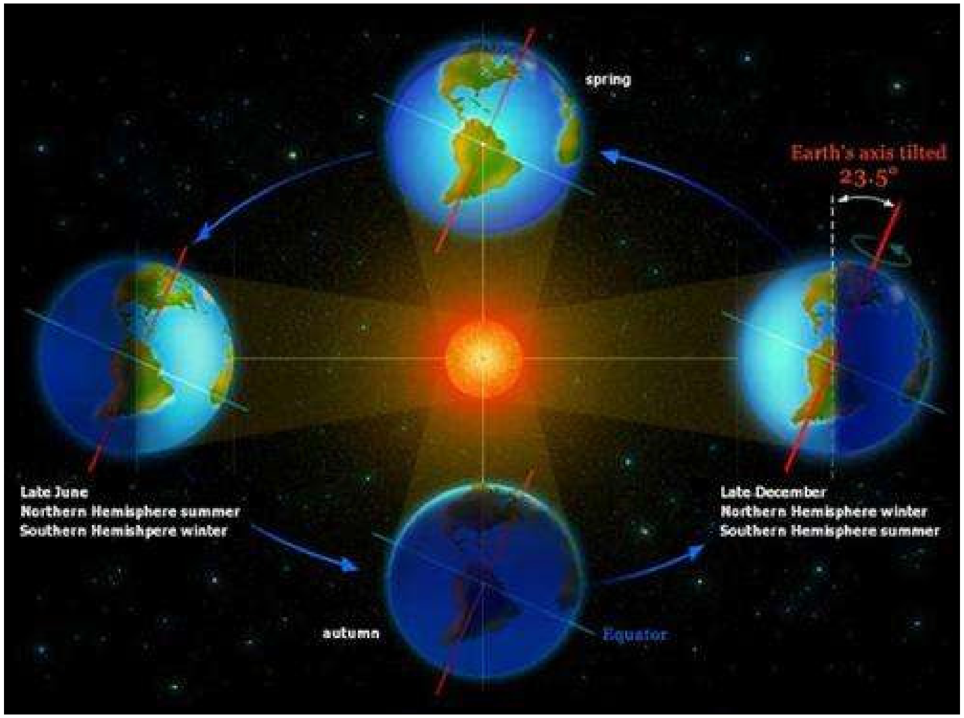
Atomic Clocks and their Applications

Ingredients for a clock

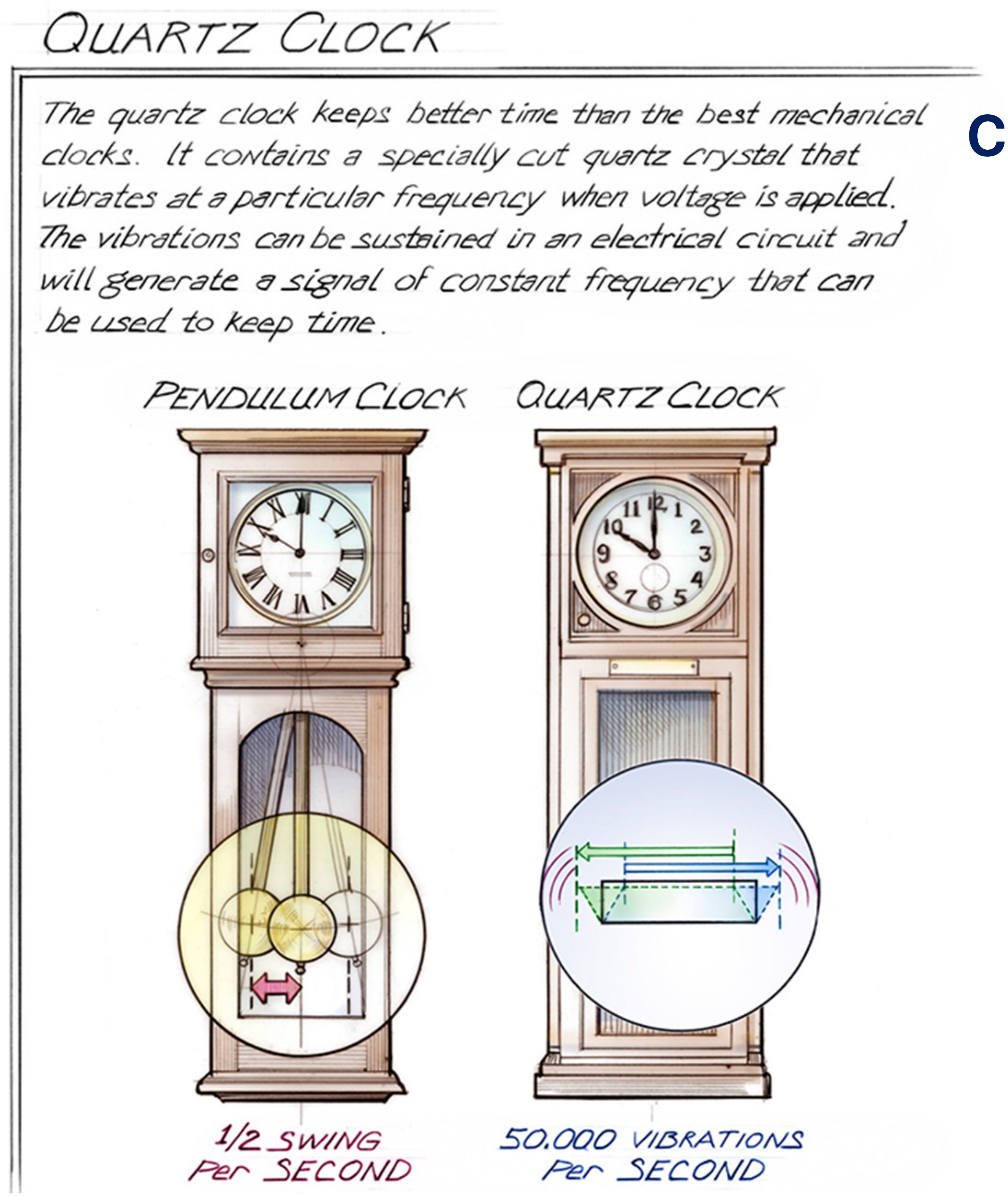
1. Need a system with **periodic behavior**:
   it cycles occur at constant frequency



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)

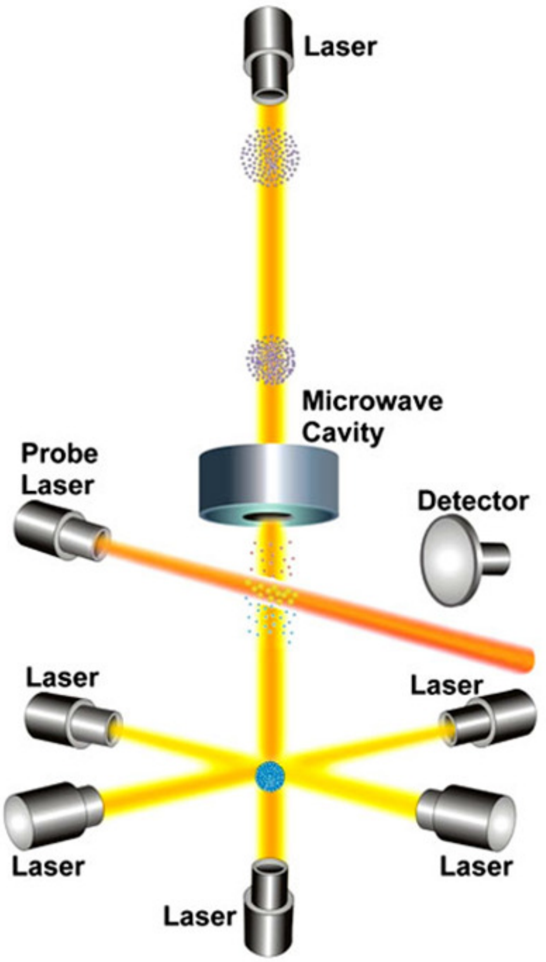


QUARTZ CLOCK

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.

timeandnavigation.si.edu

Cesium microwave atomic clock



9 192 631 770 periods per second

http://www.nist.gov

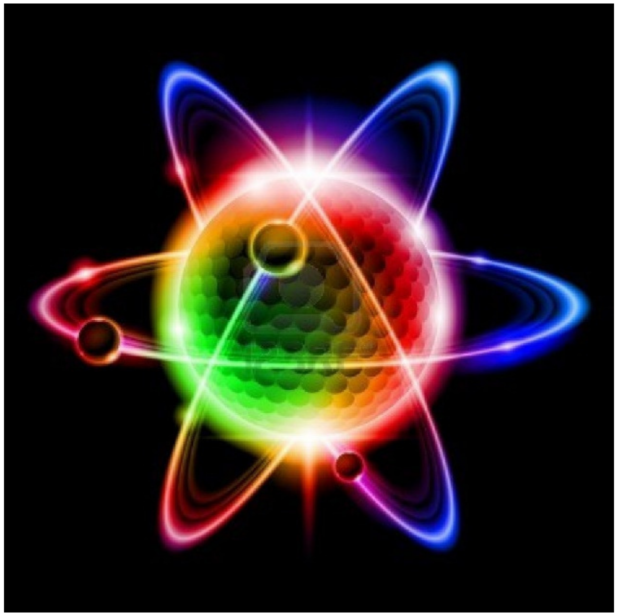
Ingredients for atomic clock

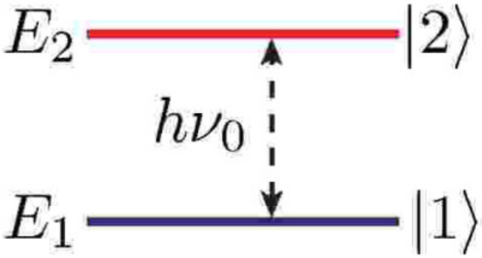
1. Atoms are all the same and will oscillate at exactly the same frequency (in the same environment):
   you now have a perfect oscillator!

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





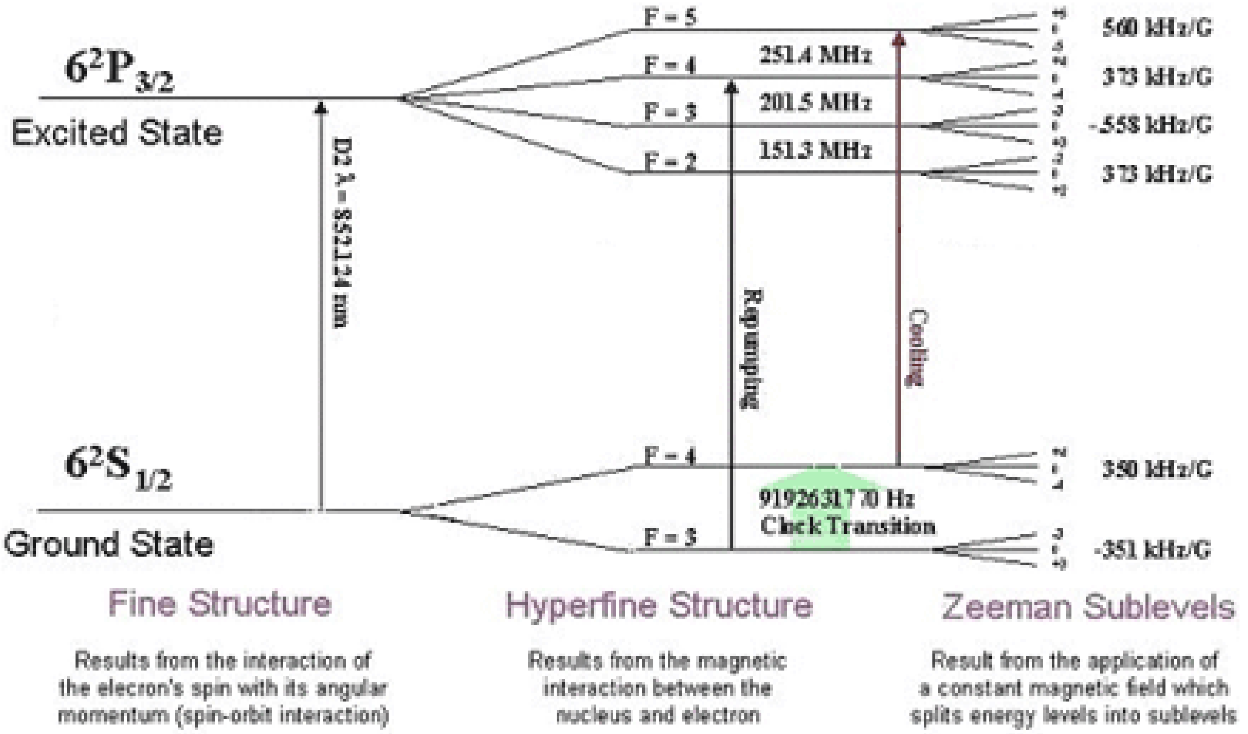
valentinagurarie.wordpress.com/tag/atom/

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

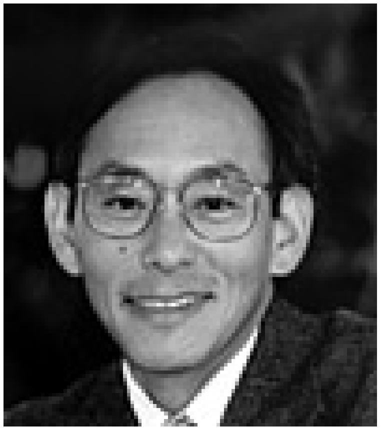
Current definition of a second

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).



New world of ultracold


Steve Chu


Claude Cohen-Tannoudji


Bill Phillips

1997
Nobel Prize
Laser cooling
and trapping

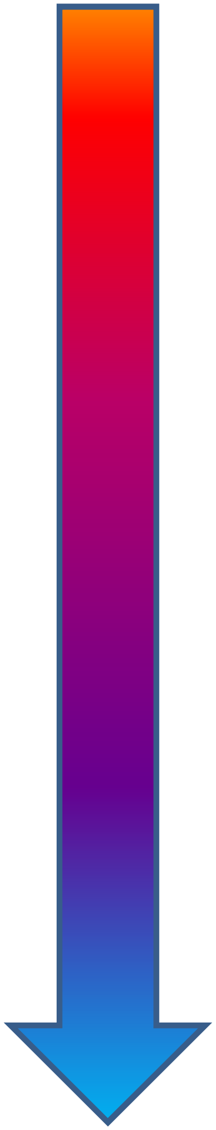

Eric Cornell


Wolfgang Ketterle


Carl Wieman

2001
Nobel Prize
Bose-Einstein
Condensation

300K



500nK

nobel.org

Laser cooling of atomic beams

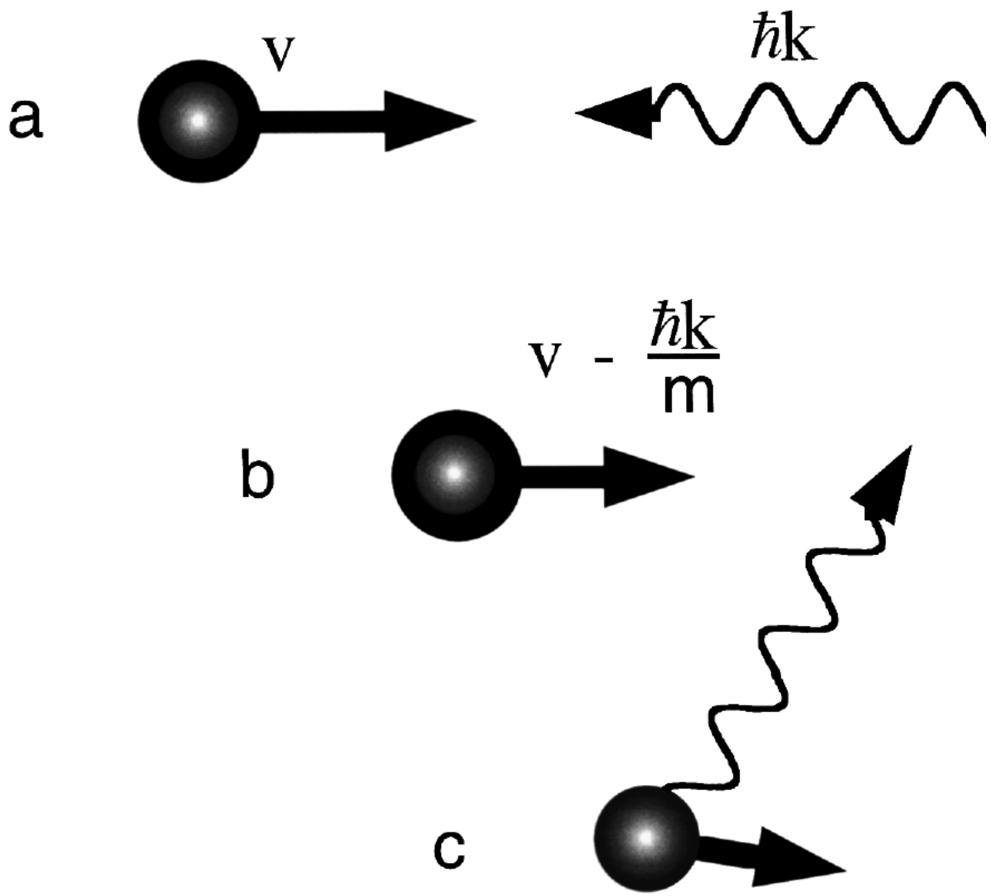
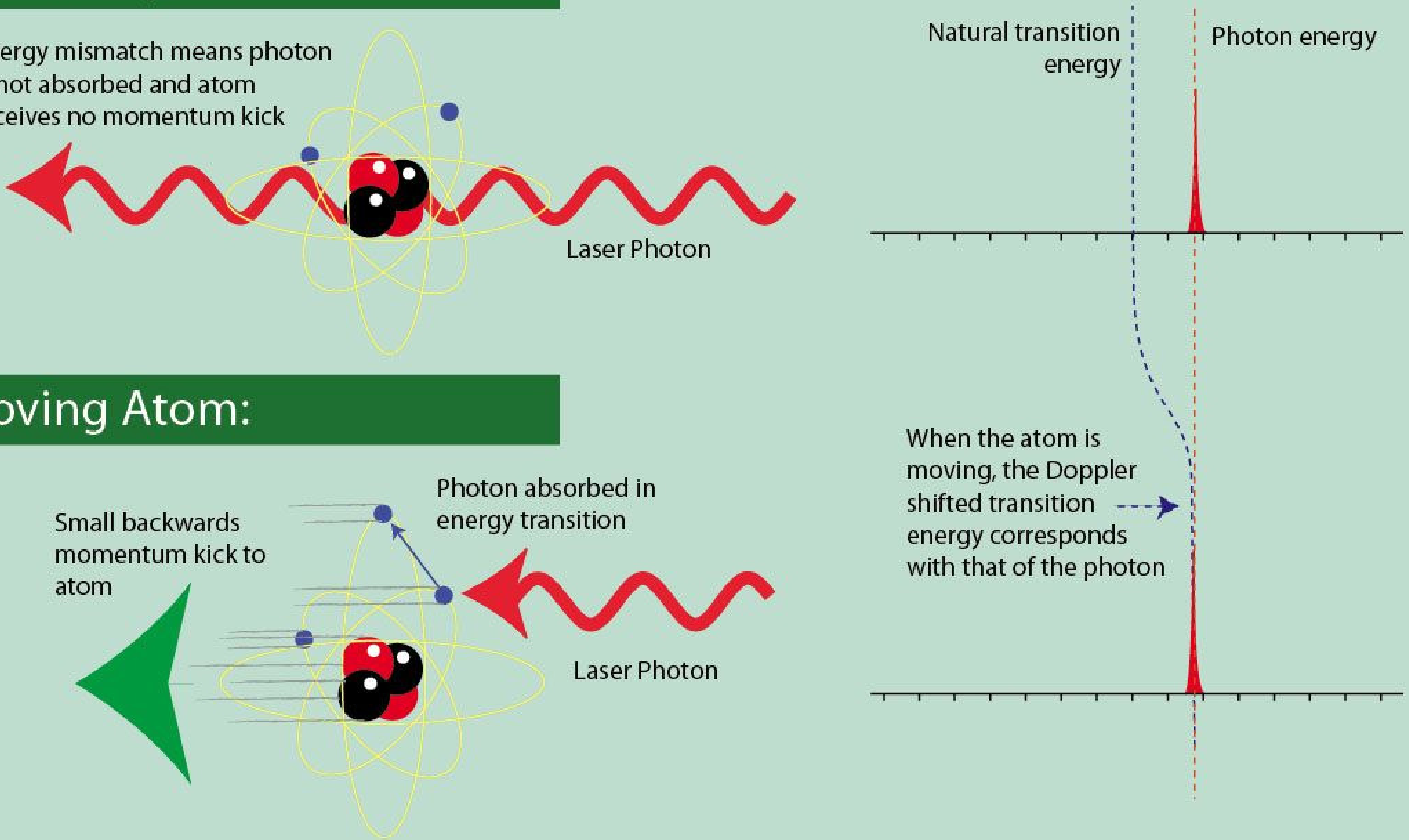


FIG. 1. (a) An atom with velocity v encounters a photon with momentum $\hbar k = h/\lambda$; (b) after absorbing the photon, the atom is slowed by $\hbar k/m$; (c) after re-radiation in a random direction, on average the atom is slower than in (a).

Laser Cooling



Stationary Atom:

Energy mismatch means photon is not absorbed and atom receives no momentum kick

Laser Photon

Natural transition energy

Photon energy

Moving Atom:

Small backwards momentum kick to atom

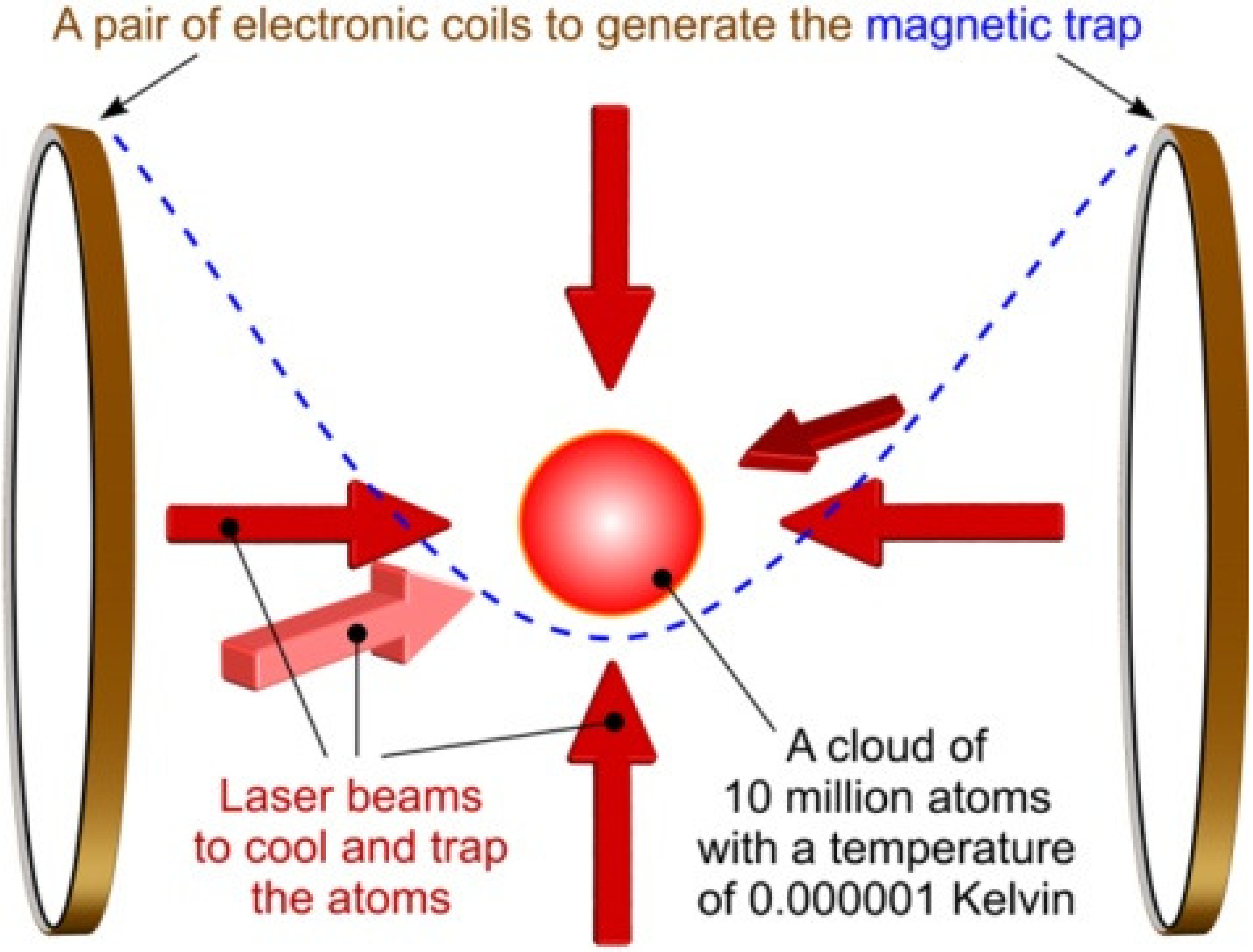
Photon absorbed in energy transition

Laser Photon

When the atom is moving, the Doppler shifted transition energy corresponds with that of the photon

sciencewise.anu.edu.a

Magneto-optical trapping (MOT)

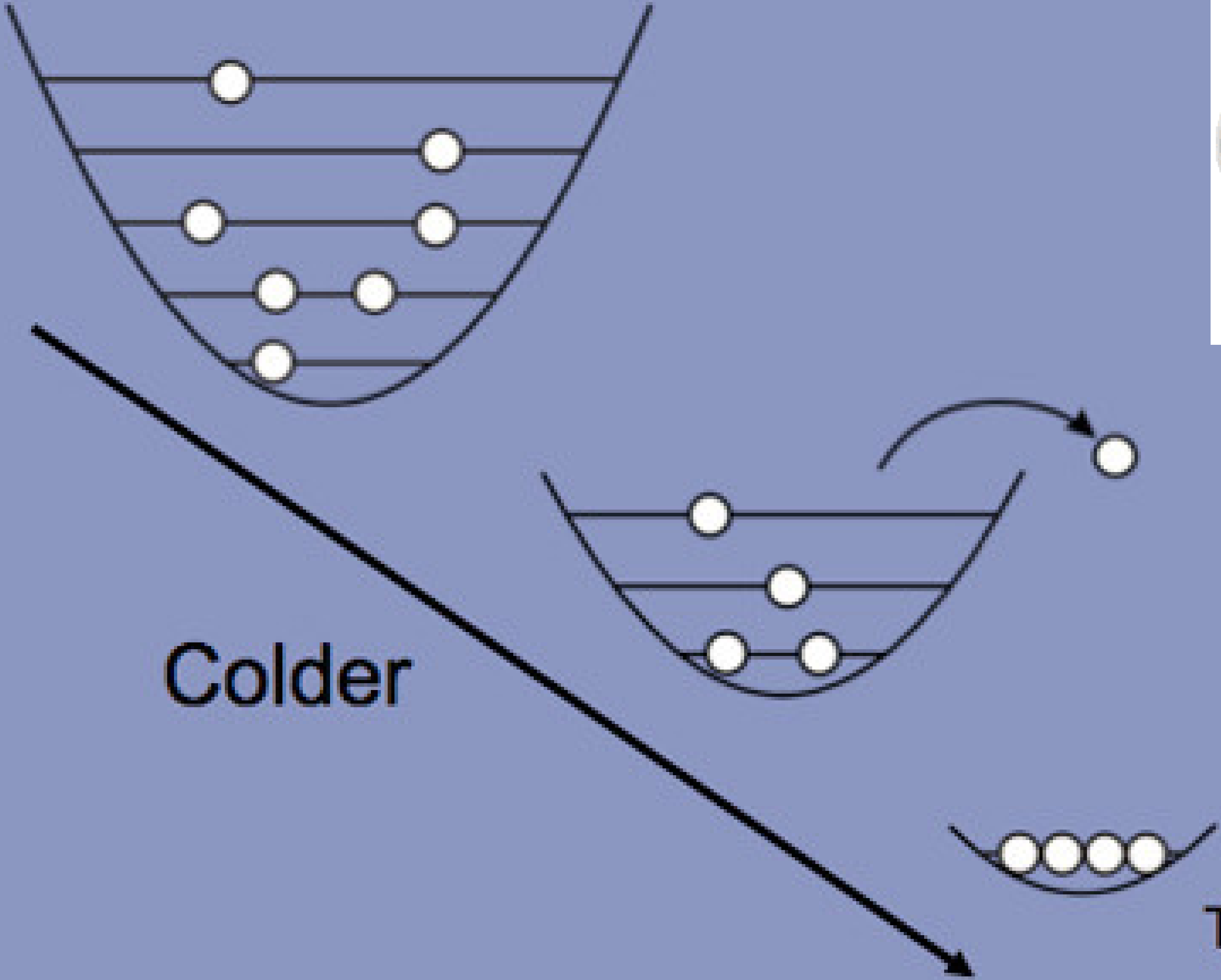


A pair of electronic coils to generate the magnetic trap

Laser beams
to cool and trap
the atoms

A cloud of
10 million atoms
with a temperature
of 0.000001 Kelvin

BEC: Cool by evaporation

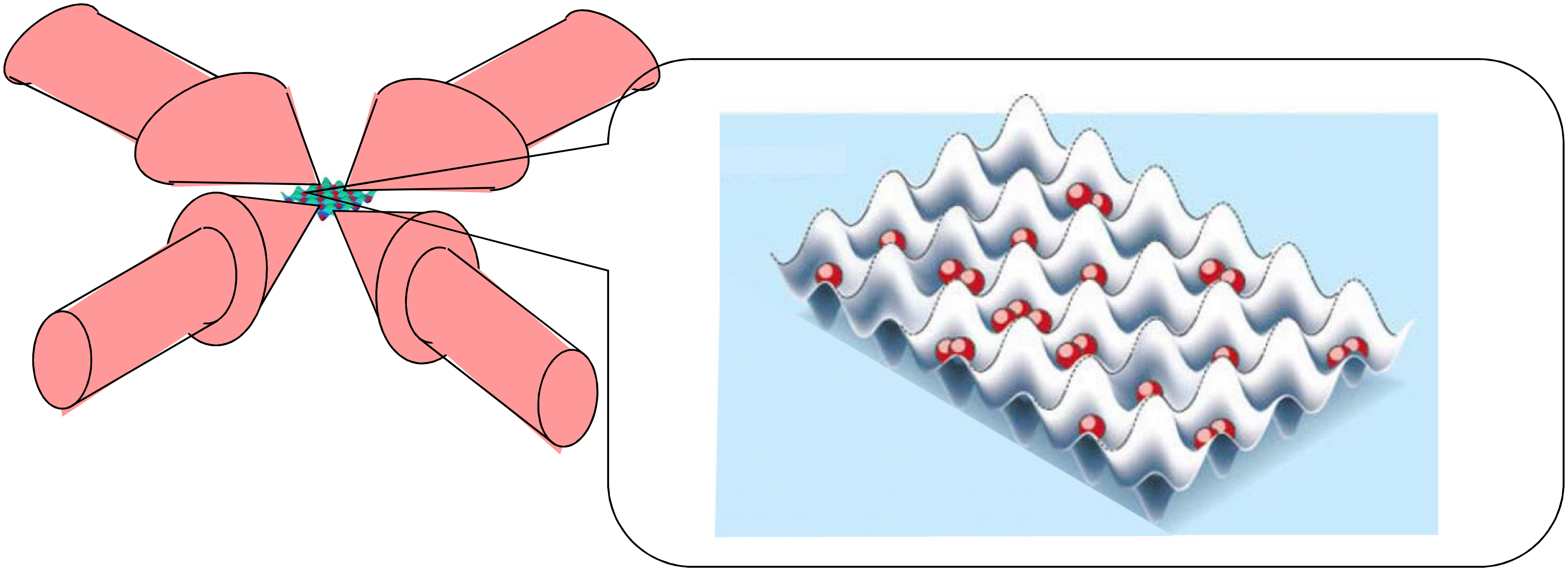


Colder

Temp ~ 50 nK

Evaporative cooling

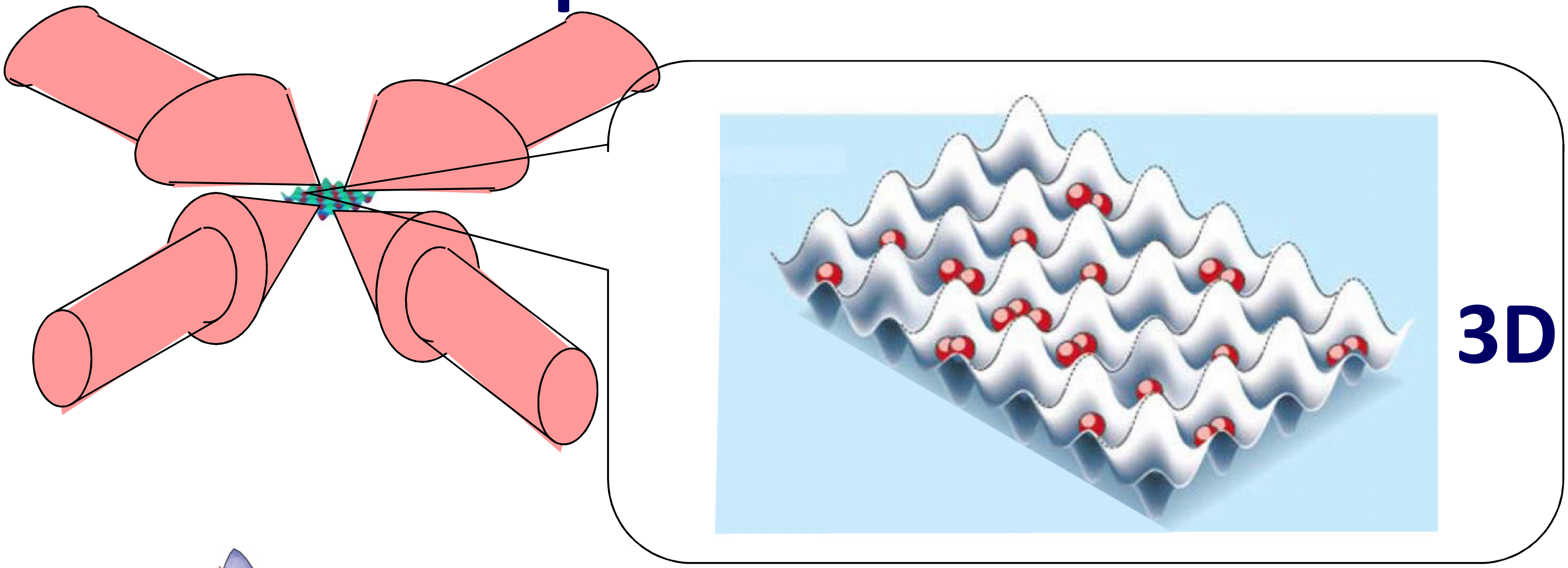
Making crystals from light: atoms in Optical Lattices

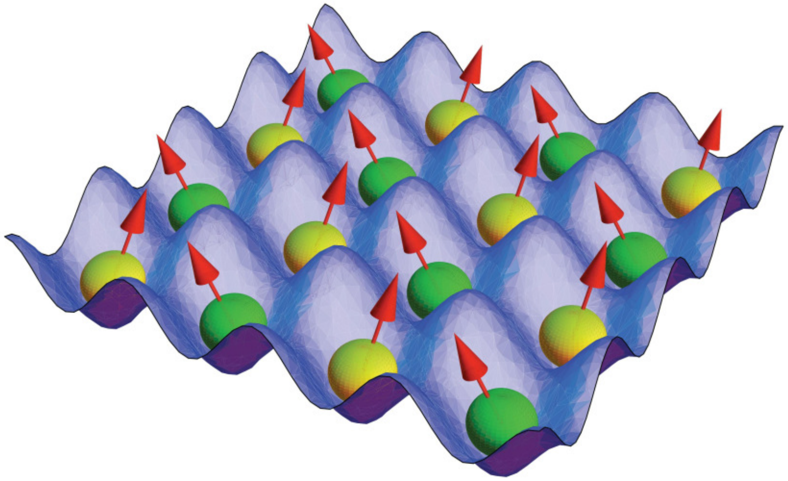


An optical lattice works as follows. When atoms are exposed to a laser field that is not resonant with an atomic optical transition (and thus does not excite the atomic electrons), they experience a conservative potential that is proportional to the laser intensity. With two counterpropagating laser fields, a standing wave is created and the atoms feel a periodic potential. With three such standing waves along three orthogonal spatial directions, one obtains a three-dimensional optical lattice. The atoms are trapped at the minima of the corresponding potential wells.

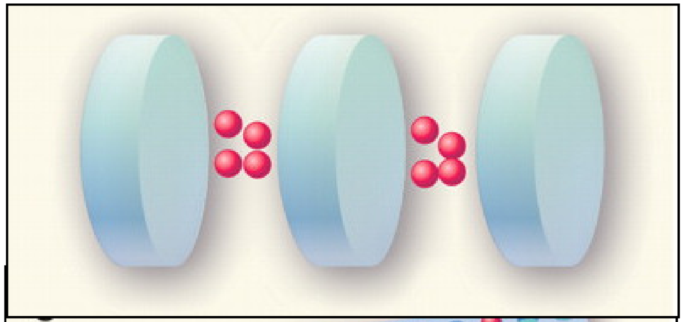
Adapted from: Eugene Demler

Making crystals from light: atoms in Optical Lattices

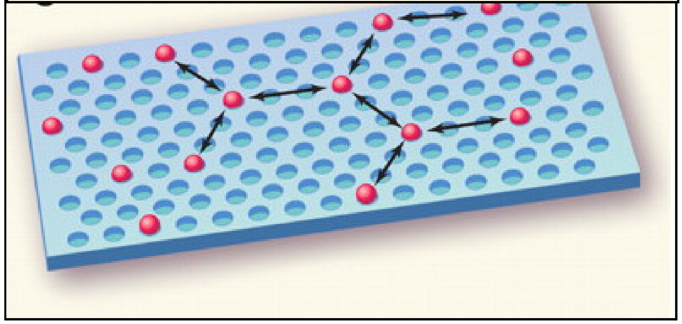




Spin state control

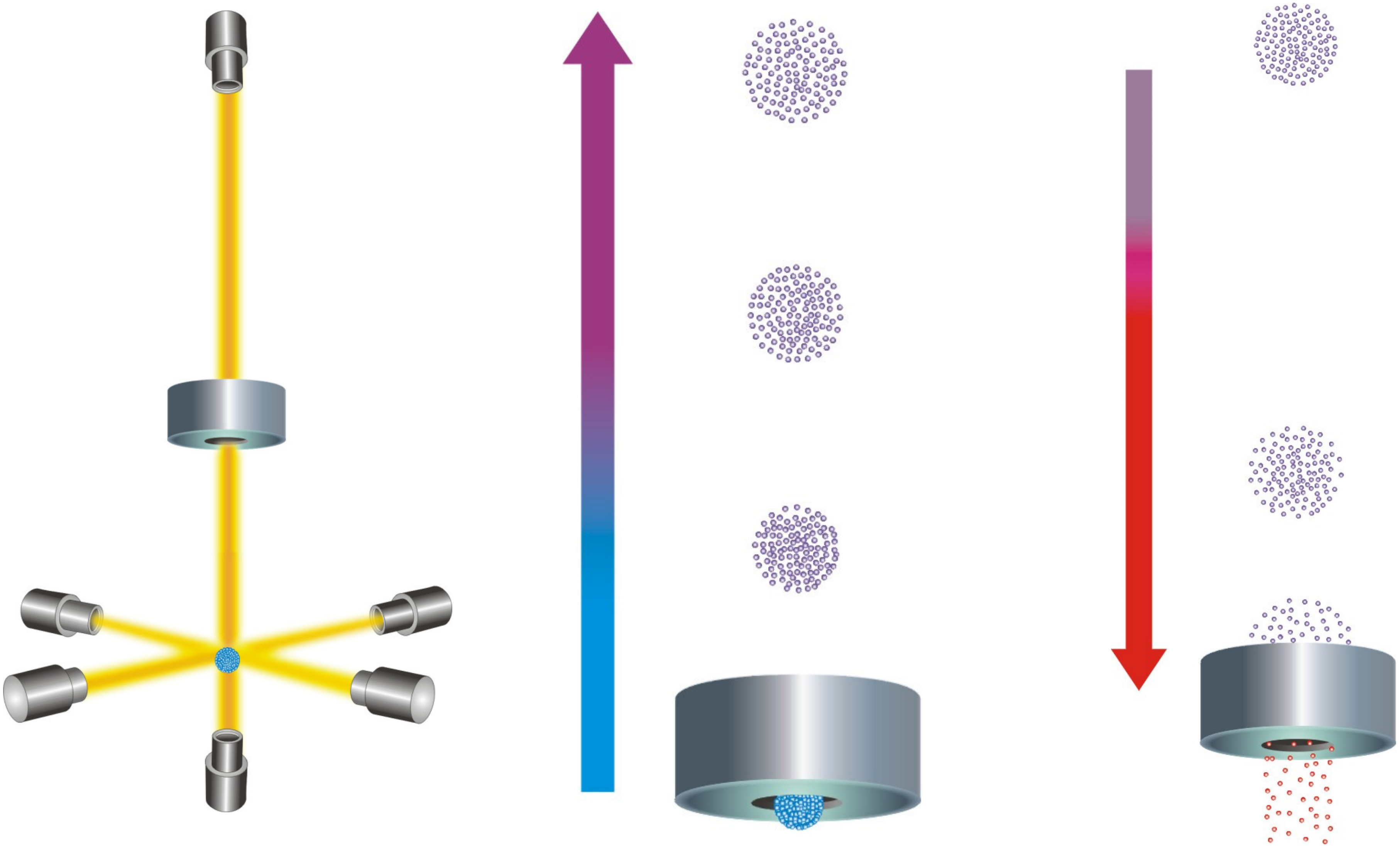


2D



1D

Cesium atomic clock



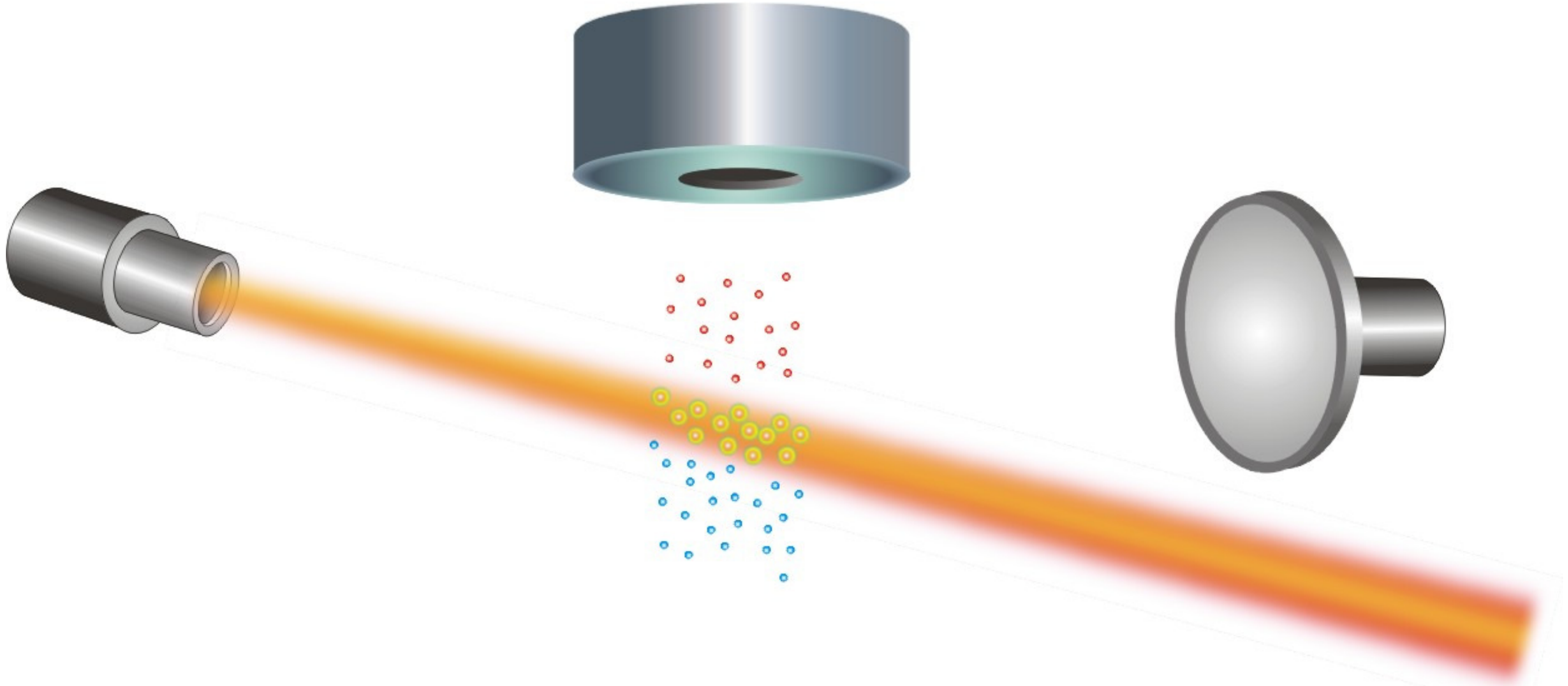
A gas of cesium atoms enters the clock's vacuum chamber. Six lasers slow the movement of the atoms and force them into a spherical cloud at the intersection of the laser beams.

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).

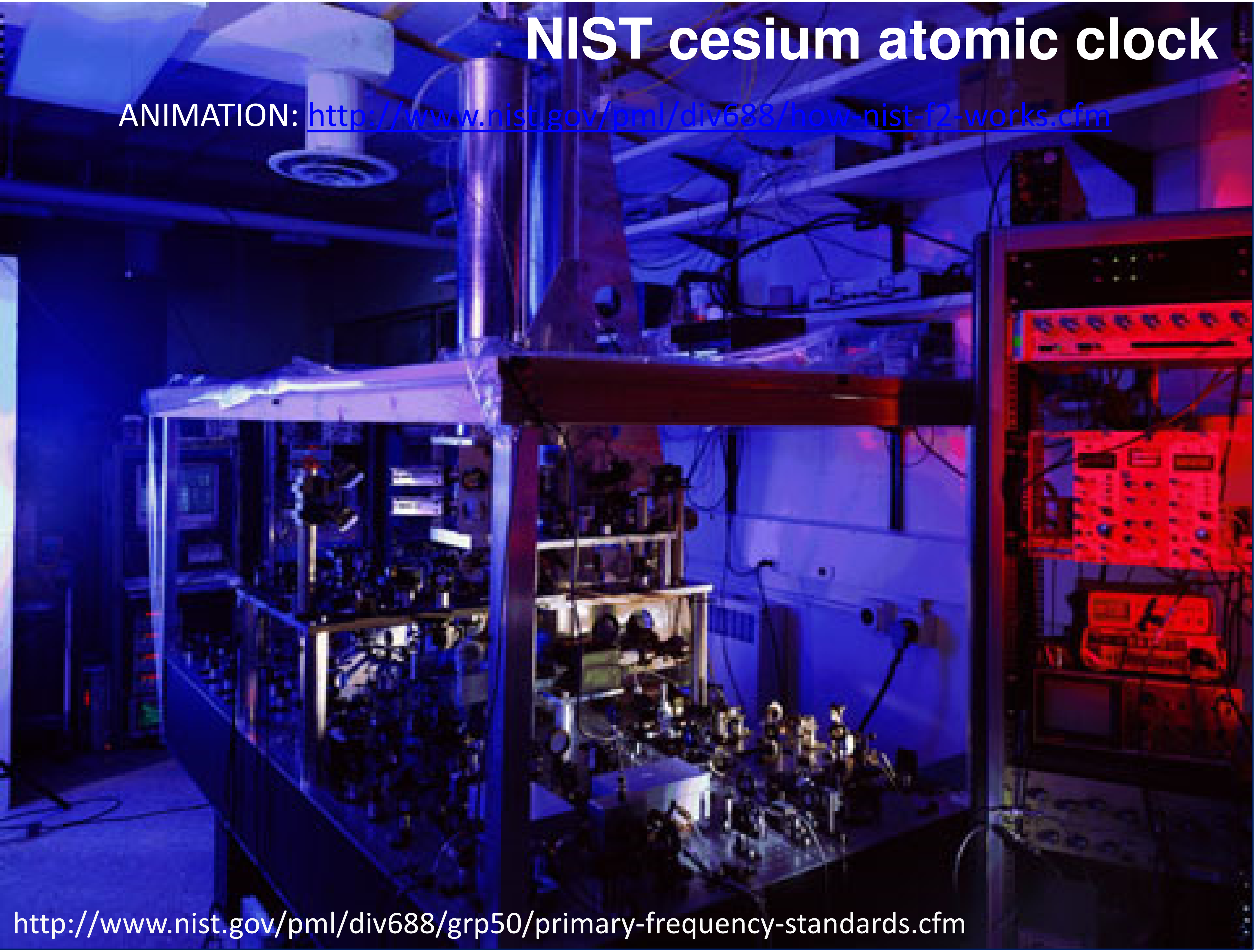
The entire process is repeated many times while the microwave energy in the cavity is tuned to different frequencies until the maximum fluorescence of the cesium atoms is determined.

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

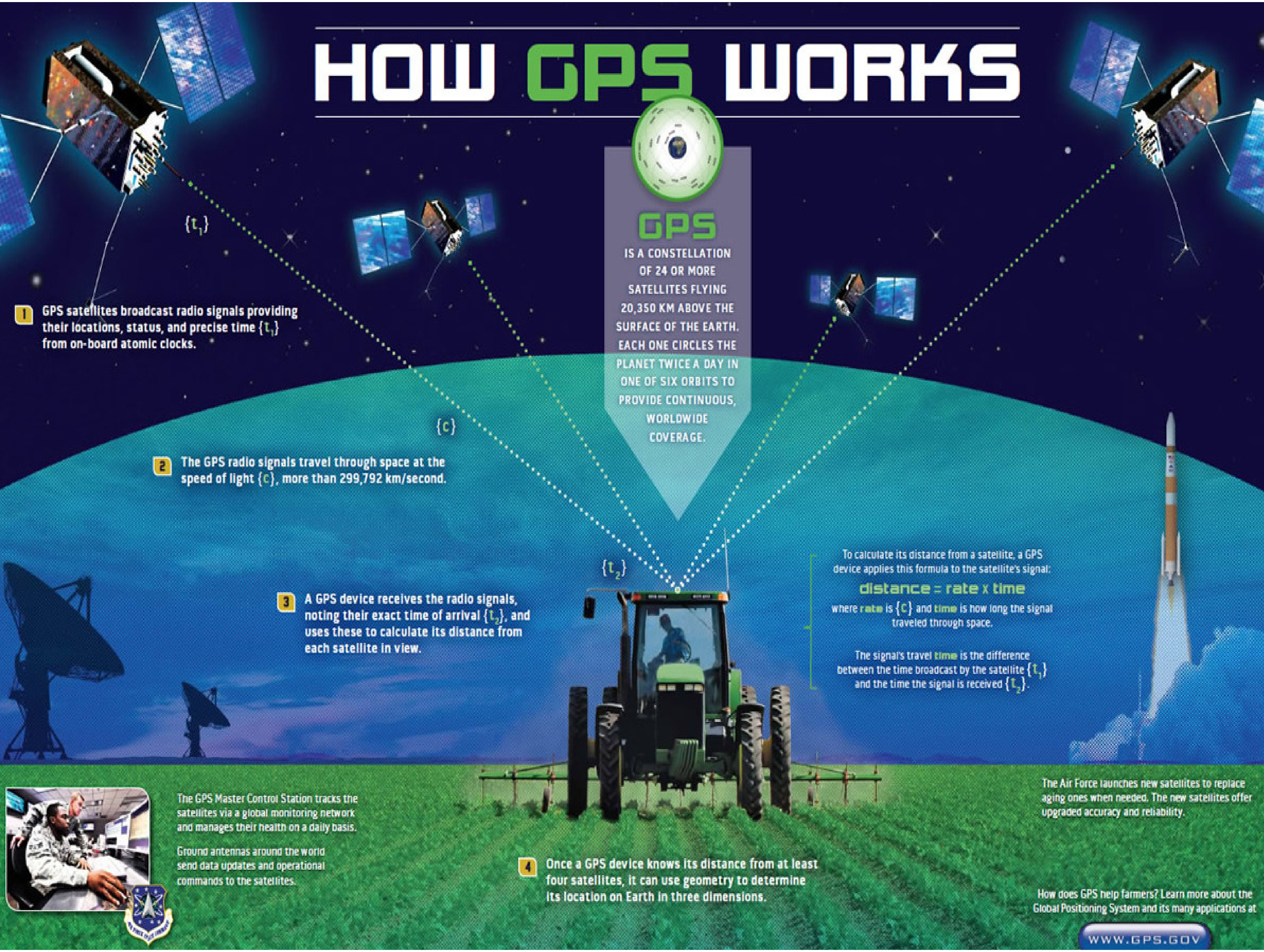
NIST cesium atomic clock

ANIMATION: http://www.nist.gov/pml/div688/how-nist-f2-works.cfm



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.

1. **GPS satellites broadcast radio signals providing their locations, status, and precise time $\{t_1\}$ from on-board atomic clocks.**

2. **The GPS radio signals travel through space at the speed of light $\{c\}$, more than 299,792 km/second.**

3. **A GPS device receives the radio signals, noting their exact time of arrival $\{t_2\}$, 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 $\{t_1\}$ and the time the signal is received $\{t_2\}$.

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 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.

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

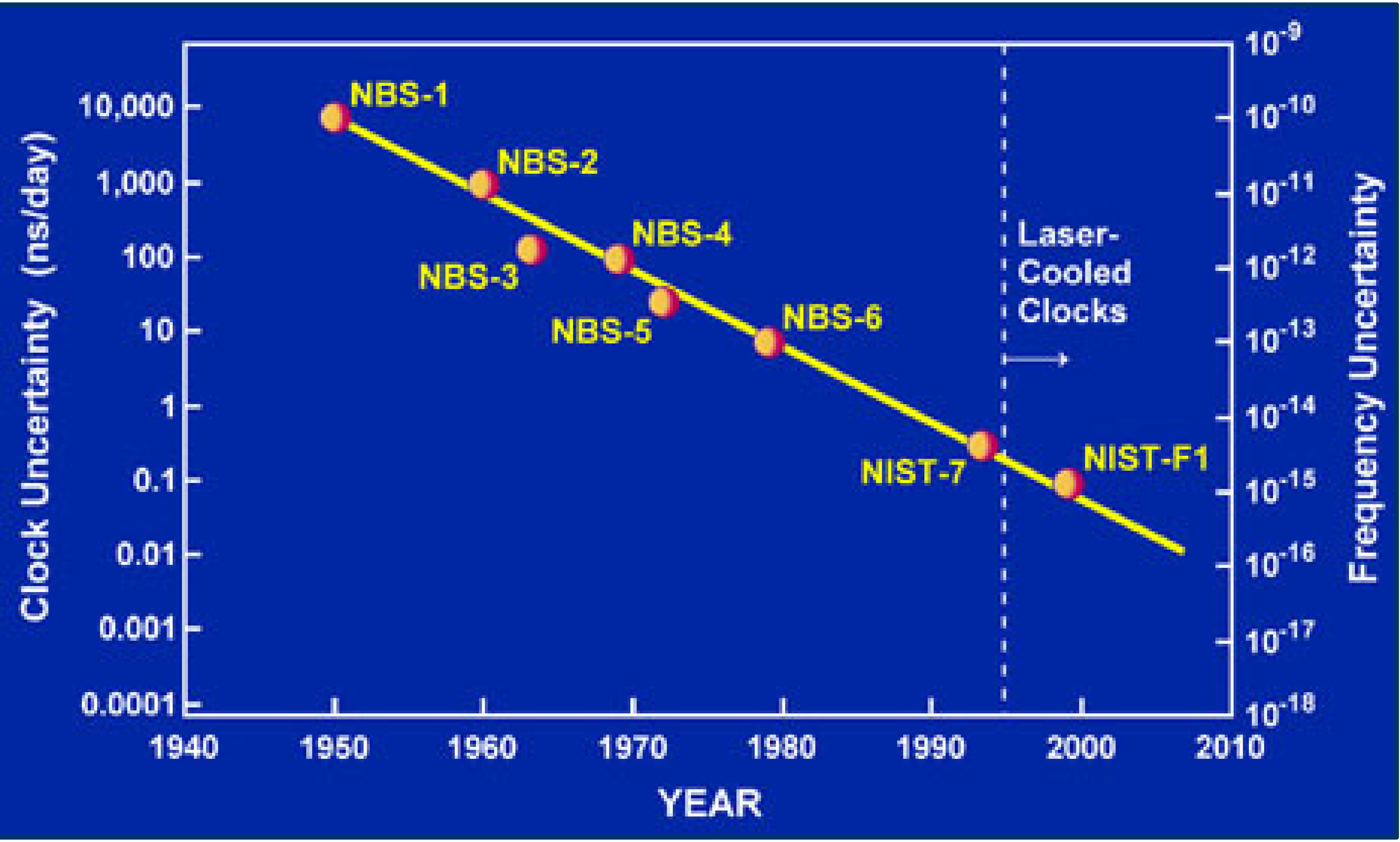
WWW.GPS.GOV

http://www.wiley.com/college/strahler/0471480533/animations/ch03_animations/animation3.html

https://www.youtube.com/watch?v=o4gYnbGXD6o

https://www.youtube.com/watch?v=QqLIlEW4ACw

Cesium atomic clocks

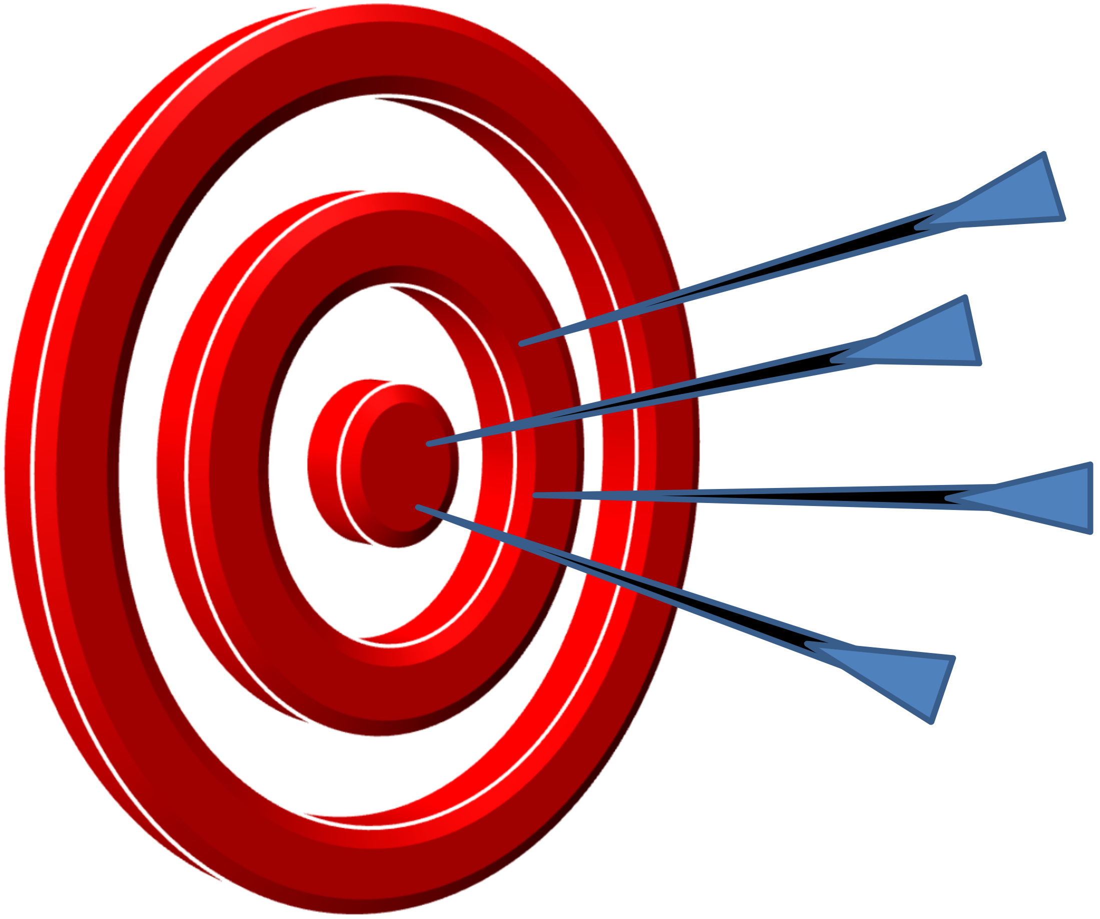


www.nist.gov

How good is a clock: stability

Stability is a measure of the precision with which we can measure a quantity (think of how widely scattered a group of arrows at target might be), and is usually stated as a function of averaging time since for many noise processes the precision increases (i.e., the noise is reduced through averaging) with more measurements.

The stability is usually set by the combination of the inherent frequency purity of the physical system and the signal-to-noise ratio with which we can measure the system.



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

How good is a clock: uncertainty

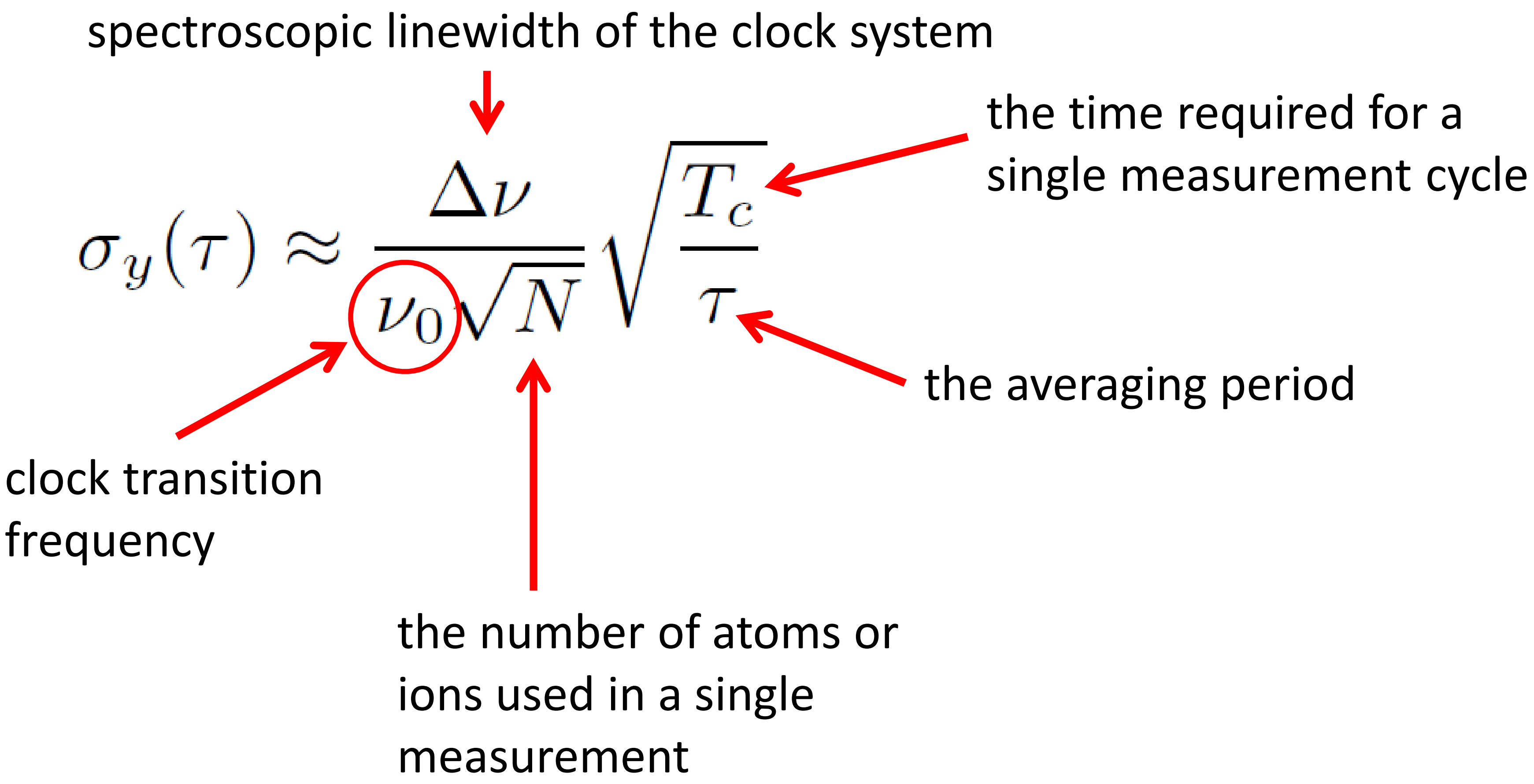
In contrast, the (absolute) **uncertainty** for an atomic clock tells us how well we understand the physical processes that can shift the measured frequency from its unperturbed (“bare"), natural atomic frequency (think of how off-centre our group of arrows might be).

Small absolute uncertainty is clearly an essential part of a good primary frequency standard and requires extensive evaluation of all known physical shifts (usually called “systematic effects").

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

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

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

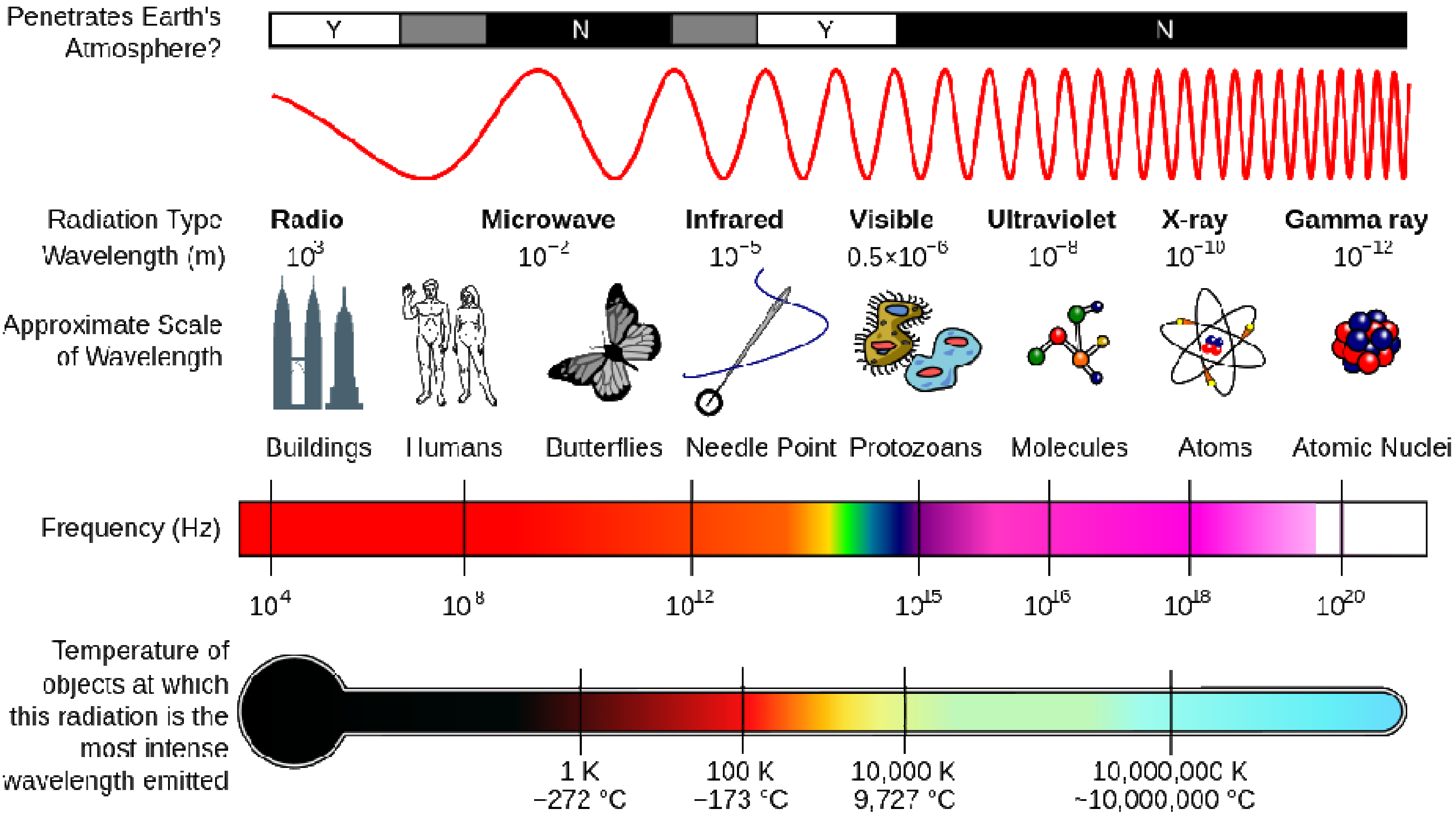
the time required for a single measurement cycle

the averaging period

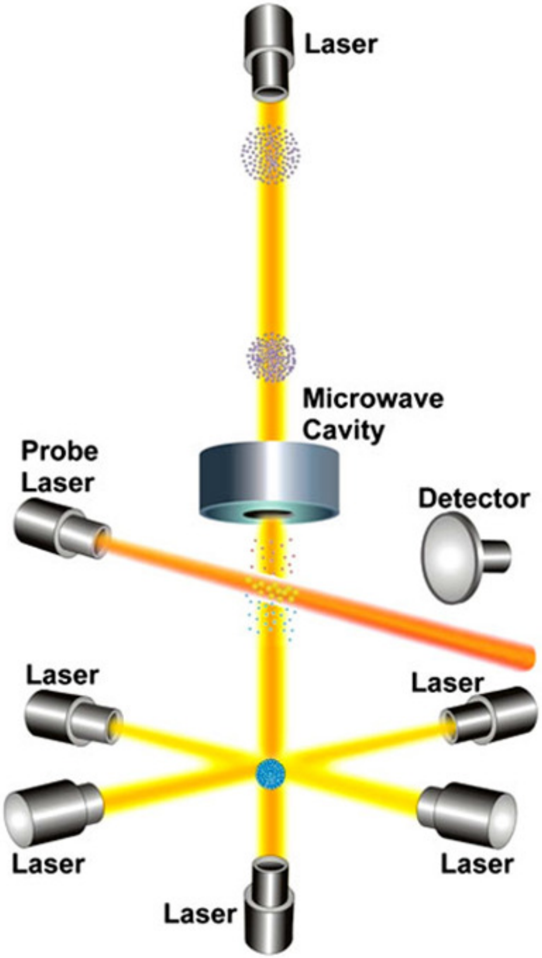
clock transition frequency

the number of atoms or ions used in a single measurement

How to build a better clock?

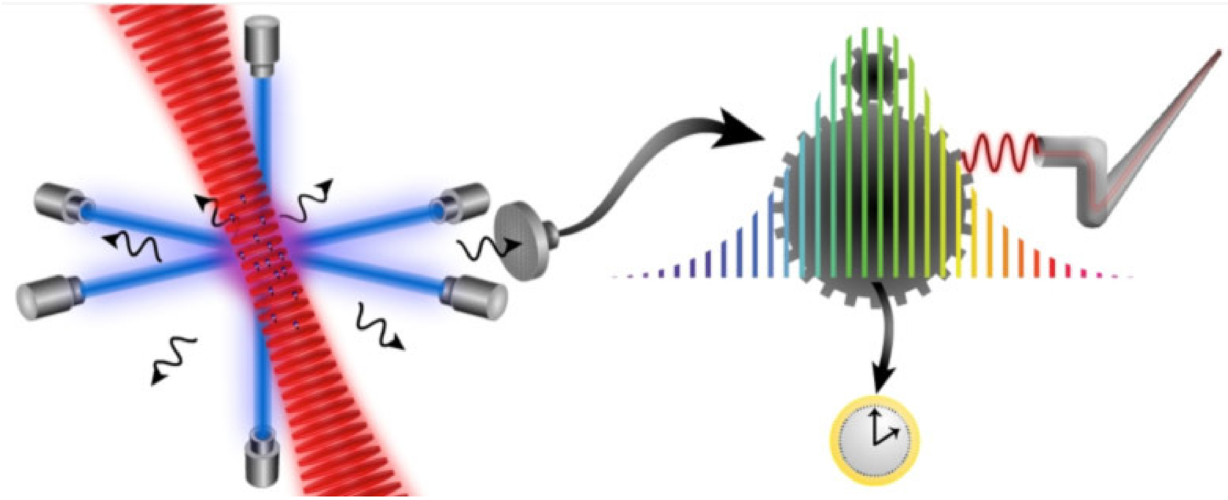


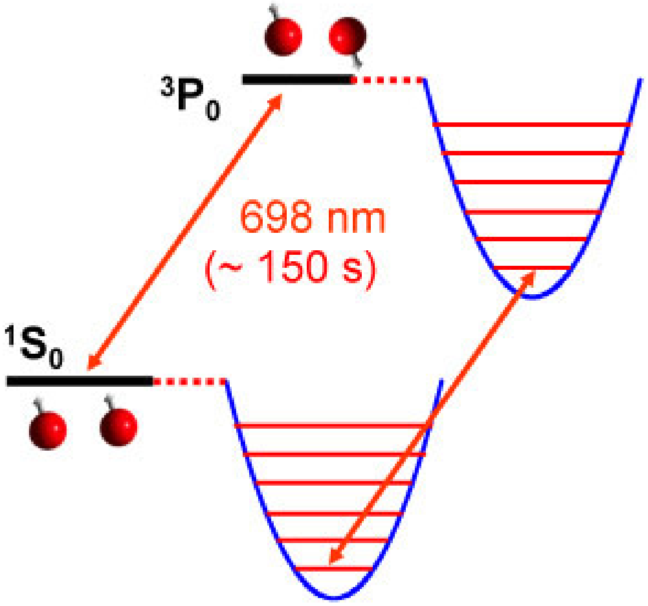
Cesium microwave atomic clock



9 x 10^9 periods per second

Strontium optical atomic clock

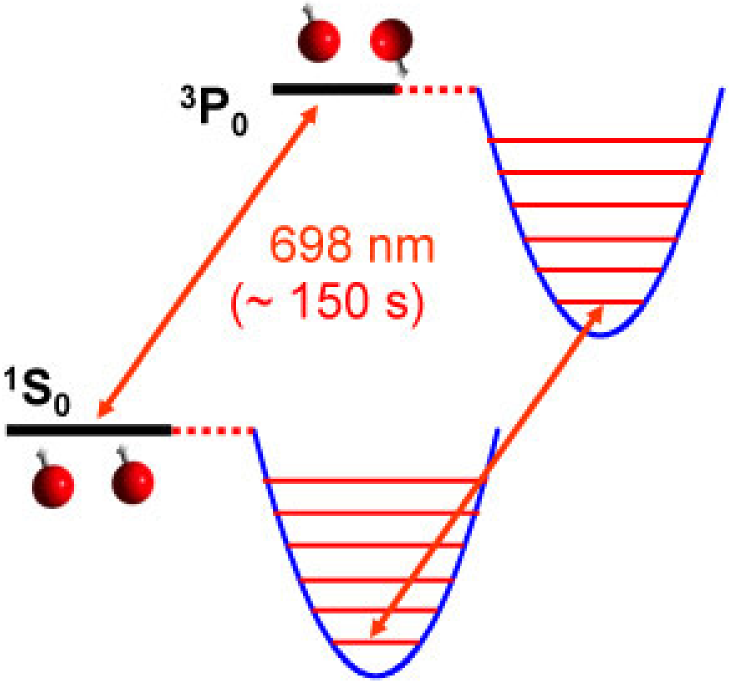




4.3 x 10^{14} periods per second

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

Problem: counting optical frequencies



Sr clock
4.3 x 10^{14} periods per second
$\Delta f \sim 10^{14}$ Hz

Fastest electronic counters
$\Delta f \sim 10^{11}$ Hz

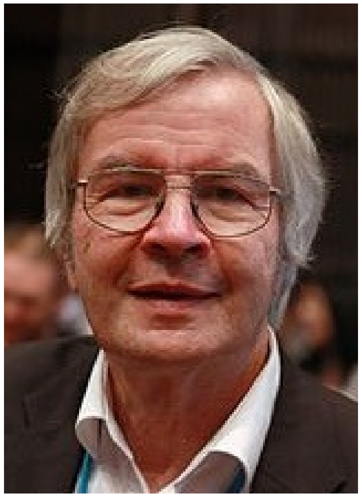
Solution:

Femtosecond laser frequency comb

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

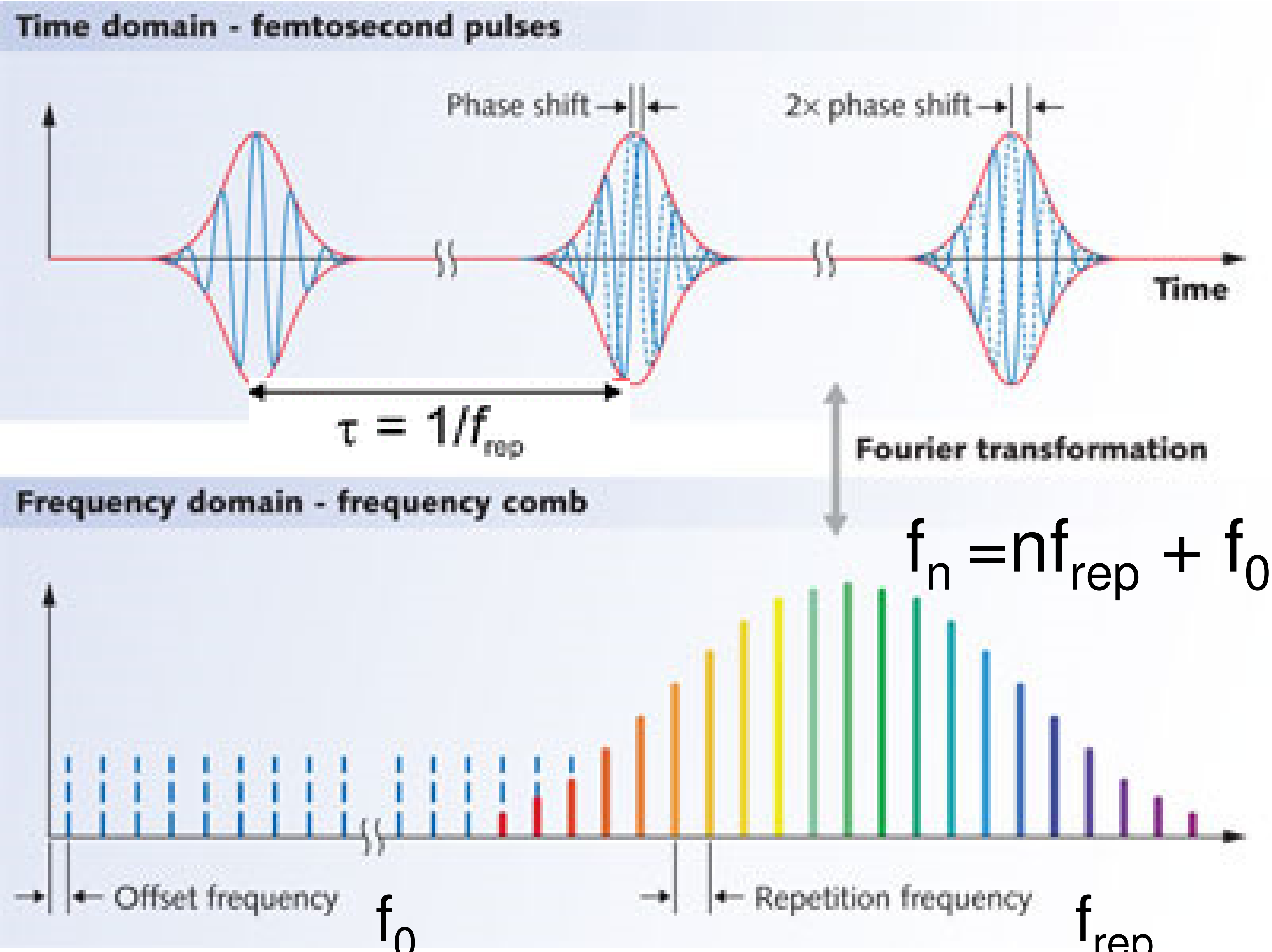
Laser-based precision spectroscopy and the optical frequency comb technique

2005 Nobel Prize



Theodor Hänsch

John Hall

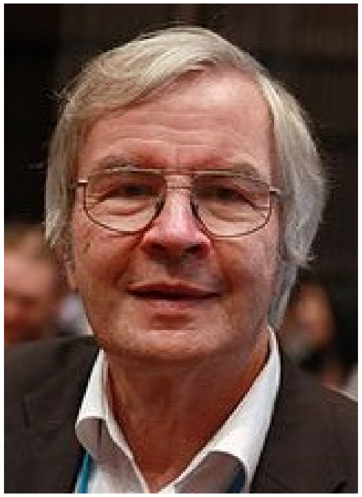


$$f_n = nf_{rep} + f_0$$

www.laserfocusworld.com

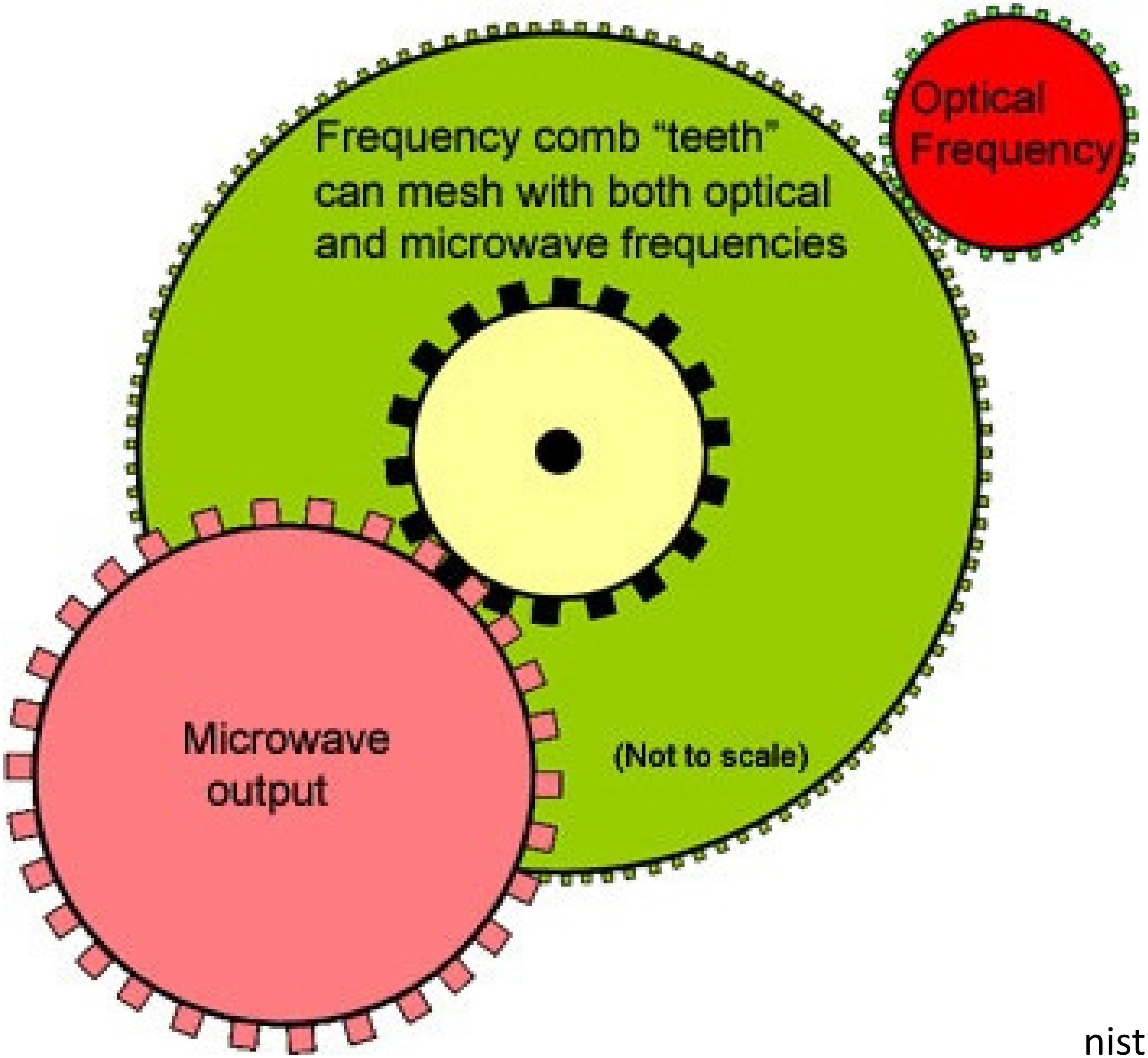
Laser-based precision spectroscopy and the optical frequency comb technique

2005 Nobel Prize



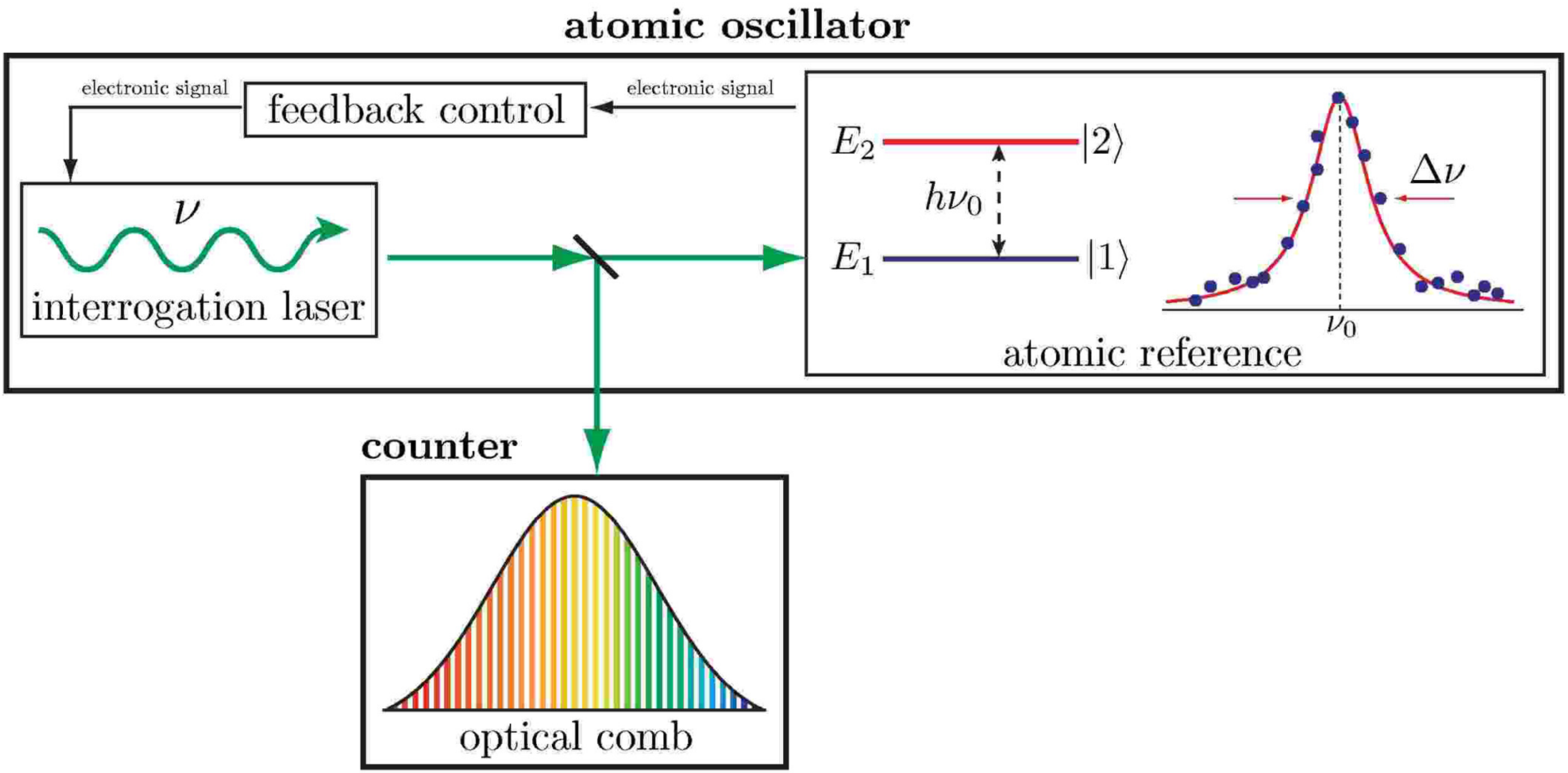
Theodor Hänsch

John Hall



nist.gov

What do we need to build a clock?



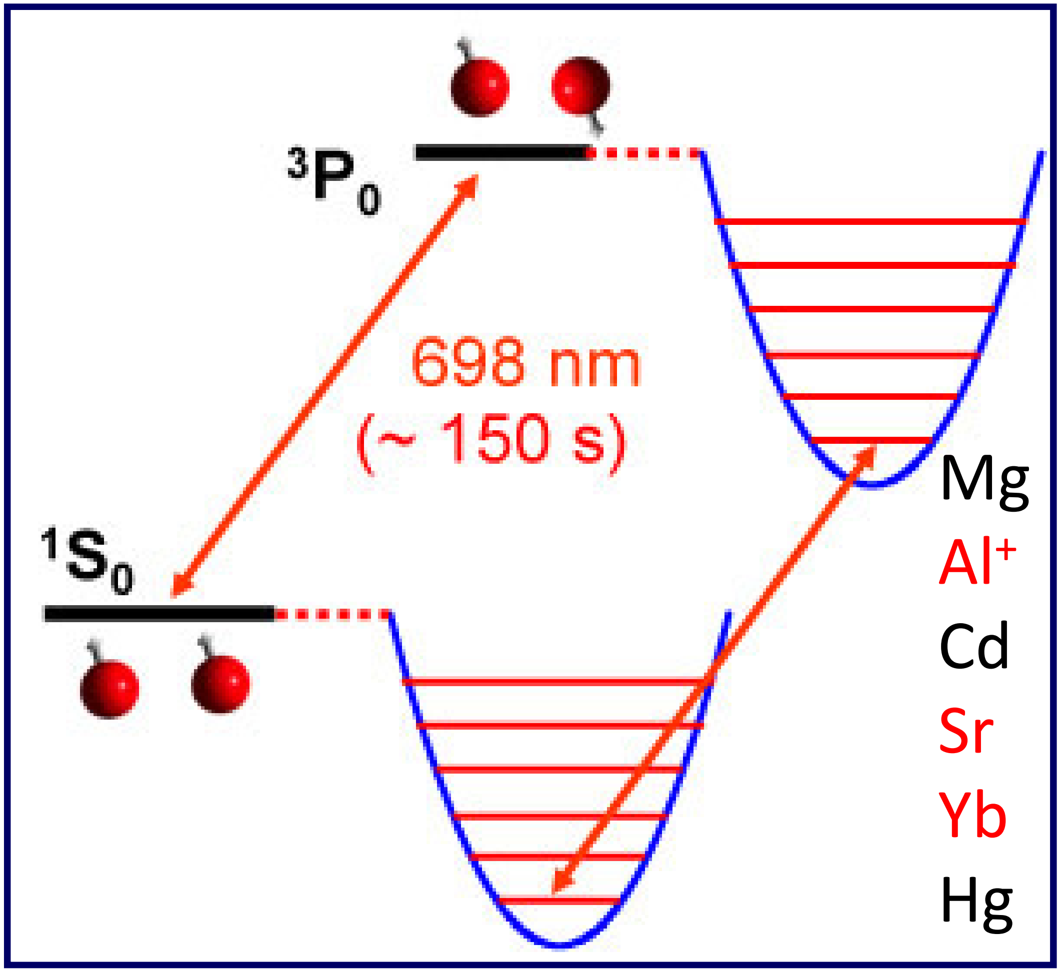
Schematic view of an optical atomic clock: the local oscillator (laser) is resonant with the atomic transition. A correction signal is derived from atomic spectroscopy that is fed back to the laser. An optical frequency synthesizer (optical frequency comb) is used to divide the optical frequency down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

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

Requirements for atomic reference

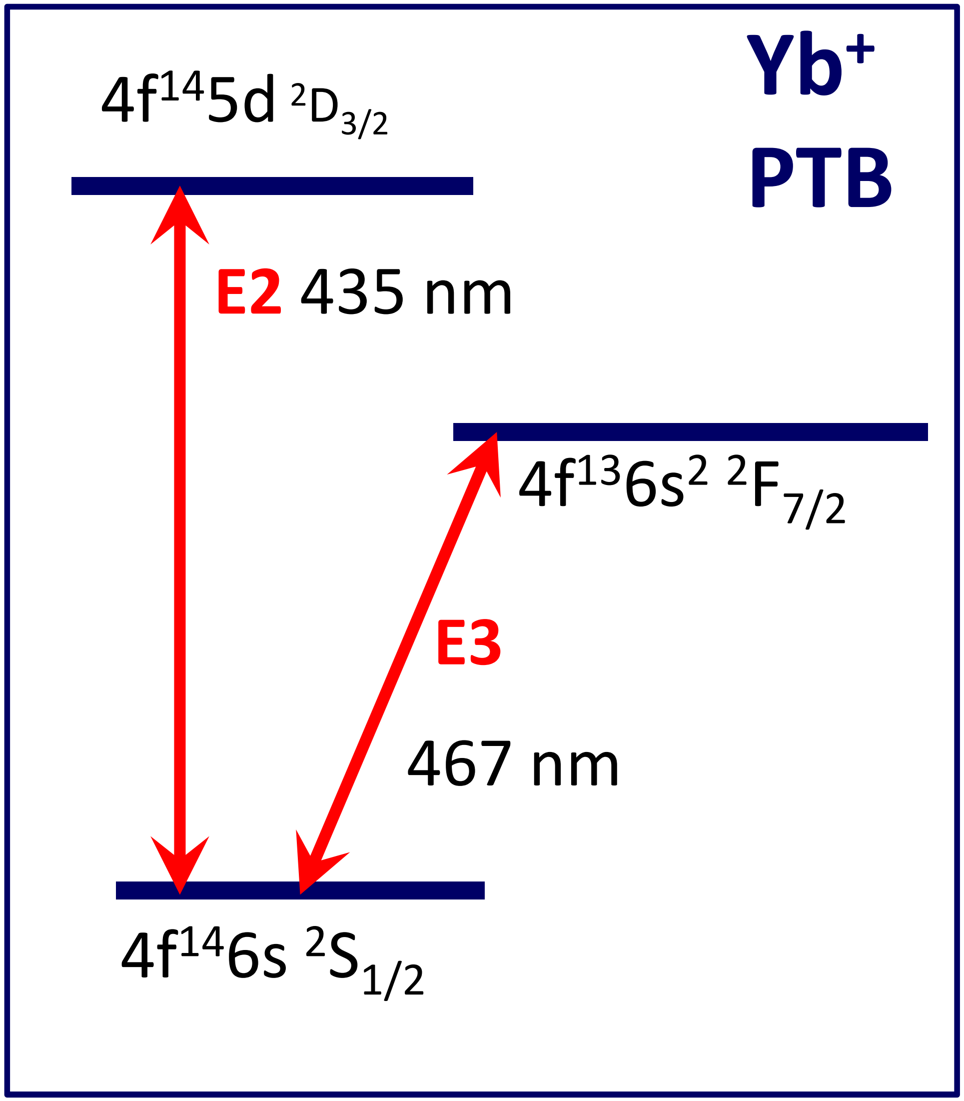
(1) Metastable level

(2) Near optical transition



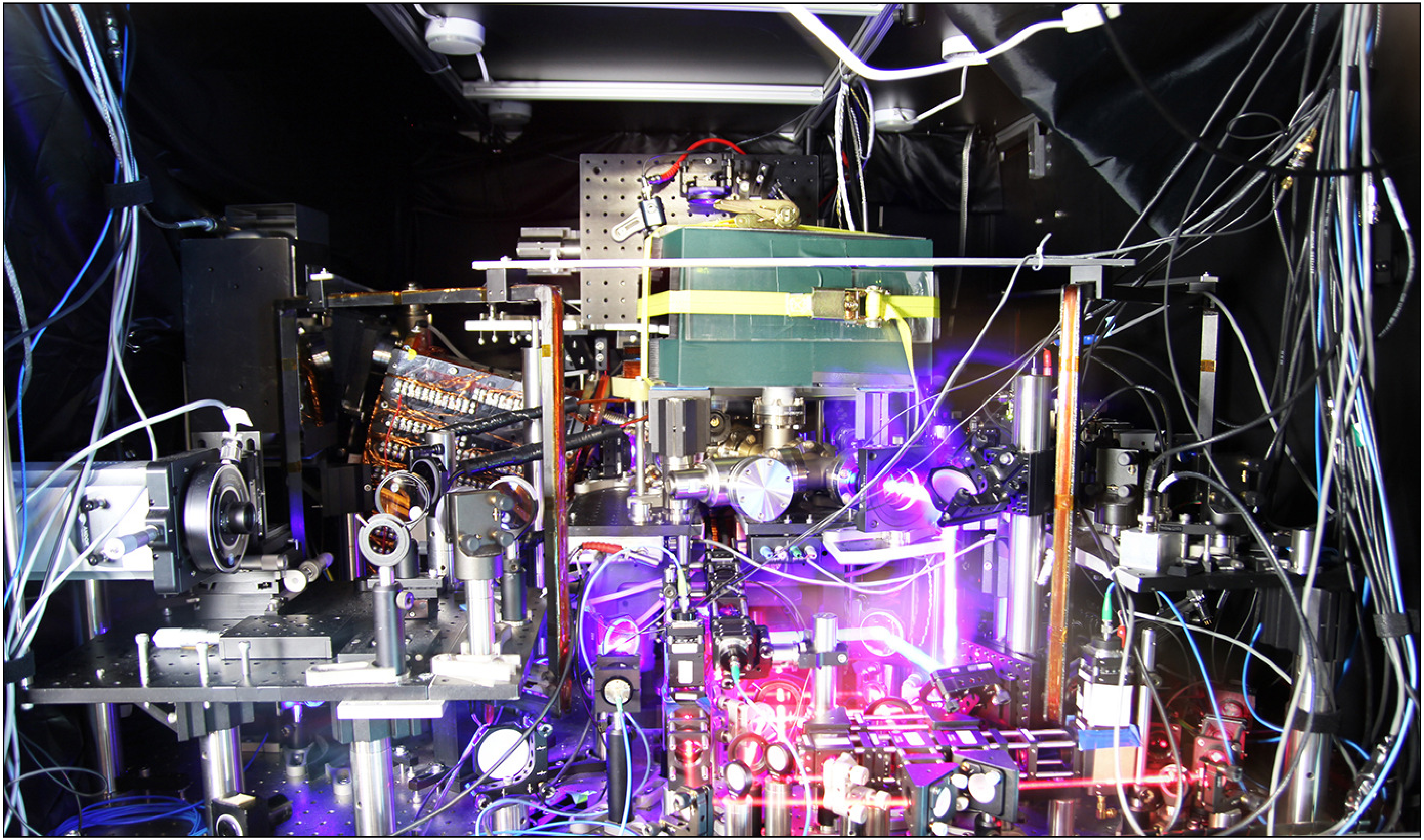
Strontium optical lattice neutral atom clock

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



Yb⁺ single trapped ion clock

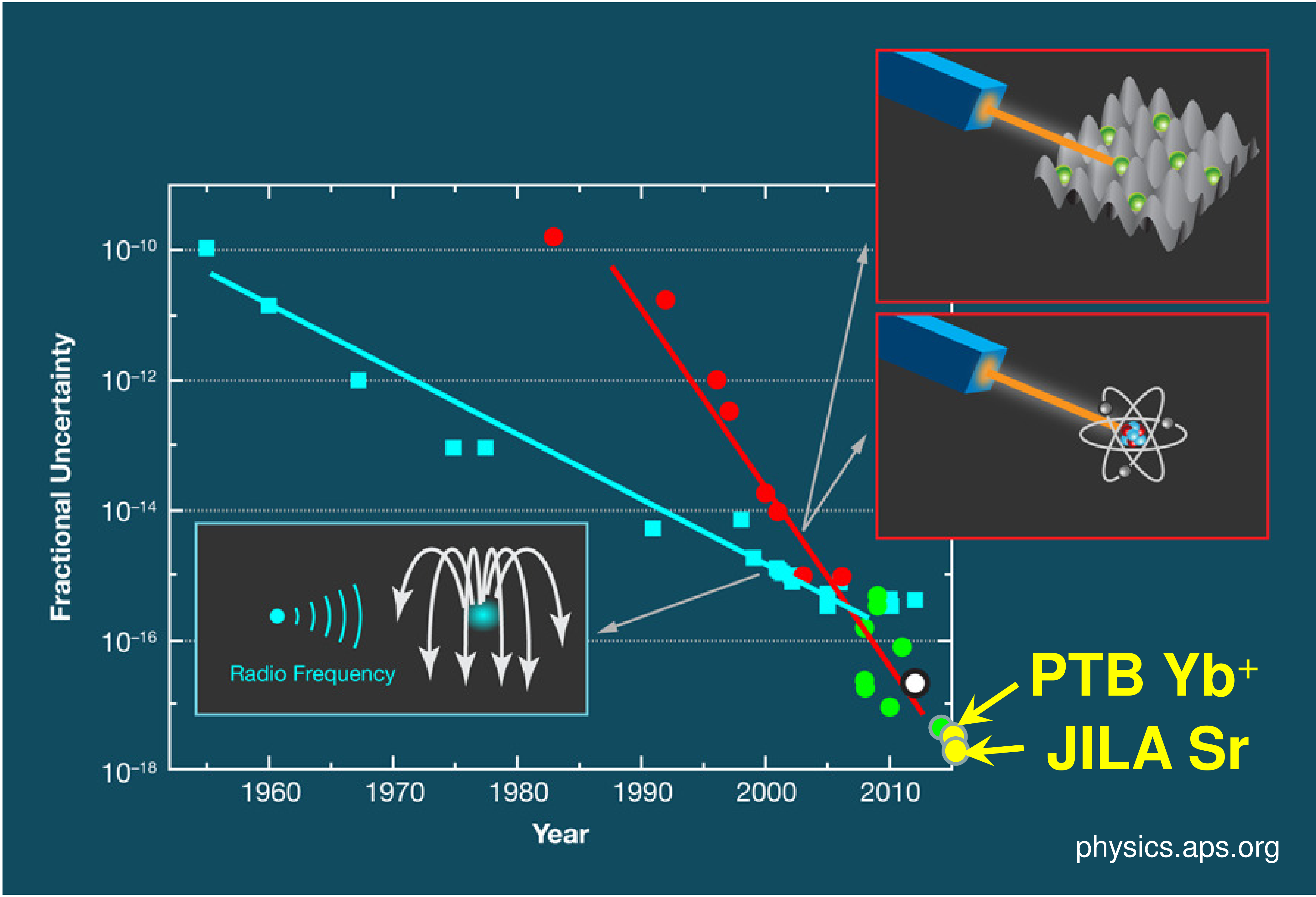
Sr clock will lose 1 second in 15 billion years !



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



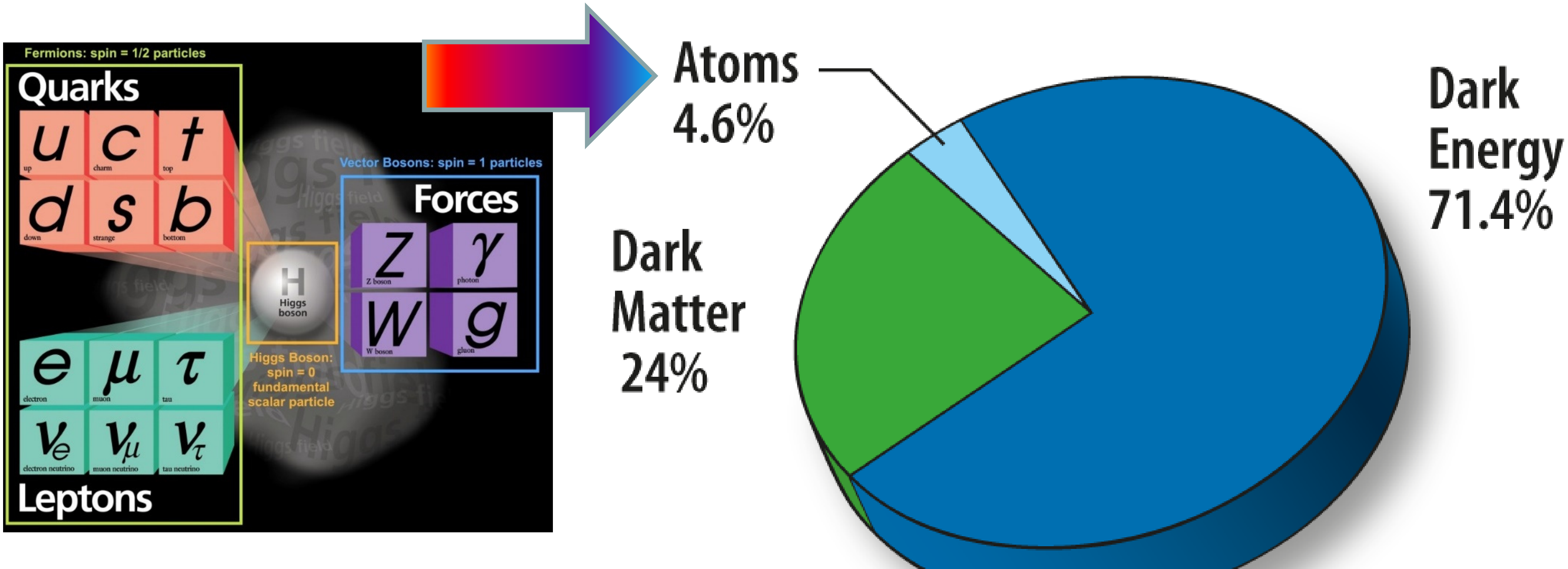
physics.aps.org

Applications of Atomic Clocks

- Improved timekeeping and synchronization capabilities
- Design of absolute gravimeters and gravity gradiometers for geophysical monitoring and research and gravity aided navigation
- Search for variation of fundamental constants
- Search for topological dark matter
- Search for violation of local Lorenz invariance
- Exploration of strongly correlated quantum many-body systems
- Other …

Metrology and the Laws of Physics

Our understanding of the Universe and its fundamental physics laws is incomplete.



Precision atomic measurements:
Do laws of physics hold within the experimental precision?

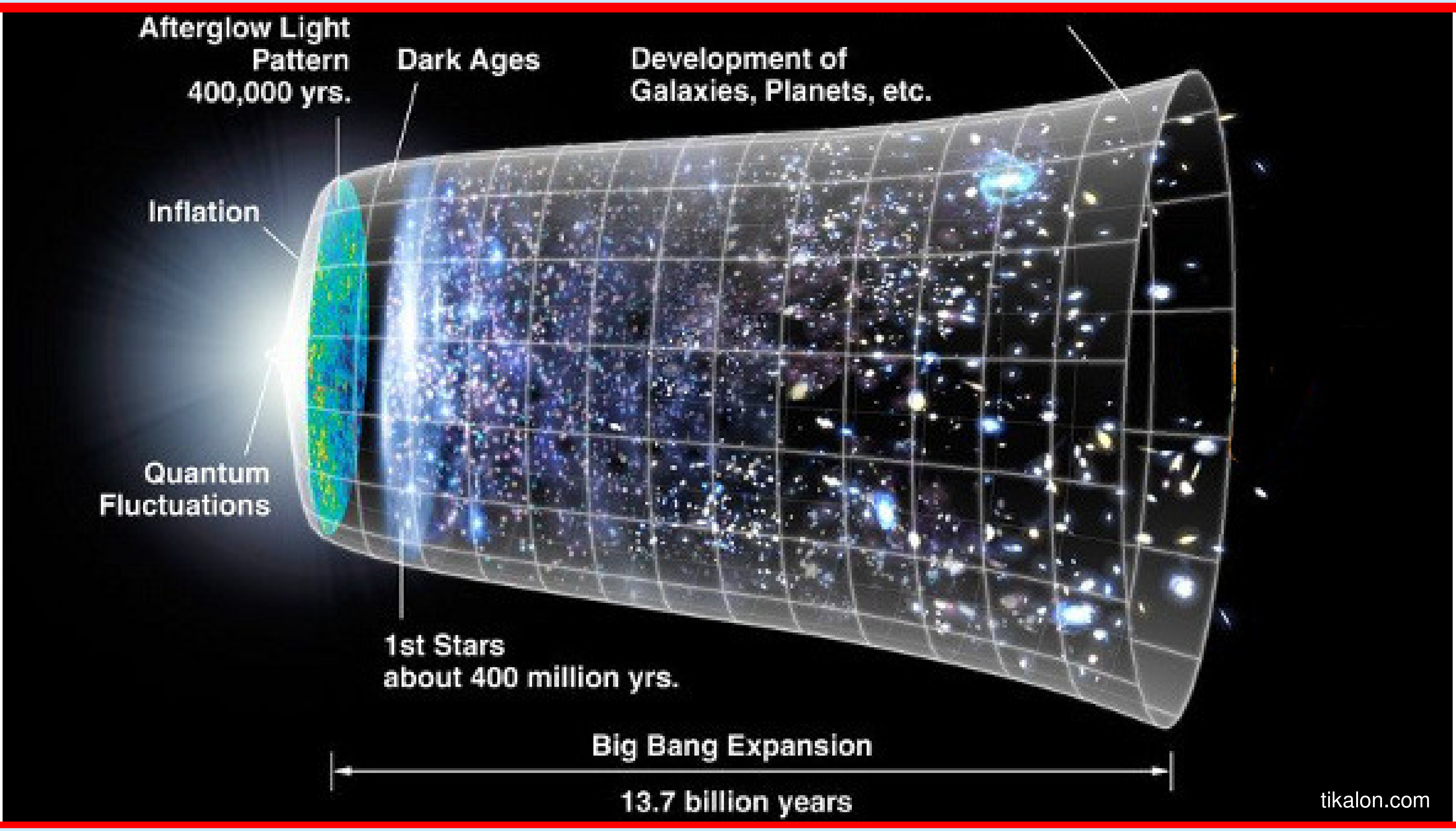
Precision atomic tests may discover new physics and will constrain new theories.

ARE FUNDAMENTAL CONSTANTS CONSTANT???

Being able to compare and reproduce experiments is at the foundation of the scientific approach, which makes sense only if the laws of nature do not depend on time and space.

J.-P. Uzan, Rev. Mod. Phys. 75, 403 (2003)

ARE FUNDAMENTAL CONSTANTS CONSTANT?

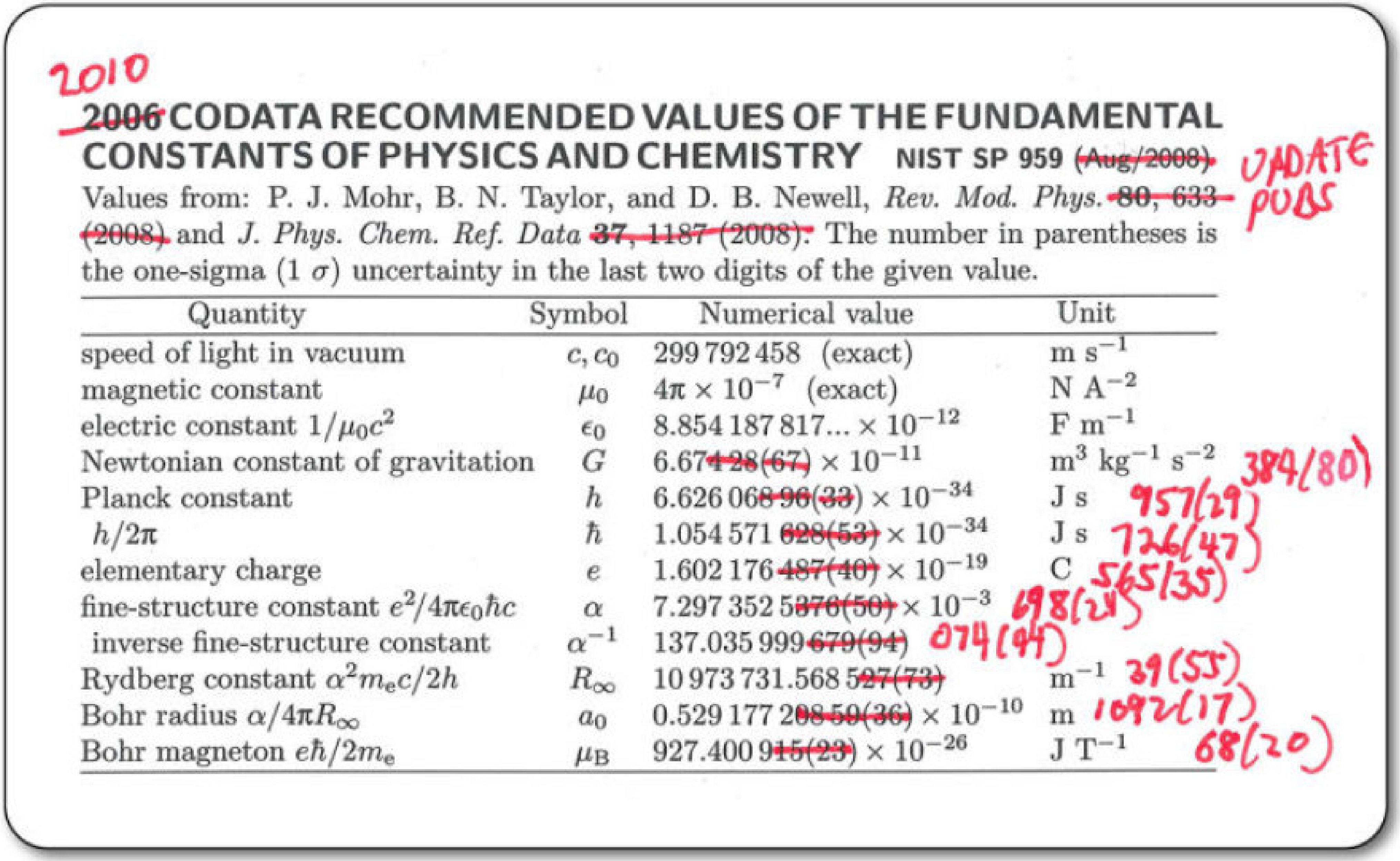


The modern theories directed toward unifying gravitation with the three other fundamental interactions suggest variation of the fundamental constants in an expanding universe.

TABLE I An abbreviated list of the CODATA recommended values of the fundamental constants of physics and chemistry based on the 2014 adjustment.

Quantity	Symbol	Numerical value	Unit	Relative std. uncert. u_r
speed of light in vacuum	c, c_0	$299\,792\,458$	$\mathrm{m\ s^{-1}}$	exact
magnetic constant	μ_0	$4\pi \times 10^{-7}$	$\mathrm{N\ A^{-2}}$	
		$= 12.566\,370\,614... \times 10^{-7}$	$\mathrm{N\ A^{-2}}$	exact
electric constant $1/\mu_0 c^2$	ϵ_0	$8.854\,187\,817... \times 10^{-12}$	$\mathrm{F\ m^{-1}}$	exact
Newtonian constant of gravitation	G	$6.674\,08(31) \times 10^{-11}$	$\mathrm{m^3\ kg^{-1}\ s^{-2}}$	4.7×10^{-5}
Planck constant	h	$6.626\,070\,040(81) \times 10^{-34}$	$\mathrm{J\ s}$	1.2×10^{-8}
$h/2\pi$	$\hbar$	$1.054\,571\,800(13) \times 10^{-34}$	$\mathrm{J\ s}$	1.2×10^{-8}
elementary charge	e	$1.602\,176\,6208(98) \times 10^{-19}$	C	6.1×10^{-9}
magnetic flux quantum $h/2e$	Φ_0	$2.067\,833\,831(13) \times 10^{-15}$	Wb	6.1×10^{-9}
conductance quantum $2e^2/h$	G_0	$7.748\,091\,7310(18) \times 10^{-5}$	S	2.3×10^{-10}
electron mass	m_e	$9.109\,383\,56(11) \times 10^{-31}$	kg	1.2×10^{-8}
proton mass	m_p	$1.672\,621\,898(21) \times 10^{-27}$	kg	1.2×10^{-8}
proton-electron mass ratio	m_p/m_e	$1836.152\,673\,89(17)$		9.5×10^{-11}
fine-structure constant $e^2/4\pi\epsilon_0\hbar c$	α	$7.297\,352\,5664(17) \times 10^{-3}$		2.3×10^{-10}
inverse fine-structure constant	α^{-1}	$137.035\,999\,139(31)$		2.3×10^{-10}
Rydberg constant $\alpha^2 m_e c/2h$	R_∞	$10\,973\,731.568\,508(65)$	$\mathrm{m^{-1}}$	5.9×10^{-12}
Avogadro constant	N_A, L	$6.022\,140\,857(74) \times 10^{23}$	$\mathrm{mol^{-1}}$	1.2×10^{-8}
Faraday constant $N_A e$	F	$96\,485.332\,89(59)$	$\mathrm{C\ mol^{-1}}$	6.2×10^{-9}
molar gas constant	R	$8.314\,4598(48)$	$\mathrm{J\ mol^{-1}\ K^{-1}}$	5.7×10^{-7}
Boltzmann constant R/N_A	k	$1.380\,648\,52(79) \times 10^{-23}$	$\mathrm{J\ K^{-1}}$	5.7×10^{-7}
Stefan-Boltzmann constant $(\pi^2/60)k^4/\hbar^3 c^2$	σ	$5.670\,367(13) \times 10^{-8}$	$\mathrm{W\ m^{-2}\ K^{-4}}$	2.3×10^{-6}
Non-SI units accepted for use with the SI				
electron volt (e/C) J	eV	$1.602\,176\,6208(98) \times 10^{-19}$	J	6.1×10^{-9}
(unified) atomic mass unit $\frac{1}{12}m(^{12}\mathrm{C})$	u	$1.660\,539\,040(20) \times 10^{-27}$	kg	1.2×10^{-8}

www.nist.gov



2010

~~2006~~ CODATA RECOMMENDED VALUES OF THE FUNDAMENTAL CONSTANTS OF PHYSICS AND CHEMISTRY

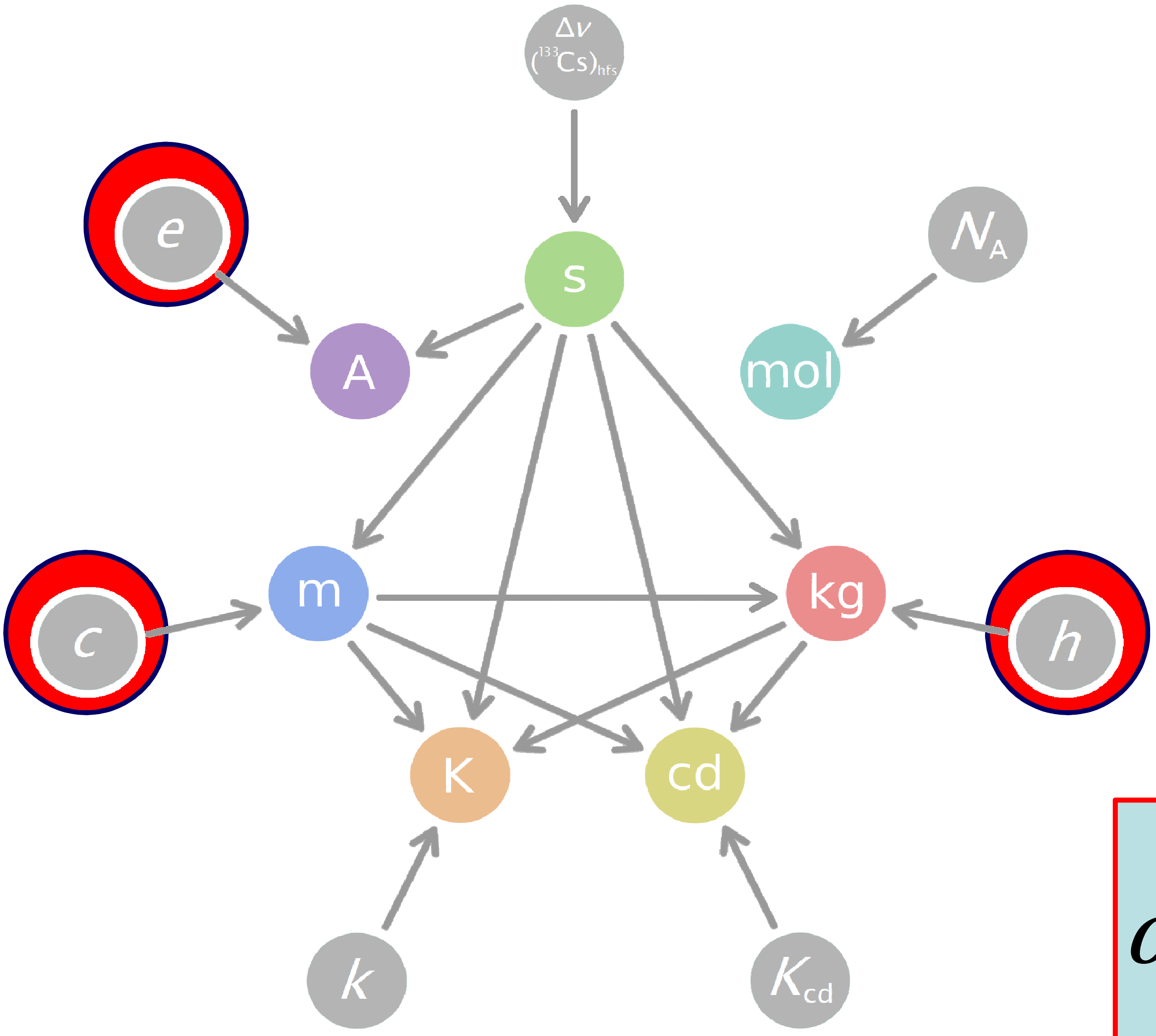
NIST SP 959 ~~(Aug/2008)~~ UPDATE PUBS

Values from: P. J. Mohr, B. N. Taylor, and D. B. Newell, *Rev. Mod. Phys.* ~~80, 633 (2008)~~ and *J. Phys. Chem. Ref. Data* ~~37, 1187 (2008)~~. The number in parentheses is the one-sigma ($1\ \sigma$) uncertainty in the last two digits of the given value.

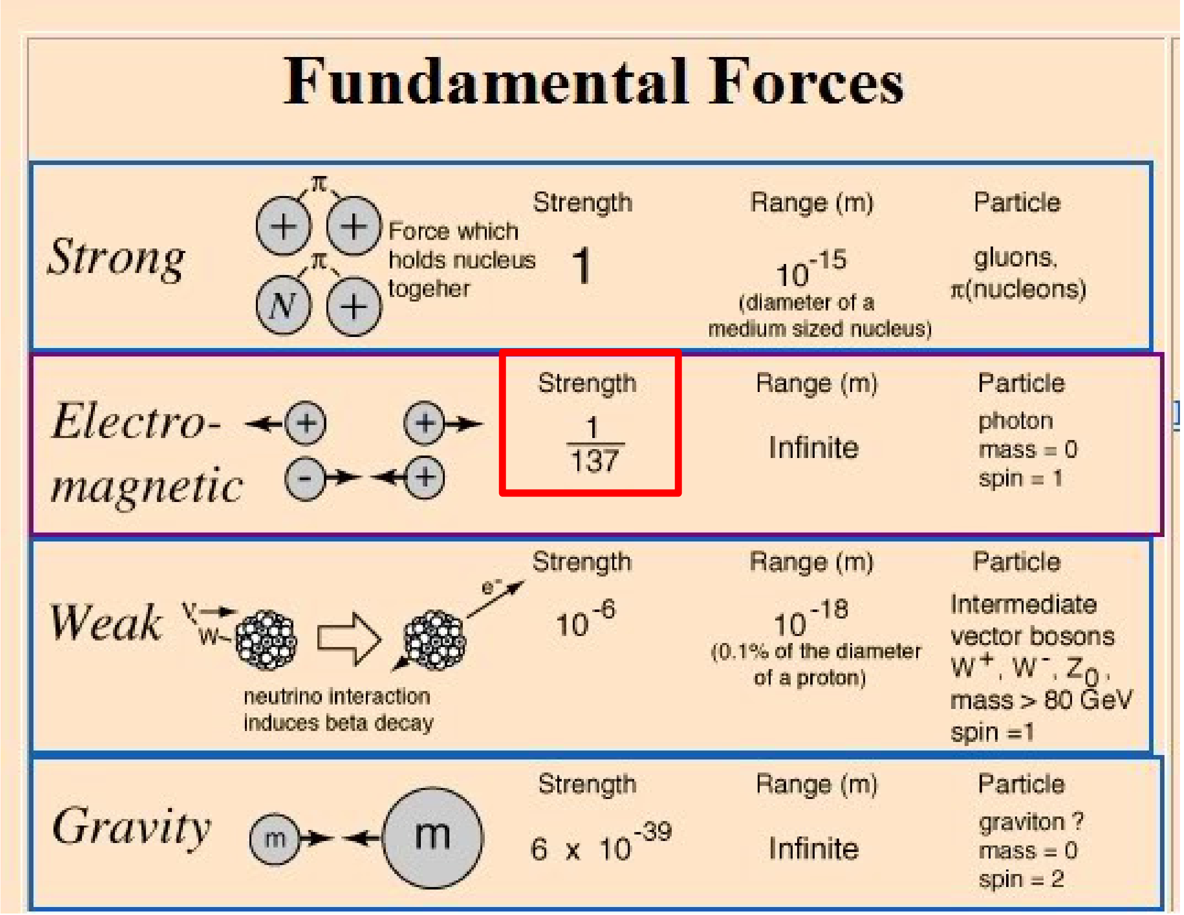
Quantity	Symbol	Numerical value	Unit
speed of light in vacuum	c, c_0	299 792 458 (exact)	$\mathrm{m\ s^{-1}}$
magnetic constant	μ_0	$4\pi \times 10^{-7}$ (exact)	$\mathrm{N\ A^{-2}}$
electric constant $1/\mu_0 c^2$	ϵ_0	$8.854\,187\,817... \times 10^{-12}$	$\mathrm{F\ m^{-1}}$
Newtonian constant of gravitation	G	6.67~~4 28(67)~~ $\times 10^{-11}$ 384(80)	$\mathrm{m^3\ kg^{-1}\ s^{-2}}$
Planck constant	h	6.626 06~~8 96(33)~~ $\times 10^{-34}$	J s 957(29)
$h/2\pi$	$\hbar$	1.054 571 ~~628(53)~~ $\times 10^{-34}$	J s 726(47)
elementary charge	e	1.602 176 ~~487(40)~~ $\times 10^{-19}$	C 565(35)
fine-structure constant $e^2/4\pi\epsilon_0\hbar c$	α	7.297 352 5~~376(50)~~ $\times 10^{-3}$ 698(24)	
inverse fine-structure constant	α^{-1}	137.035 999 ~~679(94)~~ 074(44)	
Rydberg constant $\alpha^2 m_e c/2h$	R_∞	10 973 731.568 5~~27(73)~~	$\mathrm{m^{-1}}$ 39(55)
Bohr radius $\alpha/4\pi R_\infty$	a_0	0.529 177 2~~08 59(36)~~ $\times 10^{-10}$	m 1092(17)
Bohr magneton $e\hbar/2m_e$	μ_B	927.400 9~~15(23)~~ $\times 10^{-26}$	$\mathrm{J\ T^{-1}}$ 68(20)

http://www.nist.gov/pml/div684/constants-071911.cfm

The New International System of Units based on Fundamental Constants



$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c}$$



Fundamental Forces

		Strength	Range (m)	Particle
Strong	Force which holds nucleus togeher	1	10^{-15} (diameter of a medium sized nucleus)	gluons, π(nucleons)
Electro-magnetic		$\frac{1}{137}$	Infinite	photon mass = 0 spin = 1
Weak	neutrino interaction induces beta decay	10^{-6}	10^{-18} (0.1% of the diameter of a proton)	Intermediate vector bosons W^+, W^-, Z_0, mass > 80 GeV spin =1
Gravity		6×10^{-39}	Infinite	graviton ? mass = 0 spin = 2

http://alpcentauri.info/fundamental_forces.html

Search for the variation of the fine-structure constant α

$$\boxed{\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c}}$$

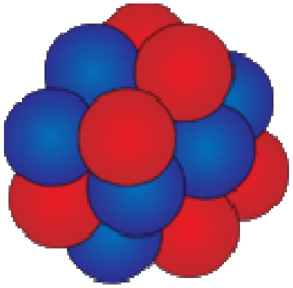
α~1/137

Life needs very specific fundamental constants!

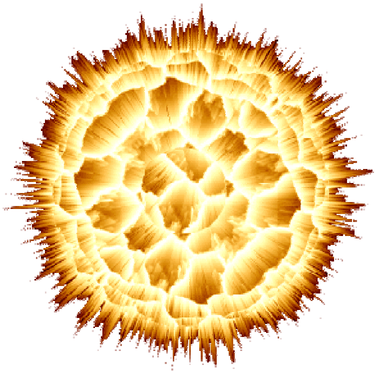
If α is too big → small nuclei can not exist

Electric repulsion of the protons **>** strong nuclear binding force

$\alpha \sim 1/137$



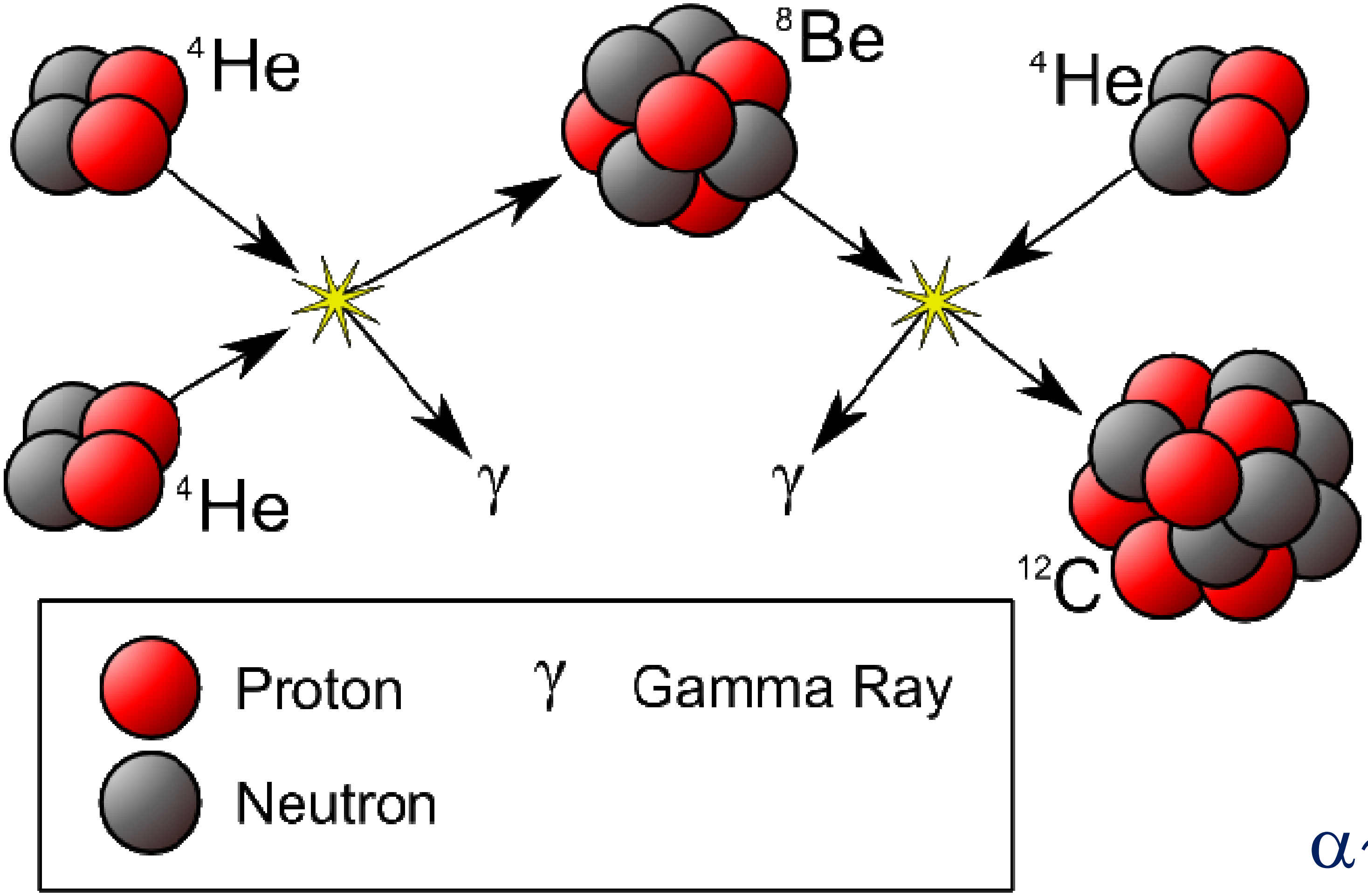
Carbon-12



$\alpha \sim 1/10$

will blow carbon apart

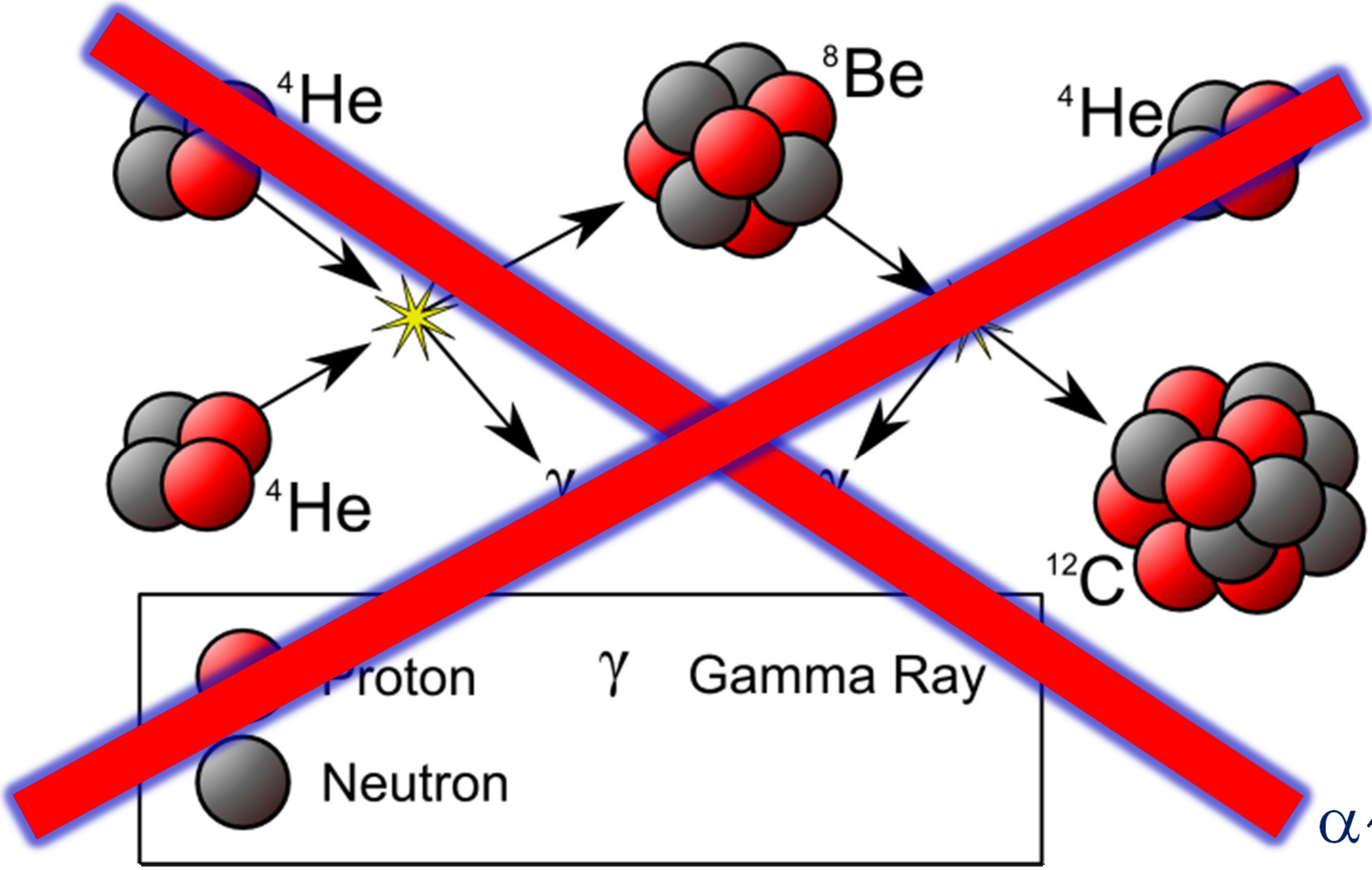
Life needs very specific fundamental constants!



$\alpha \sim 1/137$

Nuclear reaction in stars are particularly sensitive to α.
If α were different by 4%: **no carbon produced by stars**. No life.

Life needs very specific fundamental constants!

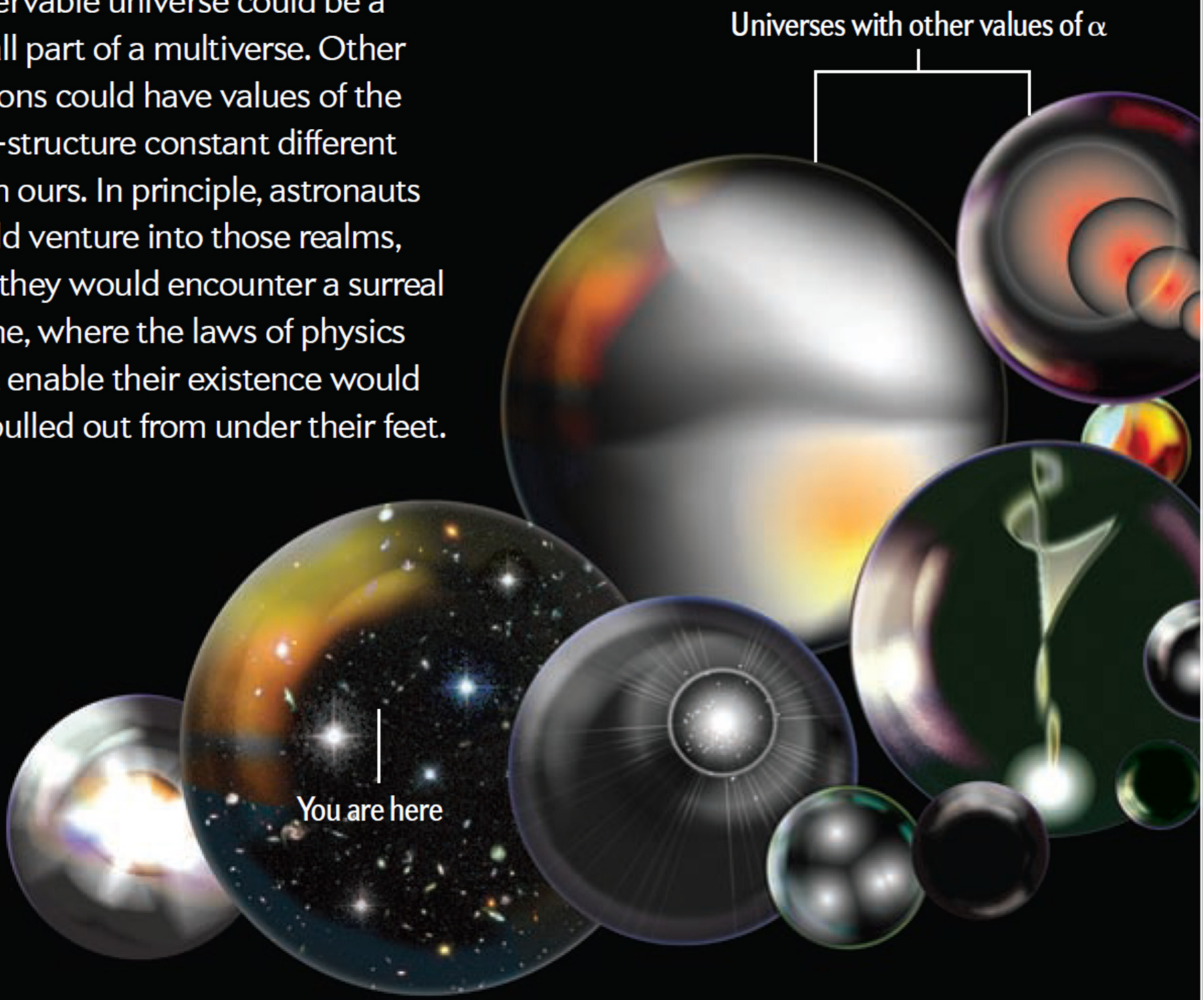


$\alpha \sim 1/132$

No carbon produced by stars:
No life in the Universe

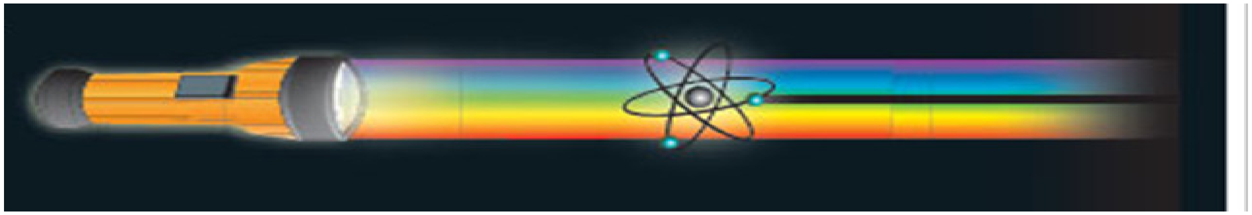
Across the Universes

In the grand scheme of things, our observable universe could be a small part of a multiverse. Other regions could have values of the fine-structure constant different from ours. In principle, astronauts could venture into those realms, but they would encounter a surreal scene, where the laws of physics that enable their existence would be pulled out from under their feet.

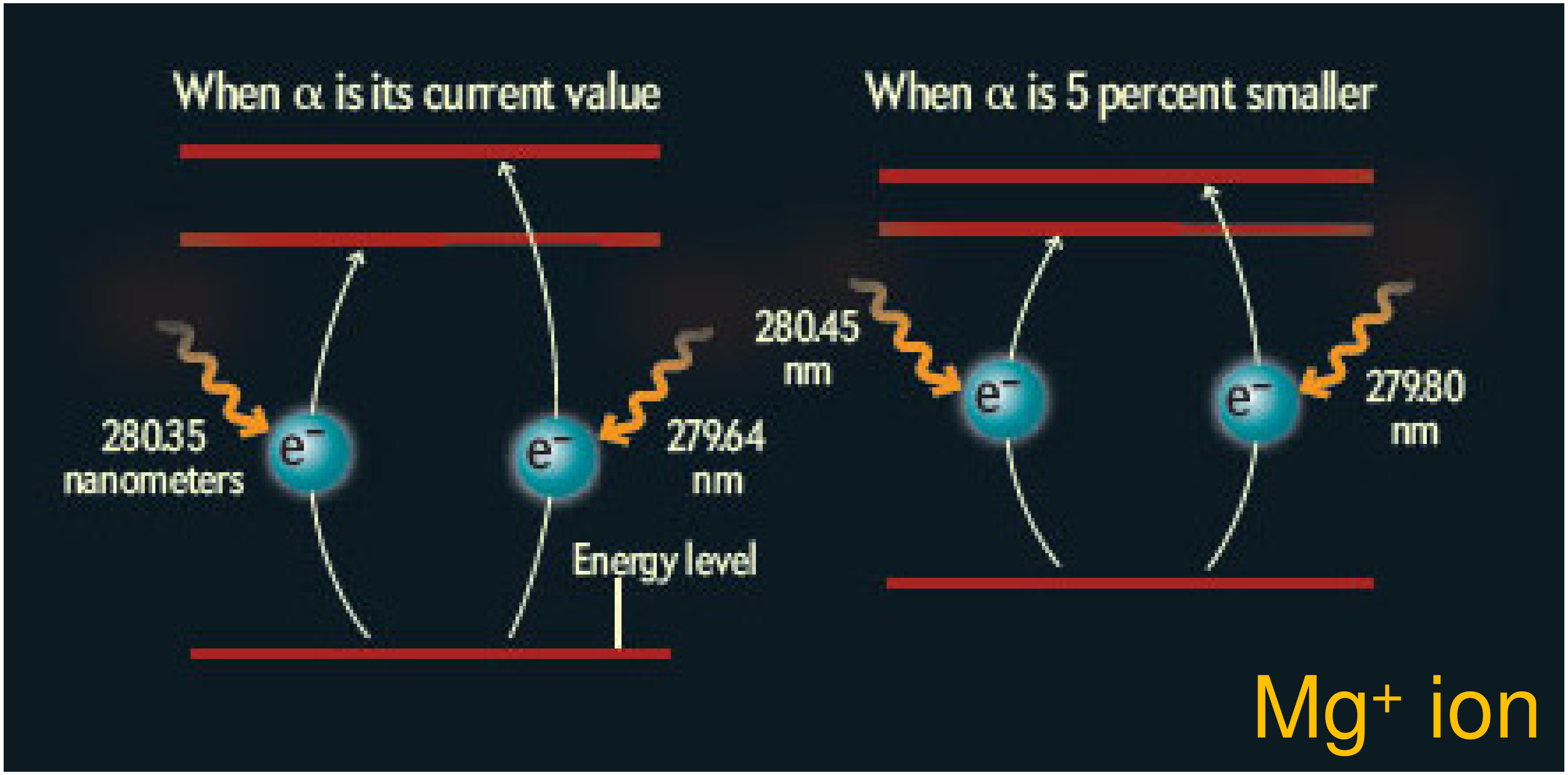


Scientific American: A Matter of Time 23, 60 (2014)

How to test if α changed with time?

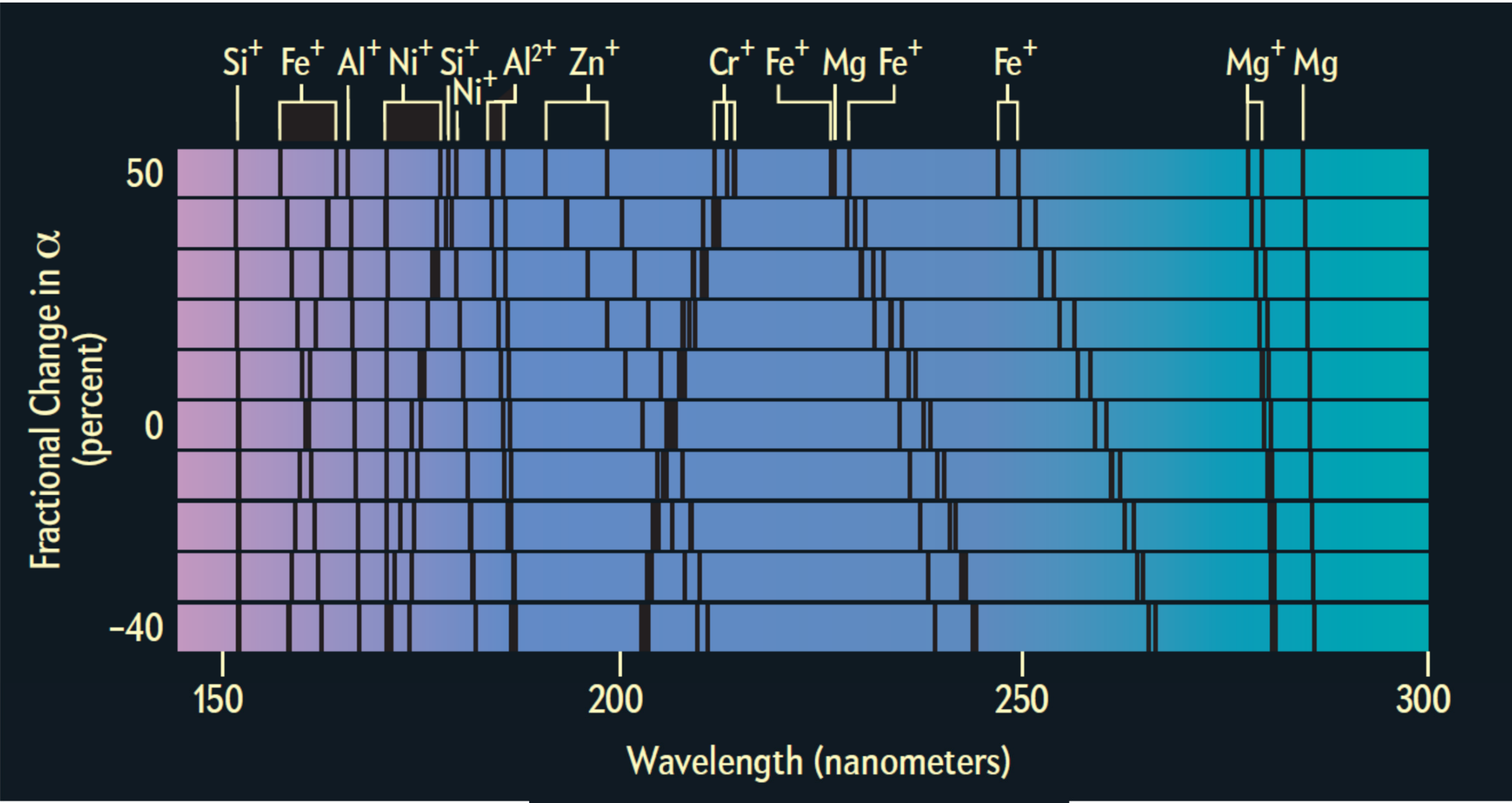


Atomic transition energies depend on α^2



Mg$^+$ ion

Scientific American Time **21**, 70 - 77 (2012)



Simulated spectra show how changing α affects the absorption of near-ultraviolet light by various atomic species. The horizontal black lines represent absorbed wavelengths. Each type of atom or ion has a unique pattern of lines.

Scientific American: A Matter of Time 23, 60 (2014)

Quasar

Quasar: "quasi-stellar radio source":

Quasar: extremely bright source, luminosity can be 100 times greater than that of the Milky Way

Compact region in the center of a massive galaxy surrounding a central supermassive (hundreds of thousands to billions of solar masses) black hole.

NASA/AP Photo, ESA/Hubble & NASA - http://www.spacetelescope.org/images/potw1403a/

Looking for Changes in Quasar Light

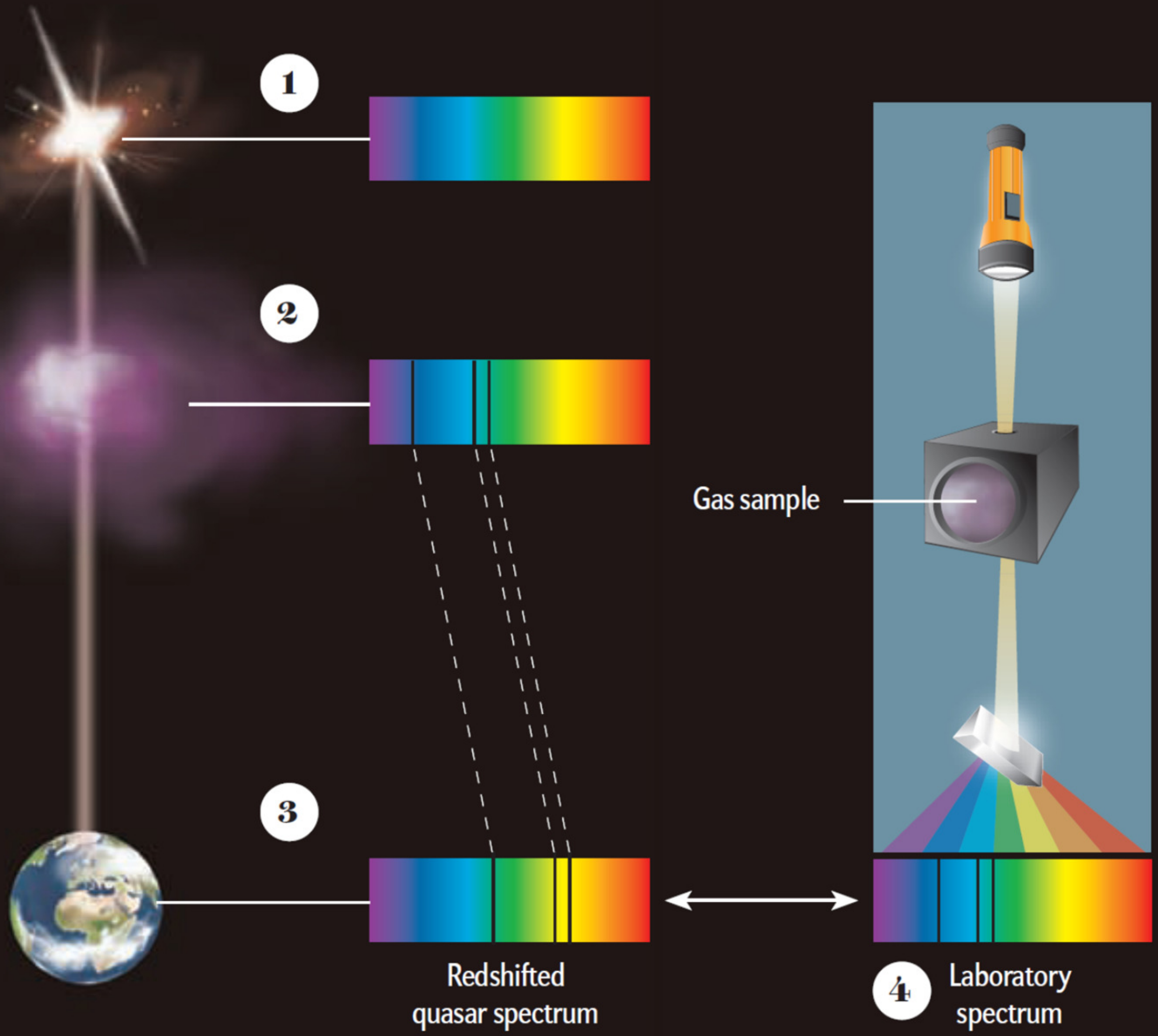
A distant gas cloud, backlit by a quasar, gives astronomers an opportunity to probe the process of light absorption—and therefore the value of the fine-structure constant—earlier in cosmic history.

① Light from a quasar begins its journey to Earth billions of years ago with a smooth spectrum.

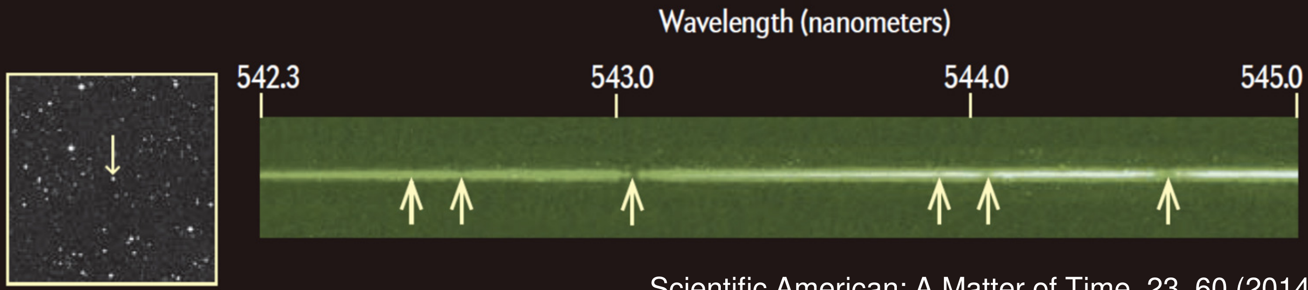
② On its way, the light passes through one or more gas clouds. The gas blocks specific wavelengths, creating a series of black lines in the spectrum. For studies of the fine-structure constant, astronomers focus on absorption by metals.

③ By the time the light arrives on Earth, the wavelengths of the lines have been shifted by cosmic expansion. The amount of shift indicates the distance of the cloud and, hence, its age.

④ The spacing of the spectral lines can be compared with values measured in the laboratory. A discrepancy suggests that the fine-structure constant used to have a different value.

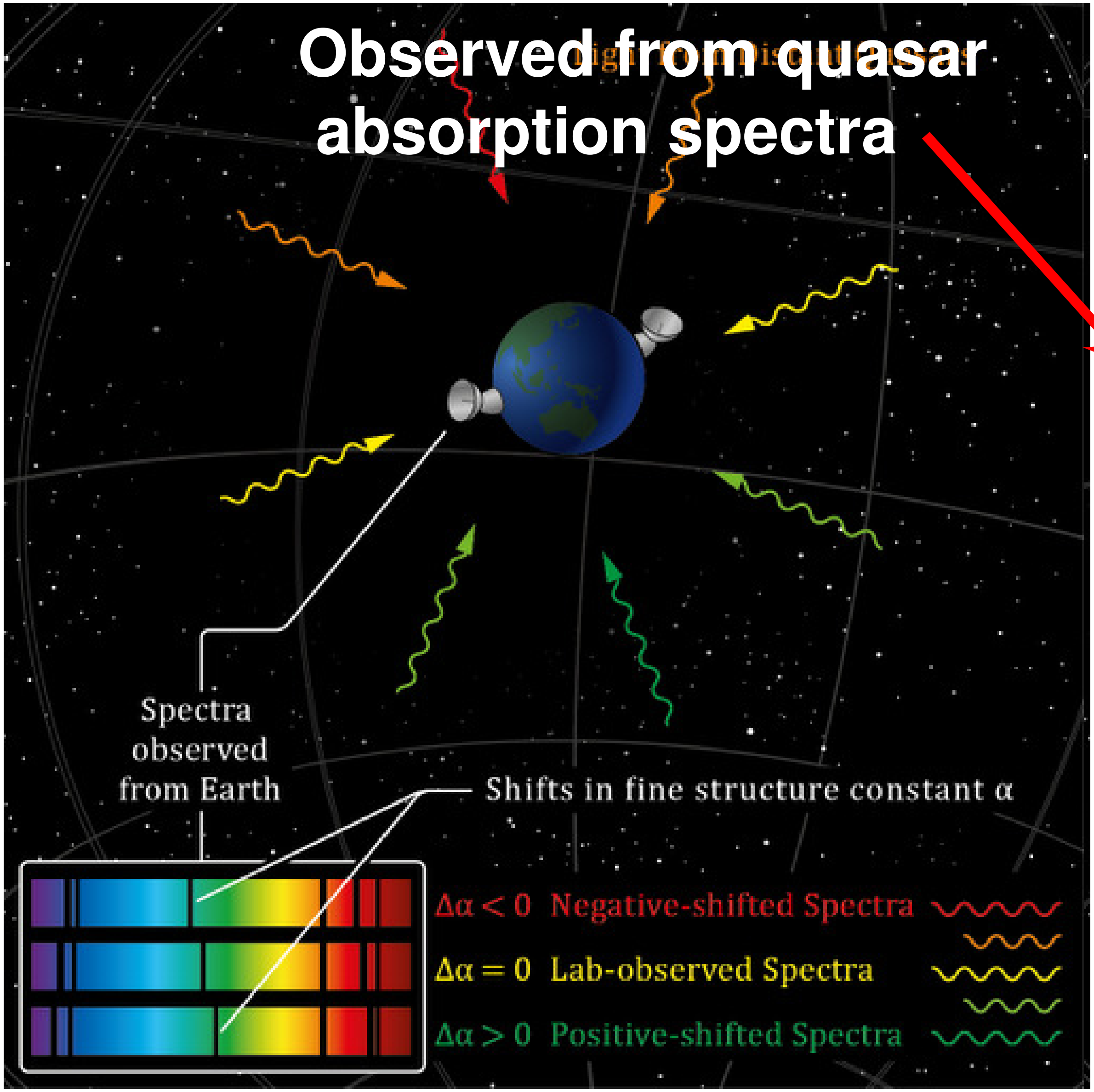


Quasar spectrum, taken at the European Southern Observatory's Very Large Telescope, shows absorption lines produced by gas clouds between the quasar (*arrow point at right*) and us. The position of the lines (*arrow points at far right*) indicates that the light passed through the clouds about 7.5 billion years ago.



Scientific American: A Matter of Time 23, 60 (2014)

Astrophysical searches for variation of fine-structure constant α



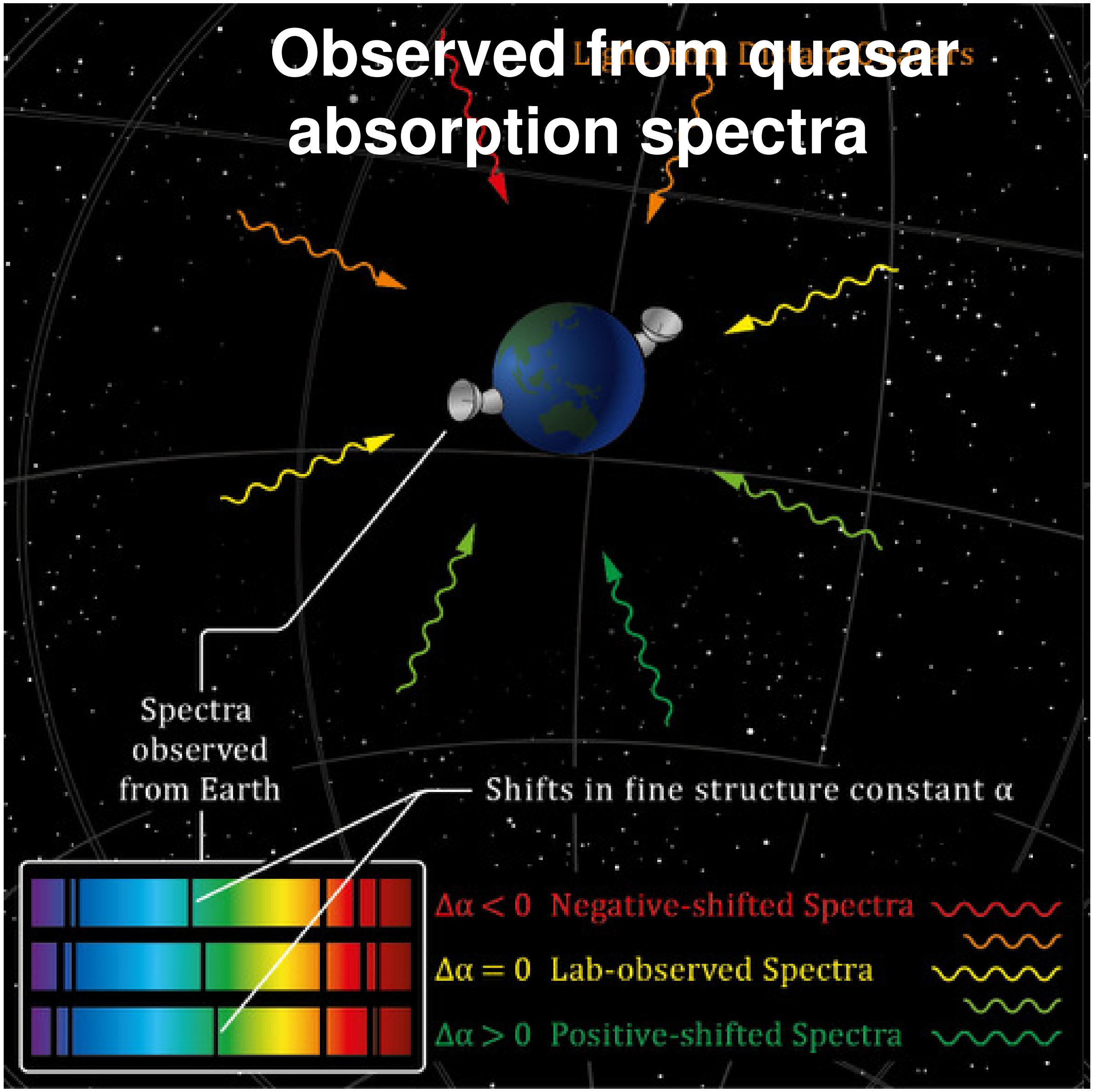
Observed from quasar absorption spectra

Laboratory frequency

$$E_Z = E_0 + q\left(\left(\frac{\alpha_Z}{\alpha_0}\right)^2 - 1\right)$$

Julian Berengut, UNSW, 2010

Astrophysical searches for variation of fine-structure constant α



Observed from quasar absorption spectra

Julian Berengut, UNSW, 2010

Conflicting results

$$\Delta\alpha/\alpha = -0.64(36)\times 10^{-5}$$

Murphy et al., 2007
Keck telescope, 143 systems,
23 lines, 0.2<z<4.2

$$\Delta\alpha/\alpha = -0.06(0.06)\times 10^{-5}$$

Srianand et al, 2004: VL telescope, 23 systems, 12 lines, Fe II, Mg I, Si II, Al II, 0.4<*z<2.3*

Molaro et al., 2007

$$\Delta\alpha/\alpha = -0.12(1.8)\times 10^{-6}$$

Z=1.84

$$\Delta\alpha/\alpha = 5.7(2.7)\times 10^{-6}$$

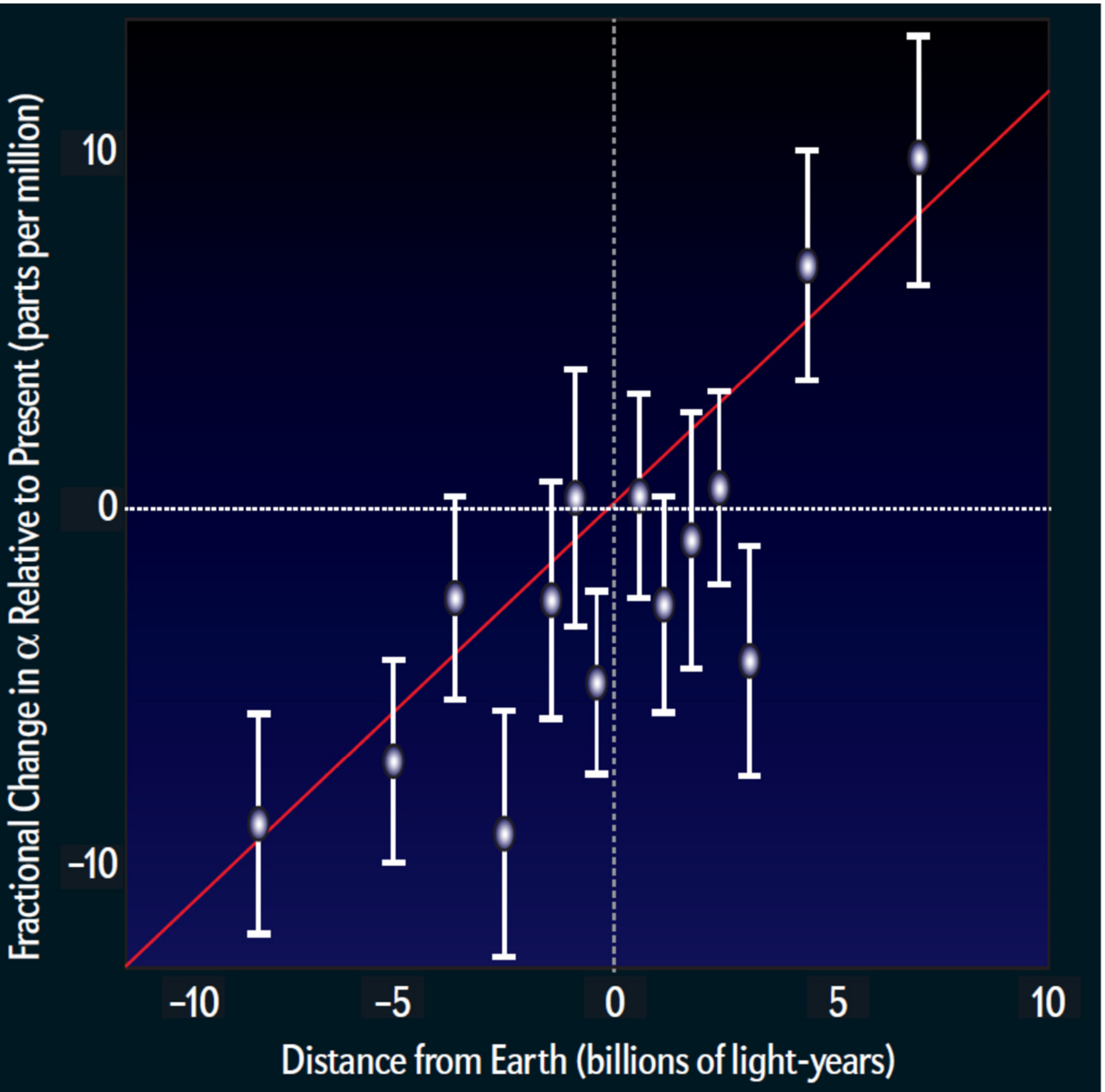
PRL 107, 191101 (2011) PHYSICAL REVIEW LETTERS week ending 4 NOVEMBER 2011

Indications of a Spatial Variation of the Fine Structure Constant

J. K. Webb,[1] J. A. King,[1] M. T. Murphy,[2] V. V. Flambaum,[1] R. F. Carswell,[3] and M. B. Bainbridge[1]

A Special Axis

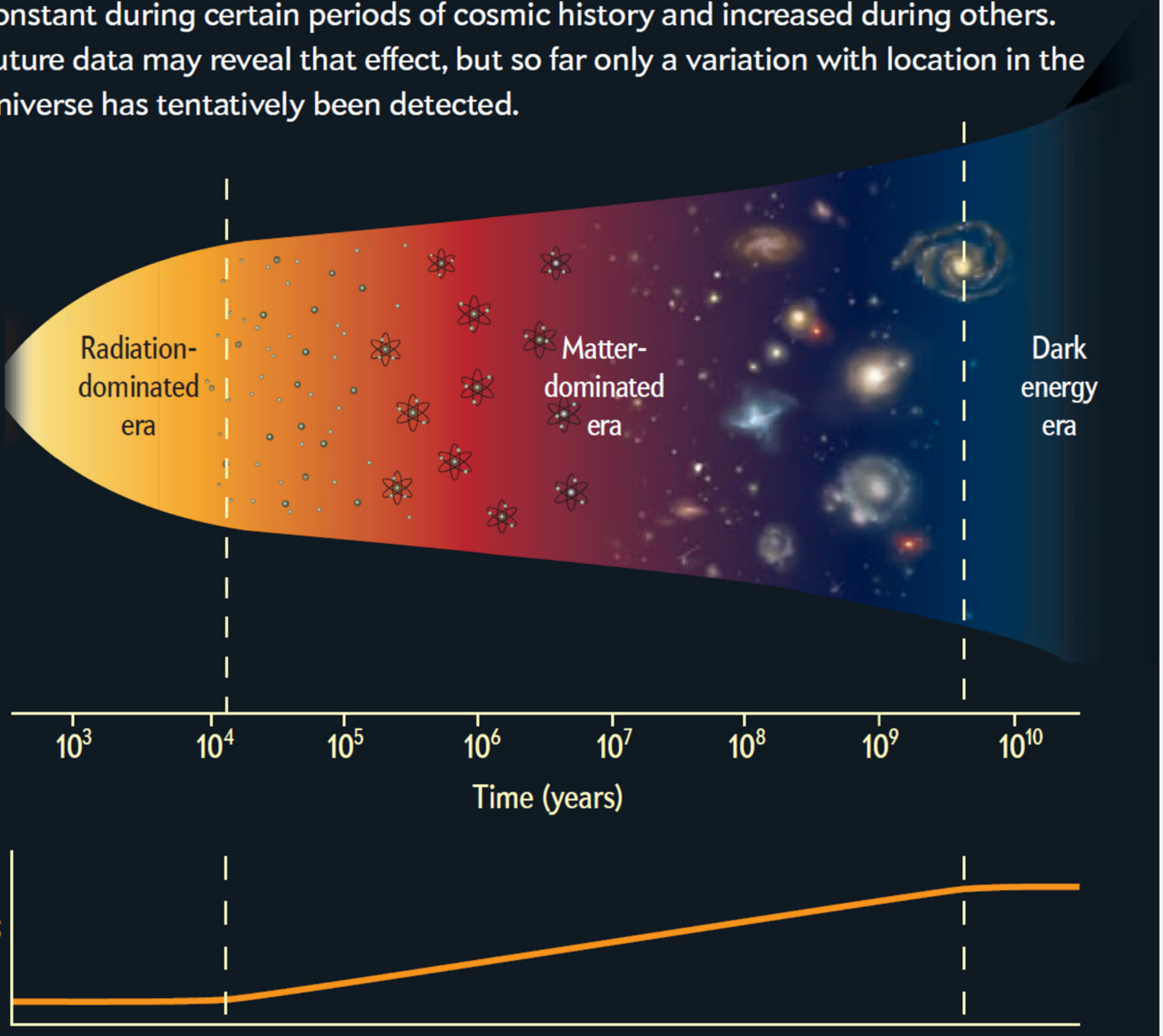
Alpha changes the most along an apparently "special" axis through the universe—increasing at greater distances from Earth and decreasing in the opposite direction (shown as negative distances). Remote regions of our universe may have quite different values.



Scientific American: A Matter of Time 23, 60 (2014)

Sometimes It Changes, Sometimes Not

According to the authors' theory, the fine-structure constant should have stayed constant during certain periods of cosmic history and increased during others. Future data may reveal that effect, but so far only a variation with location in the universe has tentatively been detected.



Scientific American: A Matter of Time 23, 60 (2014)

Can we look for variation of fundamental constants in a lab?

YES!

NEED ULTRA-PRECISE ATOMIC CLOCKS

Laboratory searches for variation of fundamental constants

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c}$$

Measure the ratio R of two clock frequencies

$$R = \frac{\omega_1}{\omega_2} = A \times [\alpha]^{K_\alpha} \times \left[\frac{m_e}{m_p}\right]^{K_e} \times \left[\frac{m_q}{\Lambda_{QCD}}\right]^{K_q}$$

Ratio of
mass of electron to
mass of the proton

Ratio of
mass of quark to
quantum
chromodynamics
scale

Laboratory searches for variation of fundamental constants

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c}$$

Measure the ratio R of two clock frequencies

$$R = \frac{\omega_1}{\omega_2} = A \times [\alpha]^{K_\alpha} \times \left[\frac{m_e}{m_p}\right]^{K_e} \times \left[\frac{m_q}{\Lambda_{QCD}}\right]^{K_q}$$

Measure the ratio R of two optical clock frequencies: sensitive only to α-variation

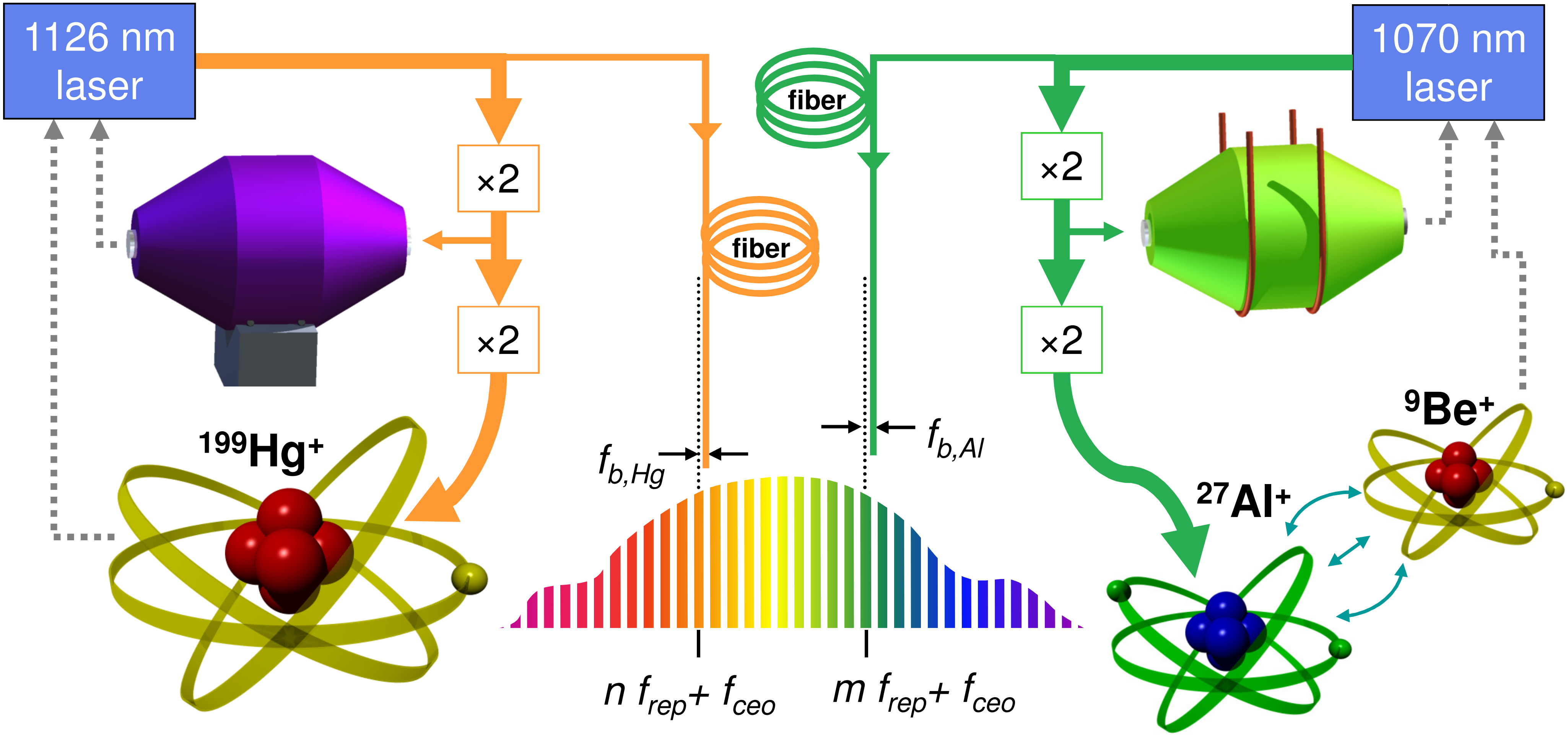
$$\omega = \omega_0 + q\left(\frac{\alpha^2}{\alpha_0^2} - 1\right)$$

Calculate with good precision

from Jim Bergquist’ tal

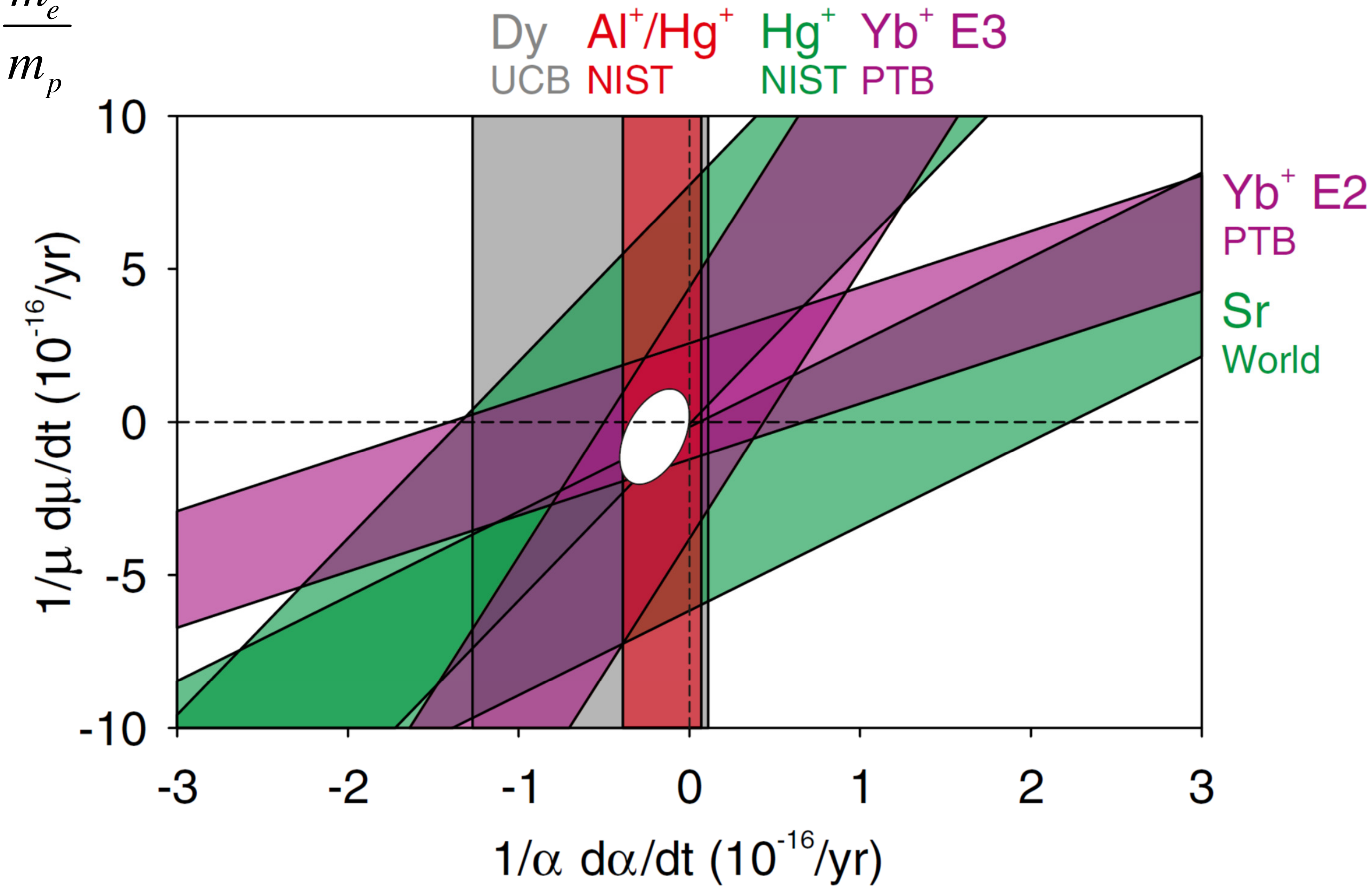
Al+/Hg+ Comparison

Frequency-comb locked to Hg+ measure beat with Al+



Science 319, 1808 (200

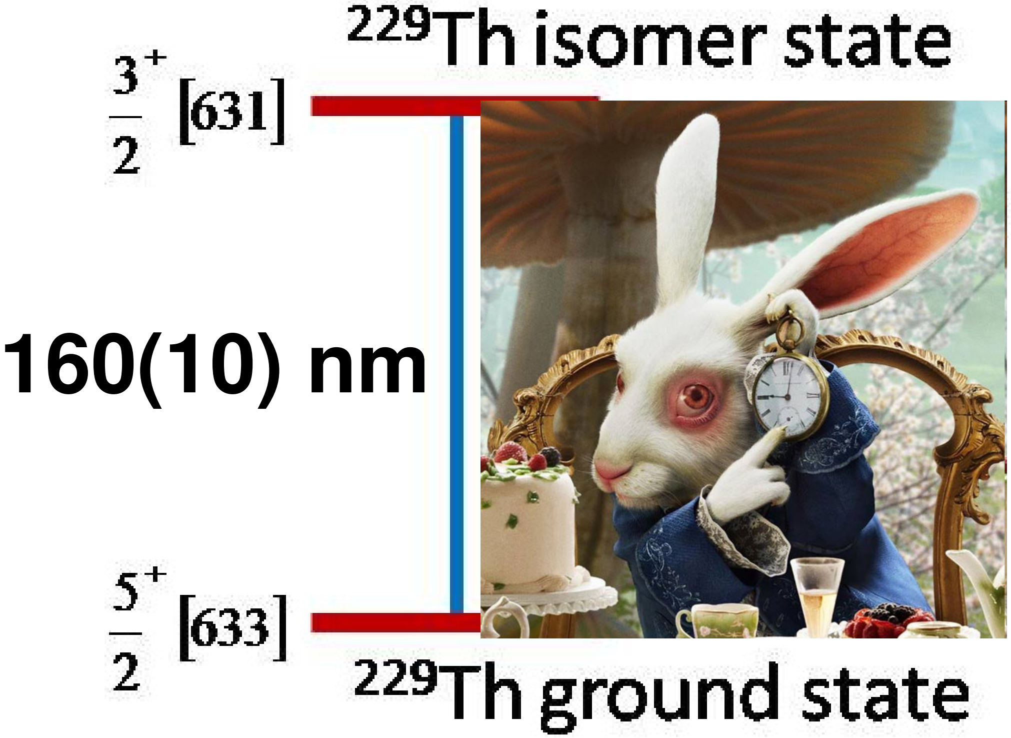
$$\mu = \frac{m_e}{m_p}$$



Constraints on temporal variations of α and μ from comparisons of atomic transition frequencies. Phys. Rev. Lett.113, 210802 (2014)

Th^{3+} nuclear clock

Th nuclear clock:
Nuclear isomer transition in 229 Thorium has been suggested as an etalon transition in a new type of optical frequency standard.



^{229}Th isomer state

$\frac{3}{2}^{+}$ [631]

160(10) nm

$\frac{5}{2}^{+}$ [633]

^{229}Th ground state

Other applications of atomic clocks

nature physics

LETTERS

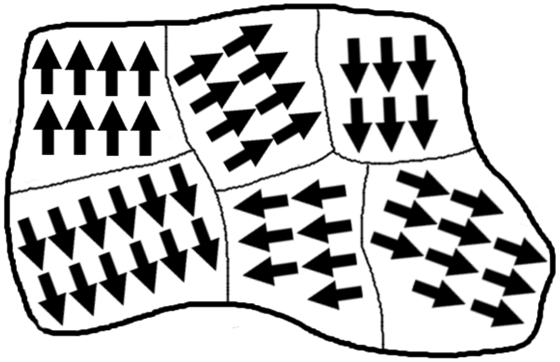
PUBLISHED ONLINE: 17 NOVEMBER 2014 | DOI: 10.1038/NPHYS3137

Hunting for topological dark matter with atomic clocks

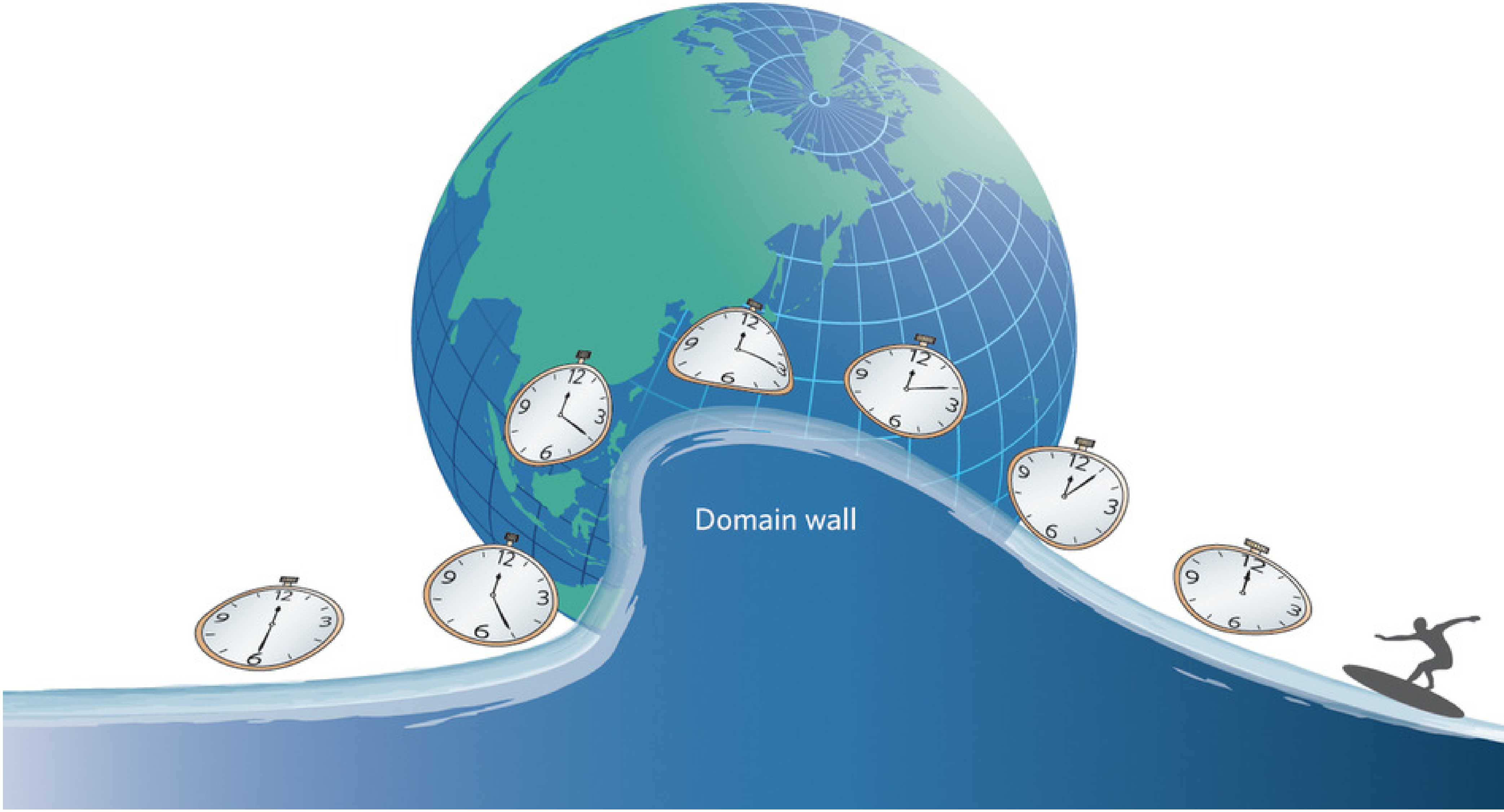
A. Derevianko[1]* and M. Pospelov[2,3]

Instead of the usual assumption of a mostly homogenous distribution, dark matter might be clumped to form point-like monopoles, one-dimensional strings or two-dimensional sheets that are called domain walls.

Such topological dark matter may have formed when the early Universe cooled down after the Big Bang, similar to the domains formed in a ferromagnet below its Curie temperature.



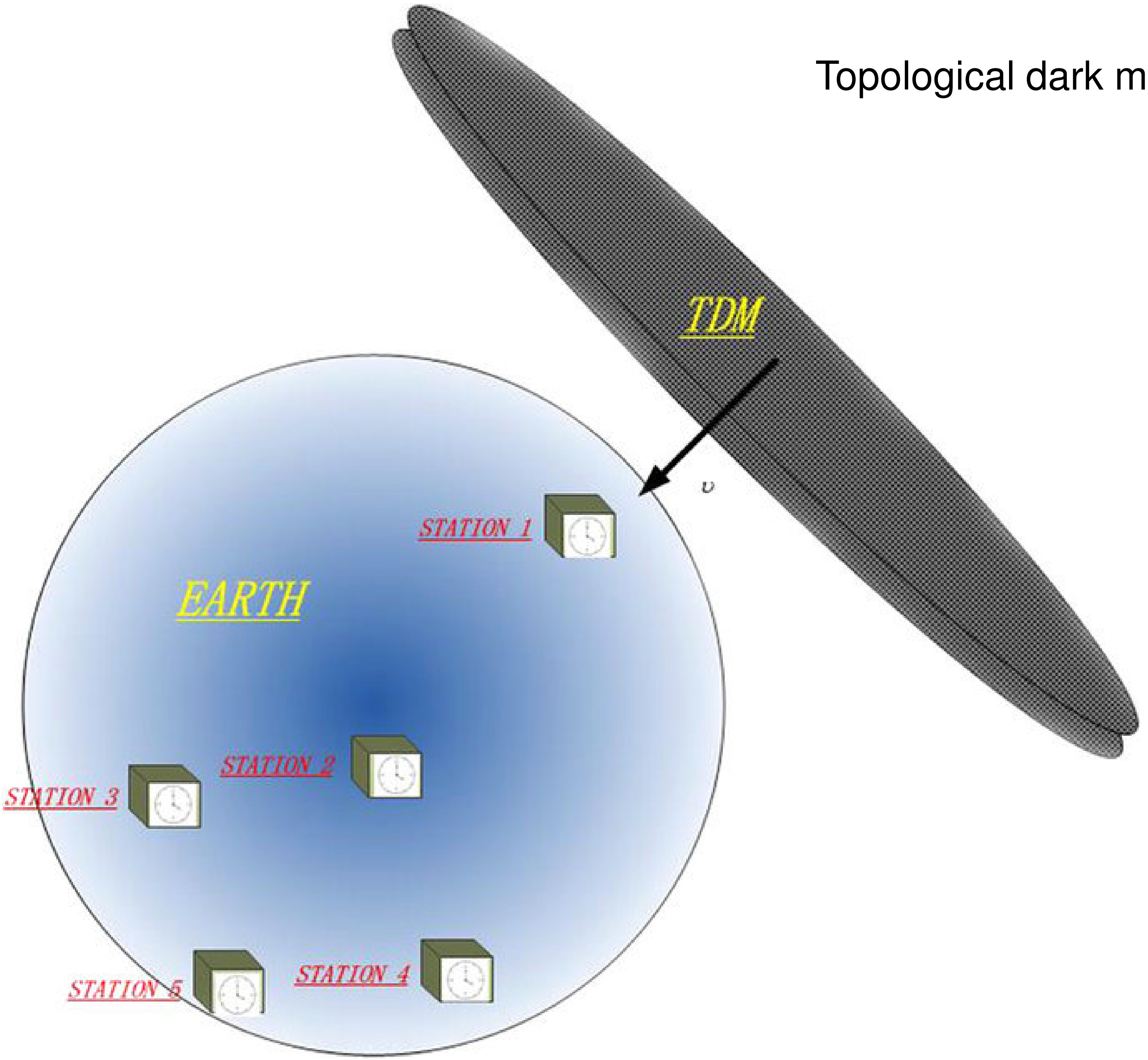
If we assume that the size of the defects is comparable to the size of the Earth or smaller, and if they occur frequently enough so that the Earth will pass through one of them we can detect this with atomic clocks.



Topological dark matter may be detected by measuring changes in the synchronicity of a global network of atomic clocks, such as the Global Positioning System, as the Earth passes through the domain wall.

Nature Physics **10**, 906 (2014)

Topological dark matter



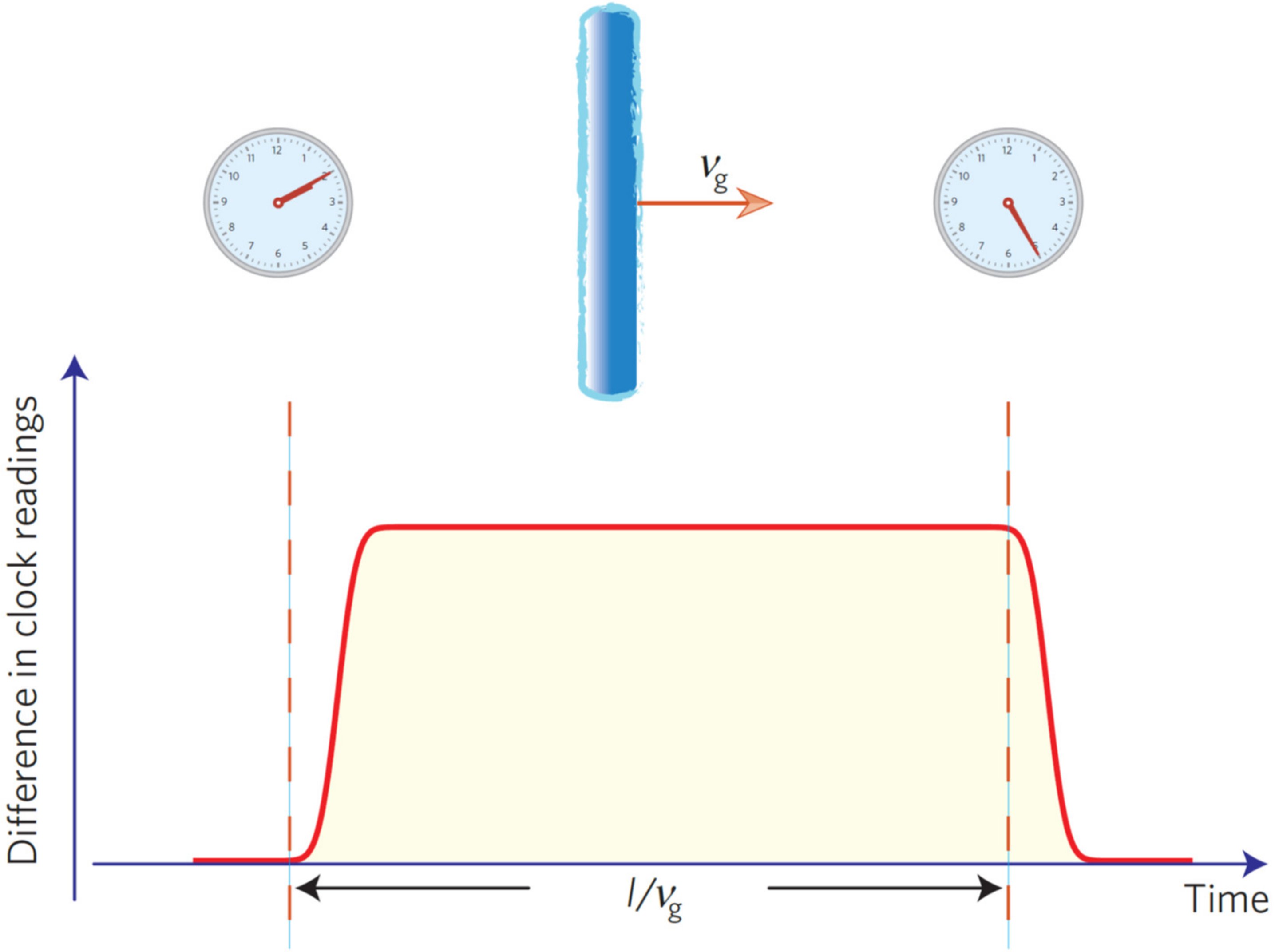


Figure 1 | Concept of a dark-matter search using atomic clocks. By monitoring time discrepancies between two spatially separated clocks one could search for the passage of topological defects, such as the domain wall pictured here.

A. Derevianko and M. Pospelov, Nature Phys. 10, 933 (2014)

Atomic clocks for design of absolute gravimeters and gravity gradiometers for geophysical monitoring and research

Clock can measure difference in height (gravitational redshift)

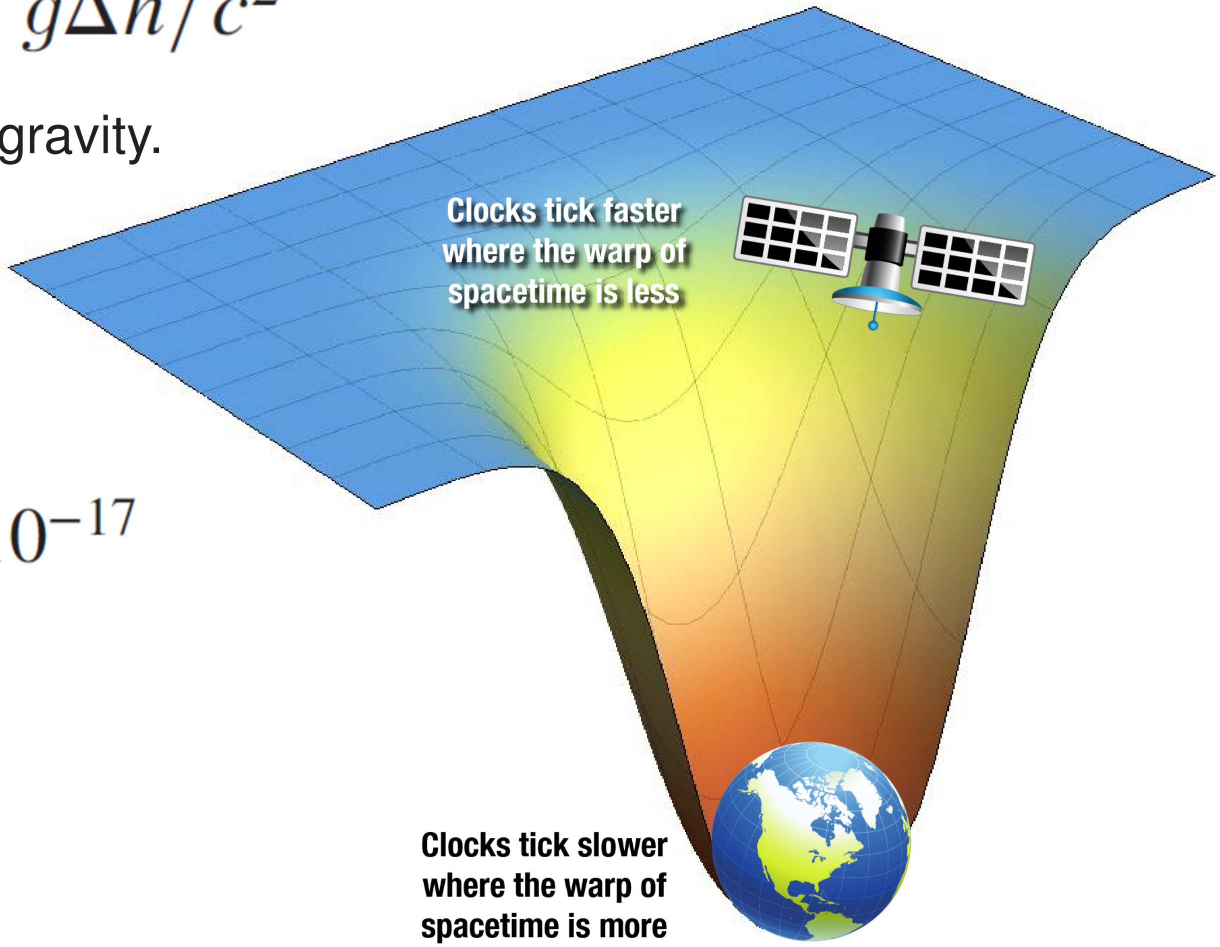
As predicted by relativity and the equivalence principle, if a gravitational potential difference exists between a source (one clock) and an observer (another clock, otherwise identical), the two clocks run at different rates.

On the surface of the Earth a clock that is higher by Δh than another

clock runs faster by $\delta f / f_0 = g \Delta h / c^2$

where g is the local acceleration of gravity.

$$\Delta h = 10 \text{ cm}, \quad \delta f / f_0 \simeq 10^{-17}$$



Optical Clocks and Relativity. *Science*. Sept. 24, 2010: Comparing two “quantum logic” clocks with Al+ trapped ions

Two time dilation effects:

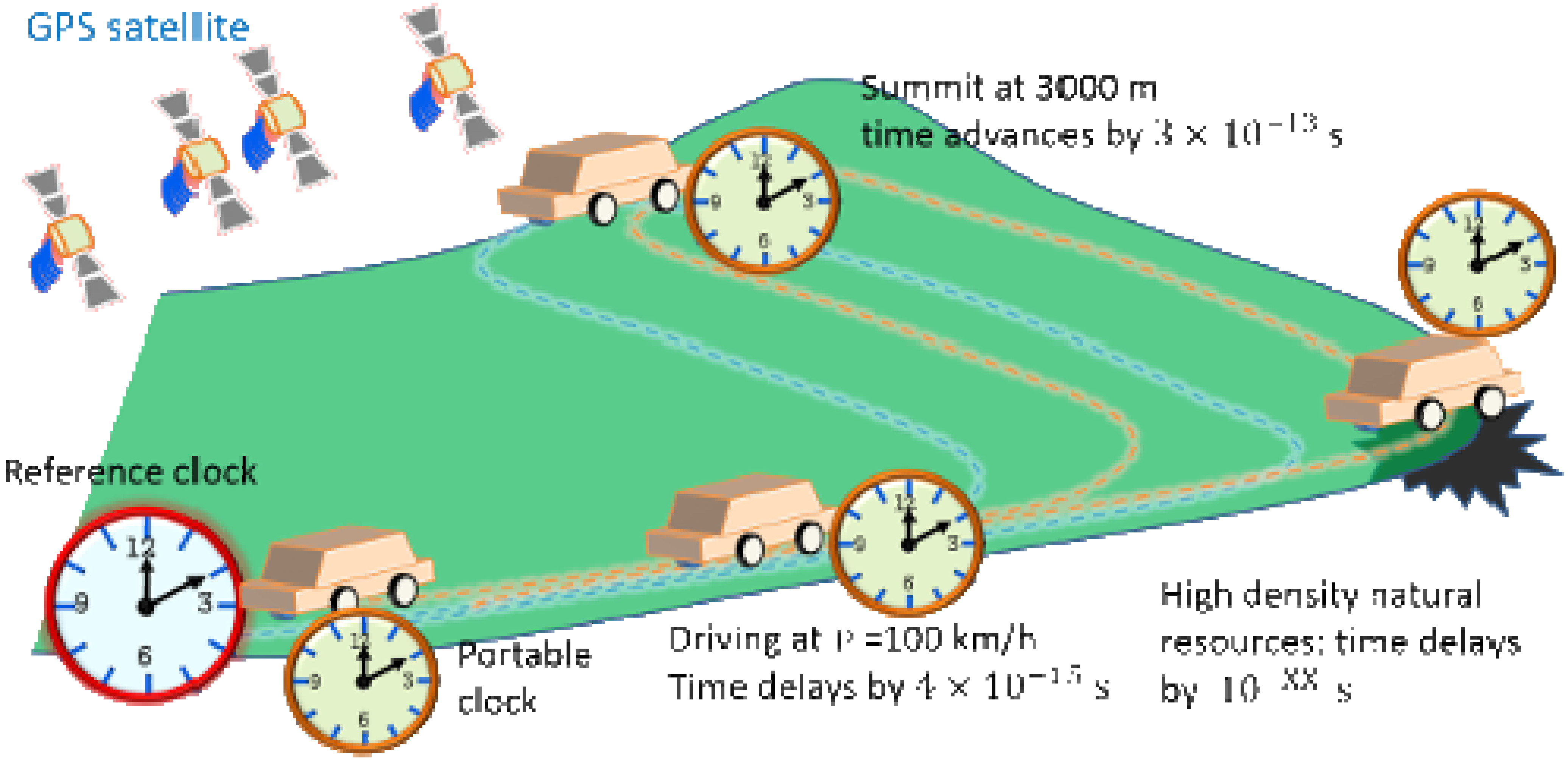
(1) Time passes faster at higher elevations—a curious aspect of Einstein's theories of relativity that previously has been measured by comparing clocks on the Earth's surface and a high-flying rocket.

Physicists at the National Institute of Standards and Technology (NIST) have measured this effect at a more down-to-earth scale of 33 centimeters, or about 1 foot. Current clocks can detect tis effect to a few cm.

(2) Time passes more slowly when you move faster– clocks can test it for speeds at 10m/s (36 km/h).

http://www.nist.gov/public_affairs/releases/aluminum-atomic-clock_092310.cfm

Cryogenic optical-lattice clocks will enable mapping Earth's gravity via general relativity



Monitoring volcanoes with ground-based atomic clocks

http://phys.org/news/2015-06-volcanoes-ground-based-atomic-clocks.html