Probing new physics with atomic clocks

MARIANNA SAFRONOVA

Light Dark World 2018
KAIST, Daejeon, South Korea

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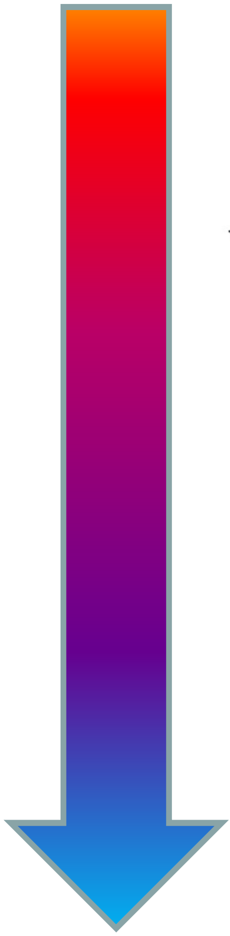
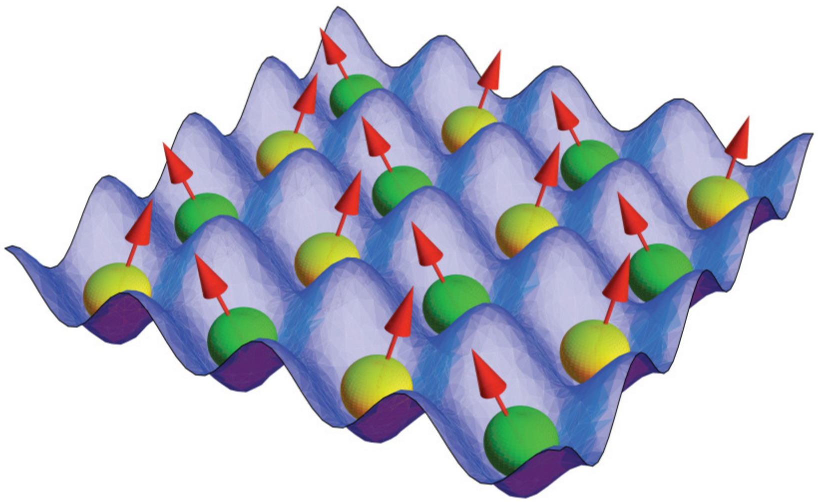
jqi Joint Quantum Institute

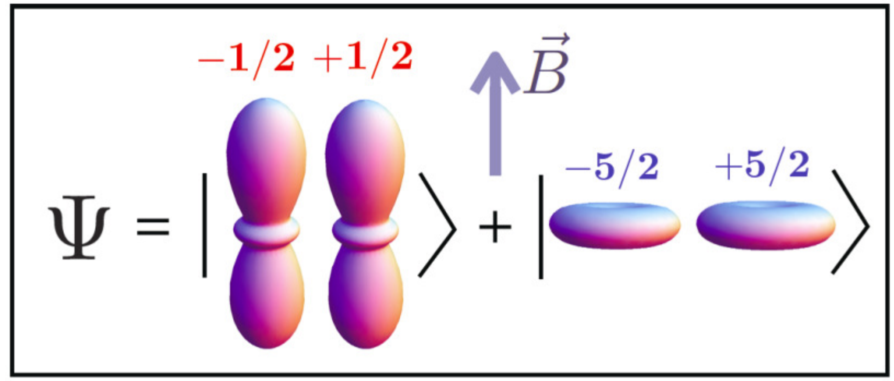
Extraordinary progress in the control of atomic systems

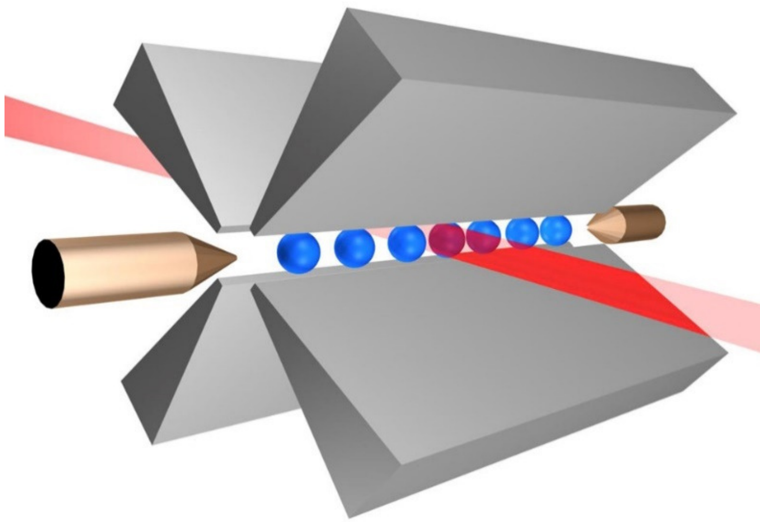
300K

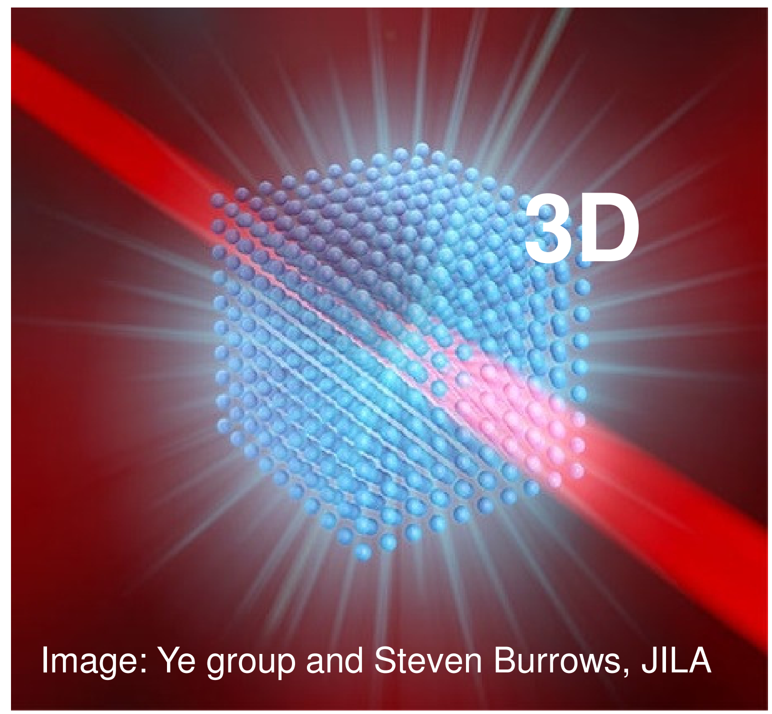


nK



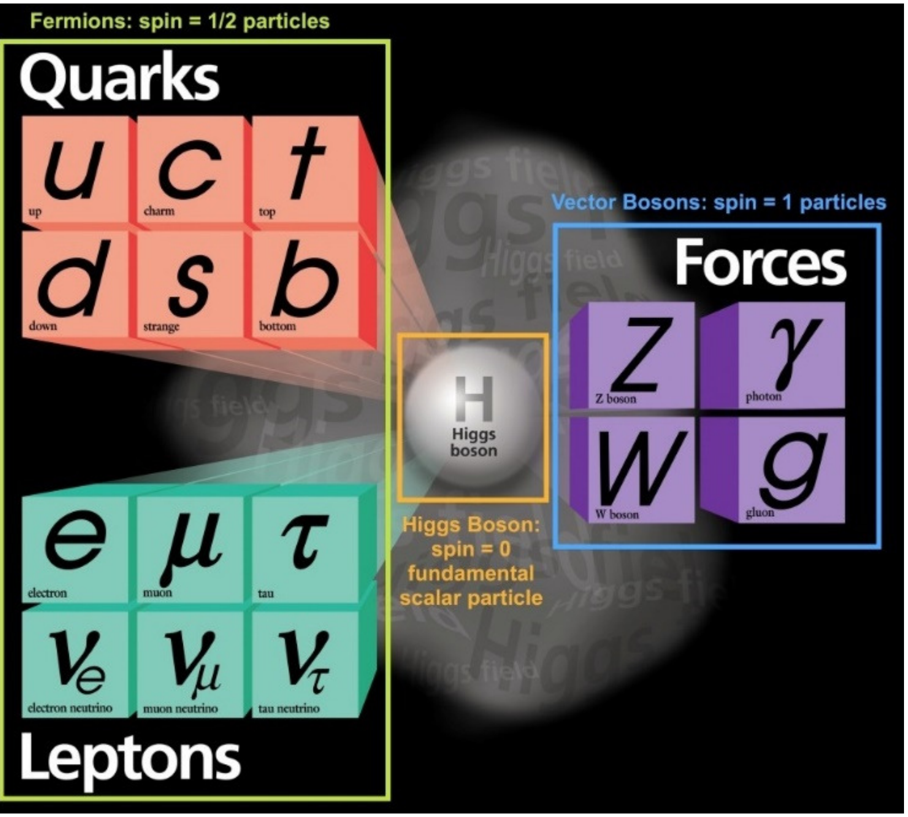


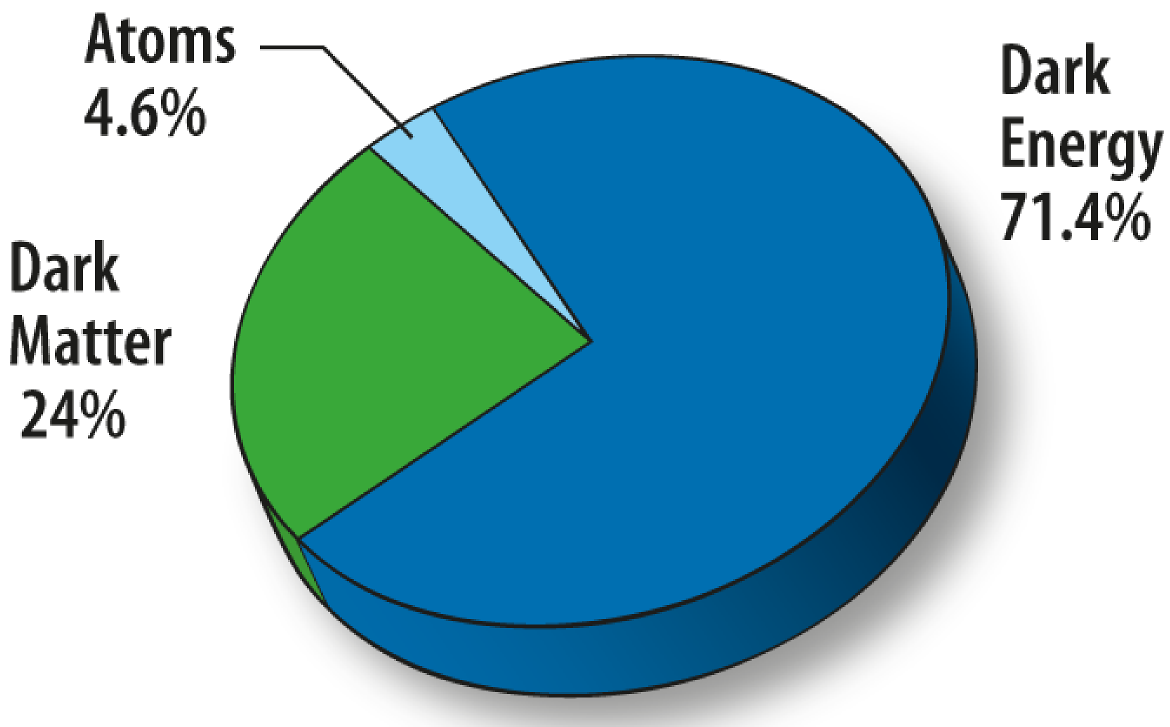




Ultracold **Trapped** **Precisely controlled**

Now it is a great time to use **atomic and molecular physics precision experiments** for physics beyond the standard model (BSM) searches!





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

Search for New Physics with Atoms and Molecules

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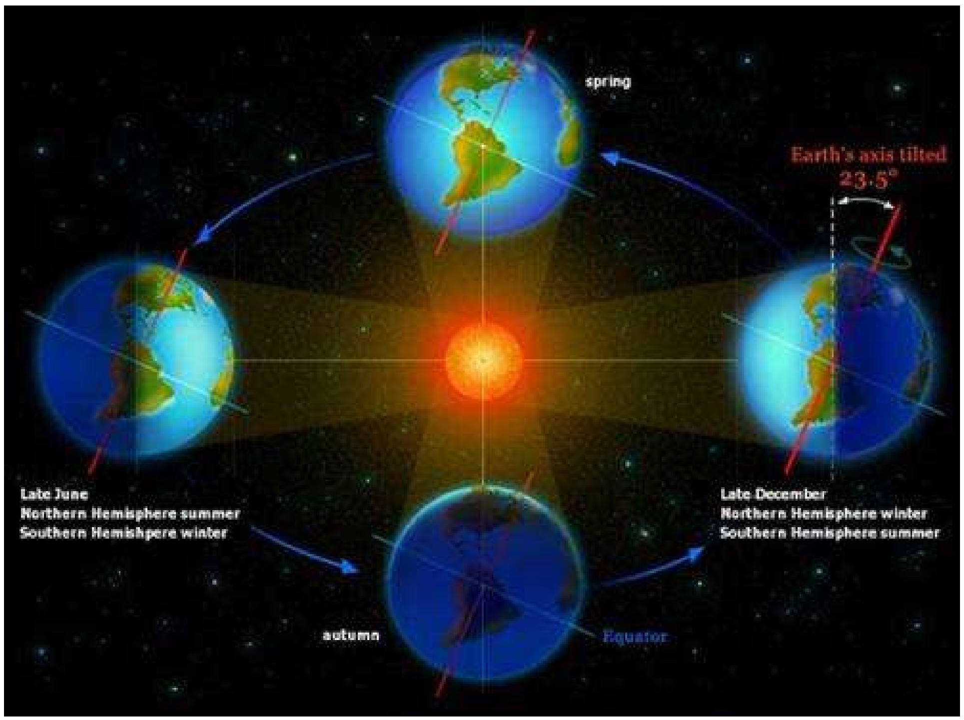
[2]Joint Quantum Institute, National Institute of Standards and Technology and the University of Maryland, College Park, Maryland, USA,
[3]Helmholtz Institute, Johannes Gutenberg University, Mainz, Germany,
[4]University of California, Berkeley, California, USA,
[5]Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA
[6]Yale University, New Haven, Connecticut, USA,
[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.

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)

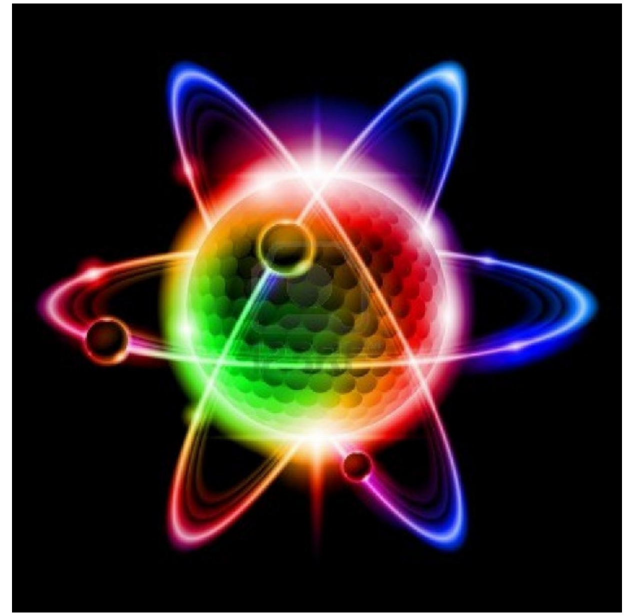
Ingredients for an atomic clock

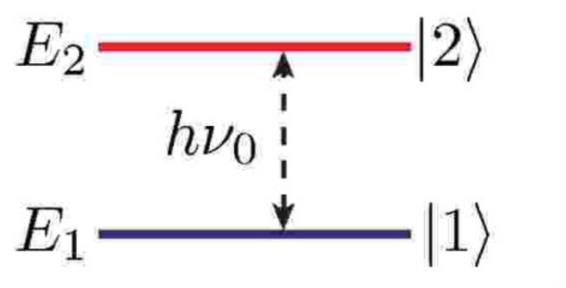
1. Atoms are all the same and will oscillate at exactly the same frequency (in the same environment): **you now have a perfect oscillator!**

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

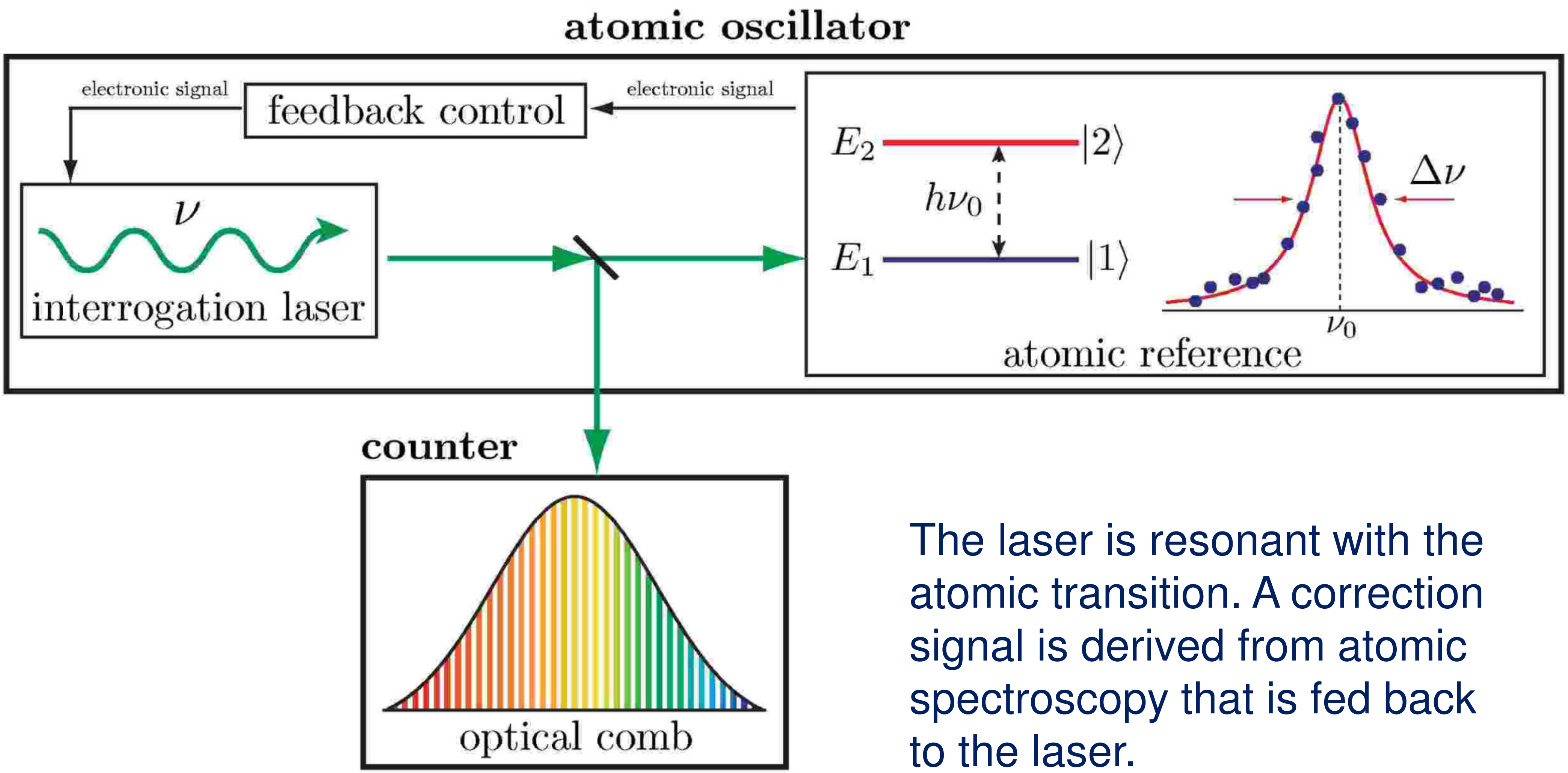




valentinagurarie.wordpress.com/tag/atom/

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

How optical atomic clock works

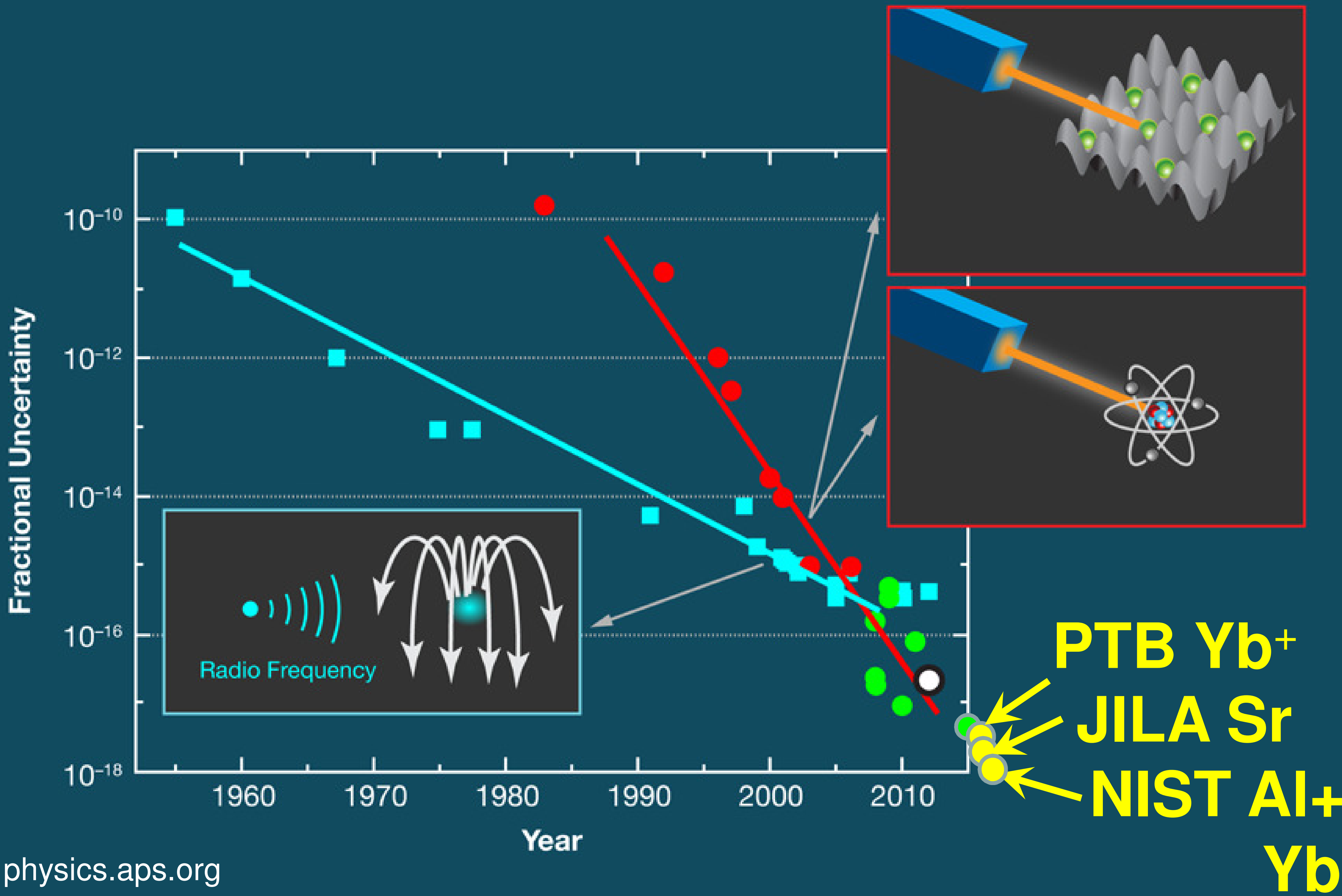


The laser is resonant with the atomic transition. A correction signal is derived from atomic spectroscopy that is fed back to the laser.

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

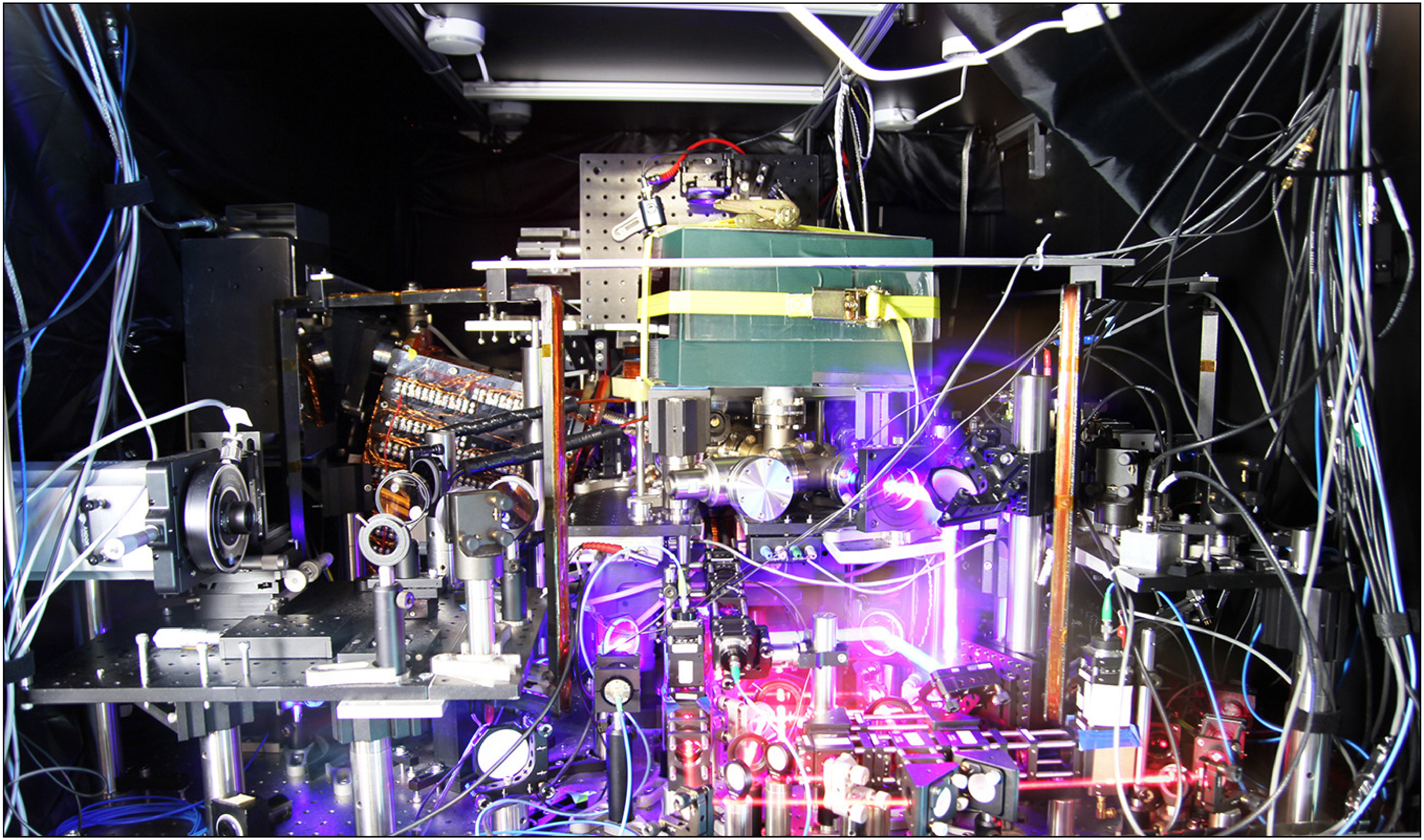
From: Poli et al. “Optical atomic clocks”, La rivista del Nuovo Cimento 36, 555 (2018) arXiv:1401.2378v2

Optical vs. microwave clocks



physics.aps.org

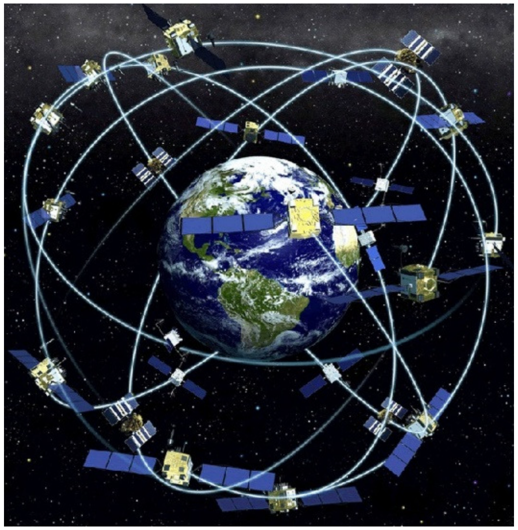
Sr clock will lose 1 second in 15 billion years !



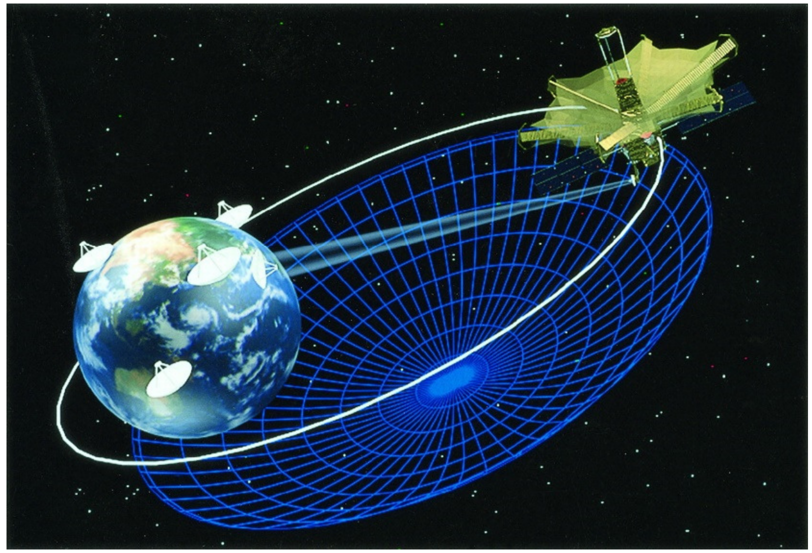
Nicholson et al., Nature Comm. 6, 6896 (2015) **Sr: 2×10^{-18}**

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

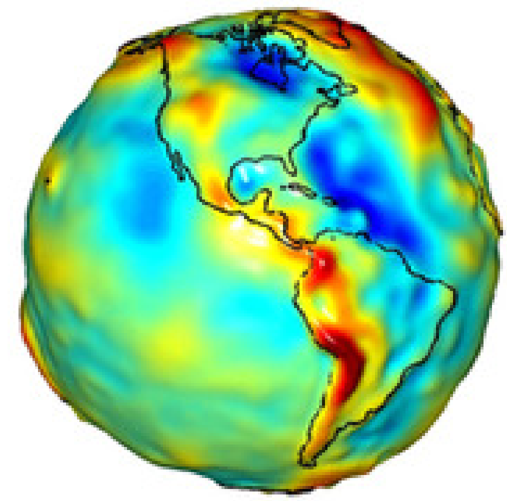
Applications of atomic clocks



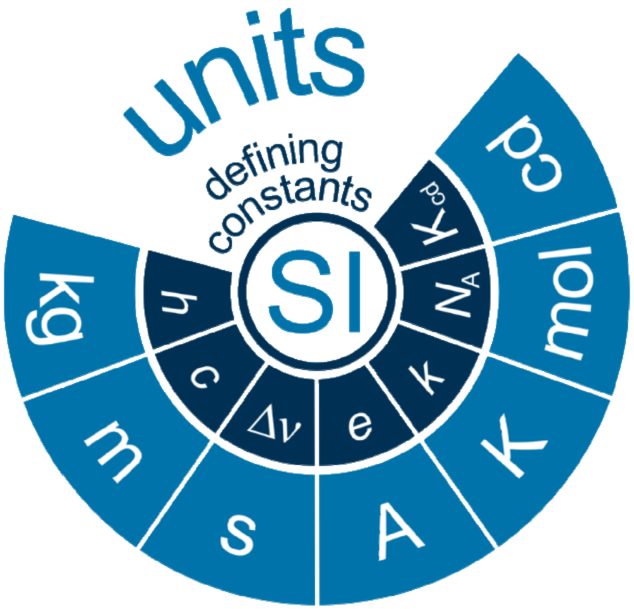
GPS



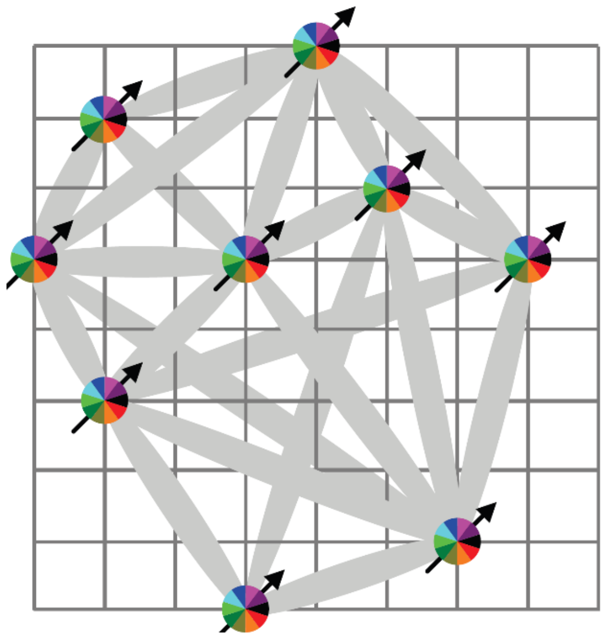
Very Long Baseline Interferometry



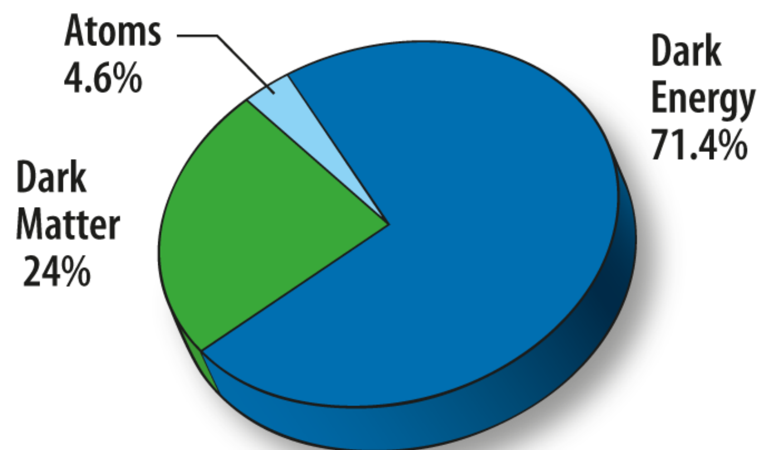
Relativistic geodesy



Definition of the second



Quantum simulation



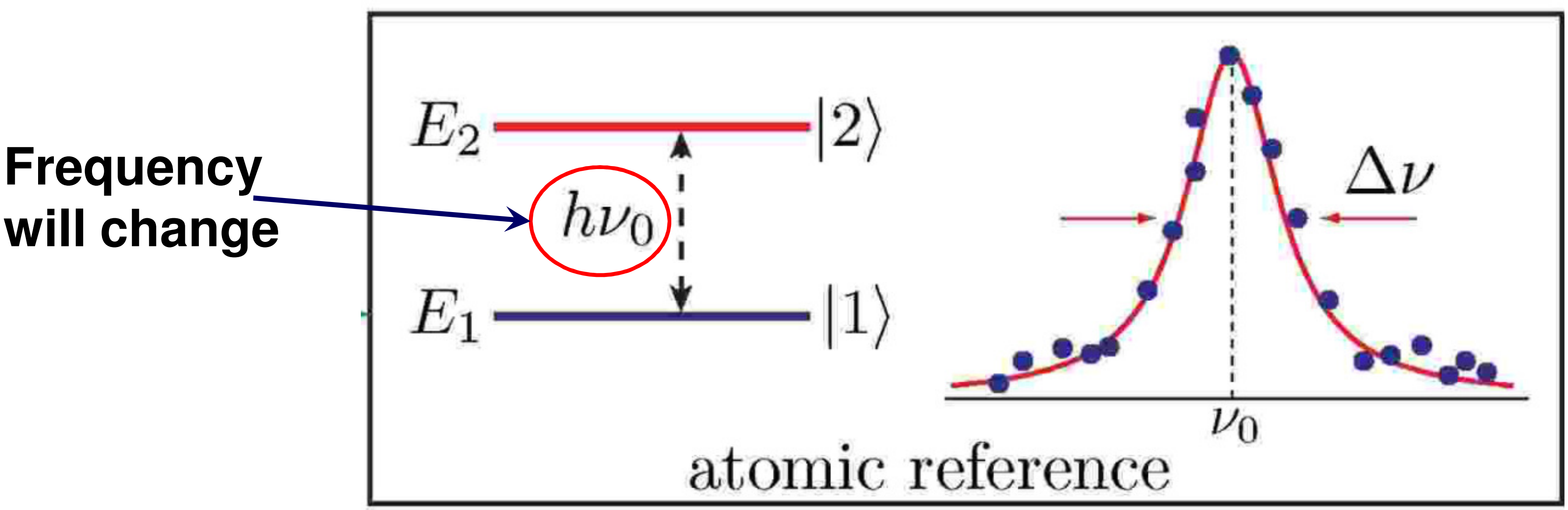
Search for physics beyond the Standard Model

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.

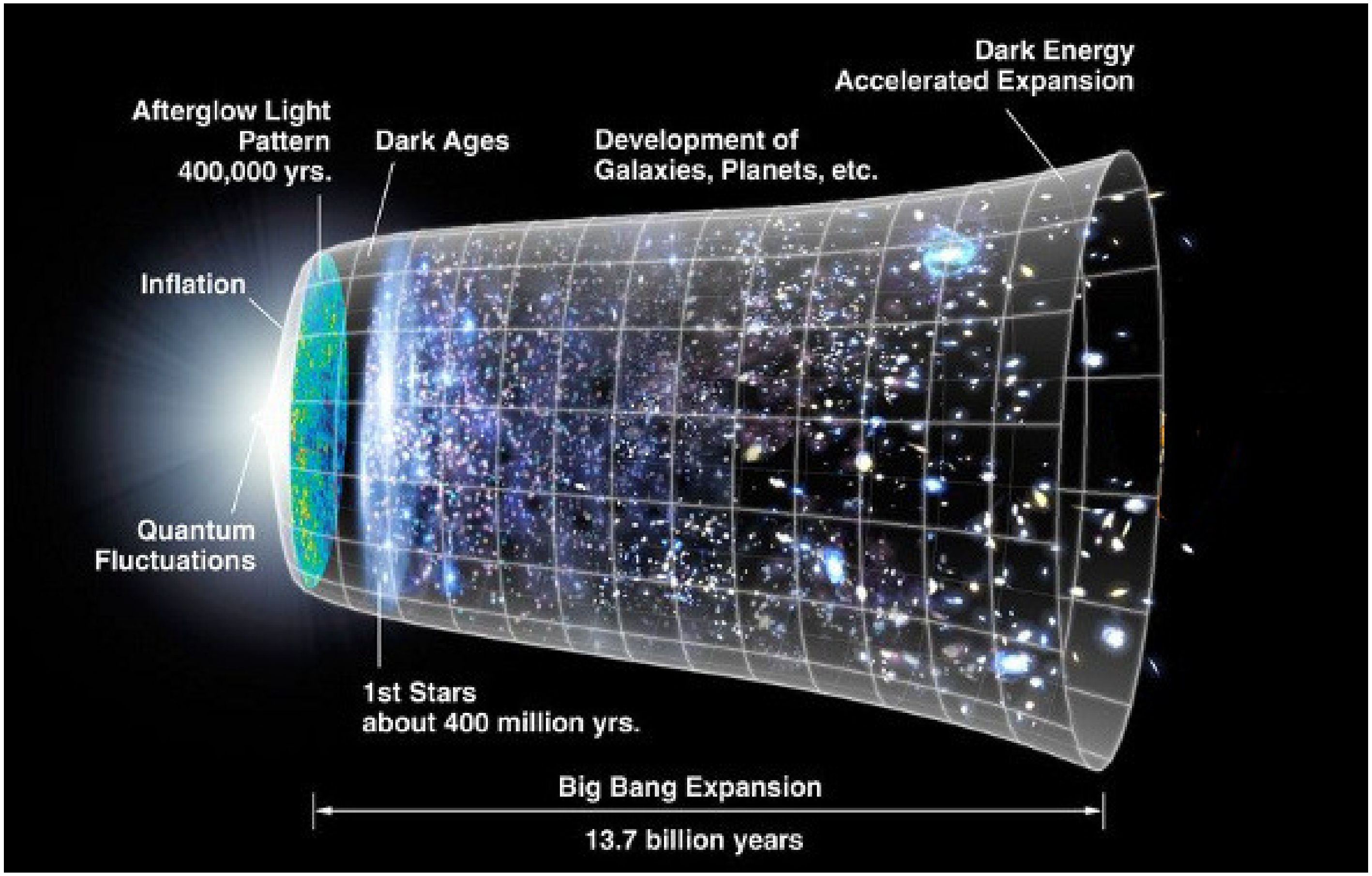


Variation of fundamental constants

Theories with varying dimensionless fundamental constants

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

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



Laboratory searches for variation of fundamental constants

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

1. Frequency of **optical** transitions

$$\nu \simeq cR_\infty A F(\alpha)$$ **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

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

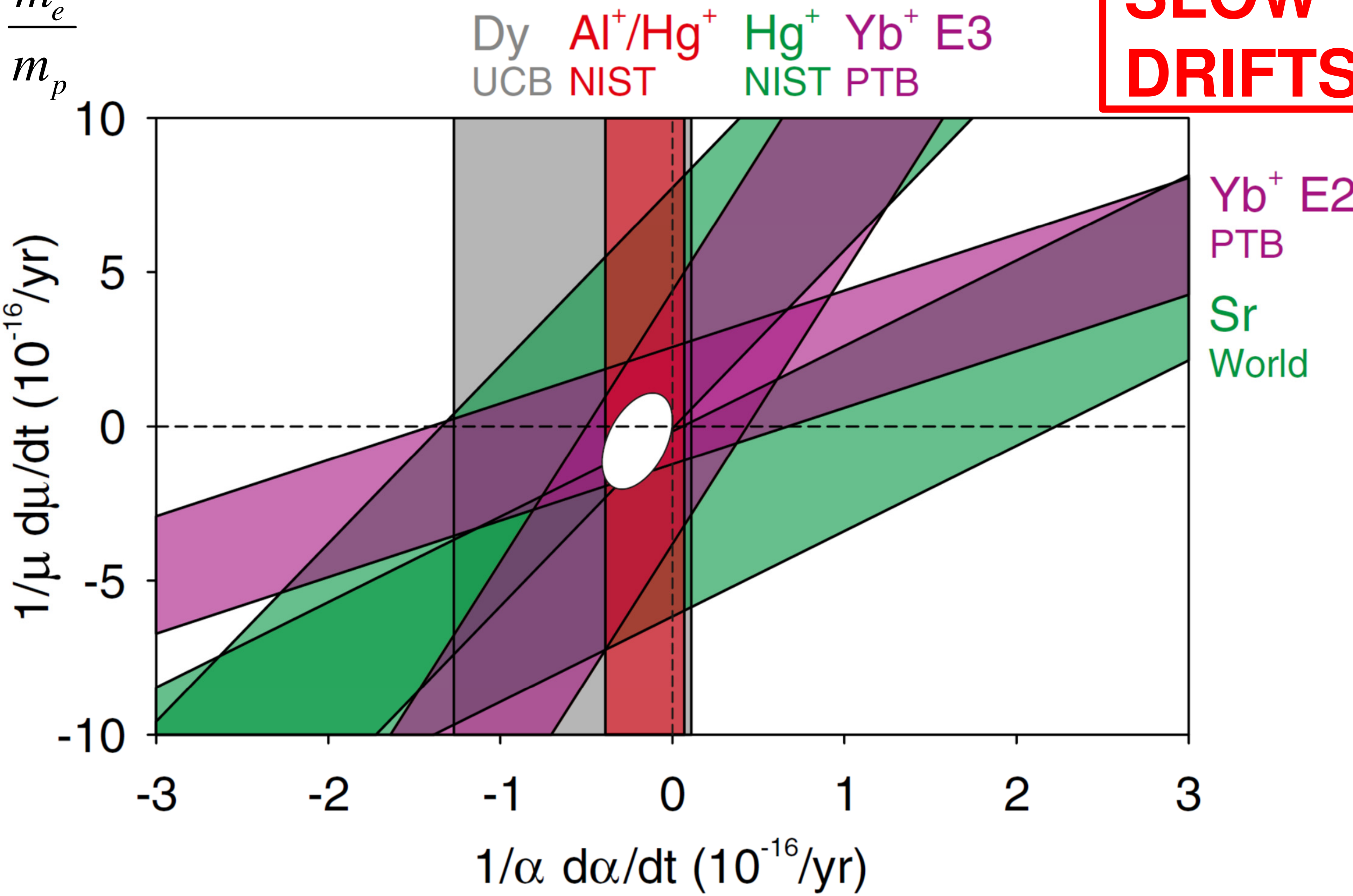
Test of α-variation

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

Easier to measure large effects!

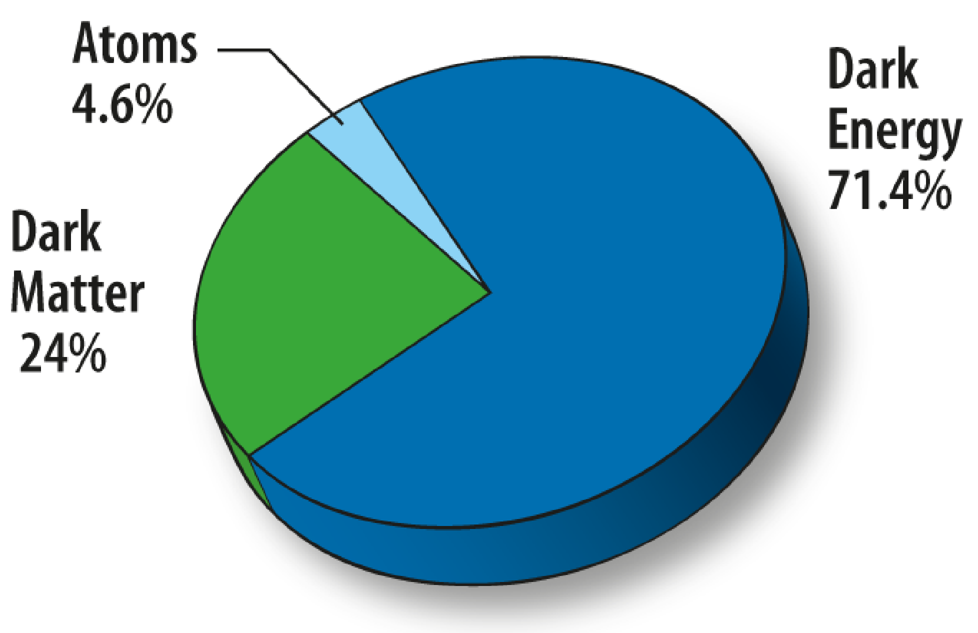
$$\mu = \frac{m_e}{m_p}$$

SLOW DRIFTS

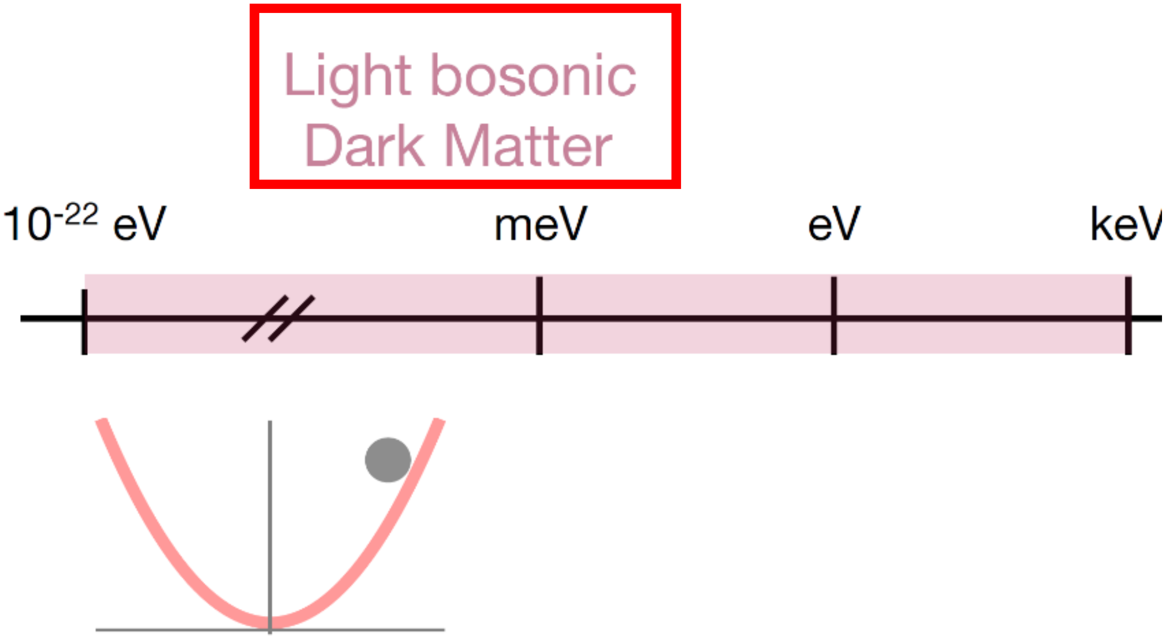


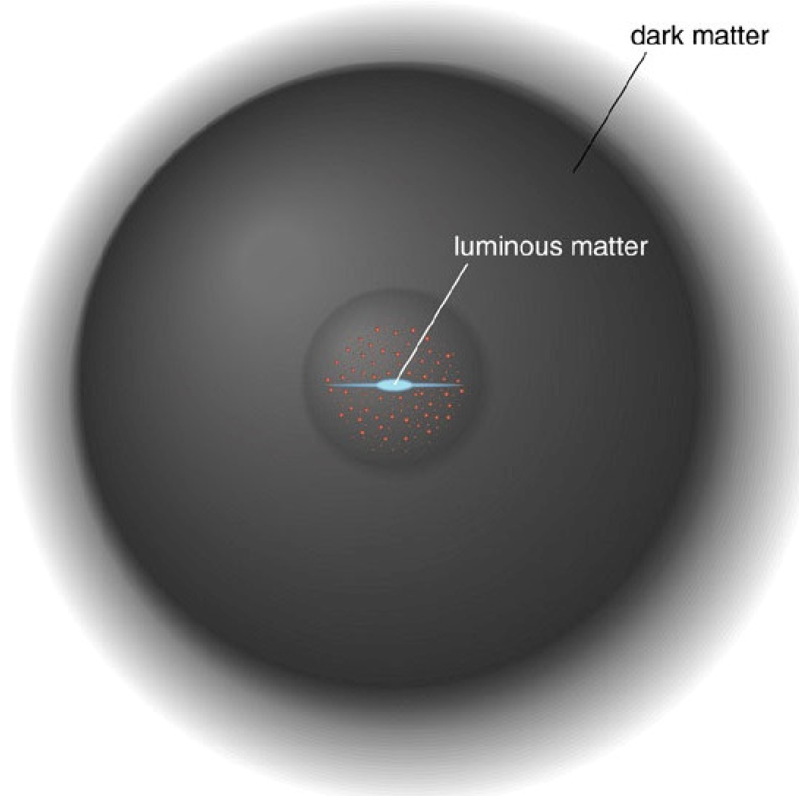
Constraints on temporal variations of α and μ from comparisons of atomic transition frequencies. Huntemann et al., PRL 113, 210802 (2014)

Variation of fundamental constants and dark matter



The dark matter





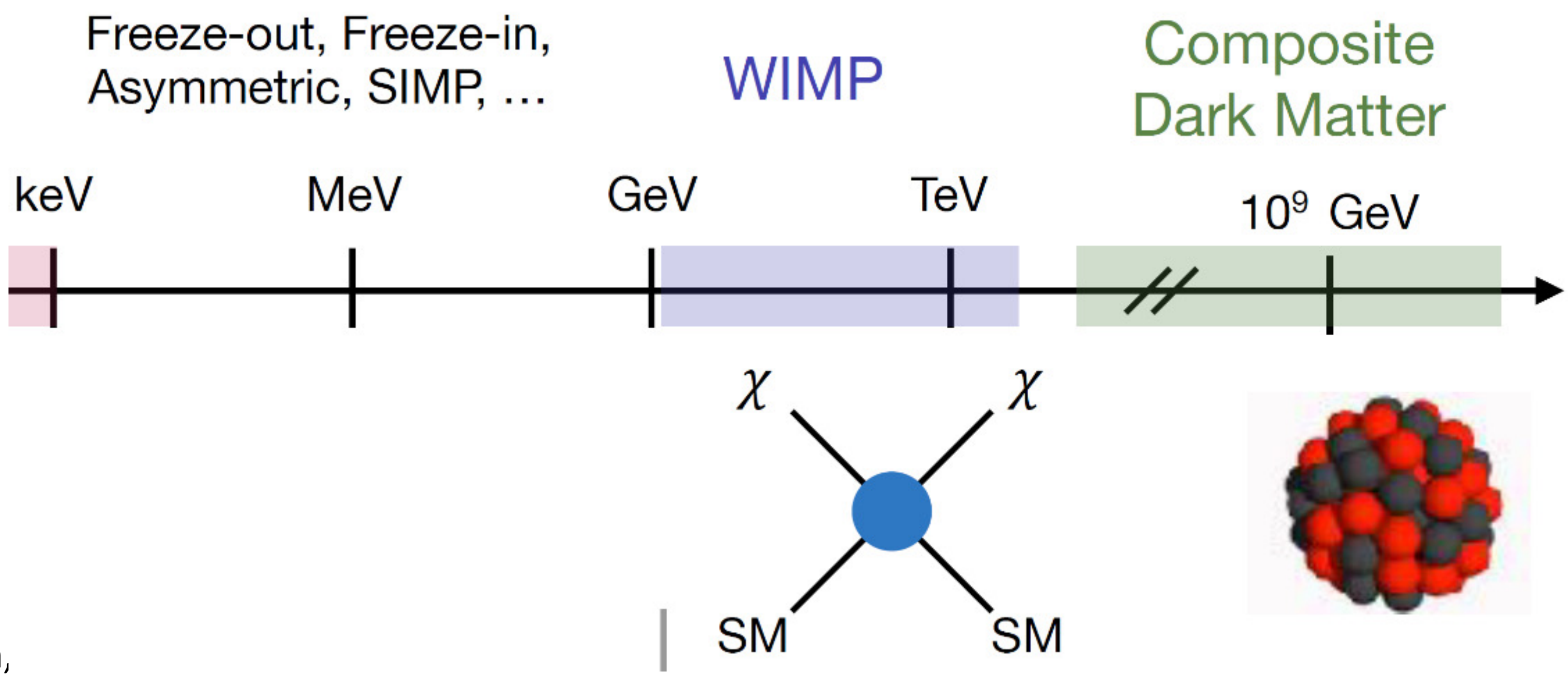


Image credit: Simon Knapen,

Ultralight scalar particles: dark matter

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

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

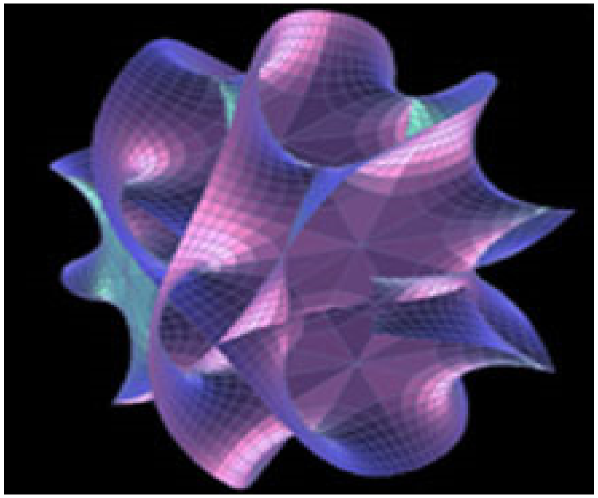
λ_{dB} is the de Broglie wavelength of the particle.

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

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

Dilatonic couplings to the Standard Model

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



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

Ultralight dark matter

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

Dark matter coupling to the Standard Model

$$\mathcal{L}_\phi = \kappa\phi\left[+ \frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{A\mu\nu} - d_{m_e}m_e\bar{e}e - \sum_{i=u,d}(d_{m_i} + \gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$$

Dark matter

photons

gluons

electrons

quarks

Measure: couplings d_i vs. DM mass

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

Ultralight dark matter searches with clocks

Comparing frequencies of **hyperfine to optical** clocks

$$\frac{\delta(\nu_2/\nu_1)}{(\nu_2/\nu_1)} \simeq [d_{m_e} - d_g + M_A d_{\hat{m}} + d_e(K_2 - K_1)]\,\kappa\phi(t)$$

Dark matter

Comparing frequencies of **optical to optical** clocks

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

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

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

Enhancement factor

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}
1000	1 mHz	4×10^{-18}
10^{6}	10^{-6}	4×10^{-21}

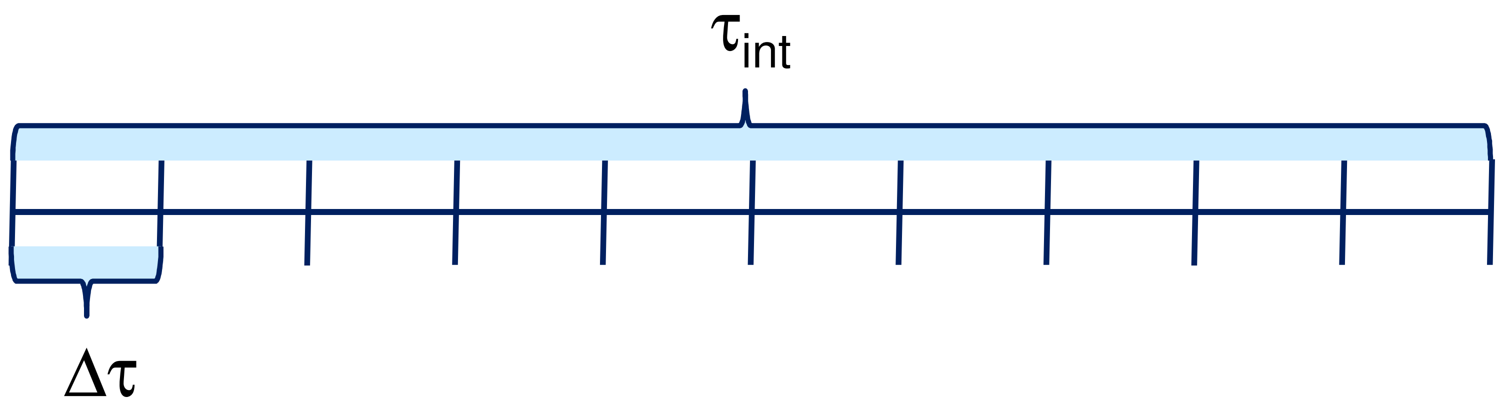
One oscillation per second

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)

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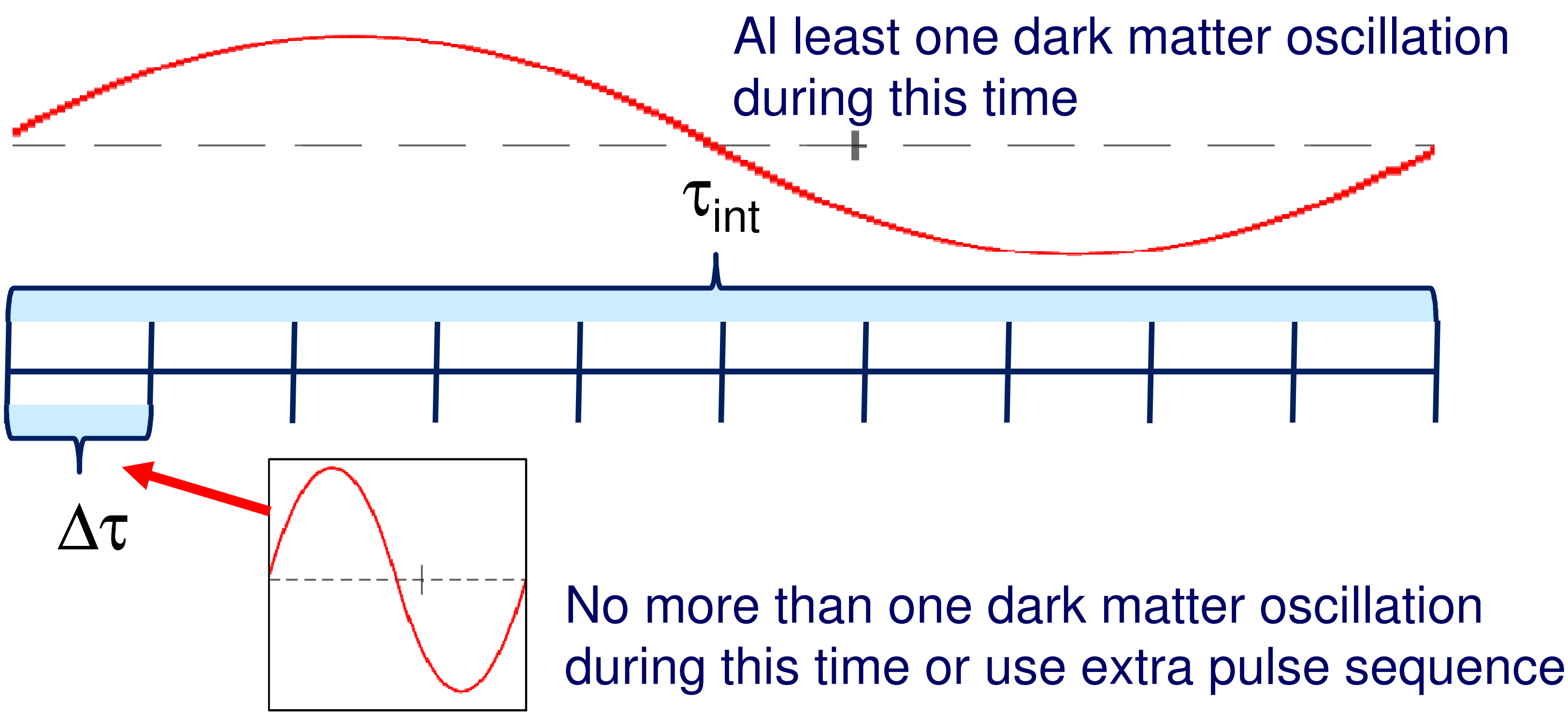

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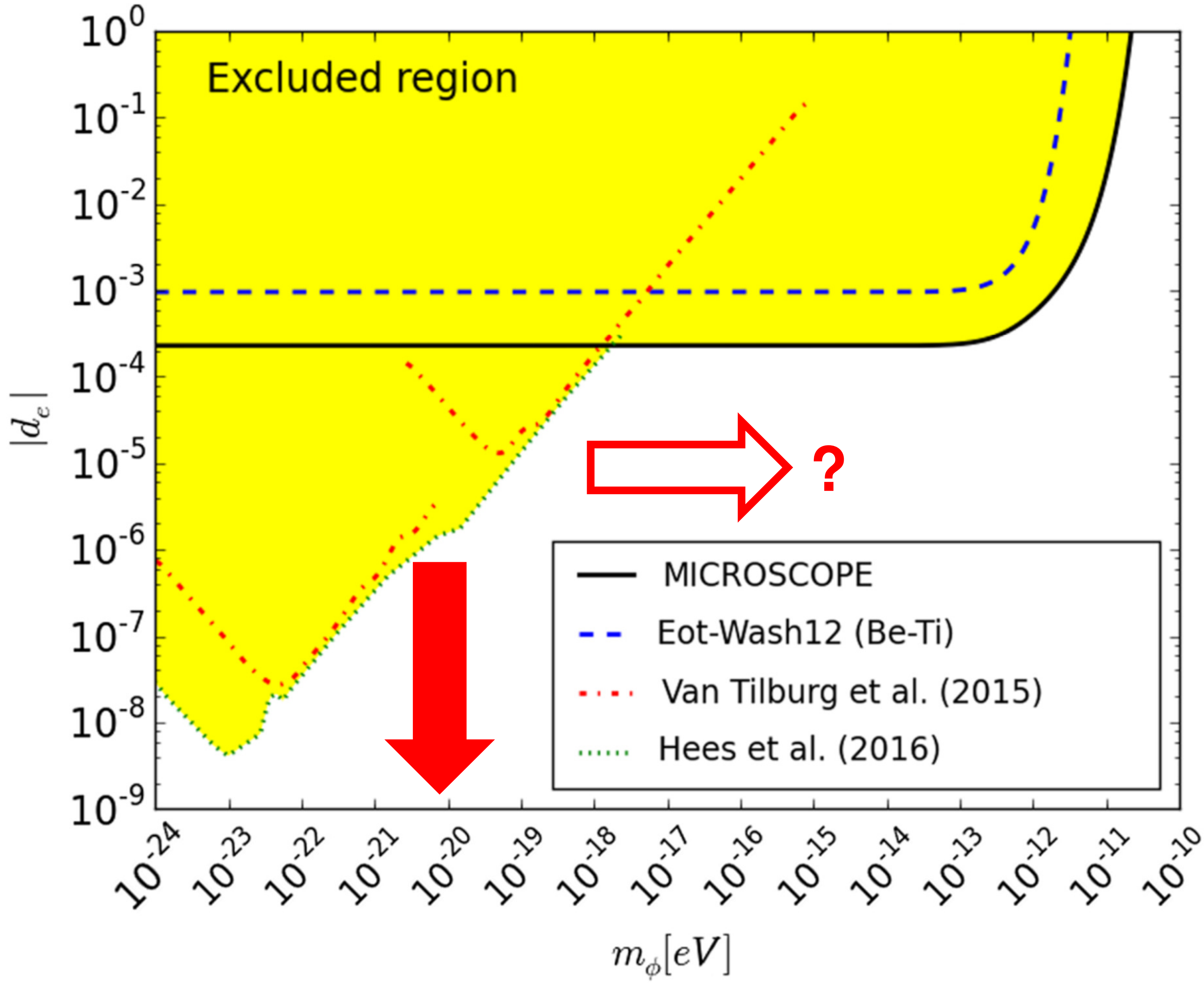


From PRL 120, 141101 (2018)

nature physics

LETTERS

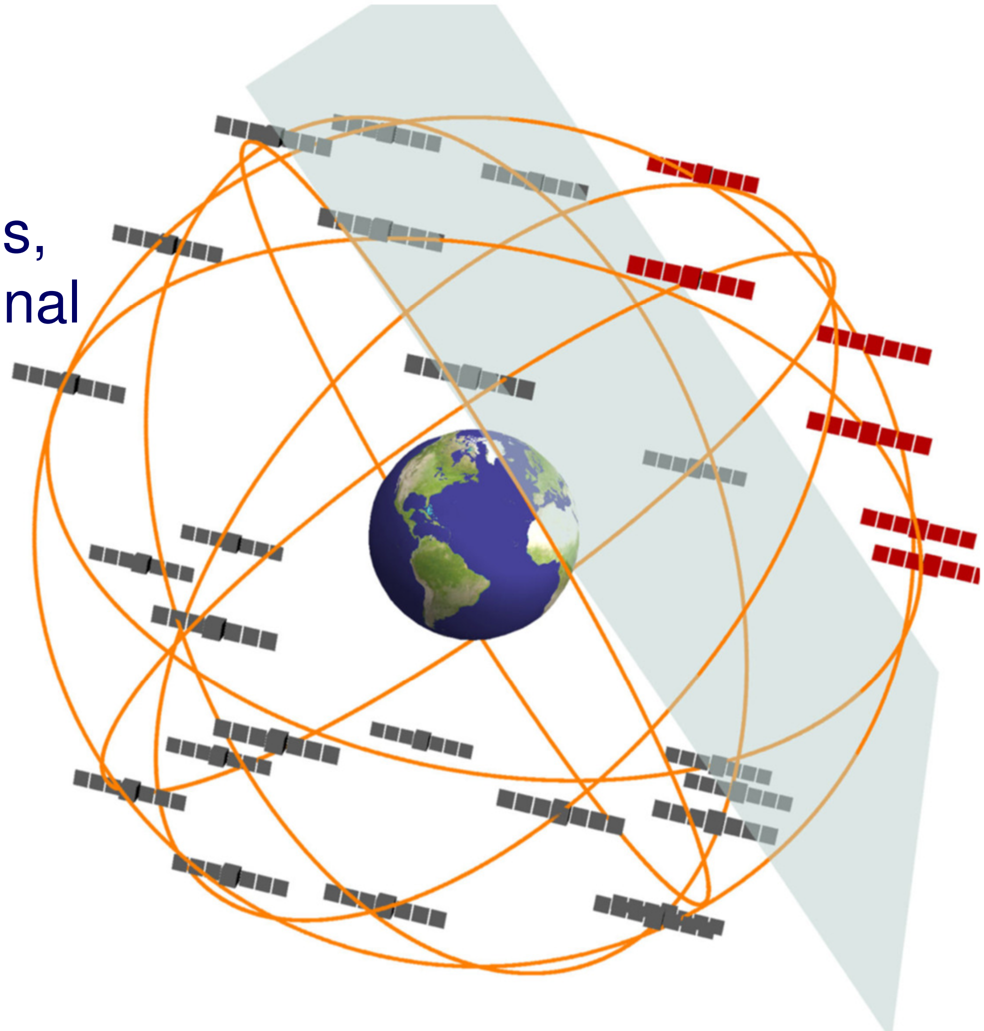
PUBLISHED ONLINE: 17 NOVEMBER 2014 | DOI: 10.1038/NPHYS3137

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).

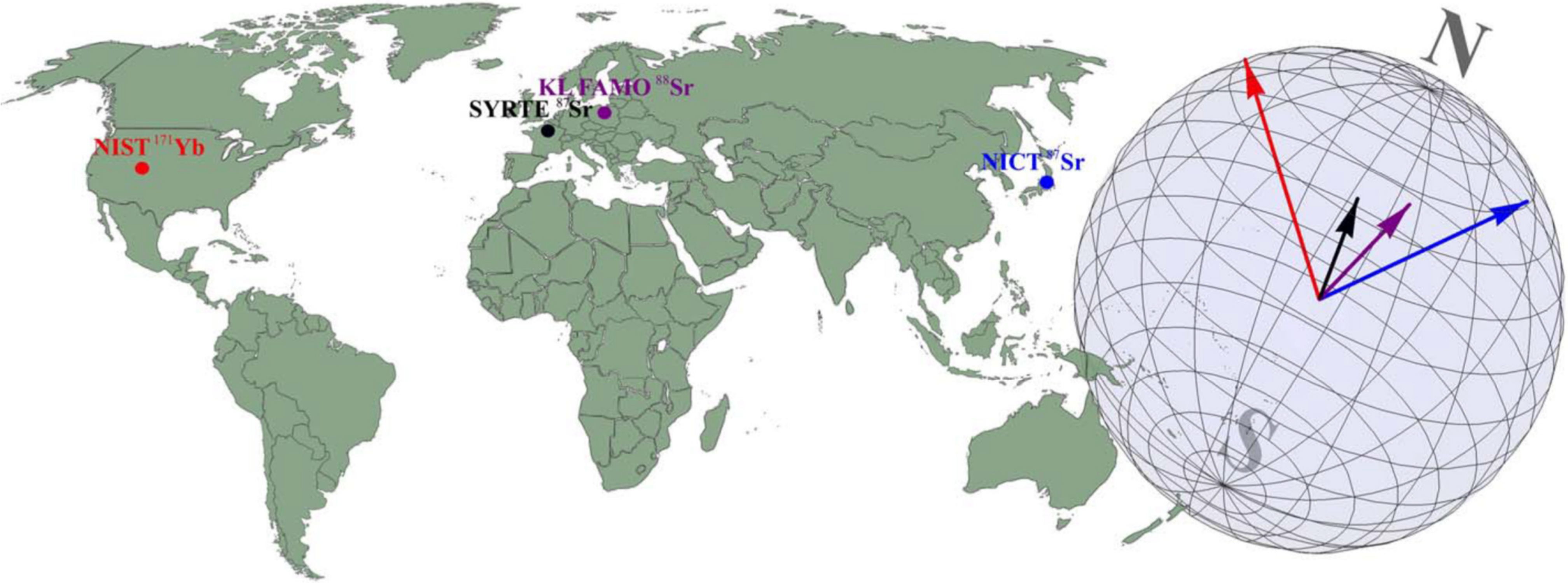


If they are large (size of the Earth) and frequent enough they may be detected by measuring changes in the synchronicity of a global network of atomic clocks, such as the Global Positioning System.

GPM.DM collaboration: Roberts at el., Nature Communications 8, 1195 (2017)

APPLIED PHYSICS

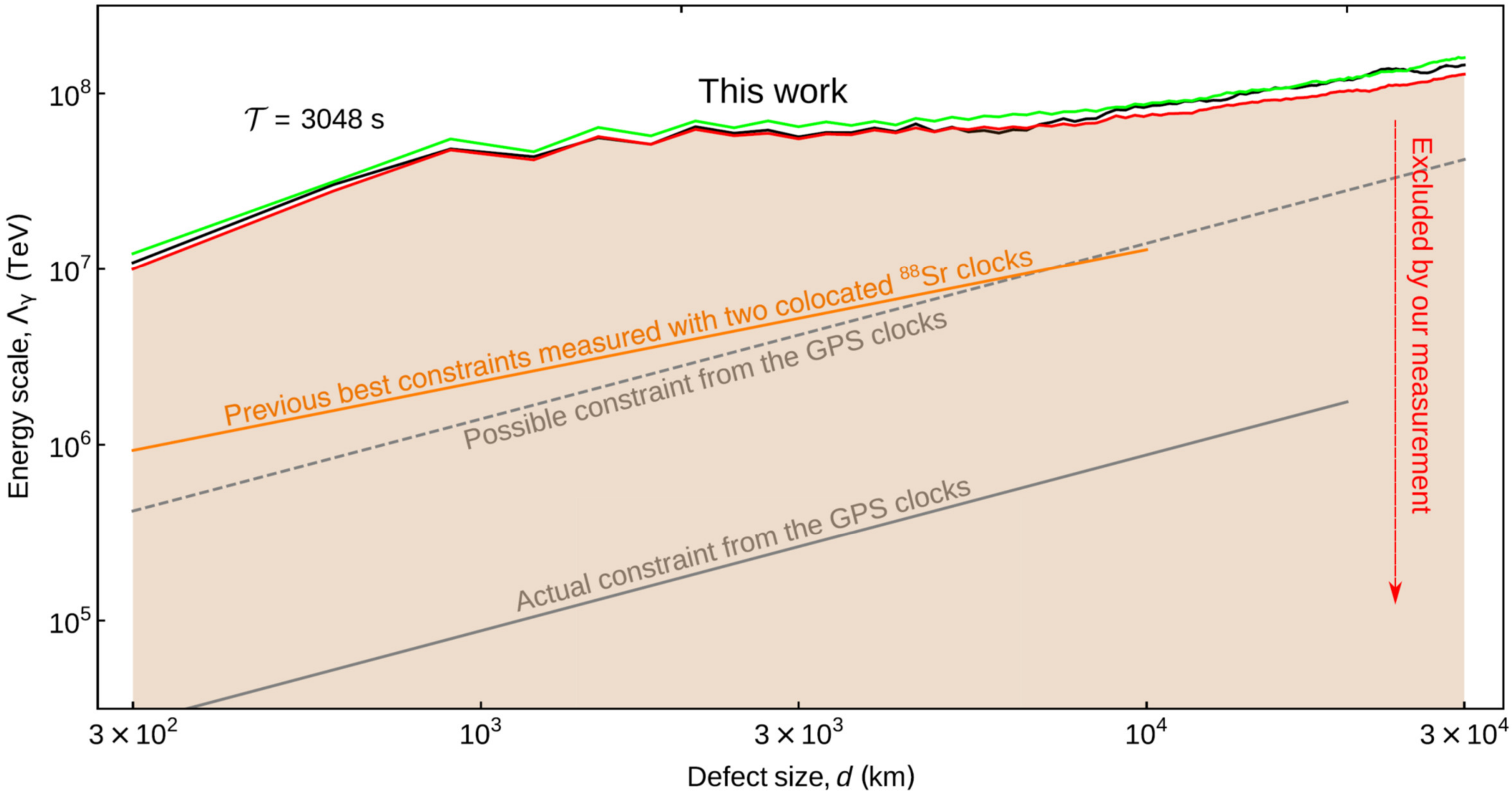
New bounds on dark matter coupling from a global network of optical atomic clocks



Global sensor network. The participating Sr and Yb optical lattice atomic clocks reside at NIST, Boulder, CO, USA, at LNE-SYRTE, Paris, France, at KL FAMO, Torun, Poland, and at NICT, Tokyo, Japan

Wcisło et al., Sci. Adv. 4: eaau4869 (2018)

Wcisło et al., Sci. Adv. 4 (2018)



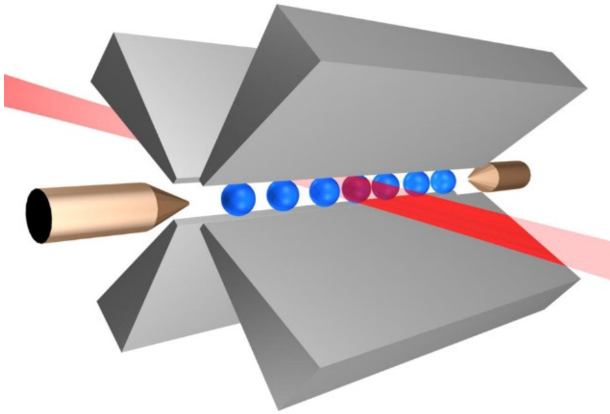
Constraints on the coupling of dark matter to electromagnetism.
The energy scale Λ which inversely parametrizes the strength of the DM-SM coupling as a function of the wall width d.

How to improve laboratory searches for the variation of fundamental constants & dark matter?

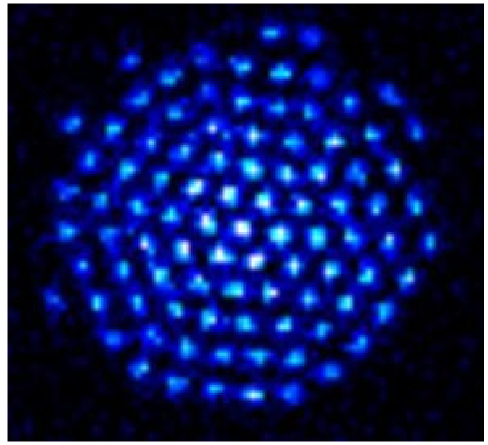
1. Improve uncertainties of current clocks – **two (?)** more orders.

2. Improve stabilities of the clock ratio measurements (particularly with trapped ion clocks).

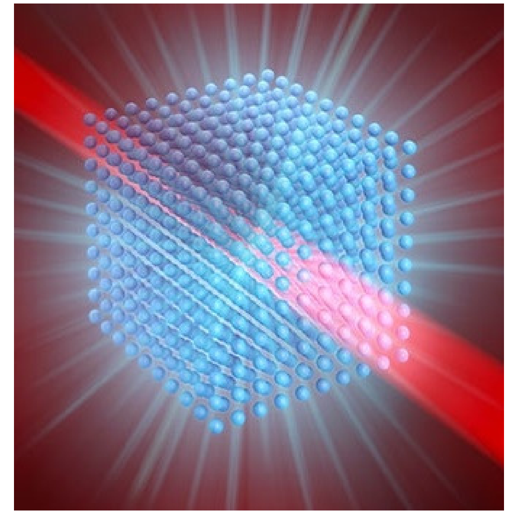
The Future Advances in Atomic Clocks



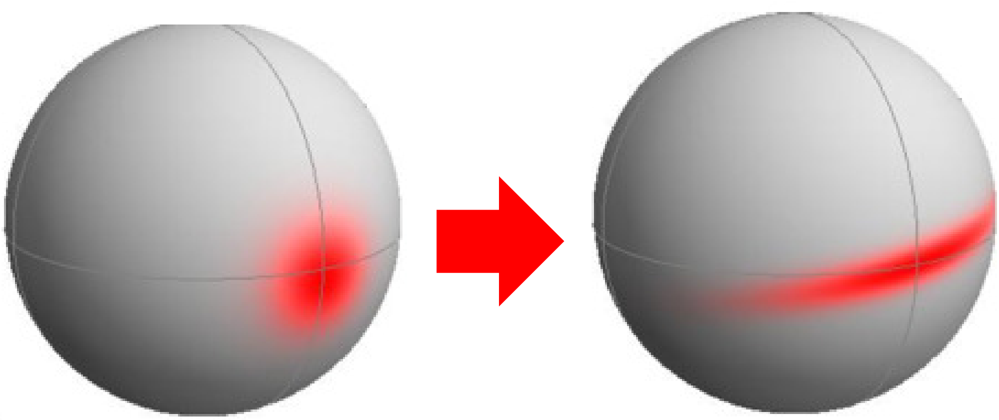
Ion chains



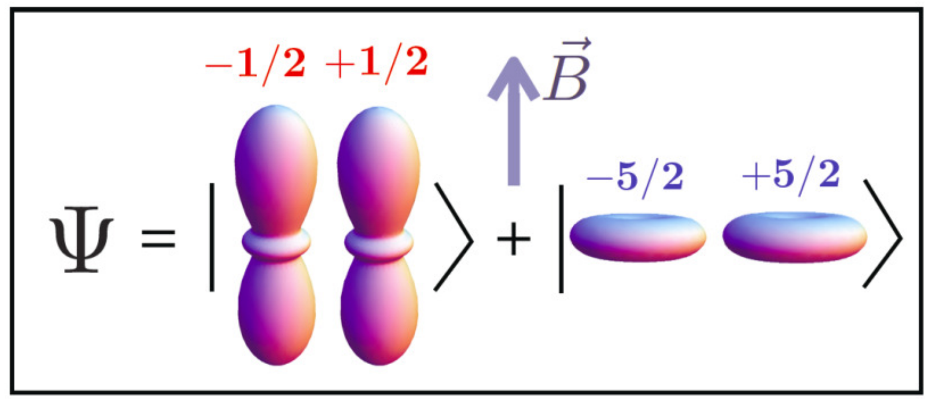
Large ion crystals



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

How to improve laboratory searches for the variation of fundamental constants & dark matter?

1. Improve uncertainties of current clocks – **two (?)** more orders.

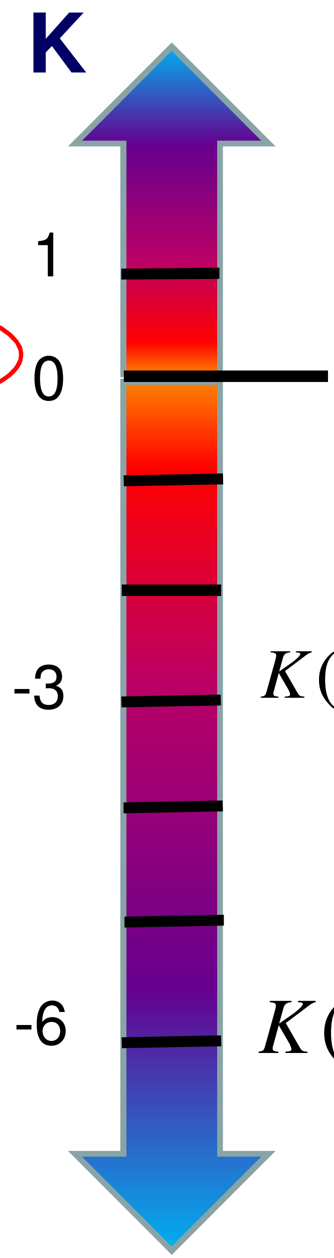
2. Improve stabilities of the clock ratio measurements (particularly with trapped ion clocks).

Clock sensitivity to all types of the searches for the variation of fundamental constants, including dark matter searches require as large enhancement factors K to maximize the signal.

3. Build new clocks based on different systems

   a. Highly-charged ions
   b. Nuclear clock
   c. New Yb two-transition clock scheme
   d. Molecular clocks

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

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

Excellent stability N ~ 1000

$K(Hg^+) = -2.9$

Single ion clocks, N = 1

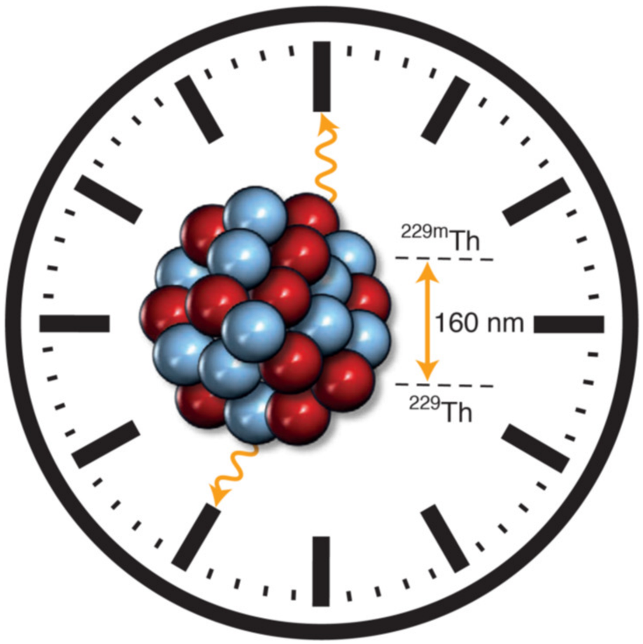
$K(Yb^+ E3) = -6$

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

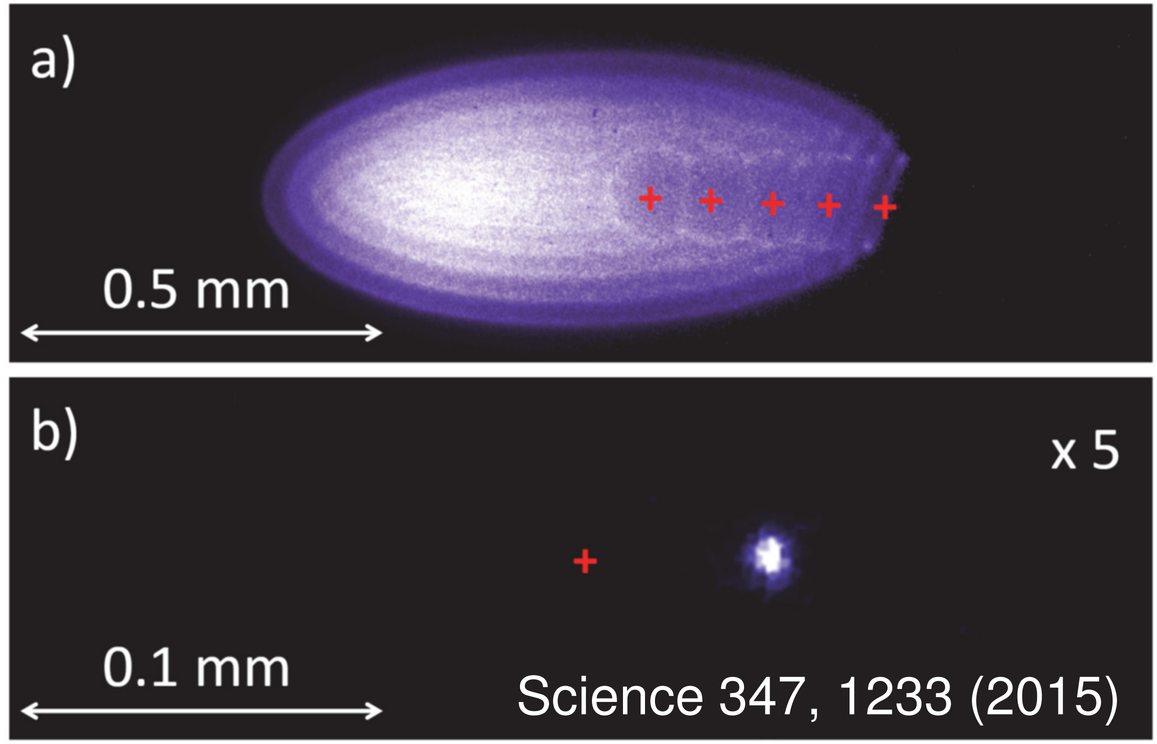
$$\Delta E(\alpha) = \Delta E_0 + \Delta q \left[\left(\frac{\alpha}{\alpha_0} \right)^2 - 1 \right]$$

CAN WE GET LARGE K IN NEW CLOCKS?

The Future: New Atomic Clocks



Nuclear clock



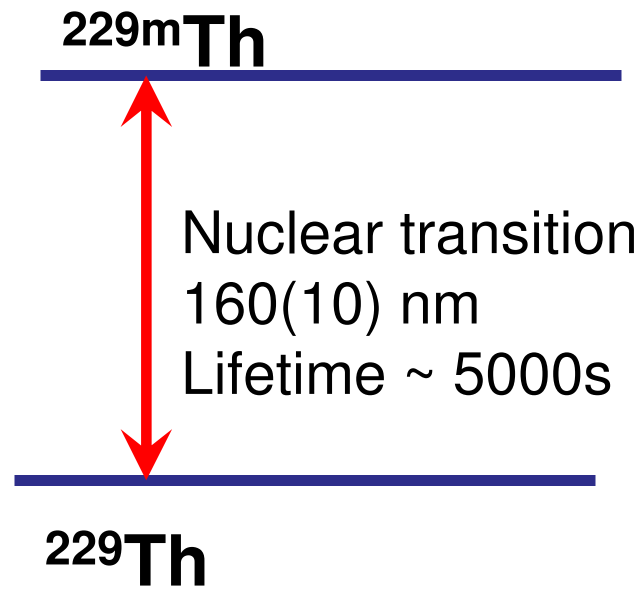
Clocks with ultracold highly charged ions

First demonstration of quantum logic spectroscopy at PTB, Germany last month

Th nuclear clock

Only 7.8eV energy of a nuclear transition (laser-accessible) !

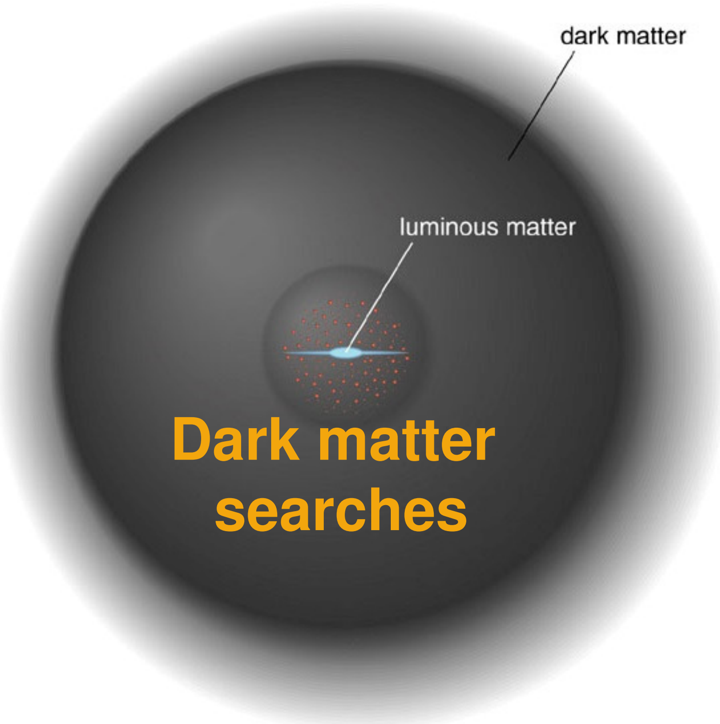
Large (MeV) Coulomb energy difference compensated by MeV difference in the nuclear binding energy?



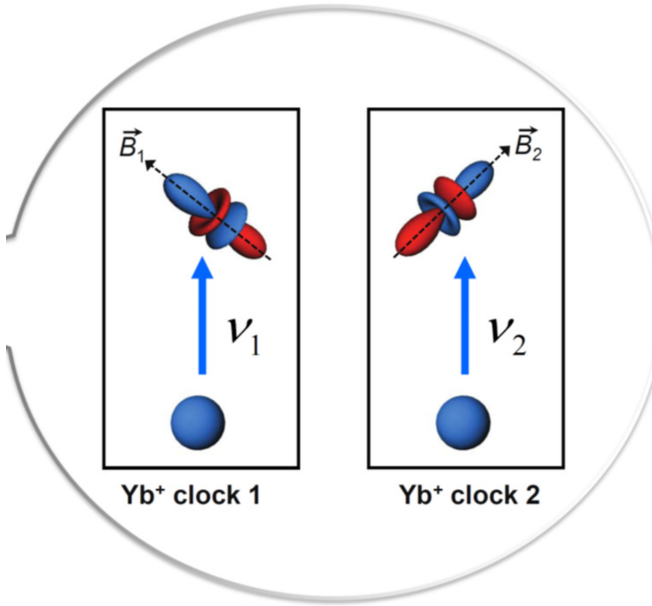
Then, possible 4-5 orders of magnitude enhancement to the variation of α and $\frac{m_q}{\Lambda_{QCD}}$ but orders of magnitude uncertainty in the enhancement factors.

Provides access to couplings of Standard Model particles to dark matter via other terms besides the d_e (E&M).

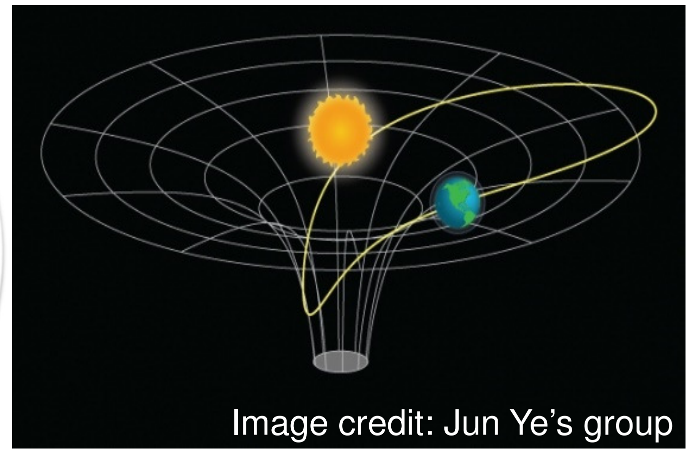
Search for physics beyond the Standard Model with atomic clocks



Dark matter searches

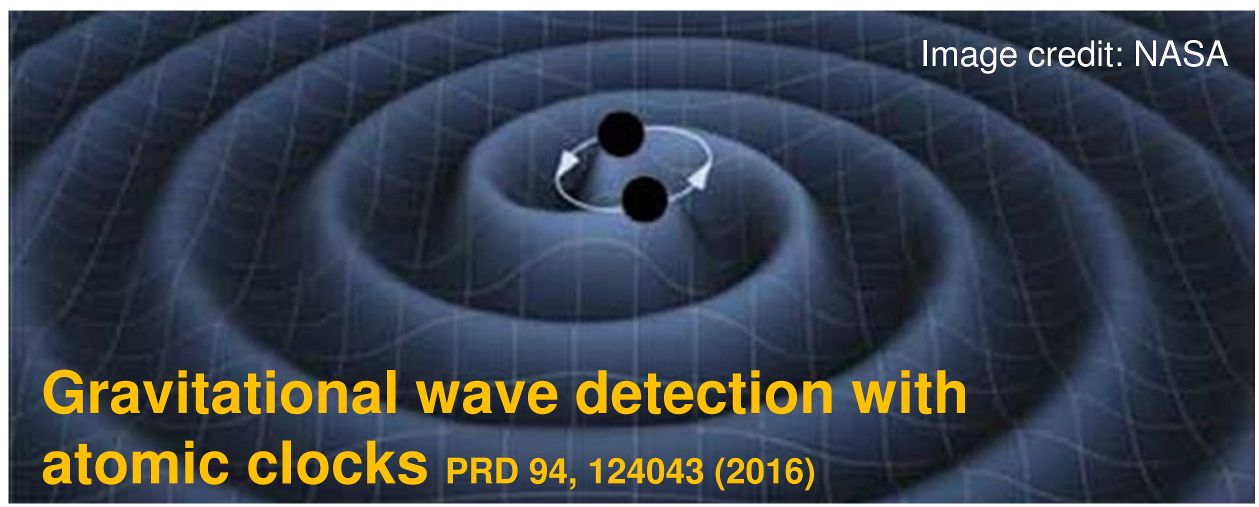


Search for the violation of Lorentz invariance



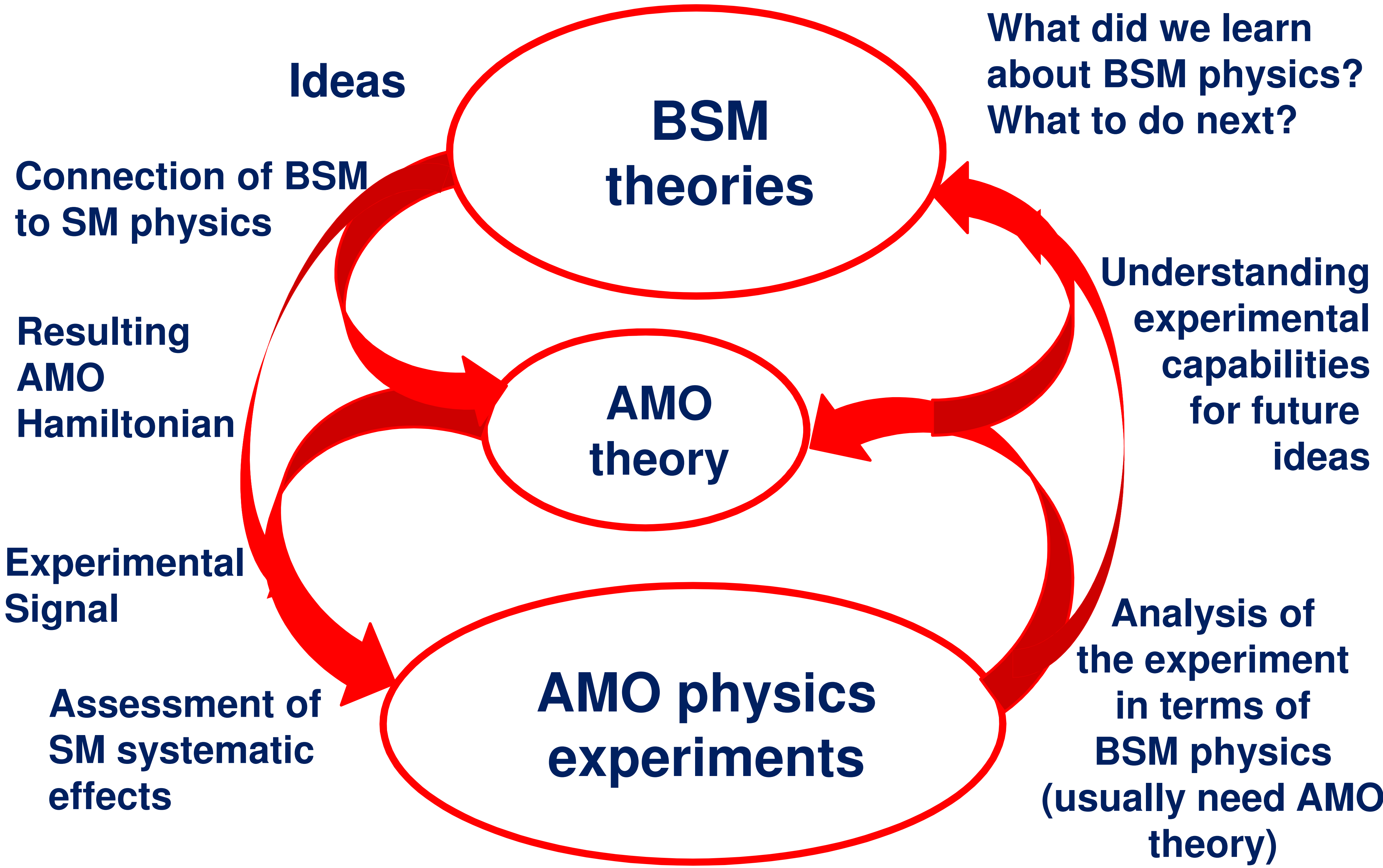
Tests of the equivalence principle

Are fundamental constants constant? α



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

Need to build much stronger connections!

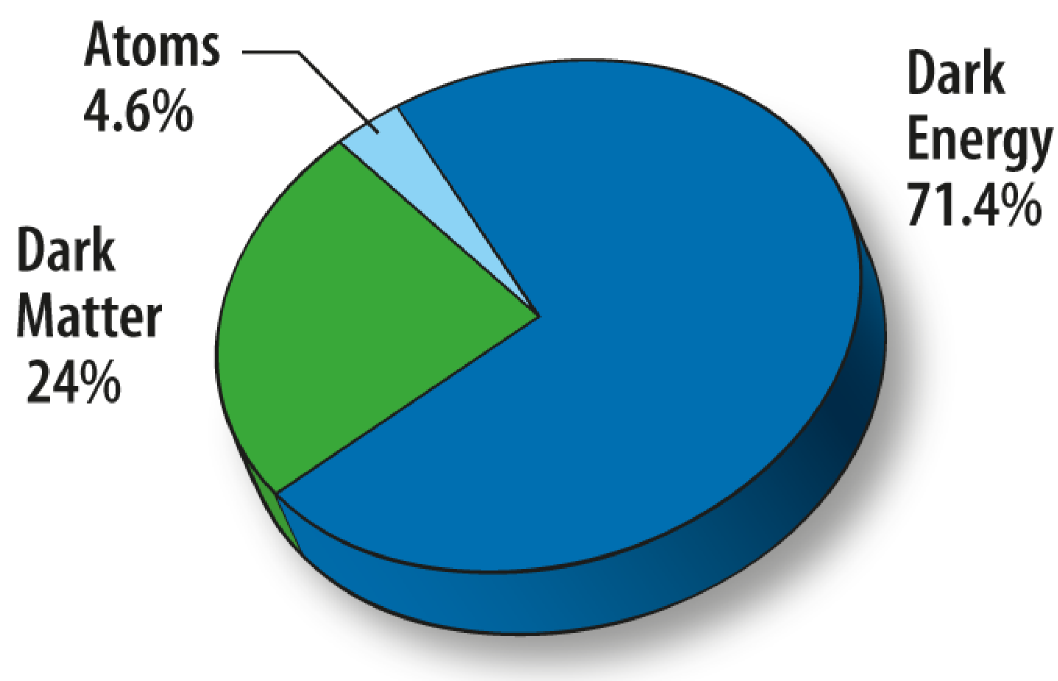


Atomic clocks:

Great potential for discovery of new physics

Many more orders of magnitude improvement coming in the next 10 years!

NEW IDEAS?



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