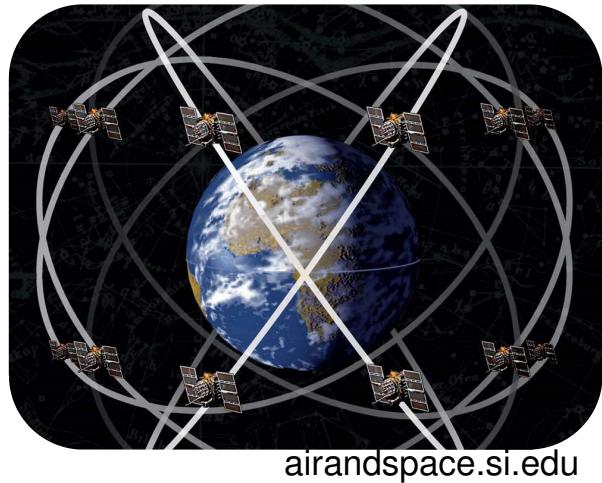


Поиск изменения фундаментальных констант и тёмной материи с атомными часами

MARIANNA
SAFRONOVA
Moscow, Russia

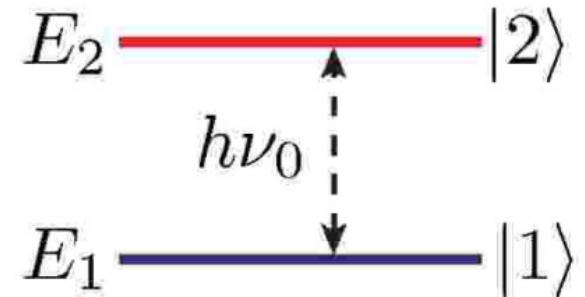
Перспективные стандарты времени и
частоты на атомных и ядерных переходах



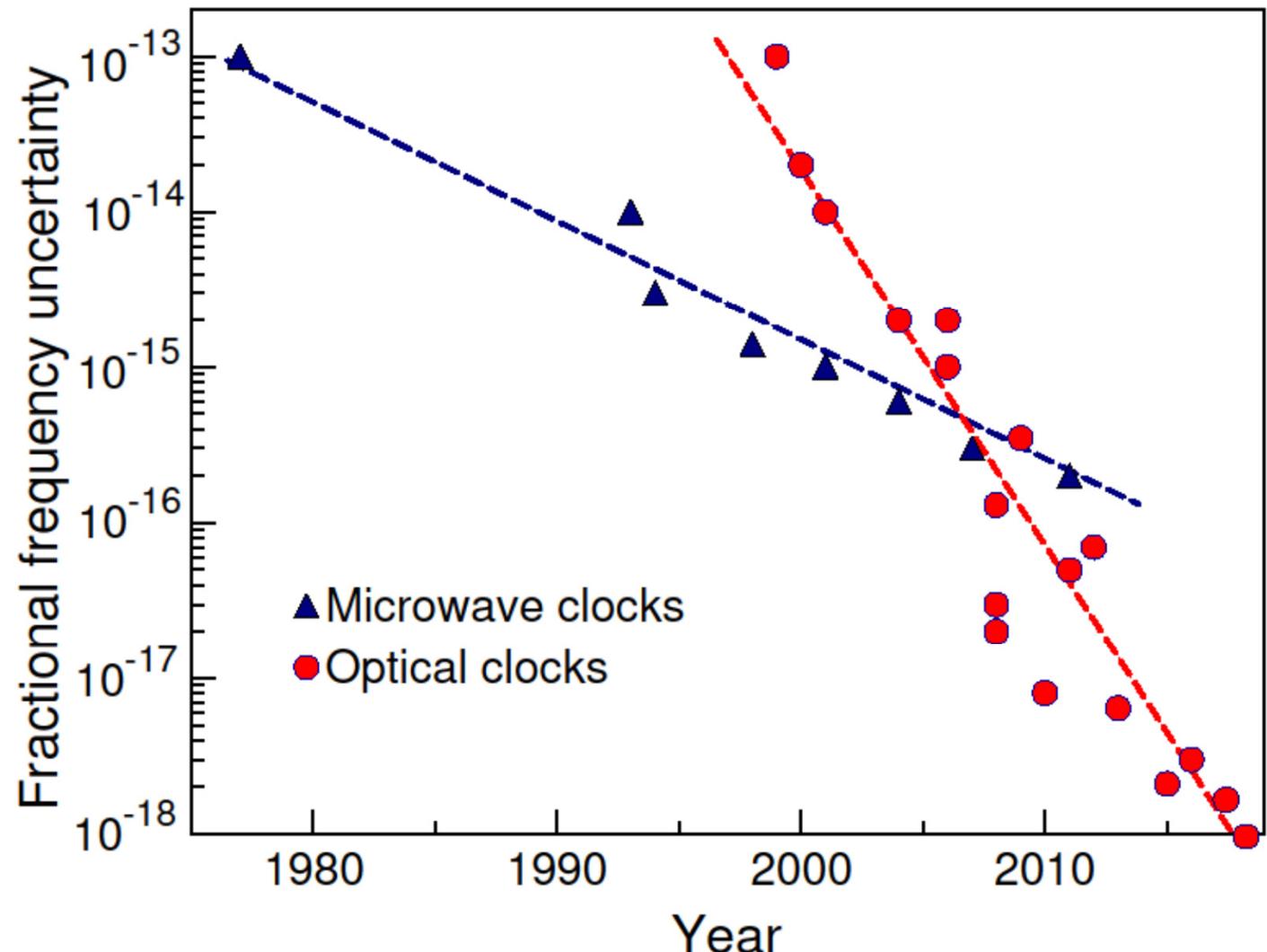


airandspace.si.edu

GPS satellites:
microwave
atomic clocks

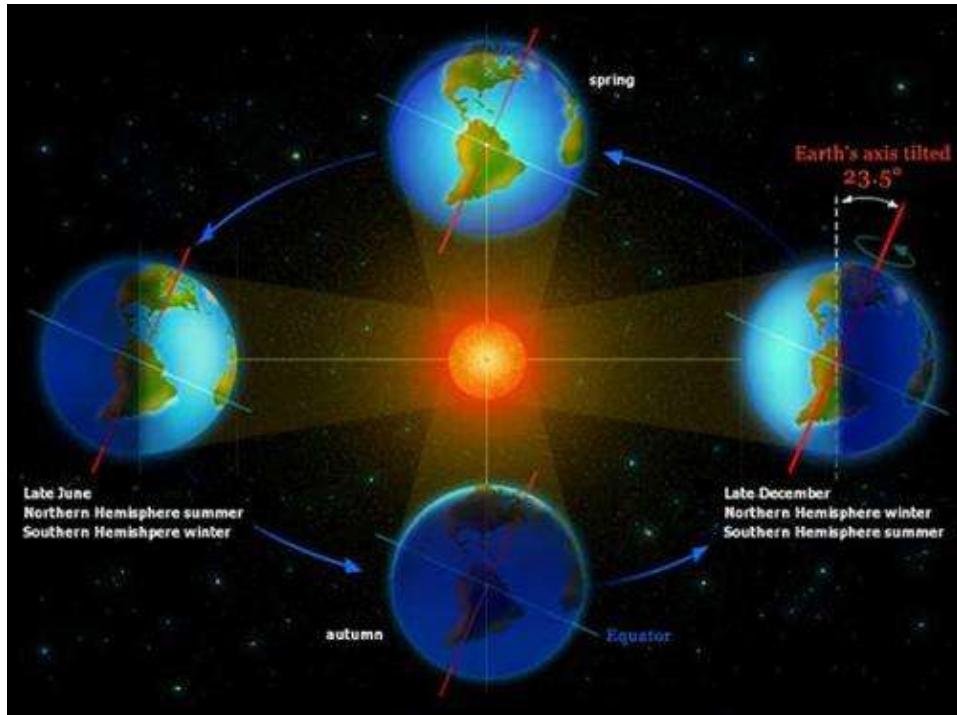


Atomic
clocks will
not lose one
second in
**30
billion
years**



Ingredients for a clock

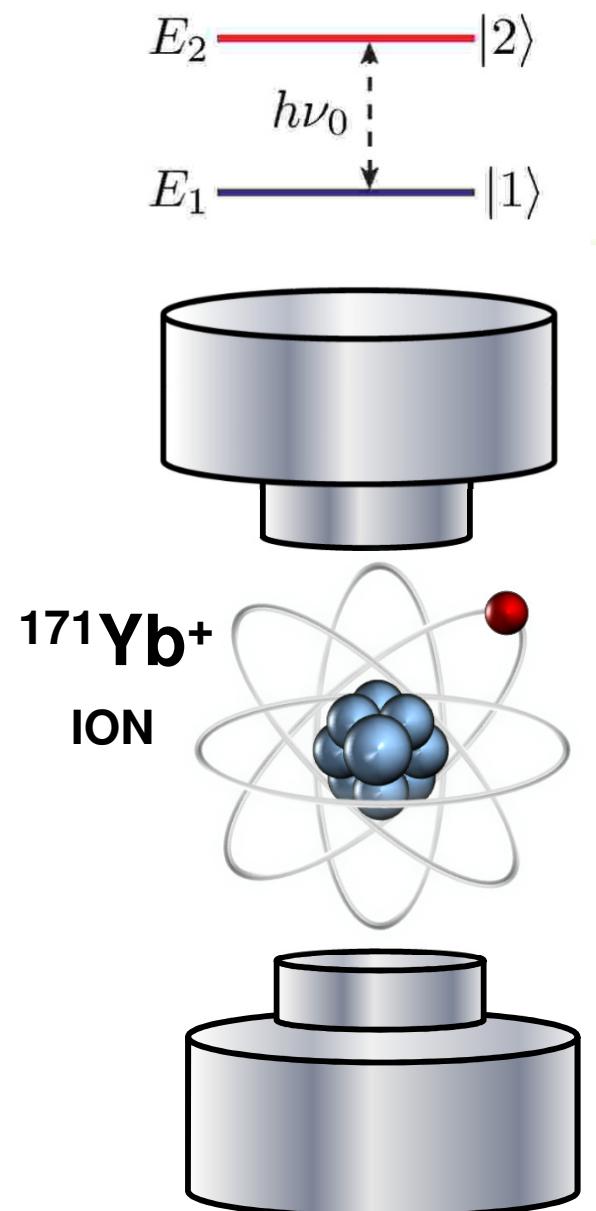
1. Need a system with **periodic behavior**:
it cycles occur at constant frequency



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

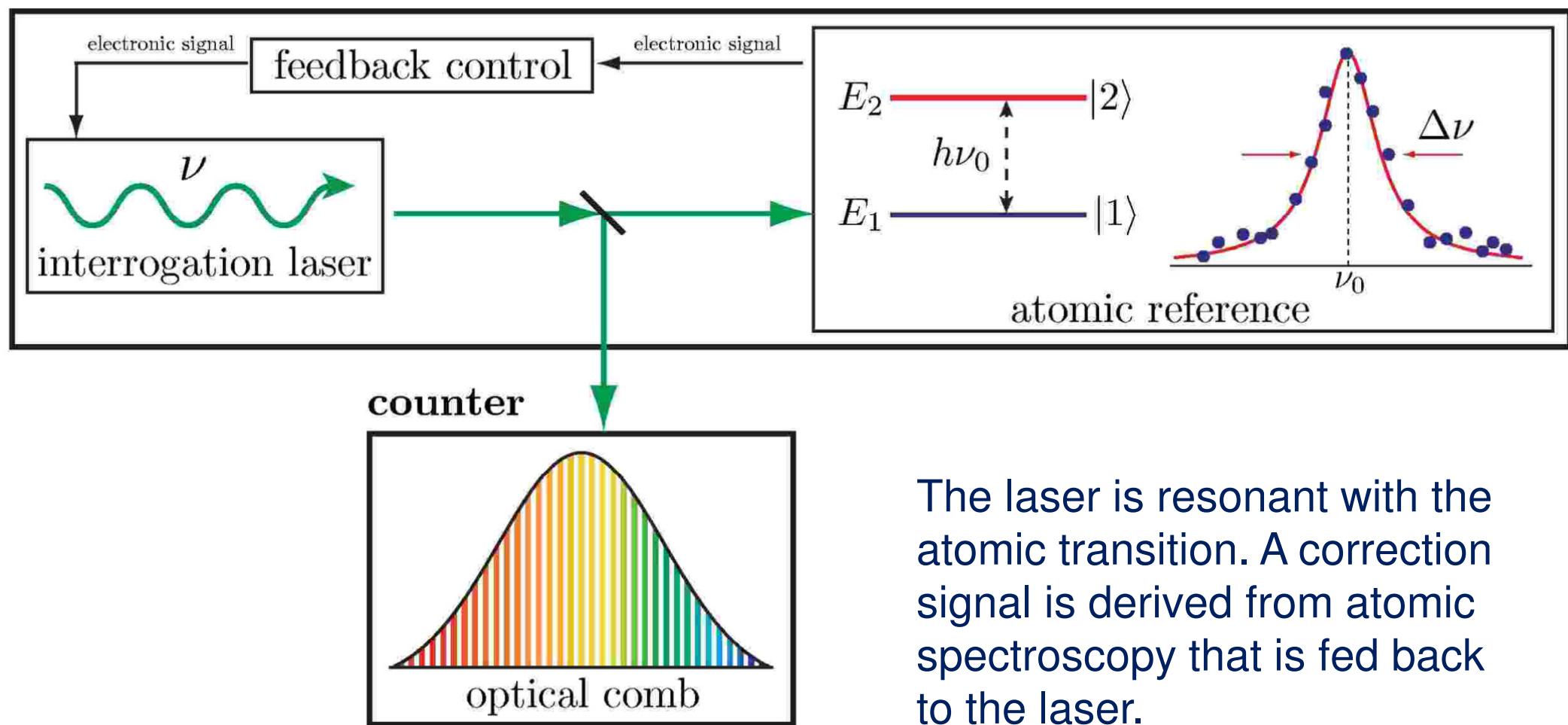
Ingredients for an atomic clock

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



How optical atomic clock works

atomic oscillator



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

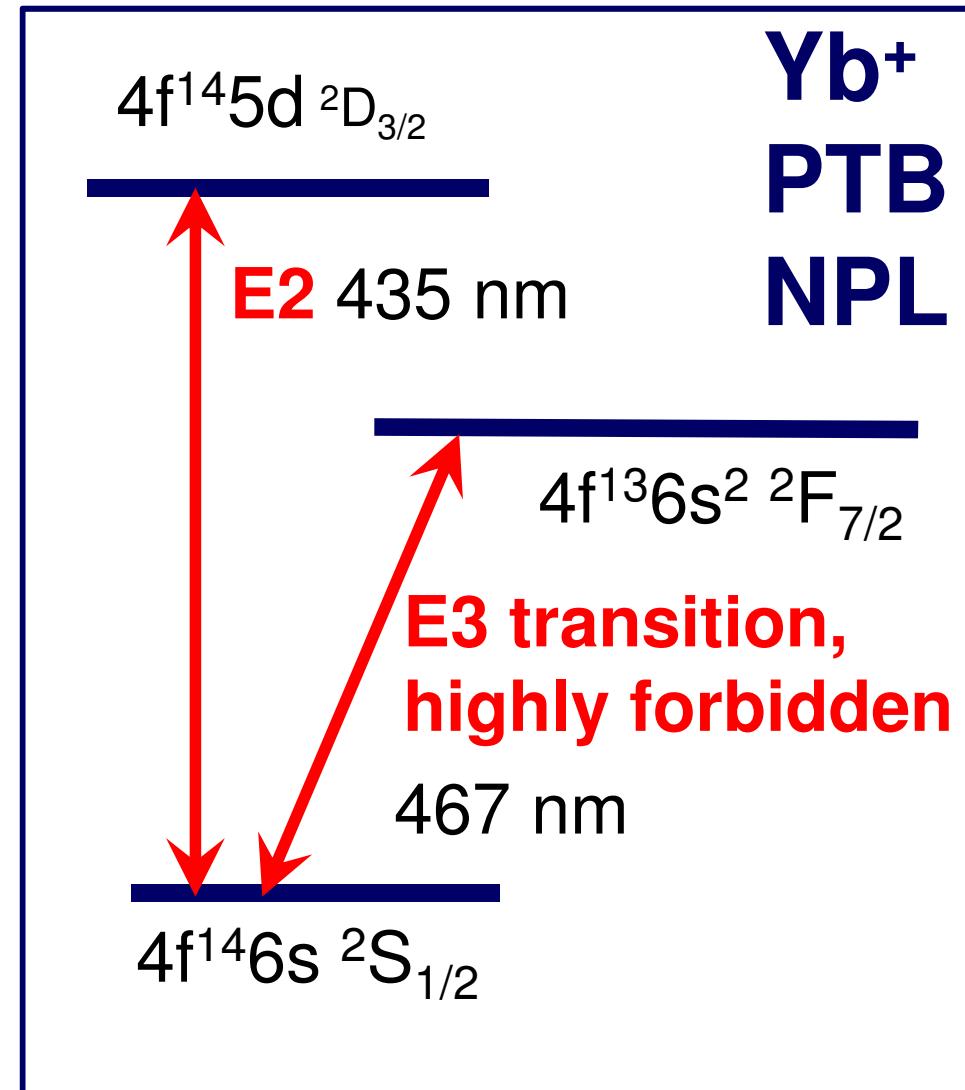
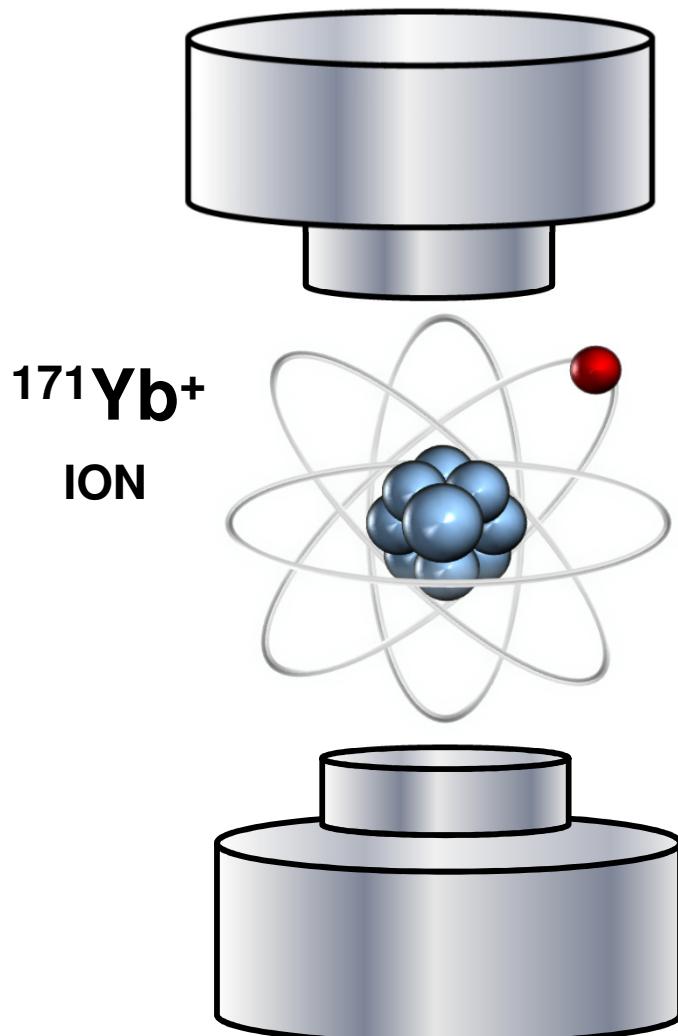
An optical frequency synthesizer (optical frequency comb) is used to divide the optical frequency down to countable microwave or radio frequency signals.

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

Trapped single ion clocks

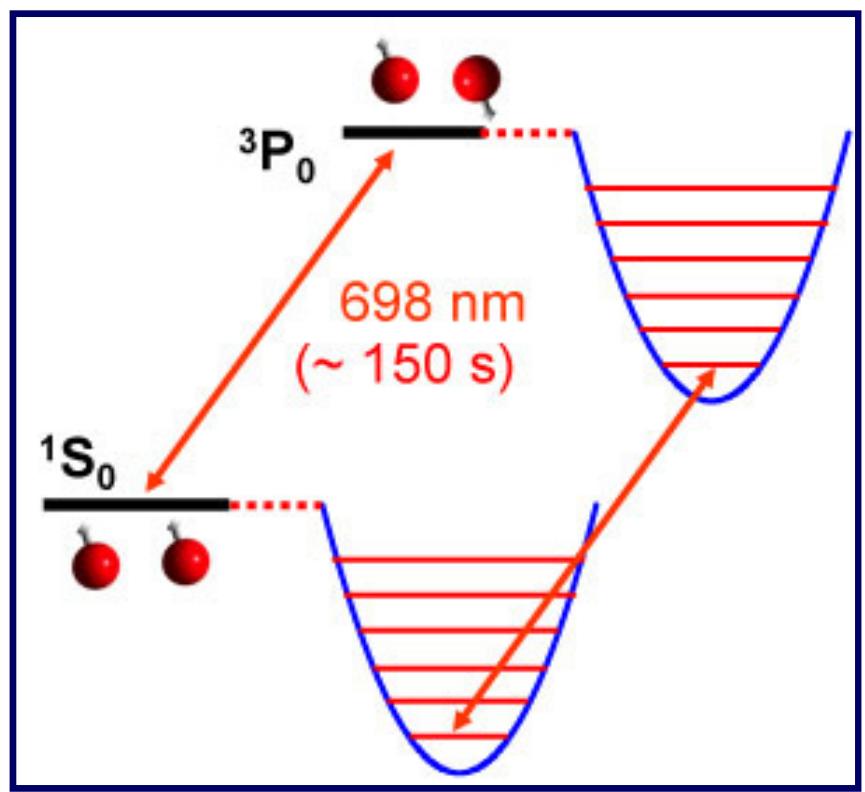
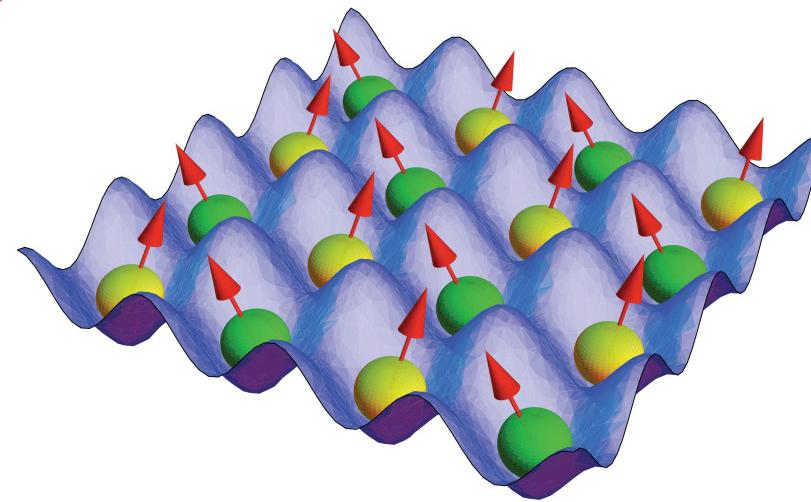
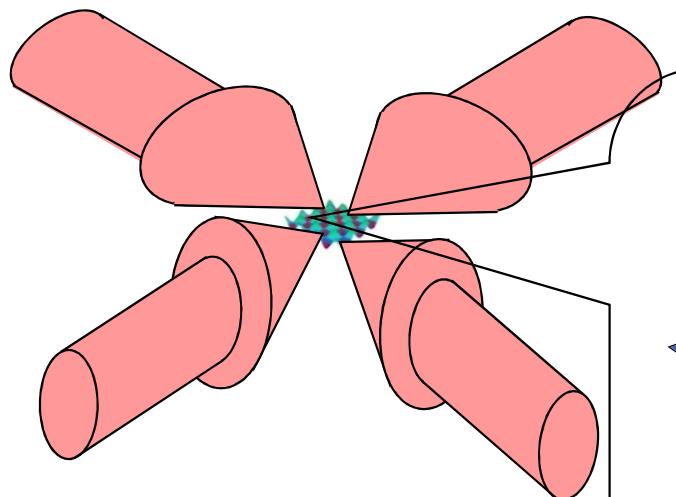
Requirements for an atomic clock

- (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

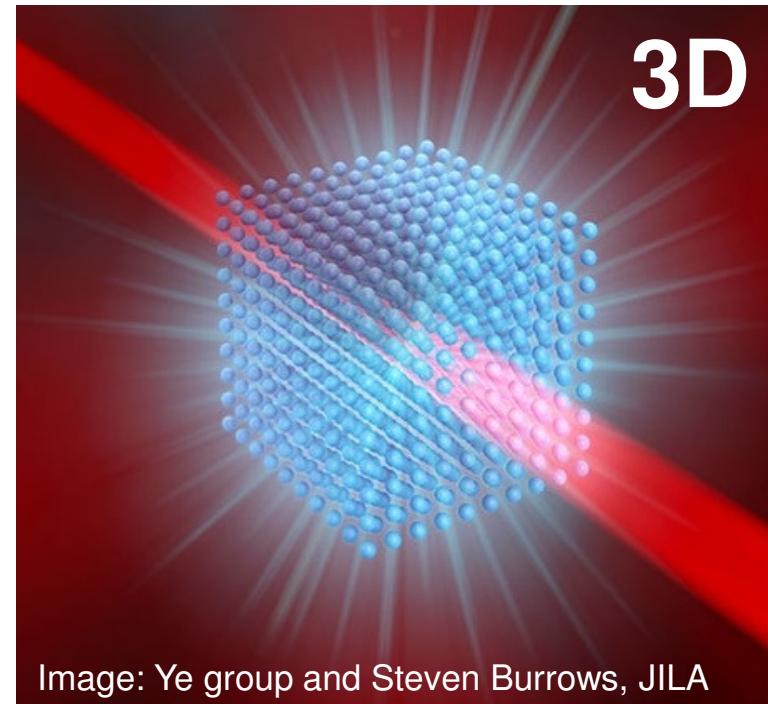
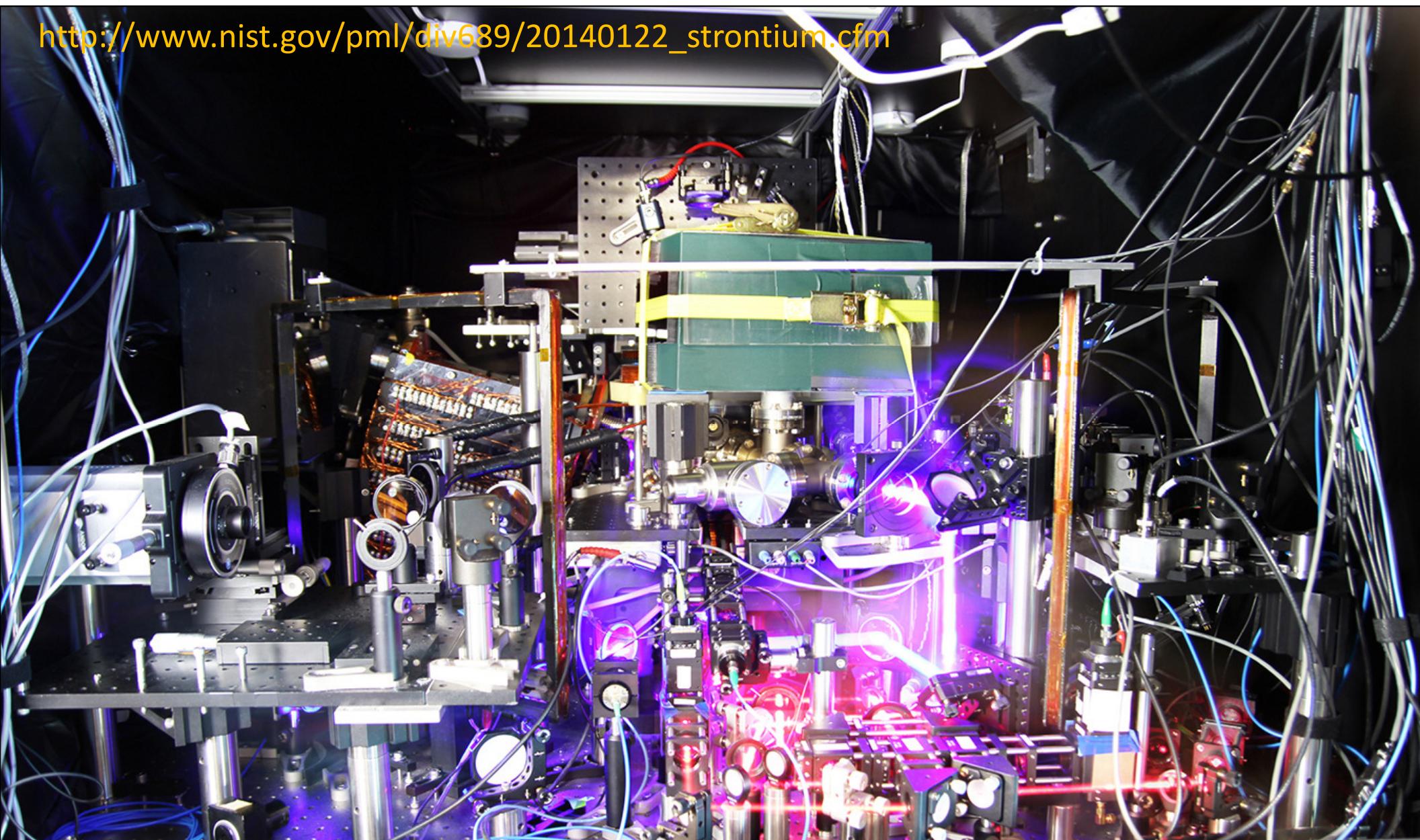


Image: Ye group and Steven Burrows, JILA

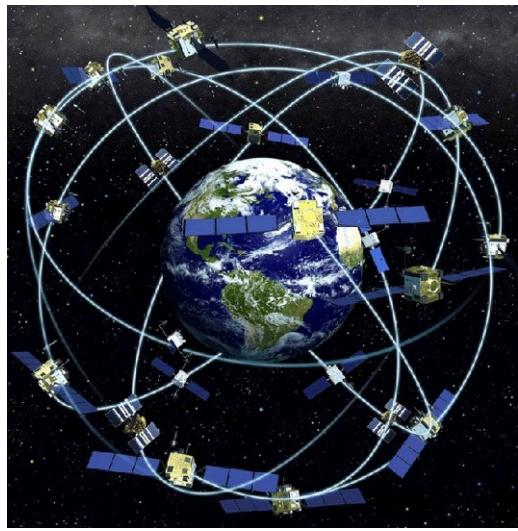
Sr clock: 2×10^{-18} uncertainty

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

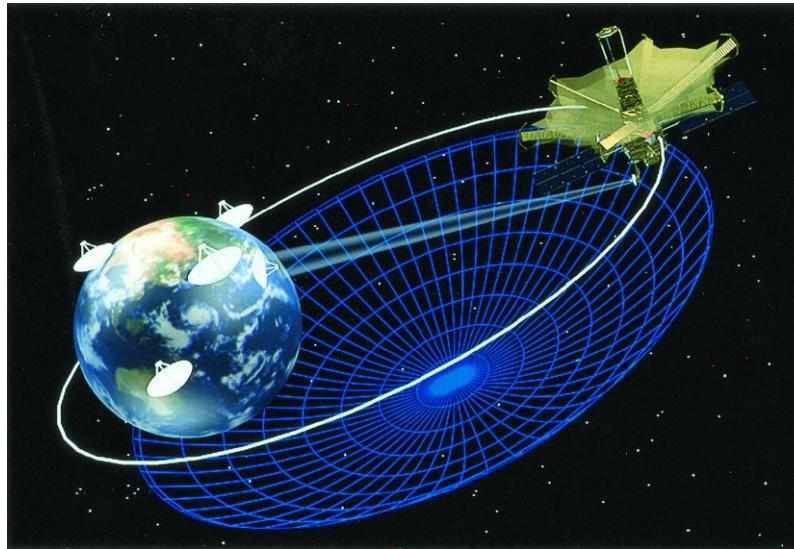


T. L. Nicholson, S. L. Campbell, R. B. Hutson, G. E. Marti, B. J. Bloom, R. L. McNally, W. Zhang, M. D. Barrett, M. S. Safronova, G. F. Strouse, W. L. Tew, and J. Ye, Nature Commun. 6, 6896 (2015).

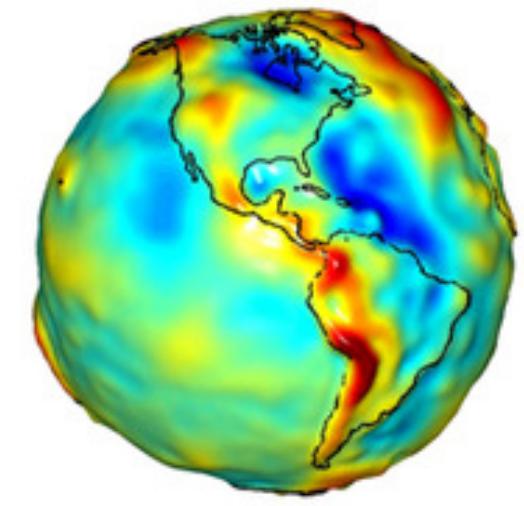
Applications of atomic clocks



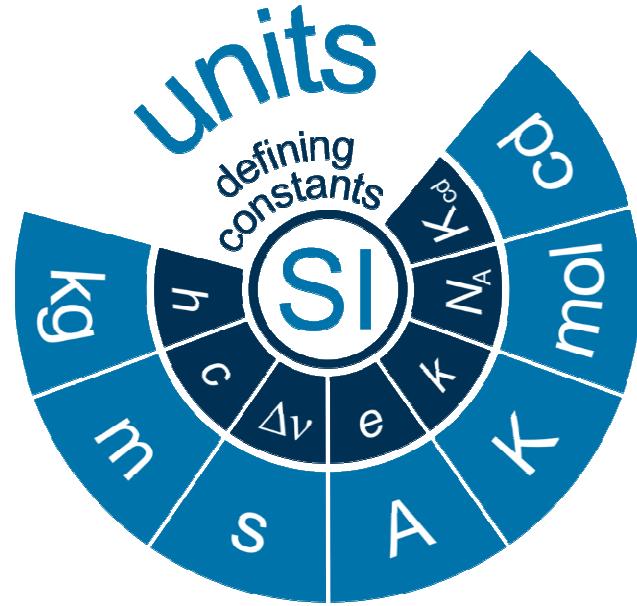
GPS



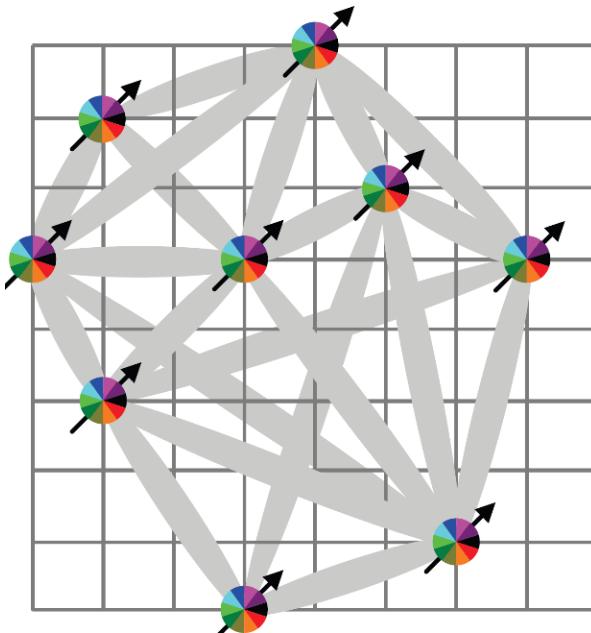
Very Long Baseline Interferometry



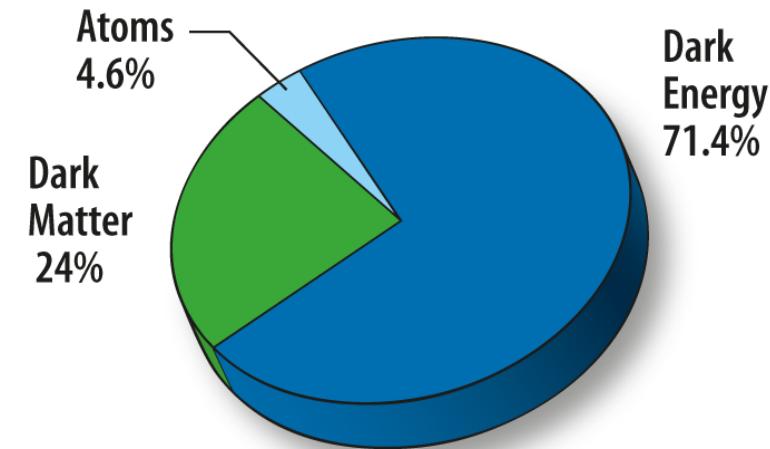
Relativistic geodesy



Definition of the second



Quantum simulation

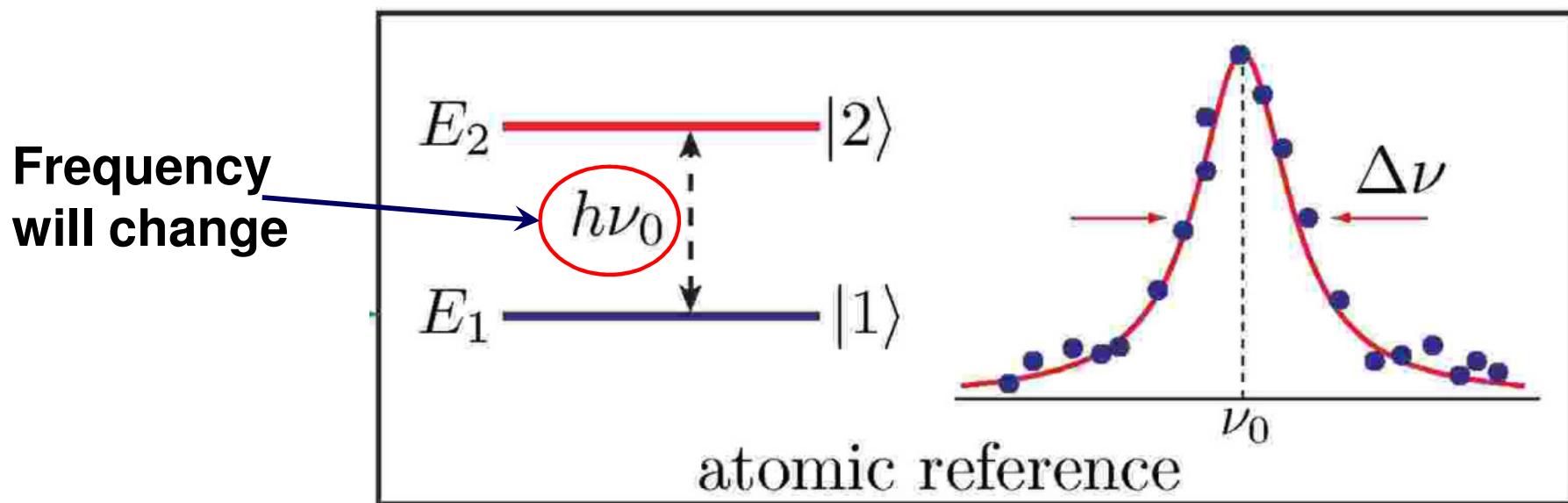


Search for physics
beyond the
Standard Model

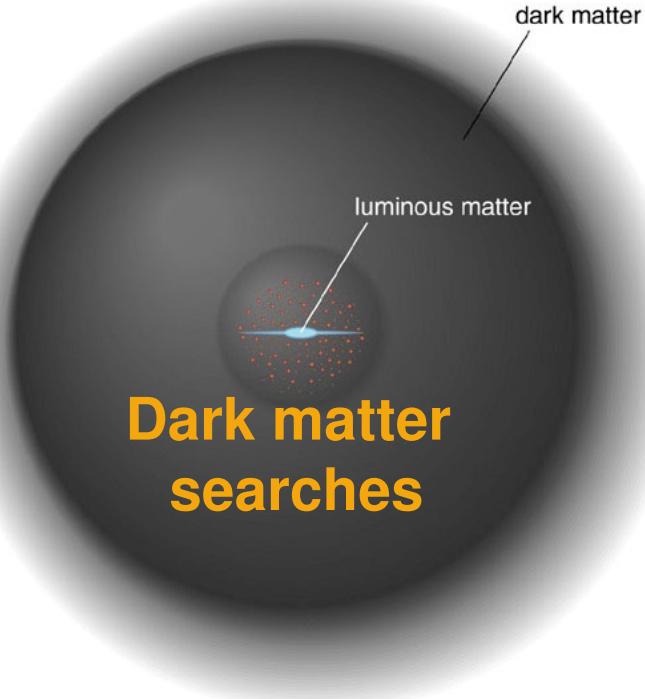
Search for physics beyond the standard model with atomic clocks

Atomic clocks can measure and compare frequencies to exceptional precisions!

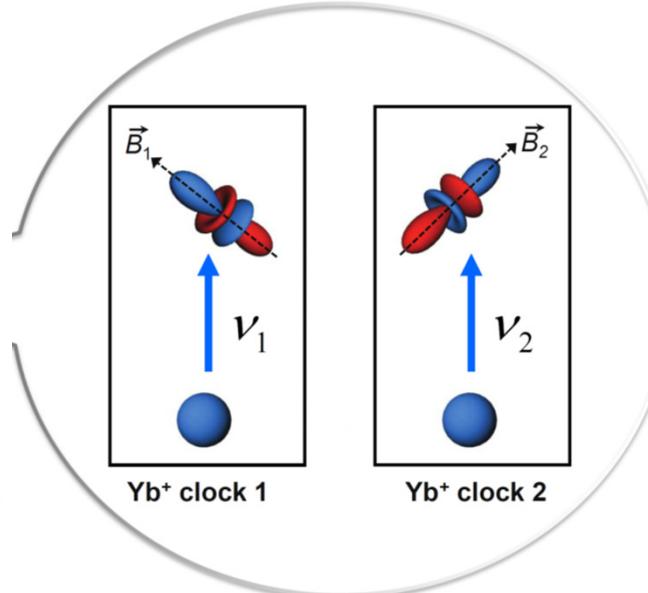
If fundamental constants change (now)
due to for various “new physics” effects
atomic clock may be able to detect it.



Search for physics beyond the Standard Model with atomic clocks



Dark matter searches



Search for the violation
of Lorentz invariance

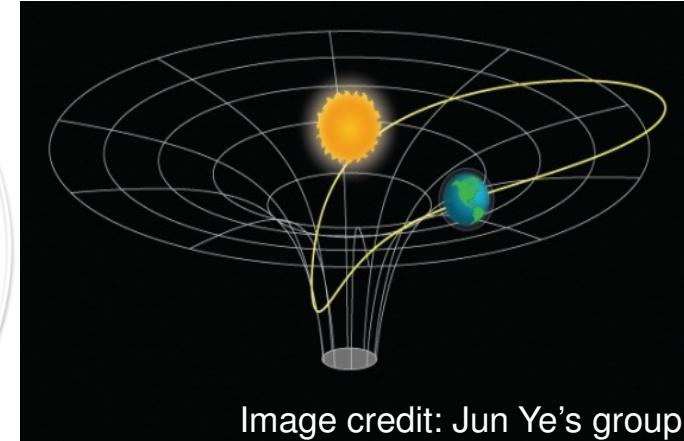
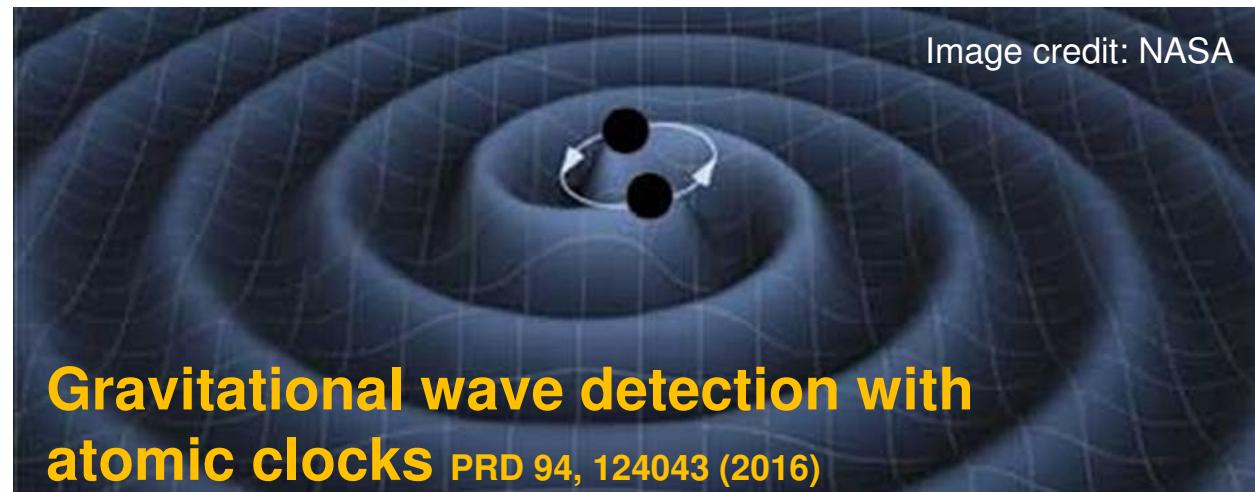


Image credit: Jun Ye's group

Tests of the
equivalence
principle

Are
fundamental
constants
constant?



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

Image credit: NASA

VARIATION OF
FUNDAMENTAL
CONSTANTS

Laboratory searches for variation of fundamental constants

1. Frequency of **optical** transitions

$$\nu \simeq cR_\infty AF(\alpha) \quad \text{Depends only on } \alpha$$

$$\alpha = \frac{1}{4\pi\epsilon_0} \frac{e^2}{\hbar c}$$

2. Frequency of **hyperfine** transitions

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

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

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 (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

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

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

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

Frequency ratio

accuracy

10^{-18}

100

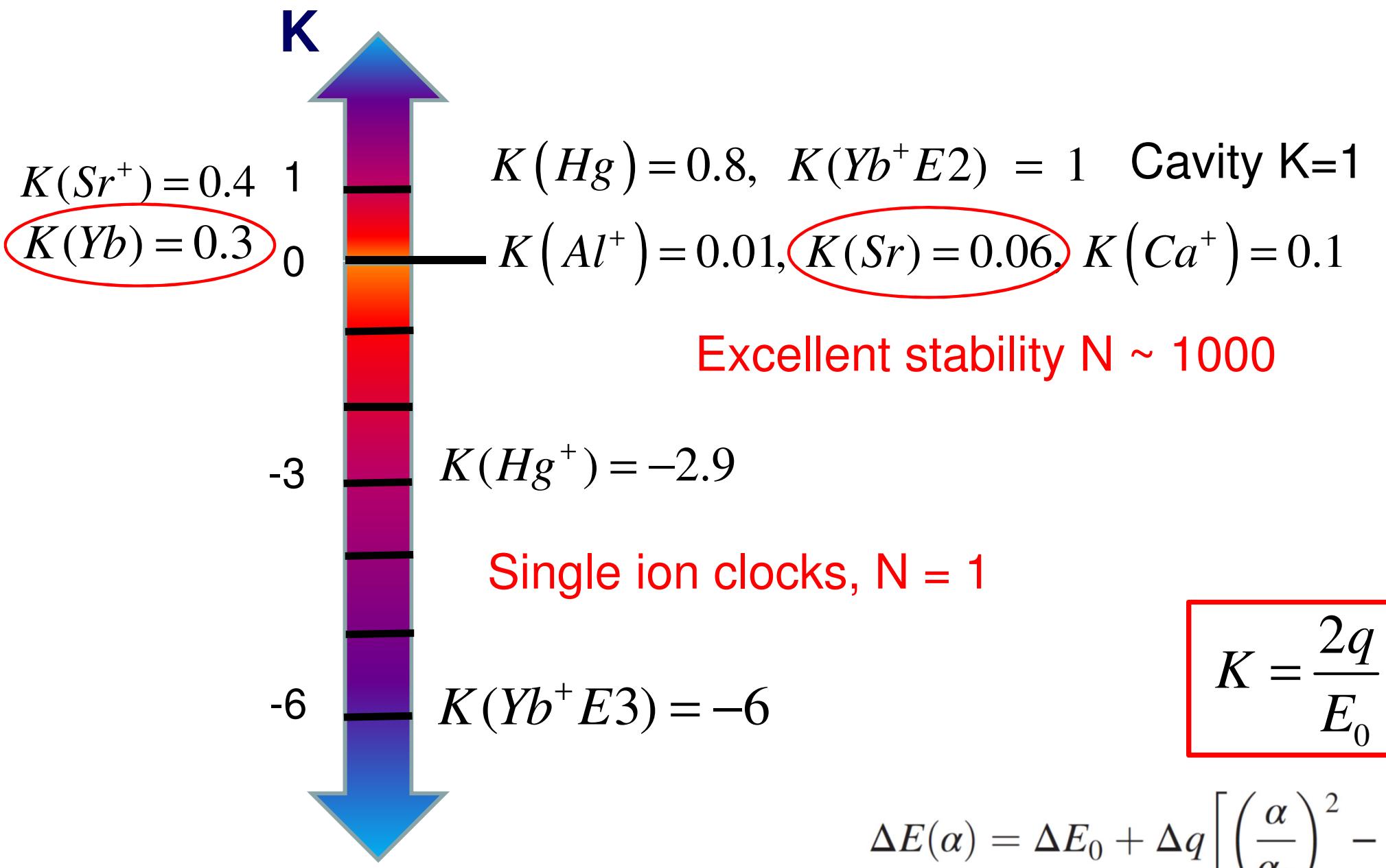
10^{-20}



Test of α -variation

Easier to measure large effects!

α -variation enhancement factors for current clocks



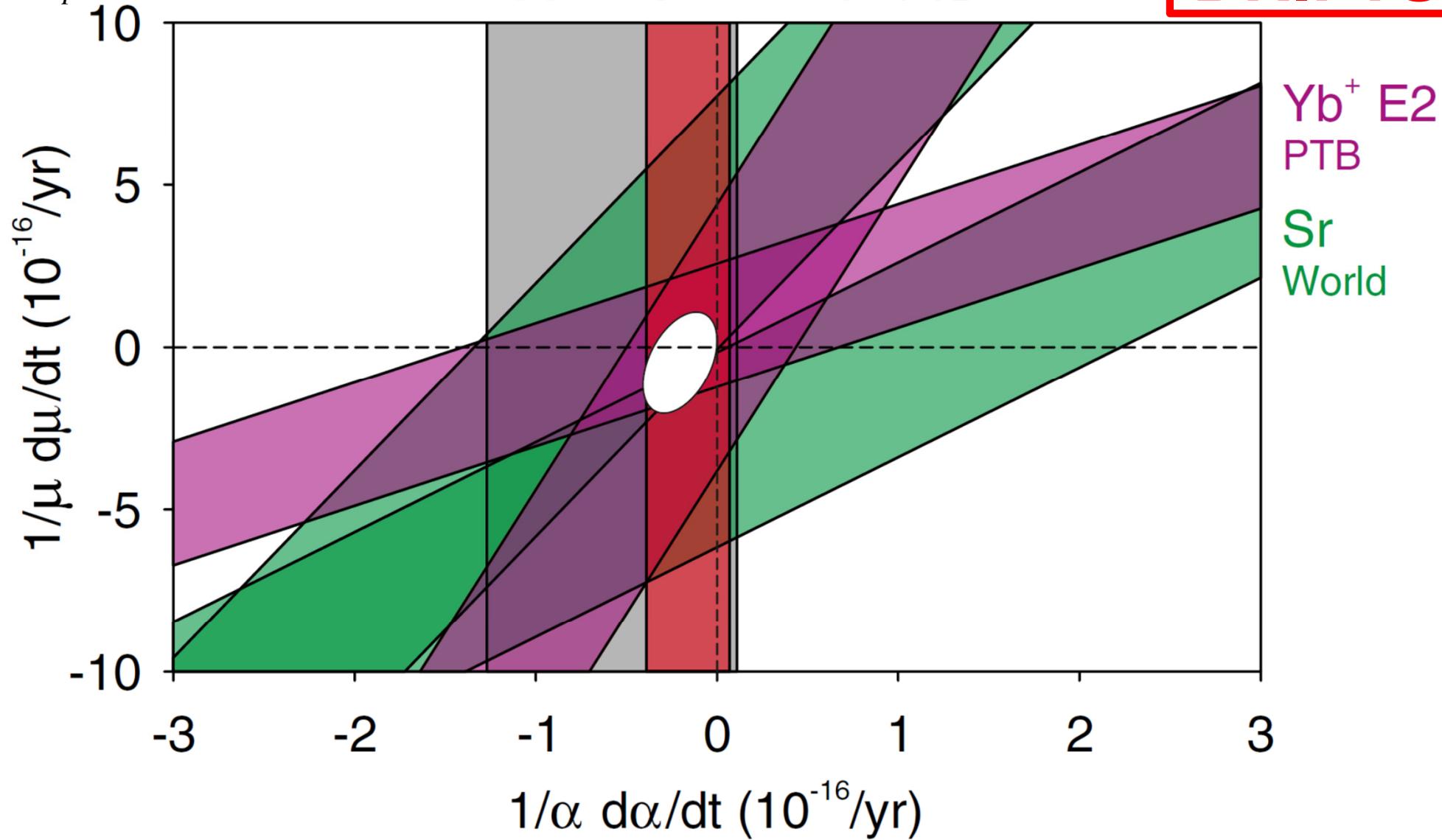
$$\Delta E(\alpha) = \Delta E_0 + \Delta q \left[\left(\frac{\alpha}{\alpha_0} \right)^2 - 1 \right]$$

CAN WE GET LARGE K IN NEW CLOCKS?

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

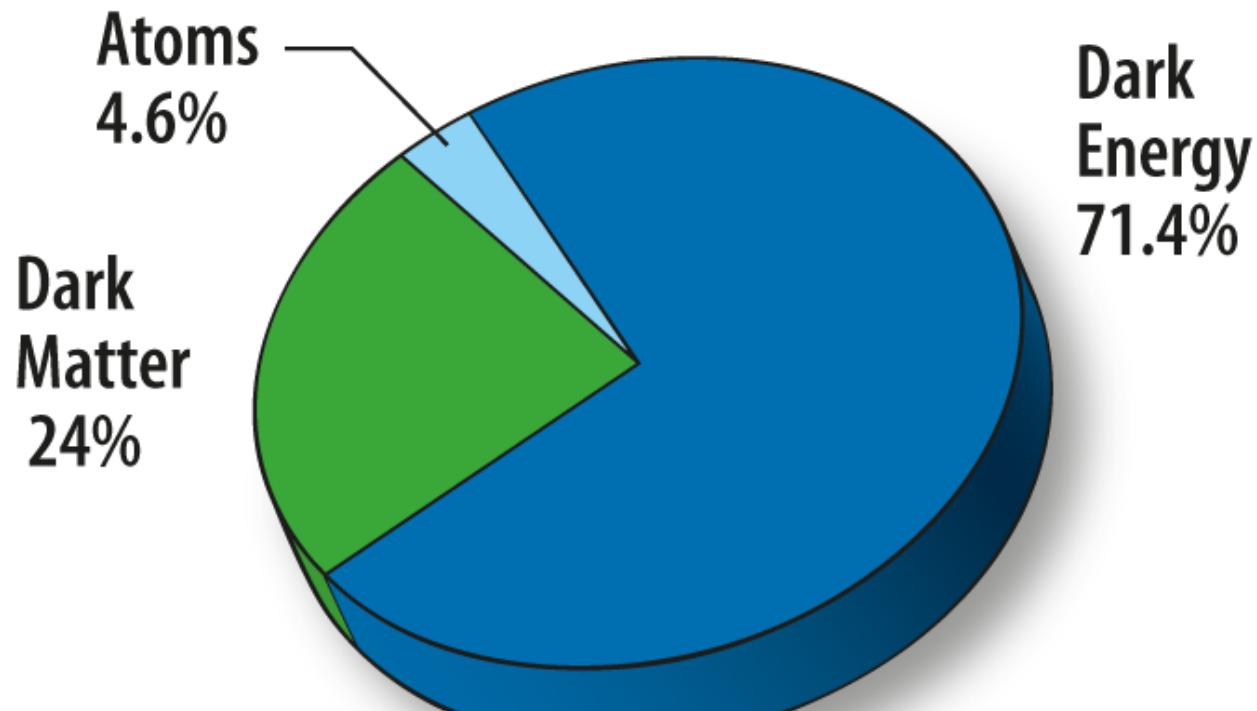
Dy UCB
Al⁺/Hg⁺ NIST
Hg⁺ NIST
Yb⁺ E3 PTB

**SLOW
DRIFTS**

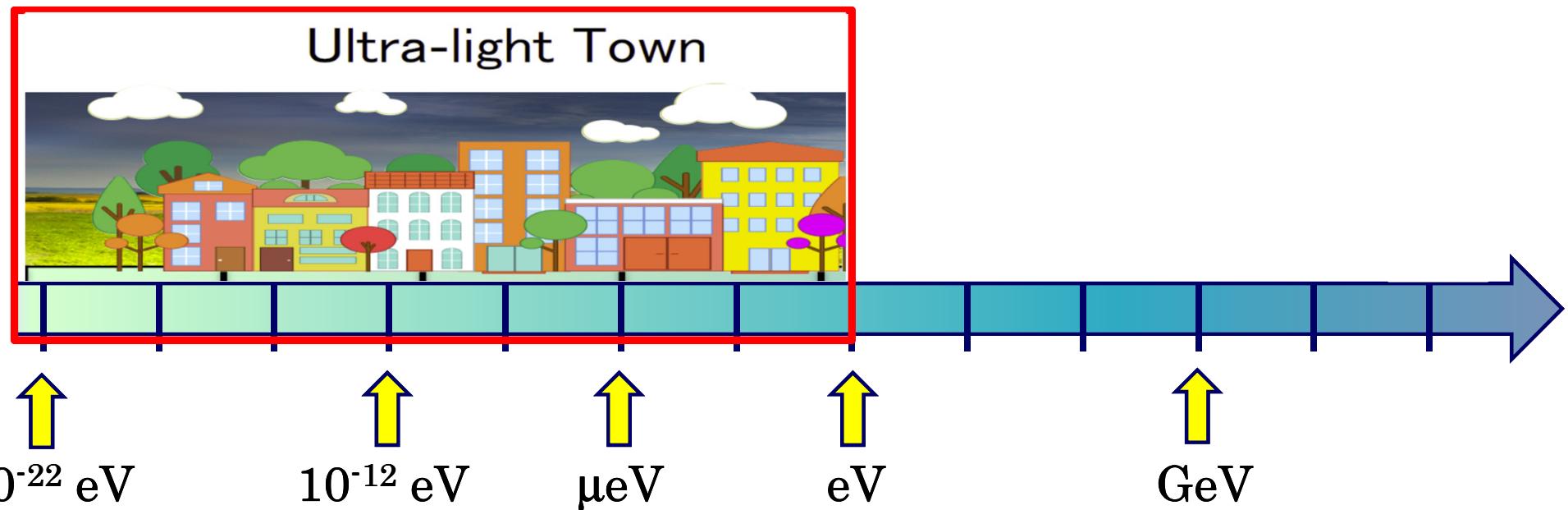


Constraints on temporal variations of α and μ from comparisons of atomic transition frequencies. Huntemann et al., PRL 113, 210802 (2014)

Атомные и ядерные часы - детекторы темной материи



Как найти сверхлегкую темную материю?

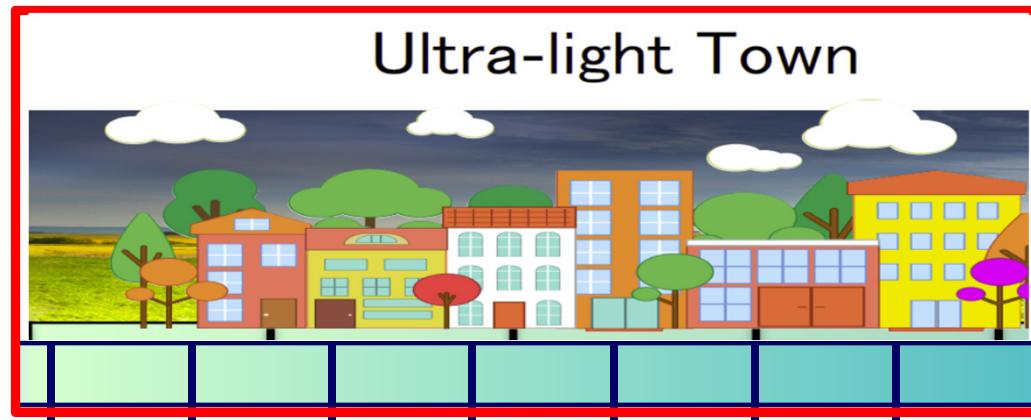


Сверхлегкая темная материя должна быть бозонной - Ферми
скорость для темной материи с массой > 10 eV выше
скорости убегания нашей Галактики.

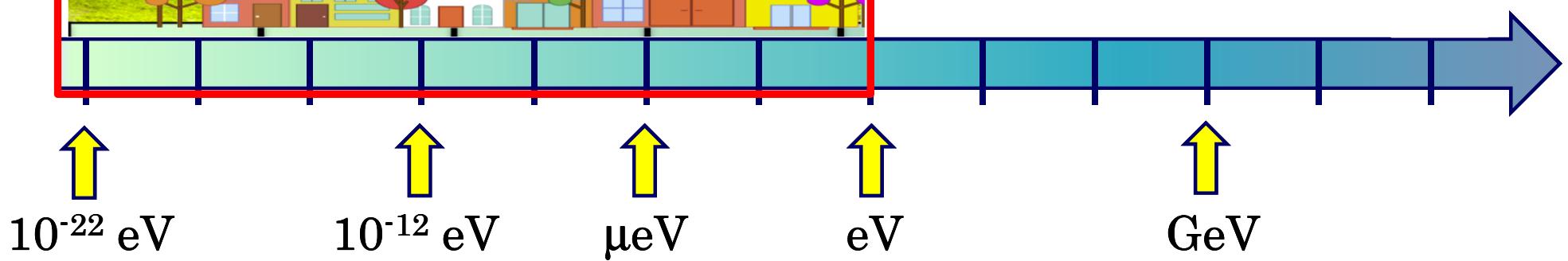
Бозонная темная материя с массой $m_\phi < 1\text{eV}$:

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

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

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

Dark matter coupling to the Standard Model

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

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

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

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

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

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

**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

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

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

Ultralight dark matter

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

DM virial velocities ~ 300 km/s

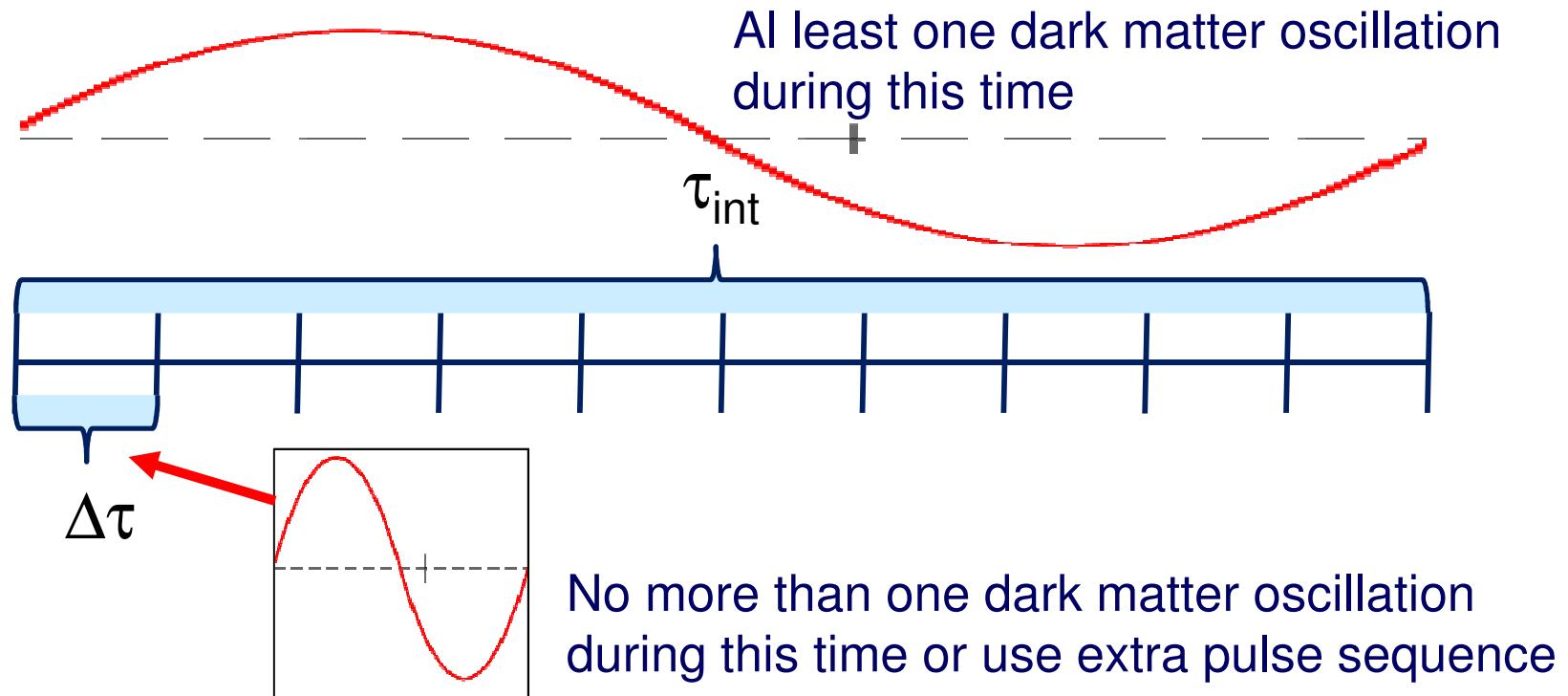
Dark matter parameters

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

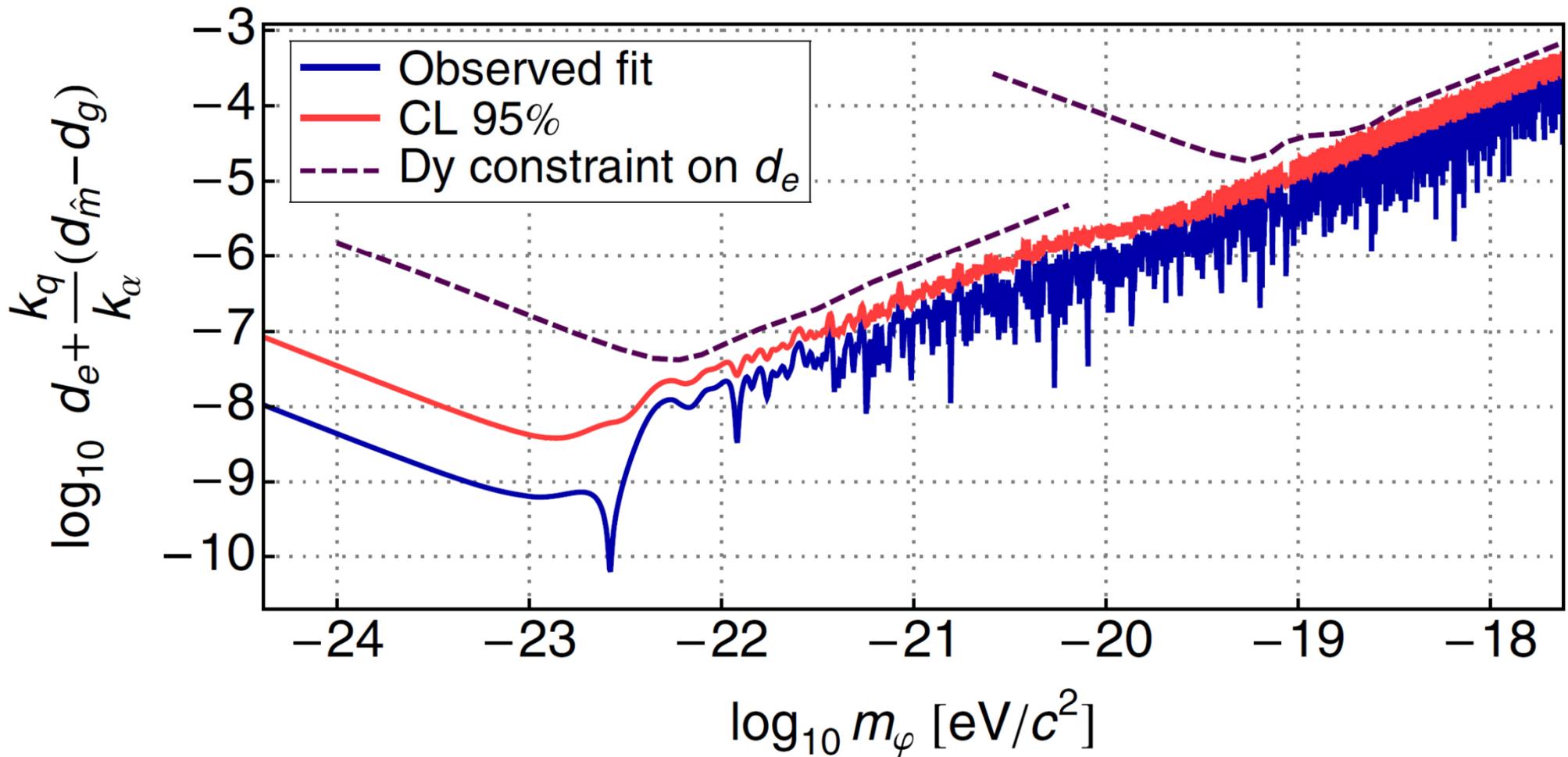
Make N such measurements, preferably regularly spaced



Detection signal:

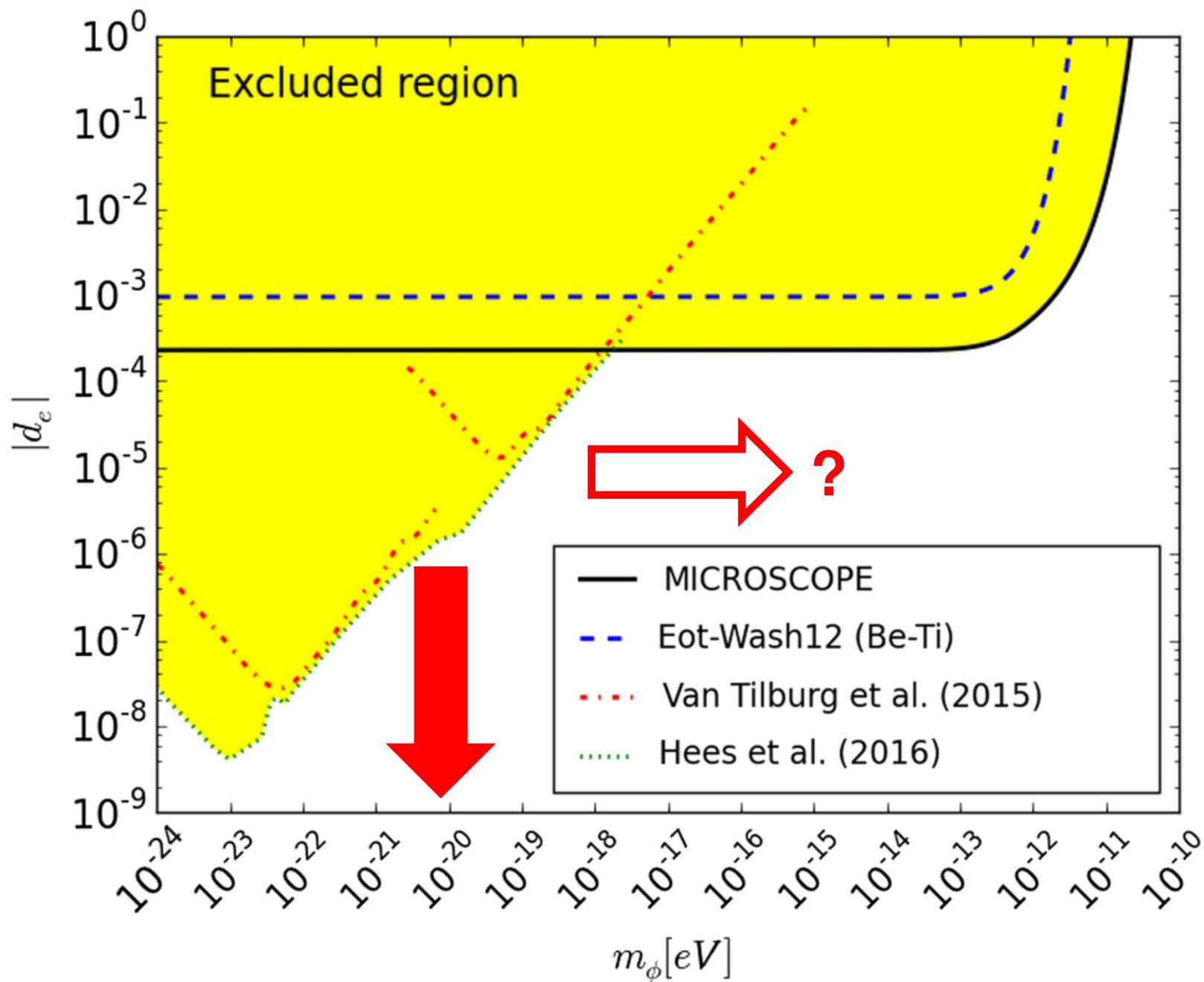
A peak with monochromatic frequency $f = 2\pi/m_\phi$ in the discrete Fourier transform of this time series.

Experimental results



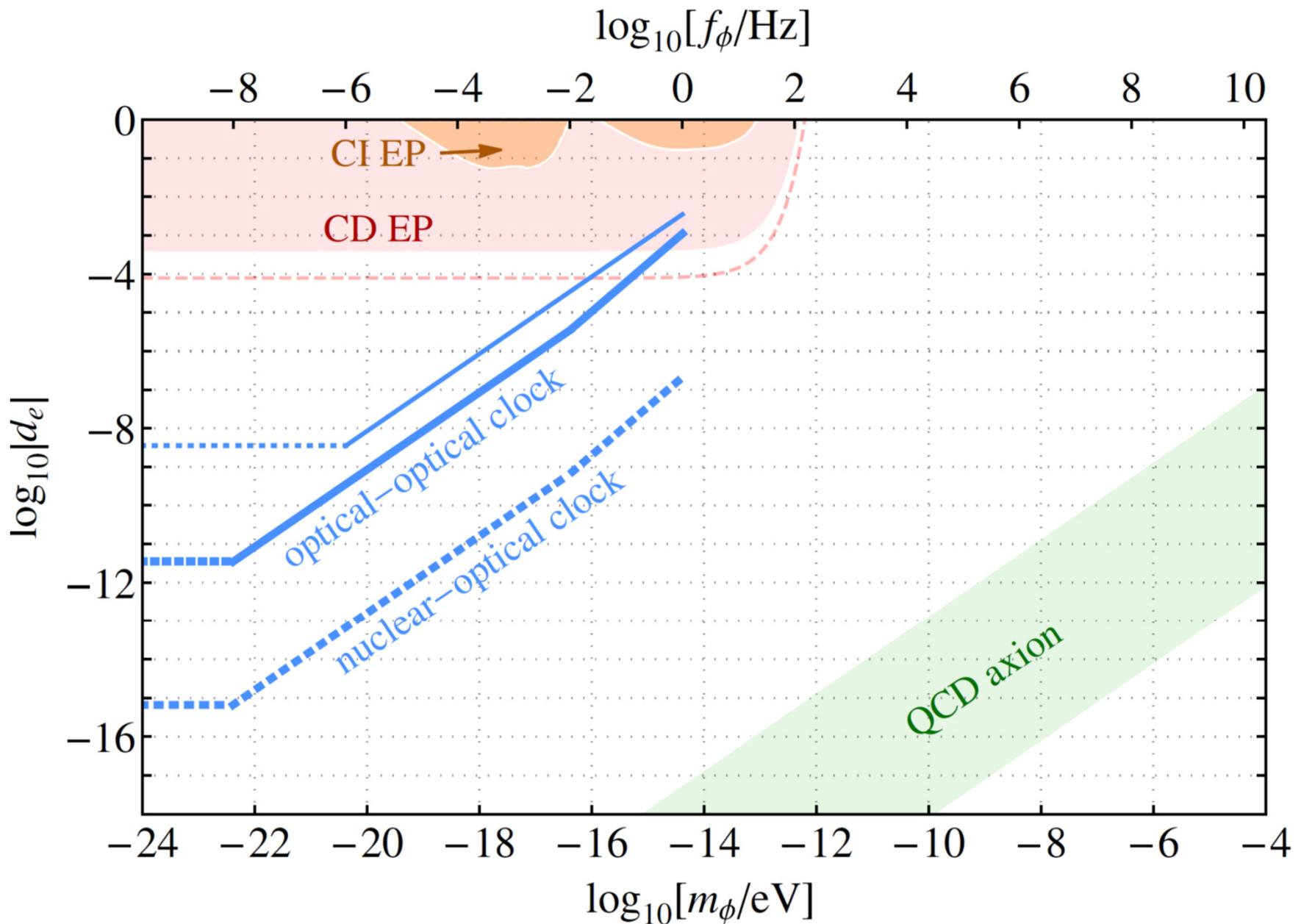
Dy: K. Van Tilburg, N. Leefer, L. Bougas, and D. Budker, Phys. Rev. Lett. 115, 011802 (2015).

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

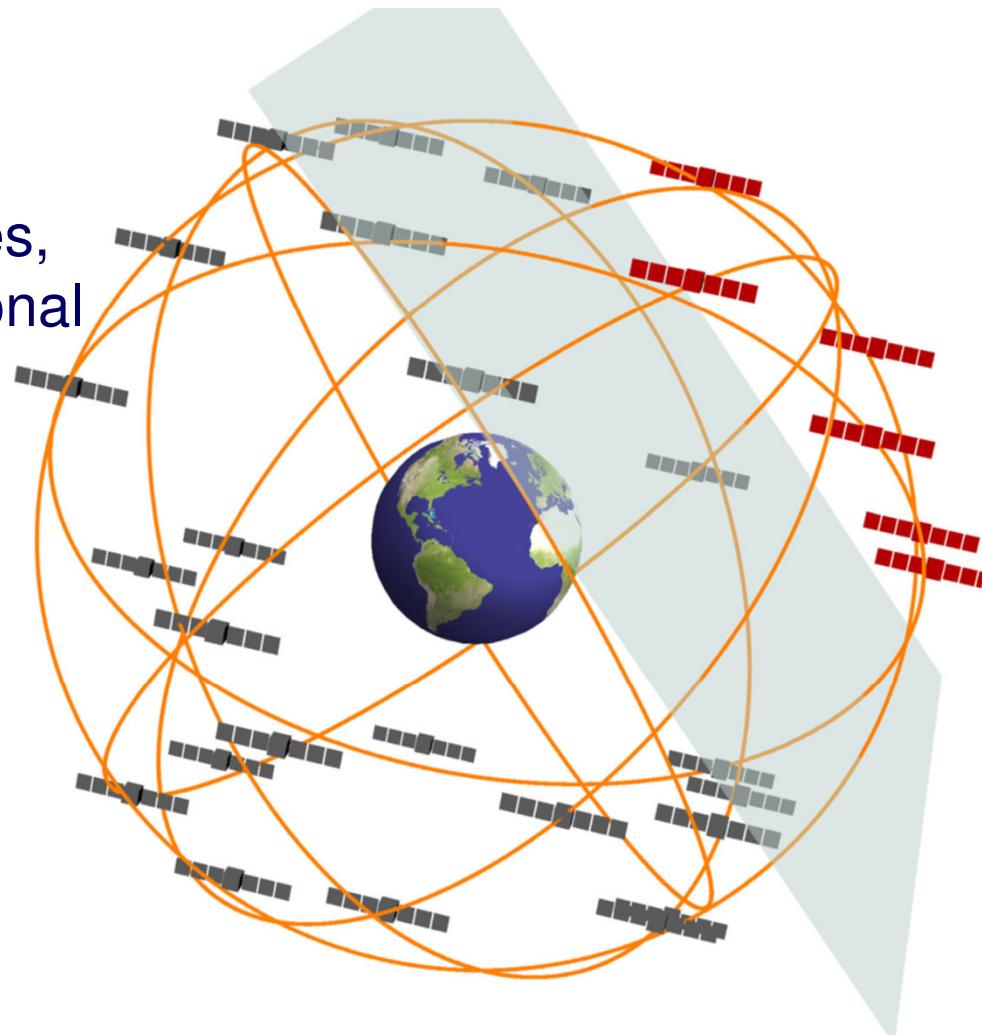


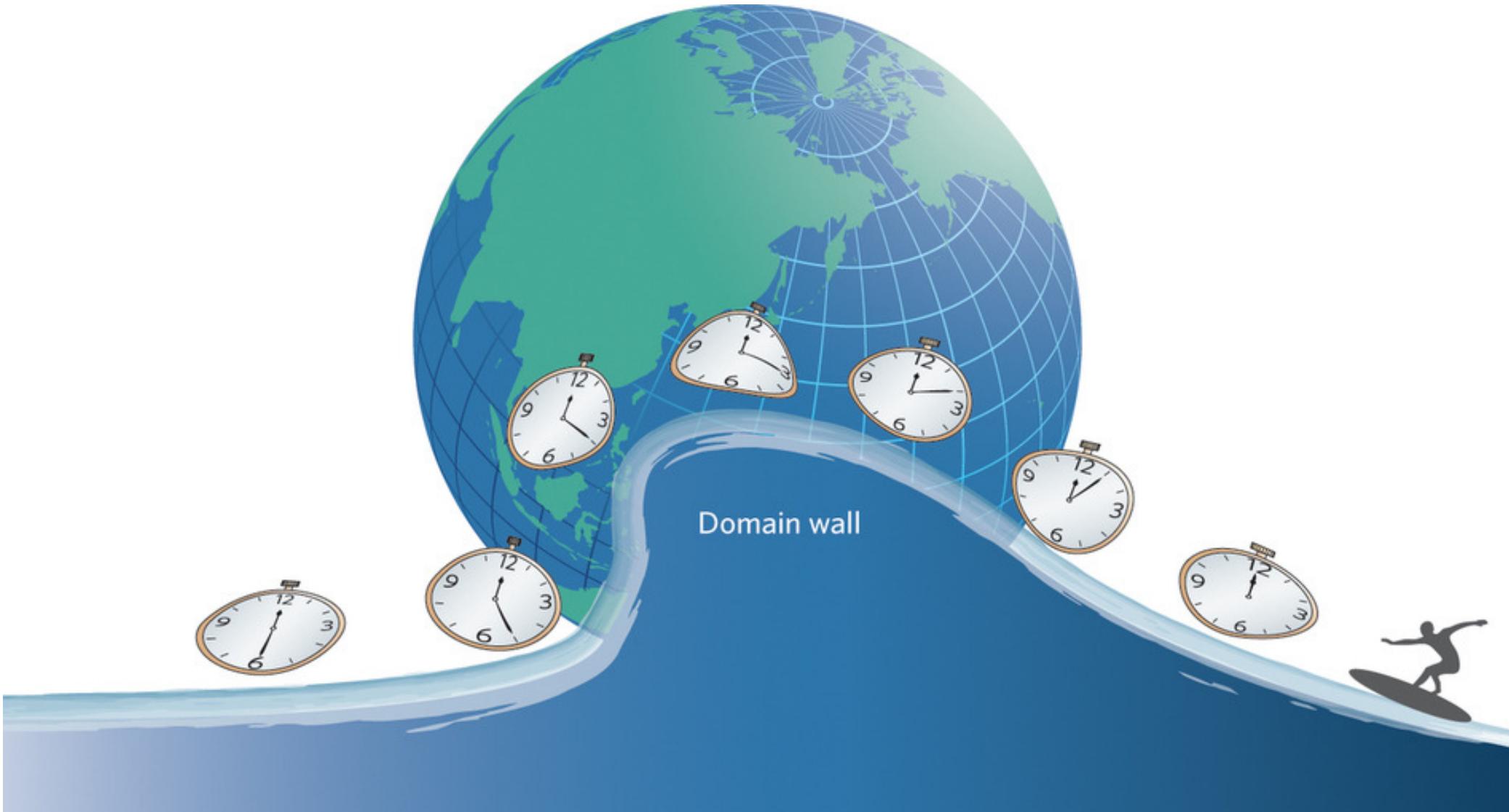
Hunting for topological dark matter with atomic clocks

A. Derevianko^{1*} and M. Pospelov^{2,3}

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

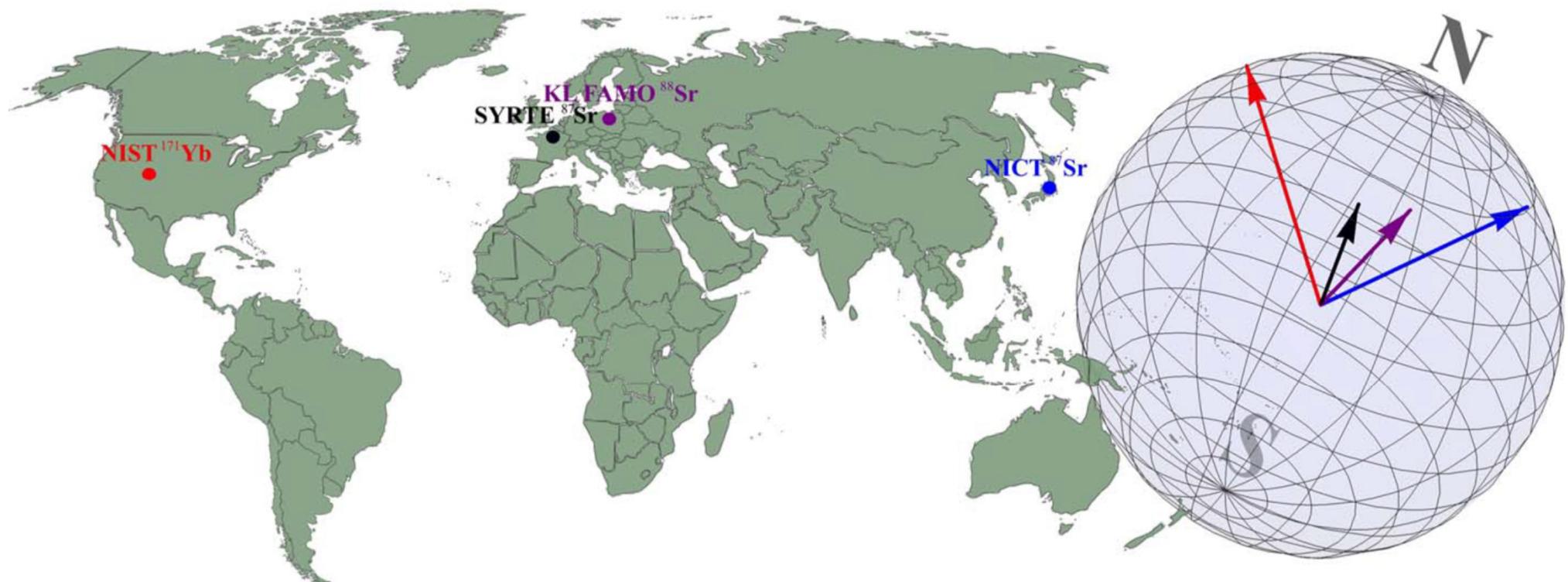
If they are large (size of the Earth) and frequent enough they may be detected by measuring changes in the synchronicity of a global network of atomic clocks, such as the Global Positioning System.



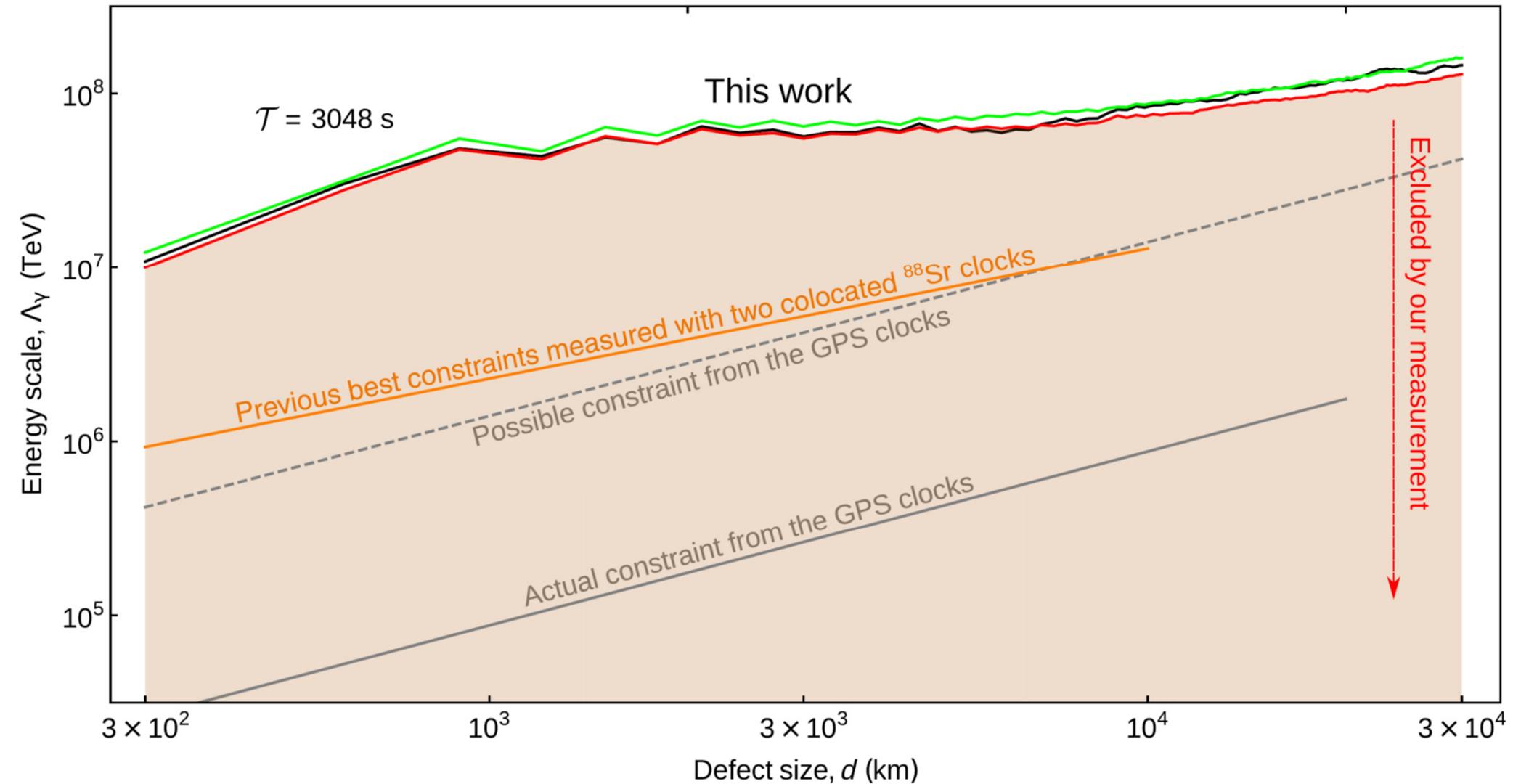


Topological dark matter may be detected by measuring changes in the synchronicity of a global network of atomic clocks, such as the Global Positioning System, as the Earth passes through the domain wall.

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



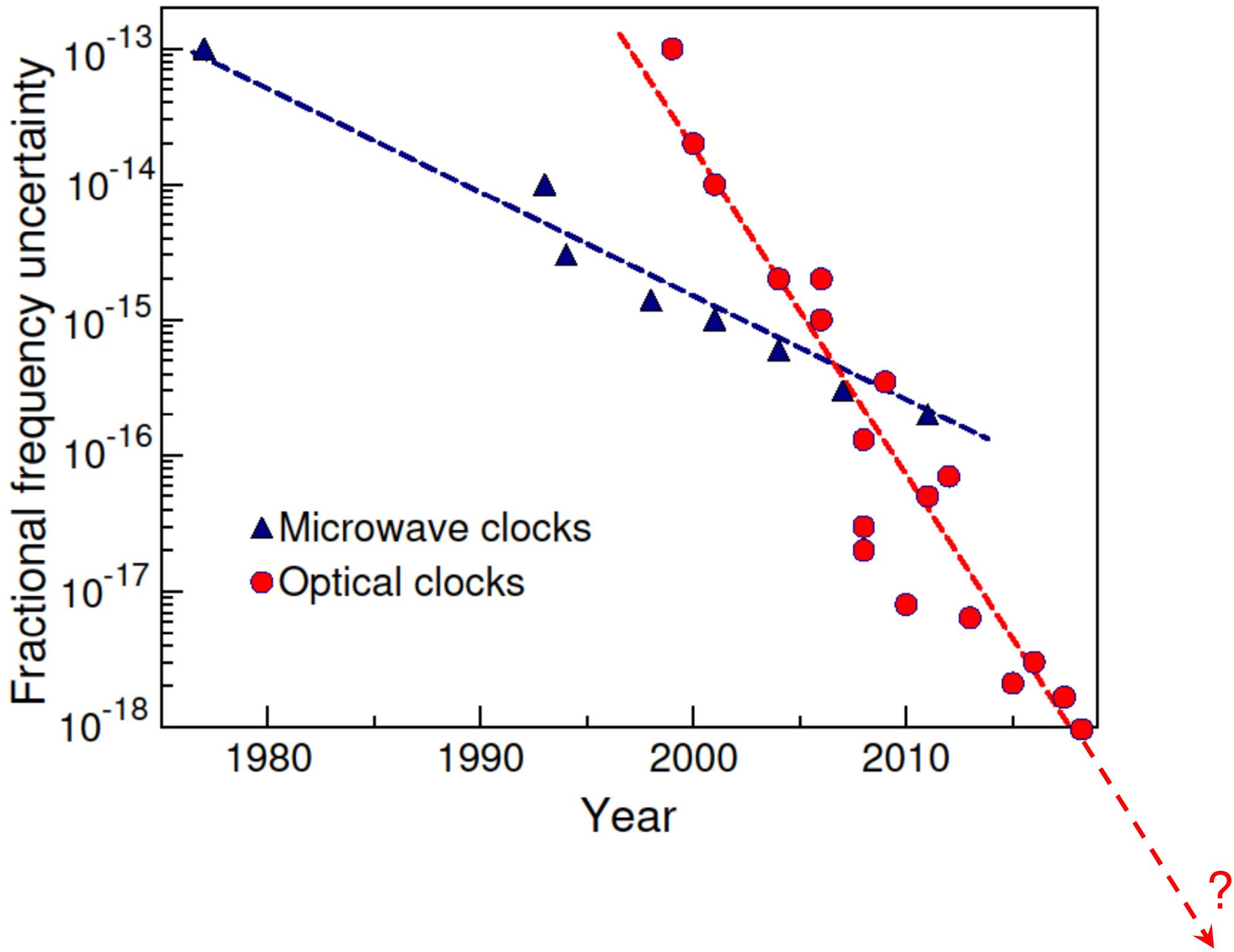
Constraints on the coupling of dark matter to electromagnetism.
 The energy scale Λ which inversely parametrizes the strength of the
 DM-SM coupling as a function of the wall width d .

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



Multipolar Polarizabilities and Hyperpolarizabilities in the Sr Optical Lattice Clock

S. G. Porsev,^{1,2} M. S. Safronova,^{1,3} U. I. Safronova,⁴ and M. G. Kozlov^{2,5}

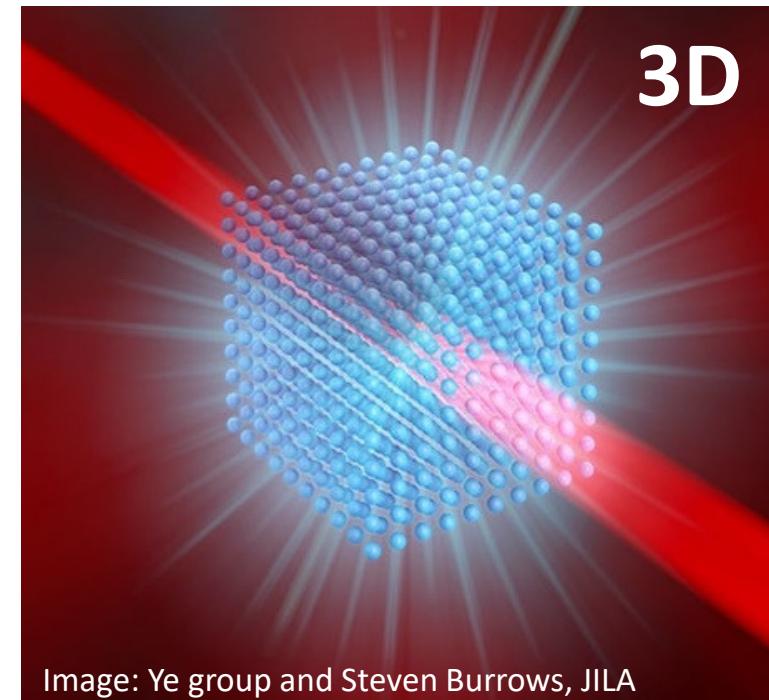
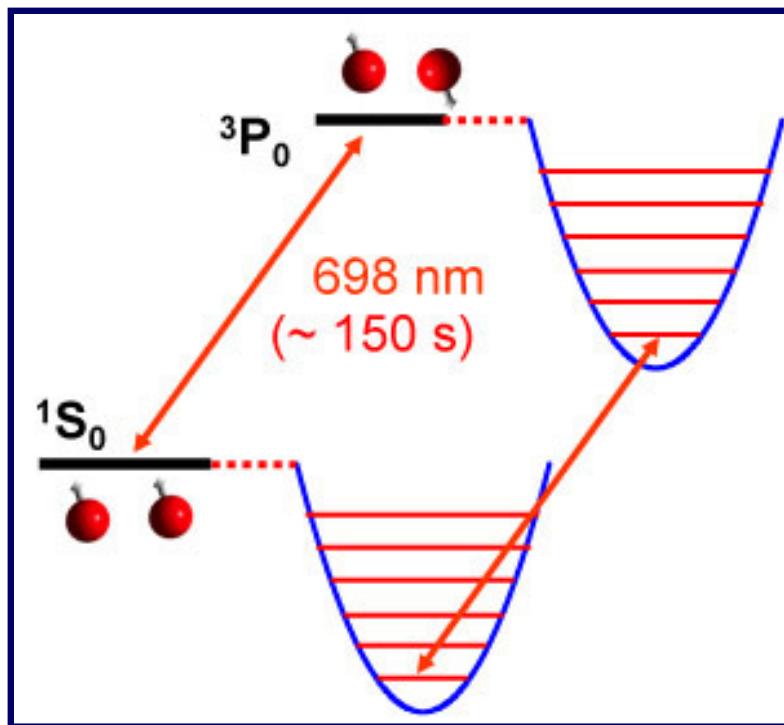
¹*Department of Physics and Astronomy, University of Delaware, Newark, Delaware 19716, USA*

²*Petersburg Nuclear Physics Institute of NRC “Kurchatov Institute”, Gatchina, Leningrad District 188300, Russia*

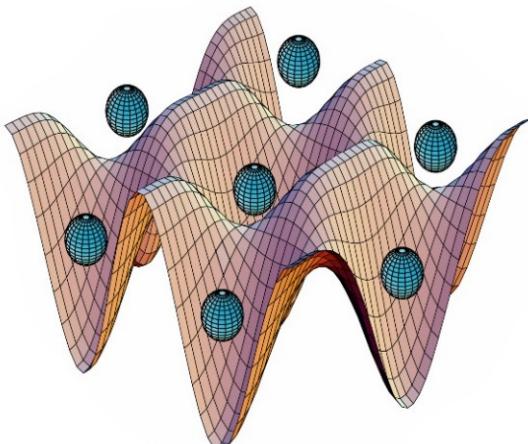
³*Joint Quantum Institute, National Institute of Standards and Technology and the University of Maryland, Gaithersburg, Maryland 20742, USA*

⁴*Physics Department, University of Nevada, Reno, Nevada 89557, USA*

⁵*St. Petersburg Electrotechnical University “LETI,” Prof. Popov Street 5, 197376 St. Petersburg, Russia*



Lattice clock operate at magic wavelengths



$$U \propto \alpha(\lambda) \leftarrow \begin{array}{l} \text{Frequency-dependent} \\ \text{electric dipole} \end{array} \text{ polarizability}$$

$$U_A \approx U_B \quad \text{at the magic wavelength}$$

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

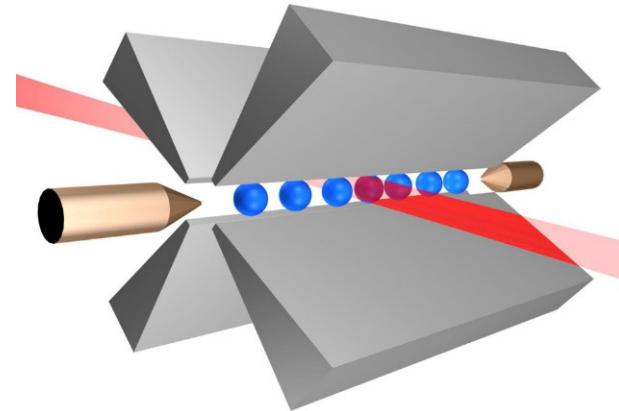
$$U(\omega) \approx -[\alpha^{E1}(\omega) - \{\alpha^{M1}(\omega) + \alpha^{E2}(\omega)\}k^2x^2] \mathcal{E}_0^2 - \beta(\omega) \mathcal{E}_0^4.$$
$$k = \frac{\omega}{c}$$

Multipolar polarizability shifts

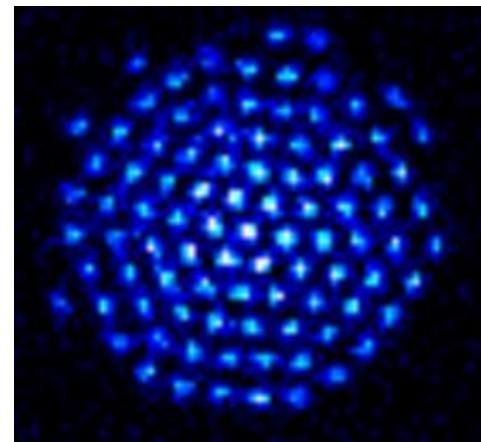
- Magnetic-dipole polarizability $\alpha^{M1}(\omega)$
- Electric-quadrupole polarizability $\alpha^{E2}(\omega)$

Hyperpolarizability $\beta(\omega)$

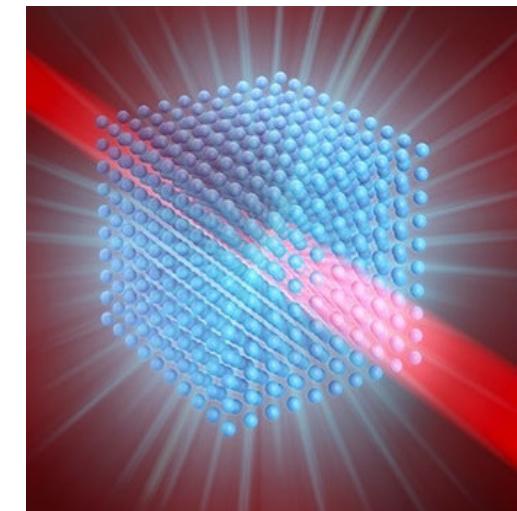
The Future Advances in Atomic Clocks



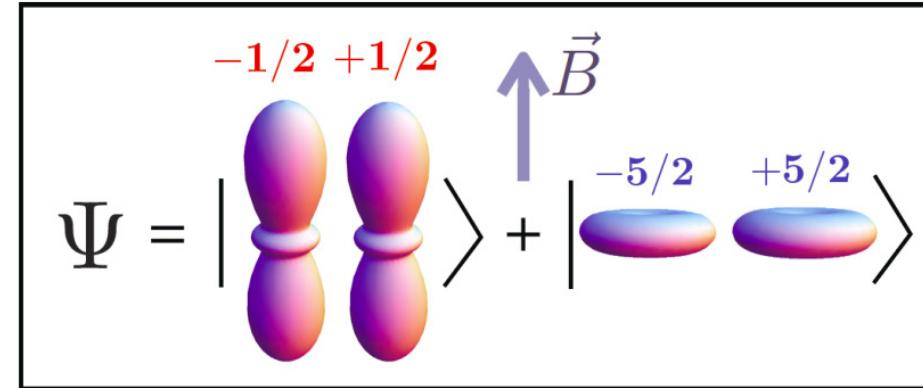
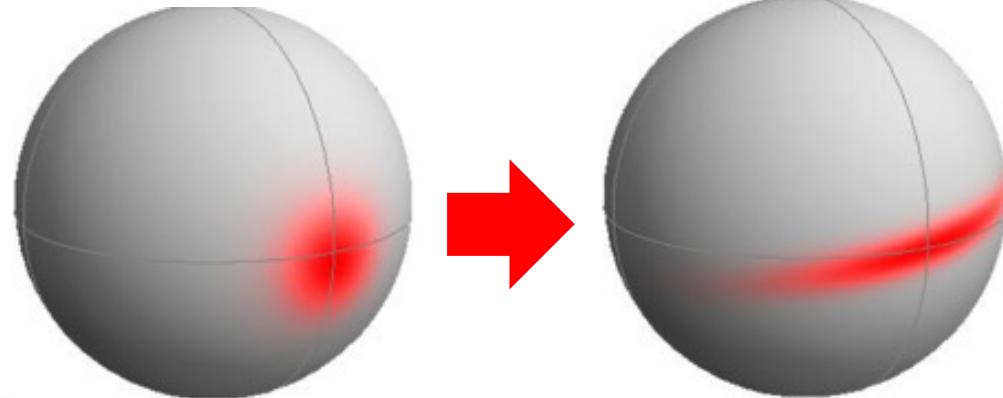
Ion chains



Large ion crystals



3D optical lattice clocks

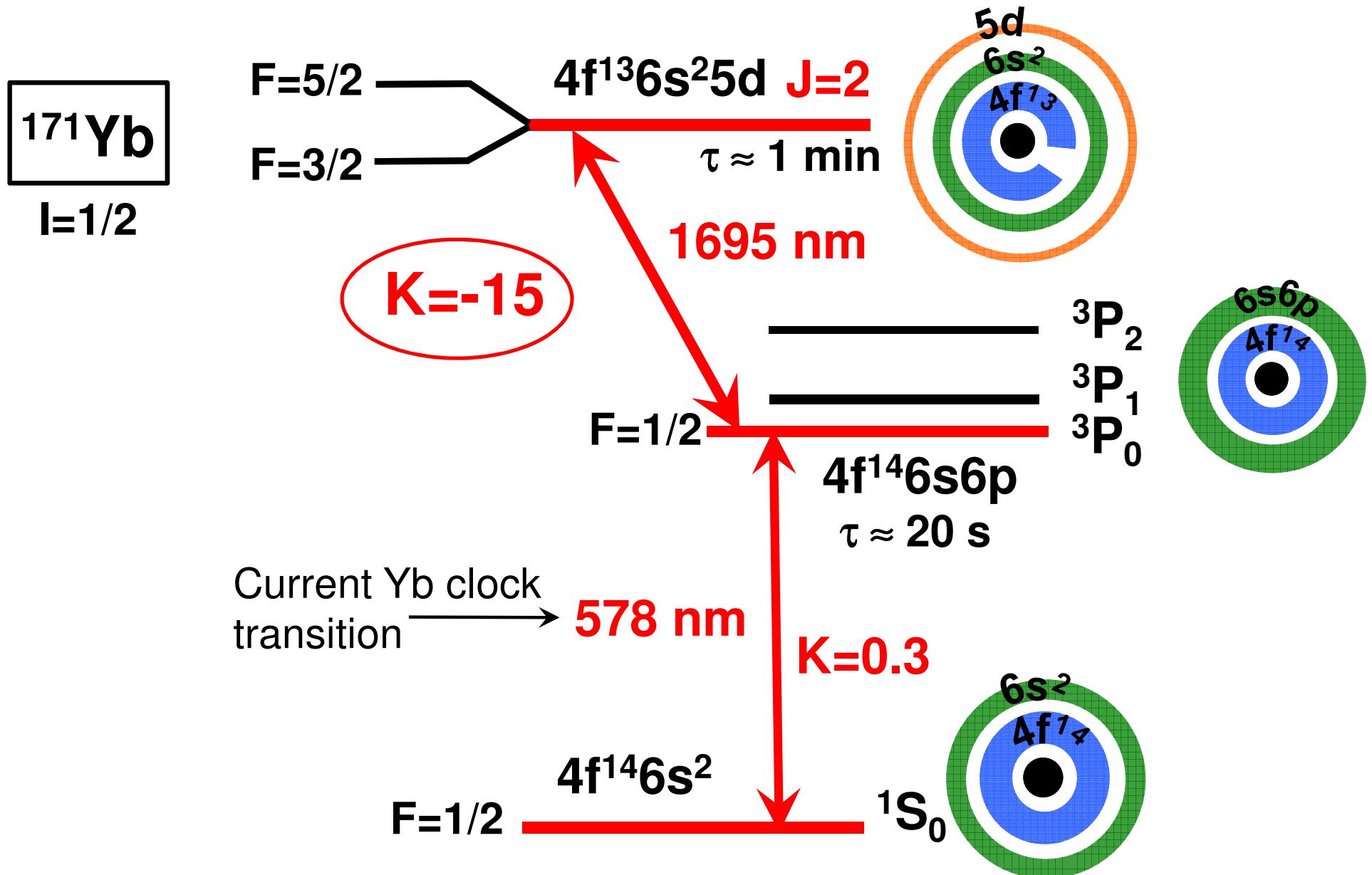


Measurements beyond the quantum limit

Entangled clocks

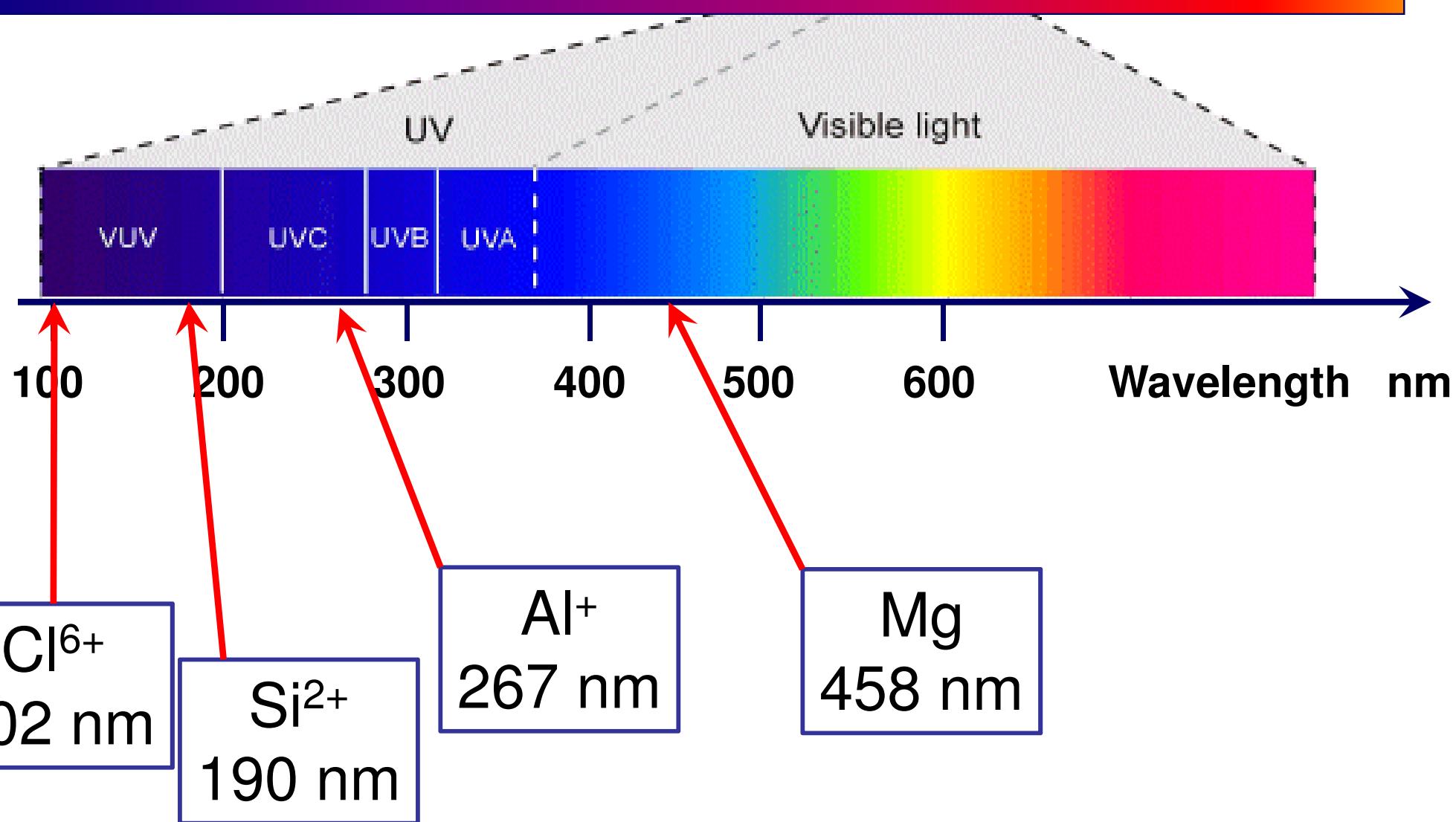
Orders of magnitude improvements with current clocks

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 ???



$3s^2 \text{ } ^1\text{S}_0 - 3s3p \text{ } ^3\text{P}_0$ transition in Mg-like ions

Atomic Properties of the Elements

Group
1
IA

1	$^2S_{1/2}$
H	Hydrogen 1.00794 $1s^1$ 13.984

1

3	$^2S_{1/2}$
Li	Lithium 6.941 $1s^2 2s^1$ 5.3917

2

11	$^2S_{1/2}$
Na	Sodium 22.989770 [Ne]3s ¹ 5.1391

3

12	1S_0
Mg	Magnesium 24.3050 [Ne]3s ² 7.6462

4

19	$^2S_{1/2}$
K	Potassium 39.0983 [Ar]4s ¹ 4.3407

5

37	$^2S_{1/2}$
Rb	Rubidium 85.4678 [Kr]5s ¹ 4.1771

J. C. Berengut et al., Phys.
Rev. Lett. 105, 120801 (2010).M. S. Safronova et al., Phys.
Rev. Lett. 113, 030801 (2014).3 4 5 6 7 8 9 10 11 12
IIIB IVB VB VIB VIIIB VIII IB IIB

NIST

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Physics Laboratory physics.nist.gov		Standard Reference Data Group www.nist.gov/srd				
13	III A	14	IV A	15	V A	16
5	$^2P_{1/2}$	6	3P_0	7	$^4S_{3/2}$	8
B		C		N		O
Boron 10.811 $1s^2 2s^2 2p$ 8.2980		Carbon 12.0107 $1s^2 2s^2 2p^2$ 11.2603		Nitrogen 14.0057 $1s^2 2s^2 2p^3$ 14.5341		Oxygen 15.9994 $1s^2 2s^2 2p^4$ 13.6181
17	VII A	18		9	$^2P_{3/2}$	10
13	$^2P_{1/2}$	14	3P_0	15	$^4S_{3/2}$	16
Al	Aluminum 26.981538 [Ne]3s ² 3p ¹ 5.9858	Si	Silicon 28.0855 [Ne]3s ² 3p ² 8.1517	P	Phosphorus 30.973761 [Ne]3s ² 3p ⁴ 10.4867	S
Sulfur 32.065 [Ne]3s ² 3p ⁴ 10.3600		Cl	Chlorine 35.453 [Ne]3s ² 3p ⁵ 12.9676	Ar	Argon 39.948 [Ne]3s ² 3p ⁶ 15.7595	
32	3P_0	33	$^4S_{3/2}$	34	3P_2	35
Ga	Gallium 69.723 [Ar]3d ¹⁰ 4s ² 7.8994	Ge	Germanium 72.64 [Ar]3d ¹⁰ 4s ² 7.8786	As	Arsenic 74.92160 [Ar]3d ¹⁰ 4s ⁴ p ³ 9.7524	Br
Tellurium 127.60 [Ar]3d ¹⁰ 5s ² 5p ⁴ 10.4513		Se	Selenium 78.96 [Ar]3d ¹⁰ 4s ⁴ p ⁴ 11.8138	Kr	Krypton 83.798 [Ar]3d ¹⁰ 4s ⁴ p ⁶ 13.9995	
53	$^2P_{3/2}$	54	1S_0			
I	Iodine 126.90447 [Ar]3d ¹⁰ 5s ² 5p ⁵ 10.4513	Xe	Xenon 131.293 [Ar]3d ¹⁰ 5s ² 5p ⁶ 12.1298			

Sn

Sn –like Ba⁶⁺Sn-like Pr⁹⁺ $5p6s\ ^3P_0$ $5p^2\ ^1S_0$ $5p4f\ J=3$ $5p^2\ ^1S_0$ 1D_2

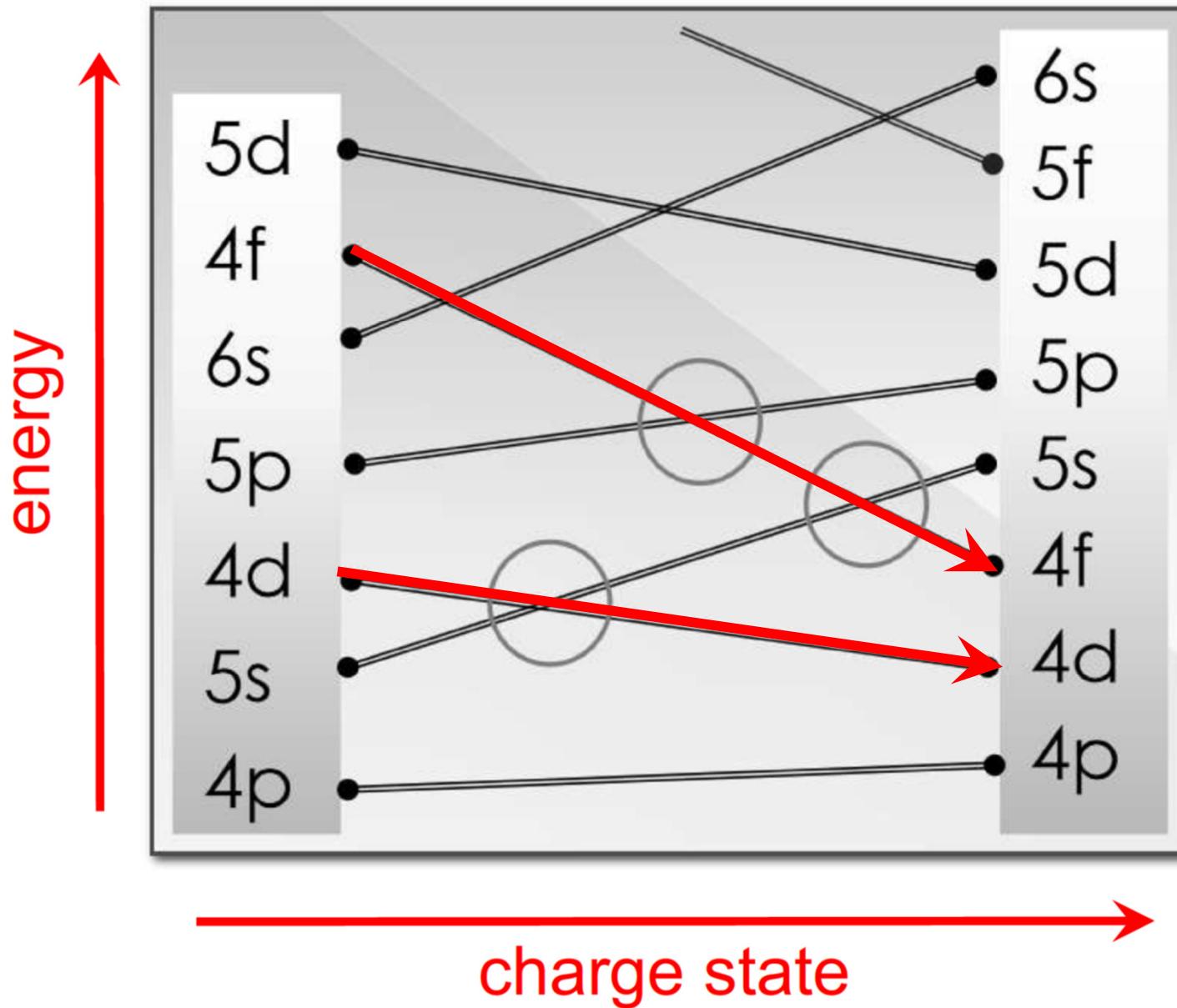
495(13) nm

 1D_2 $^3P_{1,2}$ $5p^2\ ^3P_{0,1,2}$ 3P_0

289 nm

163 nm

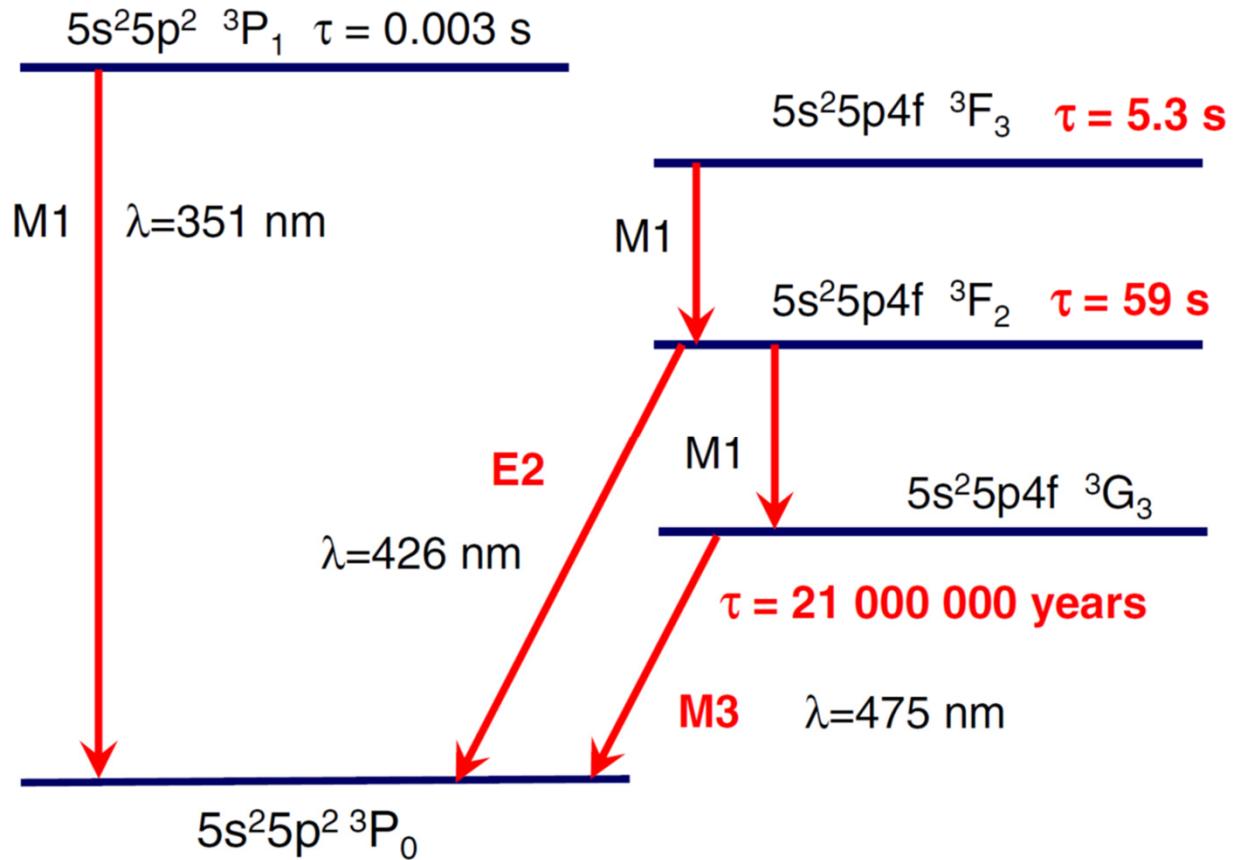




Schematic of the shell order in neutral atoms (left) and in hydrogen-like ions (right). One can see that the “diving” of 4d and 4f shells result in level crossings in the areas marked by circles.

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

Group
1
IAPERIODIC TABLE
Atomic Properties of the Elements

1

2

3

Period

19 ⁻² S _{1/2} K Potassium 39.0983 [Ar]4s ¹ 4.3407	20 ⁻¹ S ₀ Ca Calcium 40.078 [Ar]4s ² 6.1132	21 ⁻² D _{3/2} Sc Scandium 44.95910 [Ar]3d ¹ 4s ² 6.5615	22 ⁻³ F ₂ Ti Titanium 47.867 [Ar]3d ² 4s ² 6.8281	23 ⁻⁴ F _{3/2} V Vanadium 50.9415 [Ar]3d ³ 4s ² 6.7665	24 ⁻⁷ S ₃ Cr Chromium 51.9961 [Ar]3d ⁵ 4s ¹ 7.6740	25 ⁻⁶ S _{5/2} Mn Manganese 54.938049 [Ar]3d ⁵ 4s ² 7.4340	26 ⁻⁵ D ₄ Fe Iron 55.845 [Ar]3d ⁶ 4s ² 7.9024	27 ⁻⁴ F _{9/2} Co Cobalt 58.933200 [Ar]3d ⁷ 4s ² 7.8810	28 ⁻³ F ₄ Ni Nickel 58.6934 [Ar]3d ⁸ 4s ² 7.6398	29 ⁻² S _{1/2} Cu Copper 63.546 [Ar]3d ¹⁰ 4s ¹ 7.7264	30 ⁻¹ S ₀ Zn Zinc 65.409 [Ar]3d ¹⁰ 4s ² 9.3942	31 ⁻² P _{1/2} Ga Gallium 69.723 [Ar]3d ¹⁰ 4s ² 4p ¹ 9.5993	32 ⁻³ P ₀ Ge Germanium 72.64 [Ar]3d ¹⁰ 4s ² 4p ² 7.8994	33 ⁻⁴ S _{3/2} As Arsenic 74.92160 [Ar]3d ¹⁰ 4s ² 4p ³ 9.7886	34 ⁻³ P ₂ Se Selenium 78.96 [Ar]3d ¹⁰ 4s ² 4p ⁴ 9.7524	35 ⁻² P _{3/2} Br Bromine 79.904 [Ar]3d ¹⁰ 4s ² 4p ⁵ 11.8138	36 ⁻¹ S ₀ Kr Krypton 83.798 [Ar]3d ¹⁰ 4s ² 4p ⁶ 13.9996
37 ⁻² S _{1/2} Rb Rubidium 85.4678 [Kr]5s ¹ 4.1771	38 ⁻¹ S ₀ Sr Strontium 87.62 [Kr]5s ² 5.6949	39 ⁻² D _{3/2} Y Yttrium 88.90585 [Kr]4d ⁵ s ² 6.2173	40 ⁻⁶ D _{1/2} Zr Zirconium 91.224 [Kr]4d ⁴ 5s ² 6.6339	41 ⁻⁷ S ₃ Nb Niobium 92.90538 [Kr]4d ⁴ 5s ¹ 6.7589	42 ⁻⁶ S _{5/2} Tc Technetium 95.94 [Kr]4d ⁵ 5s ² 7.0000	43 ⁻⁴ F ₅ Ru Ruthenium 101.07 [Kr]4d ⁷ 5s ¹ 7.3665	44 ⁻⁵ F _{9/2} Rh Rhodium 102.90550 [Kr]4d ⁸ 5s ¹ 7.5762	45 ⁻¹ S ₀ Pd Palladium 106.42 [Kr]4d ⁹ 5s ¹ 8.3369	46 ⁻² S _{1/2} Ag Silver 107.8682 [Kr]4d ¹⁰ 5s ¹ 8.9938	47 ⁻³ S _{1/2} Cd Cadmium 112.411 [Kr]4d ¹⁰ 5s ² 9.1148	48 ⁻² P _{1/2} In Indium 114.818 [Kr]4d ¹⁰ 5s ² 4p ¹ 10.4375	49 ⁻³ P ₀ Sn Tin 118.710 [Kr]4d ¹⁰ 5s ² 4p ² 10.4375	50 ⁻⁴ S _{3/2} Sb Antimony 121.760 [Kr]4d ¹⁰ 5s ² 4p ³ 10.4375	51 ⁻⁵ P ₂ Te Tellurium 127.60 [Kr]4d ¹⁰ 5s ² 4p ⁴ 10.4375	52 ⁻³ P _{3/2} I Iodine 128.92447 [Kr]4d ¹⁰ 5s ² 4p ⁵ 10.4375	54 ⁻¹ S ₀ Xe Xenon 131.293 [Kr]4d ¹⁰ 5s ² 4p ⁶ 10.4375	
55 ⁻² S _{1/2} Cs Cesium 132.90545 [Xe]6s ¹ 3.8939	56 ⁻¹ S ₀ Ba Barium 137.327 [Xe]6s ² 5.2117	72 ⁻³ F ₂ Hf Hafnium 178.49 [Xe]4f ¹⁴ 5d ² 6s ² 6.8251	73 ⁻⁴ F ₂ Ta Tantalum 191.9479 [Xe]4f ¹⁴ 5d ³ 6s ² 7.5400	74 ⁻⁵ D _{3/2} W Tungsten 183.84 [Xe]4f ¹⁴ 5d ⁴ 6s ² 7.8640	75 ⁻⁶ S _{5/2} Re Rhenium 190.23 [Xe]4f ¹⁴ 5d ⁵ 6s ² 7.8335	76 ⁻⁵ D _{5/2} Os Osmium 192.217 [Xe]4f ¹⁴ 5d ⁶ 6s ² 8.4382	77 ⁻⁶ F _{9/2} Ir Iridium 195.07 [Xe]4f ¹⁴ 5d ⁷ 6s ² 8.9570	78 ⁻³ D _{3/2} Pt Platinum 196.9655 [Xe]4f ¹⁴ 5d ⁸ 6s ² 9.2255	79 ⁻² S _{1/2} Au Gold 196.9655 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 9.2255	80 ⁻¹ S ₀ Hg Mercury 200.59 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 10.4375	81 ⁻² P _{1/2} Hg Mercury 200.59 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 10.4375	82 ⁻³ P ₀ Hg Mercury 200.59 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 10.4375	83 ⁻⁴ S _{3/2} Hg Mercury 200.59 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 10.4375	84 ⁻⁵ P ₂ Hg Mercury 200.59 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 10.4375	85 ⁻⁶ D _{3/2} Hg Mercury 200.59 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 10.4375		
87 ⁻² S _{1/2} Fr Francium (223) [Rn]7s ¹ 4.0727	88 ⁻¹ S ₀ Ra Radium (226) [Rn]7s ² 5.2784	104 ⁻³ F ₂ ? Rf Rutherfordium (261) [Rn]5f ¹⁴ 6d ² 7s ² 6.0?	105 ⁻⁶ D _{1/2} Db Dubnium (262)	106 ⁻⁷ S ₃ Sg Seaborgium (266)	107 ⁻⁸ F ₀ Bh Bohrium (264)	108 ⁻⁹ F ₀ Hs Meitnerium (277)	109 ⁻¹⁰ F ₀ Mt Ununnilium (268)	110 ⁻¹¹ F ₀ Uun Ununnilium (281)	111 ⁻¹² F ₀ Uuu Ununnilium (282)	112 ⁻¹³ F ₀ Uub Ununnilium (285)	114 ⁻¹⁴ F ₀ Uuq Ununquadium (289)	116 ⁻¹⁵ F ₀ Uuh Ununhexium (292)	117 ⁻¹⁶ F ₀ Uus Ununhexium (293)				

Atomic Number
Symbol
Name
Atomic Weight⁺
Ground-state Configuration
Ionization Energy (eV)

Ground-state Level
Lanthanides
Actinides

57 ⁻² D _{5/2} La Lanthanum 138.9055 [Xe]5d ¹ 6s ² 5.5769	58 ⁻¹ G ₄ Ce Cerium 140.116 [Xe]4f ¹ 5d ⁶ 6s ² 5.5387	59 ⁻¹ I _{9/2} Pr Praseodymium 140.90765 [Xe]4f ² 5d ⁶ 6s ² 5.572	60 ⁻¹ I ₄ Nd Neodymium 144.24 [Xe]4f ³ 5d ⁶ 6s ² 5.5620	61 ⁻¹ H _{5/2} Pm Promethium 144.92 [Xe]4f ⁴ 5d ⁶ 6s ² 5.5524	62 ⁻¹ F ₀ Sm Samarium 150.36 [Xe]4f ⁵ 5d ⁶ 6s ² 5.5424	63 ⁻¹ S _{7/2} Eu Europium 151.964 [Xe]4f ⁶ 5d ⁶ 6s ² 5.5324	64 ⁻² D _{9/2} Gd Gadolinium 157.25 [Xe]4f ⁷ 5d ⁶ 6s ² 5.5224	65 ⁻⁸ H _{5/2} Tb Terbium 158.92534 [Xe]4f ⁸ 5d ⁶ 6s ² 5.5124	66 ⁻⁵ I _{15/2} Dy Dysprosium 162.500 [Xe]4f ⁹ 5d ⁶ 6s ² 5.5024	67 ⁻¹ D _{5/2} Ho Holmium 164.93032 [Xe]4f ¹⁰ 5d ⁶ 6s ² 5.4924	68 ⁻³ H ₈ Er Erbium 167.259 [Xe]4f ¹¹ 5d ⁶ 6s ² 5.4824	69 ⁻² F _{7/2} Tm Thulium 168.93421 [Xe]4f ¹² 5d ⁶ 6s ² 5.4724	70 ⁻¹ S ₀ Yb Ytterbium 173.04 [Xe]4f ¹⁴ 5d ⁶ 6s ² 5.4624	71 ⁻² D _{3/2} Lu Lutetium 174.967 [Xe]4f ¹⁴ 5d ⁶ 6s ² 5.4524
89 ⁻² D _{5/2} Ac Actinium (227) [Rn]6d ⁷ s ² 5.17	90 ⁻¹ F ₂ Th Thorium (232.0381) [Rn]5f ¹ 6d ⁷ s ² 5.89	91 ⁻¹ K _{11/2} Pa Protactinium (231.03588) [Rn]5f ² 6d ⁷ s ² 6.1941	92 ⁻¹ L _{11/2} U Uranium (238.02891) [Rn]5f ³ 6d ⁷ s ² 6.2657	93 ⁻¹ L _{11/2} Np Neptunium (237) [Rn]5f ⁴ 6d ⁷ s ² 6.0260	94 ⁻¹ F ₀ Pu Plutonium (244) [Rn]5f ⁵ 6d ⁷ s ² 5.9738	95 ⁻¹ S _{7/2} Am Americium (243) [Rn]5f ⁶ 6d ⁷ s ² 5.9914	96 ⁻² D _{9/2} Cm Curium (247) [Rn]5f ⁷ 6d ⁷ s ² 6.1979	97 ⁻⁸ H _{5/2} Bk Berkelium (247) [Rn]5f ⁸ 6d ⁷ s ² 6.2817	98 ⁻⁵ I ₈ Cf Californium (251) [Rn]5f ⁹ 6d ⁷ s ² 6.42	99 ⁻¹ I _{15/2} Es Einsteinium (252) [Rn]5f ¹⁰ 6d ⁷ s ² 6.50	100 ⁻³ H ₈ Fm Fermium (257) [Rn]5f ¹¹ 6d ⁷ s ² 6.58	101 ⁻² F _{7/2} Md Mendelevium (258) [Rn]5f ¹² 6d ⁷ s ² 6.65	102 ⁻¹ S ₀ No Nobelium (259) [Rn]5f ¹³ 6d ⁷ s ² 6.75	103 ⁻² P _{3/2} ? Lr Lawrencium (262) [Rn]5f ¹⁴ 6d ⁷ s ² 4.9?

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

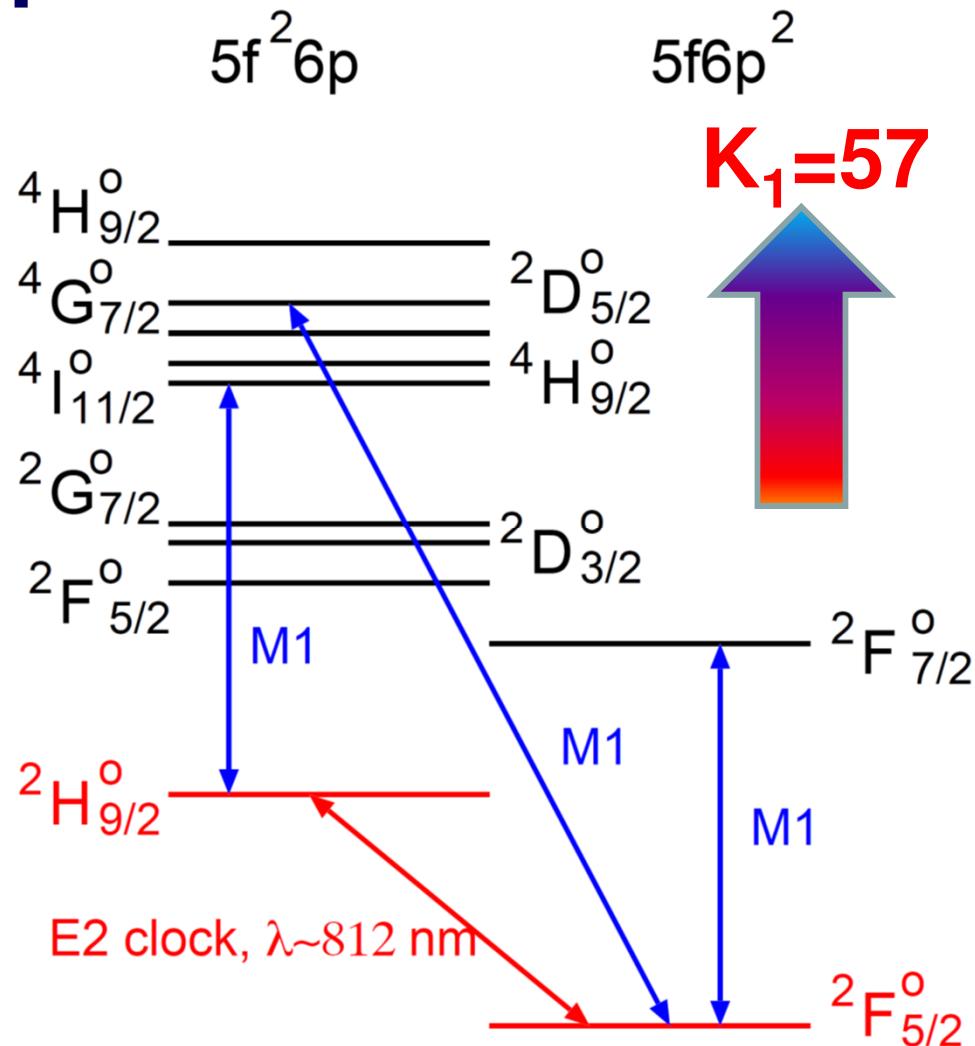
(3) **Holes in 4f shell:** $4f^{12}$, $4f^{13}$ Ir^{16+} , Ir^{17+} , W ions

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

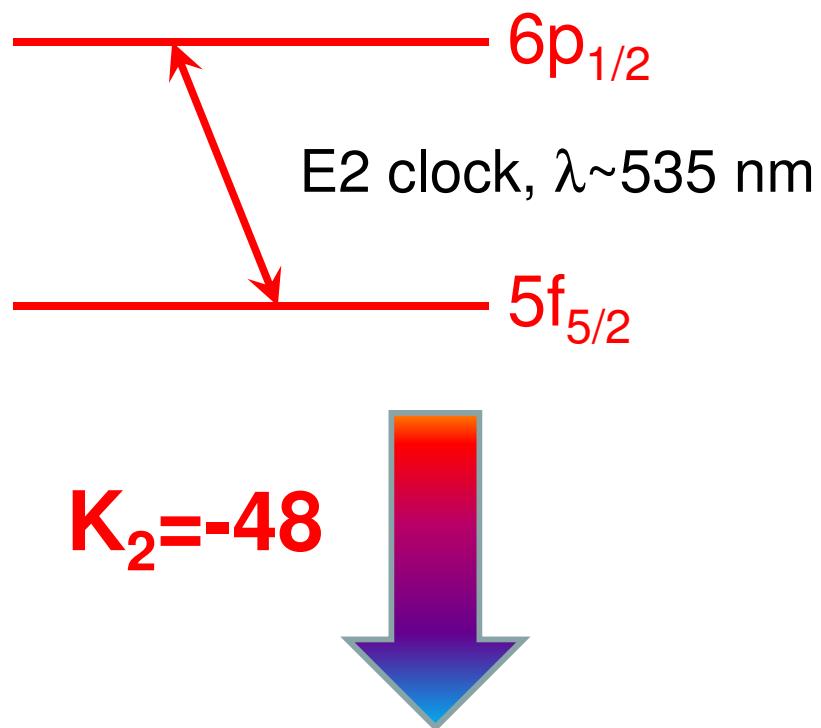
(5) **H-like heavy ions:** Bi^{82+} optical hyperfine structure
transition – “better Cs clock”

Factor of 100 enhancement for α -variation!

Cf^{15+}



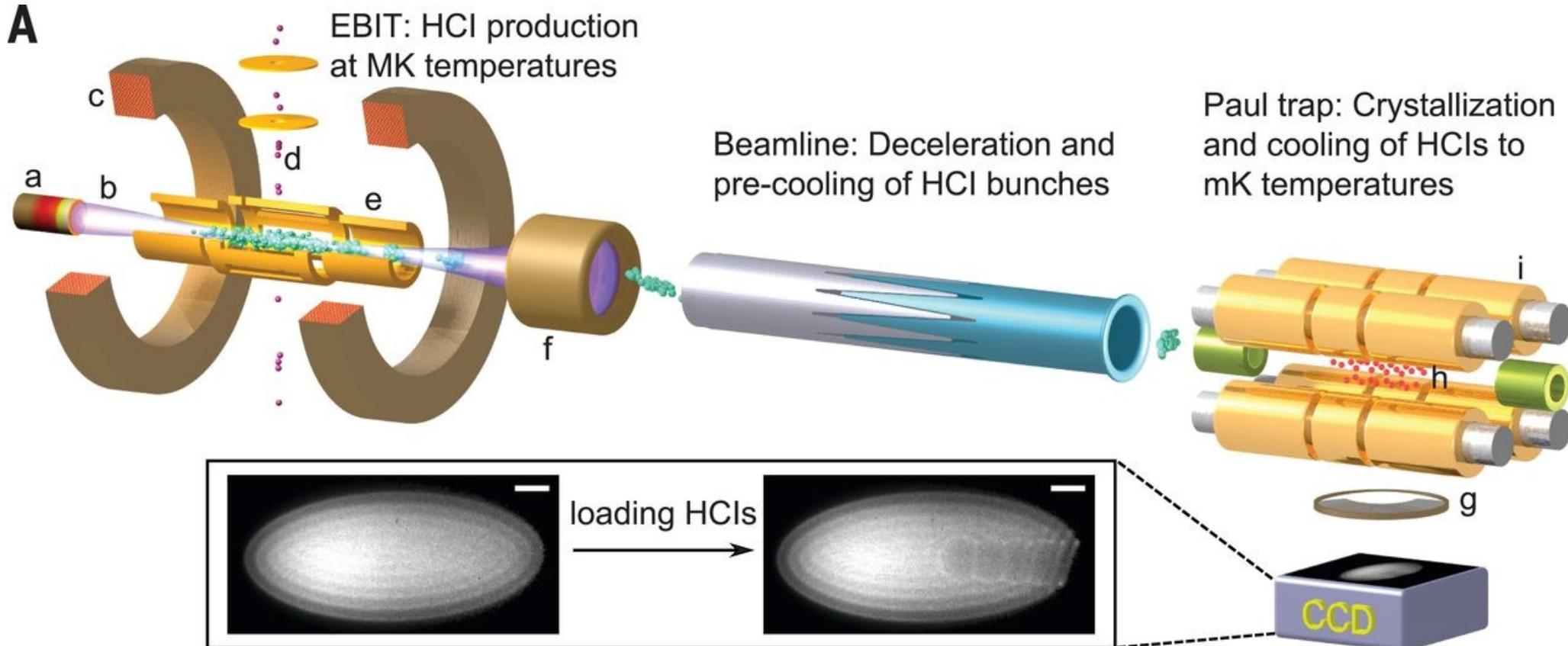
Cf^{17+}



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

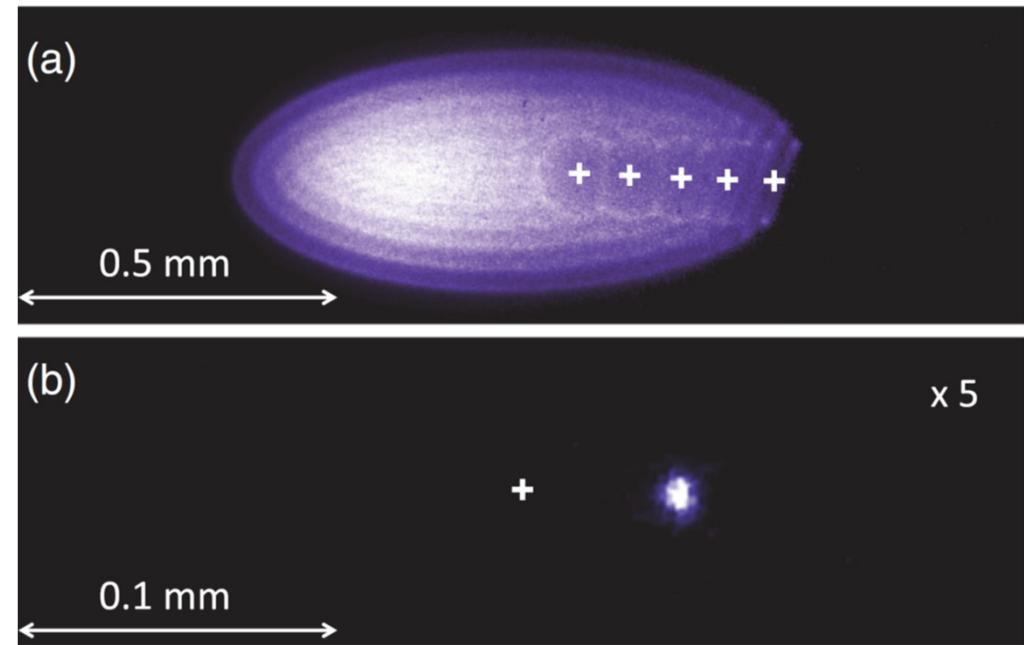
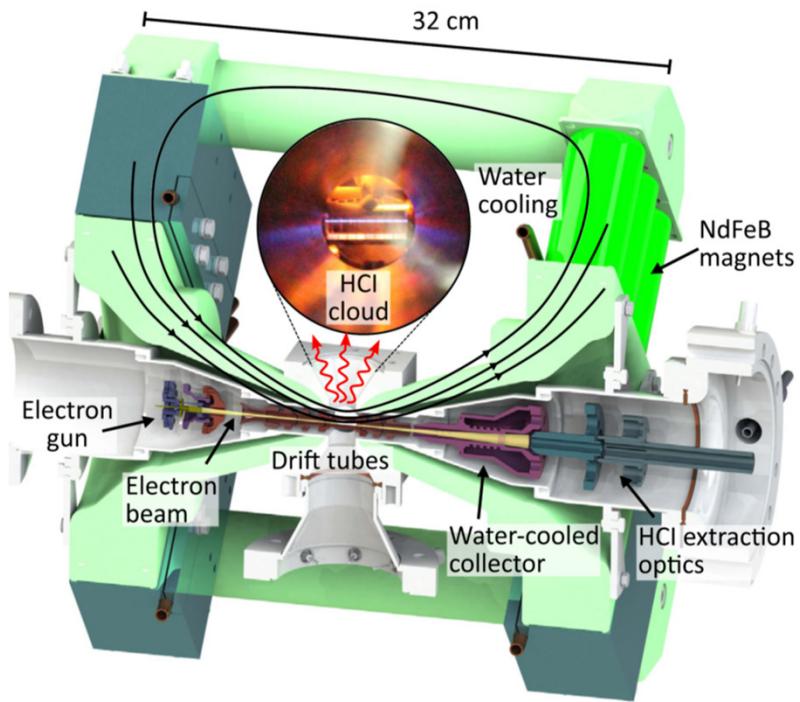
Coulomb crystallization of highly charged ions

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‡}

A

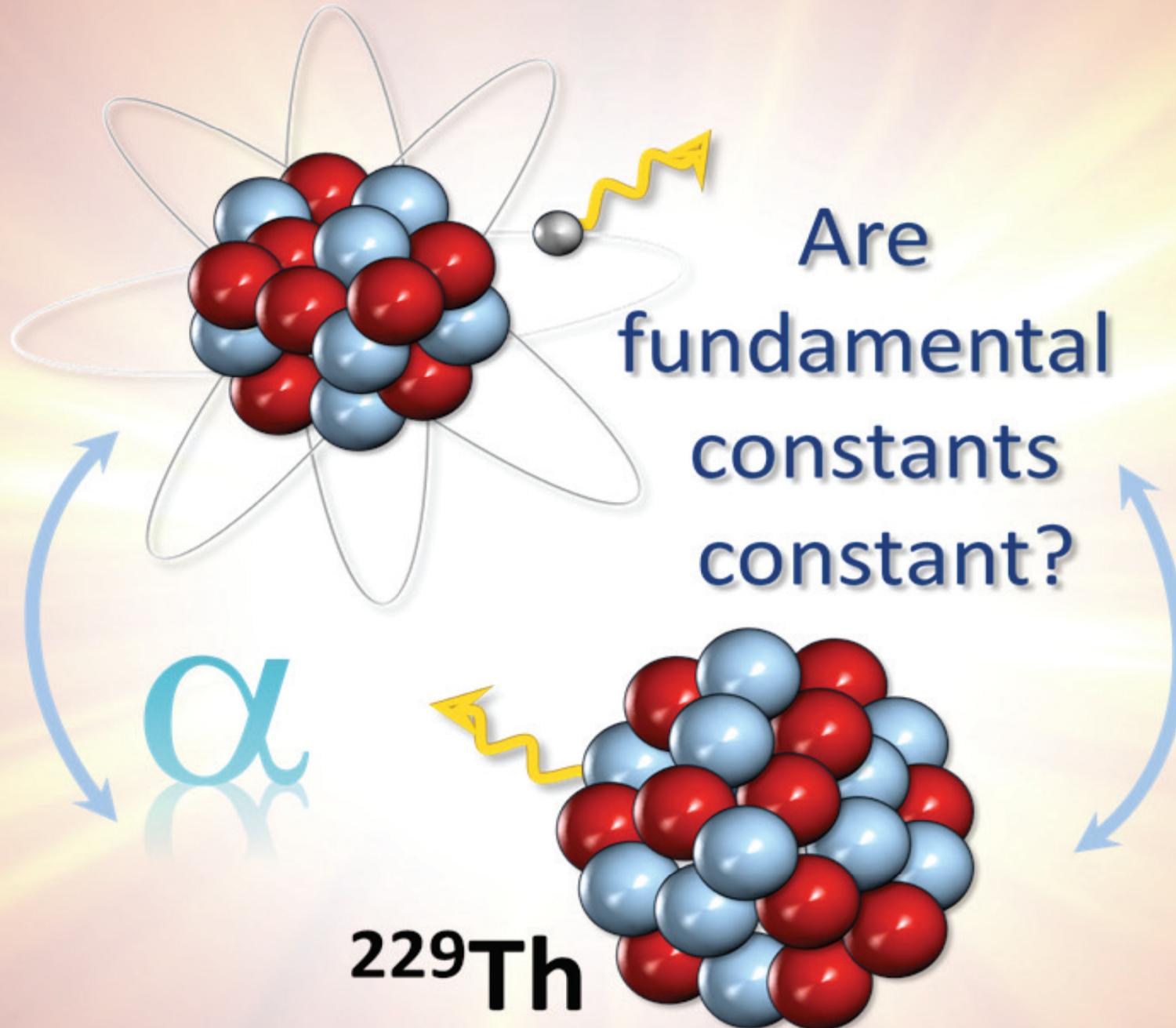
Highly charged ions: Optical clocks and applications in fundamental physics

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

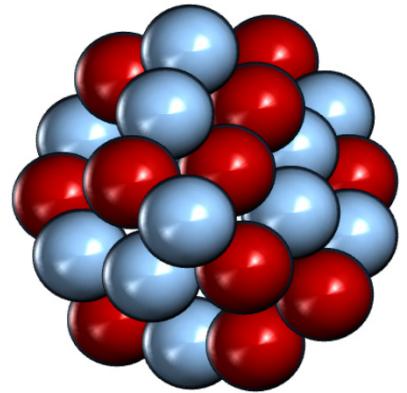


PTB, Germany, November 2018: **First demonstration of quantum logic with a highly charged ion, Ar^{13+}**
2019: Improved frequency measurement from 10^{-7} to 10^{-15} level!

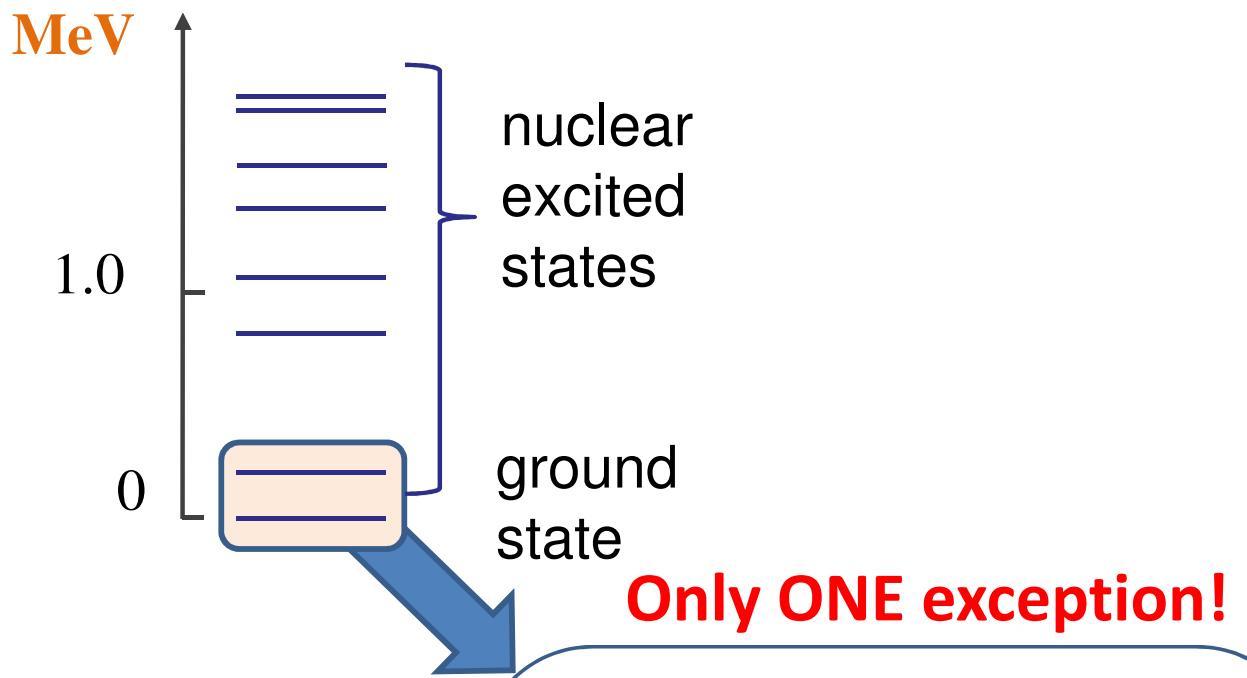
From atomic to nuclear clocks!



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

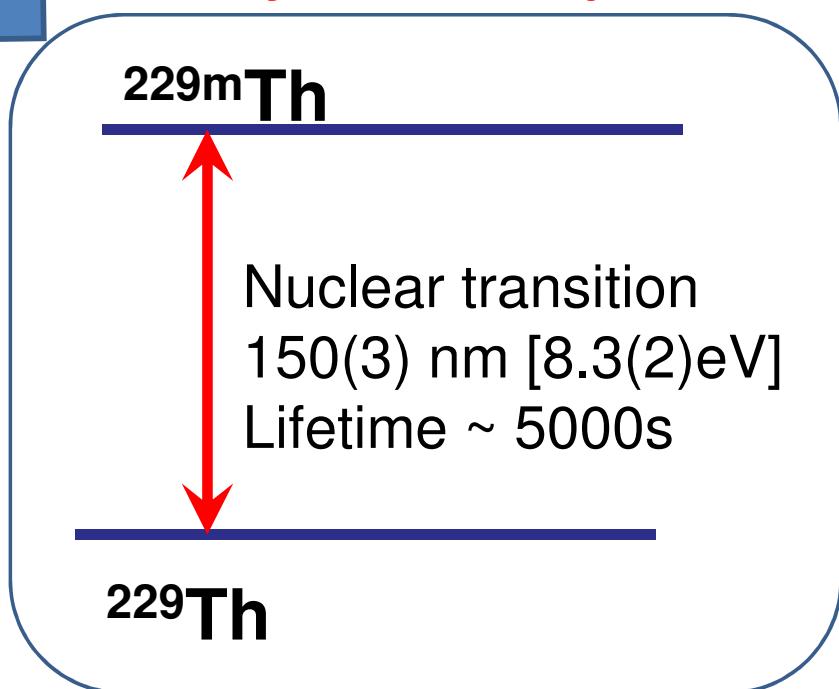


Atomic
Nucleus

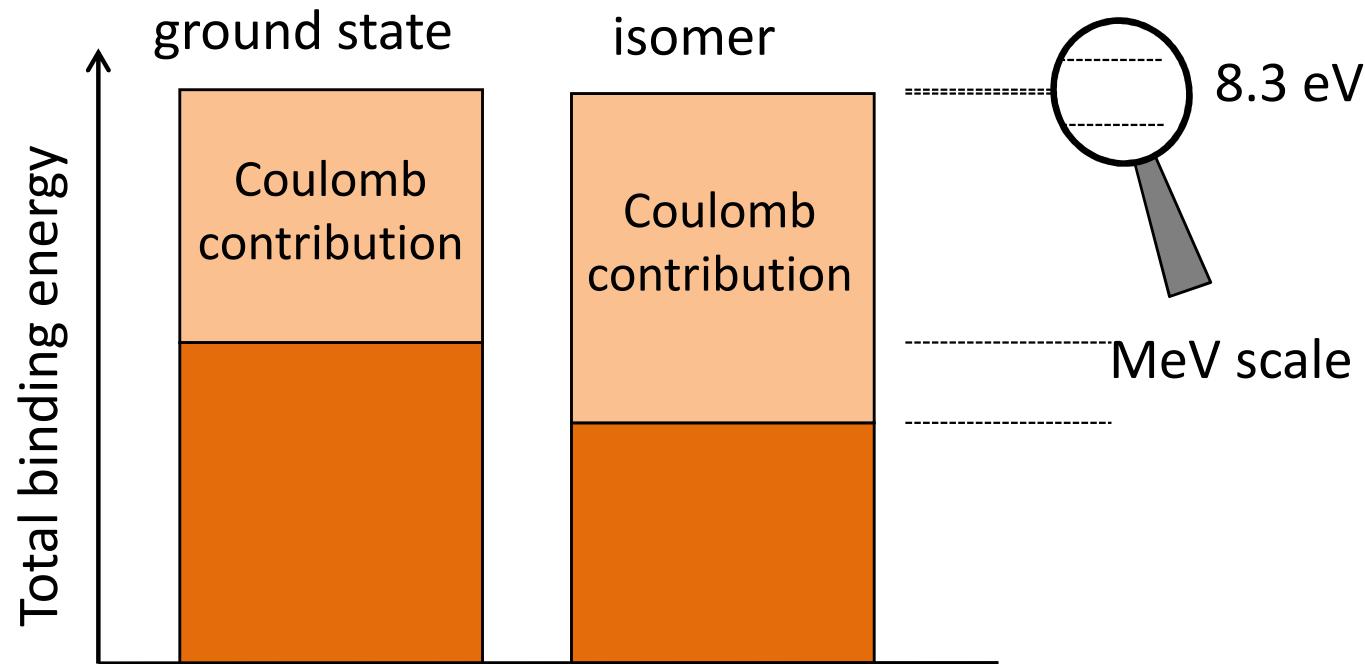


Laser spectroscopic characterization of the
nuclear clock isomer ^{229}mTh , Thielking *et al.*,
Nature 556, 321 (2018)

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!

**VERY WIDE SCOPE OF AMO
DARK MATTER AND NEW
PHYSICS SEARCHES –
SEE OUR REVIEW**

Search for New Physics with Atoms and Molecules

M.S. Safronova^{1,2}, D. Budker^{3,4,5}, D. DeMille⁶, Derek F. Jackson Kimball⁷, A. Derevianko⁸ and C. W. Clark²

¹University of Delaware, Newark, Delaware, USA,

²Joint Quantum Institute, National Institute of Standards and Technology and the University of Maryland, College Park, Maryland, USA,

³Helmholtz Institute, Johannes Gutenberg University, Mainz, Germany,

⁴University of California, Berkeley, California, USA,

⁵Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA

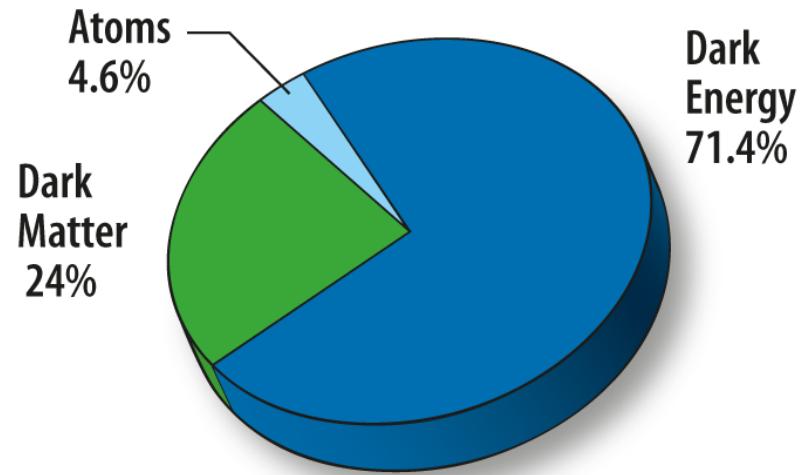
⁶Yale University, New Haven, Connecticut, USA,

⁷California State University, East Bay, Hayward, California, USA,

⁸University 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!**