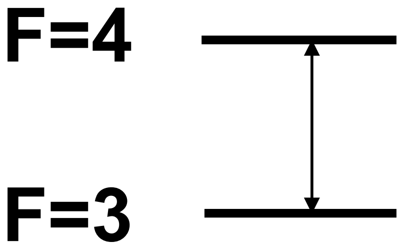
Atomic clocks

Cesium primary frequency standard:

HFS of 6s:



F=4

F=3

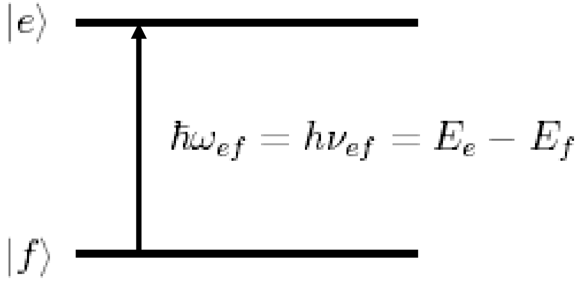
$\nu = 9\ 192\ 631\ 770$ Hz

Also: Rb, Cd^+, Ba^+, Yb^+, Hg^+, etc.

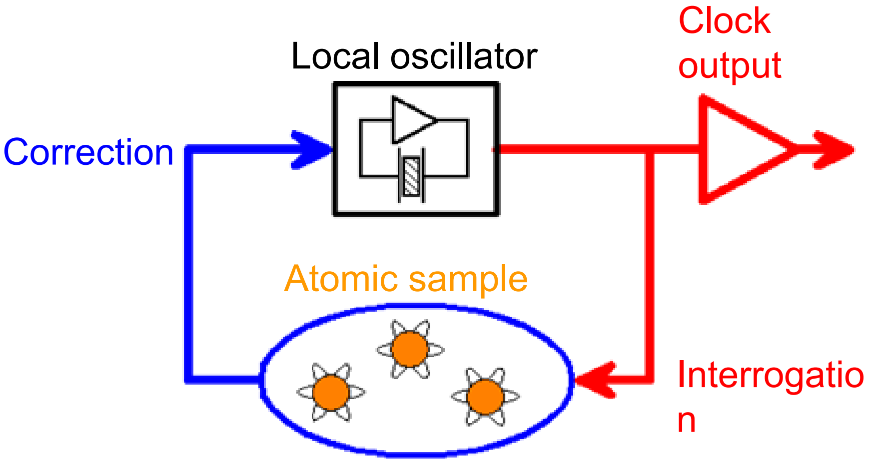
E.g. $\nu(Hg^+) = 40\ 507\ 347\ 996.841\ 59(14)(41)$ Hz

(D. J. Berkeland *et al*, 1998).

Atomic Clocks: Basic Principles



$$\hbar\omega_{ef} = h\nu_{ef} = E_e - E_f$$



Local oscillator

Clock output

Correction

Atomic sample

Interrogation

$$\omega(t) = \omega_{ef} \times (1 + \varepsilon + y(t))$$

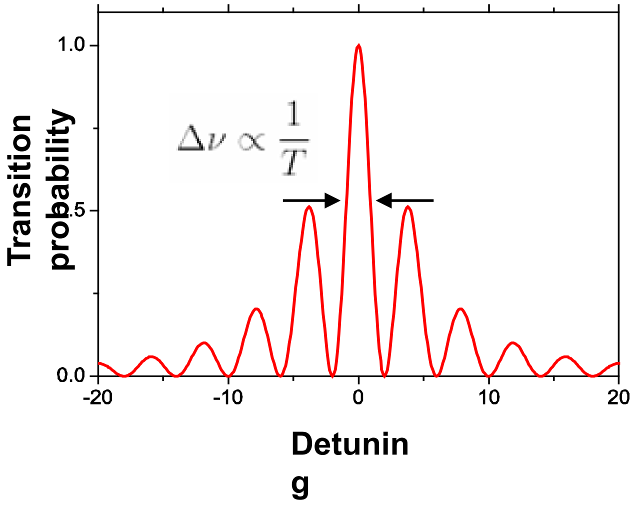
Inaccuracy: ε

Fractional frequency fluctuations: $y(t)$

Fractional frequency instability: $\sigma_y(\tau) \propto \frac{\sigma_{\delta P}}{Q_{at}}\sqrt{\frac{T_c}{\tau}}$

Fluctuations of the transition probability: $\sigma_{\delta P}$

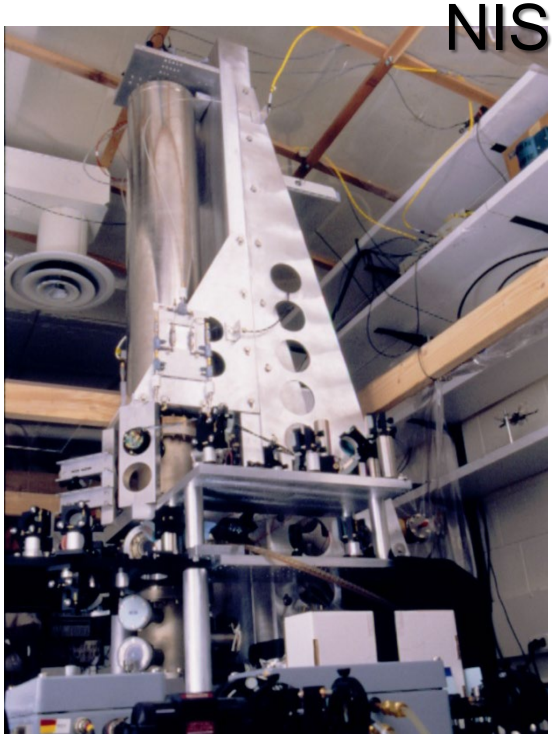
Atomic quality factor: $Q_{at} = \frac{\nu_{ef}}{\Delta\nu} \propto \nu_{ef} T$

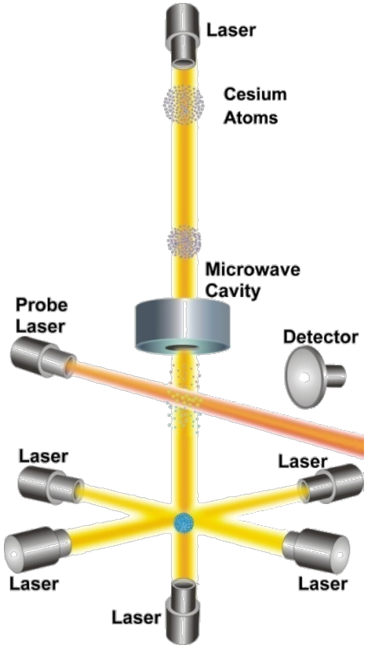


Frequency Standards

PRIMARY FREQUENCY STANDARD FOR THE UNITED STATES

NIST-F1 Atomic Fountain Clock





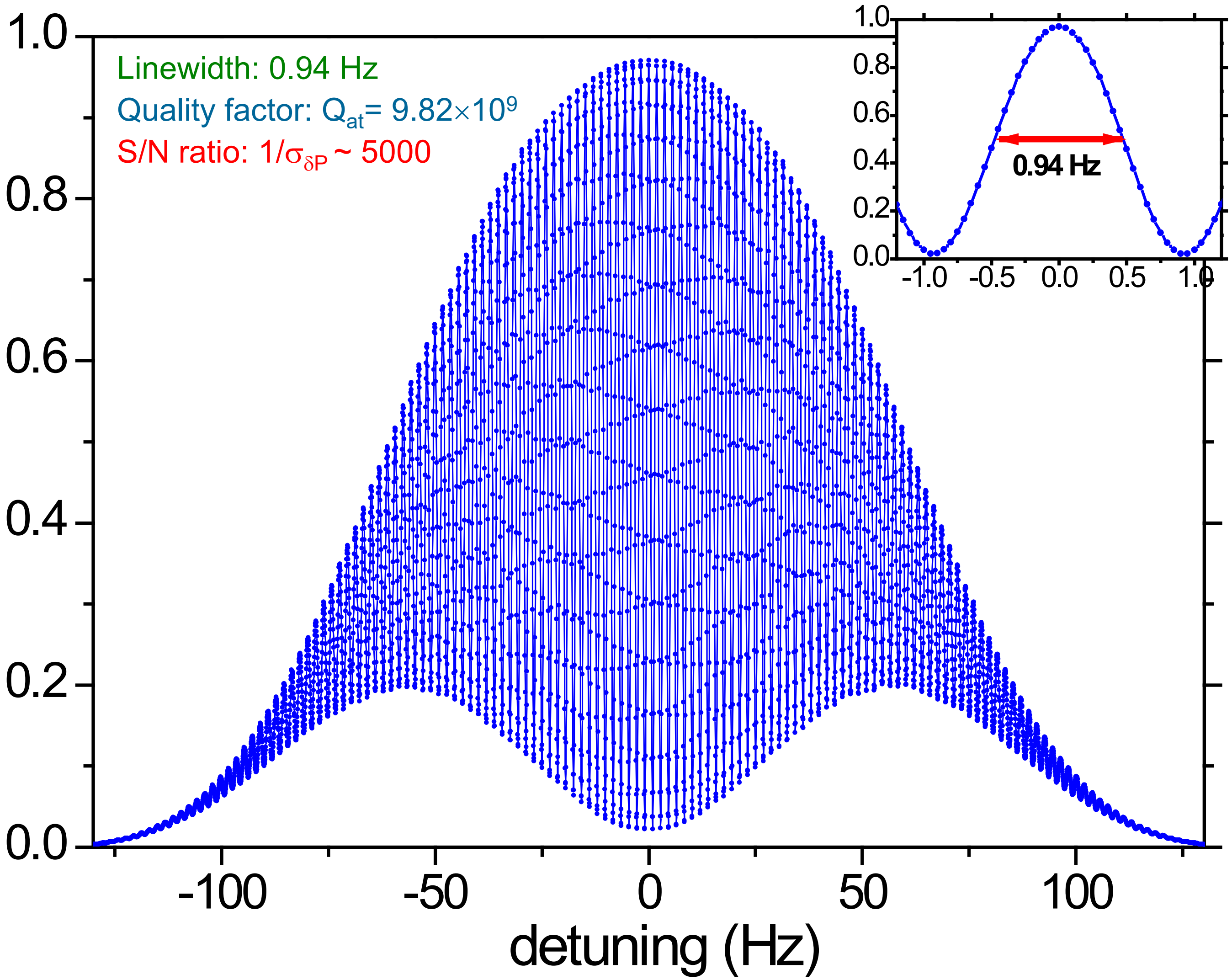
1 second is defined as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the ^{133}Cs atom.

Current accuracy (uncertainty):

- 3×10^{-16} second.
- 25 trillionths of a second per day.
- 1 second in 100 million years.

Re-evaluation of all systematic effects after move to new labs

Ramsey spectroscopy

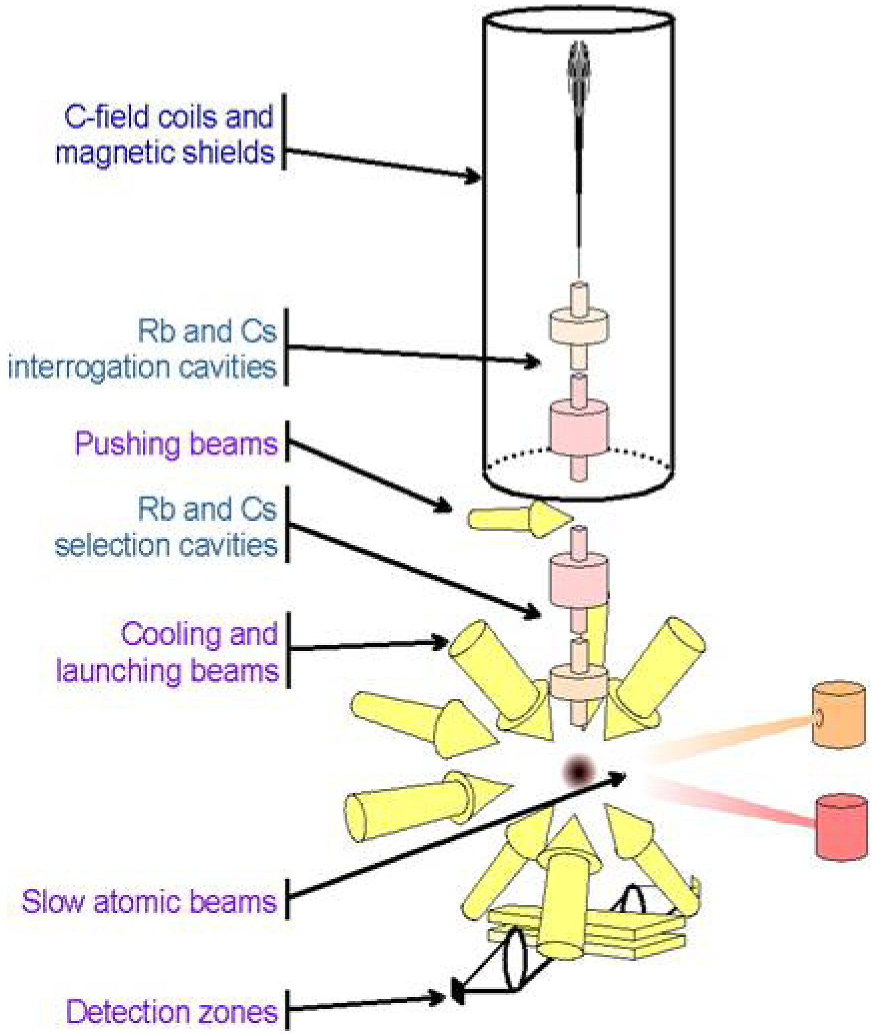


Linewidth: 0.94 Hz

Quality factor: $Q_{at} = 9.82\times10^{9}$

S/N ratio: $1/\sigma_{\delta P} \sim 5000$

Atomic fountain clock



Typical parameters:

$N_{at} \sim 10^9$

$\sigma \sim 3$ mm

$T \sim 1\ \mu K$

$v \sim 4$ m/s

$H \sim 1$ m

$100\text{ ms} \leq T_{load} \leq 500\text{ ms}$

$1.1\text{ s} \leq T_{cycle} \leq 1.5\text{ s}$

From the μ-wave to the optical domain

$$\sigma_y(\tau) = \frac{1}{\pi}\frac{\Delta\nu}{\boxed{\nu_0}}\frac{1}{\sqrt{N_{at}}}\sqrt{\frac{T_c}{\tau}}$$

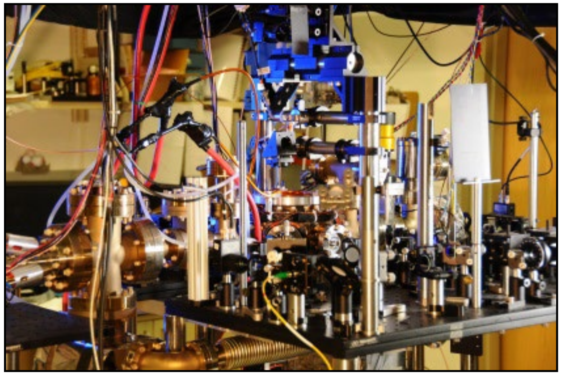
- Fractional frequency instability at the quantum projection noise
  - $\Delta\nu \sim$ 1Hz, limited by the interaction time (effect of gravity)
  - $N_{at} \sim 10^6$, limited by cooling and trapping techniques, collisional shift, etc.
- Solution: increase ν_0 → optical transition show a potential increase of 5 orders of magnitude
  - μ-wave fountain clocks: $\sigma_y(\tau) \sim 10^{-14}\tau^{-1/2}$
  - Optical clocks: $\sigma_y(\tau) \sim 10^{-18}\tau^{-1/2}$
- Accuracy → theoretical studies foresee the possibility of reaching the 10^{-18} regime
- Major difficulties:
  - Measurements of optical frequencies (frequency-comb generator)
  - Recoil and first order Doppler effects
  - Downconversion noise of the interrogation oscillator (Dick effect)

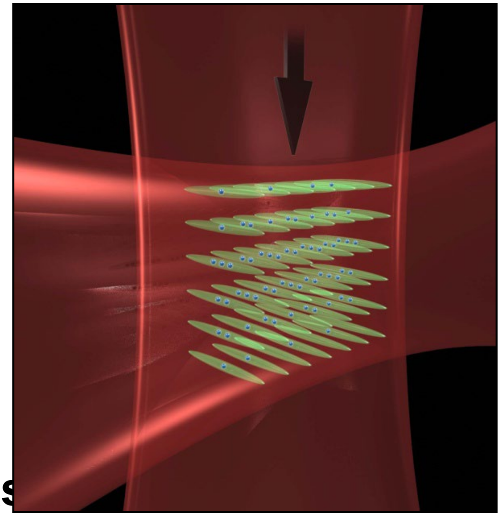
Frequency Standards

SECONDARY STANDARDS: OPTICAL CLOCKS

Al^+	1124 THz	Ions
Hg^+	1064 THz	
Yb	520 THz	Neutrals
Ca	456 THz	
Sr	429 THz	

$\Delta f/f \sim 6 \times 10^{-18}$

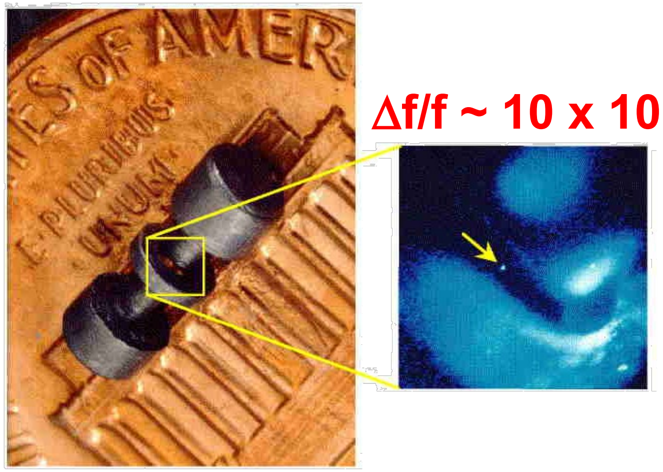




Sr or YB optical lattice clocks

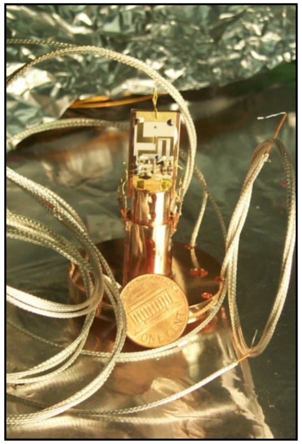
Single Hg ion trap

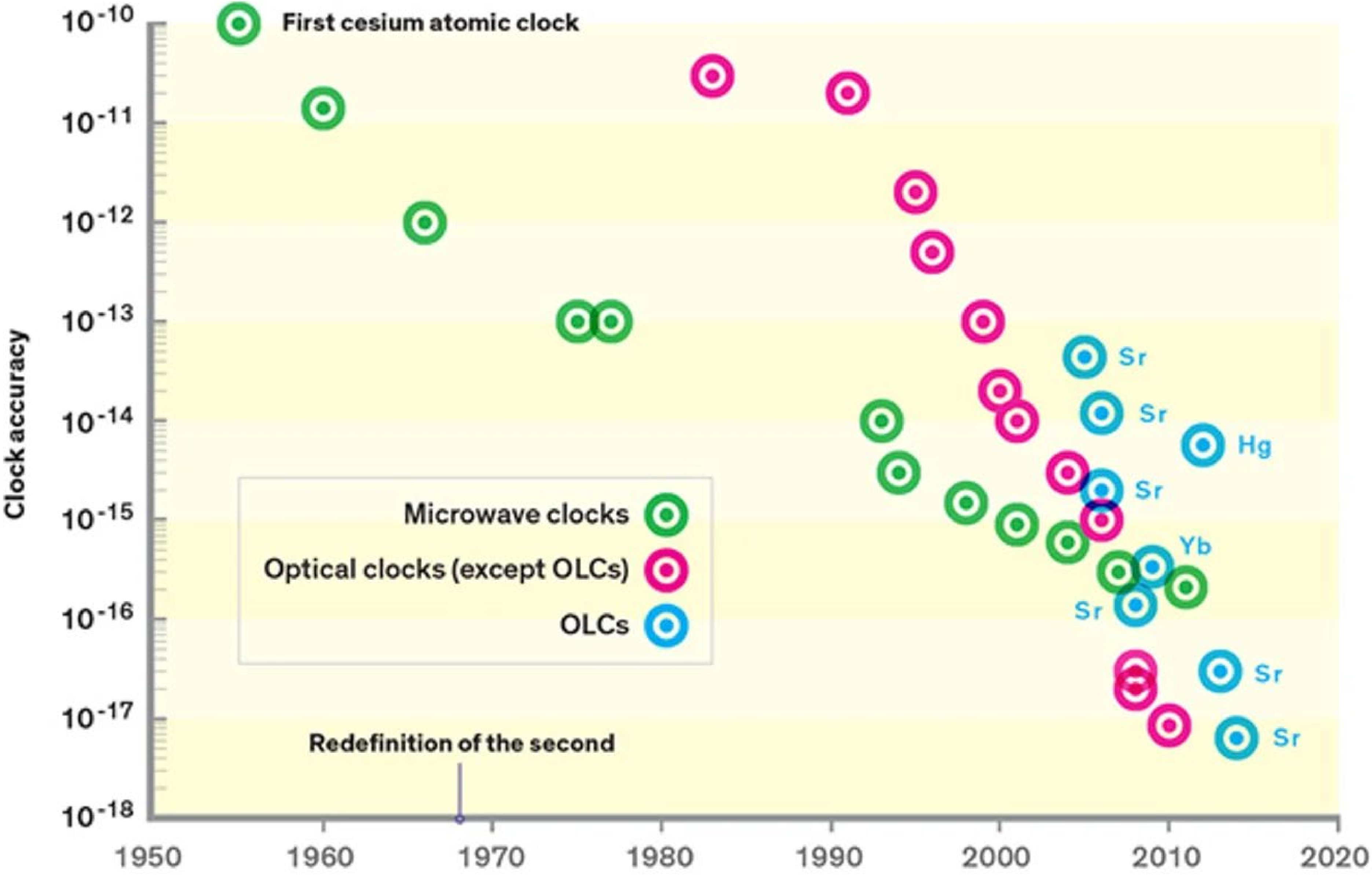
$\Delta f/f \sim 10 \times 10^{-18}$



$\Delta f/f \sim 8 \times 10^{-18}$

Al ion logic clock




First cesium atomic clock
Clock accuracy
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
Microwave clocks
Optical clocks (except OLCs)
OLCs
Sr
Sr
Hg
Sr
Yb
Sr
Sr
Sr
Redefinition of the second
1950
1960
1970
1980
1990
2000
2010
2020