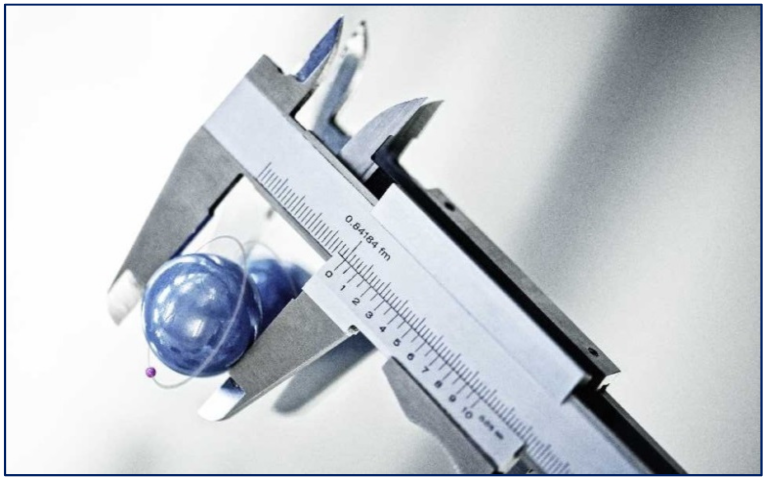
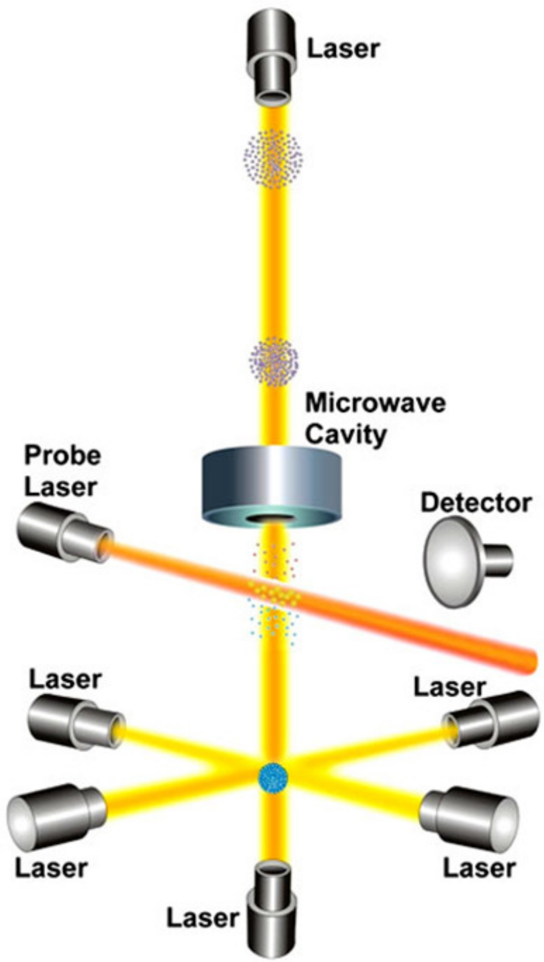
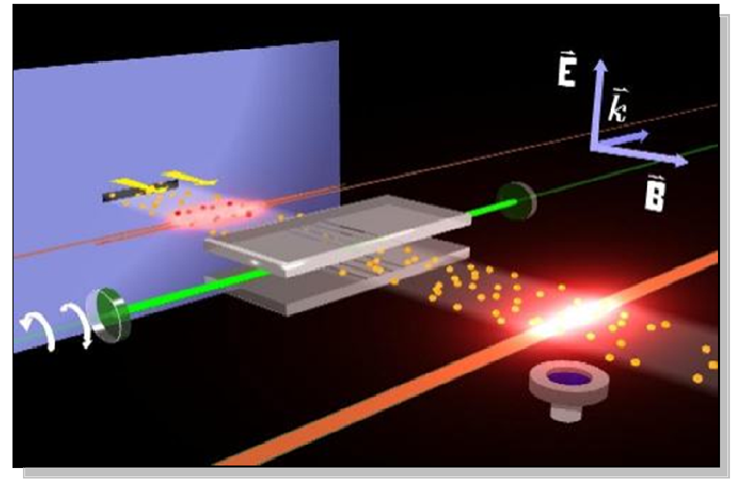
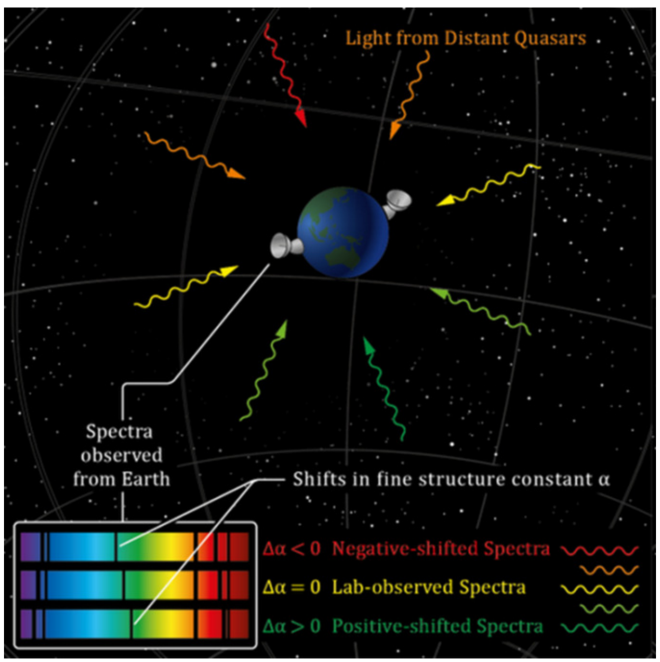
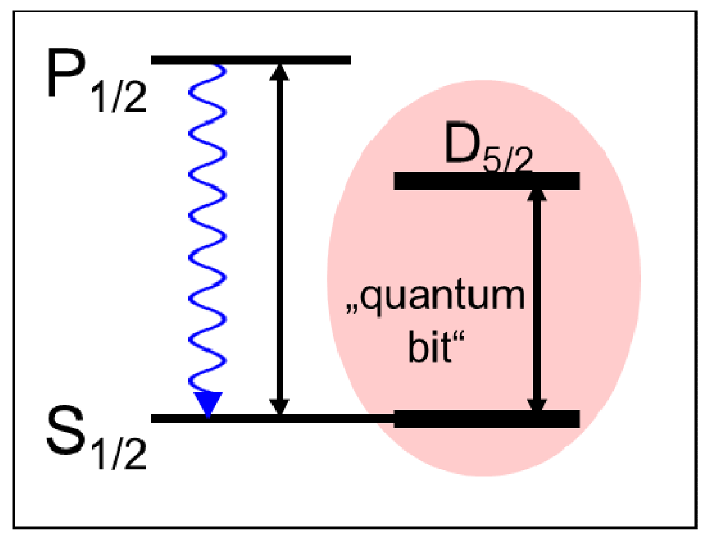
Modern Applications of Atomic Physics



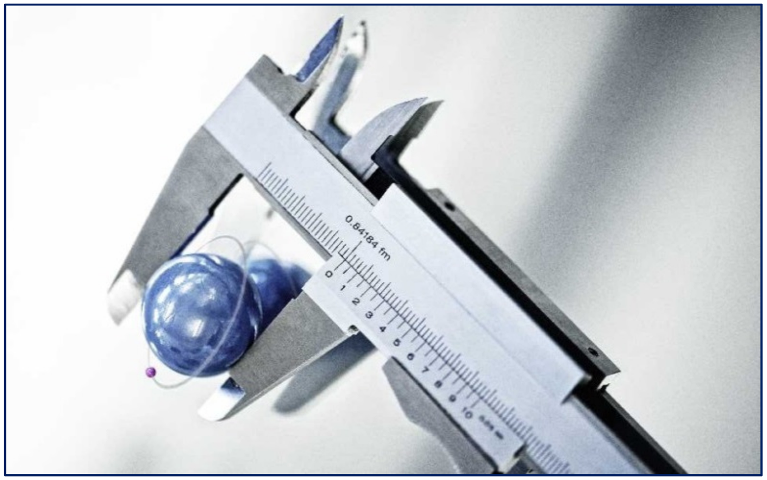


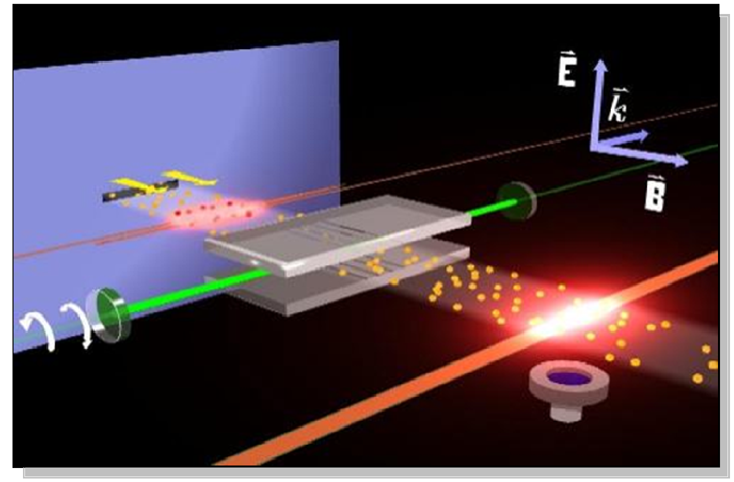


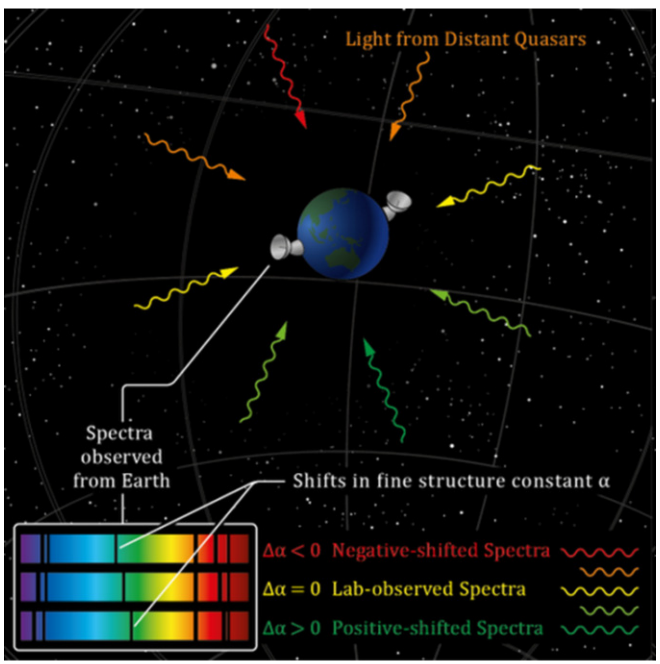


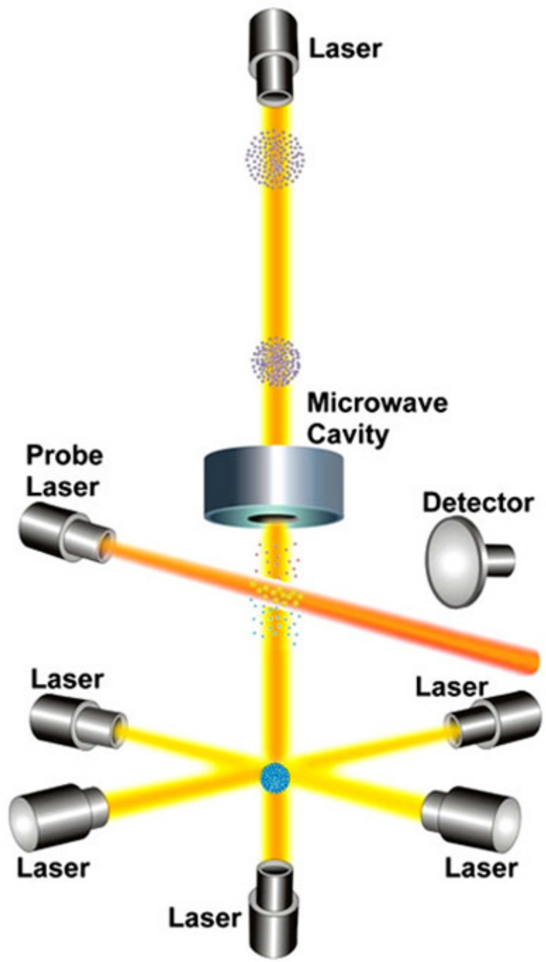


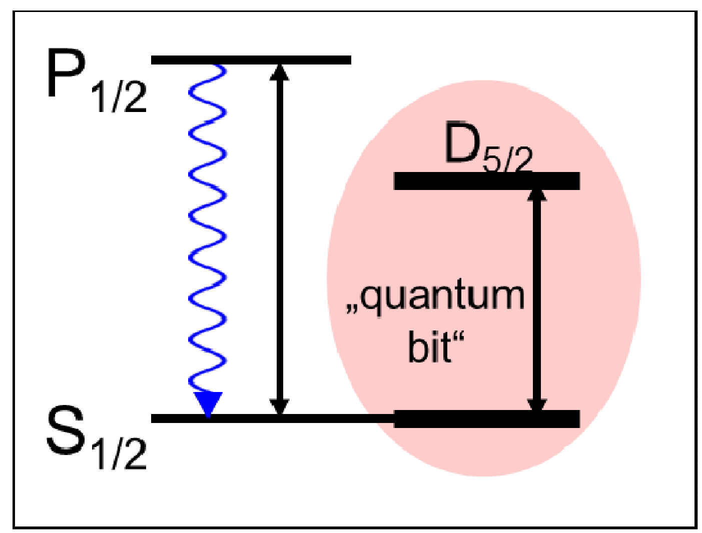
Modern Applications of Quantum Mechanics







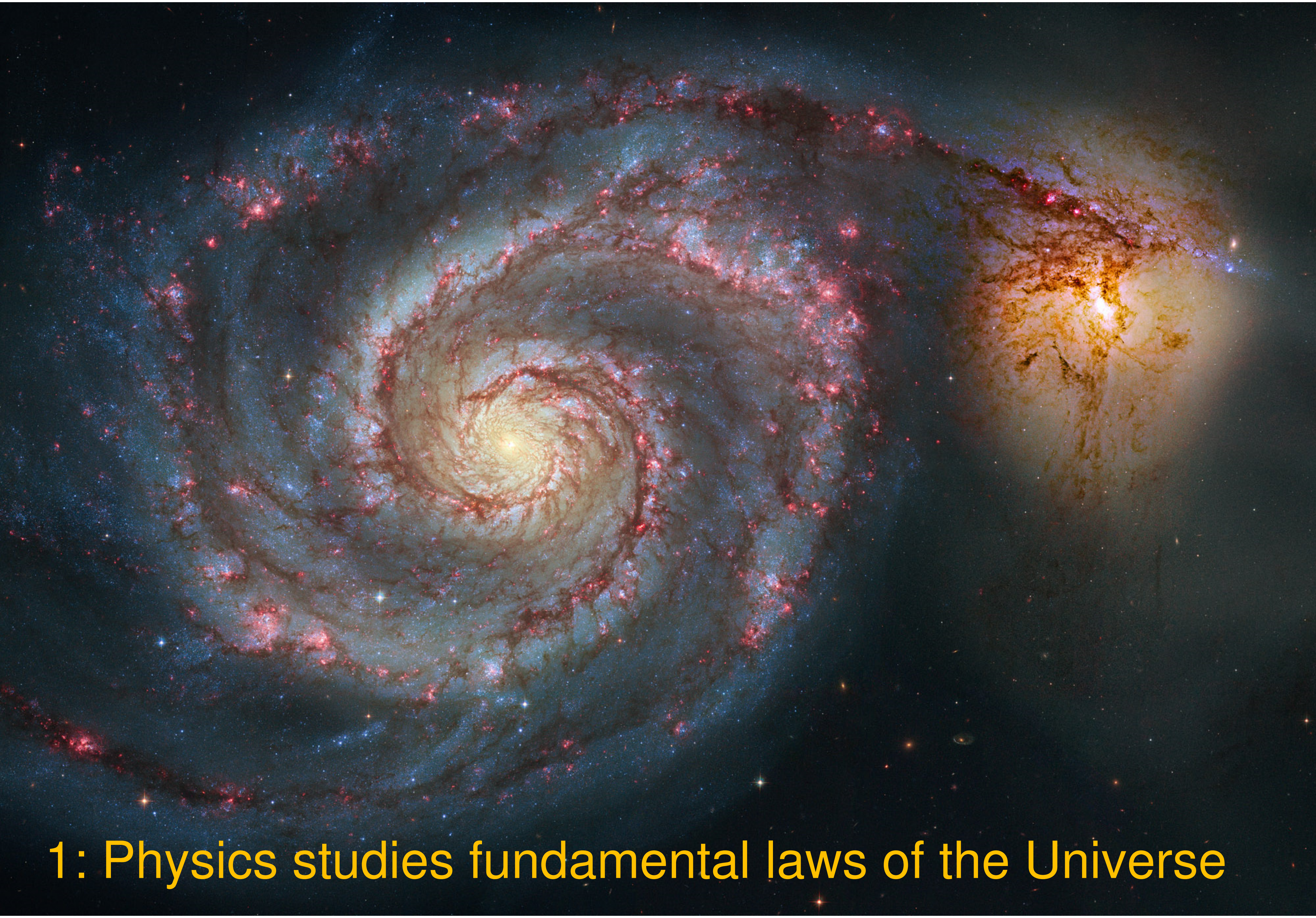




What is Physics for ?

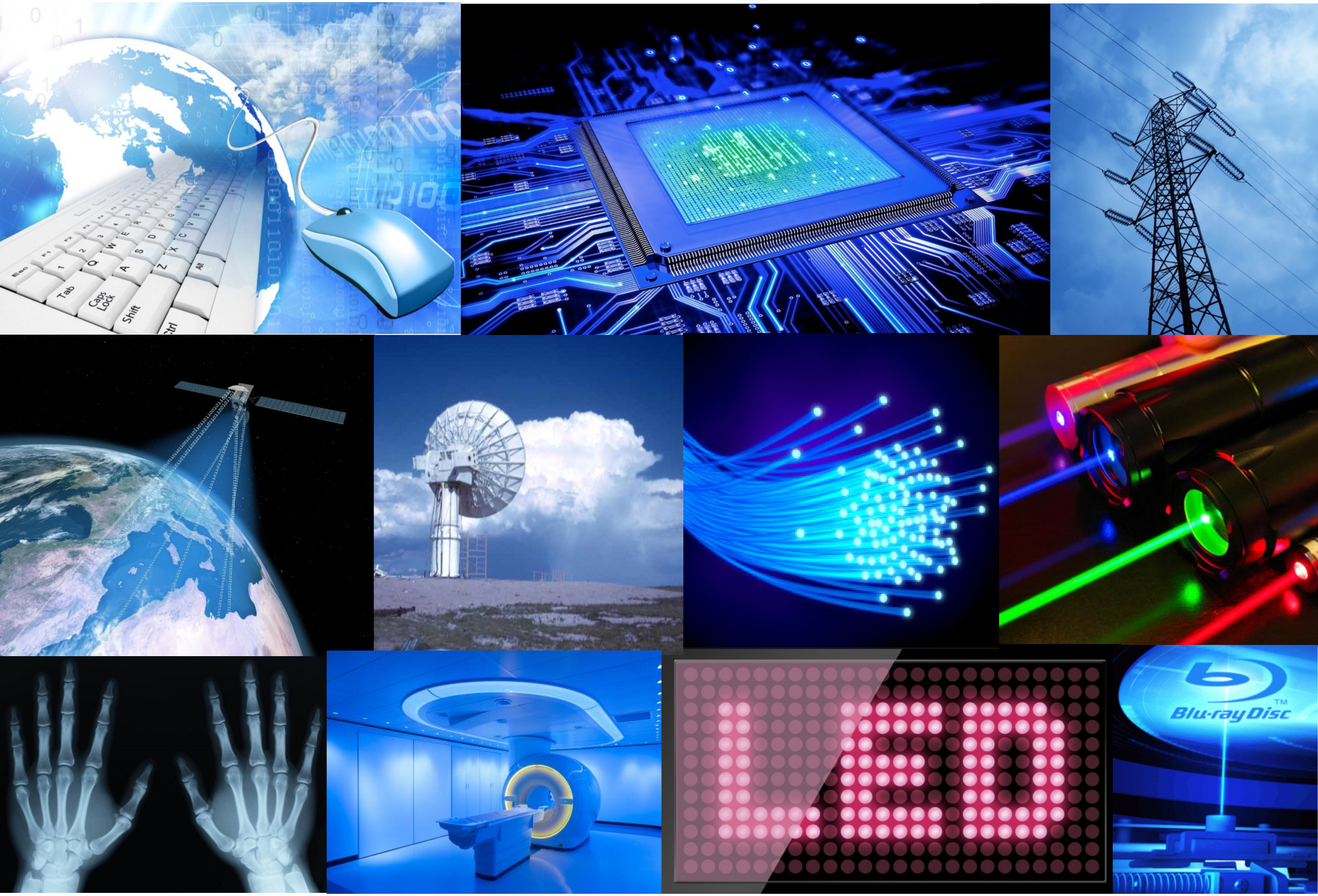
What is Physics for ?

Dictionary: physics is "the study of matter, energy, and the interaction between them"



http://apod.nasa.gov/apod/ap080614.html

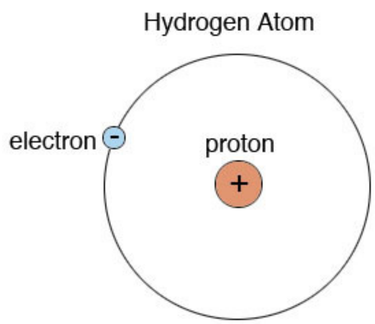
2: Physics enables future technologies



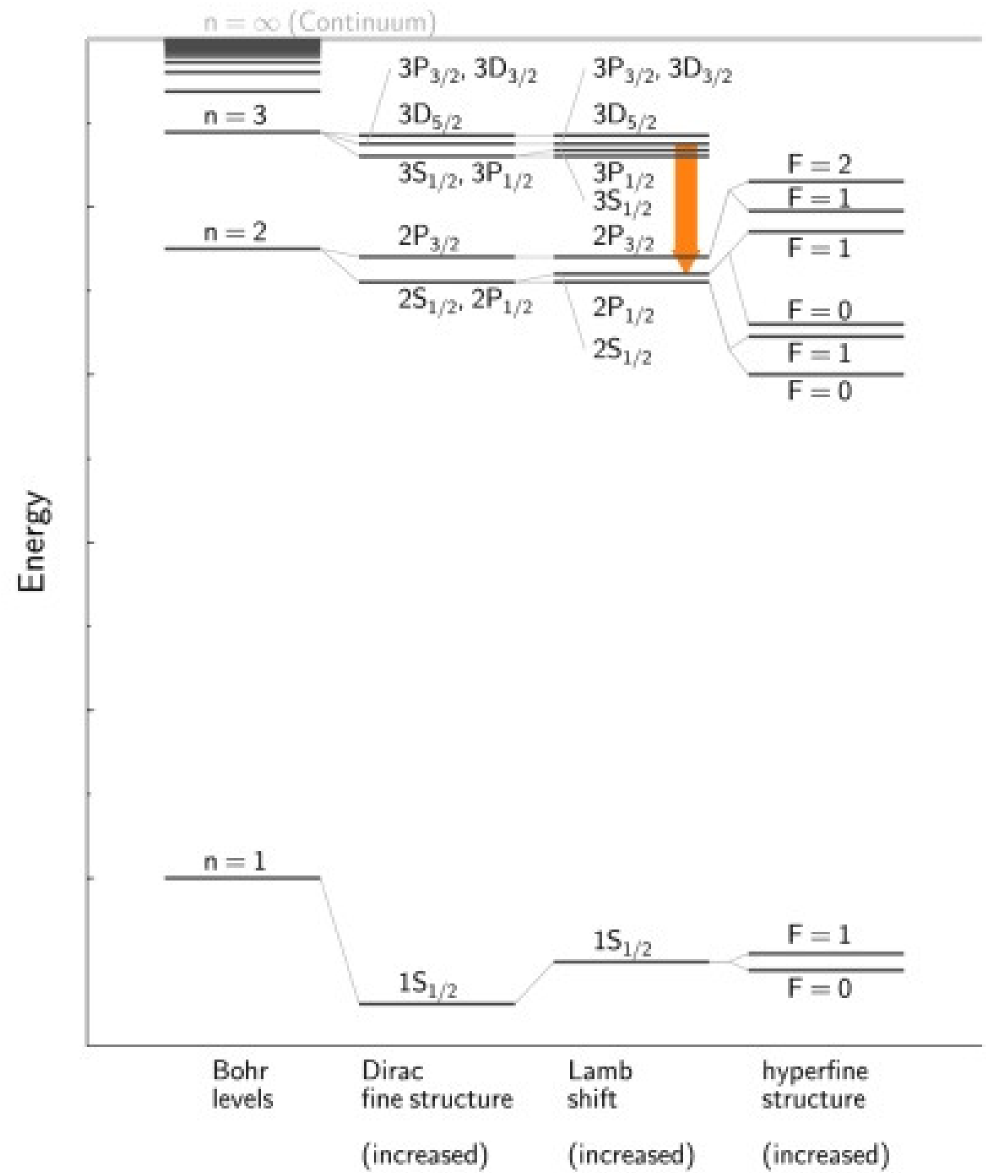
Topic 1: The proton radius puzzle

https://muhy.web.psi.ch/wiki/index.php/Main/NEWS

How to measure the (rms) radius of the proton?

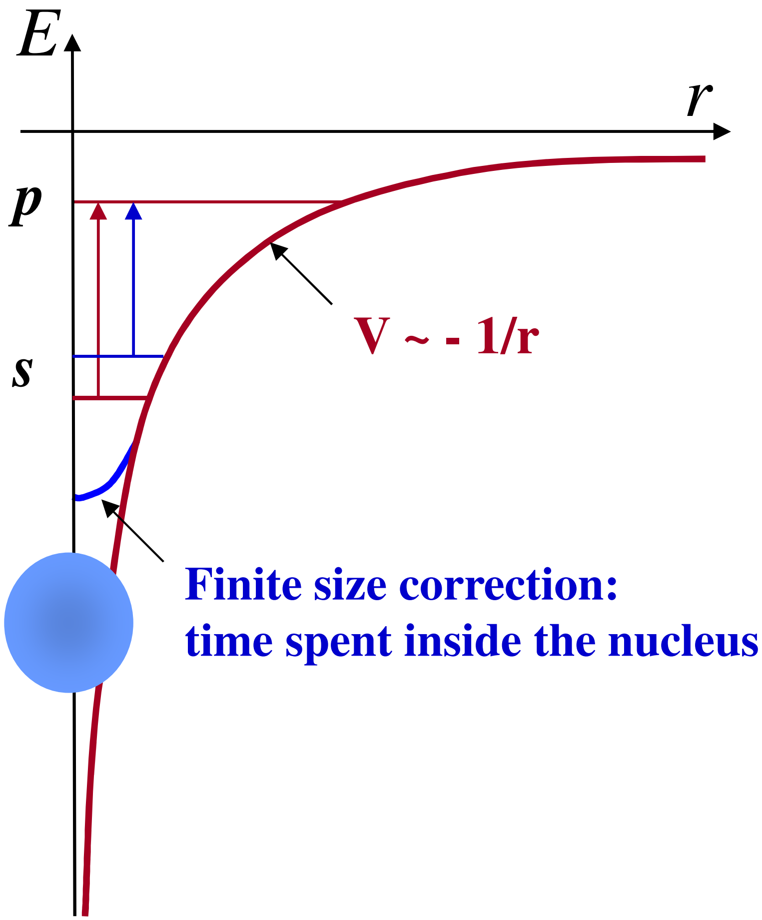


Energy levels of the hydrogen atom



Finite radius → level shifts

Measurement of transitions → measure nuclear size

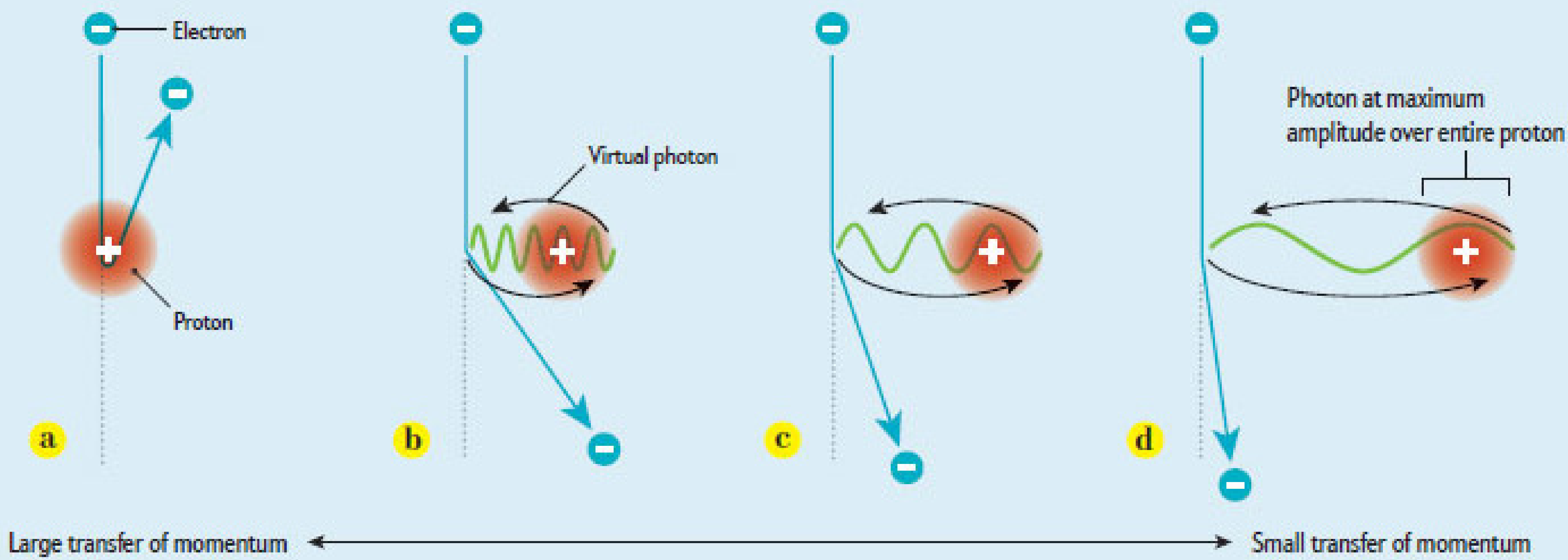


1. Measure the transition energies between different levels
2. Calculate all corrections to these energies
3. Extract the corrections to the energies due to a proton radius
   $\sim (Z\alpha)\, R_p^2\, |\Psi(0)|^2$
4. Extract the rms radius
5. Repeat for many transitions and average

Another way to measure the radius of the proton: scattering

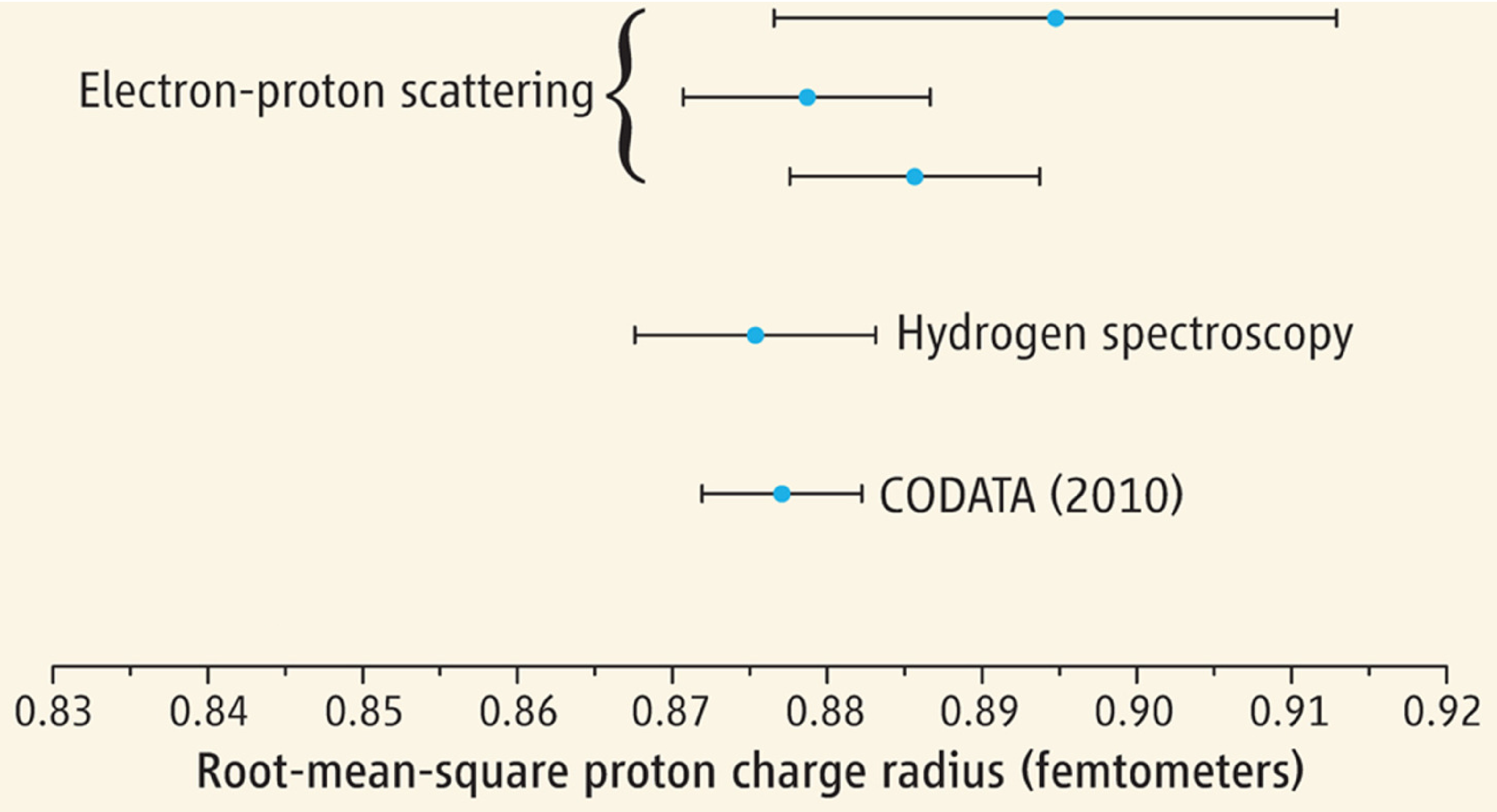
Scattershot Proton Measurement

Electron-scattering experiments fire a beam of electrons at hydrogen gas (which is mostly protons) and measure how the electrons scatter. Quantum electrodynamics (QED) describes these interactions using the exchange of "virtual" photons. An electron that hits a proton exchanges an extremely short-wavelength photon **a**. Short wavelengths imply higher energies that vigorously alter the electron's course. Electrons that pass farther from the proton produce progressively longer-wavelength photons (**b** *through* **d**) and smaller deflections. Information about the proton radius is encoded in the longest wavelengths. Imagine that the interaction between the photon and the proton is dependent on the photon's amplitude. To register the whole proton, the wavelength must be so long that the amplitude does not change over the entire extent of the proton's width **d**.



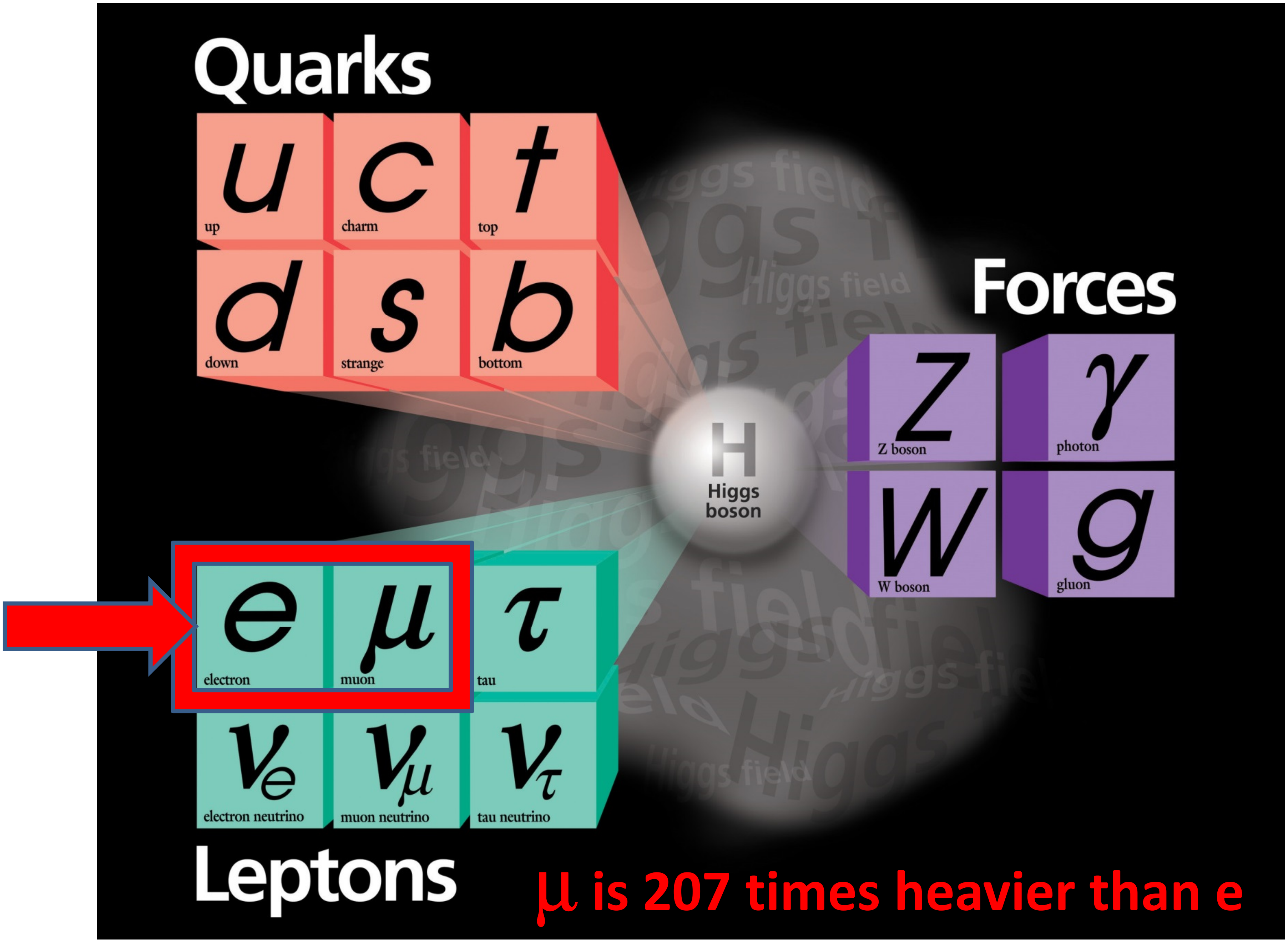
Scientific American **310**, 32 - 39 (2014)

Results of the measurements



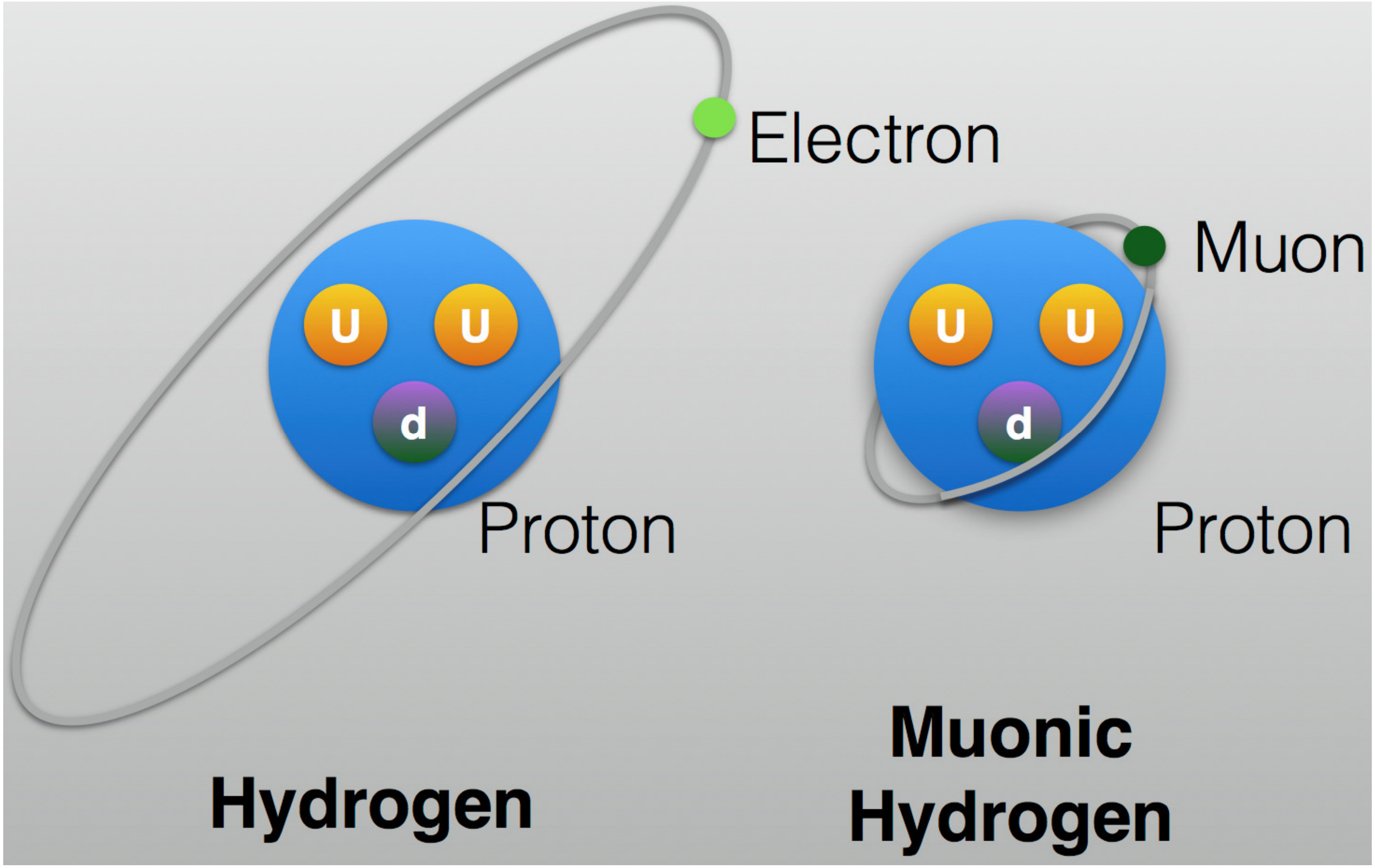
https://muhy.web.psi.ch/wiki/index.php/Main/NEWS

Even better way to measure the proton radius: replace electron by a muon



scienceblog.com

Even better way to measure the proton radius

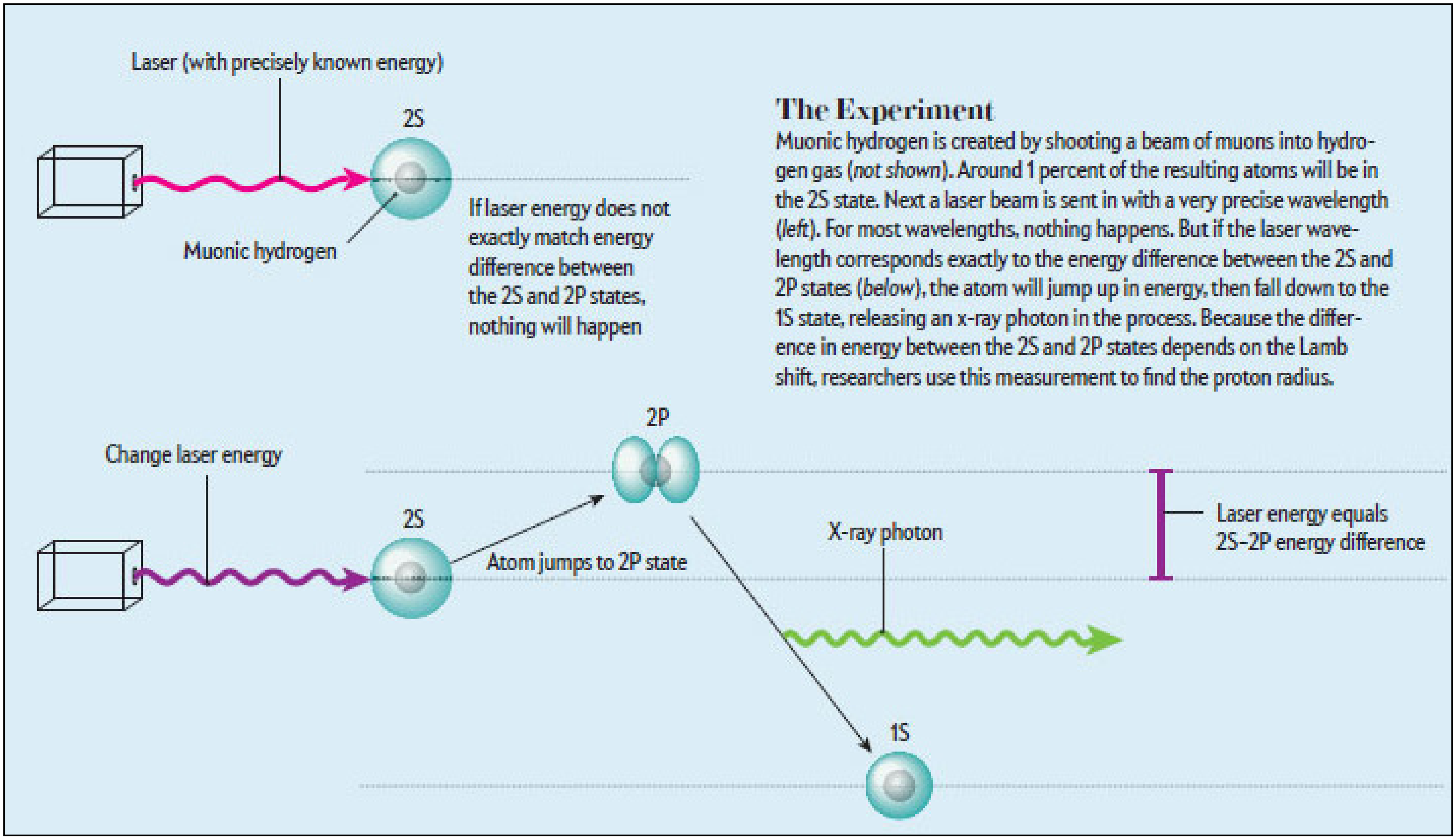


Probability for a lepton to be inside the proton $\propto$ to its mass cubed, $(207)^3 =$ 8 869 743 enhancement for a muon !

http://www.ust.edu.tw/

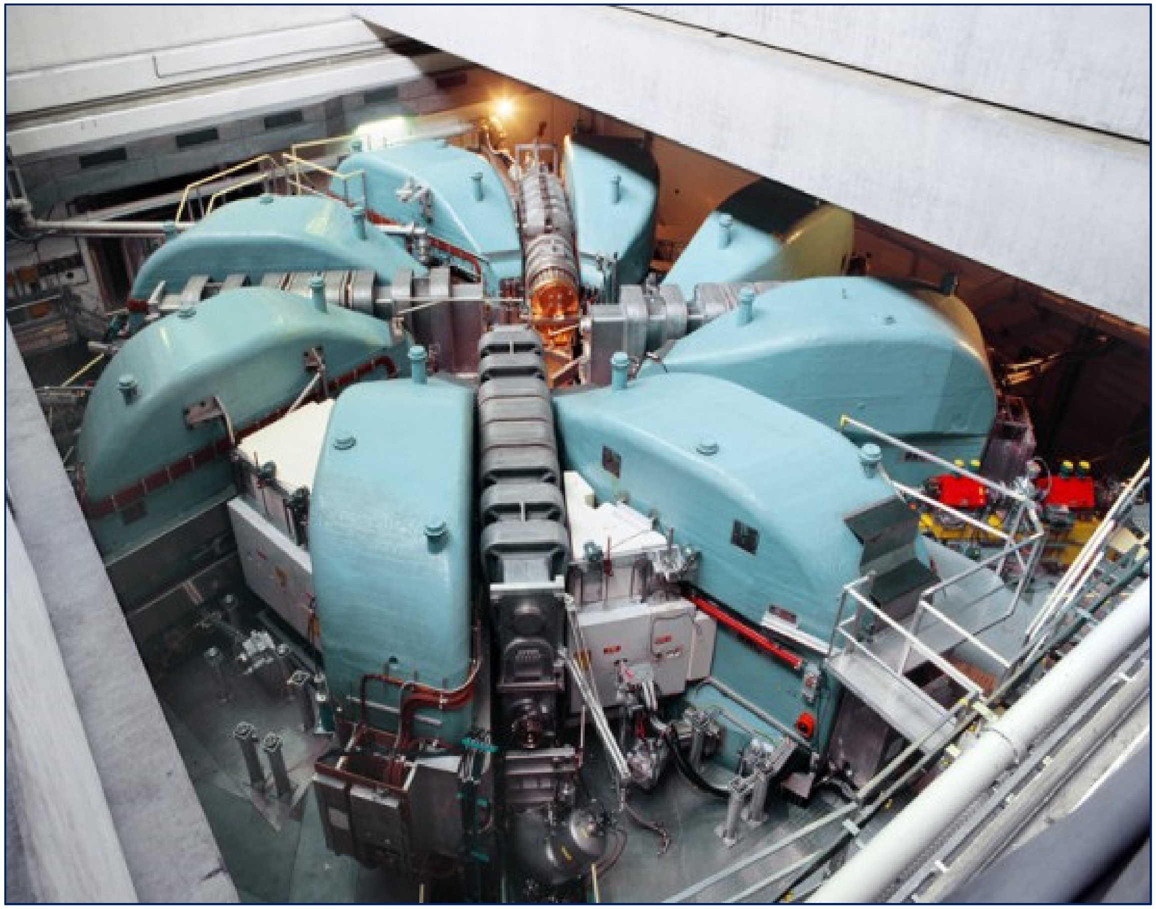
Muonic hydrogen experiment

Paul Scherrer Institute (Switzerland)



Scientific American **310**, 32 - 39 (2014)

Muonic hydrogen experiment



Timeline:

1997 Experiment proposed

1999 Experiment approved

2002 Assembly completed

2003 First “real” run

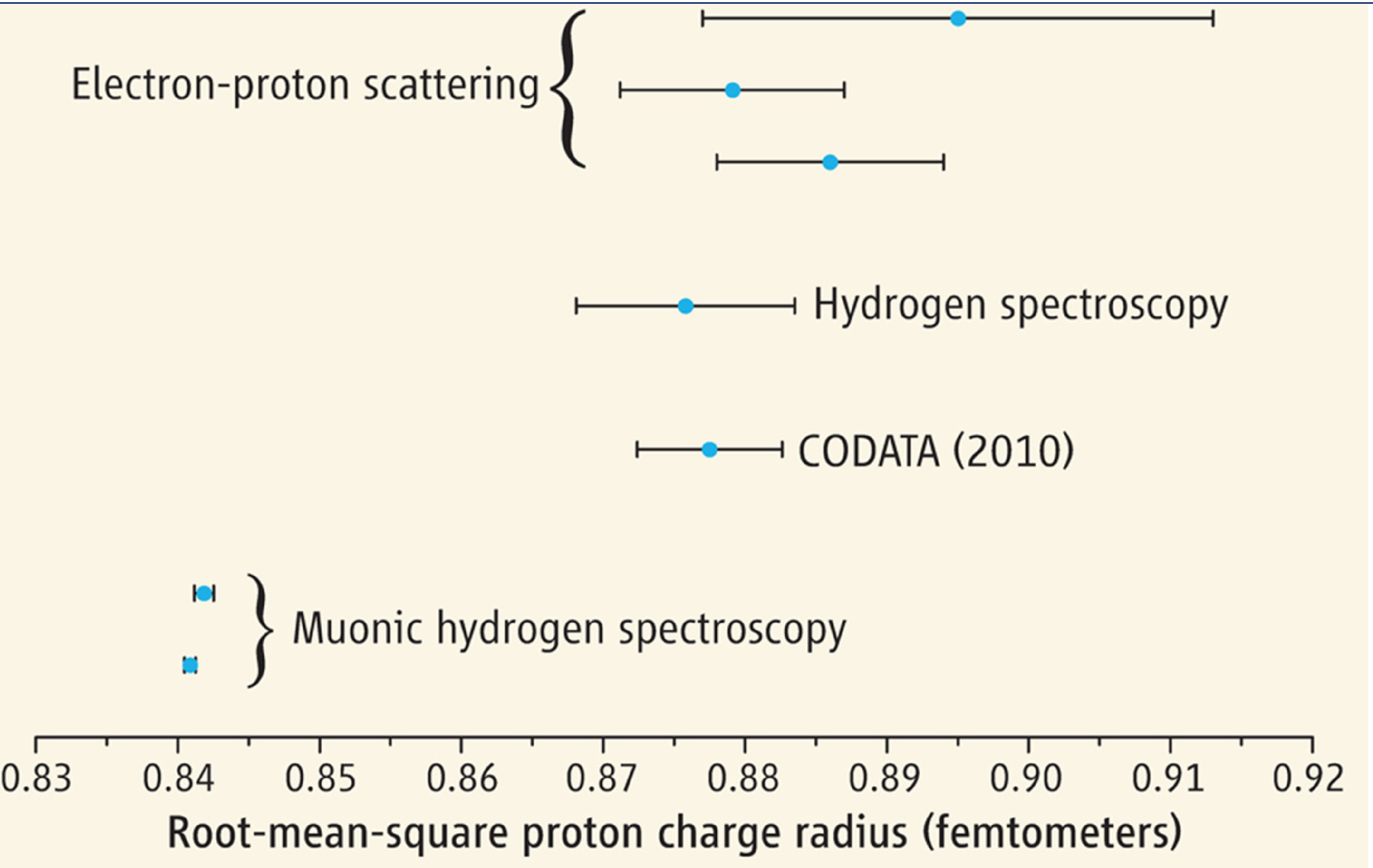
2006-2007 Major redesign, new runs

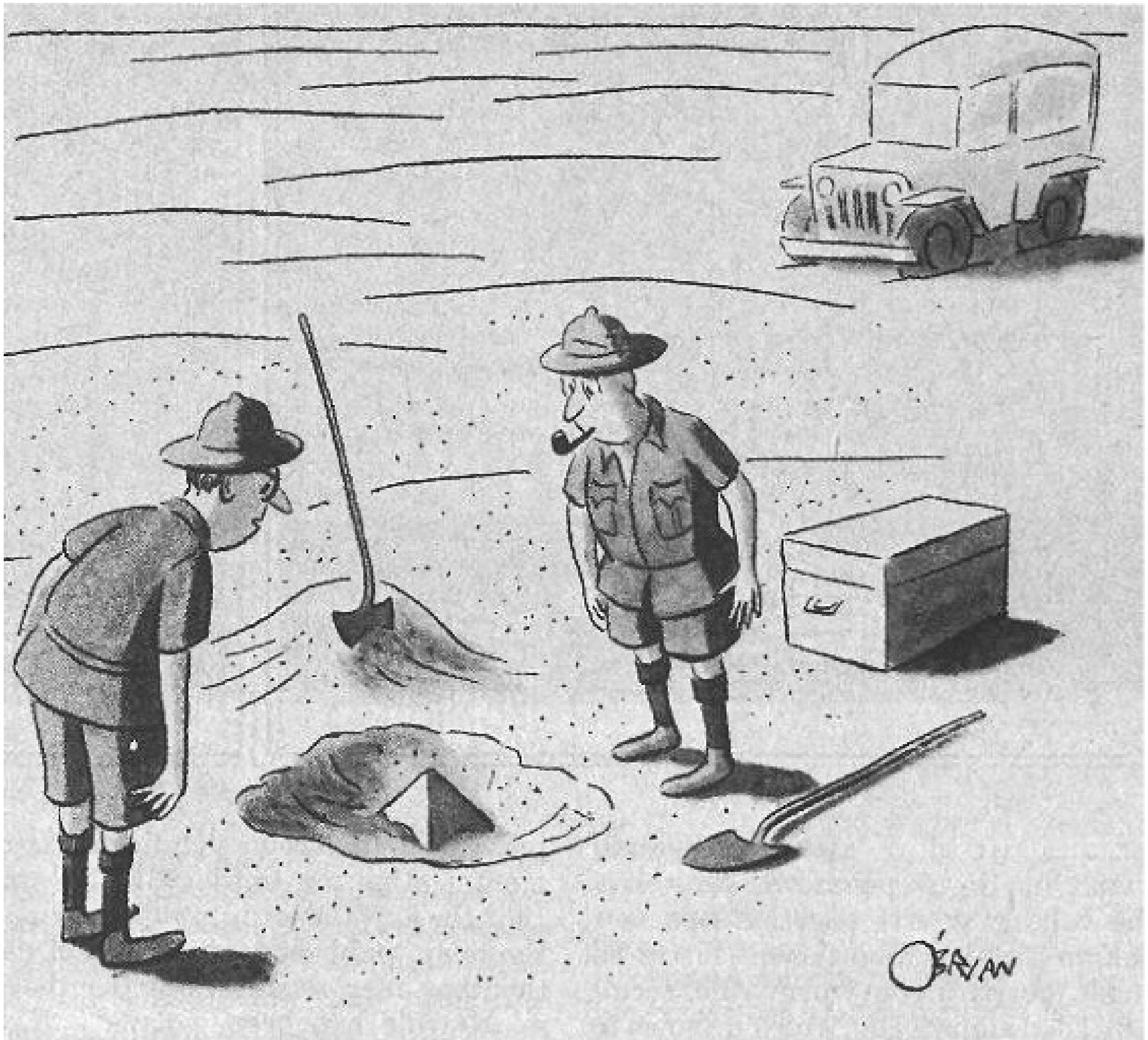
2009 Last chance to run

The proton accelerator at the Paul Scherrer Institute, which was used to create the muons used in this experiment.

Photo: Paul Scherrer Institute

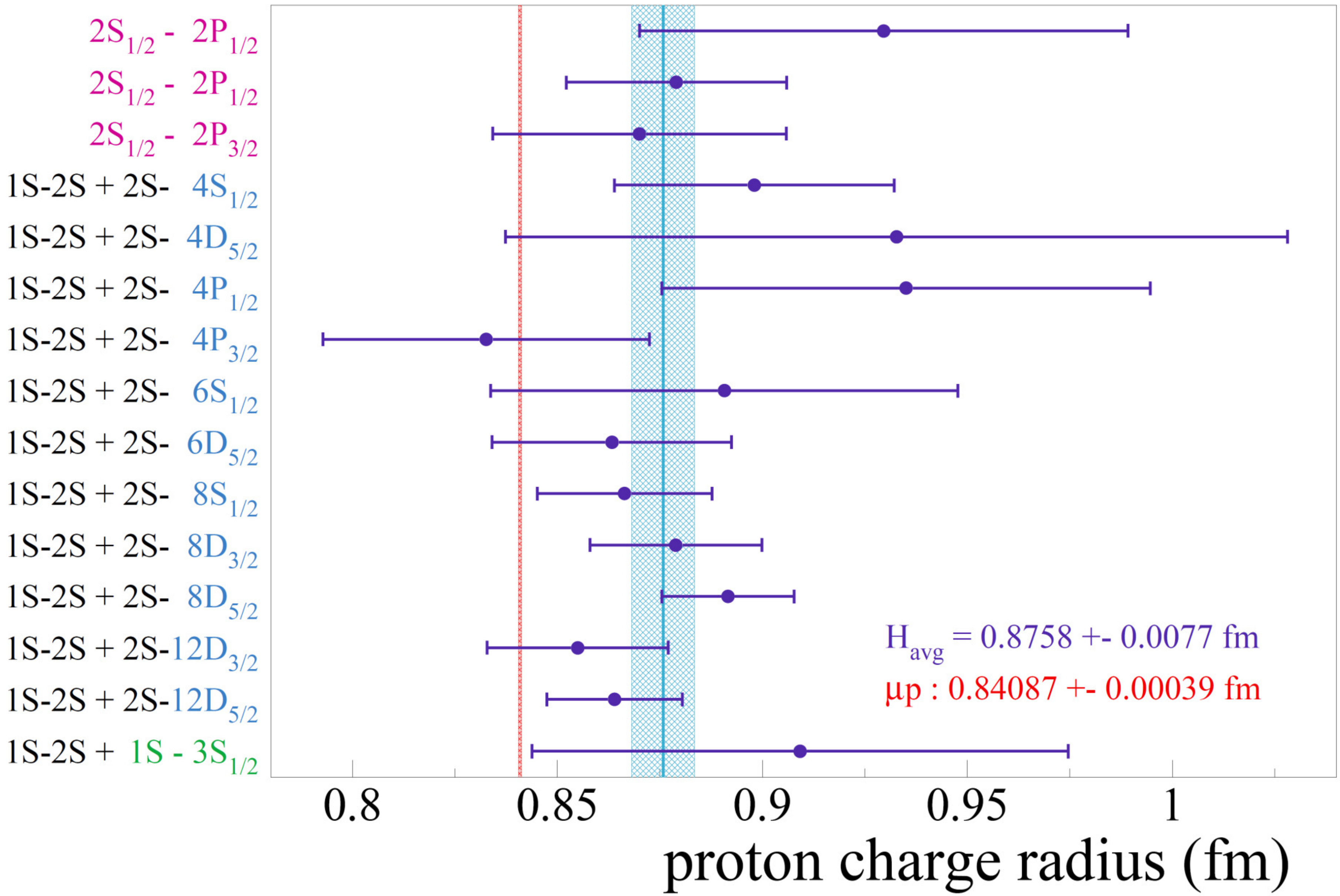
Proton radius puzzle





"This could be the discovery of the century. Depending, of course, on how far down it goes."

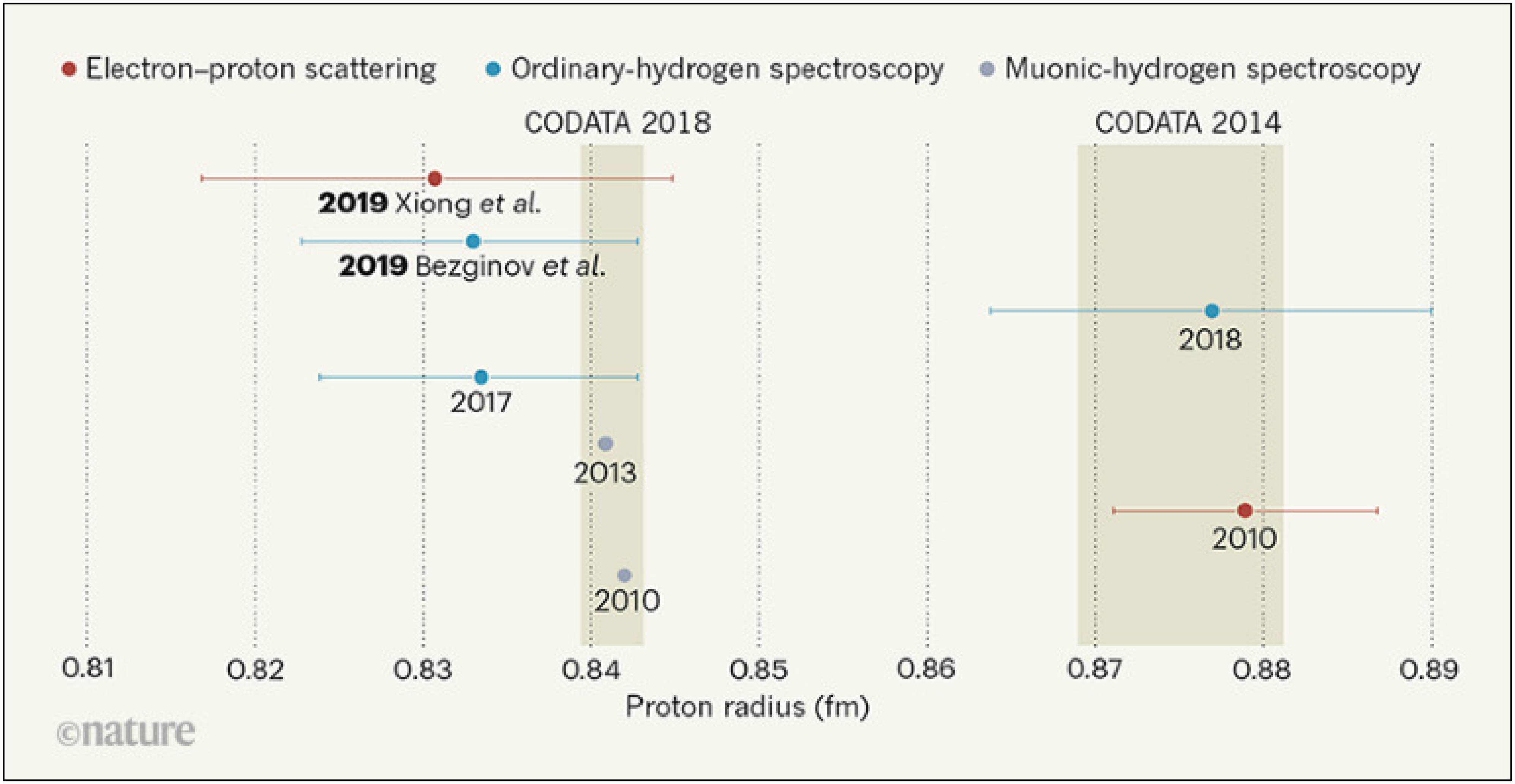
Close up: Hydrogen Spectroscopy



R. Pohl et al., Annu. Rev. Nucl. Part. Sci. 63, 175 (2013)

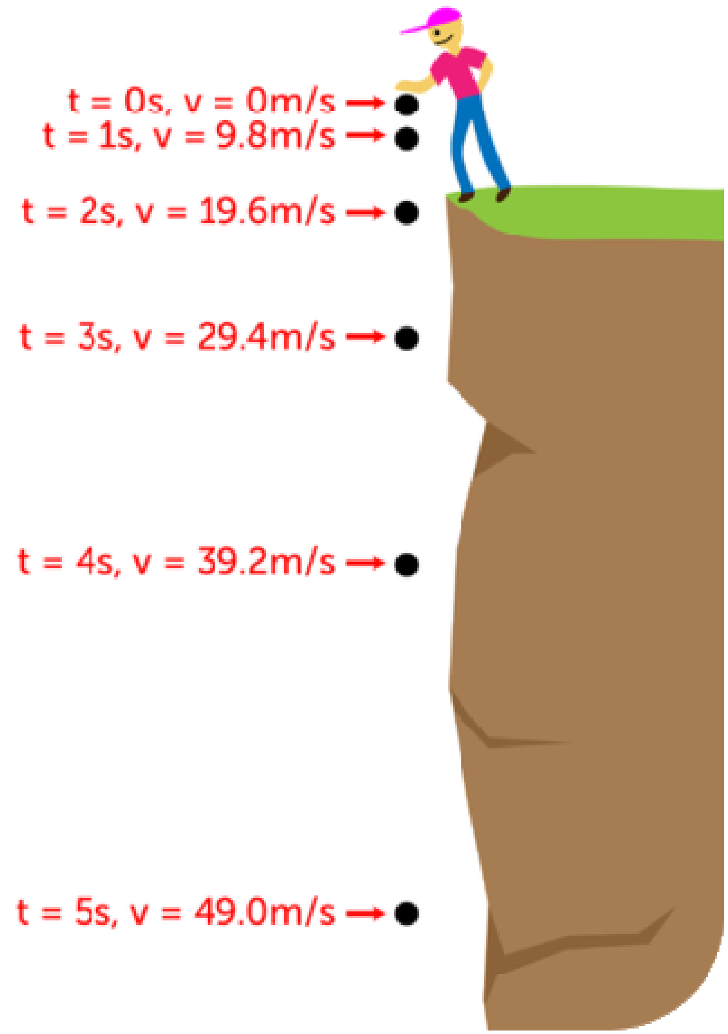
Proton radius puzzle resolved

New hydrogen measurements redone



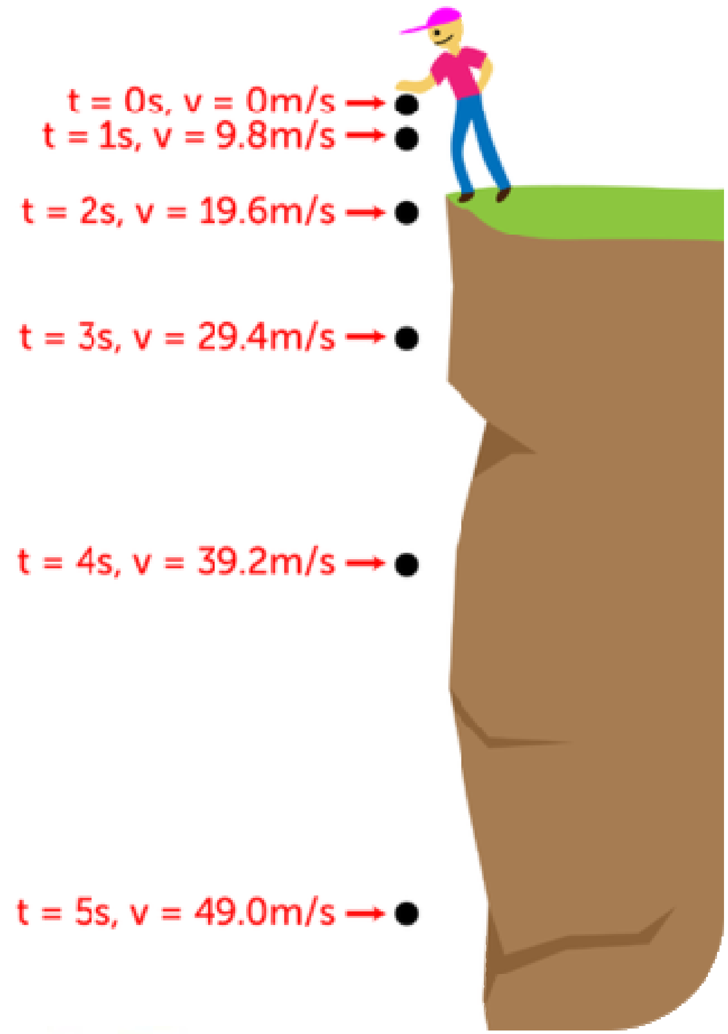
https://www.nature.com/articles/d41586-019-03364-z

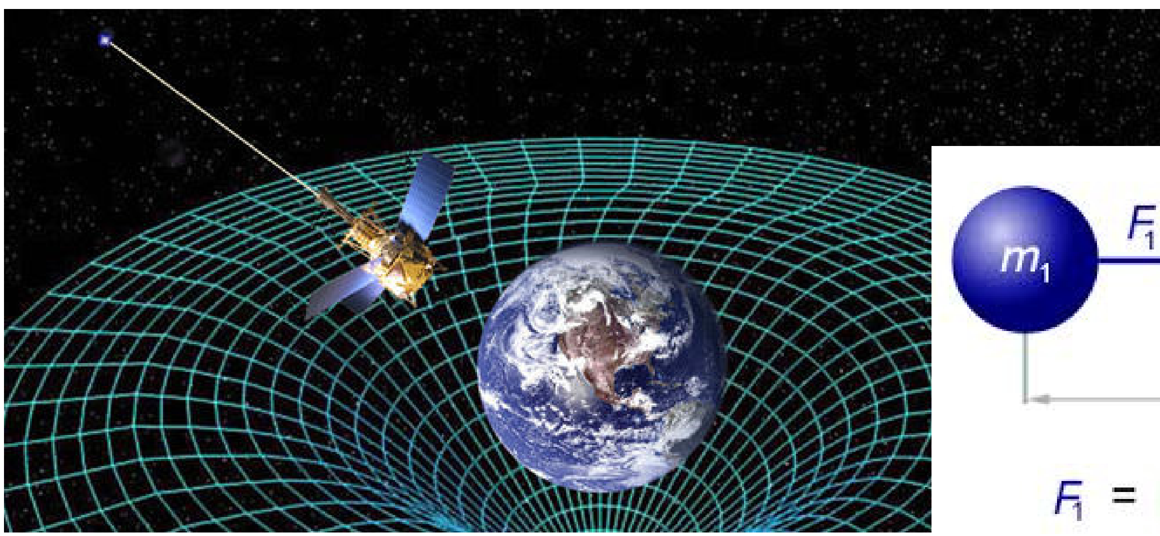
Topic 2: Fundamental constants

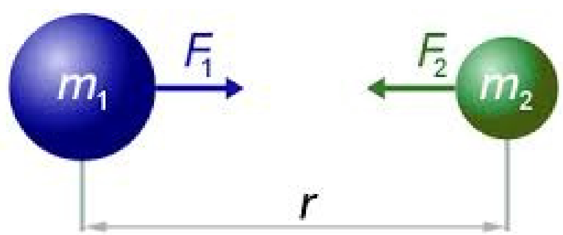


$$g = \frac{Gm_E}{R_E^2} \approx 9.80 \frac{\mathrm{m}}{\mathrm{s}^2}$$

Topic 2: Fundamental constants







$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

$$g = \frac{Gm_E}{R_E^{\,2}} \approx 9.80\,\frac{\text{m}}{\text{s}^2}$$

FUNDAMENTAL CONSTANTS

Quantity	*Symbol*	*Numerical Value*
Speed of light (in vacuum)	c	3.00×10^{8} m s^{-1}
Gravitational constant	G	6.67×10^{-11} N m^2 kg^{-2}
Avogadro's number	N_A	6.02×10^{23} molecules mole^{-1}
Universal gas constant	R	8.31 J K^{-1} mole^{-1}
Boltzmann constant	k_B	1.38×10^{-23} J K^{-1}
		8.62×10^{-5} eV K^{-1}
Stefan's constant	σ	5.67×10^{-8} W m^{-2} K^{-4}
Atomic mass unit	u	1.66×10^{-27} kilograms
Coulomb constant	k	9.00×10^{9} N m^2 C^{-2}
	$\varepsilon_0 = 1/4\pi k$	8.85×10^{-12} C^2 N^{-1} m^2
Biot-Savart constant	k'	10^{-7} T m A^{-1}
Electron charge	$-e$	-1.60×10^{-19} coulombs
Electron mass	m_e	9.11×10^{-31} kilograms
Proton charge	e	1.60×10^{-19} coulombs
Proton mass	m_p	1.673×10^{-27} kilograms
Neutron mass	m_n	1.675×10^{-27} kilograms
Planck's constant	h	6.63×10^{-34} J s
		4.14×10^{-15} eV s
	$\hbar = h/2\pi$	1.055×10^{-34} J s
		6.58×10^{-16} eV s
Rydberg constant	R_H	1.10×10^{7} metres^{-1}
Bohr radius	a_0	5.29×10^{-11} metres
Bohr magneton	μ_B	9.27×10^{-24} J T^{-1}

Note: we are still measuring them …

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 (1σ) 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)~~ $\times 10^{-11}$	$\mathrm{m^3\ kg^{-1}\ s^{-2}}$	384(80)
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 20~~8 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)

From NIST Tech Beat: July 19, 2011

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)

Which fundamental constants to consider?

A pragmatic approach: choose a theoretical framework so that the set of undetermined fixed parameters is fully known. Then, try to determine if these values are constant.

It only makes sense to **consider the variation of dimensionless ratios:**

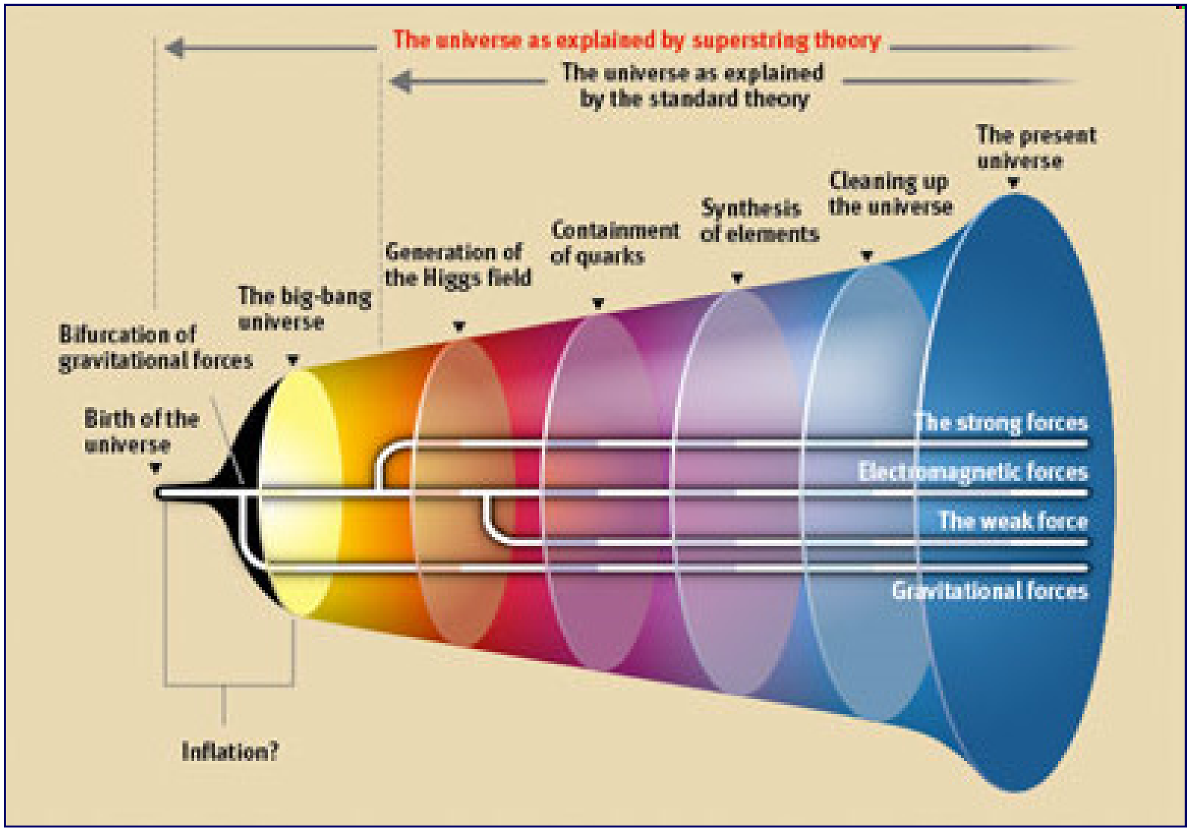
Fine-structure constant $\alpha_{\mathrm{EM}} = \frac{e^2}{\hbar c} \sim 1/137.036$

Electron or quark mass/QCD strong interaction scale $\frac{m_{e,q}}{\Lambda_{QCD}}$

The electron-proton mass ratio $\frac{m_e}{M_P}$

…

Possible sources for variation of the fundamental constants



Unification theories

↓

Extra space dimensions

↓

Variation of the fundamental constants in an expanding universe

Scalar fields ?

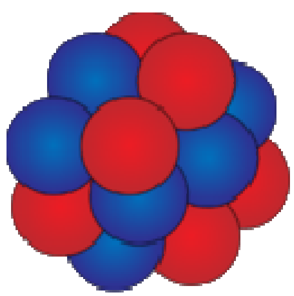
Life needs very specific fundamental constants!

Life needs very specific fundamental constants!

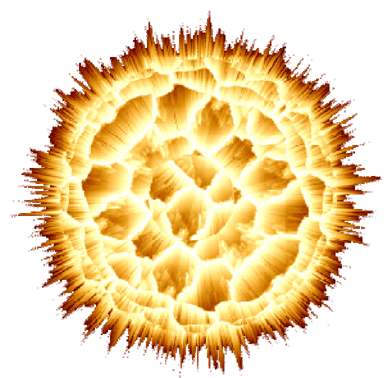
If α is too big → small nuclei can not exist

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

$\alpha \sim 1/137$



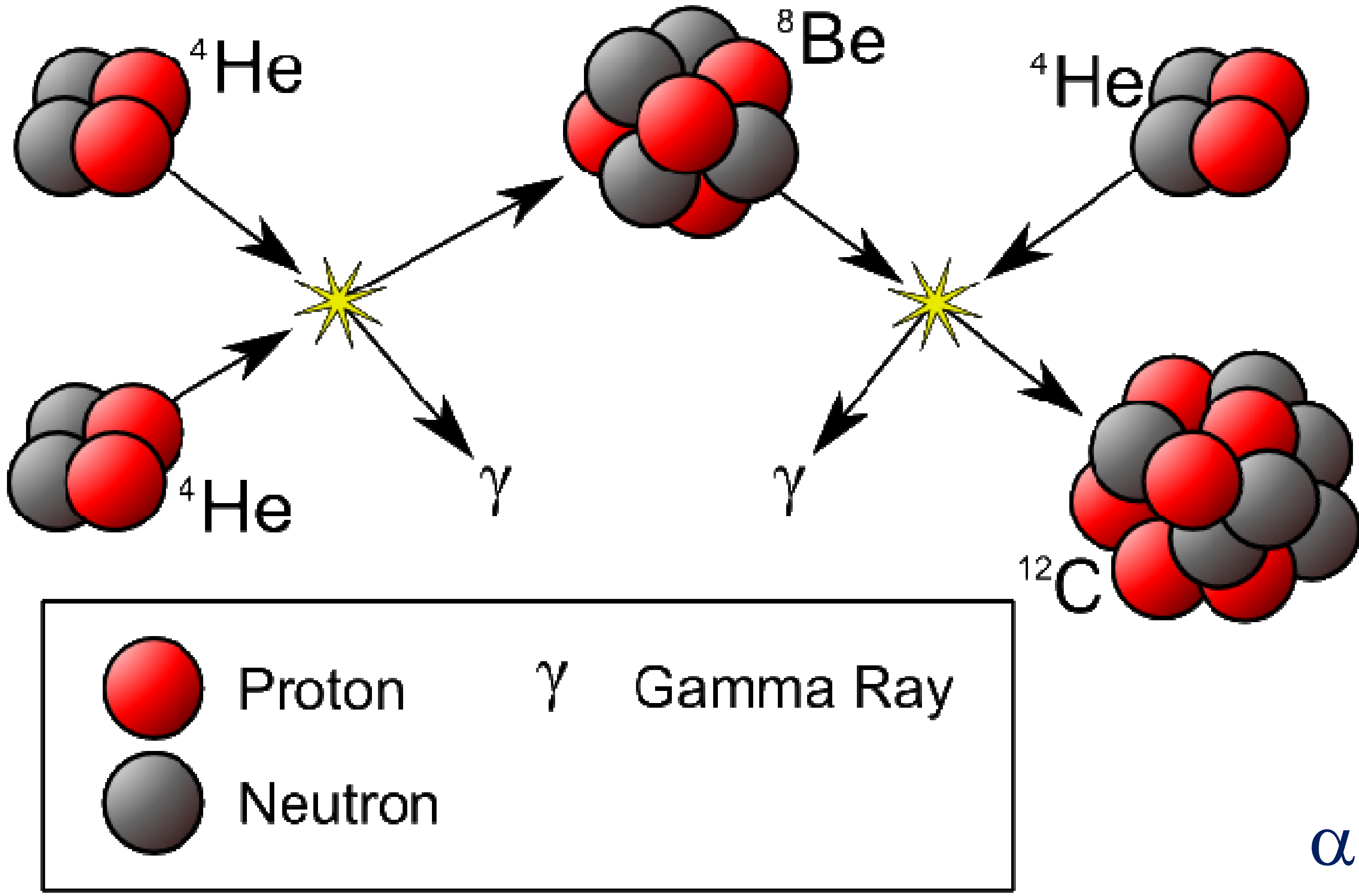
Carbon-12



$\alpha \sim 1/10$

will blow carbon apart

Life needs very specific fundamental constants!

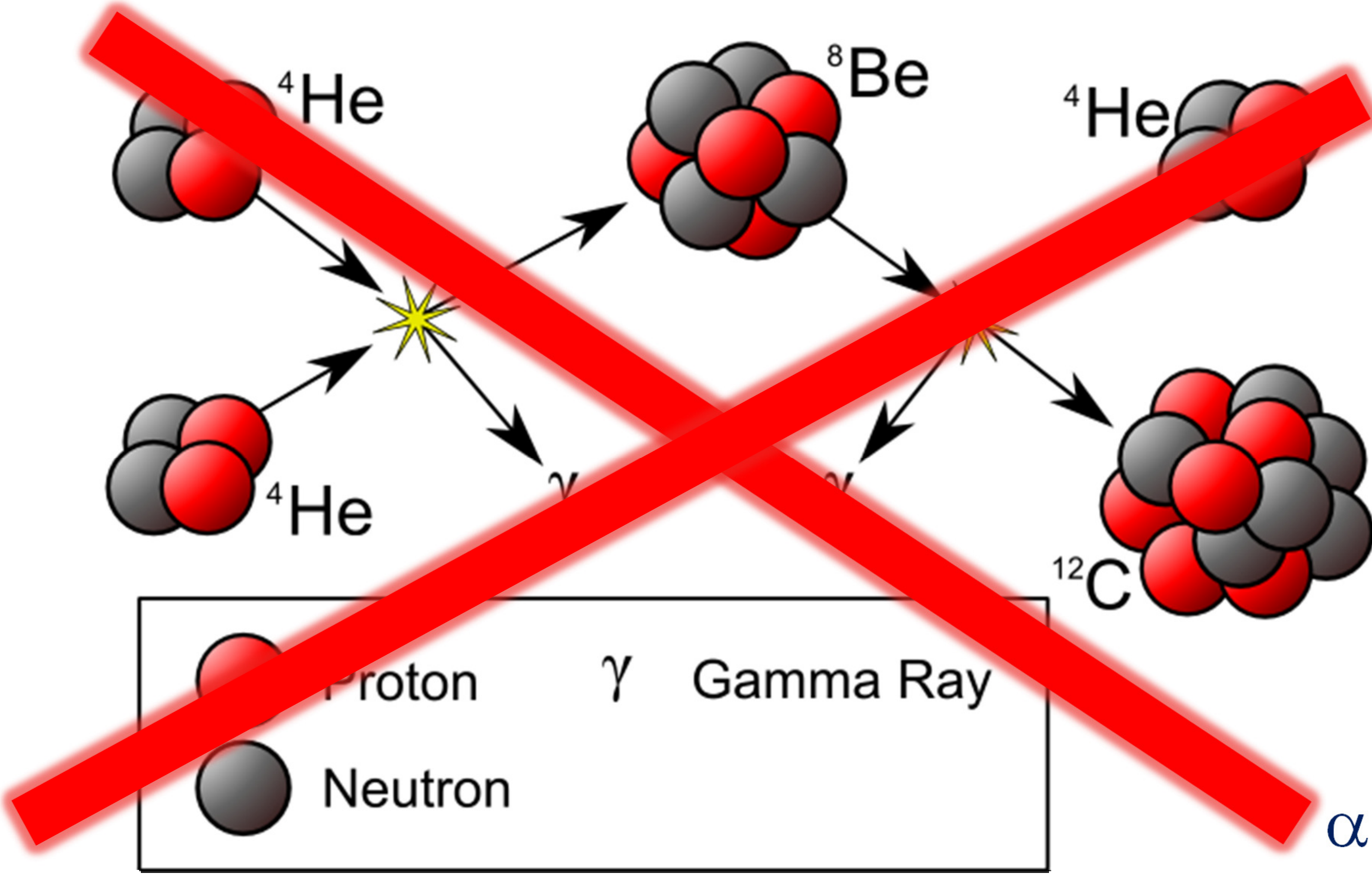


$\alpha \sim 1/137$

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!

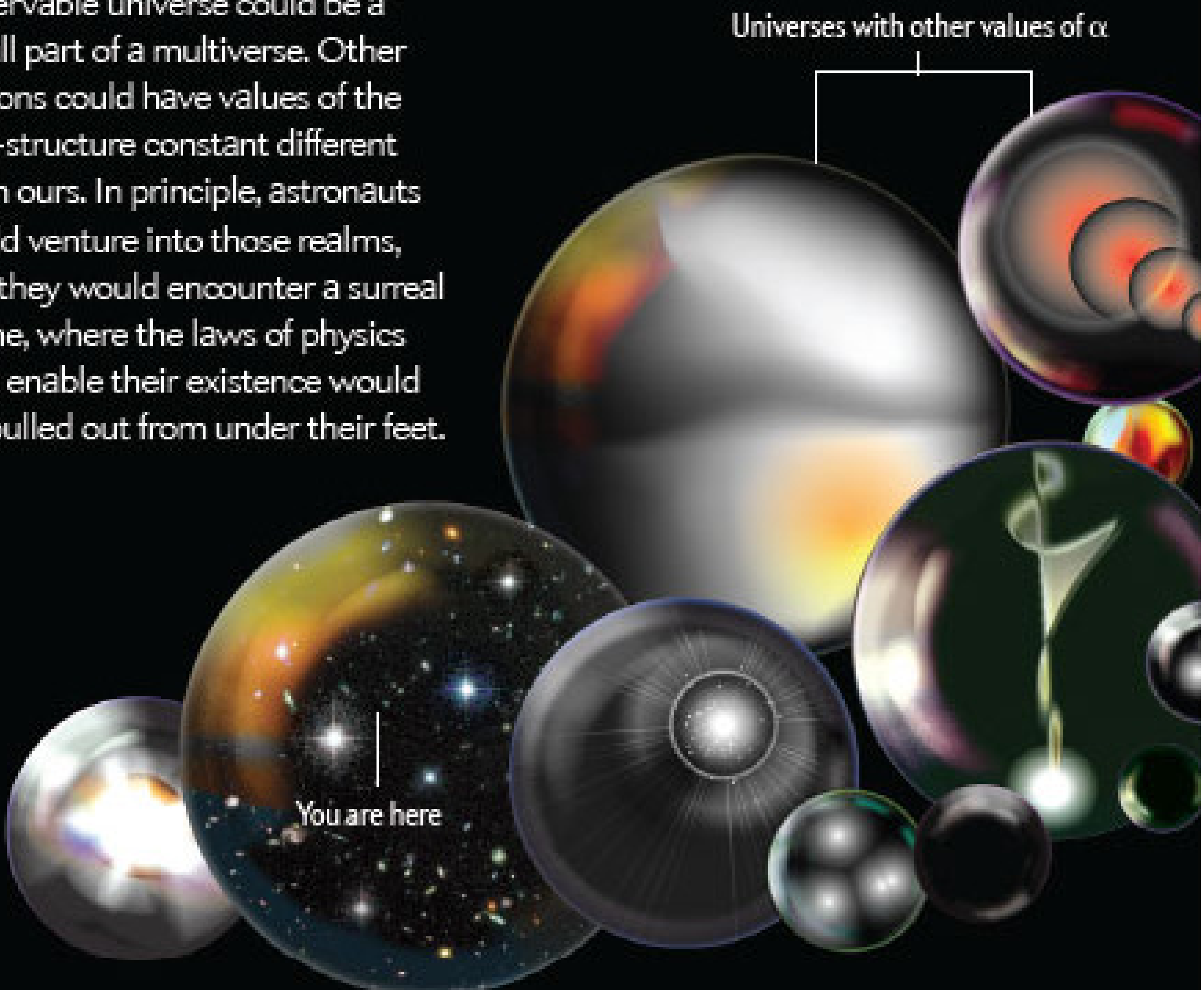


$\alpha \sim 1/132$

No carbon produced by stars:
No life in the Universe

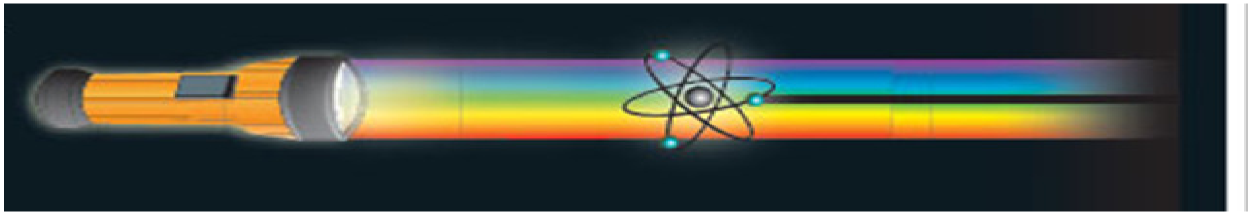
Across the Universes ???

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.

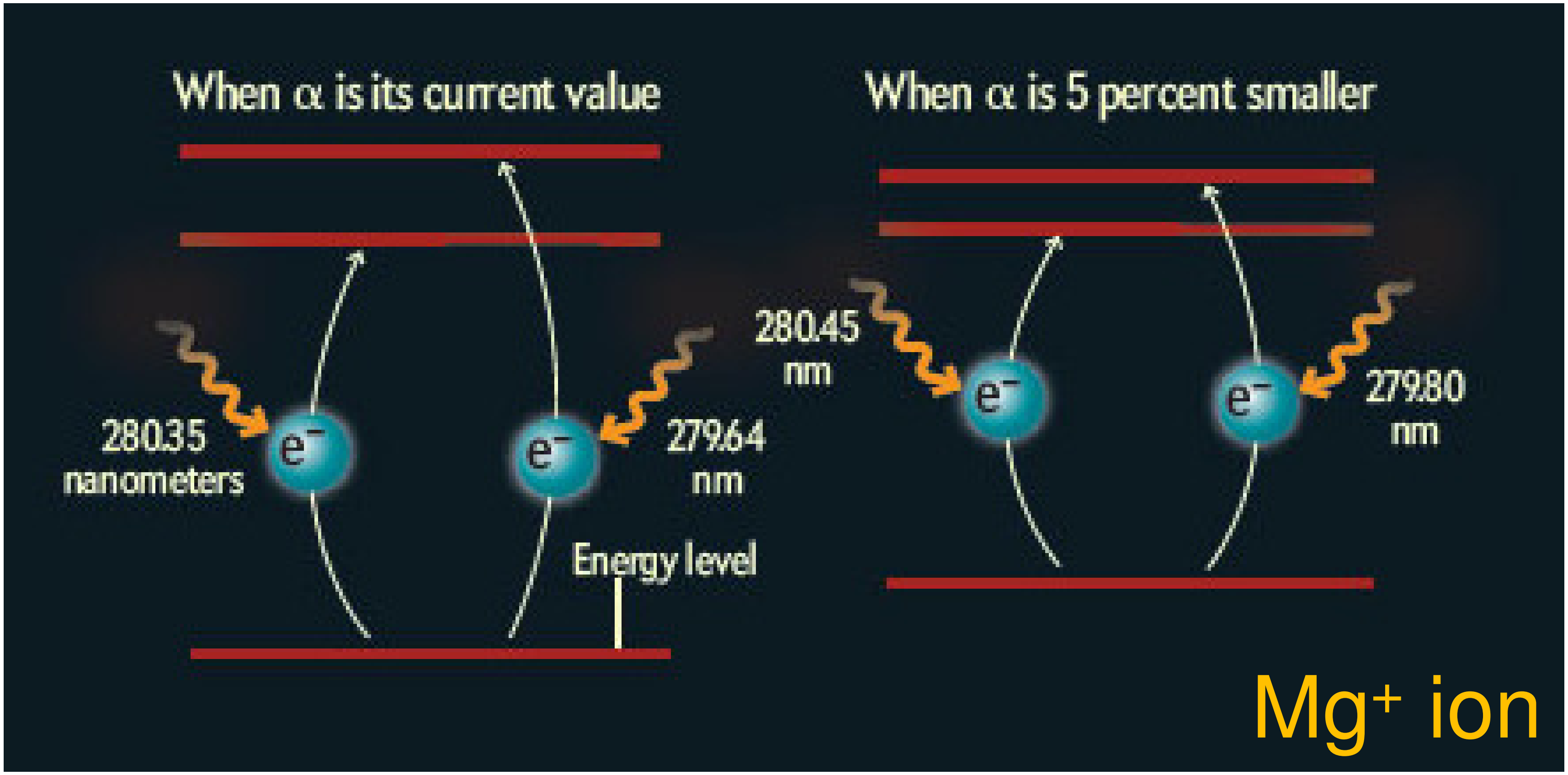


Scientific American Time **21**, 70 - 77 (2012)

How to test if α changed with time?

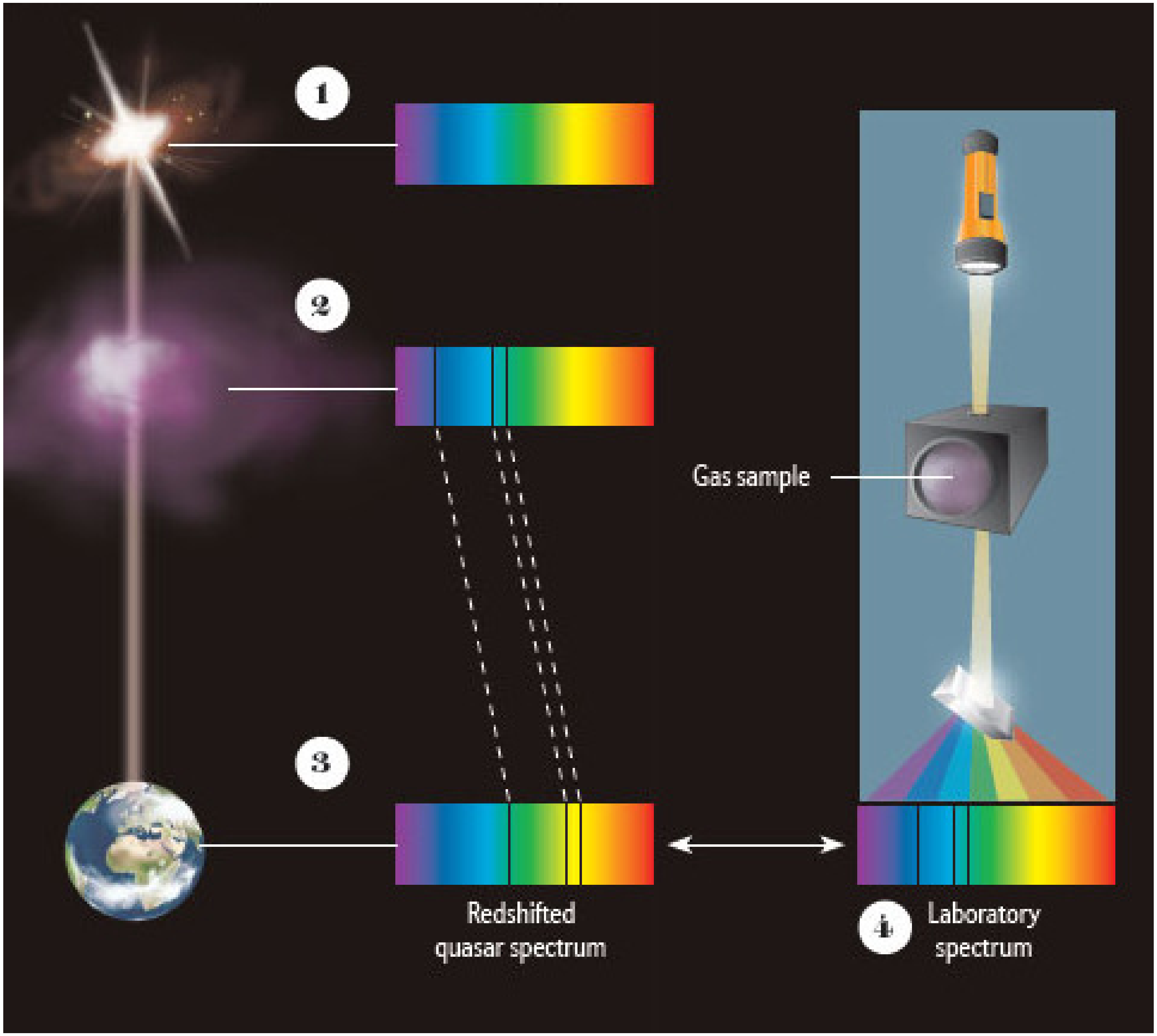


Atomic transition energies depend on α^2

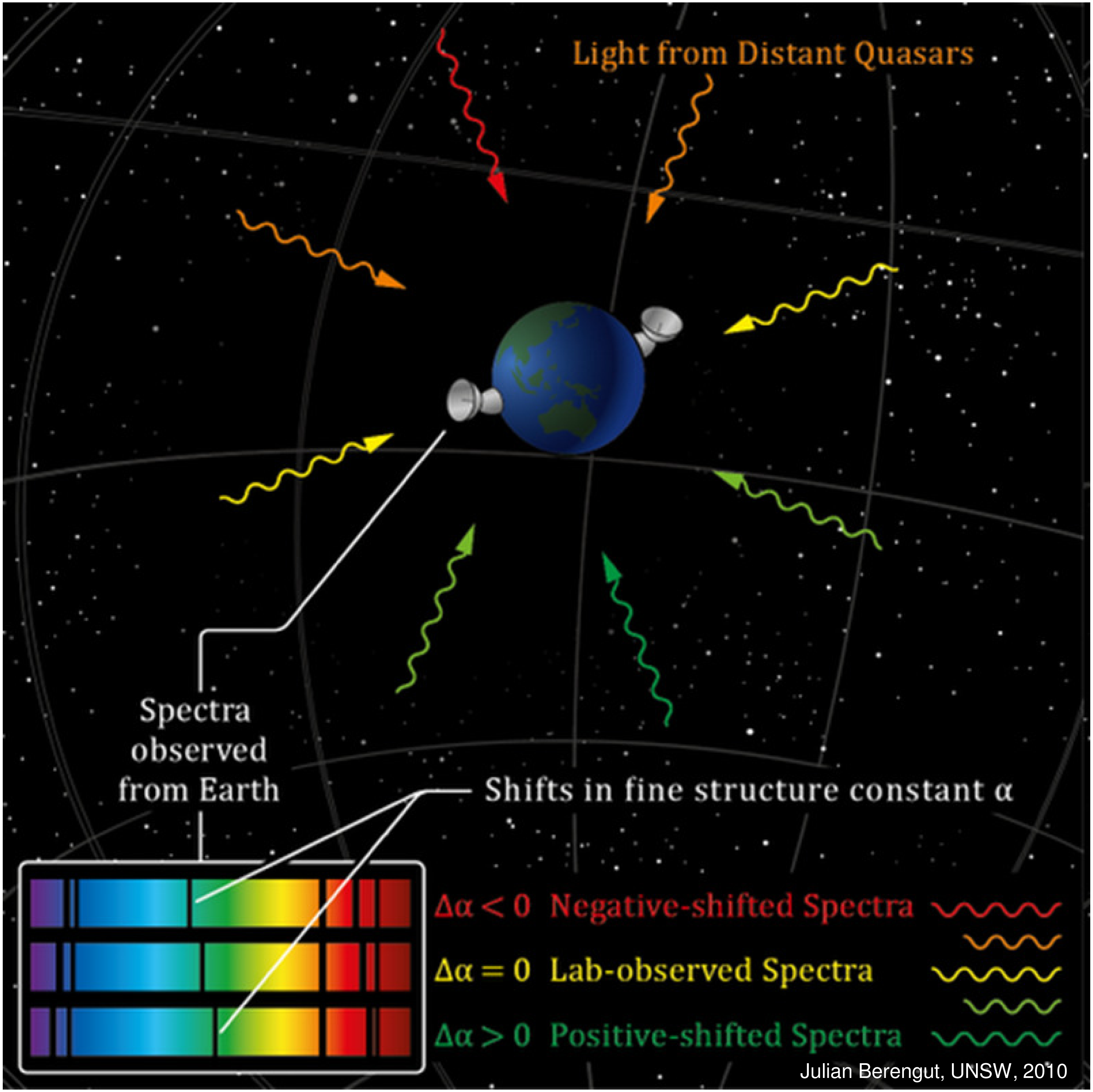


Scientific American Time **21**, 70 - 77 (2012)

Astrophysics searches for variation of α: looking for changes in quasar light



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



Light from Distant Quasars
Spectra observed from Earth
Shifts in fine structure constant α
Δα < 0 Negative-shifted Spectra
Δα = 0 Lab-observed Spectra
Δα > 0 Positive-shifted Spectra
Julian Berengut, UNSW, 2010

Conflicting results

Murphy et al., 2003: Keck telescope,
143 systems, 23 lines, 0.2<z<4.2

$$\Delta\alpha/\alpha = -0.54(12)\times 10^{-5}$$

Quast et al, 2004: VL telescope,
1 system, Fe II, 6 lines

$$\Delta\alpha/\alpha = -0.4(1.9)(2.7)\times 10^{-6}$$

Molaro et al., 2007

Z=1.84

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

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

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

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

Murphy et al., 2007

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

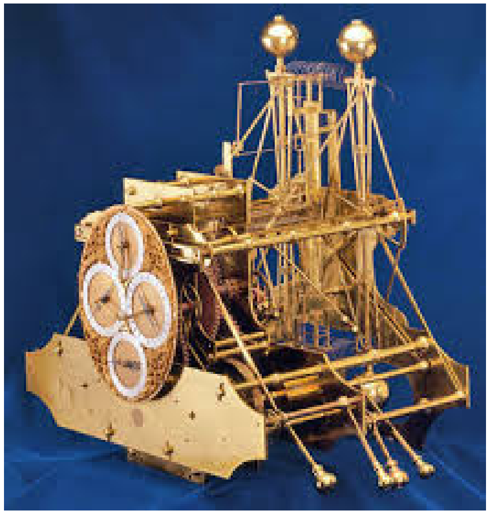
Can we look for α–variation in a lab?

YES!

TOPIC 3

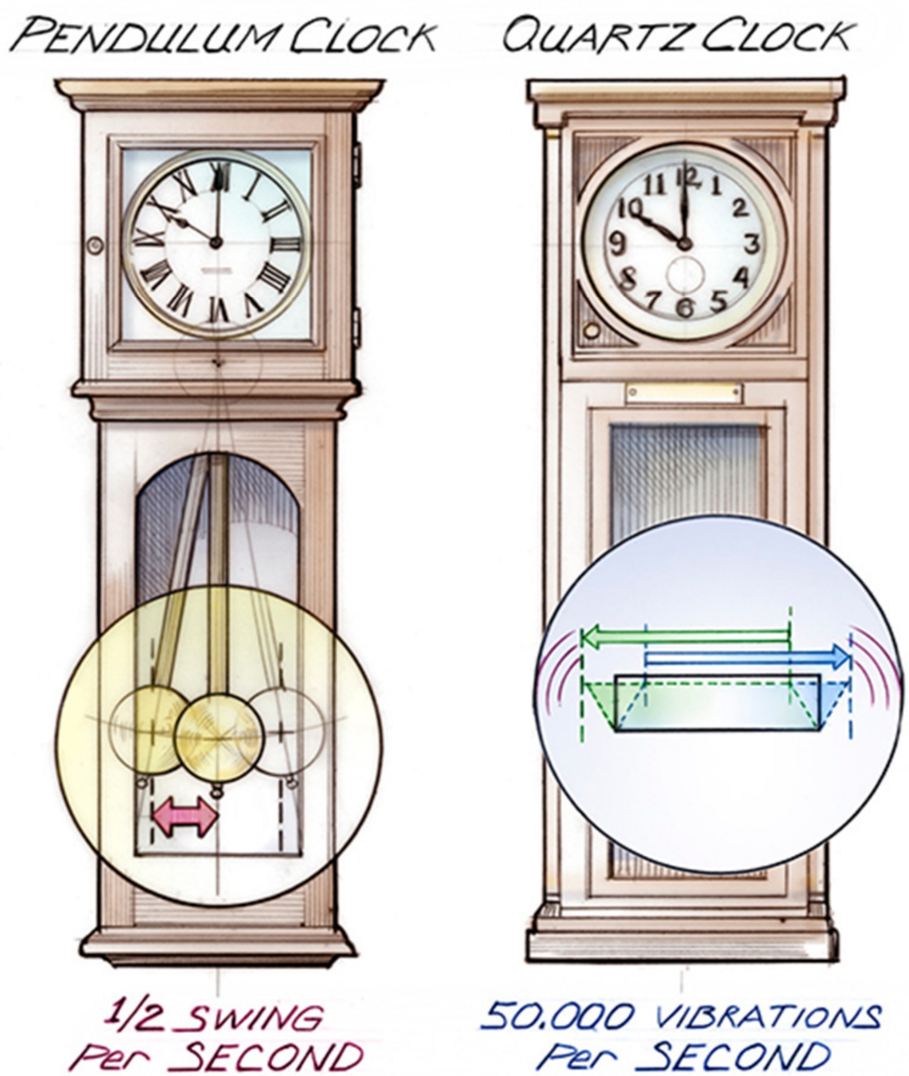
NEED ATOMIC CLOCKS

Clocks



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.



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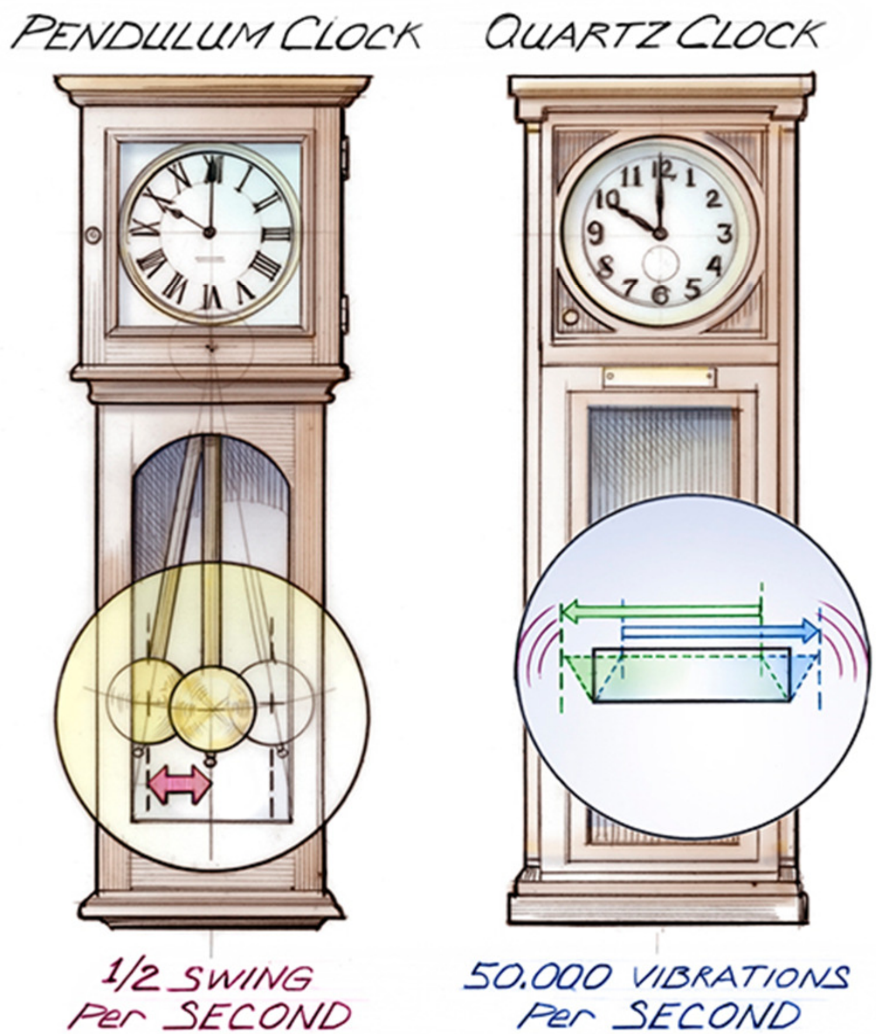
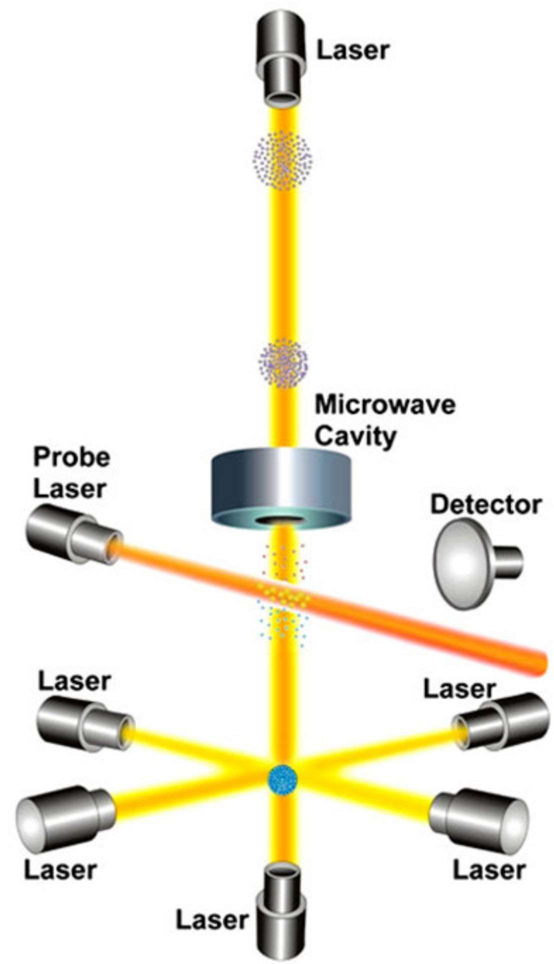


Cesium microwave atomic clock

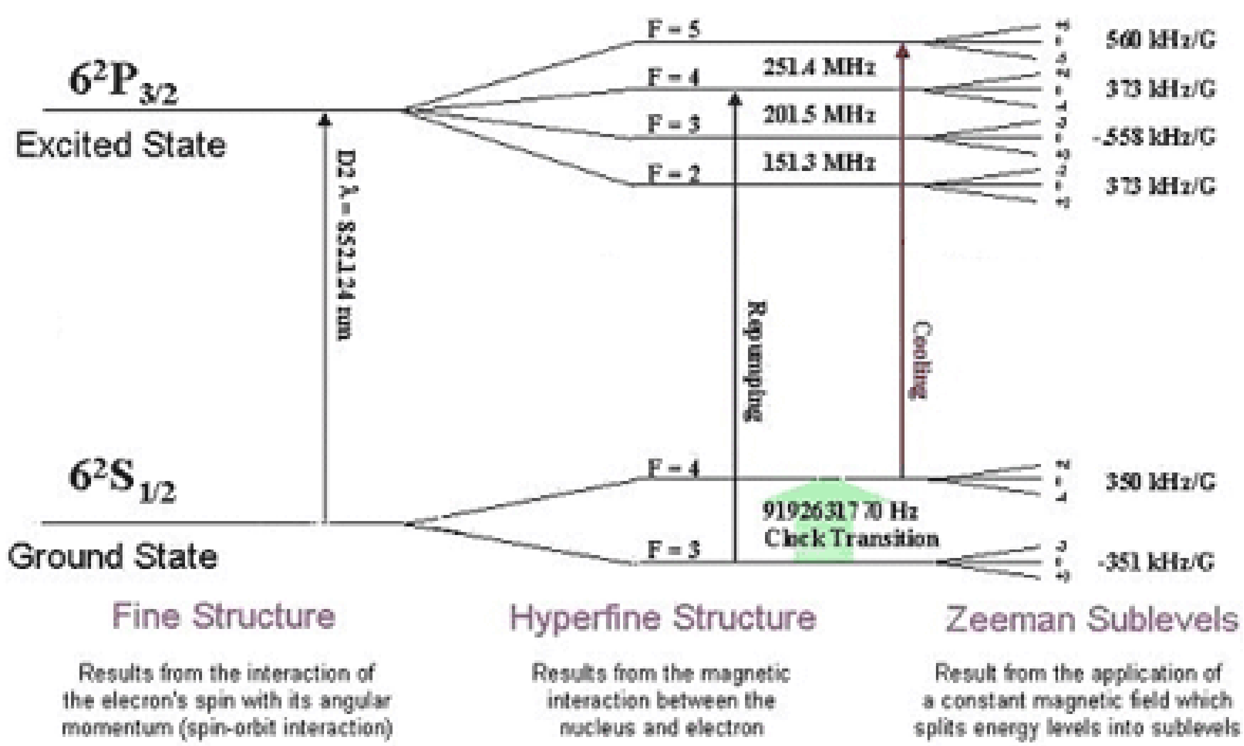


9 192 631 770 periods per second

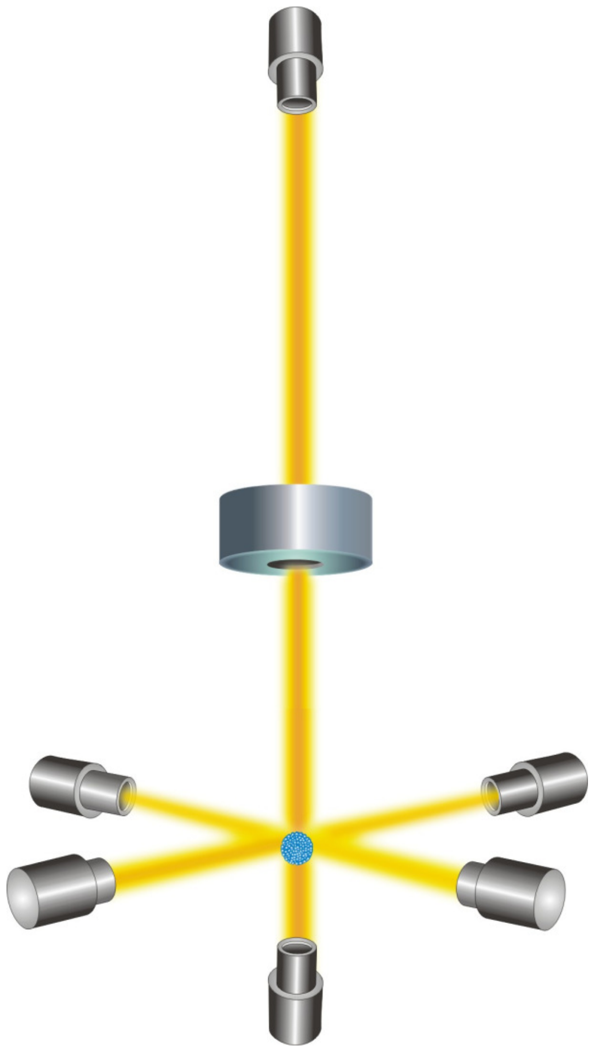
Current definition of a second:

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.

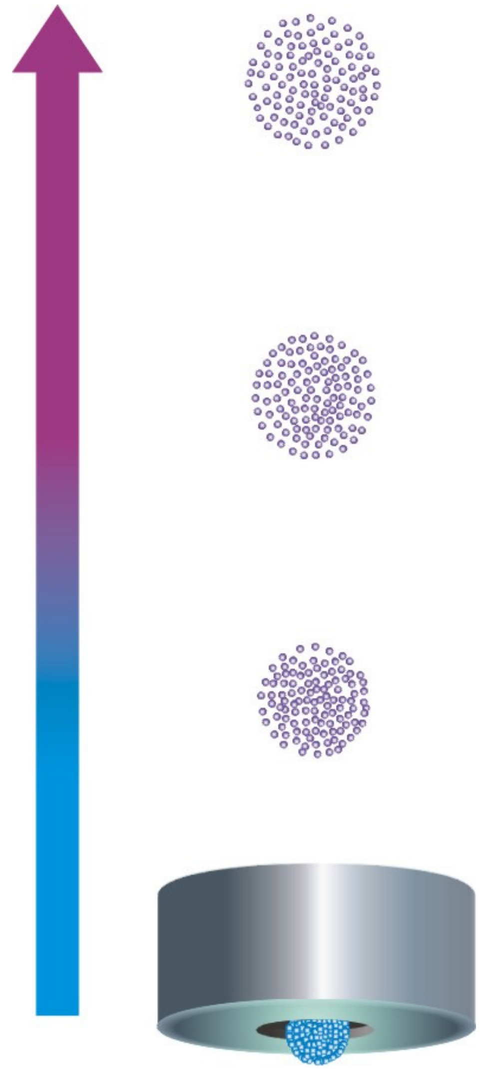
1997: the periods would be defined for a cesium atom at rest, and approaching the theoretical temperature of absolute zero (0 K).



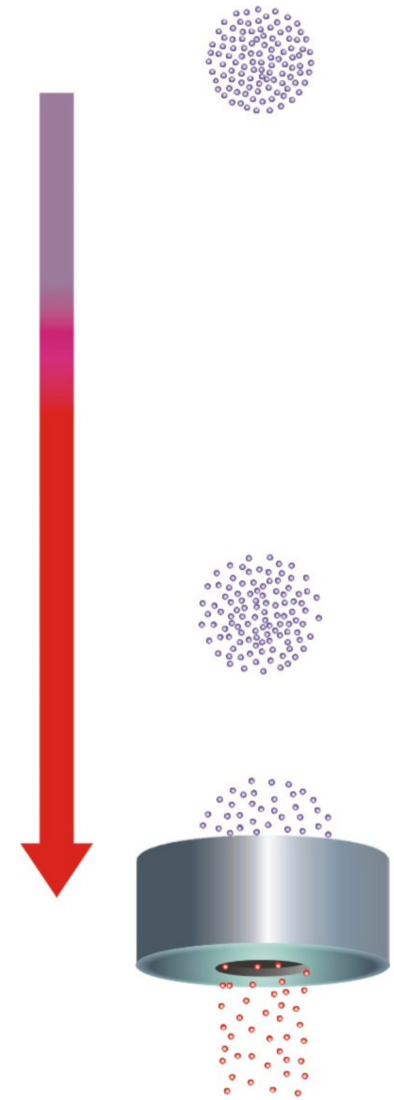
Cesium atomic clock



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.



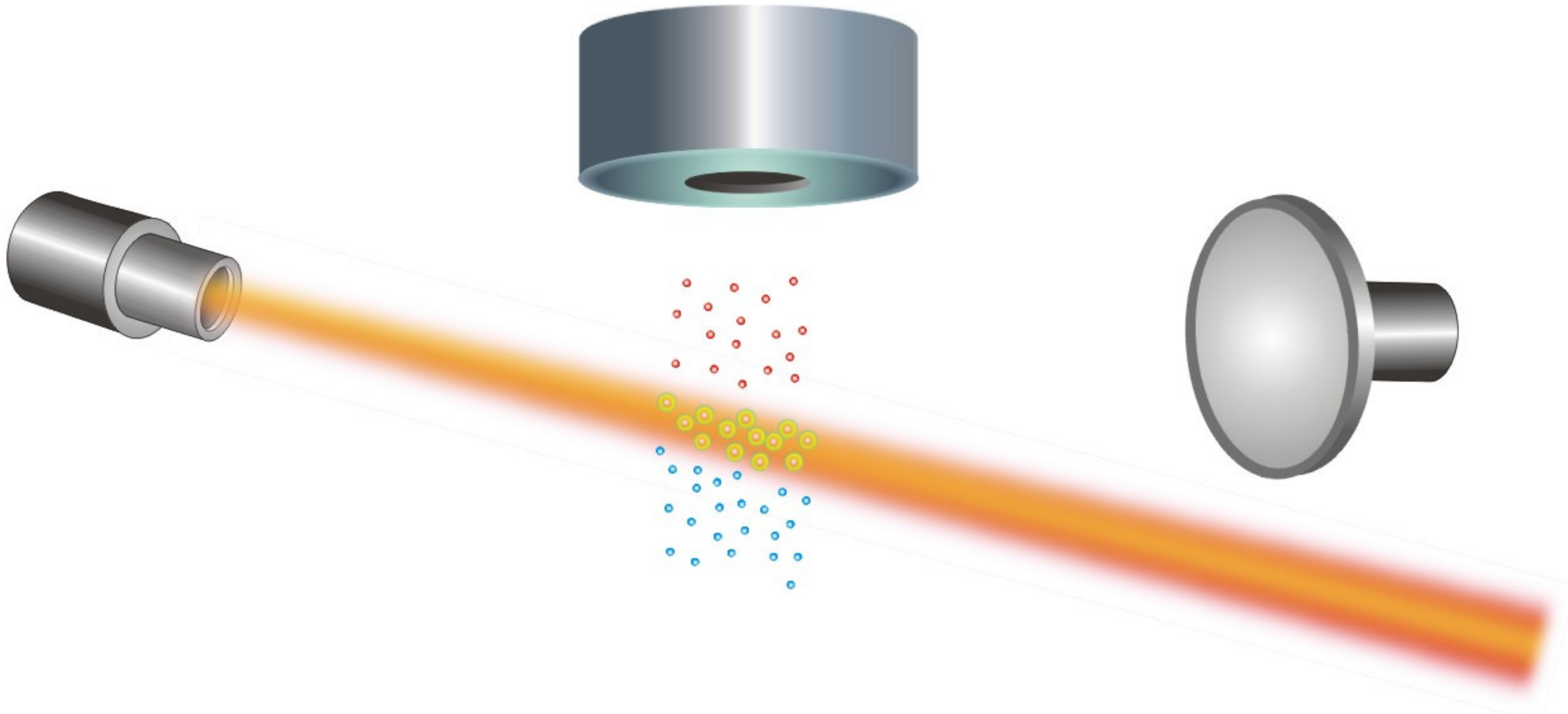
The ball is tossed upward by two lasers through a cavity filled with microwaves. All of the lasers are then turned off.



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.

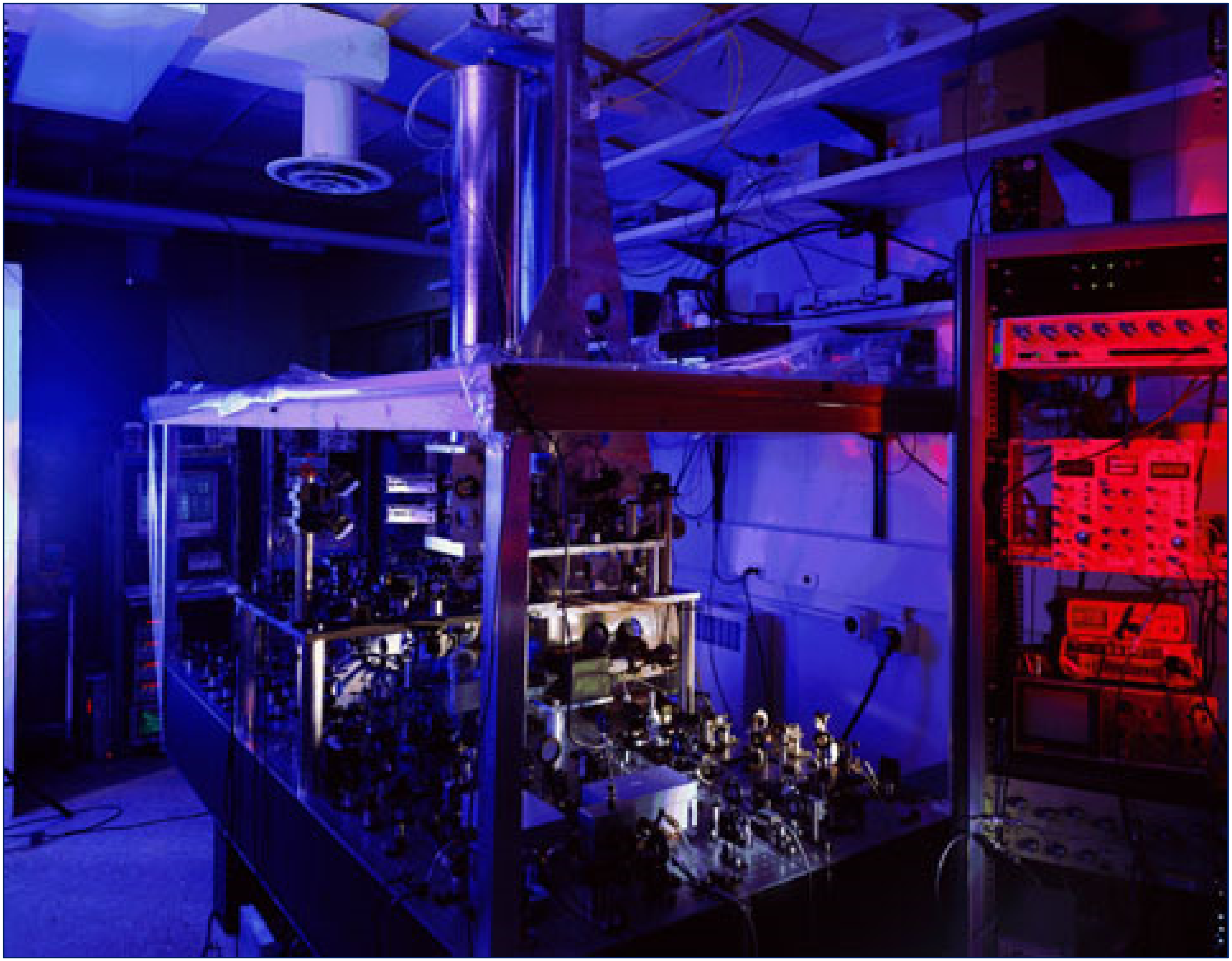
This fluorescence is measured by a detector (right).

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.

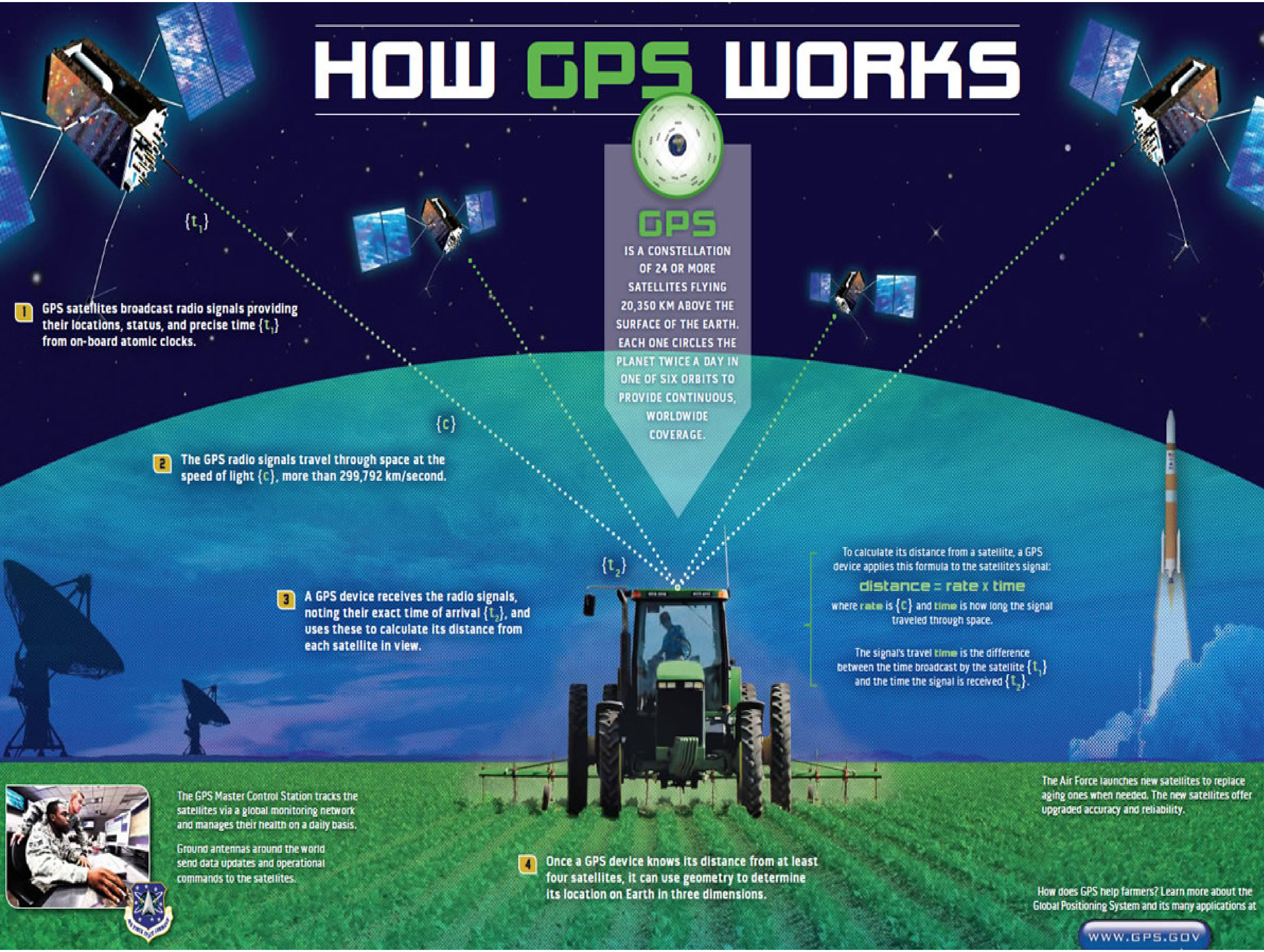
This point defines the natural resonance frequency of cesium, which is used to define the second.

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

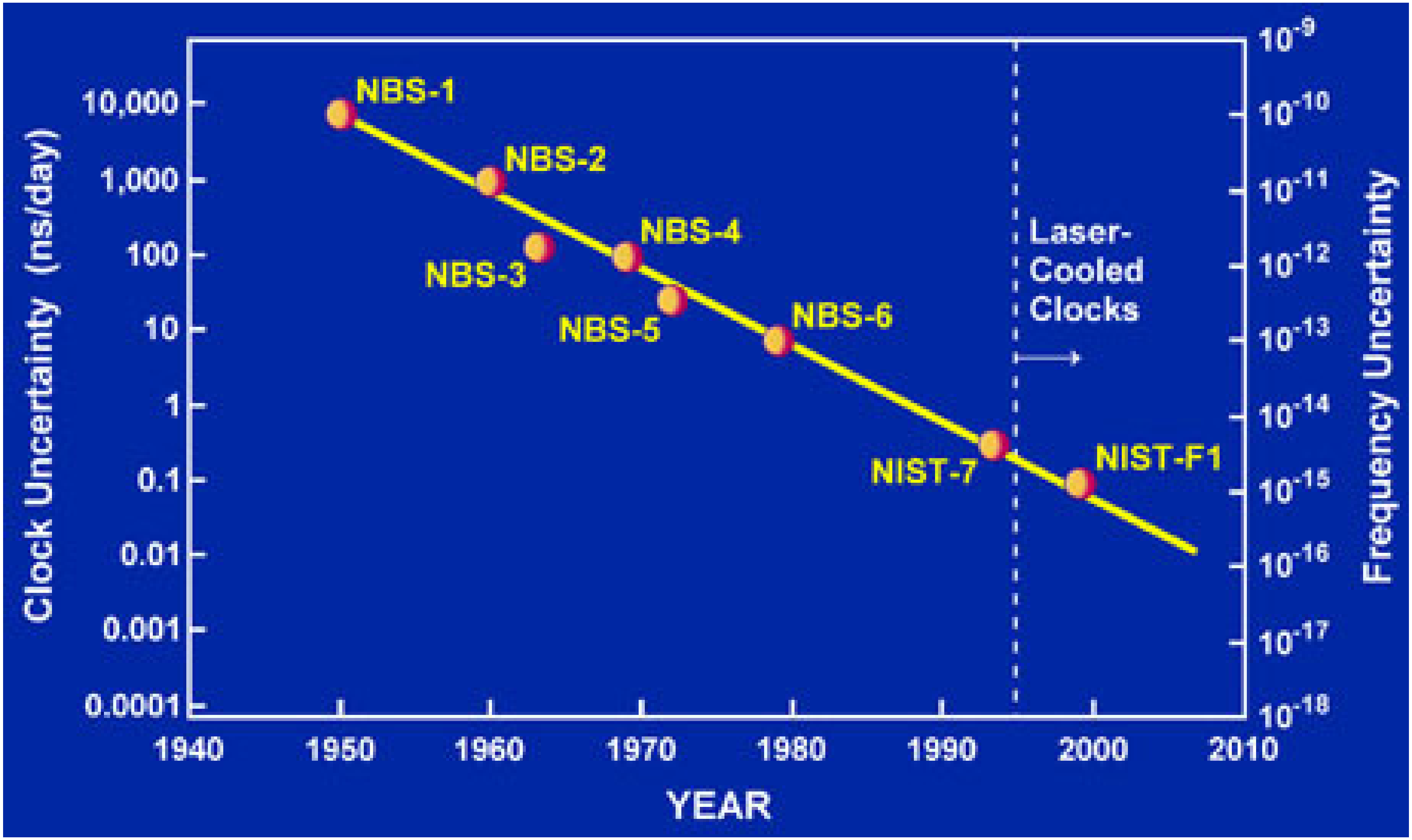
NIST Cs clock



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

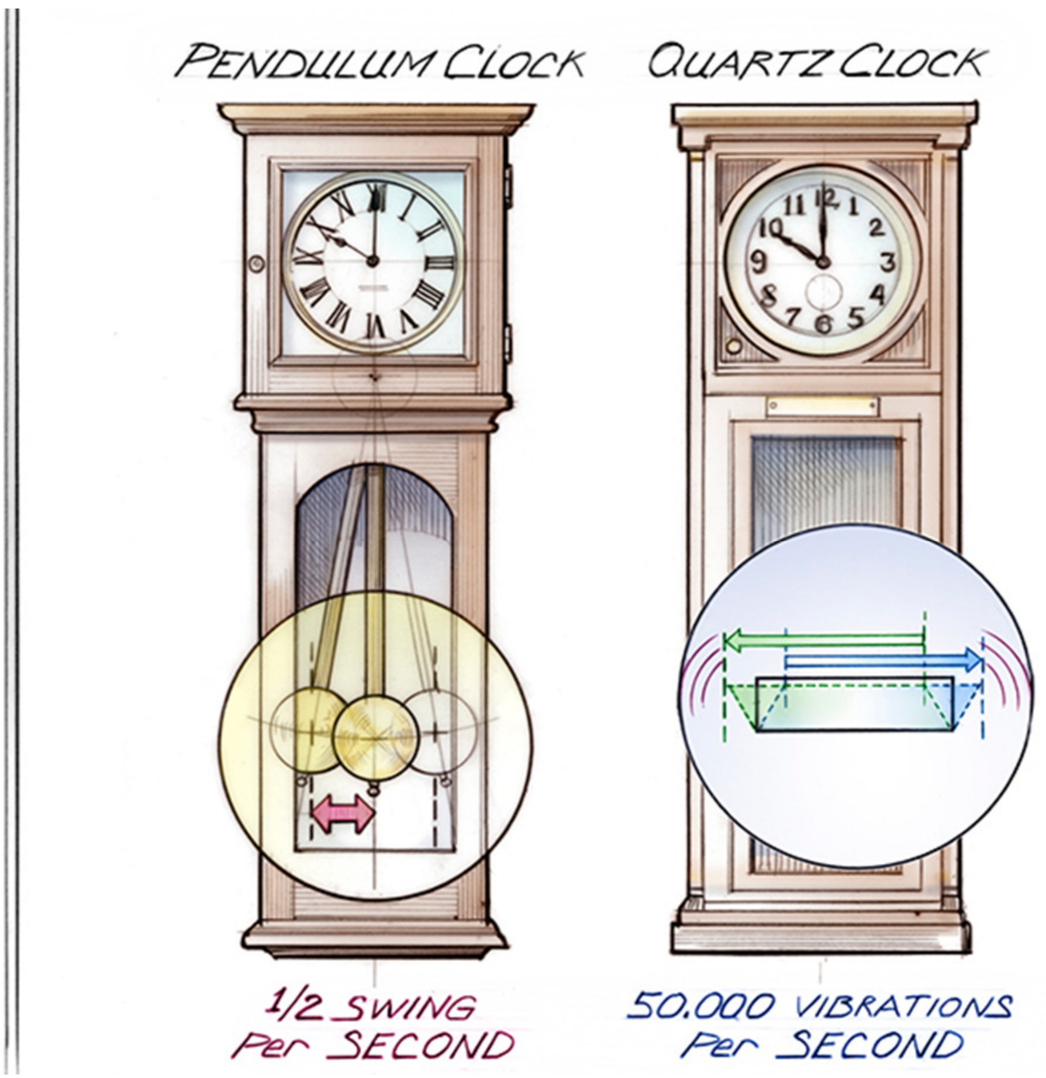


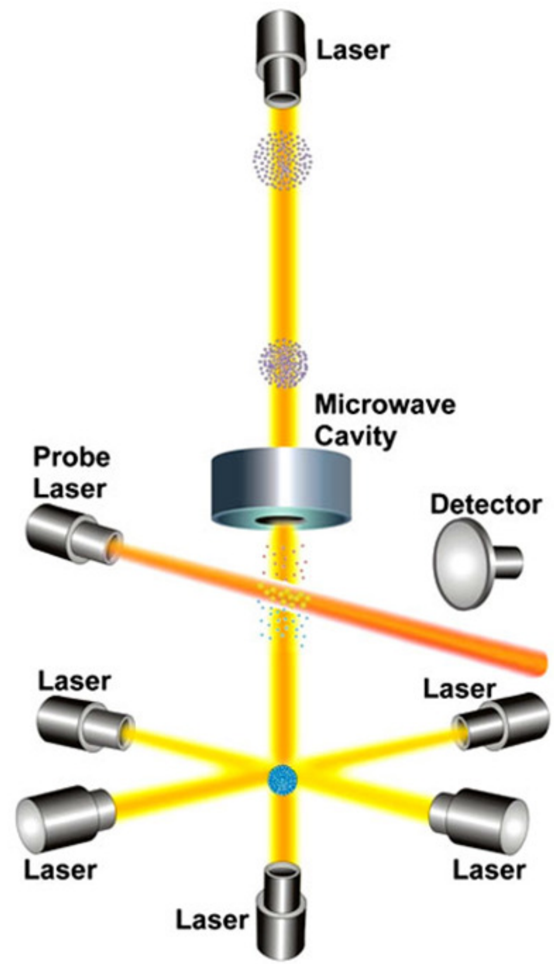
HOW GPS WORKS
GPS
IS A CONSTELLATION OF 24 OR MORE SATELLITES FLYING 20,350 KM ABOVE THE SURFACE OF THE EARTH. EACH ONE CIRCLES THE PLANET TWICE A DAY IN ONE OF SIX ORBITS TO PROVIDE CONTINUOUS, WORLDWIDE COVERAGE.
{t1}
1 GPS satellites broadcast radio signals providing their locations, status, and precise 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)
10,000
1,000
100
10
1
0.1
0.01
0.001
0.0001
Frequency Uncertainty
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 more accurate clock? Need more periods per second!

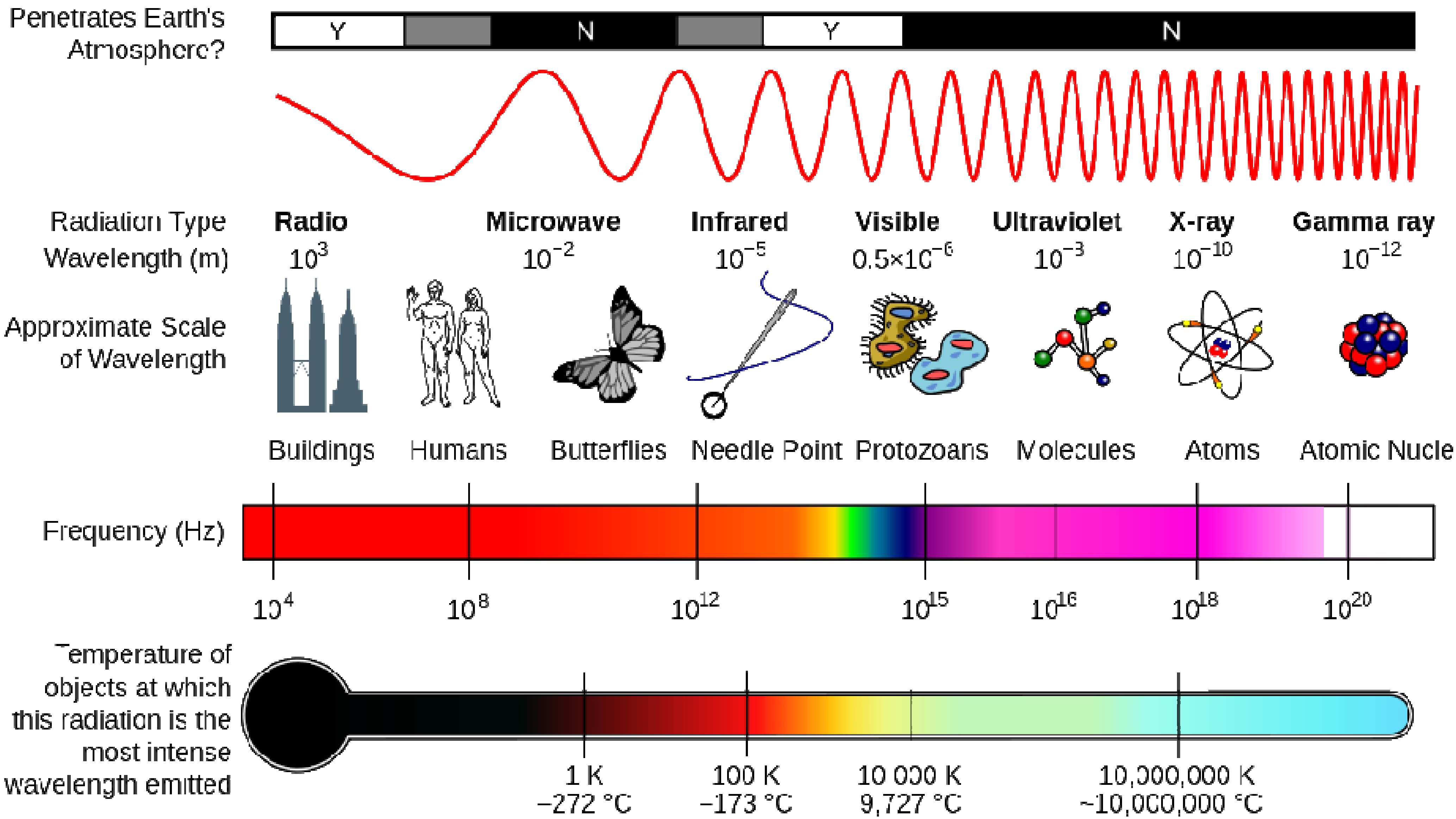




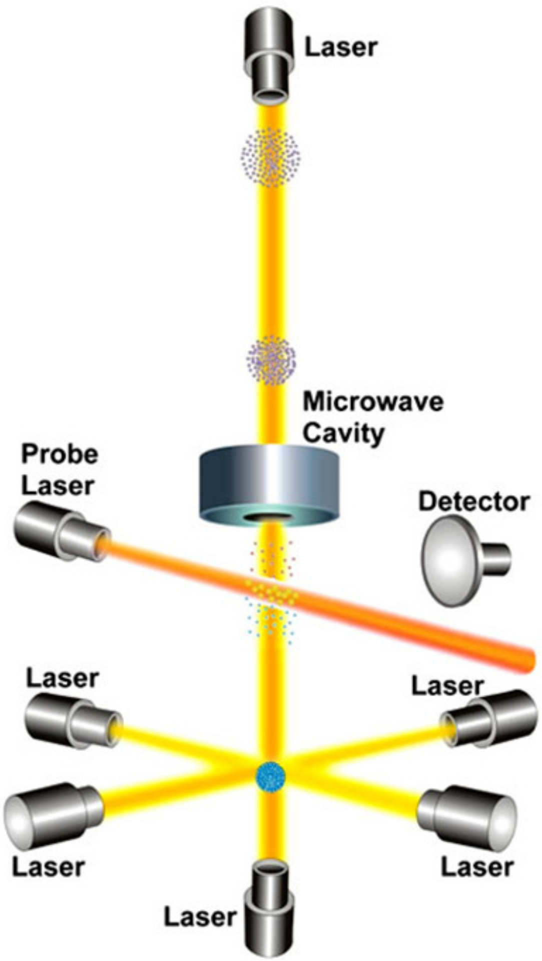
9 192 631 770 periods per second

timeandnavigation.si.edu

How to build a more accurate clock?
Need more periods per second!

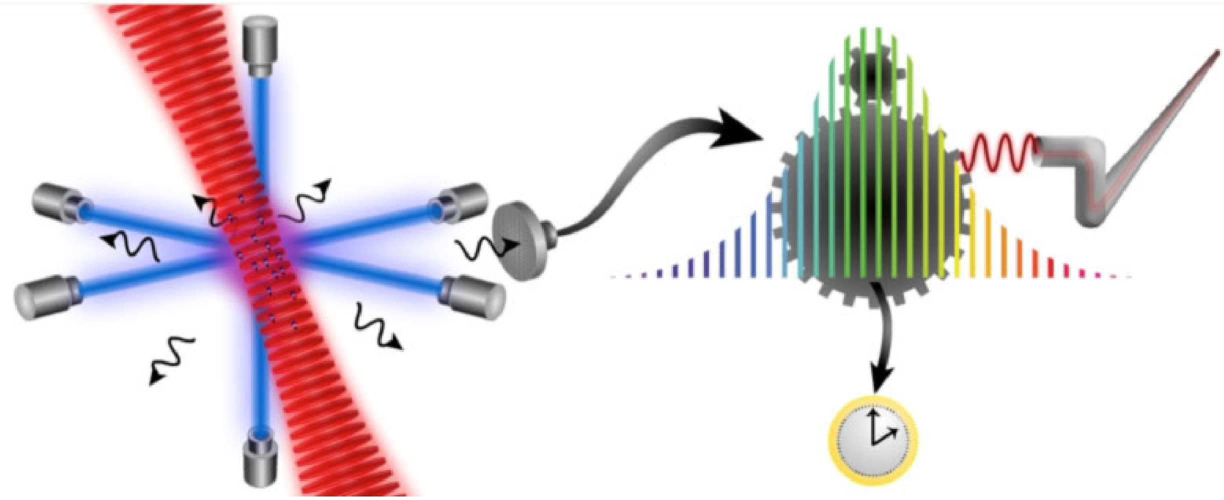


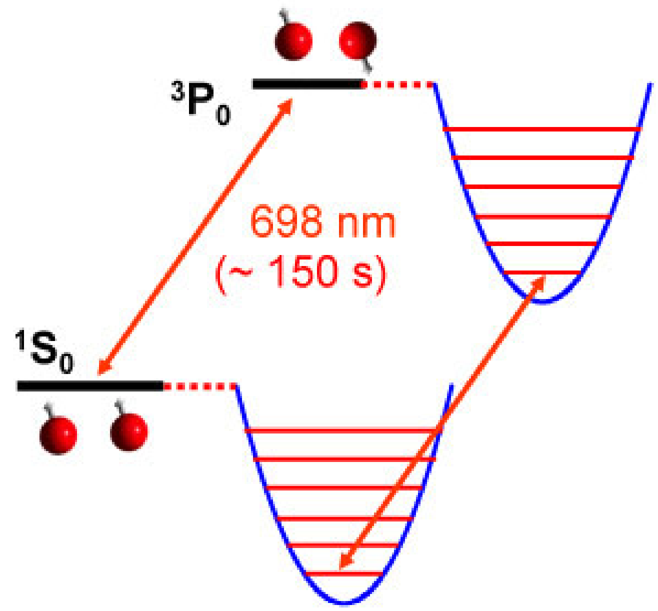
Cesium microwave atomic clock



9 x 10^9 periods per second

Strontium optical atomic clock

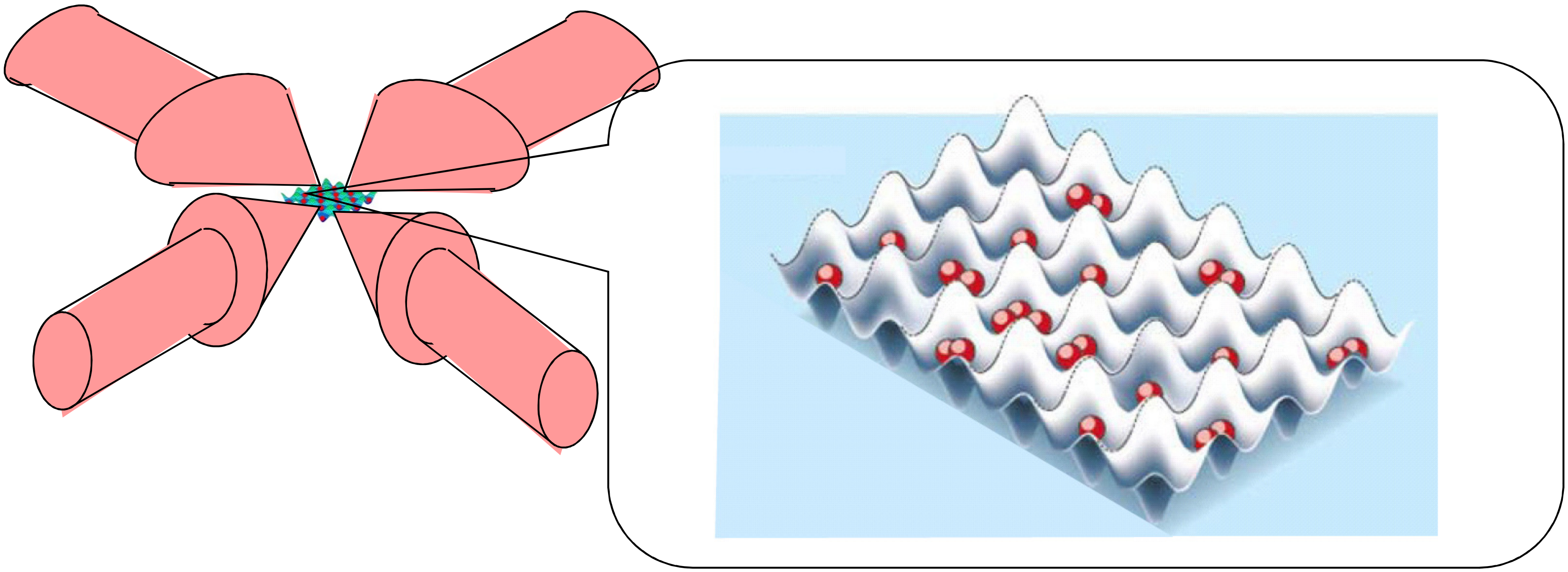




4.3 x 10^{14} periods per second

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

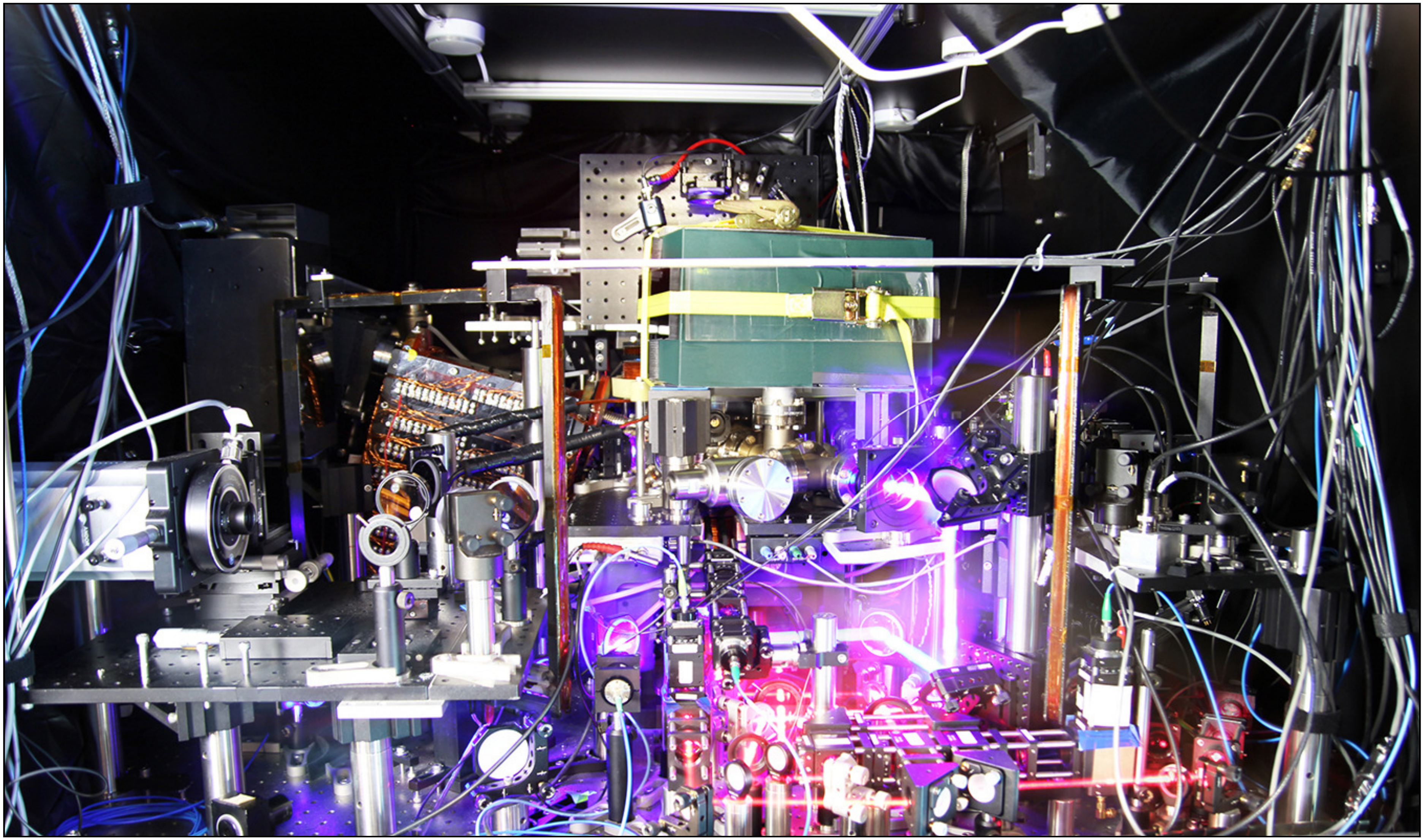
Atoms in optical lattices



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.

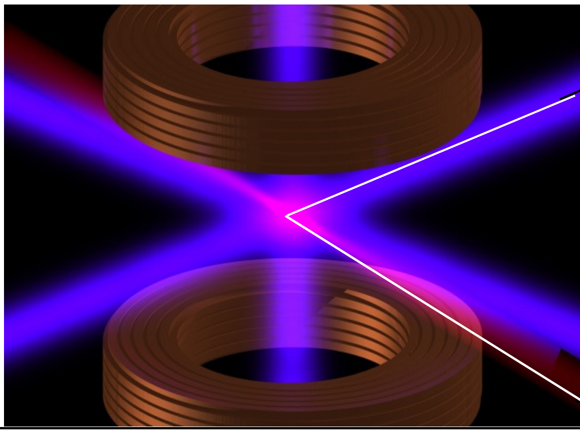
Adapted from: Eugene Demler

Strontium optical atomic clock



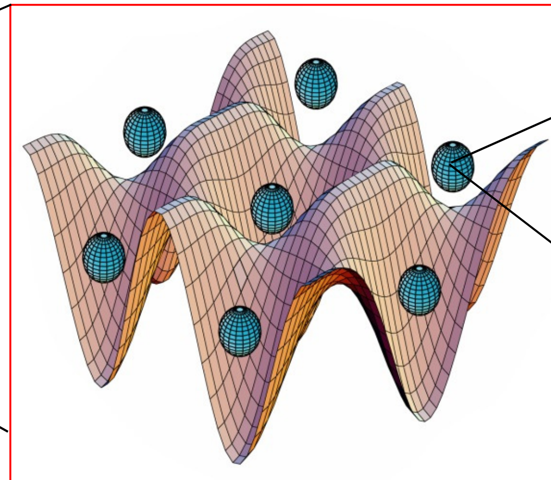
http://www.nist.gov/pml/div689/20140122_strontium.cfm

MOTIATION: NEXT GENERATION ATOMIC CLOCKS

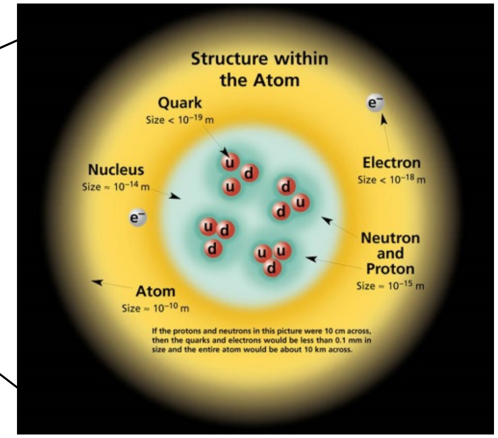


Next - generation ultra precise atomic clock

NIST Yb clock



Atoms trapped by laser light



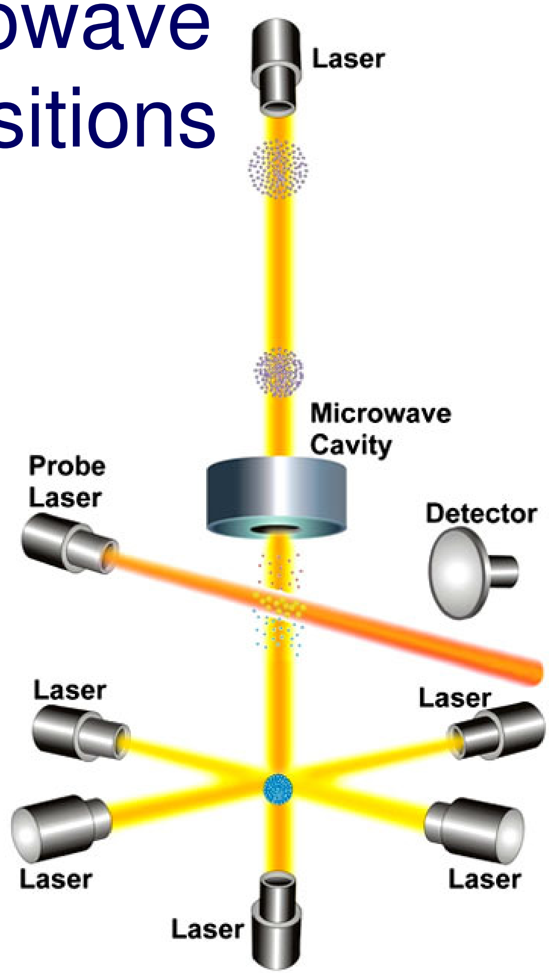
http://CPEPweb.org

The ability to develop more precise optical frequency standards is essential for new tests of fundamental physics, search for the variation of fundamental constants, and very-long-baseline interferometry for telescope array synchronization.

More precise clocks will enable the development of extremely sensitive quantum-based tools for geodesy, hydrology, and climate change studies, inertial navigation, and tracking of deep-space probes.

Atomic frequency standards

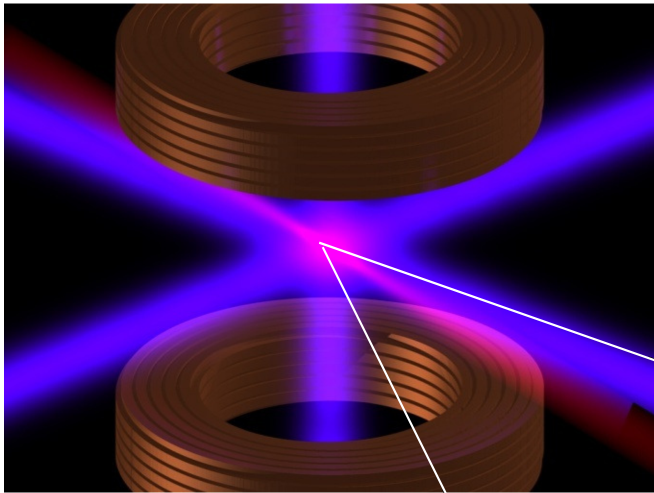
Microwave Transitions



Cs: 4×10^{-16}

M. A. Lombardi, T. Heavner, and S. Jefferts, Measure: J. Meas.Sci. 2, 74 (2007).

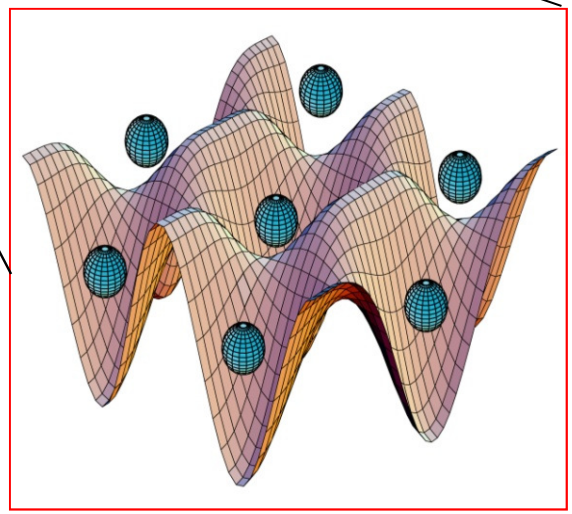
Optical Transitions



Neutral atoms in optical lattices

Single ion

Th: nuclear clock?



Sr: 6.4×10^{-18}

B. J. Bloom et al., Nature 506, 71 (2014)

Back to our question: Can we look for α–variation in a lab?

Different optical atomic clocks use transitions that have different contributions of the relativistic corrections to frequencies.

Therefore, comparison of these clocks can be used to search for α–variation.

The most precise laboratory test of α–variation has been carried out at NIST [1] by measuring the frequency ratio of Al^{+} and Hg^{+} optical atomic clocks with a fractional uncertainty of 5.2×10^{-17}.

Repeated measurements during the year yielded a constraint on the temporal variation of $\dot{\alpha}/\alpha = -1.6(2.3)\times10^{-17}$.

[1] T. Rosenband et al.,Science 319, 1808 (2008).

Topic 4:
Quantum Information

Why quantum information?

Information is physical!

Any processing of information

is always performed by physical means

Bits of information obey laws of classical physics.

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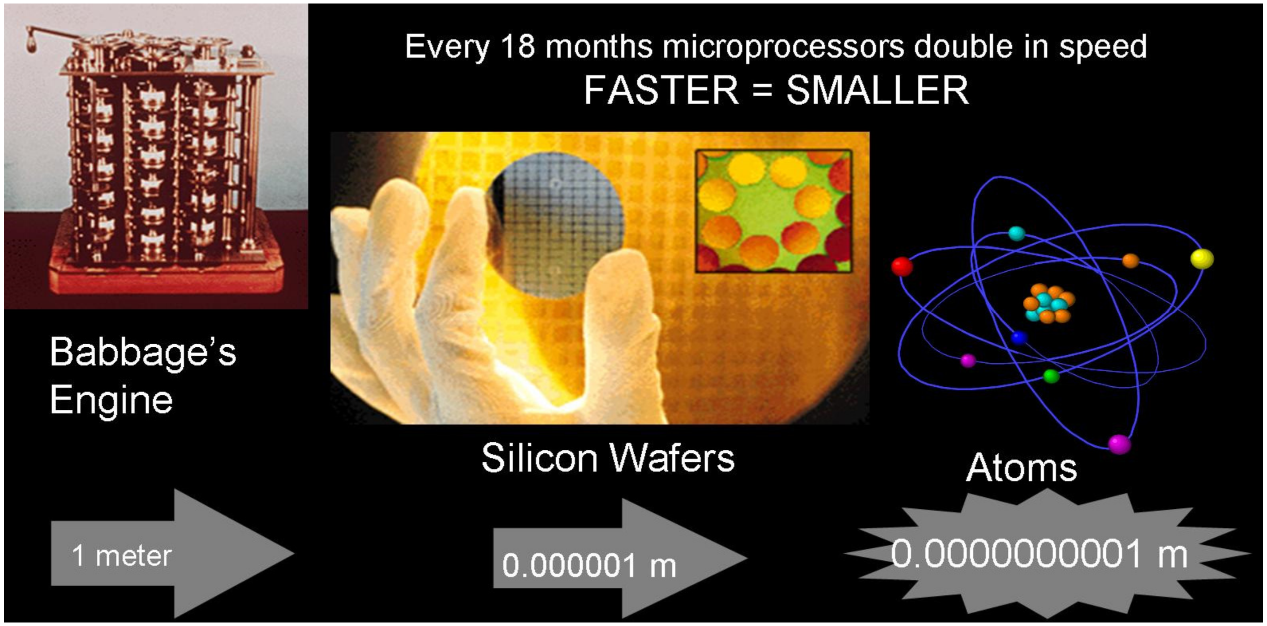
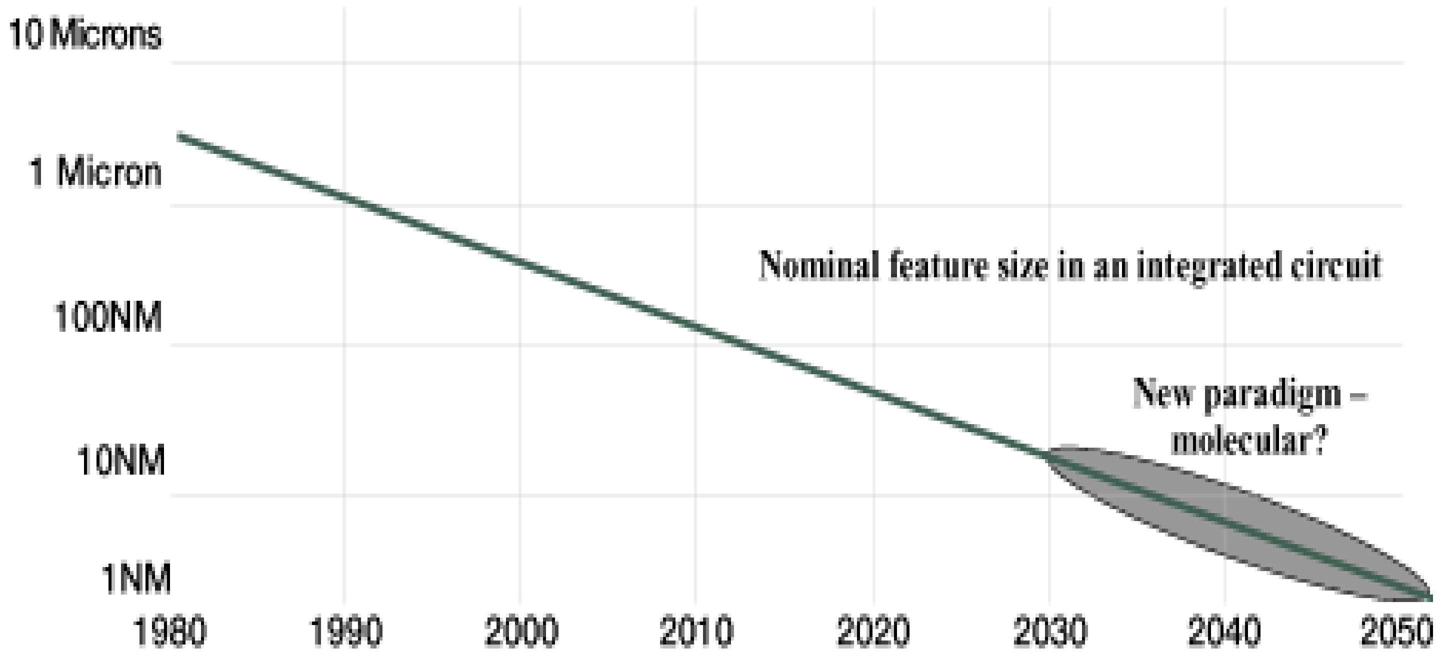
Bits of information obey laws of classical physics.



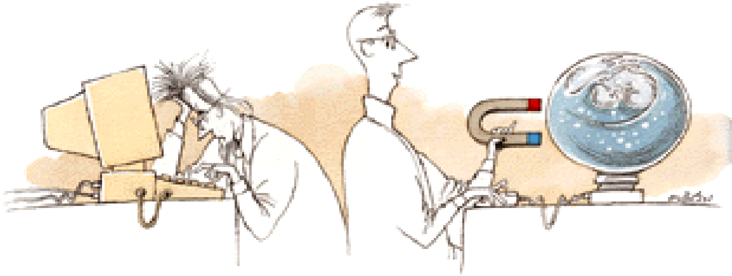
Why Quantum Computers?



Computer technology is making devices smaller and smaller…

…reaching a point where classical physics is no longer a suitable model for the laws of physics.

Bits & Qubits



Fundamental building blocks of classical computers:

BITS

STATE:

Definitely

0 or 1

Fundamental building blocks of quantum computers:

Quantum bits

or

QUBITS

Basis states: $|0\rangle$ and $|1\rangle$

Superposition:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Bits & Qubits

Fundamental building blocks of classical computers:

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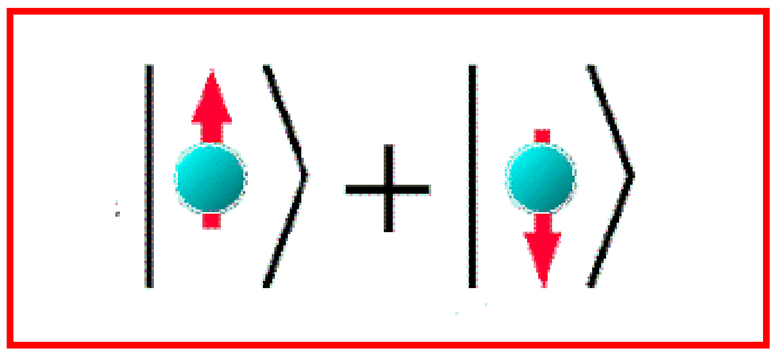
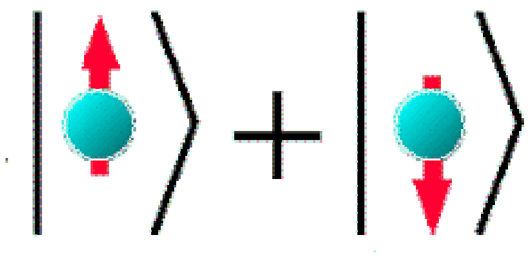
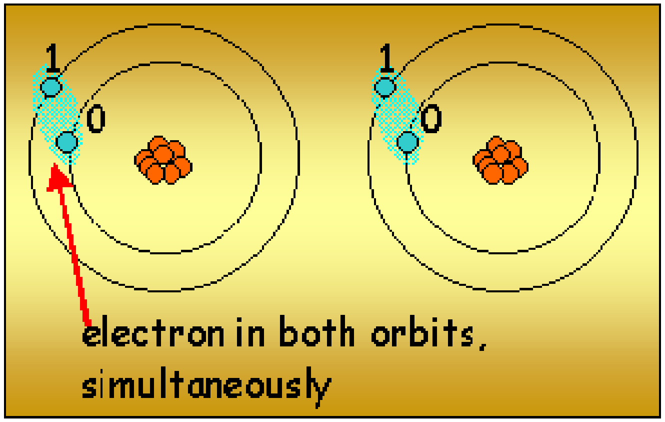
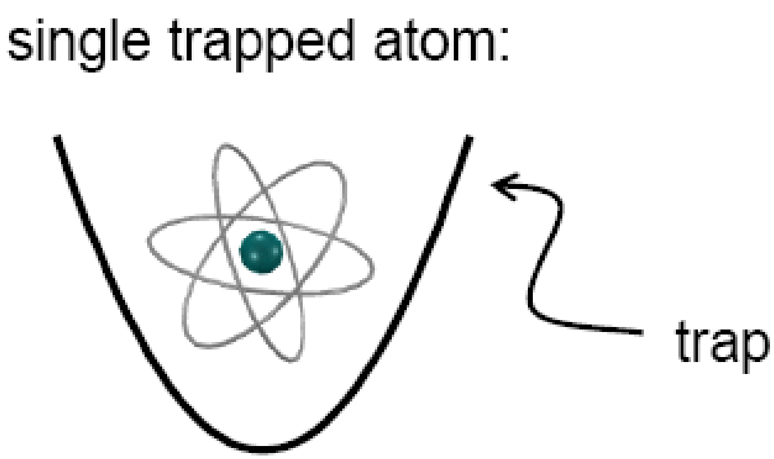
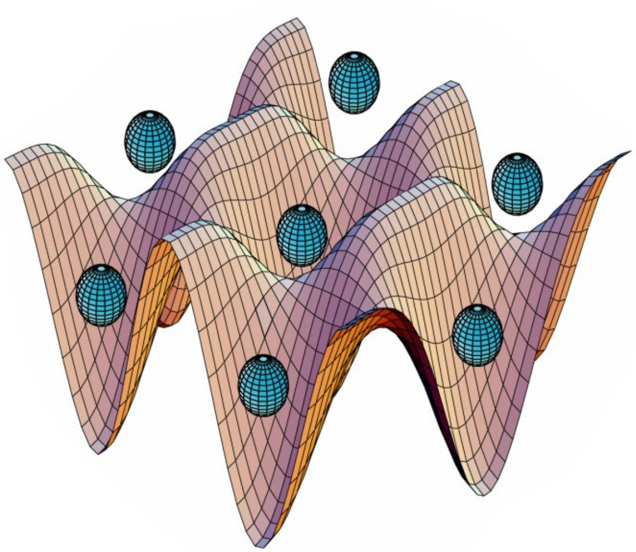


Qubit: any suitable two-level quantum system





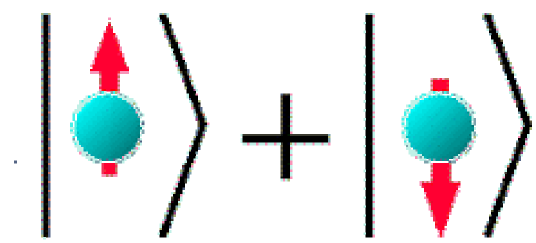




Bits & Qubits: primary differences

Superposition

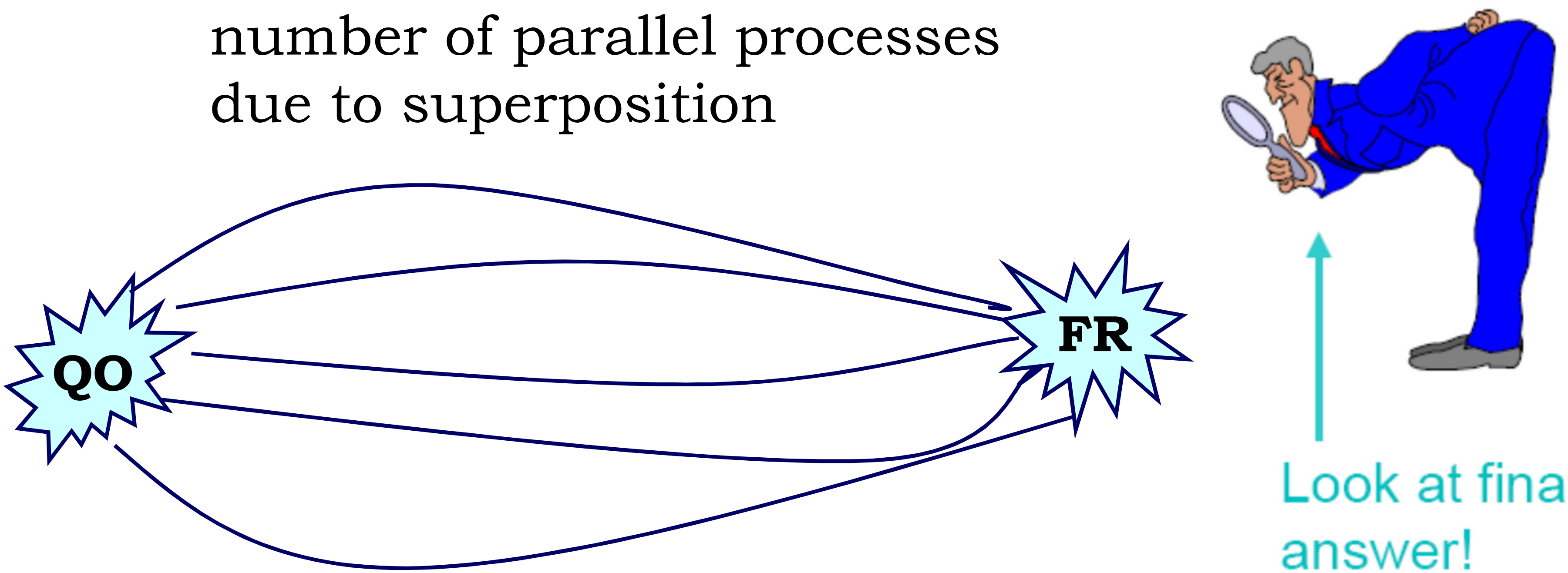
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$



Bits & Qubits: primary differences

Measurement

- Classical bit: we can find out if it is in state 0 or 1 and the measurement will not change the state of the bit.
- Qubit: Quantum calculation: number of parallel processes due to superposition



Bits & Qubits: primary differences

- Superposition
- Measurement

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

- Classical bit: we can find out if it is in state 0 or 1 and the measurement will not change the state of the bit.
- Qubit: we cannot just measure α and β and thus determine its state! We get either $|0\rangle$ or $|1\rangle$ with corresponding probabilities $|\alpha|^2$ and $|\beta|^2$.

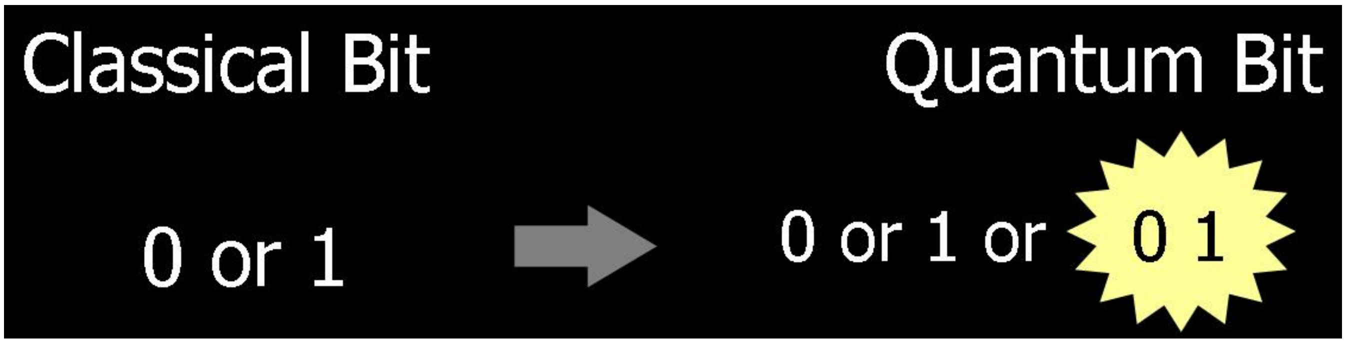
$$|\alpha|^2 + |\beta|^2 = 1$$

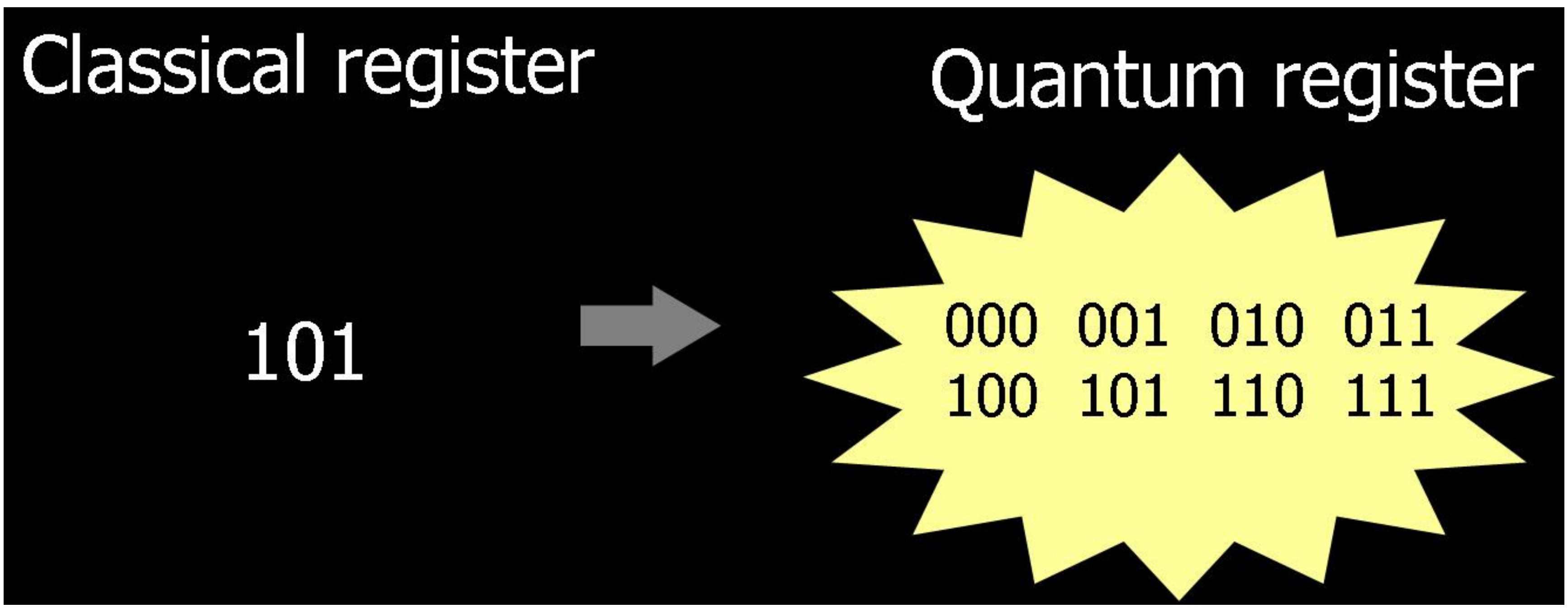
- The measurement changes the state of the qubit!

Hilbert space is a big place!

- Carlton Caves

Multiple qubits





Hilbert space is a big place!

- Carlton Caves

Multiple qubits

- Two bits with states 0 and 1 form four definite states 00, 01, 10, and 11.
- Two qubits: can be in superposition of four computational basis set states.

$$|\psi\rangle = \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle$$

2 qubits	4 amplitudes
3 qubits	8 amplitudes
10 qubits	1024 amplitudes
20 qubits	1 048 576 amplitudes
30 qubits	1 073 741 824 amplitudes
500 qubits	More amplitudes than our estimate of number of atoms in the Universe!!!

Entanglement

$$|\psi\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

Results of the measurement

First	qubit	0	1
Second qubit		0	1

$$|\psi\rangle \neq |\alpha\rangle \otimes |\beta\rangle \longrightarrow$$

Entangled states

What do we need to build a quantum computer?

- **Qubits** which retain their properties.

  Scalable array of qubits.

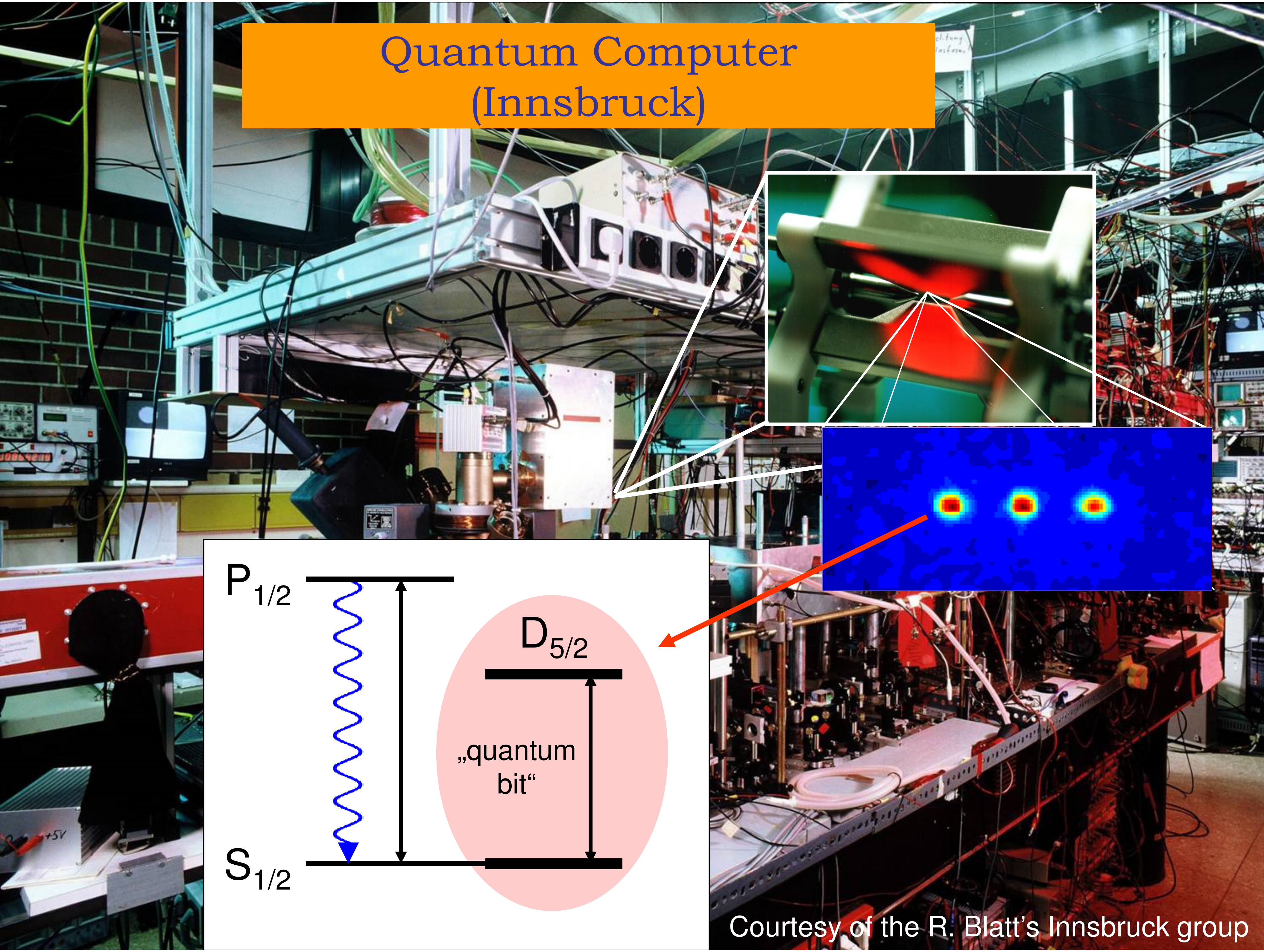
- **Initialization:** ability to prepare one certain state repeatedly on demand. Need continuous supply of $|0\rangle$.

- **Universal set of quantum gates.** A system in which qubits can be made to evolve as desired.

- **Long relevant decoherence times.**

- Ability to efficiently **read out the result.**

Quantum Computer (Innsbruck)



Experimental proposals

- Liquid state NMR
- **Trapped ions**
- Cavity QED
- **Trapped atoms**
- Solid state schemes
- And other ones …

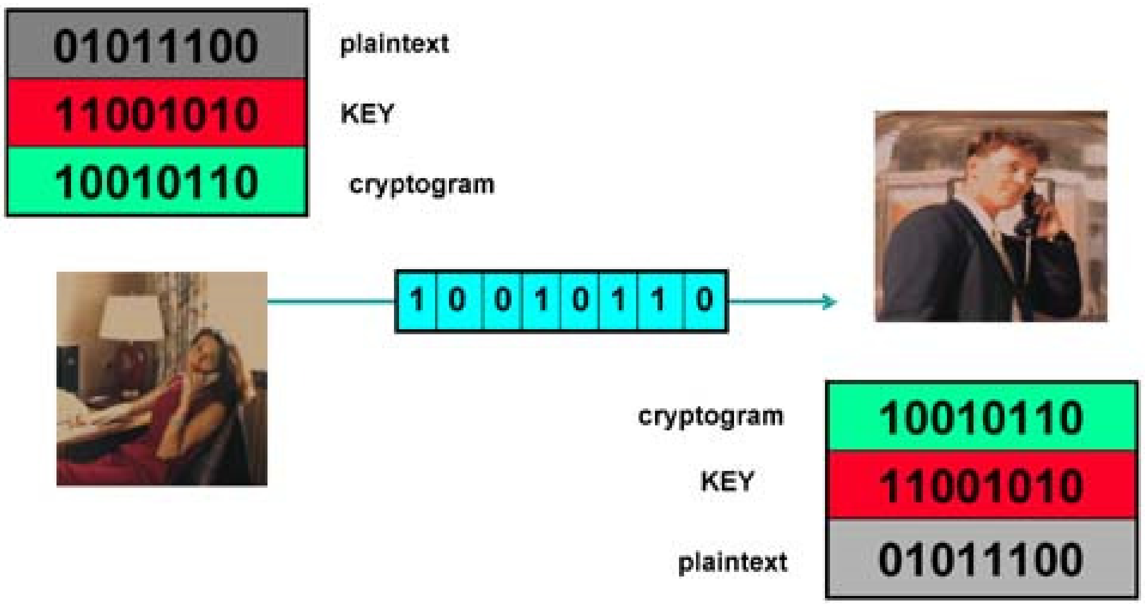
Quantum cryptography

Classical cryptography

Scytale - the first known mechanical device to implement permutation of characters for cryptographic purposes

Classical cryptography

Private key cryptography



How to securely transmit a private key?

Key distribution

A central problem in cryptography:
the key distribution problem.

1) Mathematics solution: public key cryptography.
2) Physics solution: quantum cryptography.

Public-key cryptography relies on the computational difficulty of certain hard mathematical problems (computational security)

Quantum cryptography relies on the laws of quantum mechanics (information-theoretical security).

Quantum key distribution

- Quantum mechanics: quantum bits cannot be copied or monitored.
- Any attempt to do so will result in altering it that can not be corrected.
- Problems
  - Authentication
  - Noisy channels

TOPIC 5

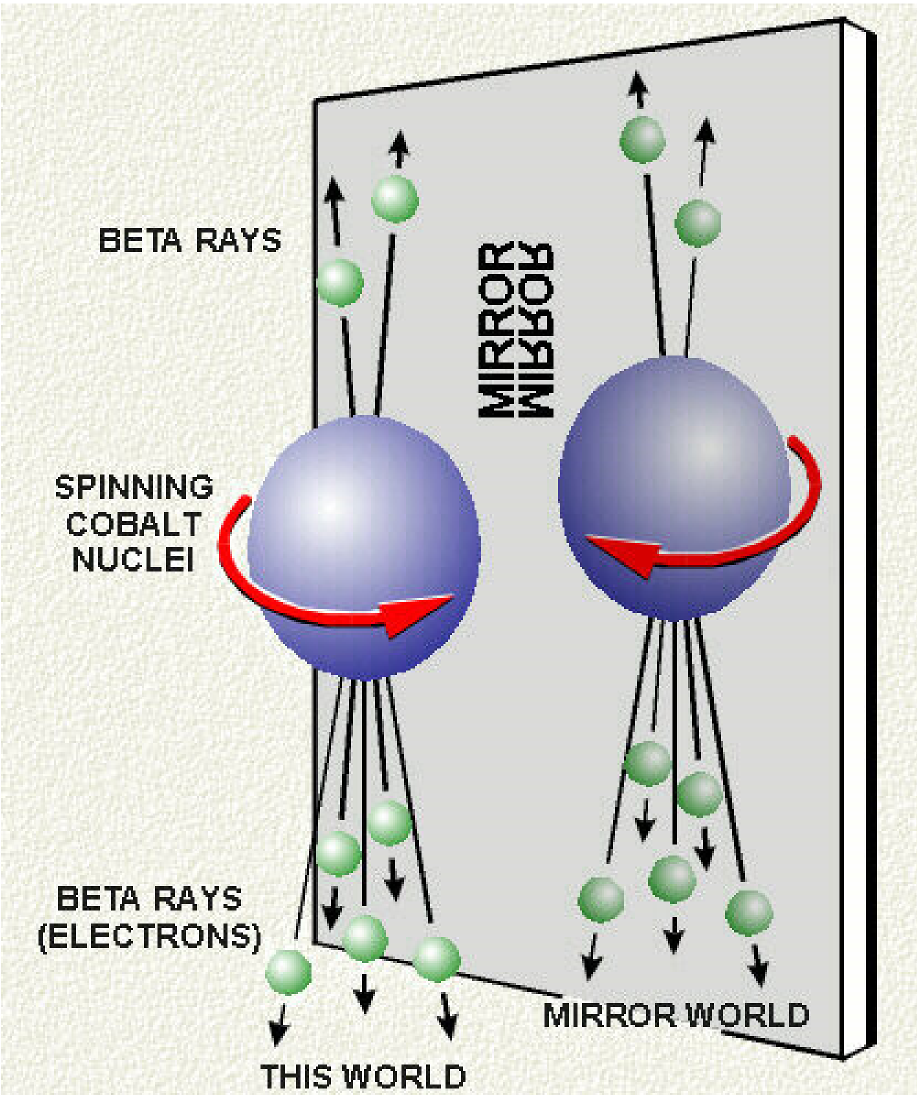
STUDIES OF FUNDAMENTAL SYMMETIRES

Transformations and Symmetries

Translation	→	Momentum conservation
Translation in time	→	Energy conservation
Rotation	→	Conservation of angular momentum
[C] Charge conjugation	→	C-invariance
[P] Spatial inversion	→	Parity conservation (P-invariance)
[T] Time reversal	→	T-invariance
[CP]		
[CPT]		

Parity Violation

$$\vec{r} \rightarrow -\vec{r}$$



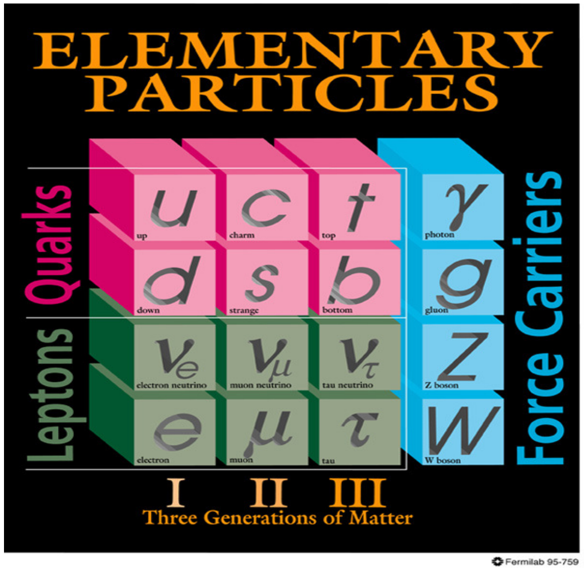
Parity-transformed world:

Turn the mirror image upside down.

The parity-transformed world is not identical with the real world.

Weak (Electr
Flavor
Quarks, Leptons
W^+ W^- Z^0
0.8
10^{-4}
10^{-7}

Parity is not conserved.



STANDARD MODEL

PROPERTIES OF THE INTERACTIONS

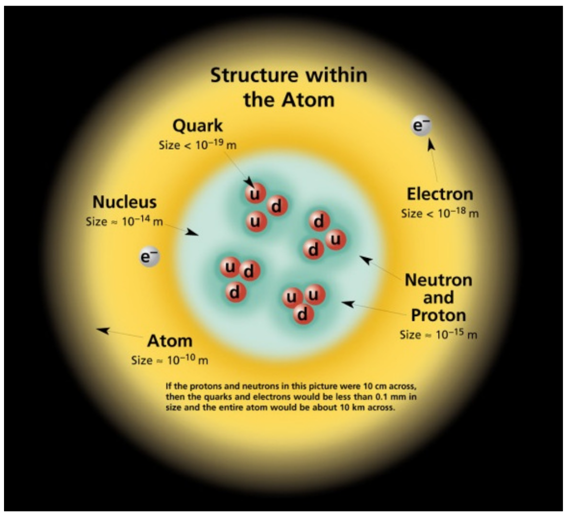
Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

PARITY VIOLATION IN ATOMS

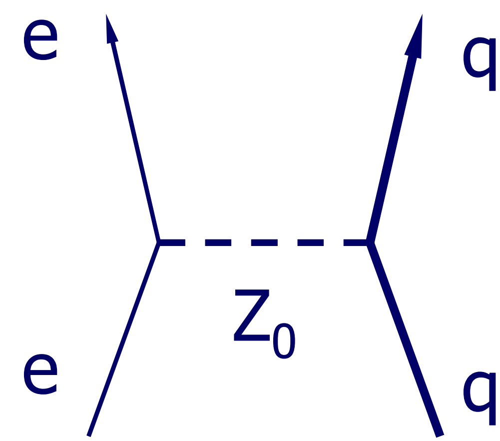
Searches for new physics beyond the Standard Model

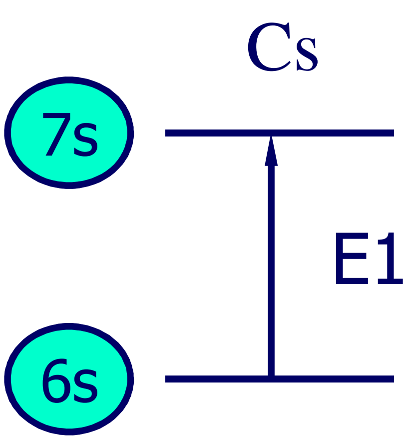
Weak Charge Q_W

$$Q_W = -N + Z(1 - 4\sin^2\theta_W)$$



Q_W quantifies the strength of the electroweak coupling between atomic electrons and quarks of the nucleus.

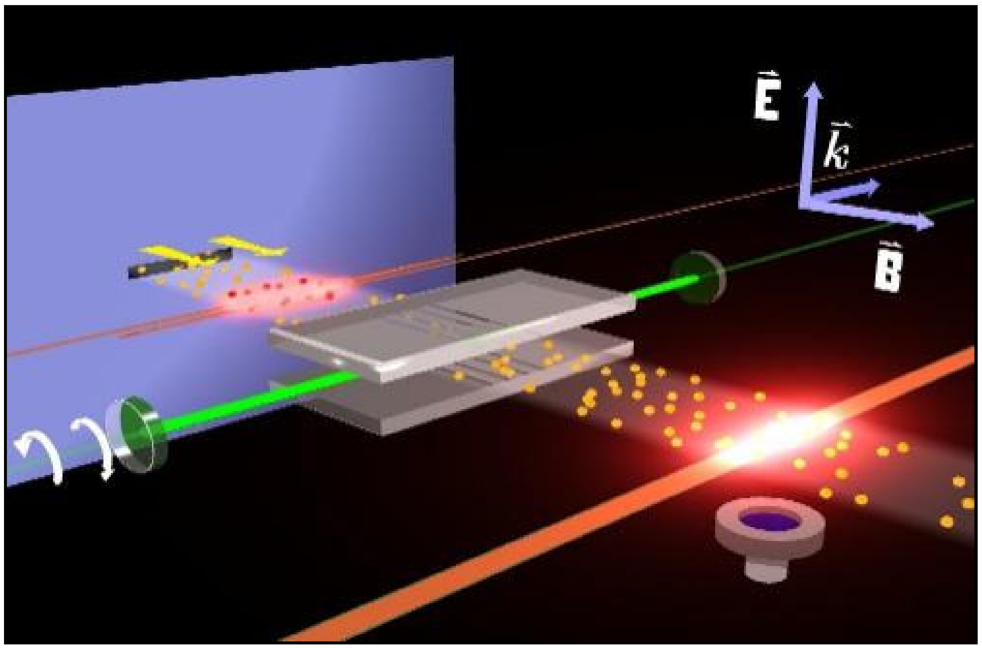




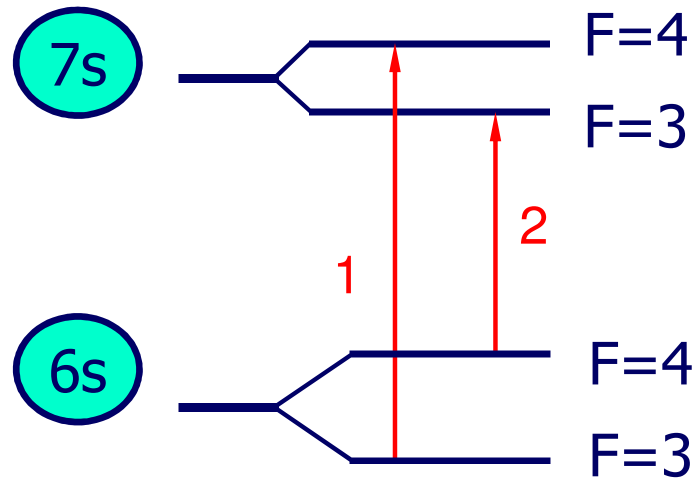
Non-zero transition amplitude
PNC amplitude E_{PNC}

The most precise measurement of PNC amplitude (in cesium)

C.S. Wood et al. Science 275, 1759 (1997)



0.3% accuracy



$$\frac{\mathrm{Im}\left(E_{\mathrm{PNC}}\right)}{\beta} = \begin{cases} -1.6349(80)\ ^{\mathrm{mV}}\!/_{\mathrm{cm}} & 1 \\ -1.5576(77)\ ^{\mathrm{mV}}\!/_{\mathrm{cm}} & 2 \end{cases}$$

NEED ATOMIC THEORY TO GET Q_W FROM THE EXPERIMENT

Reducing theory uncertainty: Why is it so difficult?

$$\left|\Psi_v\right\rangle = \Omega\left|\Psi_v^{(0)}\right\rangle$$

Exact wave function

Many-body operator,
describes excitations from lowest-order

Dirac-Hartree-Fock
wave function (lowest order)

Cs: 55 electrons → **55-fold excitations to get exact wave function**

Even for 100 function basis set → 100^{55}

Approximate methods: perturbation theory does not converge well,
Need to use all-order methods (coupled-cluster method and correlation potential method)

Atomic physics tests of the standard model, Cs nucleus

Standard Model $Q_W = -73.16(3)$

1999 analysis of Cs experiment showed 2.5σ deviation from the Standard Model

Most current result:

Atomic physics [1] $Q_W = -73.16(29)_{exp}(20)_{th}$

[1] S. G. Porsev, K. Beloy and A. Derevianko, PRL 102, 181601 (2009)

Confirms fundamental "running" (energy dependence) of the electroweak force over energy span 10 MeV → 100 GeV

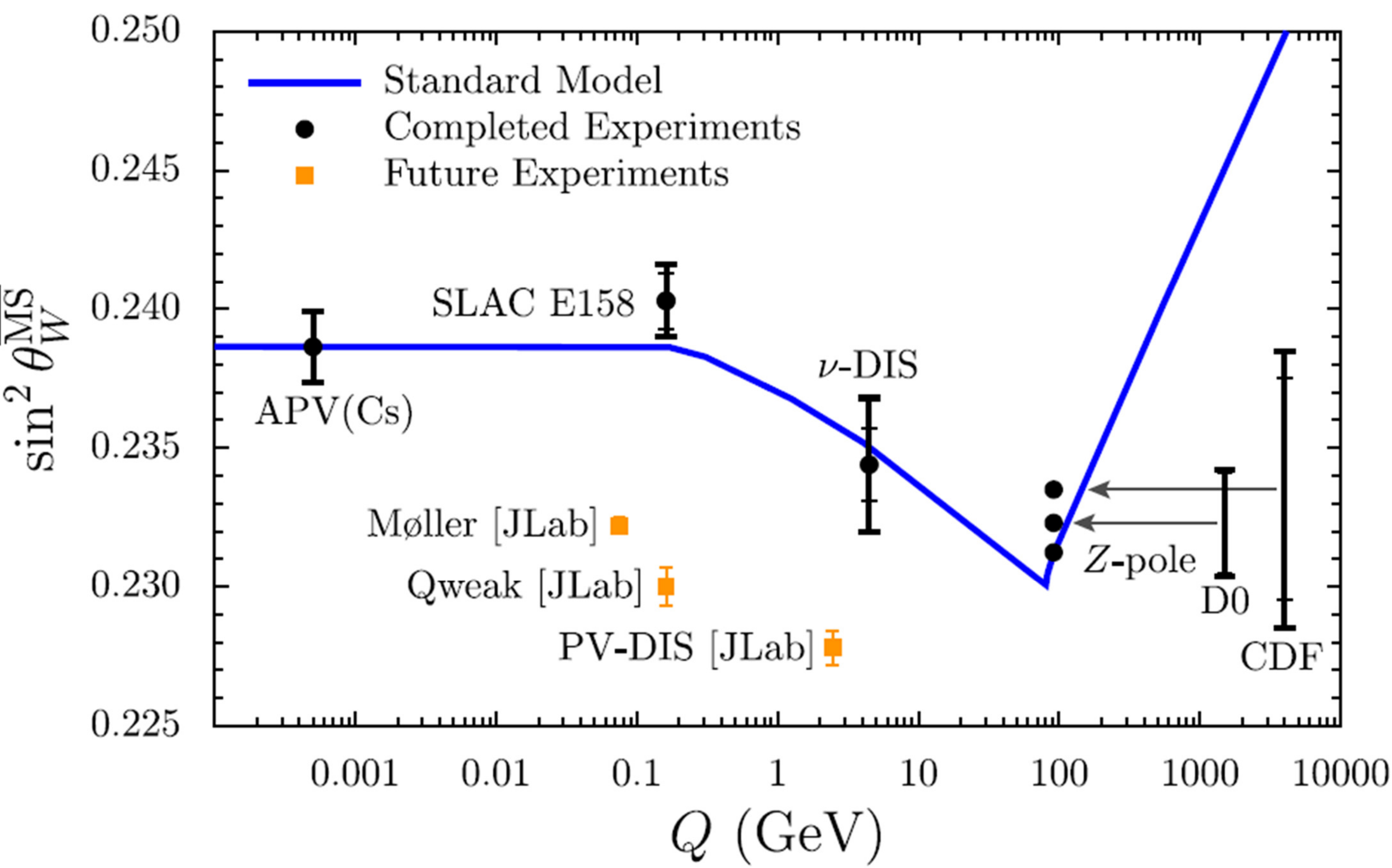
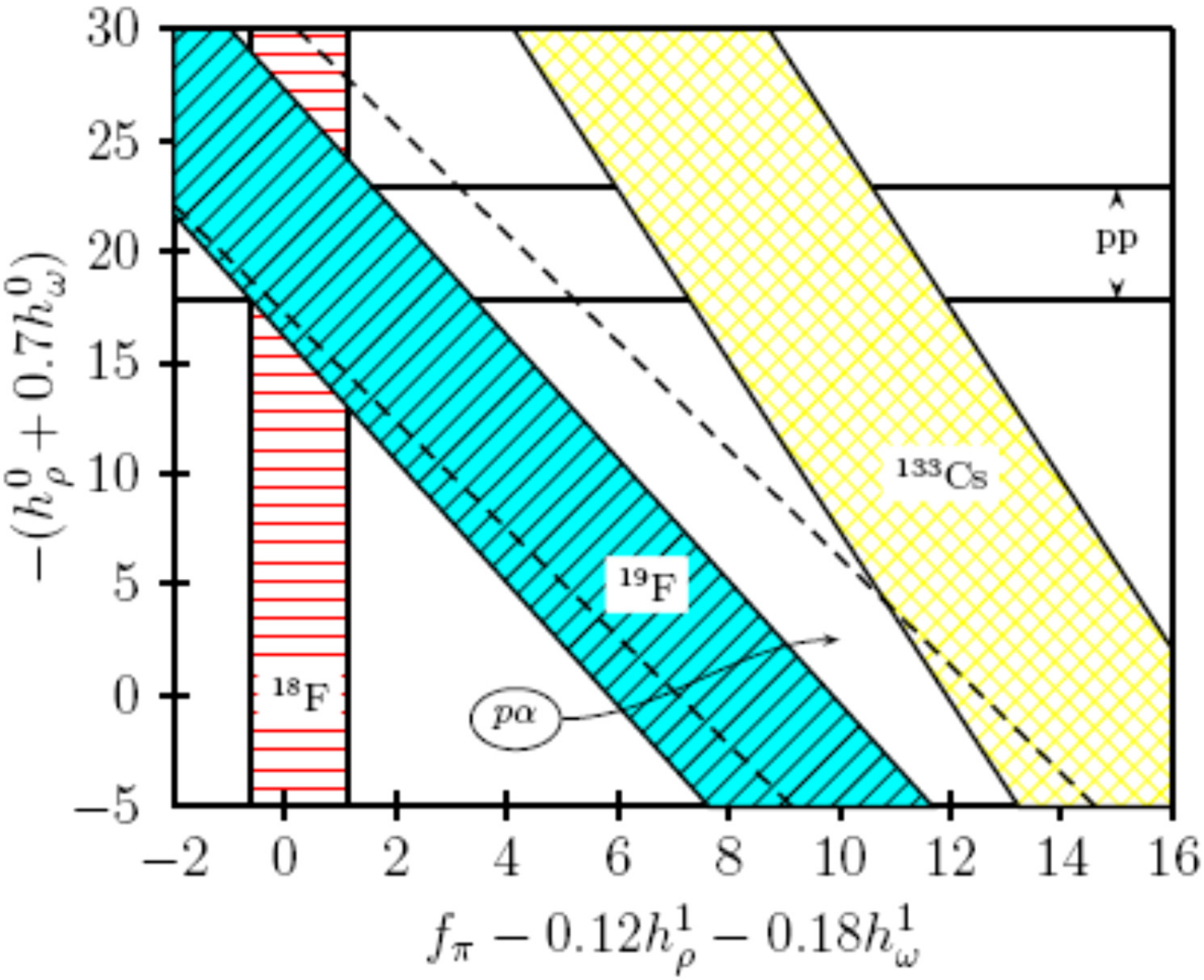


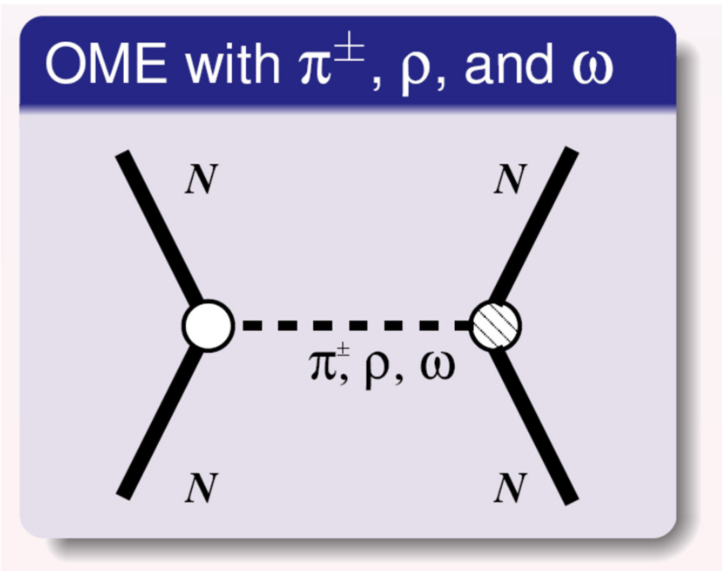
Figure is from Bentz *et al. Phys. Lett. B****693***, 462 (2010).

Constraints on nuclear weak coupling contants



Meson exchange picture

Building blocks:
nucleon, mesons, and
their couplings



From: Cheng-Pang Liu

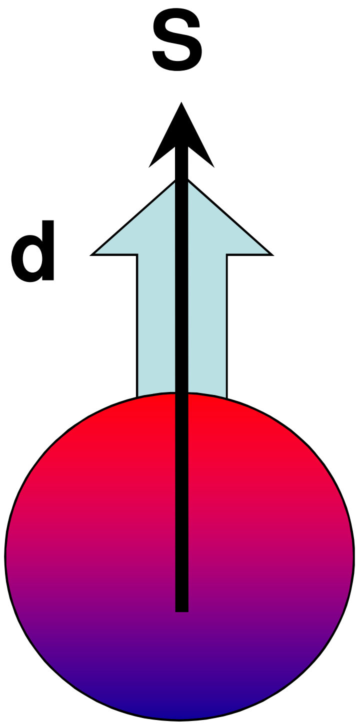
W. C. Haxton and C. E. Wieman, Ann. Rev. Nucl. Part. Sci. 51, 261 (2001)

Transformations and Symmetries

Translation	→	Momentum conservation
Translation in time	→	Energy conservation
Rotation	→	Conservation of angular momentum
[C] Charge conjugation	→	C-invariance
[P] Spatial inversion	→	Parity conservation (P-invariance)
[T] Time reversal	→	T-invariance
[CP]		
[CPT]		

Permanent electric-dipole moment (EDM)

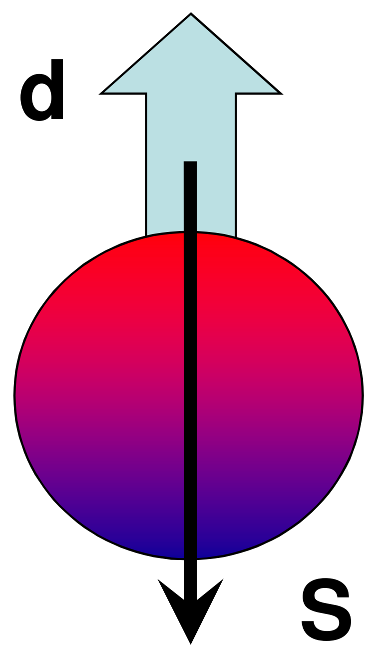
Time-reversal invariance must be violated for an elementary particle or atom to possess a permanent EDM.



$$t \rightarrow -t$$

$$\vec{\mathbf{S}} \rightarrow -\vec{\mathbf{S}}$$

$$\vec{\mathbf{d}} \rightarrow \vec{\mathbf{d}}$$

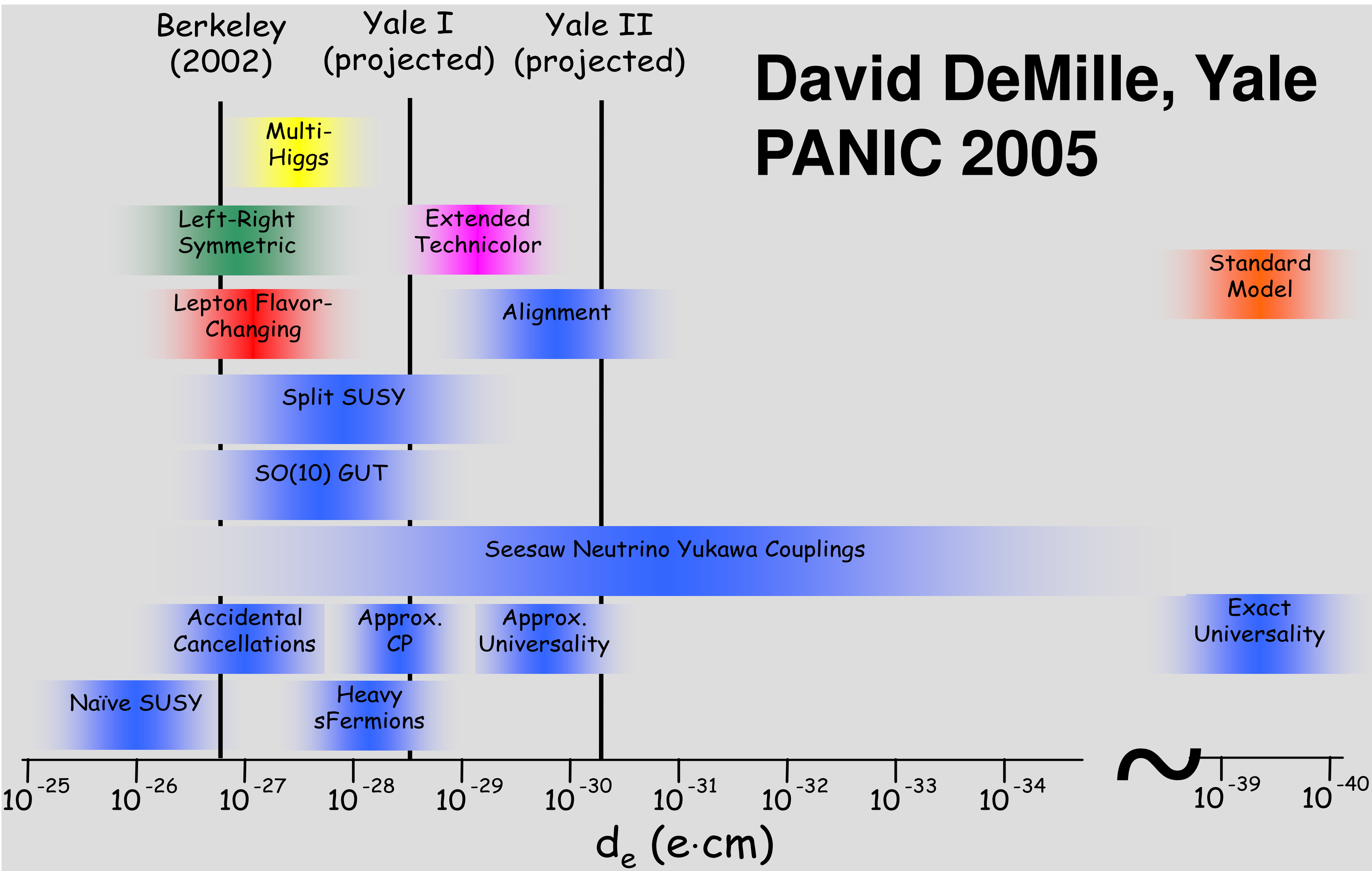


$$\vec{\mathbf{d}} = d\,\frac{\vec{\mathbf{S}}}{S}$$

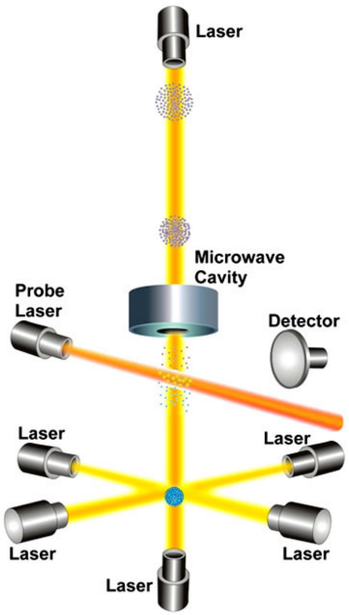
$$d = 0$$

EDM and New physics

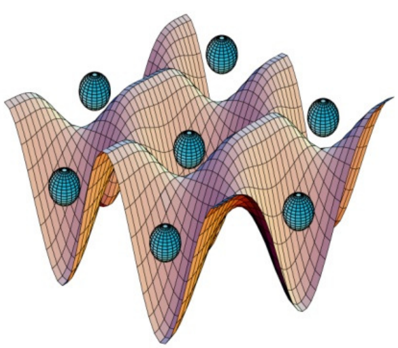
Many theories beyond the Standard Model predict EDM within or just beyond the present experimental capabilities.

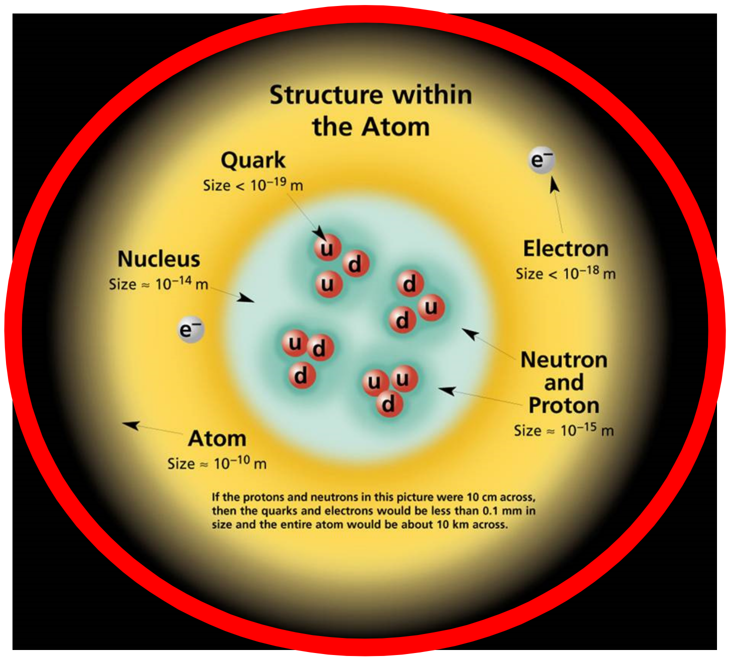


CONCLUSION



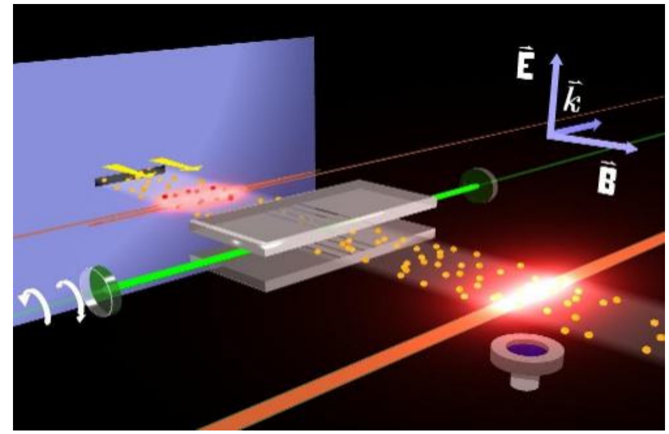
Atomic Clocks

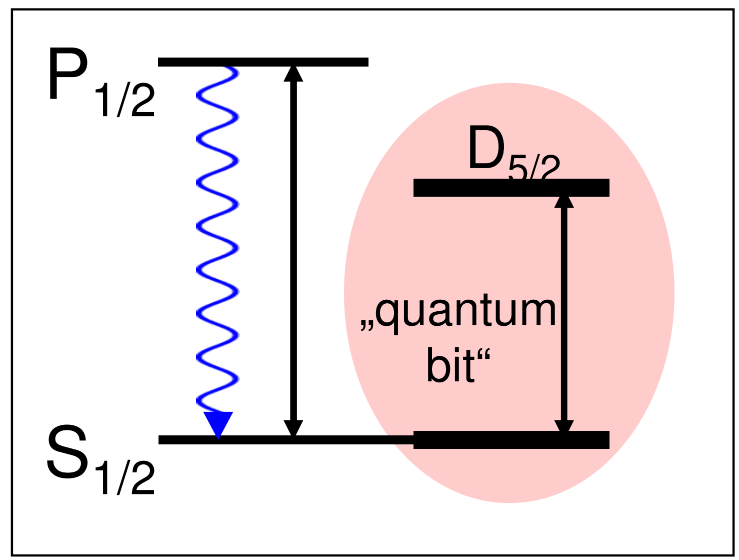




Future:
New Physics
New Technologies

Search for new physics





Quantum information