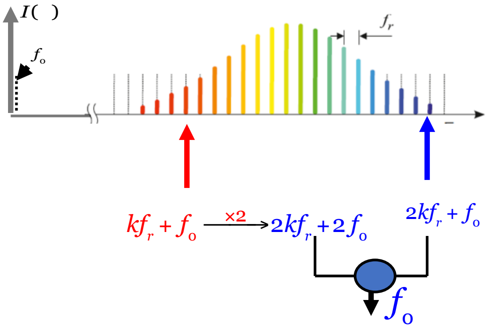
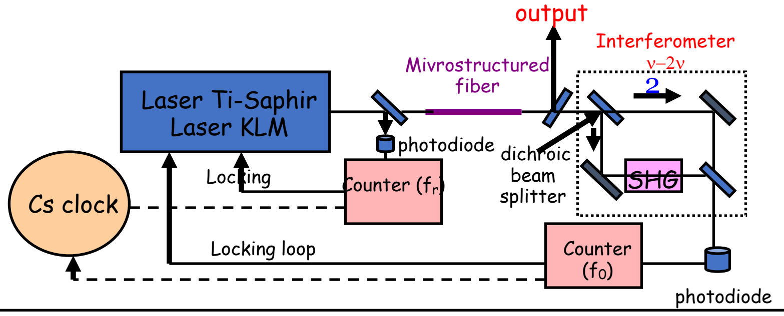


Image T.Hänsch

Calibrated frequency comb

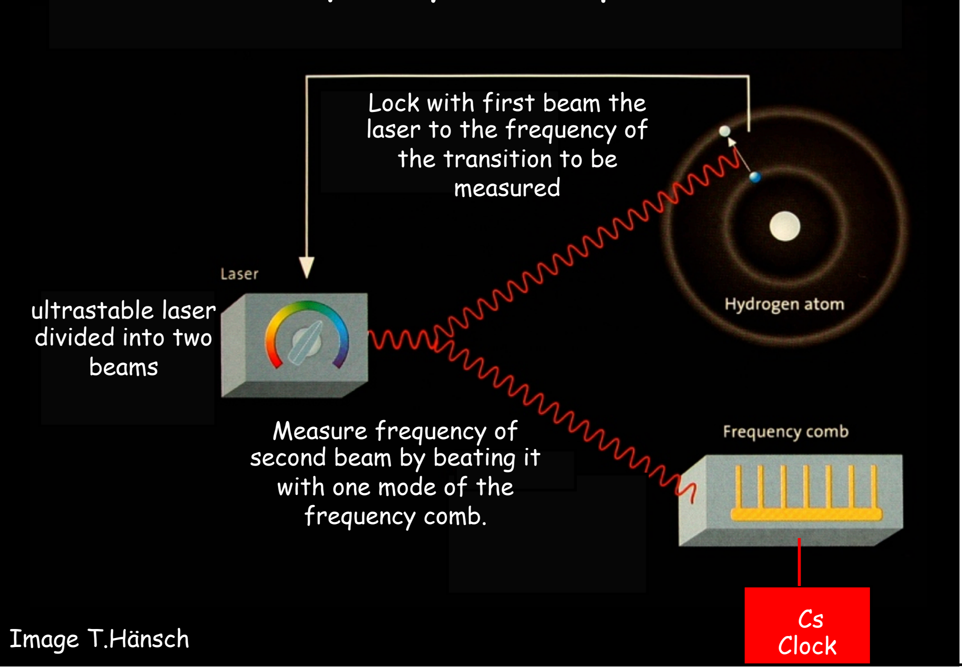


f_r is measured by counting the beat note between two successive modes of the comb. f_0 is determined by beating the second harmonic of one of the low frequency modes of the comb with the mode close to the double frequency in the high frequency part of the spectrum. In order to lock f_0 and f_r (measured by a Cs clock), one adjusts the length L of the laser cavity and the light intensity.



Sketch of the frequency comb set-up realizing a frequency multiplier allowing to count on a table top optical frequencies with a microwave clock

Count the frequency of an optical transition



Lock with first beam the laser to the frequency of the transition to be measured

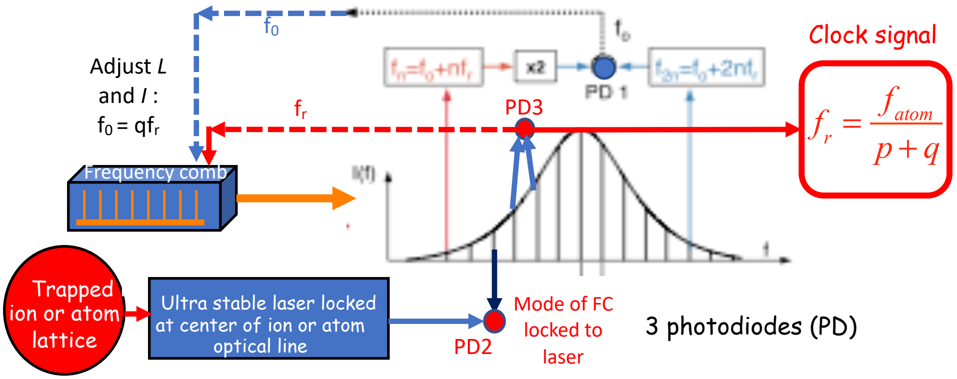
ultrastable laser divided into two beams

Measure frequency of second beam by beating it with one mode of the frequency comb.

Image T.Hänsch

Optical frequency clocks

The precision of the frequency determination of atomic and molecular lines is now limited by the definition of the second based on the microwave Cs fountain clock. Its uncertainty - about 10^{-16}-10^{-17} per day of averaging – is the present limit, while the stability of frequency comb lasers locked on an ultra-narrow atomic optical transition is two to three orders of magnitude better. Metrologists are thus considering to redefine the second based on such an optical transition in Strontium or Ytterbium atoms. Instead of using the FC as multipliers of radiofrequencies allowing to relate optical frequencies to the Cs standard, an optical clocks will employ them as frequency dividers playing the role of an escape mechanism refered to an ultra-stable optical standard . The extremely high quality factor of optical transitions towards metastable states gives to these clocks a stability and a precision far superior than that of microwave clocks. The principle of the optical clock operation is sketched below.



Adjust *L* and *l* : $f_0 = qf_r$

Frequency comb

Trapped ion or atom lattice

Ultra stable laser locked at center of ion or atom optical line

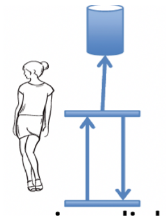
PD2

Mode of FC locked to laser

3 photodiodes (PD)

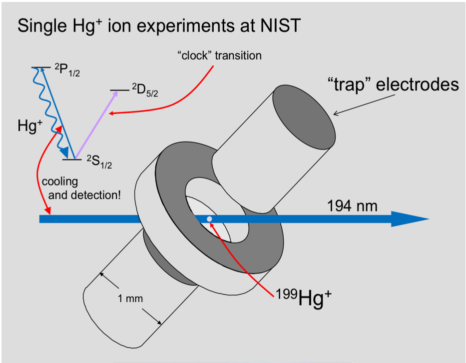
Clock signal

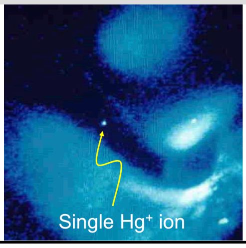
$$f_r = \frac{f_{atom}}{p+q}$$



Light pulses making round trips between mirrors of FC recall Alice's and Bob's clocks of Einstein's relativity thought experiments!

Single trapped ion optical clock





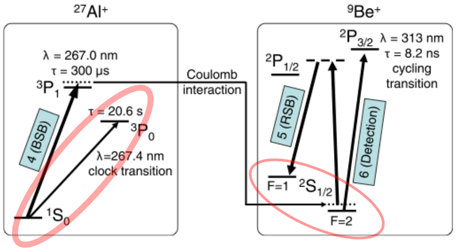
First single ion optical clock (Hg⁺) The electric quadripole transition $^2S_{1/2} \rightarrow {}^2D_{5/2}$ at 1.064 10^{15} Hz (282 nm) is excited by the second harmonic of a ultra-stable laser (line width 0.2 Hz) at 563 nm. The natural width of the atomic line is 2 Hz. The ion is laser cooled and detected on its "strong" ultraviolet transition $^2S_{1/2} \rightarrow {}^2P_{1/2}$ at 194 nm. The $^2S_{1/2}$ to $^2D_{5/2}$ clock line is recorded by the *quantum jump method*: the fluorescence induced by the strong 194 nm laser is suddenly interrupted when the laser operating on the clock transition brings the ion in the $^2D_{5/2}$ state). The rate of quantum jumps is recorded as the frequency of the clock transition laser is swept around resonance. The beating of this laser with one mode of the FC is used to lock the comb (see previous page).

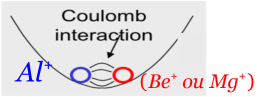
Relative uncertainty ~7. $10^{-15}/\sqrt{\tau}$.

(S.Diddams et al, Science 293, 825 (2001).

Al^+ ion detected by coupling to "reading" ion

Clock transition: $^1S_0 \rightarrow {}^3P_0$ in Al^+





Copy clock qubit (Al^+) on reading qubit, initially in |F=2> (Be^+):

First apply $^1S_0 \rightarrow {}^3P_1$ π pulse on 1st "blue side band" (BSB on Al^+):

$$\left|{}^1S_0\right\rangle_{Al} \otimes \left|n=0\right\rangle \otimes \left|F=2\right\rangle_{Be} \rightarrow \left|{}^3P_1\right\rangle_{Al} \otimes \left|n=1\right\rangle \otimes \left|F=2\right\rangle_{Be}$$

Then Raman F=2→F=1 π pulse on "red side band" (RSB on Be^+):

$$\left|{}^3P_1\right\rangle_{Al} \otimes \left|n=1\right\rangle \otimes \left|F=2\right\rangle_{Be} \rightarrow \left|{}^3P_1\right\rangle_{Al} \otimes \left|n=0\right\rangle \otimes \left|F=1\right\rangle_{Be}$$

Detection: cycles on the F = 2 → $^2P_{3/2}$ Be^+ line

$\left|{}^1S_0\right\rangle_{Al}$ = no Be^+ fluorescence ; $\left|{}^3P_0\right\rangle_{Al}$ = fluorescence Be^+

Advantages of Al^+: very narrow clock line ($^1S_0$ to $^3P_0$ line at 267.4 nm with 20s excited state life-time, highly insensitive to stray E and B fields.

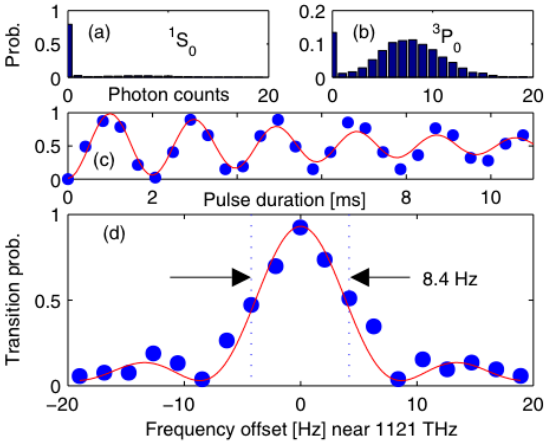
Drawback: no convenient transition for cooling and detection.

Solution: **Trap** Al^+ with an auxiliary ion (Be^+ or Mg^+). This ion, cooled by laser, gets in thermal equilibrium with Al^+ ("sympathetic" cooling via the Coulomb interaction).

A quantum gate copies the clock qubit ($^1S_0$, $^3P_0$ in Al^+) on the read-out qubit (F=1, F=2 hyperfine ground states in the case of Be^+) by excitation of one vibration quantum of a common mode of oscillation of the Al^+-Be^+ ion pair.

The Al^+-Be^+ clock signal

T.Rosenband et al, Phys.Rev.Lett. 98, 220801 (2007)



Al ion interrogated by clock laser, then submitted to the Al-Be gate. State of clock qubit measured by absence or presence of Be fluorescence

Rabi oscillation of clock transition detected on Be fluorescence

Clock resonance:

Rabi spectroscopy of the $^1S_0$ to $^3P_0$ transition (100 ms excitation of Rabi π pulse at resonance)

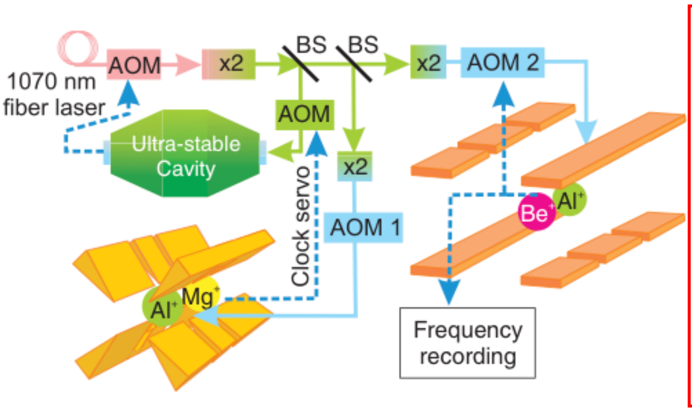
Frequency measured by a frequency comb spectrometer using the Cs microwave clock as reference:

$$\nu_{Al} = 1\,121\,015\,393\,207\,851\,(6)\ Hz$$

The uncertainty comes from the Cs standard clock. To test the stability of the optical clock, one must compare it to another one of same kind…

Comparing two Al^+ optical clocks

Comparing an Al-Be and an Al-Mg clock. The same fibre-laser at 1070 nm, whose second harmonic is locked on an ultrastable cavity, probes by its 4th harmonic (at 267.4 nm) the two Al^+ ions. An acousto-optic modulator (AOM) is used to lock the fibre-laser on the Al-Mg clock with an offset fixed by the acousto-optic modulator AOM1. The probe frequency of the Al-Be clock is locked by the modulator AOM2. The difference between the frequencies of the AOM1 and AOM2 modulators indicates the mismatch between the two clocks.



Relative uncertainty $=2.8\,10^{-15}/\sqrt{\tau}$

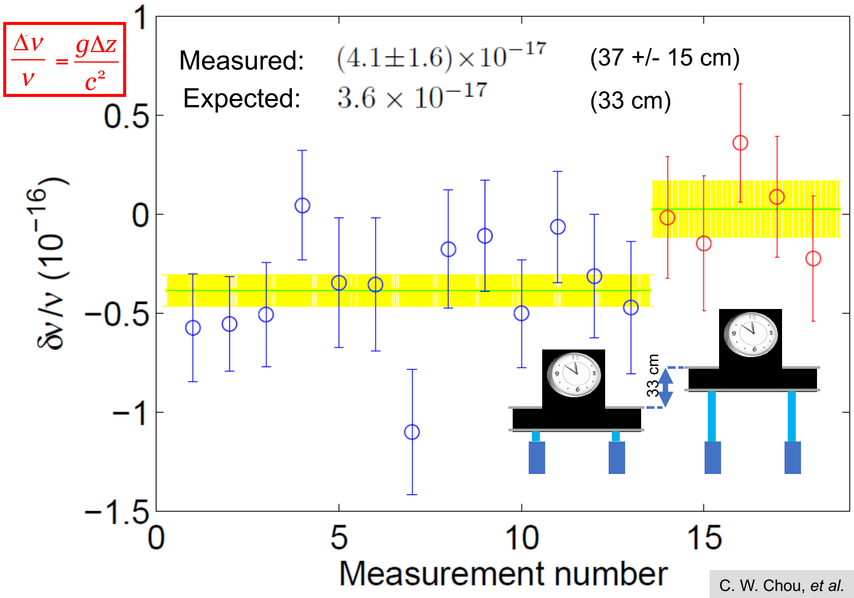
Frequency difference averaged over one day (precision limit)

$\sim 10^{-17}$

C.W.Chou et al, Phys.Rev.Lett. 104, 070802 (2010)

General relativity test: frequency difference between two Al^+ clocks vertically separated by 33 cm

$$\frac{\Delta\nu}{\nu}=\frac{g\Delta z}{c^2}$$



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

Neutral atoms optical clocks

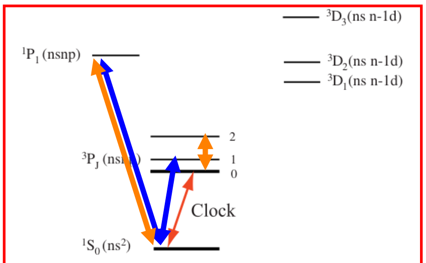
Comparison between the performance of the Al^+ clock with a fountain microwave Cesium clock: The Al^+ clock has a quality factor $Q = \nu/\Delta\nu \sim 10^{14}$, ~ about 10^4 times larger than the Q factor of the standard Cs clock, but it operates with a single ion (recycled about every second) while each cycle of the Cs clock (which lasts also one second) implies about $N = 10^6$ atoms, which gives an S/N advantage ~ 10^3 to the Cs clock. *Finally, the optical ion clock decreases the uncertainty over the microwave clock by a factor of the order of 10.*

In order to exploit better the potential precision advantage of optical transitions with a large Q factor, it is necessary to probe an ensemble of N atoms with N >> 1. This is impossible with trapped ions which perturb each other. The solution is to build clocks with neutral atoms trapped in an optical lattice with one atom per lattice site. These clocks are now being developed in many metrology labs (Tokyo, Boulder, Paris, Braunschweig..). The atoms employed have two outer electrons (Sr, Yb..) and have clock transitions with a very large Q factor ($^1S_0$ to $^3P_0$ transition).

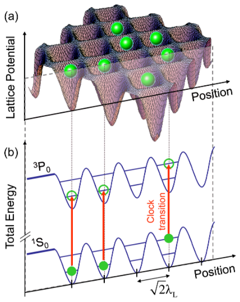
The atoms experience energy light shifts in the optical potential wells in which they are trapped. These shifts depend on the polarizability of the levels which are in general different for the two levels involved in the clock transition. There are however « magic » wavelengths for which the two polarizabilities are equal. The transition frequency is then independent of the light intensity. *(The idea of the magic wavelength was given by Katori et al, PRL, 103, 153004 (2009)).*

Principle of Sr and Yb optical clocks

Derevianko et Katori, RMP 83, 331 (2011).

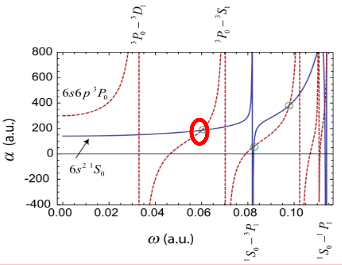


Sr and Yb levels showing the clock transition and the transitions used for pumping, cooling and detection

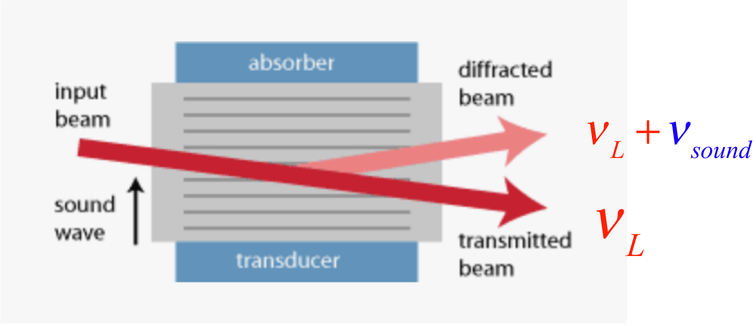


Atoms in optical lattice. The 2 levels of the clock transition experience the same potential at magic wavelength

The polarizabilities of the 2 levels of the clock transition cross each other at a magical frequency of the trapping lasers (ω expressed here in atomic units: 1a.u = $2\pi \times 4.13\ 10^{16} s^{-1}$). The magical wavelength is 759 nm for Yb.

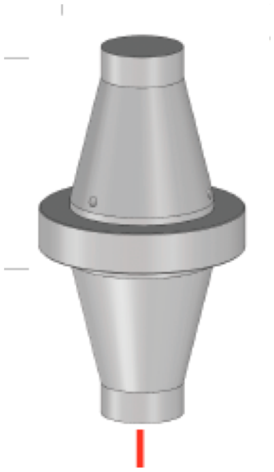


Principle of Acousto optic modulator shifting optical frequency by an adjustable sound wave frequency

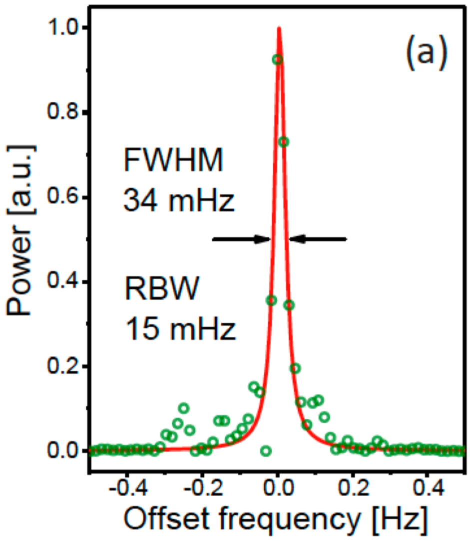


Diffraction on a moving grating: combination of
Bragg scattering and Doppler effect

Laser locked on Ultra-stable Silicon Cavity:



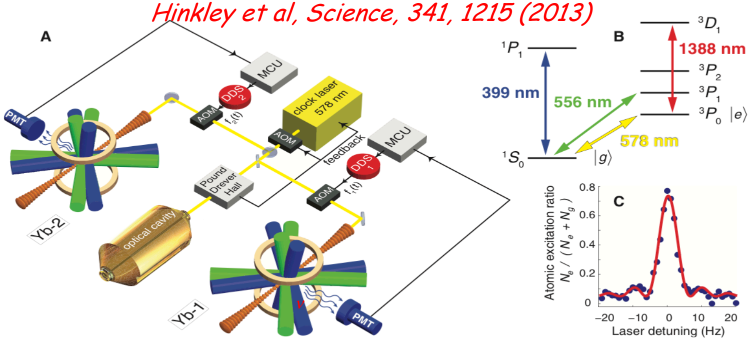
Jun Ye et al, JILA Boulder



Comparing to ^{171}Yb clocks

Hinkley et al, Science, 341, 1215 (2013)

Sketch of set-up comparing the two clocks, energy level diagram and Rabi spectrum of the clock transition ~ 5Hz width



$$V_{Yb} = 518\ 295\ 836\ 590\ 865{,}2(0{,}7)Hz$$

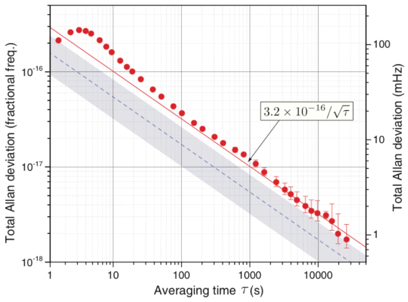
Relative uncertainty of the Yb clock versus the measuring τ. The slope yields:

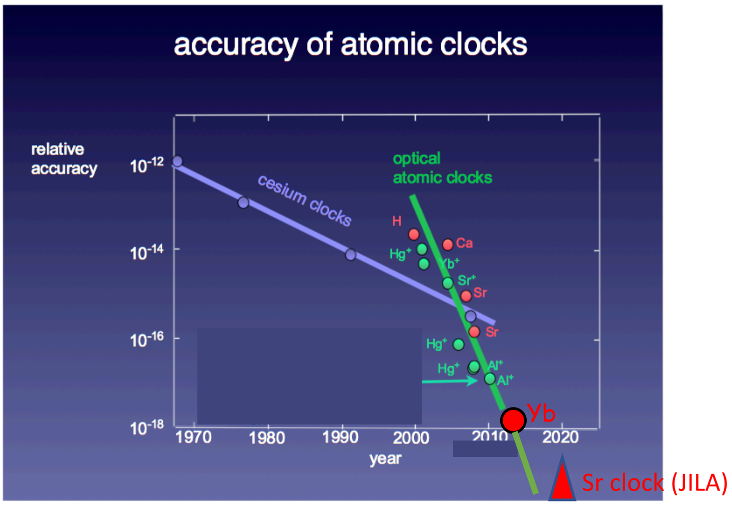
$$= 3{,}2\,10^{-16} / \sqrt{\tau}$$

The uncertainty (over 1 day):

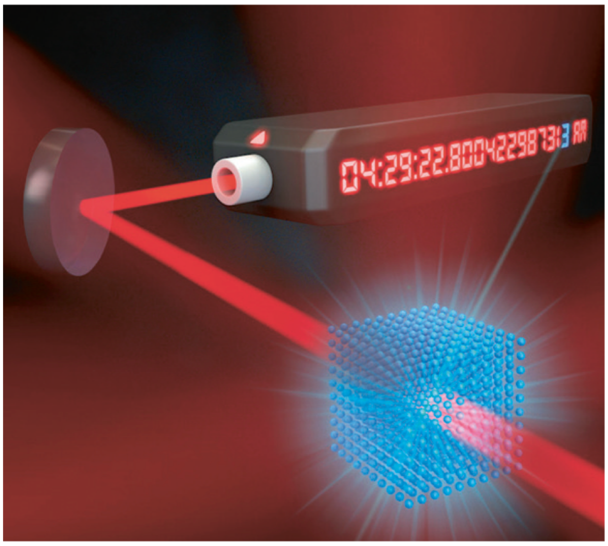
$$\sim 10^{-18}$$

One order of magnitude won over the Al+ clock (N~ 1000 atoms instead of 1 ion)





Optical clocks have an uncertainty smaller by three orders of magnitudes than the best Cs fountain clocks. The best precision today (~10^{-19}) corresponds to a deviation of about a tenth of a second over the age of the universe!



The JILA Strontium Clock (Jun Ye et al)

Uncertainty
< 10^{-19} per day

1/20 second time mismatch between two clocks synchronized at the origin of the Universe

Gravitational red shift observed for altitude difference of about 1mm

(*Nature* **volume 602**, pages 420–424 (2022))

Conclusion of Lecture 12

Time can now be measured with a precision such that two optical clocks do not deviate by more than a fraction of a second over the age of the universe. The definition of the second, based today on the Cs microwave clock standard, will probably soon be redefined with improved precision as a multiple of the period of an Ytterbium or Strontium optical clock. The time defined by these clocks will have to be accompanied by a precise specification of their position with respect to the gravitational field they experience.

These clocks, on ground or embarked in satellites, will allow physicists to test with increased precision the special and general relativity theories. They will also test cosmological theories predicting variations over time of fundamental constants (fine structure constant and ratio of electron over proton mass). With still increased sensitivity, they could be used to detect the tiny change in space-time curvature produced by gravitational waves. At a more practical level, they could also be used to improve navigation systems or to develop probes sensitive to small variations of the gravitational field due to spatial inhomogeneities or temporal variations of mass densities below ground (applications to geodesy and geophysics or to the detection of small motions of earth plaques announcing earthquakes or volcano activity).

Another prospective improvement could come from the development of clocks based on transitions between energy levels in nuclei, falling in the γ ray domain. This will require research to identify narrow γ ray nuclear lines and to extend the frequency comb technology. to the XUV and γ ray domains.