Systèmes de Référence Temps-Espace

SYRTE

Atomic time: past, present & future realizations

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Journée scientifique : la seconde atomique à cinquante ans
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Topics covered in this presentation

- Concepts underpinning atomic time

- 3 generations of atomic frequency standards

- From frequency standards to timescales

- Frequency standards in the curved space-time

Periodic phenomena and the idea of time

- **Humans perceive phenomena that seem to repeat regularly**
  - Day/night cycles, oscillations of a pendulum, cardiac cycles, etc.

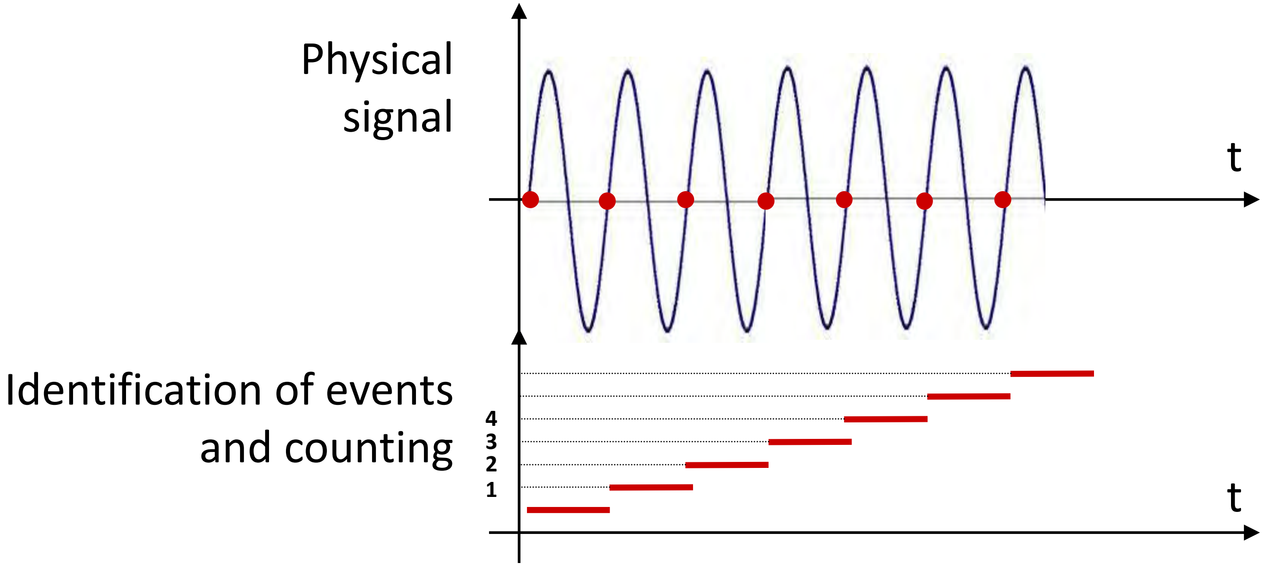
- **Succession of identical events can be counted and labelled**
  - Sun at meridian, extremum of pendulum motion, etc.

- **Labelled events can be used to mark other phenomena**
  - Works if no error is made in counting and if the origin of counting process is agreed upon

- **Many different such scales are found consistent at some level**
  - →leads to the idea, to the possibility and to the usefulness of time, the continuous variable *t* used in physics

Fundamentals of realizing time intervals

❑ **Observing and counting a periodic physical signal**



❑ **Quality of time intervals determined by the stability of chosen periodic phenomenon**

- → **Frequency standard** to generate periodic signal whose frequency is as stable as possible

❑ **Realization of time intervals should be as universal as possible**

A universal & (almost) perfect reference

- **Atoms have quantized, discrete energy levels**

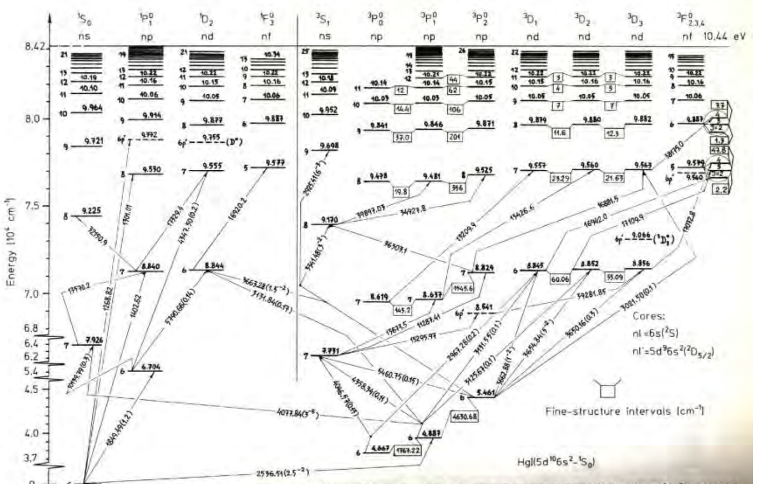
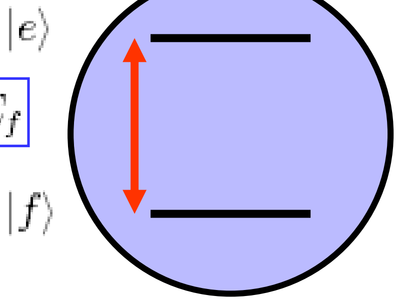


Fig. 7.42. Combined partial energy-level – Grotrian diagram with absorption oscillator strengths for mercury

- **Energy differences between levels correspond to frequencies**
  - via Planck's relation

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



- **Bohr frequencies of an unperturbed atom are thought to be perfectly stable and universal**
  - Two atoms of the same atomic species are identical
  - Atoms do not wear up or age

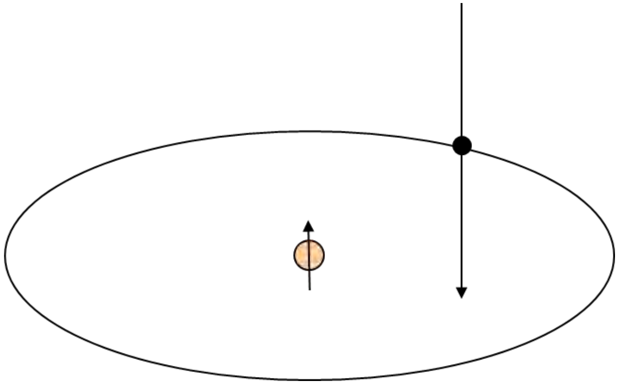
Definition of the SI second

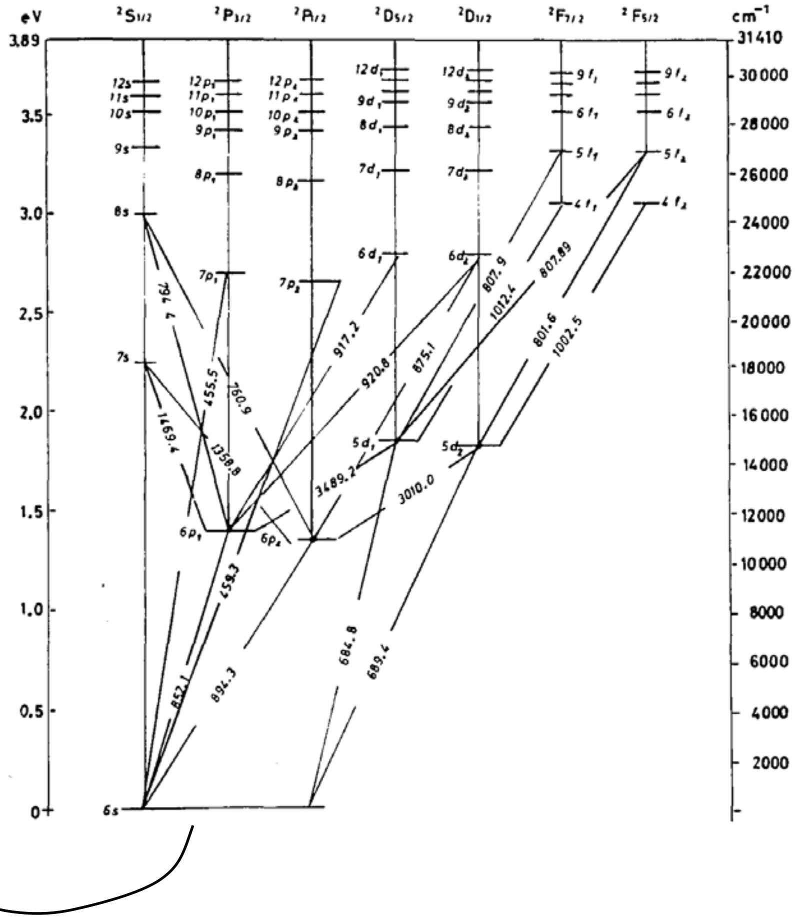
❑ Definition

- *The second is 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 caesium 133 atom.*

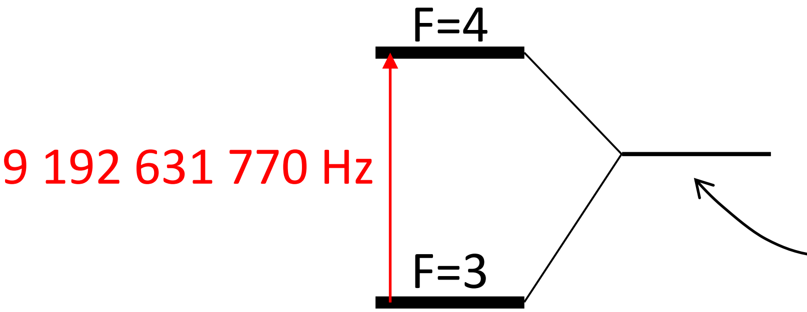
❑ Hyperfine interaction

- Between nuclear spin and electronic spin



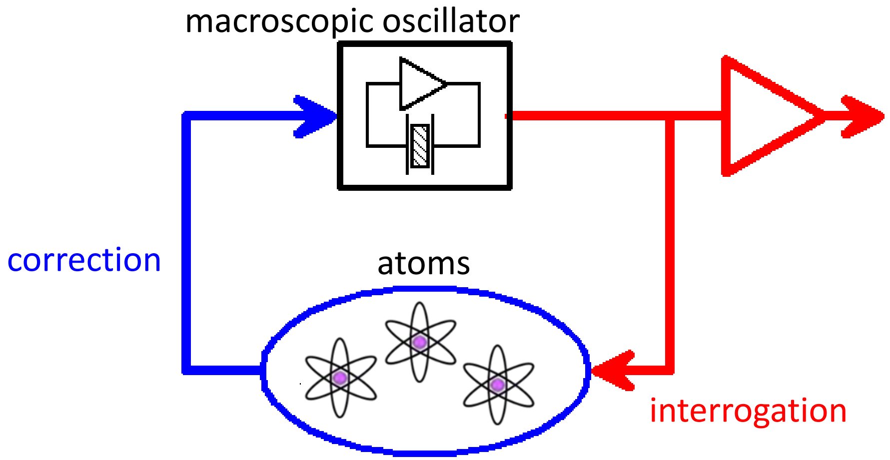


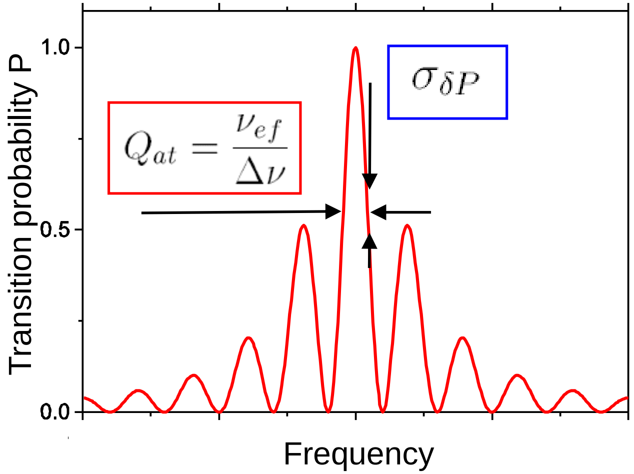
❑ Levels



Principle of atomic frequency standards

❑ Building blocks of an atomic frequency standard





❑ Output of a frequency standard

- Macroscopic, practically usable oscillatory electromagnetic signal whose frequency is connected to the atomic transition
- With frequency offset and noise

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

❑ Essential properties of atomic frequency standards

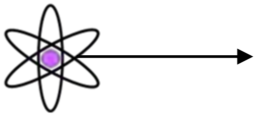
- Accuracy: overall uncertainty on ε
- Stability: statistical properties of $y(t)$, characterized with $\sigma_y(\tau)$

Physics underneath (stability and) accuracy

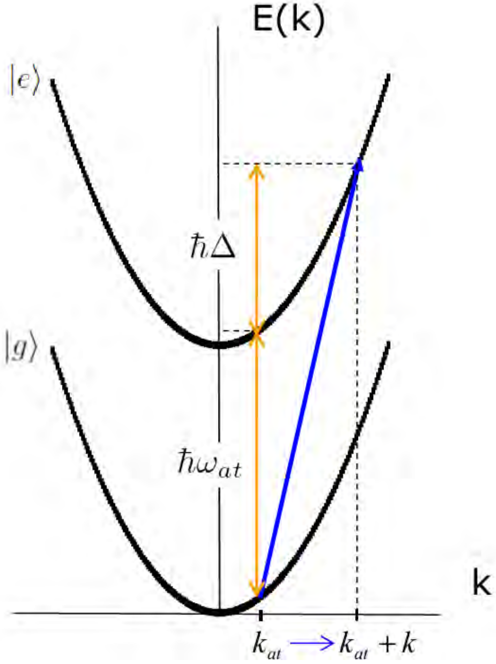
❑ Effects of external motion

- Kinetic energy adds to the internal energy

  a continuum of energy
- →Limitation of interrogation duration
- →Doppler shift
- →Recoil shift
- →Relativistic time dilation



$$E_{\text{kin}} = \frac{1}{2} m_{at} v^2$$



❑ A concern for all atomic frequency standards

- Magnitude of Doppler shift
- →hot atoms: 100 m.s^{-1} → $\frac{\delta\nu}{\nu} \sim \frac{v}{c} \sim 3 \times 10^{-6}$

❑ Three generations of atomic frequency standard

- →enabled and characterized by breakthroughs in ways to dealing with external motion

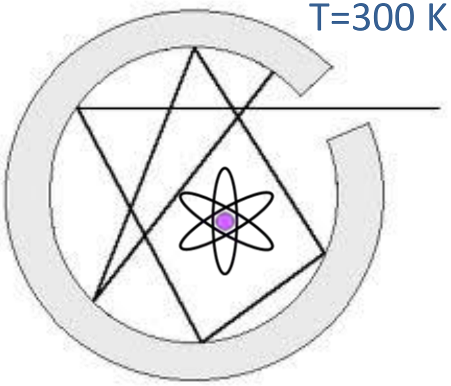
Physics underneath (stability and) accuracy

❑ Effect of thermal radiation

- Blackbody radiation = electromagnetic radiation in thermal equilibrium with the environment, described by Planck's law, Stefan-Boltzmann law, etc.
- Atoms are unavoidably immersed into this field
- →Fluctuating electric (and magnetic) field

$$\langle E^2\rangle^{1/2} = 831.9\ \mathrm{V.m}^{-1} \quad \mathrm{at} \quad T_0 = 300\ \mathrm{K}$$

$$\langle E^2\rangle = K_E\left(\frac{T}{T_0}\right)^4$$



- →Causing a frequency shift

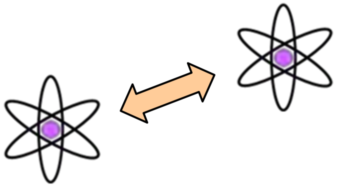
$\sim$ -1.7×10^{-14} for Cs

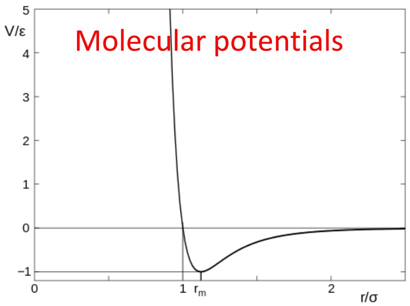
$$\delta\nu \simeq -\frac{1}{2\pi\hbar}\times\frac{1}{2}\Delta\alpha\langle E^2\rangle$$

atomic coefficient

external field

❑ Interatomic interactions





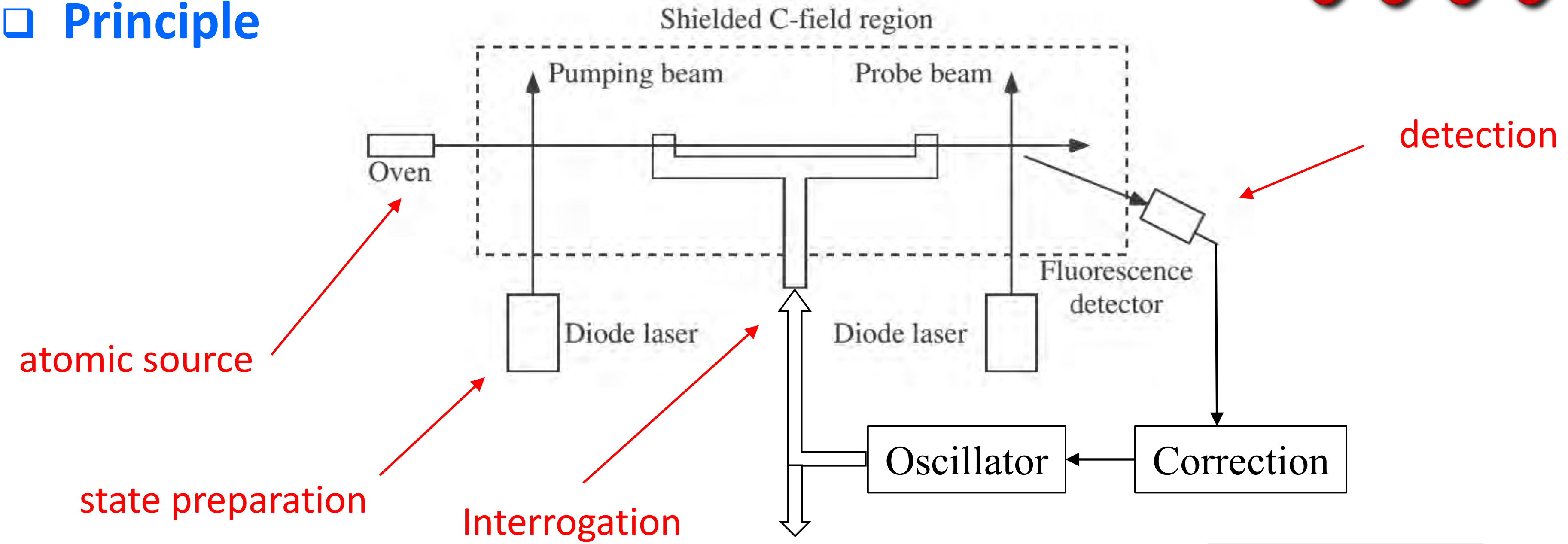
- Shift depends on atomic density
- Can exhibit complex physics especially in the cold/ultra-cold regime

❑ Plenty of other physical and technical effects

- Frequency standards do not come with a comprehensive list

1^{st} generation: thermal atomic beam

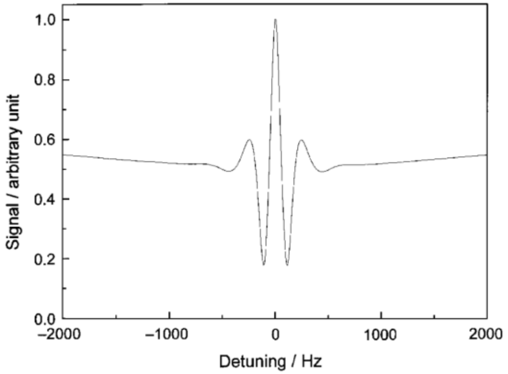
❑ Principle



❑ Characteristics

- Velocity/velocity spread ~ 100 $m.s^{-1}$
- $\Delta\nu \sim 100$ Hz , $Q_{at} \sim 10^8$
- Stability: 3.5×10^{-13} in 1 s
- Accuracy: 5×10^{-15}

Error no larger than <1 hour over the age of the Universe



❑ Control of external motion

- Standing wave in Ramsey cavity, beam reversal, determination of velocity distribution

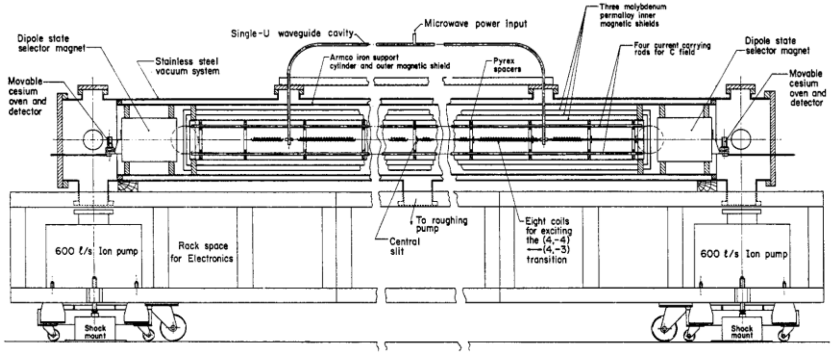
Thermal beam primary frequency standards

❑ Institutes

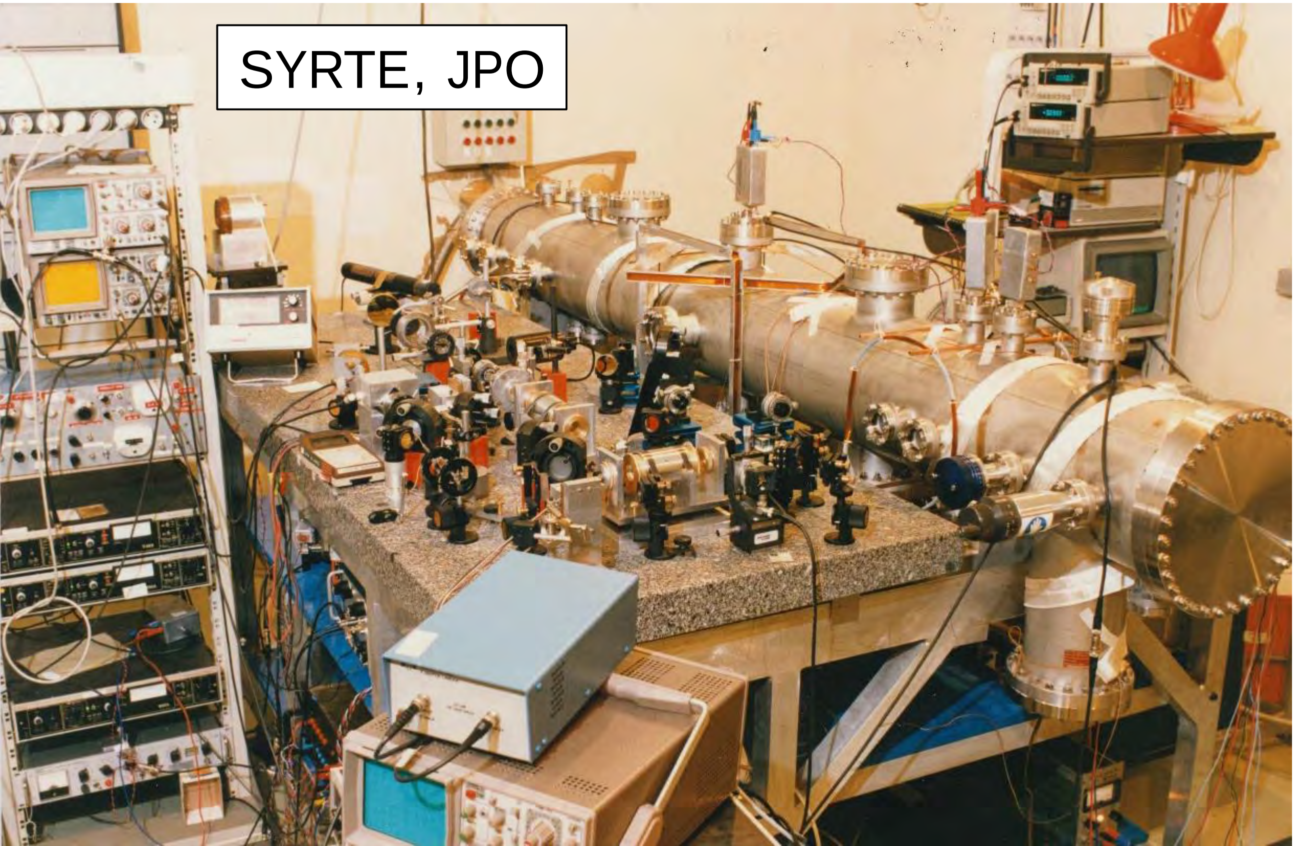
- NIST, PTB, NRC, CRL, SYRTE, etc.

❑ Use until now

- Cs transition first observed in 1952
- PTB-CS1 & CS2 still calibrating TAI
- SYRTE-JPO stopped in 2010



NRC, CESIUM V

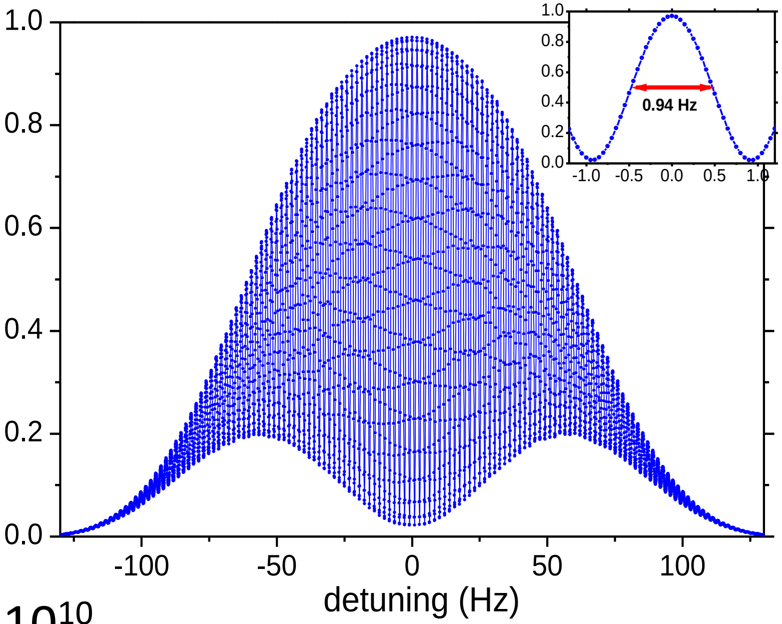


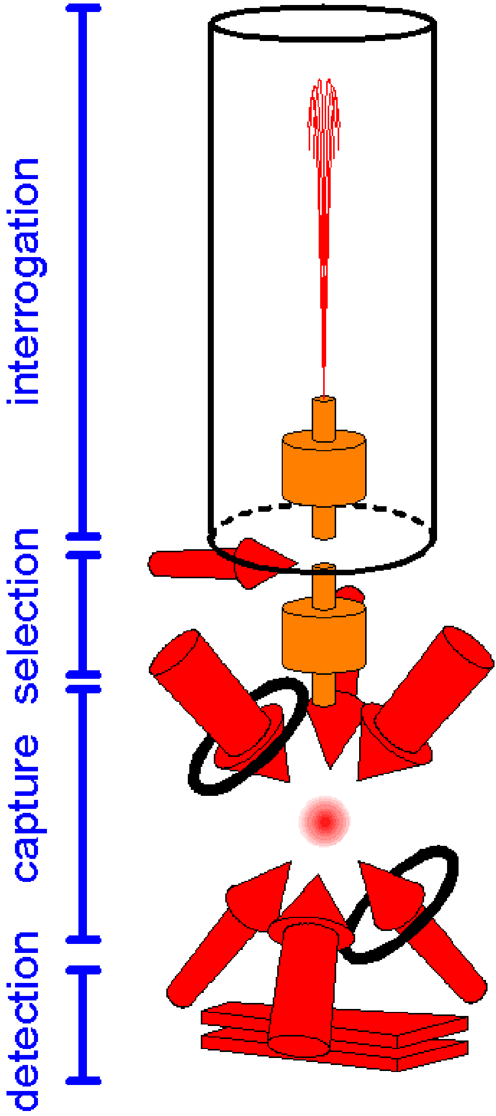
SYRTE, JPO

2nd generation: laser-cooled atomic fountain

❑ Principle

- Laser-cooled atomic sample
- Velocity spread ~ 1 cm.s^{-1}





❑ Characteristics

- $\Delta\nu \sim 1$ Hz , $Q_{at} \sim 10^{10}$
- Stability: 1.5×10^{-14} in 1 s
- Accuracy: 2×10^{-16}

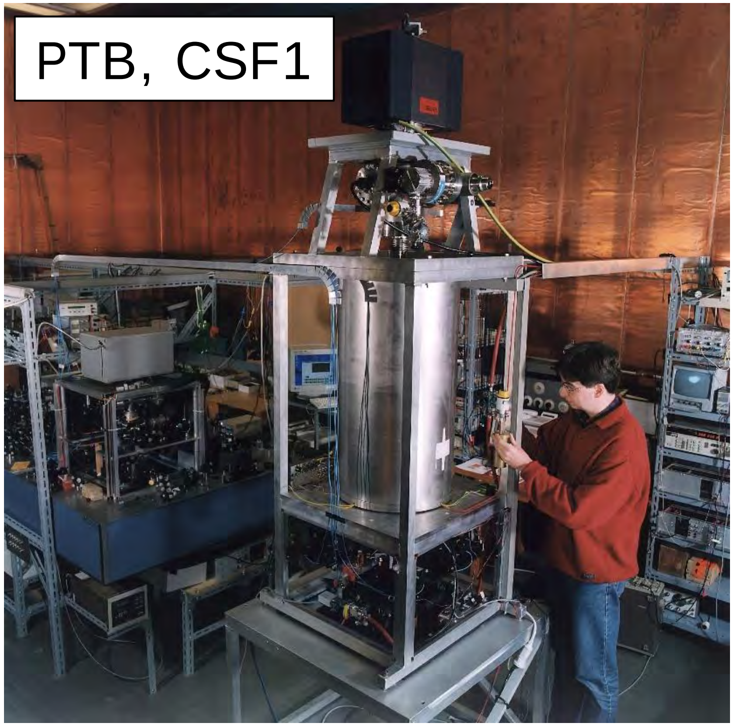
Error no larger than <100 s over the age of the Universe

❑ Control of external motion

- Cold atoms, standing wave in Ramsey cavity, reversal of trajectories due to gravity

Fountain primary frequency standards

- ❑ **Institutes**
  - SYRTE, PTB, NPL, NIST, INRIM, etc.
  - Proof-of-principle 1989 (Stanford) & 1991 (LKB with SYRTE+NIST)
  - 1st fountain standard 1995 (SYRTE)
- ❑ **Define the accuracy of TAI**
  - →accuracy delivered to users
- ❑ **Used to steer some local timescales**
  - UTC(USNO), UTC(PTB), UTC(OP)


PTB, CSF1


SYRTE, FO1

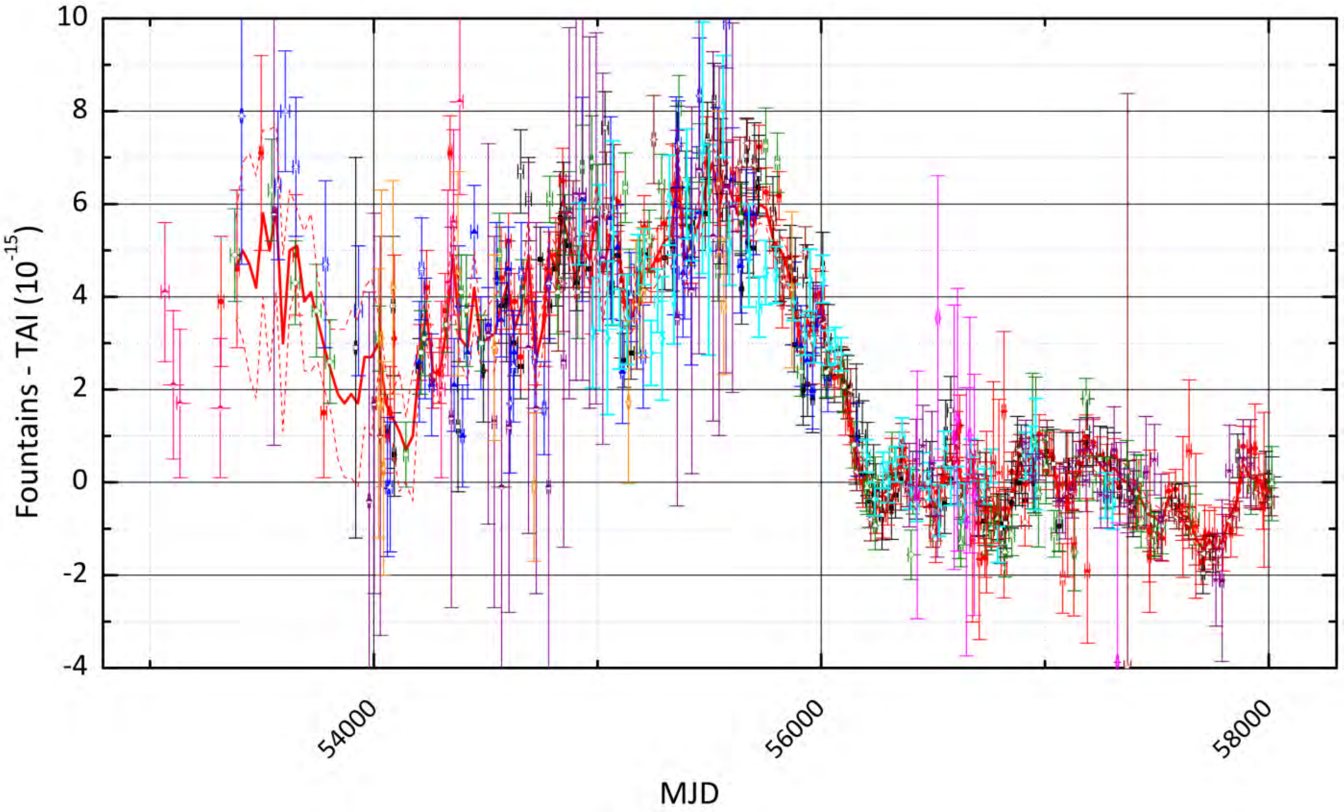
TAI calibration's by primary frequency standard

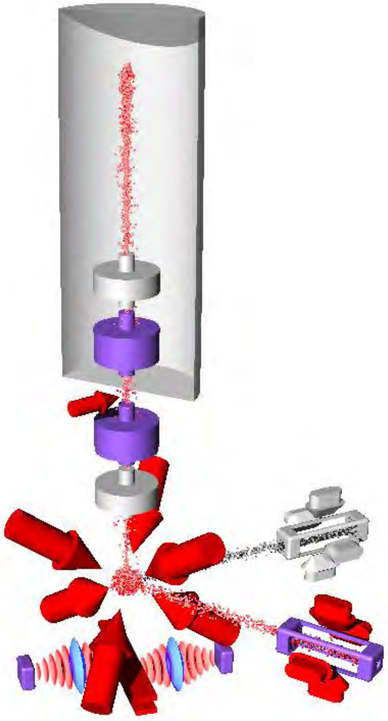
A demanding task

- 14 Cs fountains from 10 institutes contributed at least once
- The vast majority of calibrations come from 3-4 institutes
- Over 15 years, LNE-SYRTE provided >200 calibrations, more than 40%

Not only with Cs

- SYRTE pioneered using a **secondary representation of the SI second**, the ^{87}Rb hyperfine transition



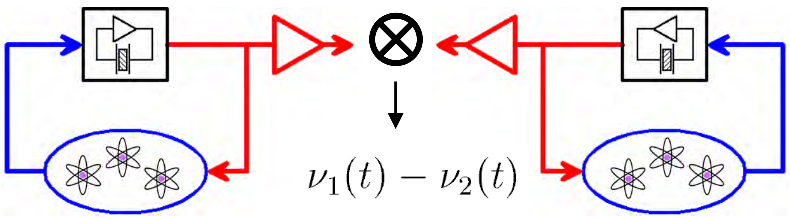


SYRTE, FO2-Cs & FO2-Rb

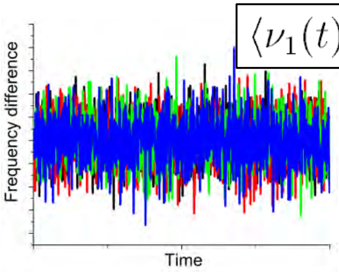
From frequency standards to timescales

❑ How to know that the accuracy is (probably) right?

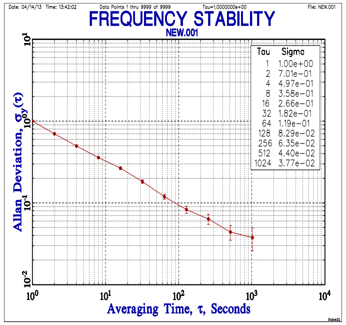
- → Comparisons of 2 (or more) identical standards are essential



$$\nu_1(t) - \nu_2(t)$$



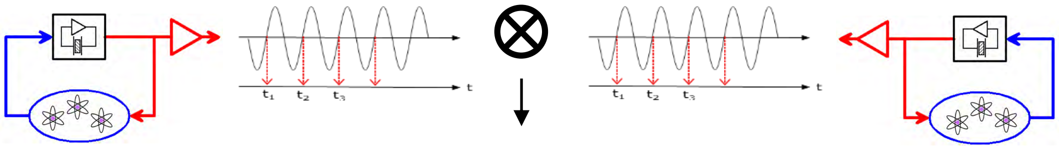
$$\langle \nu_1(t) - \nu_2(t) \rangle_\tau = 0\ ?$$



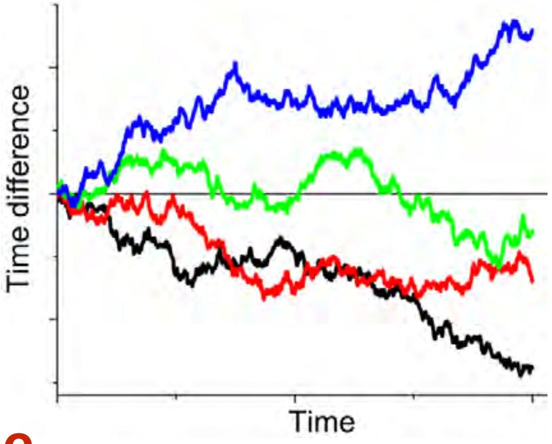
Tau	Sigma
1	1.00e+00
2	7.01e−01
4	4.97e−01
8	3.58e−01
16	2.66e−01
32	1.82e−01
64	1.19e−01
128	8.29e−02
256	6.35e−02
512	4.40e−02
1024	3.77e−02

❑ Two completely independent timescales diverge from each other

- → random walk (or worse) of the time difference



$$T_1(t) - T_2(t)$$



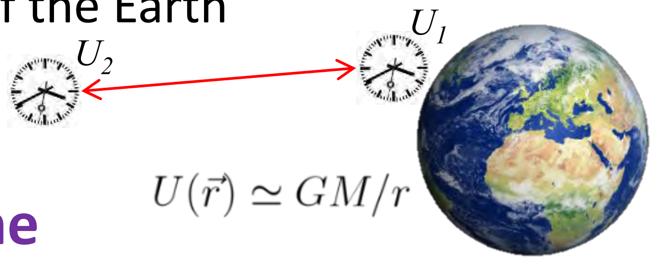
❑ A single shared conventional reference timescale

- Needed for consistent worldwide timekeeping
- →TAI/UTC and local physical realizations UTC(k) steered to UTC
- Note: TAI/UTC diverges the same way with respect to an ideal representation of time

Frequency standards in the curved space-time

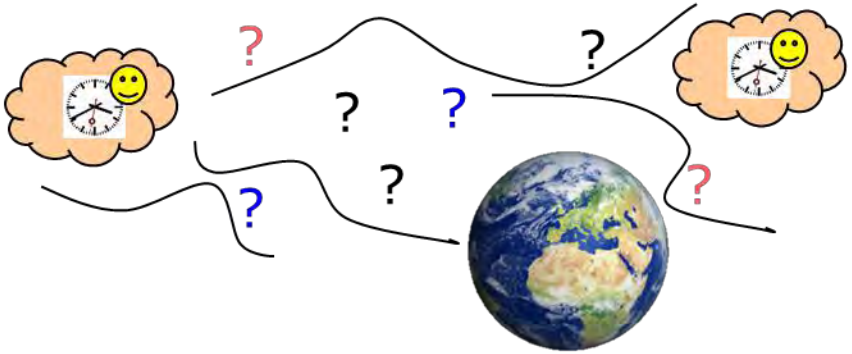
- **Space-time is modified in the vicinity of massive objects**
  - Described by Einstein's general relativity
  - → gravitational redshift: 10^{-16}/m at the surface of the Earth

$$\boxed{\frac{\nu_2}{\nu_1} = \left(1 - \frac{U_2 - U_1}{c^2}\right)}$$



$$U(\vec{r}) \simeq GM/r$$

- **A frequency standard realizes its proper time**
  - Valid only in a small surrounding volume that can be considered flat



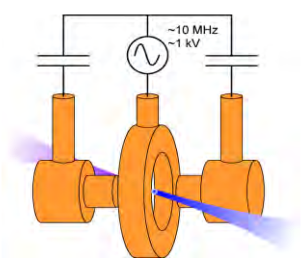
$$d\tau \simeq \left(1 - \frac{U(T,\vec{R})}{c^2} - \frac{1}{2}\frac{\vec{V}^2}{c^2}\right) dT$$

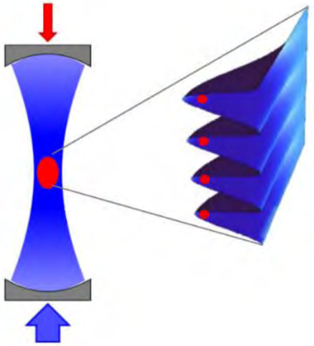
- **Unavoidably, frequency standard comparisons in the vicinity of the Earth are general relativity experiments**
  - Need to define a global coordinate system
  - Need to account for gravity precisely
  - Elaboration of TAI is no exception. *TAI is a realization of TT itself defined by a constant rate wrt to TCG, etc.*

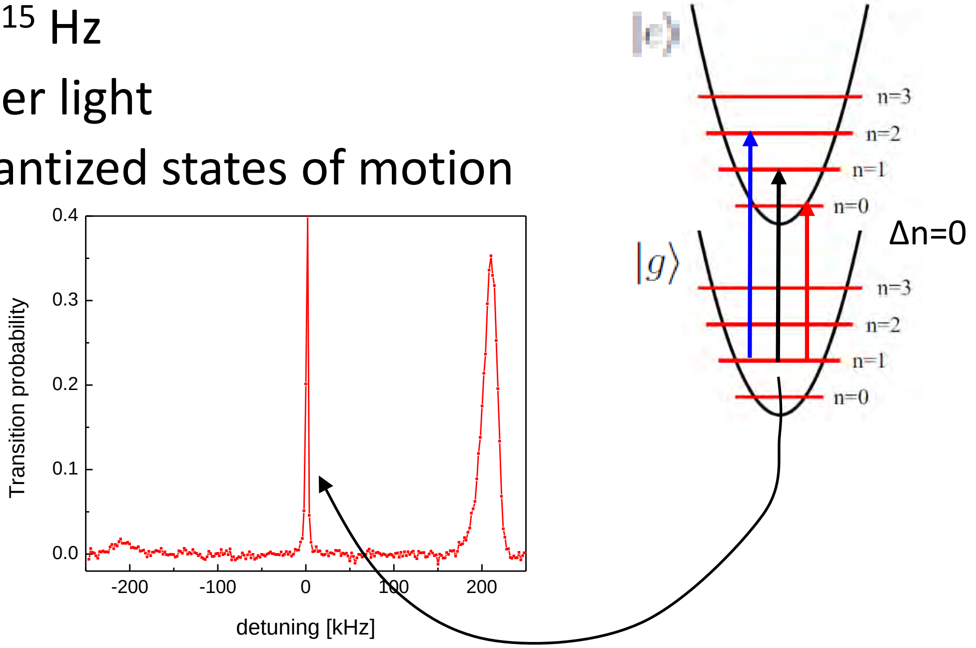
3rd generation: optical frequency standards

❑ Principle

- An optical transition: $10^{14} – 10^{15}$ Hz
- → Probed with ultra-stable laser light
- Tightly bound atoms giving quantized states of motion
- → Lamb-Dicke spectroscopy







Carrier transition

❑ Characteristics

- Δν ~ 1 Hz on the optical carrier, $Q_{at} \sim 10^{15}$
- Stability: 1.4×10^{-16} in 1 s (optical lattice clock)
- Uncertainty: as low as 2.1×10^{-18}

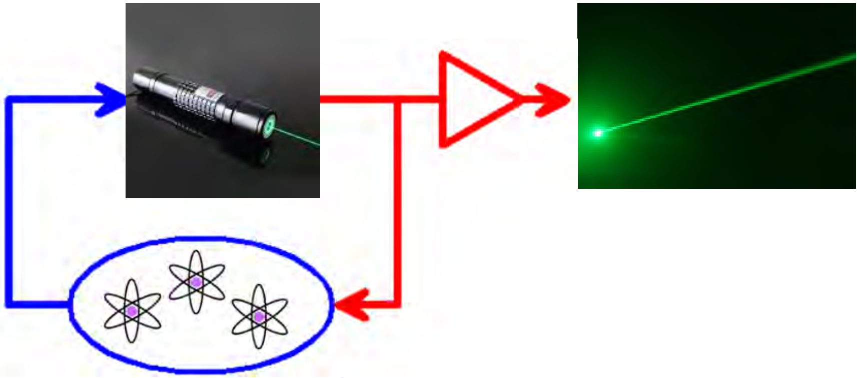
Error no larger than <1 s over the age of the Universe

❑ Control of external motion

- Motional effects in sidebands, carrier transition essentially unaffected
- BUT: need to care about effects of the trap

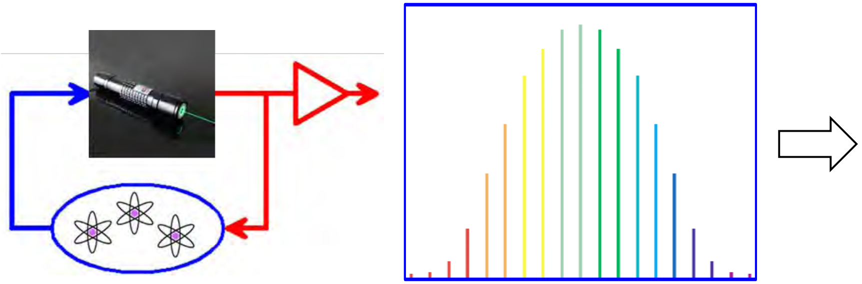
Optical frequency standards

❑ The output is laser light with ultra-stable frequency



❑ Optical frequency comb

- To connect optical frequencies between them
- To connect optical domain to microwave domain



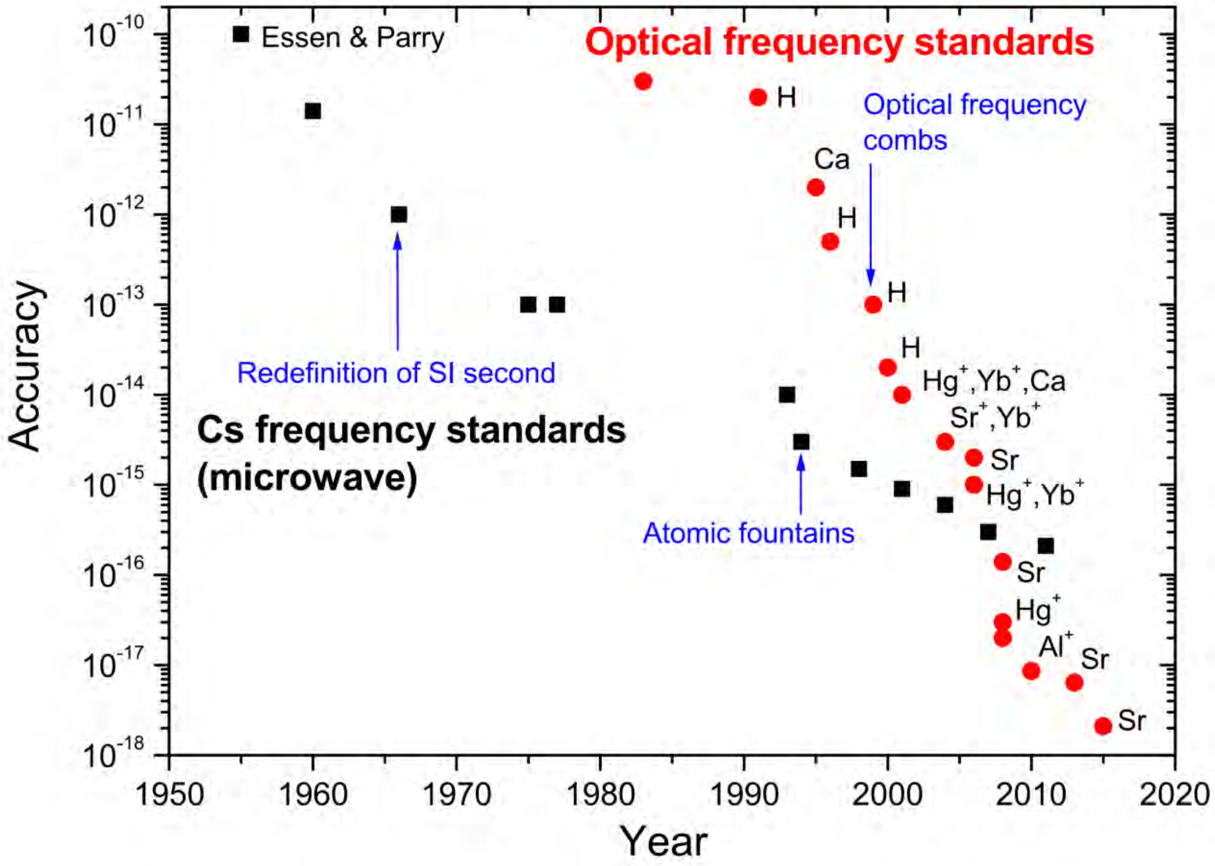
Microwave signal referenced to the optical transition

Compatible with existing schemes and systems

❑ First calibrations of TAI with an optical frequency standard

- Pioneered by SYRTE with strontium optical lattice clocks (^{87}Sr $^{1}S_0$-$^{3}P_0$ transition)
- Can be done only if the absolute frequency of the new transition has been measured accurately, close of the limit of primary frequency standard

Progress of frequency standards over time



- ❑ **Points toward a redefinition of the second**
  - Based optical transition(s)
  - Potentially, more fundamental definitions also possible

$$h\nu = \Delta E = \Delta m c^2$$

- ❑ **Cs frequency standard defined a "high standard"**
  - In terms of operability, service to TAI, etc.
  - → Optical frequency standards have to demonstrate their readiness