BIG ISSUES IN PHYSICS

Variation of the Fundamental Constants of Nature

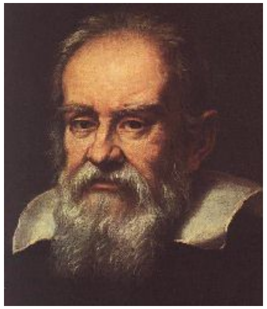
Which constants are fundamental ?

Do we understand the constants and their values ?

Dimensionless and Dimensional constants

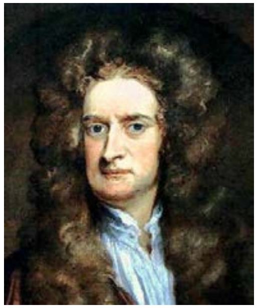
Various Phenomena in various epochs as a test ground

Constants Fundamental ?



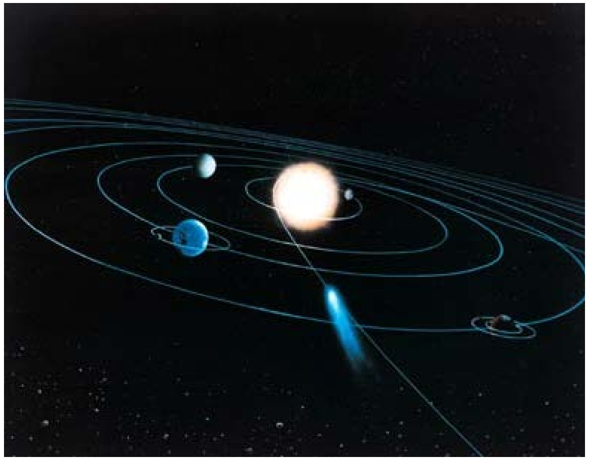
Galilei Galileo

$$F = mg$$



Isaac Newton

$$F = G\frac{Mm}{r^2}$$



Fundamental constant: "parameter that cannot be calculated for known physics"

Dimensionless Constants

$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c}$$

$$\mu = \frac{\mathrm{M_p}}{\mathrm{m_e}} = 1836.15267245(75)$$

α = 1/137.035 999 710 (96)

Wolfgang Pauli

The Ratio of Proton and Electron Masses

FRIEDRICH LENZ
Düsseldorf, Germany
(Received April 5, 1951)

THE most exact value at present[1] for the ratio of proton to electron mass is 1836.12±0.05. It may be of interest to note that this number coincides with $6\pi^5 = 1836.12$.

[1] Sommer, Thomas, and Hipple, Phys. Rev. **80**, 487 (1950).

Physical Review 82 (1951) 554

Note: α is a running coupling constant

See paper "Trialogue"
Duff, Okun, Veneziano
and Discussion Duff

The Large Number Hypothesis

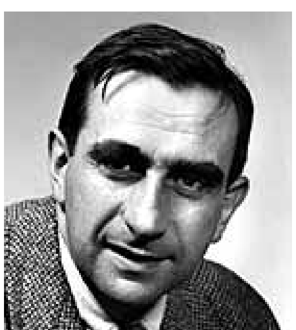
Dirac

$$N_1 = \frac{ct}{e^2/m_e c^2} = 10^{40}$$ size of universe/size of electron

$$N_2 = \frac{e^2}{G m_e M_p} = 10^{40}$$ force ratio between e and p (EM/gravitation)

$$N = \frac{c^3 t}{G M_p} = 10^{80}$$ number of protons in the universe

Large number hypothesis: $N_1 = N_2 = \sqrt{N} \propto t$ via $G \propto 1/t$



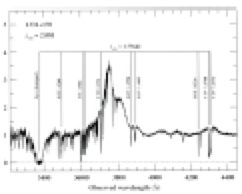
Teller

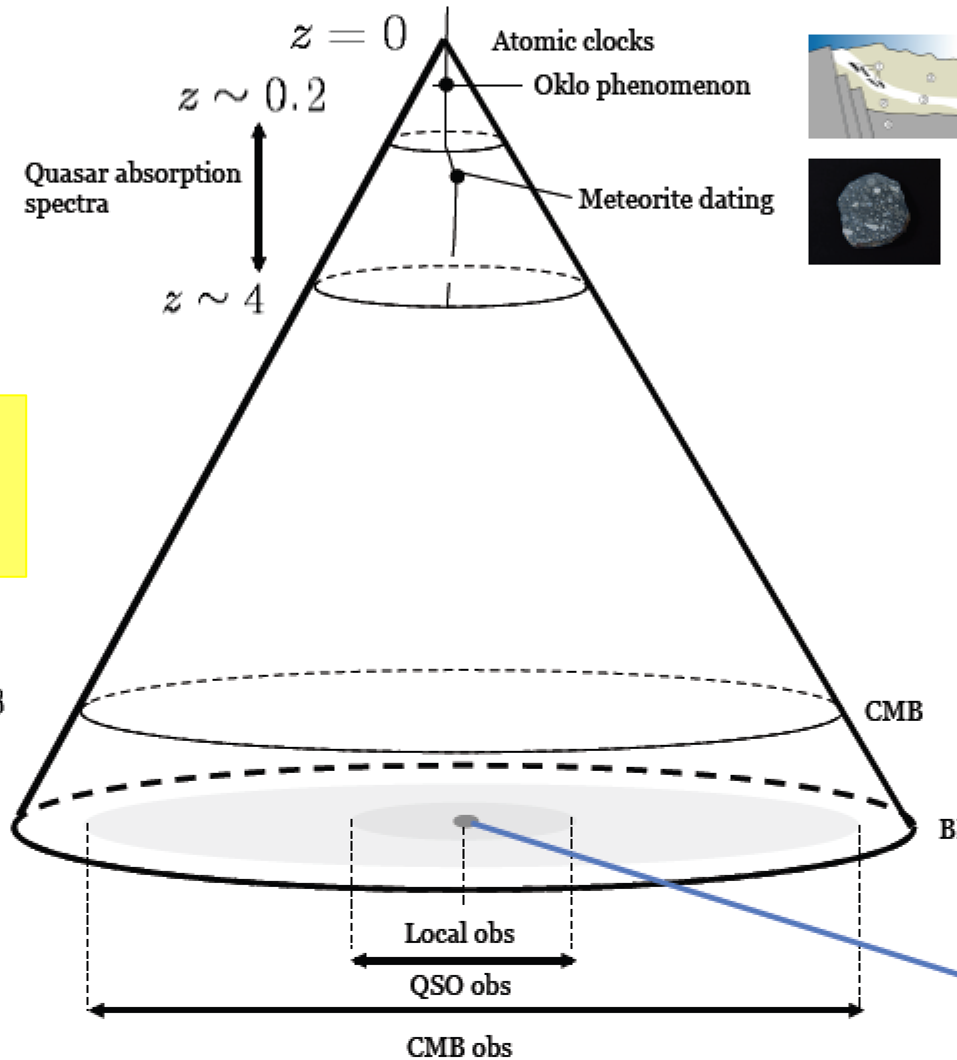
Paleonthology

Dirac's paper (1937)
Teller's paper (1948)
Gamov's paper (1967)

Outcome of Dirac's paper:
Constancy of fundamental constants
must be experimentally verified

Testing variation of constants in various epochs

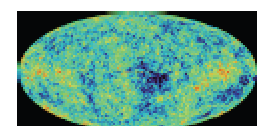


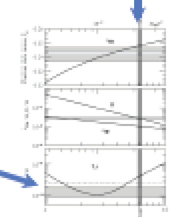


$z = 0.14$

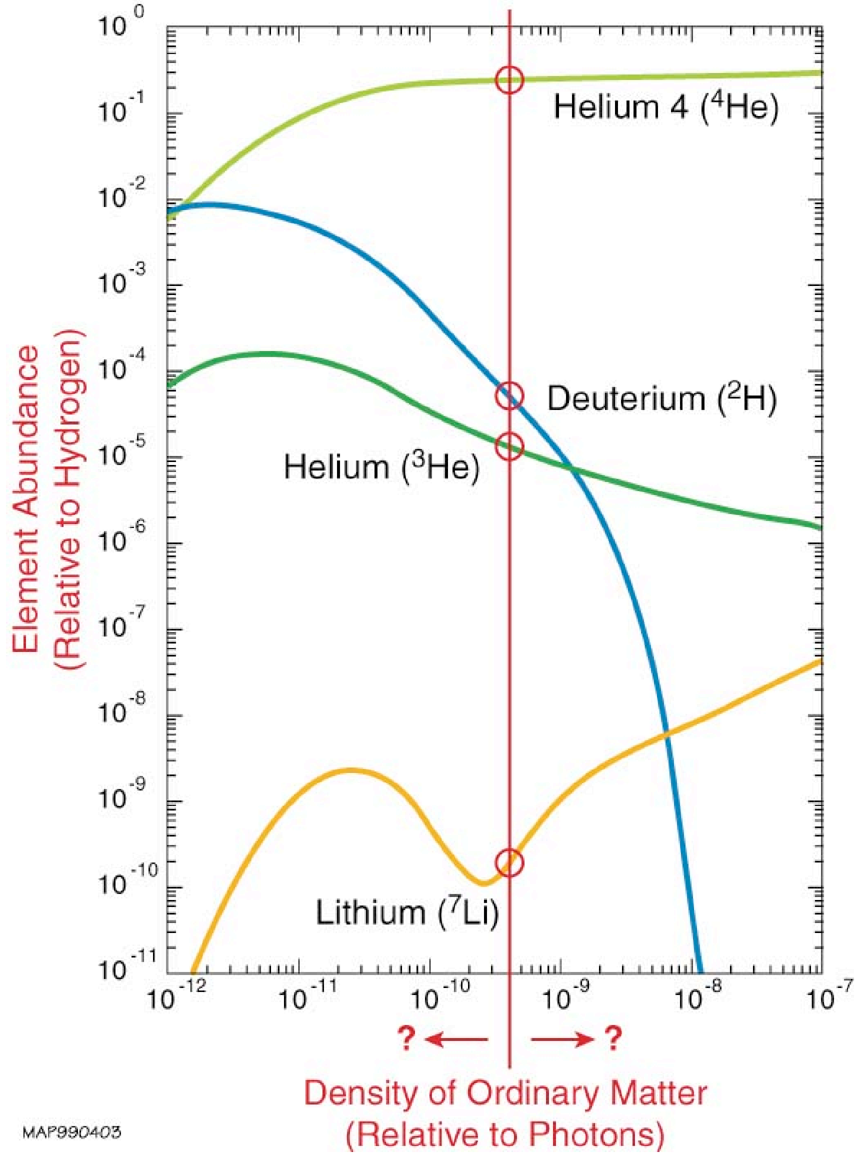
$z = 0.43$

$$T = T_0\left[1 - \frac{1}{(1+z)^{3/2}}\right]$$





Constants in the early Universe



Big Bang Nuclear Synthesis

Driving Mechanism:

-Where do the neutrons go ?
-How long do the neutrons live ?

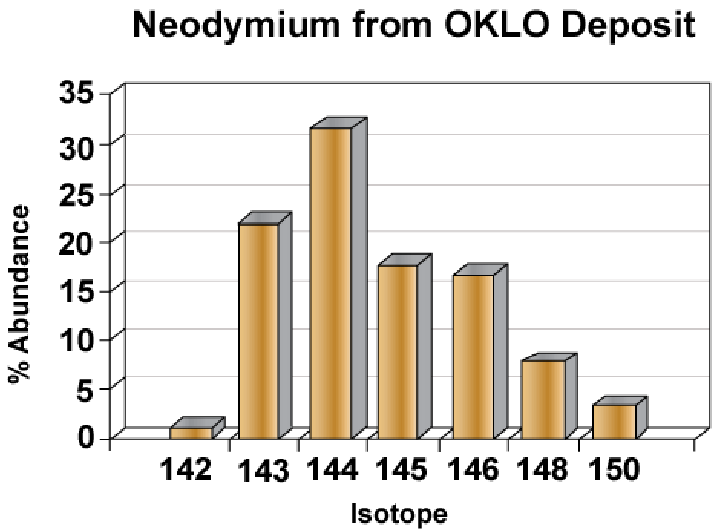
See paper Olive (2000)

The OKLO phenomenon at z = 0.16

$^{235}U/^{238}U$ = 0.717 % (usually 0.720 %)
so 0.003 % missing ^{235}U ?
Fission products found

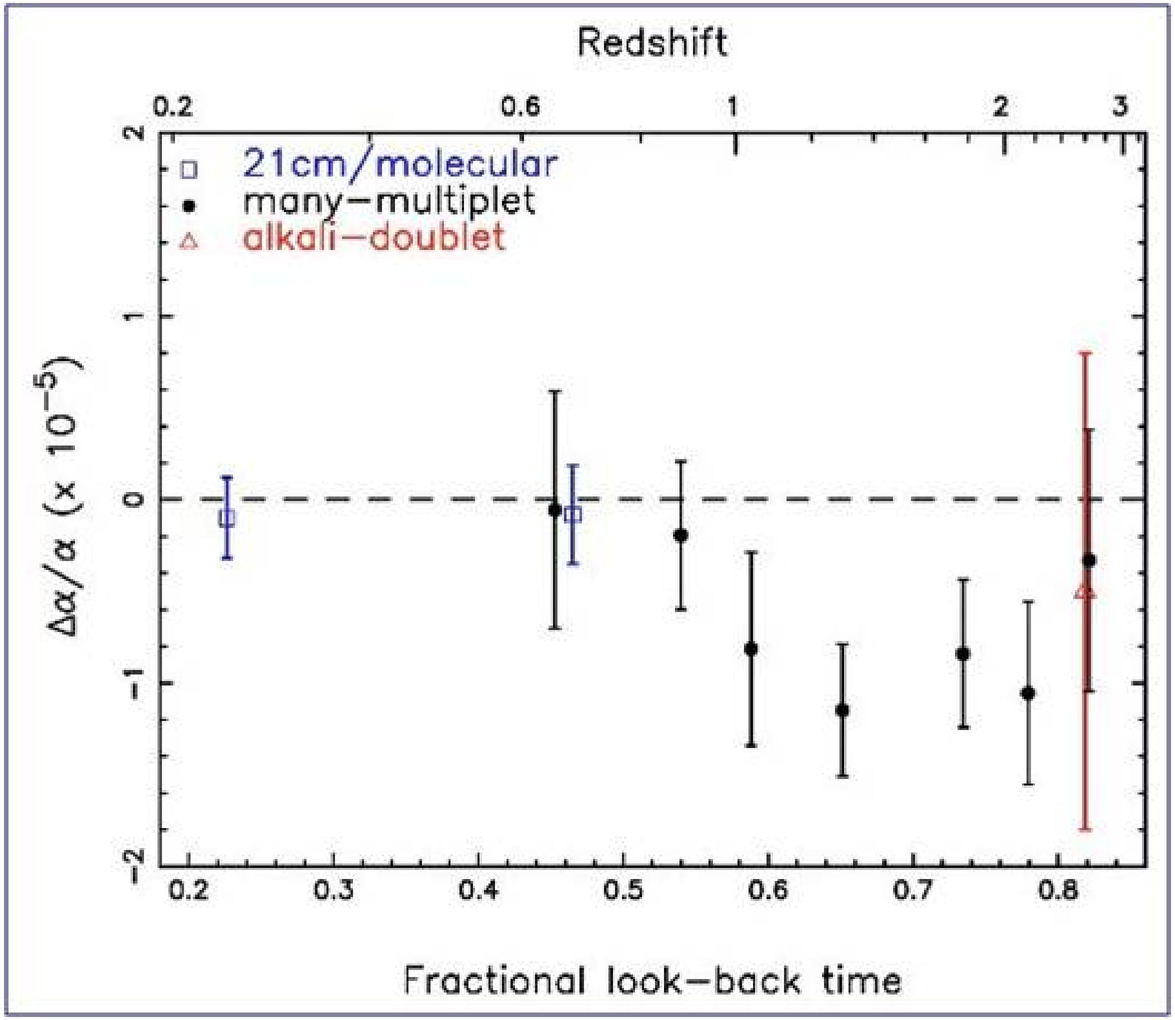
Resonant capture of ^{149}Sm -> ^{150}Sm
Level in ^{149}Sm has changed < 20 meV
α constant at 10^{-8} level

A. Shlyakter



Paper Shlyakter (1976)

Atomic Spectra from Quasars



Paper Webb/Flambaum/Barrow (1999)

Constraints from Radioactive Decays

$$^{238}_{92}U \rightarrow ^{235}_{90}Th + ^{4}_{2}He$$

Decay rates of ^{235}U, ^{238}U, and ^{235}Th
and constraint by the lifetime of the Earth

Isotopic abundances $\Delta\alpha / \alpha < 10^{-4}$

(Dyson 1972)

General $\Delta\alpha$ would have resulted in a different nuclear chart,
with other elements stable
some stable elements subject to radiative decay

(Dicke 1959)

Analysis of some radio-active isotope, and/or isotope abundances in meteorites

Discuss :
look-back times
systematics

Spectroscopy of atoms and molecules

1. On a Cosmological time scale

   Quasar spectra, absorbing galaxies at high redshift
   Availability of existing species
   Sensitivity of Atoms and Molecules

2. On a Laboratory time scale

   Ultraprecision metrology with stable lasers
   Frequency comb lasers
   Atomic clocks
   Any choice of species

Ultra-precision metrology with lasers

PRL **100**, 150801 (2008) PHYSICAL REVIEW LETTERS week ending 18 APRIL 2008

Stability of the Proton-to-Electron Mass Ratio

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(Received 7 December 2007; published 18 April 2008)

We report a limit on the fractional temporal variation of the proton-to-electron mass ratio as $\frac{1}{(m_P/m_e)}\frac{\partial}{\partial t}(m_P/m_e) = (-3.8 \pm 5.6)\times 10^{-14}\ \mathrm{yr}^{-1}$, obtained by comparing the frequency of a rovibrational transition in SF_6 with the fundamental hyperfine transition in Cs. The SF_6 transition was accessed using a CO_2 laser to interrogate spatial 2-photon Ramsey fringes. The atomic transition was accessed using a primary standard controlled with a Cs fountain. This result is direct and model-free.

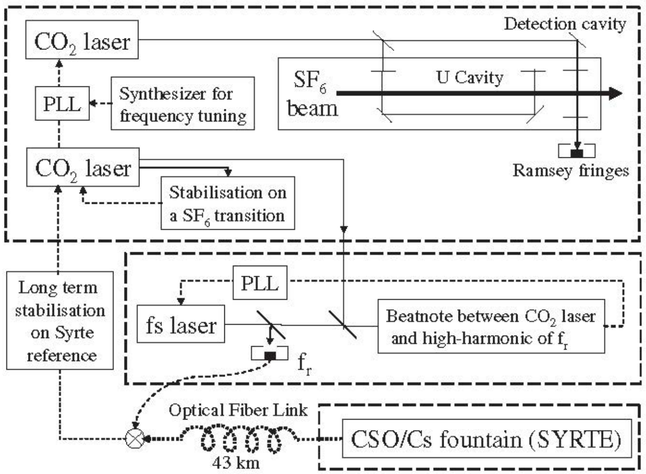


FIG. 1. Experimental setup.

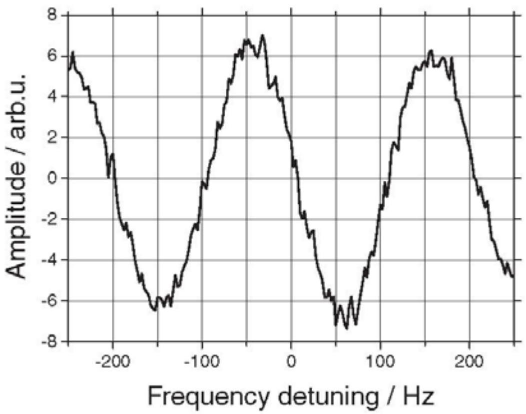


FIG. 2. Fringes at 200 Hz, obtained using a 1 m interzone separation. Experimental conditions: pure SF_6 beam, input pressure 5×10^5 Pa, 12 mW inside U cavity FM modulation at 115 Hz index 0.43, 75 μW inside the detection cavity, time constant for detection 0.1 s. Average of 5 up-down sweeps, 200 points, averaging 1 s per point. Signal-to-noise ratio 30.

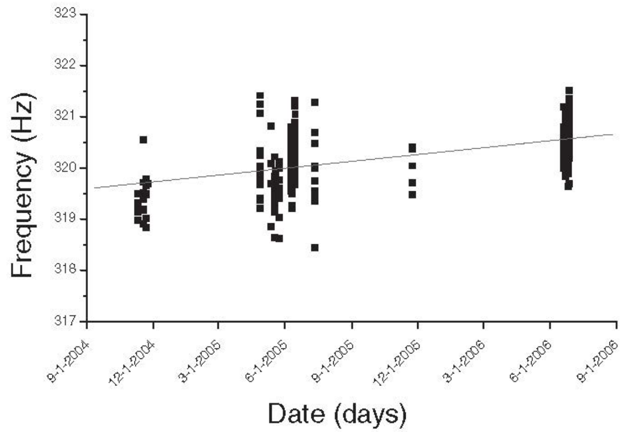
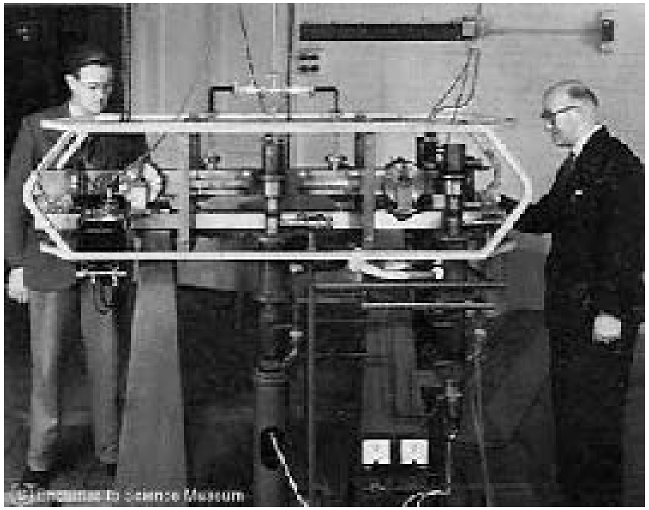


FIG. 3. Absolute frequency of the central fringe displayed as a function of time. The y axis is offset by 28 412 764 347 000 Hz. The least-squares best fit line has a slope of $1.88 \times 10^{-14}\ \mathrm{yr}^{-1}$.

The time/frequency standard; Clocks



NPL-UK
1955

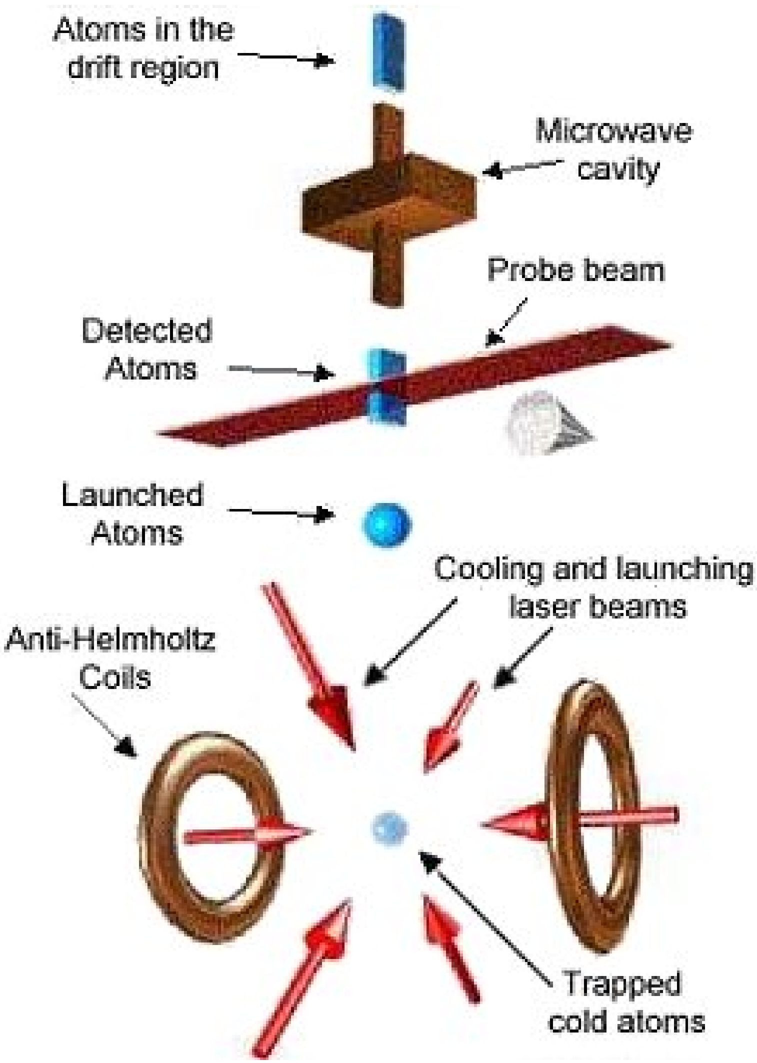
HP-Standard Cs clock

A "cesium(-beam) atomic clock" (or "cesium-beam frequency standard") is a device that uses as a reference the exact frequency of the microwave spectral line emitted by atoms of the metallic element cesium, in particular its isotope of atomic weight 133 ("Cs-133"). The integral of frequency is time, so this frequency, **9,192,631,770 hertz** (Hz = cycles/second), provides the fundamental unit of time, which may thus be measured by cesium clocks.

Note:
Definition of the meter by:

C = 299792458 m/s

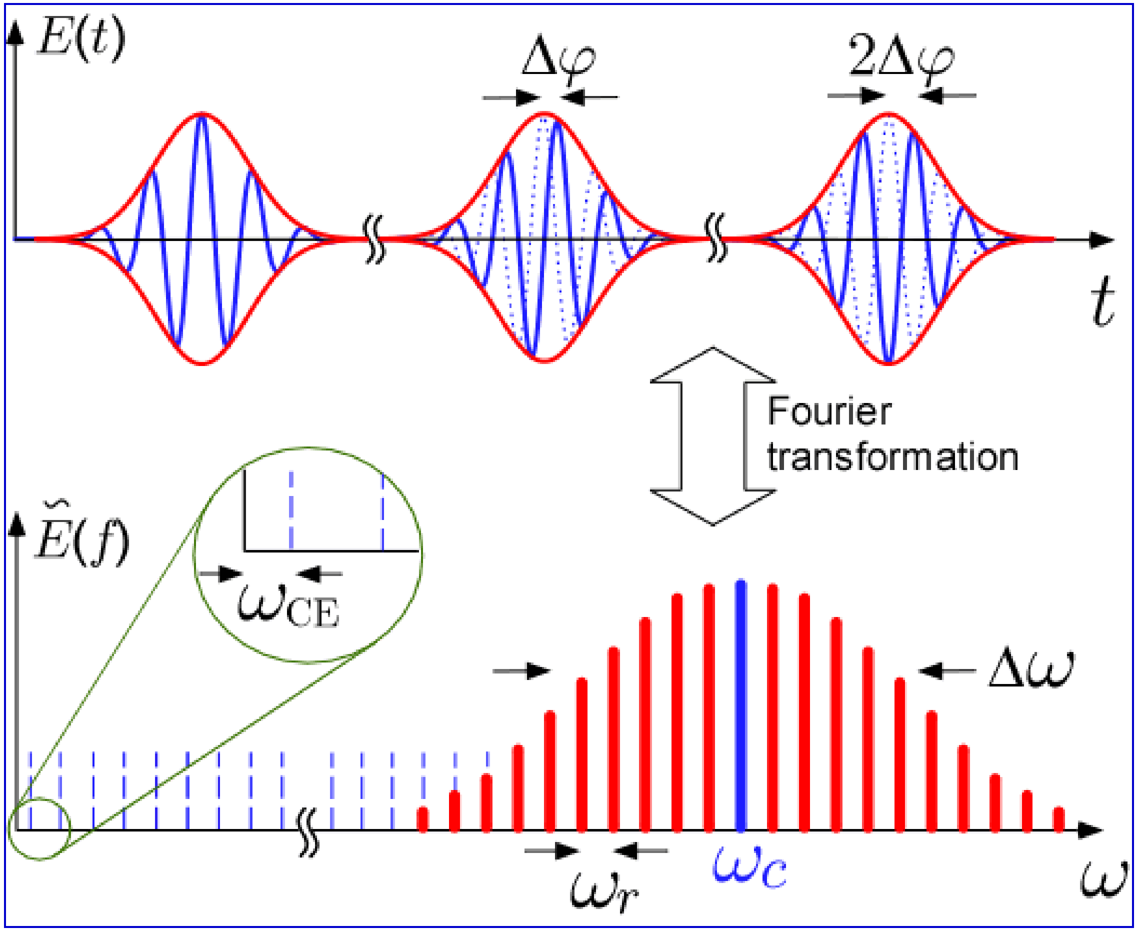
Better representation of the Cs Clock



Time-of-flight broadening

Ramsey spectroscopy

Frequency Comb Lasers

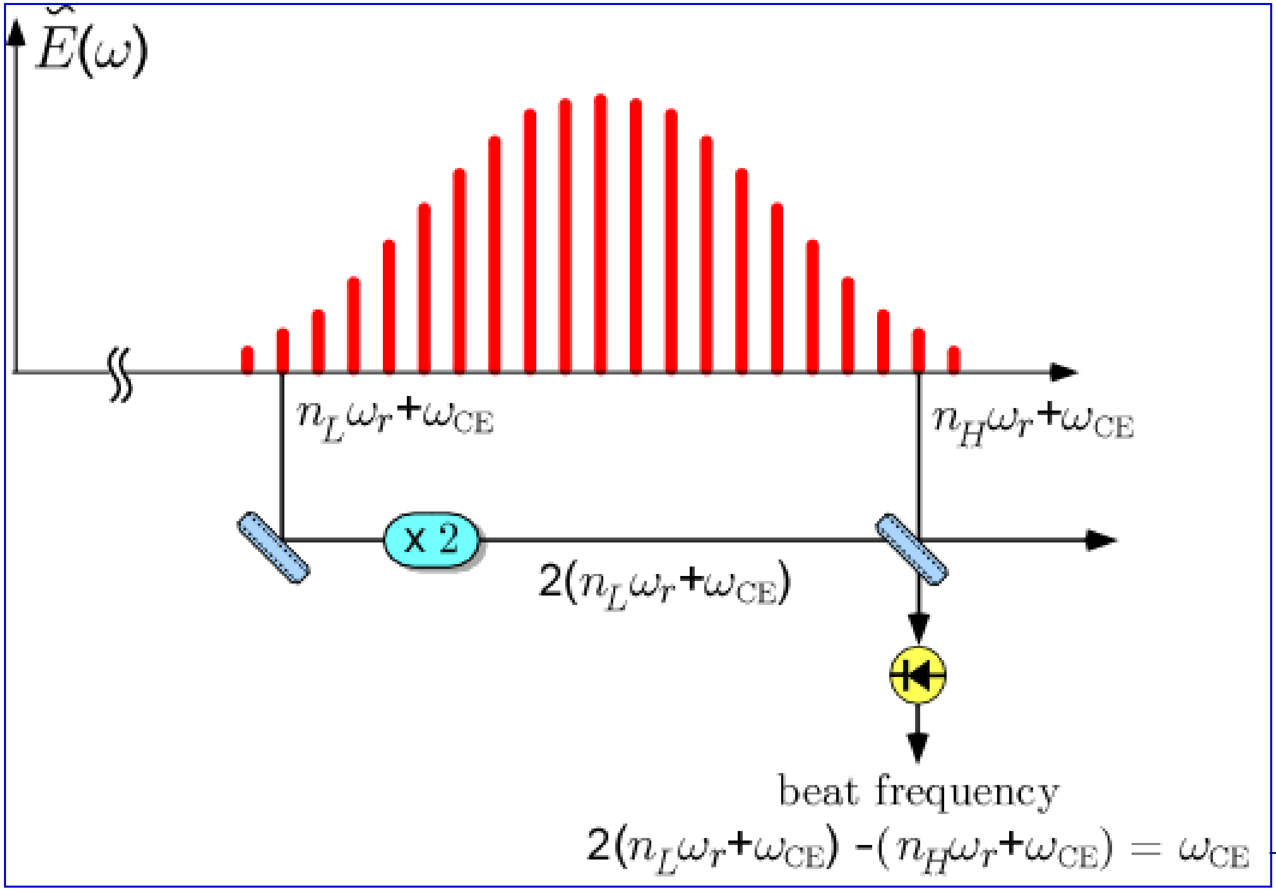


2005

$\omega_n = n\omega_{rep} + \omega_{CE}$

Linking Optical frequencies
to an RF-clock

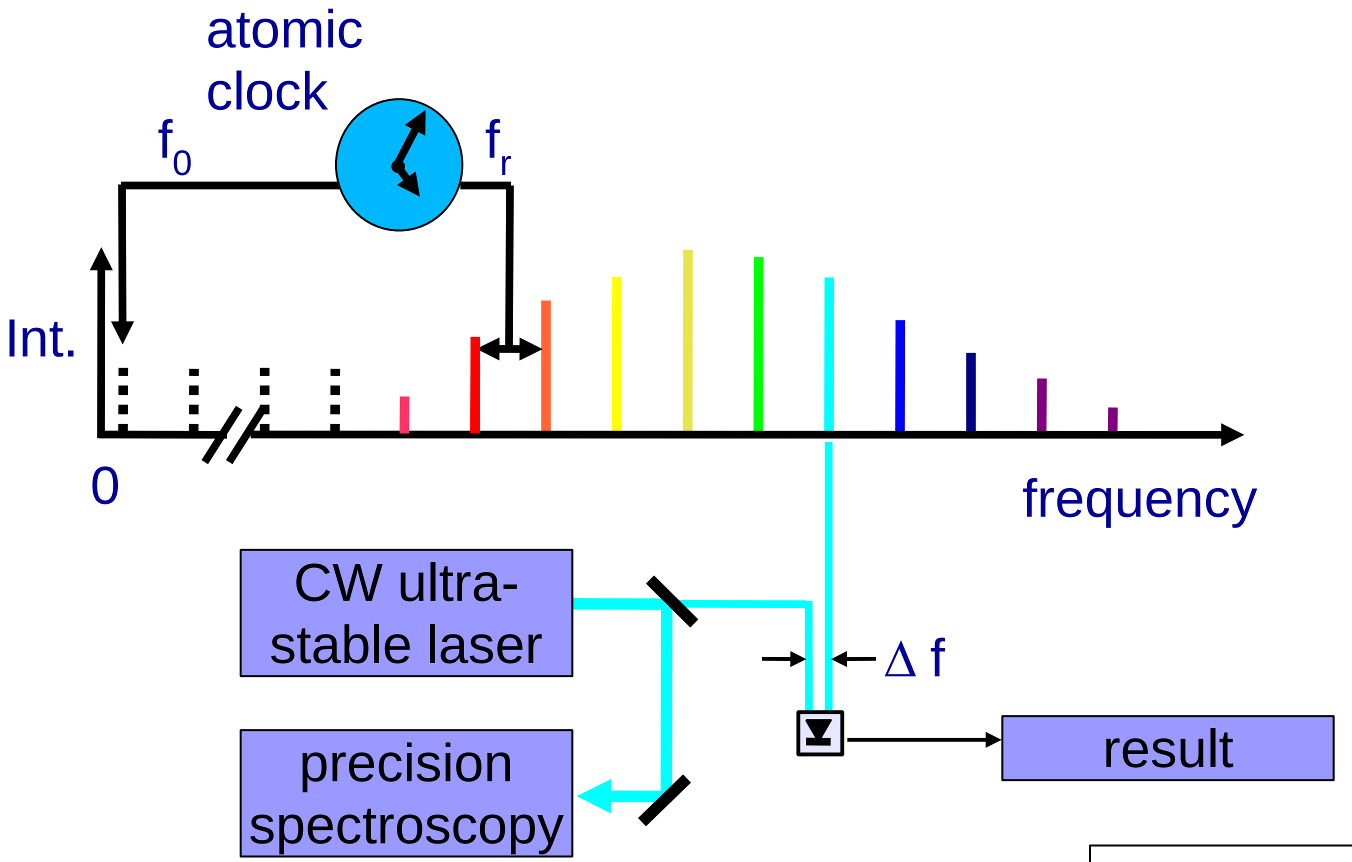
Frequency Comb Lasers



feedback

"Self-referencing" and locking to clock

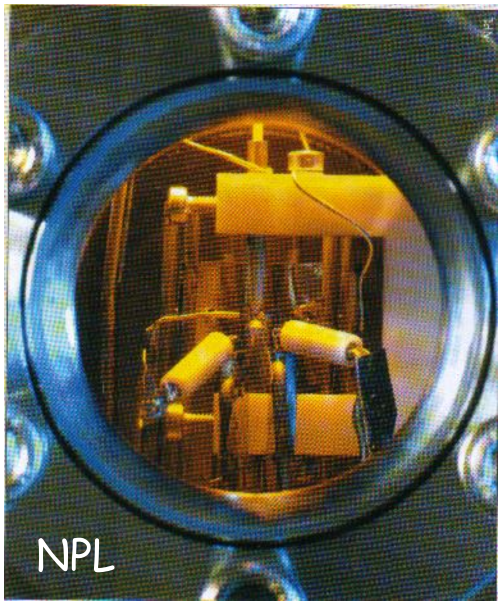
Frequency Comb Calibration of a Laser



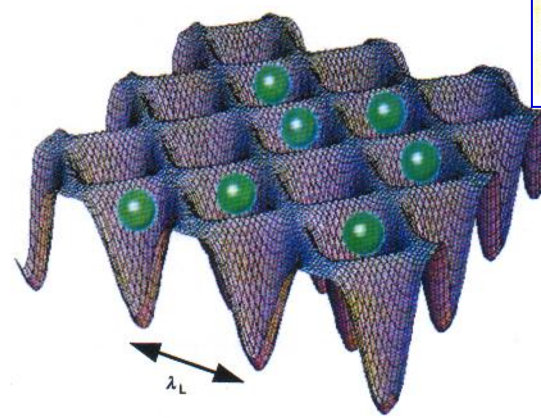
$$f_{result} = \Delta f + n f_{rep} \pm f_0$$

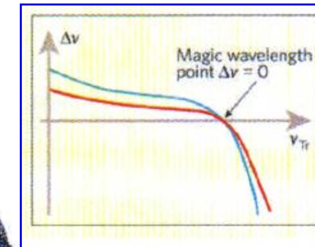
Toward optical clocks

(Single) Ion traps



Optical lattice





Faster realization of a standard at higher frequencies

The most accurate clock - almost

PRL **104,** 070802 (2010) PHYSICAL REVIEW LETTERS week ending 19 FEBRUARY 2010

Frequency Comparison of Two High-Accuracy Al^+ Optical Clocks

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(Received 23 November 2009; published 17 February 2010)

We have constructed an optical clock with a fractional frequency inaccuracy of 8.6×10^{18}, based on quantum logic spectroscopy of an Al^+ ion. A simultaneously trapped Mg^+ ion serves to sympathetically laser cool the Al^+ ion and detect its quantum state. The frequency of the ${}^1S_0 \leftrightarrow {}^3P_0$ clock transition is compared to that of a previously constructed Al^+ optical clock with a statistical measurement uncertainty of 7.0×10^{18}. The two clocks exhibit a relative stability of $2.8 \times 10^{15}\tau^{1/2}$, and a fractional frequency difference of -1.8×10^{17}, consistent with the accuracy limit of the older clock.

TABLE I. Systematic effects that shift the clock from its ideal unperturbed frequency. Shifts and uncertainties given are in fractional frequency units ($\Delta\nu/\nu$). See text for discussion.

Effect	Shift (10^{18})	Uncertainty (10^{18})
Excess micromotion	−9	6
Secular motion	−16.3	5
Blackbody radiation shift	−9	3
Cooling laser Stark shift	−3.6	1.5
Quad. Zeeman shift	−1079.9	0.7
Linear Doppler shift	0	0.3
Clock laser Stark shift	0	0.2
Background-gas collisions	0	0.5
AOM freq. error	0	0.2
Total	−1117.8	8.6

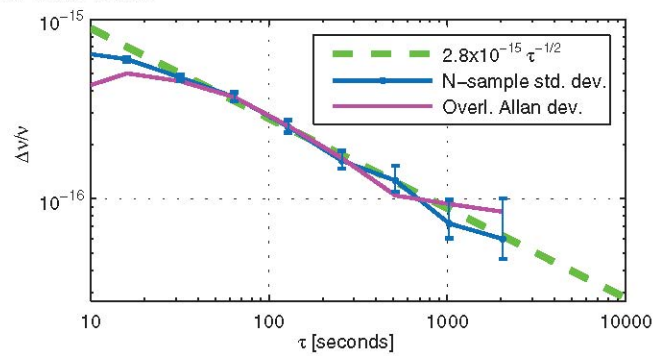

FIG. 2 (color). Clock stability. Fractional frequency uncertainty vs averaging period (τ) for a comparison between the two Al^+ clocks (10 700 s duration). Overlapping Allan deviation and N-sample standard deviation are shown [24]. For each comparison measurement the coefficient of the $\tau^{1/2}$ asymptote is estimated and used to derive the measurement's statistical uncertainty. The $2.8 \times 10^{15}\tau^{1/2}$ asymptote is reached for averaging periods that are longer than the servo time constant of 10 s.

Not absolute !!

2014

LETTER

doi:10.1038/nature12941

An optical lattice clock with accuracy and stability at the 10^{-18} level

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With control of black-body radiation