Search for New Physics with Atoms and Molecules

MARIANNA SAFRONOVA

June 2019,
Ameland
Netherlands

Summer school Search for new physics with low-energy precision tests

NSF
NIST
Office of Naval Research
ONR
USN
Science & Technology

University of Delaware
jqi Joint Quantum Institute

Please ask questions during the lecture!

THE BENEFITS OF ASKING QUESTIONS

You will learn more.

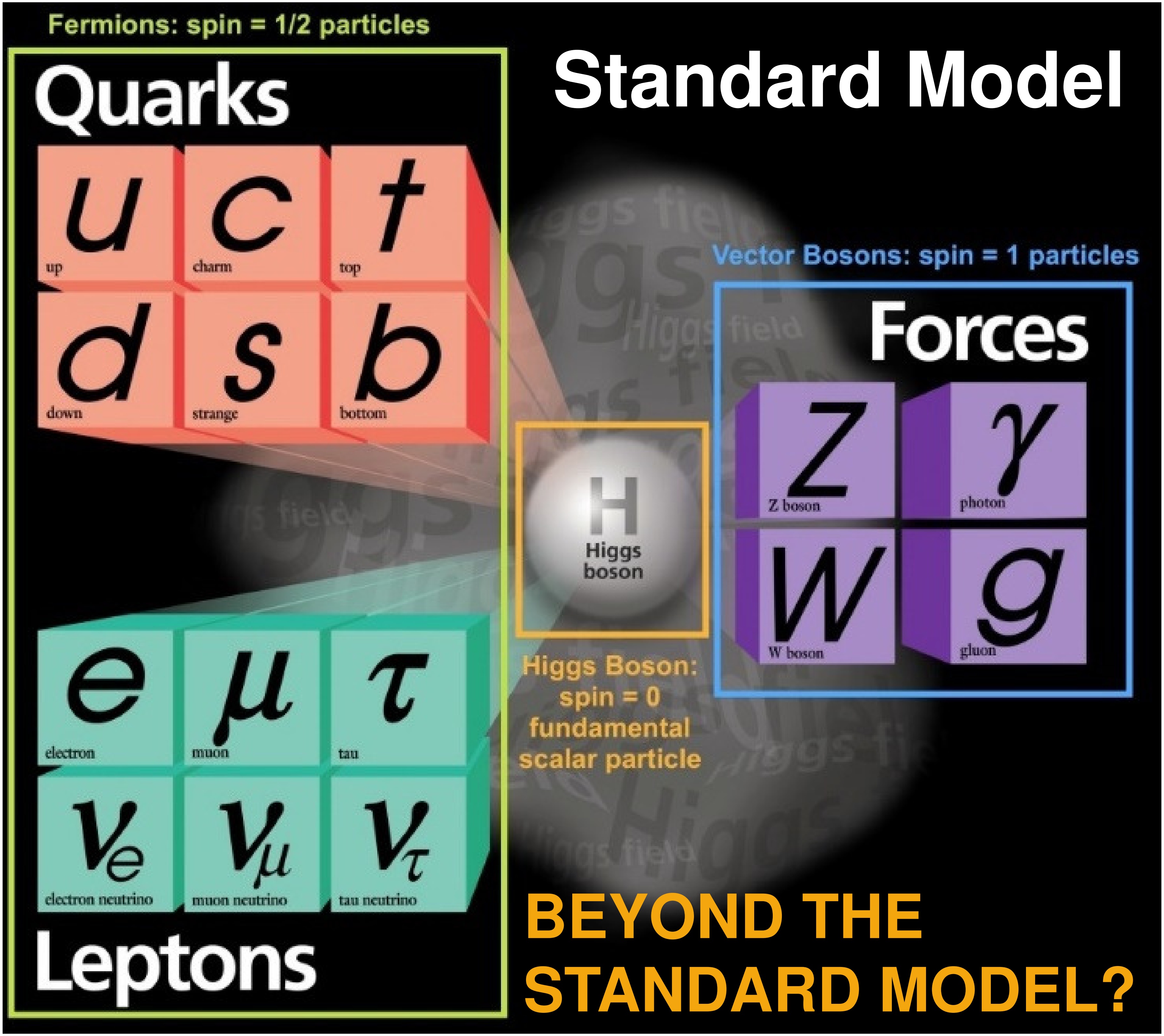
The summer school will be more fun for you.

Great practice for the future.

You will stay awake ☺

OVERVIEW

- **Problems with the standard model**
- **Introduction: precision measurements for new physics searches**
- **Introduction to atomic clocks & variation of fundamental constants**

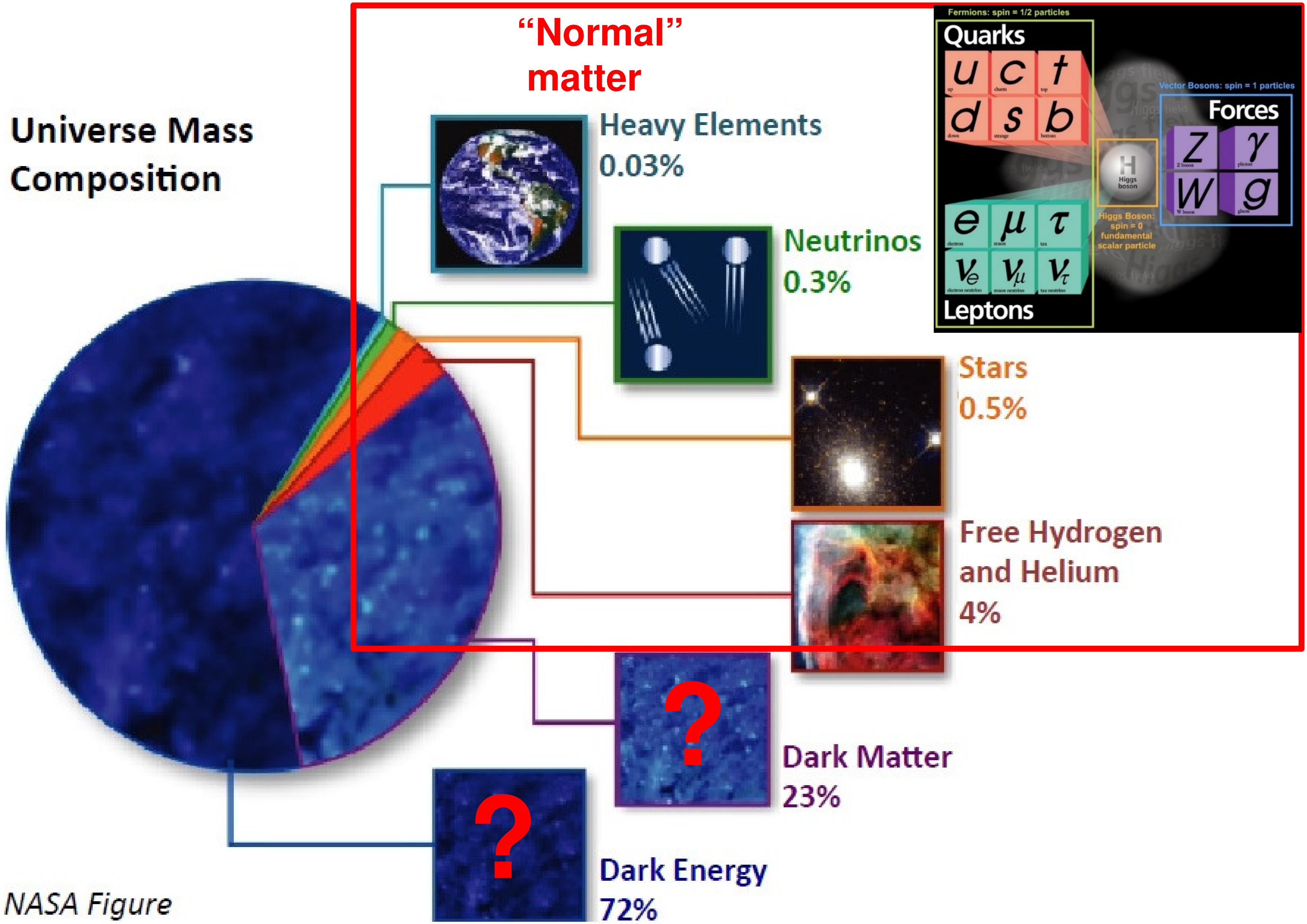

Fermions: spin = 1/2 particles
Standard Model
Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Vector Bosons: spin = 1 particles
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
Higgs Boson: spin = 0 fundamental scalar particle
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons
BEYOND THE STANDARD MODEL?

What is Wrong with the Standard Model?

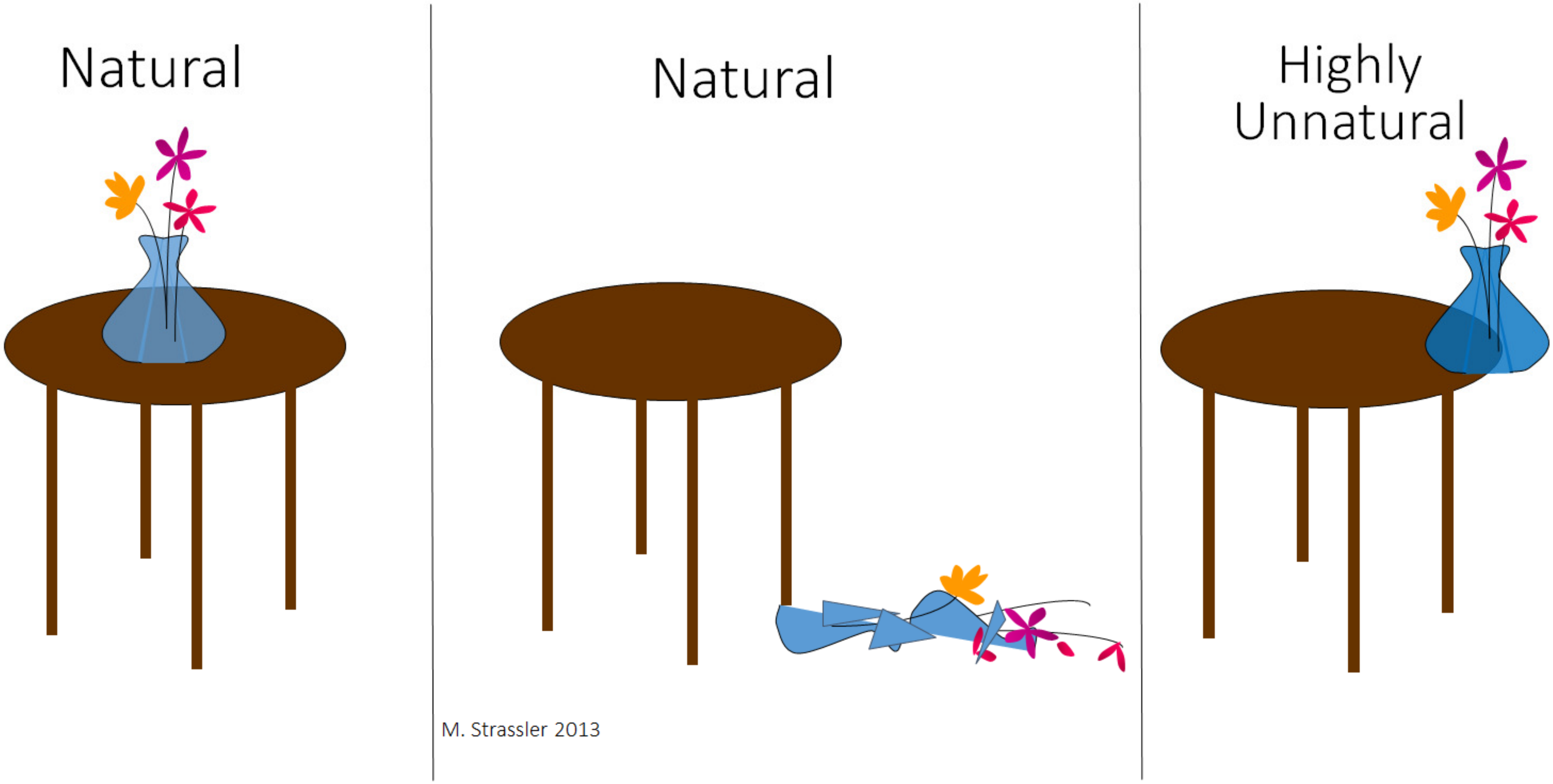
According to the Standard Model

Our Universe can not exist !

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



Hierarchy problems
Why is the Universe the way it is?
Naturalness



https://profmattstrassler.com/articles-and-posts/particle-physics-basics/the-hierarchy-problem/naturalness/

Hierarchy problems: weak scale

Why the Higgs field vacuum expectation value is so small, average value 246 GeV **(really NOT natural).**

Natural: Universes will have the Higgs field "fully on" Particles at Plank scale masses, turning into black holes.

Natural: Higgs field is "off" - no masses.

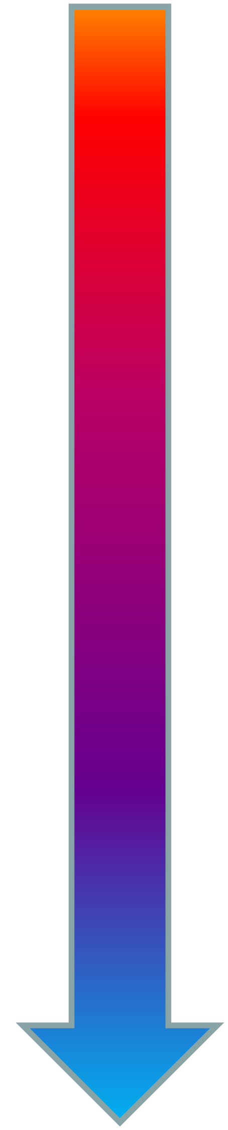
The problem is that corrections to Higgs mass from even obvious loop with top quark results in quadratic divergences ($1/k^2$), putting the mass back to Plank scale. The main issue is that there are a lot of corrections which are then very large but all nearly cancel out, which is very puzzling.

Solutions: supersymmetry, dynamical electroweak symmetry breaking (technicolor), little Higgs, twin Higgs, **dynamical explanation (relaxation)**.

A Very Brief Story of Advances in AMO Physics

Advances in AMO Physics: New world of ultracold

300K



500nK

Steve Chu

Claude Cohen-Tannoudji

Bill Phillips

1997
Nobel Prize
Laser cooling and trapping

Eric Cornell

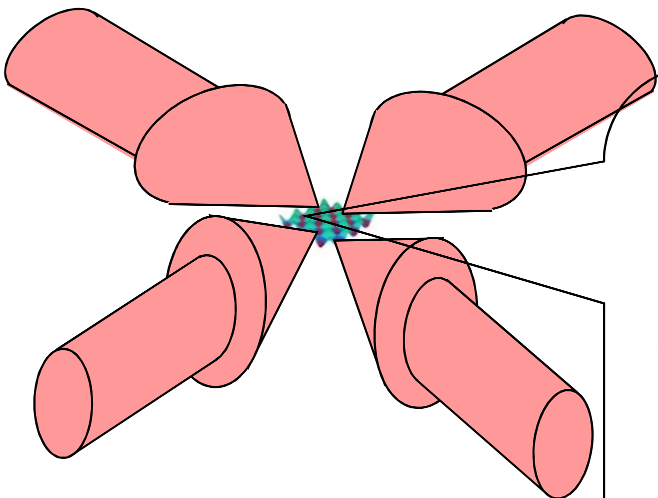
Wolfgang Ketterle

Carl Wieman

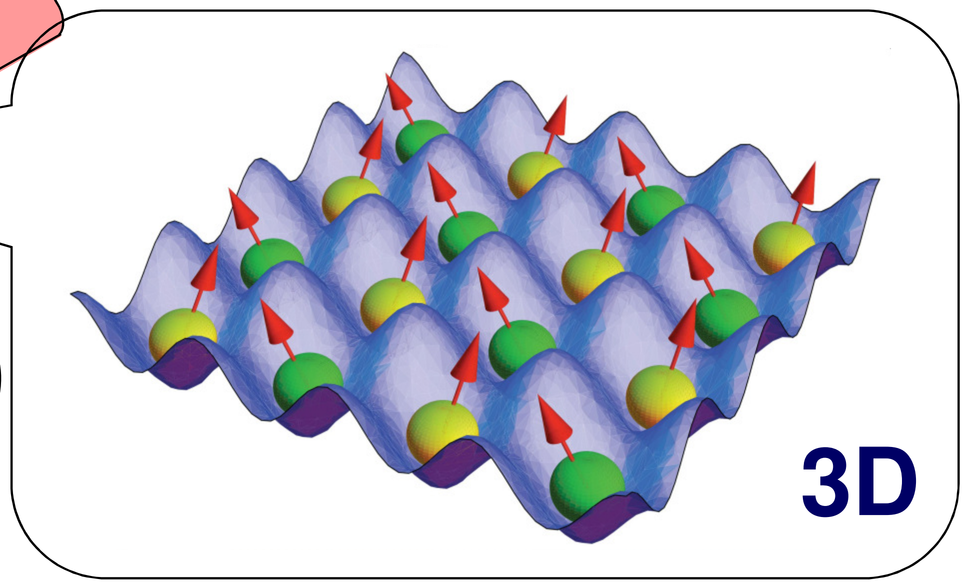
2001
Nobel Prize
Bose-Einstein Condensation

nobel.org

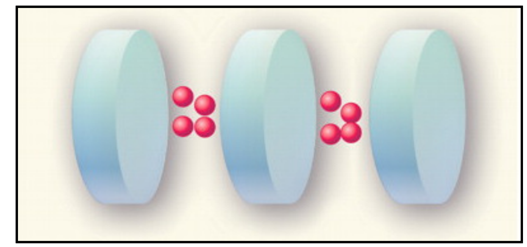
Trapping neutral atoms and ions

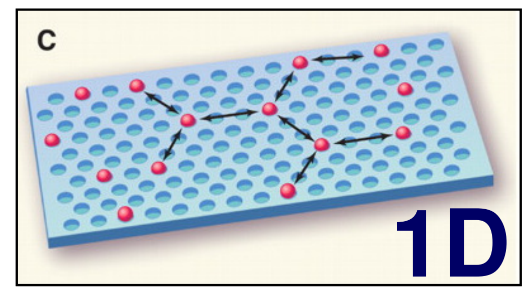


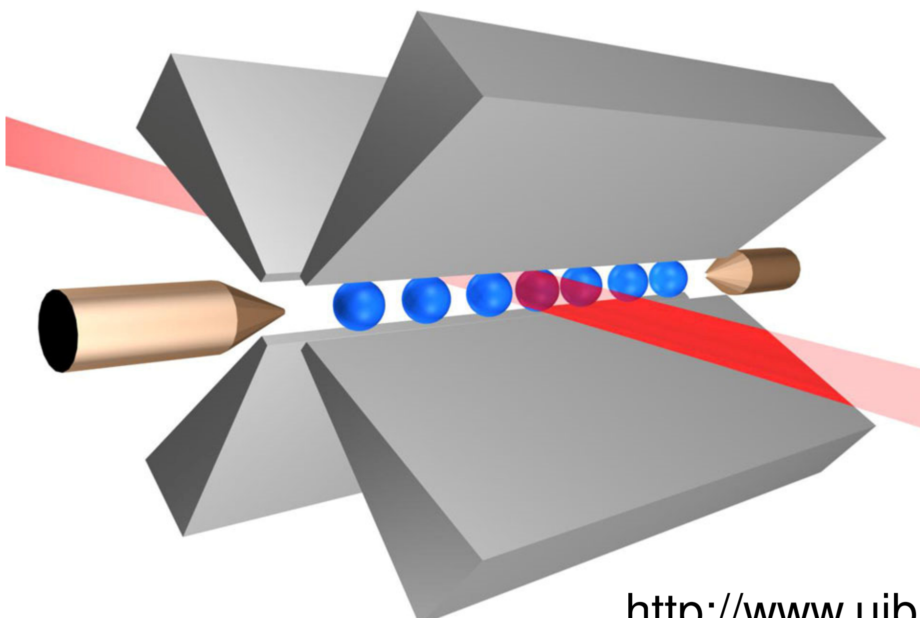
Optical Lattices: crystals of light



2D







Trapped ion chains

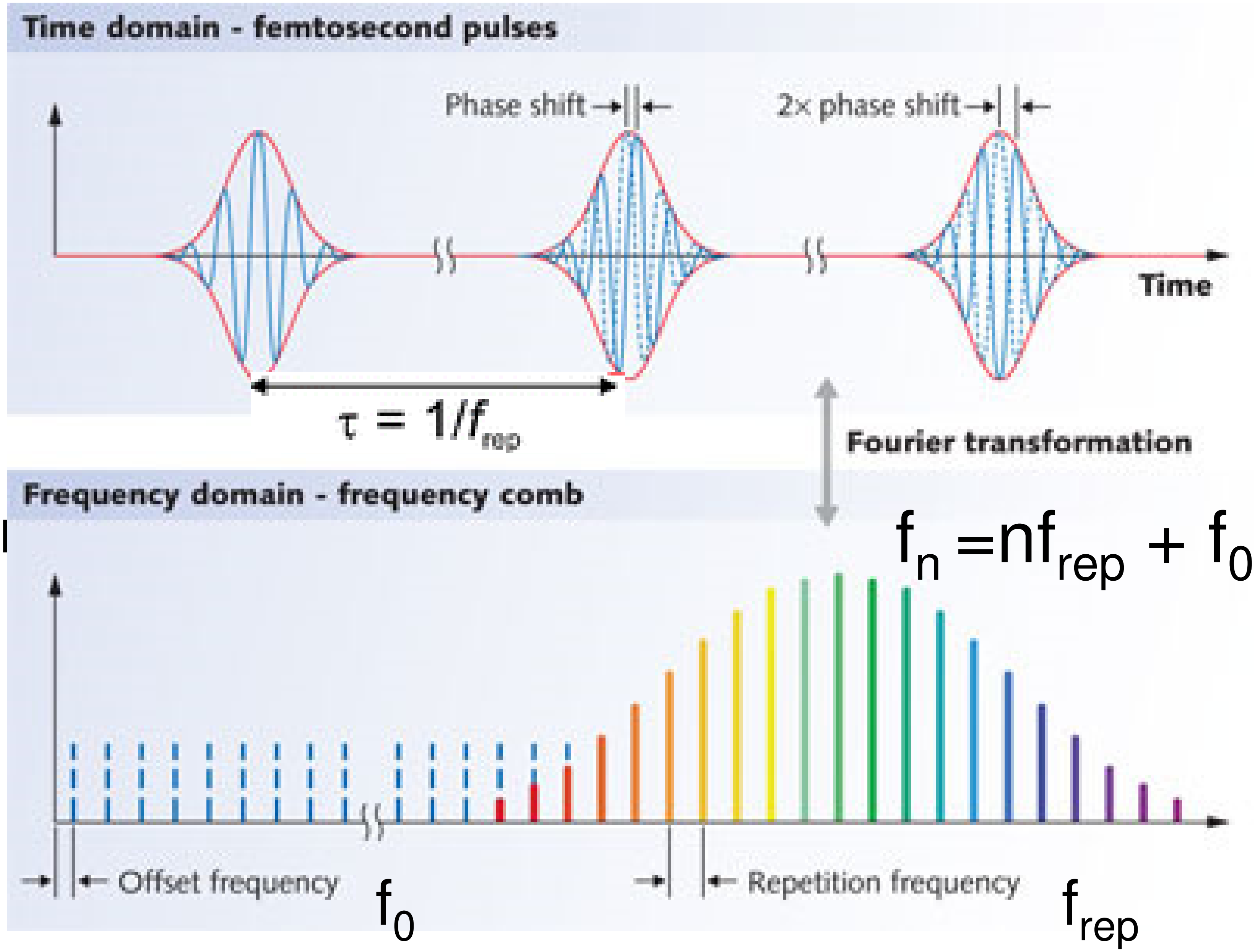
http://www.uibk.ac.at/th-physik/qo/research/trappedions.html

2005 Nobel Prize

Laser-based precision spectroscopy and the optical frequency comb technique

Theodor Hänsch

John Hall



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

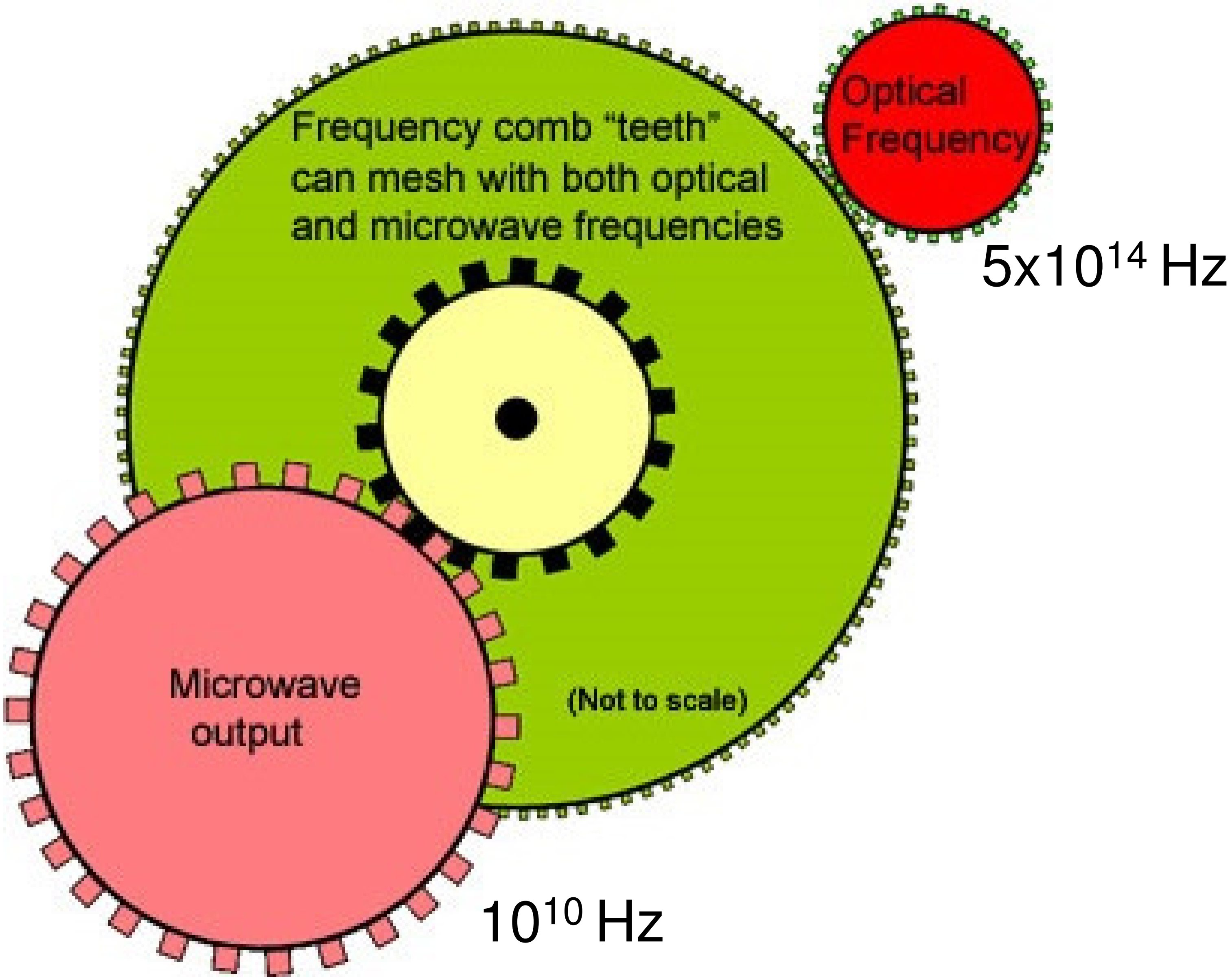
www.laserfocusworld.com

How to "count" optical frequencies

2005 Nobel Prize

Theodor Hänsch

John Hall

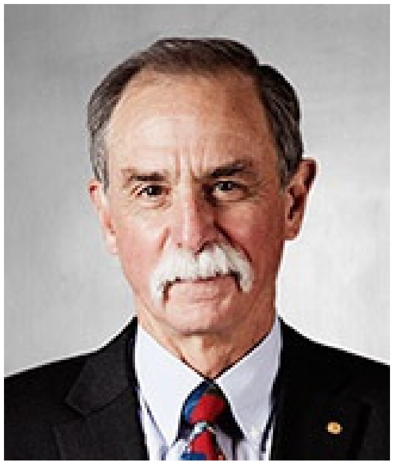


Laser-based precision spectroscopy and the optical frequency comb technique

nist.gov

Quantum Control: measuring and manipulation of individual quantum systems

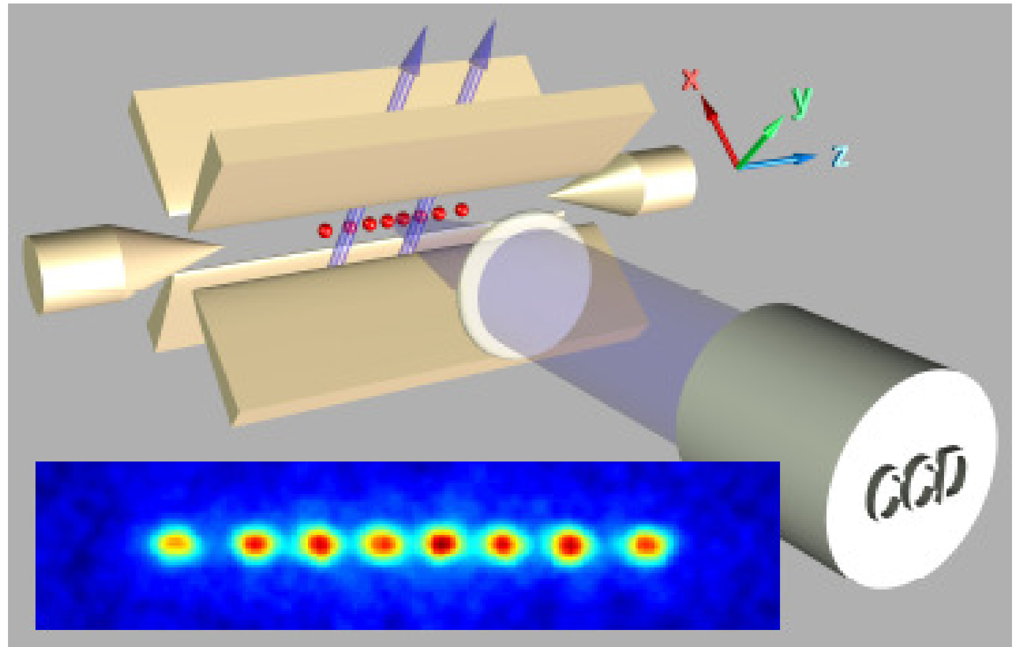
2012 Nobel prize



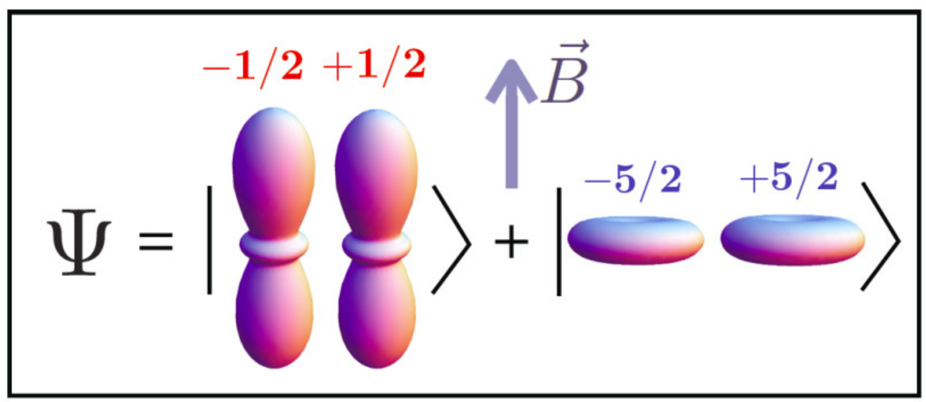
David Wineland

Serge Haroche

nobel.org



Picture of a string of ions

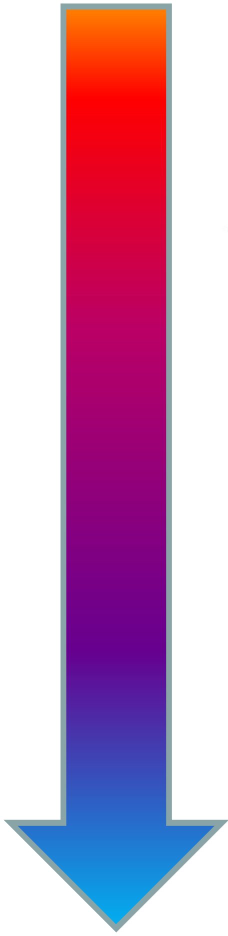


Ca^+
$3d_{5/2}$

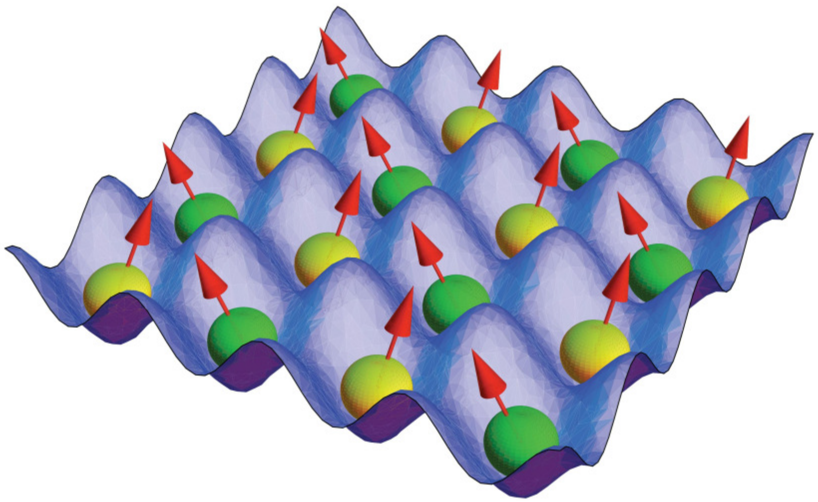
Making quantum superposition of two ions

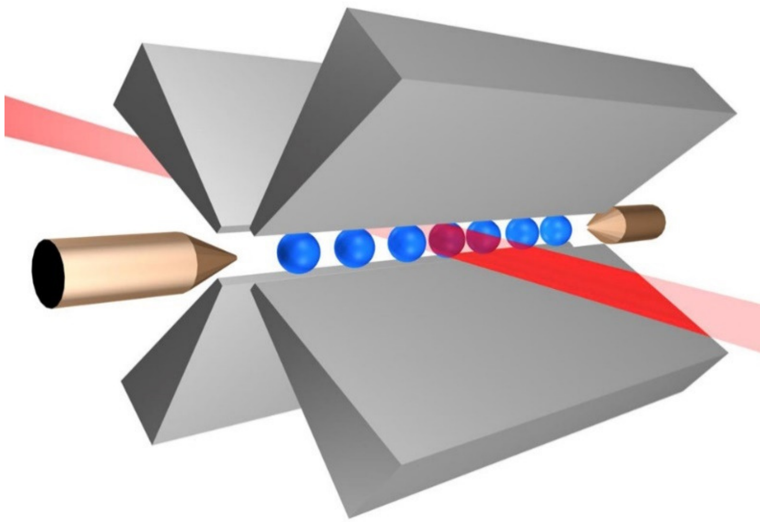
Extraordinary progress in the control of atomic systems

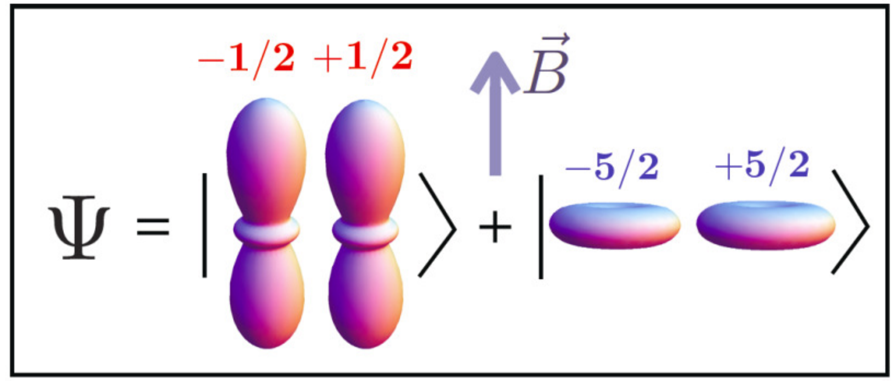
300K

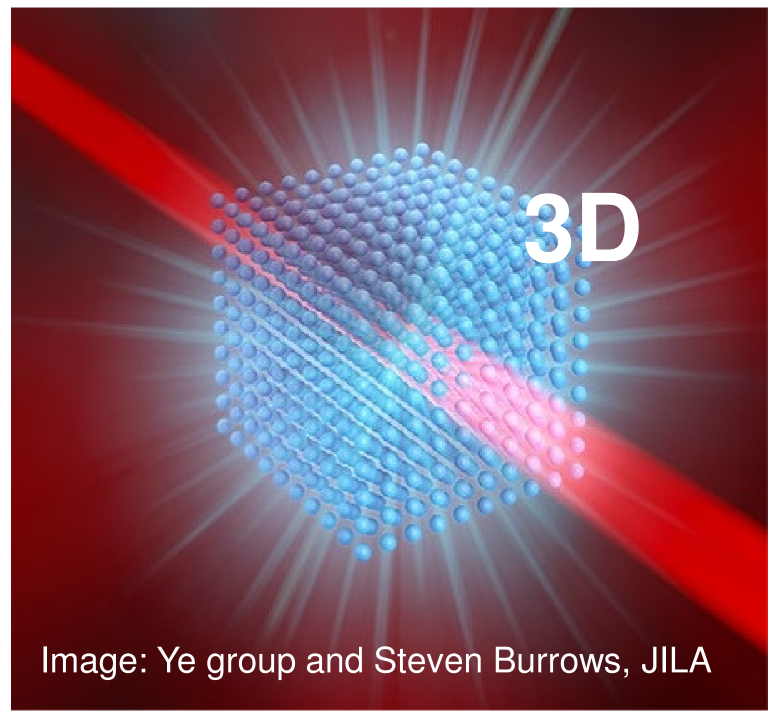


nK









Ultracold **Trapped** **Precisely controlled**

Advances in Precision Atomic physics tools

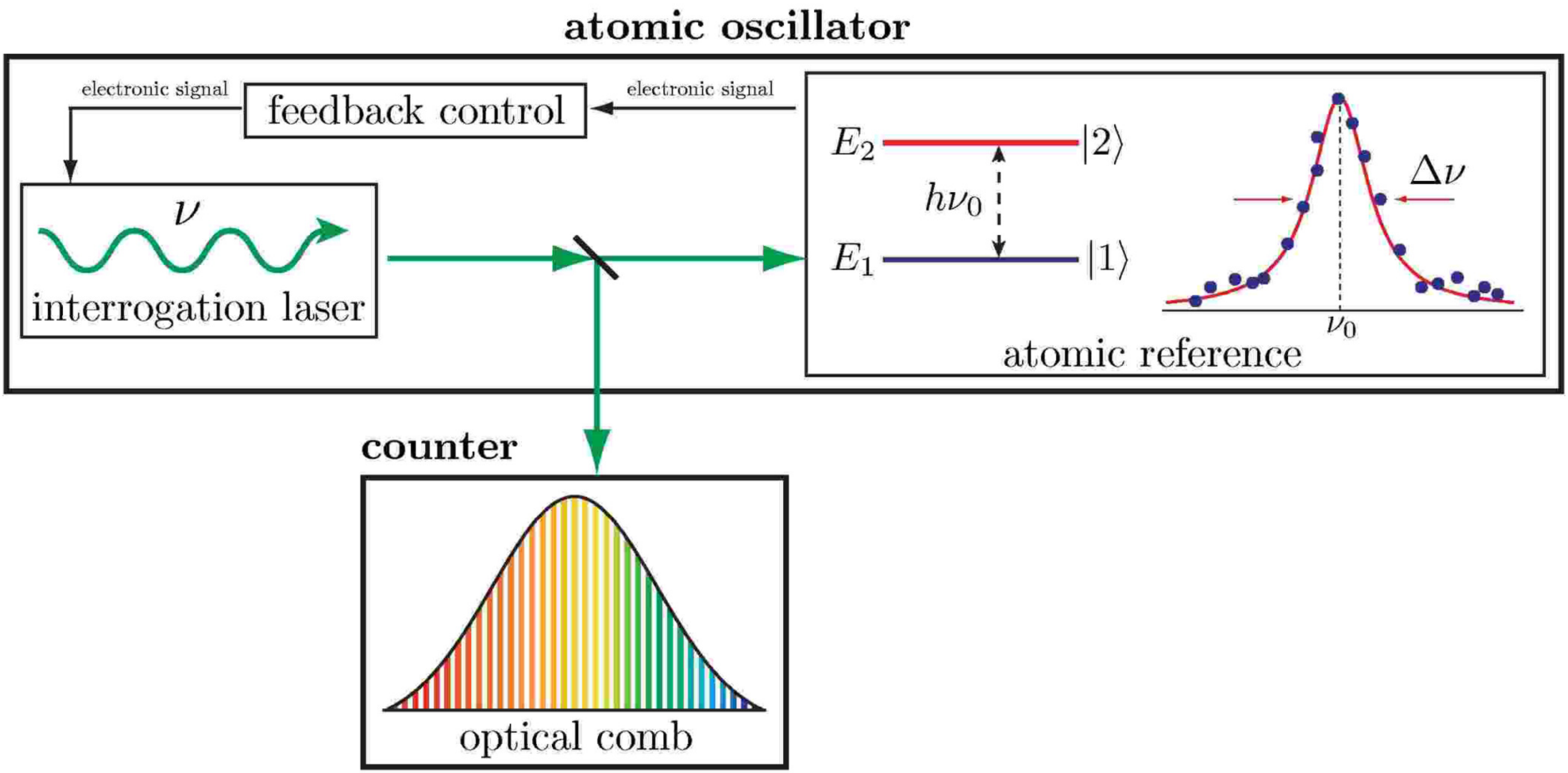
- Atomic clocks
- Atom and Light interferometers

  Matter Waves!
- Atomic magnetometers

- Ultracold and trapped atoms and ions
- Cold molecular beams
- Quantum information technologies

- New: Cooling of highly-charged ions
- New: UV frequency combs
- In progress: laser cooling of molecules

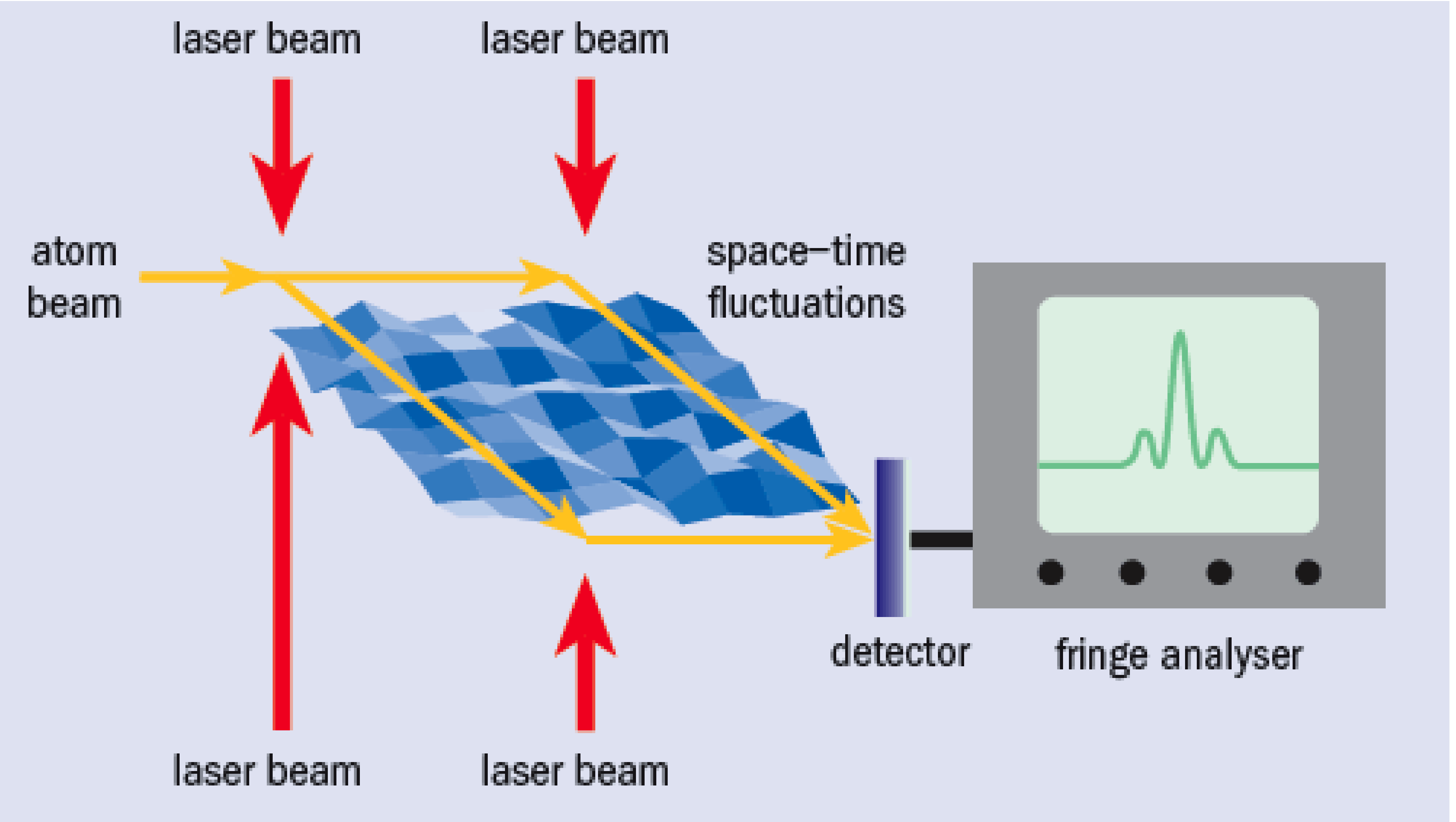
Optical atomic clock



Measure optical frequencies to exceptional precision: 10^{-18}

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

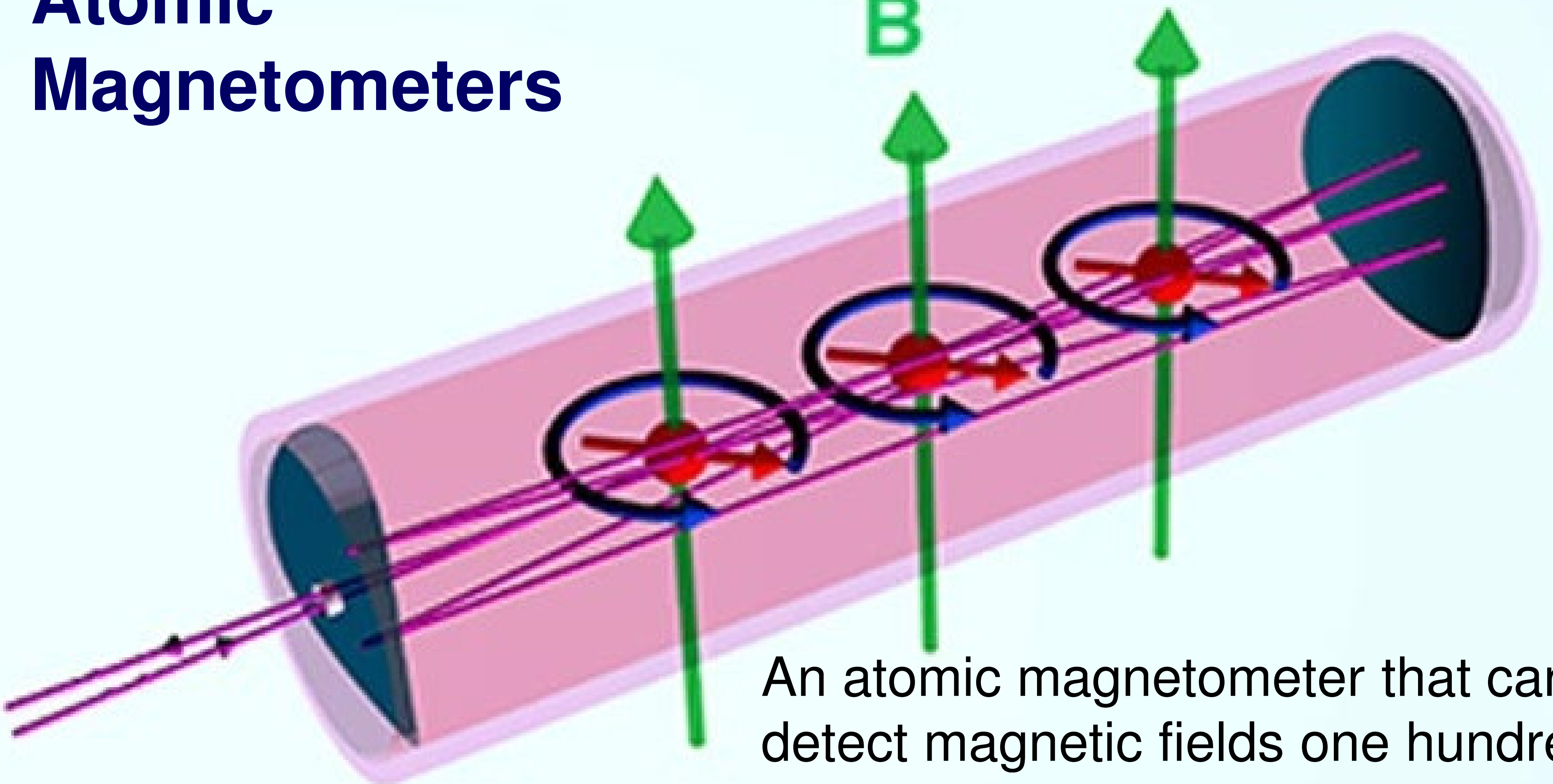
Atom Interferometers



Measure the phase difference to exceptional precision

http://images.iop.org/objects/ccr/cern/46/8/18/CCEcan1_10-06.gif

Atomic Magnetometers



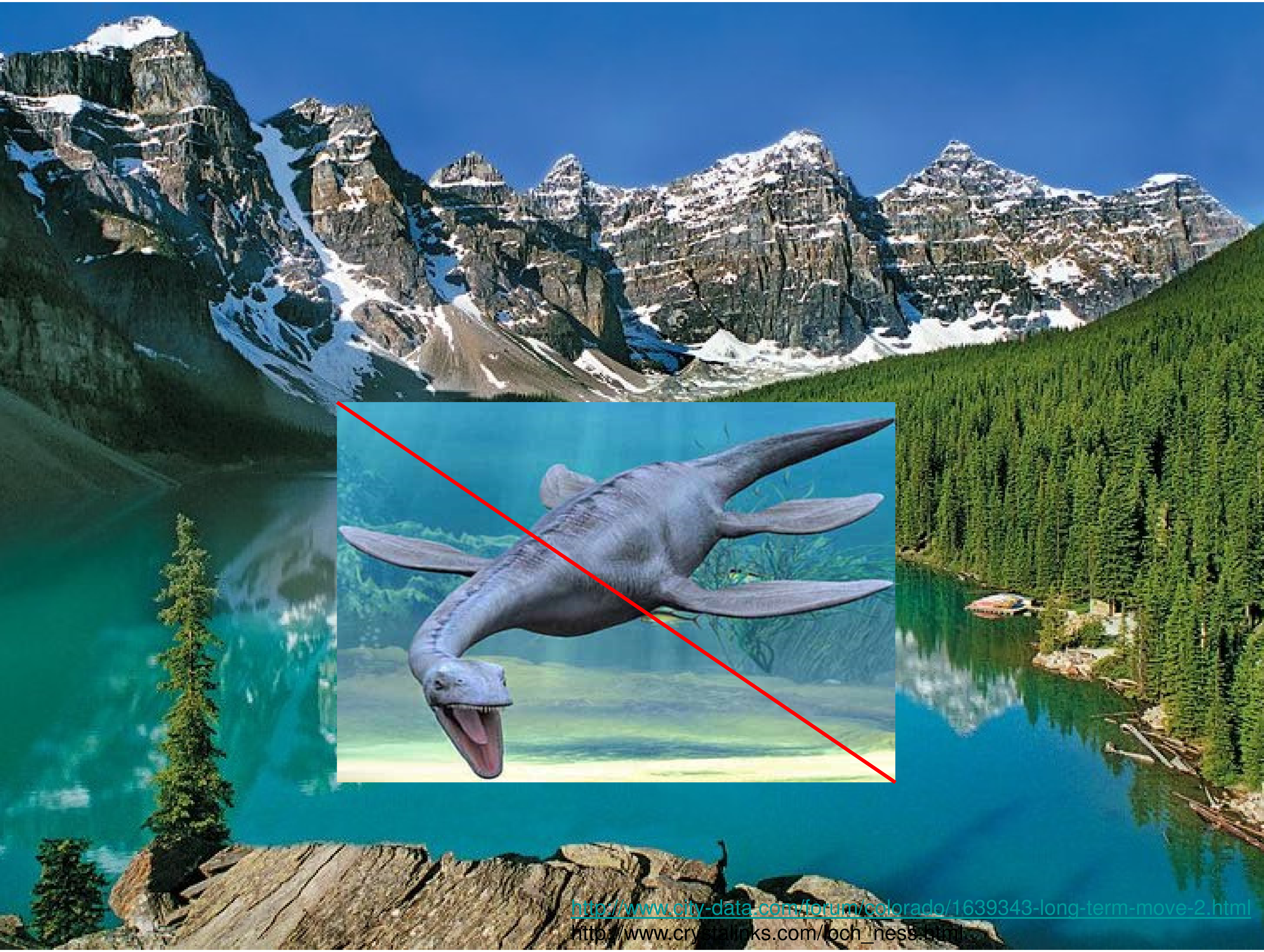
An atomic magnetometer that can detect magnetic fields one hundred billion times smaller than the Earth's!

Measure magnetic field to exceptional precision

http://physicsworld.com/cws/article/news/2013/apr/24/

WHY NOW?

It is a great time to use AMO experiments for BSM physics searches!



http://www.city-data.com/forum/colorado/1639343-long-term-move-2.html
http://www.crystalinks.com/loch_ness.html

AMO and the Laws of Physics

- **Precision atomic experiments (clocks, magnetometers, interferometers, quantum information, …):**
  Do laws of physics hold within the experimental precision?

- **Types of "search for new physics" experiments:**

(1) Data already exist and just have to be interpreted.

(2) Experiments can be done with some modifications of existing set ups.

(3) New dedicated experiments.

play.google.com

Need atomic and molecular theory to search for new physics!

- **New ideas:** what other fundamental tests can be done with atoms and molecules?
- **Propose new experiments**: select systems with the largest enhancements of effects of interest
- **Calculate properties** of systems
- Analyze experiments to **extract possible new physics**
- Propose **new tools for precision measurements**
  New clock proposals: Th nuclear clock, highly-charged ions?

Very Wide Scope of AMO New Physics Searches

REVIEWS OF MODERN PHYSICS, VOLUME 90, APRIL–JUNE 2018

Search for New Physics with Atoms and Molecules

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[7]California State University, East Bay, Hayward, California, USA,
[8]University of Nevada, Reno, Nevada, USA

This article reviews recent developments in tests of fundamental physics using atoms and molecules, including the subjects of parity violation, searches for permanent electric dipole moments, tests of the CPT theorem and Lorentz symmetry, searches for spatiotemporal variation of fundamental constants, tests of quantum electrodynamics, tests of general relativity and the equivalence principle, searches for dark matter, dark energy and extra forces, and tests of the spin-statistics theorem. Key results are presented in the context of potential new physics and in the broader context of similar investigations in other fields. Ongoing and future experiments of the next decade are discussed.

Review chapters:

1. **Search for variation of fundamental constants**

   Atomic clocks & spectroscopy, astrophysics studies of atomic and molecular spectra, molecular frequency measurements

2. **Precision tests of Quantum Electrodynamics**

   Precision frequency measurements with electrons, lightest atoms (H, He, etc.), muonic hydrogen, highly-charged ions, exotic atoms, others

3. **Atomic parity violation**

   Beam experiments, cold trapped atoms and ions.

   Need heavy atoms: Cs, Tl, Fr, Ra+, Ra ,… molecules in the future

4. **Time-reversal violation: electric dipole moments and related phenomena**

   Cold molecular beams, trapped molecular ions, future: ultracold atoms, laser-cooled (polyatomic) molecules

5. **Tests of the CPT theorem, matter-antimatter comparisons**

   Not tabletop, proton/antiproton, single ion traps, (cold) antihydrogen

6. **Searches for exotic spin-independent interactions**

   Future: ultracold atoms as force sensors, atom interferometry, etc.

6. **Review of laboratory searches for exotic spin-dependent interactions**

   Magnetometry (spin-precession), precision theory/experiment comparisons (frequencies), networks or magnetometers and clocks, precision isotope shift measurements

7. **Searches for light dark matter (all precision tools)**
   - Microwave cavity axion experiments
   - Spin-precession axion experiments
   - Radio axion searches
   - Atomic clocks and accelerometers, and spectroscopy
   - Exotic spin-dependent forces due to axions/ALPs
   - Magnetometer and clock networks for detection of transient DM signals

8. **General relativity and gravitation**

   Atom interferometry

9. **Lorentz symmetry tests**

   Atomic clocks, magnetometers, quantum control of trapped ions, spectroscopy, rotating cavities

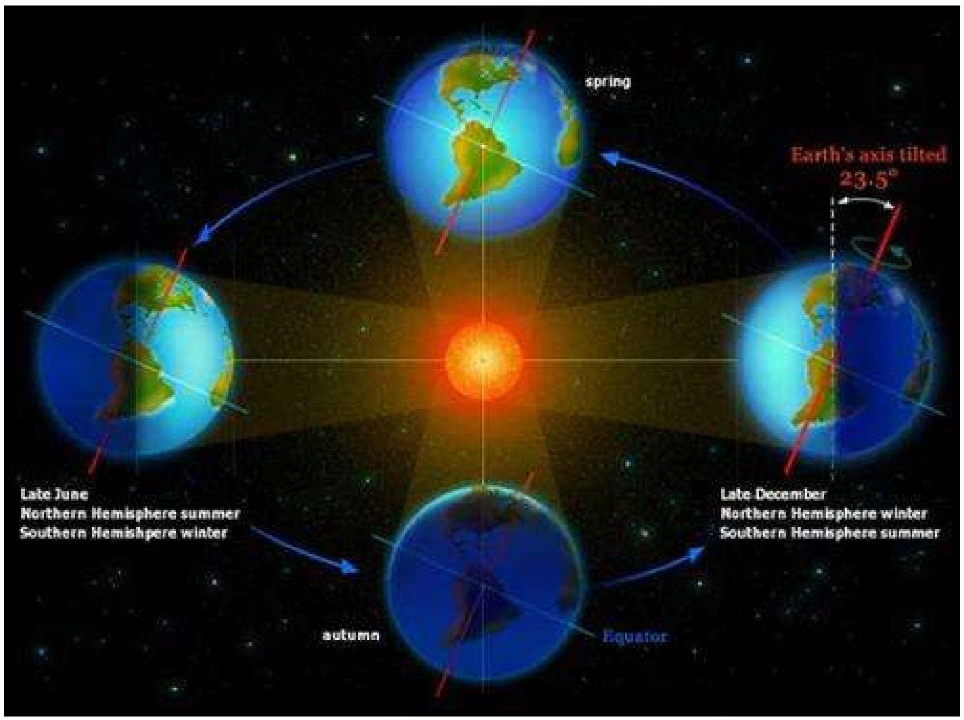
10. **Search for violations of quantum statistics**

    Search for Pauli-forbidden atomic or molecular transitions

SEARCH FOR PHYSICS BEYOND THE STANDARD MODEL WITH ATOMIC CLOCKS

Ingredients for a clock

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



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

NOAA/Thomas G. Andrews

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

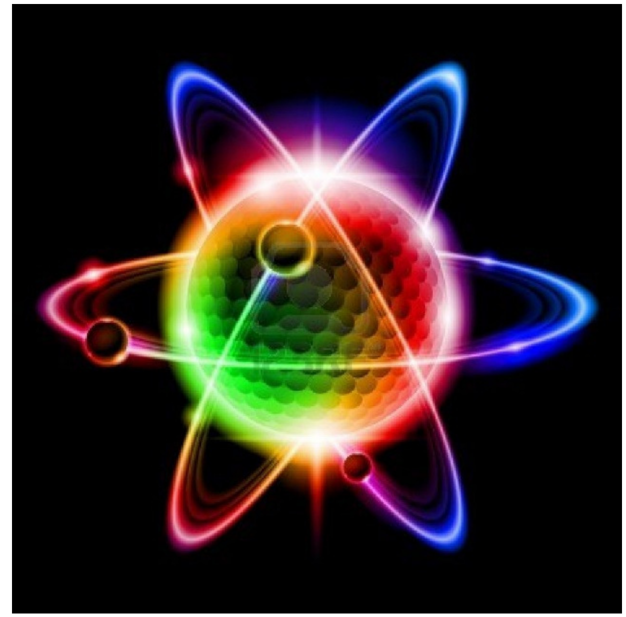
Ingredients for an atomic clock

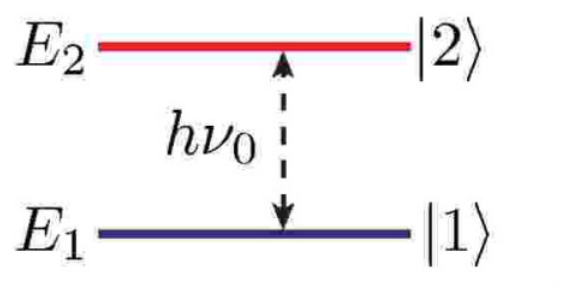
1. Atoms are all the same and will oscillate at exactly the same frequency (in the same environment): **you now have a perfect oscillator!**

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

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

4. Count cycles of this signal

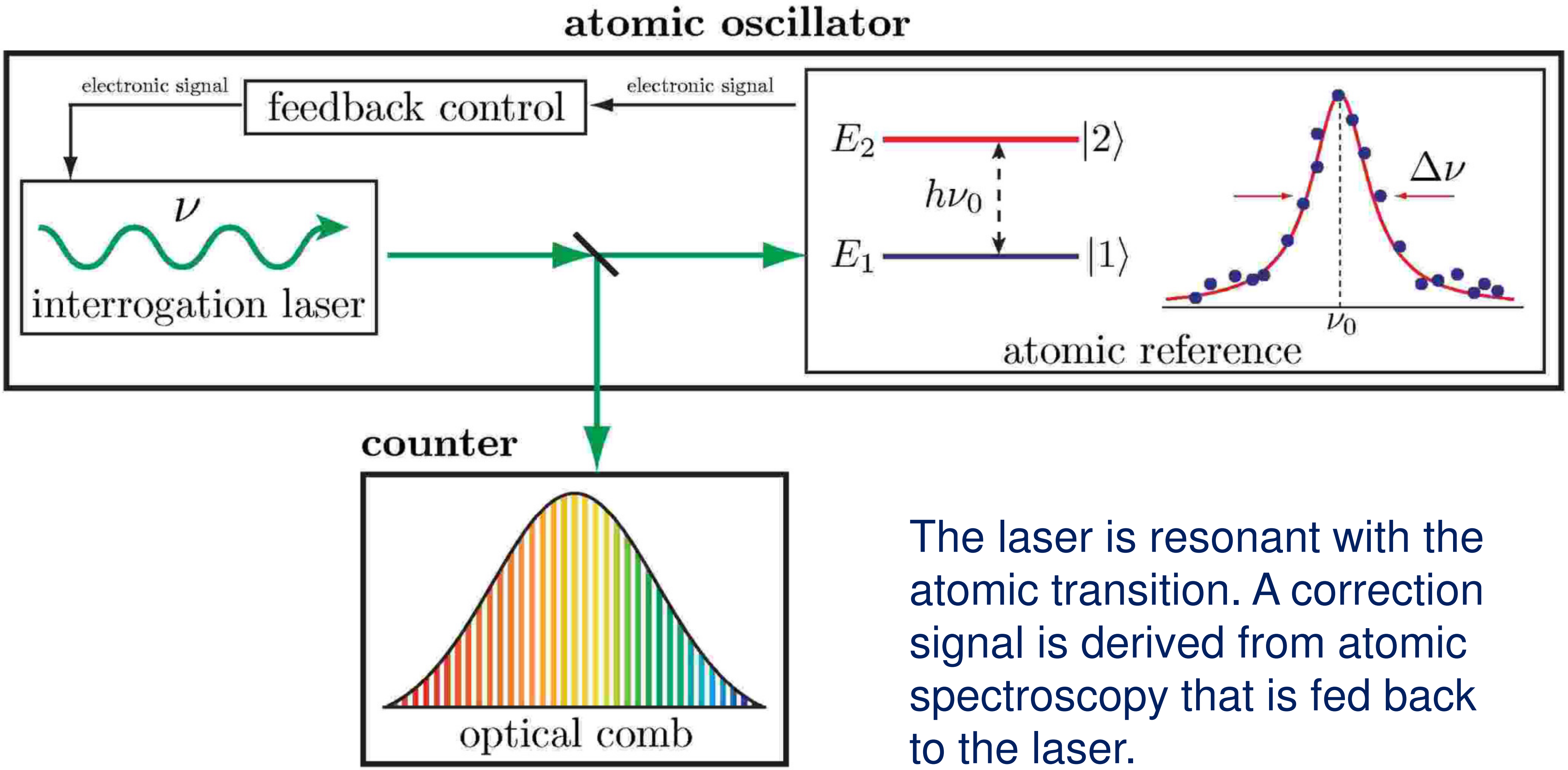




valentinagurarie.wordpress.com/tag/atom/

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

How optical atomic clock works

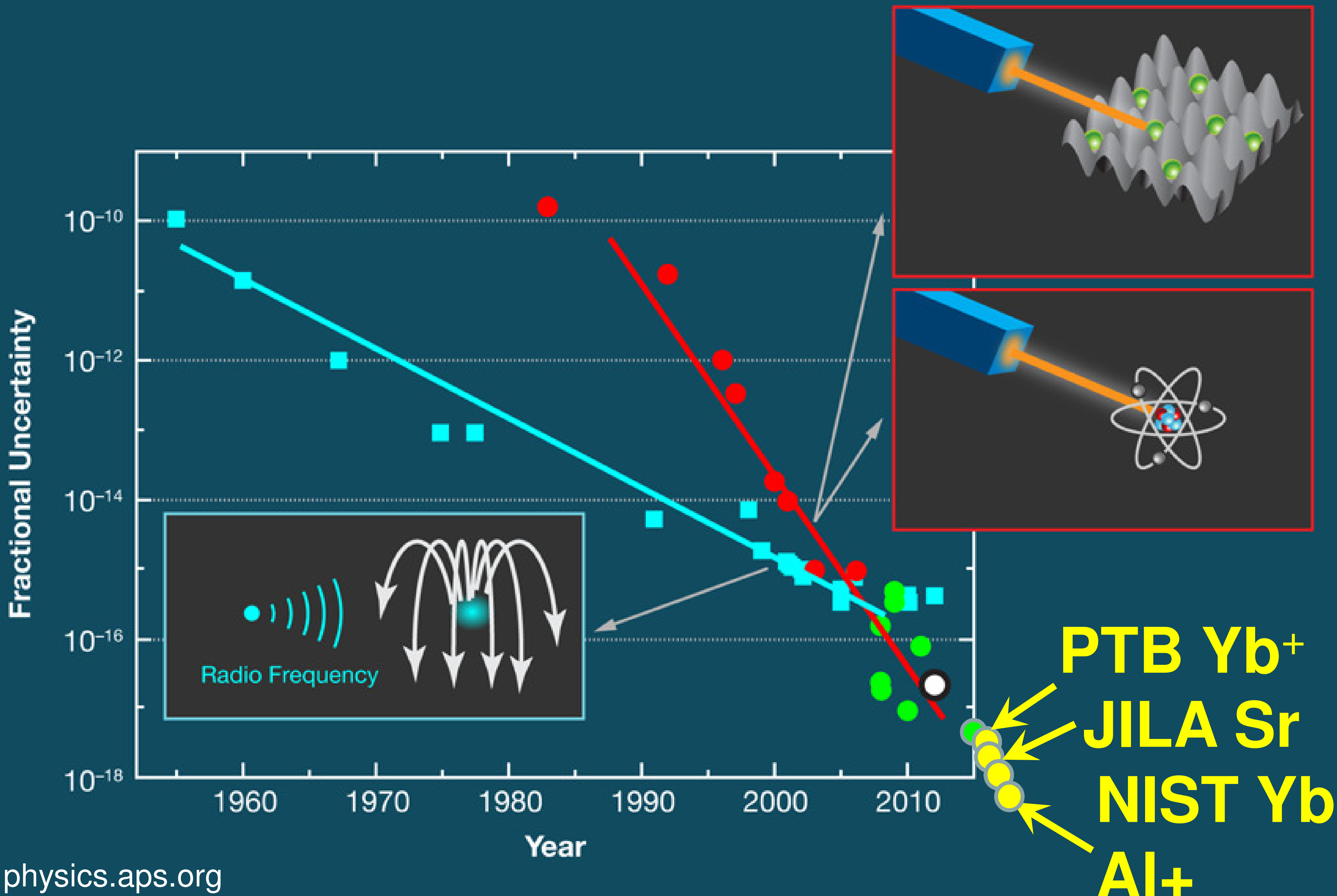


The laser is resonant with the atomic transition. A correction signal is derived from atomic spectroscopy that is fed back to the laser.

An optical frequency synthesizer (optical frequency comb) is used to divide the optical frequency down to countable microwave or radio frequency signals.

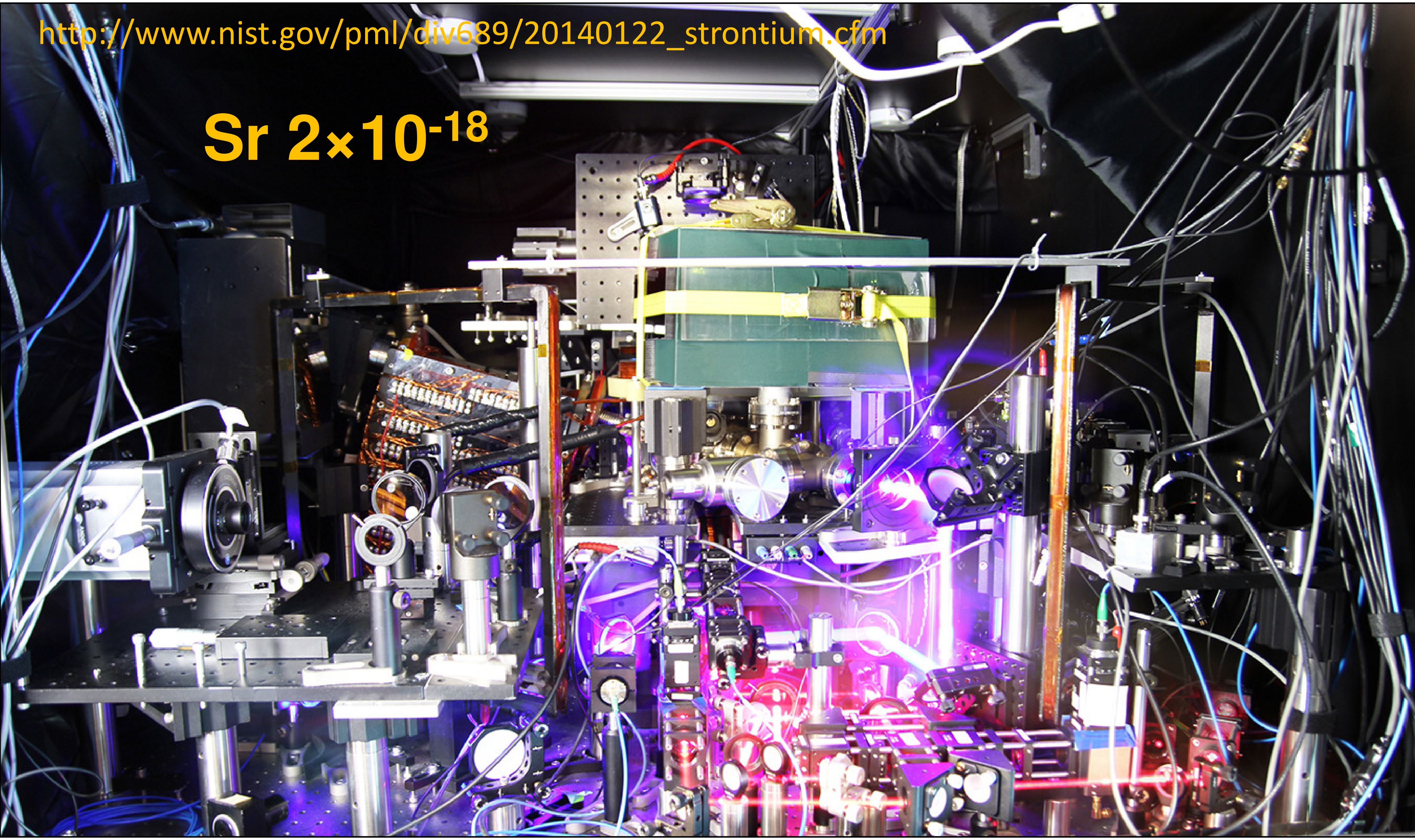
From: Poli et al. “Optical atomic clocks”, La rivista del Nuovo Cimento 36, 555 (2018) arXiv:1401.2378v2

Optical vs. microwave clocks



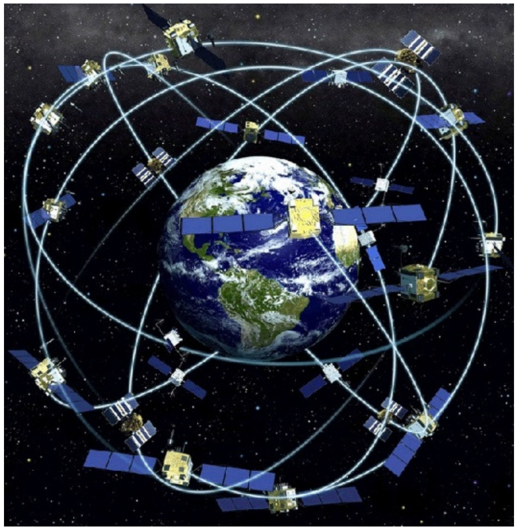
physics.aps.org

Sr clock will lose 1 second in 15 billion years !

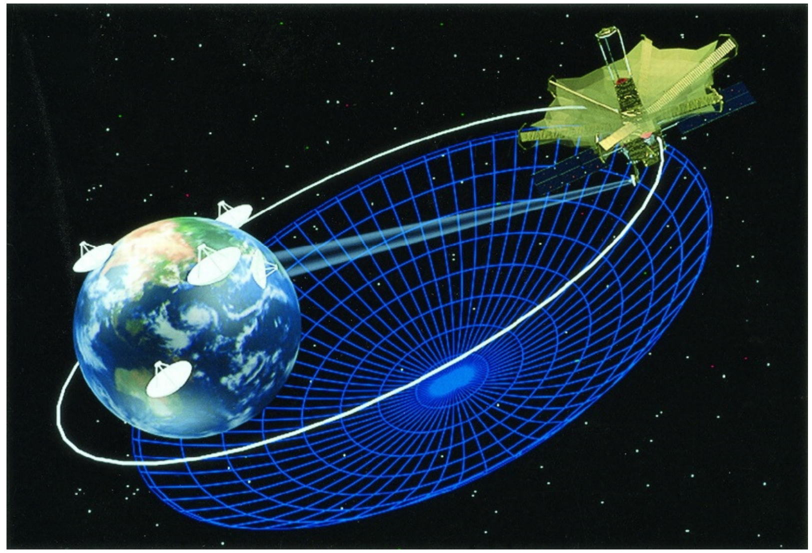


T. L. Nicholson, S. L. Campbell, R. B. Hutson, G. E. Marti, B. J. Bloom, R. L. McNally, W. Zhang, M. D. Barrett, M. S. Safronova, G. F. Strouse, W. L. Tew, and J. Ye, Nature Commun. 6, 6896 (2015).

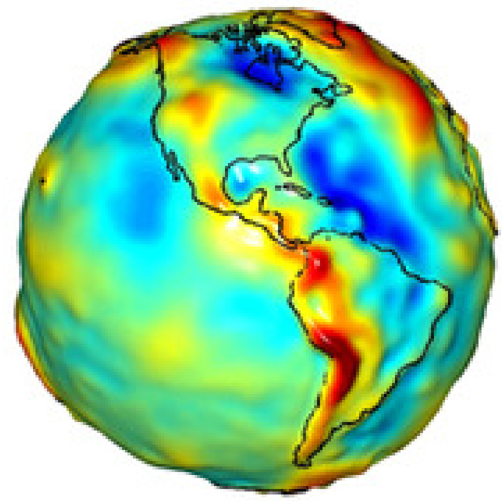
Applications of atomic clocks



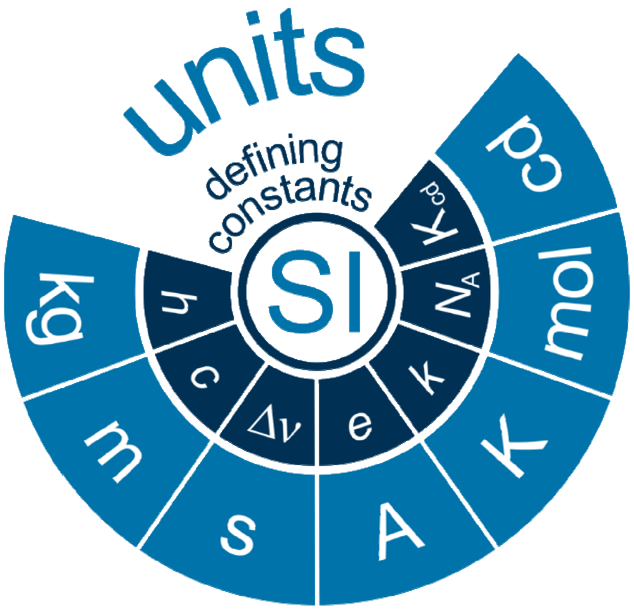
GPS



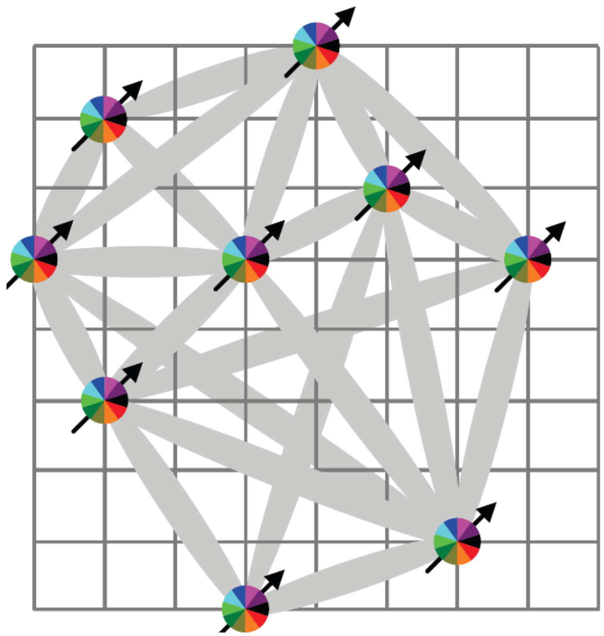
Very Long Baseline Interferometry



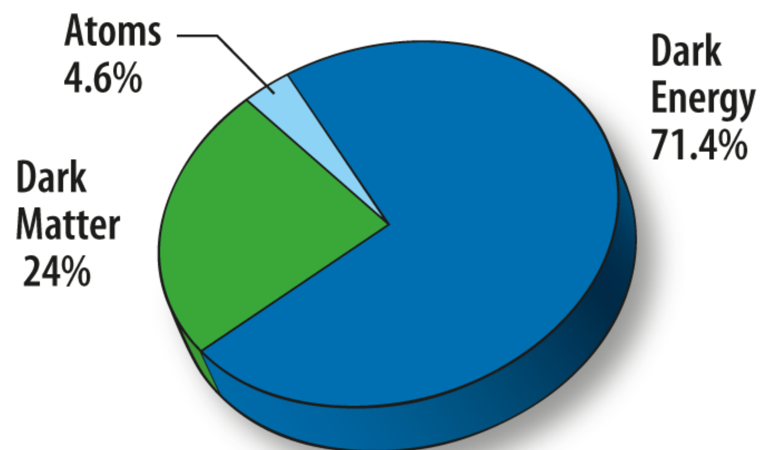
Relativistic geodesy



Definition of the second



Quantum simulation



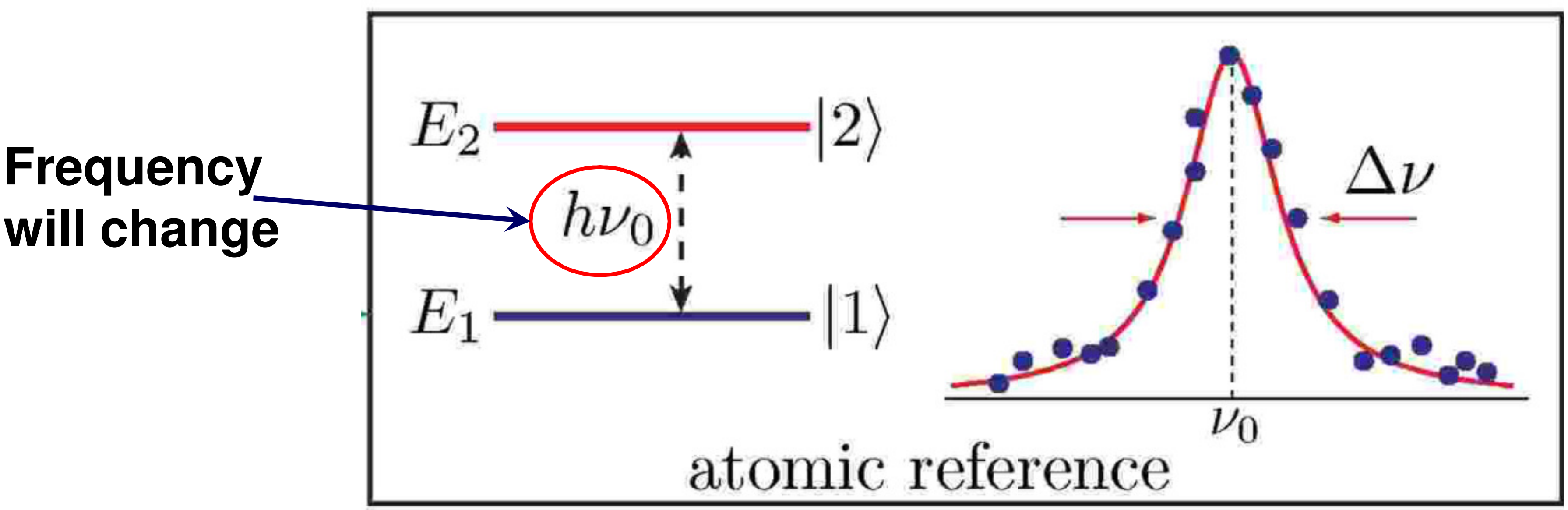
Search for physics beyond the Standard Model

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

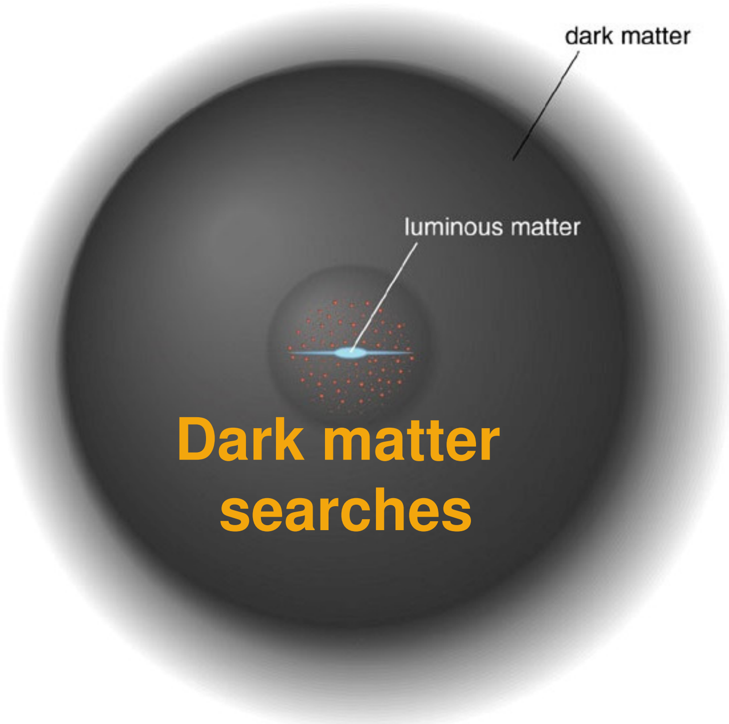
Search for physics beyond the standard model with atomic clocks

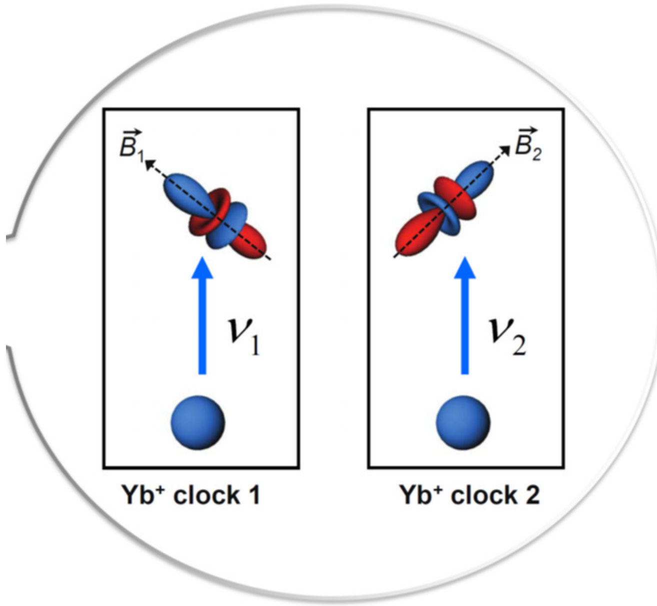
Atomic clocks can measure and compare frequencies to exceptional precisions!

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

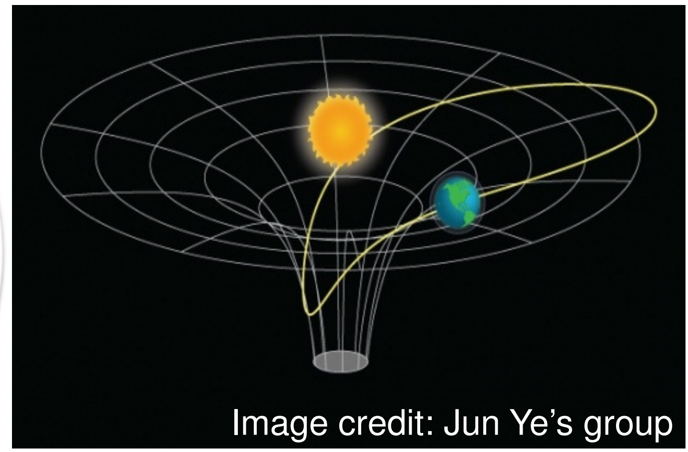


Search for physics beyond the Standard Model with atomic clocks



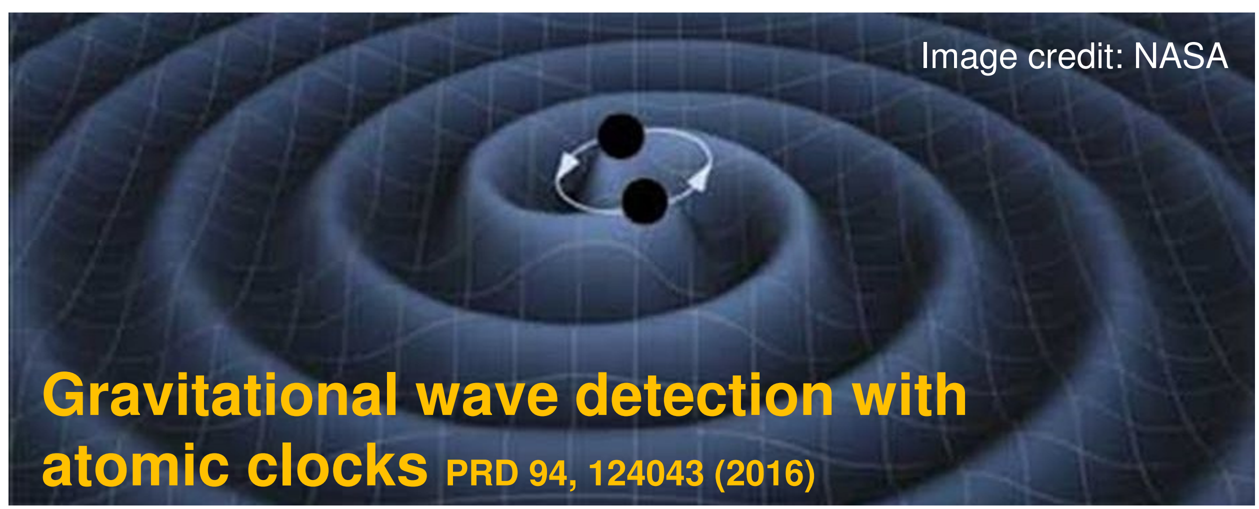


Search for the violation of Lorentz invariance



Tests of the equivalence principle

Are fundamental constants constant? α



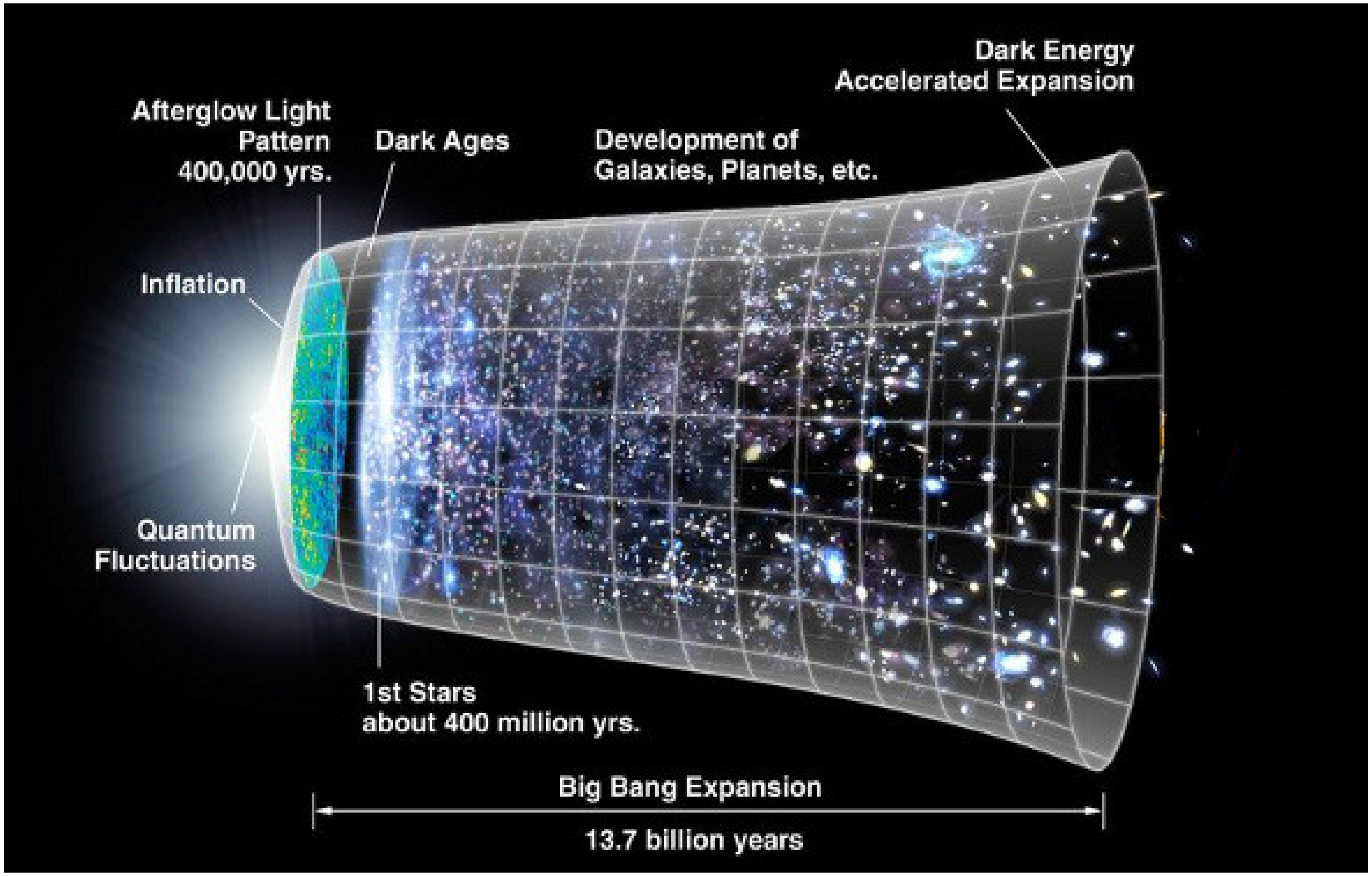
Variation of Fundamental Constants

Variation of fundamental constants

Theories with varying dimensionless fundamental constants

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

- String theories
- Other theories with extra dimensions
- Loop quantum gravity
- Dark energy theories: chameleon and quintessence models
- **…Various light scalars**

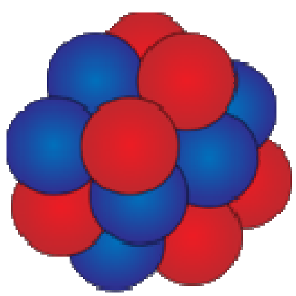


Life needs very specific fundamental constants!

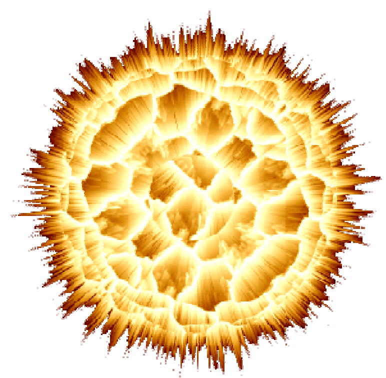
If α is too big $\rightarrow$ small nuclei can not exist

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

$\alpha \sim 1/137$



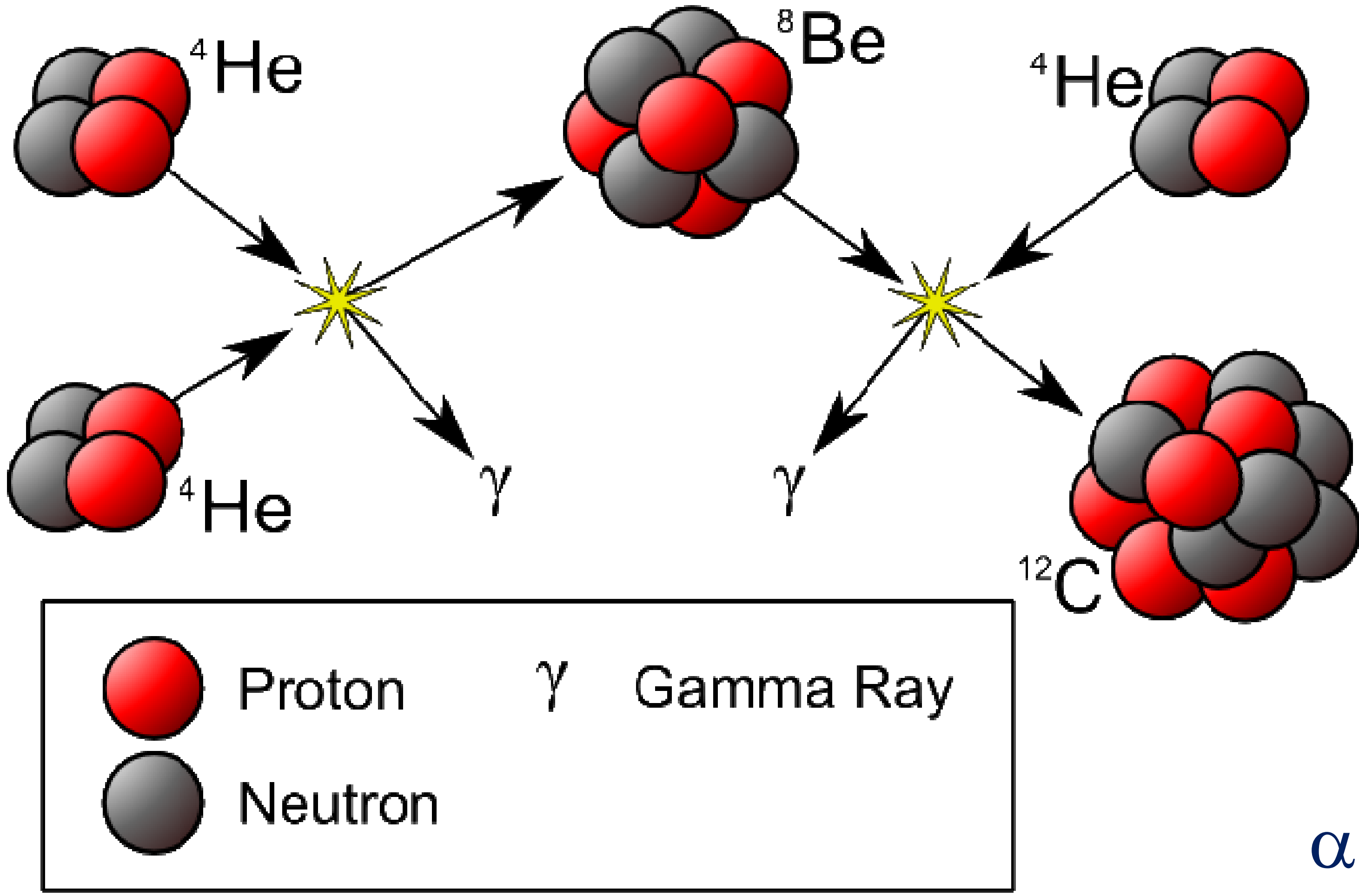
Carbon-12



$\alpha \sim 1/10$

will blow carbon apart

Life needs very specific fundamental constants!

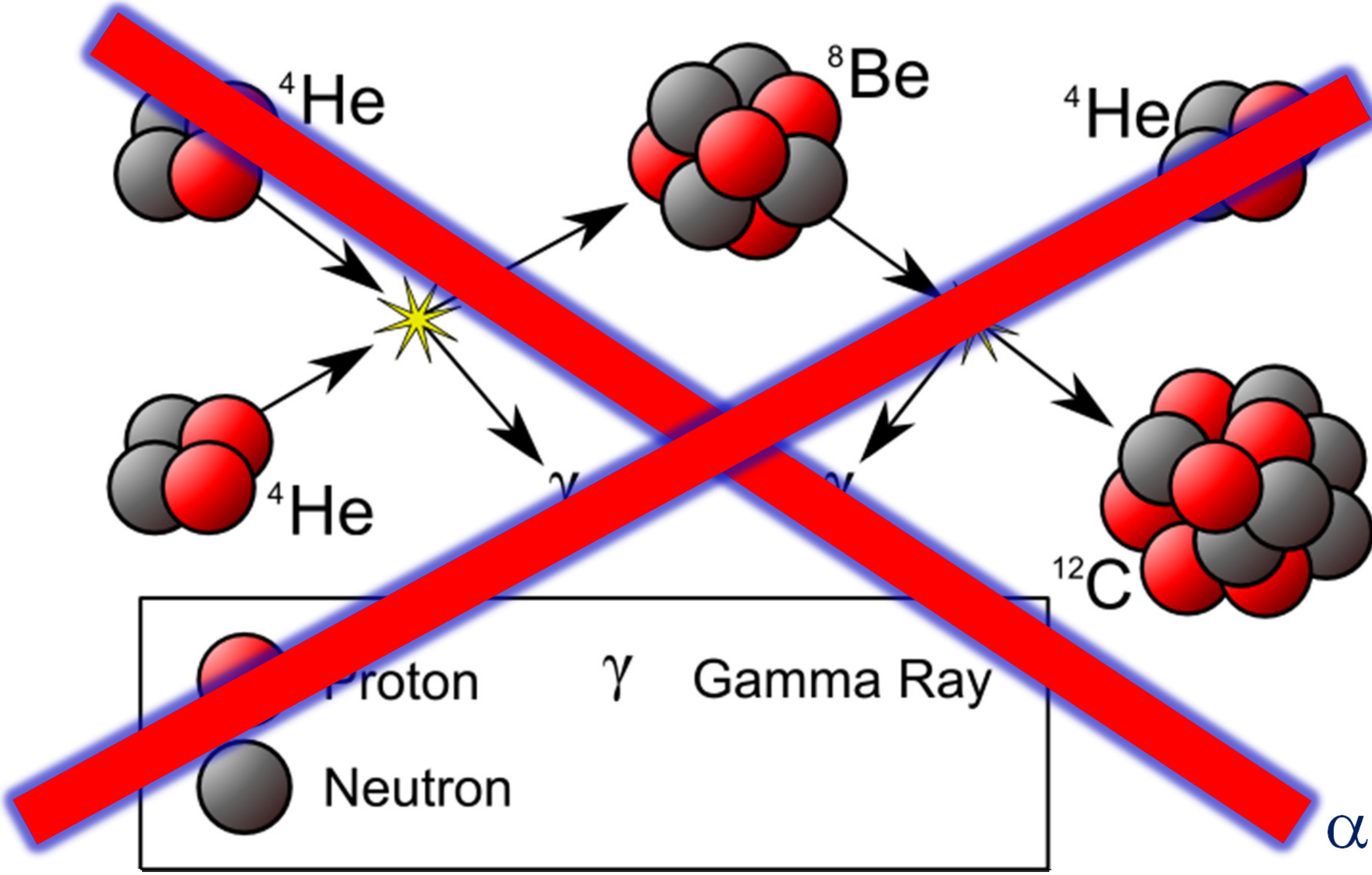


$\alpha \sim 1/137$

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!



$\alpha \sim 1/132$

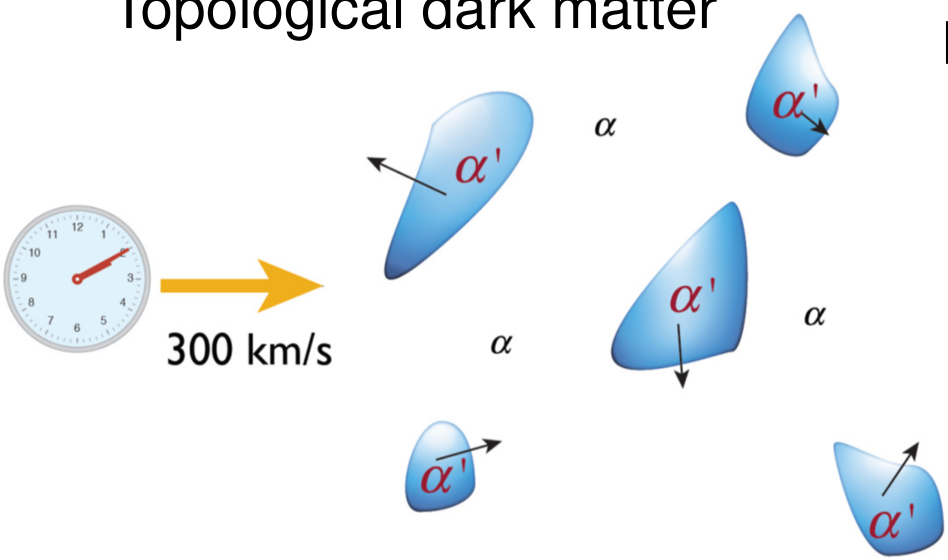
No carbon produced by stars:
No life in the Universe

How do fundamental constants vary?

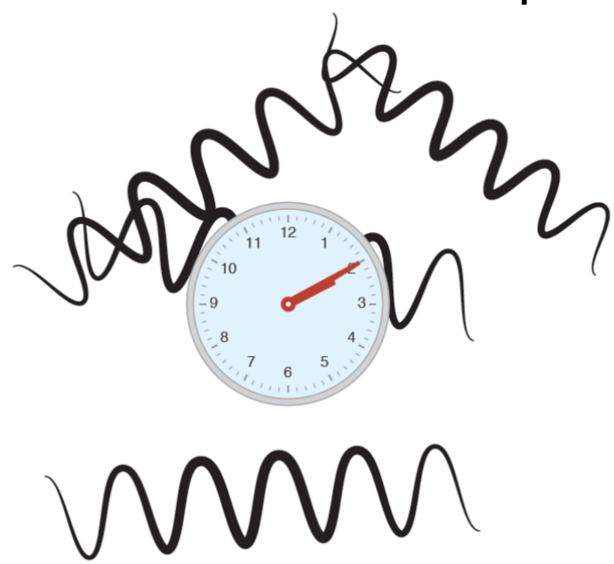
- Slow drifts
- Transient variations
- Oscillations
- Stochastic

Dark energy?

Topological dark matter



Dilaton dark matter or axion-like particles



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

How do fundamental constants vary?

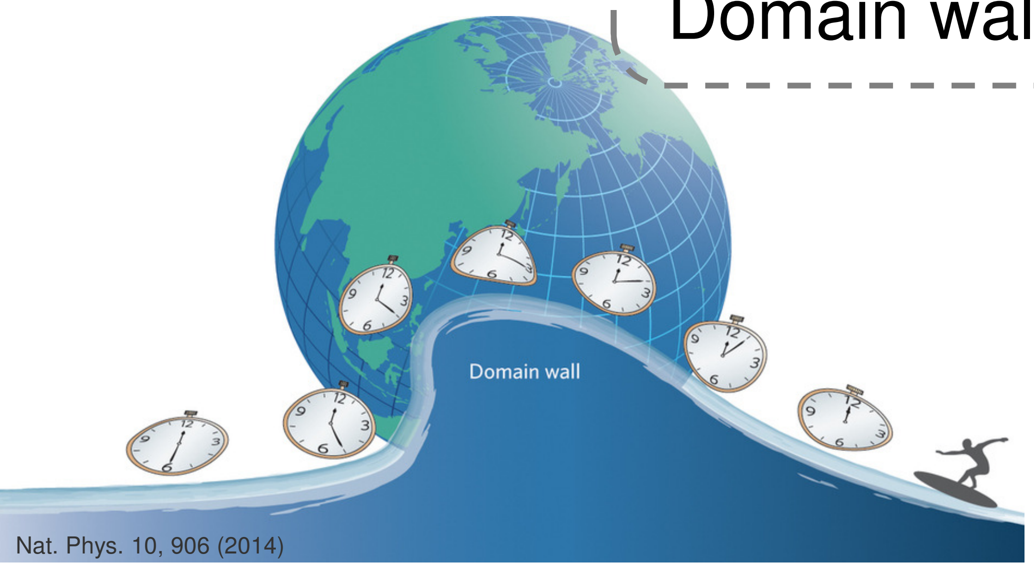
Spatial variations

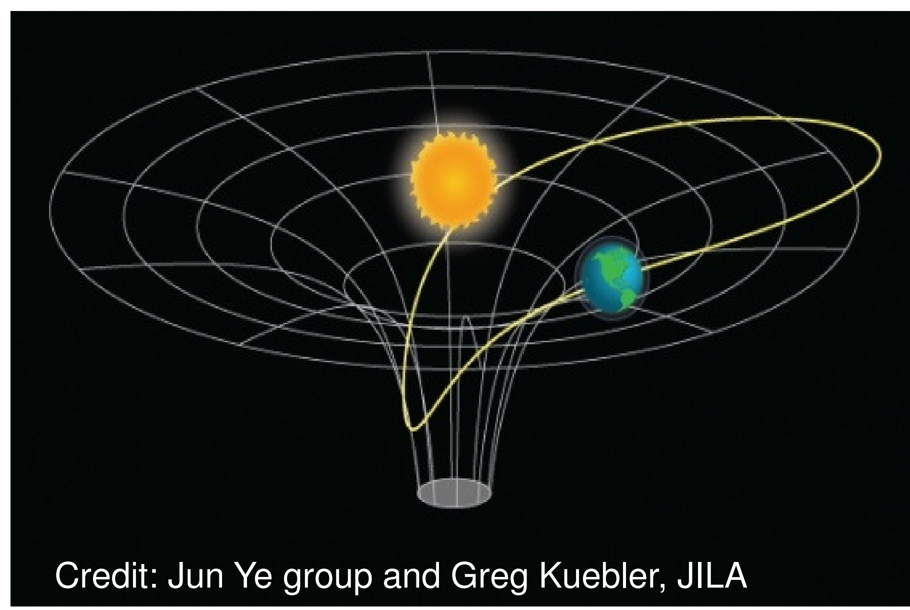
Cosmological spatial variation: gradient of cosmic $\phi(r)$ field

Cosmological spatial variation Domain walls

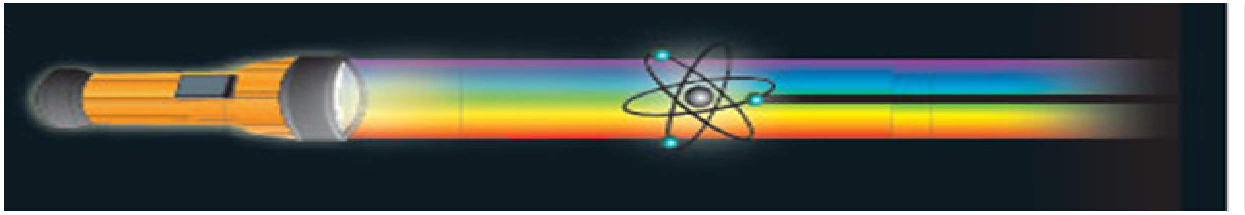
Dependence on matter density: Chameleons

Dependence on gravity

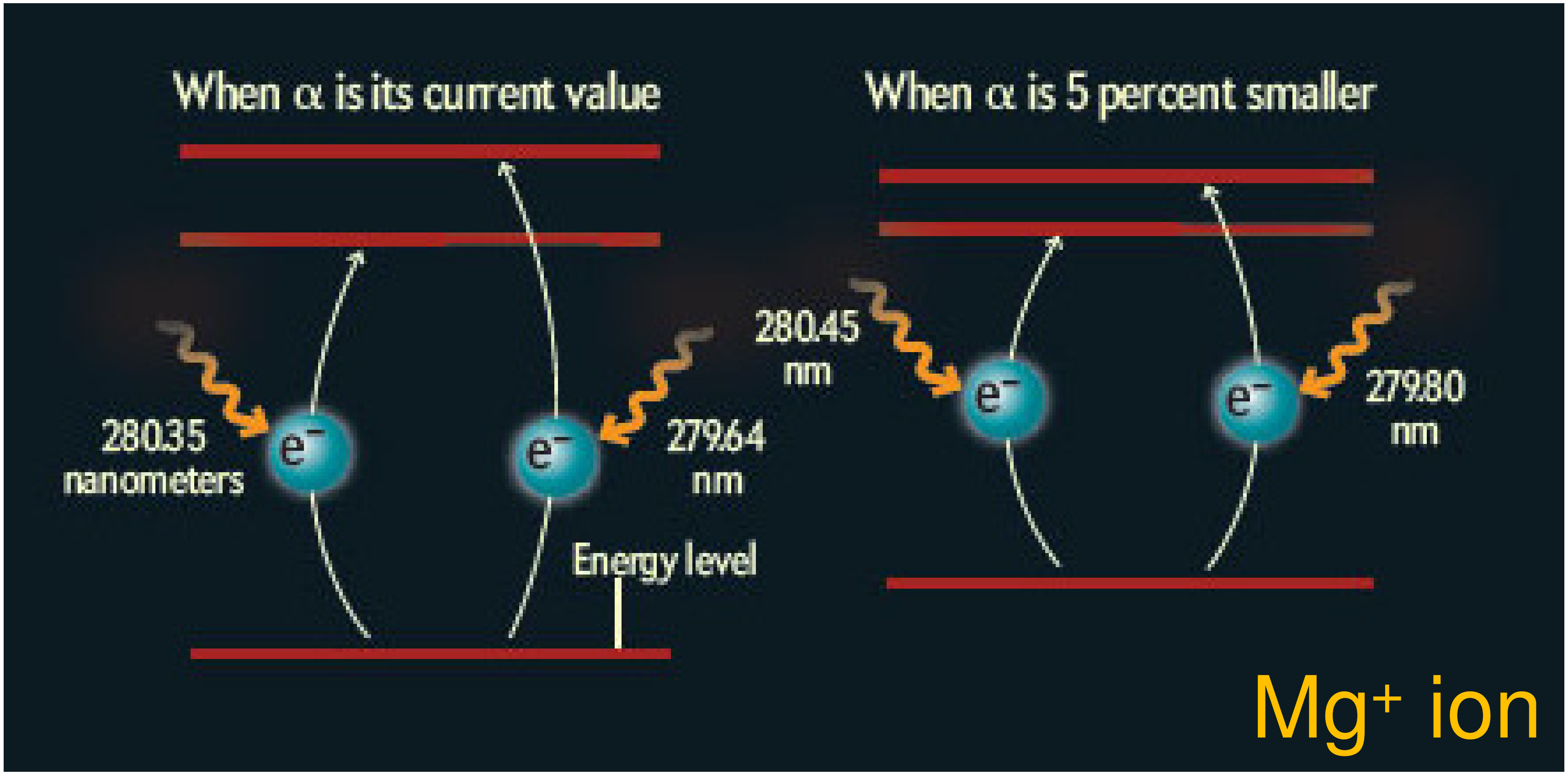




How to test if α changed with time?

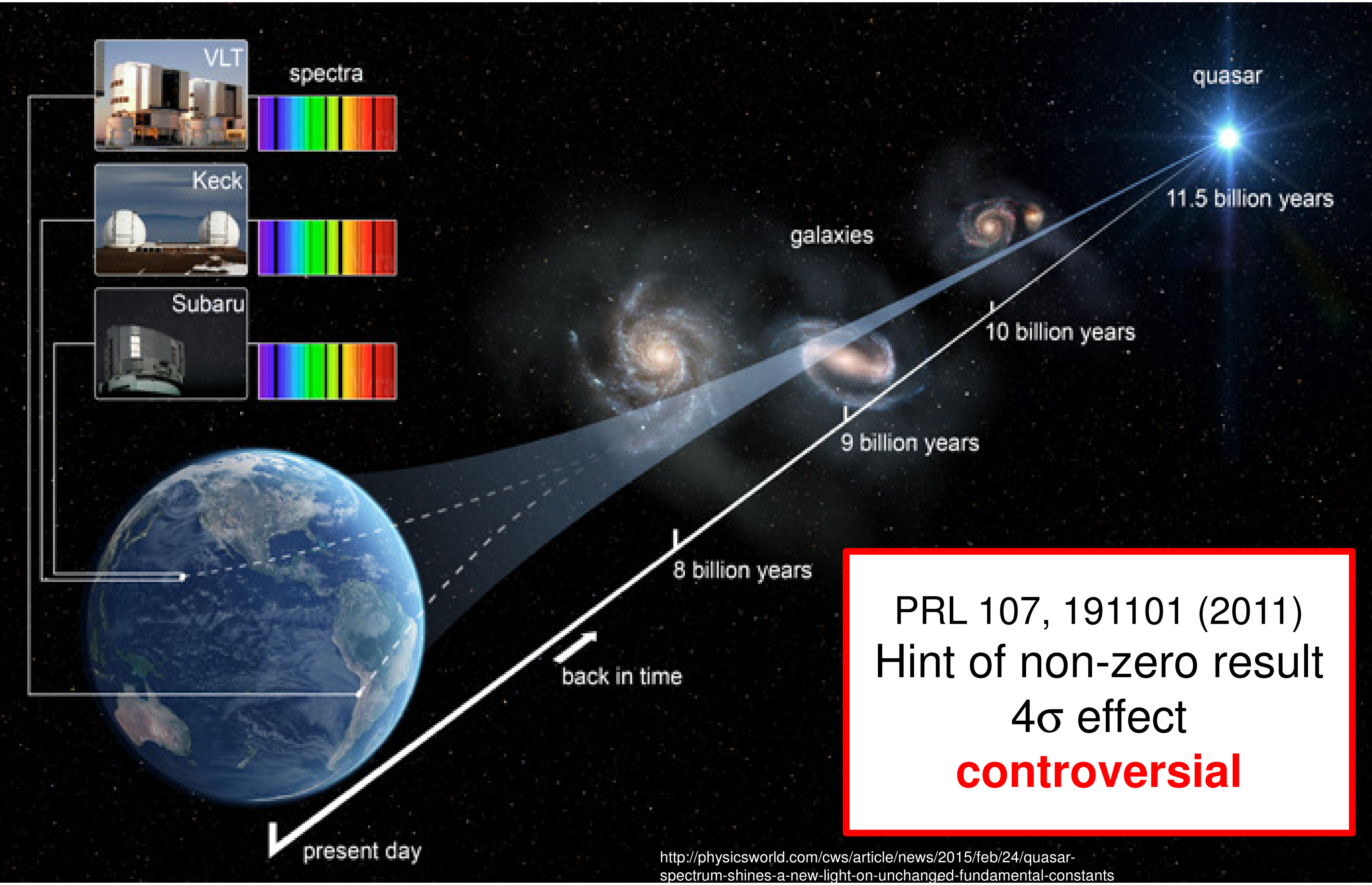


Atomic transition energies depend on α^2



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

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

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

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

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

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

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

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

Comparing different types of transitions probes different constants

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

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

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

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

Calculate with good precision

Sensitivity of optical clocks to α-variation

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

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

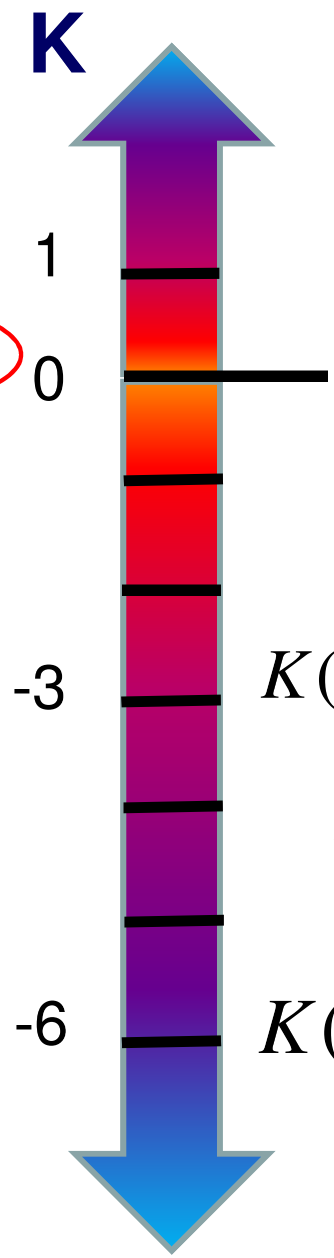
$$\frac{\partial}{\partial t}\ln\frac{v_2}{v_1} = (K_2 - K_1)\frac{1}{\alpha}\frac{\partial\alpha}{\partial t}$$

Test of α-variation

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

Easier to measure large effects!

α-variation enhancement factors for current clocks



$K(Sr^+) = 0.4$

$K(Yb) = 0.3$

$K(Hg) = 0.8, \quad K(Yb^+ E2) = 1$ Cavity K=1

$K(Al^+) = 0.01, \quad K(Sr) = 0.06, \quad K(Ca^+) = 0.1$

Excellent stability N ~ 1000

$K(Hg^+) = -2.9$

Single ion clocks, N = 1

$K(Yb^+ E3) = -6$

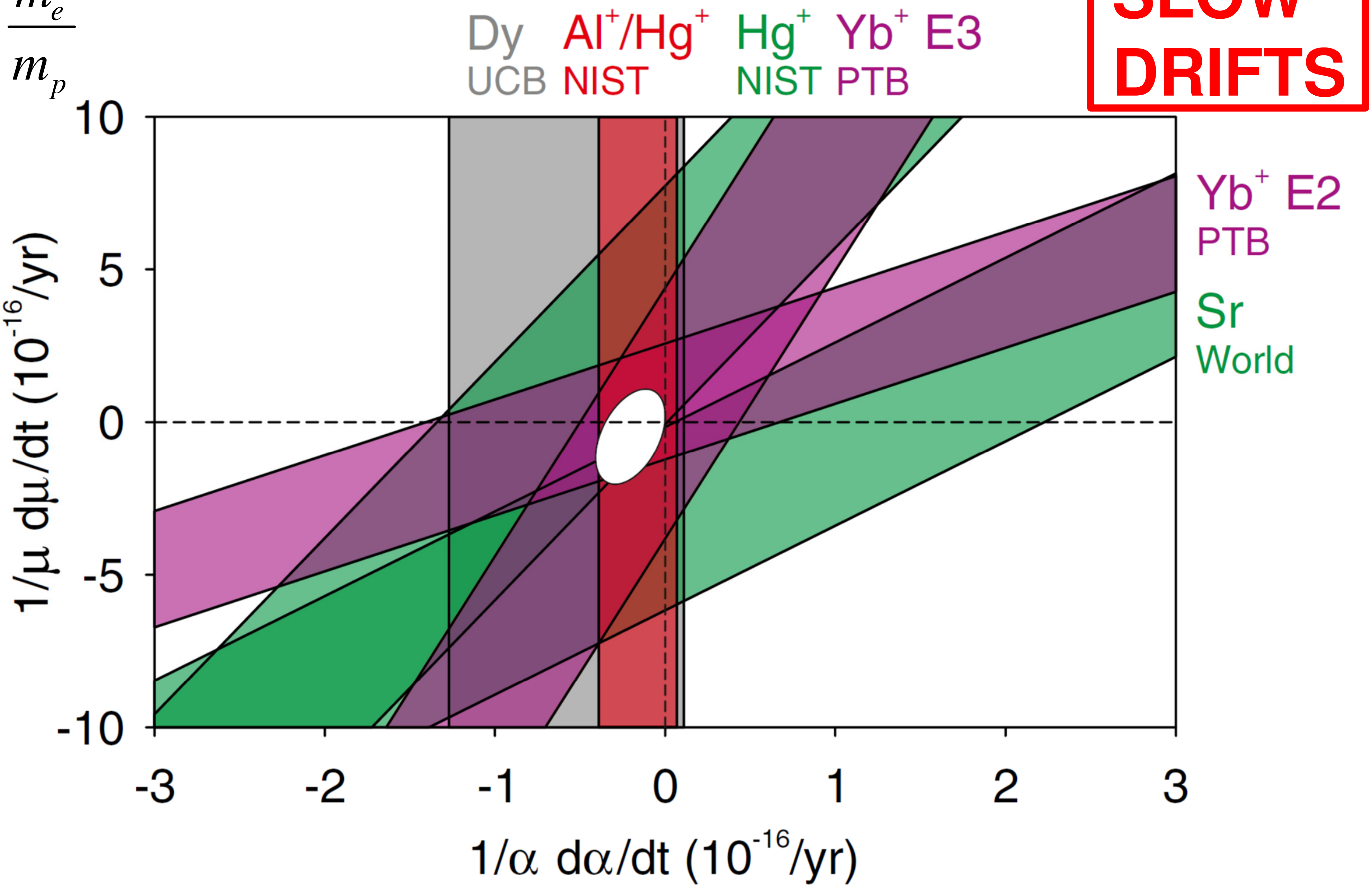
$$K = \frac{2q}{E_0}$$

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

CAN WE GET LARGE K IN NEW CLOCKS? – NEXT LECTURES

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

SLOW DRIFTS



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

MORE ON DARK MATTER SEARCHES WITH CLOCKS LATER …