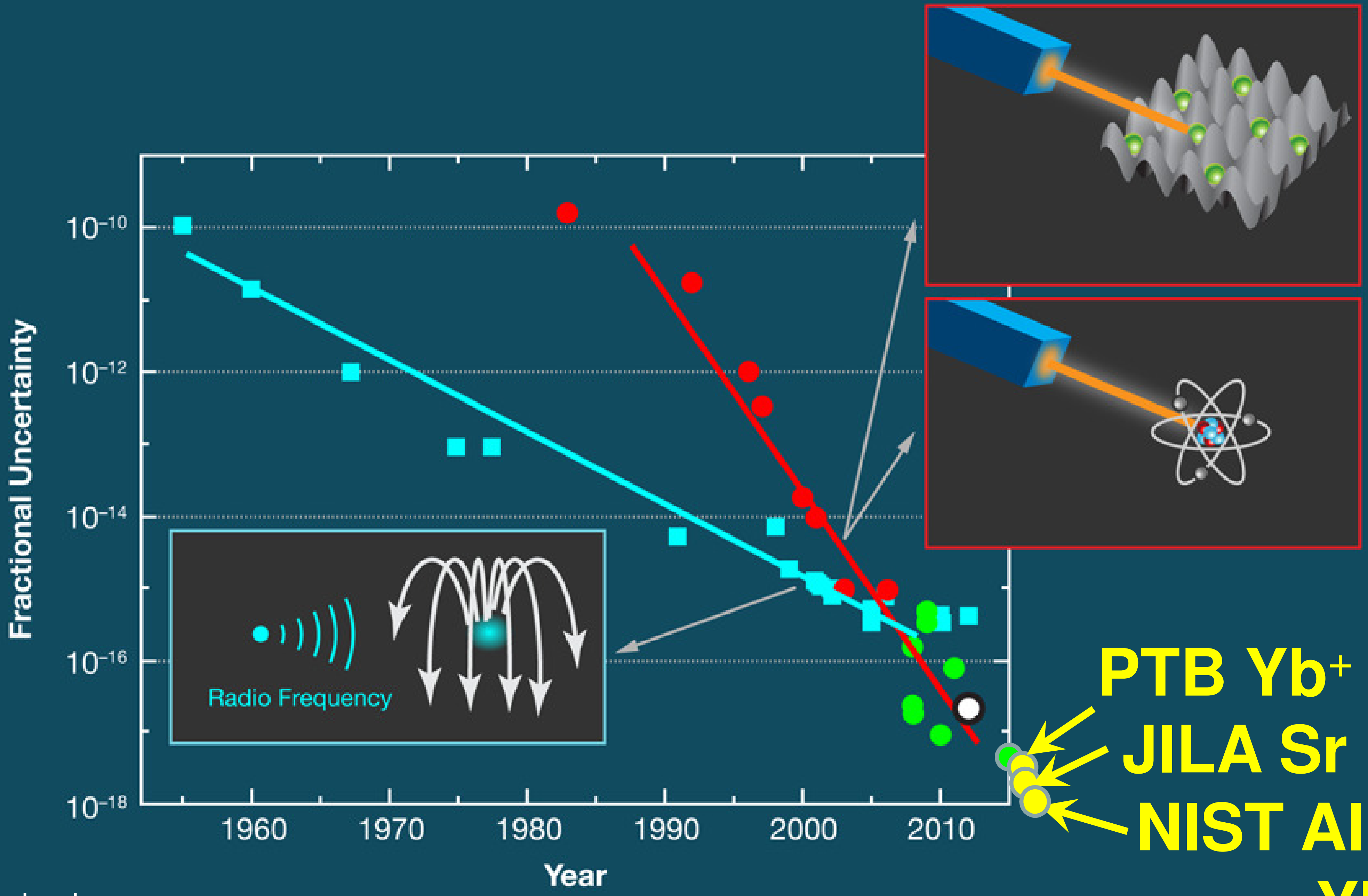
Search for physics beyond the standard model with Atomic Clocks

Optical vs. microwave clocks



PTB Yb^+

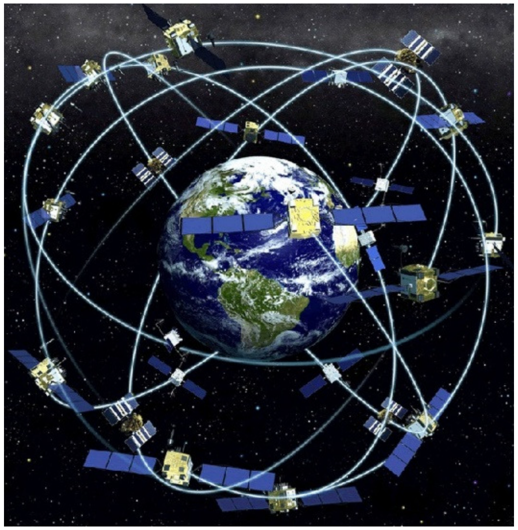
JILA Sr

NIST Al+

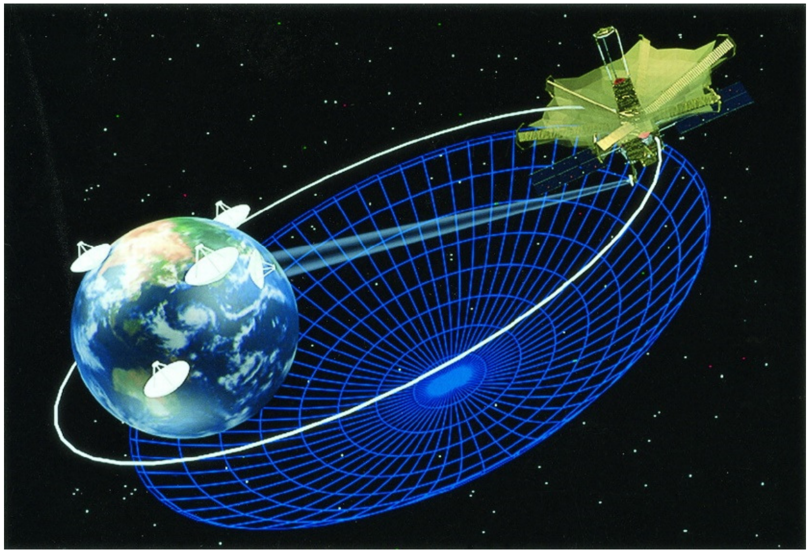
Yb

physics.aps.org

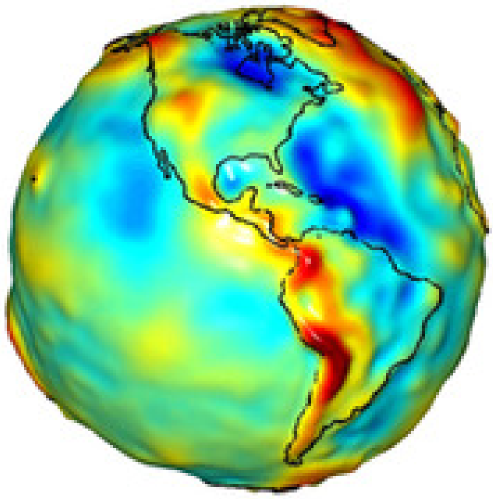
Applications of atomic clocks



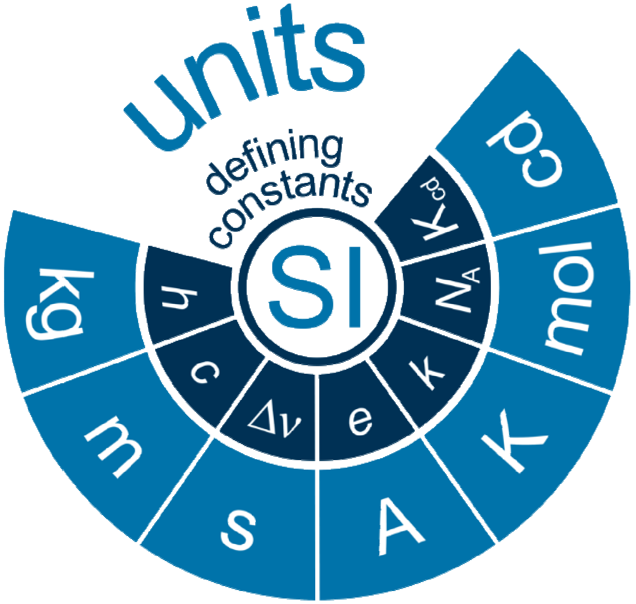
GPS



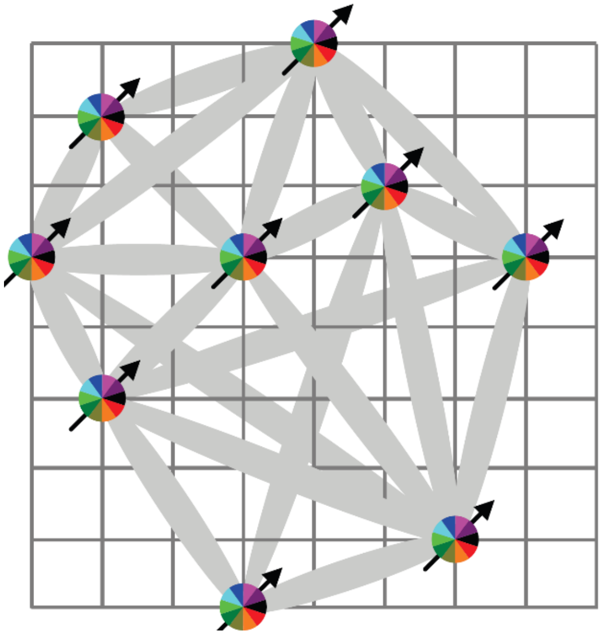
Very Long Baseline Interferometry



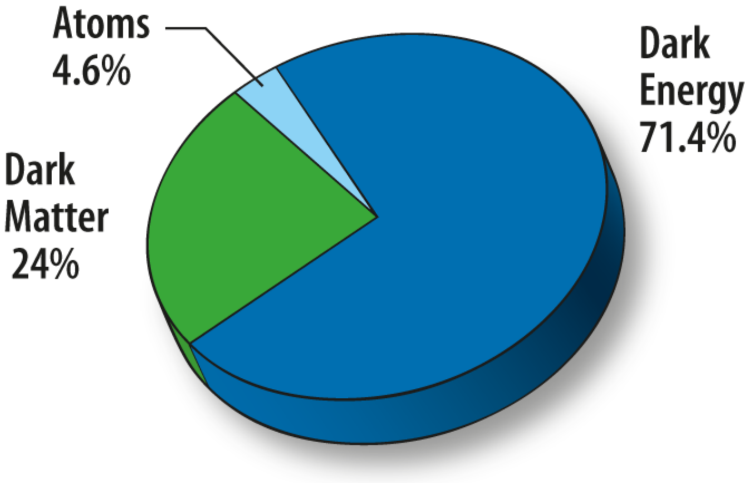
Relativistic geodesy



Definition of the second



Quantum simulation



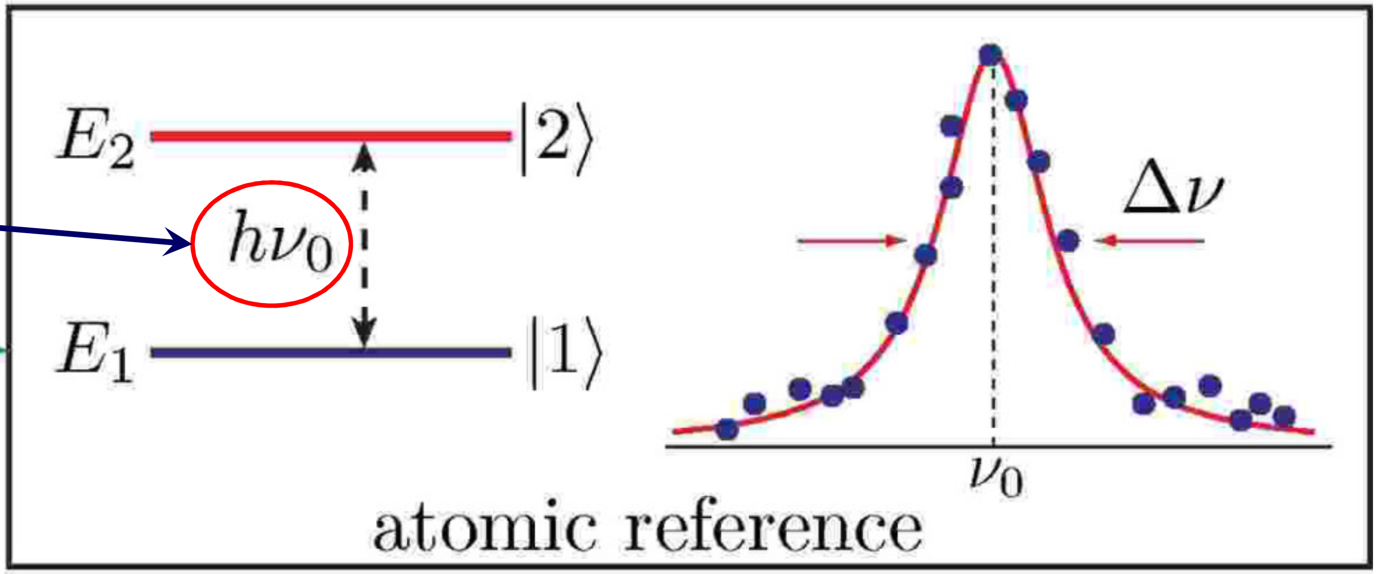
Search for physics beyond the Standard Model

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

Search for physics beyond the standard model with atomic clocks

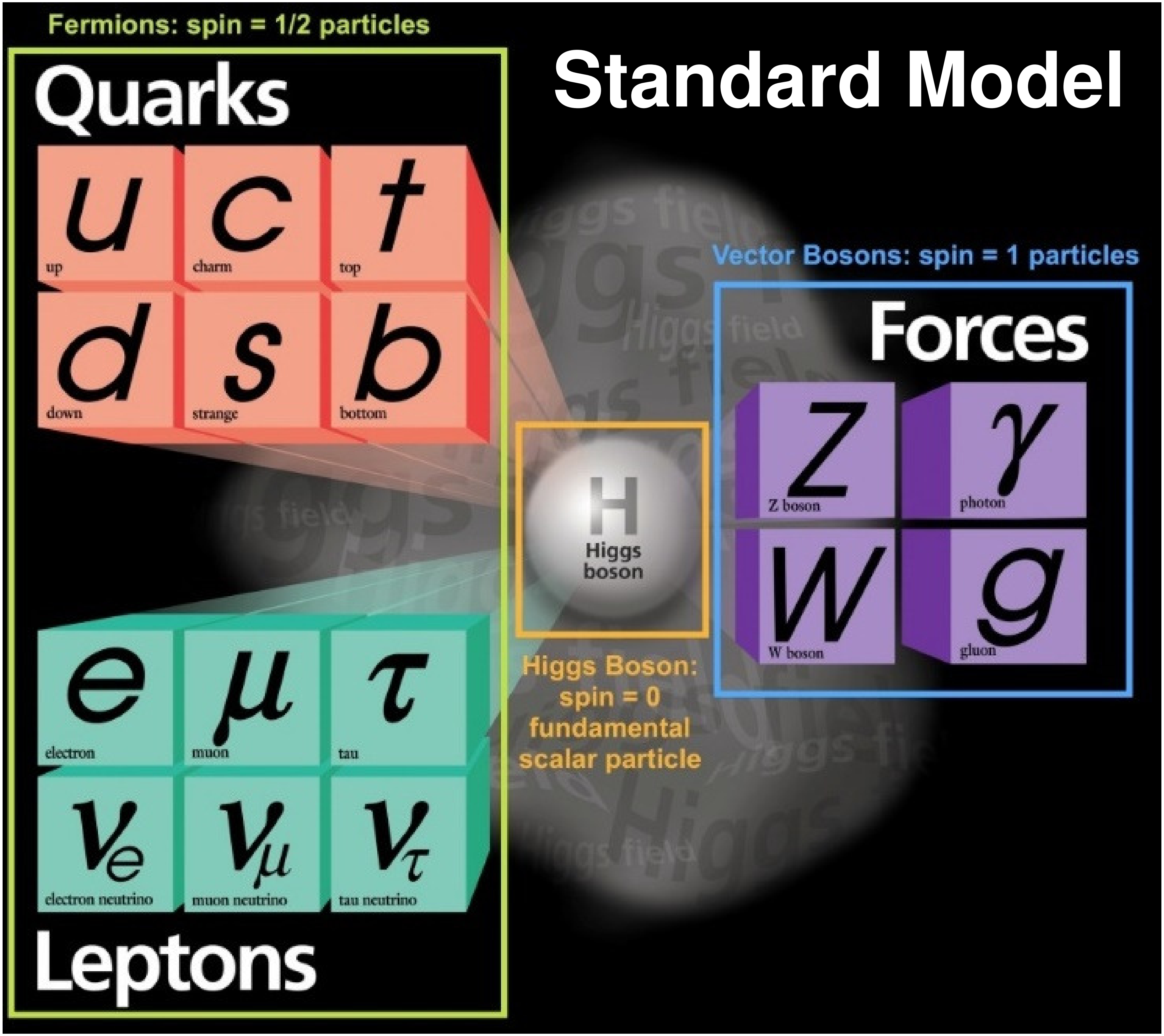
Atomic clocks can measure and compare frequencies to exceptional precisions!

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

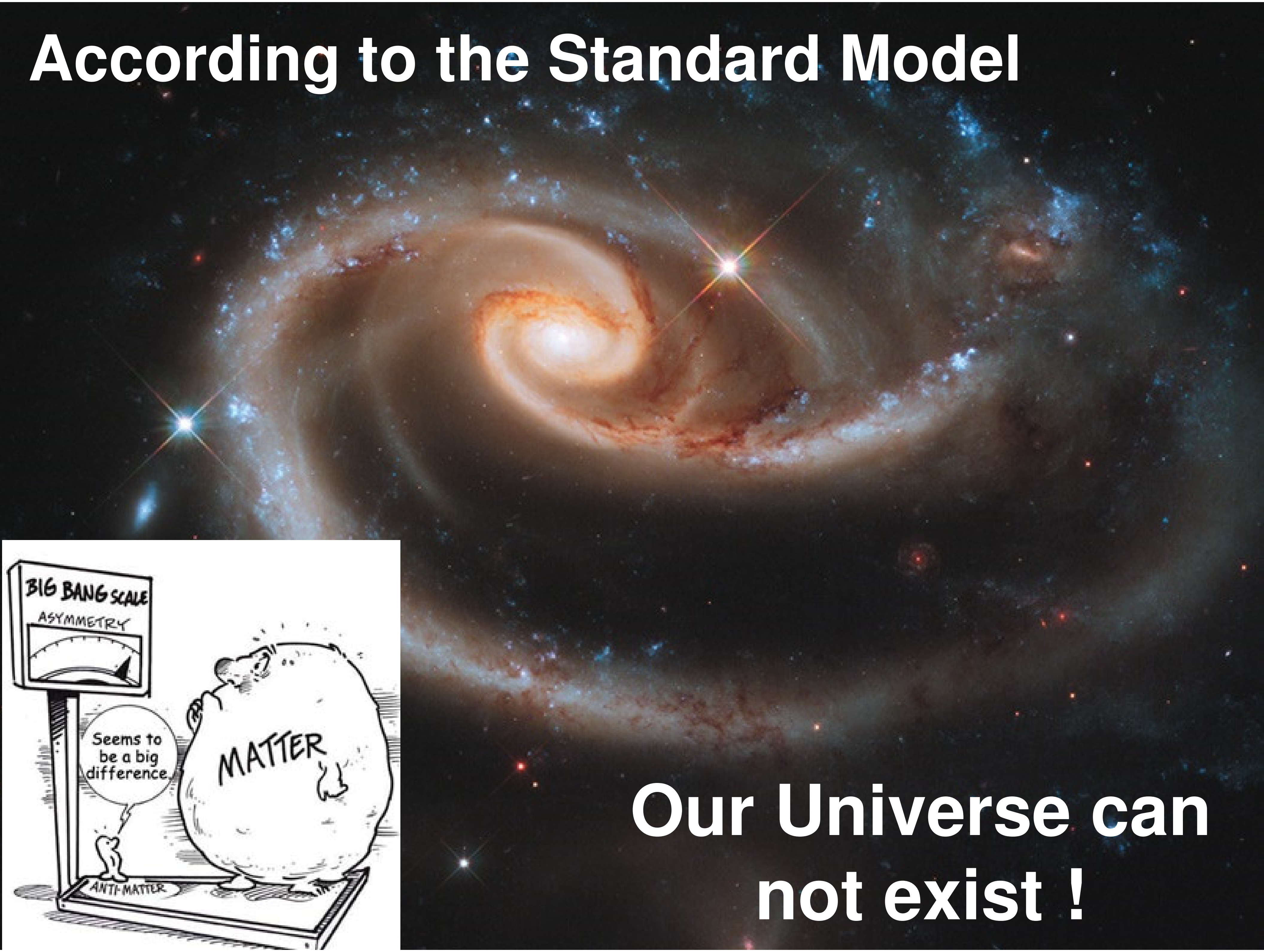


Frequency will change

Standard Model

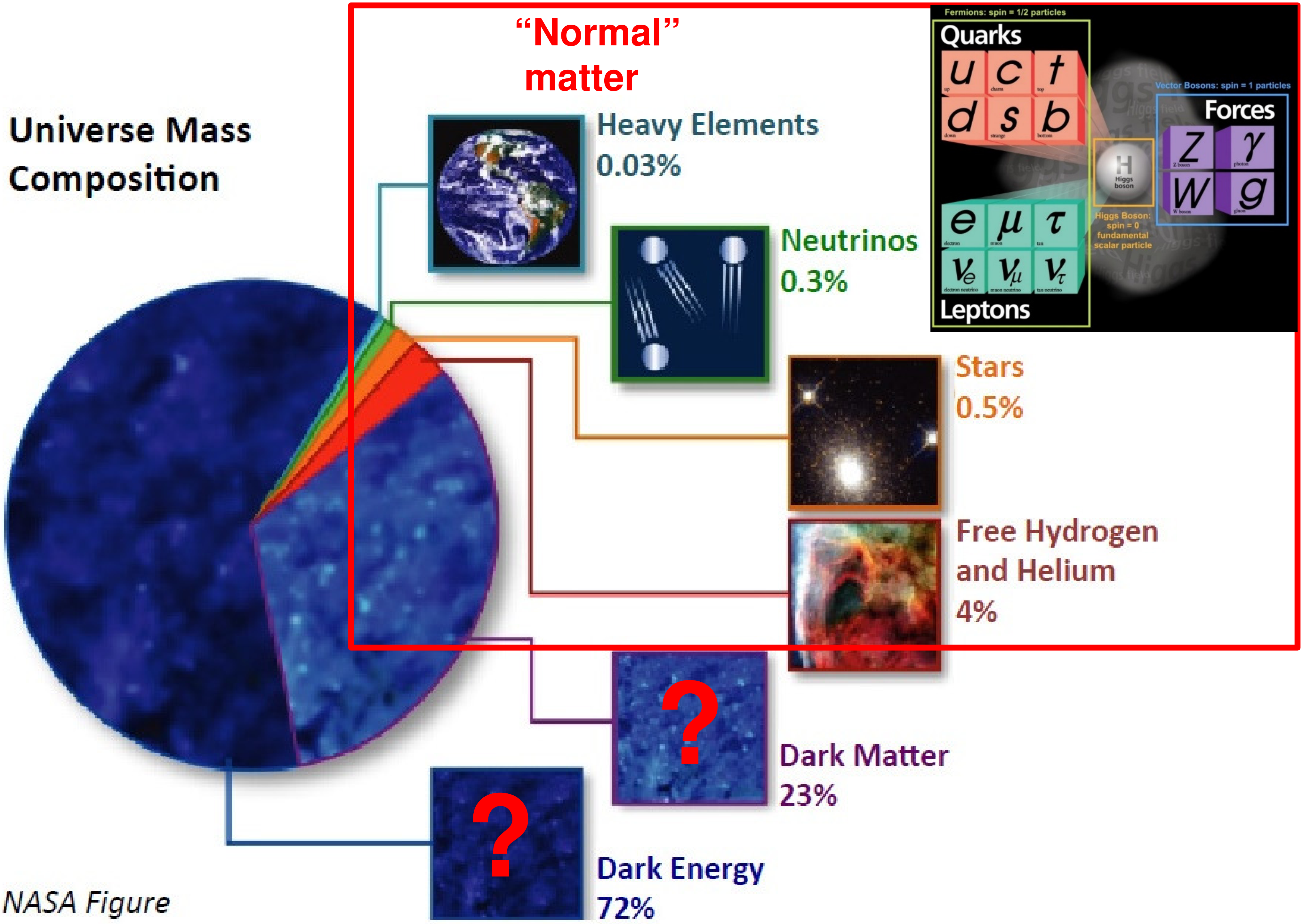


According to the Standard Model



Our Universe can not exist !

We don’t know what most of the Universe is!



“Normal” matter

Universe Mass Composition

Heavy Elements 0.03%

Neutrinos 0.3%

Stars 0.5%

Free Hydrogen and Helium 4%

Dark Matter 23%

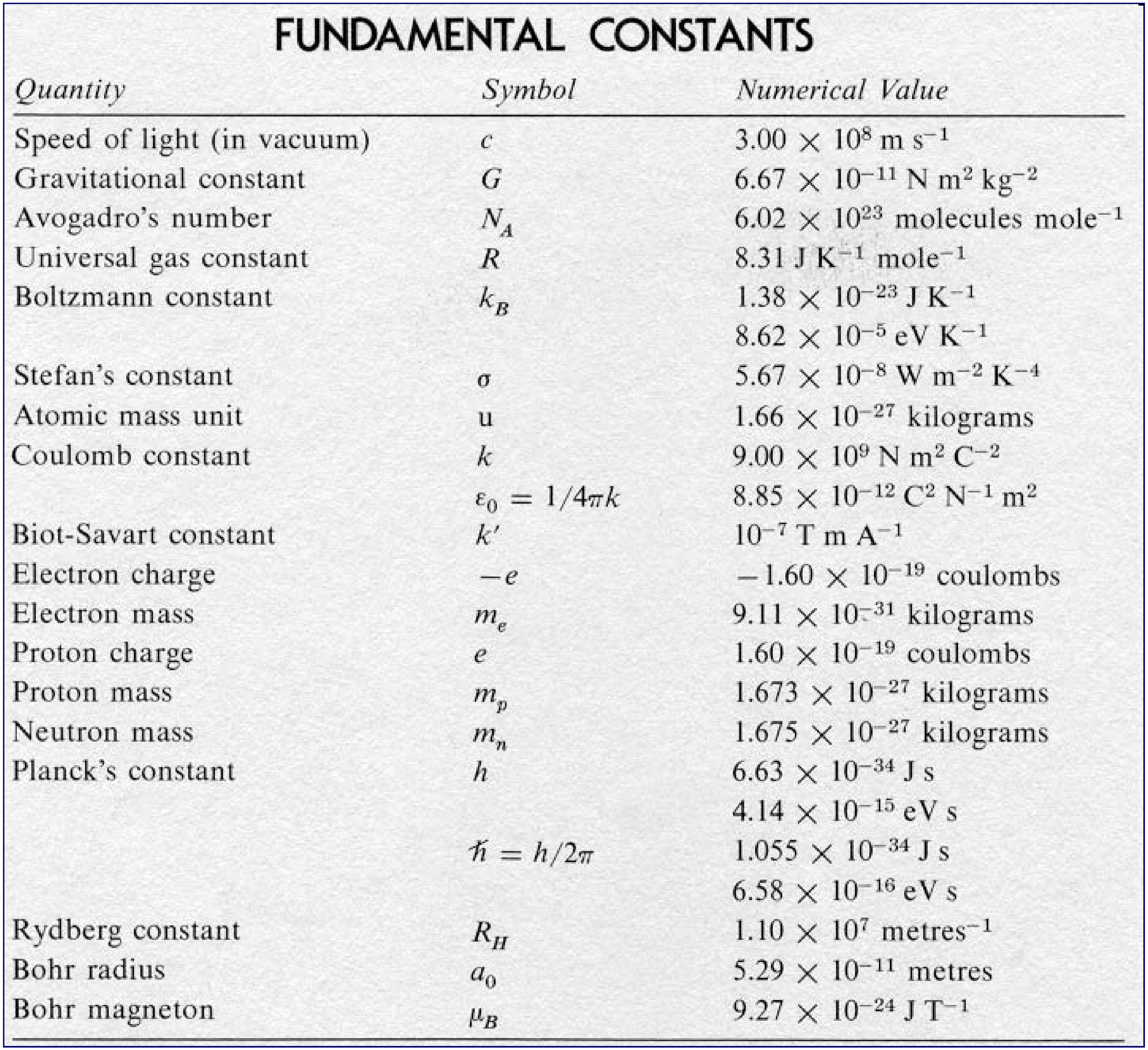
Dark Energy 72%

NASA Figure

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.

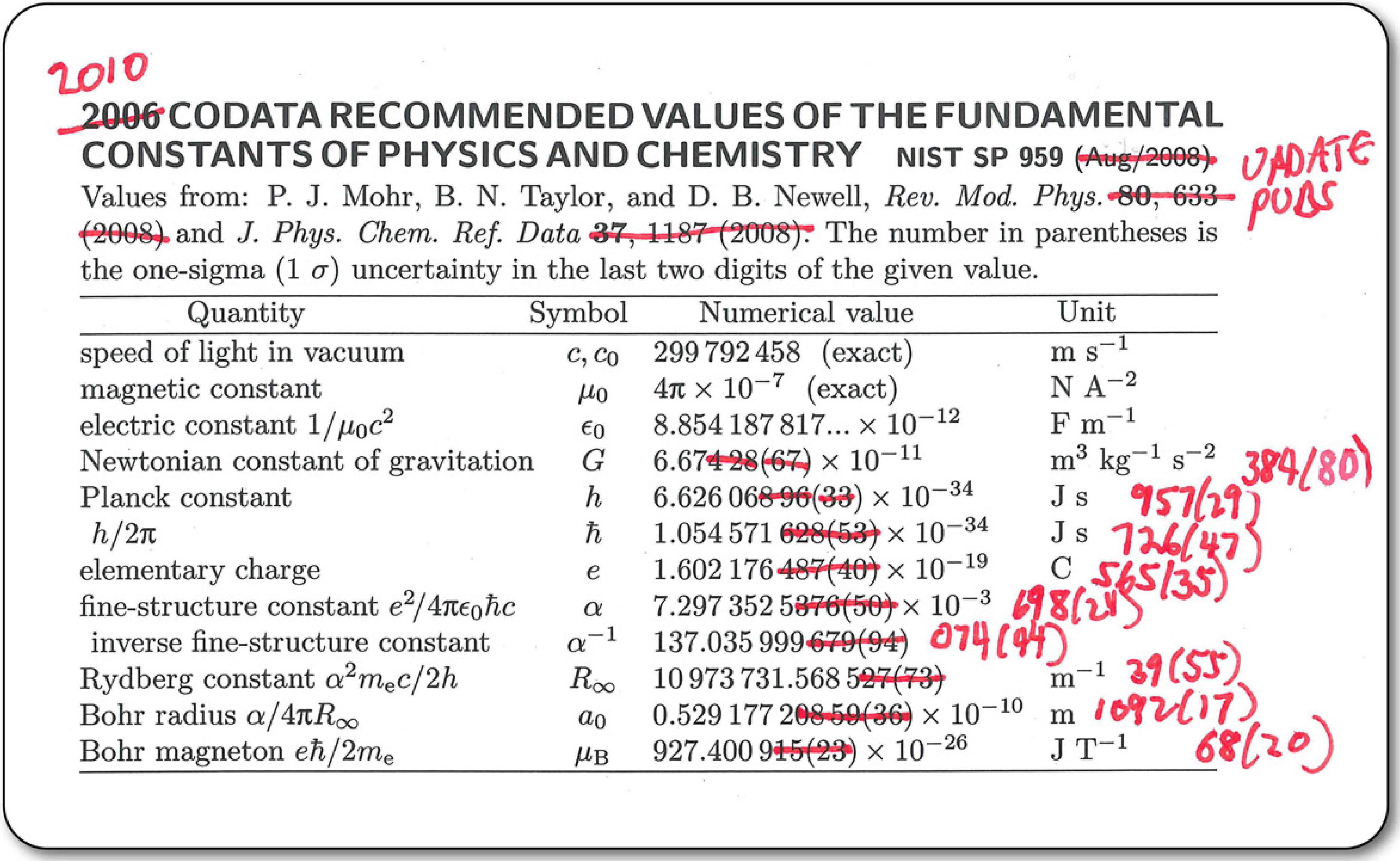
J.-P. Uzan, Rev. Mod. Phys. 75, 403 (2003)



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 (1 σ) 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... × 10^{-12}	$\mathrm{F\ m^{-1}}$	
Newtonian constant of gravitation	G	6.67~~4 28(67)~~ × 10^{-11}	$\mathrm{m^3\ kg^{-1}\ s^{-2}}$	384(80)
Planck constant	h	6.626 06~~8 96(33)~~ × 10^{-34}	J s	957(29)
$h/2\pi$	$\hbar$	1.054 571 ~~628(53)~~ × 10^{-34}	J s	726(47)
elementary charge	e	1.602 176 ~~487(40)~~ × 10^{-19}	C	565(35)
fine-structure constant $e^2/4\pi\epsilon_0\hbar c$	α	7.297 352 5~~376(50)~~ × 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)~~ × 10^{-10}	m	1092(17)
Bohr magneton $e\hbar/2m_e$	μ_B	927.400 9~~15(23)~~ × 10^{-26}	$\mathrm{J\ T^{-1}}$	68(20)

From NIST Tech Beat: July 19, 2011

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:**

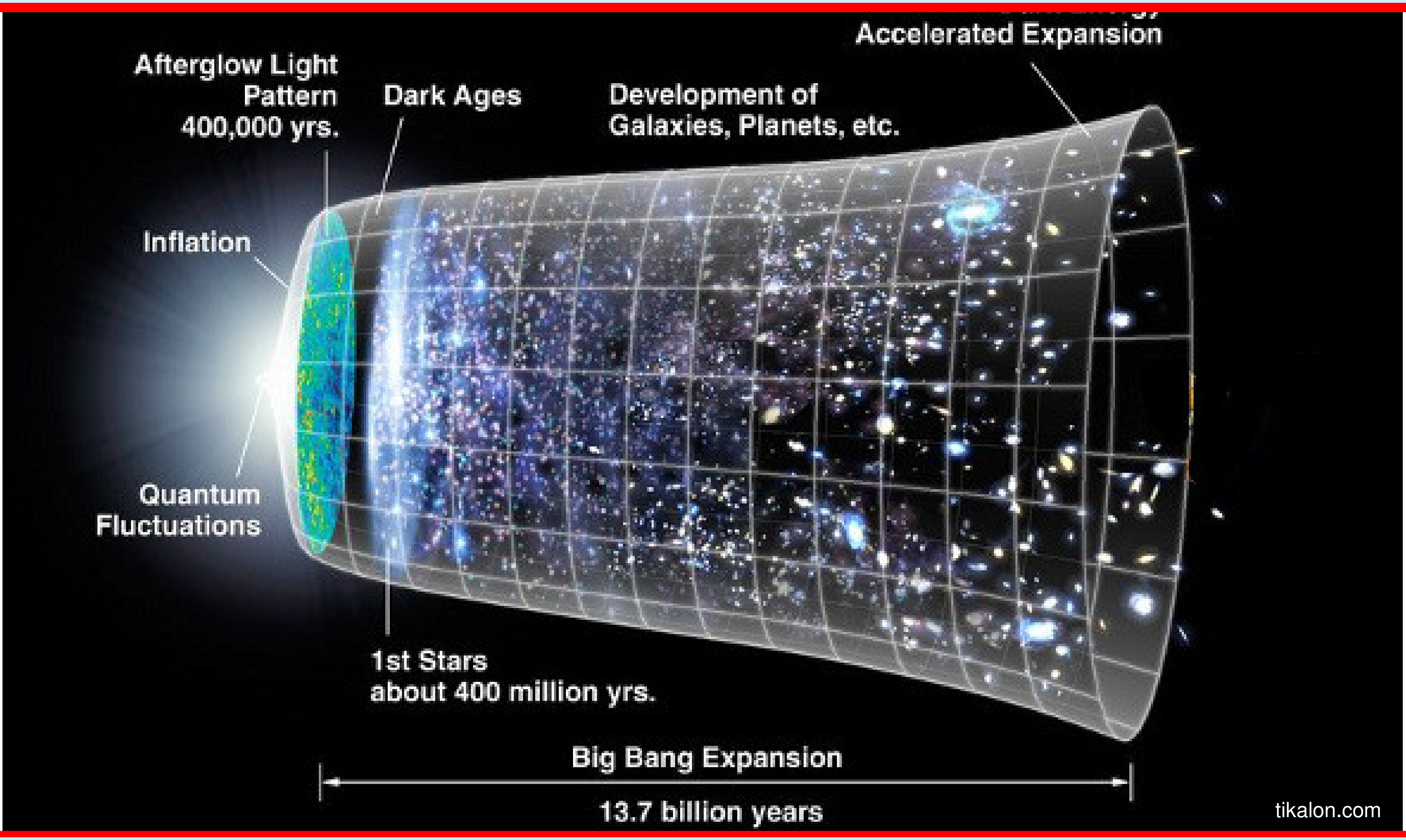
Fine-structure constant $\alpha_{\mathrm{EM}} = \frac{e^2}{\hbar c} \sim 1/137.036$

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

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

…

VARIATION OF FUNDAMENTAL CONSTANTS



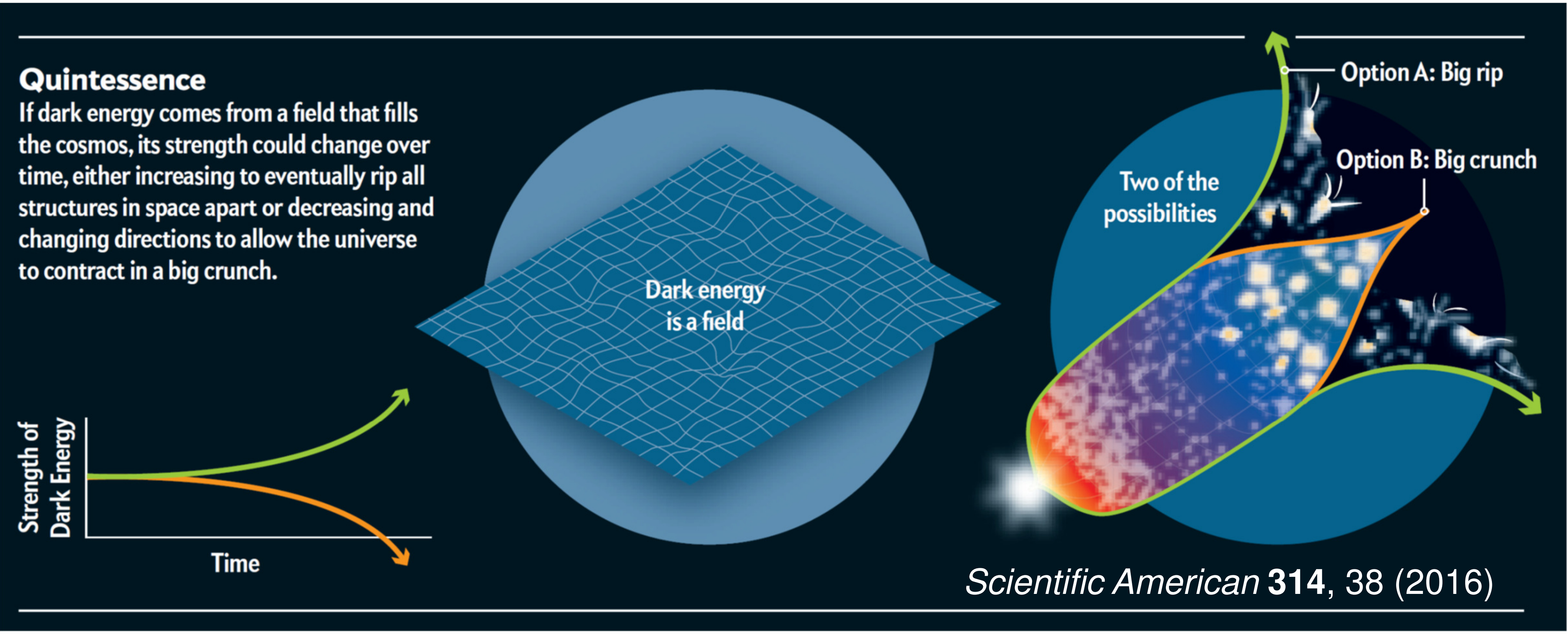
The modern theories directed toward unifying gravitation with the three other fundamental interactions suggest variation of the fundamental constants in an expanding universe.

Variation of fundamental constants

Theories with varying dimensionless fundamental constants

- String theories
- Other theories with extra dimensions
- Loop quantum gravity
- Dark energy theories: chameleon and quintessence models
- …many others

J.-P. Uzan, Living Rev. Relativity 14, 2 (2011)



Quintessence

If dark energy comes from a field that fills the cosmos, its strength could change over time, either increasing to eventually rip all structures in space apart or decreasing and changing directions to allow the universe to contract in a big crunch.

Scientific American **314**, 38 (2016)

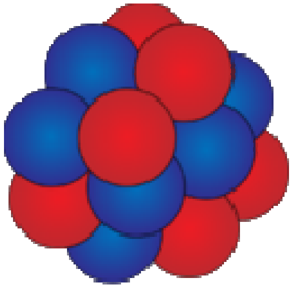
Life needs very specific fundamental constants!

$$\alpha = \frac{e^2}{\hbar c} \sim 1/137$$

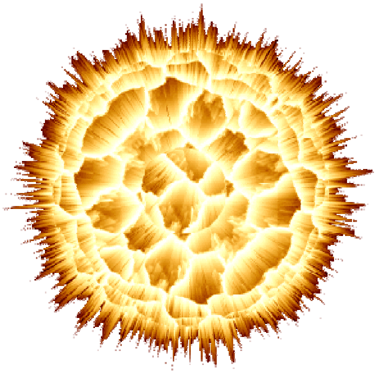
If α is too big $\rightarrow$ small nuclei can not exist

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

$\alpha \sim 1/137$



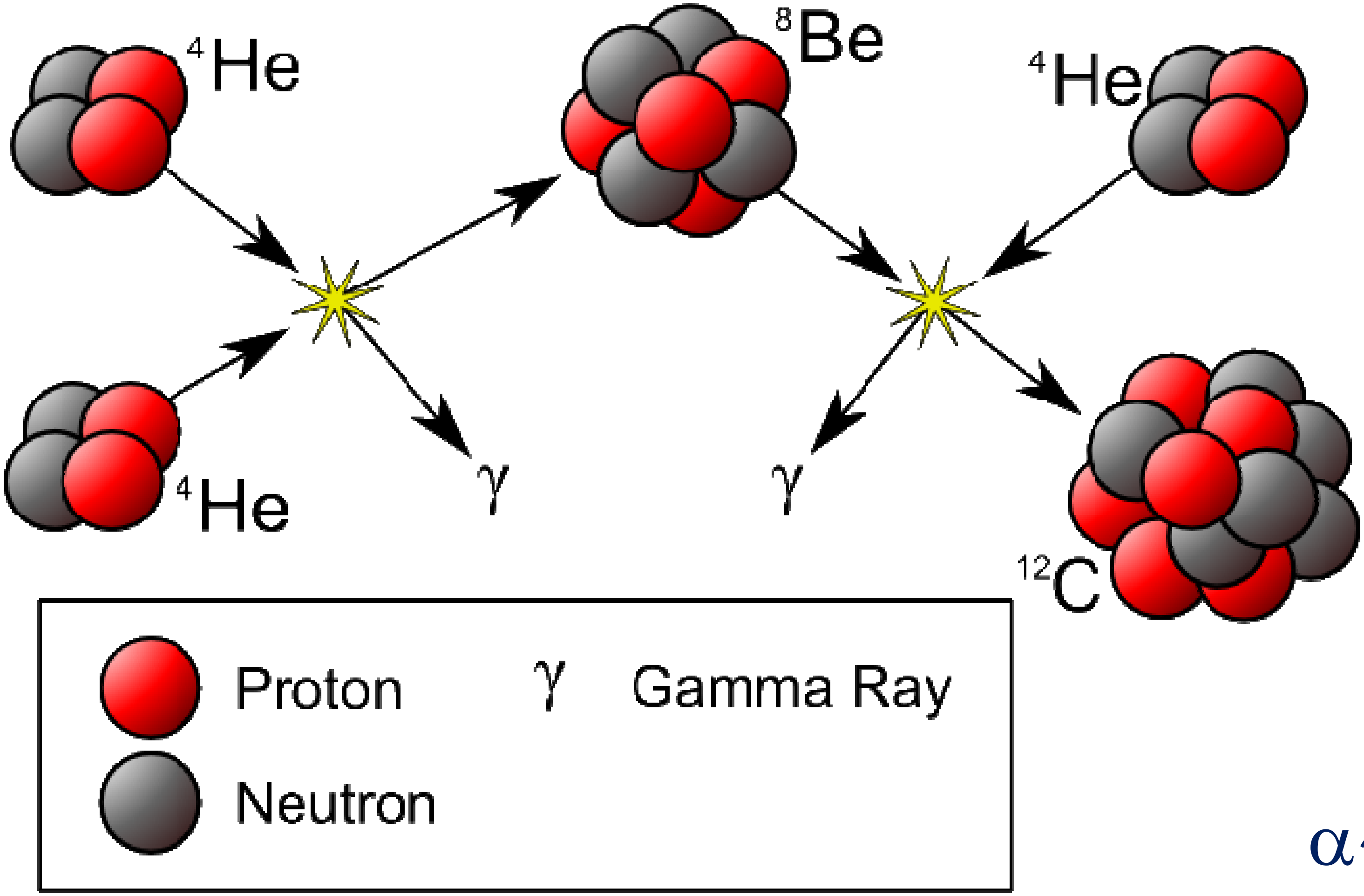
Carbon-12



$\alpha \sim 1/10$

will blow carbon apart

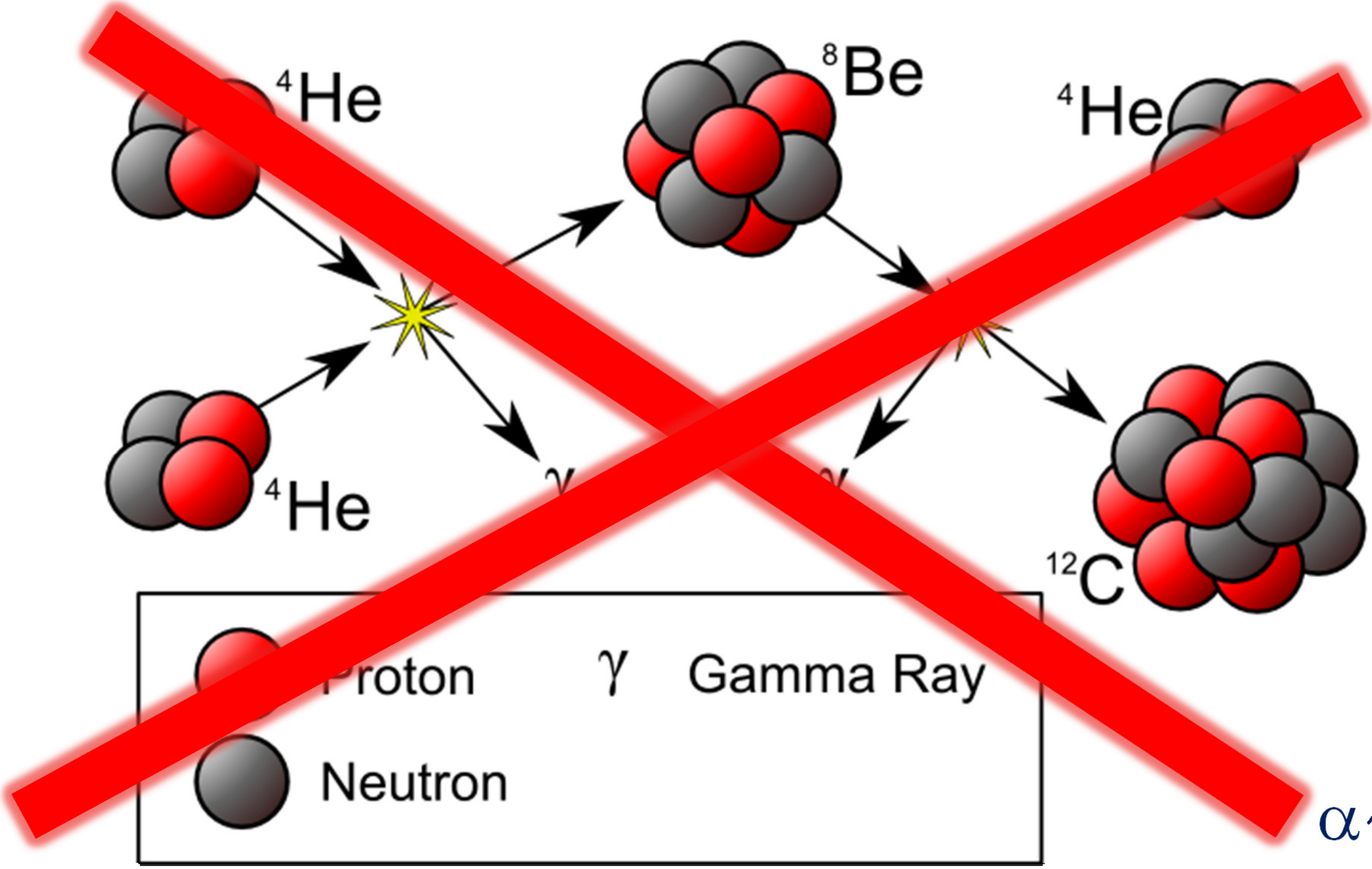
Life needs very specific fundamental constants!



$\alpha \sim 1/137$

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

How do fundamental constants vary?

Slow drifts

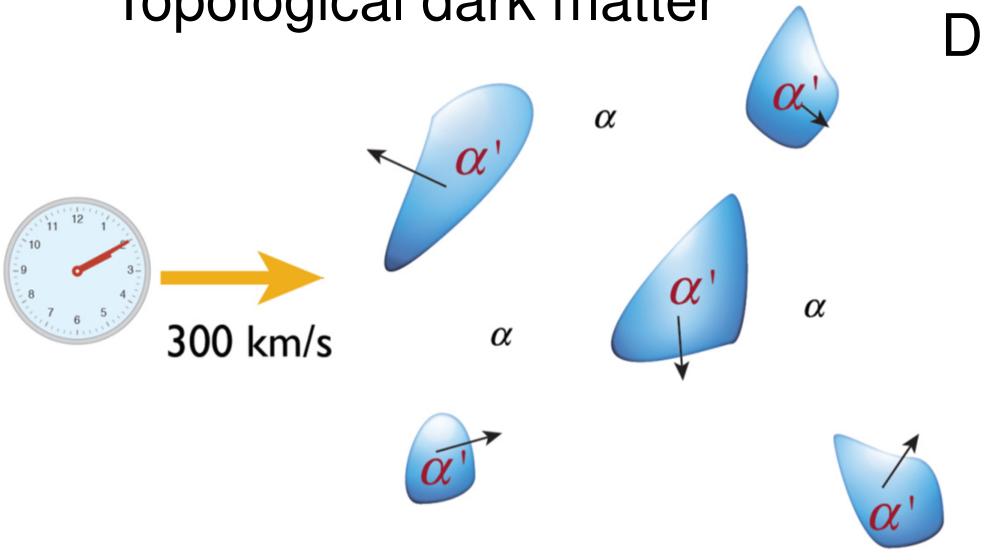
Transient variations

Oscillations

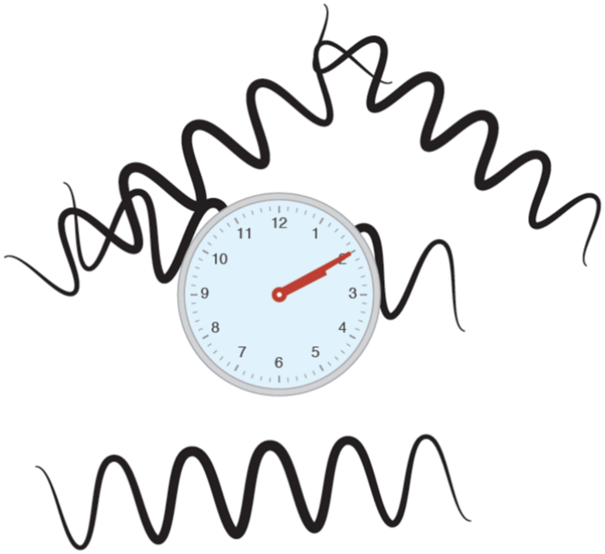
Stochastic

Dark energy?

Topological dark matter



Dilaton dark matter or axion-like particles



A. Derevianko, Conf. Ser. **723** (2016) 012043

How do fundamental constants vary?

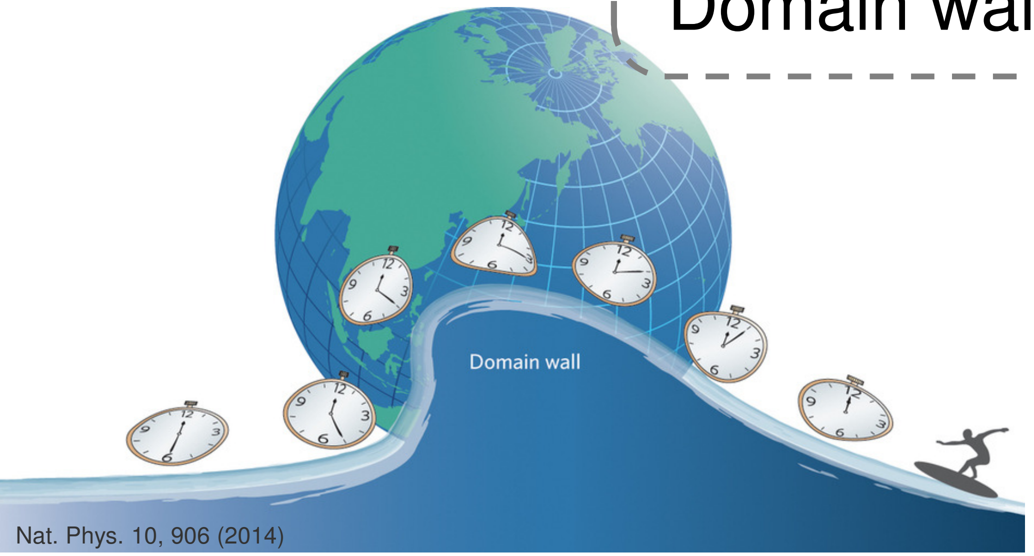
Spatial variations

Cosmological spatial variation: gradient of cosmic $\phi(r)$ field

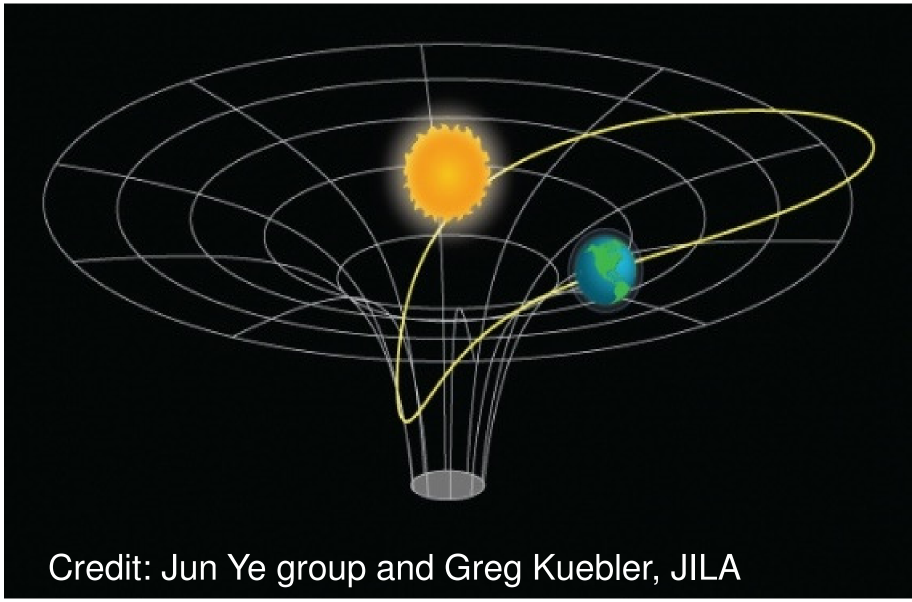
Cosmological spatial variation Domain walls

Dependence on matter density: Chameleons

Dependence on gravity

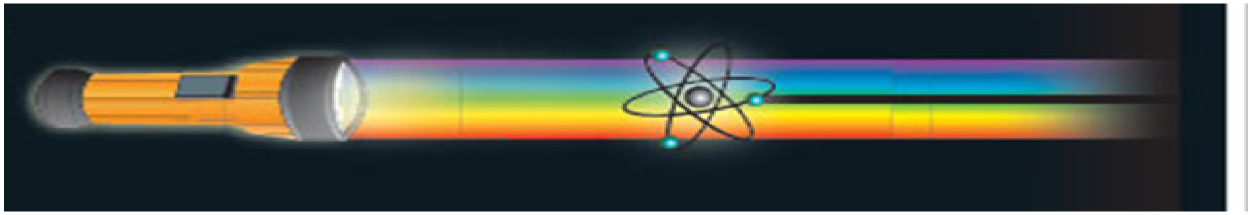


Nat. Phys. 10, 906 (2014)

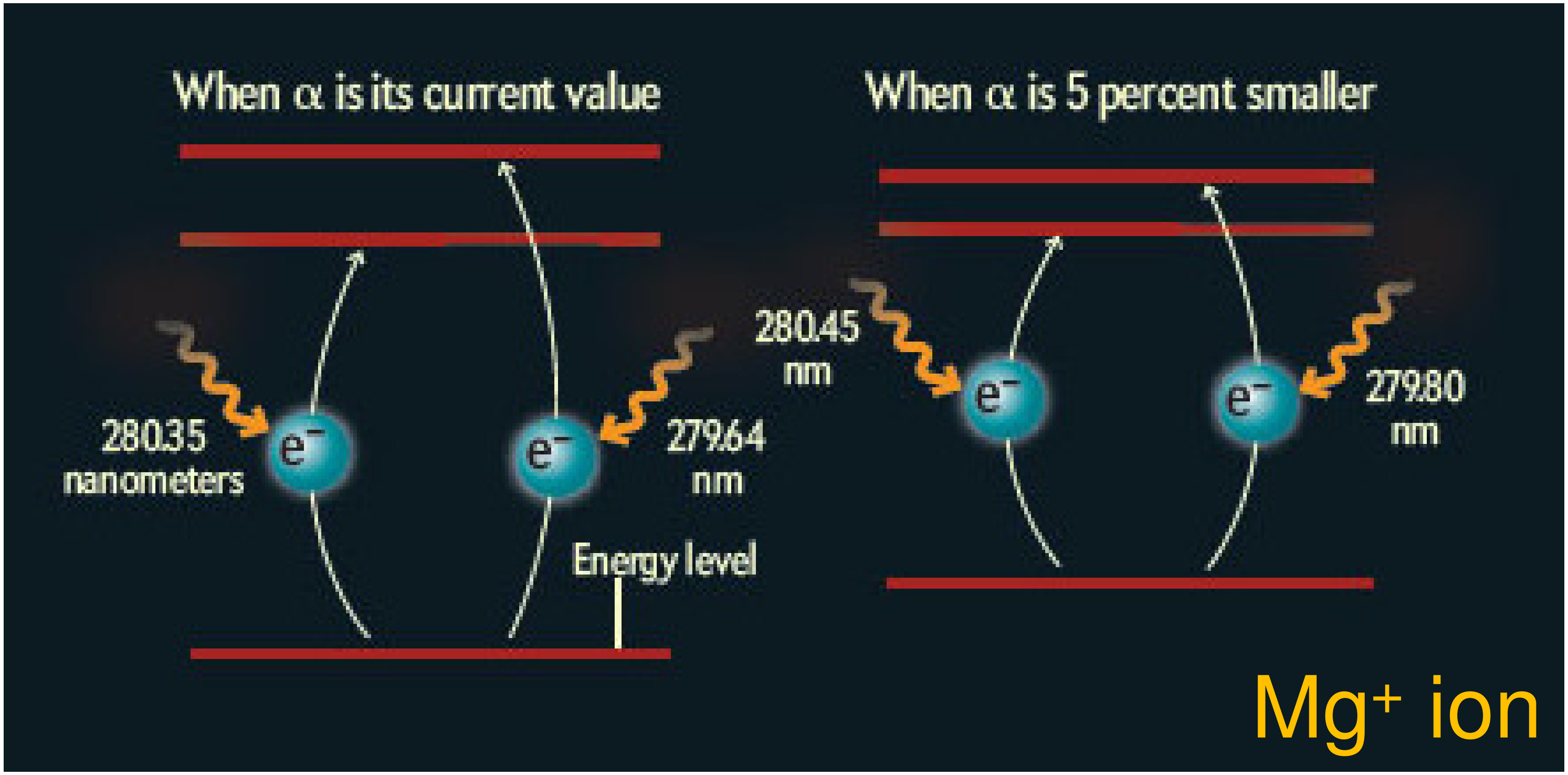


Credit: Jun Ye group and Greg Kuebler, JILA

How to test if α changed with time?

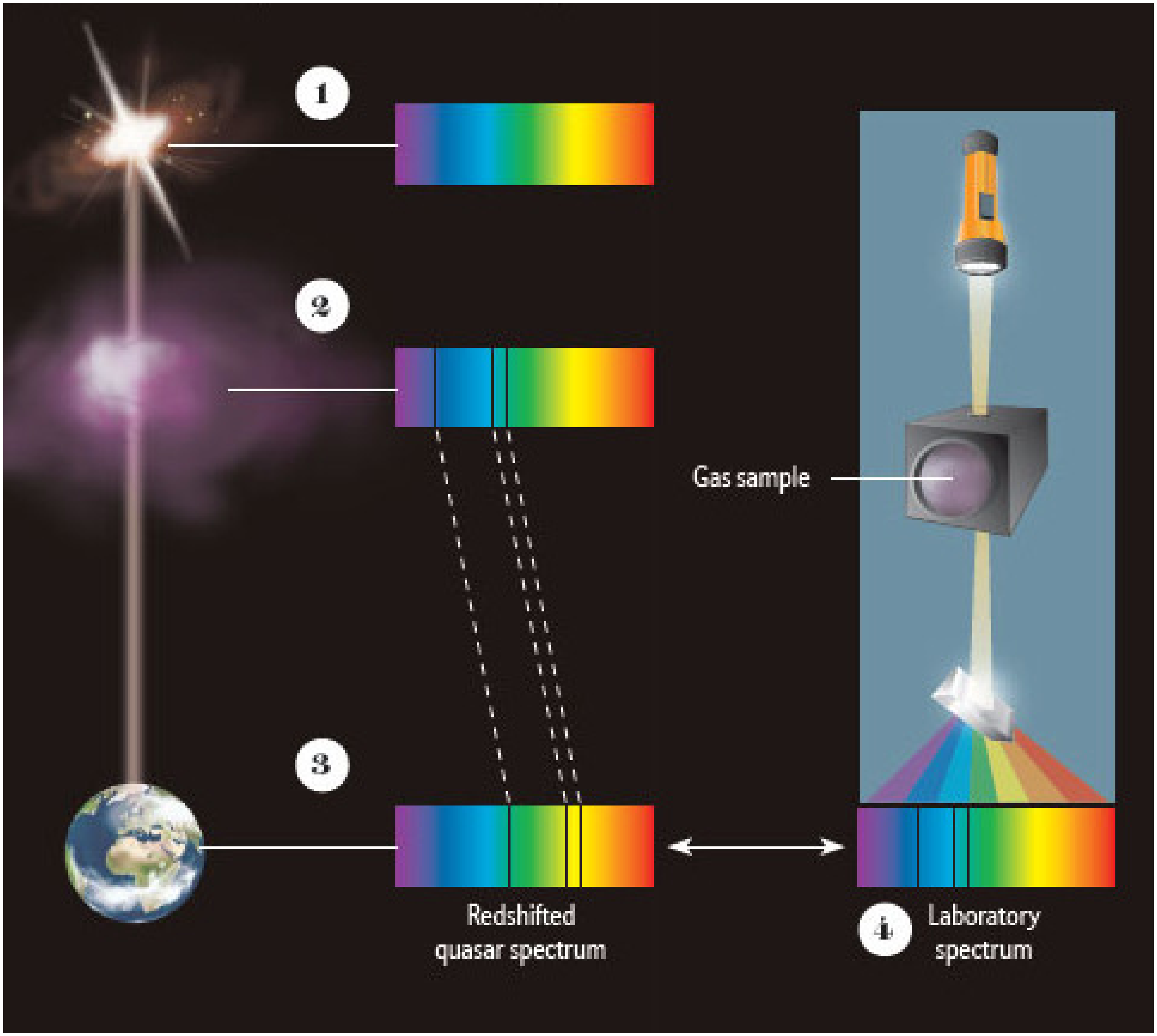


Atomic transition energies depend on α^2

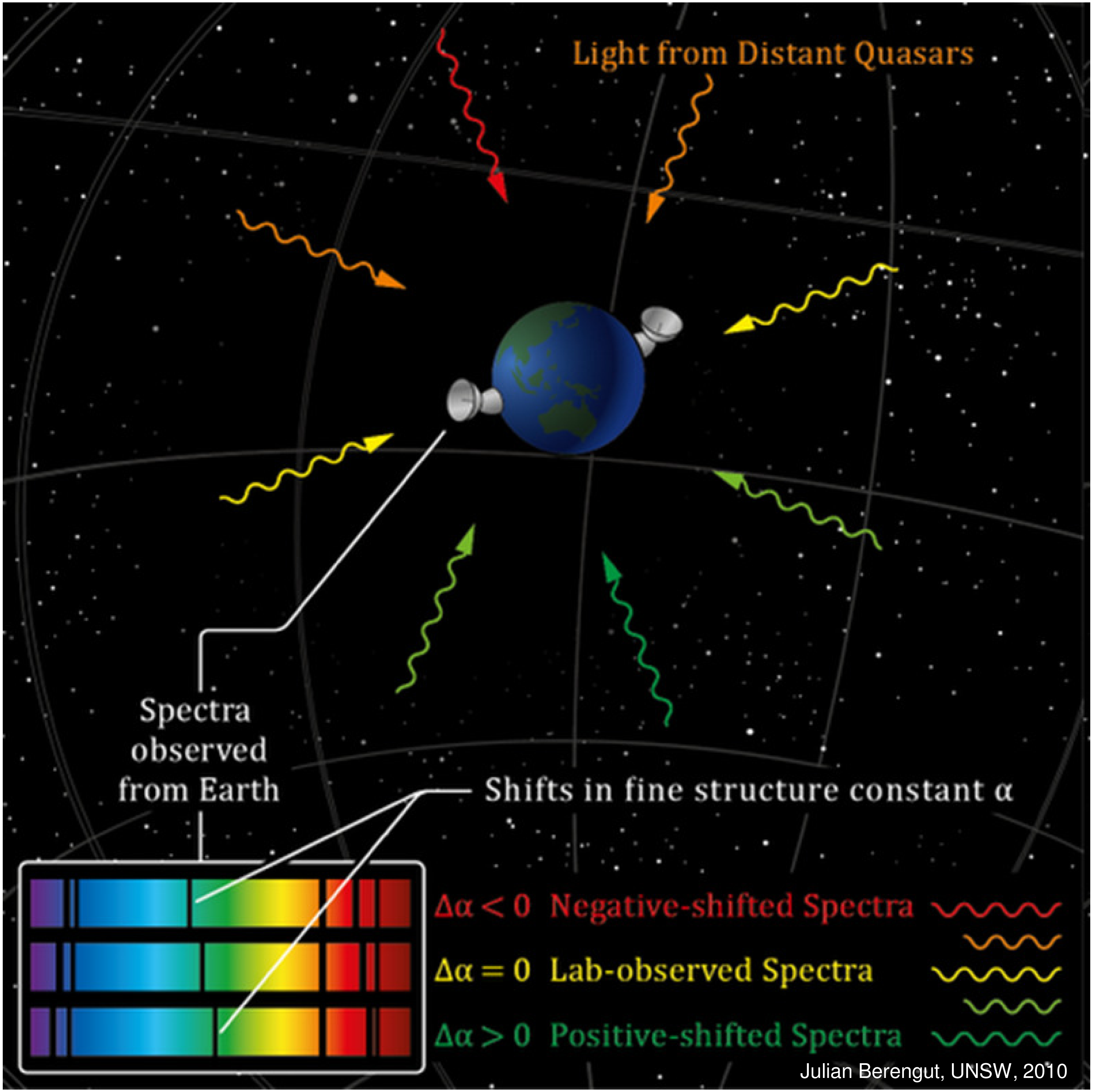


Scientific American Time **21**, 70 - 77 (2012)

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



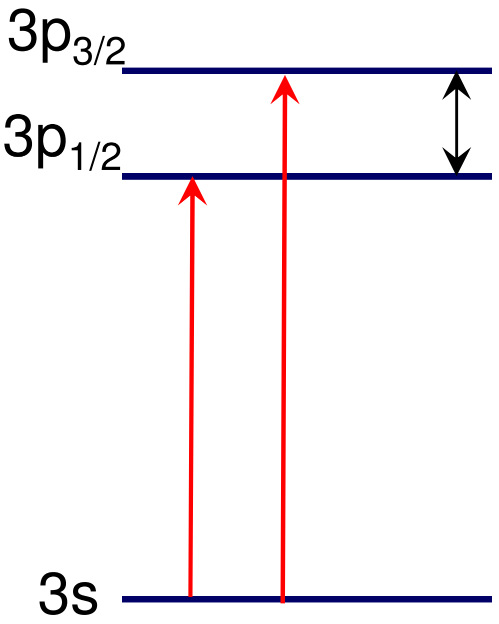
Scientific American Time **21**, 70 - 77 (2012)



Julian Berengut, UNSW, 2010

Astrophysical searches for α–variation

Alkali-doublet method



$$\Delta E_{\mathrm{FS}} \propto (Z\alpha)^2$$

Na, Mg^{+}, Si^{3+}

Observed at red shift z

$$\frac{\Delta\alpha}{\alpha} = \frac{1}{2}\left(\frac{[\Delta E_{FS}]_z}{[\Delta E_{FS}]_0} - 1\right)$$

Observed on Earth

Murphy et al. (2001) $\frac{\Delta\alpha}{\alpha} = -0.5(1.3)\times 10^{-5}$

Astrophysical searches for α–variation

Many-multiplet method: compare spectra of different atoms

Relativistic correction to the energy

Contributions of many-body effects

$$\frac{\Delta}{E} \propto \frac{1}{n^*}(Z\alpha)^2\left(\frac{1}{j+1/2}-C\right)$$

Transition energies depend on α^2,
Need atomic calculations to find corresponding factor q

Observed from quasar absorption spectra

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

Laboratory frequency

Conflicting results

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

$$\Delta\alpha/\alpha = -0.54(12)\times10^{-5}$$

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

$$\Delta\alpha/\alpha = -0.4(1.9)(2.7)\times10^{-6}$$

Molaro et al., 2007

$$\Delta\alpha/\alpha = -0.12(1.8)\times10^{-6}$$

Z=1.84

$$\Delta\alpha/\alpha = 5.7(2.7)\times10^{-6}$$

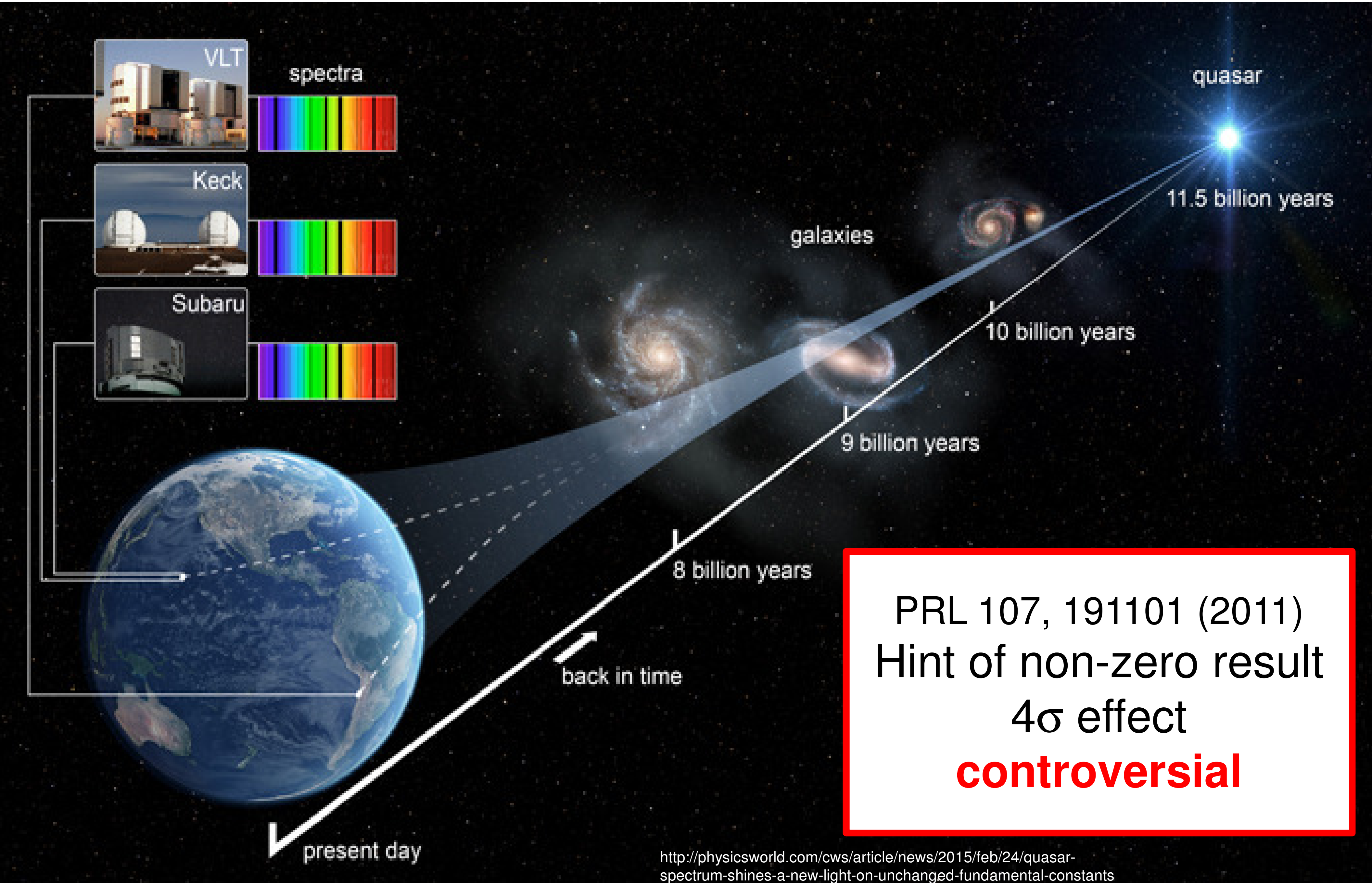
Srianand et al, 2004: VL telescope, 23 systems, 12 lines,
Fe II, Mg I, Si II, Al II, $0.4<z<2.3$

$$\Delta\alpha/\alpha = -0.06(0.06)\times10^{-5}$$

Murphy et al., 2007

$$\Delta\alpha/\alpha = -0.64(36)\times10^{-5}$$

Astrophysical searches for variation of fundamental constants



PRL 107, 191101 (2011)

Hint of non-zero result

4σ effect

controversial

http://physicsworld.com/cws/article/news/2015/feb/24/quasar-spectrum-shines-a-new-light-on-unchanged-fundamental-constants

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.

Laboratory searches for variation of fundamental constants

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

1. Frequency of optical transitions

$$\nu \simeq cR_\infty AF(\alpha)$$

Depends only on α

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

2. Frequency of hyperfine transitions

$$\nu_{\text{hfs}} \simeq cR_\infty A_{\text{hfs}} \times g_i \times \frac{m_e}{m_p} \times \alpha^2 F_{\text{hfs}}(\alpha)$$

Depends on α, μ, g-factors (quark masses to QCD scale)

2. Transitions in molecules: μ only, μ and α, or all three

$$E_{\text{el}} : E_{\text{vib}} : E_{\text{rot}} \sim 1 : \bar{\mu}^{1/2} : \bar{\mu}$$

$$\bar{\mu} = 1/\mu$$

Comparing different types of transitions probes different constants

(1) Measure the ratio R of optical to hyperfine (microwave Cs or Rb) clock frequencies:

sensitive α, μ, g-factors (quark masses to QCD scale)

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

$$E = E_0 + \underset{\uparrow}{q}\left(\frac{\alpha^2}{\alpha_0^2} - 1\right)$$

Calculate with good precision

Sensitivity of **optical clocks** to α-variation

$$E = E_0 + \boldsymbol{q}\left(\frac{\alpha^2}{\alpha_0^2} - 1\right)$$

Enhancement factor

$$K = \frac{2q}{E_0}$$

Need: large K for at least one for the clocks

Best case: large K_2 and K_1 of opposite sign for clocks 1 and 2

$$\frac{\partial}{\partial t}\ln\frac{v_2}{v_1} = (K_2 - K_1)\frac{1}{\alpha}\frac{\partial \alpha}{\partial t}$$

Test of α-variation

Frequency ratio accuracy 10^{-18} 100 10^{-20}

Easier to measure large effects!

Laboratory searches for α–variation

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

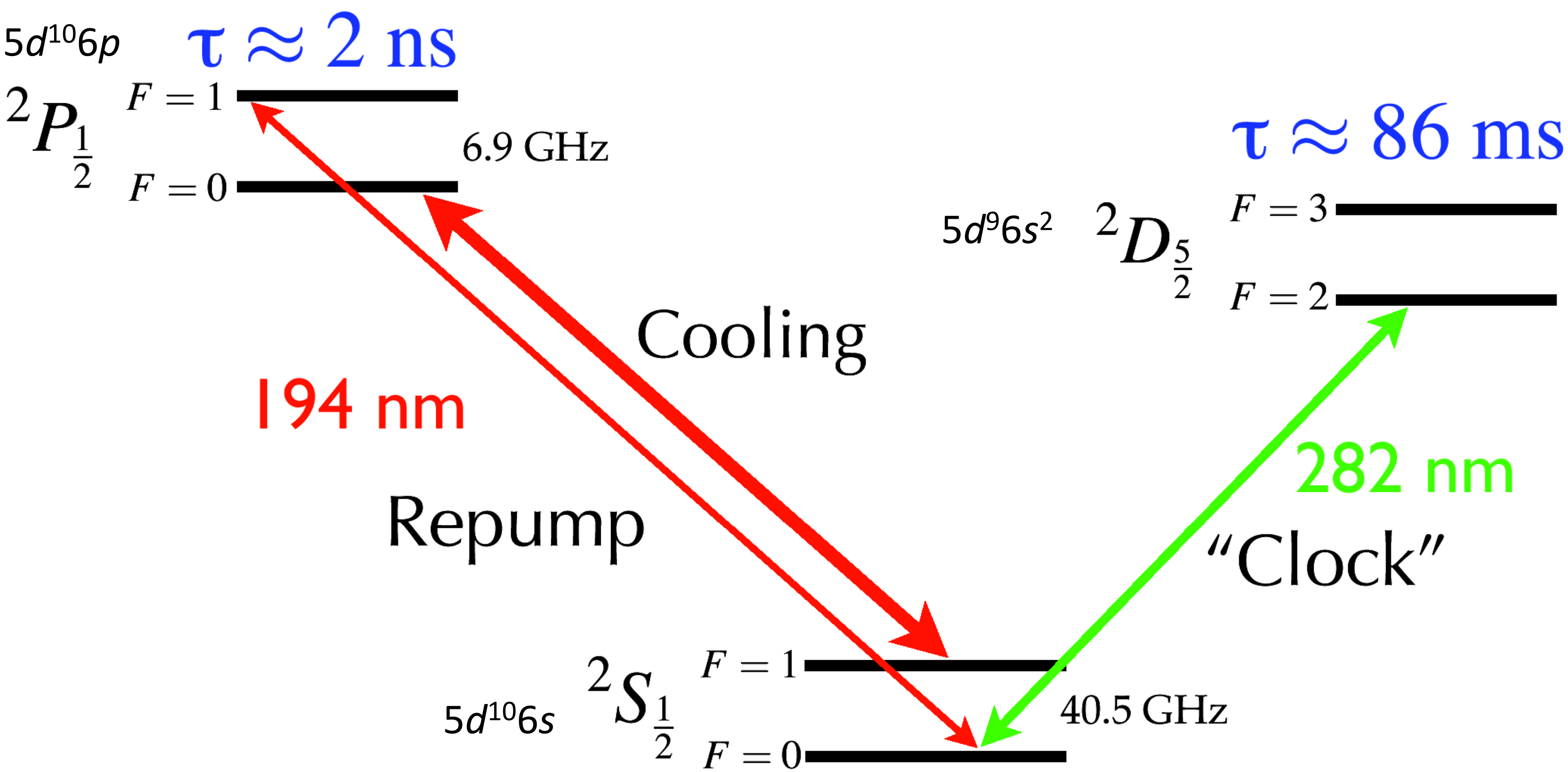
$$\nu(x) = \nu_0 + \boldsymbol{q}x \qquad x = (\alpha/\alpha_0)^2 - 1$$

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

NIST [Rosenband et al., Science 319, 1808 (2008)]
Al^+ / Hg^+ atomic clocks

$$\dot{\alpha}/\alpha = -1.6(2.3)\times 10^{-17}\ \mathrm{y}^{-1}$$

$^{199}\mathrm{Hg}^{+}$ Energy Levels



$5d^{10}6p$ $\tau \approx 2$ ns

$^2P_{\frac{1}{2}}$

$F = 1$

6.9 GHz

$F = 0$

$\tau \approx 86$ ms

$5d^{9}6s^{2}$ $^2D_{\frac{5}{2}}$

$F = 3$

$F = 2$

Cooling

194 nm

Repump

282 nm

"Clock"

$5d^{10}6s$ $^2S_{\frac{1}{2}}$

$F = 1$

40.5 GHz

$F = 0$

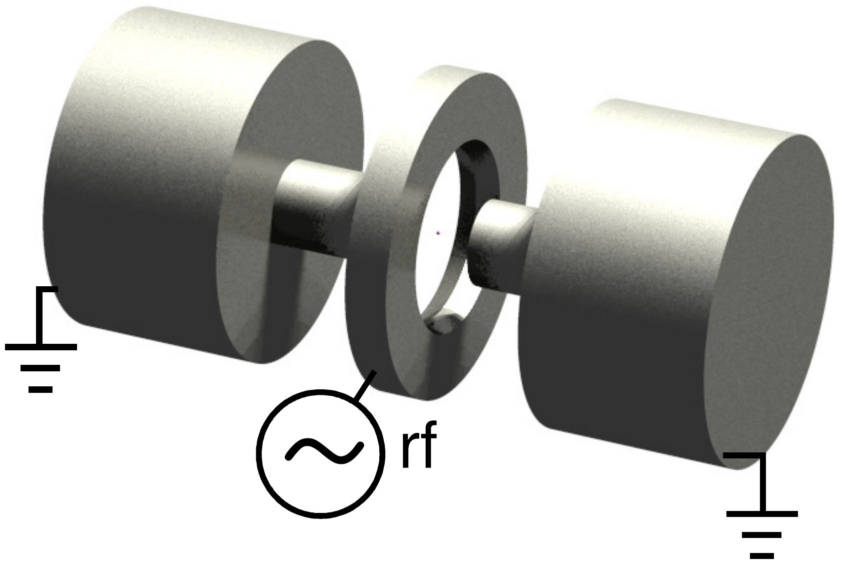
- Atomic line $Q \approx 5 \times 10^{14}$
- State detection by electron shelving.

from Jim Bergquist' talk NIST

Trapped ions in an rf trap

- No static **E** or **B** fields;
  Trap acts on total charge of ion,
  not internal structure

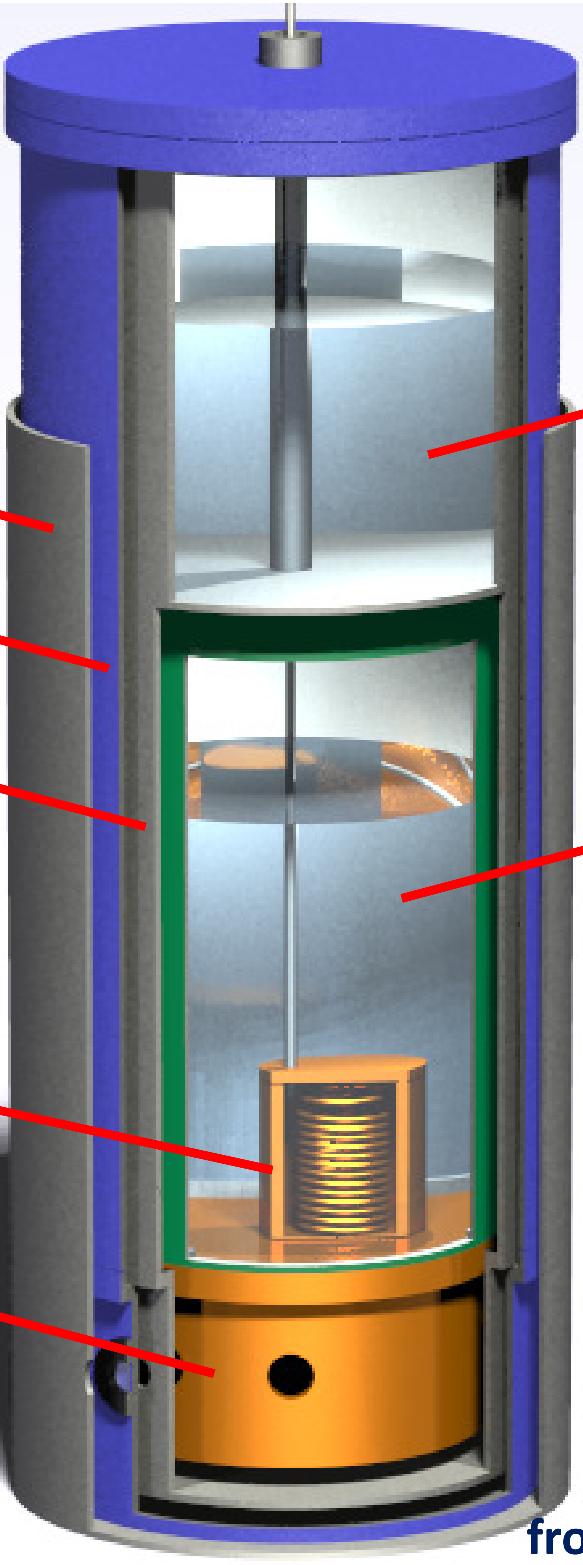
- Trap ion at trap center where
  trapping fields approach zero



- Can operate in tight-confinement (Lamb-Dicke) regime

⇒ First-order doppler free.
2nd-order doppler shift (time dilation)
due to micromotion will limit accuracy $\frac{\Delta f}{f_0} \sim 10^{-18}$

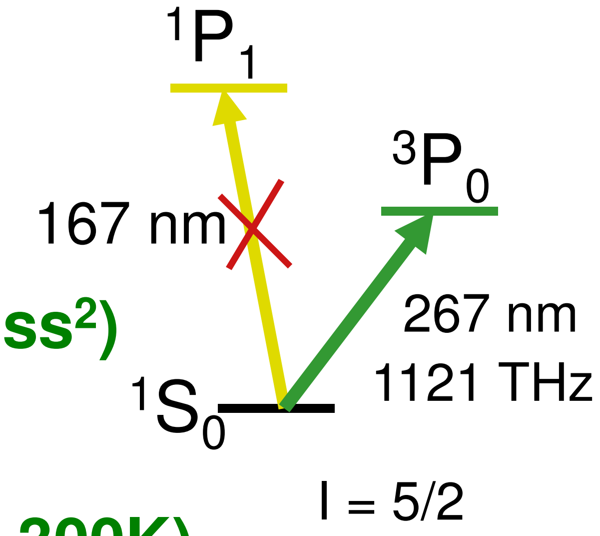
from Jim Bergquist' talk NIST



- Long storage times
- Environmental isolation
  - Low collision rate
  - Low blackbody

from Jim Bergquist' talk NIST

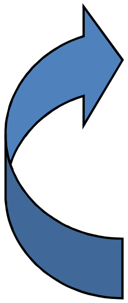
Some facts about Al^+



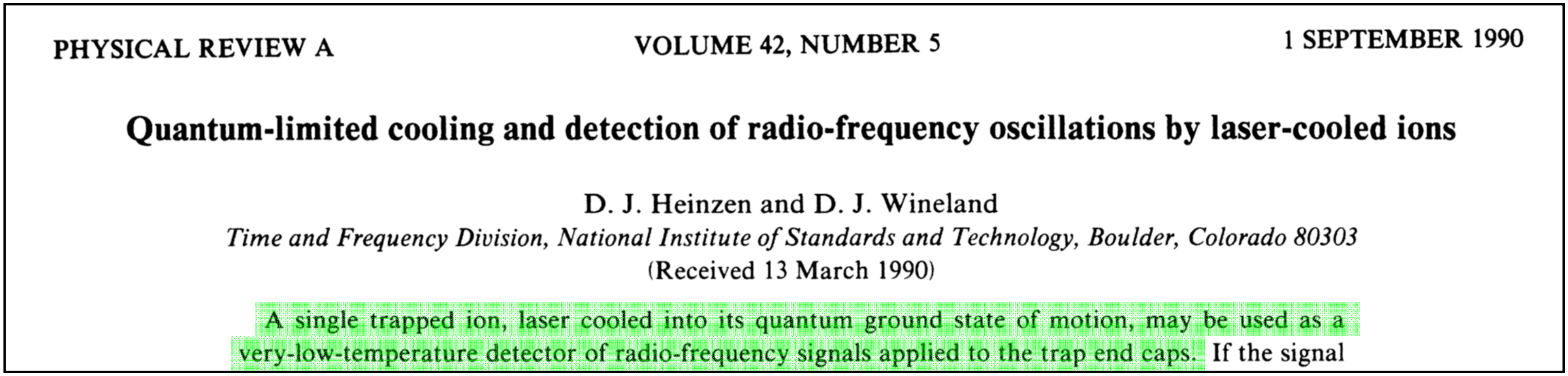
- **8 mHz linewidth clock transition**
- **Small quadratic Zeeman shift (6×10^{-16} /Gauss^2)**
- **Negligible electric-quadrupole shift (J=0)**
- **Smallest known blackbody shift (8×10^{-18} at 300K)**
- **Linear Zeeman shift 4 kHz/Gauss (easily compensated)**
- **Light mass (2nd order Doppler shifts)**
- **No accessible strong transition for cooling & state detection**

from Jim Bergquist' talk

Clock state transfer to Be$^+$ (simplified)



1. Cool to motional quantum ground state with Be$^+$
2. Depending on clock state, add vibrational energy via Al$^+$
3. Detect vibrational energy via Be$^+$



PHYSICAL REVIEW A VOLUME 42, NUMBER 5 1 SEPTEMBER 1990

Quantum-limited cooling and detection of radio-frequency oscillations by laser-cooled ions

D. J. Heinzen and D. J. Wineland

Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80303

(Received 13 March 1990)

A single trapped ion, laser cooled into its quantum ground state of motion, may be used as a very-low-temperature detector of radio-frequency signals applied to the trap end caps. If the signal

from Jim Bergquist' talk

Using two ions

Clock ion (Al⁺) for very accurate spectroscopy

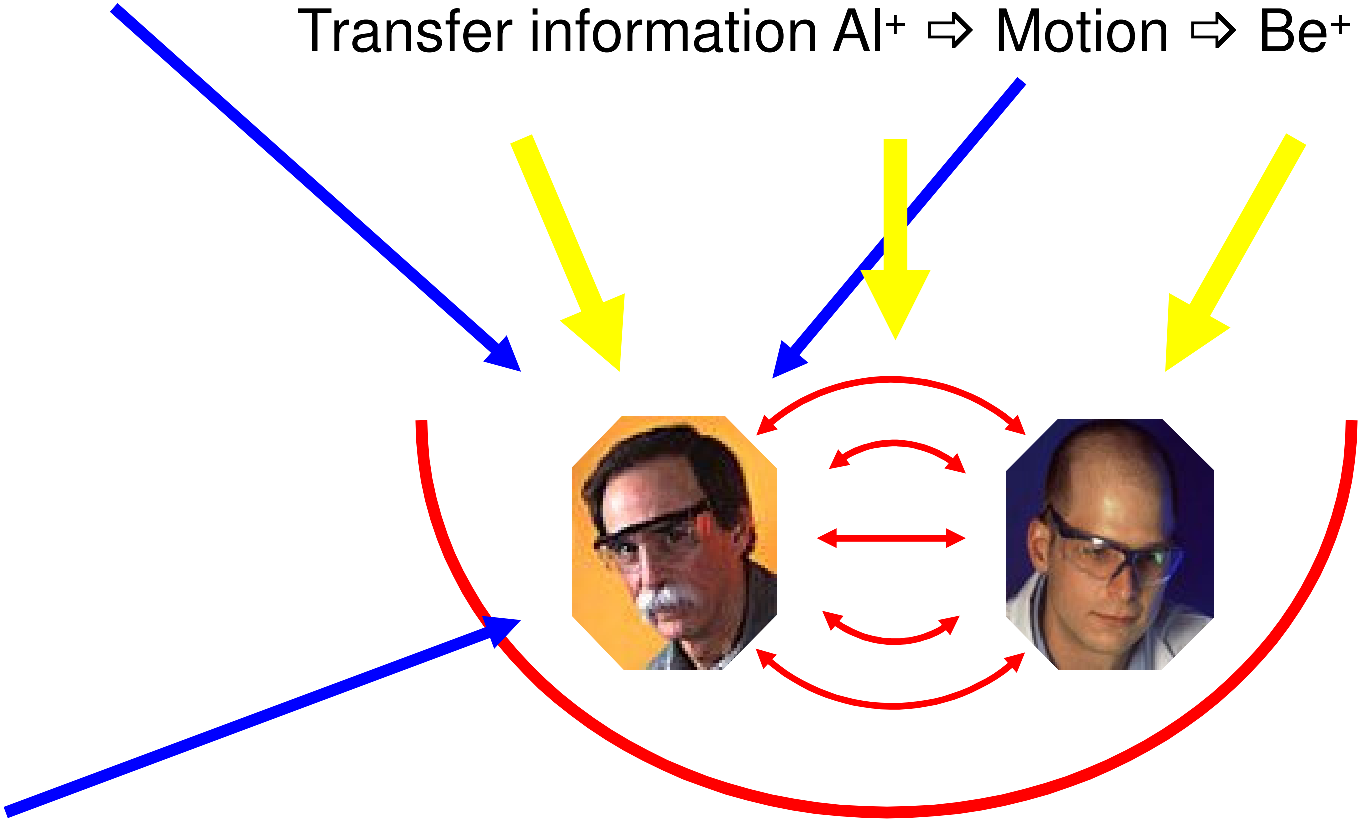
Logic ion (Be⁺) for cooling and readout

Coulomb-force couples the motion of the ions

⇒ Cooling Be+ leads to cooling of Al+

Ion motion is quantized (n=0, 1, …)

Transfer information Al⁺ ⇨ Motion ⇨ Be⁺

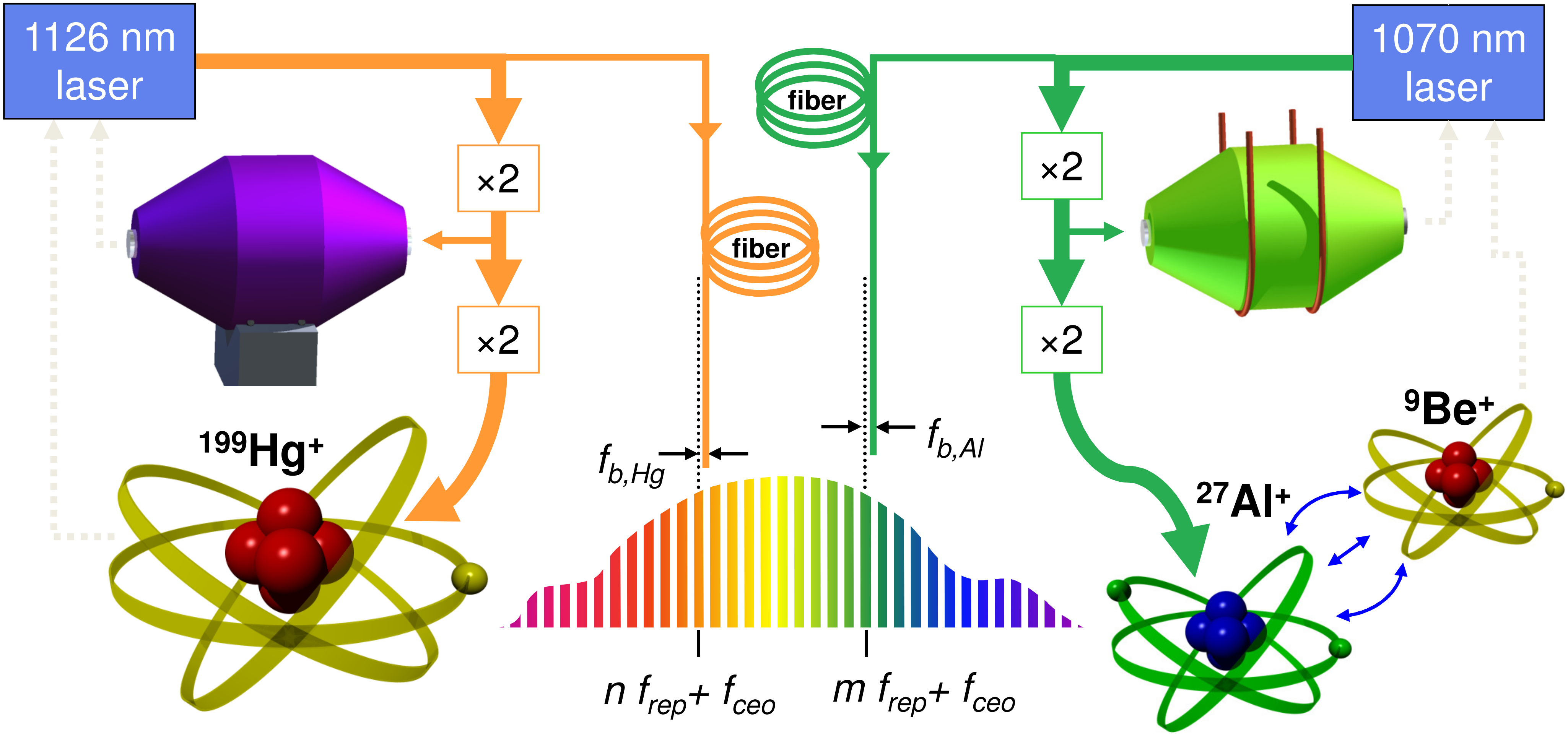


from Jim Bergquist’ talk

from Jim Bergquist' talk

Al+/Hg+ Comparison

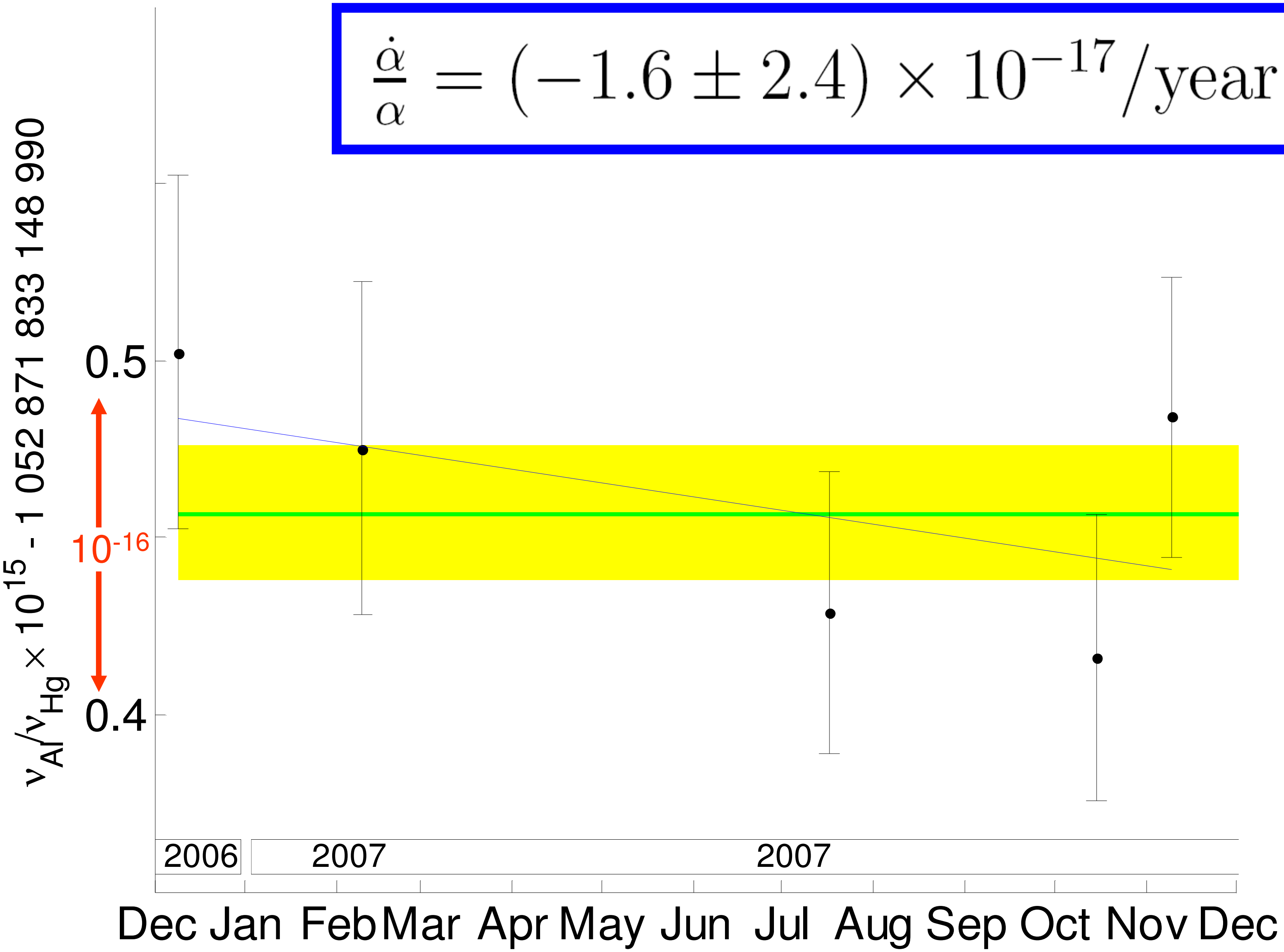
fs-comb locked to Hg+
measure beat with Al+



from Jim Bergquist' talk

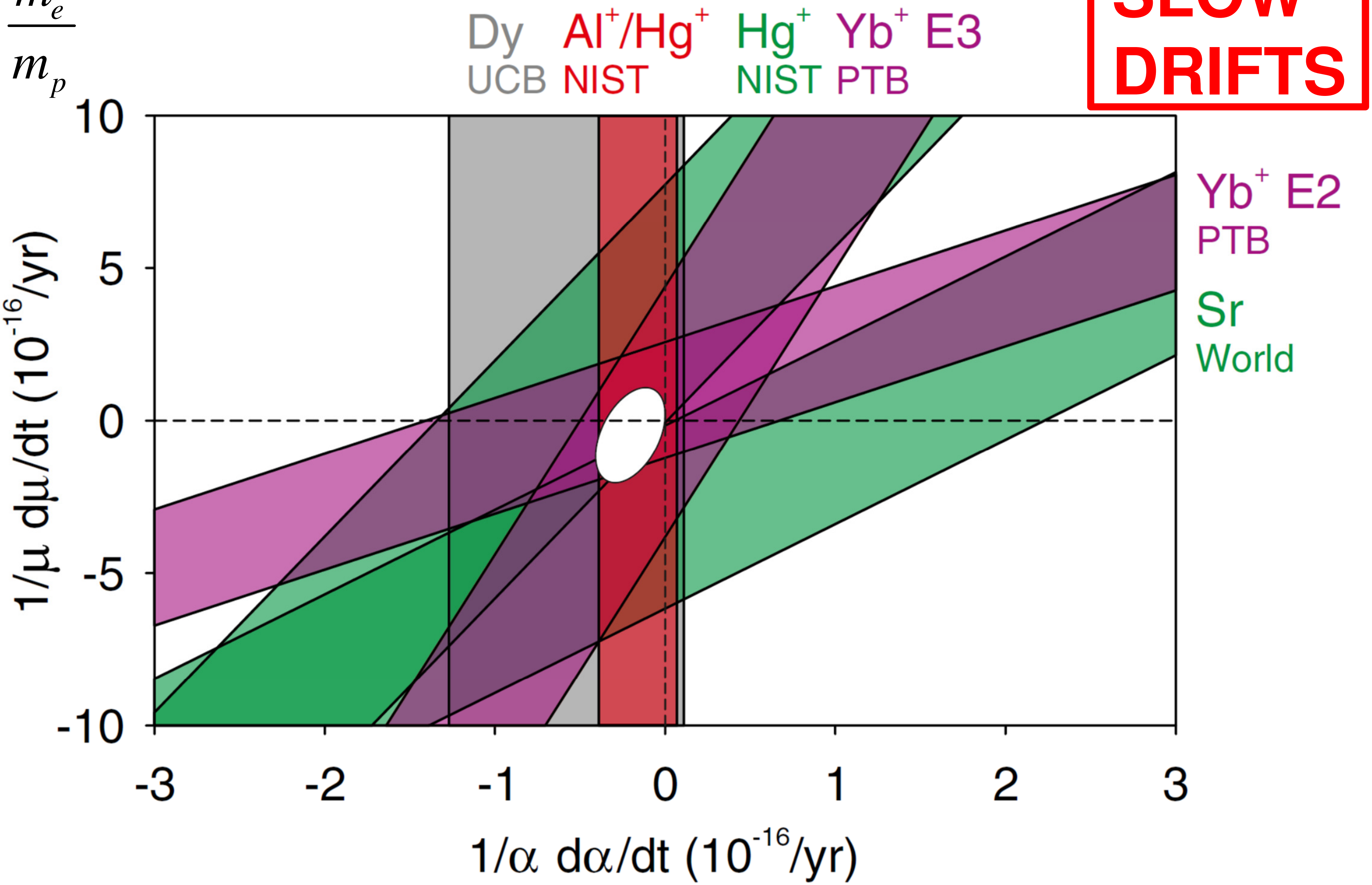
Al+/Hg+ Comparison

$$\frac{\dot{\alpha}}{\alpha} = (-1.6 \pm 2.4) \times 10^{-17}/\text{year}$$



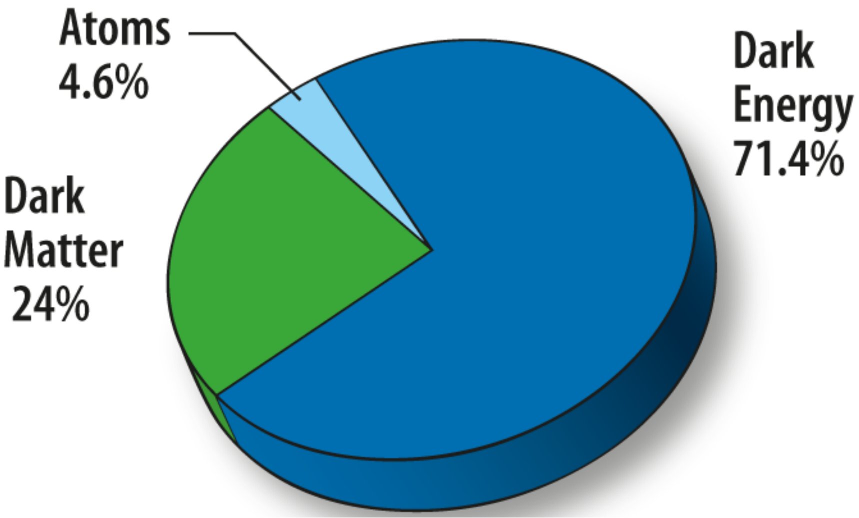
$$\mu = \frac{m_e}{m_p}$$

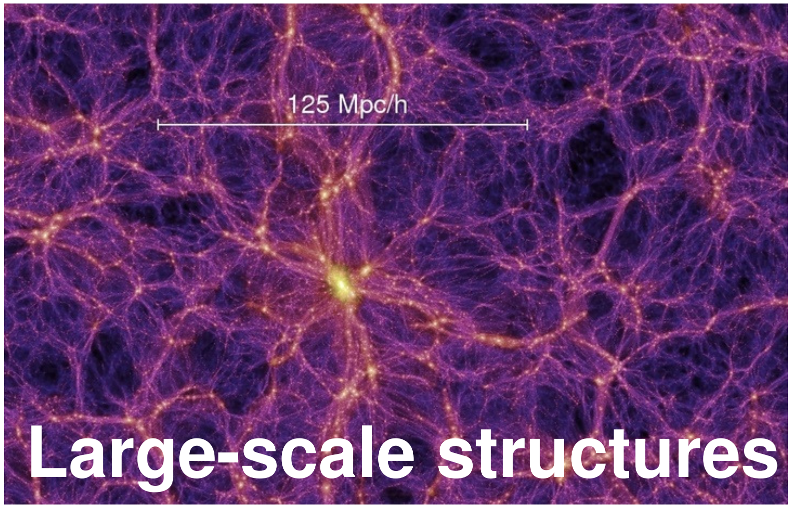
SLOW DRIFTS



Constraints on temporal variations of α and μ from comparisons of atomic transition frequencies. Huntemann et al., PRL 113, 210802 (2014)

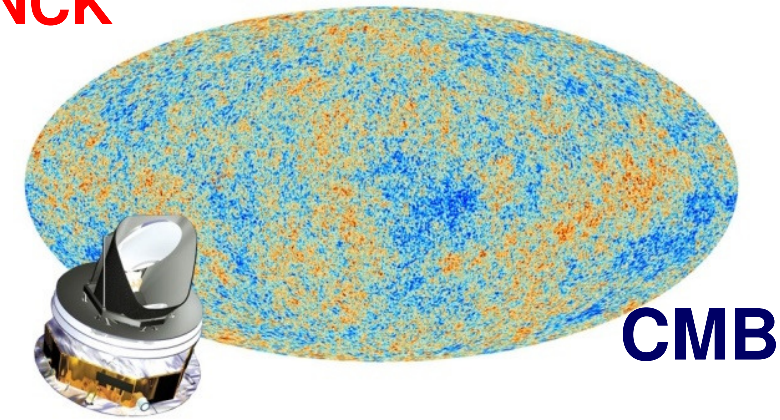
Variation of fundamental constants and dark matter





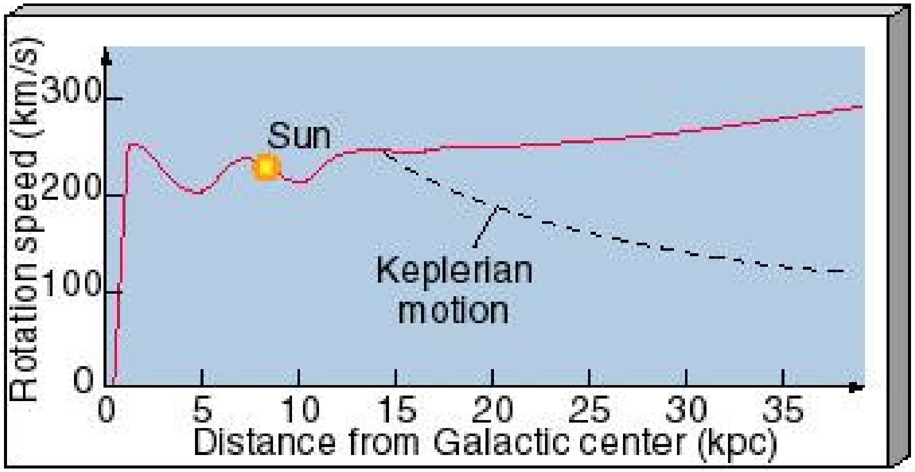
Large-scale structures

PLANCK



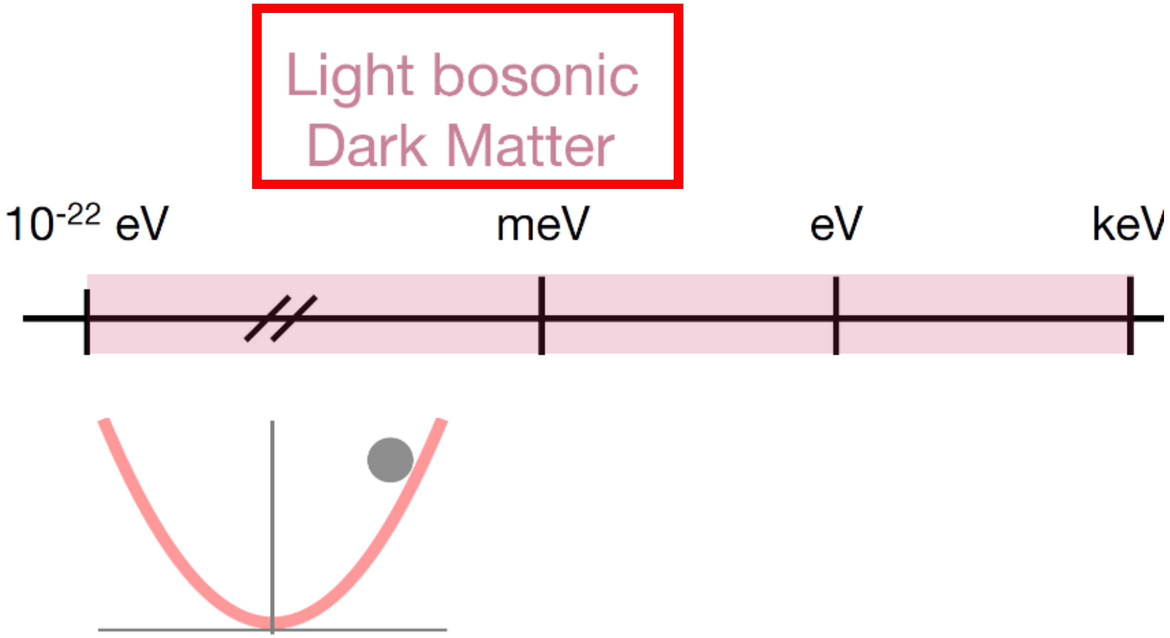
CMB

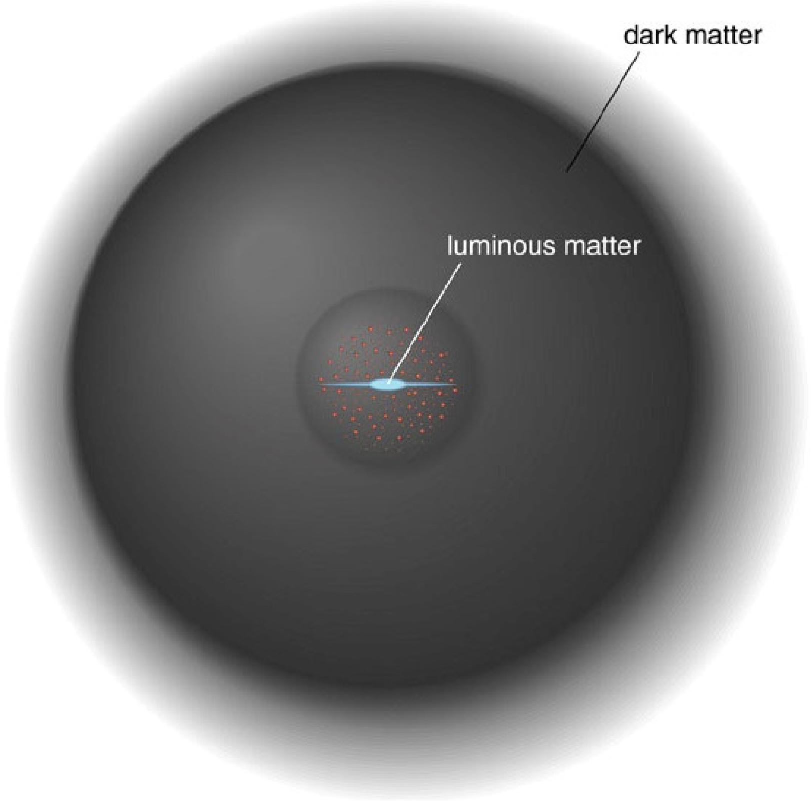
Rotation curves



Gravitational lensing

The dark matter





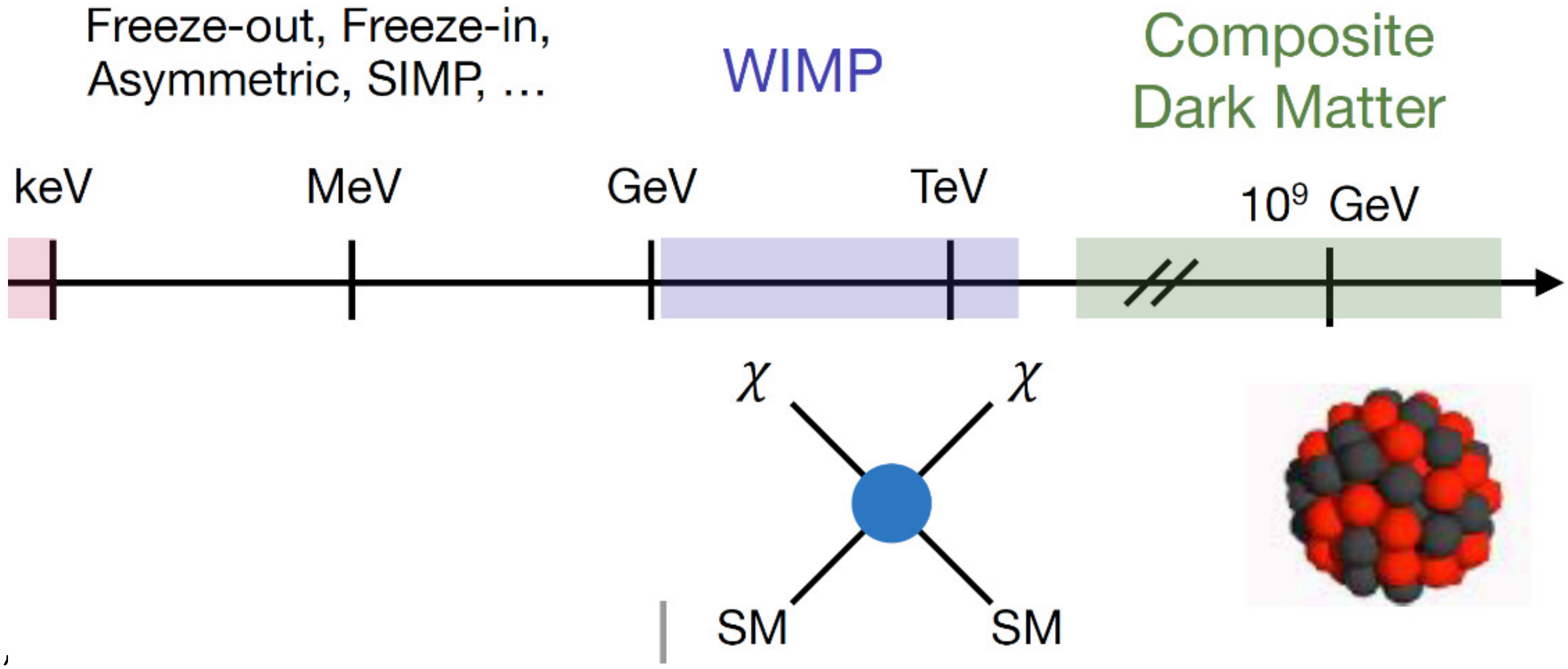


Image credit: Simon Knapen,

Ultralight dark matter

Bosonic dark matter (DM) with mass $m_\phi < 1\text{eV}$

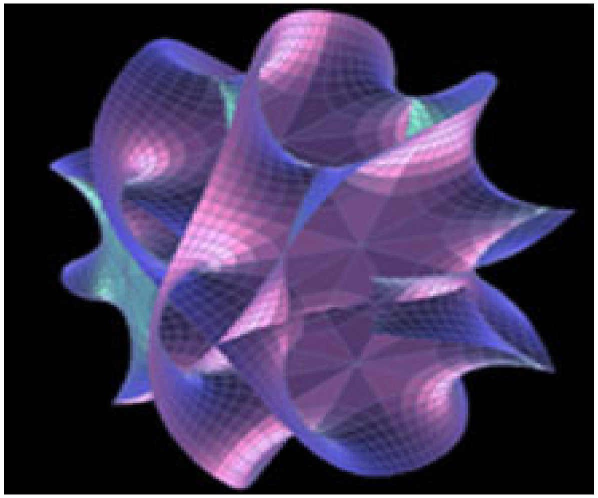
Dark matter density in our Galaxy > λ_{dB}^{-3}

λ_{dB} is the de Broglie wavelength of the particle.

Then, the scalar dark matter exhibits coherence and behaves like a wave.

$$\phi(t) = \phi_0 \cos\left(m_\phi t + \bar{k}_\psi \times \bar{x} + \dots\right)$$

Dilatons: appears in theories with extra dimensions when the volume of the compactified dimensions is allowed to vary.



Dilatonic couplings to the Standard Model

$$\frac{\phi}{M^*}\mathcal{O}_{\text{SM}}$$

A. Arvanitaki et al., PRD 91, 015015 (2015)

Ultralight dark matter

$$\phi(t) = \phi_0 \cos\left(m_\phi t + \bar{k}_\phi \times \bar{x} + \ldots\right)$$

DM virial velocities ~ 300 km/s

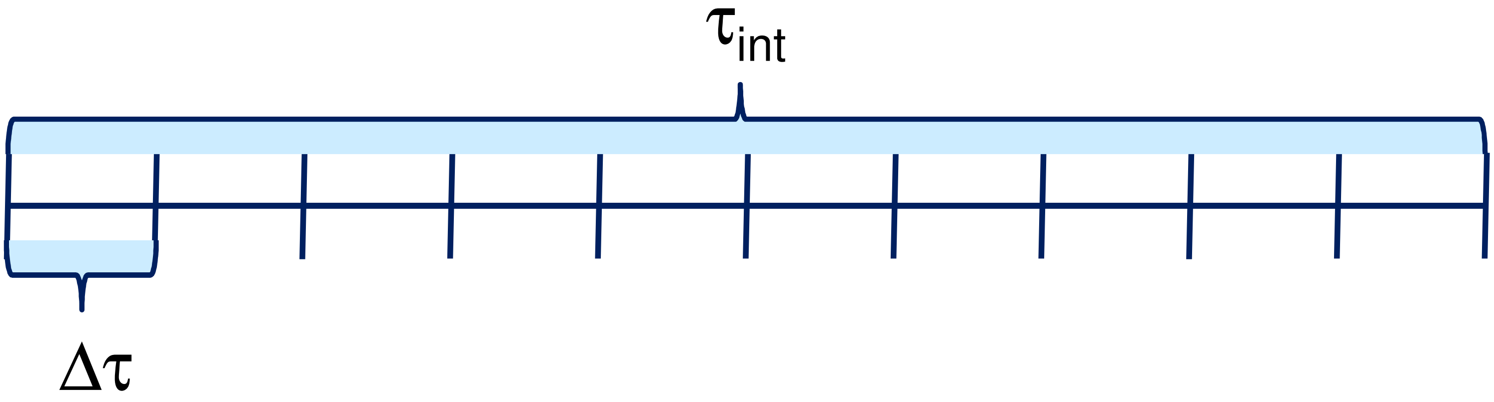
Dark matter parameters

τ [s]	$f = 2\pi/m_\phi$ [Hz]	m_ϕ [eV]	
10^{-6}	1 MHz	4×10^{-9}	
10^{-3}	1 kHz	4×10^{-12}	
1	1	4×10^{-15}	One oscillation per second
1000	1 mHz	4×10^{-18}	
10^{6}	10^{-6}	4×10^{-21}	One oscillation per 11 days

Clock measurement protocols for the dark matter detection

Single clock ratio measurement: averaging over time τ_1

Make N such measurements, preferably regularly spaced



Detection signal:

A peak with monochromatic frequency $f = 2\pi/m_\phi$ in the discrete Fourier transform of this time series.

A. Arvanitaki et al., PRD 91, 015015 (2015)

Measuring ratios of optical clock frequencies for dark matter detection

$$\boxed{\frac{\delta(\nu_2/\nu_1)}{(\nu_2/\nu_1)}} \simeq d_e(K_2 - K_1)\kappa\phi(t)$$

Need:

- **Best short-term stability σ_1 at $\Delta\tau$**
- Long total measurement time to improve sensitivity

$$\sigma_N = \sigma_1/\sqrt{N}$$

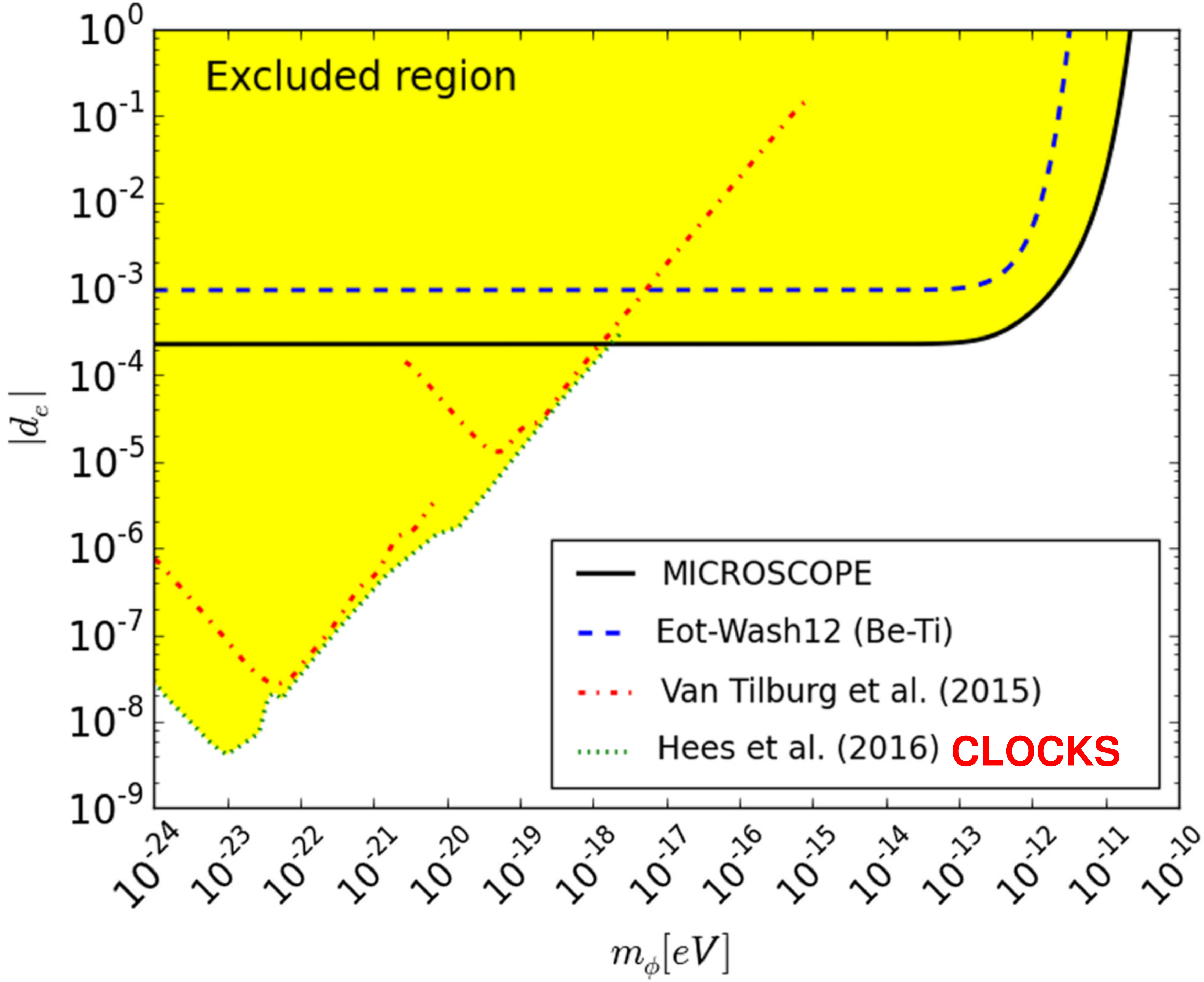
But: only until you reach the DM coherence time

$$\tau_{\text{coh}} \simeq 2\pi(m_\phi v^2)^{-1} \qquad v \approx 10^{-3}$$

(Not an issue for 10^6 s)

- **Lowest systematic uncertainty**
- **Largest possible enhancement factor combination (K_2-K_1)**

Experimental constraints for dilaton dark matter



CLOCKS

nature physics

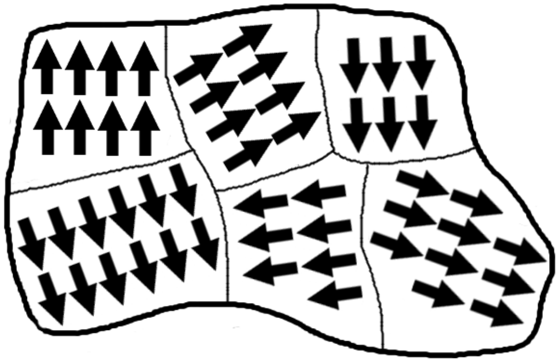
LETTERS

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

Transient variations

Hunting for topological dark matter with atomic clocks

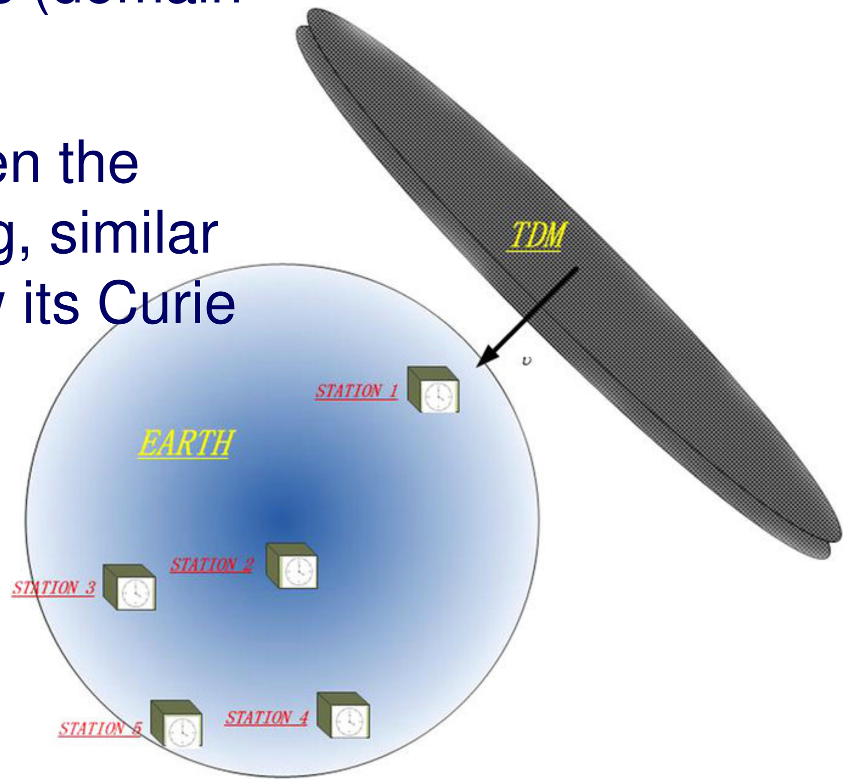
A. Derevianko[1]* and M. Pospelov[2,3]



Dark matter clumps: point-like monopoles, one-dimensional strings or two-dimensional sheets (domain walls).

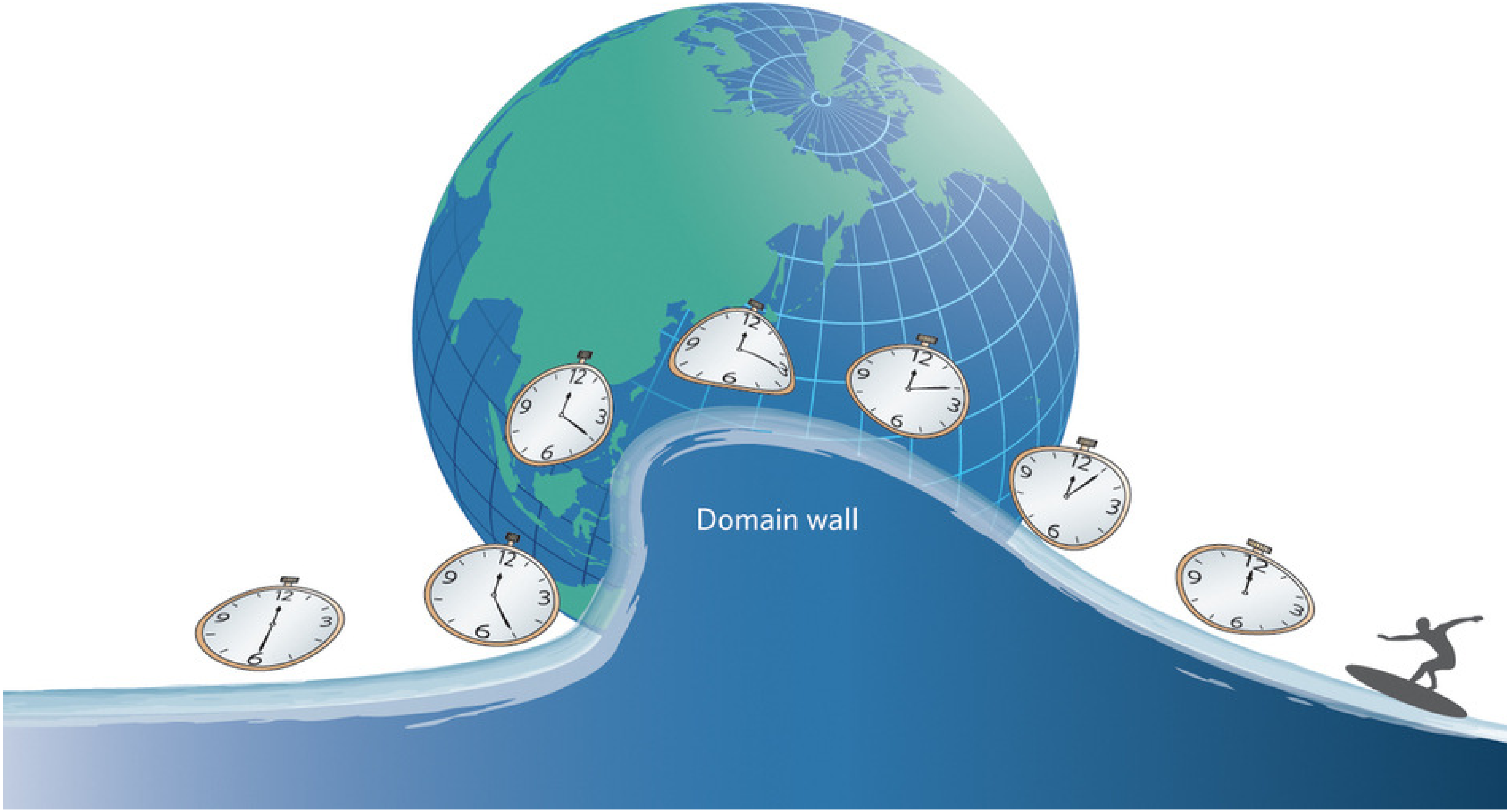
Topological dark matter may have formed when the early Universe cooled down after the Big Bang, similar to the domains formed in a ferromagnet below its Curie temperature.

If they are large (size of the Earth) and frequent enough we can detect this with atomic clocks.



Yang at al., Scientific Reports 5, 11469 (2015)

Nature Communications 8, 1195 (2017)

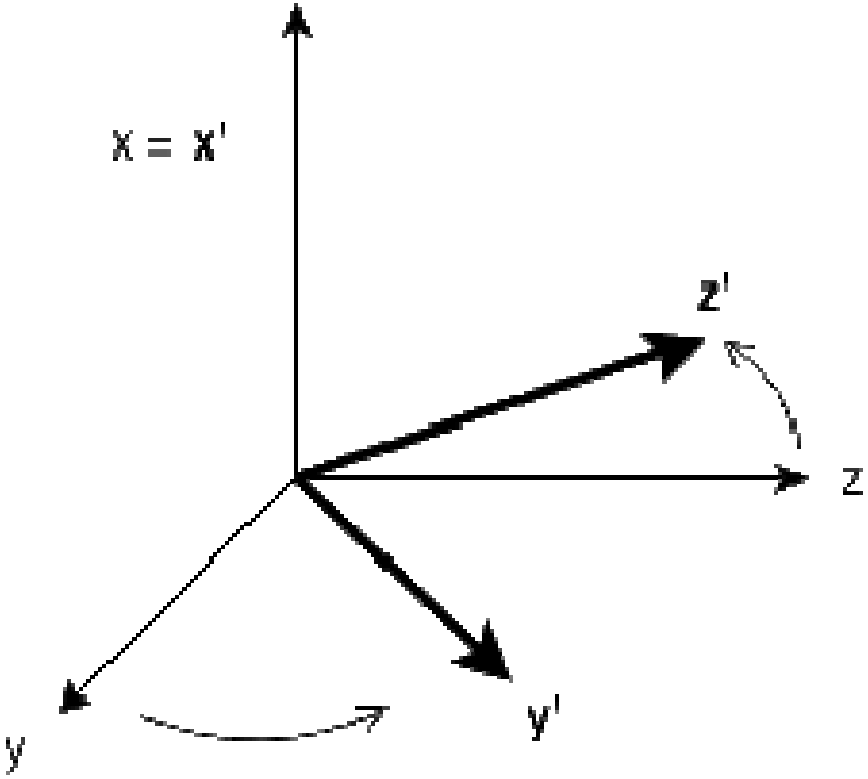


Topological dark matter may be detected by measuring changes in the synchronicity of a global network of atomic clocks, such as the Global Positioning System, as the Earth passes through the domain wall.

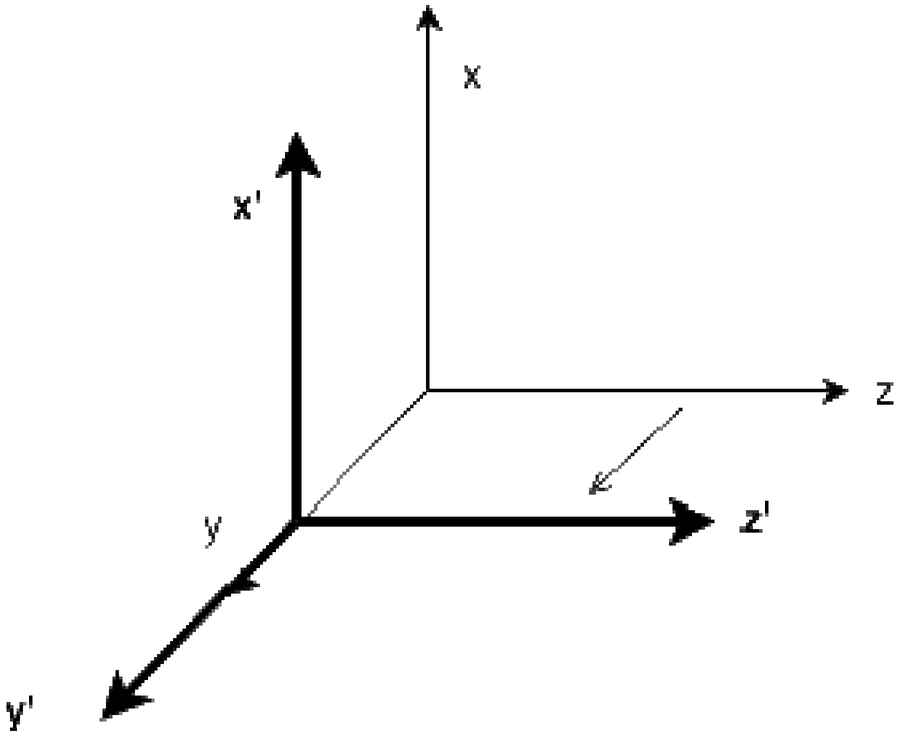
Rana Adhikari, Paul Hamiton & Holger Müller, Nature Physics 10, 906 (2014)

Search for the violation of the Lorentz invariance

Lorentz invariance: the laws of physics that govern a physical system are unchanged for different system orientations or velocities.



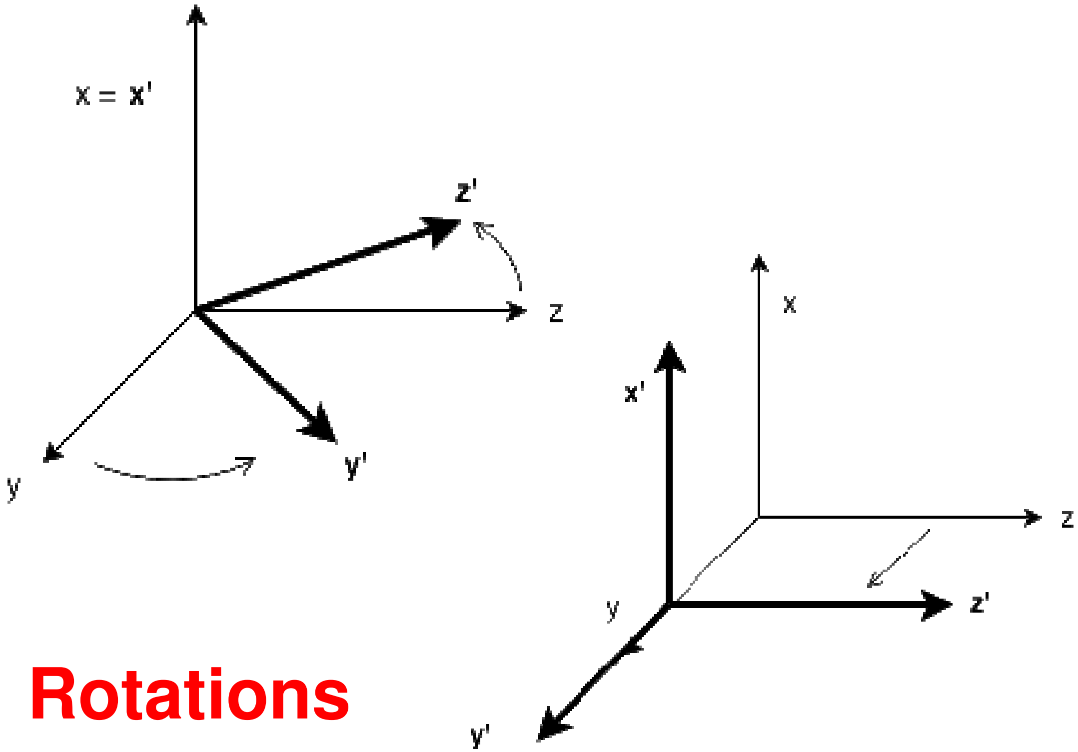
Rotations



Boosts

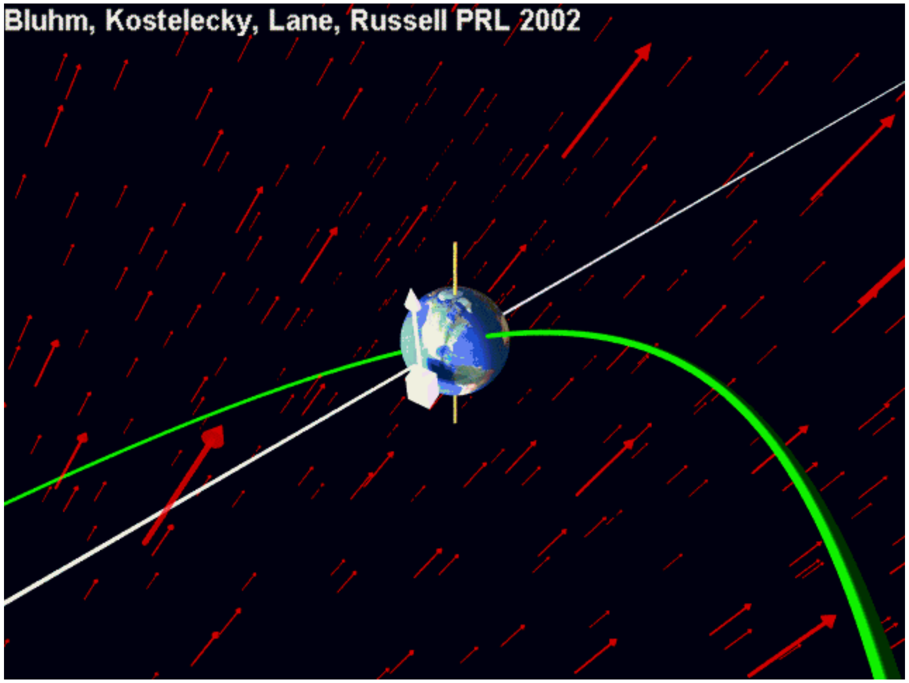
Search for the violation of the Lorentz invariance

Lorentz invariance: the laws of physics that govern a physical system are unchanged for different system orientations or velocities.



Rotations

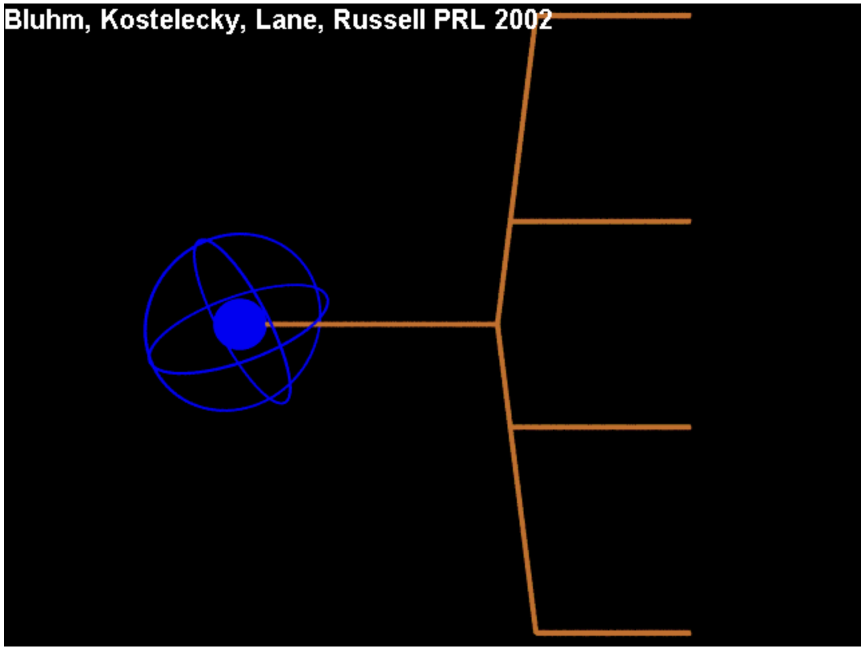
Boosts


Bluhm, Kostelecky, Lane, Russell PRL 2002

Animation credit: http://www.physics.indiana.edu/~kostelec/mov.html

The basic idea of atomic physics tests of Lorentz invariance:

Atomic energy levels are affected differently by Lorentz violation: transition frequency will change when experimental set up rotates or moves



Experimental strategy:

(1) Pick two energy levels that should shift differently due to Lorentz violation.

(2) Turn on magnetic field to define a quantization axis.

(3) Keep measuring the transition frequency between these two levels while Earth rotates and and moves around the Sun. **[DO NOT ROTATE EXPERIMENT YOURSELF].**

Animation credit: http://www.physics.indiana.edu/~kostelec/mov.html

Measure frequency difference of two Yb+ PTB clocks to probe Lorentz violation

Two orders of magnitude improvement in sensitivity

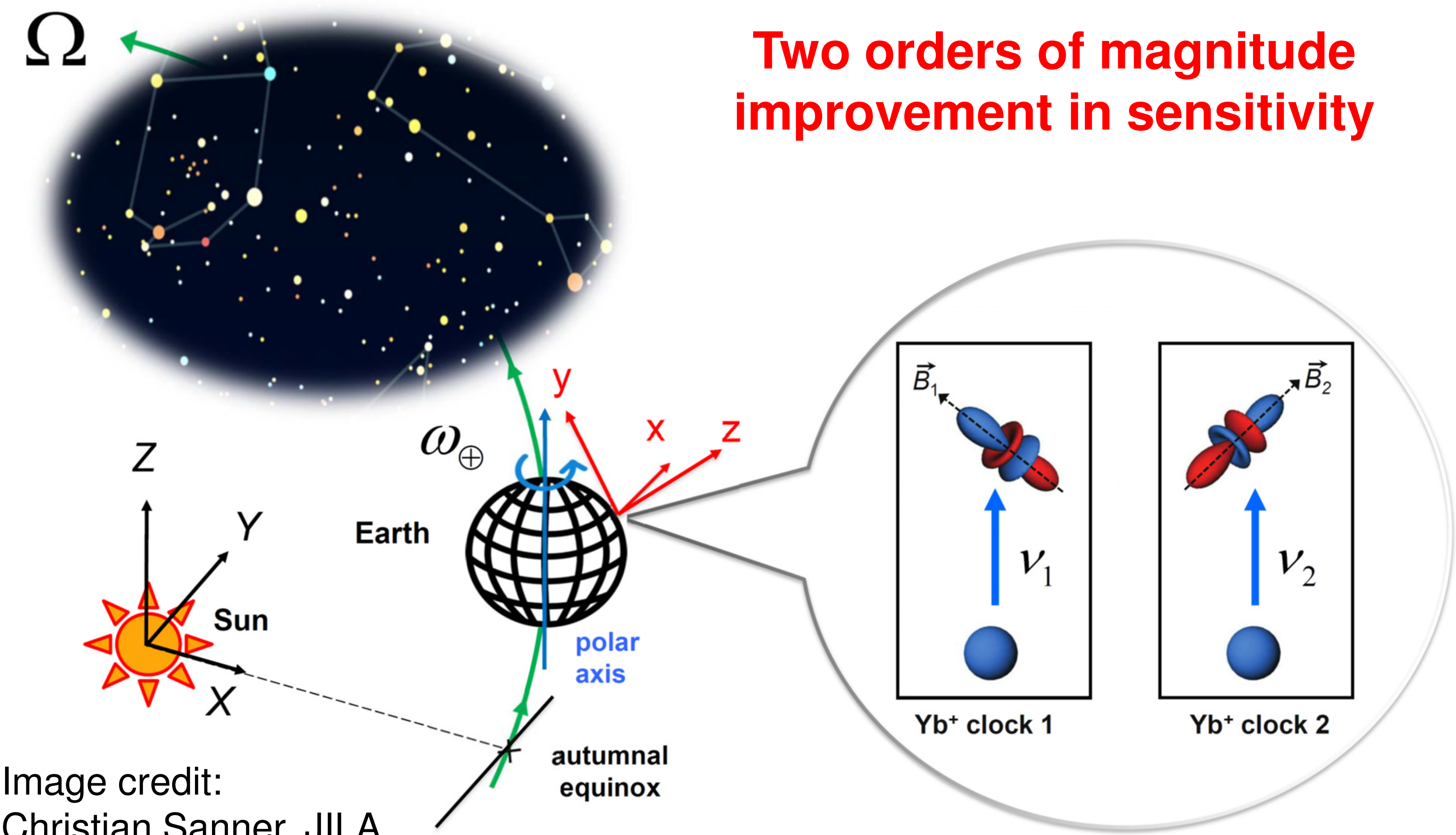
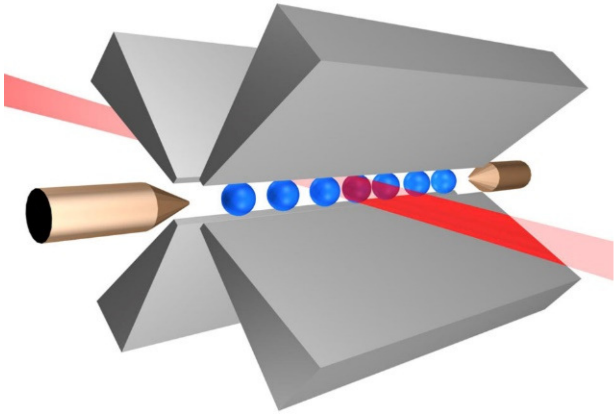


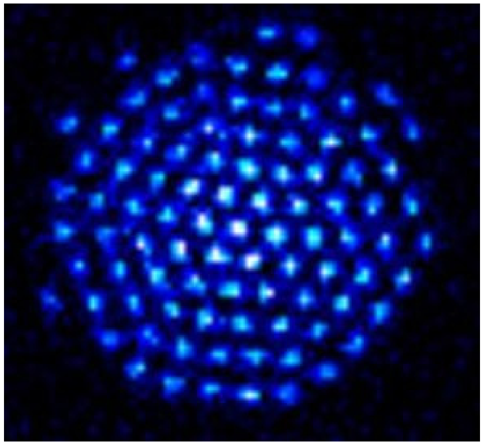
Image credit:
Christian Sanner, JILA

$$\Delta\nu = \nu_1 - \nu_2$$

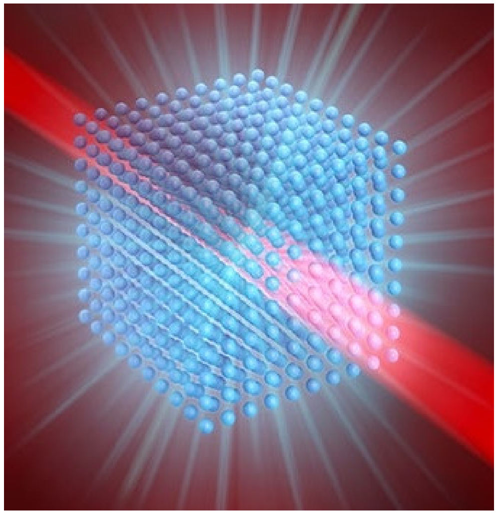
The Future: Atomic Clocks in the Next Quantum Revolution



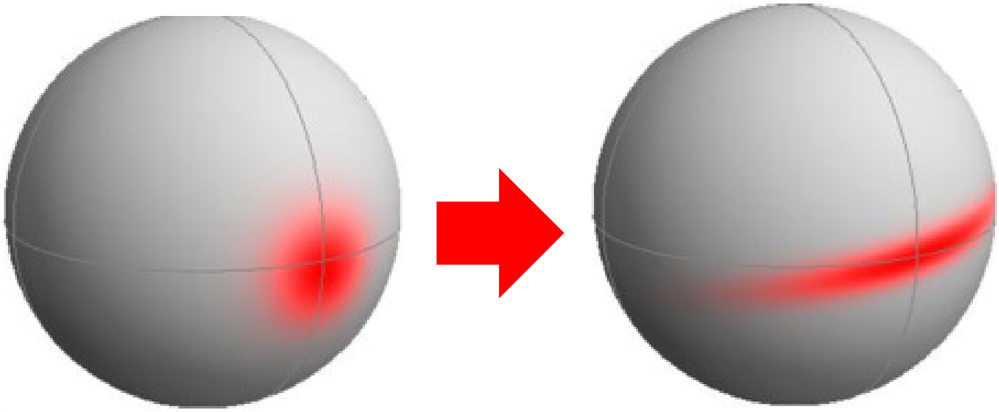
Ion chains



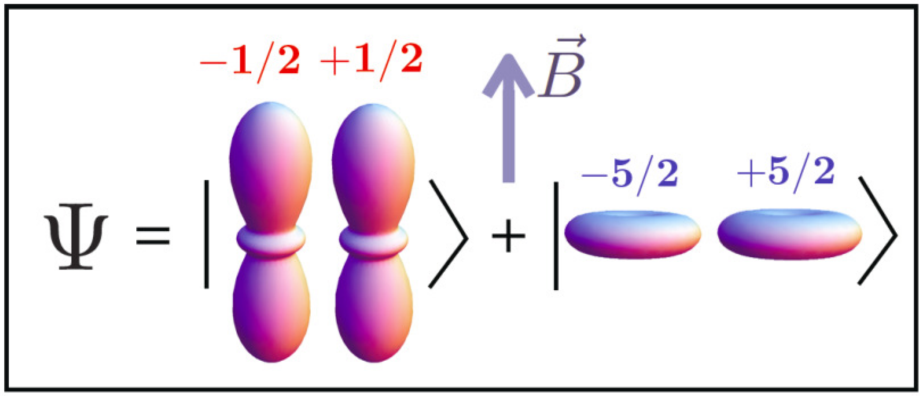
Large ion crystals



3D optical lattice clocks



Measurements beyond the quantum limit

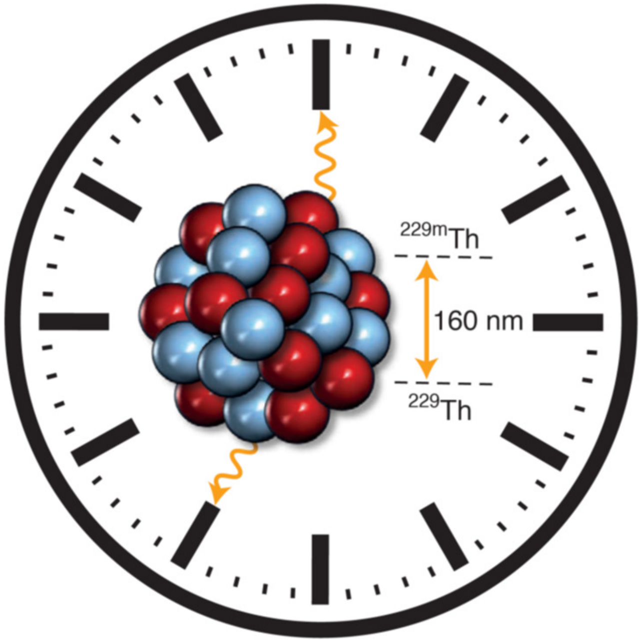


Entangled clocks

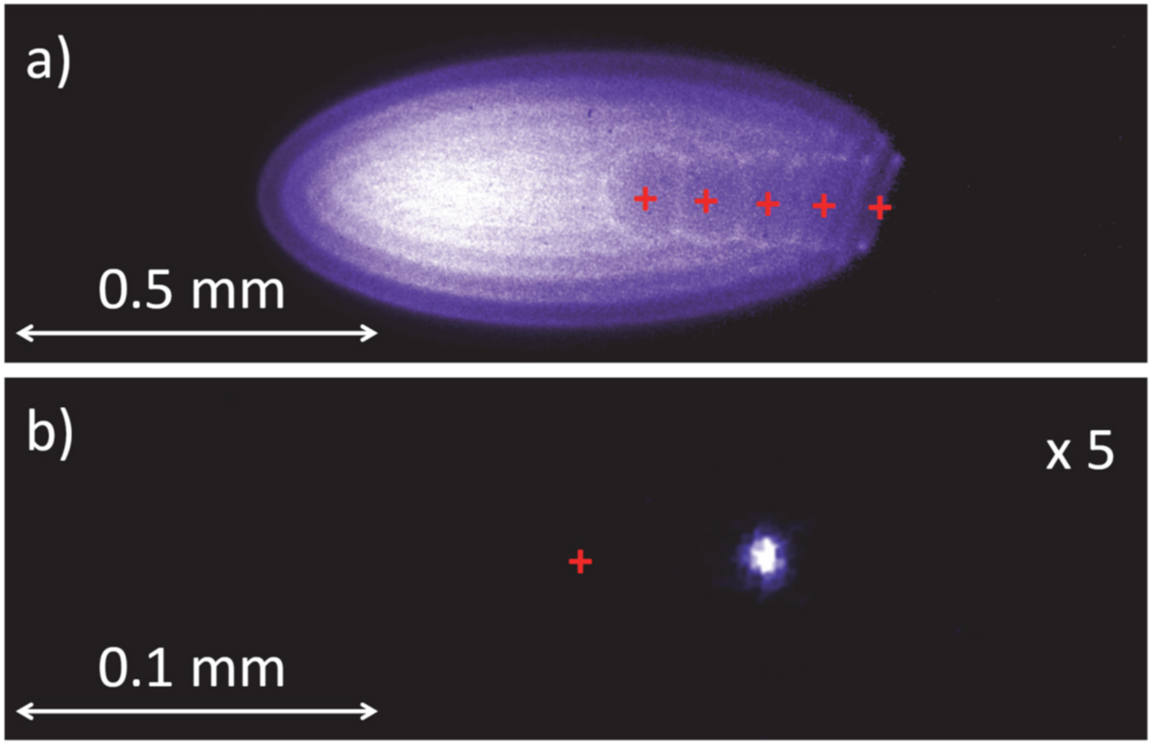
Orders of magnitude improvements with current clocks

Image credits: NIST, Innsbruck group, MIT Vuletic group, Ye JILA group

The Future: Atomic Clocks in the Next Quantum Revolution



Nuclear clock



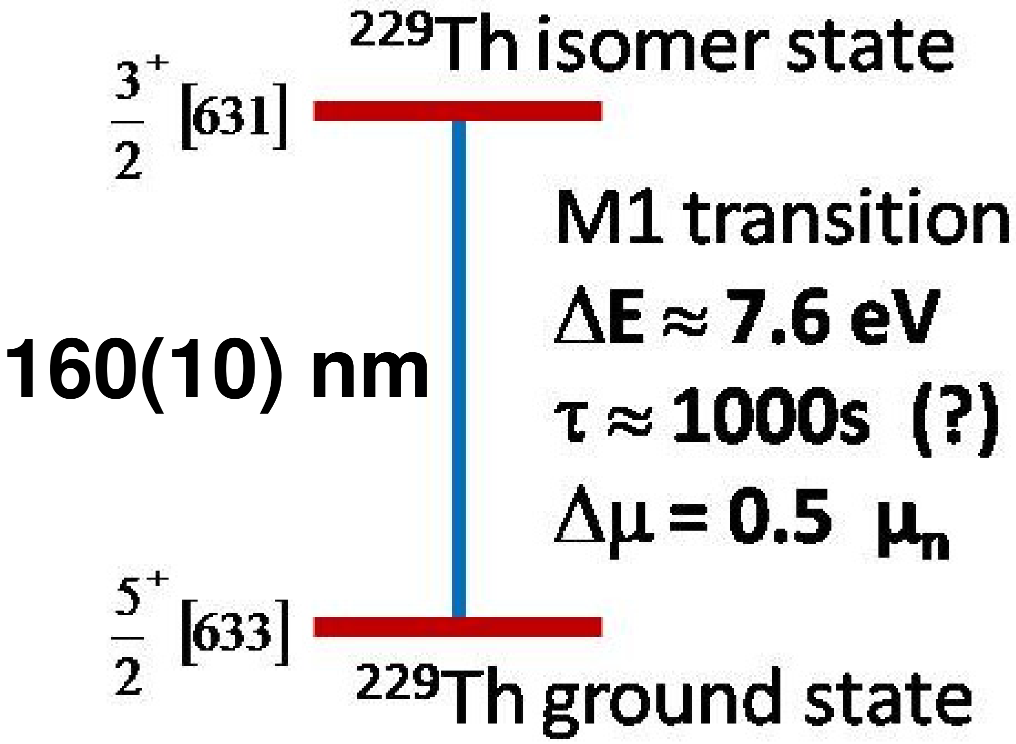
Clocks with ultracold highly charged ions

Science 347, 1233 (2015)

Th ion 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

M1 transition

$\Delta E \approx 7.6$ eV

$\tau \approx 1000$s (?)

$\Delta\mu = 0.5\ \mu_n$

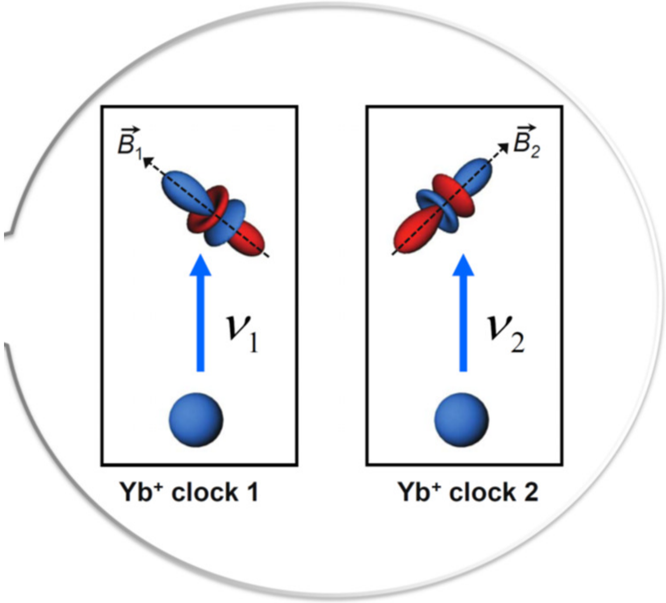
$\frac{5}{2}^{+}$ [633]

^{229}Th ground state

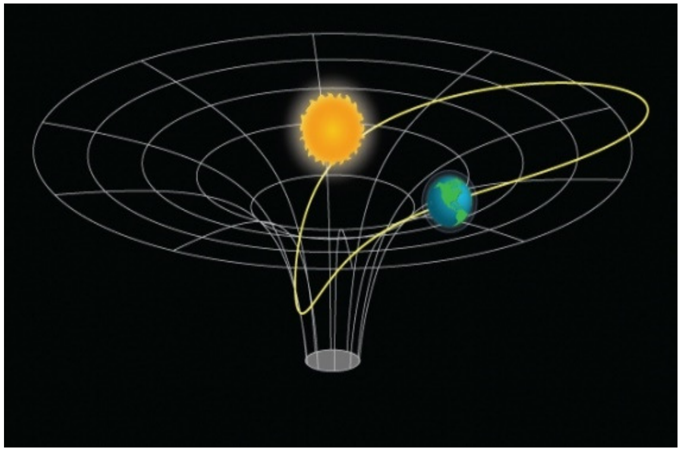
Possible orders of magnitude enhancement to the variation of α and $\frac{m_q}{\Lambda_{QCD}}$ but orders of magnitude uncertainty in the enhancement factors.

Atomic Clocks of the Next Quantum Revolution: Quantum-science Enabled Discoveries

What is dark matter ?



Quantum gravity and violation of Lorentz invariance?



Does equivalence principle breaks down?

Are fundamental constants constant? α

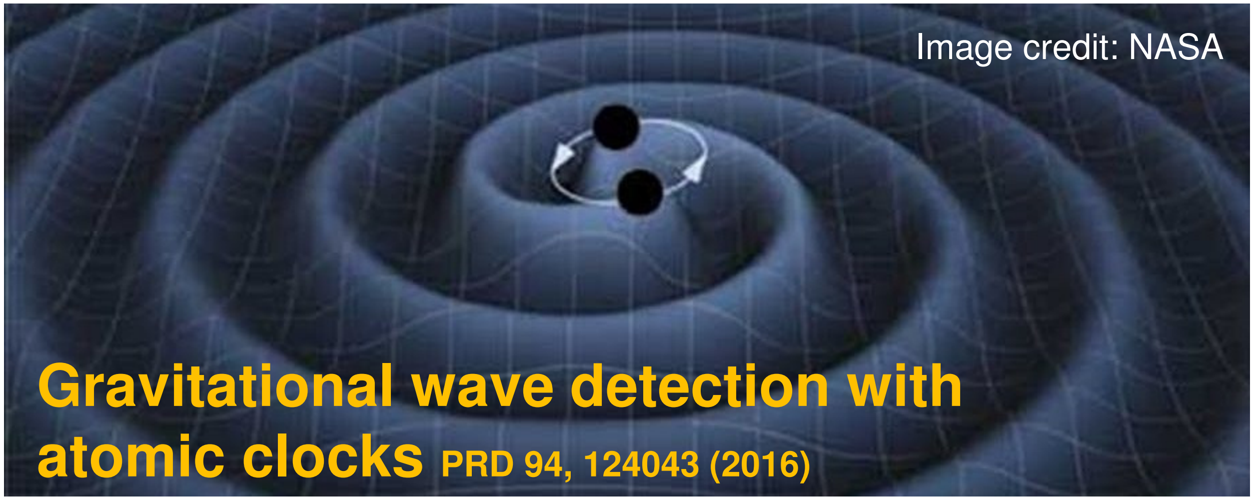


Image credit: NASA

Gravitational wave detection with atomic clocks PRD 94, 124043 (2016)