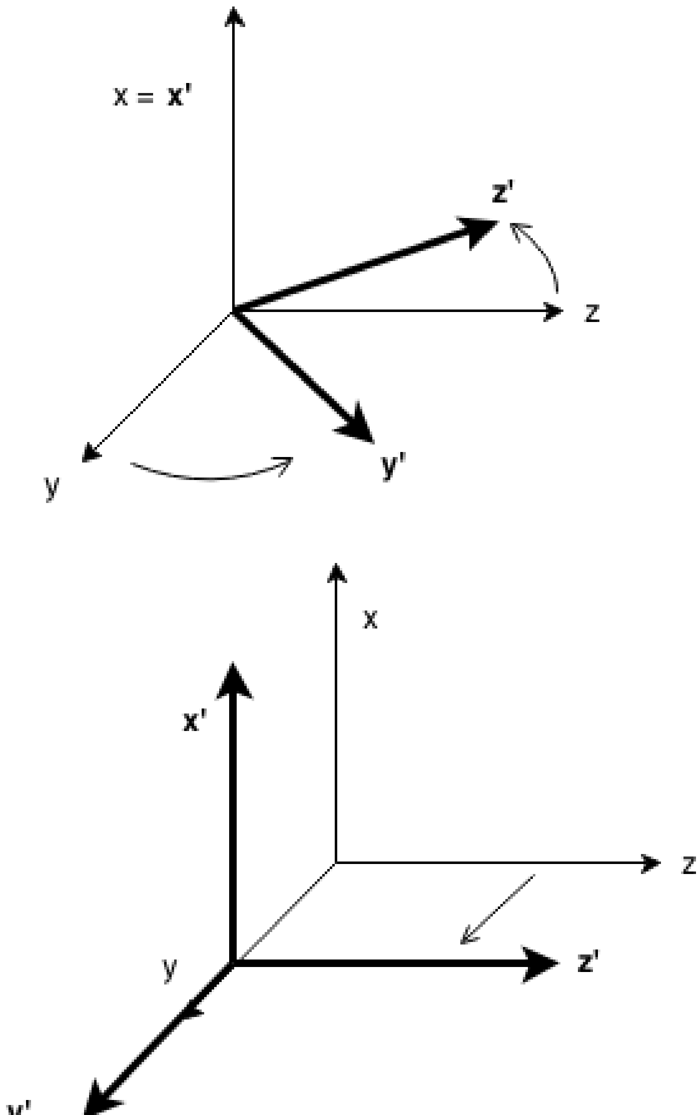
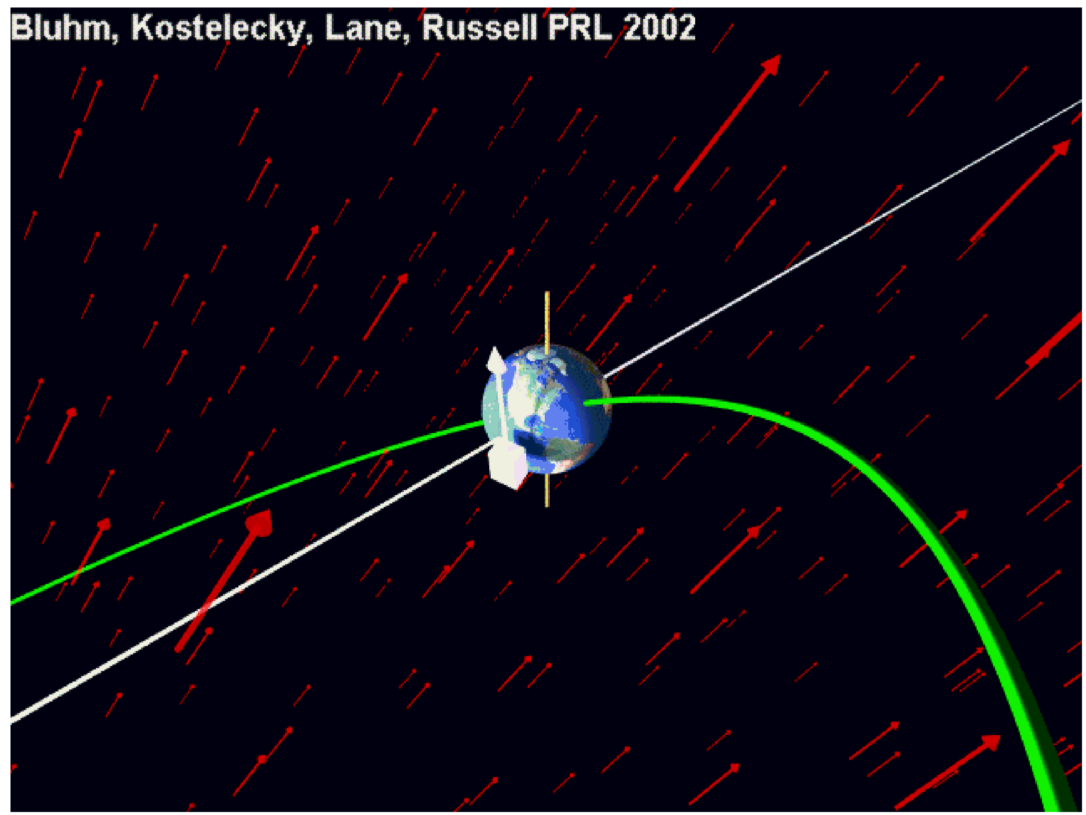
Searches for the violation of Lorentz invariance with atomic systems

MARIANNA SAFRONOVA

Discrete Symmetries in Particle, Nuclear and Atomic Physics and implications for our Universe

Lorentz invariance: the laws of physics that govern a physical system are unchanged for different system orientations or velocities.





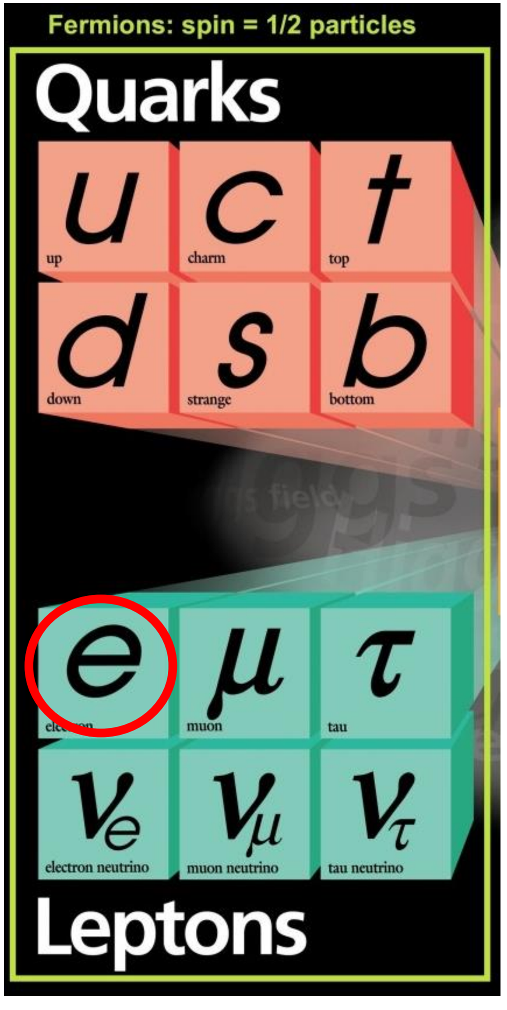
Animation credit: http://www.physics.indiana.edu/~kostelec/mov.html

Standard Model Extension

Spin ½ Dirac fermion ψ with mass m

$$L = \frac{1}{2} i \bar{\psi} \gamma_\nu \overleftrightarrow{\partial}^\nu \psi - \bar{\psi} m \psi$$

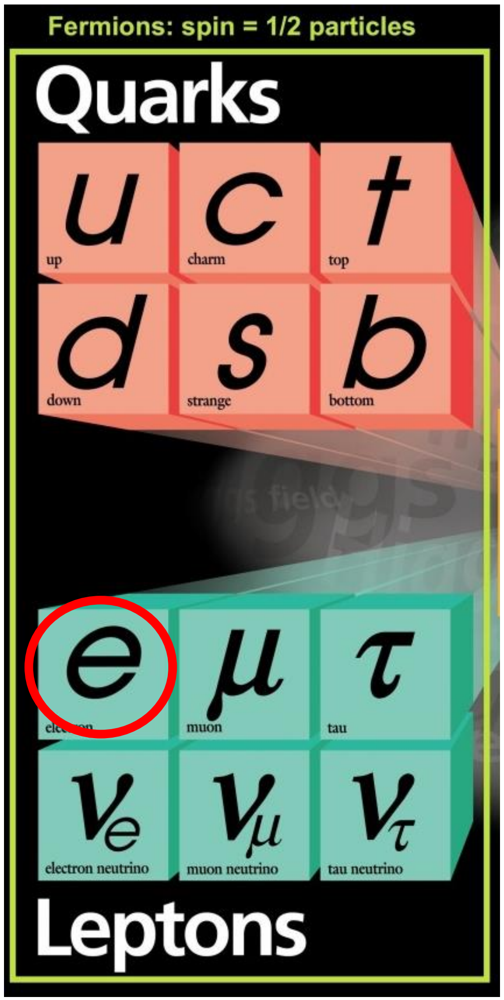
Standard Model



γ_ν are Dirac matrices

Kostelecky & Lane, Phys. Rev. D 60, 116010 (1999)

Standard Model Extension



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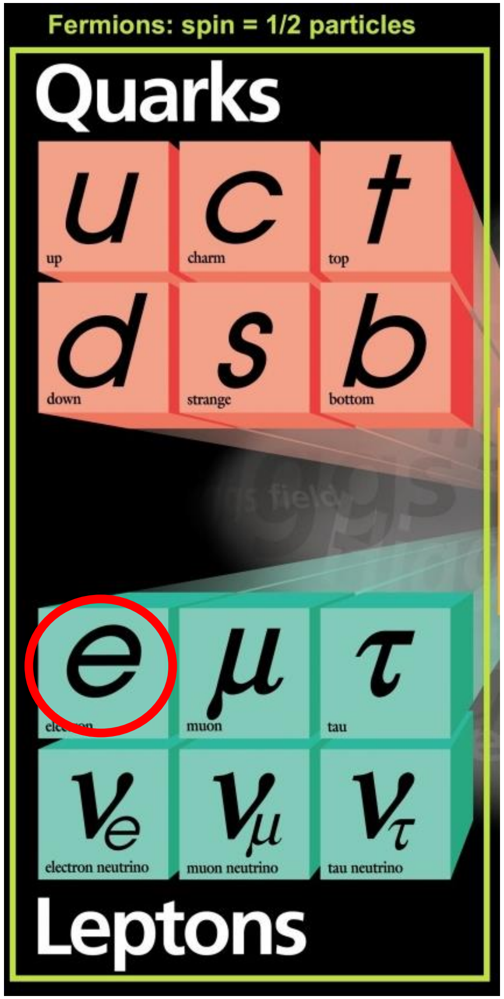

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Standard Model

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Standard Model Extension

$$\Gamma_\nu := \gamma_\nu + c_{\mu\nu}\gamma^\mu + \underbrace{d_{\mu\nu}\gamma_5\gamma^\mu}_{\text{CPT-violating}}$$

This talk: test Lorentz violation by probing cμυ Coefficients in the electron-photon sector

γ_ν are Dirac matrices

Kostelecky & Lane, Phys. Rev. D 60, 116010 (1999)

Violation of Lorentz Symmetry with bound electrons

The $c_{\mu\nu}$ tensor modifies the kinetic term in the electronic QED Lagrangian

$$T_0^{(2)} \equiv p^2 - 3{p_3}^2$$

Atomic energy levels shift!

$$\delta H = -\left(C_0^{(0)} - \frac{2U}{3c^2}c_{00}\right)\frac{\mathbf{p}^2}{2} - \frac{1}{6}C_0^{(2)}T_0^{(2)}$$

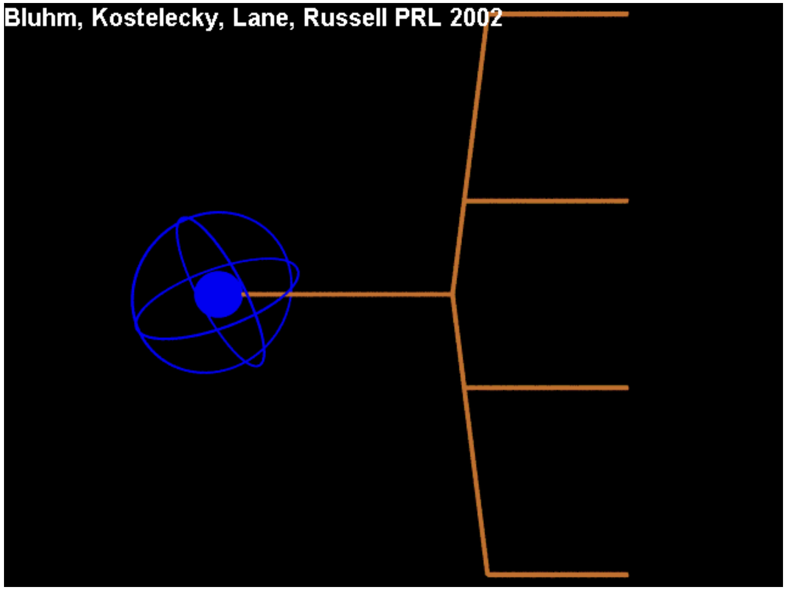
U is the Newtonian potential $-MG/r$

$${C_0}^{(0)} \equiv c_{00} + \tfrac{2}{3}c_{jj}$$ Scalar shift due to Lorentz violation

$${C_0}^{(2)} \equiv c_{11} + c_{22} - 2c_{33}$$ **Quadrupole shift due to Lorentz violation**

The basic idea of atomic physics tests of Lorentz invariance with electrons/photons:

Atomic energy levels are affected differently by Lorentz violation: transition frequency will change when experimental set up rotates or moves



Experimental strategy:

(1) Pick two energy levels that should shift differently due to Lorentz violation.

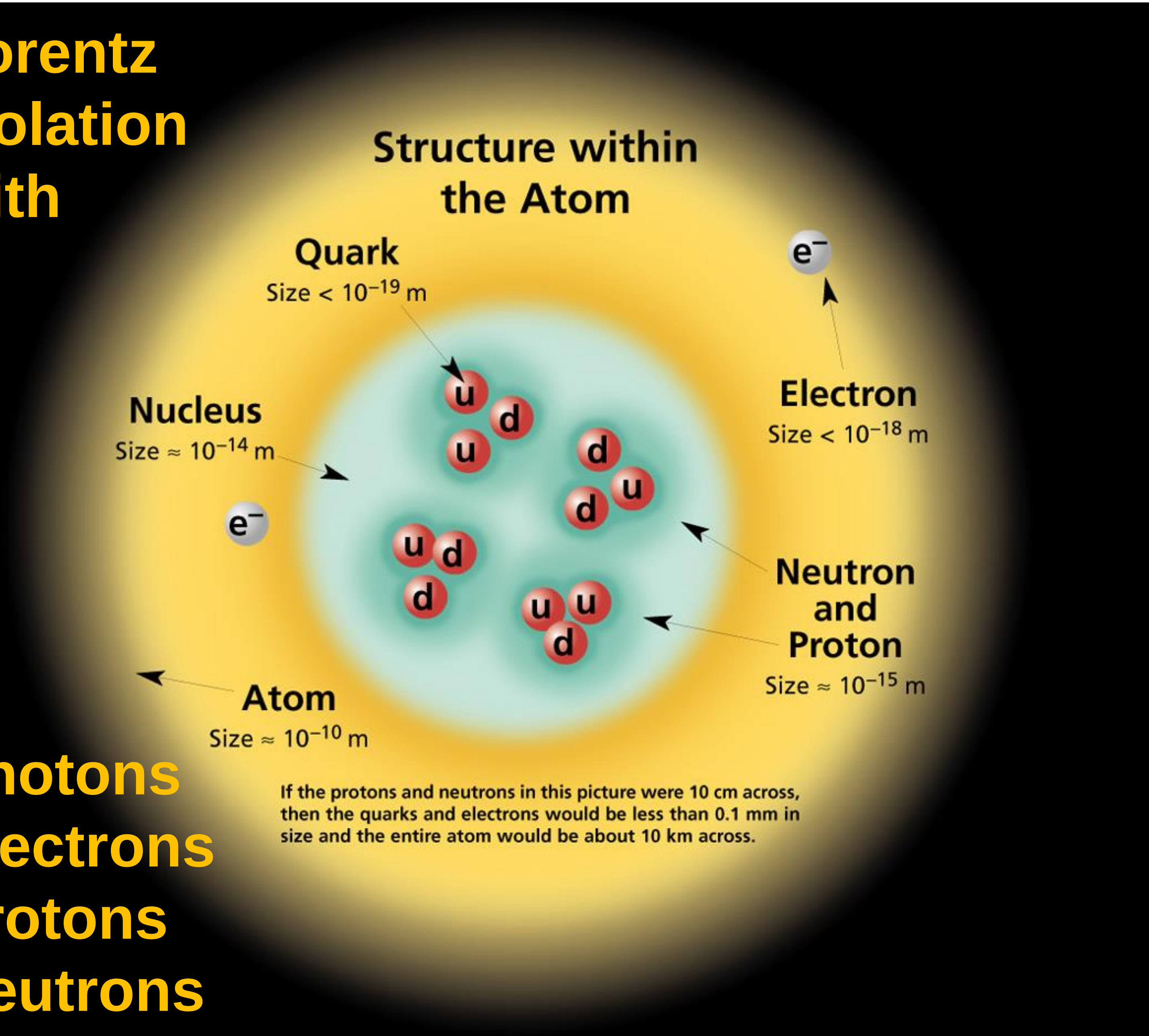
(2) Turn on magnetic field to define a quantization axis.

(3) Keep measuring the transition frequency between these two levels while Earth rotates and and moves around the Sun. **[DO NOT ROTATE EXPERIMENT YOURSELF].**

Animation is from Alan Kostelecký web site:
http://www.physics.indiana.edu/~kostelec/mov.html

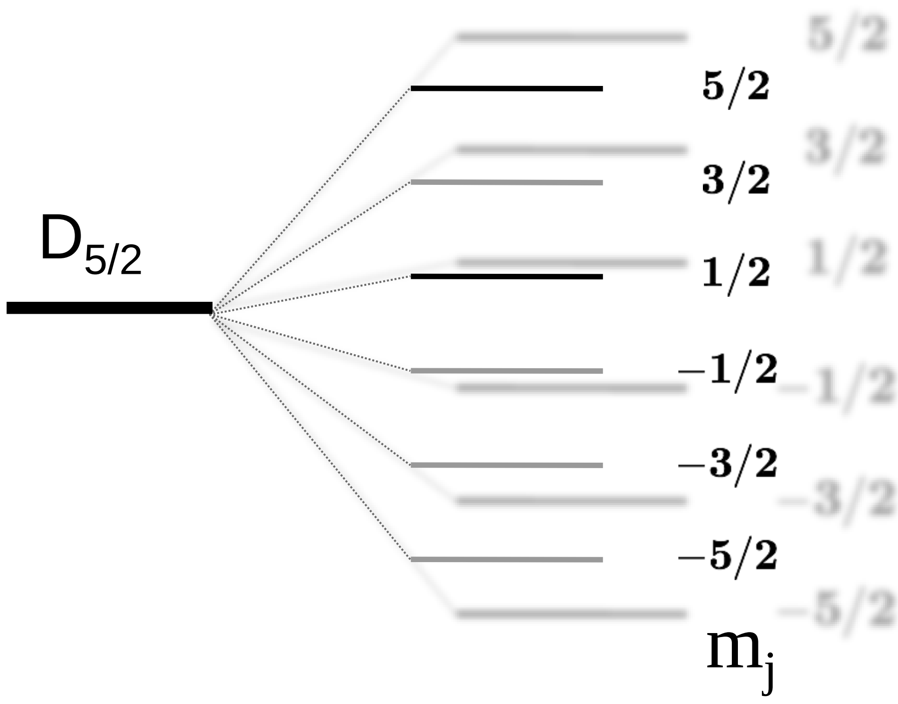
Test of Lorentz symmetry with atomic systems

Lorentz violation with



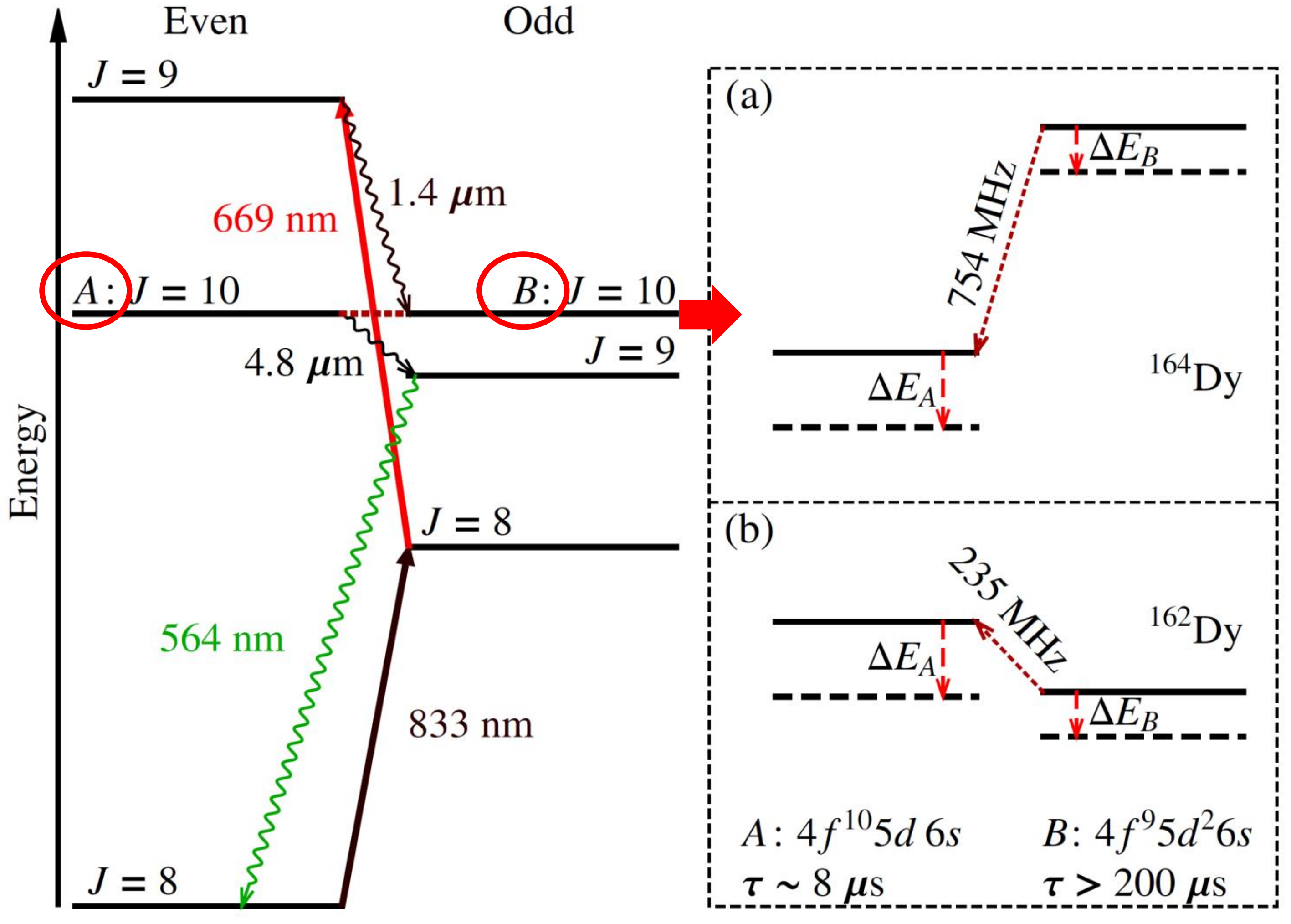
Photons
Electrons
Protons
Neutrons

Problem: Systematic errors due to magnetic field fluctuations – need to cancel these shifts



Energy levels fluctuate in varying magnetic field

Previous laboratory LV tests setting limits on $c_{\mu\nu}$ in electron-photon sector: dysprosium



Levels A and B are accidentally very close and LV effects are enhanced.

Lorentz-symmetry violation shifts the rf resonance by $\delta\omega_{\mathrm{rf}} = (\Delta E_B - \Delta E_A)/\hbar$.

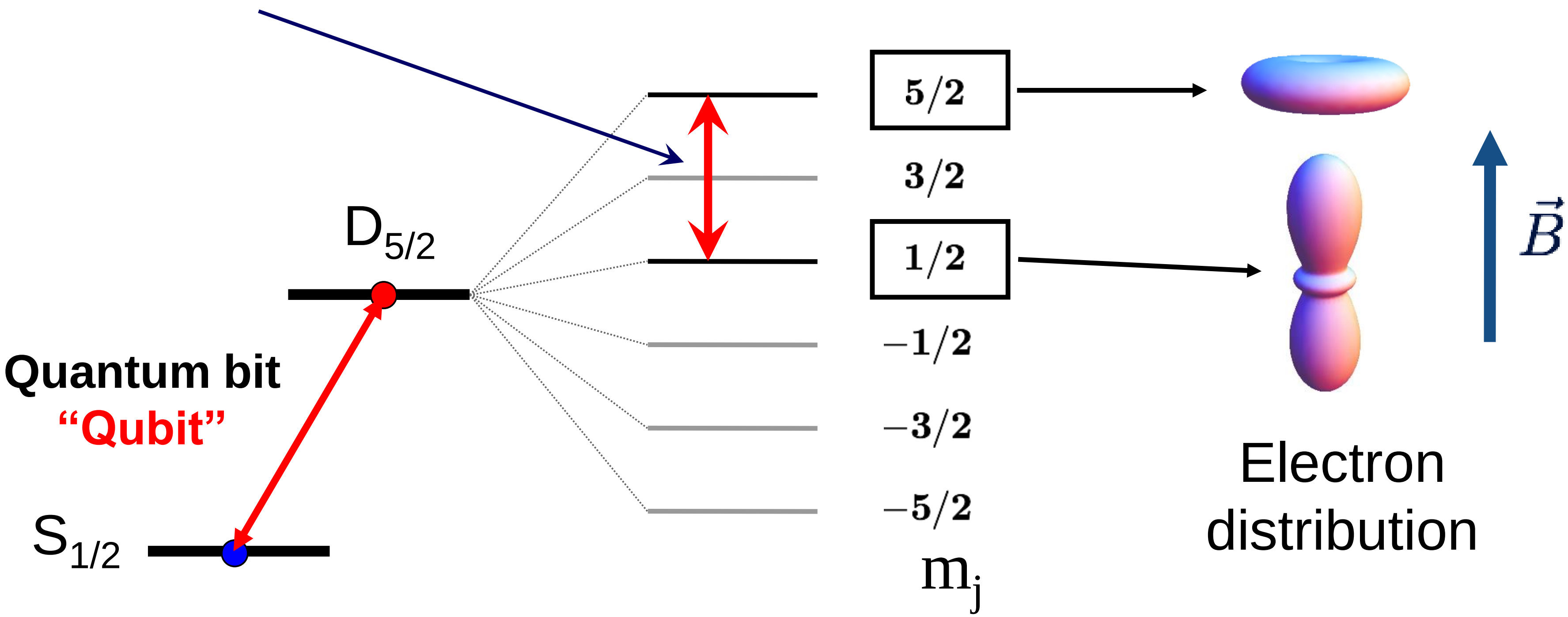
M. A. Hohensee *et al.*, Phys. Rev. Lett. 111, 050401 (2013).

Previous laboratory LV tests setting limits on $c_{\mu\nu}$ in the electron-photon sector: two trapped Ca^{+} ions

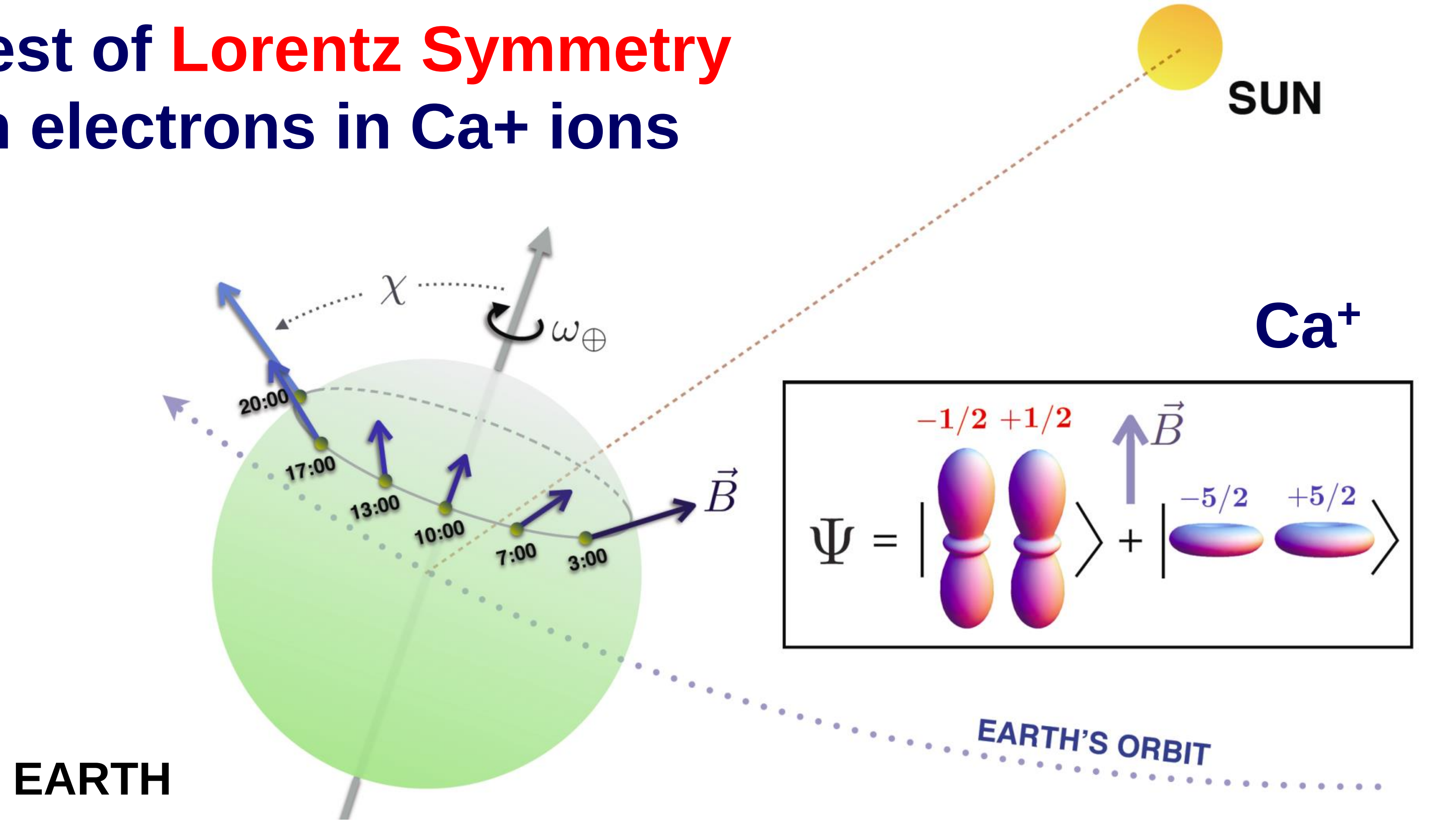
[redacted] [redacted]

Theoretical calculation of the $\langle 3d_{5/2} | T_0^{(2)} | 3d_{5/2} \rangle$ expectation value

Measure Zeeman splitting



A Test of Lorentz Symmetry with electrons in Ca+ ions



Quantum Information solution: create superposition of two ions which is protected from magnetic field fluctuations.

T. Pruttivarasin, M. Ramm, S. G. Porsev, I. I. Tupitsyn, M. Safronova, M. A. Hohensee, H. Häffner, Nature 517, 592, (2015)

What is the best atomic system?

(1) Need the largest matrix element of of Lorentz violating Hamiltonian:

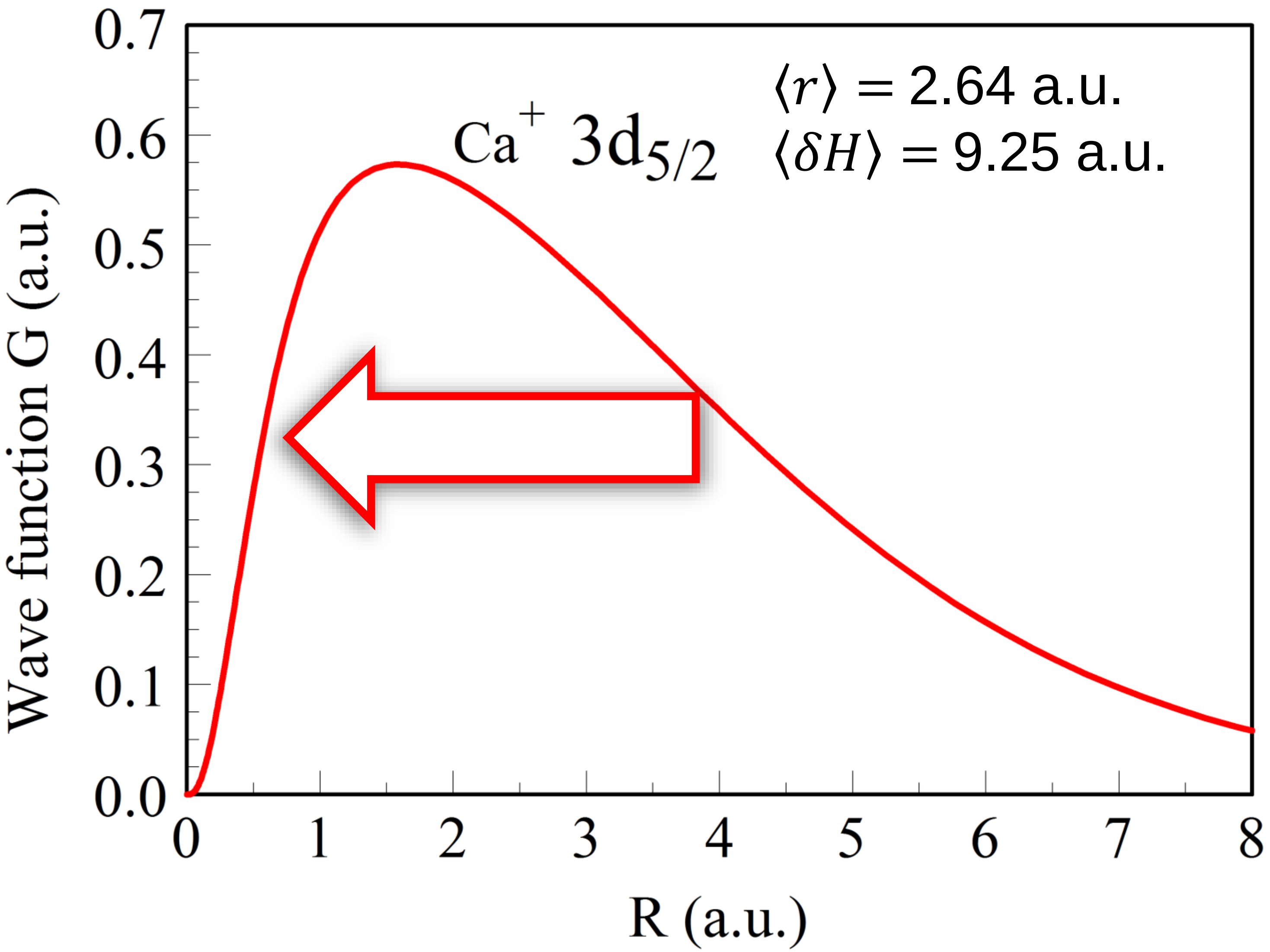
$$\delta\mathcal{H} = -C_0^{(2)} \frac{\left(\boldsymbol{p}^2 - 3p_z^2\right)}{6m_\mathrm{e}}$$

(2) Need long lifetime of the excited atomic state for Lorentz violation probe or

Find atoms with suitable ground state.

Need the largest matrix element of Lorentz violating Hamiltonian:

$$\delta\mathcal{H} = -C_0^{(2)} \frac{\left(\boldsymbol{p}^2 - 3p_z^2\right)}{6m_e}$$



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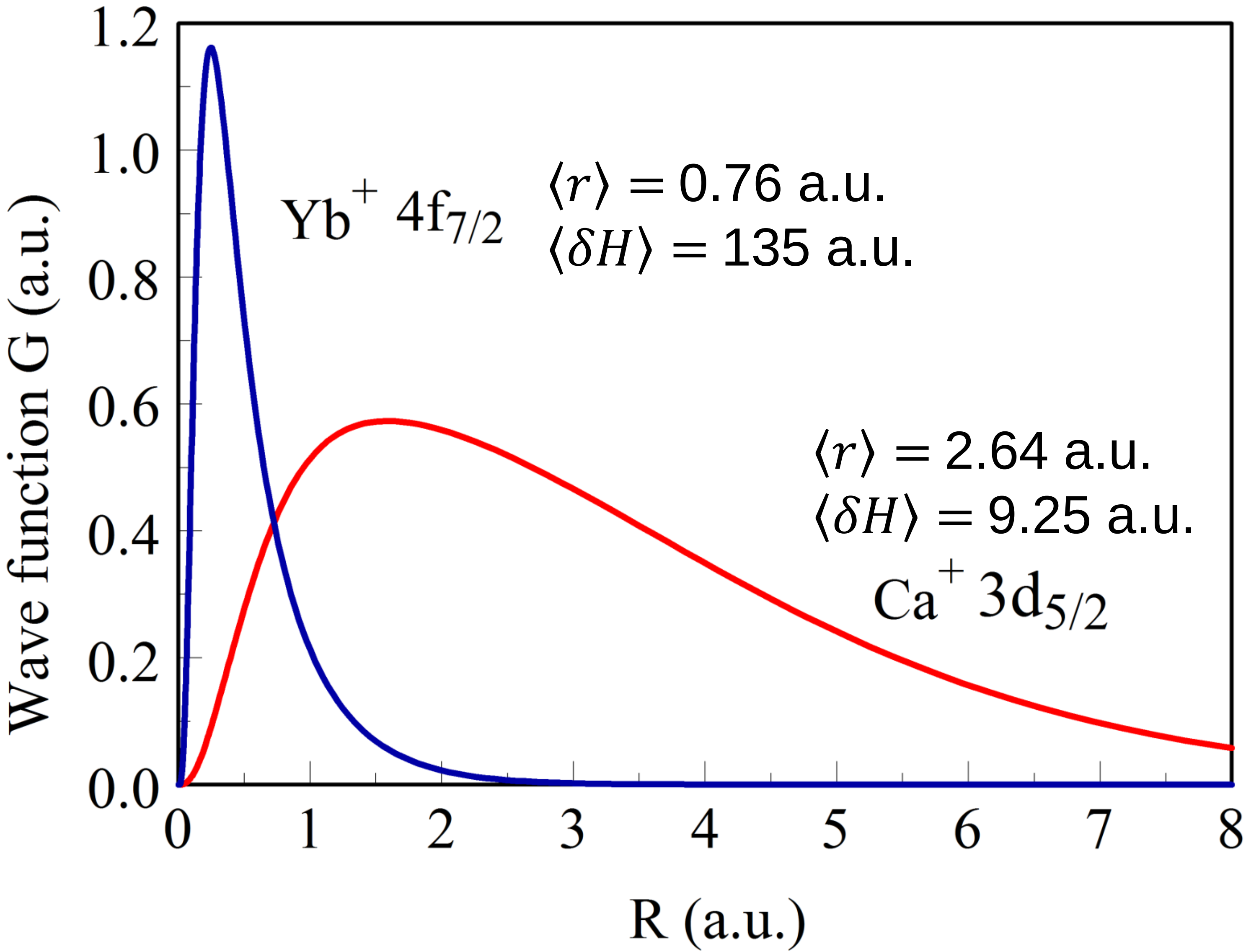
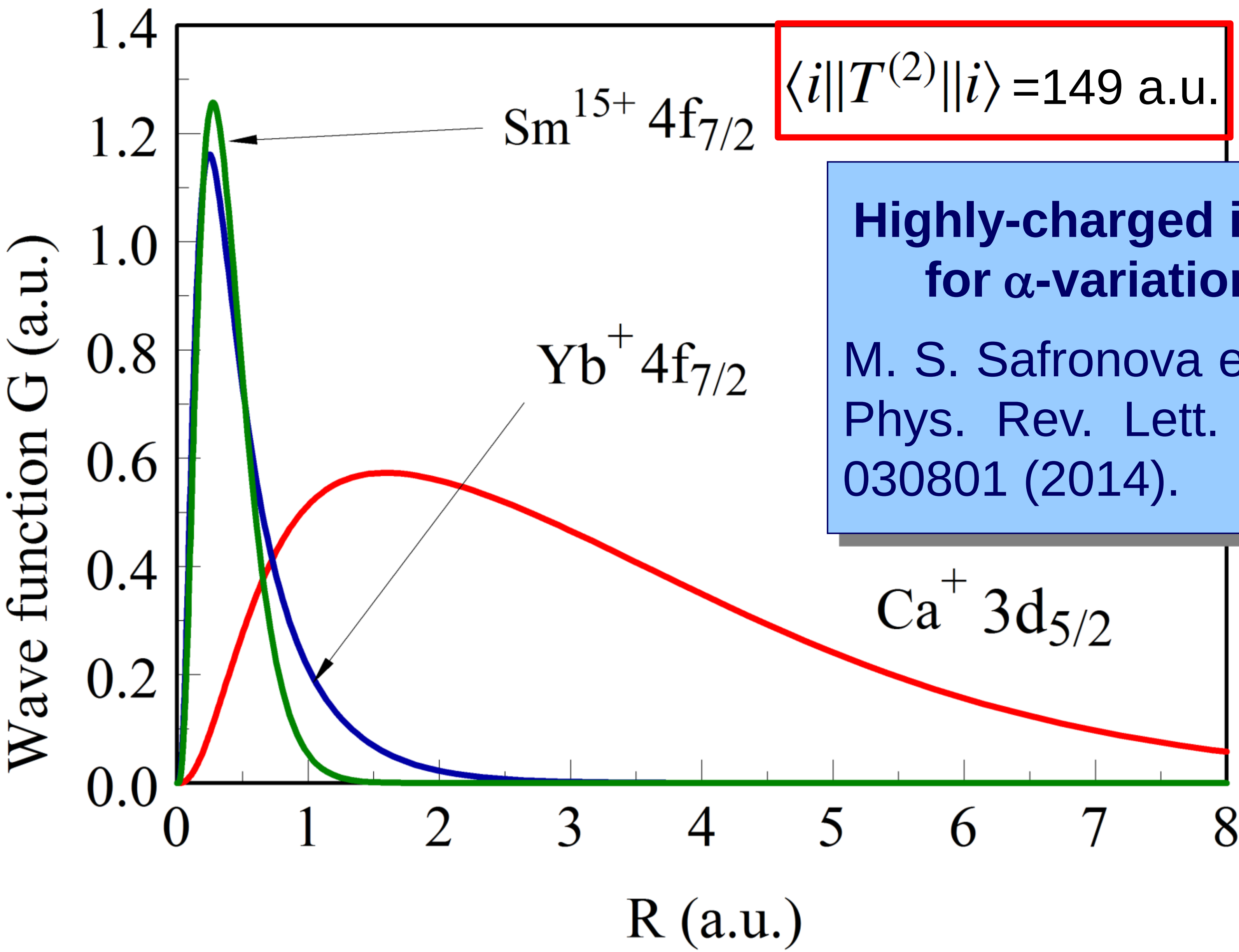


4f shell is also highly contracted in Yb^+ and highly-charged ions: LLI matrix elements are also enhanced



$\langle i \| T^{(2)} \| i \rangle$ =149 a.u.

Highly-charged ions for α-variation

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

Sensitivity to electron tensor Lorentz violation

Ion	N	Level	J	$\lvert\langle J\lVert T^{(2)}\rVert J\rangle\rvert$	$\lvert\Delta E/(hC_0^{(2)})\rvert$
Ca^+	19	$3d$	5/2	9.3	4.5×10^{15} [9]
Yb^+	69	$4f^{13}6s^2$	7/2	135 CLOCK!	6.1×10^{16} [10]
Tm	69	$4f^{13}6s^2$	7/2	141	6.4×10^{16}
Yb	70	$4f^{13}5d6s^2$	2	74	3.9×10^{16}
Th^{3+}	87	$5f$	5/2	47	2.2×10^{16}
Sm^{15+}	47	$4f$	5/2	128	5.7×10^{16}
Os^{18+}	58	$4f^{12}$	6	367	1.4×10^{17}
Pt^{20+}	58	$4f^{12}$	6	412	1.6×10^{17}
Hg^{22+}	58	$4f^{12}$	6	459	1.8×10^{17}
Pb^{24+}	58	$4f^{12}$	6	507	2.0×10^{17}
Bi^{25+}	58	$4f^{12}$	6	532	2.1×10^{17}
U^{34+}	58	$4f^{12}$	6	769	3.0×10^{17}

Optical vs. microwave 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

Non è possibile visualizzare l'immagine.

Non è possibile visualizzare l'immagine.

valentinagurarie.wordpress.com/tag/atom/

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

How atomic clock works

Non è possibile visualizzare l'immagine.

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

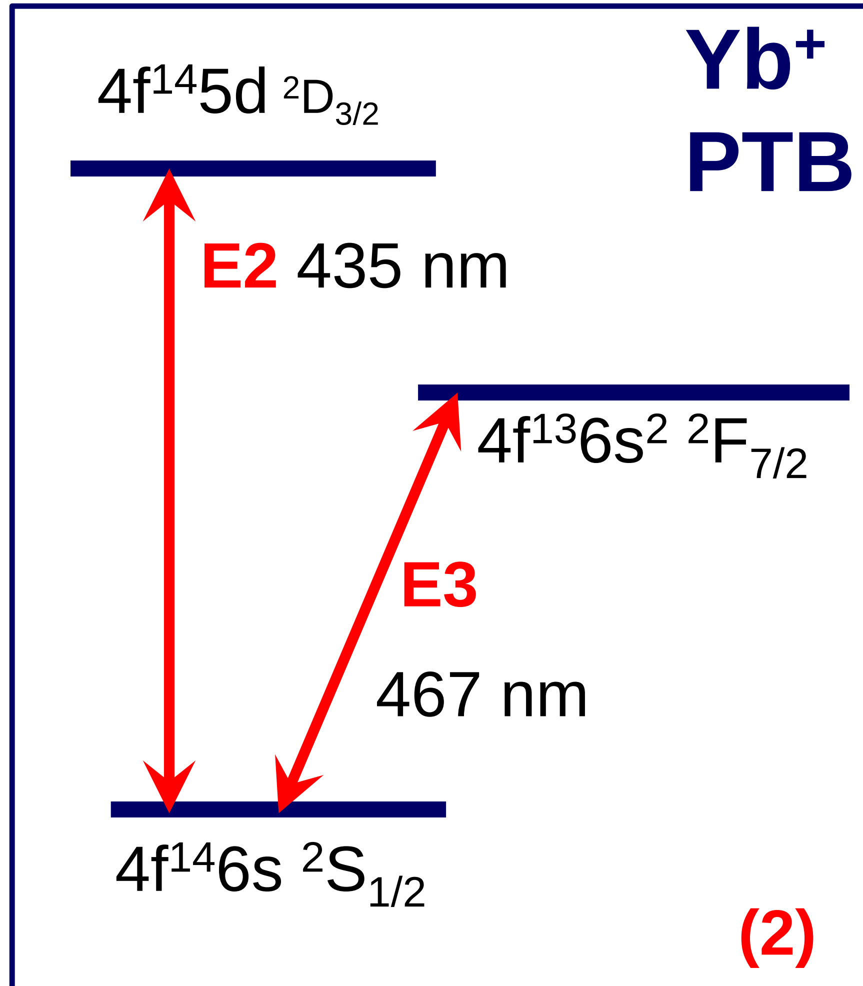
Optical atomic clocks

(1) Neutral atoms in optical lattices
(2) Single trapped ions

(1)

Mg
Al^+
Cd
Sr
Yb
Hg

Strontium optical lattice neutral atom clock



Yb^+ single trapped ion clock

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

Optical clock comparison test of Lorentz symmetry: hundredfold improved LV bounds

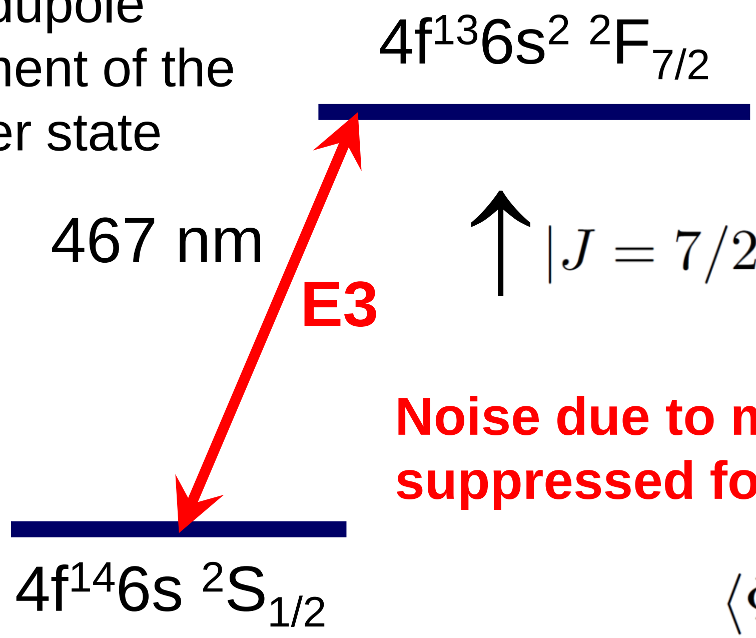
C. Sanner, N. Huntemann, R. Lange,
Chr. Tamm, E. Peik,
M. Safronova and S. Porsev

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

arXiv:1809.10742 (2018)

Two $^{171}Yb^+$ PTB clocks

Very small quadupole moment of the upper state



J=7/2 I=1/2
F=3, M=0

$$\uparrow |J = 7/2\ M_J = 1/2\rangle + |J = 7/2\ M_J = -1/2\rangle \downarrow$$

Noise due to magnetic-field fluctuation is naturally suppressed for this state Φ, but LV signal is not zero!

$$\langle \Phi | T_0^{(2)} | \Phi \rangle \approx 23.3 \text{ a.u.}$$

$$\begin{aligned}
\frac{\triangle E}{h} &\approx -5.6 \times 10^{17} \left(C_0^{(0)} - \frac{2U}{3c^2} c_{00} \right) - 2.6 \times 10^{16}\, C_0^{(2)}, && \text{excited state} \\
&\quad - (-5.4) \times 10^{17} \left(C_0^{(0)} - \frac{2U}{3c^2} c_{00} \right) && \text{ground state} \\
&= -2 \times 10^{16} \left(C_0^{(0)} - \frac{2U}{3c^2} c_{00} \right) - 2.6 \times 10^{16}\, C_0^{(2)},
\end{aligned}$$

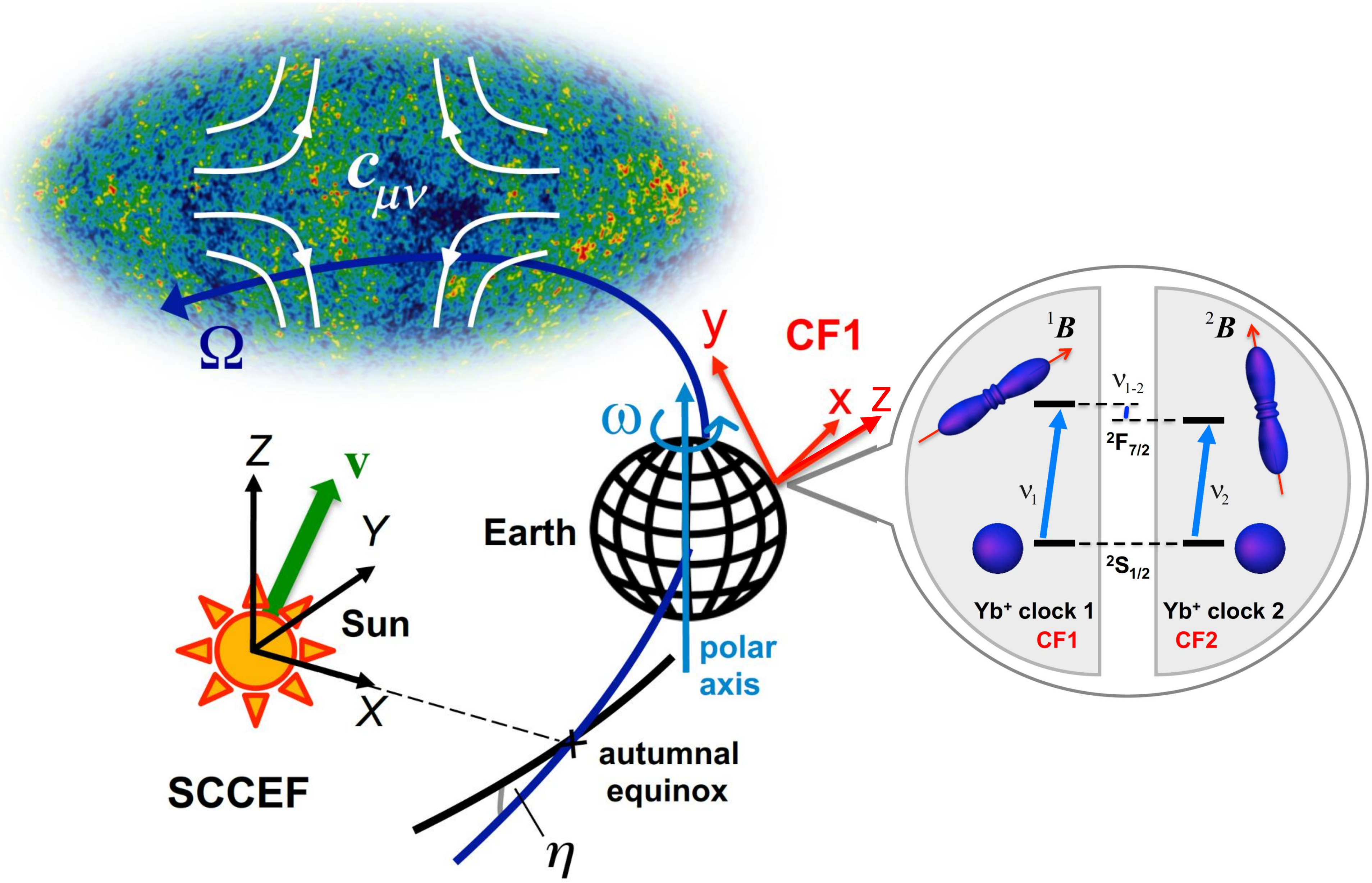
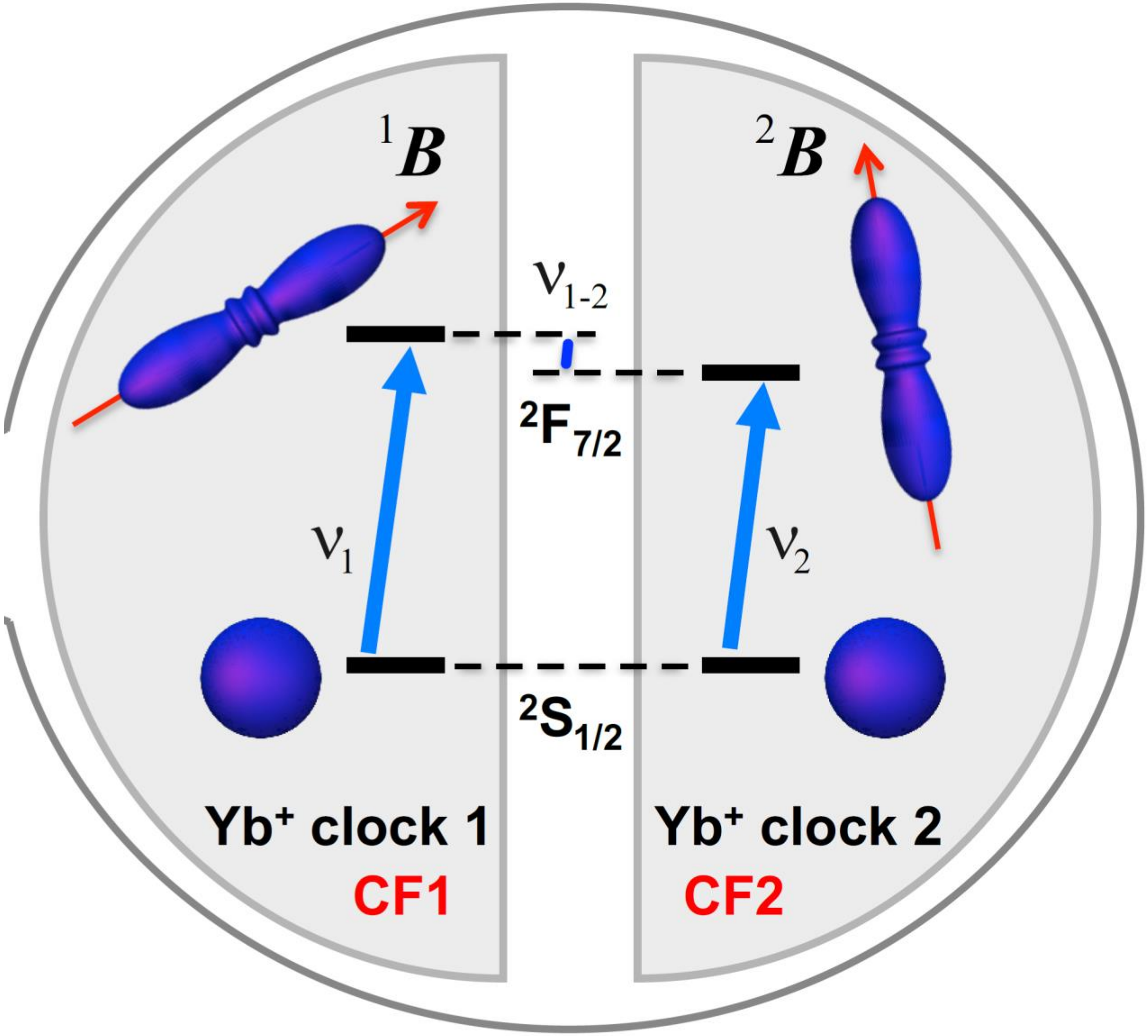
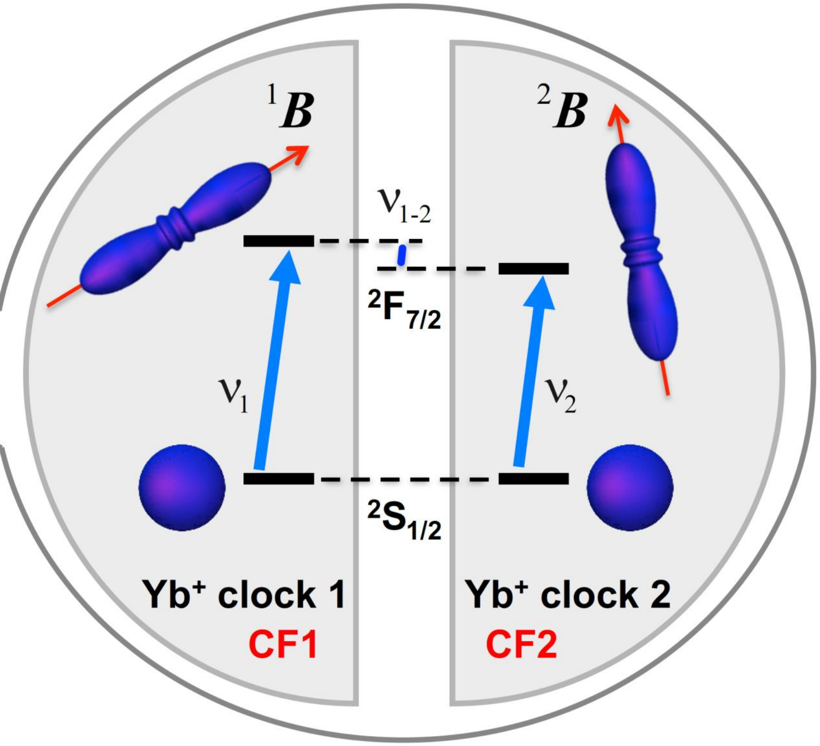


Image credit: Christian Sanner, JILA

Measure frequency difference of two clocks $\Delta\nu = \nu_1 - \nu_2$ to probe Lorentz violation





Two clocks have different quantization axes defined by the respective direction of the magnetic field and we can extract limit on

$$C_0^{(2)} = C_0^{(2)}[\mathrm{Yb1}] - C_0^{(2)}[\mathrm{Yb2}]$$

$$\nu_1 - \nu_2 = -2.6 \times 10^{16}\, C_0^{(2)}\ \mathrm{Hz}$$

Data analysis in terms of the $c_{\mu\nu}$ coefficients

$$\nu_1 - \nu_2 = -2.6 \times 10^{16}\, C_0^{(2)} \text{ Hz} \qquad C_0^{(2)} = C_0^{(2)}[\text{Yb1}] - C_0^{(2)}[\text{Yb2}]$$

$$C_0^{(2)}[\text{Yb2}] = A + \sum_{j=1}^{7} \left(C_j \cos(\omega_j T) + S_j \sin(\omega_j T)\right)$$

$$C_0^{(2)}[\text{Yb1}] = A + \sum_{j=1}^{7} \left(C_j \cos(\omega_j T + \phi_j) + S_j \sin(\omega_j T + \phi_j)\right)$$

TABLE I. The amplitudes of the $C_0^{(2)}$ frequency components in the SCCEF frame [3].

ω_j	C_j	S_j
$\omega_\oplus$	$-3\sin(2\chi)c_{XZ}$	$-3\sin(2\chi)c_{YZ}$
$2\omega_\oplus$	$-\frac{3}{2}(c_{XX} - c_{YY})\sin^2\chi$	$-3c_{XY}\sin^2\chi$
Ω	$-\frac{1}{2}\beta_\oplus\,(3\cos(2\chi)+1)\,(c_{TY}\cos\eta - 2c_{TZ}\sin\eta)$	$\frac{1}{2}\beta_\oplus c_{TX}\,(3\cos(2\chi)+1)$
$\Omega - \omega_\oplus$	$\frac{3}{2}\beta_\oplus c_{TX}\sin\eta\sin(2\chi)$	$-\frac{3}{2}\beta_\oplus\sin(2\chi)\,(c_{TY}\sin\eta + c_{TZ}(1+\cos\eta))$
$\Omega + \omega_\oplus$	$\frac{3}{2}\beta_\oplus c_{TX}\sin\eta\sin(2\chi)$	$-\frac{3}{2}\beta_\oplus\sin(2\chi)\,(c_{TZ}(1-\cos\eta) - c_{TY}\sin\eta)$
$\Omega - 2\omega_\oplus$	$-3\beta_\oplus c_{TY}\cos^2(\eta/2)\sin^2\chi$	$-3\beta_\oplus c_{TX}\cos^2(\eta/2)\sin^2\chi$
$\Omega + 2\omega_\oplus$	$3\beta_\oplus c_{TY}\sin^2(\eta/2)\sin^2\chi$	$-3\beta_\oplus c_{TX}\sin^2(\eta/2)\sin^2\chi$

$$\boxed{C_0^{(2)}(t) = c_{TX} f_1(t) + c_{TY} f_2(t) + c_{TZ} f_3(t) + c_{XZ} f_4(t) + c_{YZ} f_5(t) + c_{X-Y} f_6(t) + c_{XY} f_7(t)}$$

Results : c_{JK} coefficients

	This work	2015 results [1]
c_{X-Y}	$0.9 \pm 1.6 \times 10^{-20}$	$-0.2 \pm 2.3 \times 10^{-18}$
c_{XY}	$-6.9 \pm 8.0 \times 10^{-21}$	$-0.8 \pm 1.2 \times 10^{-18}$
c_{XZ}	$1.3 \pm 1.3 \times 10^{-20}$	$-3.4 \pm 7.9 \times 10^{-19}$
c_{YZ}	$1.7 \pm 1.3 \times 10^{-20}$	$-1.7 \pm 7.1 \times 10^{-19}$

Two orders of magnitude improvement

[1] T. Pruttivarasin et al., Nature 517, 592 (2015)
This work: C. Sanner, N. Huntemann, R. Lange, C. Tamm, E. Peik,
M. S. Safronova, S. G. Porsev, arxiv:1809.10742, submitted to Nature (2018).

(1 std. dev. uncertainties)

Results : c_{TJ} coefficients

	This work	Dy results [2]	Astrophysical limits [3]
c_{TX}	$-4.6 \pm 8.4 \times 10^{-17}$	$5.7 \pm 8.3 \times 10^{-15}$	$-1.5 \pm 5.5 \times 10^{-15}$
c_{TY}	$4.8 \pm 8.5 \times 10^{-17}$	$-8.3 \pm 7.5 \times 10^{-13}$	$0.5 \pm 1.0 \times 10^{-15}$
c_{TZ}	$-2.4 \pm 1.6 \times 10^{-16}$	$1.9 \pm 1.7 \times 10^{-12}$	$-1.0 \pm 3.0 \times 10^{-17}$

Two orders of magnitude improvement

[2] M. A. Hohensee, et al., Phys. Rev. Lett. 111, 050401 (2013)
[3] B. Altschul, Phys. Rev. D 74, 083003 (2006).
This work: C. Sanner, N. Huntemann, R. Lange, C. Tamm, E. Peik, M. S. Safronova, S. G. Porsev, arxiv:1809.10742, submitted to Nature (2018).

PHYSICAL REVIEW LETTERS **120,** 103202 (2018)

New Methods for Testing Lorentz Invariance with Atomic Systems

R. Shaniv,[1] R. Ozeri,[1] M. S. Safronova,[2,3] S. G. Porsev,[2,4] V. A. Dzuba,[5] V. V. Flambaum,[5] and H. Häffner[6]

A broadly applicable experimental proposal to search for the violation of local Lorentz invariance (LLI) with atomic systems.

The new scheme uses dynamic decoupling and can be implemented in current atomic clocks experiments, both with single ions and arrays of neutral atoms.

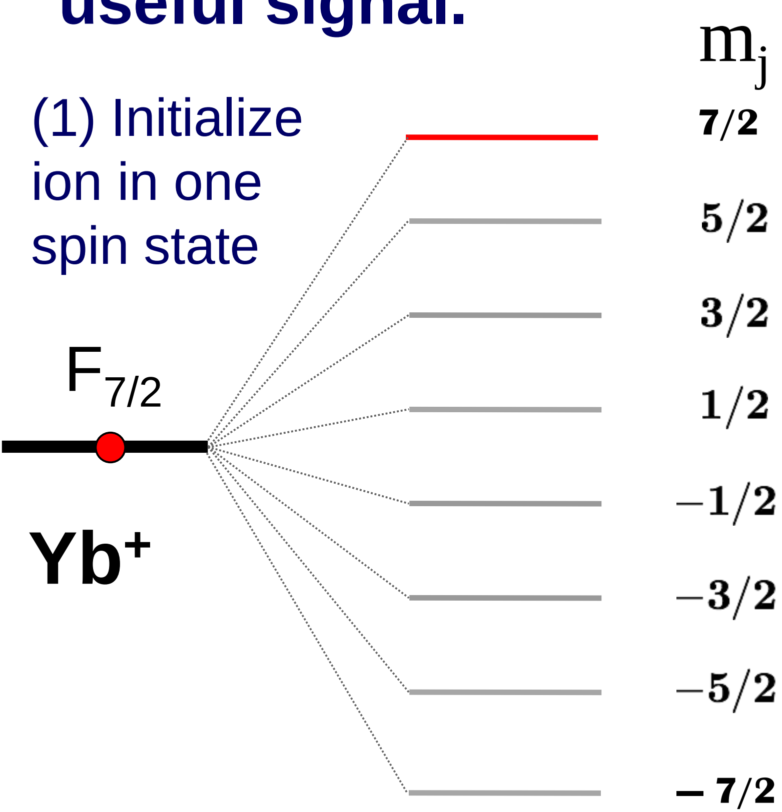
Moreover, the scheme can be performed on systems with no optical transitions, and therefore it is also applicable to highly charged ions which exhibit particularly high sensitivity to Lorentz invariance violation.

The scheme is scalable for many atoms or ions.

Main idea: use dynamic decoupling to eliminate noise due to magnetic field fluctuations

Dynamic decoupling: apply active control (microwave pulses here) to protect from noise while accumulating useful signal.

(1) Initialize ion in one spin state



(2) Apply pulse sequence which results in the following spin evolution:

$$\mathcal{U} = \exp\left(i[\delta t_w J_z + \kappa t_w J_z^2]\right) \times \exp\left(-i\pi J_y\right) \exp\left(i[2\delta t_w J_z + 2\kappa t_w J_z^2]\right) \exp\left(i\pi J_y\right) \times \exp\left(i[\delta t_w J_z + \kappa t_w J_z^2]\right).$$

$$[J_z^2,\ \exp\left(\pm i\pi J_y\right)] = 0.$$

The LV signal κJ_z^2 accumulates.

$$[J_z, \exp\left(\pm i\pi J_y\right)] \neq 0,$$

Magnetic field noise $\delta(t) J_z$ is largely reduces by averaging.

(3) Repeat n times, measure population in the initial state to extract the LV signal

$$\mathcal{U} = \exp\left(i4\kappa t_w J_z^2\right)$$

Advantages

- This method can be adapted for an ensemble of N spins, e.g., a large ion chain, ion crystal, or neutral atoms in an optical lattice.

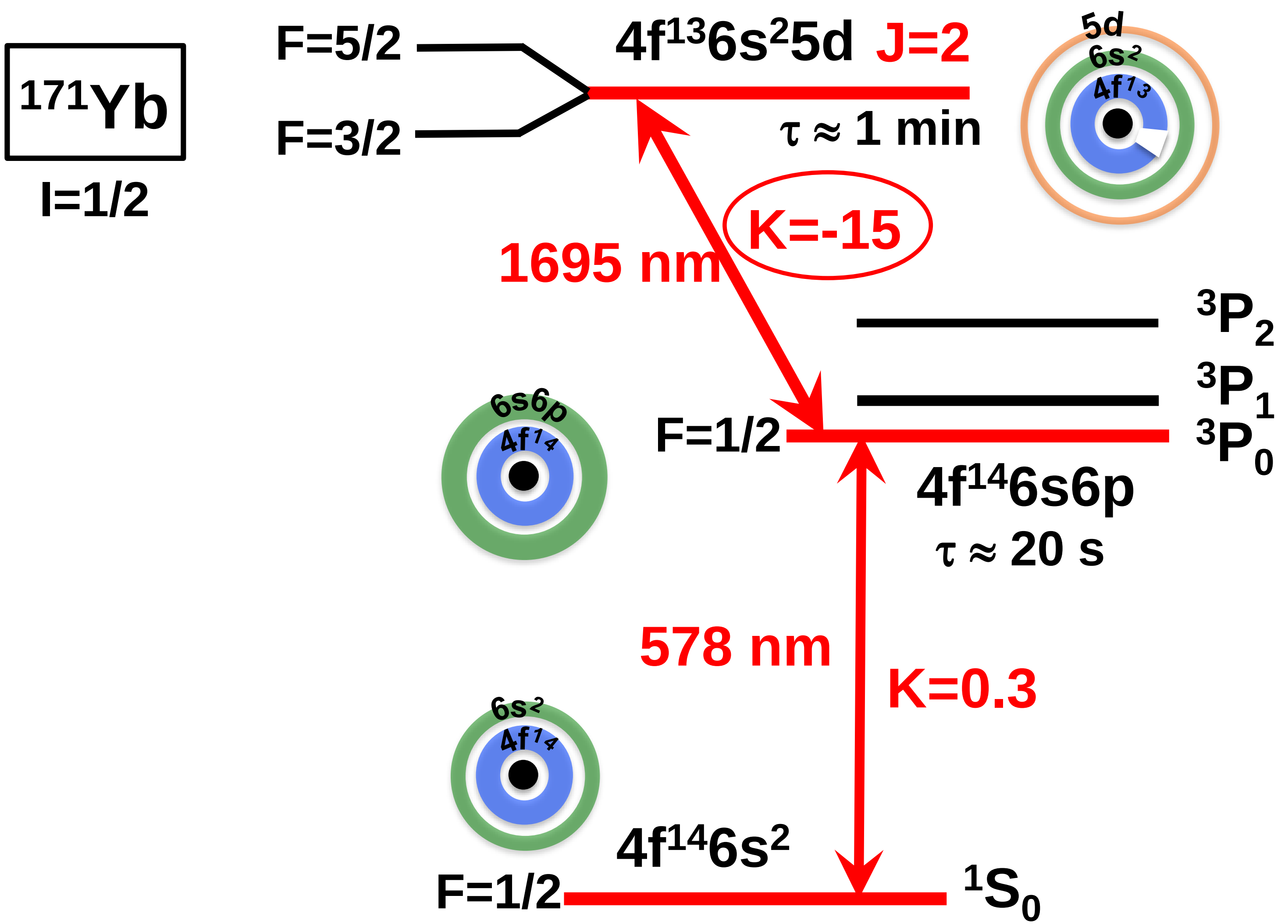
  The uncertainty in evaluating κ thus reduces by a factor of $\sqrt{N}$.

- Our procedure requires only initializing and detecting one specific state. This is useful in systems where there are no optical transition, e.g., for highly charged trapped ions.

- The coherent operations are carried out with rf pulses only, thus avoiding effects from systematic ac-Stark shifts.

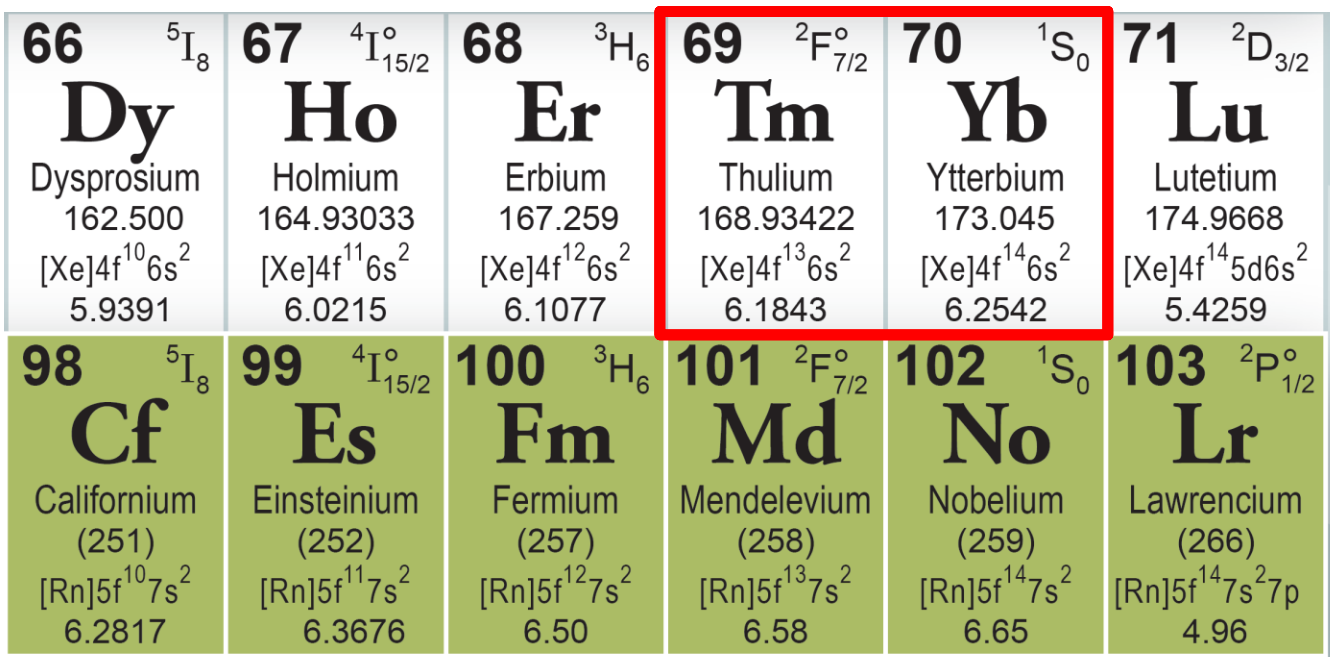
- The wavelength of the rf radiation is much longer than the motional amplitudes of the ions, allowing for high-fidelity coherent manipulation even at high temperatures.

Two clock transitions in neutral Yb



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

Ion	N	Level	J	$\lvert\langle J \Vert T^{(2)} \Vert J\rangle\rvert$	$\lvert\Delta E/(hC_0^{(2)})\rvert$
Ca^+	19	$3d$	5/2	9.3	4.5×10^{15} [9]
Yb^+	69	$4f^{13}6s^2$	7/2	135	6.1×10^{16} [10]
Tm	69	$4f^{13}6s^2$	7/2 ground state	141	6.4×10^{16}
Yb	70	$4f^{13}5d6s^2$	2	74	3.9×10^{16}



N > 1000, but need to understand if systematics arising from trapping beam ac-Stark shifts of the Zeeman components can be managed.

Great times to search for Lorentz violation and other new physics with atoms and molecules!

Time for discoveries!

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