Поиск изменения фундаментальных констант и тёмной материи с атомными часами

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Moscow, Russia

Перспективные стандарты времени и частоты на атомных и ядерных переходах

NSF
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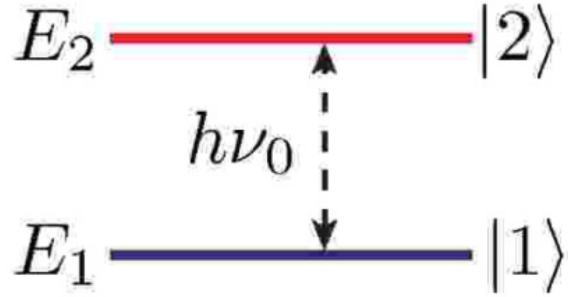
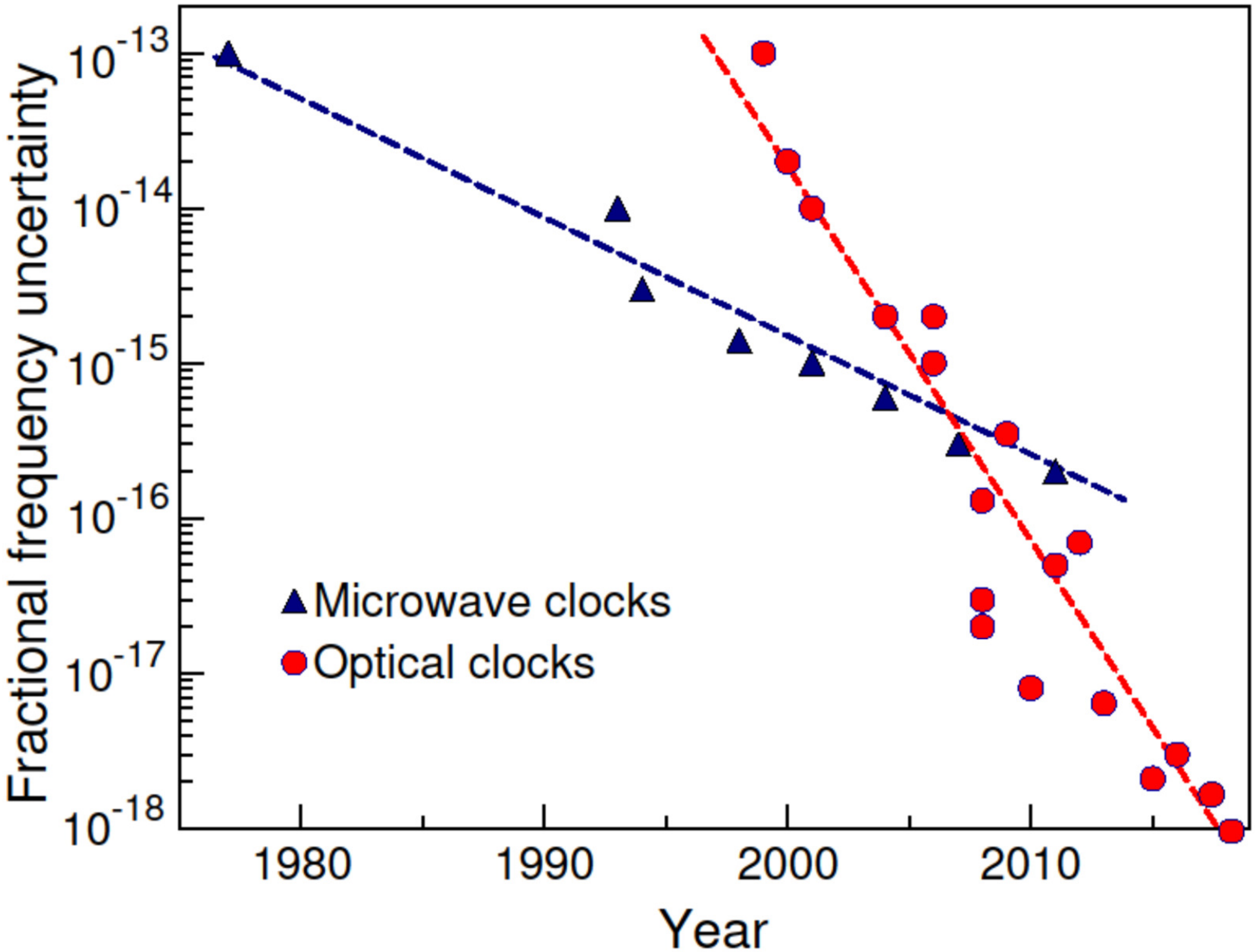
GPS satellites:
microwave
atomic clocks

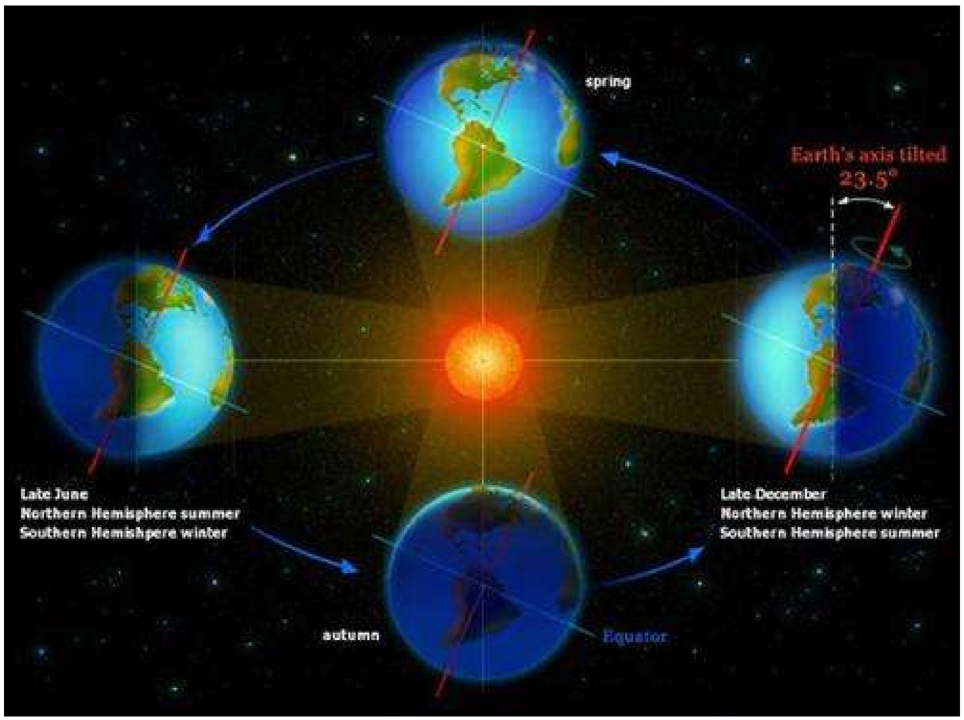


Atomic clocks will not lose one second in **30 billion years**



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)

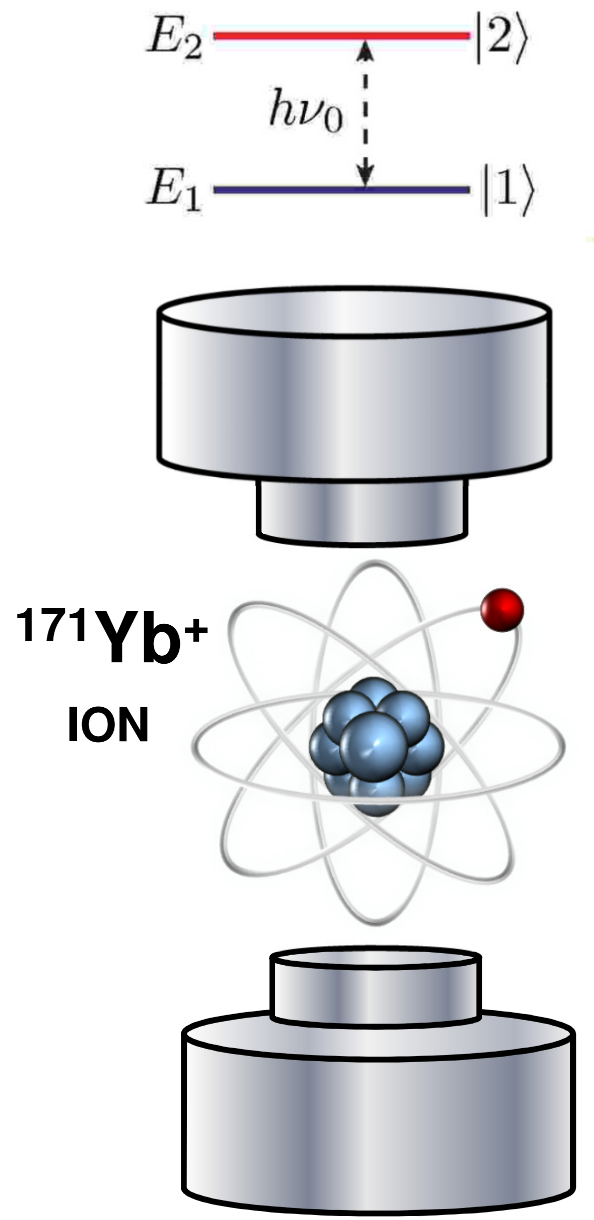
Ingredients for an atomic clock

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)

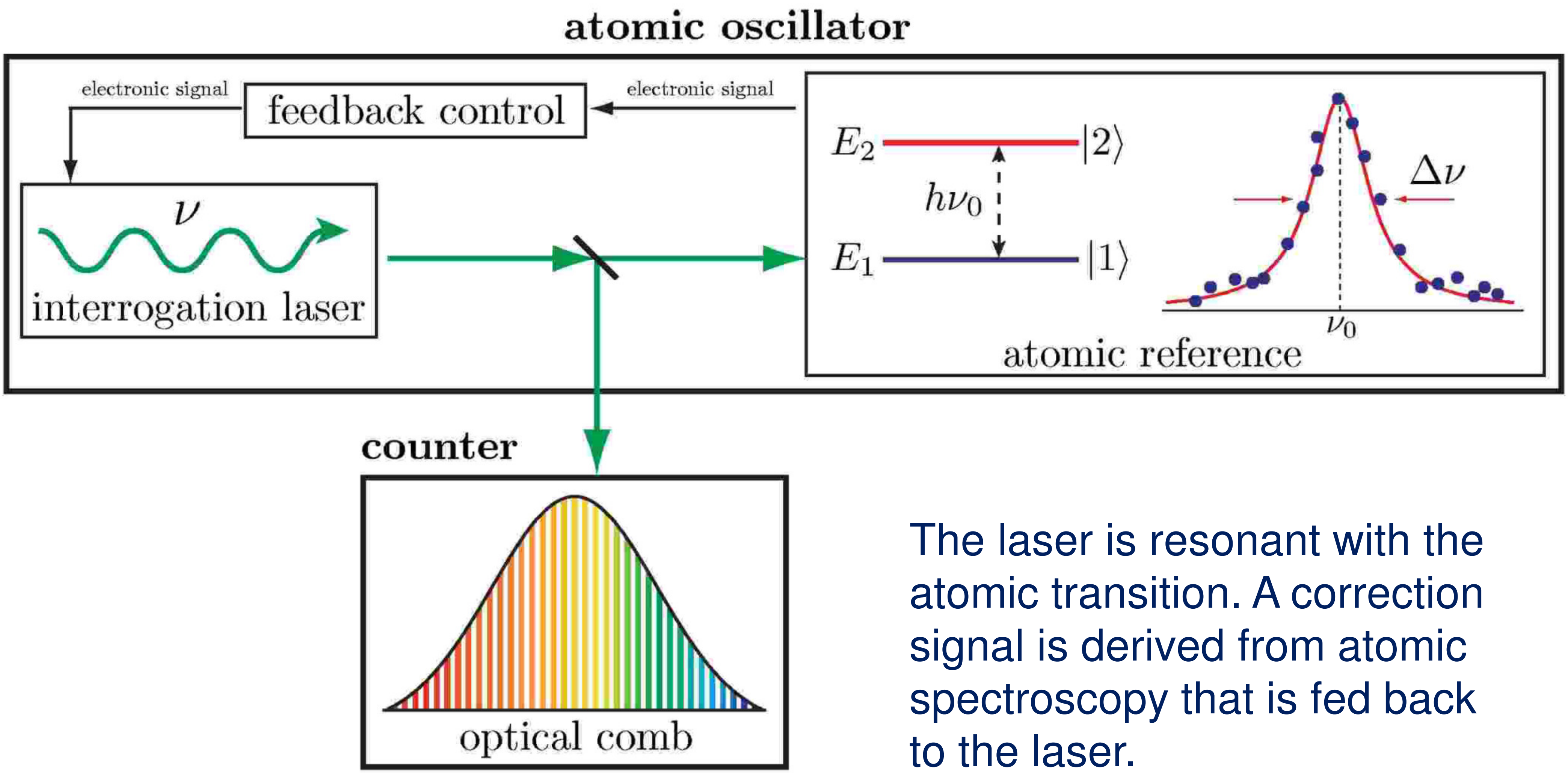
3. Build a laser in resonance with this atomic frequency

4. Measure the laser frequency:
   Count cycles of this signal



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.

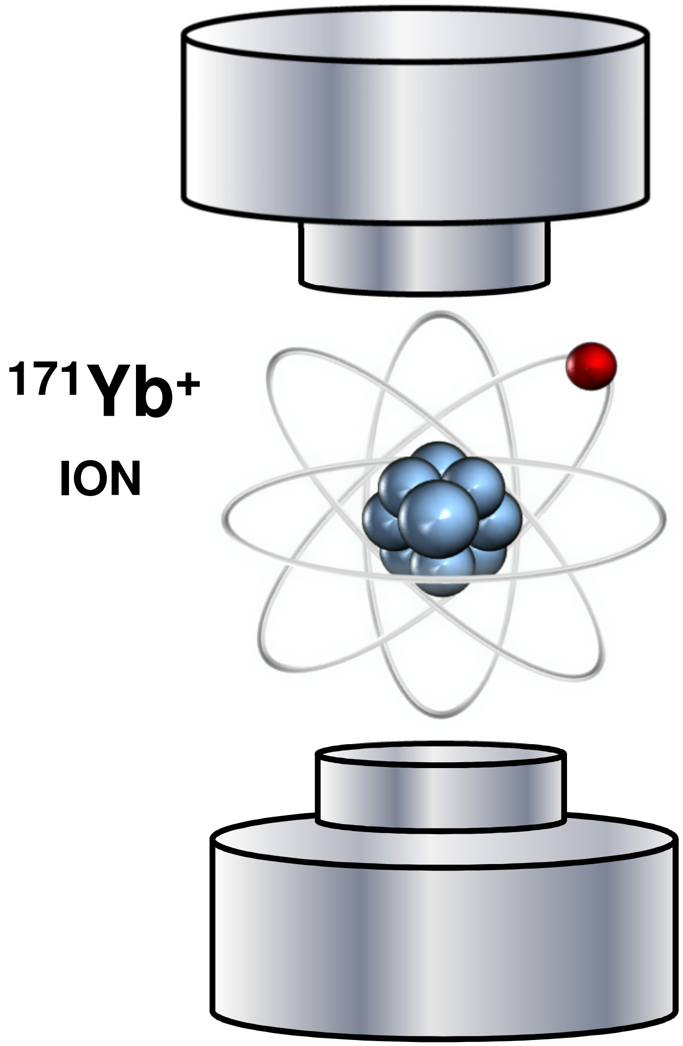
An optical frequency synthesizer (optical frequency comb) is used to divide the optical frequency down to countable microwave or radio frequency signals.

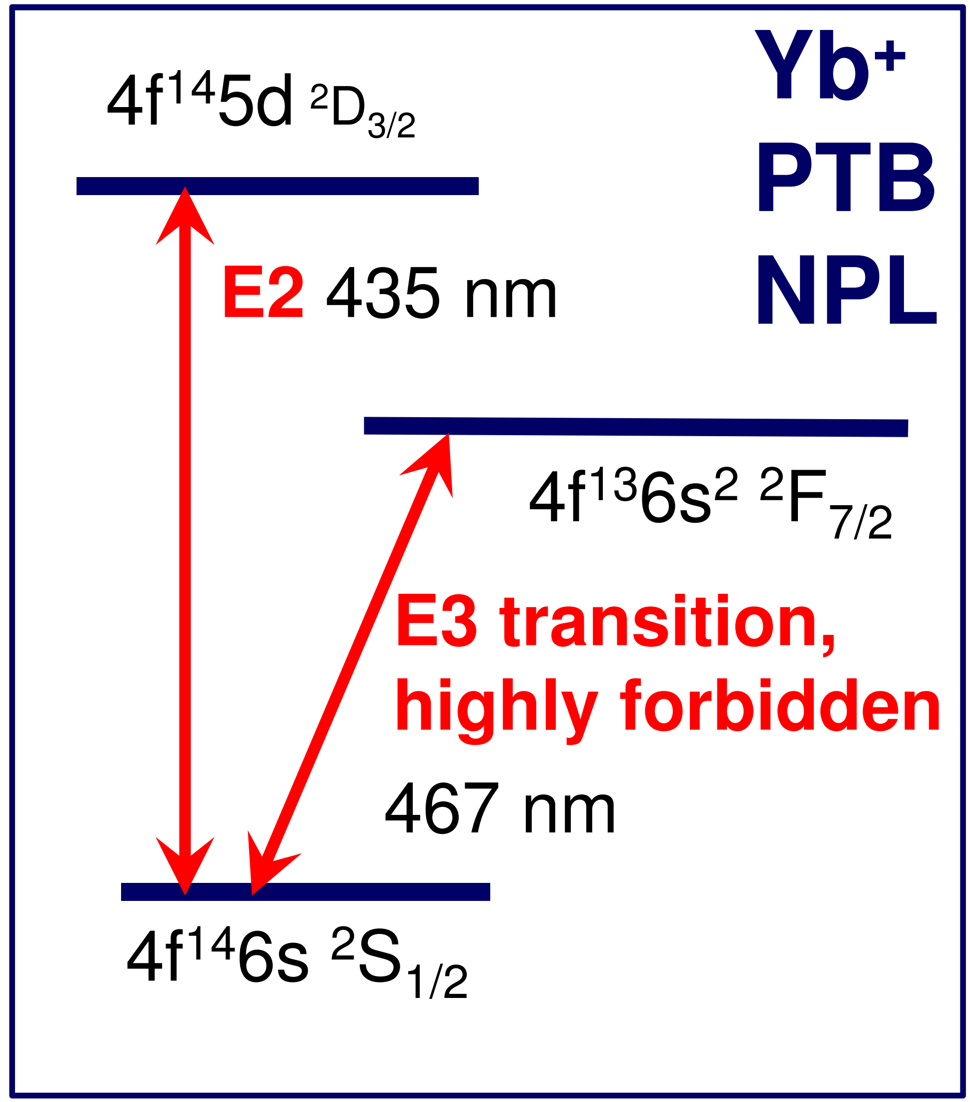
From: Poli et al. "Optical atomic clocks", La rivista del Nuovo Cimento 36, 555 (2018) arXiv:1401.2378v2

Trapped single ion clocks

Requirements for an atomic clock

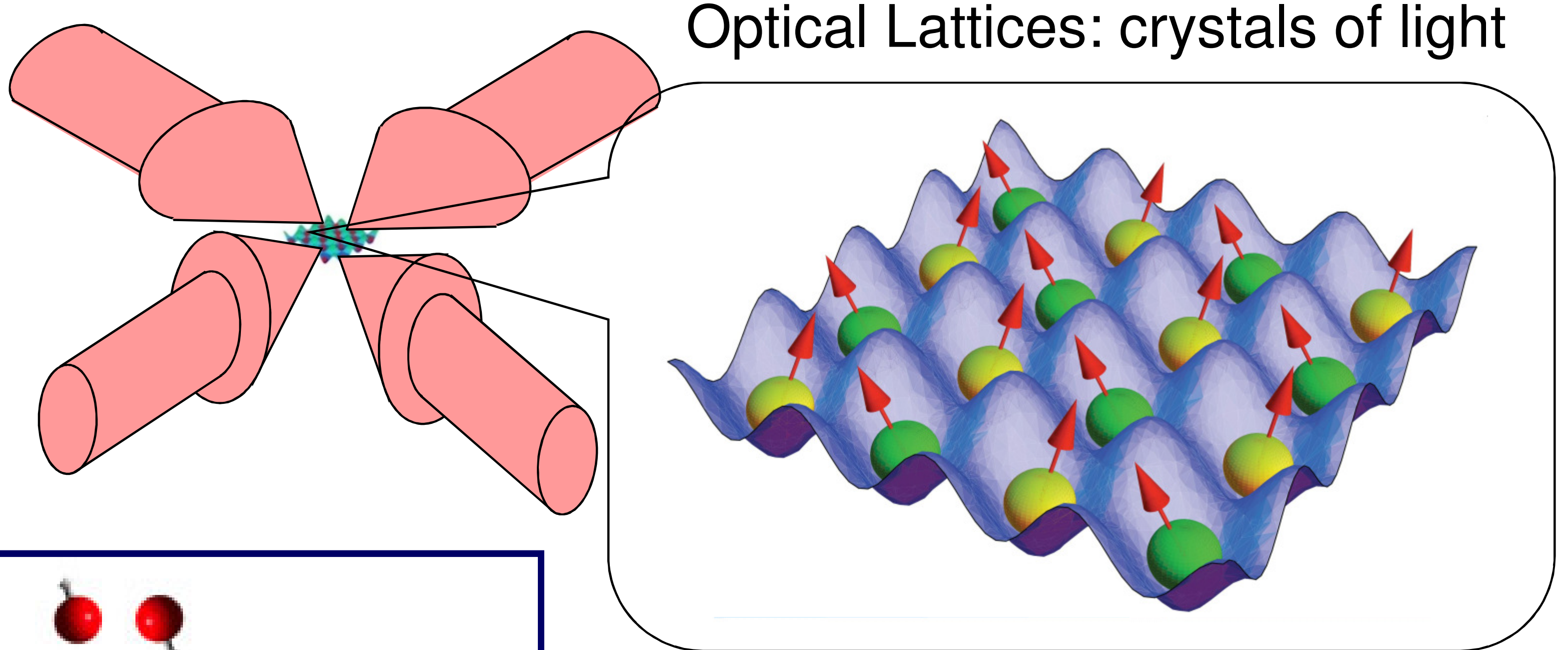
(1) Long-lived upper clock state
(2) Near optical transition

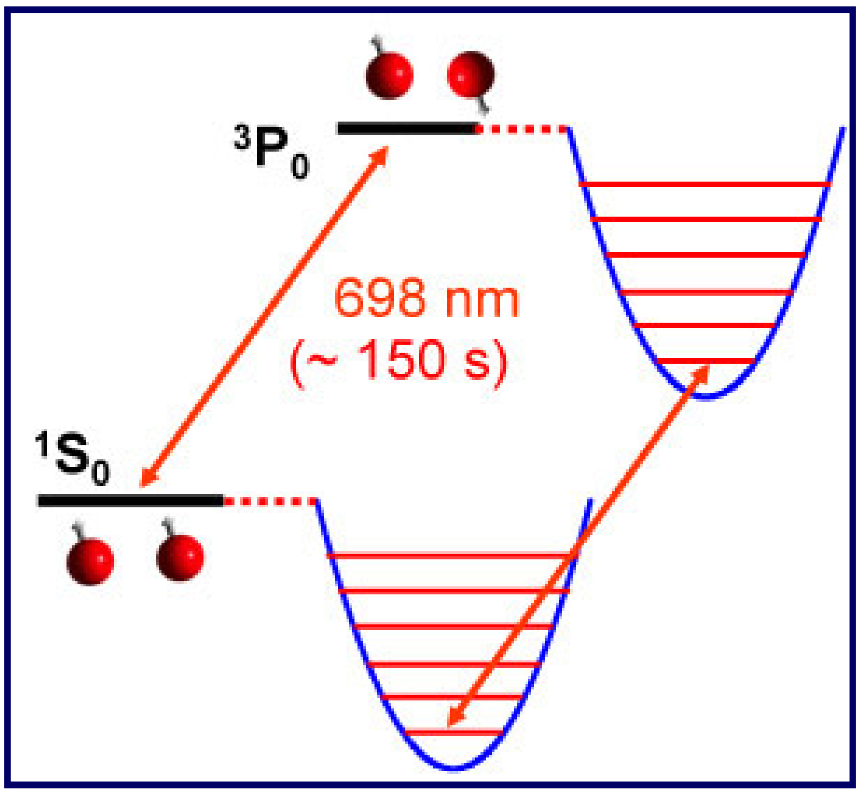




Neutral atom optical lattice clocks

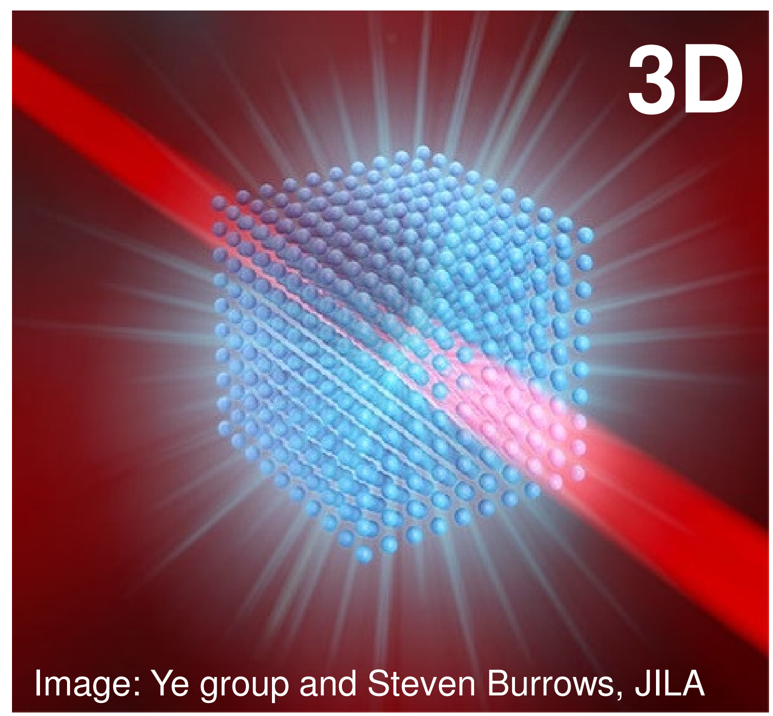
Optical Lattices: crystals of light



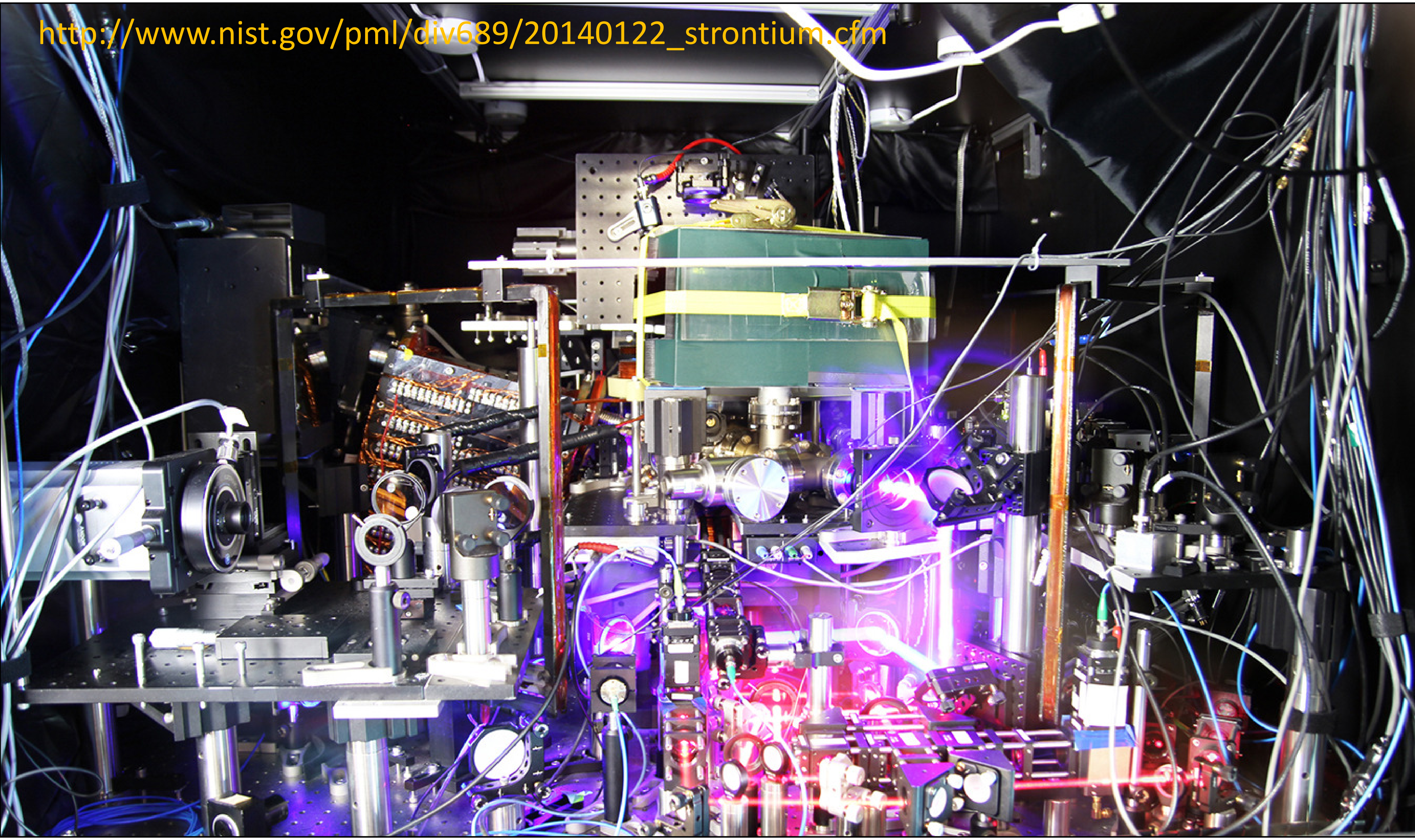


Mg
Al^+
Cd
Sr
Yb
Hg

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

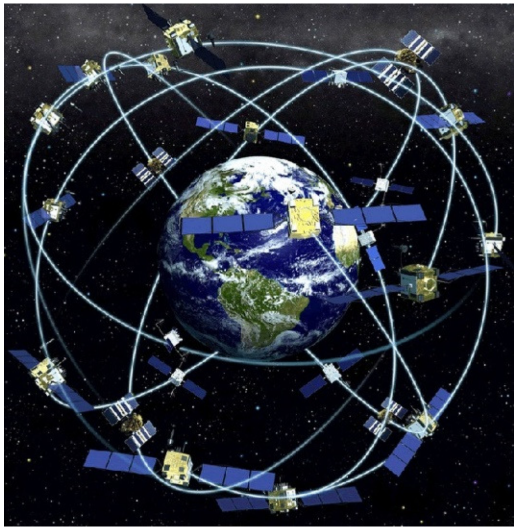


Sr clock: 2×10^{-18} uncertainty

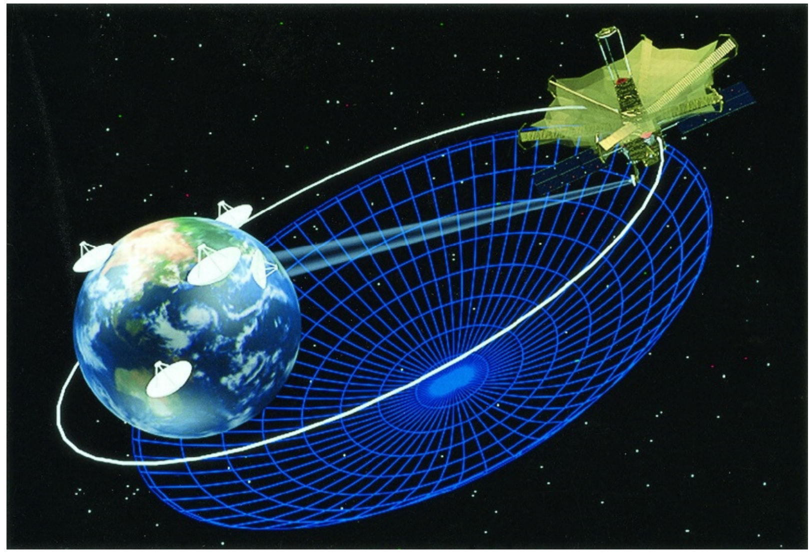


T. L. Nicholson, S. L. Campbell, R. B. Hutson, G. E. Marti, B. J. Bloom, R. L. McNally, W. Zhang, M. D. Barrett, M. S. Safronova, G. F. Strouse, W. L. Tew, and J. Ye, Nature Commun. 6, 6896 (2015).

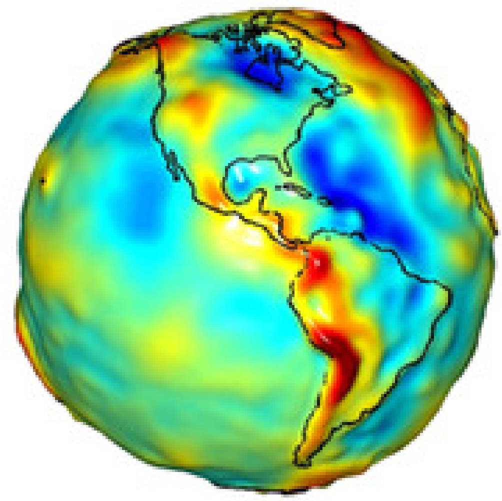
Applications of atomic clocks



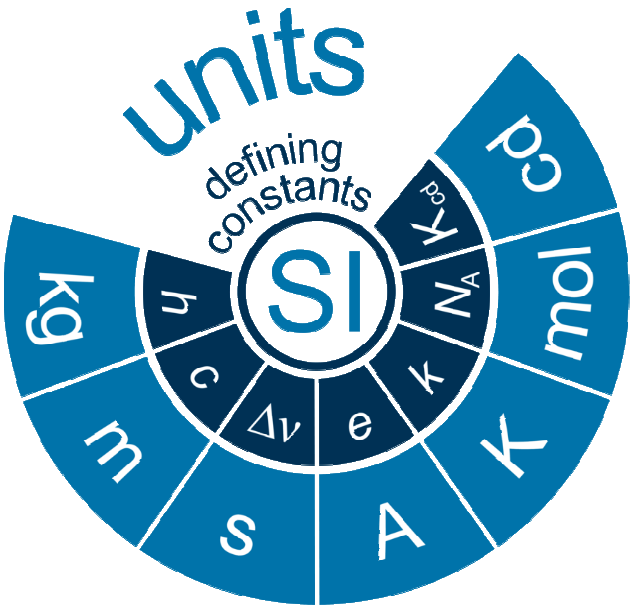
GPS



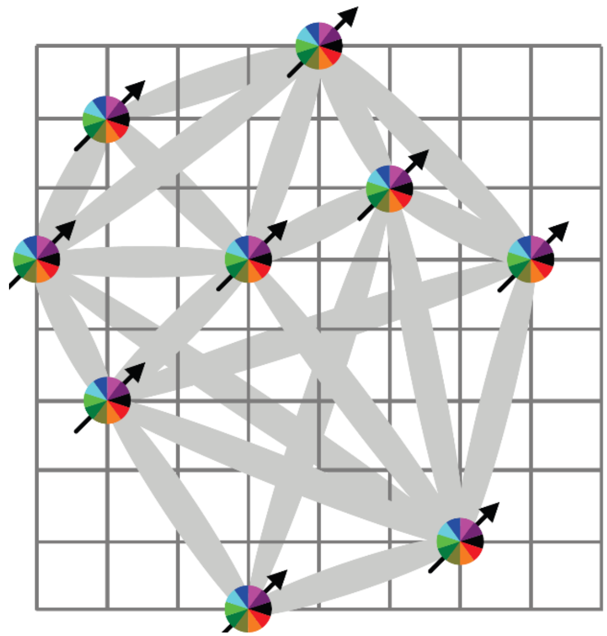
Very Long Baseline Interferometry



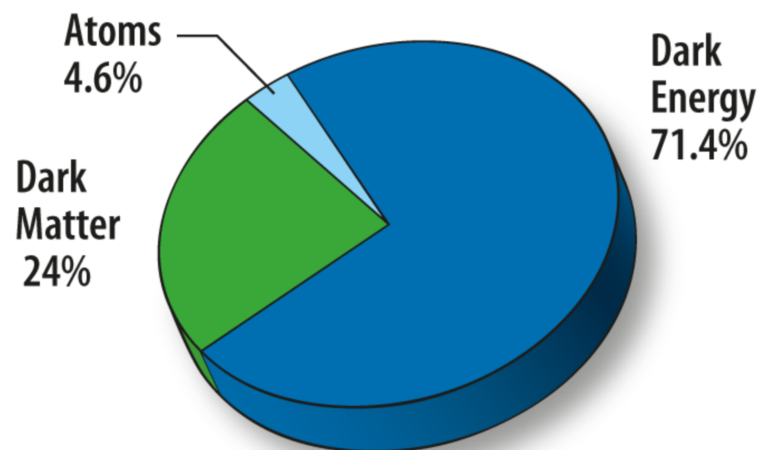
Relativistic geodesy



Definition of the second



Quantum simulation



Search for physics beyond the Standard Model

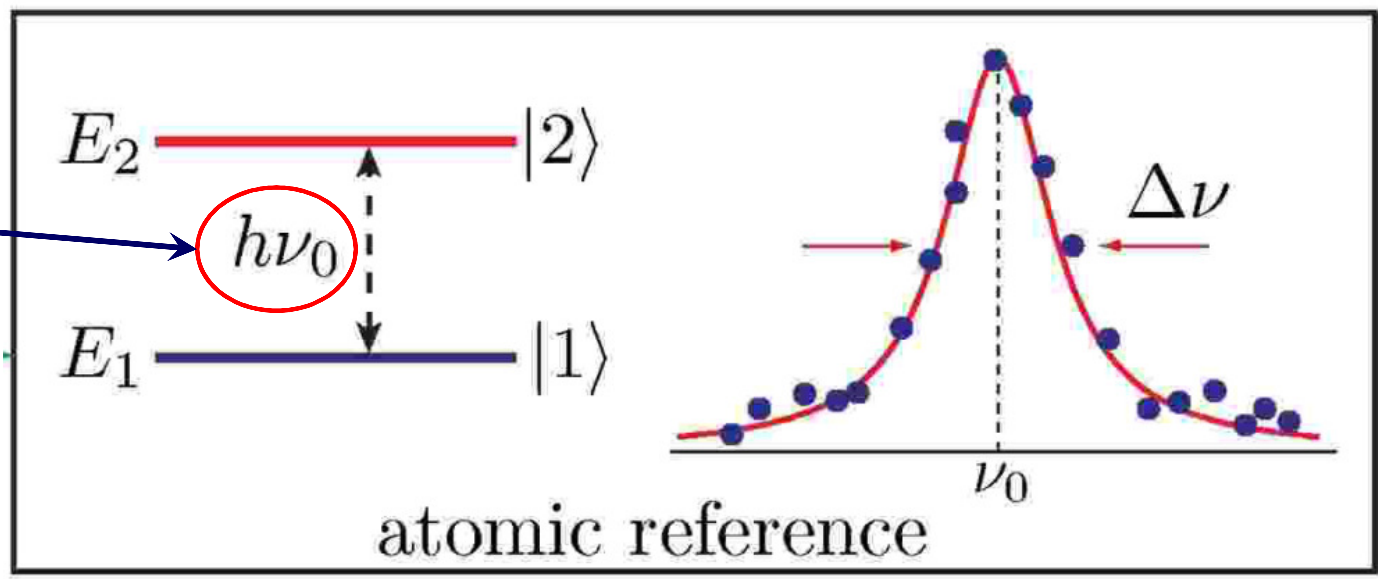
Image Credits: NOAA, Science 281,1825; 346, 1467, University of Hannover, PTB

Search for physics beyond the standard model with atomic clocks

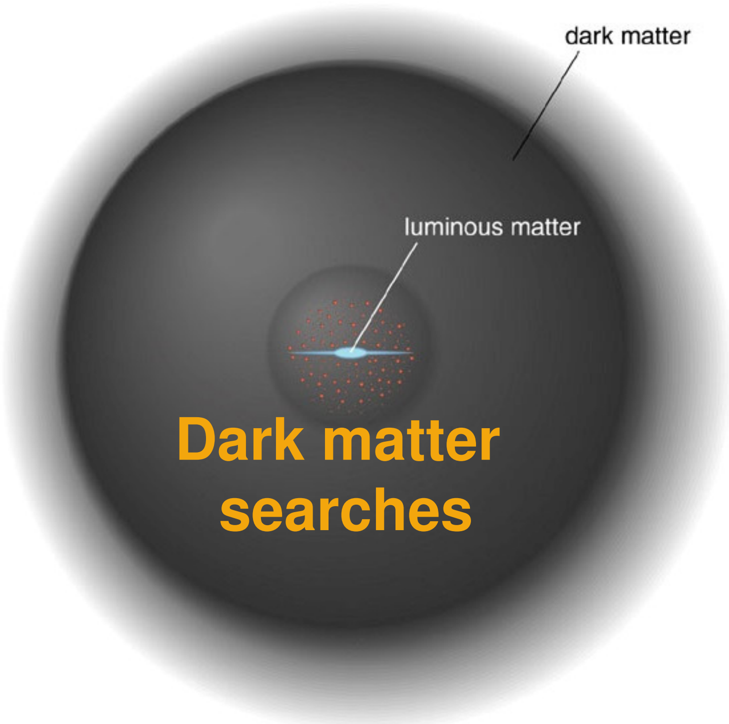
Atomic clocks can measure and compare frequencies to exceptional precisions!

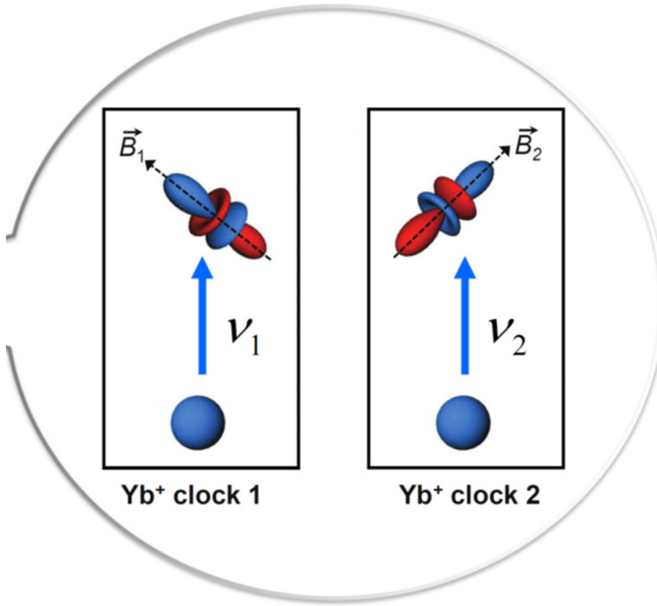
If fundamental constants change (now) due to for various "new physics" effects atomic clock may be able to detect it.

Frequency will change

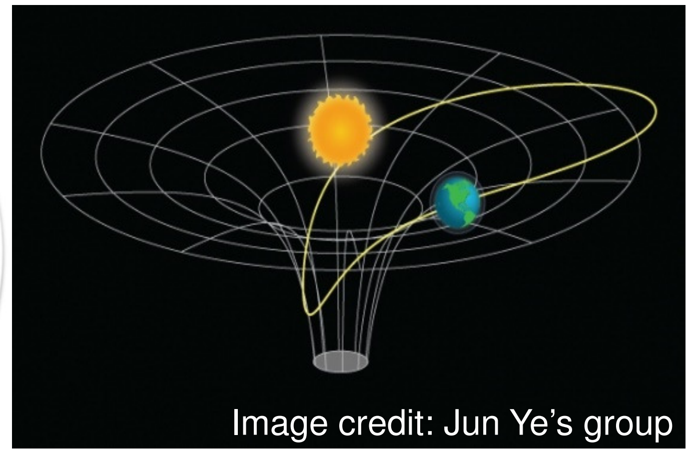


Search for physics beyond the Standard Model with atomic clocks



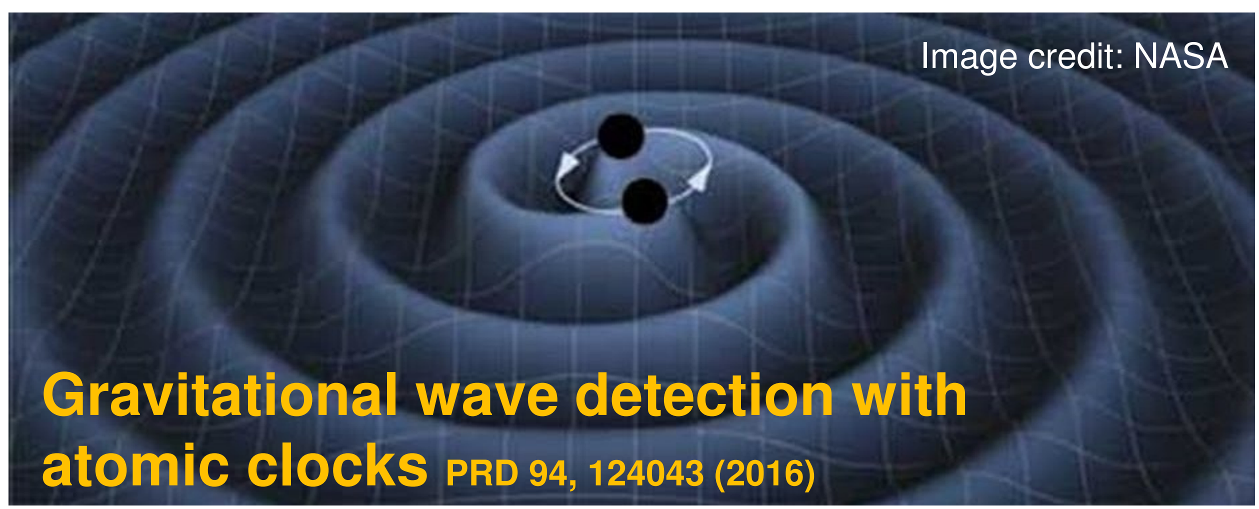


Search for the violation of Lorentz invariance



Tests of the equivalence principle

Are fundamental constants constant? α



Variation of Fundamental Constants

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

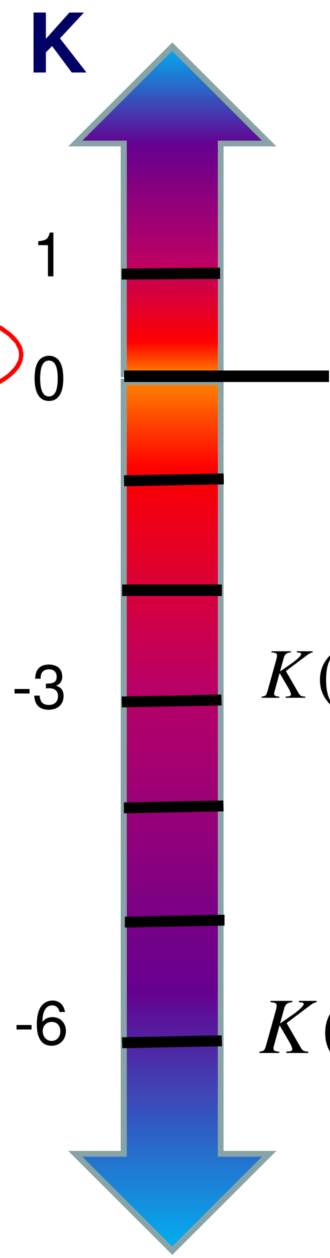
$$\frac{\partial}{\partial t}\ln\frac{\nu_2}{\nu_1} = (K_2 - K_1)\frac{1}{\alpha}\frac{\partial \alpha}{\partial t}$$

Test of α-variation

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

Easier to measure large effects!

α-variation enhancement factors for current clocks



$K(Sr^{+}) = 0.4$

$K(Yb) = 0.3$

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

$K\left(Al^{+}\right) = 0.01, K(Sr) = 0.06, K\left(Ca^{+}\right) = 0.1$

Excellent stability N ~ 1000

$K(Hg^{+}) = -2.9$

Single ion clocks, N = 1

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

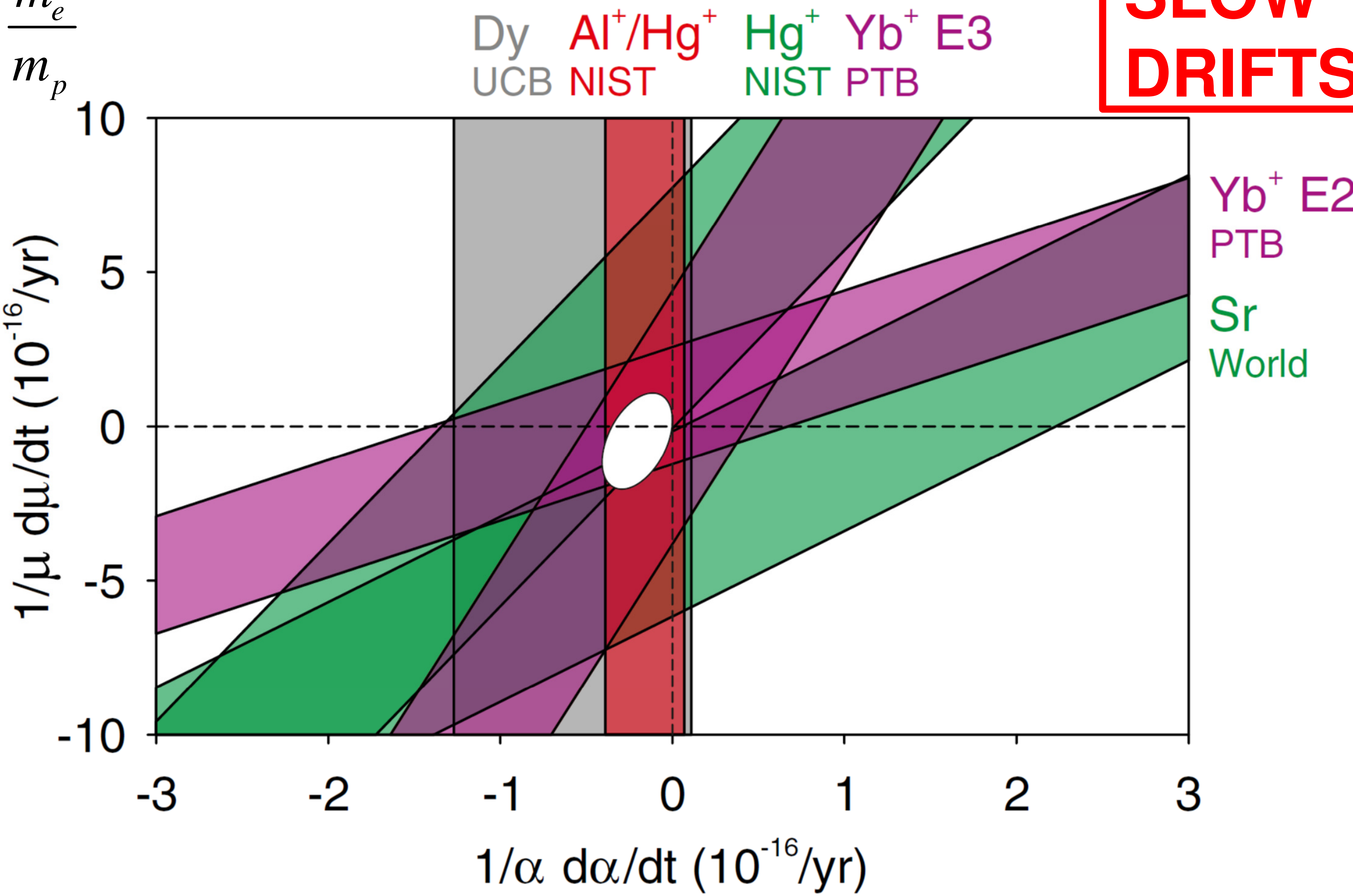
$$K = \frac{2q}{E_0}$$

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

CAN WE GET LARGE K IN NEW CLOCKS?

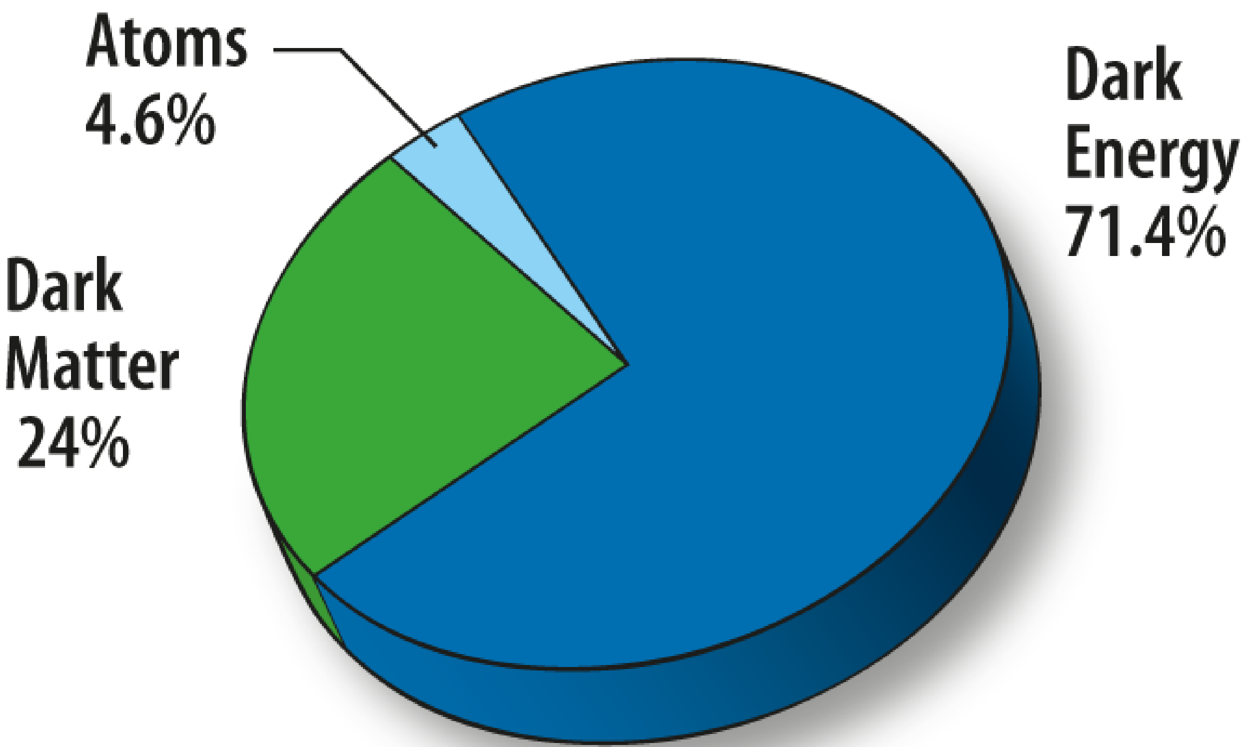
$$\mu = \frac{m_e}{m_p}$$

SLOW DRIFTS

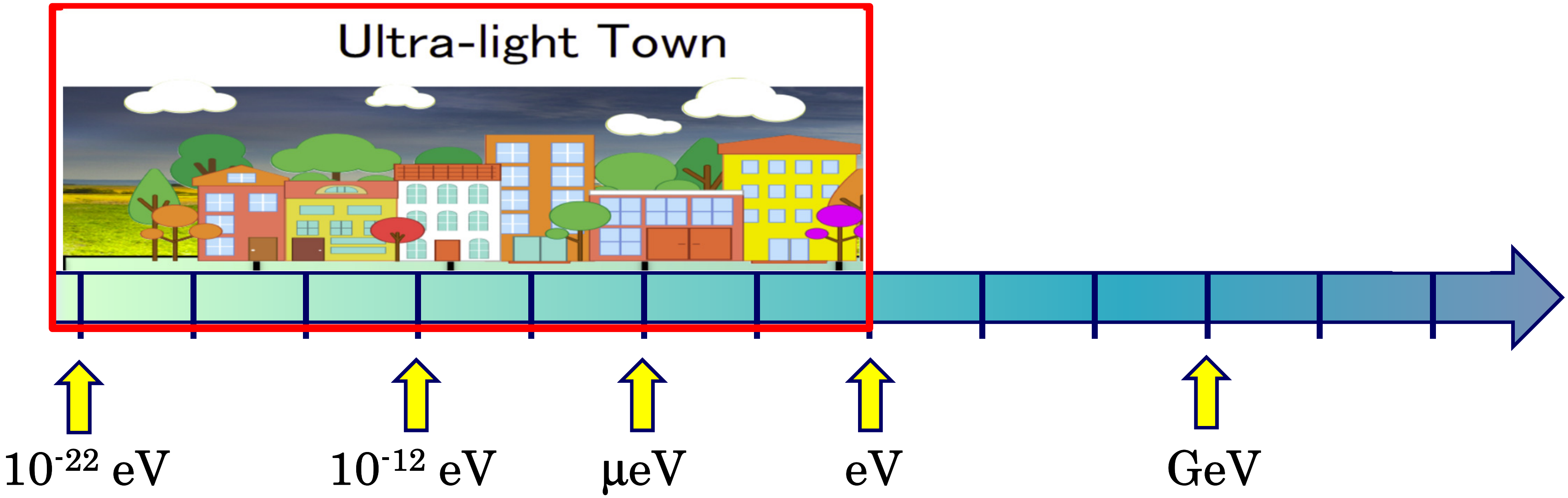


Constraints on temporal variations of α and μ from comparisons of atomic transition frequencies. Huntemann et al., PRL 113, 210802 (2014)

Атомные и ядерные часы - детекторы темной материи



Как найти сверхлегкую темную материю?

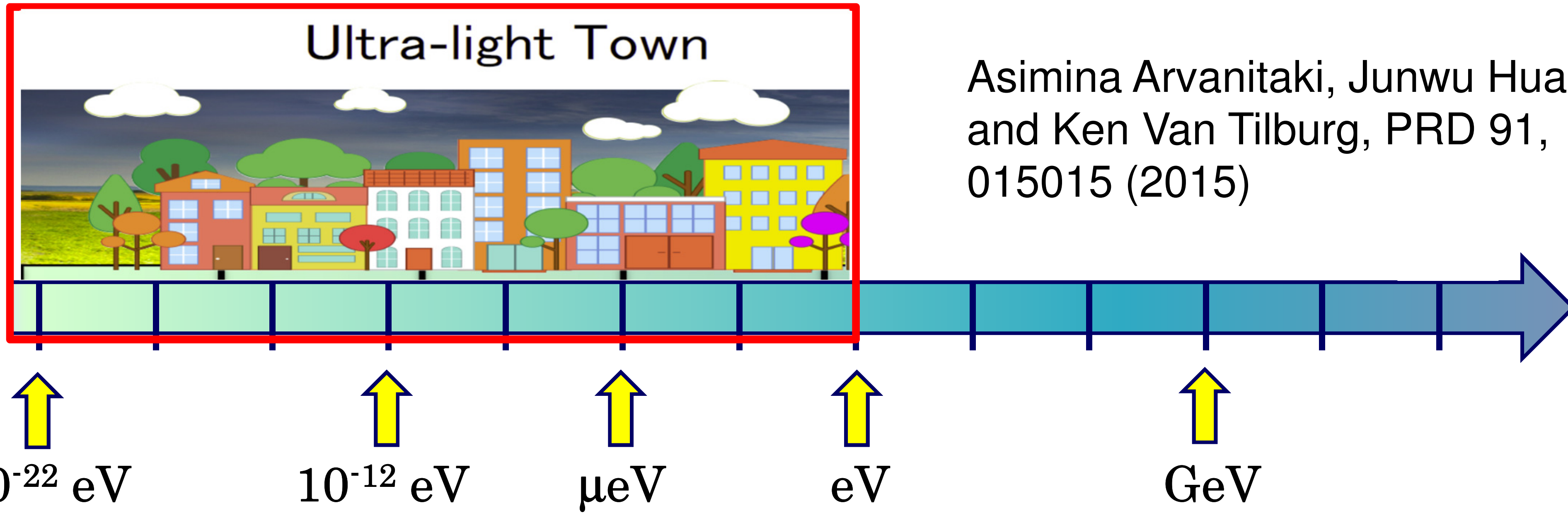


Сверхлегкая темная материя должна быть бозонной - Ферми скорость для темной материи с массой > 10 eV выше скорости убегания нашей Галактики.

Бозонная темная материя с массой $m_\phi < 1$eV:

Плотность темной материи в нашей Галактике $> \lambda_{dB}^{-3}$ где λ_{dB} это де Бройля длина волны частицы. В этом случае темная материя проявляет когерентность и ведет себя как классическое поле.

How to detect ultralight dark matter with clocks?



Asimina Arvanitaki, Junwu Huang, and Ken Van Tilburg, PRD 91, 015015 (2015)

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

couples to electromagnetic interaction and "normal matter"

It will make fundamental coupling constants and mass ratios oscillate

Atomic energy levels will oscillate so clock frequencies will oscillate

Can be detected with monitoring ratios of clock frequencies over time.

Ultralight dark matter

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

Dark matter coupling to the Standard Model

$$\mathcal{L}_\phi = \kappa\phi\left[+\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{A\mu\nu}\right.$$

Dark matter

photons

gluons

$$\left. -d_{m_e}m_e\bar{e}e - \sum_{i=u,d}(d_{m_i} + \gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$$

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

Measuring ratios of optical clock frequencies for dark matter detection

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

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

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

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

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

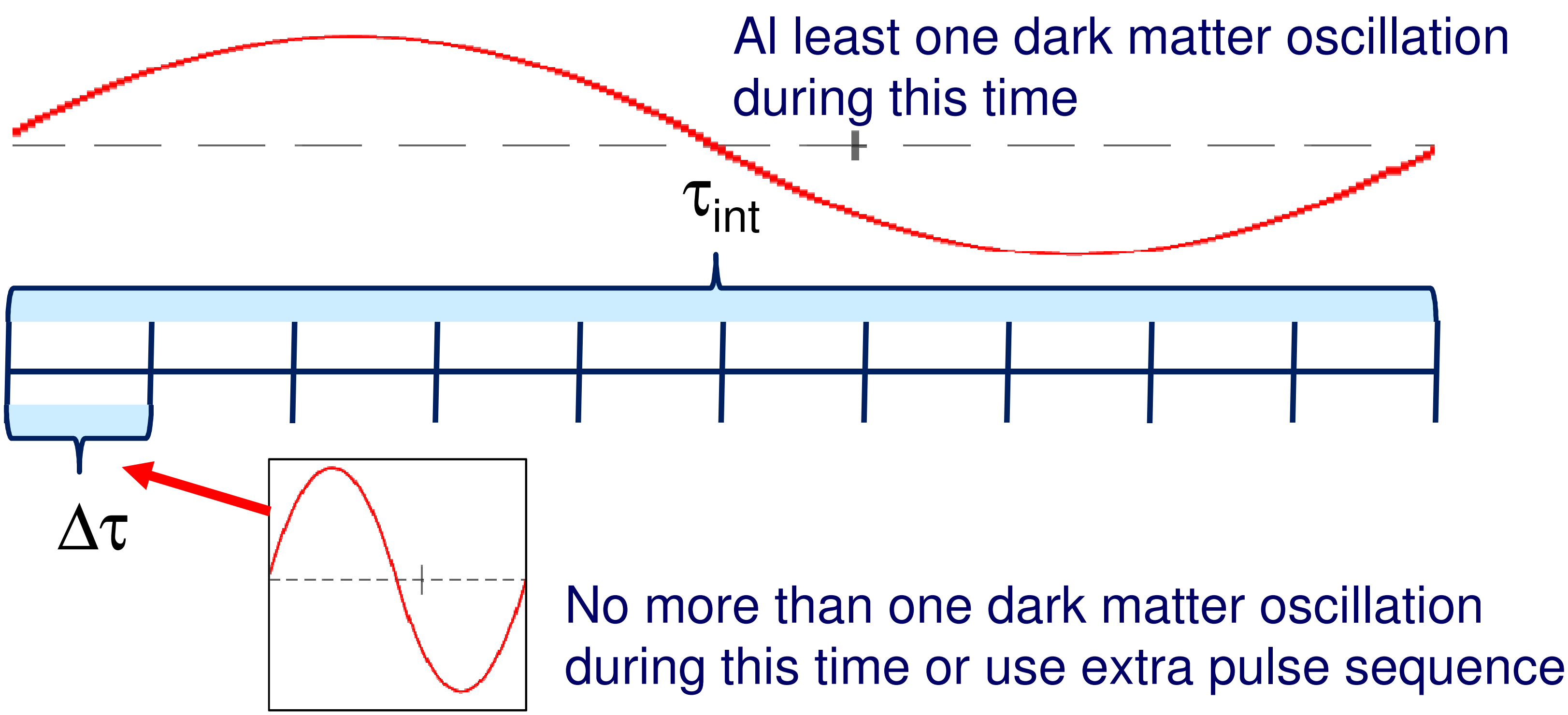
Dark matter parameters

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

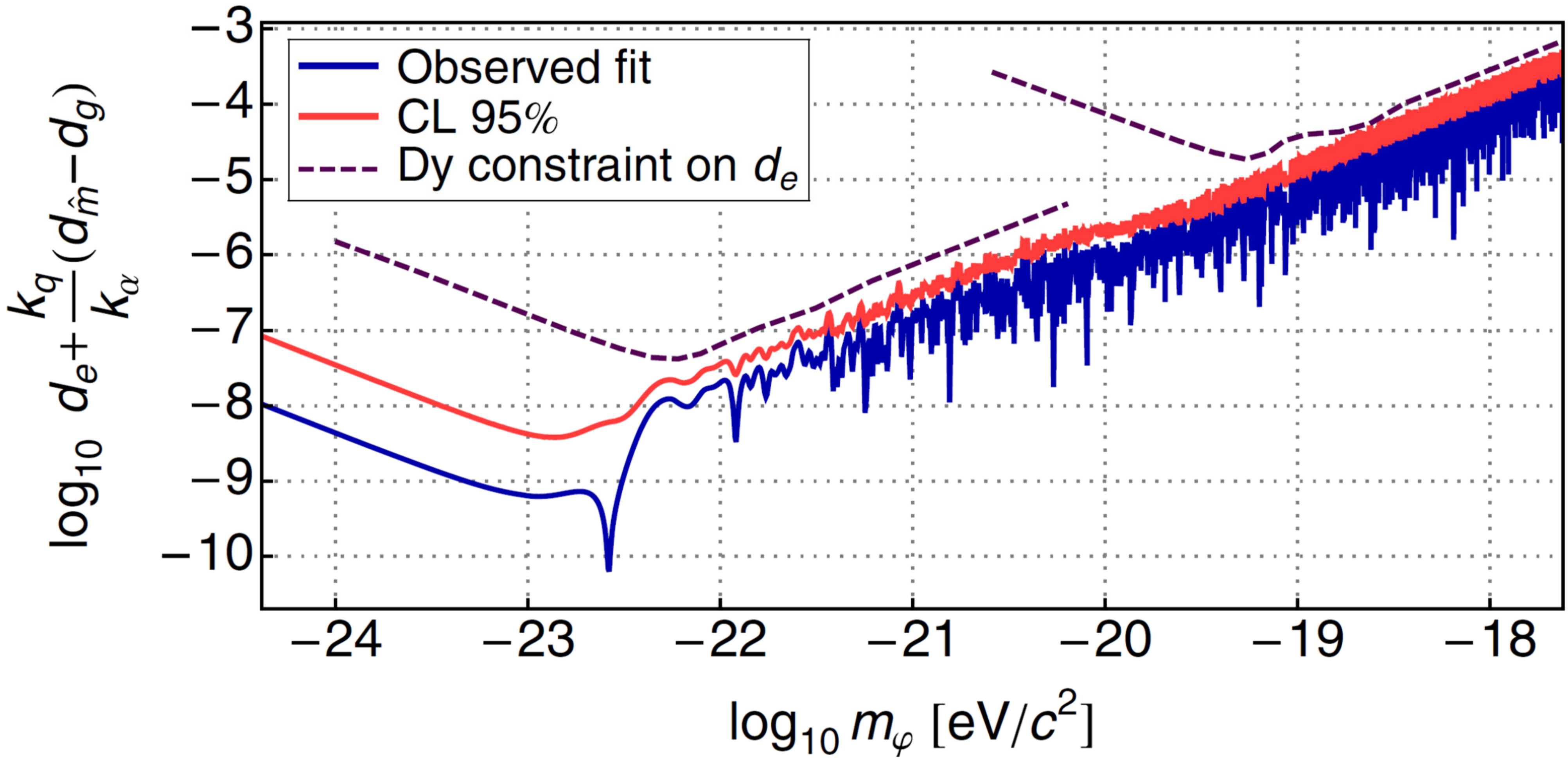


Detection signal:

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

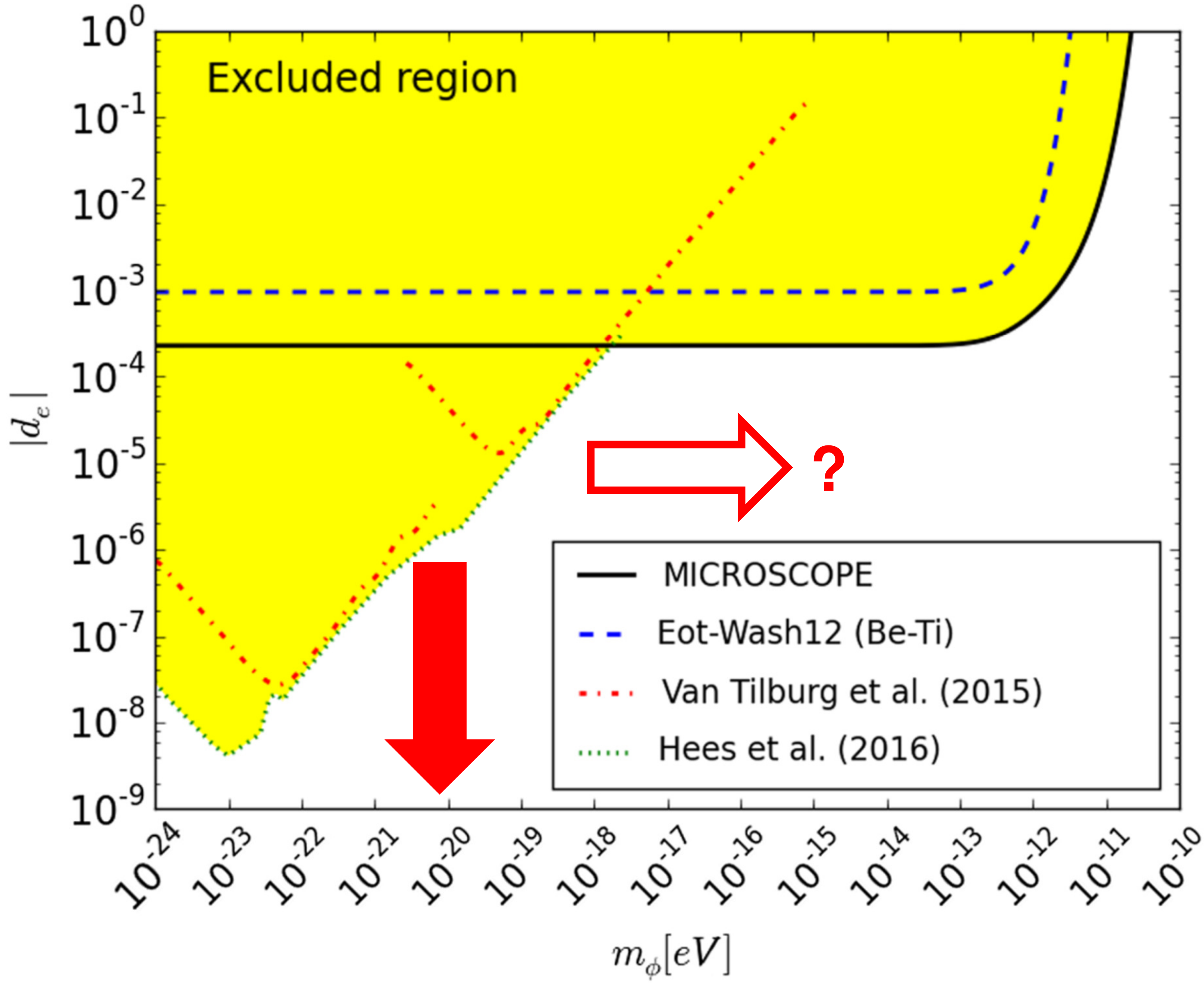
A. Arvanitaki et al., PRD 91, 015015 (2015)

Experimental results



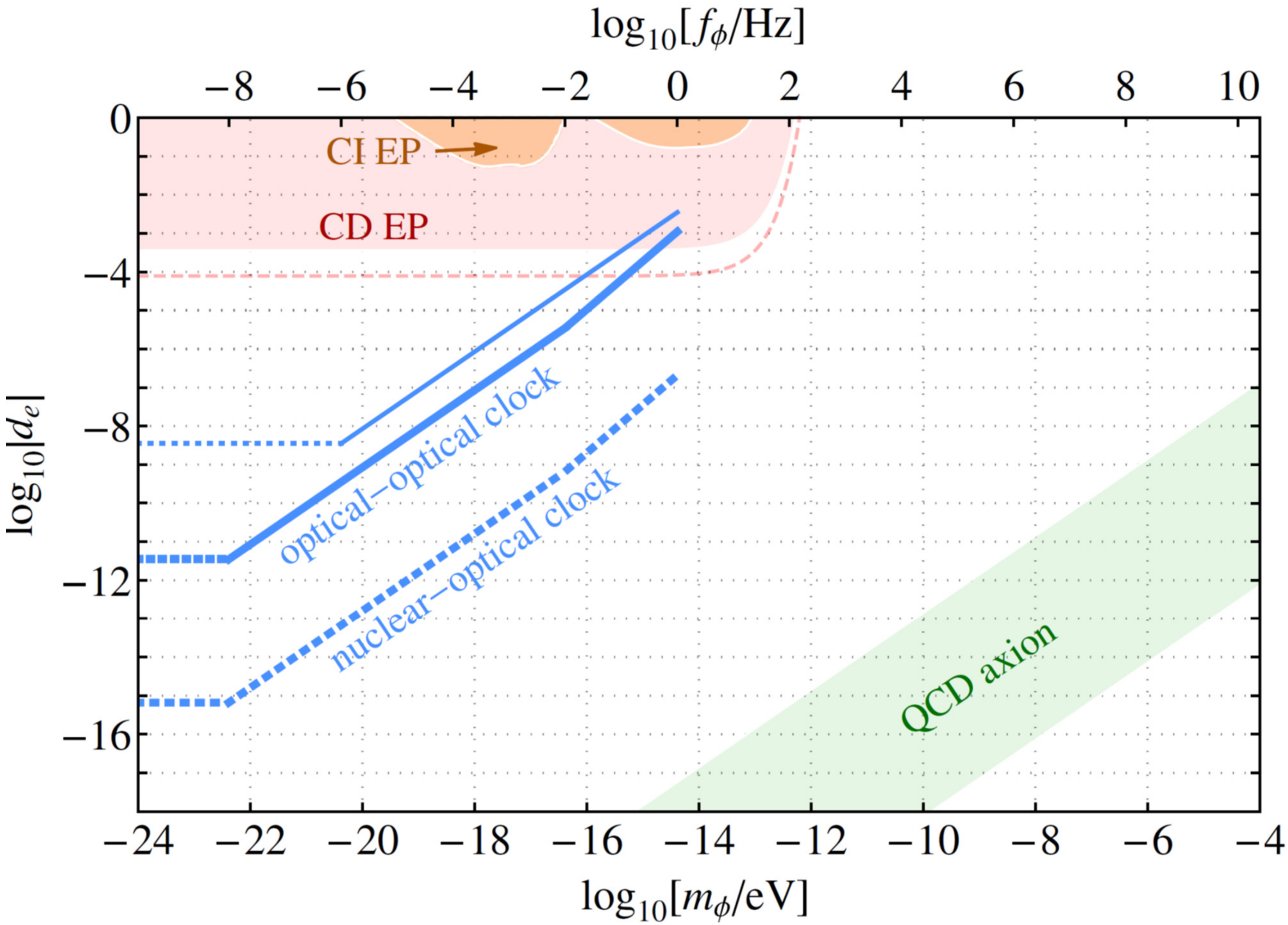
Dy: K. Van Tilburg, N. Leefer, L. Bougas, and D. Budker, Phys. Rev. Lett. 115, 011802 (2015).

Rb/Cs: A. Hees, J. Guéna, M. Abgrall, S.Bize,and P. Wolf, Phys. Rev. Lett. 117, 061301 (2016)



From PRL 120, 141101 (2018)

Projected clock limits



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

nature physics

Transient variations

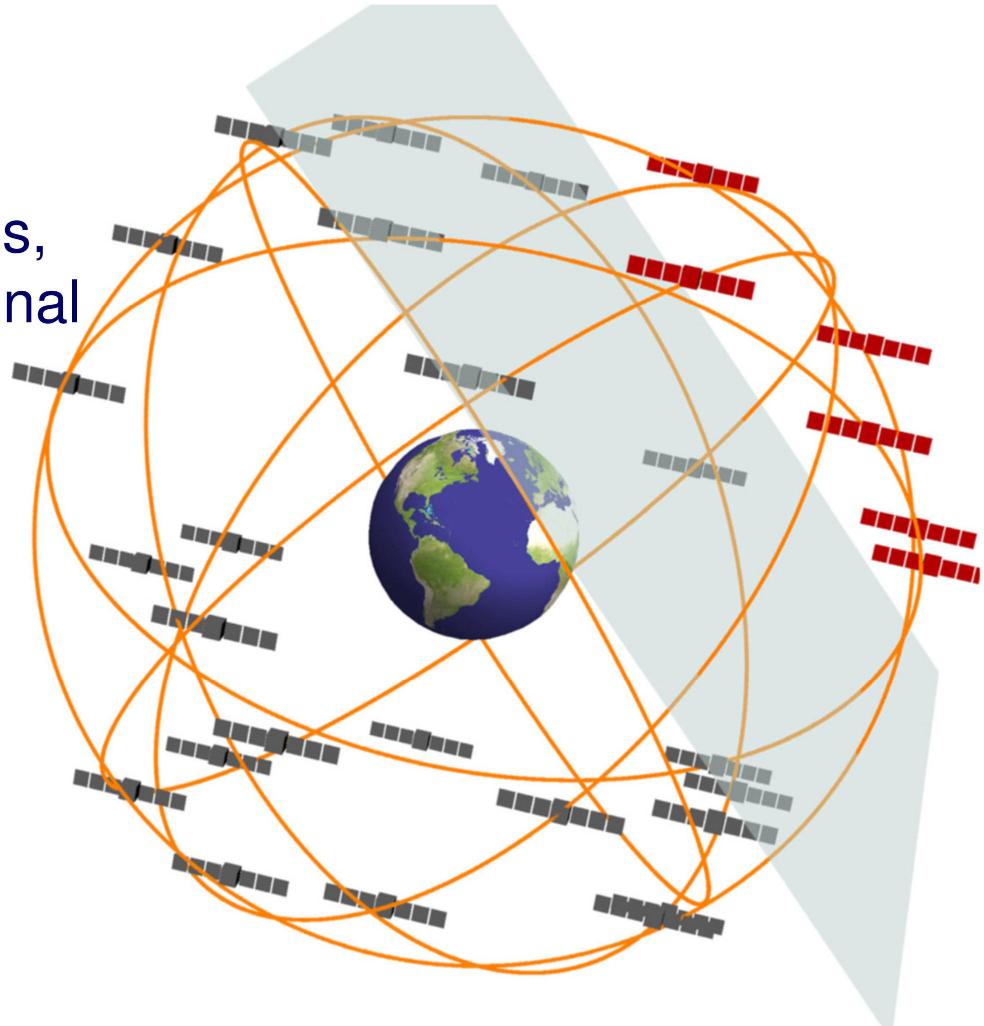
LETTERS
PUBLISHED ONLINE: 17 NOVEMBER 2014 | DOI: 10.1038/NPHYS3137

Hunting for topological dark matter with atomic clocks

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

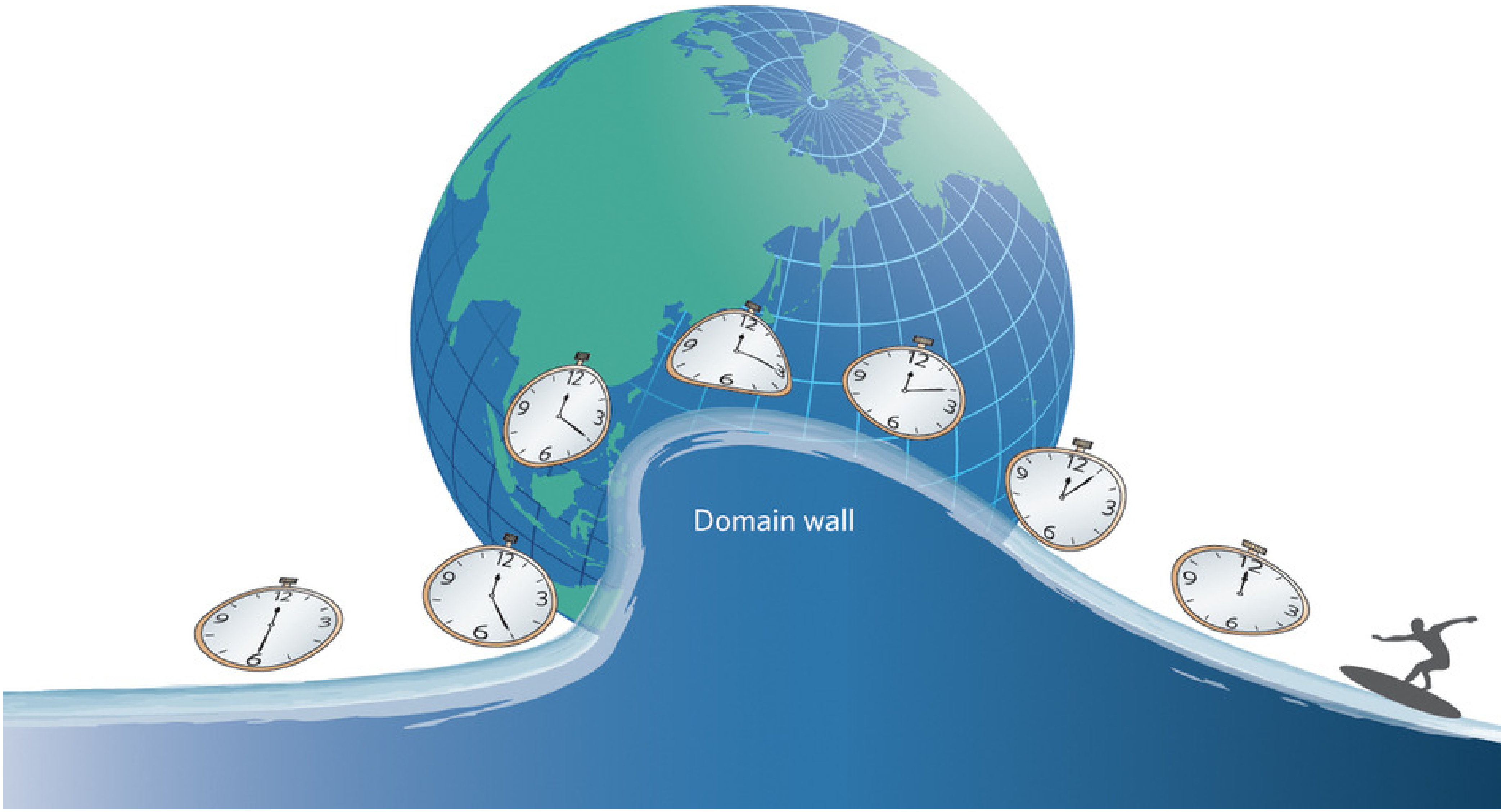
Dark matter clumps: point-like monopoles, one-dimensional strings or two-dimensional sheets (domain walls).

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)

Nature Communications 8, 1195 (2017)

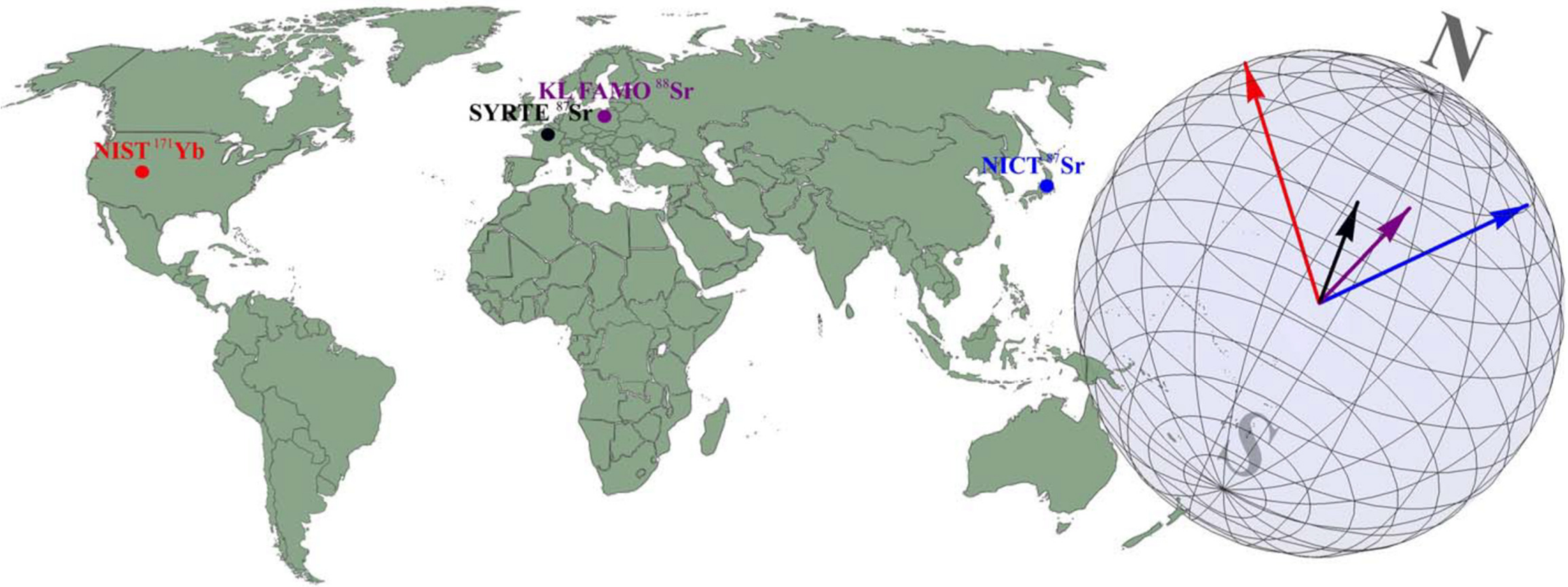


Topological dark matter may be detected by measuring changes in the synchronicity of a global network of atomic clocks, such as the Global Positioning System, as the Earth passes through the domain wall.

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

APPLIED PHYSICS

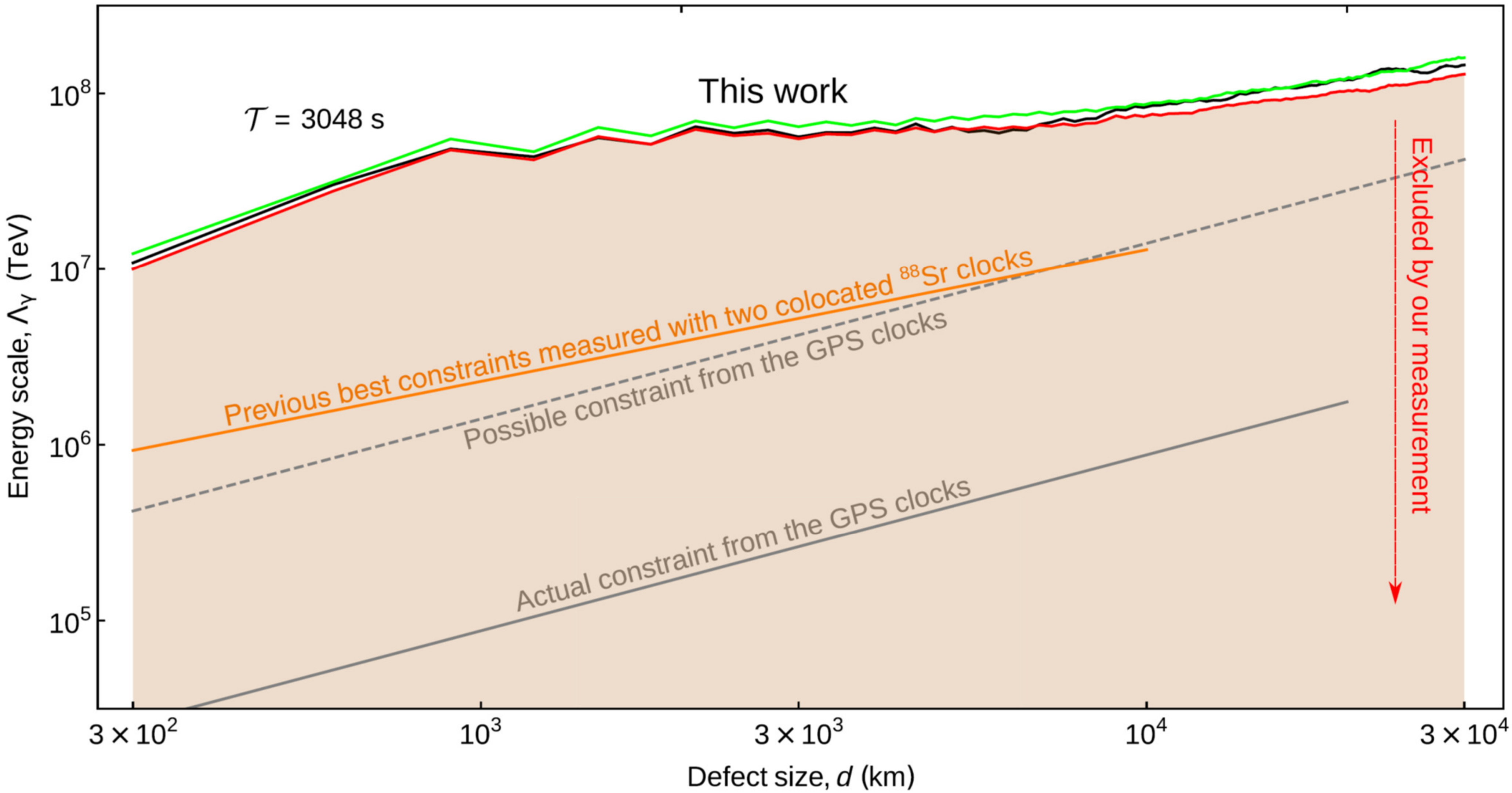
New bounds on dark matter coupling from a global network of optical atomic clocks



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?

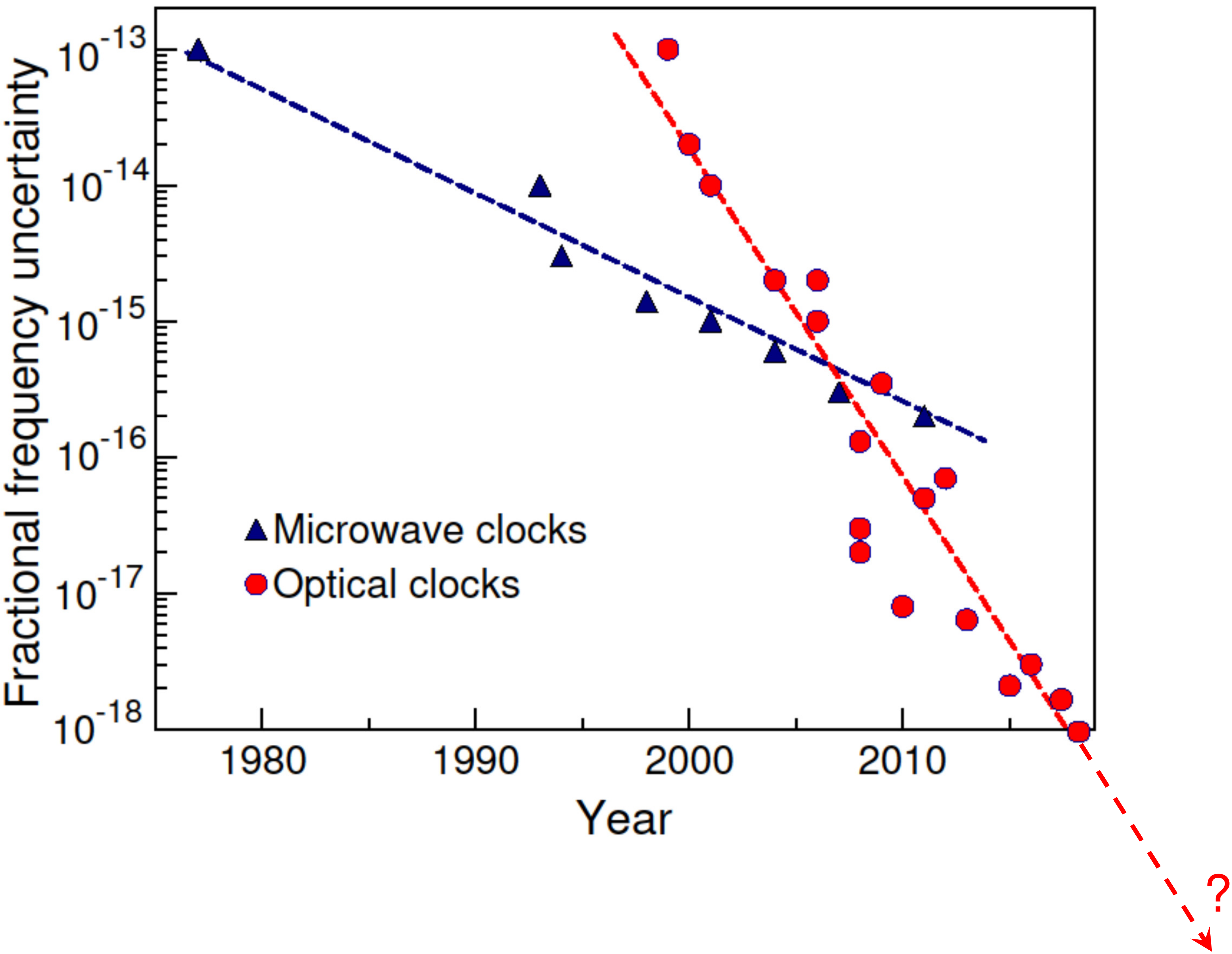
1. Improve uncertainties of current clocks – **[????]** more orders.

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



Fractional frequency uncertainty
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
1980
1990
2000
2010
Year
Microwave clocks
Optical clocks
?

PHYSICAL REVIEW LETTERS **120,** 063204 (2018)

Multipolar Polarizabilities and Hyperpolarizabilities in the Sr Optical Lattice Clock

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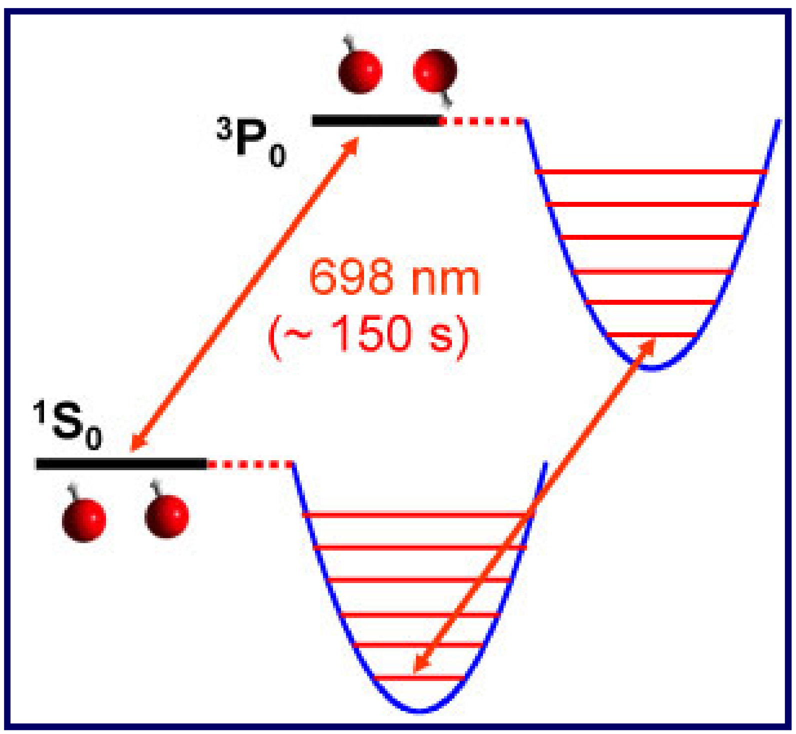
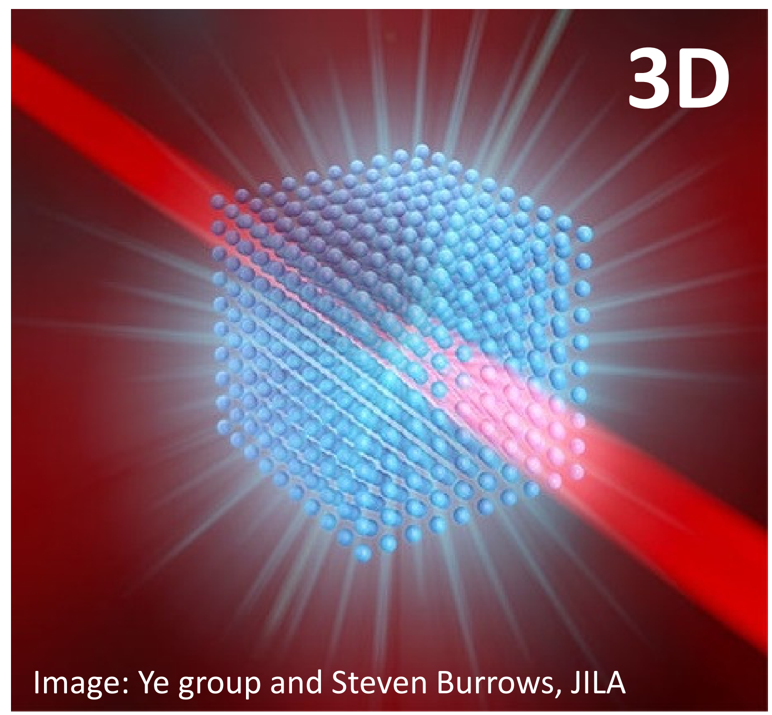
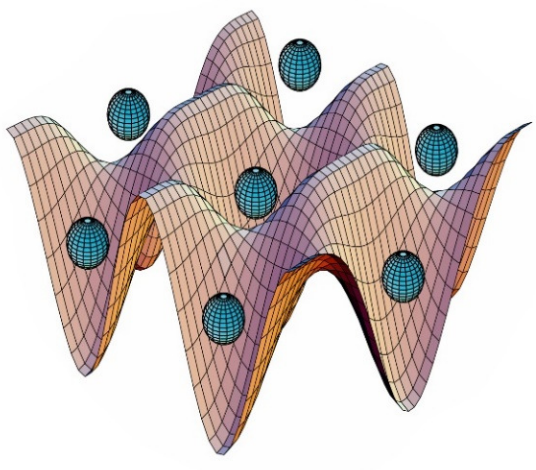
[5]*St. Petersburg Electrotechnical University "LETI," Prof. Popov Street 5, 197376 St. Petersburg, Russia*



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



Lattice clock operate at magic wavelengths



$U \propto \alpha(\lambda)$ ← Frequency-dependent **electric dipole** polarizability

$U_A \approx U_B$ at the magic wavelength

$$\alpha_A(\lambda_{magic}) = \alpha_B(\lambda_{magic})$$

$$U(\omega) \approx -[\alpha^{E1}(\omega) - \{\alpha^{M1}(\omega) + \alpha^{E2}(\omega)\} k^2 x^2] \mathcal{E}_0^2 - \beta(\omega) \mathcal{E}_0^4.$$

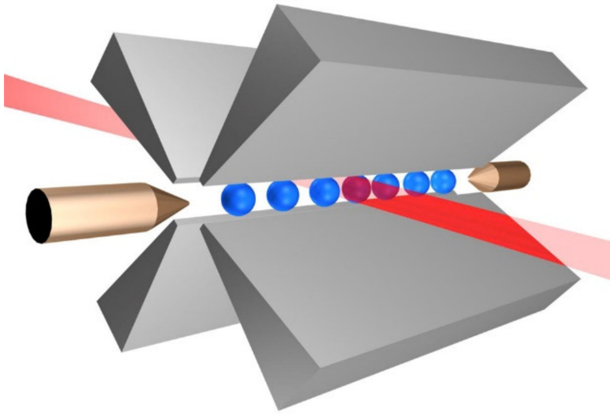
$$k = \frac{\omega}{c}$$

Multipolar polarizability shifts

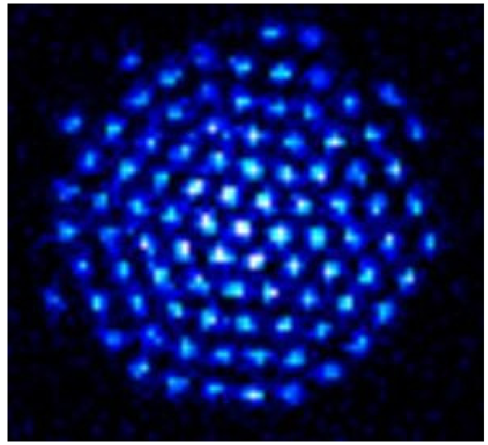
- Magnetic-dipole polarizability $\alpha^{M1}(\omega)$
- Electric-quadrupole polarizability $\alpha^{E2}(\omega)$

Hyperpolarizability $\beta(\omega)$

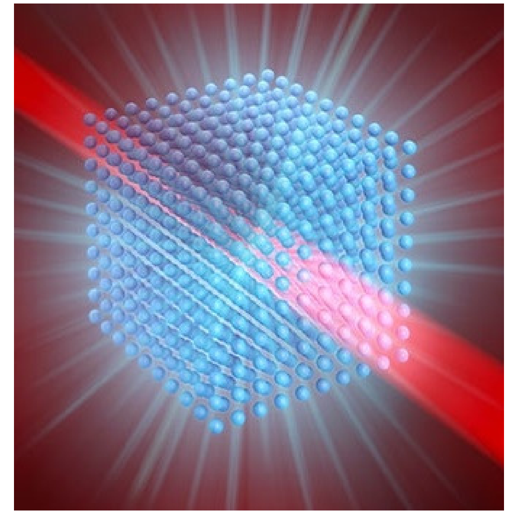
The Future Advances in Atomic Clocks



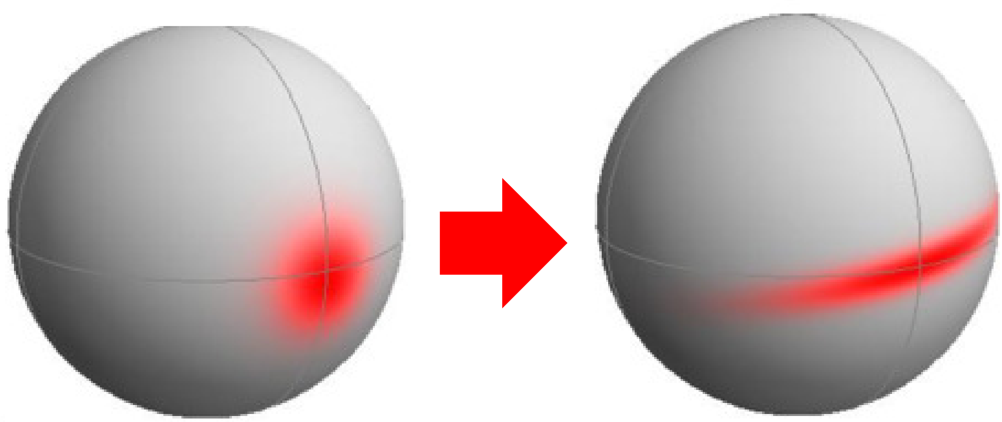
Ion chains



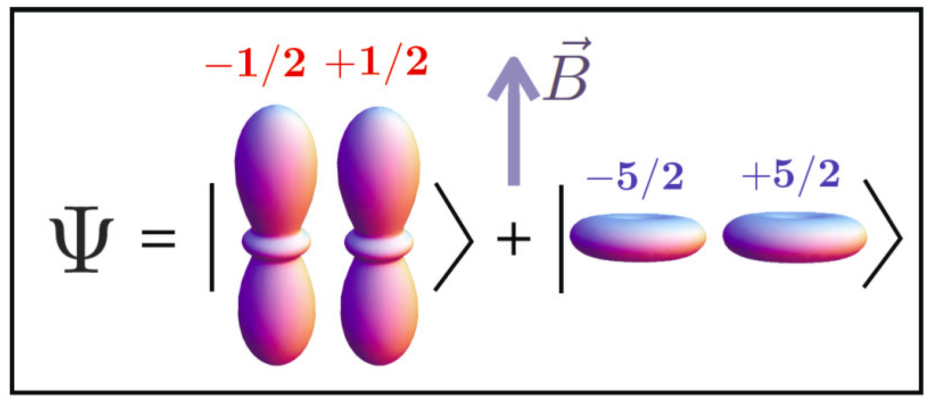
Large ion crystals



3D optical lattice clocks



Measurements beyond the quantum limit

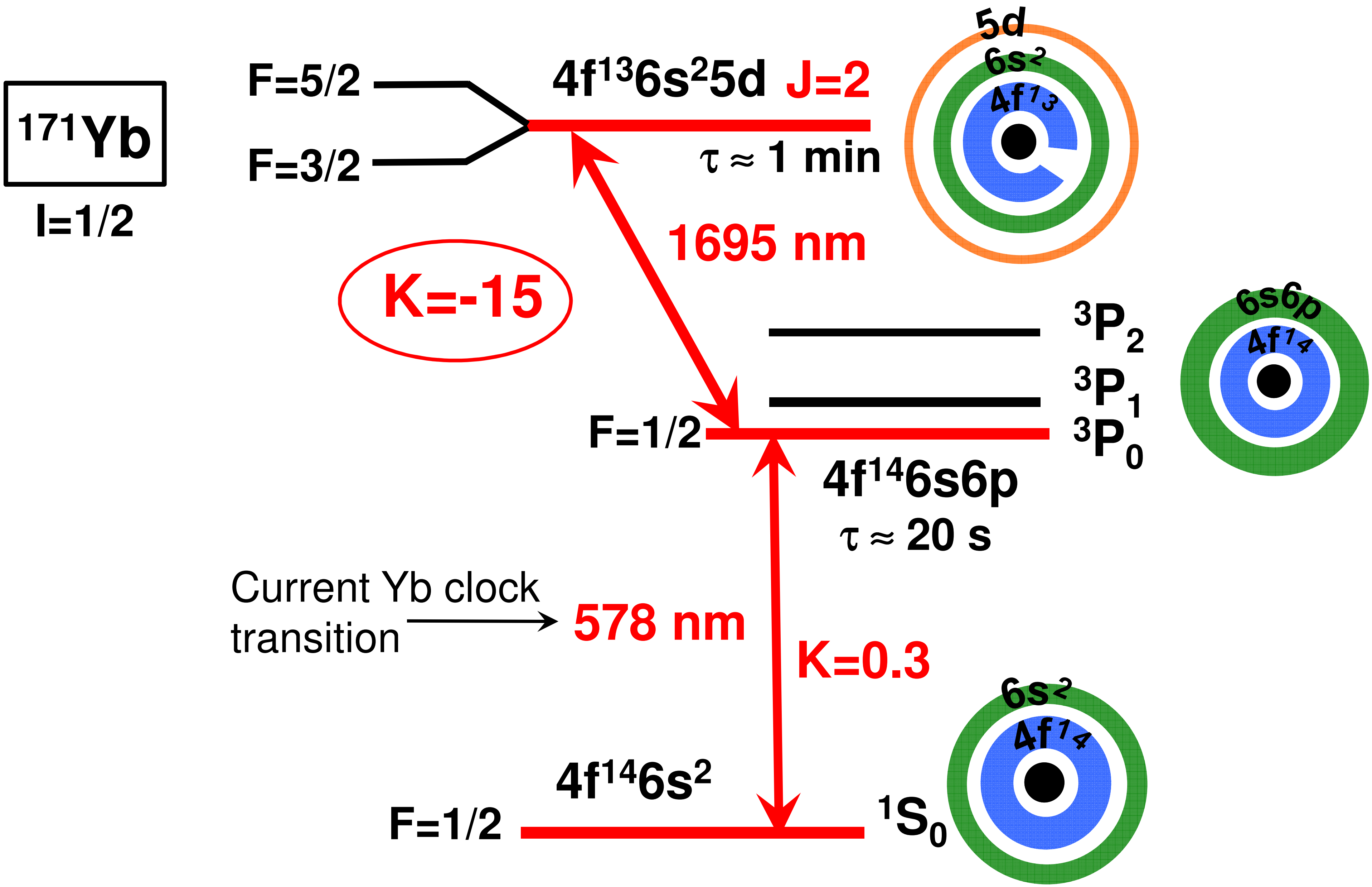


Entangled clocks

Orders of magnitude improvements with current clocks

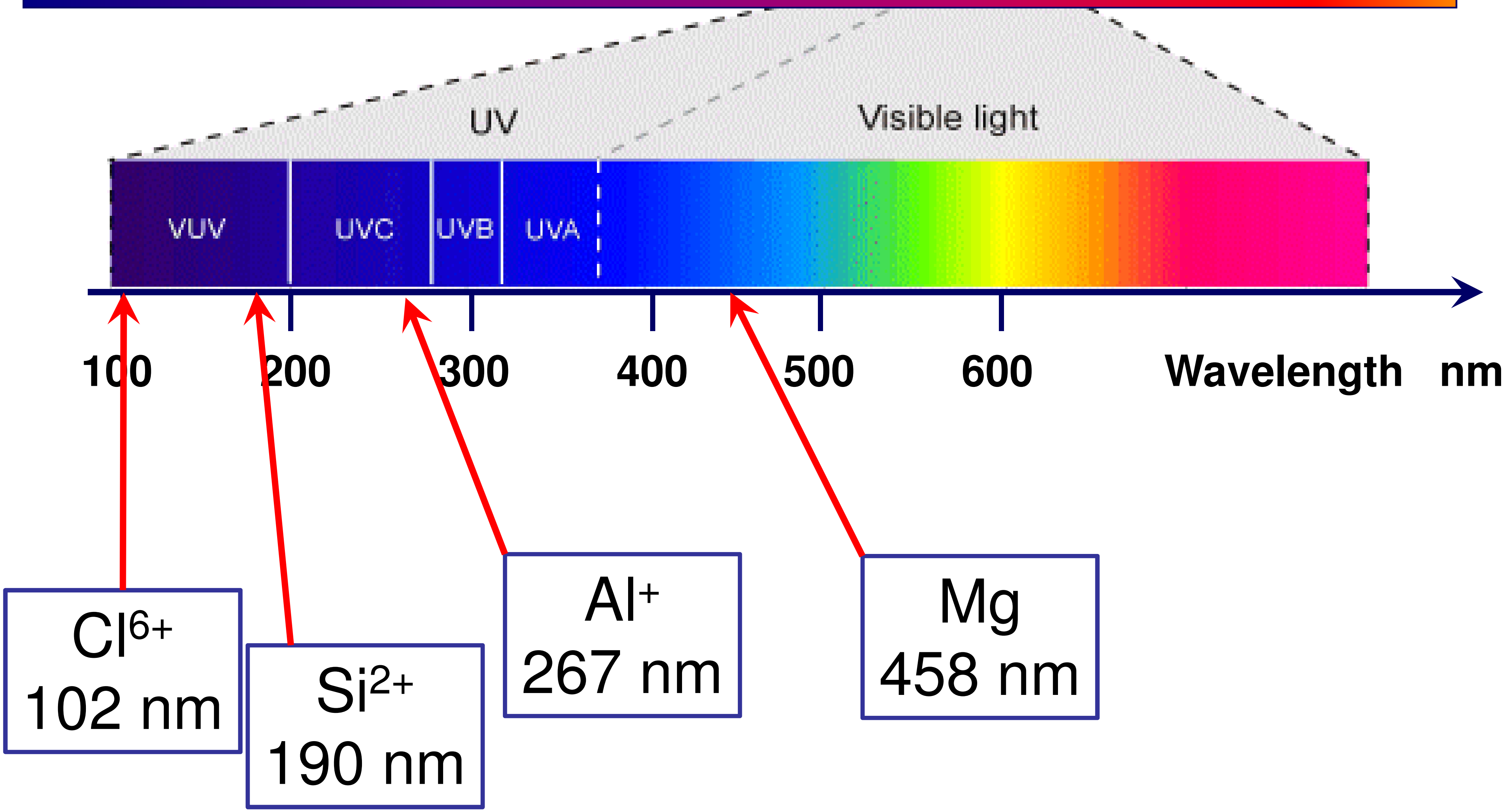
Image credits: NIST, Innsbruck group, MIT Vuletic group, Ye JILA group

Two clock transitions in neutral Yb

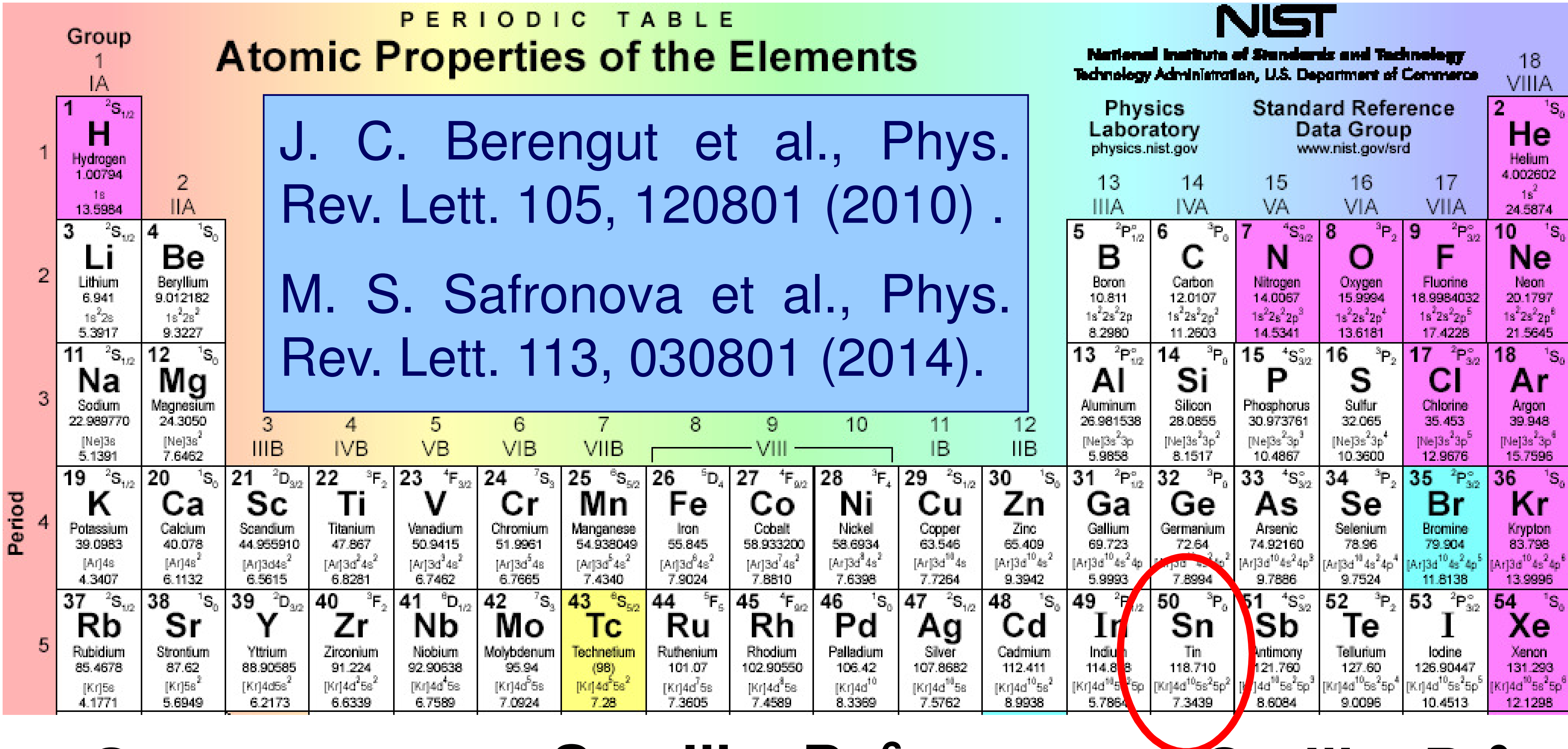


M. S. Safronova, S. G. Porsev, Christian Sanner, and Jun Ye, Phys. Rev. Lett. 120, 173001 (2018).

Highly charged ions ???



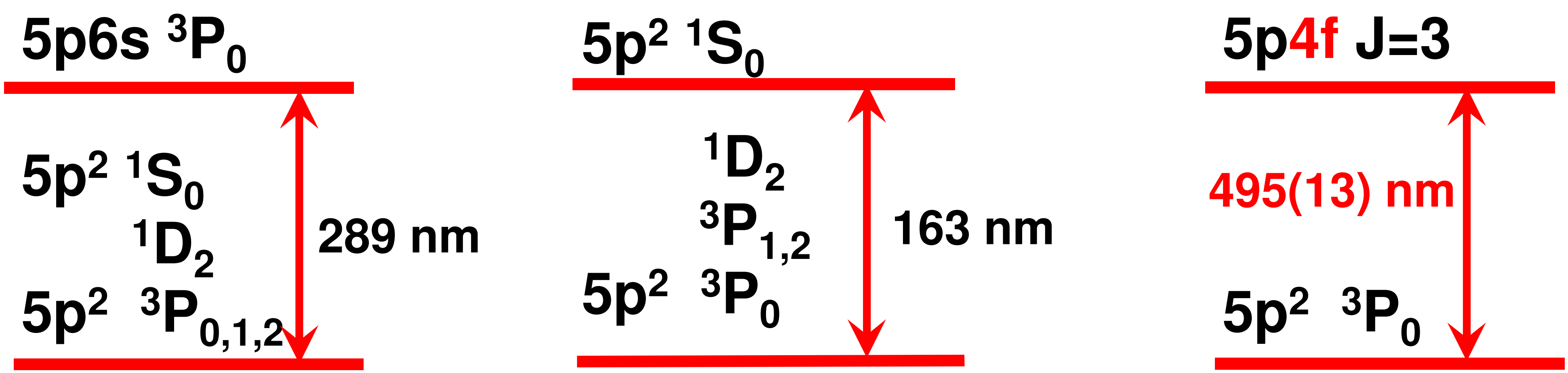
$3s^2\ ^1S_0 - 3s3p\ ^3P_0$ transition in Mg-like ions

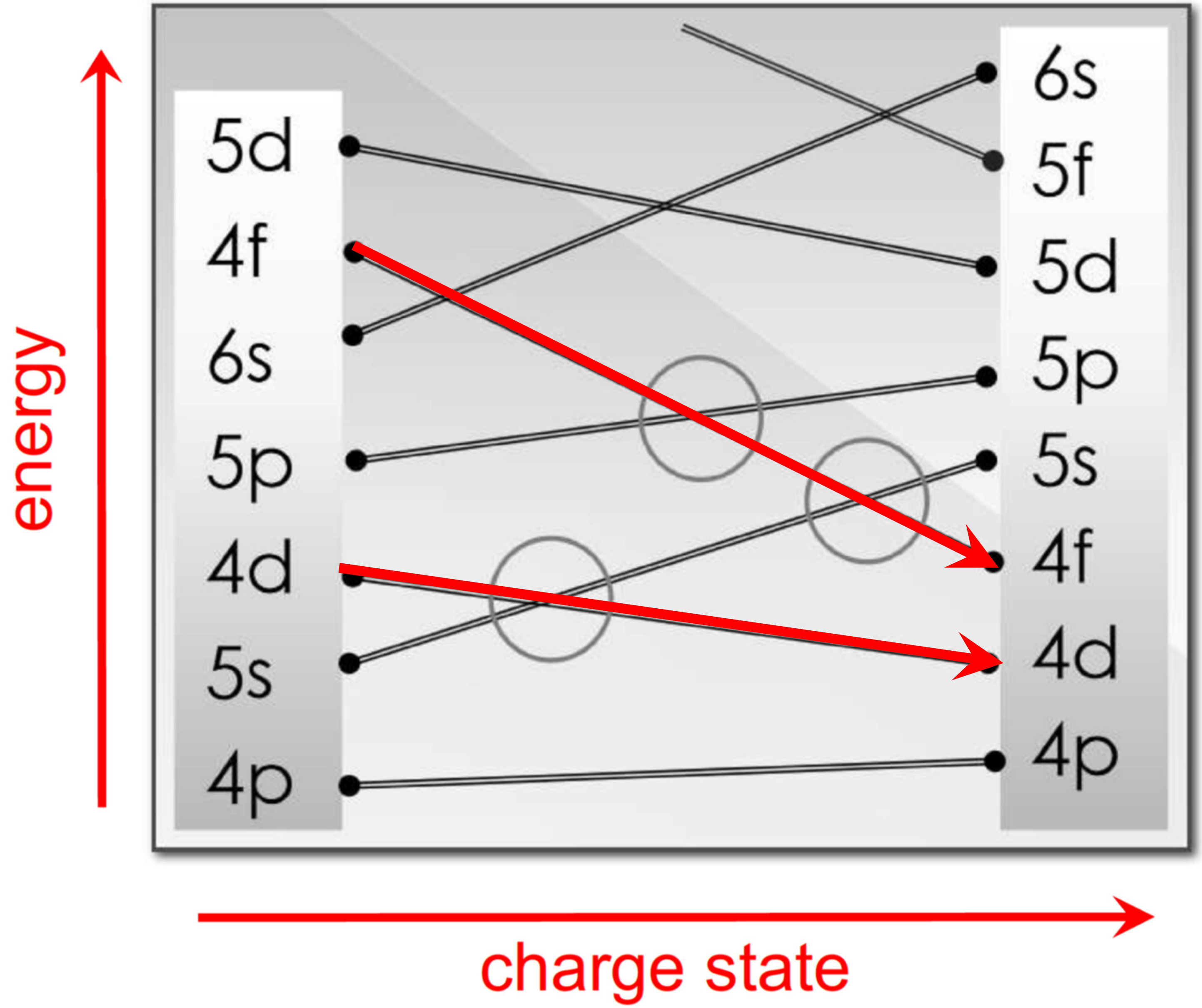


J. C. Berengut et al., Phys. Rev. Lett. 105, 120801 (2010) .

M. S. Safronova et al., Phys. Rev. Lett. 113, 030801 (2014).

Sn **Sn –like Ba^{6+}** **Sn-like Pr^{9+}**



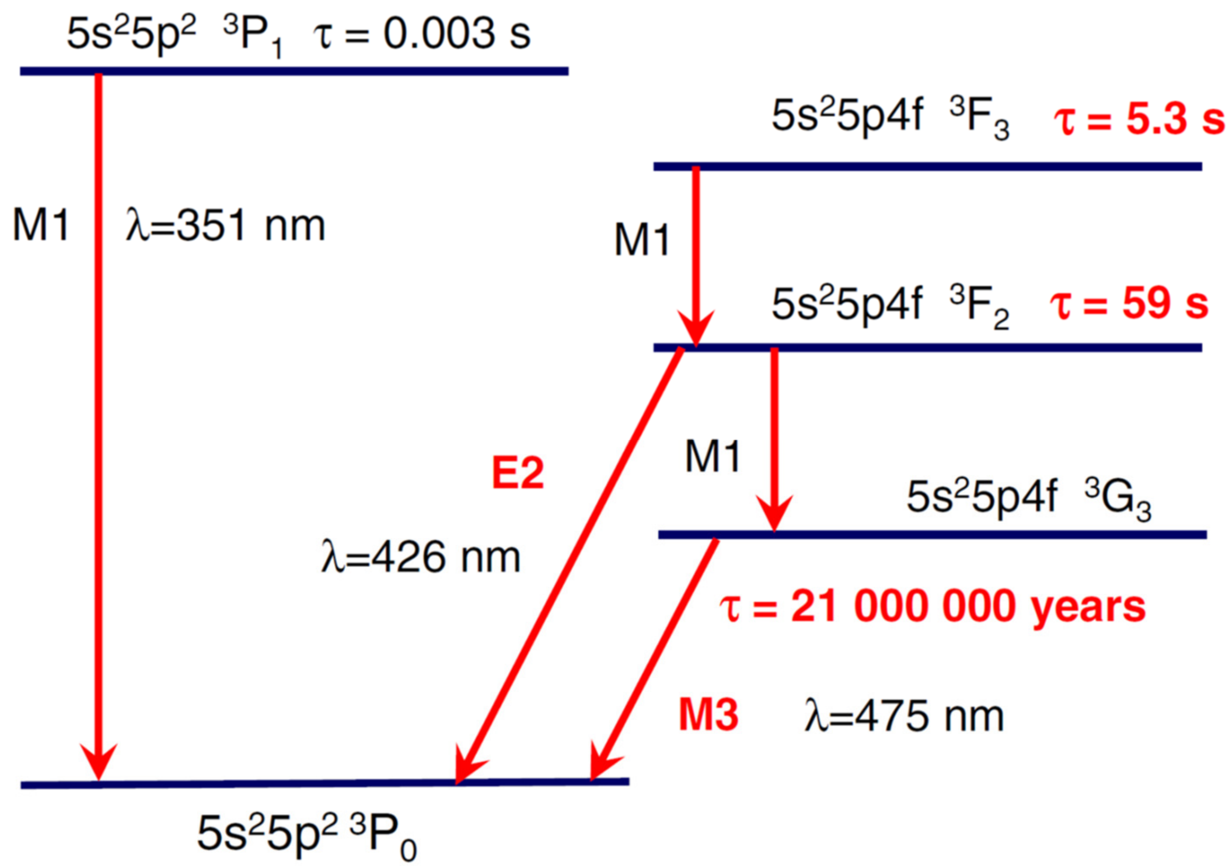


Schematic of the shell order in neutral atoms (left) and in hydrogen-like ions (right). One can see that the “diving“ of 4d and 4f shells result in level crossings in the areas marked by circles.

Highly Charged Ions: Advantages

- Large variety of metastable transitions and level structures

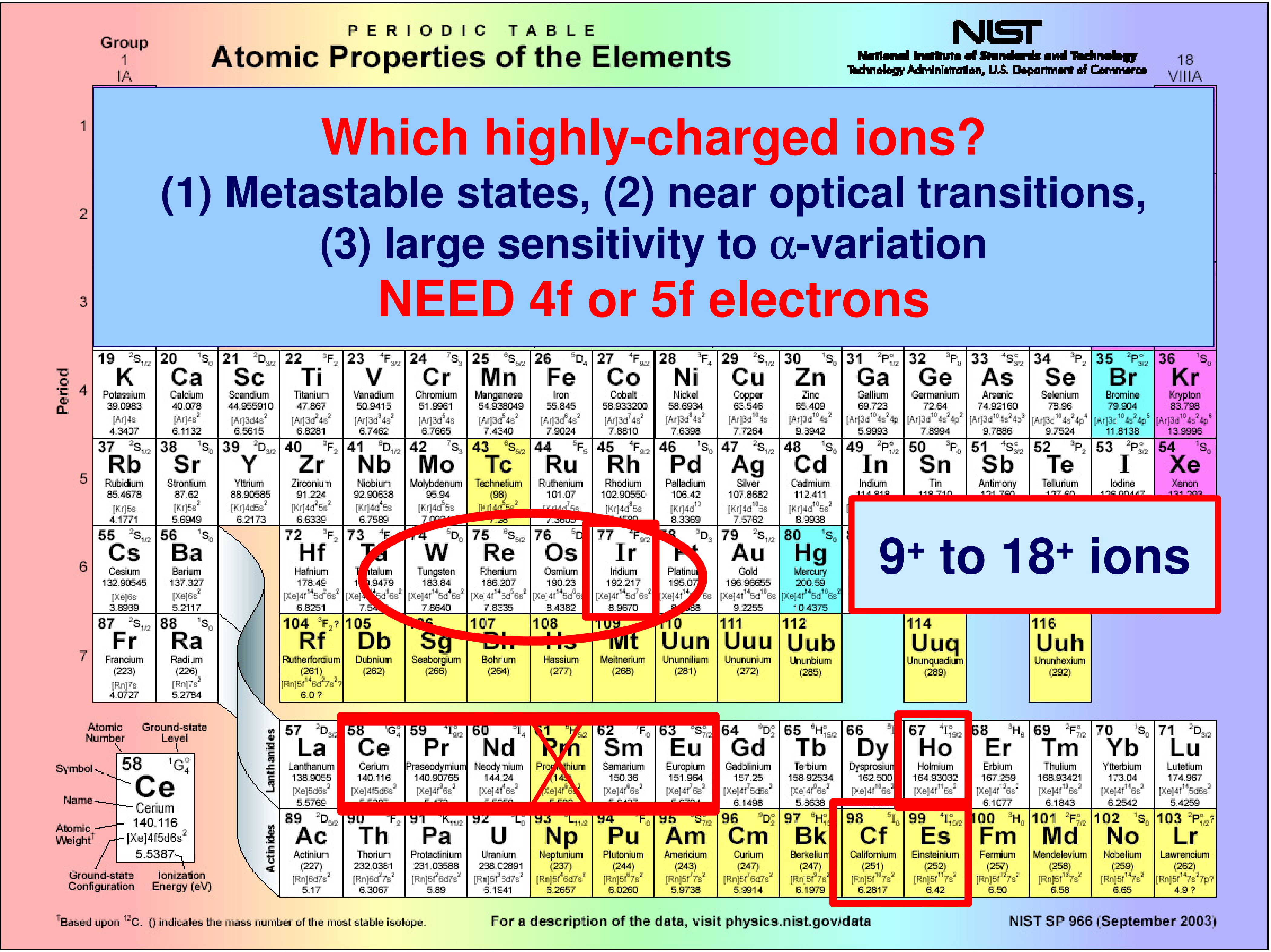
- Very compact atomic clouds – suppression of all systematics due to Stark shifts



- Strong suppression of blackbody radiation effect

- Estimated potential clock uncertainty of 10^{-19}

- Large relativistic effects – enhancement of related effects including α-variation and tests of Lorentz symmetry


PERIODIC TABLE
Atomic Properties of the Elements
NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce
Which highly-charged ions?
(1) Metastable states, (2) near optical transitions,
(3) large sensitivity to α-variation
NEED 4f or 5f electrons
9+ to 18+ ions
Lanthanides
Actinides
Atomic Number
Ground-state Level
Symbol
Name
Atomic Weight
Ground-state Configuration
Ionization Energy (eV)
Based upon 12C. () indicates the mass number of the most stable isotope.
For a description of the data, visit physics.nist.gov/data
NIST SP 966 (September 2003)

Clock proposals: Which highly-charged ions?

(1) Valence 4f electrons: 4f, $4f^2$, $4f^3$

Nd^{13+}, Sm^{15+}, Ce^{9+}, Pr^{10+}, Nd^{11+}, Sm^{13+}, Nd^{12+}, Sm^{14+}, Pr^{9+}, Nd^{10+}

(2) Valence 5f elections: 5f, $5f^2$ **Cf^{15+}, Cf^{16+}, Cf^{17+}, Es^{16+}, Es^{17+}**

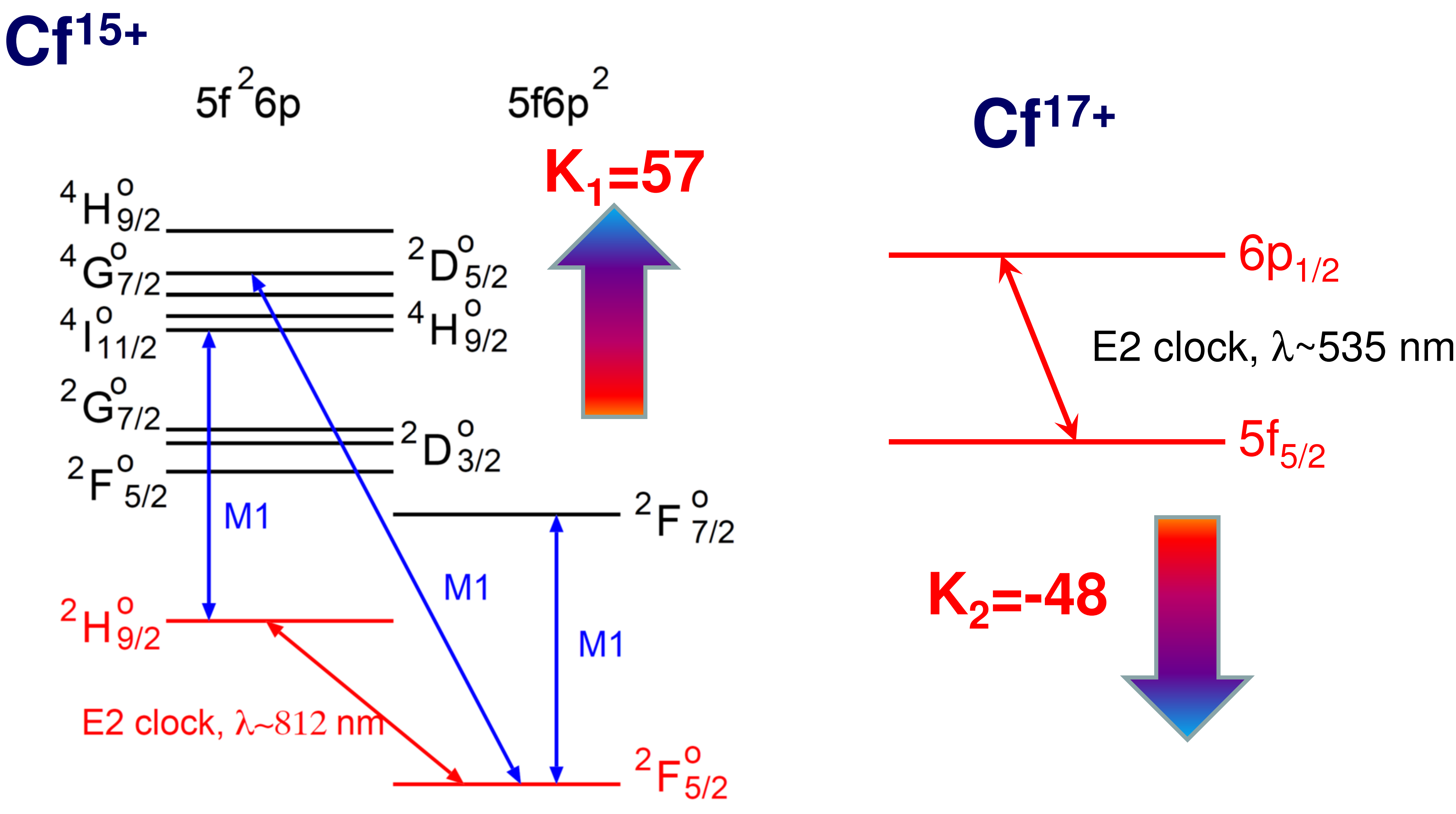
Accurate theory predictions

(3) Holes in 4f shell: $4f^{12}$, $4f^{13}$ **Ir^{16+}, Ir^{17+}, W ions**

(4) Mid-filled 4f shell: $4f^5$, $4f^6$ **Ho^{14+}**

(5) H-like heavy ions: Bi^{82+} optical hypefine structure transition – “better Cs clock”

Factor of 100 enhancement for α-variation!



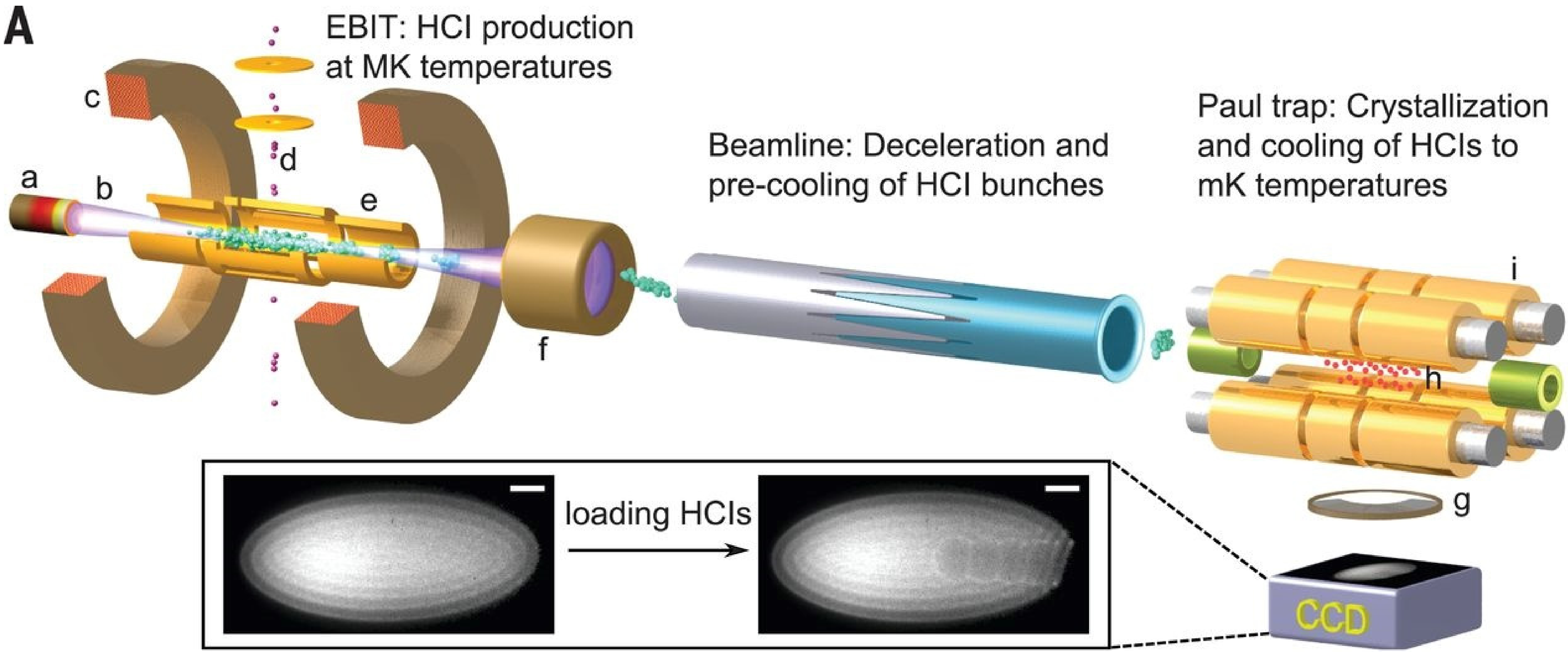
V. A. Dzuba, M. S. Safronova, U. I. Safronova, and V. V. Flambaum, Phys. Rev. A 92, 060502(R) (2015).

SYMPATHETIC COOLING

Science 347, 1233 (2015)

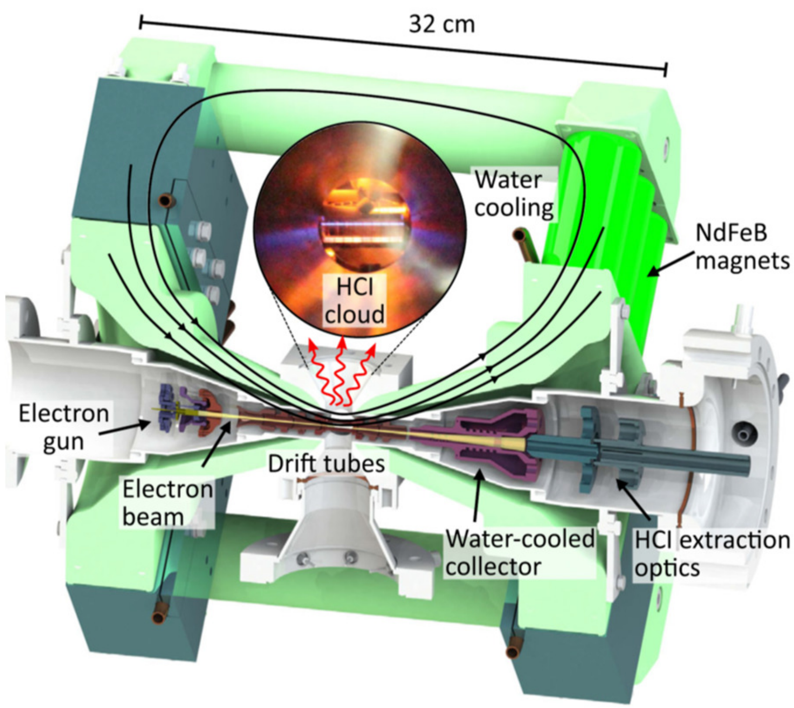
Coulomb crystallization of highly charged ions

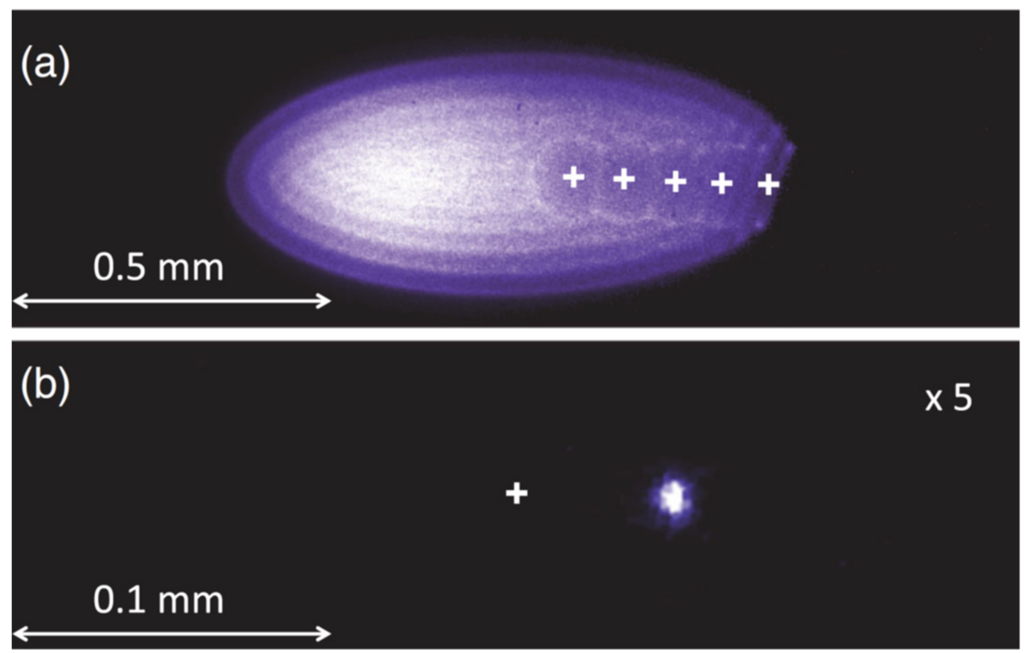
L. Schmöger,[1,2] O. O. Versolato,[1,2*] M. Schwarz,[1,2] M. Kohnen,[2] A. Windberger,[1] B. Piest,[1] S. Feuchtenbeiner,[1] J. Pedregosa-Gutierrez,[3] T. Leopold,[2] P. Micke,[1,2] A. K. Hansen,[4†] T. M. Baumann,[5] M. Drewsen,[4] J. Ullrich,[2] P. O. Schmidt,[2,6] J. R. Crespo López-Urrutia[1‡]



Highly charged ions: Optical clocks and applications in fundamental physics

M. G. Kozlov, M. S. Safronova, J. R. Crespo López-Urrutia, P. O. Schmidt, Rev. Mod. Phys. 90, 45005 (2018).

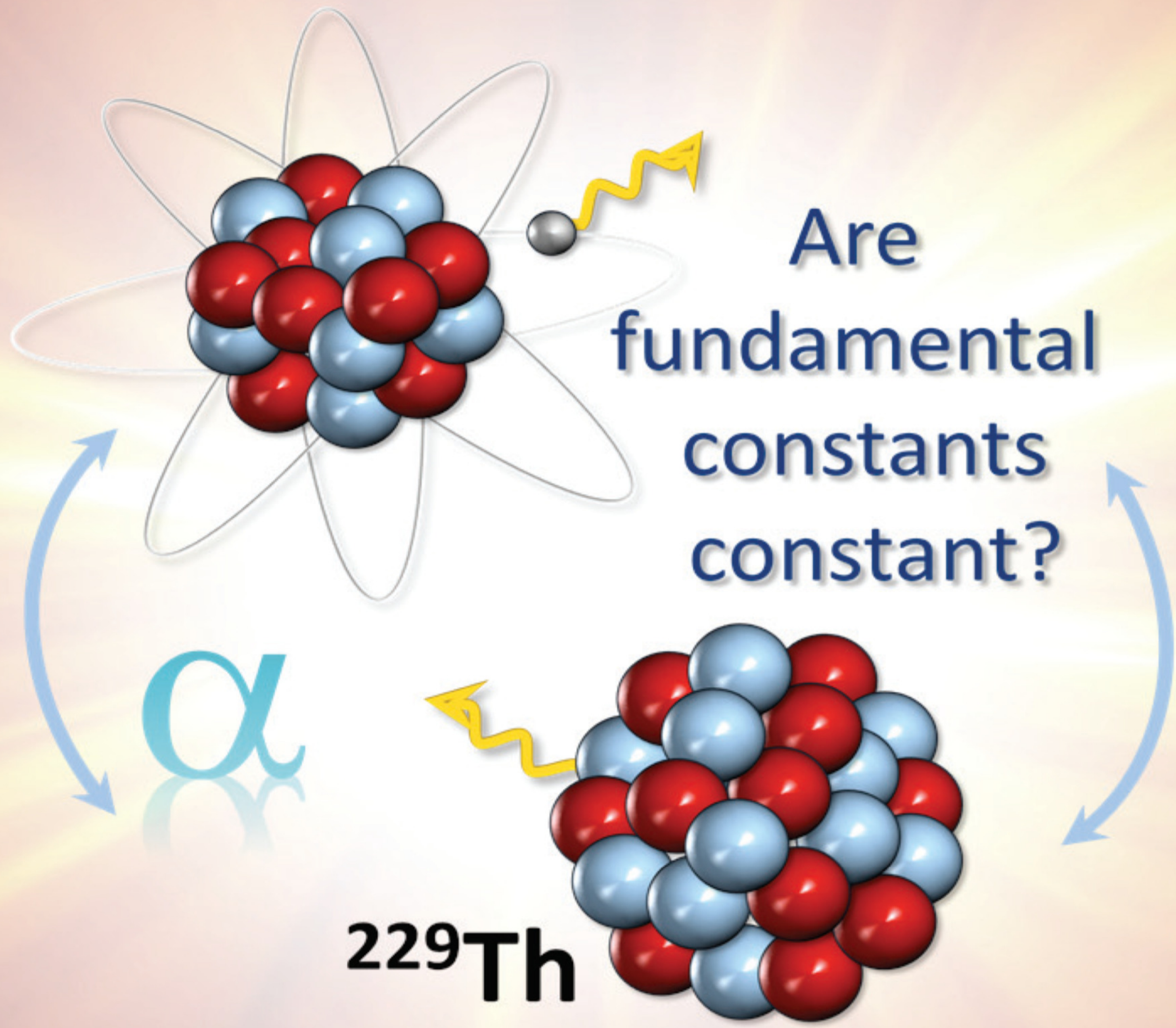




PTB, Germany, November 2018: **First demonstration of quantum logic with a highly charged ion, Ar^{13+}**

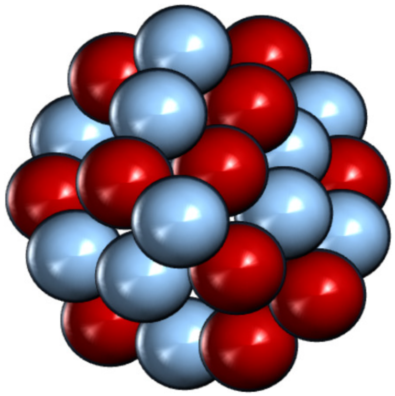
2019: Improved frequency measurement from 10^{-7} to 10^{-15} level!

From atomic to nuclear clocks!

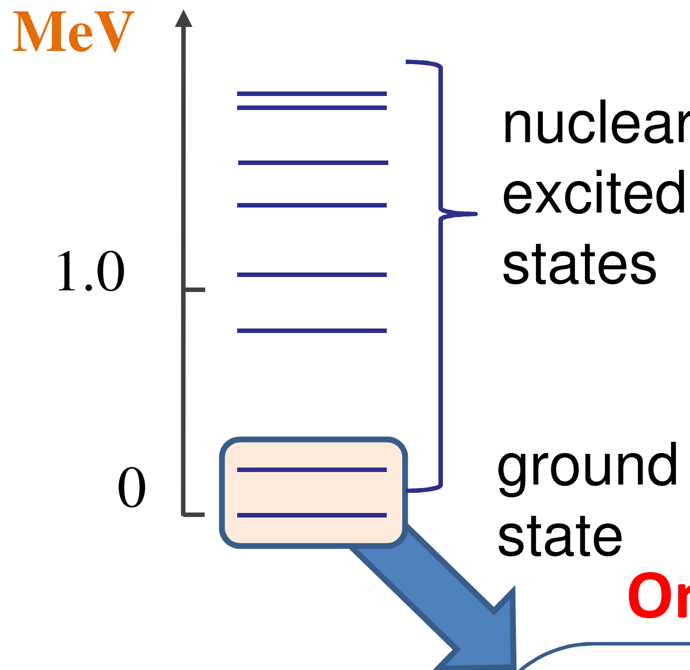


M. S. Safronova, Annalen der Physik 531, 1800364 (2019)

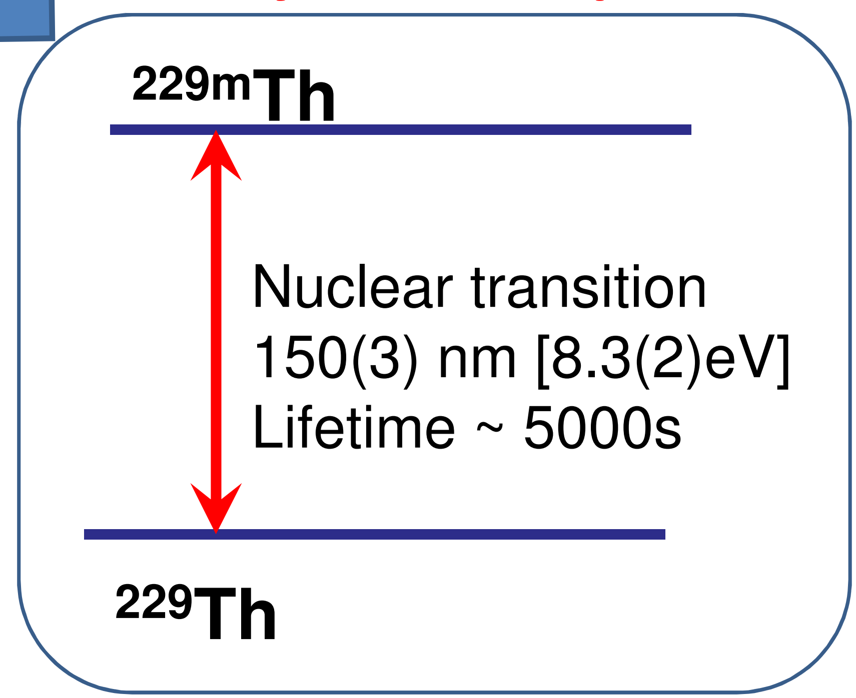
Obvious problem: typical nuclear energy levels are in MeV
Six orders of magnitude from ~few eV we can access by lasers!



Atomic Nucleus



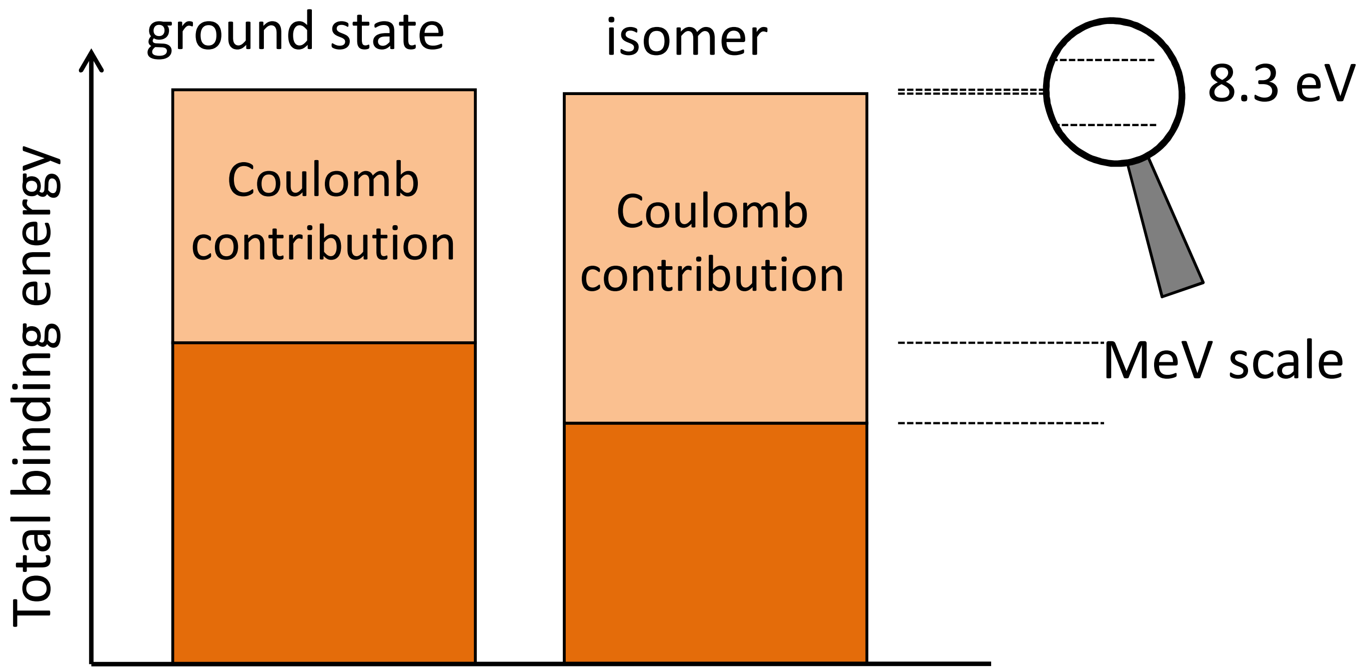
Only ONE exception!



Laser spectroscopic characterization of the nuclear clock isomer ^{229m}Th, Thielking *et al.*, Nature 556, 321 (2018)

Energy of the ^{229}Th nuclear clock transition Seiferle *et al.*, Nature 573, 243 (2019)

Th nuclear clock:
Exceptional sensitivity to new physics



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).

It is crucial to establish actual enhancement!

Picture credit: Thorsten Schumm

Very Wide Scope of AMO Dark Matter and New Physics Searches – See Our Review

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

Search for New Physics with Atoms and Molecules

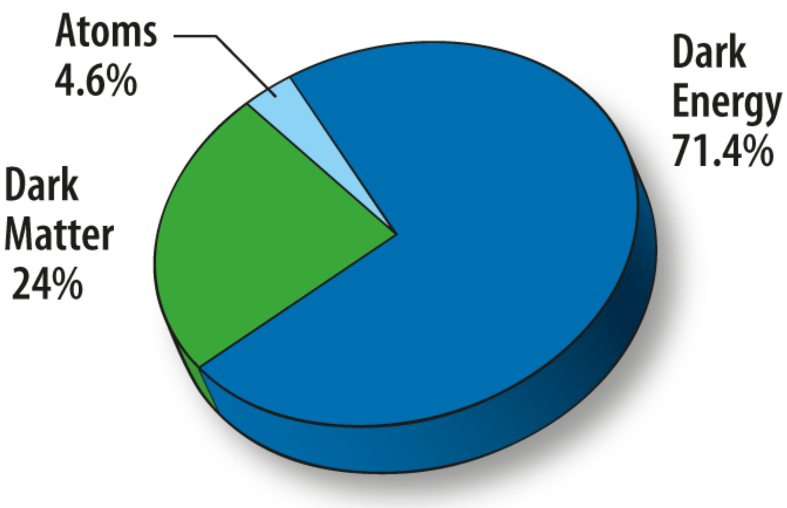
M.S. Safronova[1,2], D. Budker[3,4,5], D. DeMille[6], Derek F. Jackson Kimball[7], A. Derevianko[8] and C. W. Clark[2]

[1]University of Delaware, Newark, Delaware, USA,
[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.

Precision measurements:

Great potential for discovery of new physics



Many new developments coming in the next decade!

A recent explosion of new proposals for AMO new physics searches!