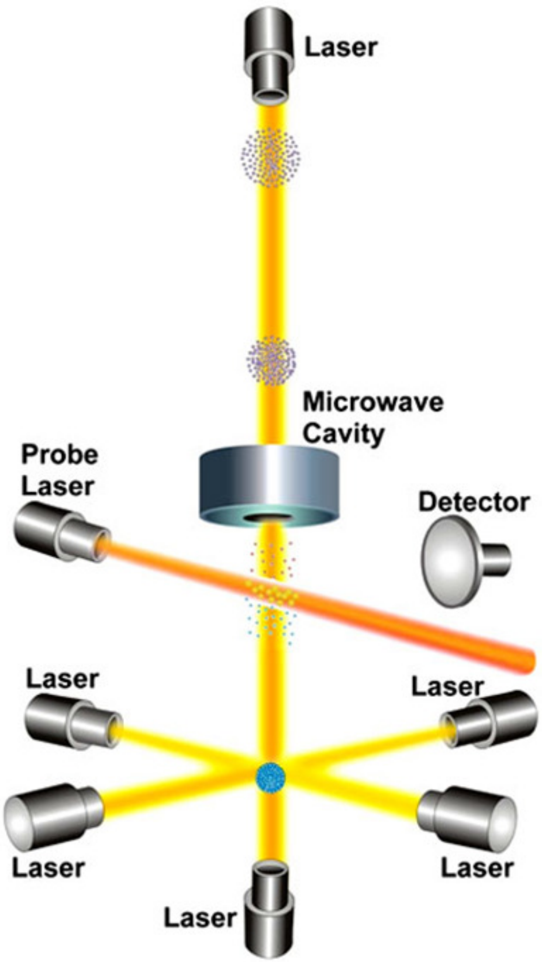
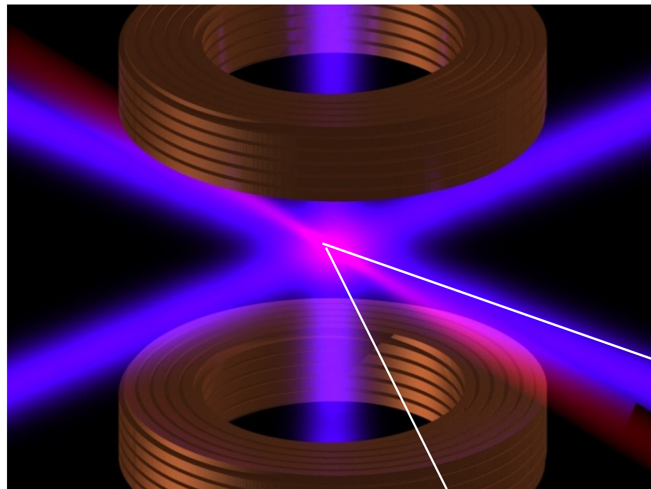
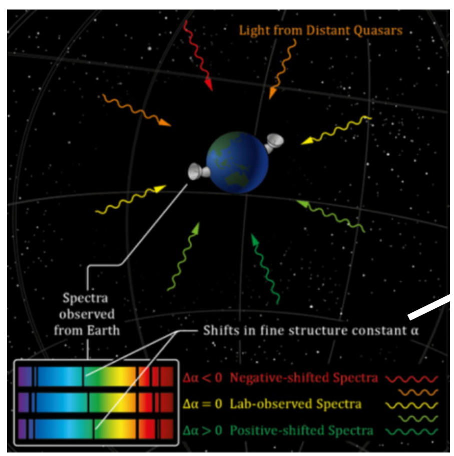
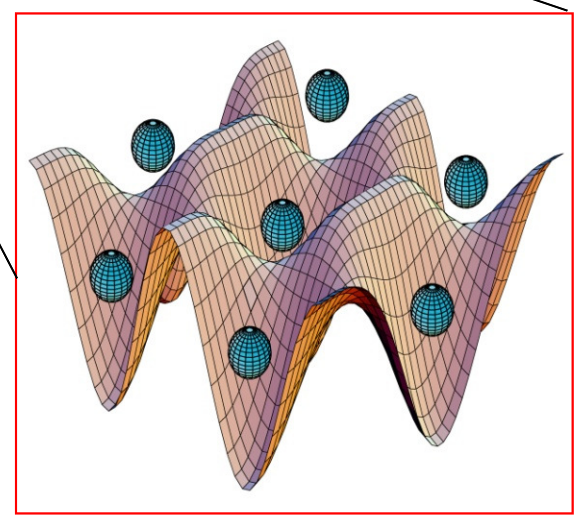
Atomic clocks

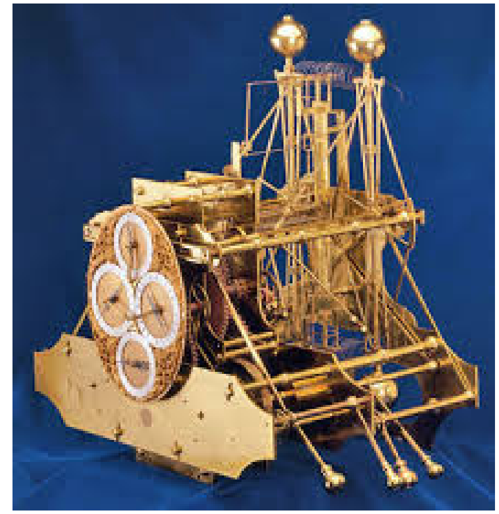






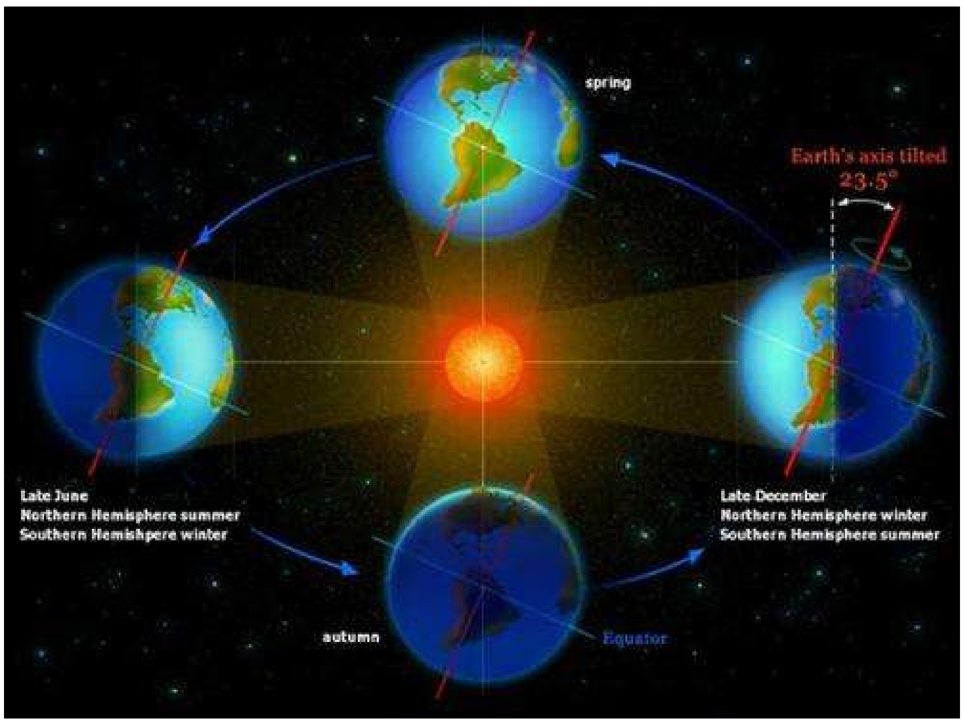


Clocks



Ingredients for a clock

1. Need a system with **periodic behavior**:
   it cycles occur at constant frequency



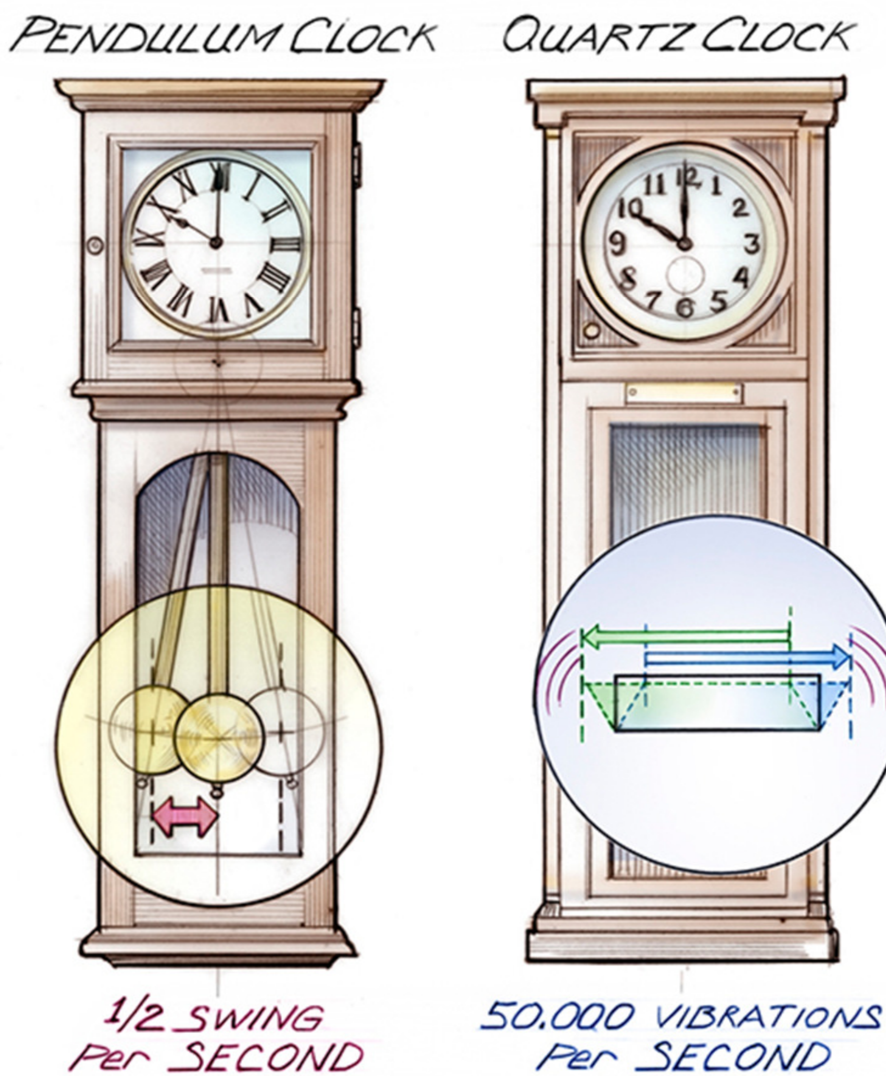
2. Count the cycles to produce time interval
3. Agree on the origin of time to generate a time scale

NOAA/Thomas G. Andrews

Ludlow et al., RMP 87, 637 (2015)

Quartz Clock

The quartz clock keeps better time than the best mechanical clocks. It contains a specially cut quartz crystal that vibrates at a particular frequency when voltage is applied. The vibrations can be sustained in an electrical circuit and will generate a signal of constant frequency that can be used to keep time.



QUARTZ CLOCK

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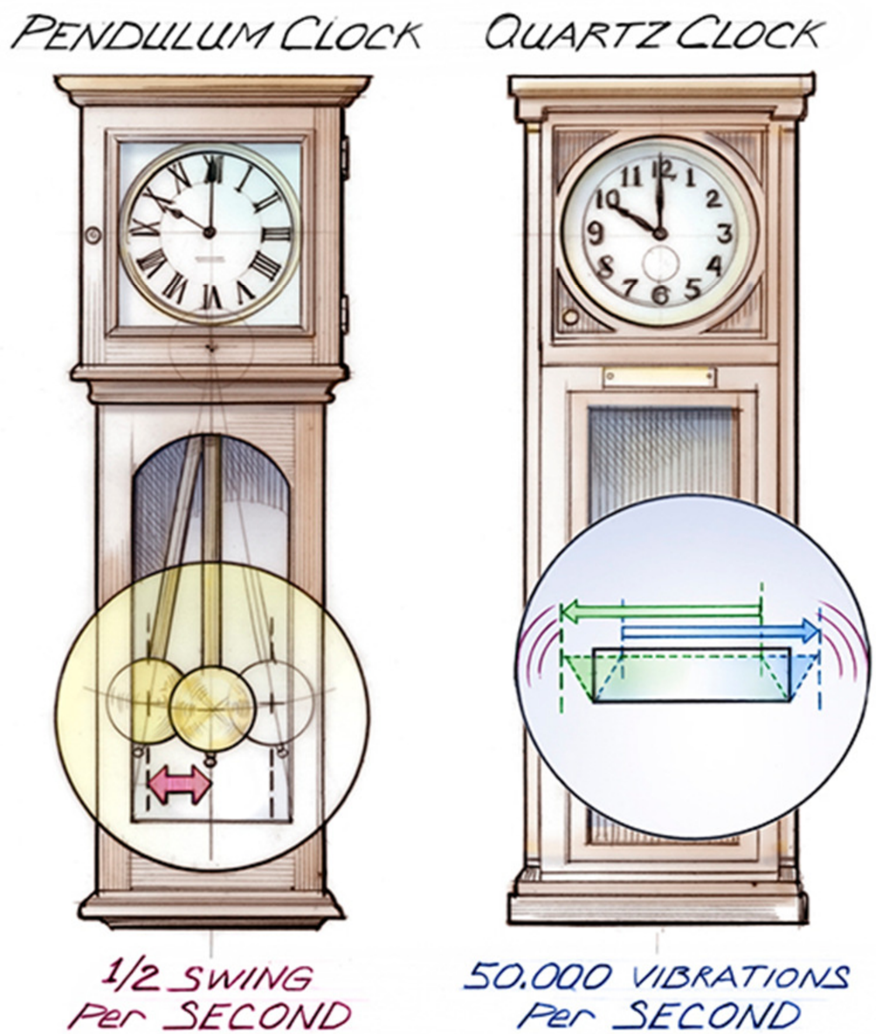
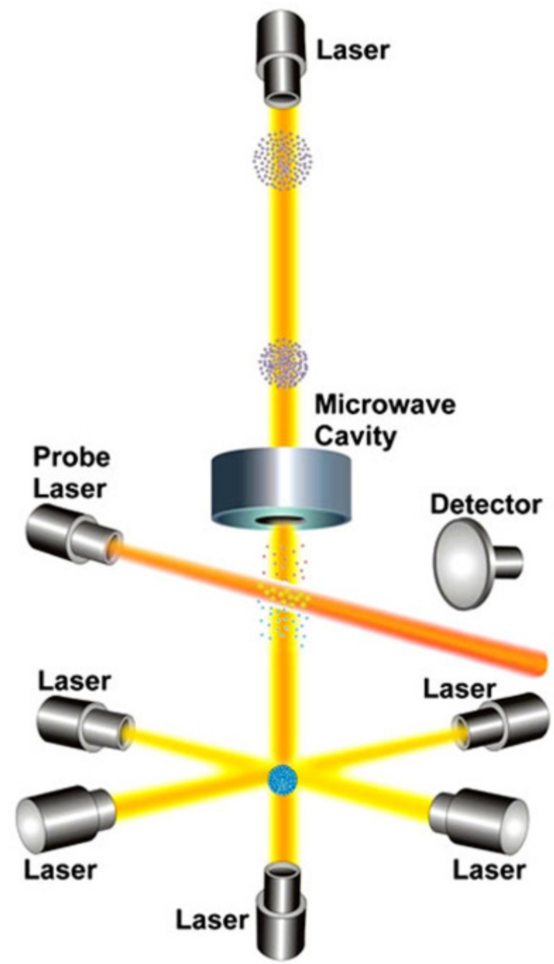


Cesium microwave atomic clock

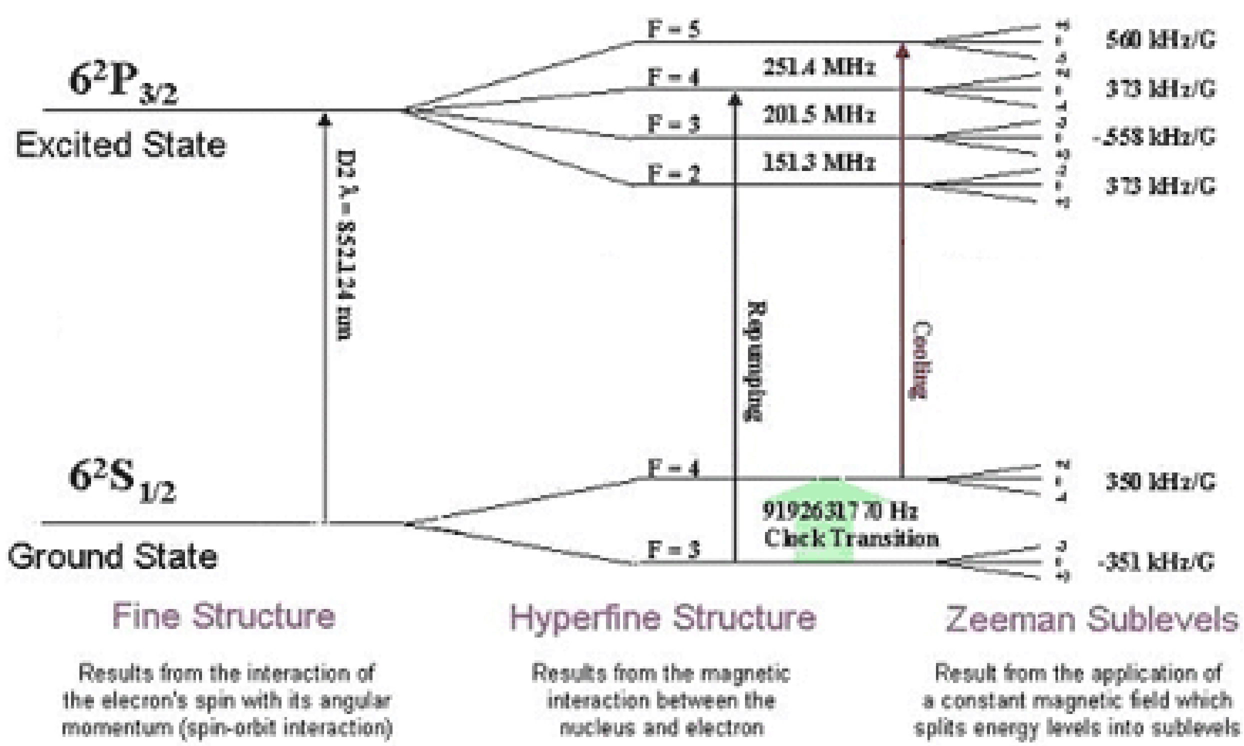


9 192 631 770 periods per second

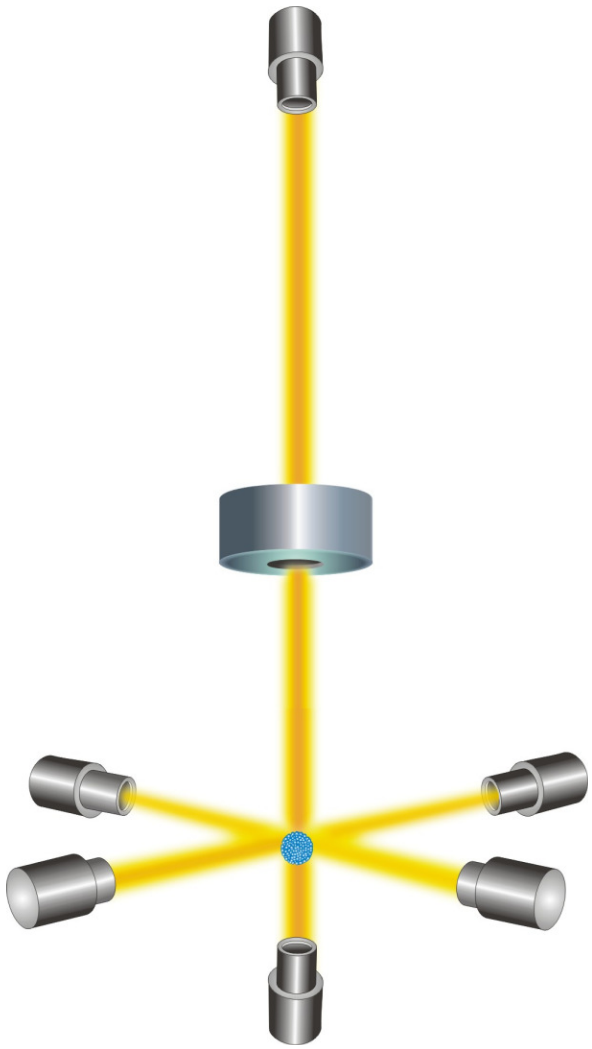
Current definition of a second:

1967: the second has been 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 cesium 133 atom.

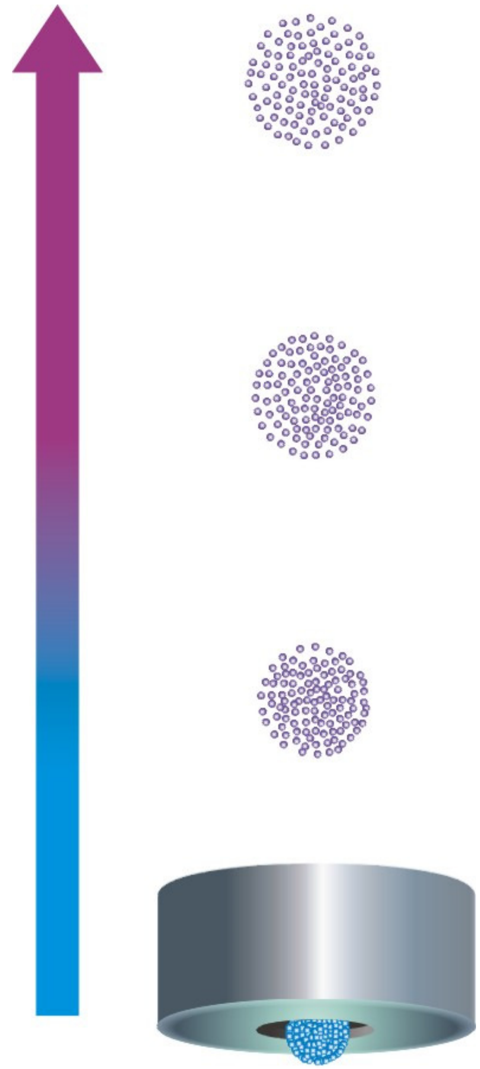
1997: the periods would be defined for a cesium atom at rest, and approaching the theoretical temperature of absolute zero (0 K).



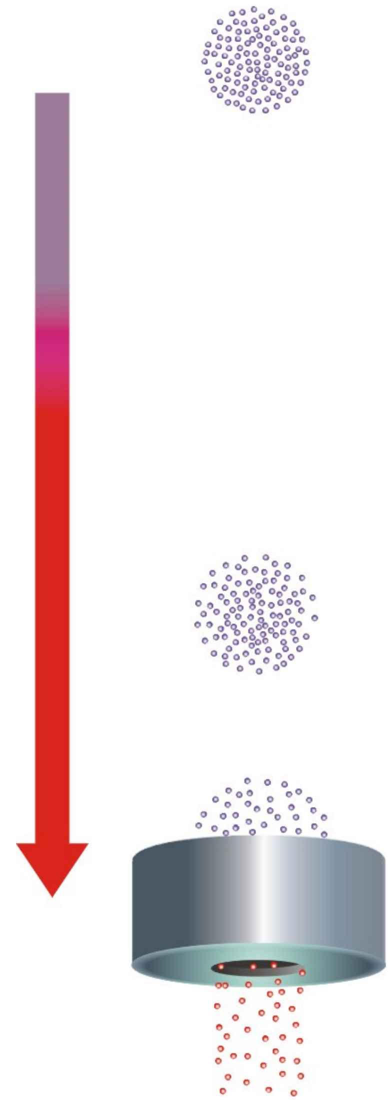
Cesium atomic clock



A gas of cesium atoms enters the clock's vacuum chamber. Six lasers slow the movement of the atoms, cooling them to near absolute zero and force them into a spherical cloud at the intersection of the laser beams.



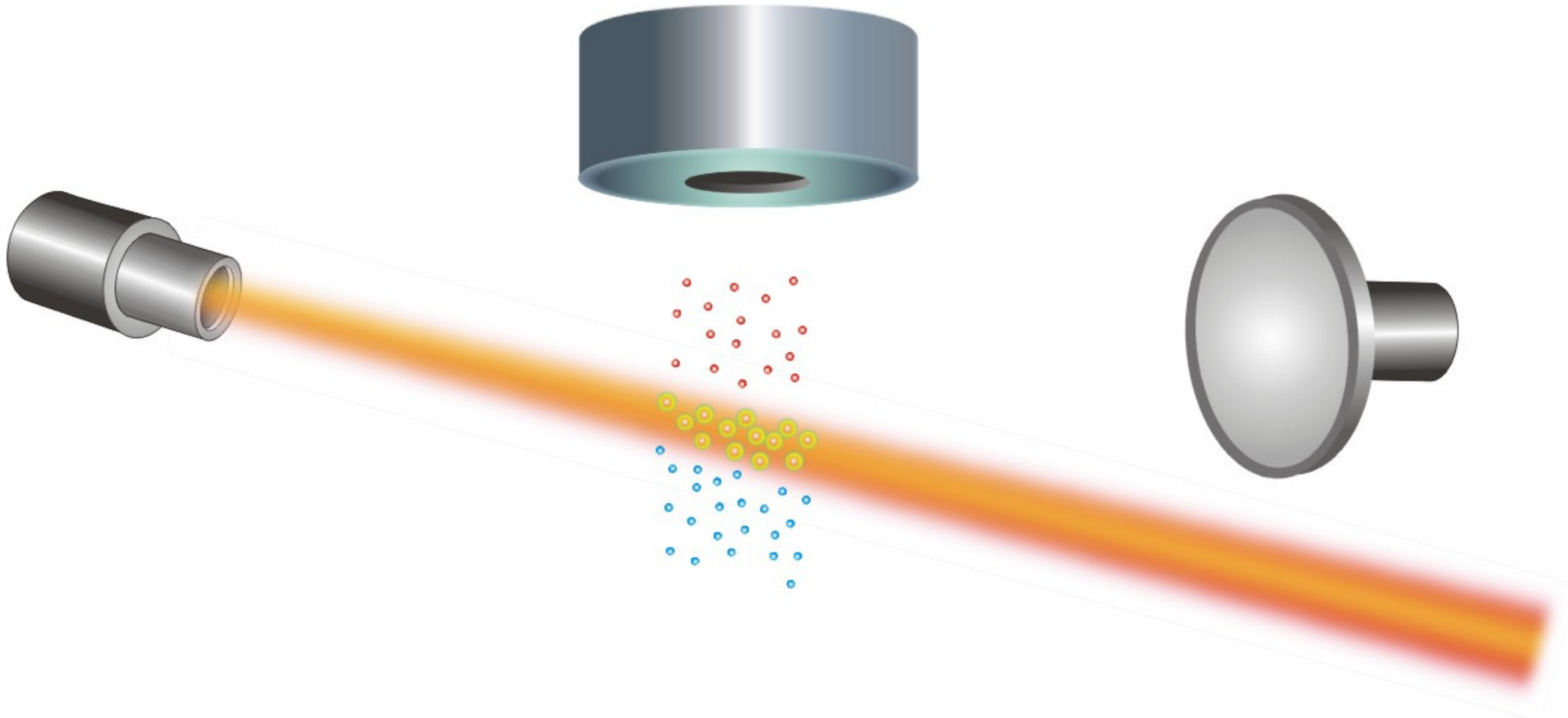
The ball is tossed upward by two lasers through a cavity filled with microwaves. All of the lasers are then turned off.



Gravity pulls the ball of cesium atoms back through the microwave cavity. The microwaves partially alter the atomic states of the cesium atoms.

http://www.nist.gov/public_affairs/releases/n99-22.cfm

Cesium atomic clock



Cesium atoms that were altered in the microwave cavity emit light when hit with a laser beam.

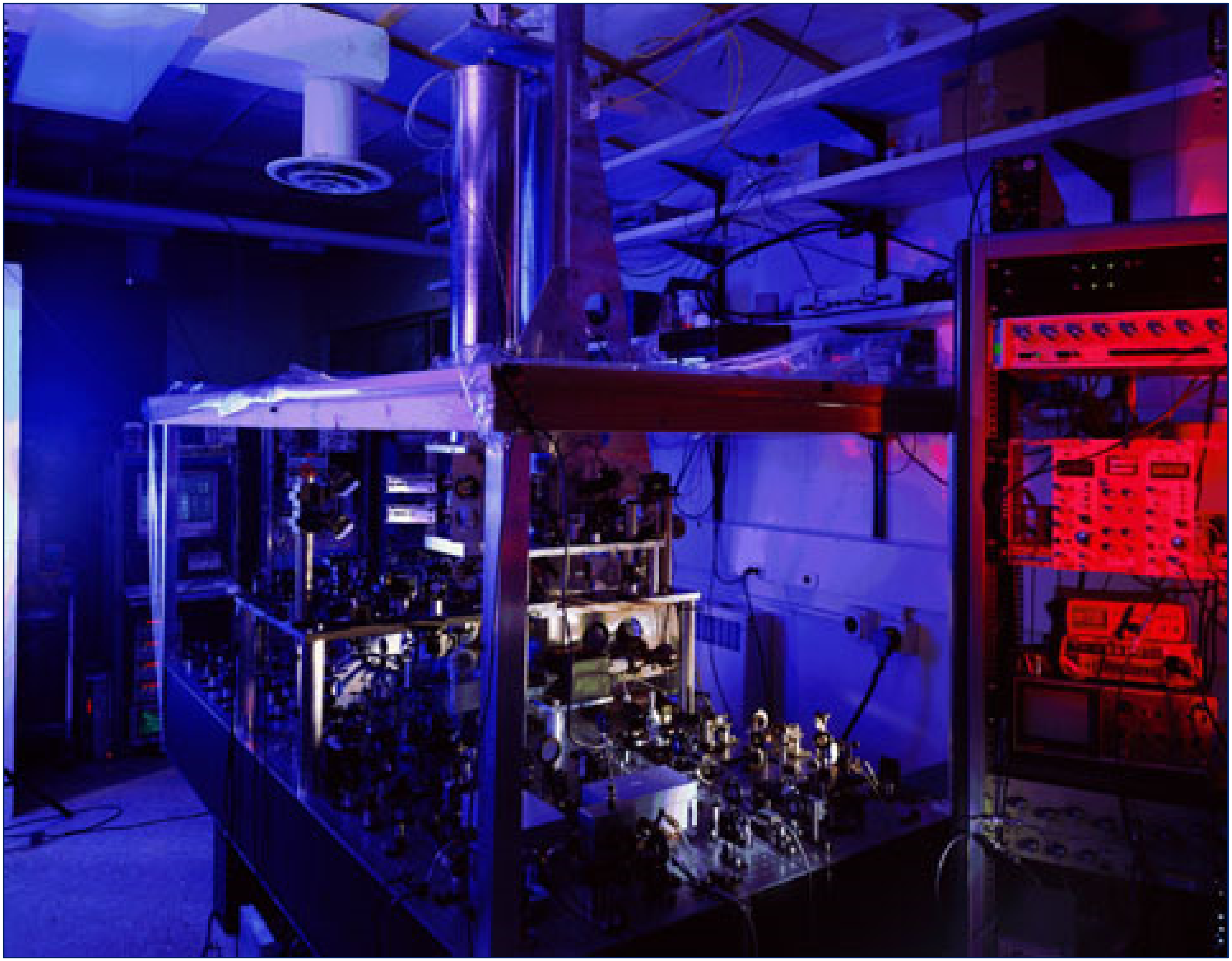
This fluorescence is measured by a detector (right).

The entire process is repeated many times while the microwave energy in the cavity is tuned to different frequencies until the maximum fluorescence of the cesium atoms is determined.

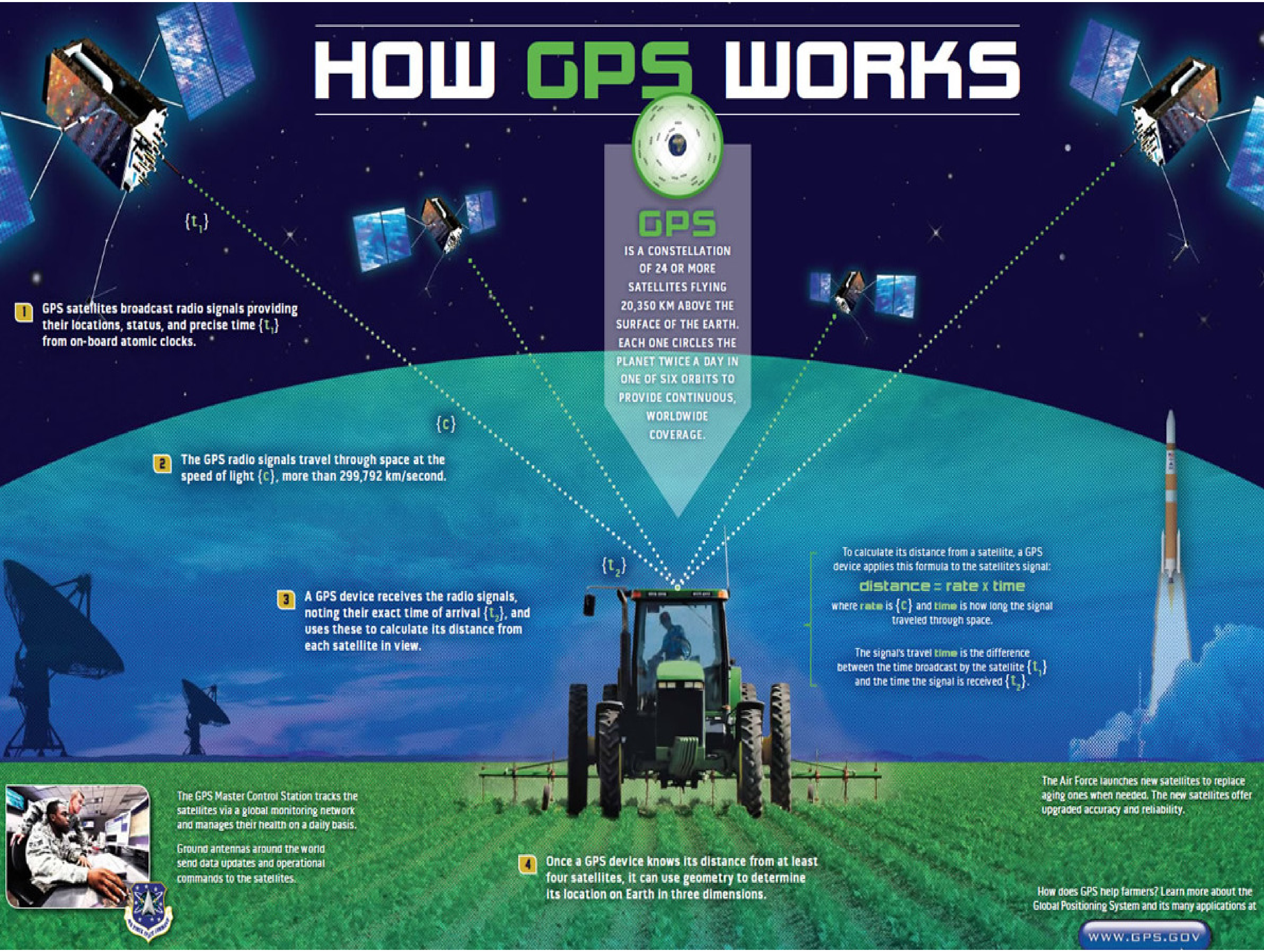
This point defines the natural resonance frequency of cesium, which is used to define the second.

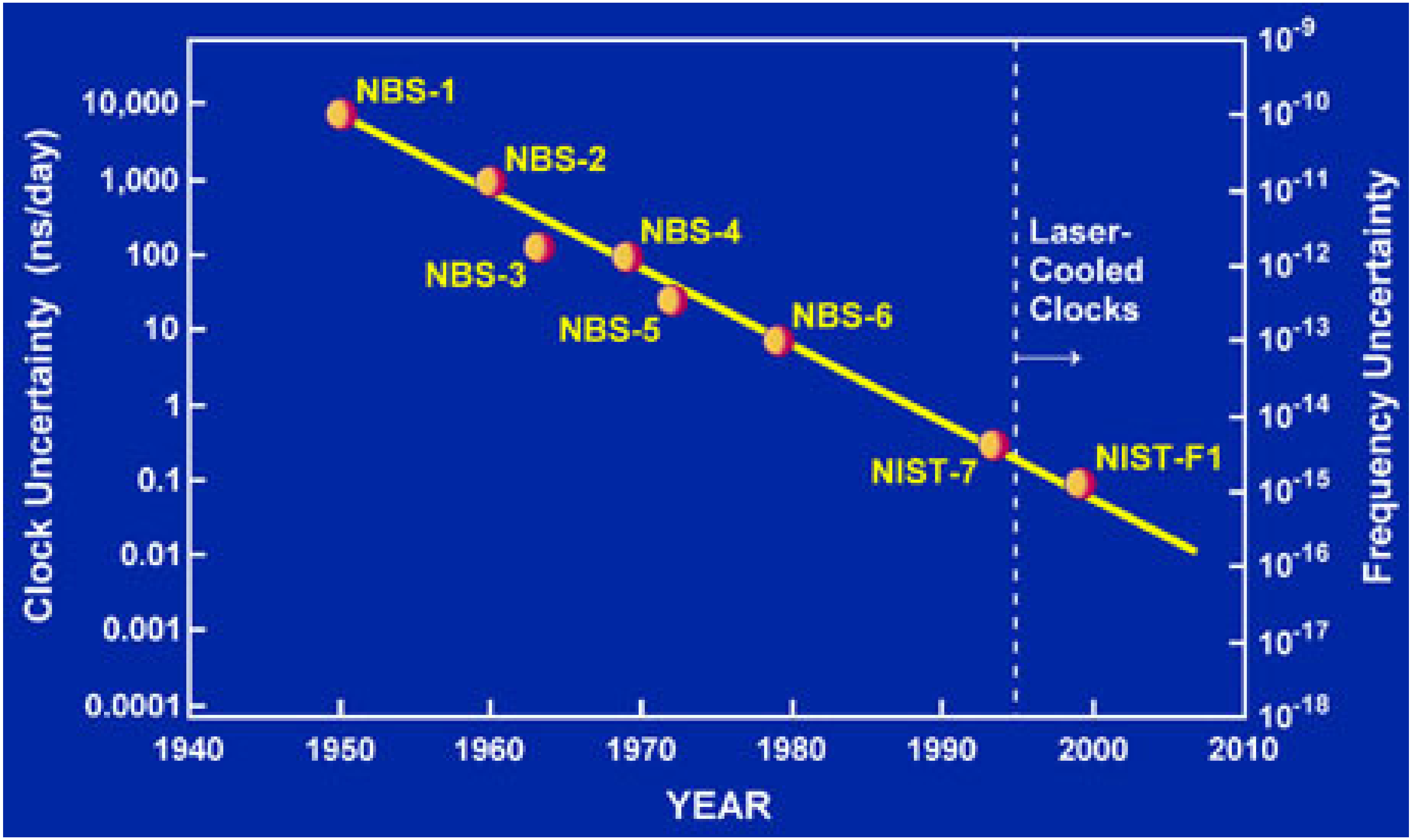
http://www.nist.gov/public_affairs/releases/n99-22.cfm

NIST Cs clock



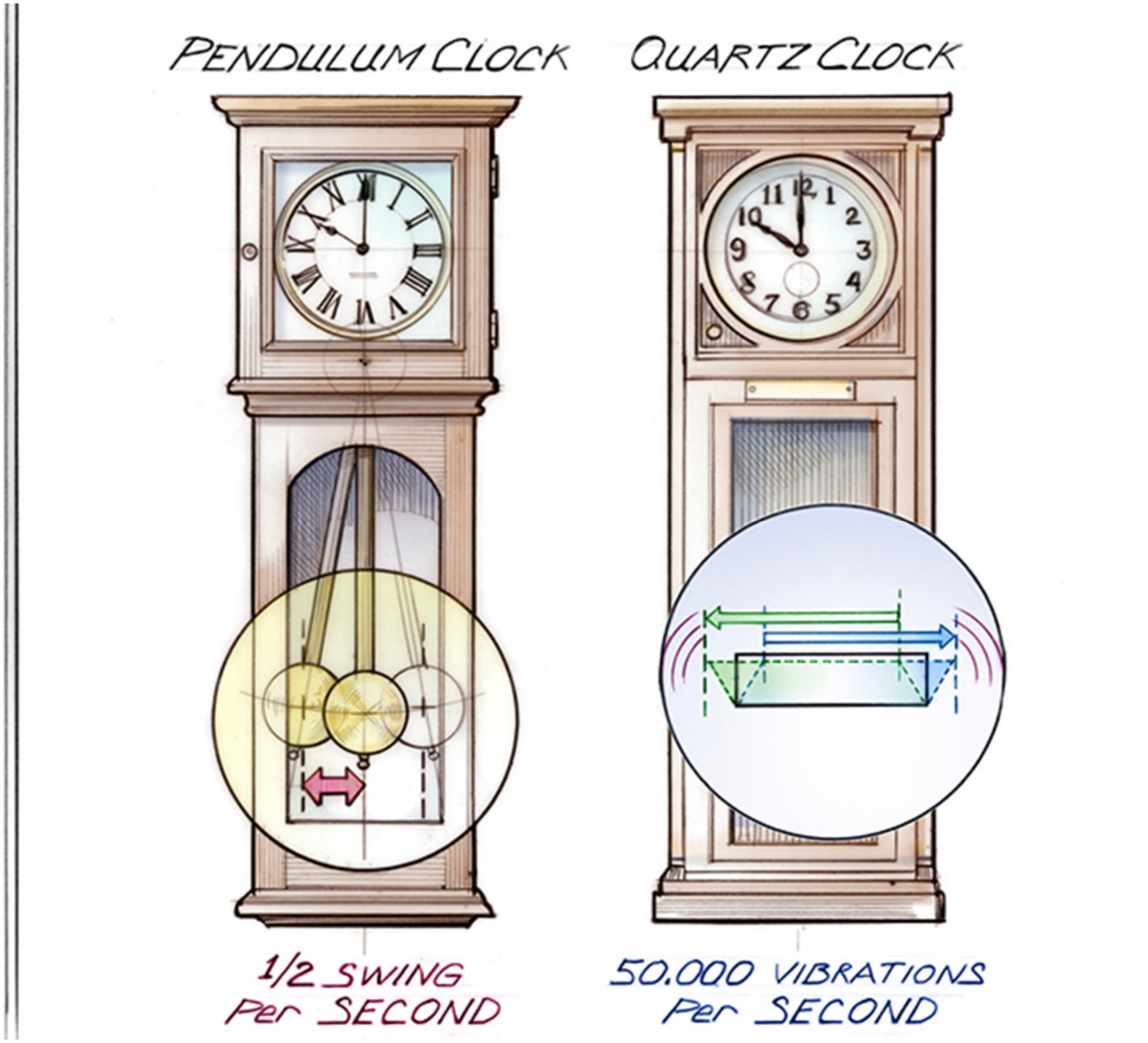
http://www.nist.gov/pml/div688/grp50/primary-frequency-standards.cfm


HOW GPS WORKS
GPS IS A CONSTELLATION OF 24 OR MORE SATELLITES FLYING 20,350 KM ABOVE THE SURFACE OF THE EARTH. EACH ONE CIRCLES THE PLANET TWICE A DAY IN ONE OF SIX ORBITS TO PROVIDE CONTINUOUS, WORLDWIDE COVERAGE.
{t1}
1 GPS satellites broadcast radio signals providing their locations, status, and precise time {t1} from on-board atomic clocks.
{c}
2 The GPS radio signals travel through space at the speed of light {c}, more than 299,792 km/second.
{t2}
3 A GPS device receives the radio signals, noting their exact time of arrival {t2}, and uses these to calculate its distance from each satellite in view.
To calculate its distance from a satellite, a GPS device applies this formula to the satellite's signal:
distance = rate x time
where rate is {c} and time is how long the signal traveled through space.
The signal's travel time is the difference between the time broadcast by the satellite {t1} and the time the signal is received {t2}.
The GPS Master Control Station tracks the satellites via a global monitoring network and manages their health on a daily basis.
Ground antennas around the world send data updates and operational commands to the satellites.
4 Once a GPS device knows its distance from at least four satellites, it can use geometry to determine its location on Earth in three dimensions.
The Air Force launches new satellites to replace aging ones when needed. The new satellites offer upgraded accuracy and reliability.
How does GPS help farmers? Learn more about the Global Positioning System and its many applications at
WWW.GPS.GOV

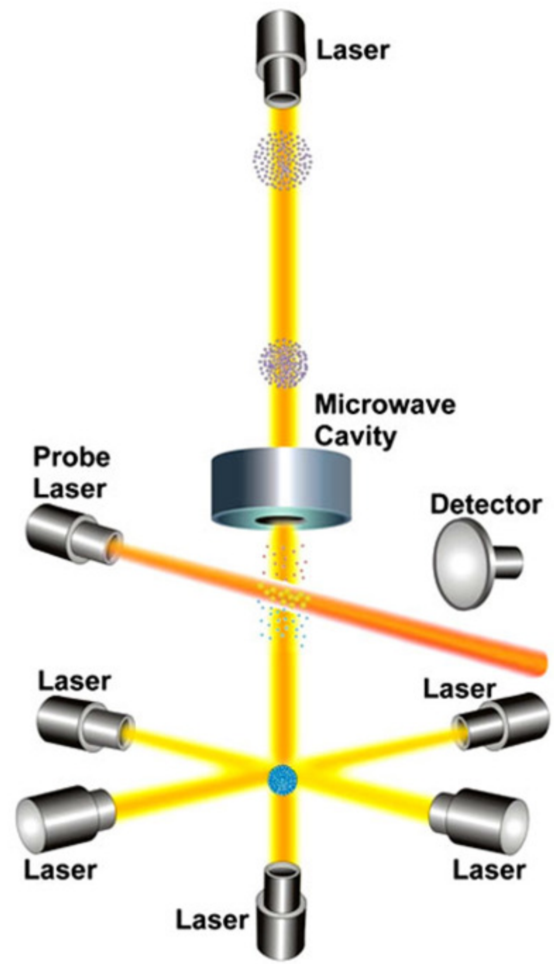


Clock Uncertainty (ns/day)
Frequency Uncertainty
10,000
1,000
100
10
1
0.1
0.01
0.001
0.0001
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
NBS-1
NBS-2
NBS-3
NBS-4
NBS-5
NBS-6
NIST-7
NIST-F1
Laser-
Cooled
Clocks
1940
1950
1960
1970
1980
1990
2000
2010
YEAR

How to build a better clock?



timeandnavigation.si.edu

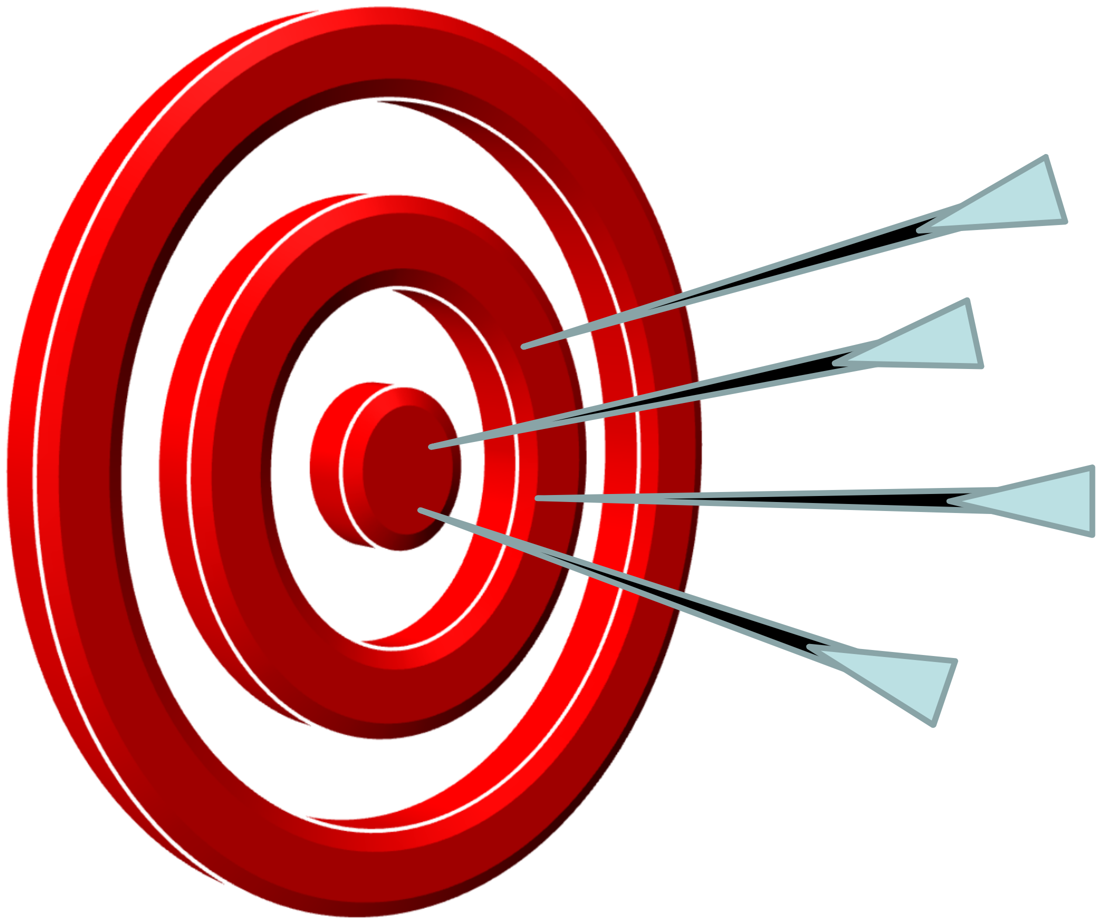


9 192 631 770 periods per second

How good is a clock: stability

Stability is a measure of the precision with which we can measure a quantity.

It is a function of averaging time since for many noise processes the precision increases (i.e., the noise is reduced through averaging) with more measurements.



Poli et al. “Optical atomic clocks”, arXiv:1401.2378v2

How good is a clock: uncertainty

In contrast, the (absolute) **uncertainty** for an atomic clock tells us how well we understand the physical processes that can shift the measured frequency from its unperturbed (“bare"), natural atomic frequency.

Requires extensive evaluation of all known physical shifts (usually called “systematic effects").

Clock instability

Let us first consider the formula for clock instability, σ_y, in the regime where it is limited by fundamental (as opposed to technical) noise sources, such as atomic statistics based on the number of atoms:

spectroscopic linewidth of the clock system

$$\sigma_y(\tau) \approx \frac{\Delta\nu}{\nu_0\sqrt{N}}\sqrt{\frac{T_c}{\tau}}$$

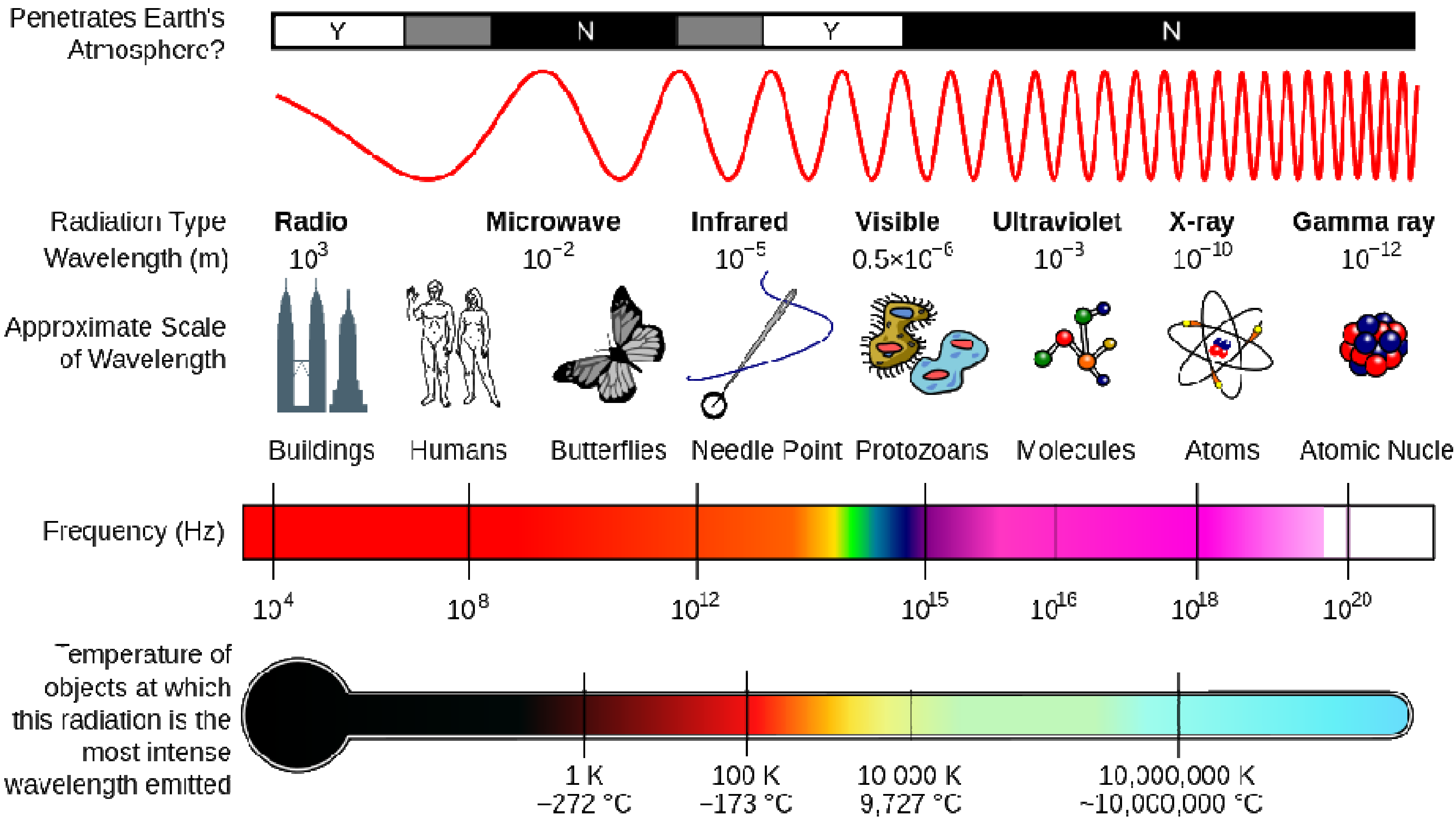
the time required for a single measurement cycle

the averaging period

clock transition frequency

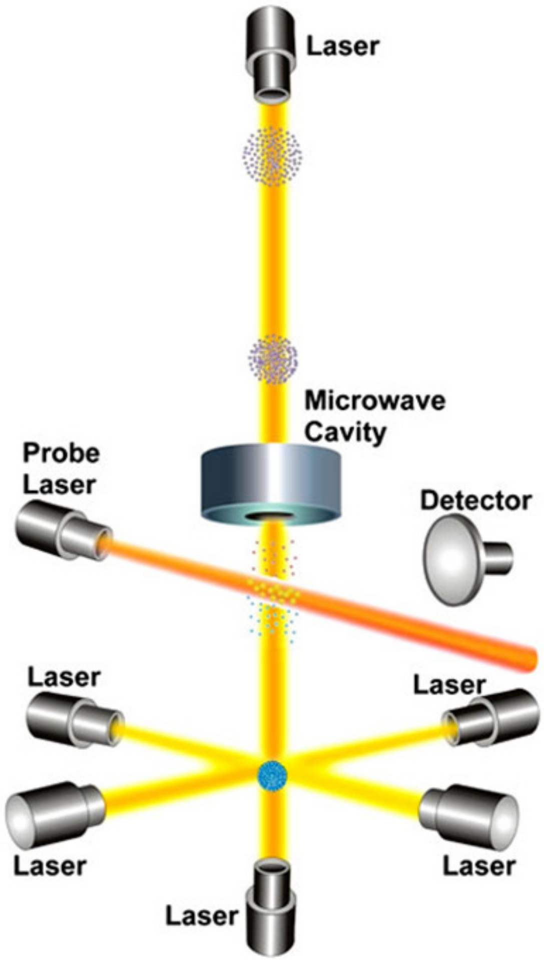
the number of atoms or ions used in a single measurement

How to build a better clock?



From microwave to optical frequencies

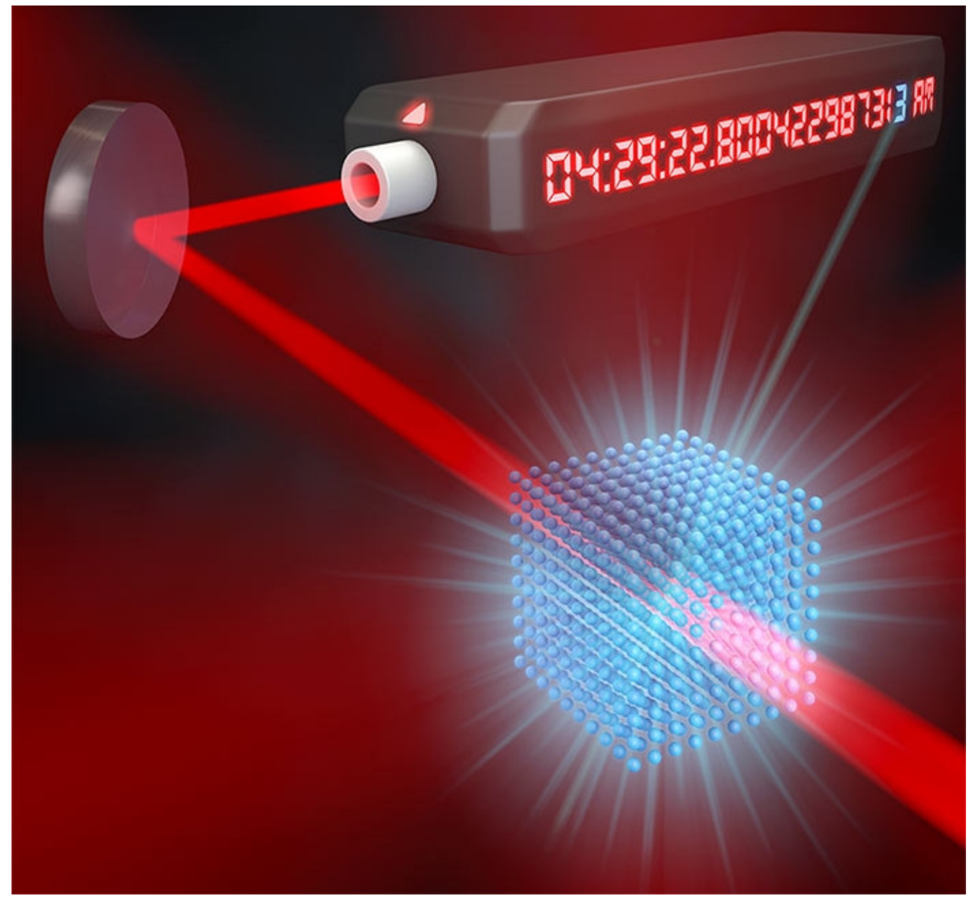
Cesium clock



9 x 10^9 periods per second

http://www.nist.gov

Strontium optical atomic clock



4.3 x 10^{14} periods per second

Image credit: Ye group and Steven Burrows, JILA

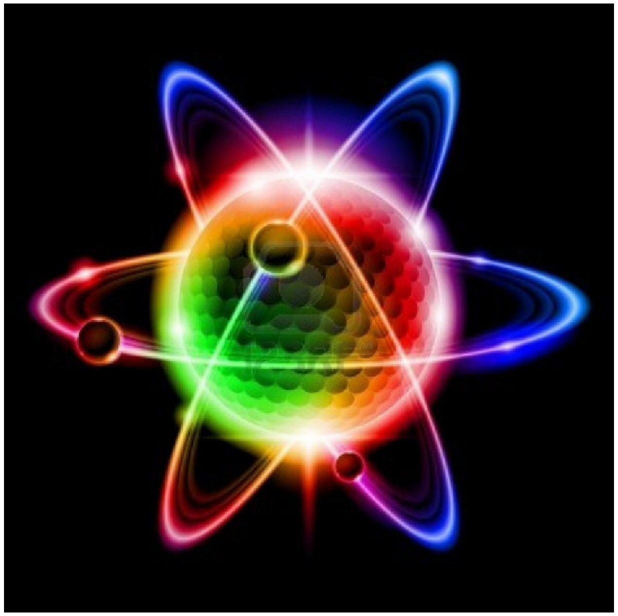
Ingredients for an atomic clock

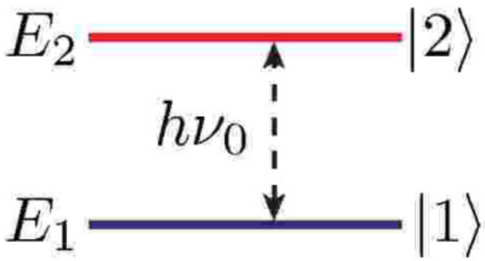
1. Atoms are all the same and will oscillate at exactly the same frequency (in the same environment): **you now have a perfect oscillator!**

2. Take a sample of atoms (or just one)

3. Build a device that produces oscillatory signal in resonance with atomic frequency

4. Count cycles of this signal

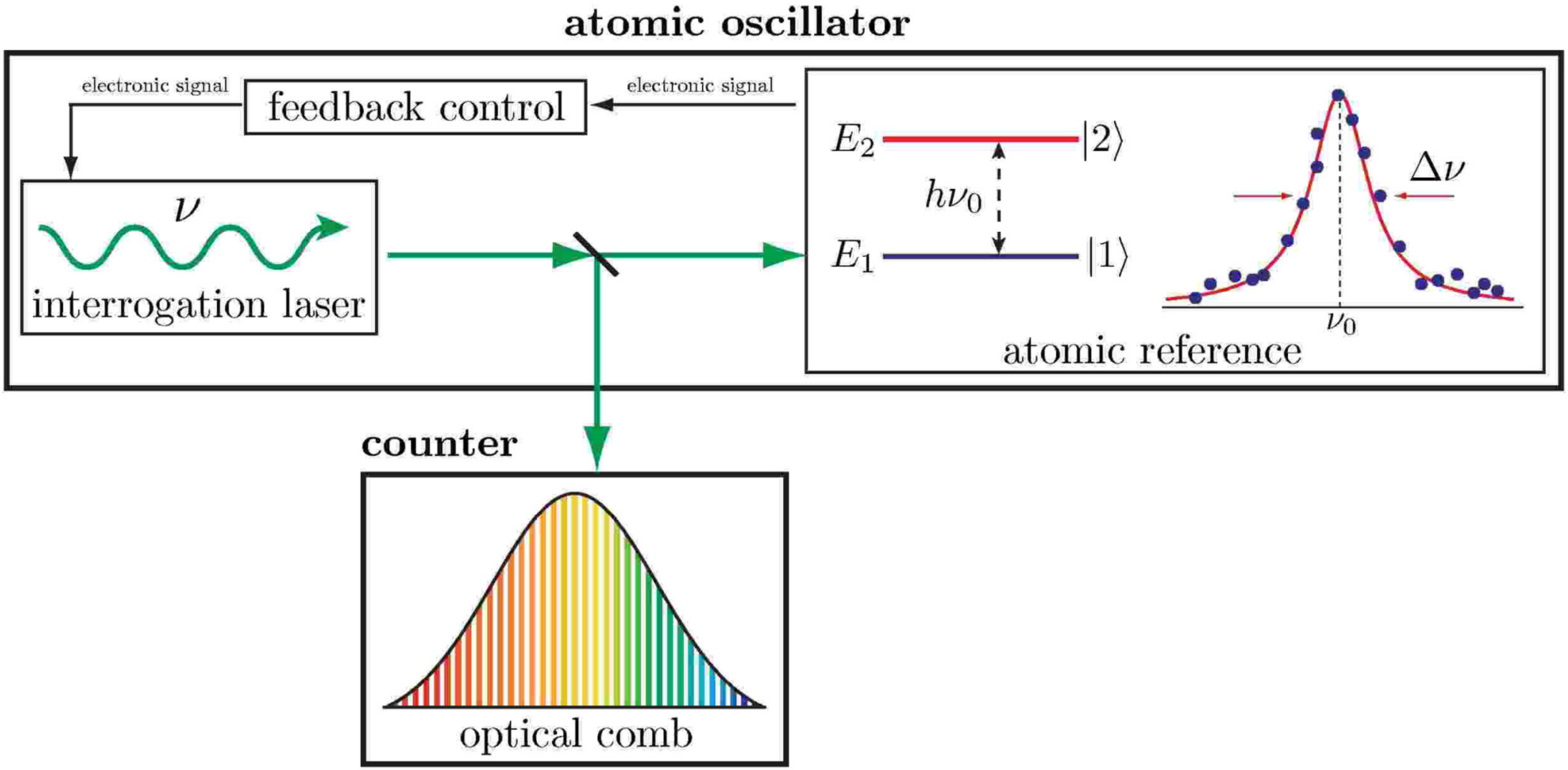




valentinagurarie.wordpress.com/tag/atom/

Ludlow et al., RMP 87, 637 (2015)

What is a clock?



Schematic view of an optical atomic clock: the local oscillator (laser) is resonant with the atomic transition. A correction signal is derived from atomic spectroscopy that is fed back to the laser. An optical frequency synthesizer (optical frequency comb) is used to divide the optical frequency down to countable microwave or radio frequency signals.

From: Poli et al. “Optical atomic clocks”, arXiv:1401.2378v2

Counting optical frequencies

Laser frequency (563 nm): $f_{\mathrm{Hg}}/2 \approx 5 \times 10^{14}$ **Hz** (!)

Interclock comparisons:

- Other optical standards (Al^+, Ca, Yb, Sr, etc.)
  Difference frequency: $\Delta f \sim 10^{14}$ Hz

- Microwave standards ($f_0 \sim 10^{10}$ Hz)
  Difference frequency: $\Delta f \sim 10^{14}$ Hz

Problem:

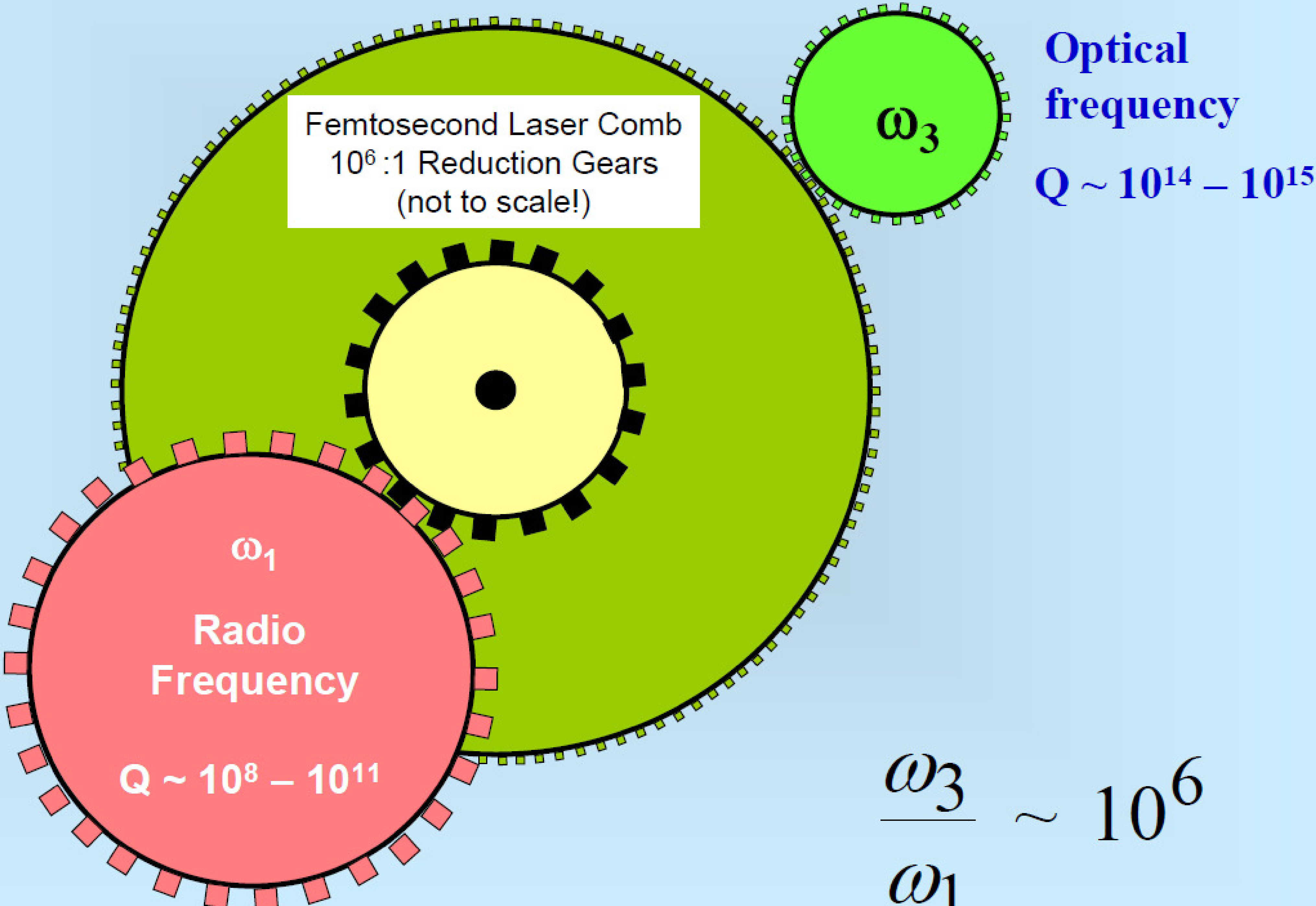
Fastest electronic counters: ~ 100 GHz (10^{11} Hz)

Solution:

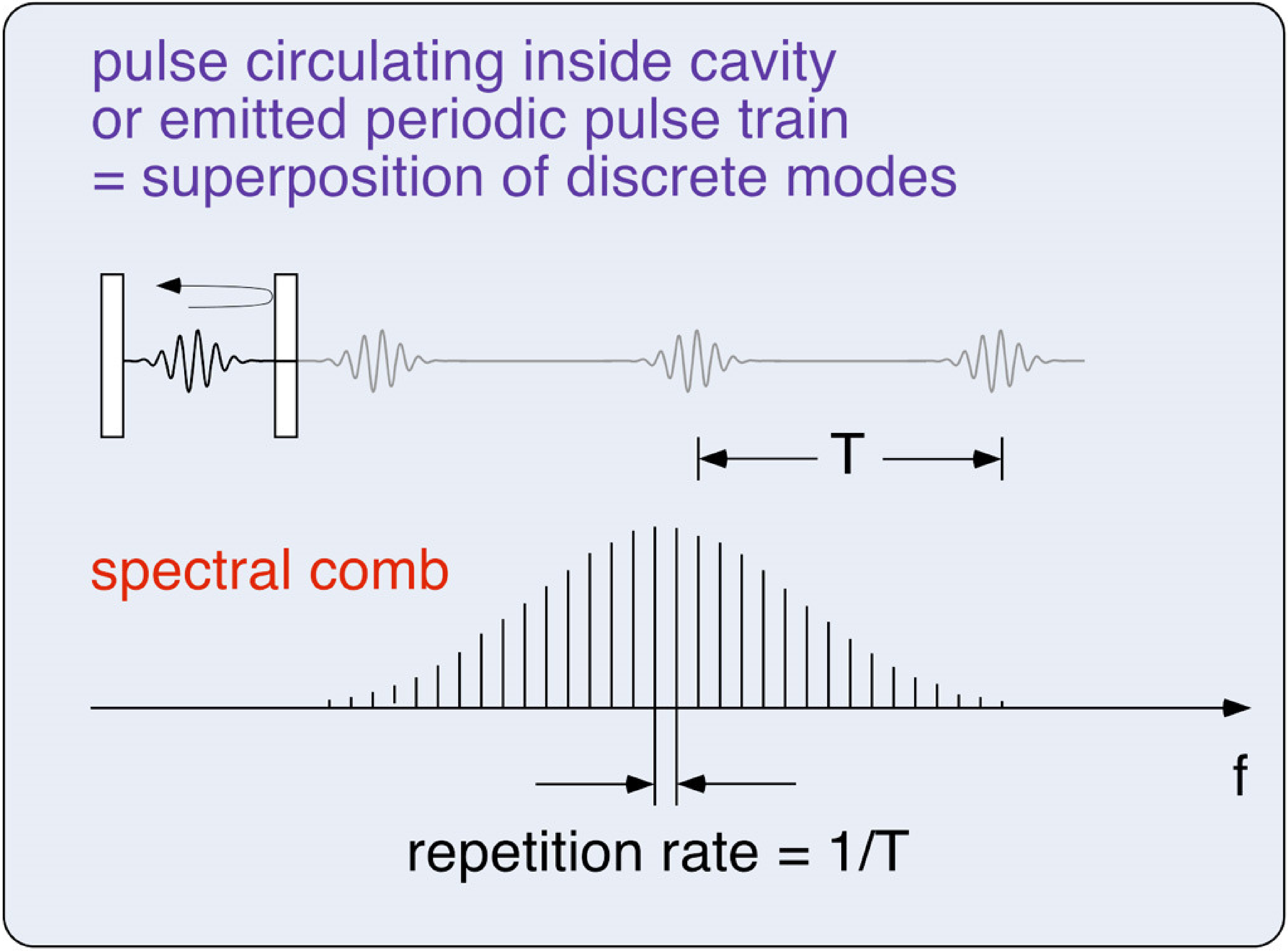
Femtosecond laser frequency comb

from Jim Bergquist' talk

from John Hall's Nobel Lecture

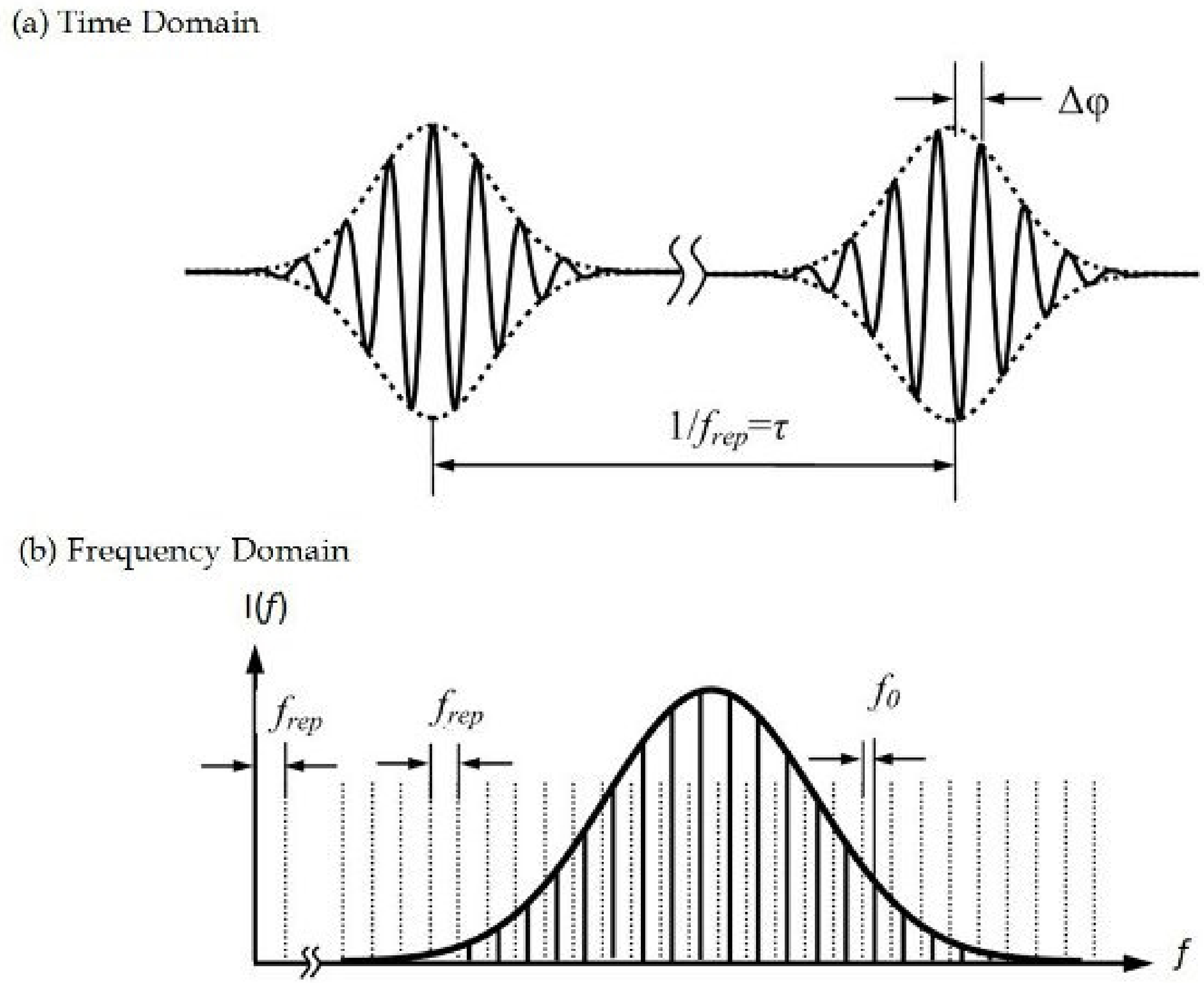


$$\frac{\omega_3}{\omega_1} \sim 10^6$$



fromTheodor W. Hänsch‘s Nobel Lecture

Femtosecond Ti:Sapphire Laser



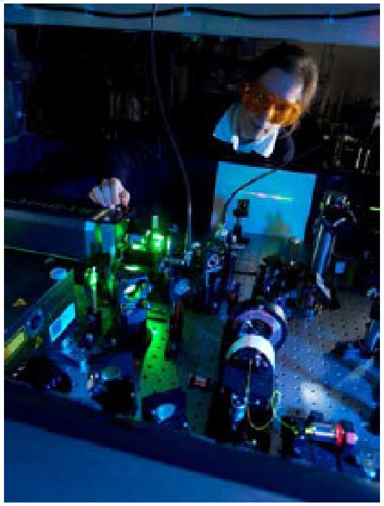
Pulse duration: ~ 10 fs $(10^{-14}$ s$)$

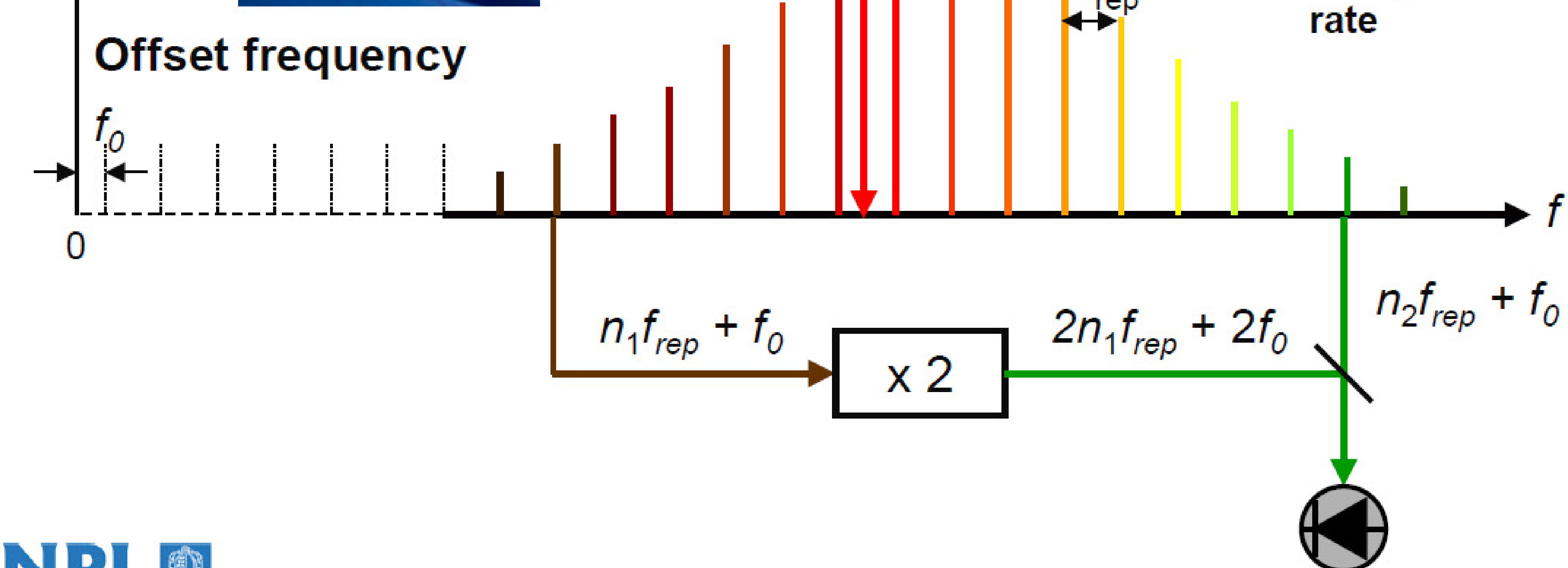
Repetition rate: $f_{\mathrm{rep}} \approx 1$ GHz $(10^{9}$ Hz$)$

from Jim Bergquist' talk

Self-referenced optical frequency comb

$$f_{probe} = m\, f_{rep} \pm f_0 \pm \delta$$

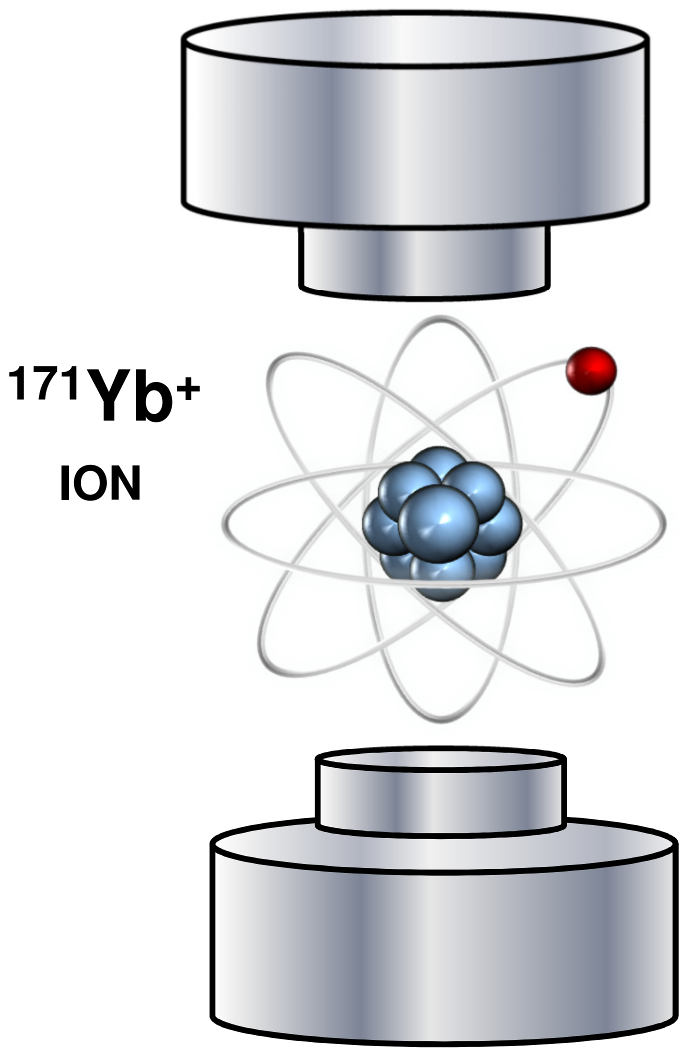


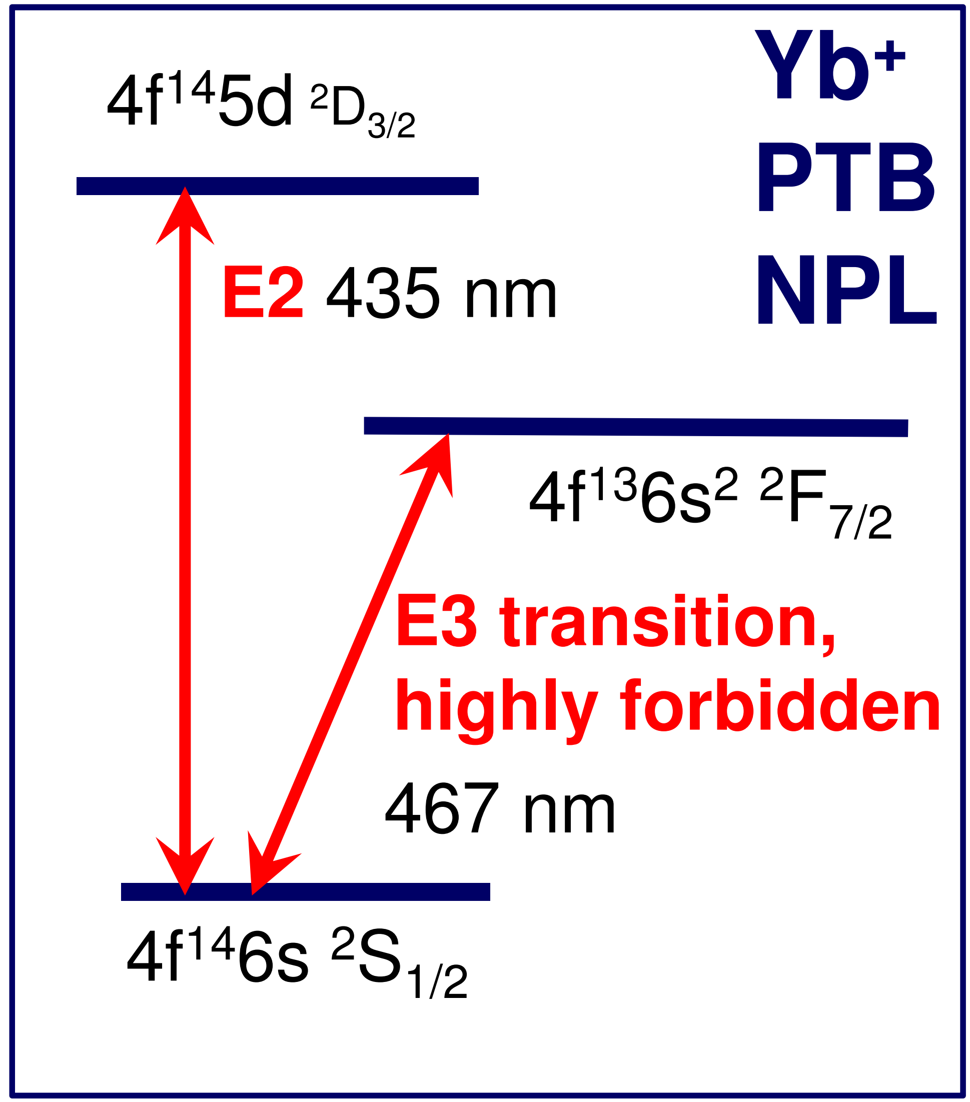


Trapped single ion clocks

Requirements for an atomic clock

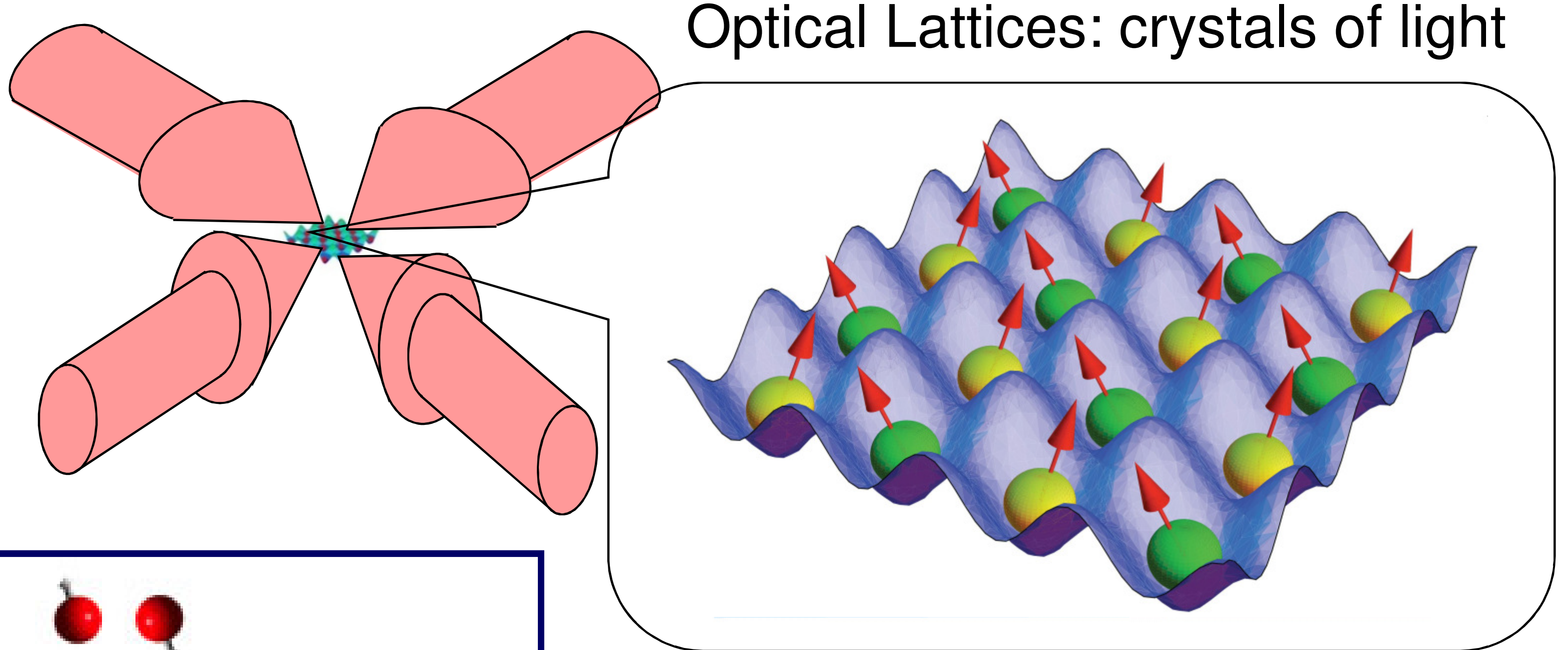
(1) Long-lived upper clock state
(2) Near optical transition

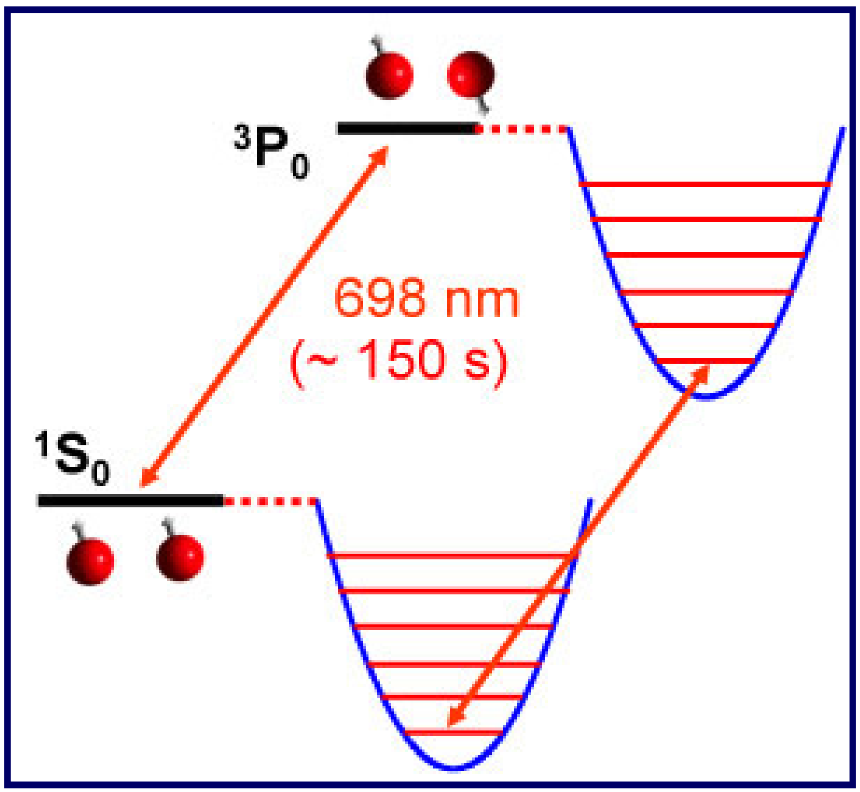




Neutral atom optical lattice clocks

Optical Lattices: crystals of light





Mg
Al^+
Cd
Sr
Yb
Hg

http://www.nist.gov/pml/div689/20140122_strontium.cfm

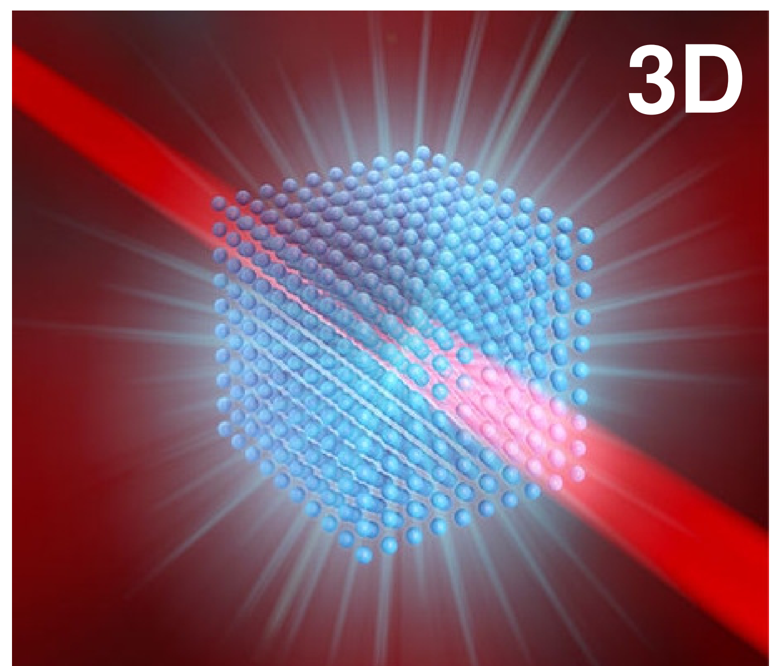
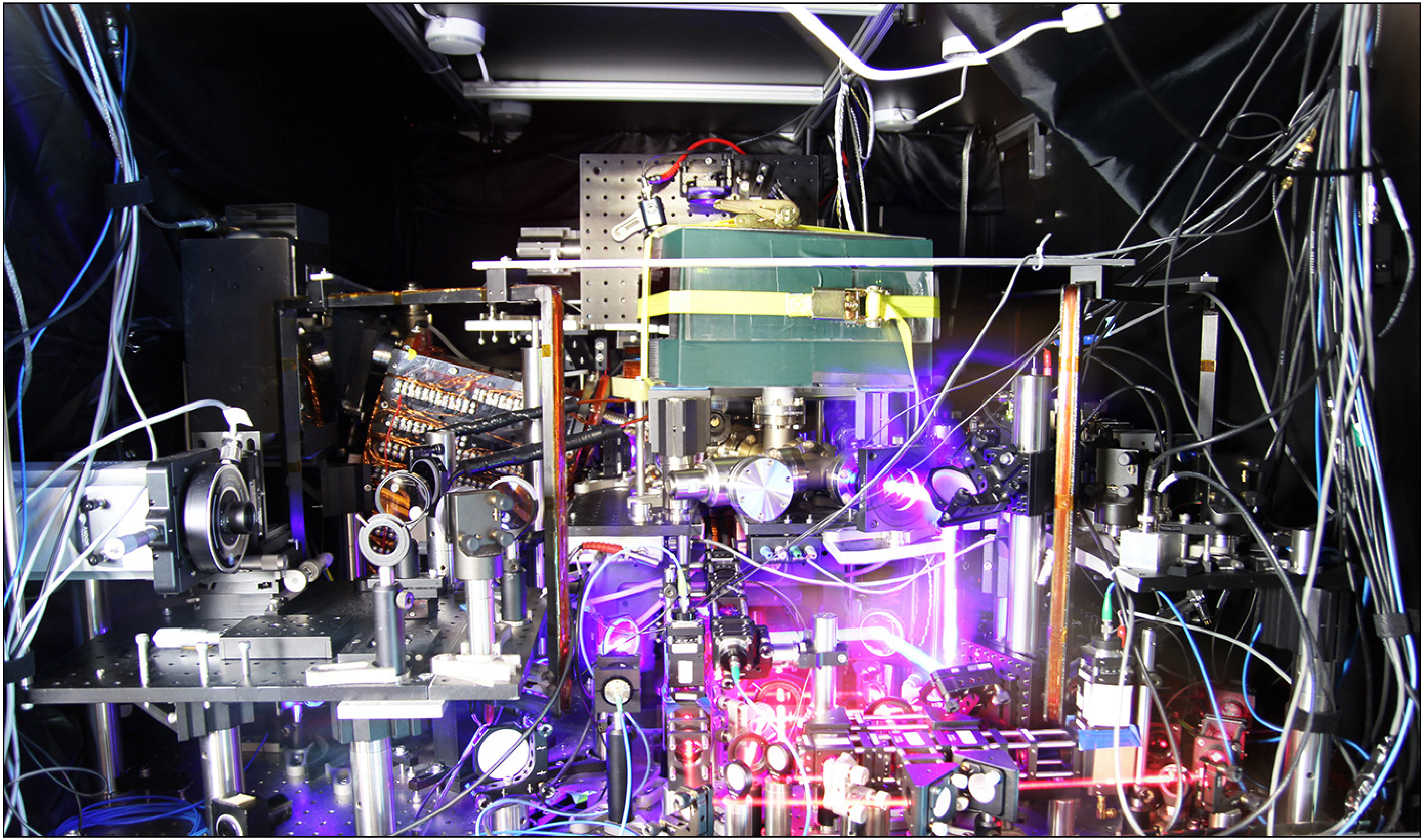


Image: Ye group and Steven Burrows, JILA

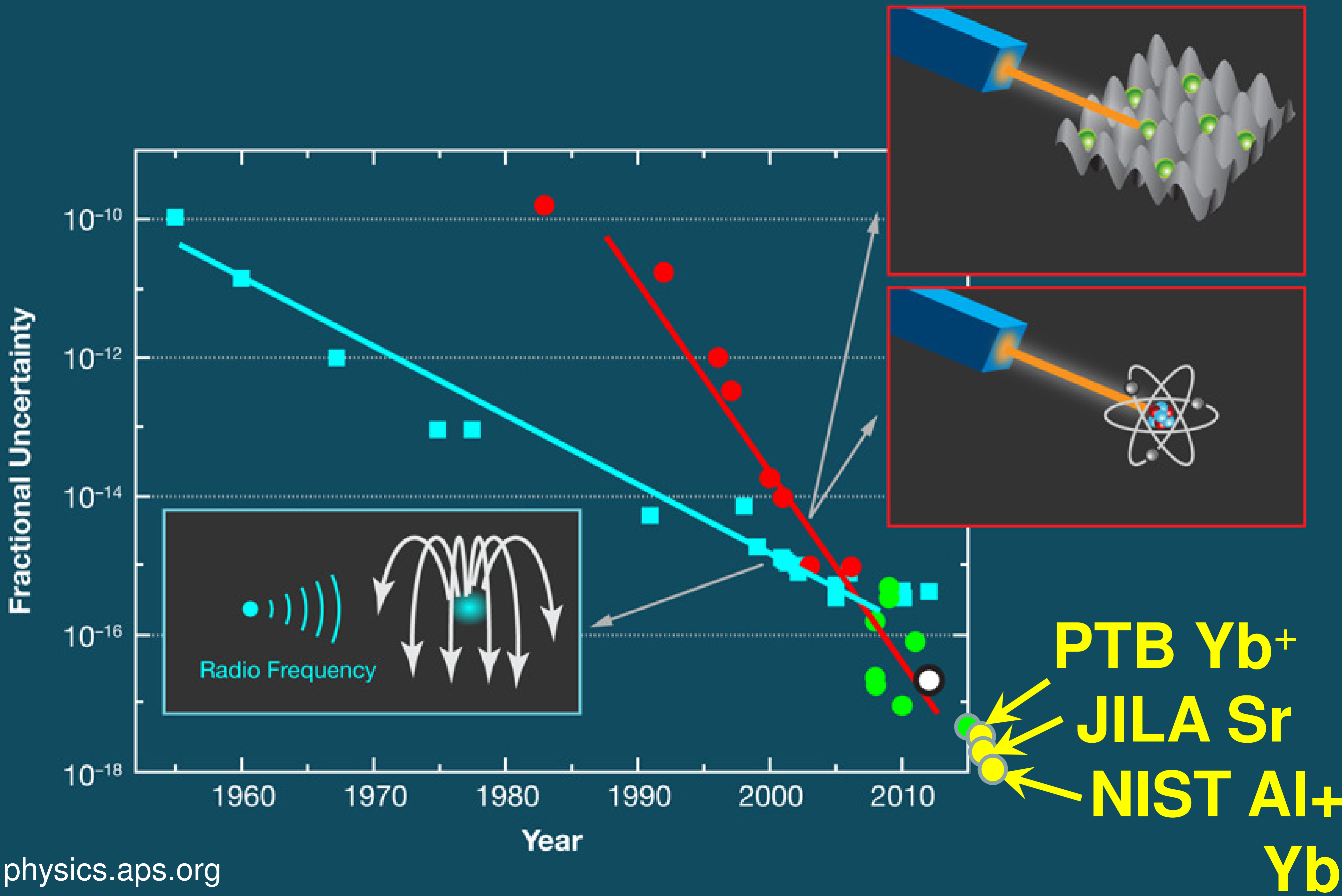
Sr clock will lose 1 second in 15 billion years !



Nicholson et al., Nature Comm. 6, 6896 (2015) **Sr: 2×10^{-18}**

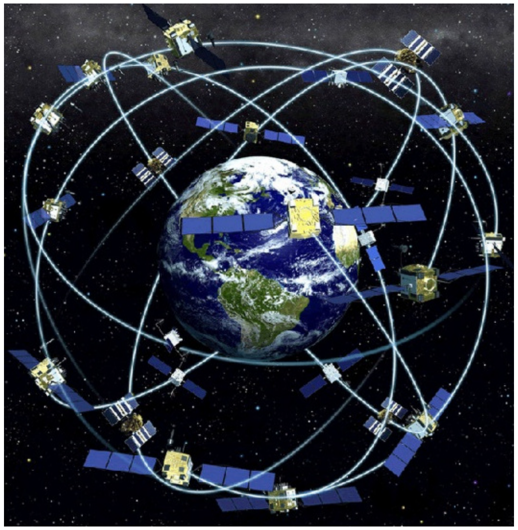
http://www.nist.gov/pml/div689/20140122_strontium.cfm

Optical vs. microwave clocks

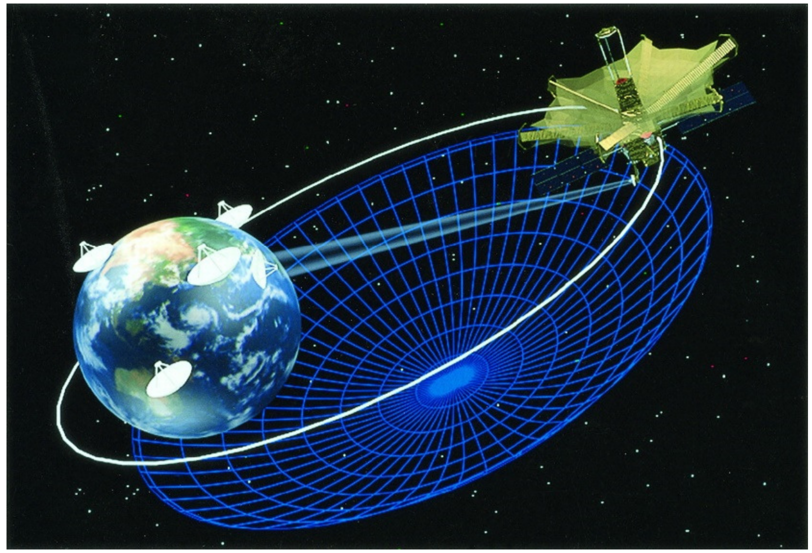


physics.aps.org

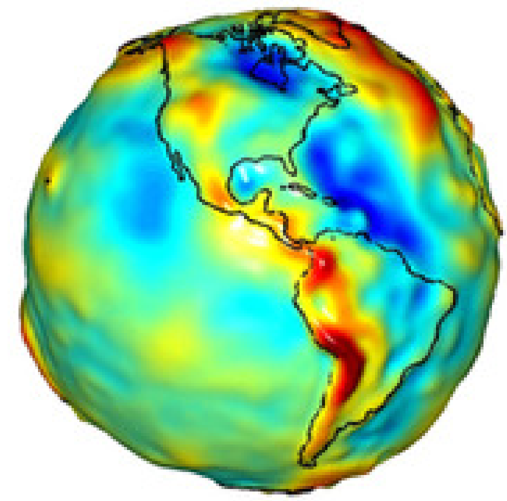
Applications of atomic clocks



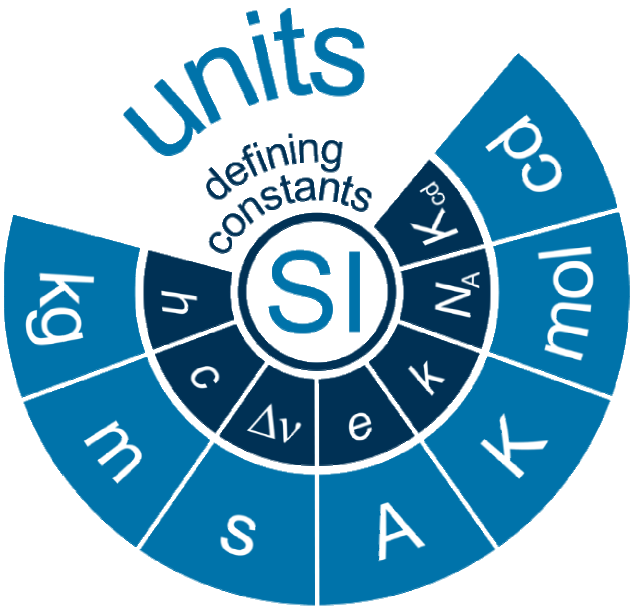
GPS



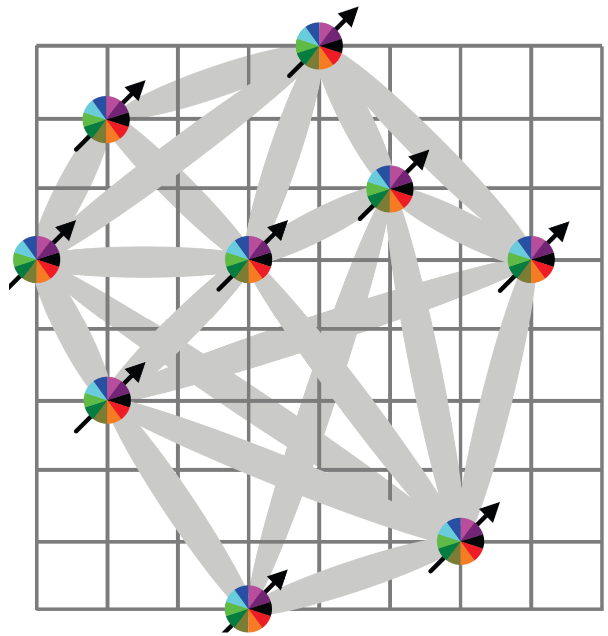
Very Long Baseline Interferometry



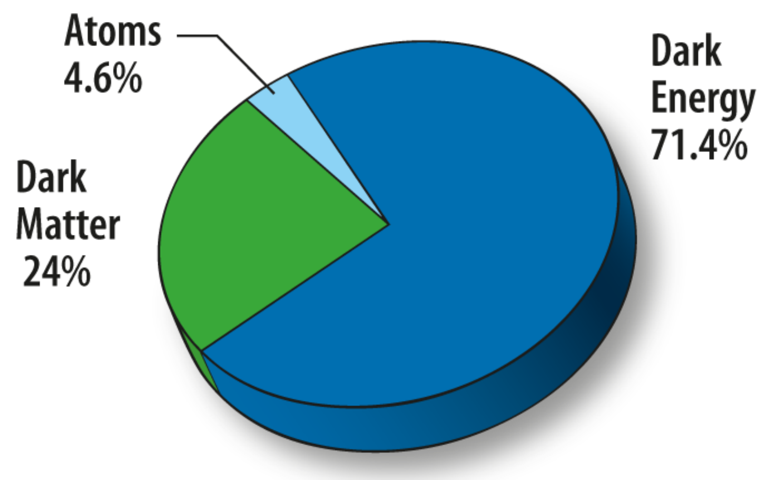
Relativistic geodesy



Definition of the second



Quantum simulation



Search for physics beyond the Standard Model

Image Credits: NOAA, Science 281,1825; 346, 1467, University of Hannover, PTB

Search for physics beyond the standard model with atomic clocks

Atomic clocks can measure and compare frequencies to exceptional precisions!

If fundamental constants change (now) due to for various "new physics" effects atomic clock may be able to detect it.

Frequency will change