GGI LECTURES ON THE THEORY OF FUNDAMENTAL INTERACTIONS 2023

TABLETOP EXPERIMENTS: LECTURE 4

DETECTING ULTRALIGHT SCALAR DARK MATTER

Marianna Safronova

Q-SEnSE
An NSF Quantum Leap Challenge Institute

https://www.colorado.edu/research/qsense/

UNIVERSITY OF DELAWARE®

thorium
nuclear clock

https://thoriumclock.eu/

Dark matter searches with atomic, molecular, and nuclear clocks

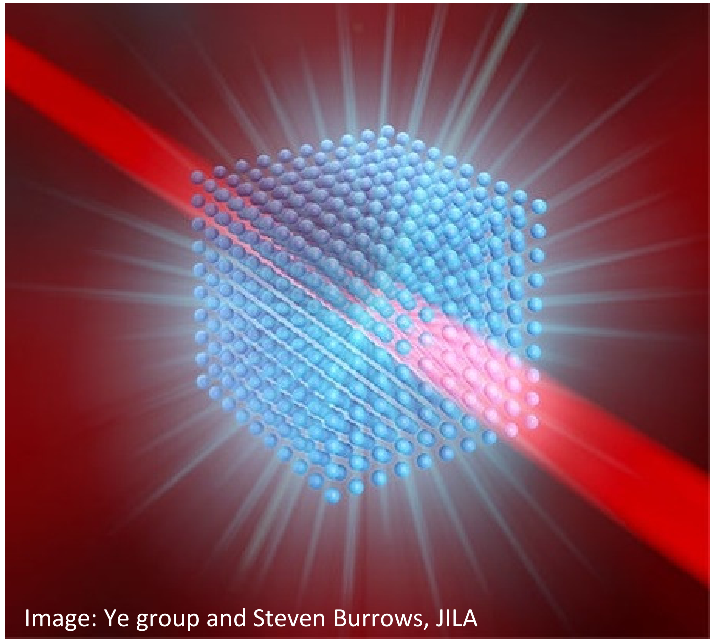
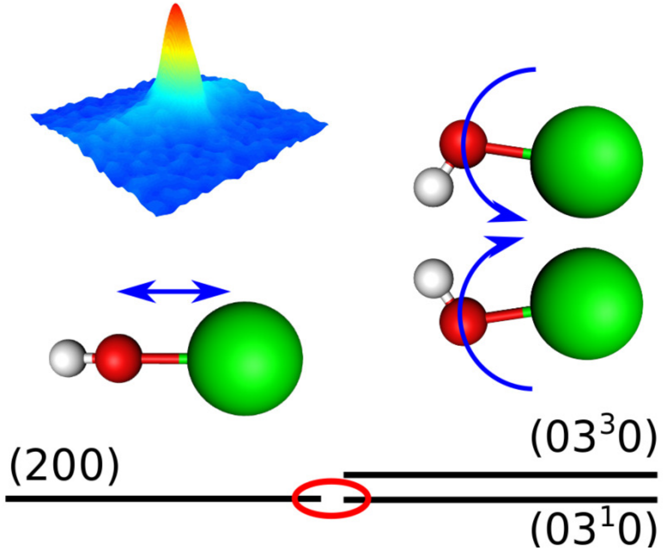
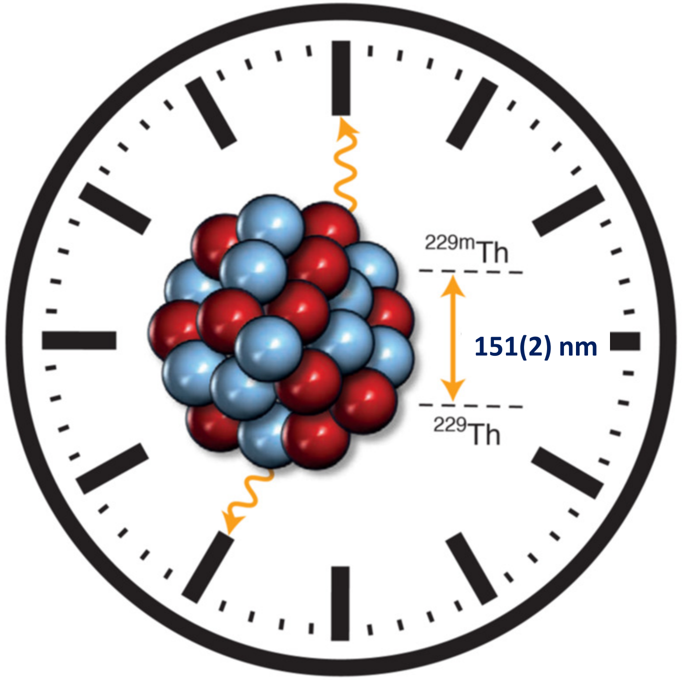


Image: Ye group and Steven Burrows, JILA





How to detect ultralight dark matter with clocks & cavities?

Oscillatory DM effects

Dark matter field $\phi(t) = \phi_0 \cos\left(m_\phi t + \bar{k}_\phi \times \bar{x} + \ldots\right)$ couples to electromagnetic interaction and "normal matter"

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

It will make fundamental coupling constants and mass ratios oscillate

Least exotic idea

Atomic, molecular, and nuclear energy levels will oscillate so clock frequencies will oscillate. **Strength of the effect depends on the transition.**
Cavity length will oscillate.

Can be detected with monitoring **ratios** of clock frequencies over time (or clock/cavity).

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}

Clocks are broadband dark matter detectors but can be made resonant

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

Variation of which fundamental constants can we probe (or which dark matter couplings)

1. Frequency of optical transitions

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

Depends only on α

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

$$\frac{d_e F_{\mu\nu}F^{\mu\nu}}{4}$$

2. Frequency of hyperfine transitions

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

$$d_{m_e} m_e \bar{\psi}_e \psi_e$$

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

Depends on α, μ, g-factors

$$\frac{m_q}{\Lambda_{\rm QCD}}$$

$$\frac{d_g \beta_3 G^a_{\mu\nu} G^{a\mu\nu}}{2g_3}$$

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

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

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

Sensitivity of optical clocks to α-variation

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

Enhancement factor

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

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

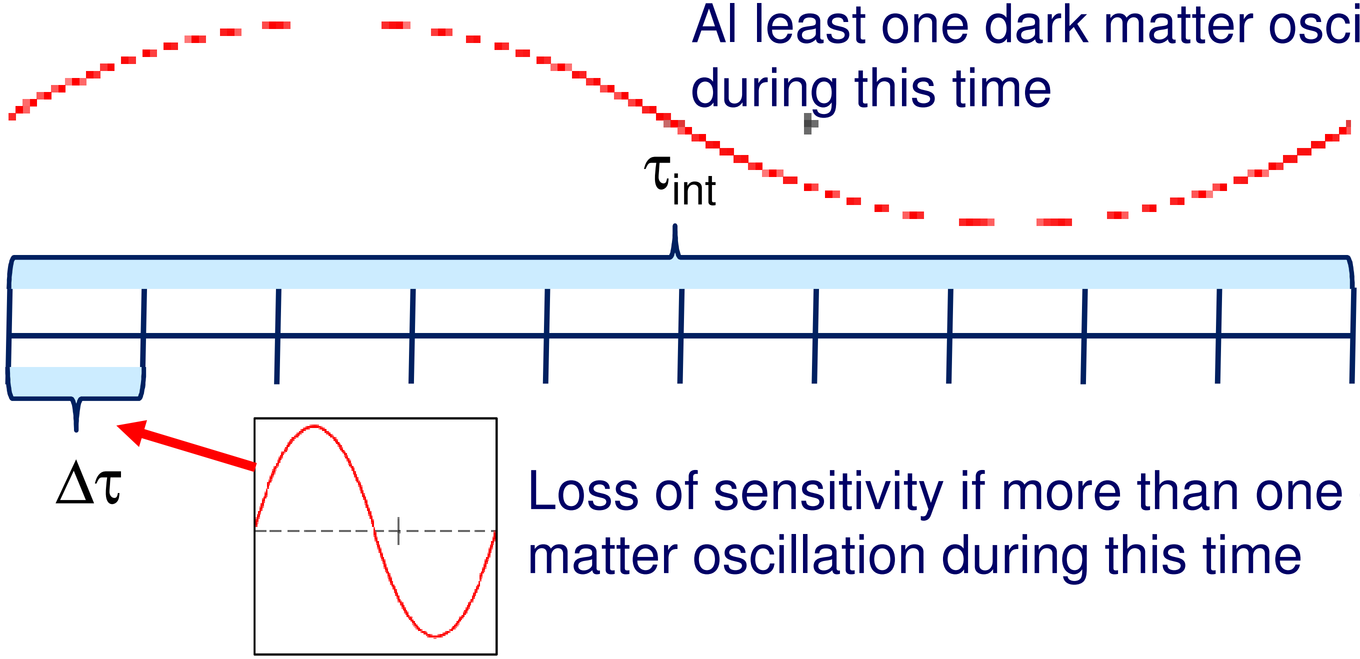
Frequency ratio accuracy 10^{-18} 100 10^{-20}

Easier to measure large effects!

Clock measurement protocols for dark matter detection

Single clock ratio measurement: averaging over time $\Delta\tau$

Make N such measurements, preferably regularly spaced

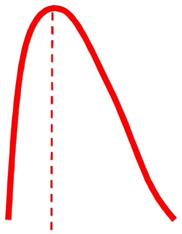


Al least one dark matter oscillation during this time

Loss of sensitivity if more than one dark matter oscillation during this time

Detection signal:

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



Solutions:

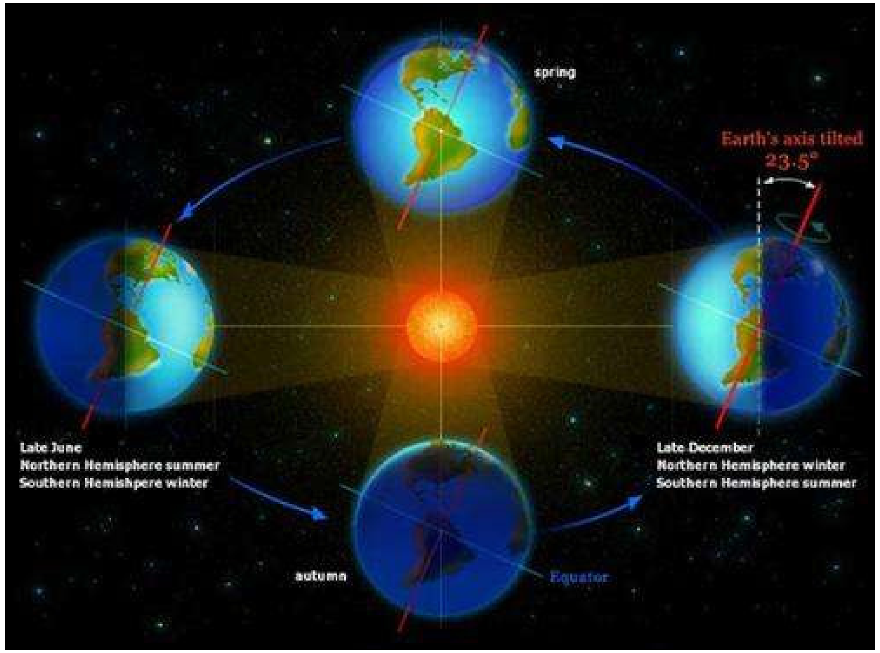
(1) Improve stability so shorter probe times are practical to use

(2) Use dynamic decoupling

How atomic clocks work?

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)

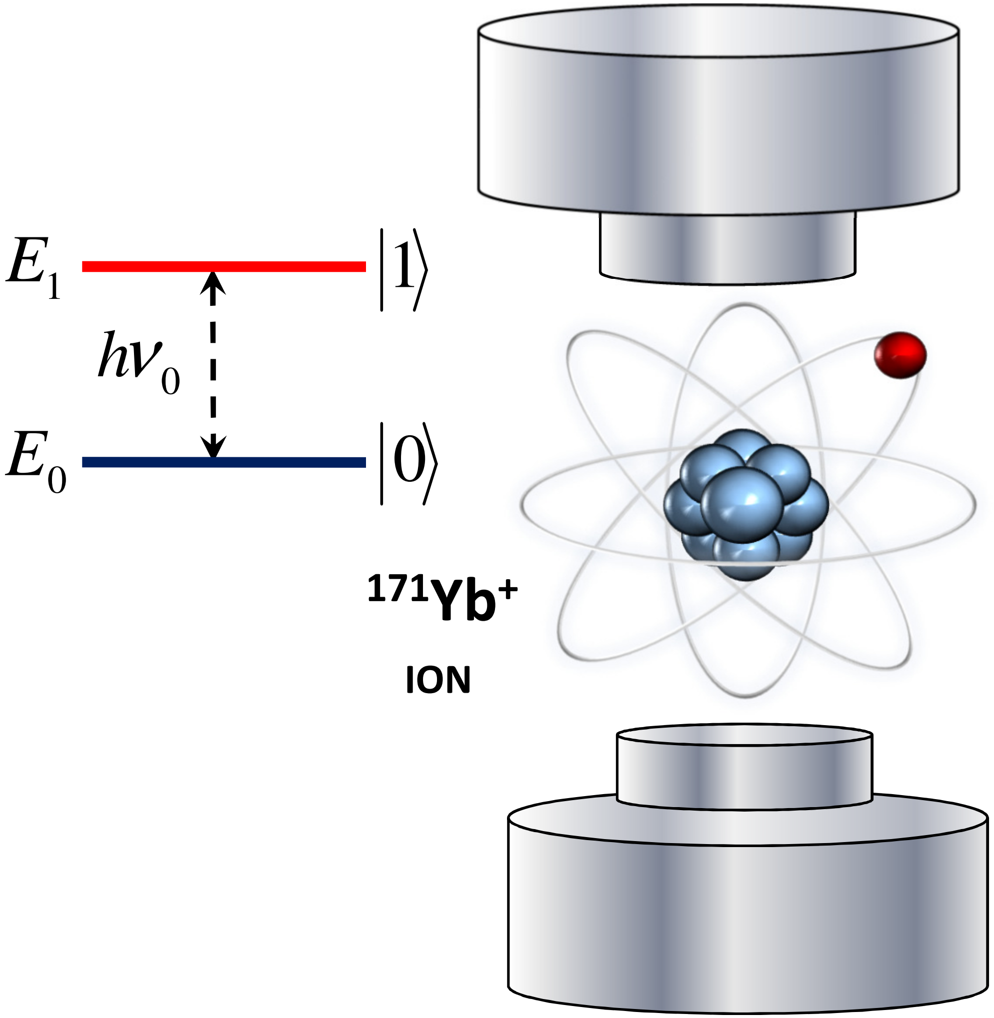
Ingredients for an atomic clock

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

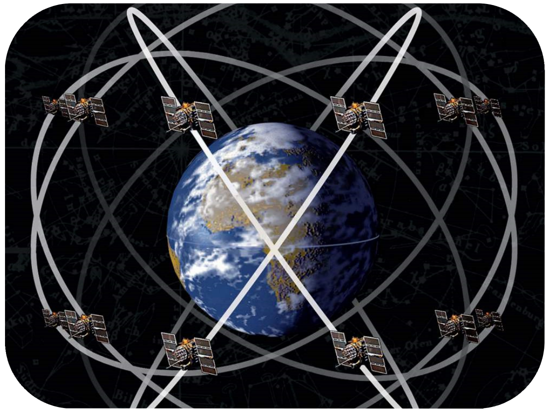
2. Take a sample of atoms (or just one)

3. Build a laser in resonance with this atomic frequency

4. Count cycles of this signal

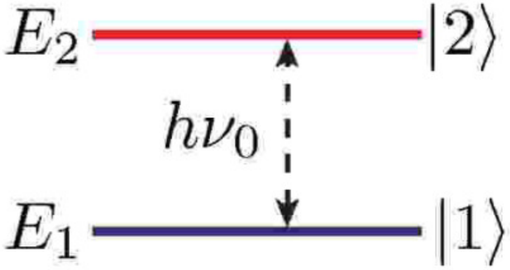


Ludlow et al., RMP 87, 637 (2015)

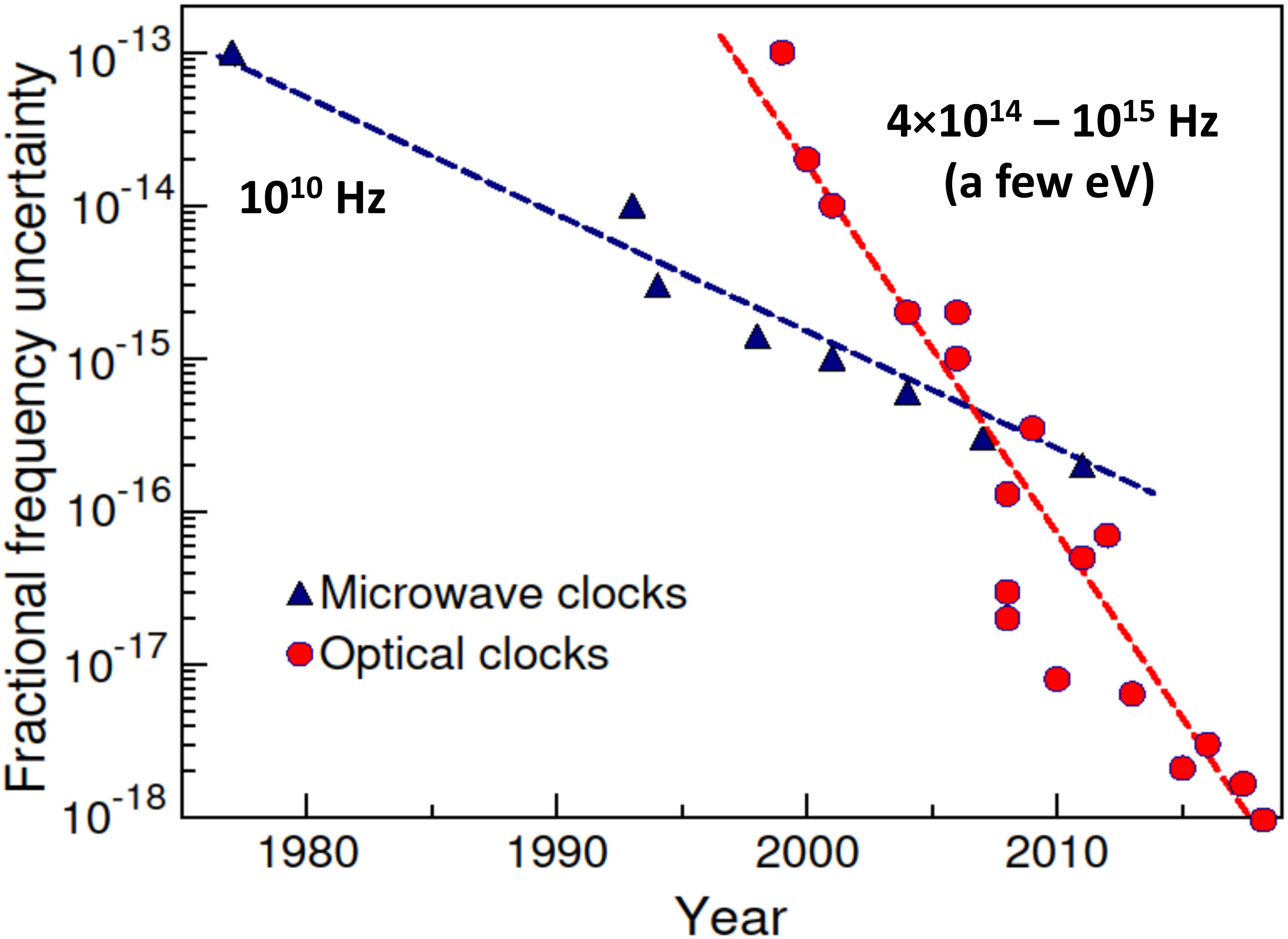


airandspace.si.edu

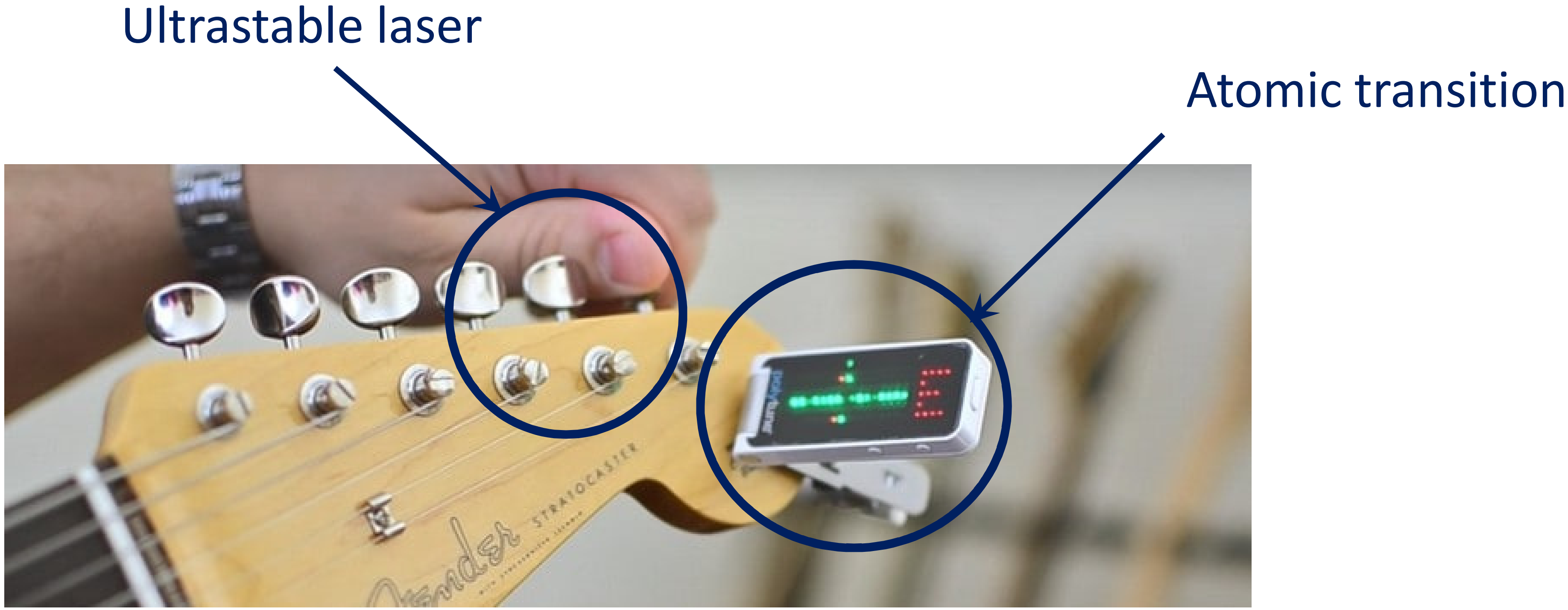
GPS satellites: microwave atomic clocks



Optical atomic clocks will not lose one second in **30 billion years**

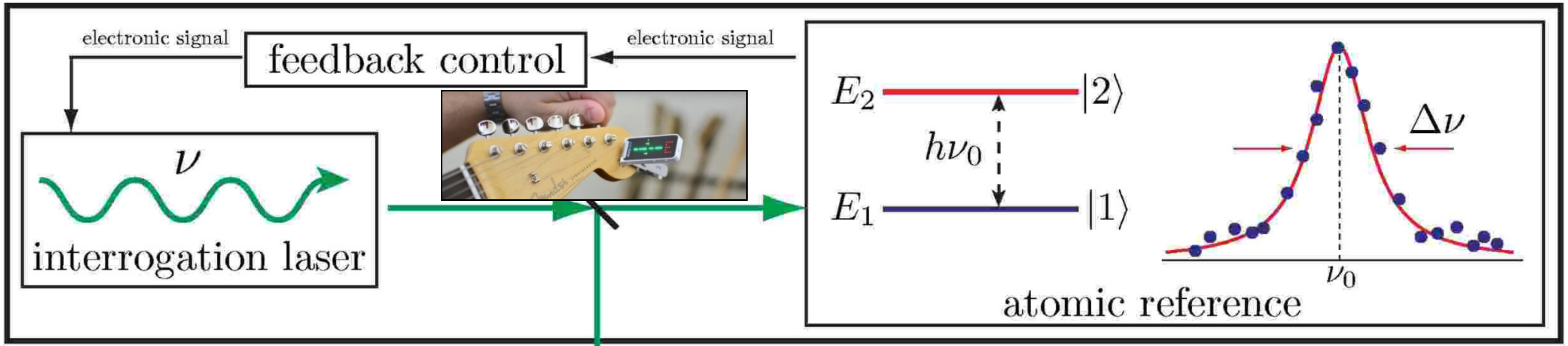


HOW OPTICAL ATOMIC CLOCK WORKS ?

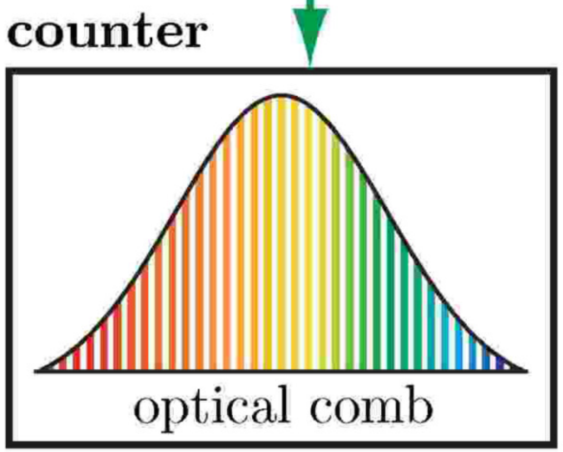


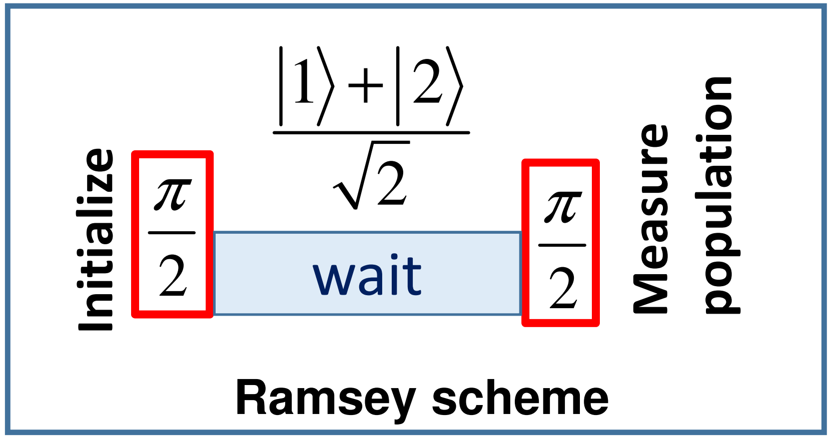
BASIC IDEA: TUNE THE LASER TO THE FREQUENCY OF THE ATOMIC TRANSITION

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

Observable: ratio of two clock frequencies

Measure a ratio of Al⁺ clock frequency to Hg⁺ clock frequency

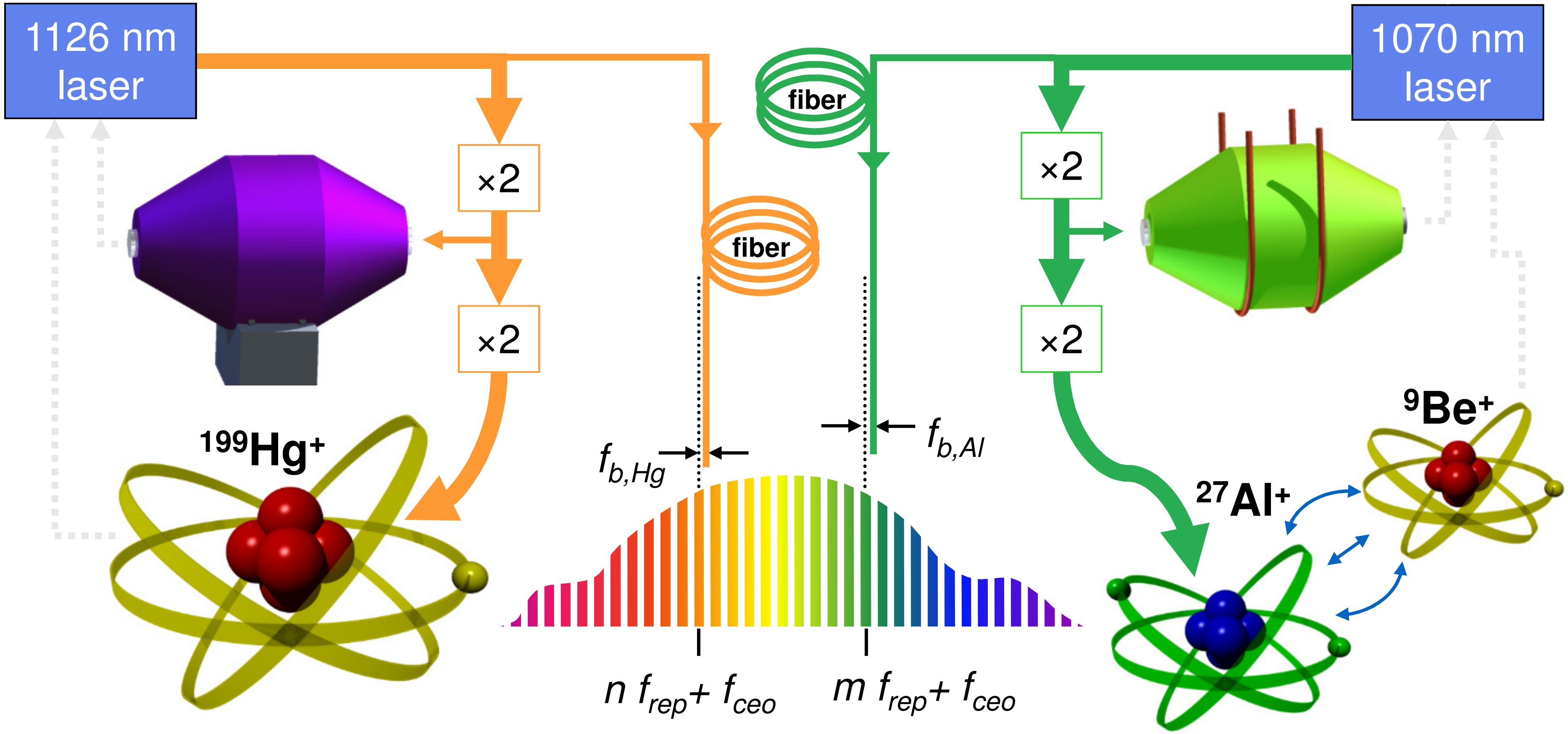
$$\frac{\nu\left(Hg^{+}\right)}{\nu\left(\mathrm{Al}^{+}\right)}$$

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

$$K\left(Al^{+}\right) = 0.01$$

Sensitivity factors

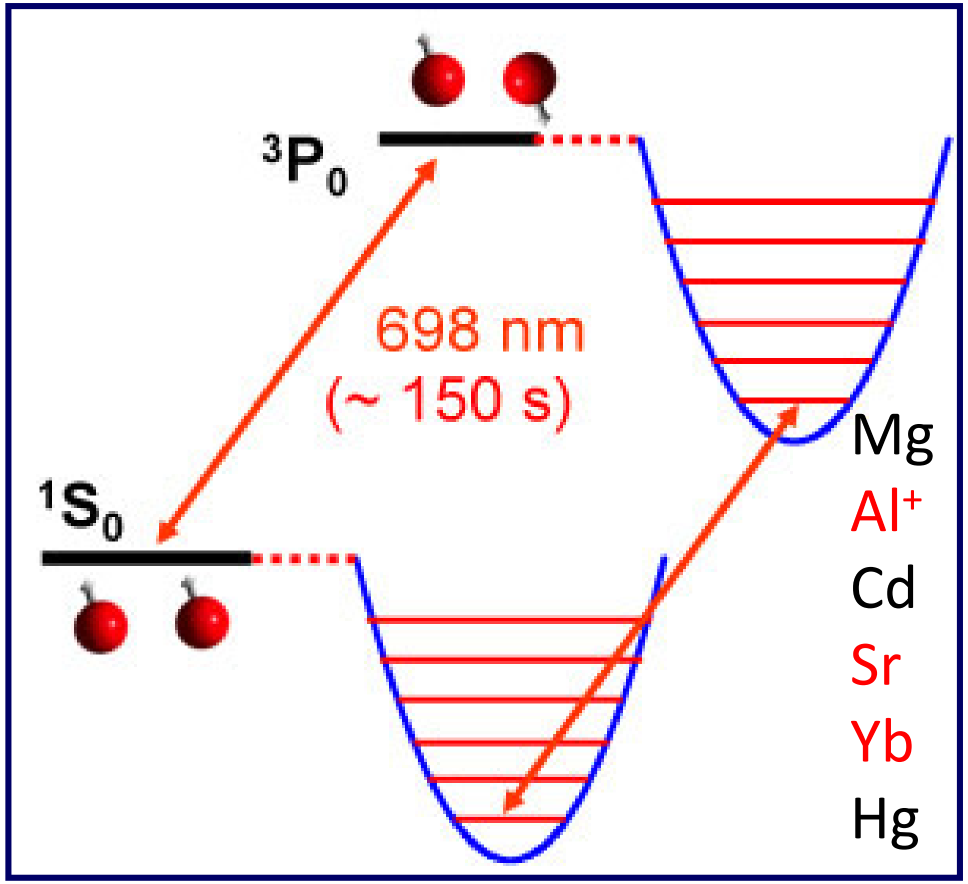
Not sensitive to α-variation, used as reference



Picture credit: Jim Bergquist

Science 319, 1808 (2008)

Neutral atoms in optical lattice vs. trapped ion clocks



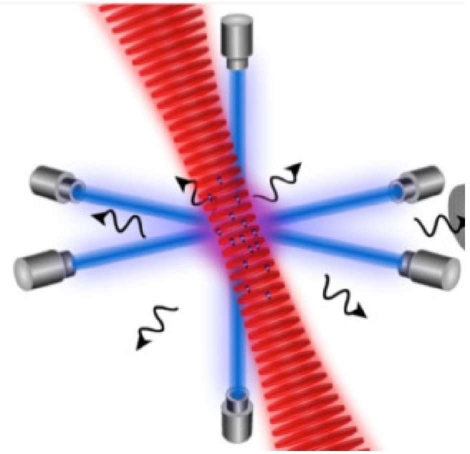
$^3P_0$

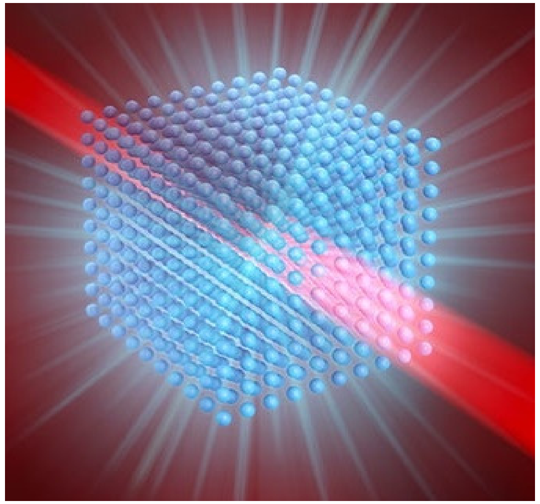
698 nm
(~ 150 s)

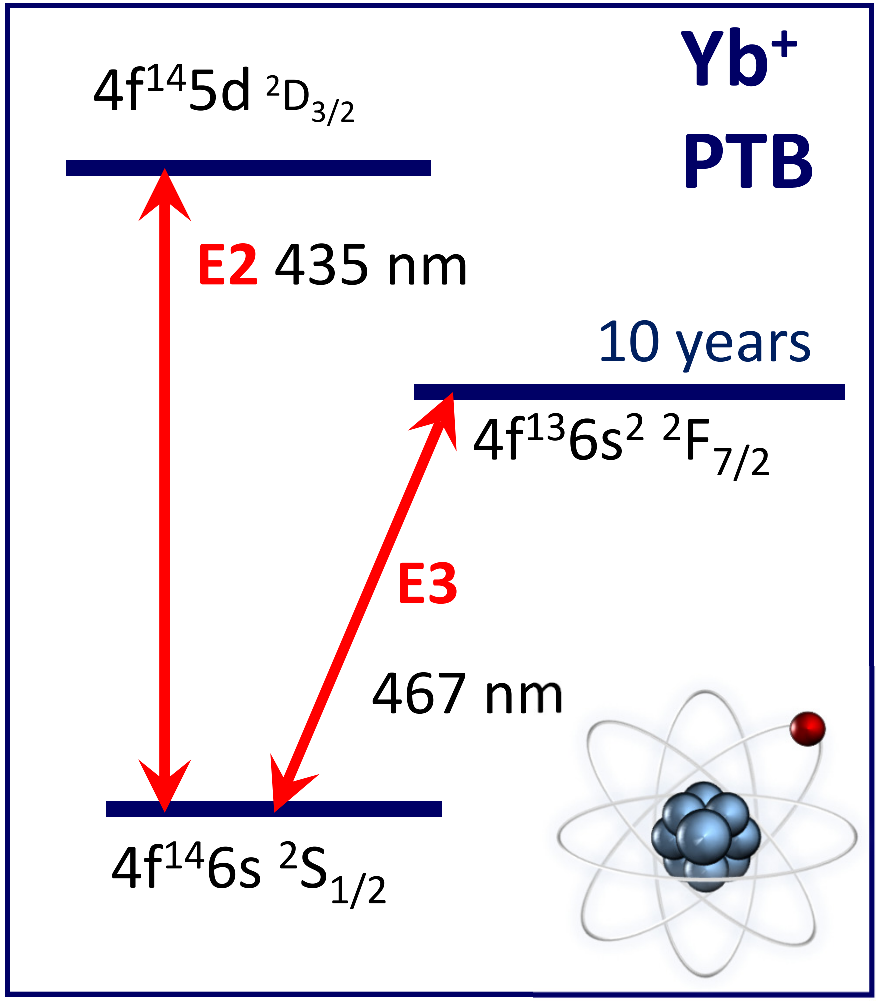
$^1S_0$

Mg
Al$^+$
Cd
Sr
Yb
Hg

Strontium optical lattice
neutral atom clock







Yb$^+$
PTB

$4f^{14}5d\ ^2D_{3/2}$

E2 435 nm

10 years

$4f^{13}6s^2\ ^2F_{7/2}$

E3

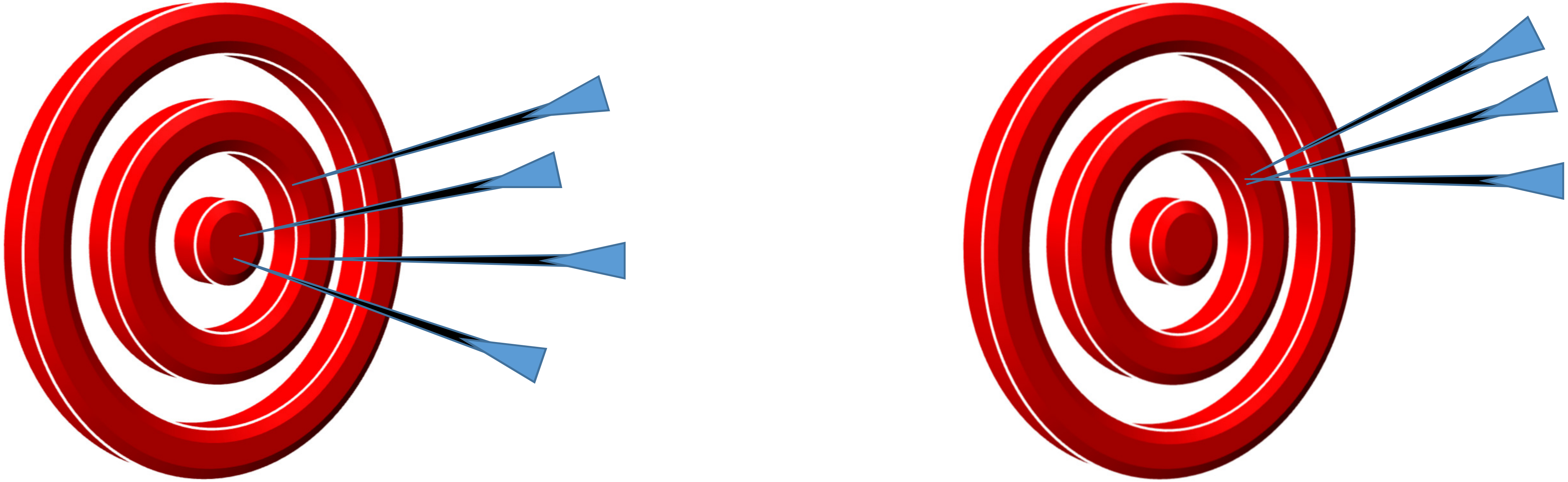
467 nm

$4f^{14}6s\ ^2S_{1/2}$

Yb⁺ single trapped ion clock

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

How good is a clock: stability and uncertainty



Stability is a measure of the precision with which we can measure a quantity.
It is usually stated as a **function of averaging time** since for many noise processes the precision increases (i.e., the noise is reduced through averaging) with more measurements.

Uncertainty: how well we understand the physical processes that can shift the measured frequency from its unperturbed (“bare"), natural atomic frequency.

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

Clock instability

Quantum projection noise limit

$$\sigma_y(\tau) \approx \frac{1}{2\pi\nu_0}\frac{1}{\sqrt{NT\tau}}$$

Clock transition frequency

The averaging period

The number of atoms or ions used in a single measurement

Duration of single measurement cycle

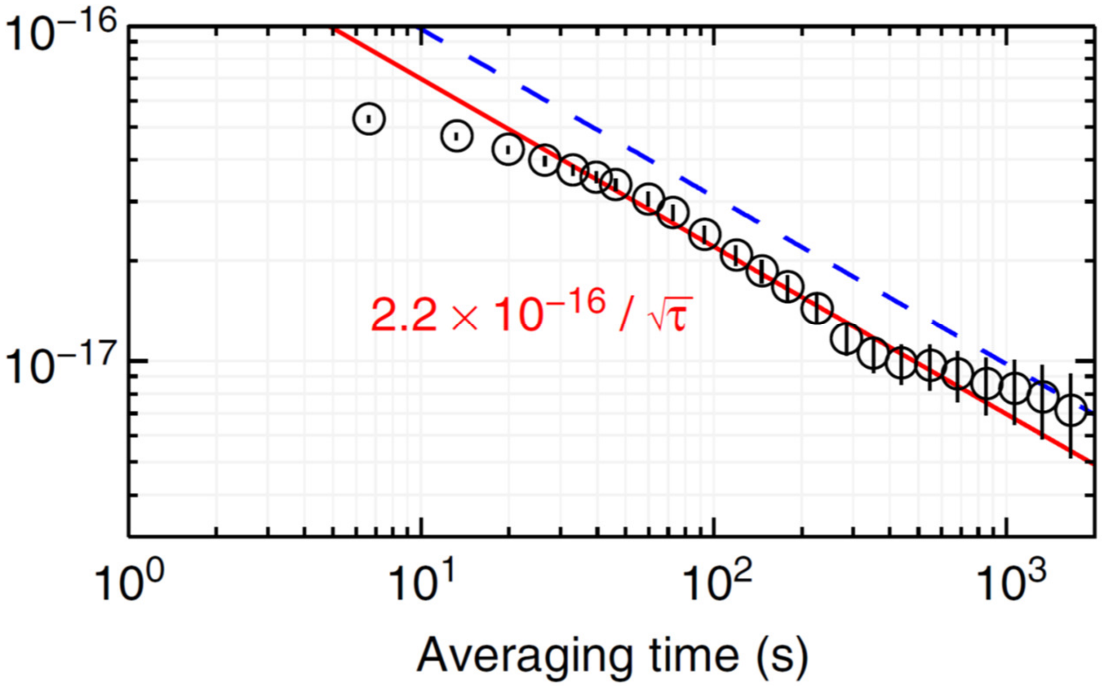
N=1 for ions for now,
1000 possible
N>1000 for neutral atoms

Limited by clock state lifetime and **laser stability**

How good is a clock: stability and uncertainty

Sr lattice clock

Stability as a function of averaging time



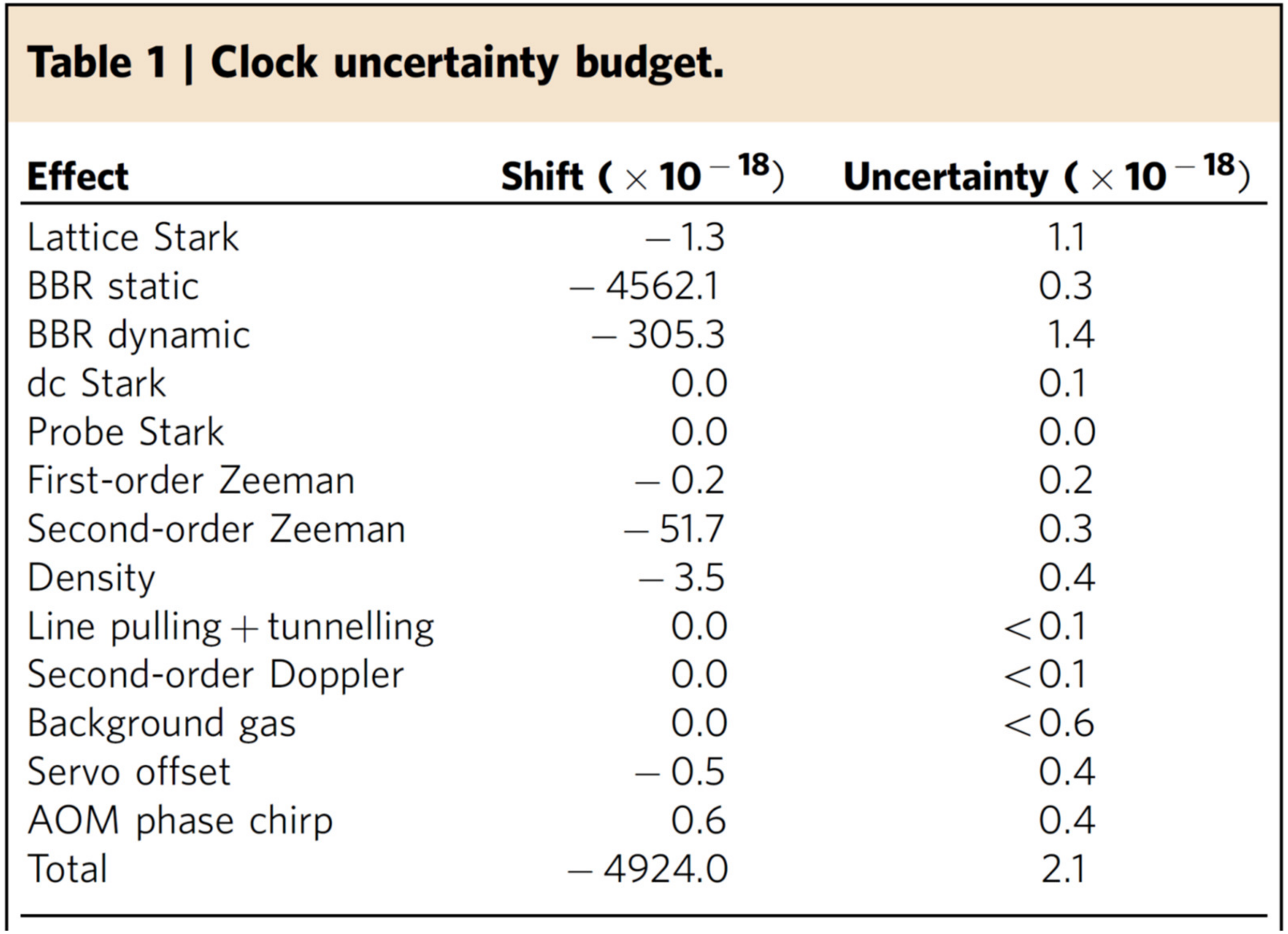


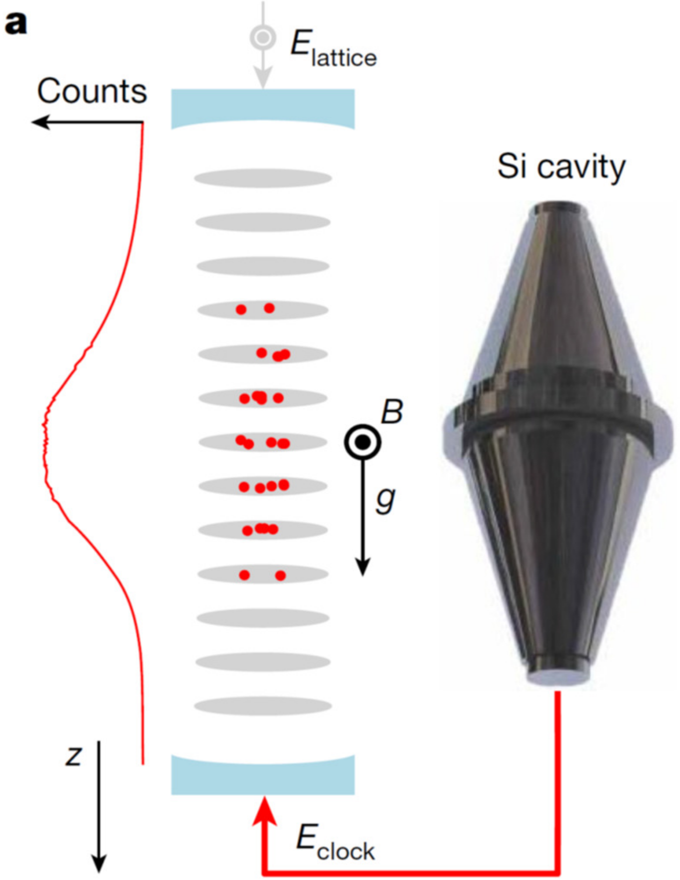
Table 1 | Clock uncertainty budget.

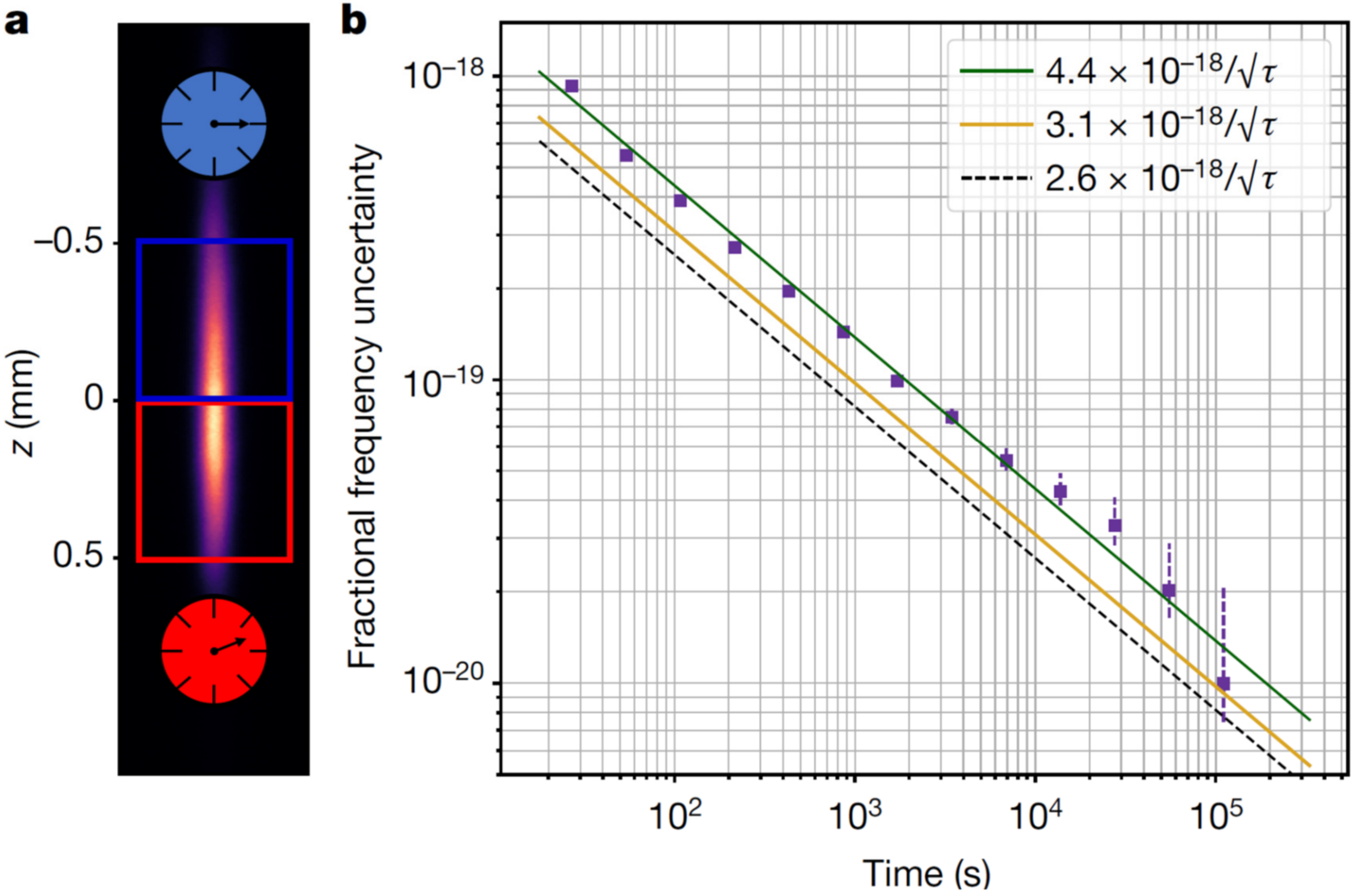
Effect	Shift ($\times 10^{-18}$)	Uncertainty ($\times 10^{-18}$)
Lattice Stark	−1.3	1.1
BBR static	−4562.1	0.3
BBR dynamic	−305.3	1.4
dc Stark	0.0	0.1
Probe Stark	0.0	0.0
First-order Zeeman	−0.2	0.2
Second-order Zeeman	−51.7	0.3
Density	−3.5	0.4
Line pulling + tunnelling	0.0	<0.1
Second-order Doppler	0.0	<0.1
Background gas	0.0	<0.6
Servo offset	−0.5	0.4
AOM phase chirp	0.6	0.4
Total	−4924.0	2.1

Systematic evaluation of an atomic clock at 2×10^{-18} total 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).

Resolving the gravitational redshift across a millimetre-scale atomic sample,

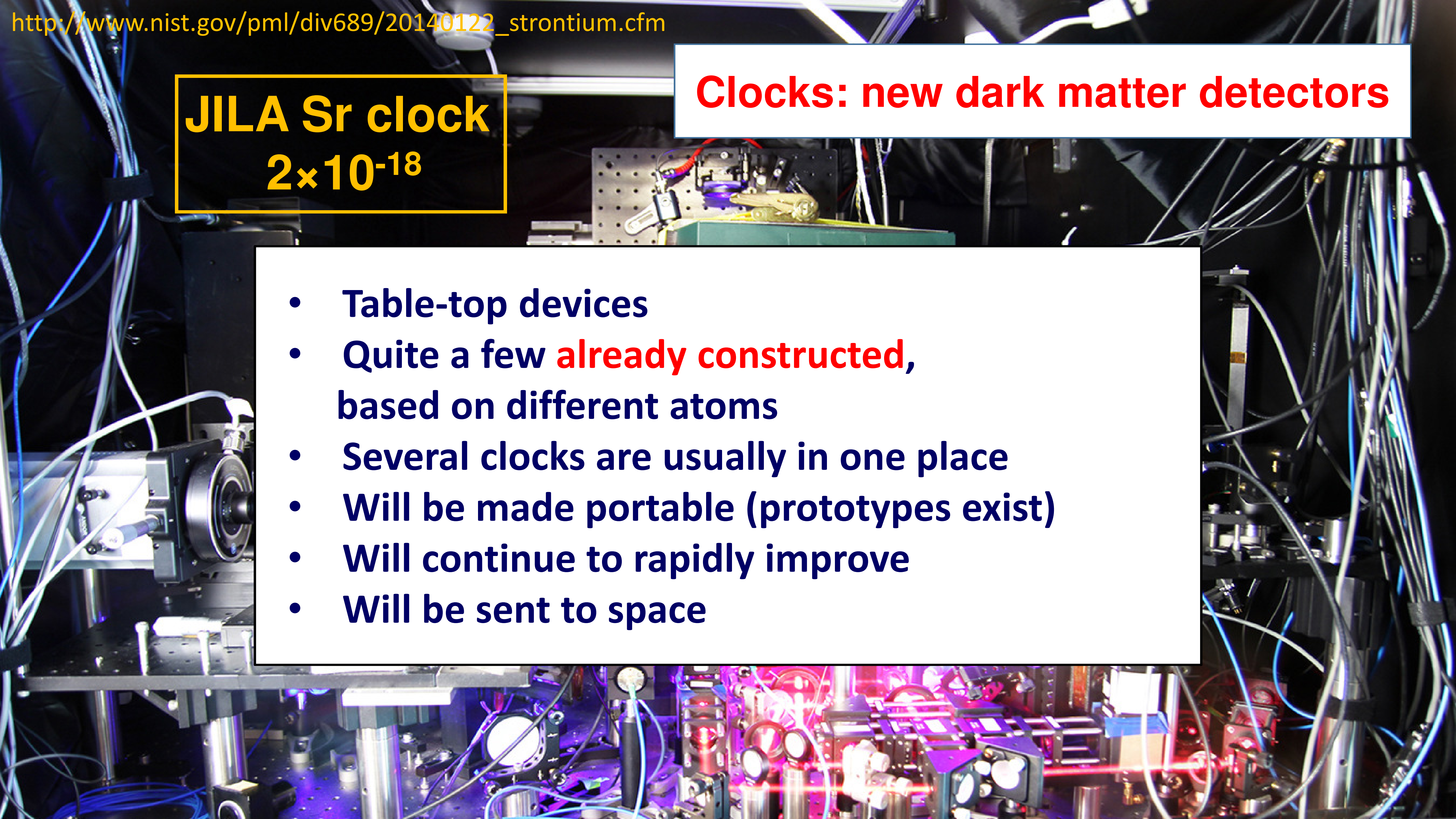
T. Bothwell, Kennedy, C., Aeppli, A., Kedar, D., Robinson, J., Oelker, E., Staron, A., and Ye, J., Nature 602, 420 (2022).





10^{-18} is reached in a few seconds!

Clocks: new dark matter detectors

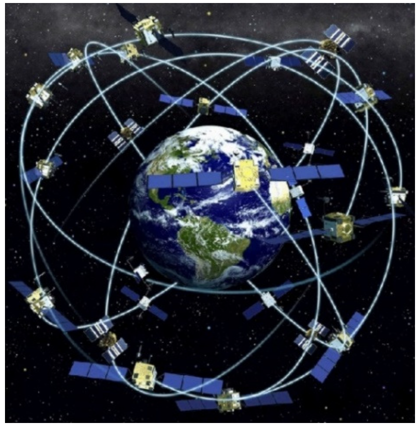


http://www.nist.gov/pml/div689/20140122_strontium.cfm

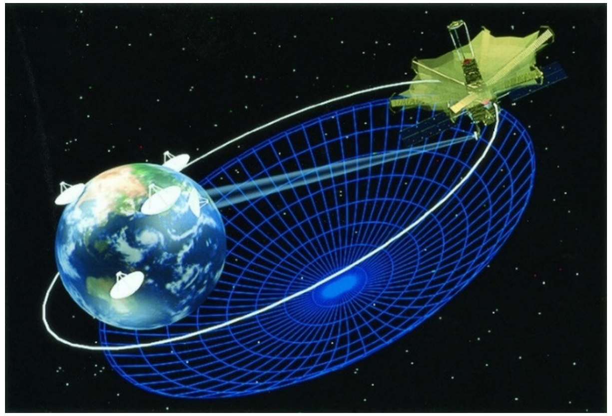
JILA Sr clock
2×10^{-18}

- Table-top devices
- Quite a few already constructed, based on different atoms
- Several clocks are usually in one place
- Will be made portable (prototypes exist)
- Will continue to rapidly improve
- Will be sent to space

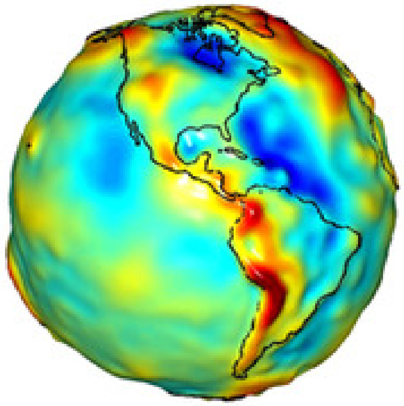
APPLICATIONS OF ATOMIC CLOCKS



GPS, deep space navigation

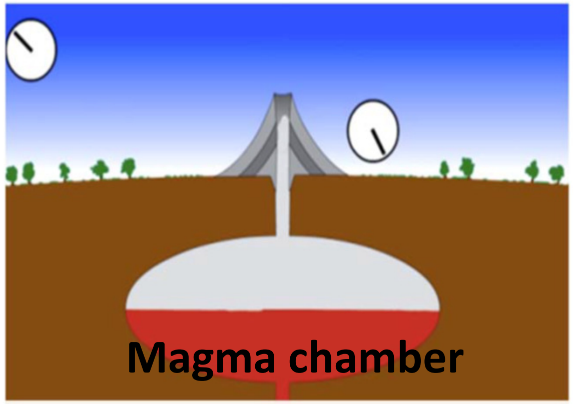


Very Long Baseline Interferometry

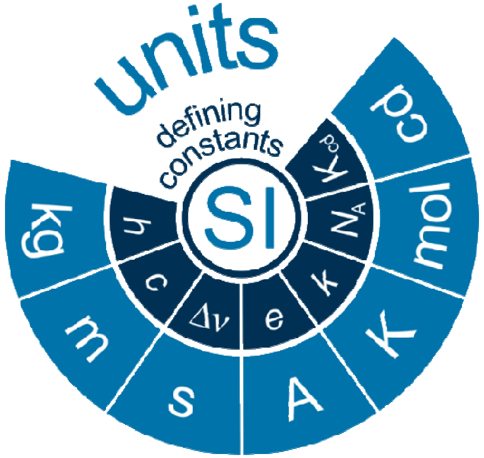


10^{-18}
1 cm
height

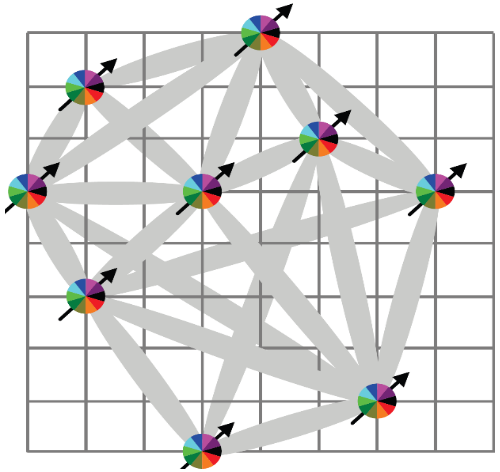
Relativistic geodesy



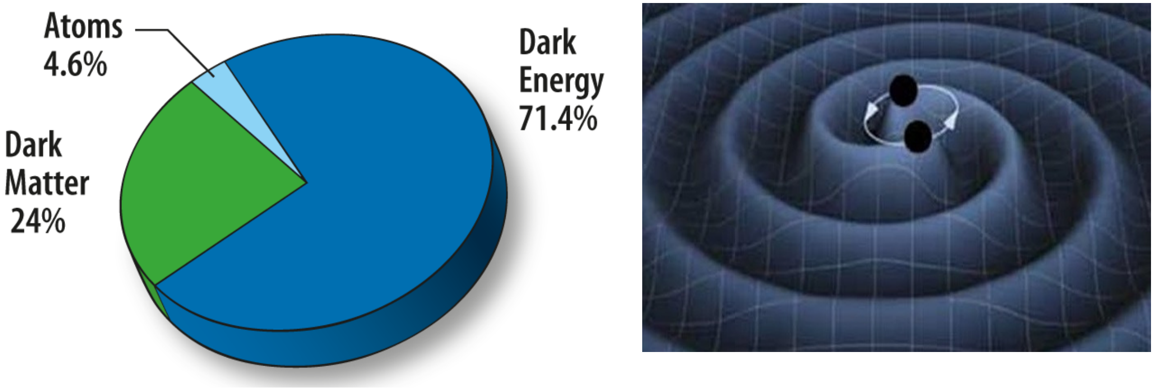
Gravity Sensor



Definition of the second



Quantum simulation

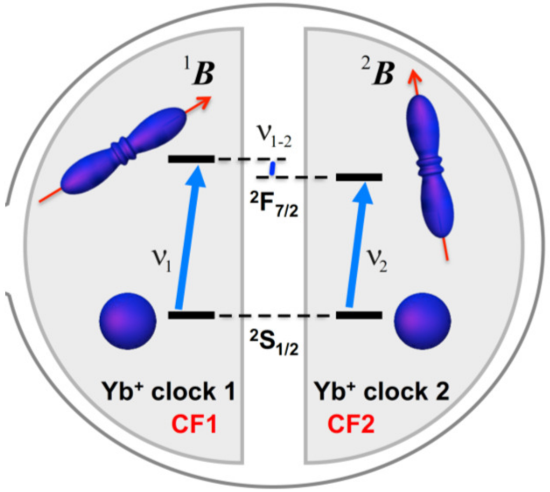


Searches for physics beyond the Standard Model

Image Credits: NOAA, Science 281,1825; 346, 1467, University of Hannover, PTB, PRD 94, 124043, Eur. Phys. J. Web Conf. 95 04009

Search for physics beyond the Standard Model with atomic clocks

Dark matter searches



Search for the violation of Lorentz invariance

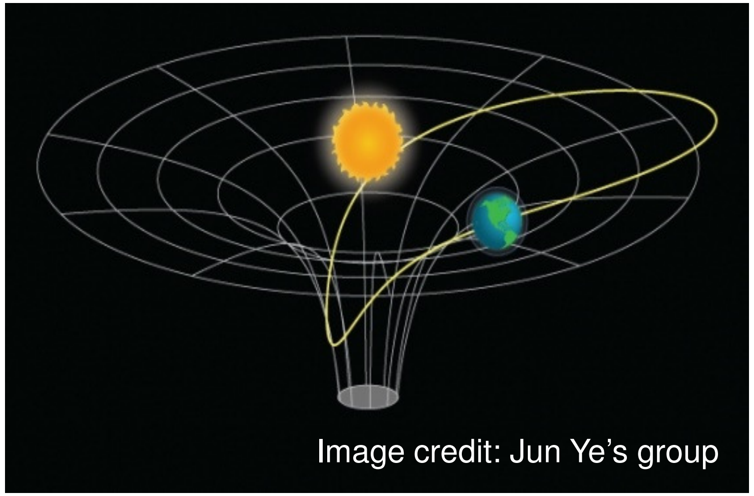


Image credit: Jun Ye's group

Tests of the position invariance

Are fundamental constants constant?

α

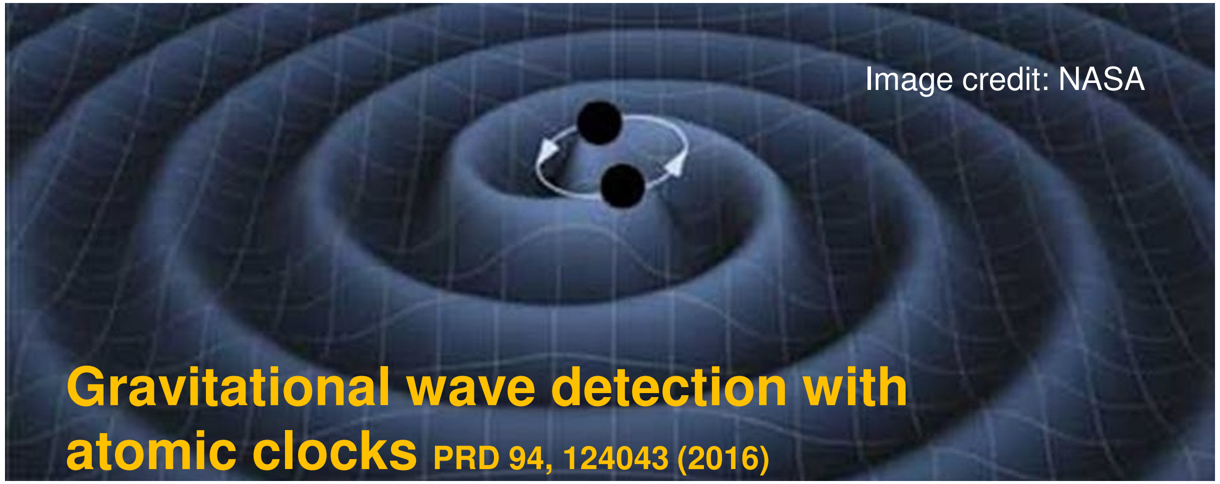
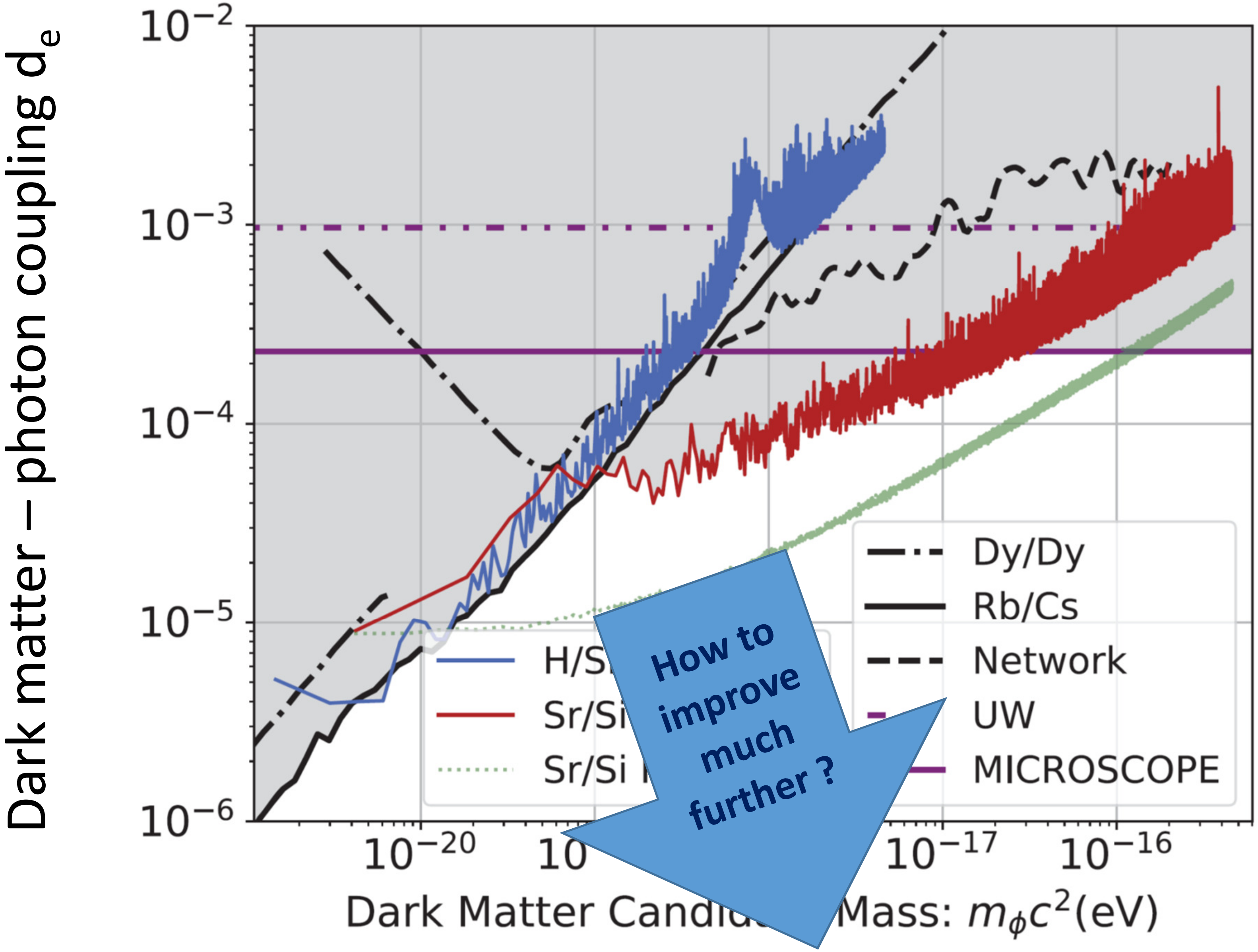


Image credit: NASA

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

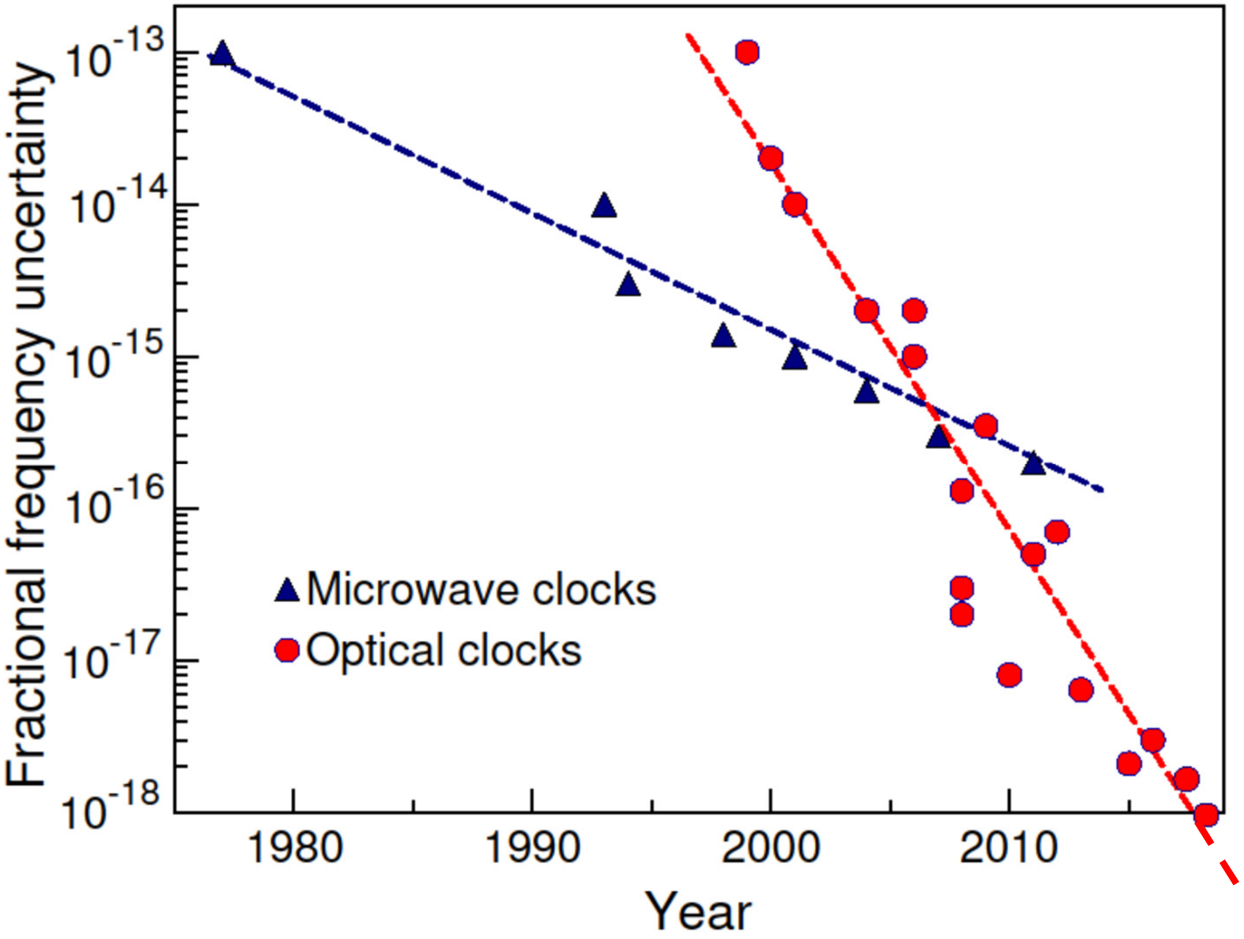
JILA Sr clock-cavity comparison C. Kennedy et al., PRL 125, 201302 (2020)

Oscillating dark matter bounds

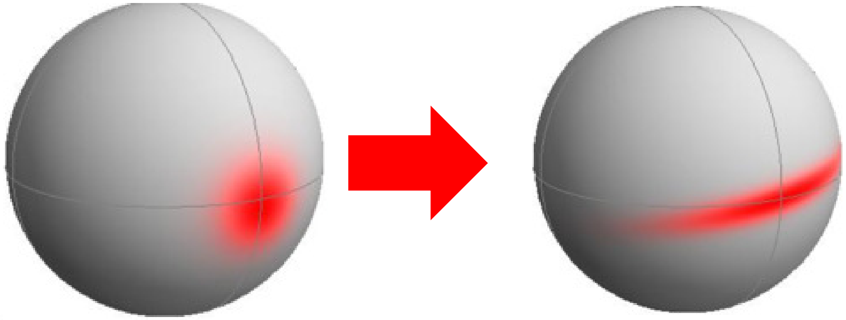


How to improve much further ?

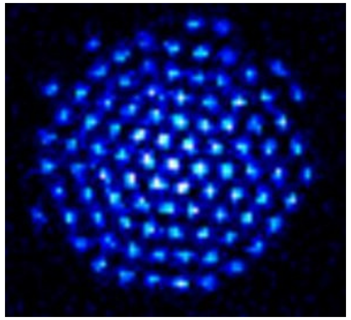
IMPROVE CLOCKS!



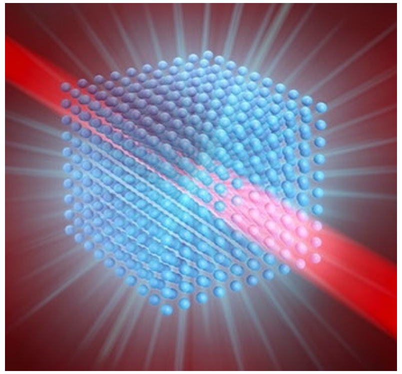
M. S. Safronova, D. Budker, D. DeMille, Derek F. Jackson-Kimball, A. Derevianko, and Charles W. Clark, Rev. Mod. Phys. 90, 025008 (2018).



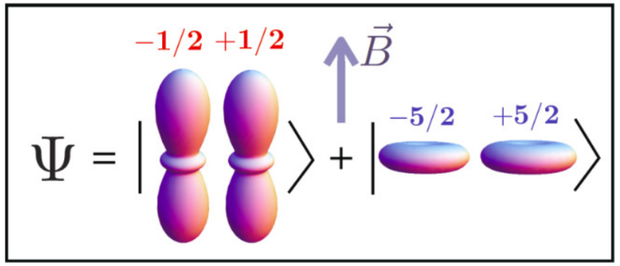
Measurements beyond the quantum limit



Large ion crystals



New designs for lattice clocks



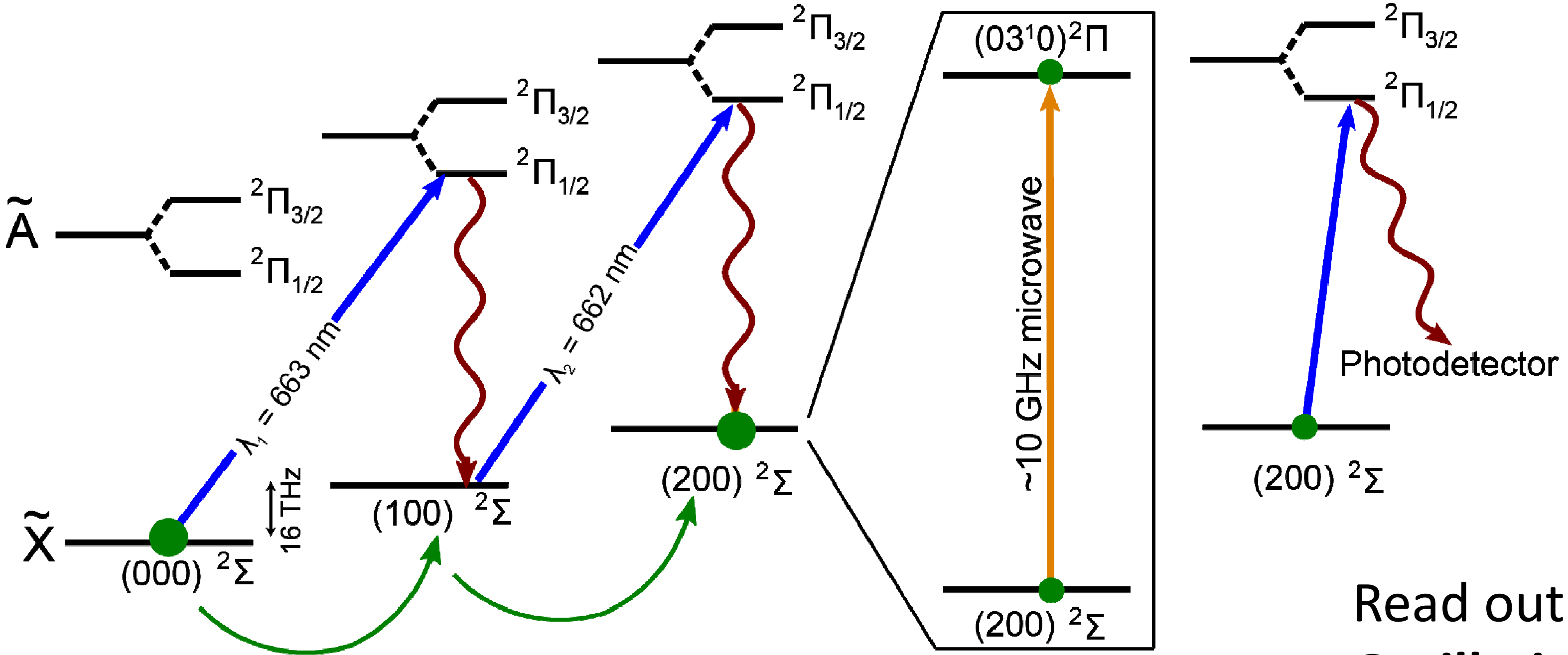
Entangled clocks

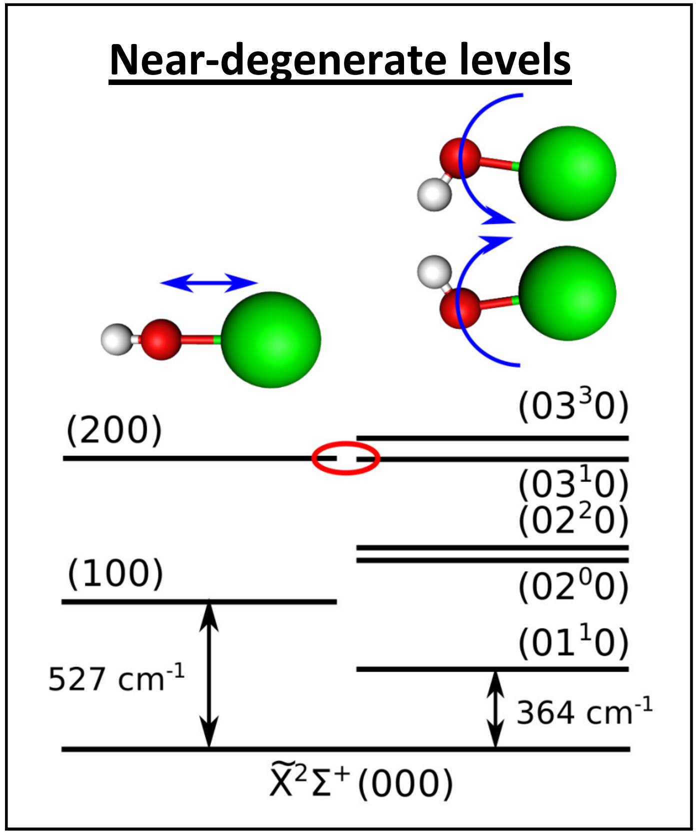
Build different clocks

(1) Enhanced sensitivity to variation of fine-structure constants (photon-DM coupling)
(2) Sensitive to variation of different fundamental constants

Scalar DM search with ultracold SrOH

- Use molecular spectroscopy to search for variation of $\mu = \frac{m_e}{m_p}$
- Ultralight dark matter has different effects on excited states
- Can take advantage of fortuitous near-degeneracies
- $\sim\ 10^{-17}/\sqrt{\text{day}}$ fractional uncertainty in $\delta\mu/\mu$




Near-degenerate levels

Optically pump into “science state”

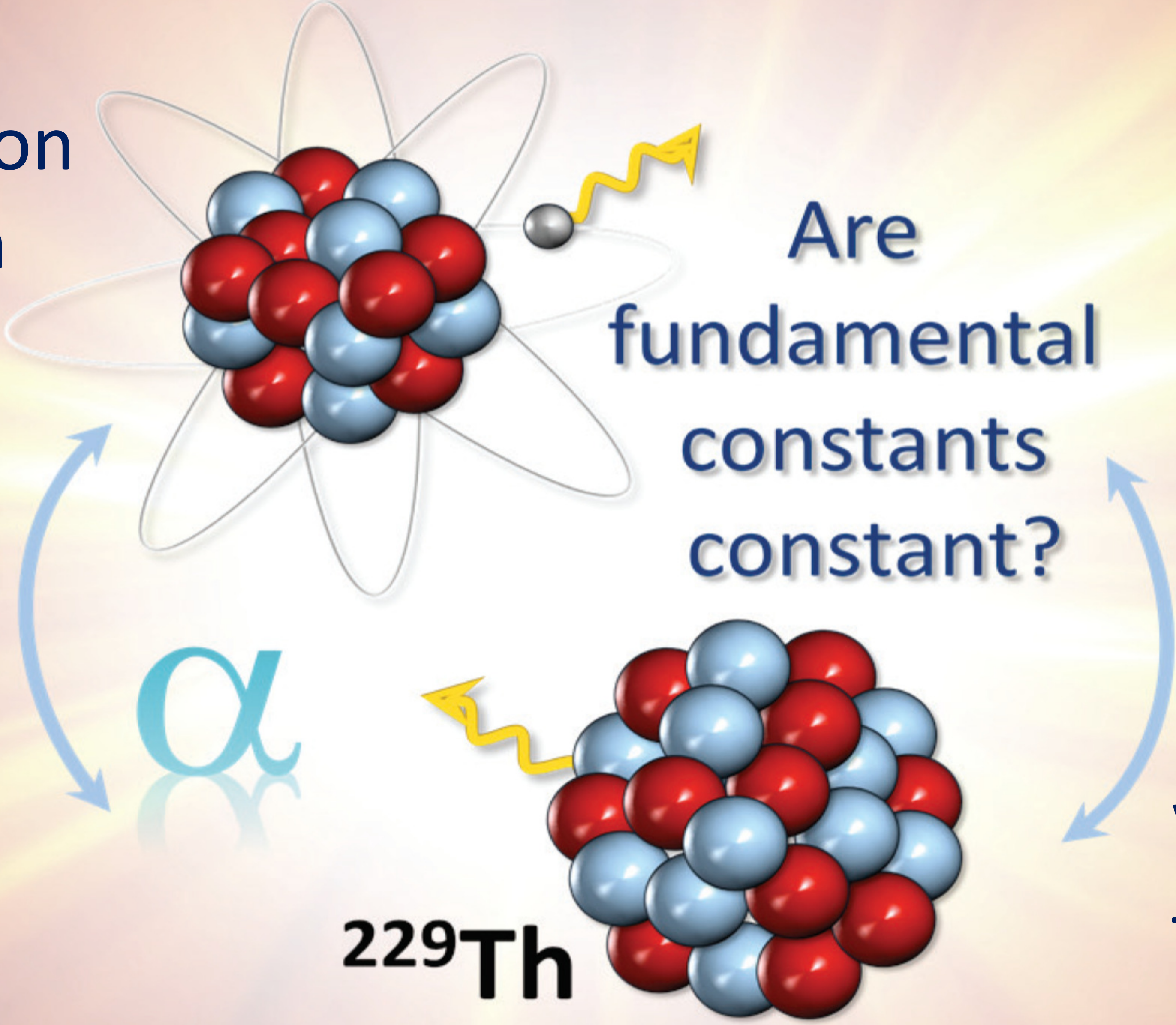
Transfer to near-degenerate vibrational state via microwaves

Read out transferred population

Oscillating resonance is a signature of dark matter

FROM ATOMIC TO NUCLEAR CLOCKS!

Clock based on transitions in atoms



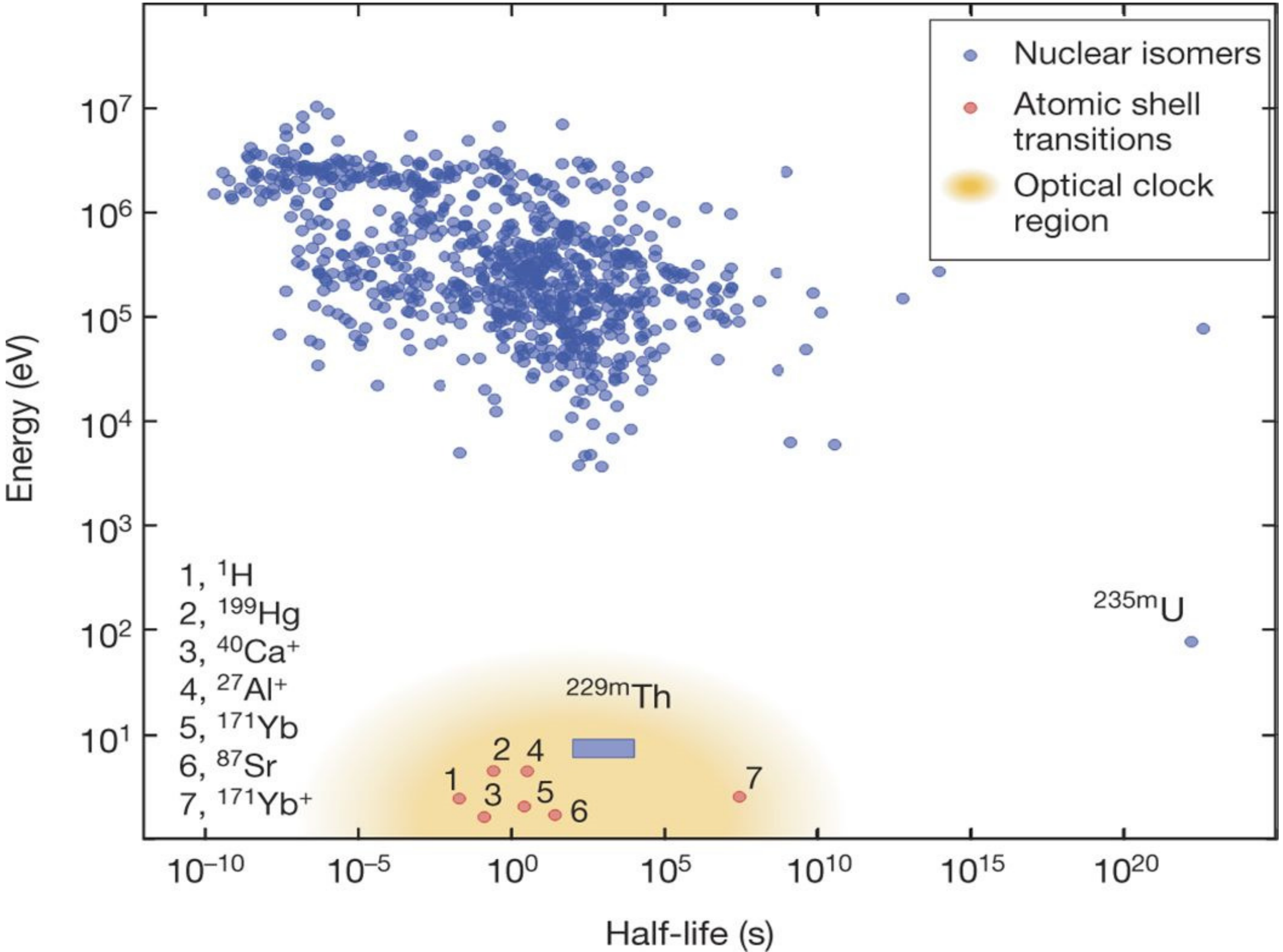
What about transitions in nuclei?

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!

Nuclear clocks?

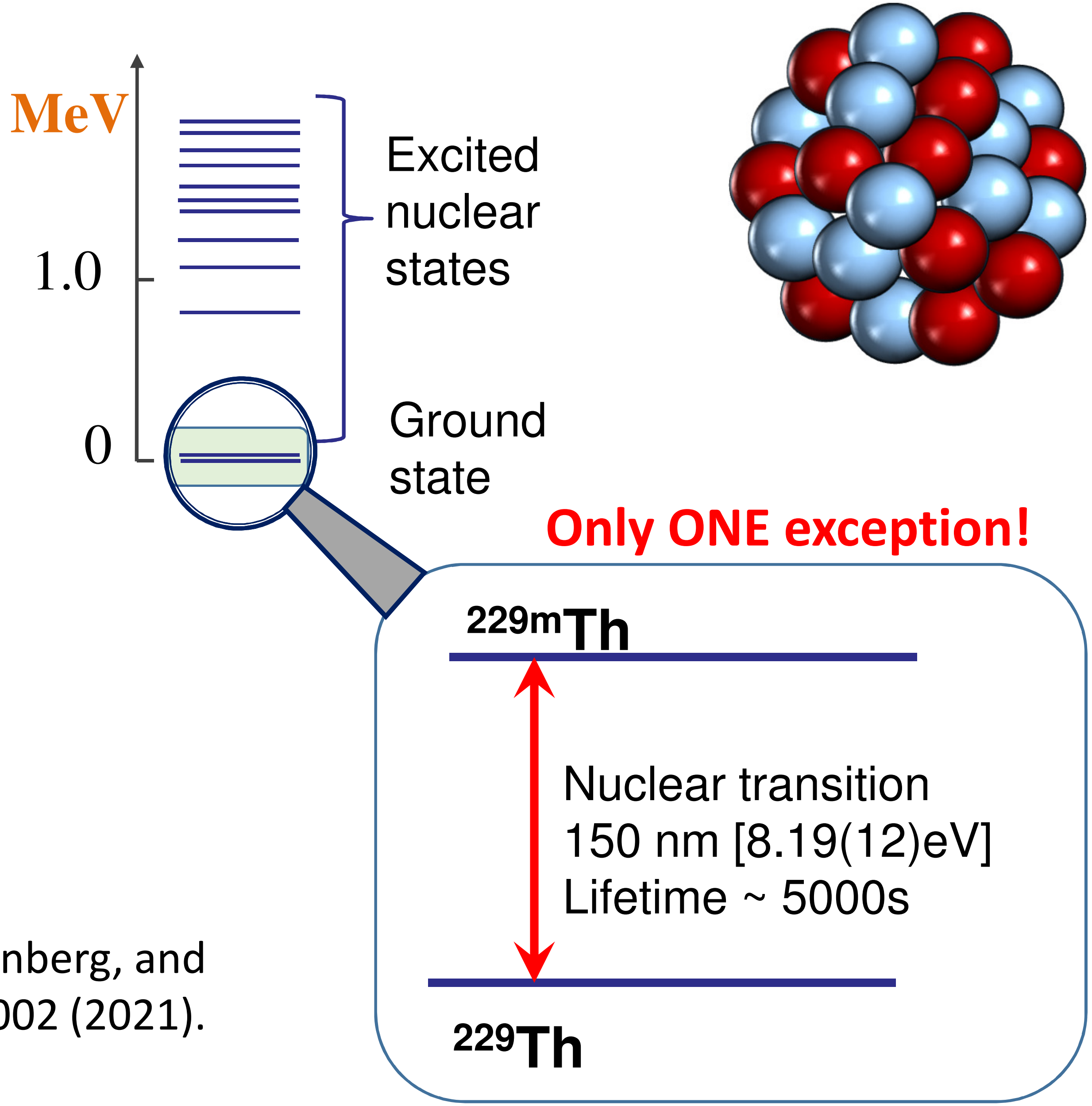


Nature 533, 47 (2016)

^{229}Th NUCLEAR CLOCK

European Research Council

Thorsten Schumm, TU Wein
Ekkehard Peik, PTB
Peter Thirolf, LMU
Marianna Safronova, UD



Excited nuclear states

Ground state

Only ONE exception!

^{229m}Th

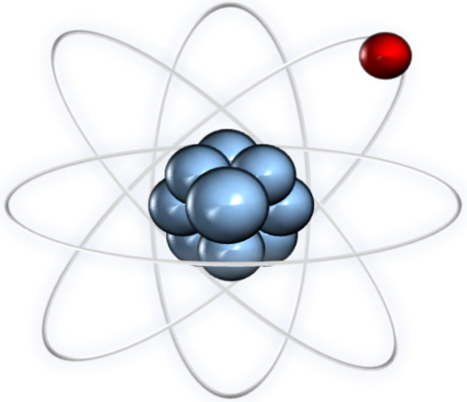
Nuclear transition
150 nm [8.19(12)eV]
Lifetime ~ 5000s

^{229}Th

Energy of the ^{229}Th nuclear clock transition:
Seiferle *et al*., Nature 573, 243 (2019)
T. Sikorsky et al., Phys. Rev. Lett. 125, 142503 (2020).

Review & ERC Synergy project plan:
E. Peik, T. Schumm, M. S. Safronova, A. Pálffy, J. Weitenberg, and P. G. Thirolf, Quantum Science and Technology 6, 034002 (2021).

Th^{3+} ion



What is different for the nuclear clock?

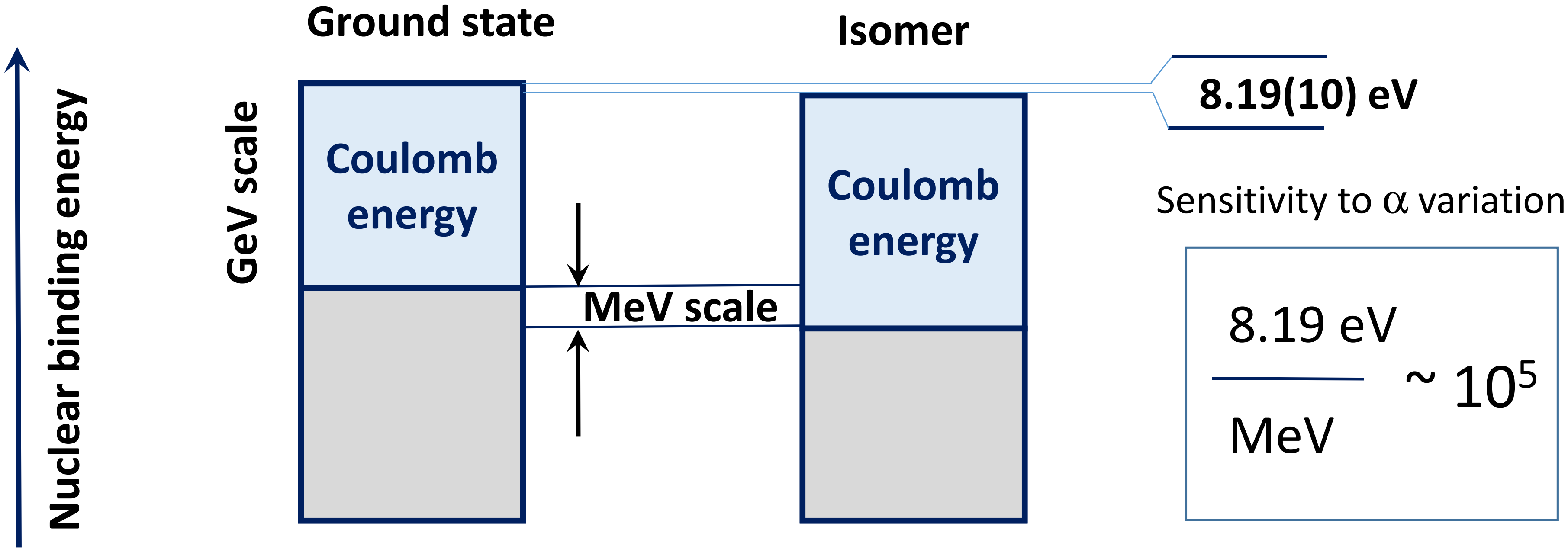
(1) Much higher sensitivity to the variation of α

(2) Nuclear clock is sensitive to other fundamental constants

(3) Nuclear clock is sensitive to coupling of dark matter to both electromagnetic and the nuclear sector of the standard model

Another possibility:
solid state nuclear
clock

Th NUCLEAR CLOCK: EXCEPTIONAL SENSITIVITY TO NEW PHYSICS


Nuclear binding energy

GeV scale

Ground state

Coulomb energy

MeV scale

Isomer

Coulomb energy

8.19(10) eV

Sensitivity to α variation

$$\frac{8.19\text{ eV}}{\text{MeV}} \sim 10^5$$

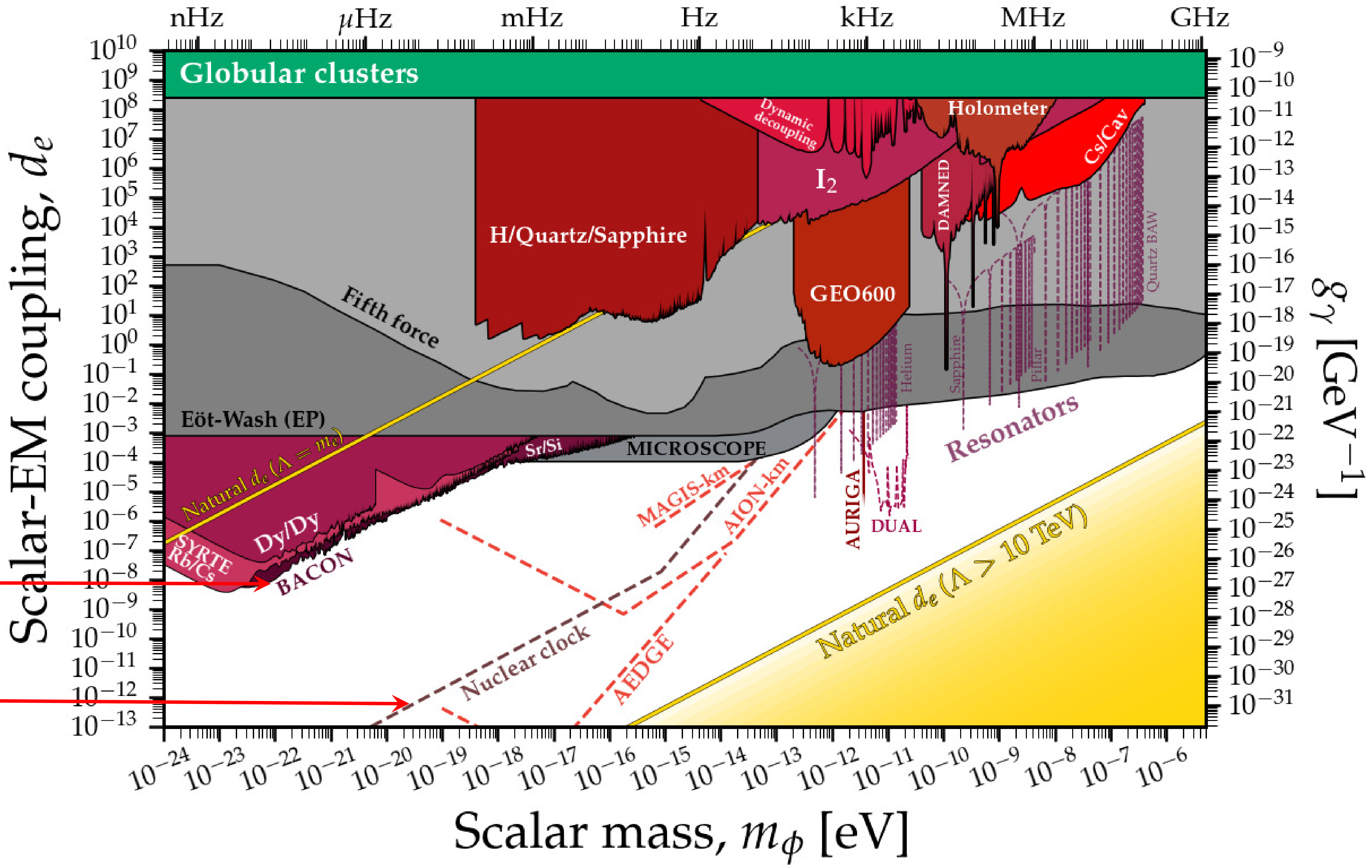
Much higher predicted sensitivity (K = 10000-100000) to the variation of α and $\frac{m_q}{\Lambda_{QCD}}$.

Nuclear clock is sensitive to coupling of dark matter to the nuclear sector of the standard model.

5 years: prototype nuclear clocks, based on both solid state and trapped ion technologies
Variation of fundamental constant and dark matter searches competitive with present clock

10 years: 10^{-18} – 10^{-19} nuclear clock, 5 - 6 orders improvement in current clock dark matter limits

$$\phi F_{\mu\nu} F^{\mu\nu}$$



Present clock limits

Projected clock limits

arXiv:2203.14915

Ultralight DM limits: https://cajohare.github.io/AxionLimits/