EDMs, ions, atoms and molecular probes of new physics

MARIANNA SAFRONOVA

January 2020
Durham, UK

2020 Quantum Sensors for Fundamental Physics School

NSF
NIST
Office of Naval Research Science & Technology ONR USN

University of Delaware

Joint Quantum Institute

Dear Students,

Please ask questions during the lectures!

THE BENEFITS OF ASKING QUESTIONS

You will learn more.

The school will be more fun for you.

Great practice for the future.

You will stay awake ☺

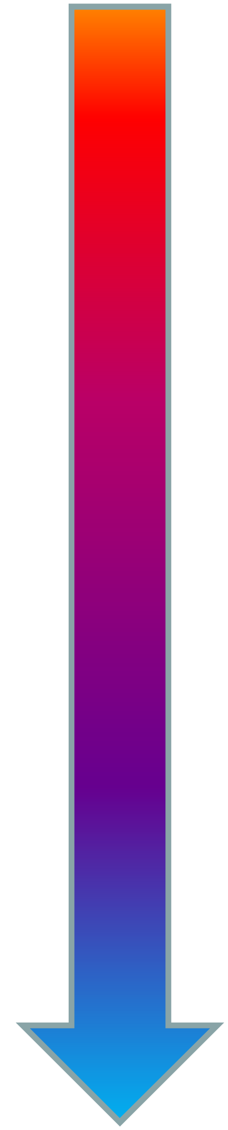
OVERVIEW

- Introduction: a broad scope of atomic and molecular new physics searches
- Dark matter searches with atomic and nuclear clocks: future perspectives
- Tests of Lorentz invariance with trapped ions & clocks
- The search for electron electric dipole moment

A Very Brief Story of Advances in AMO Physics

Advances in AMO Physics: New world of ultracold

300K



500nK

Steve Chu

Claude Cohen-Tannoudji

Bill Phillips

1997
Nobel Prize
Laser cooling and trapping

Eric Cornell

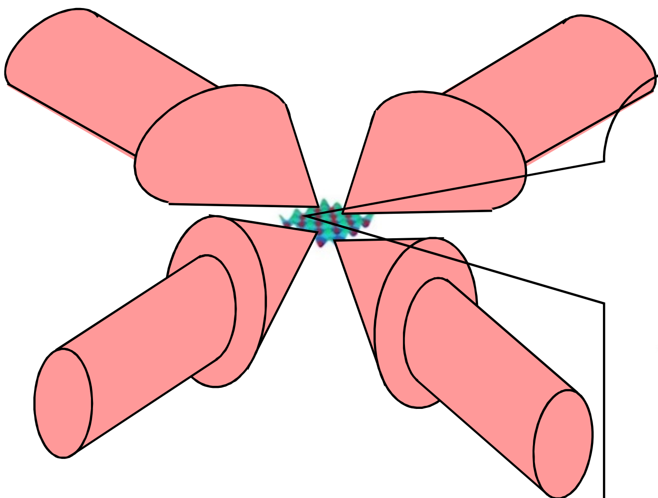
Wolfgang Ketterle

Carl Wieman

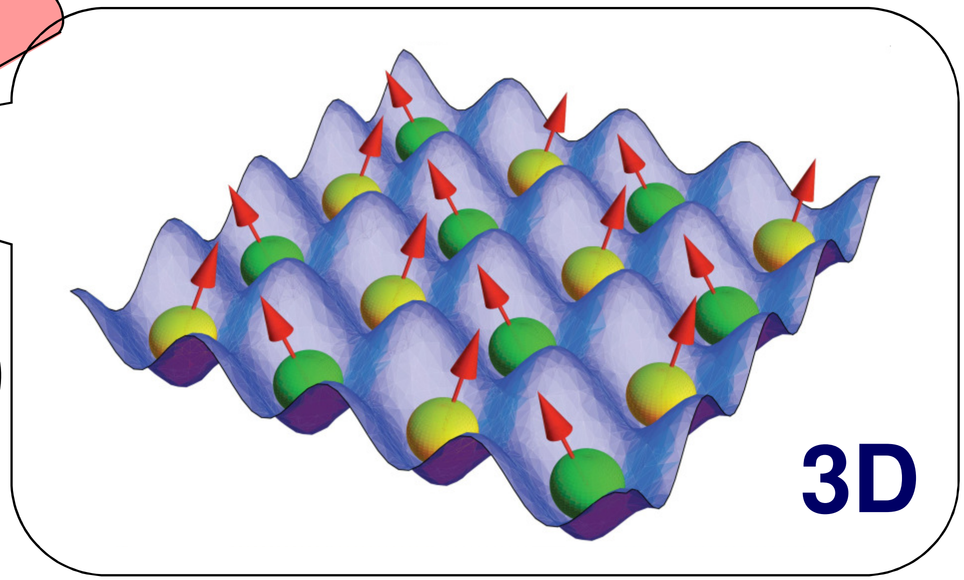
2001
Nobel Prize
Bose-Einstein Condensation

nobel.org

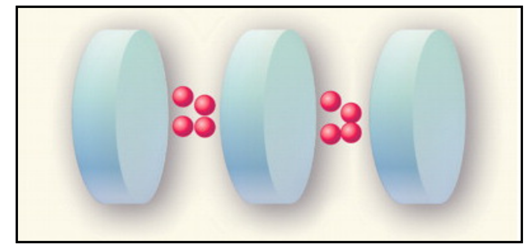
Trapping neutral atoms and ions

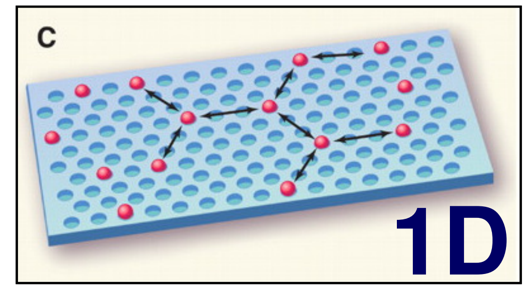


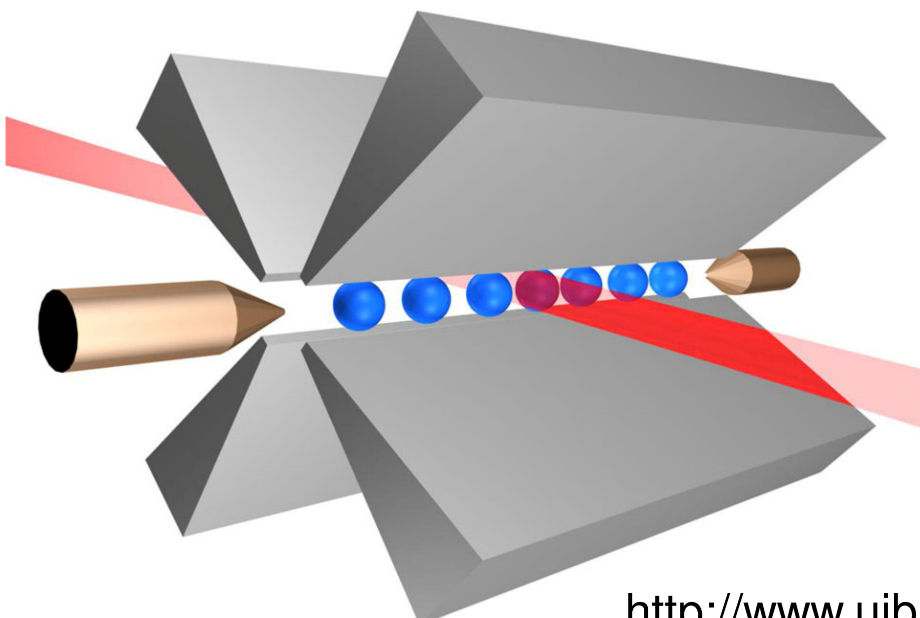
Optical Lattices: crystals of light



2D







Trapped ion chains

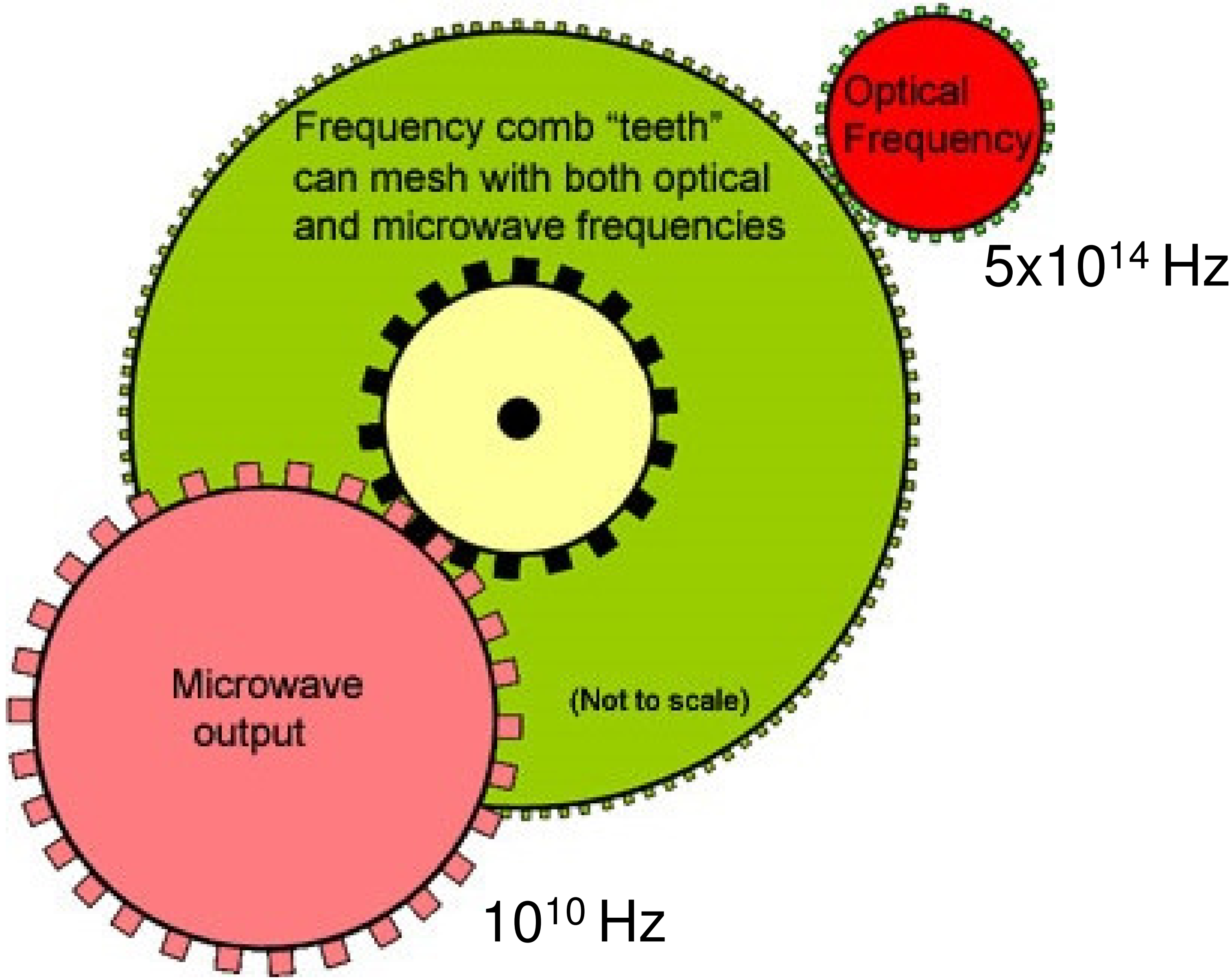
http://www.uibk.ac.at/th-physik/qo/research/trappedions.html

How to “count” optical frequencies

2005 Nobel Prize

Theodor Hänsch

John Hall

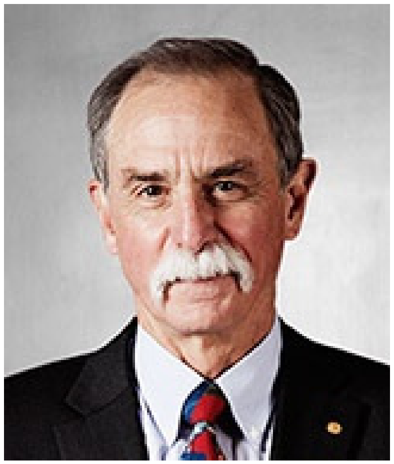


Laser-based precision spectroscopy and the optical frequency comb technique

nist.gov

Quantum Control: measuring and manipulation of individual quantum systems

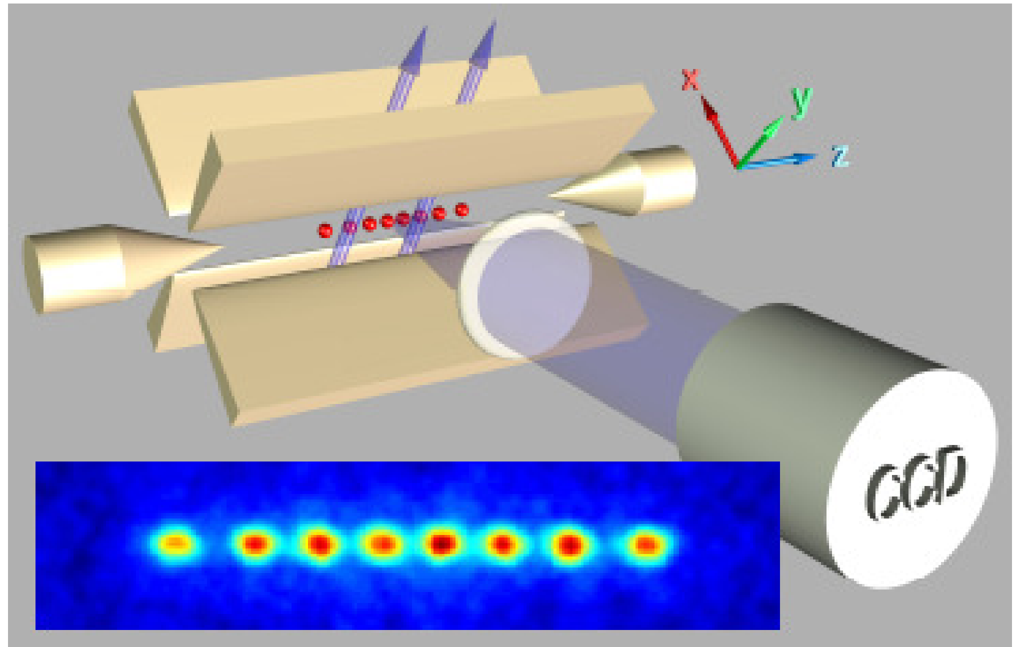
2012 Nobel prize



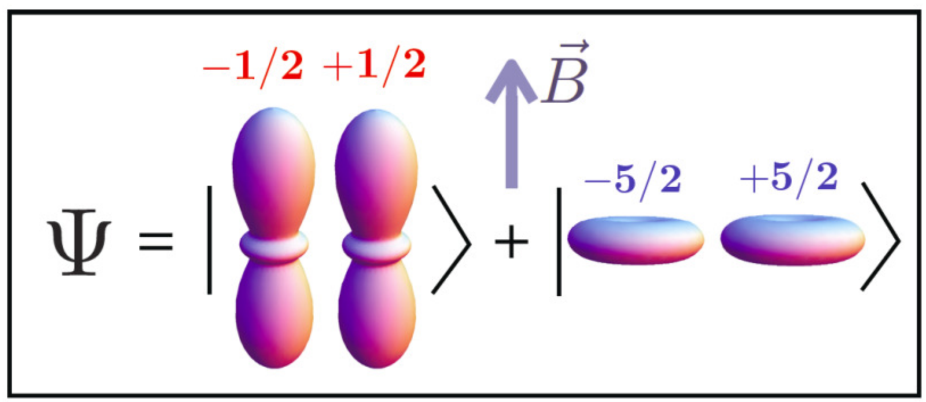
David Wineland

Serge Haroche

nobel.org



Picture of a string of ions



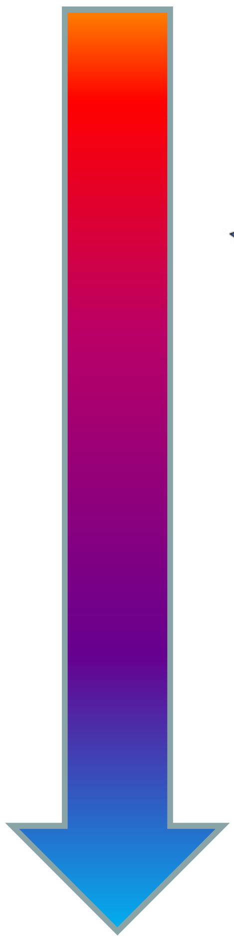
Ca^+

$3d_{5/2}$

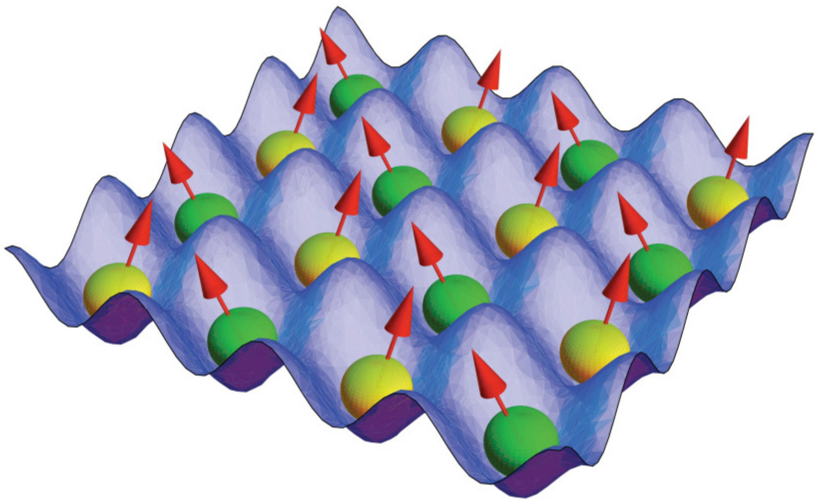
Making quantum superposition of two ions

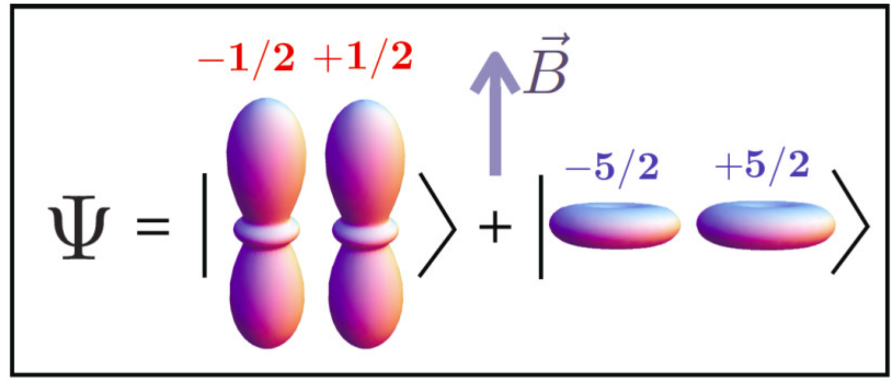
Extraordinary progress in the control of atomic systems

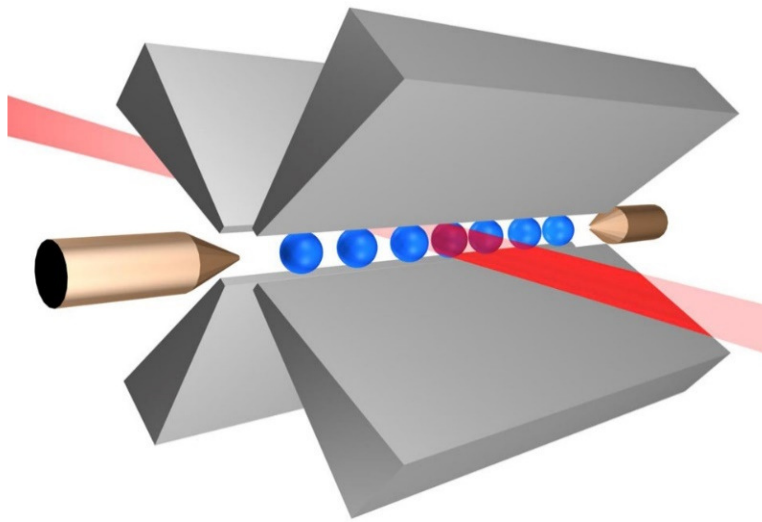
300K

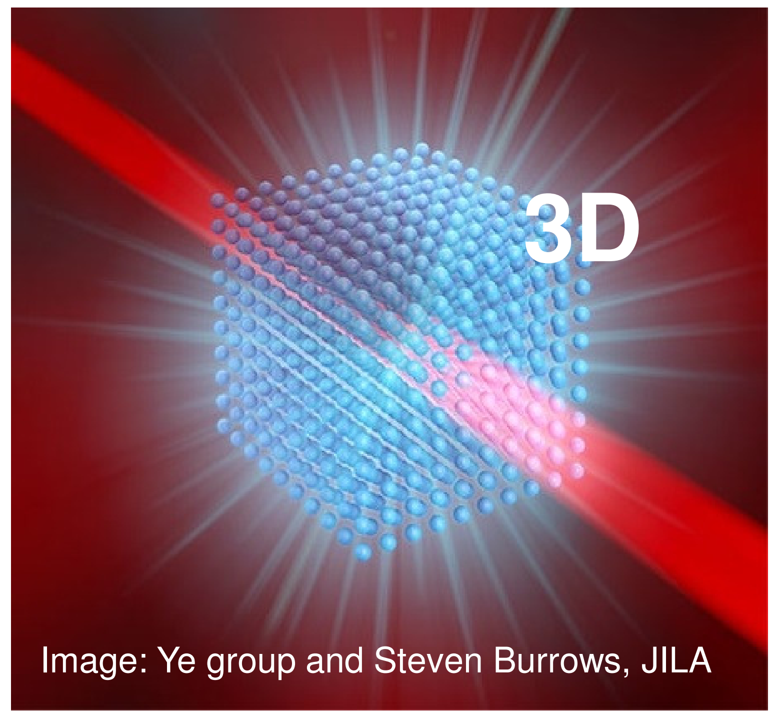


nK









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

Advances in Precision Atomic physics tools

- **Atomic clocks**
- **Atom and Light interferom**
  Matter Waves!
- **Atomic m**
-
-
- **nologies**
- **g of highly-charged ions**
- **N w: UV frequency combs**
- **In progress: laser cooling of molecules**
- **Future: molecules in optical lattices**
- **Future: nuclear clocks**

QUANTUM SENSORS WILL CONTINUE
TO RAPIDLY IMPROVE IN NEXT
DECADES, WITH NEW TECHNOLOGIES
BECOMING POSSIBLE

Very wide scope of AMO new physics searches

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.

RMP 90, 025008 (2018)

Review chapters:

1. **Search for variation of fundamental constants**

   Atomic clocks & spectroscopy, astrophysics studies of atomic and molecular spectra, molecular frequency measurements

2. **Precision tests of Quantum Electrodynamics**

   Precision frequency measurements with electrons, lightest atoms (H, He, etc.), muonic hydrogen, highly-charged ions, exotic atoms, others

3. **Atomic parity violation**

   Beam experiments, cold trapped atoms and ions.
   Need heavy atoms: Cs, Tl, Fr, Ra+, Ra ,… molecules in the future

4. **Time-reversal violation: electric dipole moments and related phenomena**

   Cold molecular beams, trapped molecular ions, future: ultracold atoms, laser-cooled (polyatomic) molecules

5. **Tests of the CPT theorem, matter-antimatter comparisons**

   Not tabletop, proton/antiproton, single ion traps, (cold) antihydrogen

6. **Searches for exotic spin-independent interactions**

   Future: ultracold atoms as force sensors, atom interferometry, etc.

6. Review of laboratory searches for exotic spin-dependent interactions

Magnetometry (spin-precession), precision theory/experiment comparisons (frequencies), networks or magnetometers and clocks, precision isotope shift measurements

7. Searches for light dark matter (all precision tools)

- Microwave cavity axion experiments
- Spin-precession axion experiments
- Radio axion searches
- Atomic clocks and accelerometers, and spectroscopy
- Exotic spin-dependent forces due to axions/ALPs
- Magnetometer and clock networks for detection of transient DM signals

8. General relativity and gravitation

Atom interferometry

9. Lorentz symmetry tests

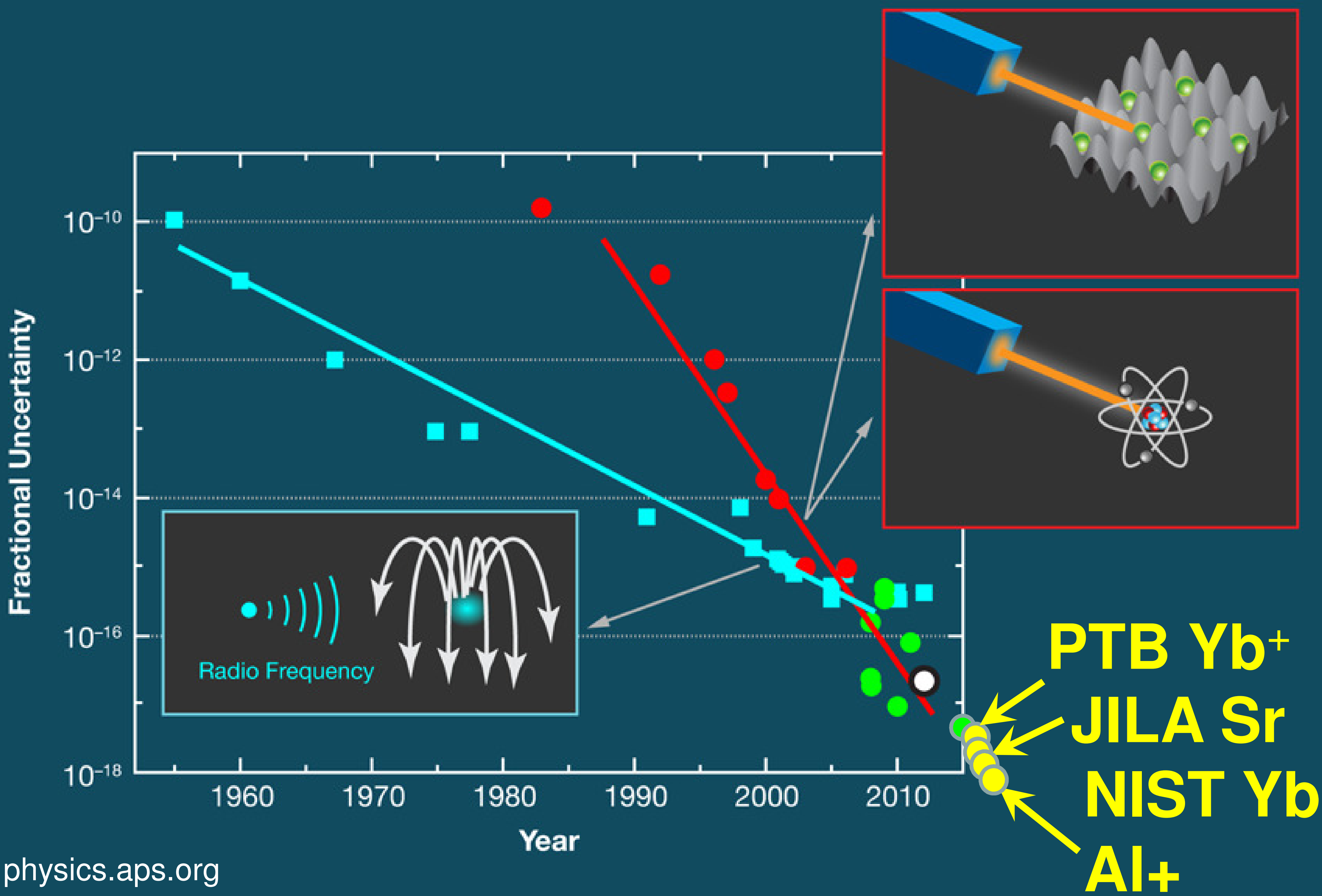
Atomic clocks, magnetometers, quantum control of trapped ions, spectroscopy, rotating cavities

10. Search for violations of quantum statistics

Search for Pauli-forbidden atomic or molecular transitions

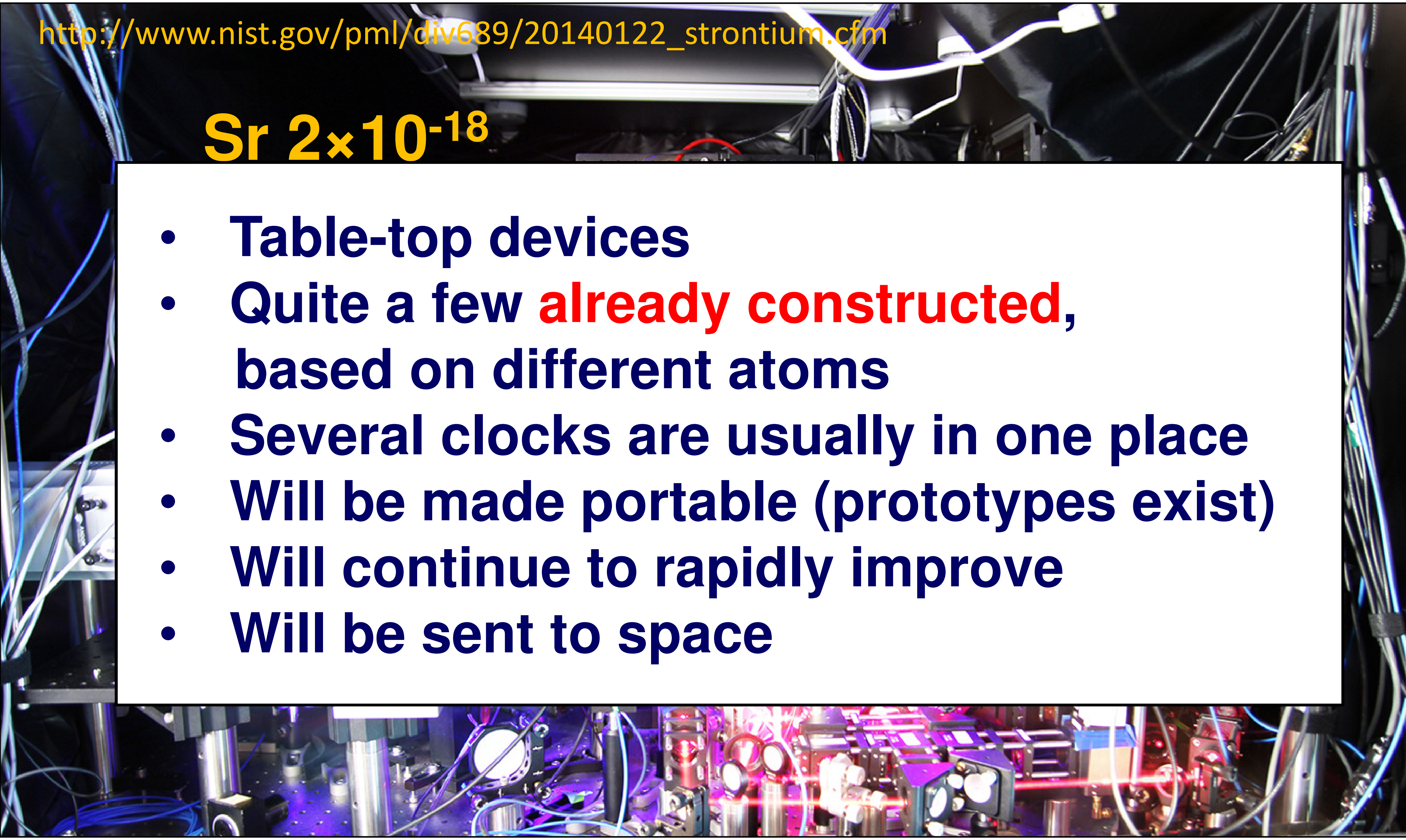
SEARCH FOR PHYSICS BEYOND THE STANDARD MODEL WITH ATOMIC CLOCKS

Optical vs. microwave clocks



physics.aps.org

Sr clock will lose 1 second in 15 billion years !



- 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

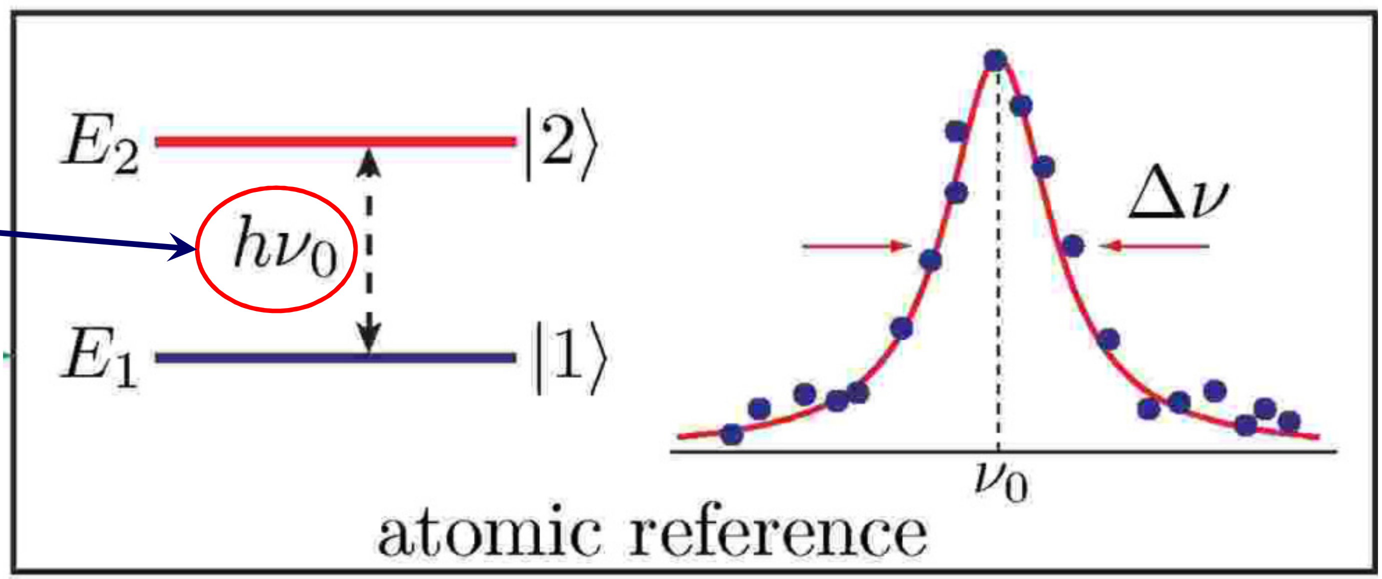
T. L. Nicholson, S. L. Campbell, R. B. Hutson, G. E. Marti, B. J. Bloom, R. L. McNally, W. Zhang, M. D. Barrett, M. S. Safronova, G. F. Strouse, W. L. Tew, and J. Ye, Nature Commun. 6, 6896 (2015).

Search for physics beyond the standard model with atomic clocks

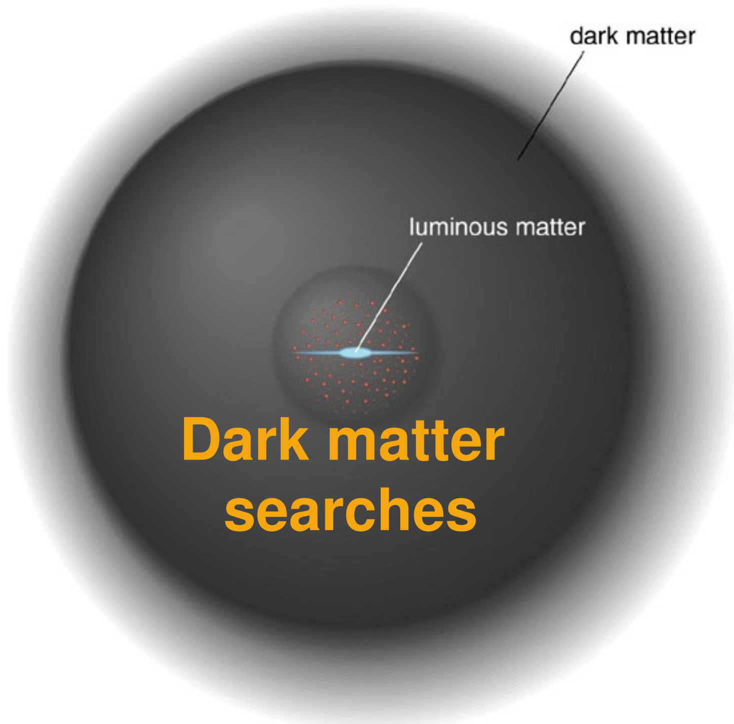
Atomic clocks can measure and compare frequencies to exceptional precisions!

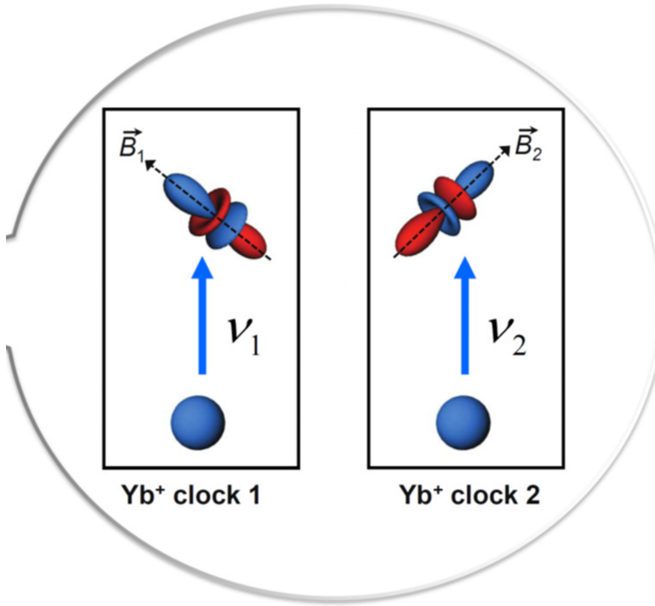
If fundamental constants change (now) due to for various "new physics" effects atomic clock may be able to detect it.

Frequency will change

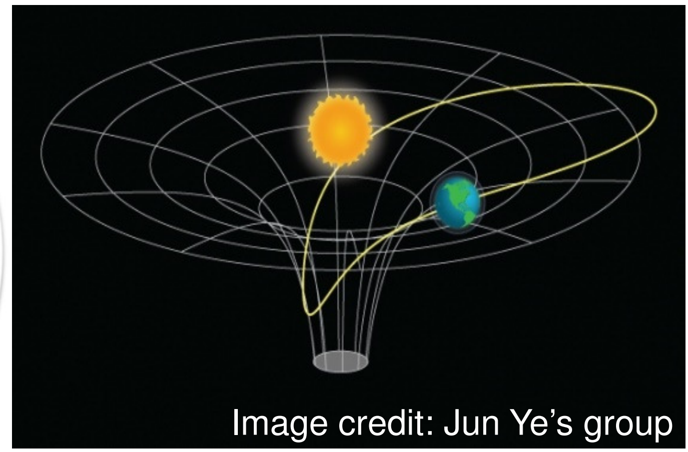


Search for physics beyond the Standard Model with atomic clocks



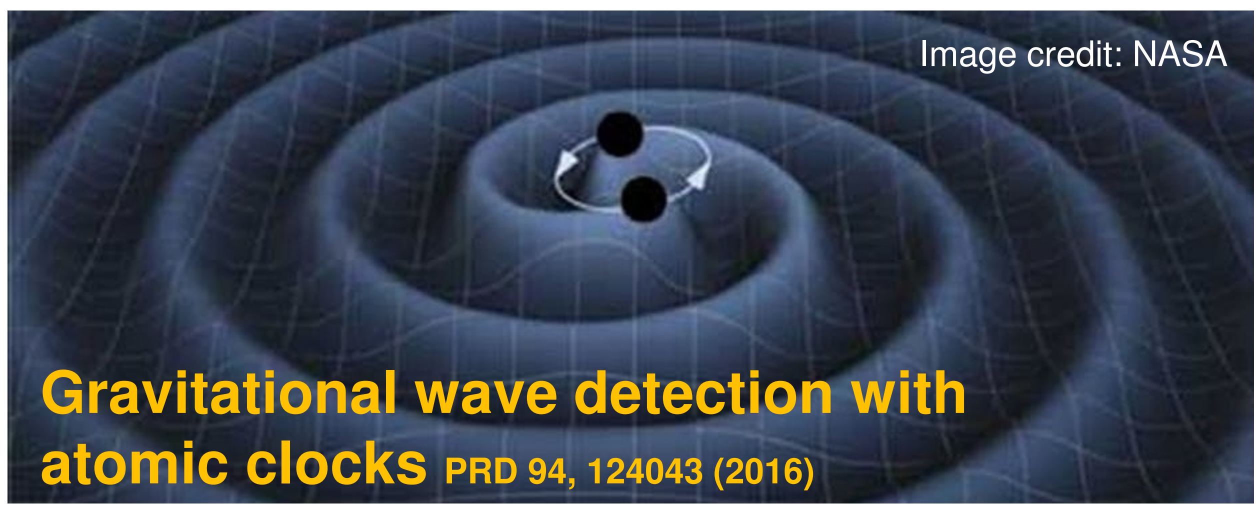


Search for the violation of Lorentz invariance



Tests of the equivalence principle

Are fundamental constants constant? α



How do fundamental constants vary?

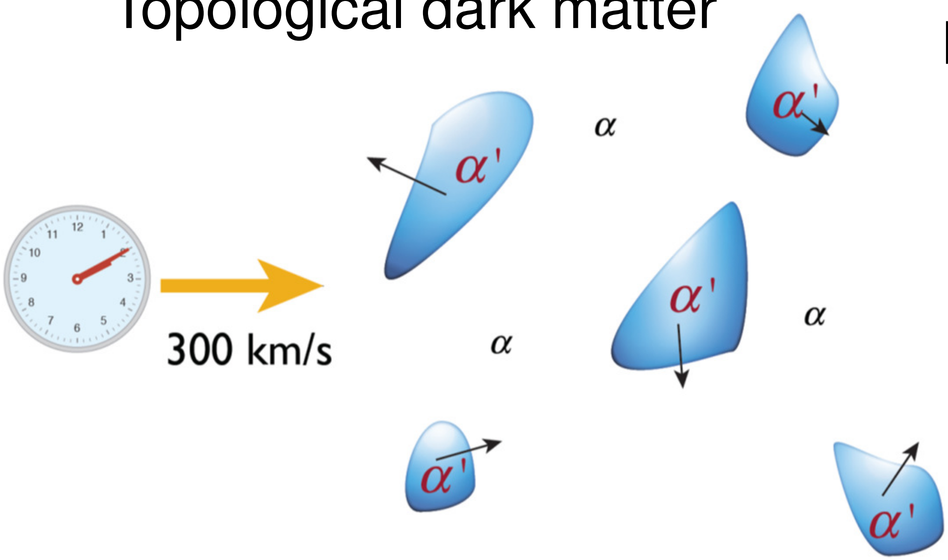
Slow drifts

Transient variations

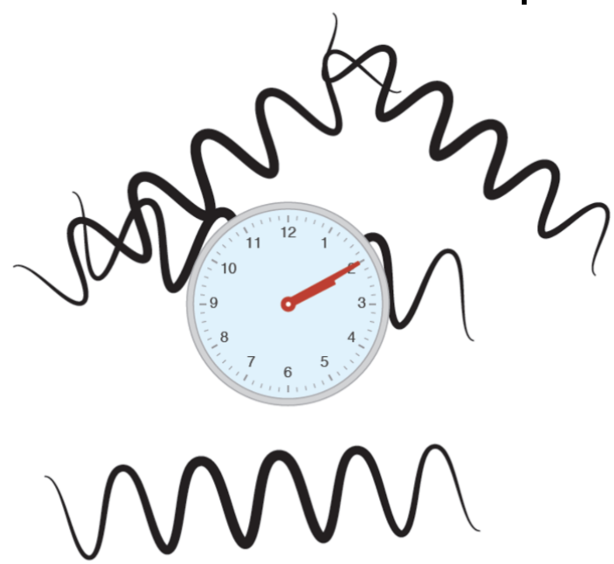
Oscillations

Stochastic

Topological dark matter



Dilaton dark matter or axion-like particles



A. Derevianko, Conf. Ser. **723** (2016) 012043

How do fundamental constants vary?

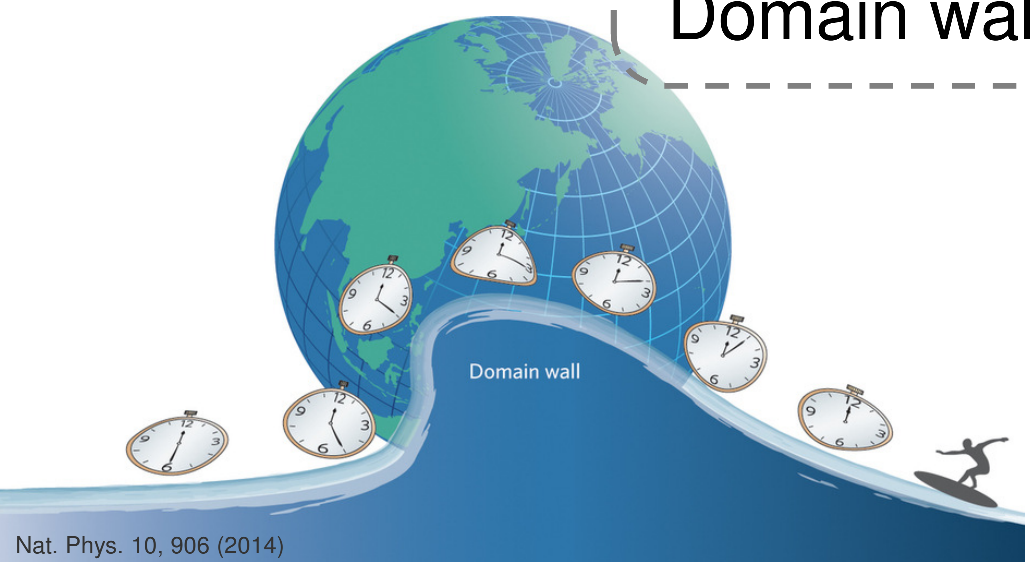
Spatial variations

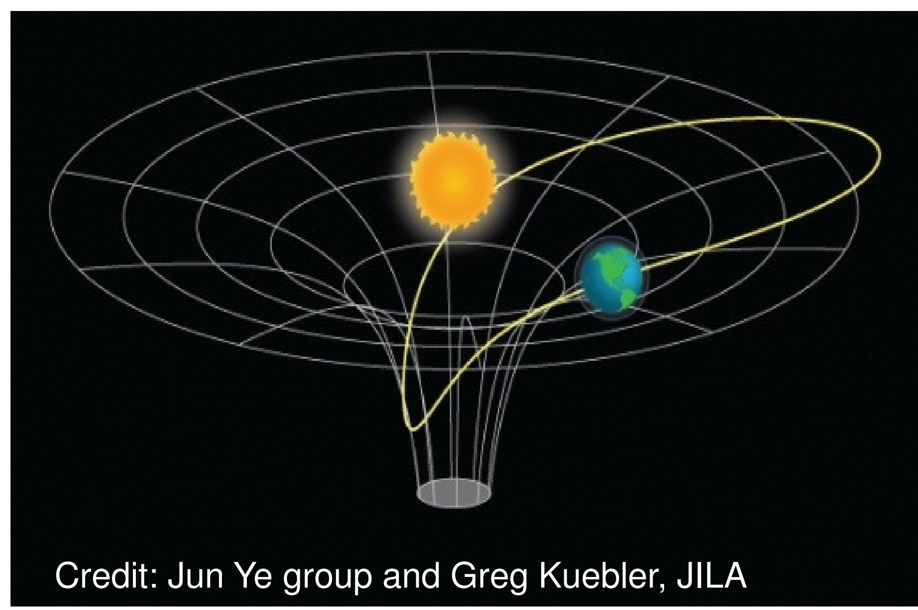
Cosmological spatial variation: gradient of cosmic $\phi(r)$ field

Cosmological spatial variation Domain walls

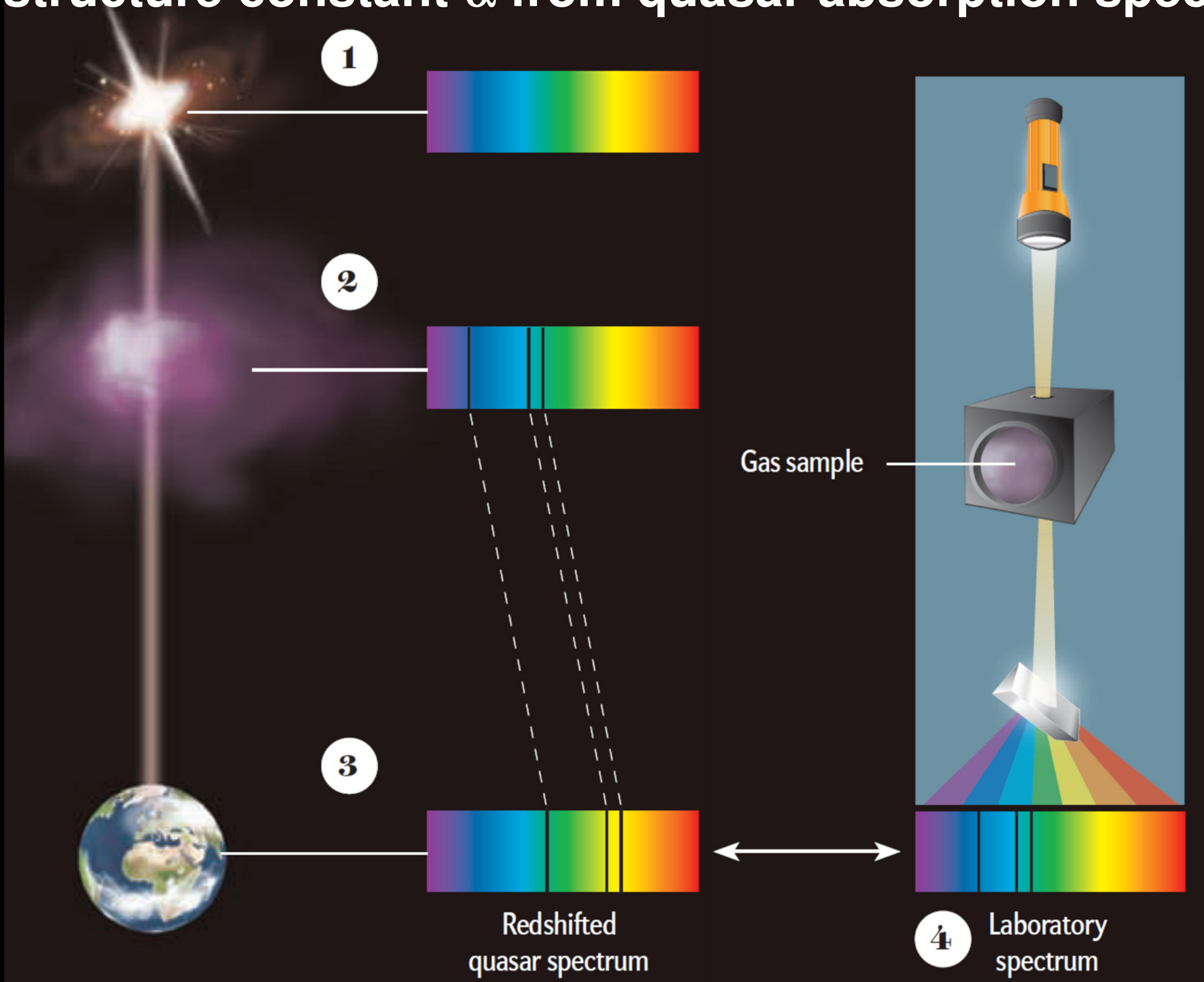
Dependence on matter density: Chameleons

Dependence on gravity





Long history of astrophysics searches for the variation of fine-structure constant α from quasar absorption spectra



Scientific American: A Matter of Time 23, 60 (2014)

Search for Time Variation of the Fine Structure Constant

John K. Webb,[1] Victor V. Flambaum,[1] Christopher W. Churchill,[2] Michael J. Drinkwater,[1] and John D. Barrow[3]
[1]*School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia*
[2]*Department of Astronomy & Astrophysics, Pennsylvania State University, University Park, Pennsylvania 16802*
[3]*Astronomy Centre, University of Sussex, Brighton, BN1 9QJ, United Kingdom*
(Received 13 February 1998; revised manuscript received 9 July 1998)

An order of magnitude sensitivity gain is described for using quasar spectra to investigate possible time or space variation in the fine structure constant α. Applied to a sample of 30 absorption systems, spanning redshifts $0.5 < z < 1.6$, we derive limits on variations in α over a wide range of epochs. For the whole sample, $\Delta\alpha/\alpha = (-1.1 \pm 0.4) \times 10^{-5}$. This deviation is dominated by measurements at $z > 1$, where $\boxed{\Delta\alpha/\alpha = (-1.9 \pm 0.5) \times 10^{-5}}$. For $z < 1$, $\Delta\alpha/\alpha = (-0.2 \pm 0.4) \times 10^{-5}$. While this is consistent with a time-varying α, further work is required to explore possible systematic errors in the data, although careful searches have so far revealed none. [S0031-9007(98)08267-2]

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **447,** 446–462 (2015) doi:10.1093/mnras/stu2420

Impact of instrumental systematic errors on fine-structure constant measurements with quasar spectra

Jonathan B. Whitmore★ and Michael T. Murphy
Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, VIC 3122, Australia

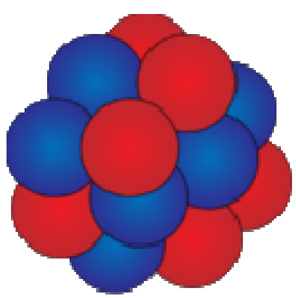
We present a new 'supercalibration' technique for measuring systematic distortions in the wavelength scales of high-resolution spectrographs. By comparing spectra of 'solar twin' stars or asteroids with a reference laboratory solar spectrum, distortions in the standard thorium–argon calibration can be tracked with $\sim$10 m s^{-1} precision over the entire optical wavelength range on scales of both echelle orders ($\sim$50–100 Å) and entire spectrographs arms ($\sim$1000–3000 Å). Using archival spectra from the past 20 yr, we have probed the supercalibration history of the Very Large Telescope-Ultraviolet and Visible Echelle Spectrograph (VLT-UVES) and Keck-High Resolution Echelle Spectrograph (HIRES) spectrographs. We find that systematic errors in their wavelength scales are ubiquitous and substantial, with long-range distortions varying between typically $\pm$200 m s^{-1} per 1000 Å.

Life needs very specific fundamental constants!

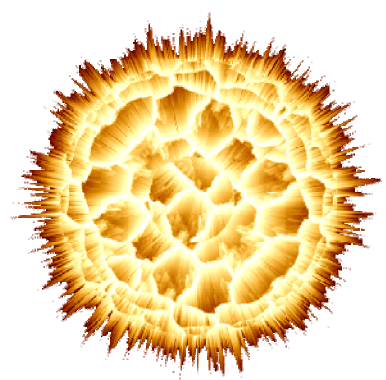
If α is too big $\rightarrow$ small nuclei can not exist

Electric repulsion of the protons **>** strong nuclear binding force

$\alpha \sim 1/137$



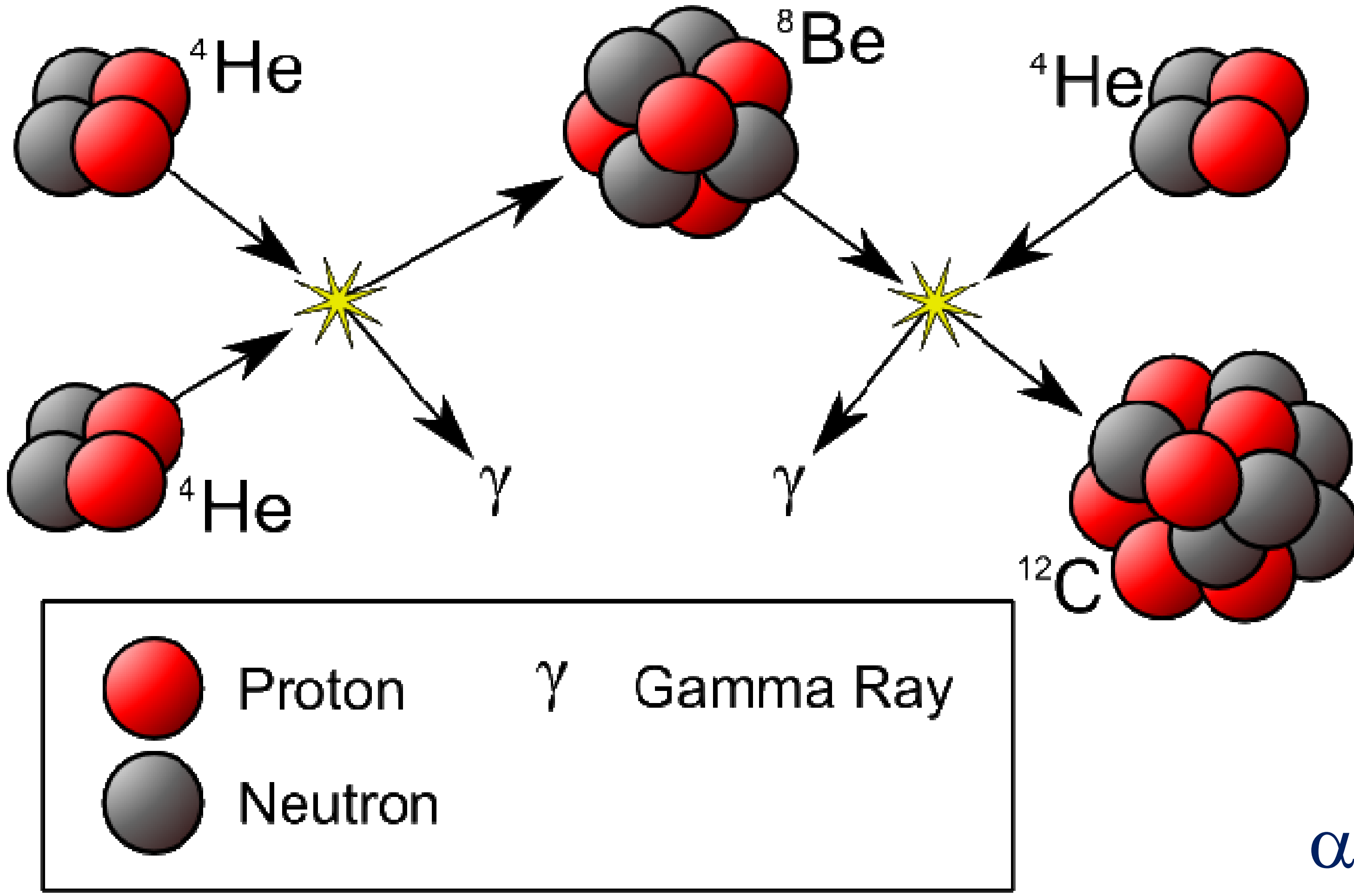
Carbon-12



$\alpha \sim 1/10$

will blow carbon apart

Life needs very specific fundamental constants!

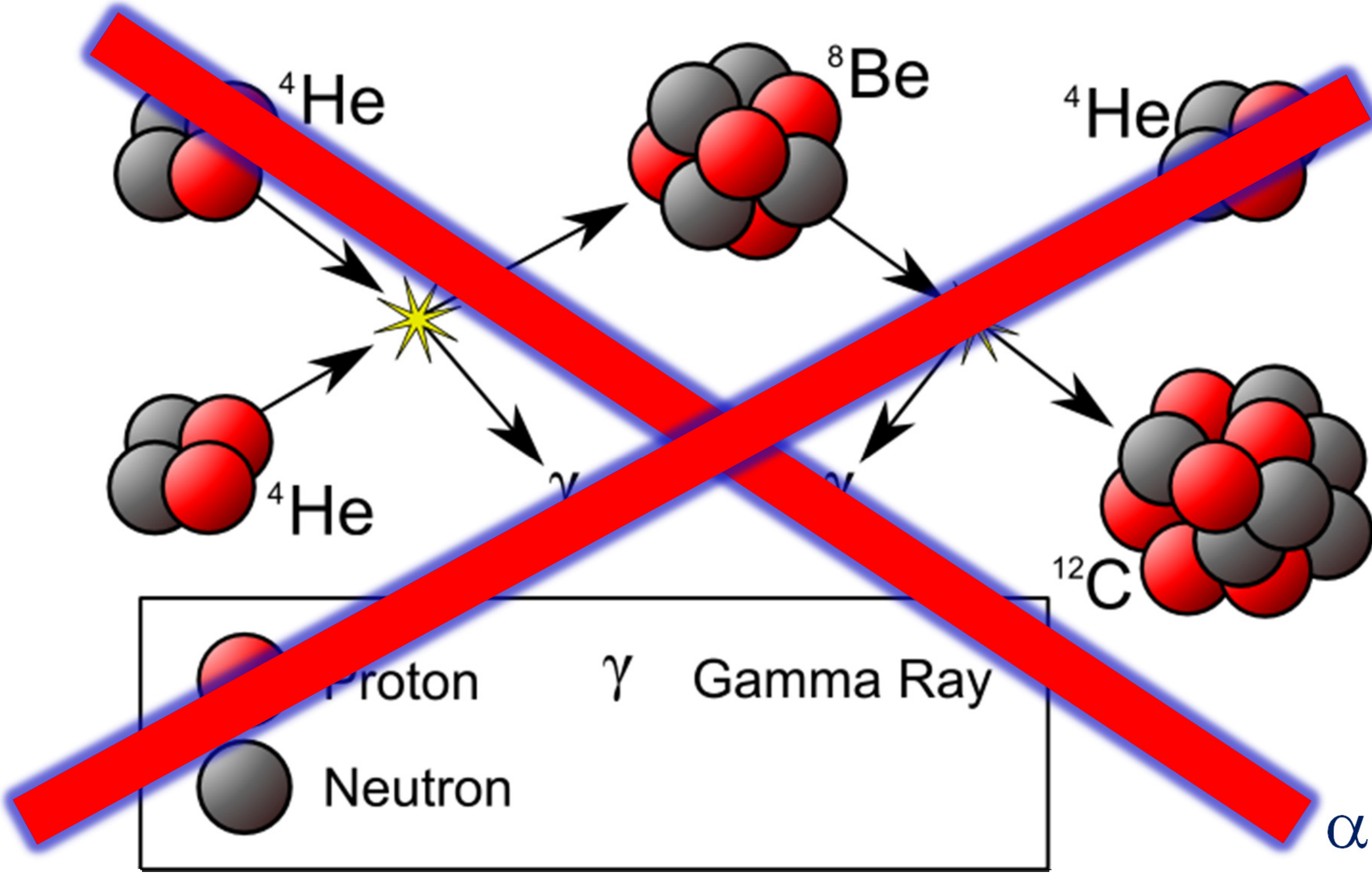


$\alpha \sim 1/137$

Nuclear reaction in stars are particularly sensitive to α.

If α were different by 4%: **no carbon produced by stars**. No life.

Life needs very specific fundamental constants!



$\alpha \sim 1/132$

No carbon produced by stars:
No life in the Universe

Laboratory searches for variation of fundamental constants

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

Frequency of optical atomic clocks

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

Depends only on α

Measure the ratio R of two optical clock frequencies: sensitive to α-variation & scalar dark matter searches

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

Calculate with good precision –
just change α in your atomic structure code

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}

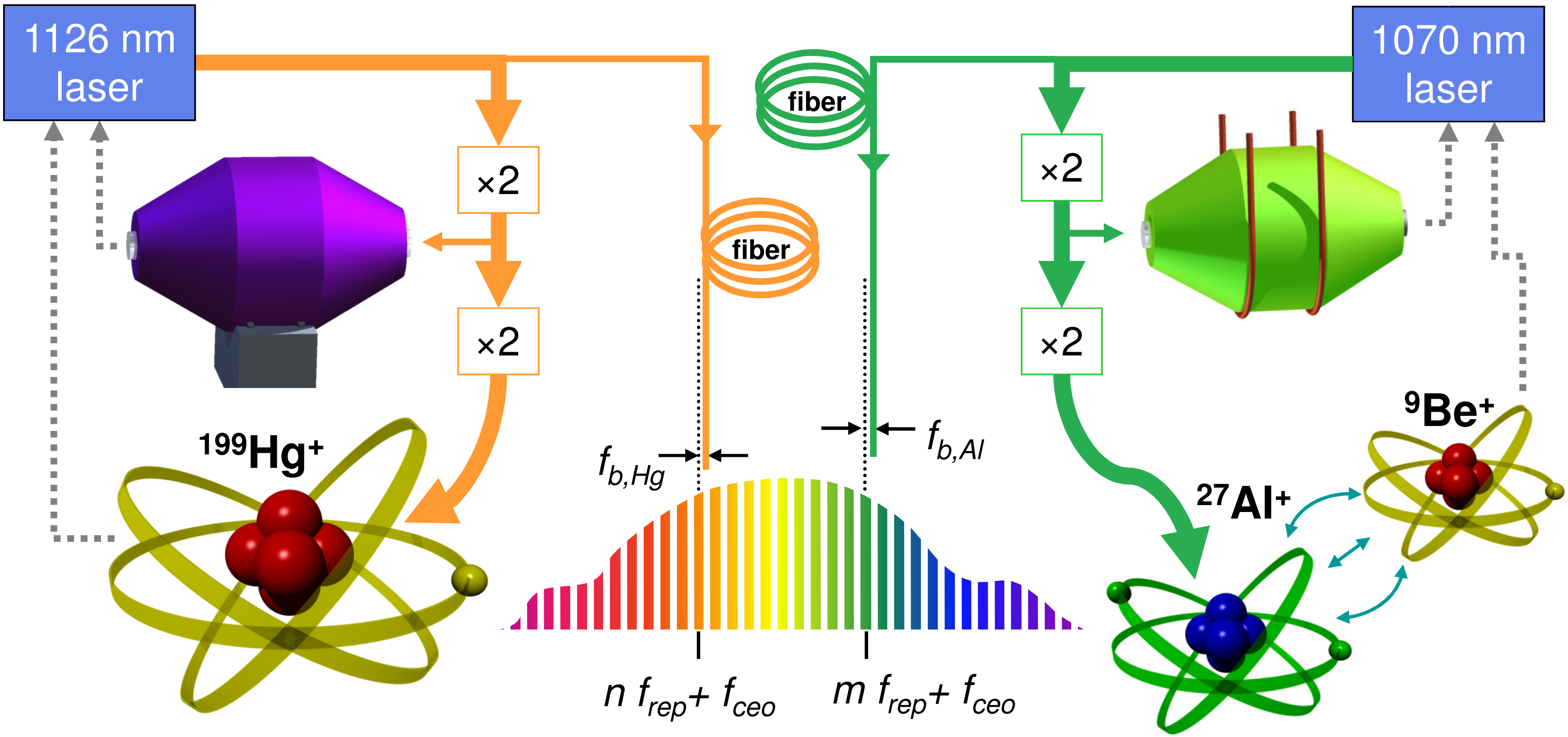
Easier to measure large effects!

Observable: ratio of two clock frequencies

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

$$\frac{\nu\left(Hg^+\right)}{\nu\left(\mathrm{Al}^+\right)} \qquad K(Hg^+) = -2.9 \qquad K\left(Al^+\right) = 0.01$$

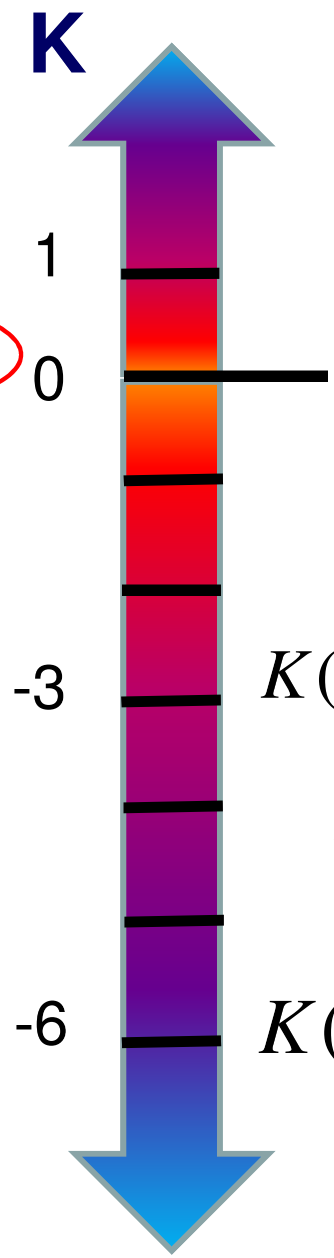
Not sensitive to DM, used as reference



Picture credit: Jim Bergquist

Science 319, 1808 (2008)

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

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

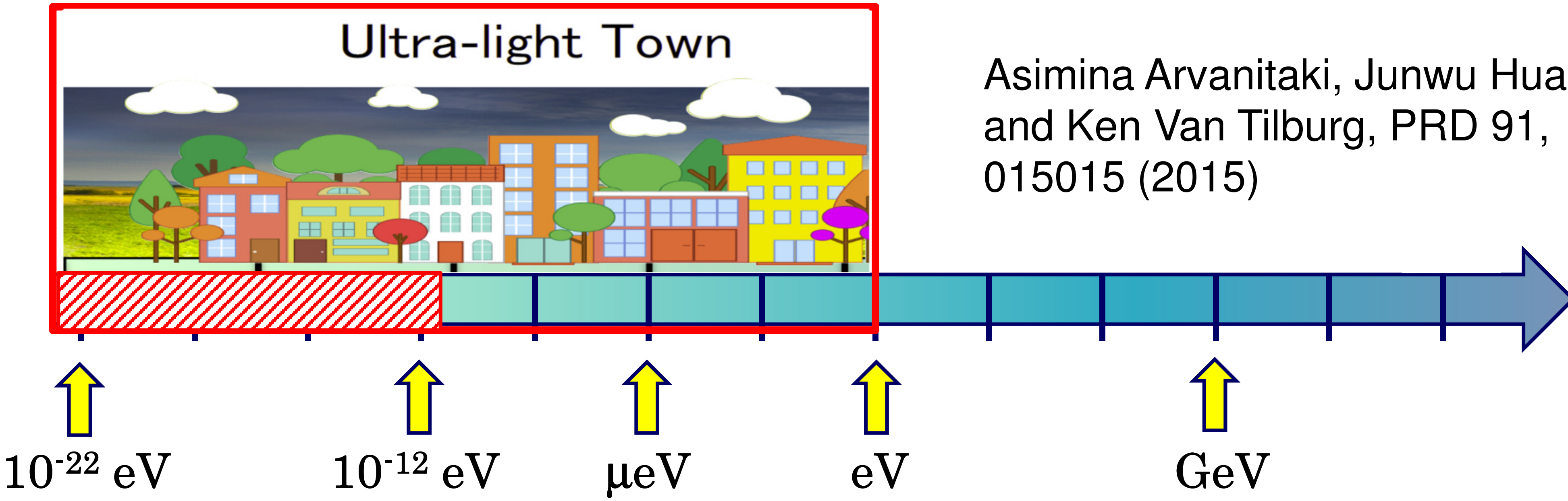
$$\boxed{K = \frac{2q}{E_0}}$$

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

CAN WE GET LARGE K IN NEW CLOCKS?

How to detect **ultralight** dark matter with clocks?

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



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

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 (or clock/cavity).

Ultralight dark matter

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

Dark matter coupling to the Standard Model

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

Dark matter

photons

gluons

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

electrons

quarks

Measure: couplings d_i vs. DM mass

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

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

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

- **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

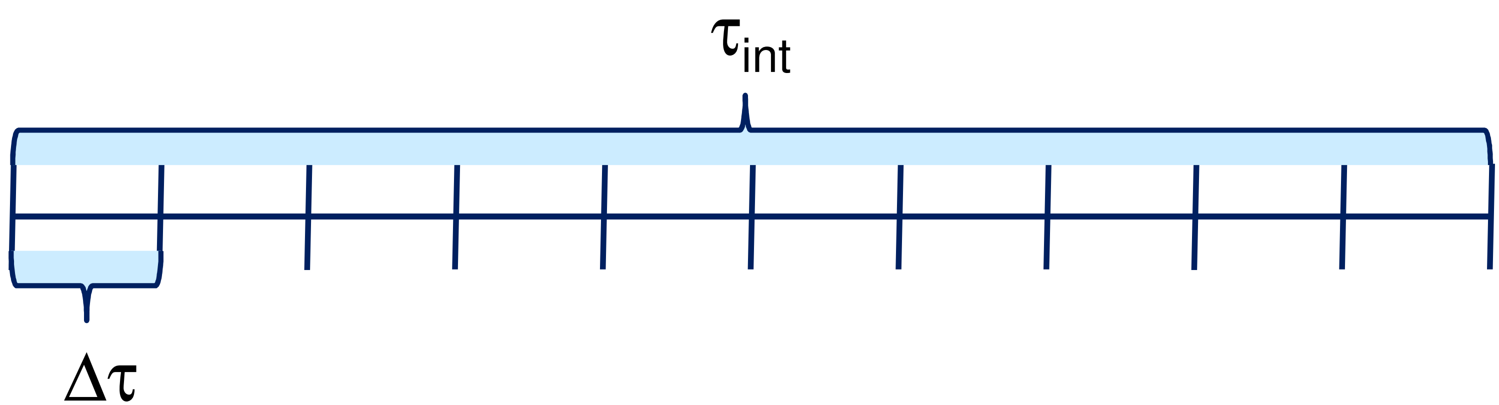
Dark matter parameters

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)

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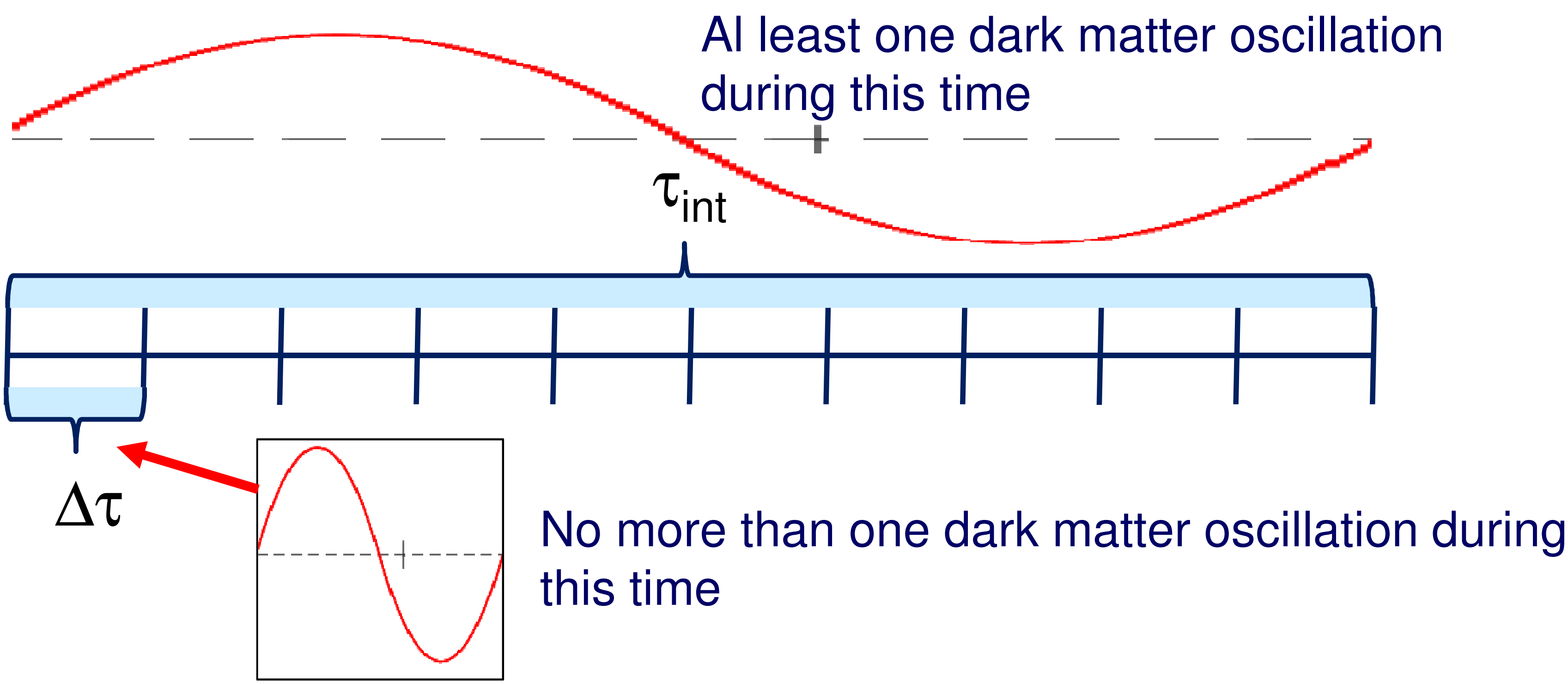

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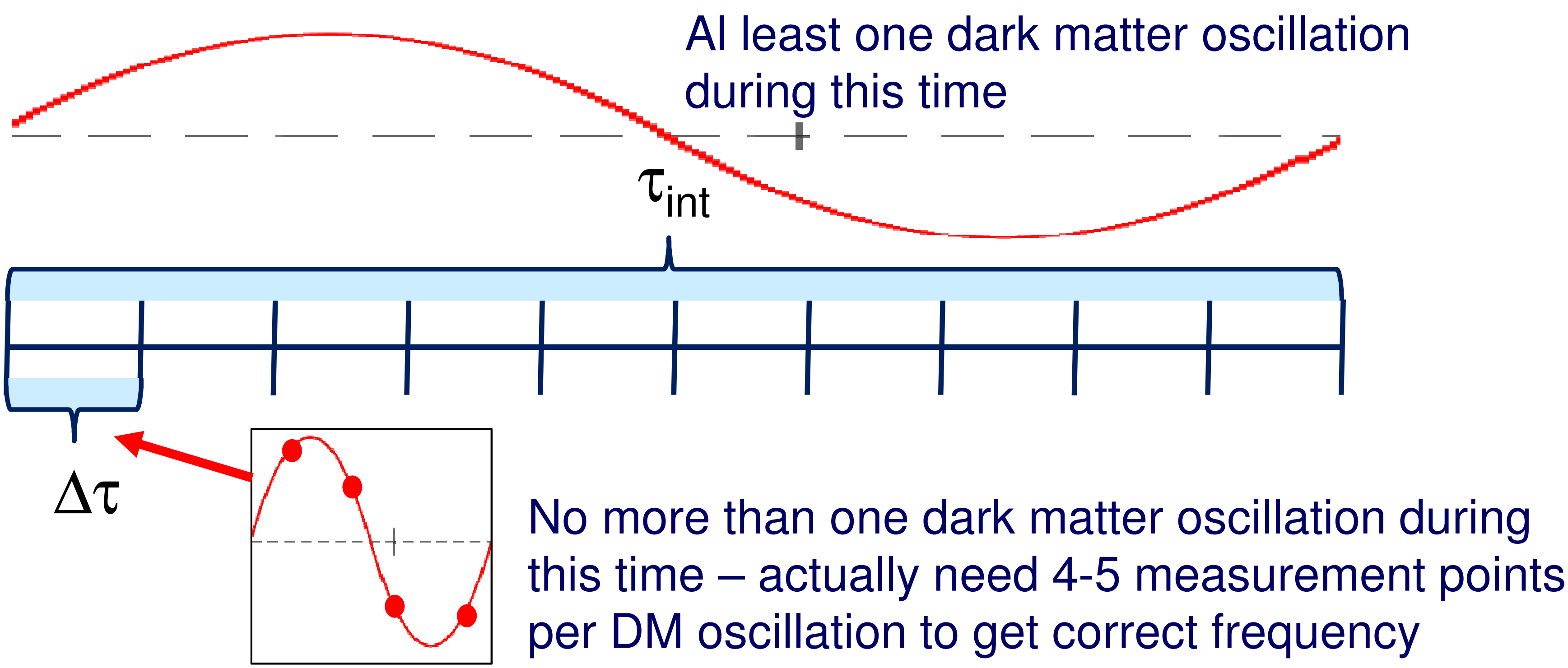
Single clock ratio measurement: averaging over time τ_1

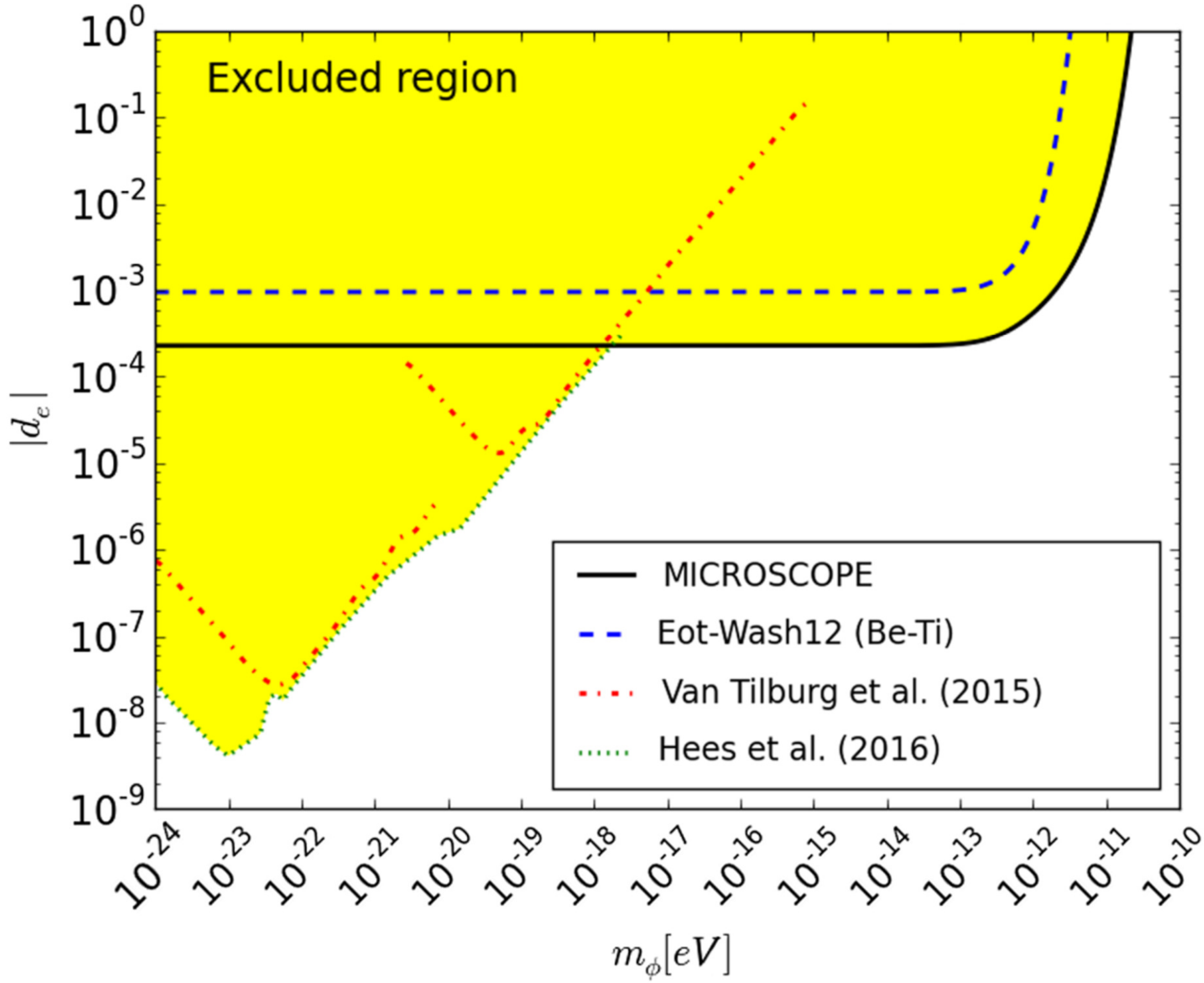
Make N such measurements, preferably regularly spaced



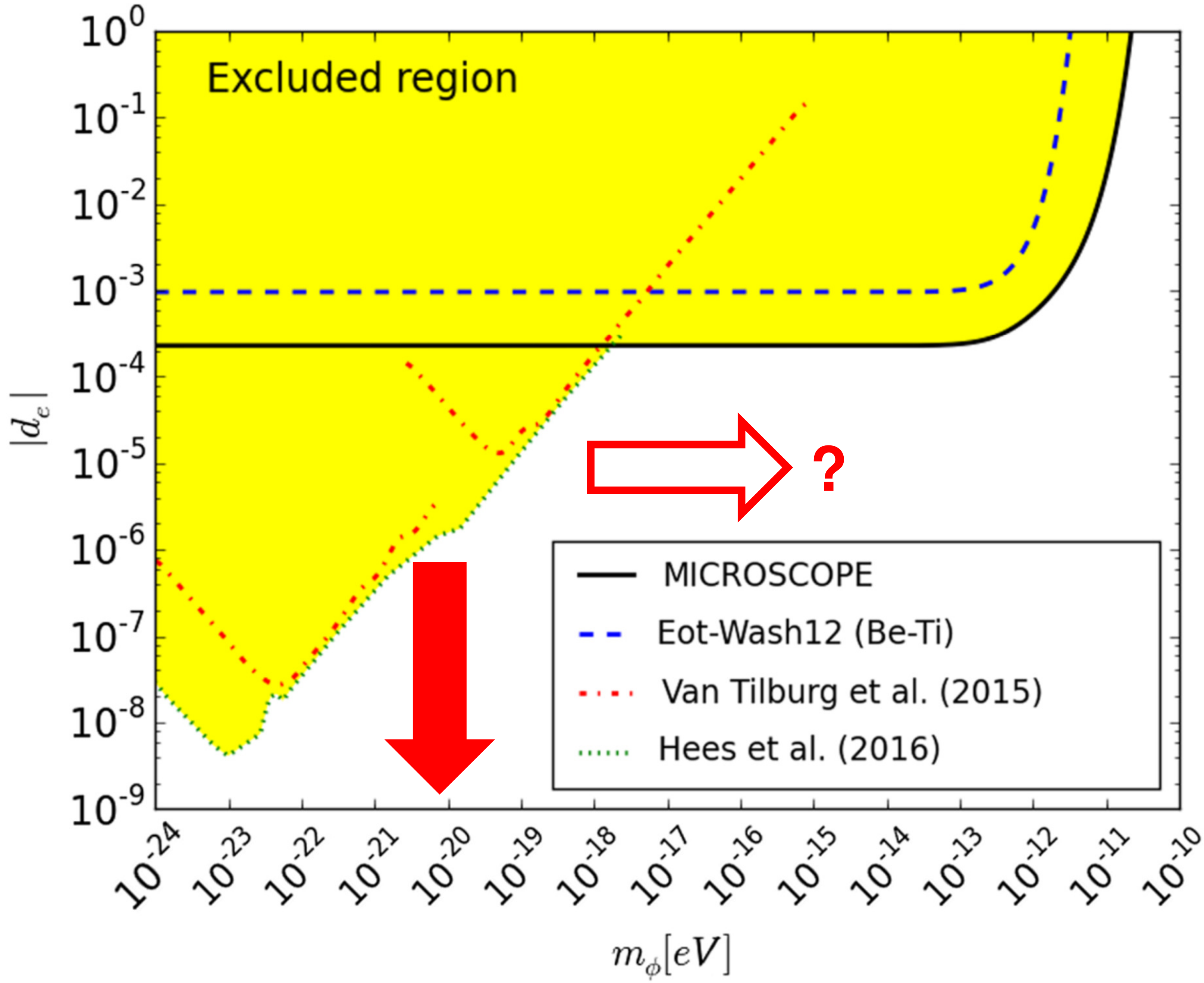
Detection signal:

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)



From PRL 120, 141101 (2018)



From PRL 120, 141101 (2018)

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

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

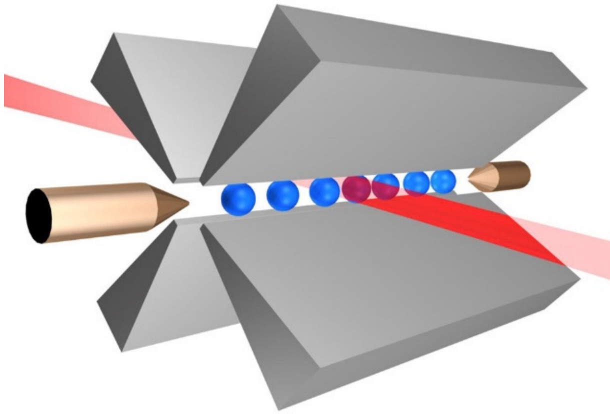
2. Improve stabilities of the clock ratio measurements (particularly with trapped ion clocks).

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.

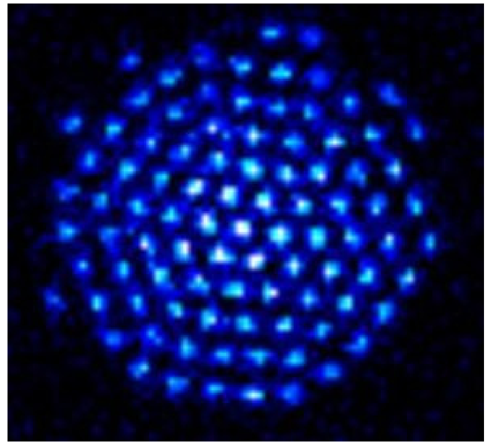
3. Build new clocks based on different systems

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

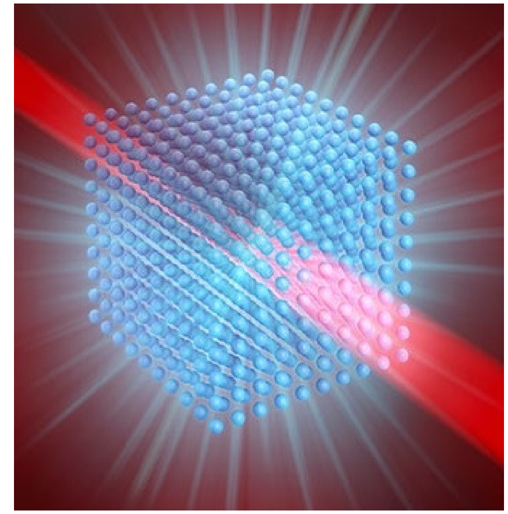
The Future Advances in Atomic Clocks



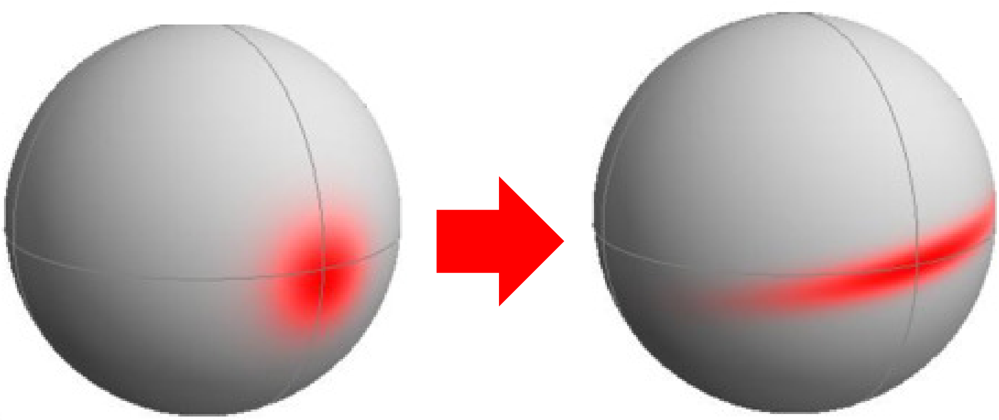
Ion chains



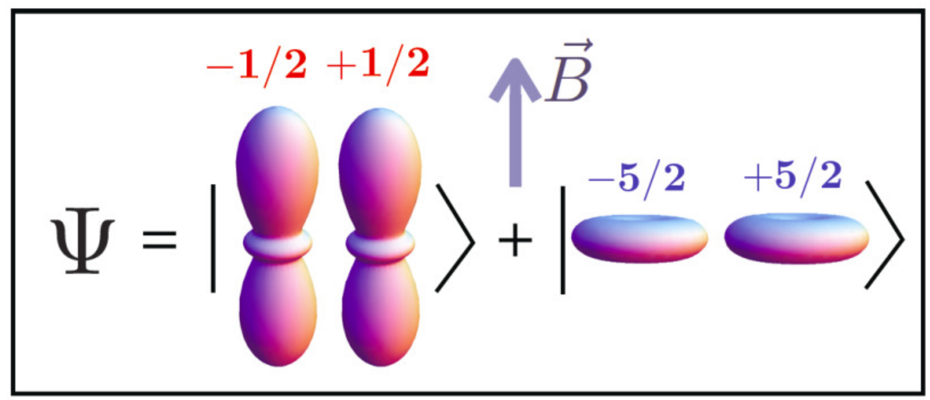
Large ion crystals



3D optical lattice clocks



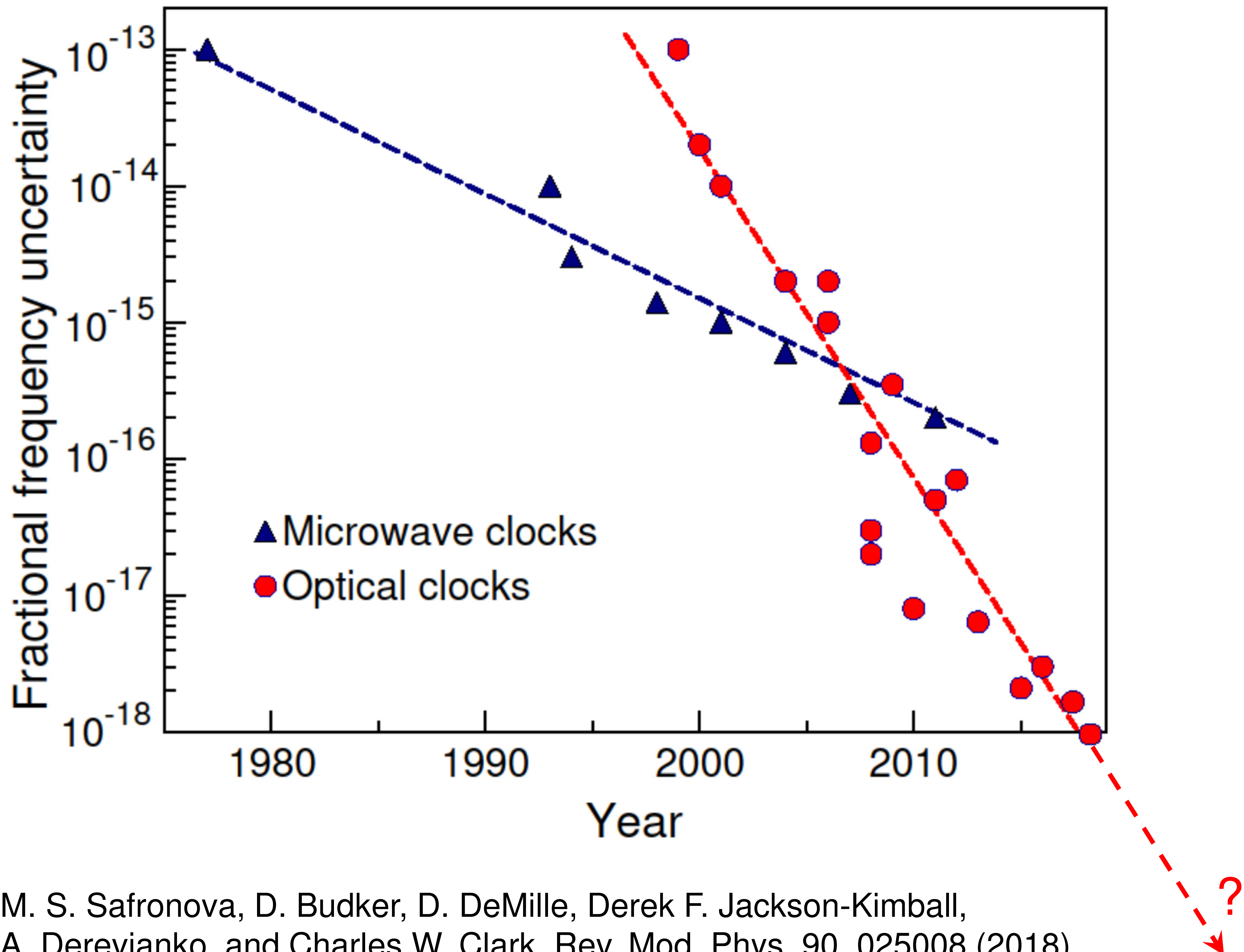
Measurements beyond the quantum limit



Entangled clocks

Orders of magnitude improvements with current clocks

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



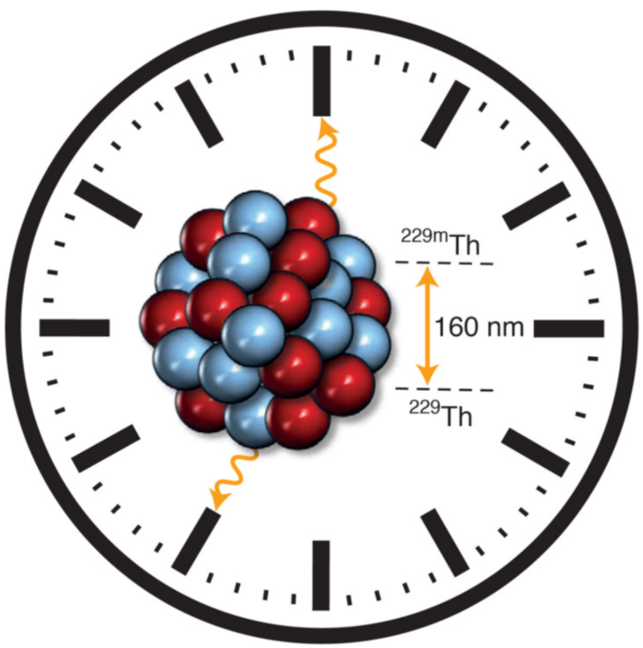
M. S. Safronova, D. Budker, D. DeMille, Derek F. Jackson-Kimball,
A. Derevianko, and Charles W. Clark, Rev. Mod. Phys. 90, 025008 (2018).

Need very precise frequency standards using systems with very large K

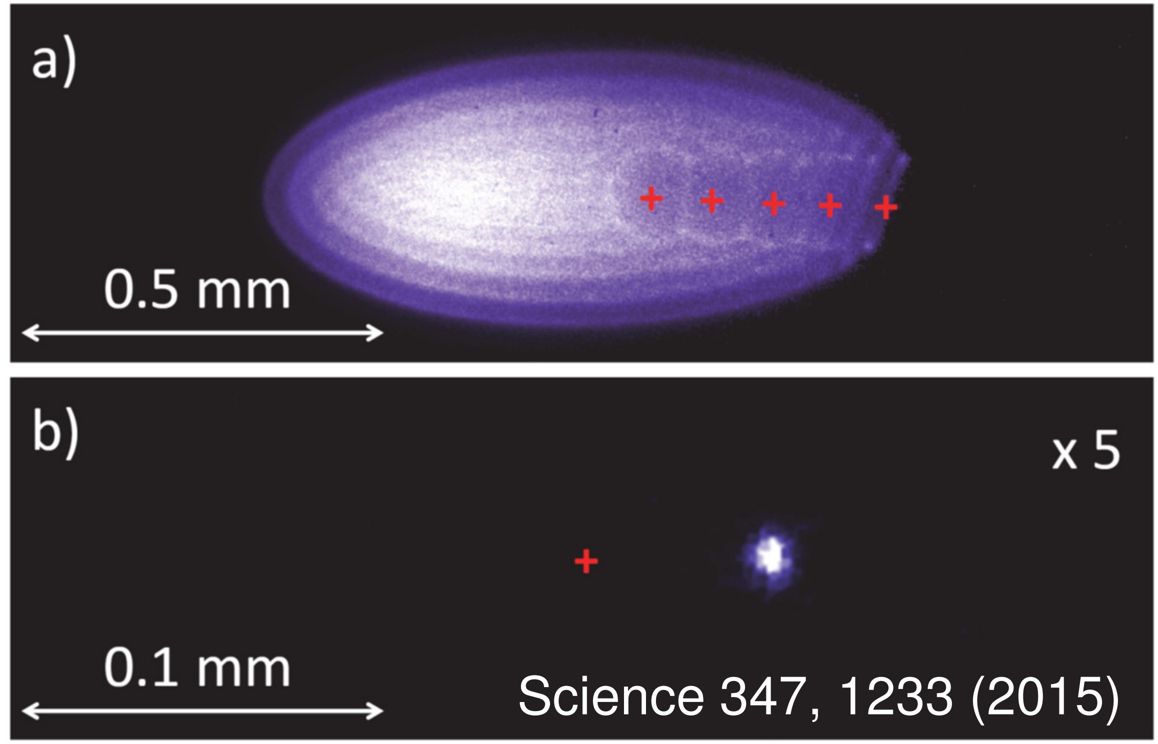
WANTED!

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

The Future: New Atomic Clocks



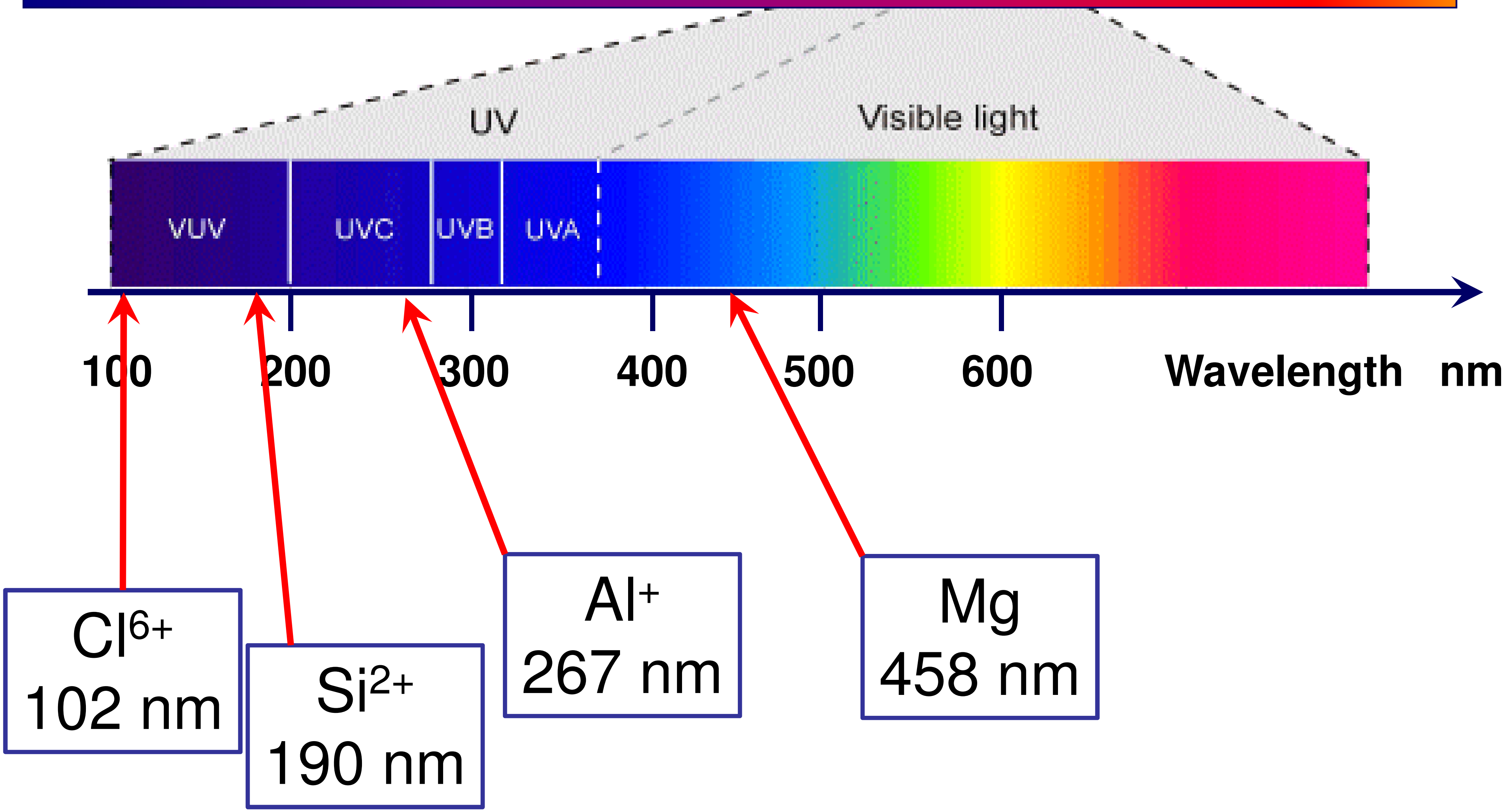
Nuclear clock



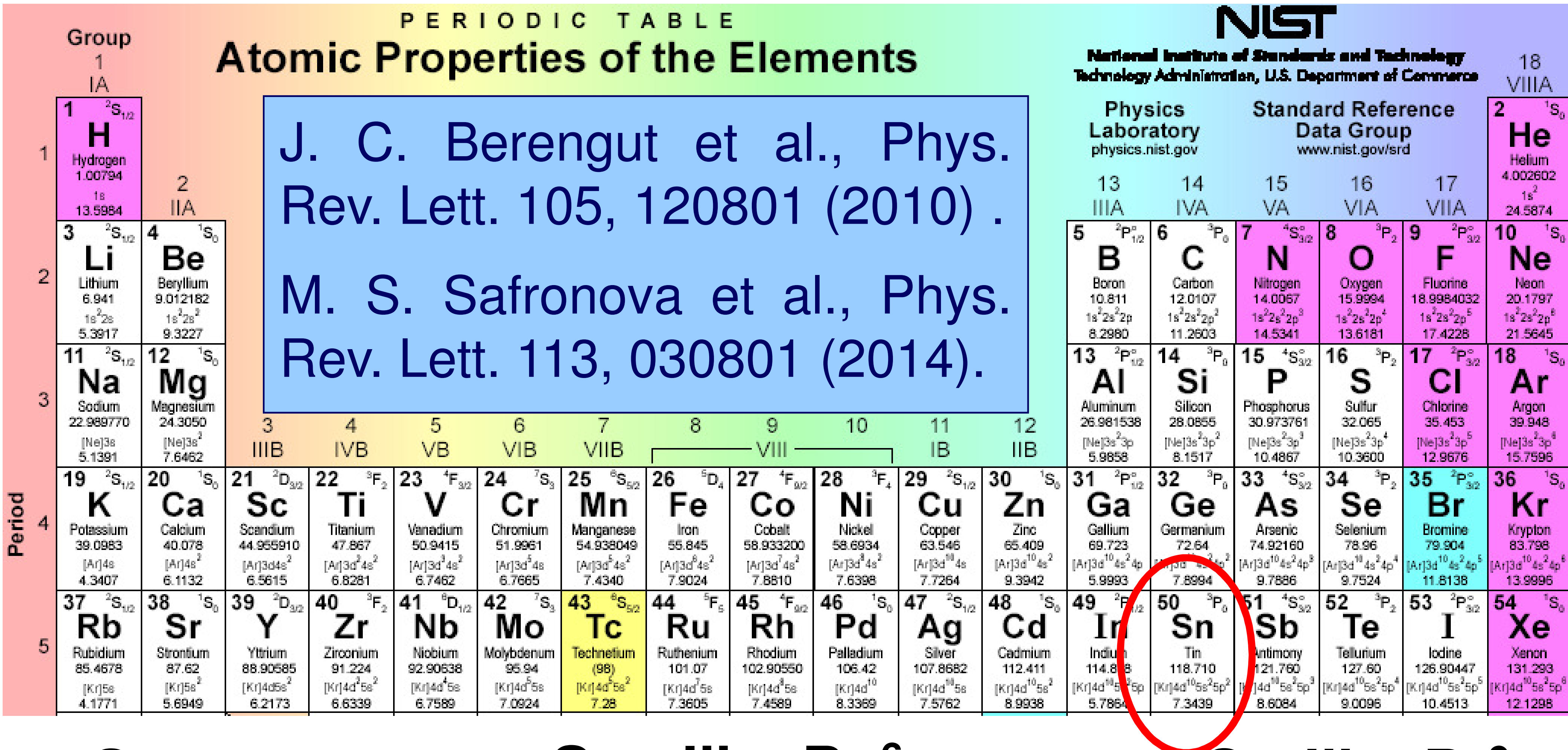
Clocks with ultracold highly charged ions

First demonstration of quantum logic spectroscopy at PTB, Germany

Highly charged ions ???



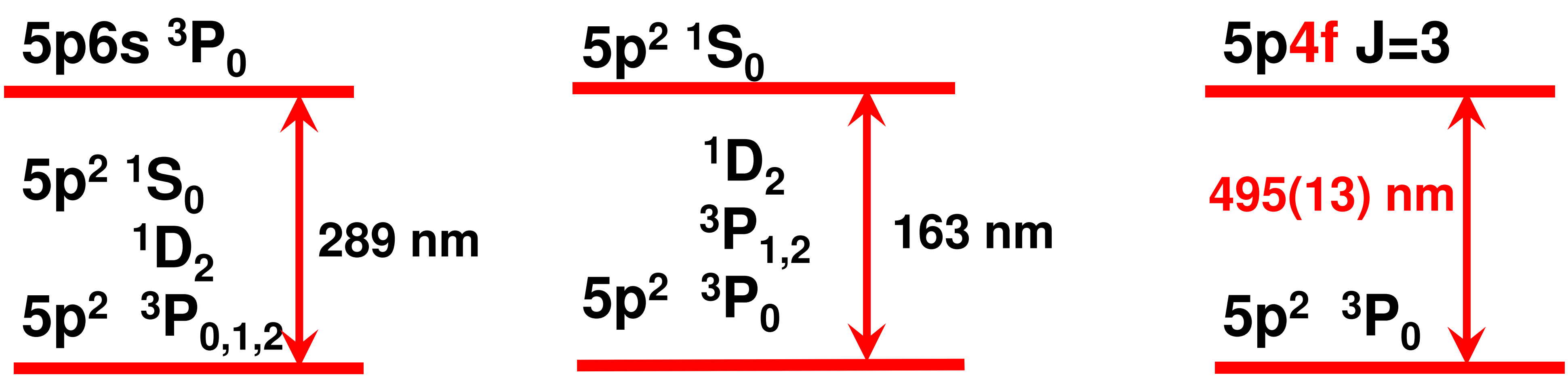
$3s^2\ {}^1S_0 - 3s3p\ {}^3P_0$ transition in Mg-like ions

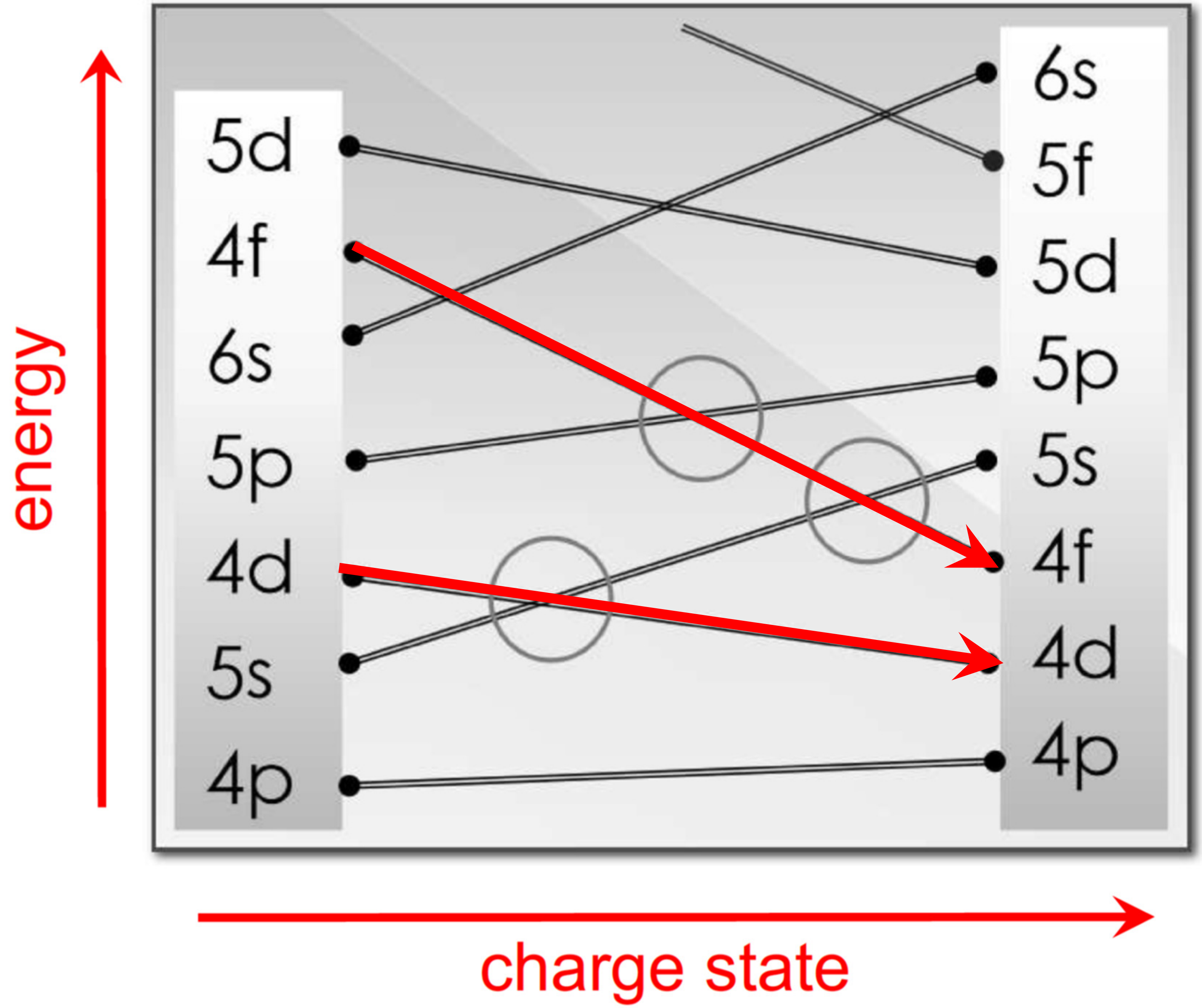


J. C. Berengut et al., Phys. Rev. Lett. 105, 120801 (2010) .

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

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



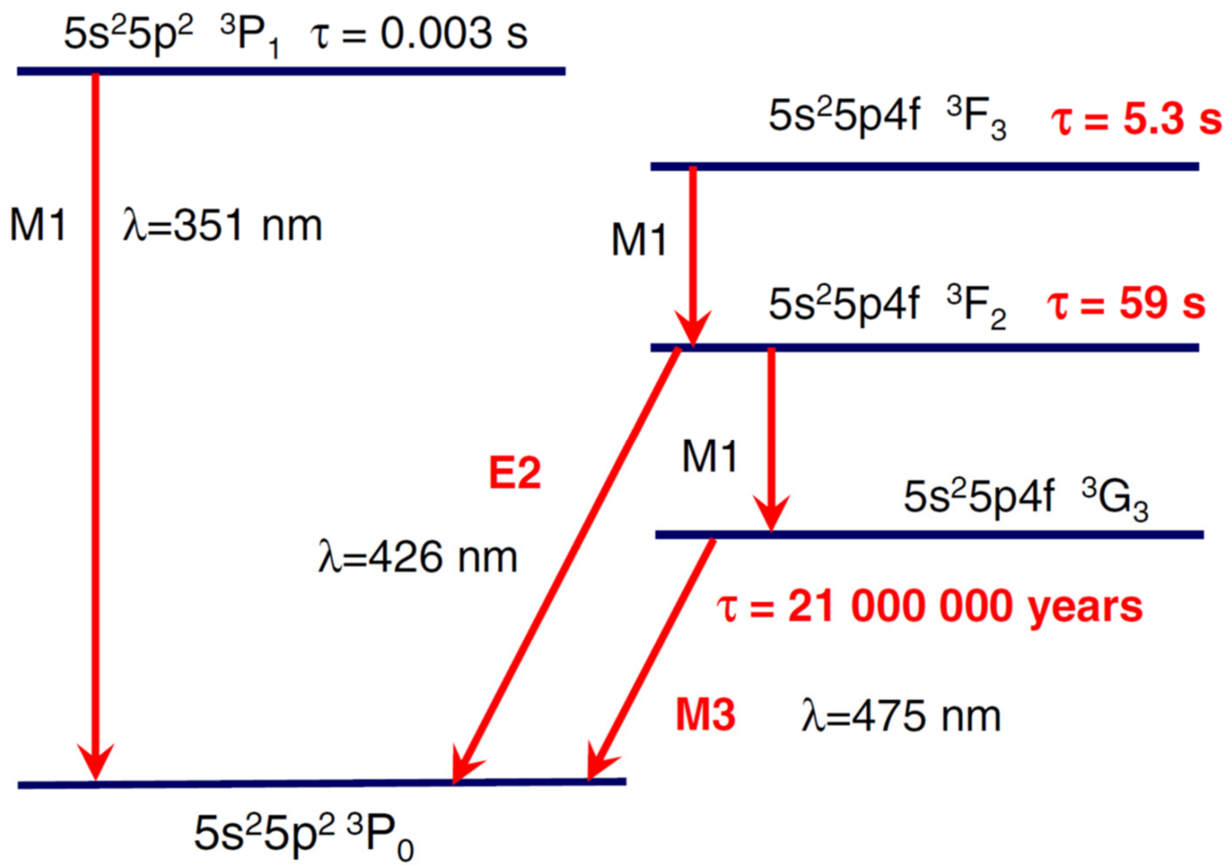


Schematic of the shell order in neutral atoms (left) and in hydrogen-like ions (right). One can see that the “diving“ of 4d and 4f shells result in level crossings in the areas marked by circles.

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}

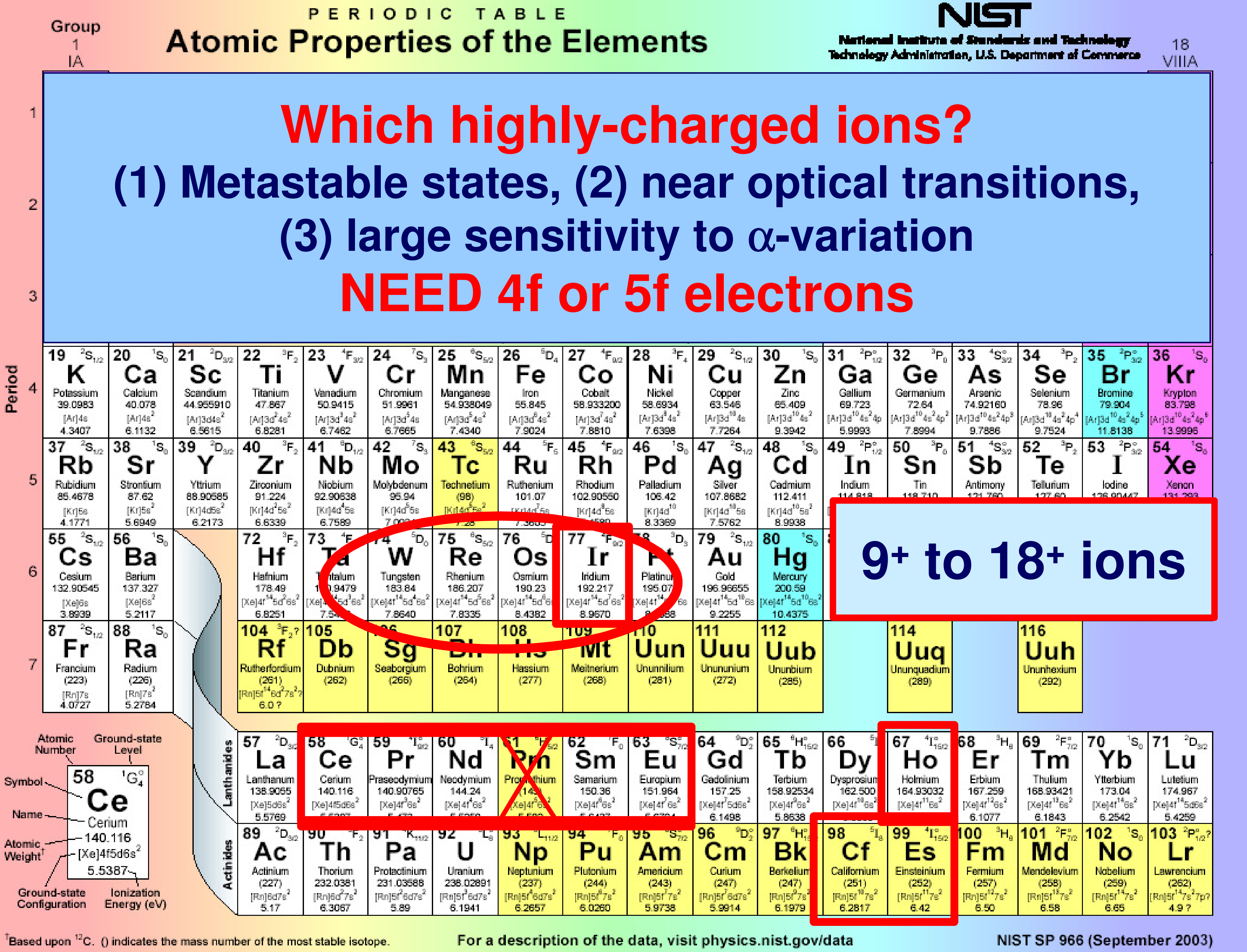
- Large relativistic effects – enhancement of related effects including α-variation and tests of Lorentz symmetry

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



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+}**

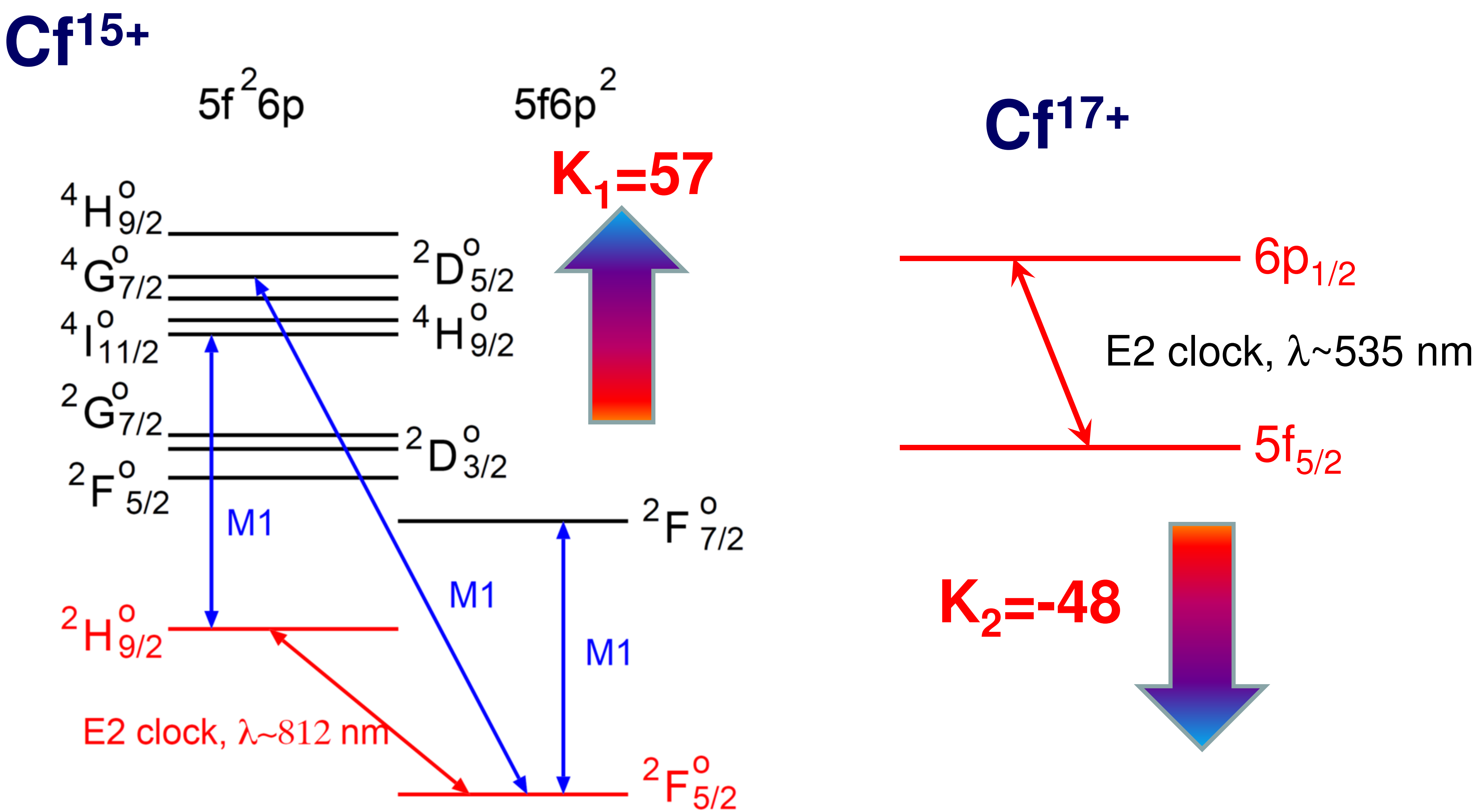
Accurate theory predictions

(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!



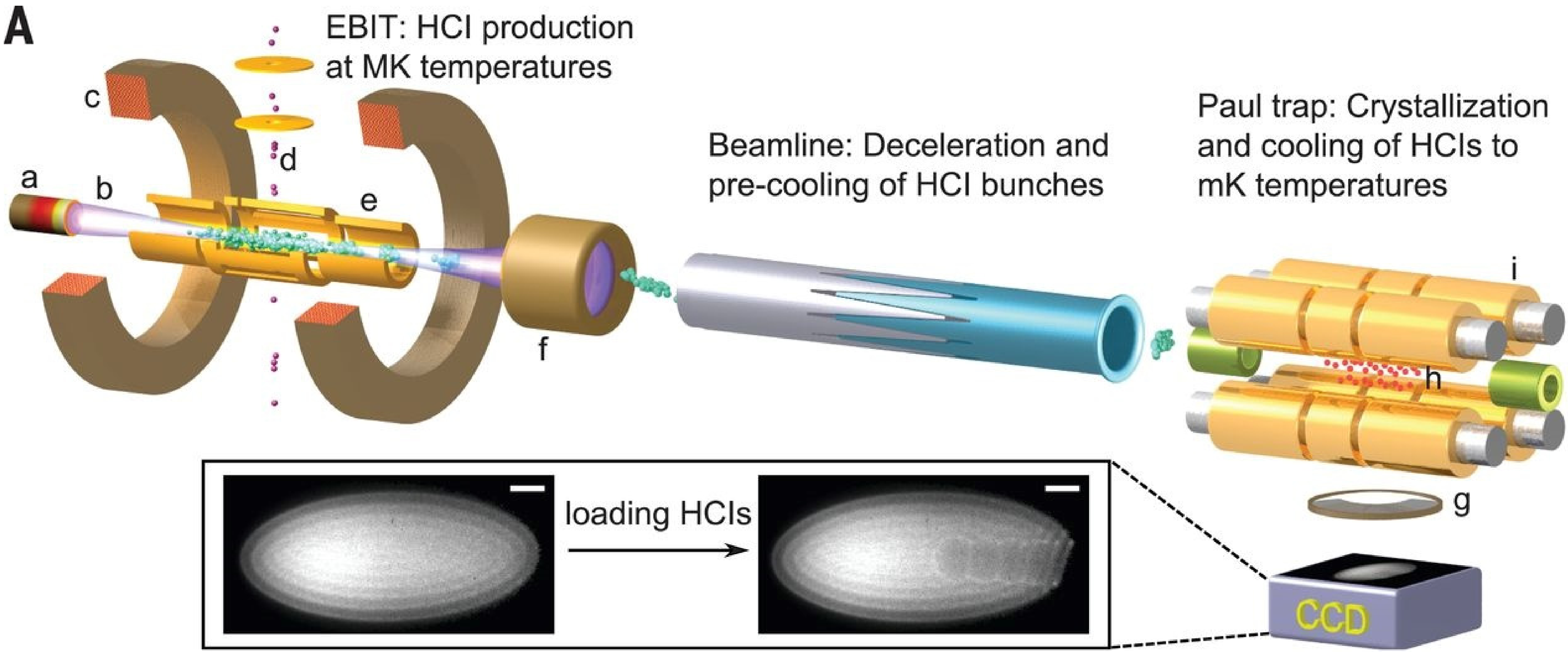
V. A. Dzuba, M. S. Safronova, U. I. Safronova, and V. V. Flambaum, Phys. Rev. A 92, 060502(R) (2015).

SYMPATHETIC COOLING

Science 347, 1233 (2015)

Coulomb crystallization of highly charged ions

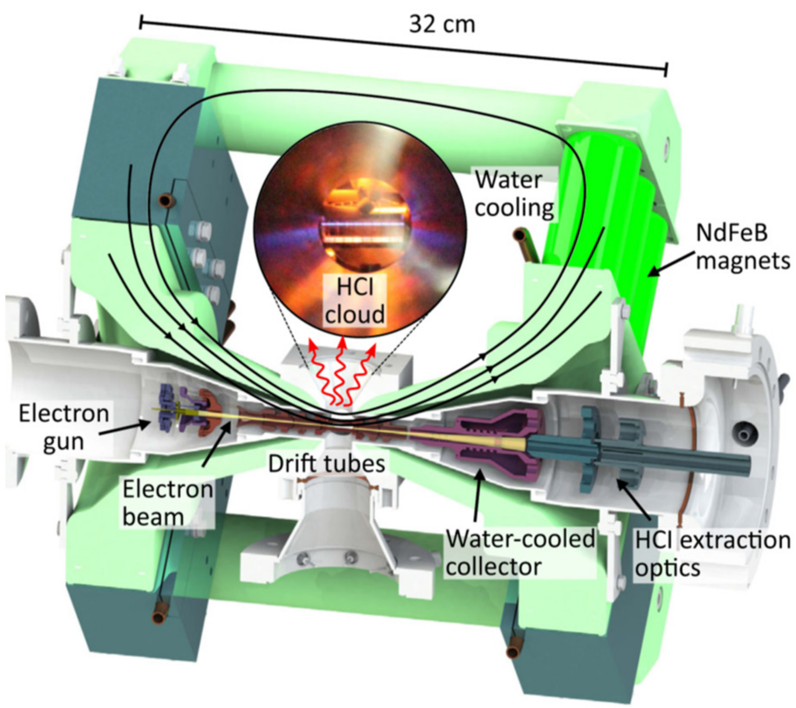
L. Schmöger,[1,2] O. O. Versolato,[1,2*] M. Schwarz,[1,2] M. Kohnen,[2] A. Windberger,[1] B. Piest,[1] S. Feuchtenbeiner,[1] J. Pedregosa-Gutierrez,[3] T. Leopold,[2] P. Micke,[1,2] A. K. Hansen,[4†] T. M. Baumann,[5] M. Drewsen,[4] J. Ullrich,[2] P. O. Schmidt,[2,6] J. R. Crespo López-Urrutia[1‡]

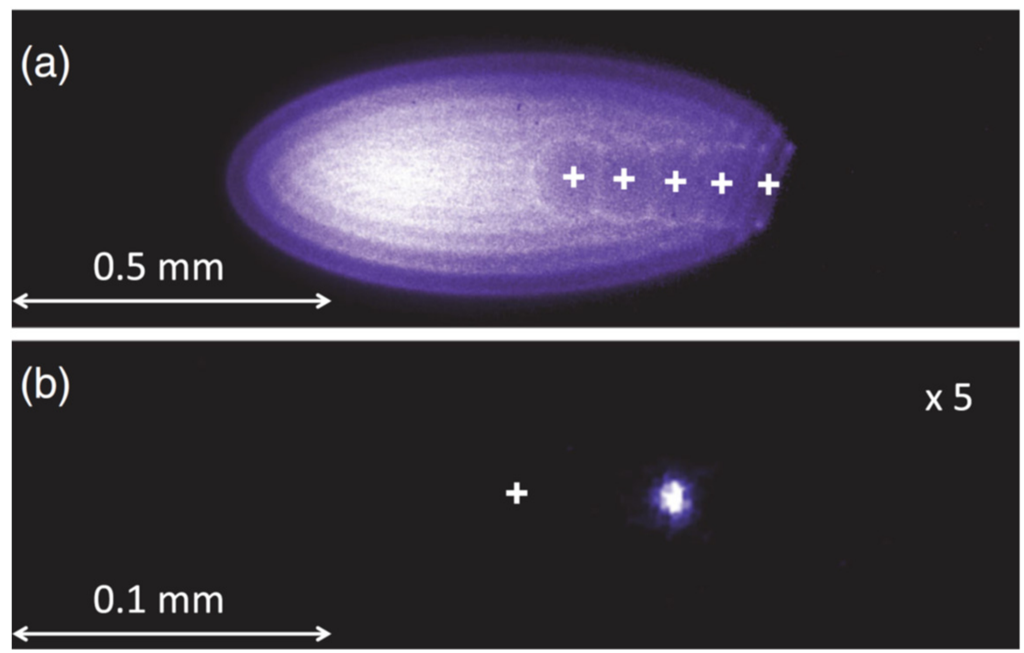


REVIEWS OF MODERN PHYSICS, VOLUME 90, OCTOBER–DECEMBER 2018

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).

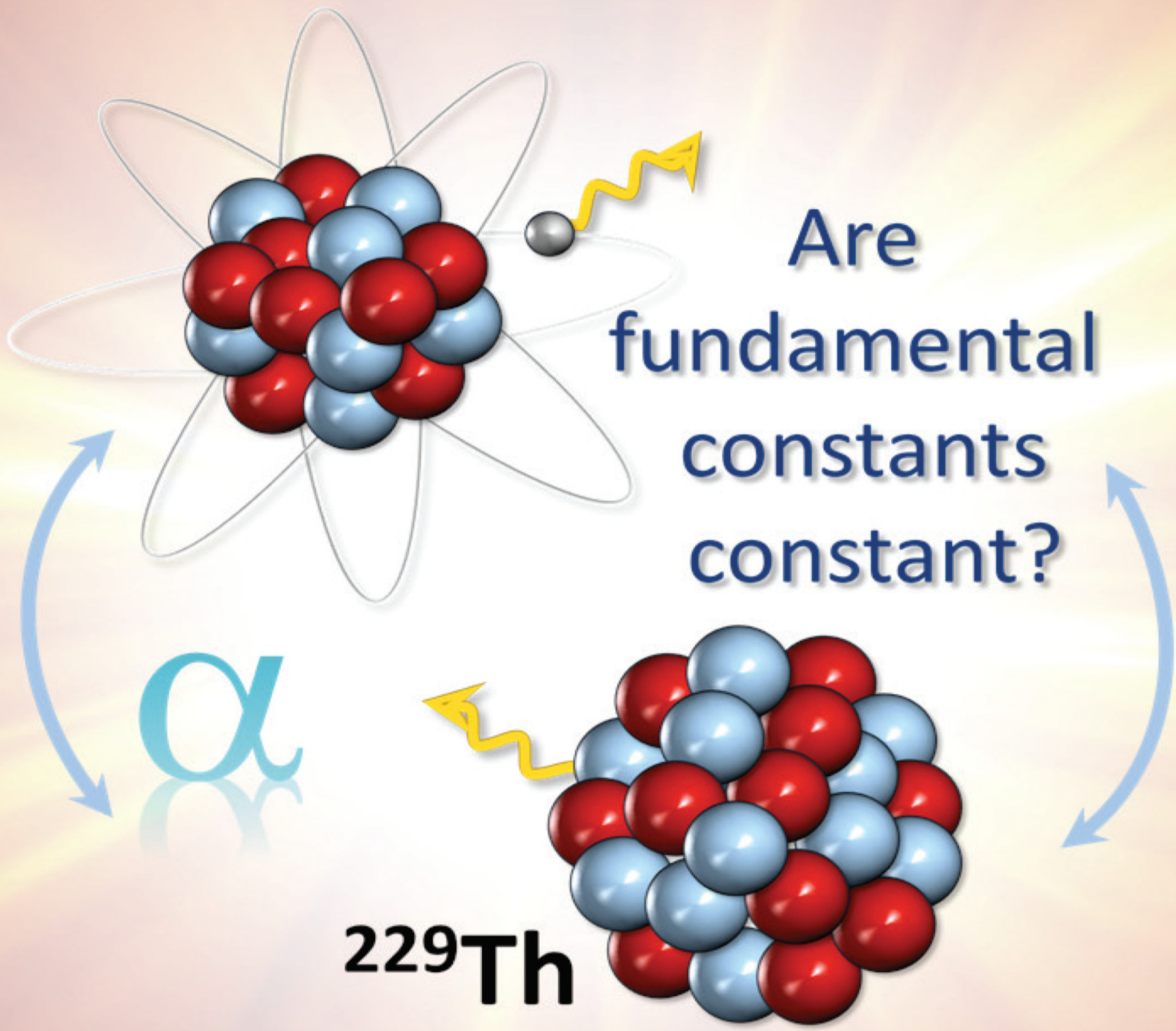




PTB, Germany, November 2018: **First demonstration of quantum logic with a highly charged ion, Ar^{13+}**

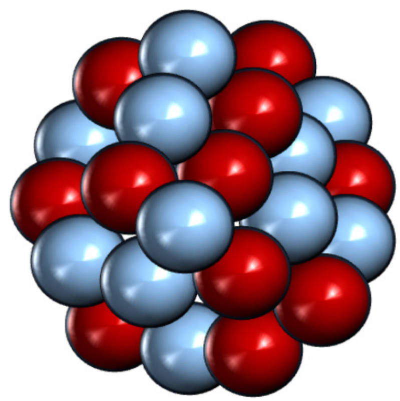
2019: Improved frequency measurement from 10^{-7} to 10^{-15} level!

From atomic to nuclear clocks!

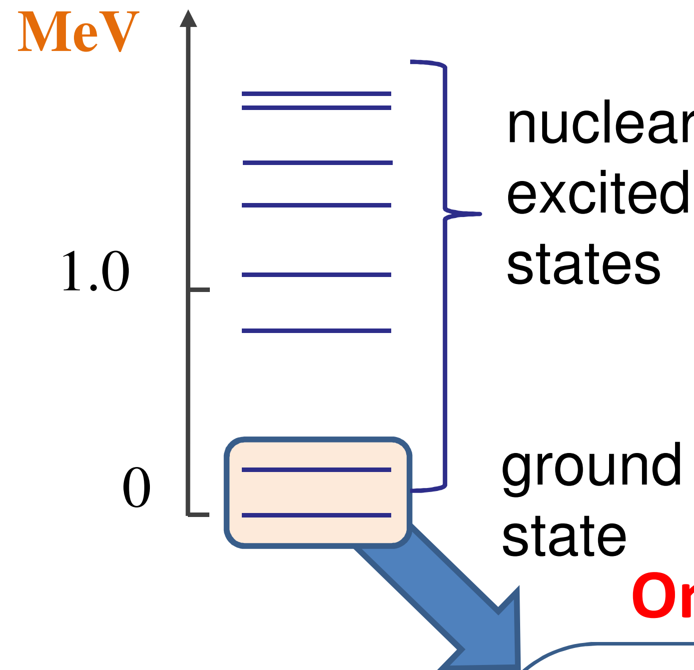


M. S. Safronova, Annalen der Physik 531, 1800364 (2019)

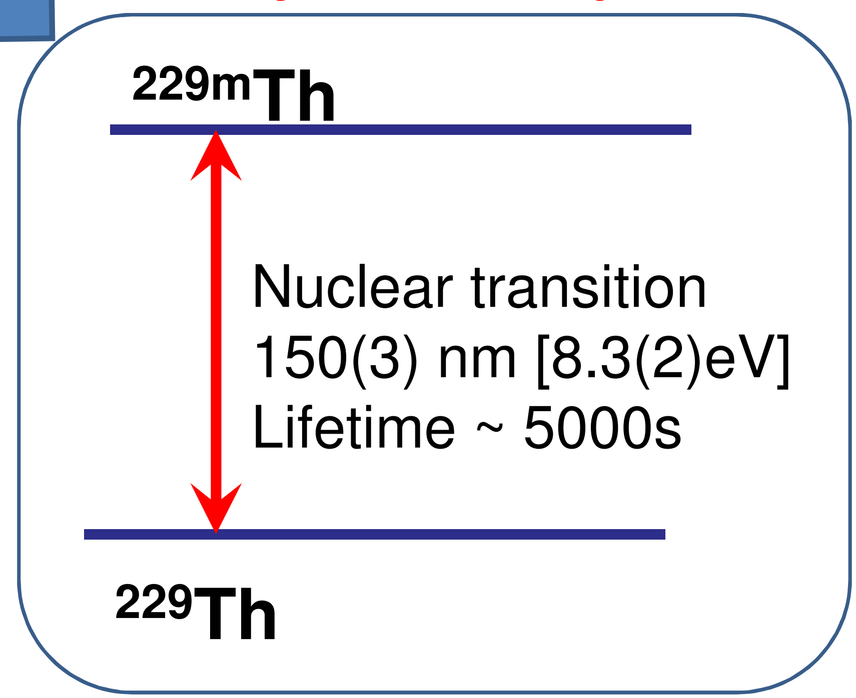
Obvious problem: typical nuclear energy levels are in MeV
Six orders of magnitude from ~few eV we can access by lasers!



Atomic Nucleus



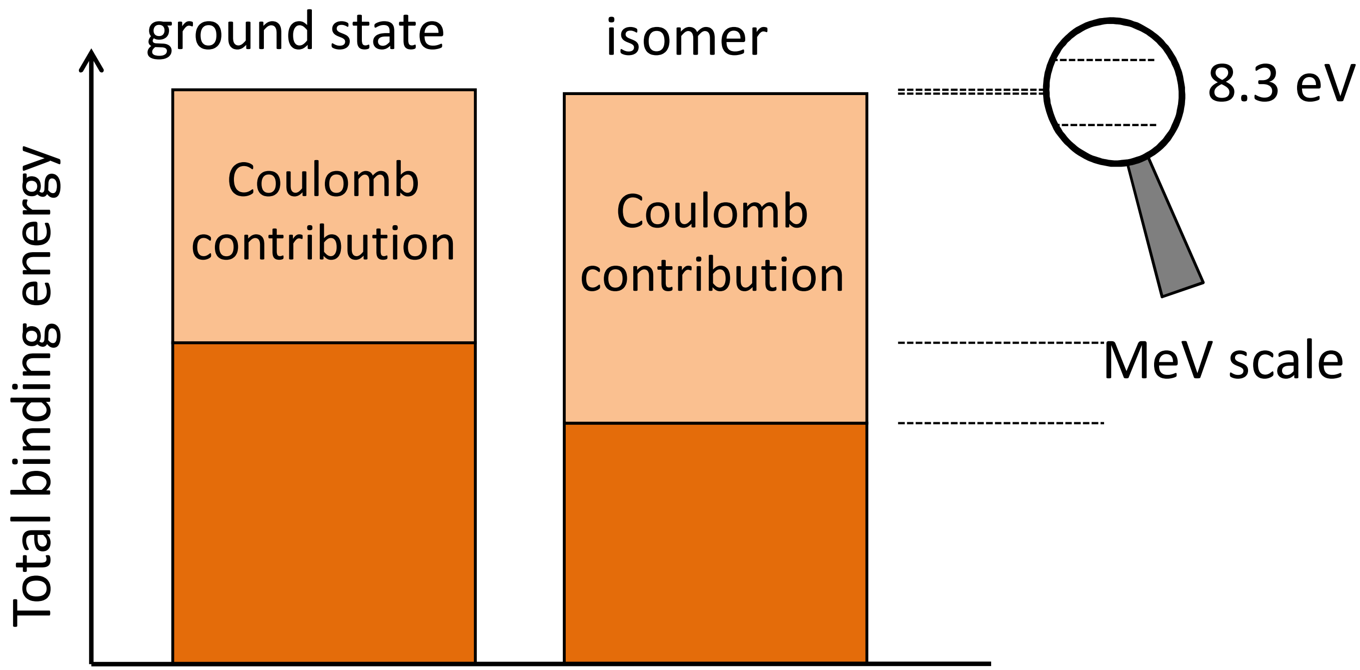
Only ONE exception!



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), d_g (particularly great for detection of relaxions) and d_{mq}

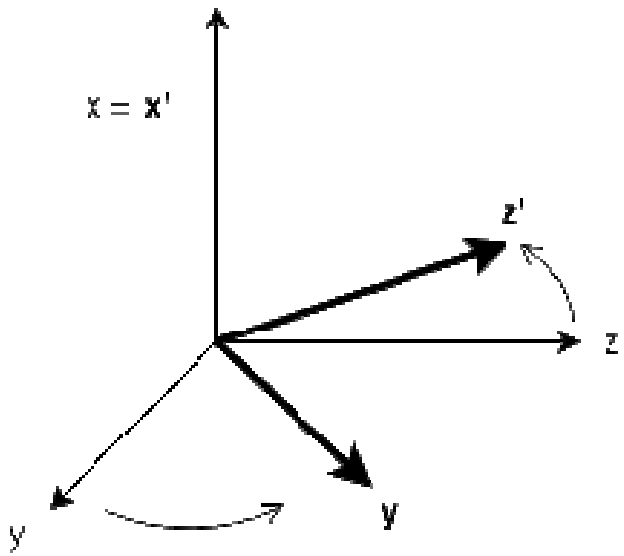
It is crucial to establish actual enhancement!

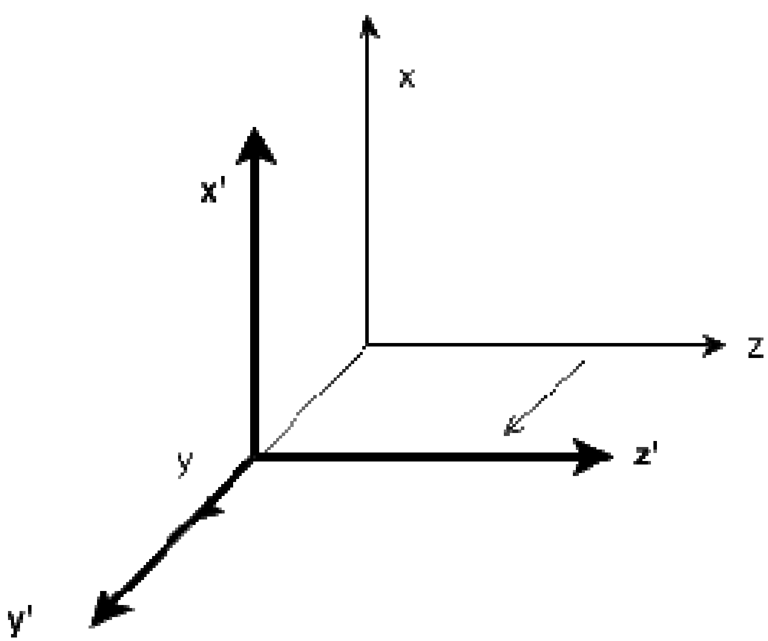
Picture credit: Thorsten Schumm

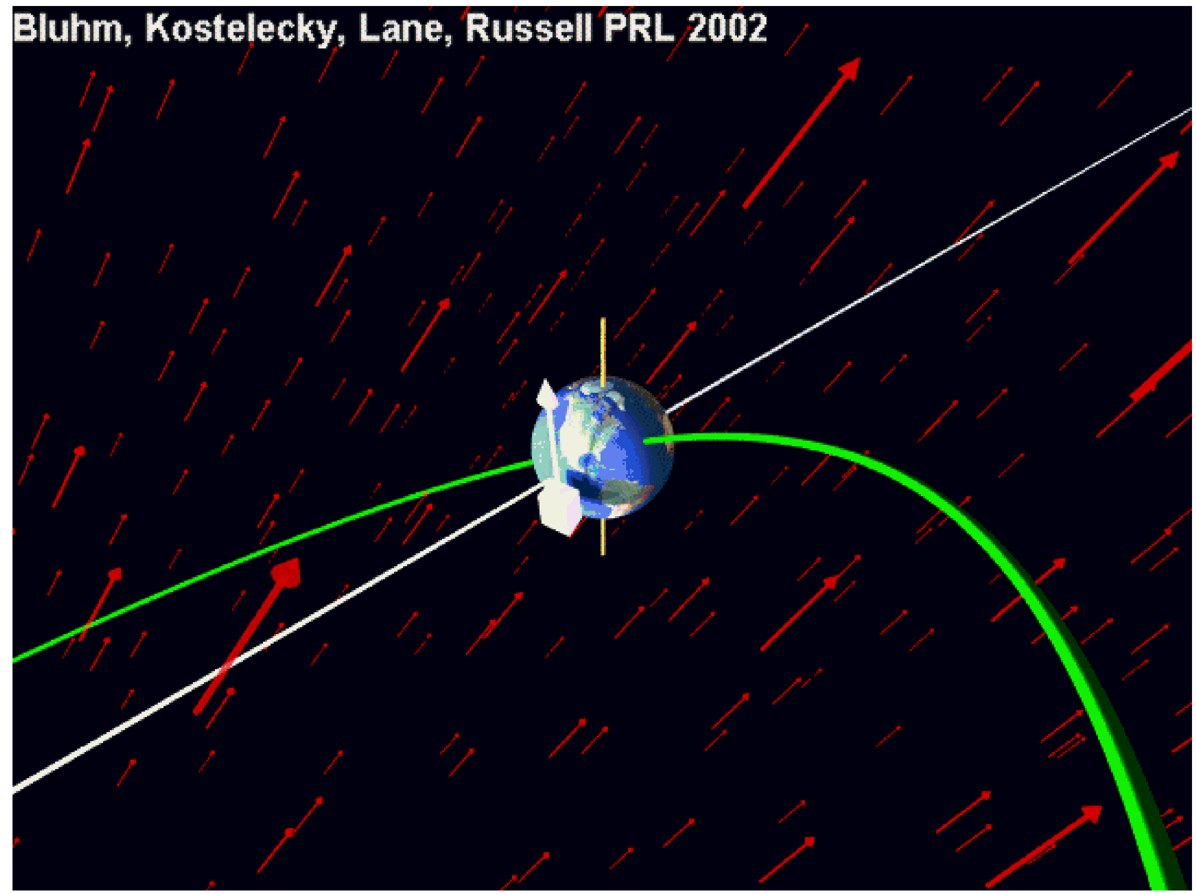
THE SEARCH FOR VIOLATION OF LORENTZ INVARIANCE

using quantum information techniques and atomic clocks

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



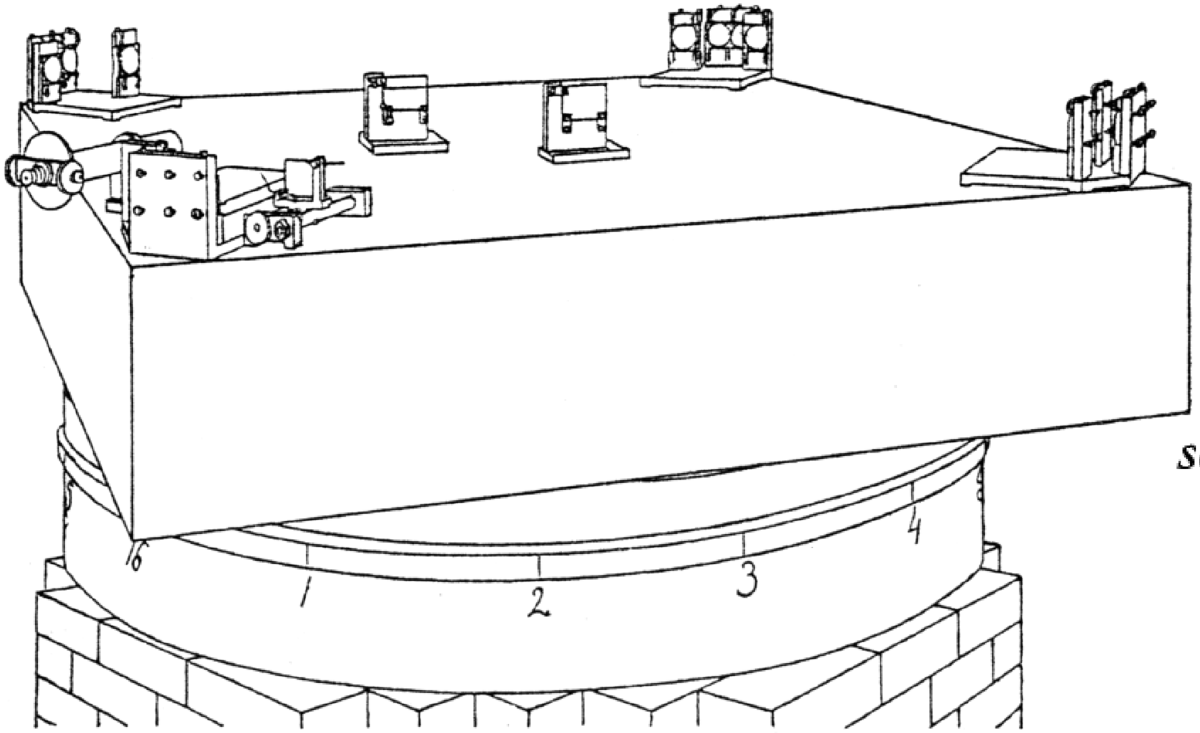


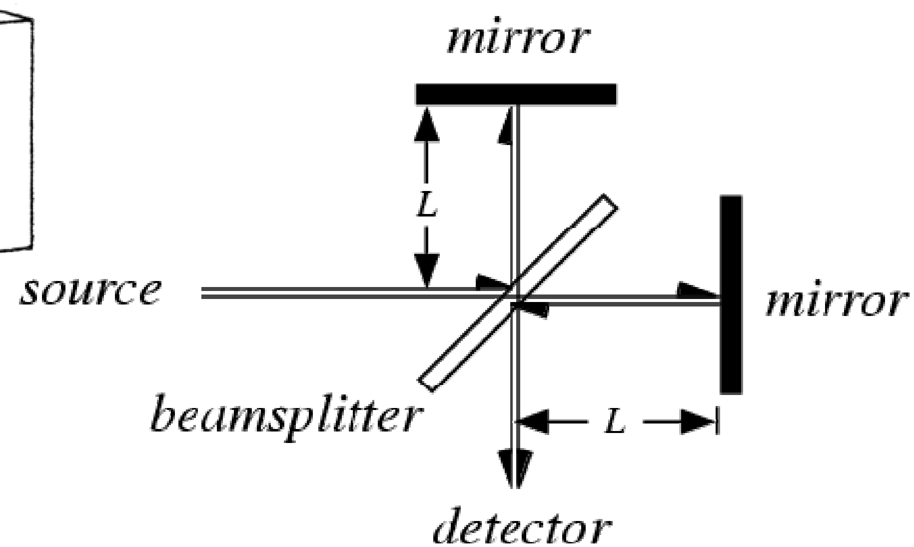


Animation credit: http://www.physics.indiana.edu/~kostelec/mov.html

A Test of Lorentz Symmetry:
The Michelson–Morley experiment

Interferometer splits a light ray into two beams travelling along orthogonal paths, reflects and recombines the beams to yield an interference pattern.

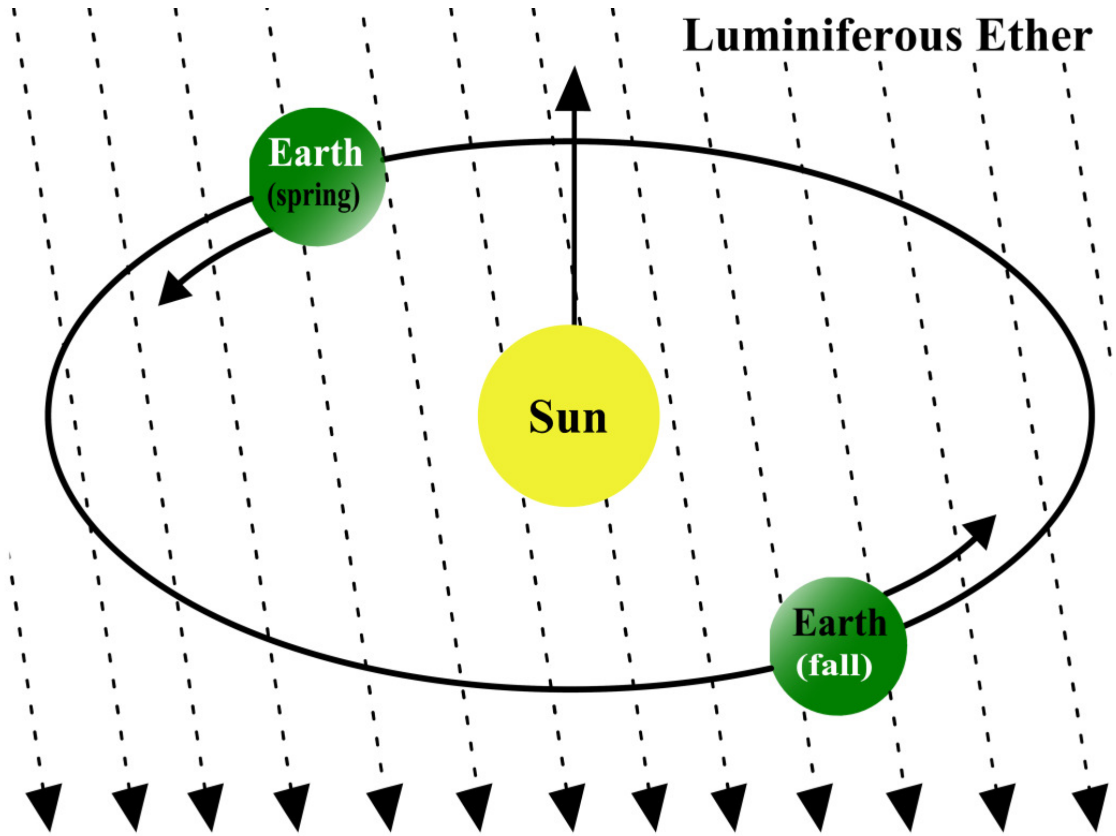




Michelson, A. A. & Morley, E. W. *Am. J. Sci.* **34**, 333–345 (1887).
http://en.wikipedia.org/wiki/Michelson%E2%80%93Morley_experiment

A Test of Lorentz Symmetry:
The Michelson–Morley experiment

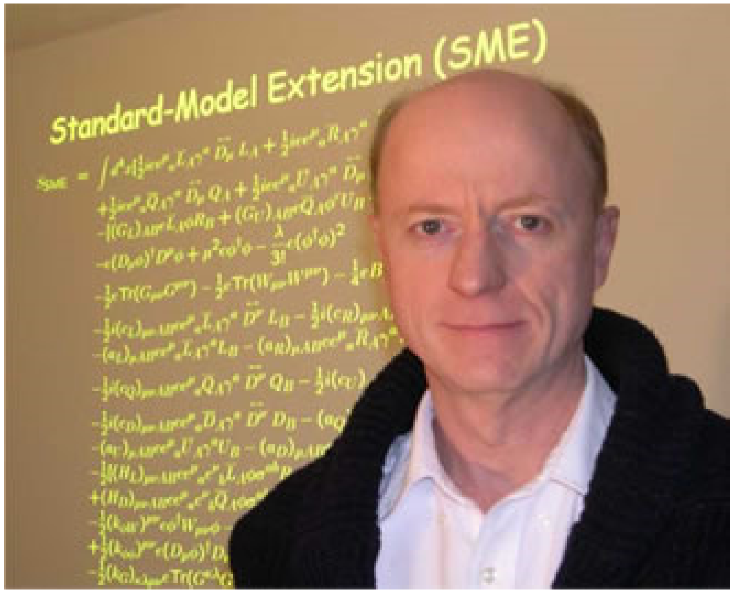
Monitor the interference pattern when changing orientation of the apparatus to test the constancy of the speed of light and hence the rotation symmetry of the laws of electrodynamics.



If the speed of light is different in different directions, then the travel times of the two beams vary as the apparatus is rotated, changing the interference pattern.

Michelson, A. A. & Morley, E. W. *Am. J. Sci.* **34**, 333–345 (1887).
http://en.wikipedia.org/wiki/Michelson%E2%80%93Morley_experiment

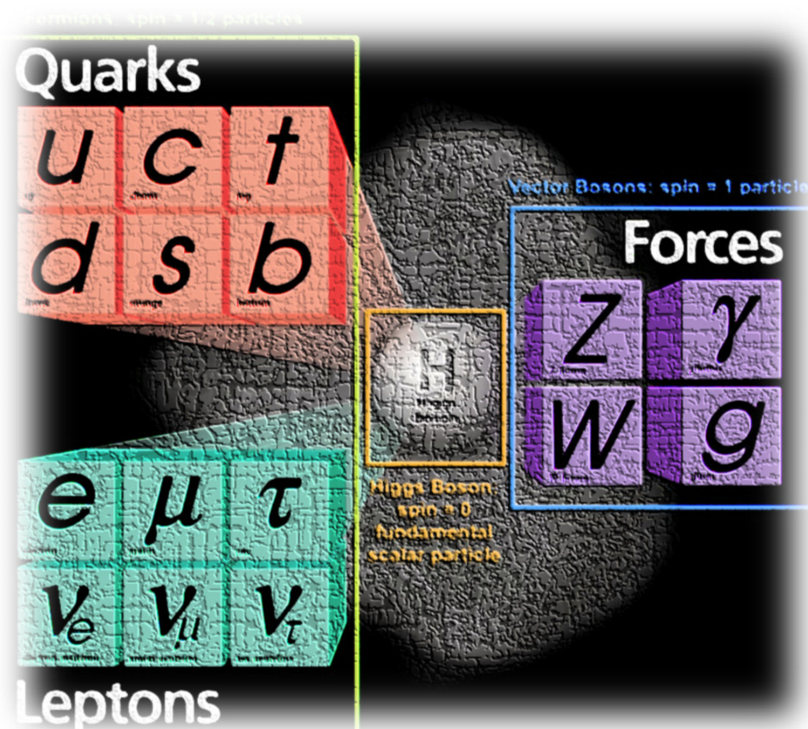
How to quantify Lorentz violation?



V. Alan Kostelecky
Indiana University

Theoretical framework to describe Lorentz and CPT violation

Standard Model Extension (SME)



Standard Model Extension (SME)

SME: a generalization of the usual Standard Model and General Relativity that has all the conventional desirable properties but that **allows for violations of Lorentz and CPT symmetry.**

SME allows systematic studies of Lorentz violation in any possible sector of the Standard Model.

SME is controlled by a set of coefficients whose values are to be determined or constrained by experiment.

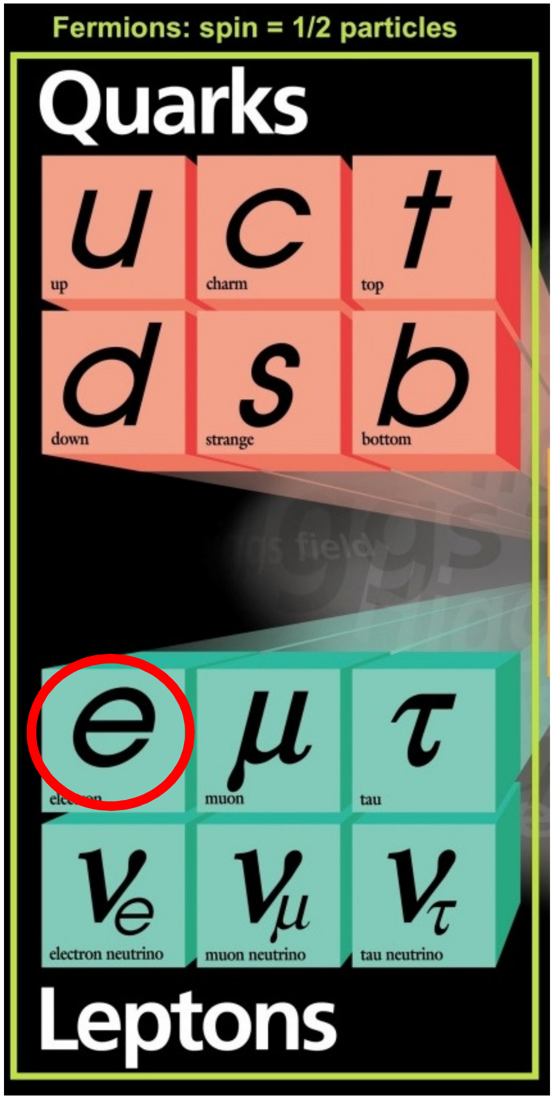
Alan Kostelecky, Neil Russell, **Data Tables for Lorentz and CPT Violation,** Rev. Mod. Phys. 83, 11 (2011)**.**

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

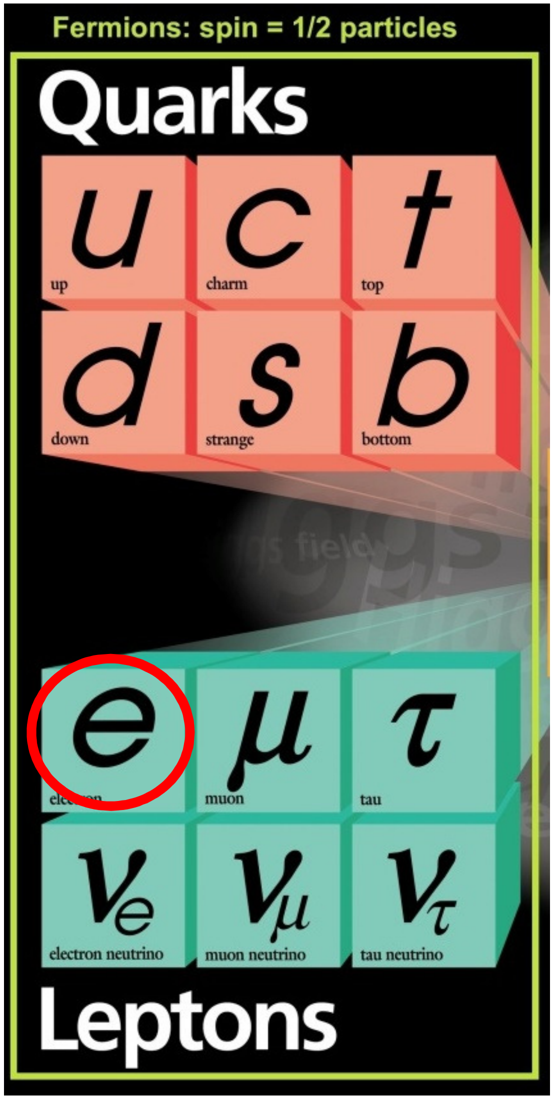


γ_ν are Dirac matrices

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

Standard Model Extension

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

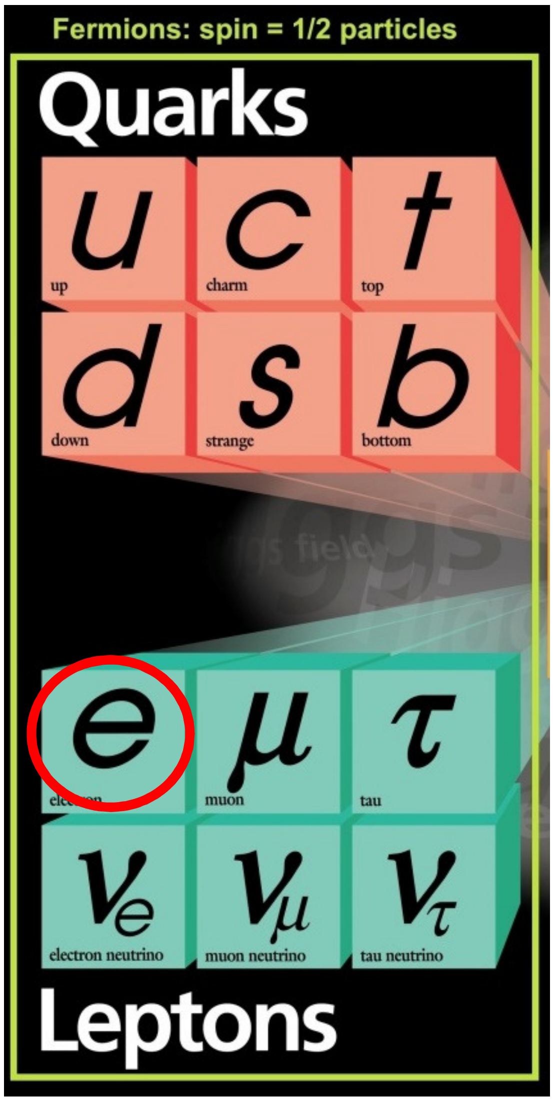
$$L = \frac{1}{2} i \, \bar{\psi} \, \Gamma_\nu \overleftrightarrow{\partial}^\nu \, \psi - \bar{\psi} M \, \psi$$

Standard Model Extension

γ_ν are Dirac matrices

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

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

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

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)

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 Extension

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

$$M := m + \underbrace{a_\mu\gamma^\mu + b_\mu\gamma_5\gamma^\mu}_{\text{CPT-violating}} + \frac{1}{2} H_{\mu\nu}\sigma^{\mu\nu}$$

Testing Lorentz violation: experiments set limits on the coefficients

$a_\mu, b_\mu, H_{\mu\nu}, c_{\mu\nu}, d_{\mu\nu}$ **for all particles**

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

This talk: setting limits on $c_{\mu\nu}$ coefficient

$c_{\mu\nu}$ is a tensor in a four-dimensional spacetime

4-vectors and tensors:

4-vector: $x^{\mu} = (x^0, x^1, x^2, x^3) = (\underset{\text{"timelike" component}}{ct}, \underbrace{x, y, z}_{\text{three "spacelike" components}})$

"timelike“ component

three "spacelike“ components

Example of 4-tensor: electromagnetic field tensor

$$F_{\mu\nu} = \begin{bmatrix} 0 & E_x/c & E_y/c & E_z/c \\ -E_x/c & 0 & -B_z & B_y \\ -E_y/c & B_z & 0 & -B_x \\ -E_z/c & -B_y & B_x & 0 \end{bmatrix}.$$

Setting limits on $c_{\mu\nu}$ Lorentz-violating coefficient

$c_{\mu\nu}$ is a tensor in a four-dimensional spacetime

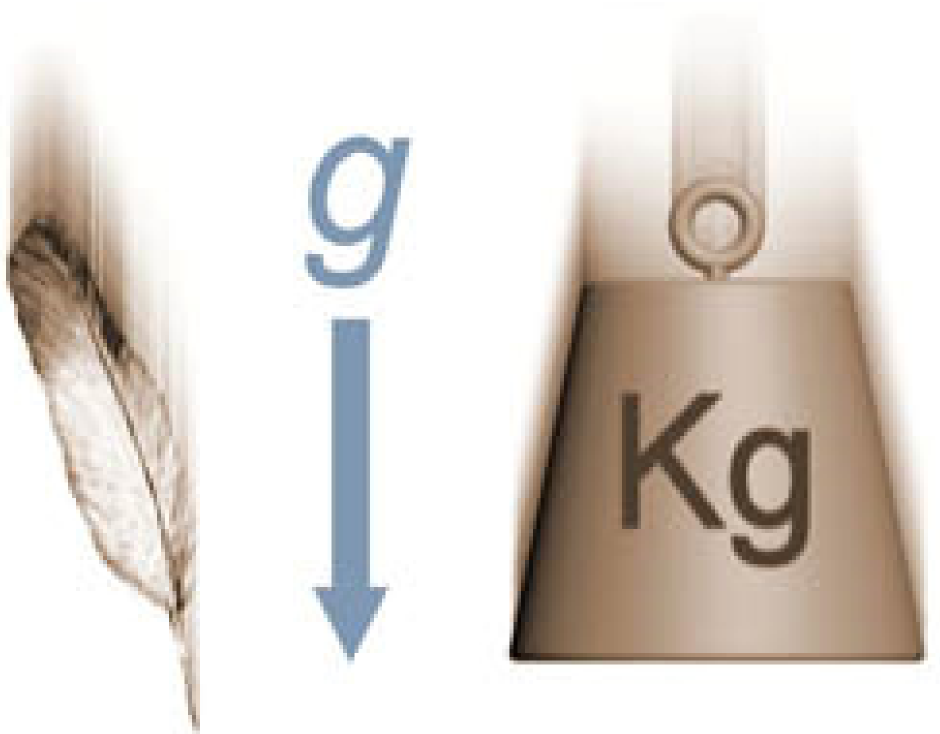
$$c_{\mu\nu} = \begin{cases} c_{TT} \\ c_{TJ} \\ c_{JK} \end{cases} \qquad \mu, \nu = \begin{matrix} T \\ J = 1, 2, 3 \end{matrix}$$

"timelike" component

three "spacelike" components

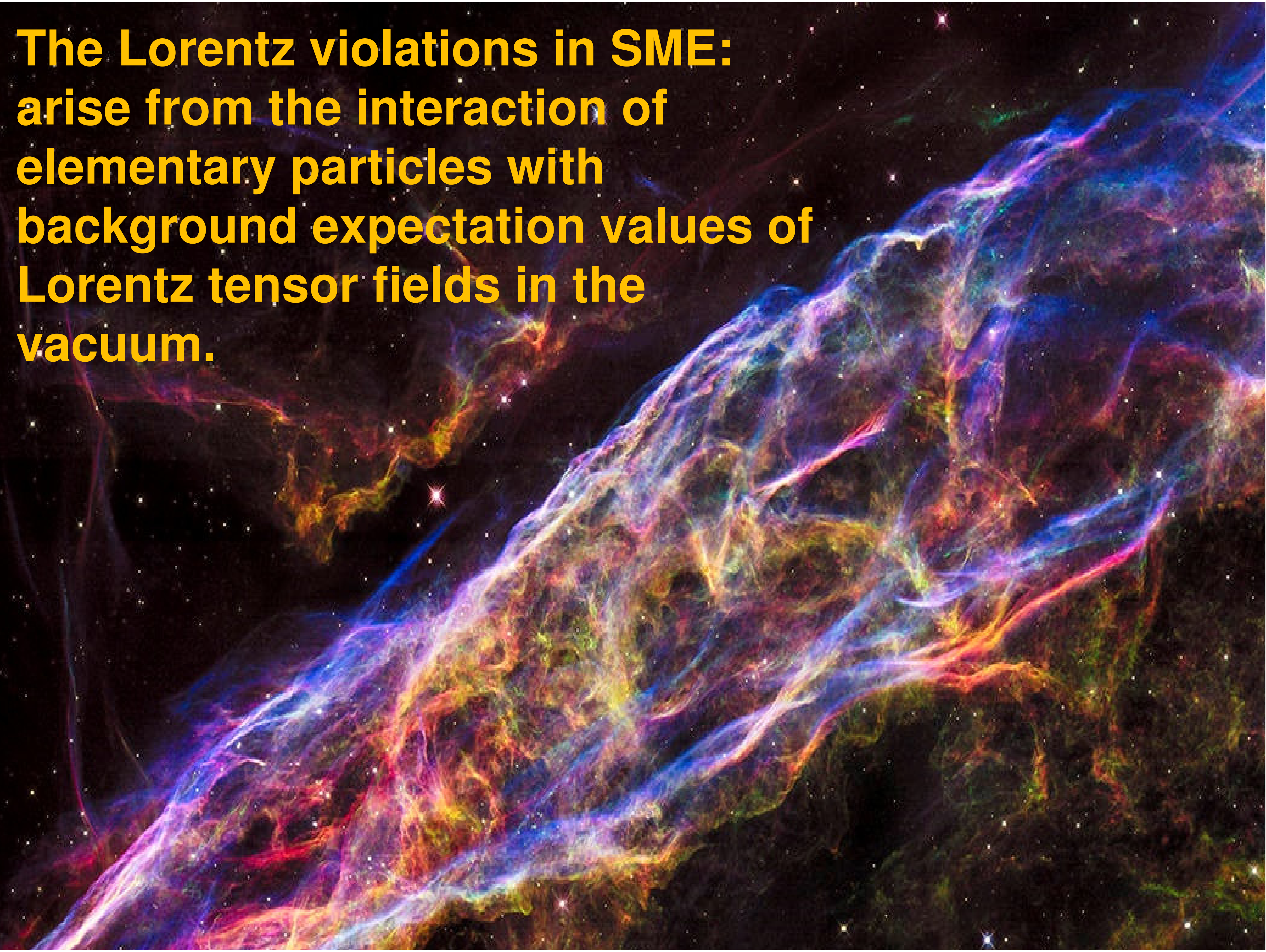
Relevance to tests of the Weak Equivalence Principle

The Weak Principle of Equivalence: all the laws of motion for freely falling particles are the same as in an unaccelerated reference frame.

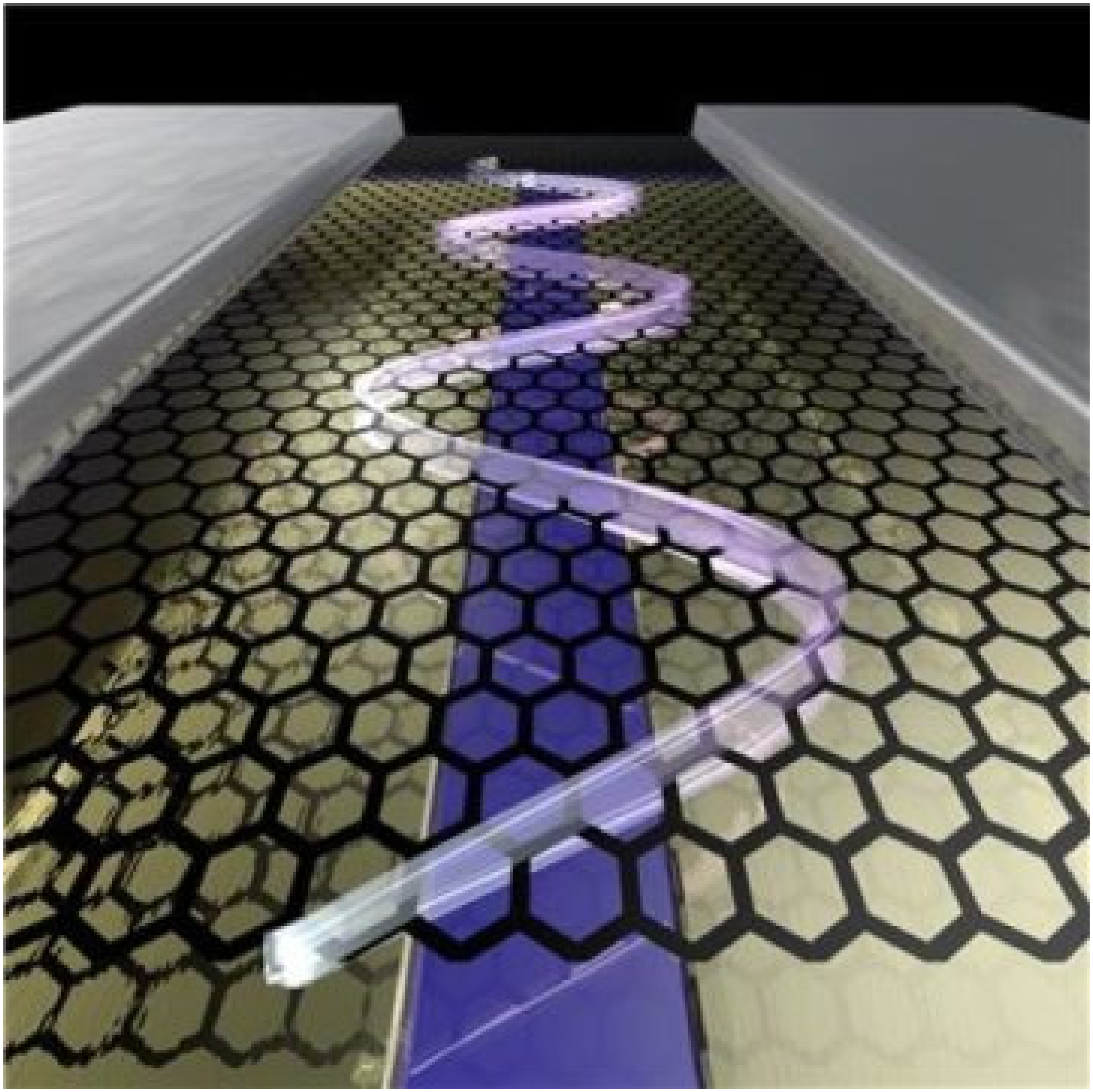


The $c_{\mu\nu}$ coefficients also give rise to violations of the **weak equivalence principle:** they cause gravity to accelerate electrons more or less strongly than other kinds of matter [Kostelecky & Tasson, 2011].

The Lorentz violations in SME: arise from the interaction of elementary particles with background expectation values of Lorentz tensor fields in the vacuum.



Analogy: behavior of the charged particle affected by the electromagnetic field of a crystal



http://www.sciencedaily.com/releases/2015/03/150303075145.htm

Very small effects!

How small?

Lorentz violating effects are suppressed by some power of R

246 GeV

$$R = \frac{\text{Electroweak scale}}{\text{Plank energy scale}} \sim 2\times10^{-17}$$

1.22×10^{19} GeV

Kostelecký, V. A. & Potting, R. CPT, strings, and meson factories. *Phys. Rev. D* **51**, 3923-3935 (1995).

Violation of Lorentz Symmetry with bound electrons

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

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

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**

Lorentz violation: what happens to atoms?

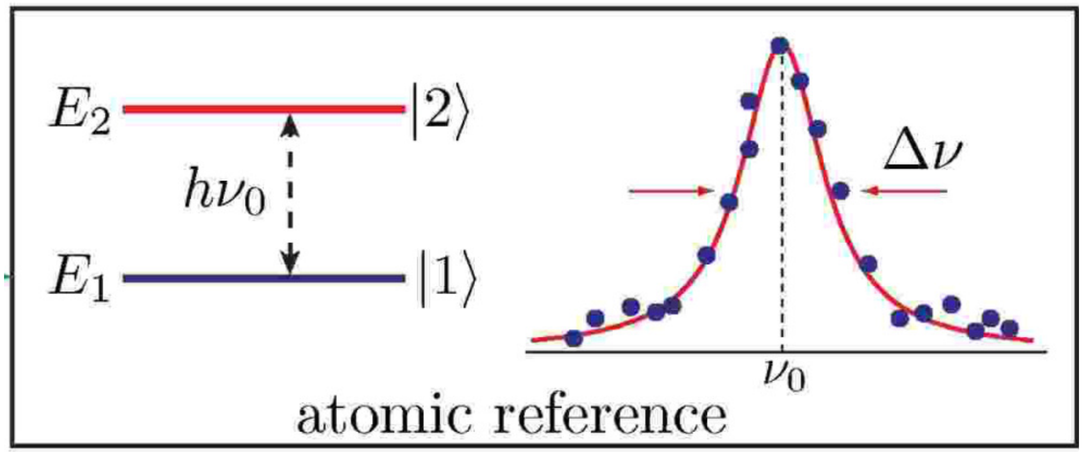
The $c_{\mu\nu}$ tensor modifies the kinetic term in the electronic QED Lagrangian

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

$$\delta H = -\frac{1}{6} C_0^{(2)} T_0^{(2)}$$

$$\boxed{C_0^{(2)} \equiv c_{11} + c_{22} - 2c_{33}}$$

Atomic energy levels shift!

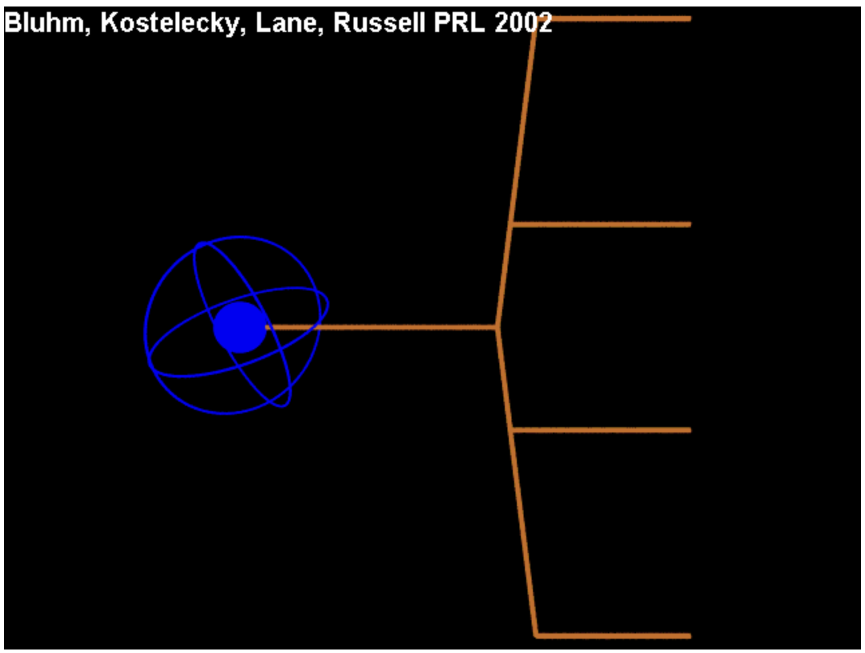


Atomic clock frequency shifts!

Quadrupole shift due to Lorentz-violating $c_{\mu\nu}$ term
Shift depends on magnetic quantum number m as m^2

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.

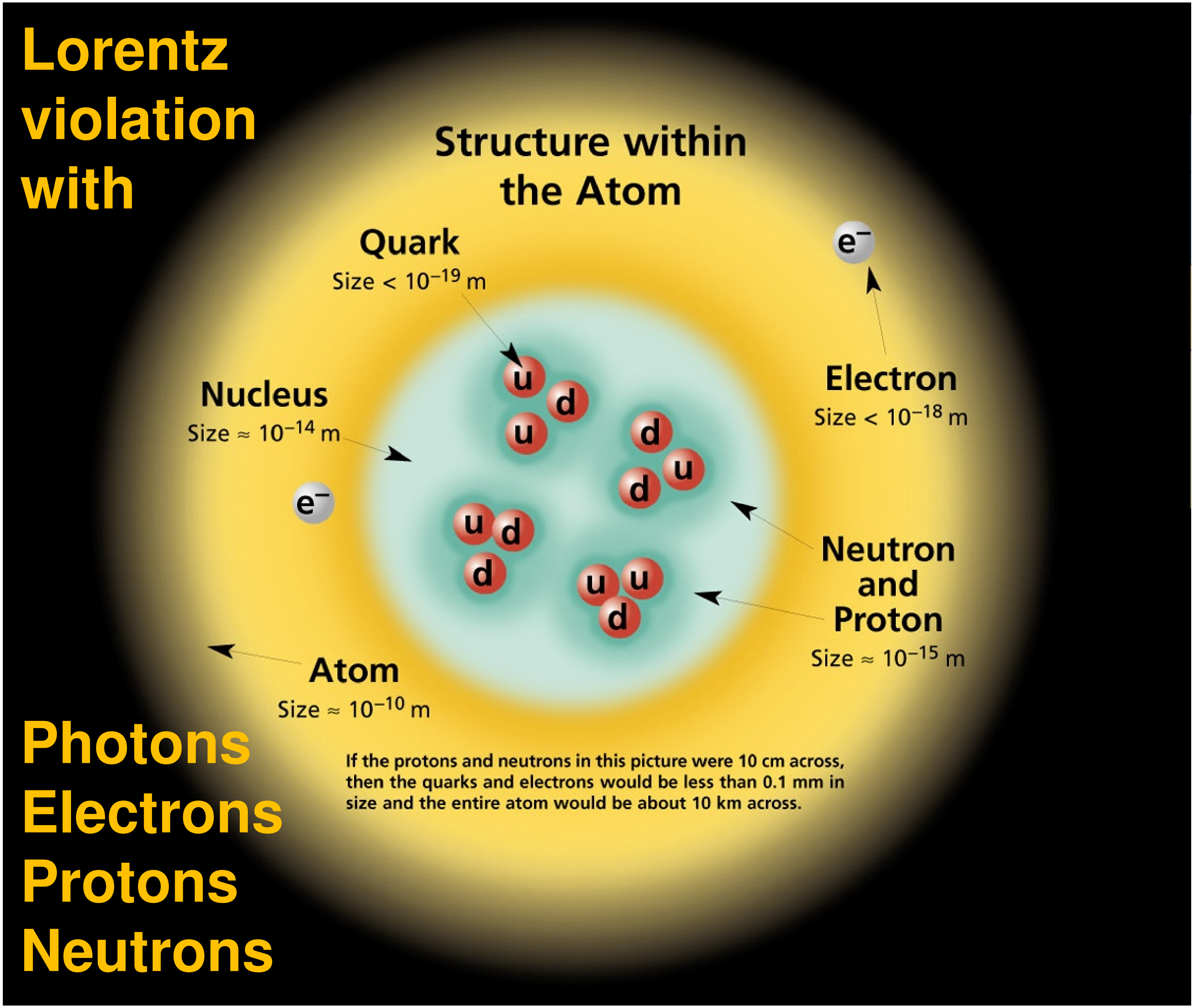
(2) Turn on magnetic field to define a quantization axis.

(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

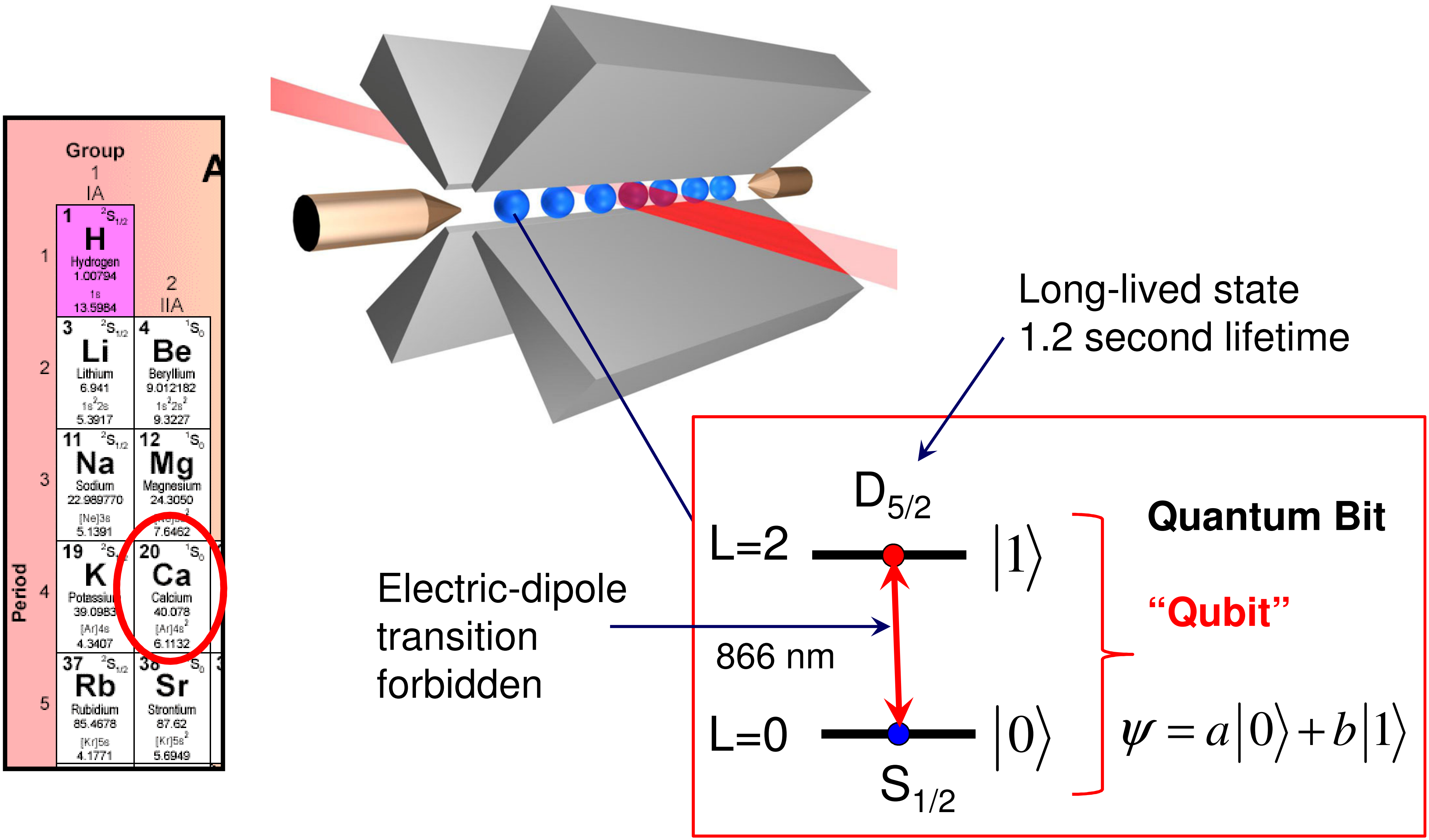
Test of Lorentz symmetry with atomic systems

Lorentz violation with



Photons
Electrons
Protons
Neutrons

Ca^+ ion: building quantum computers



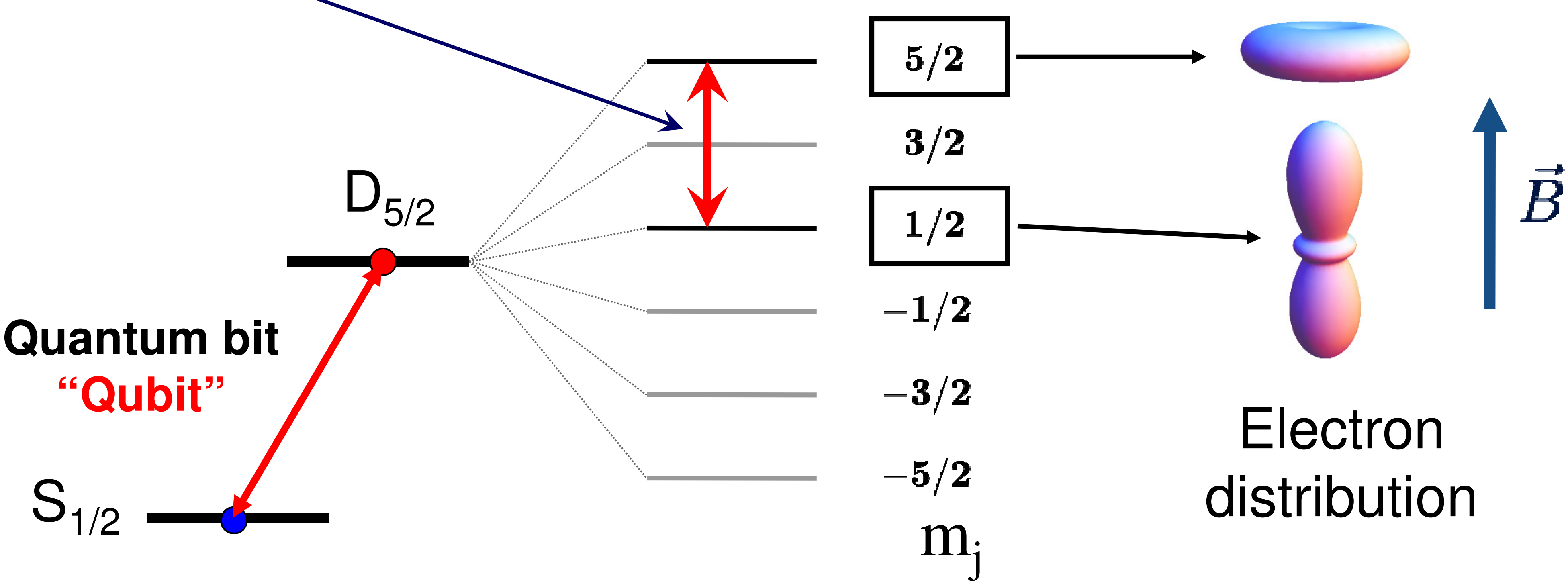
http://www.uibk.ac.at/th-physik/qo/research/trappedions.html

Previous laboratory LV tests setting limits on cμν in the electron-photon sector: two trapped Ca^+ ions

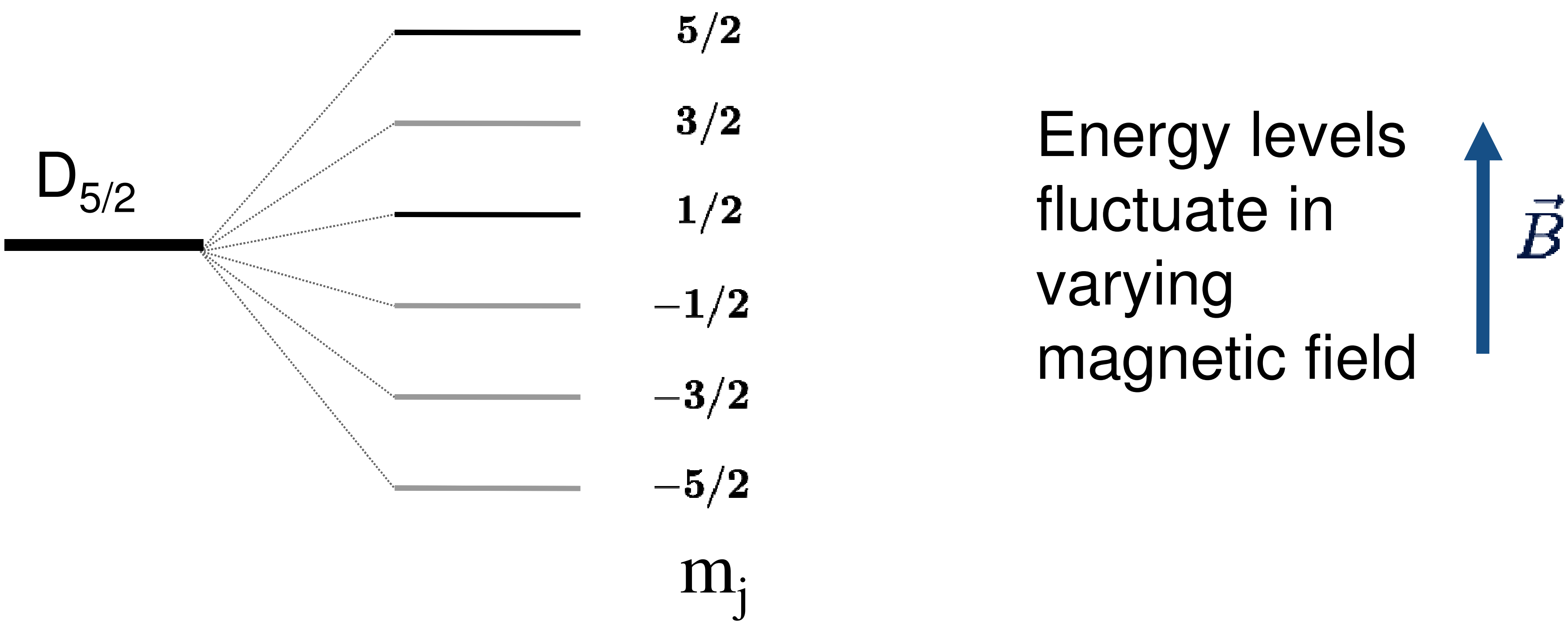
$$\frac{2}{h}\left(E_{m_J=5/2} - E_{m_J=1/2}\right) = \left(-8.9(2)\times 10^{15}\ \mathrm{Hz}\right)\times C_0^{(2)}$$

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

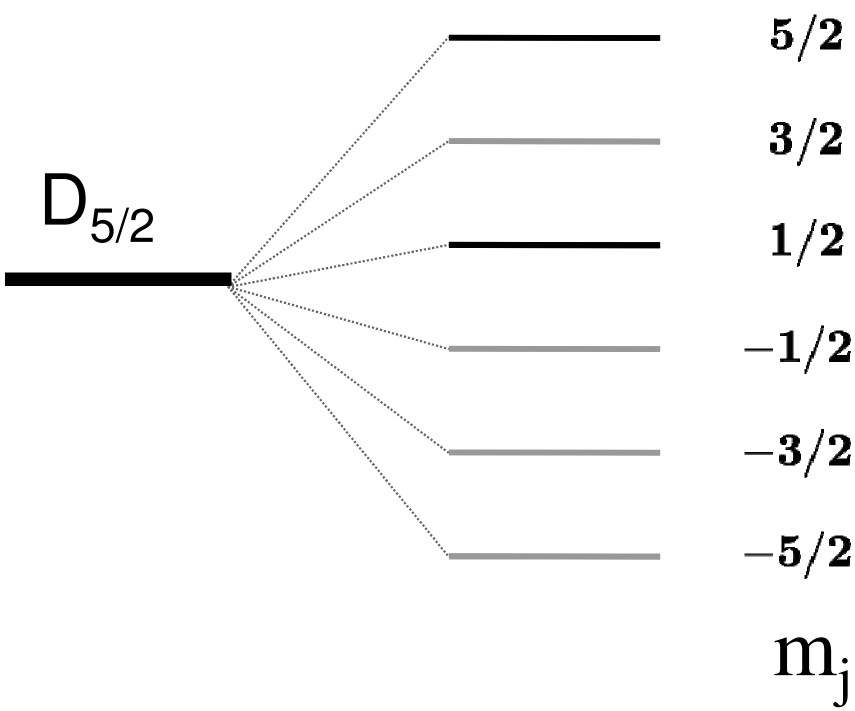
Measure Zeeman splitting



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



Problem: Systematic errors due to magnetic Field fluctuation

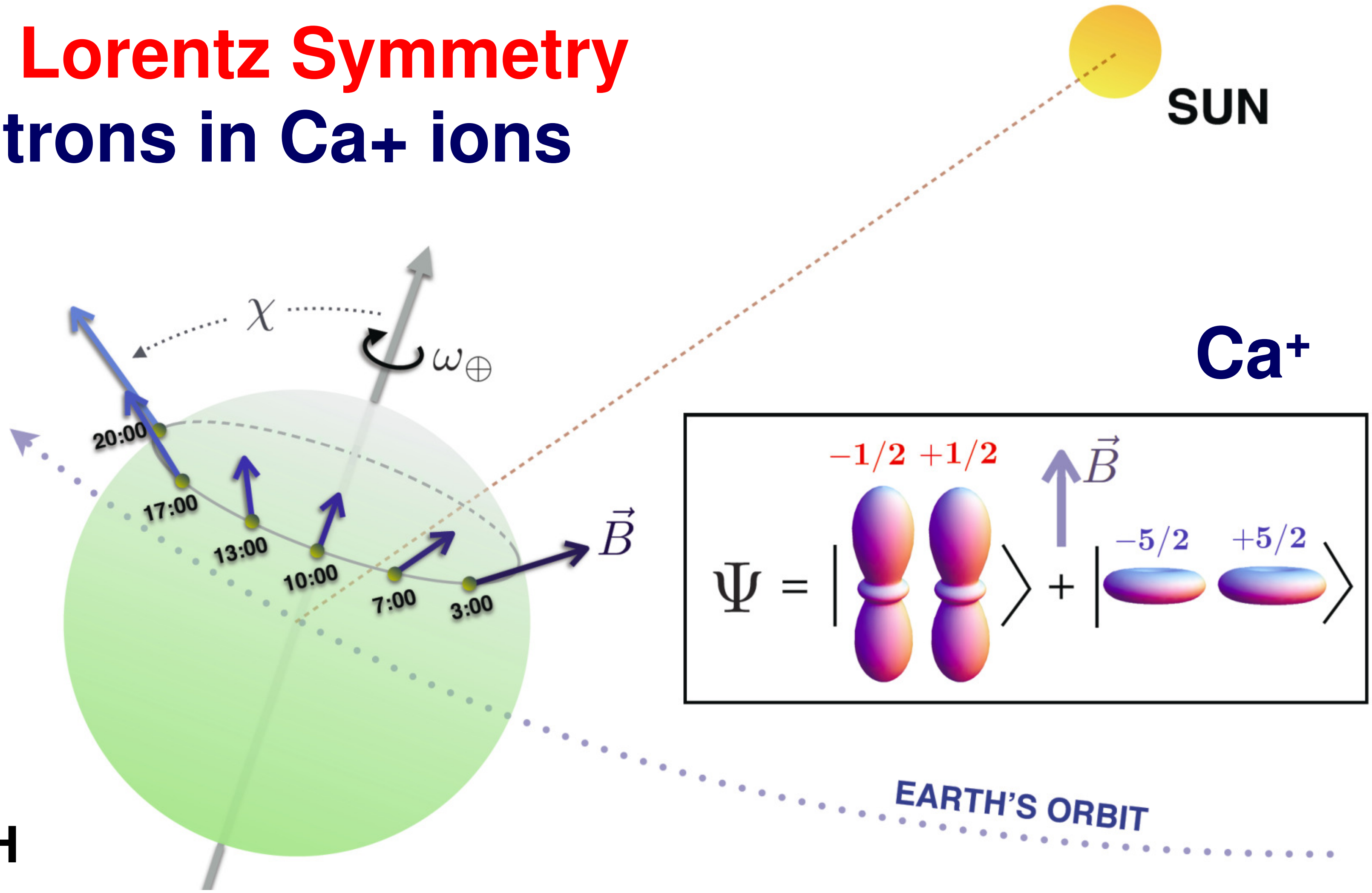


Energy levels fluctuate in varying magnetic field

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

$$|\Psi^R\rangle = \frac{1}{\sqrt{2}}\left(|\underbrace{-5/2}_{\text{Ion 1}}, \underbrace{+5/2}_{\text{Ion 2}}\rangle + |\underbrace{-1/2}_{\text{Ion 1}}, \underbrace{+1/2}_{\text{Ion 2}}\rangle \right)$$

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:

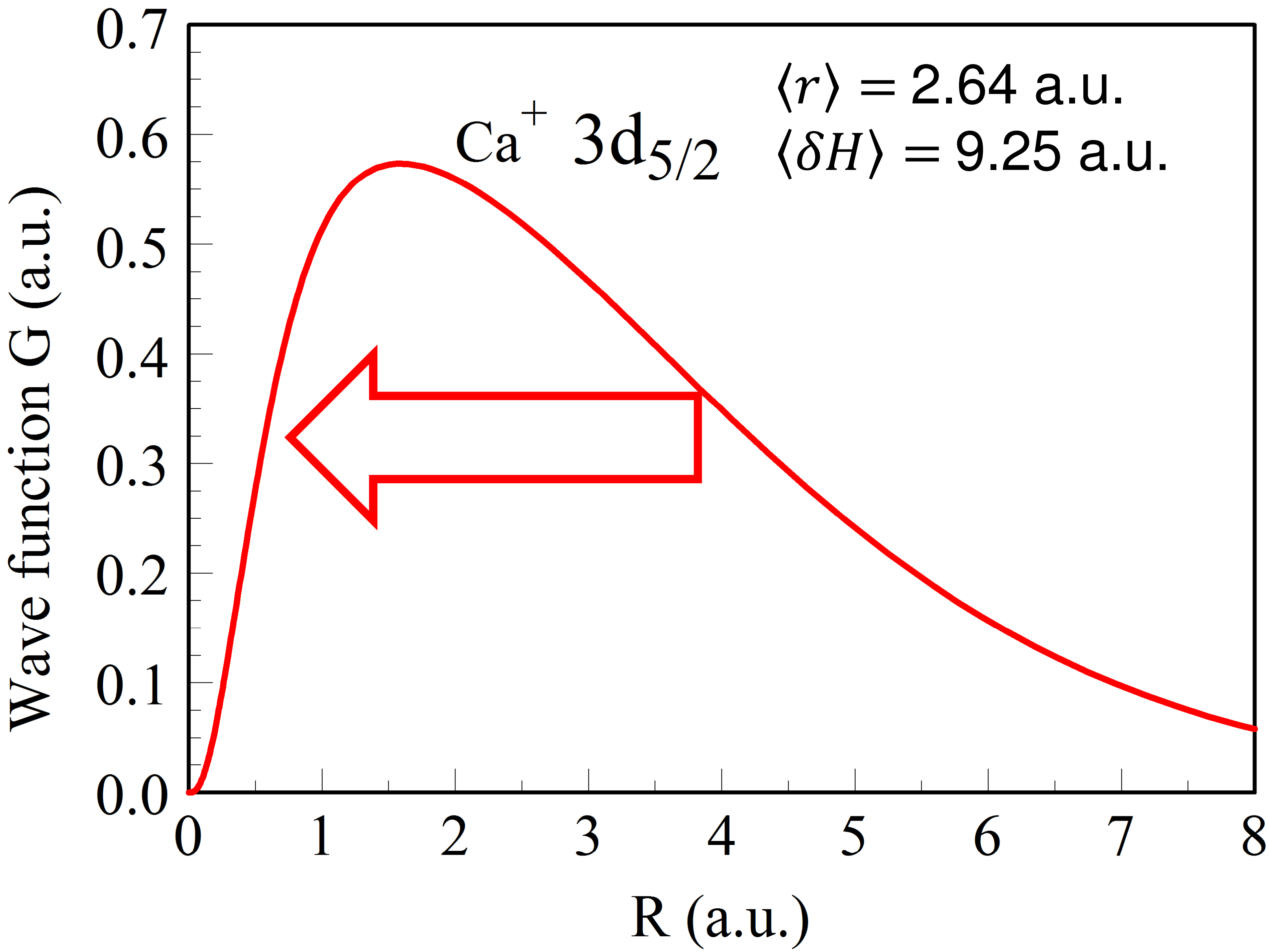
$$\delta\mathcal{H} = -C_0^{(2)} \frac{\left(\boldsymbol{p}^2 - 3p_z^2\right)}{6m_{\mathrm{e}}}$$

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

Find atoms with suitable ground state.

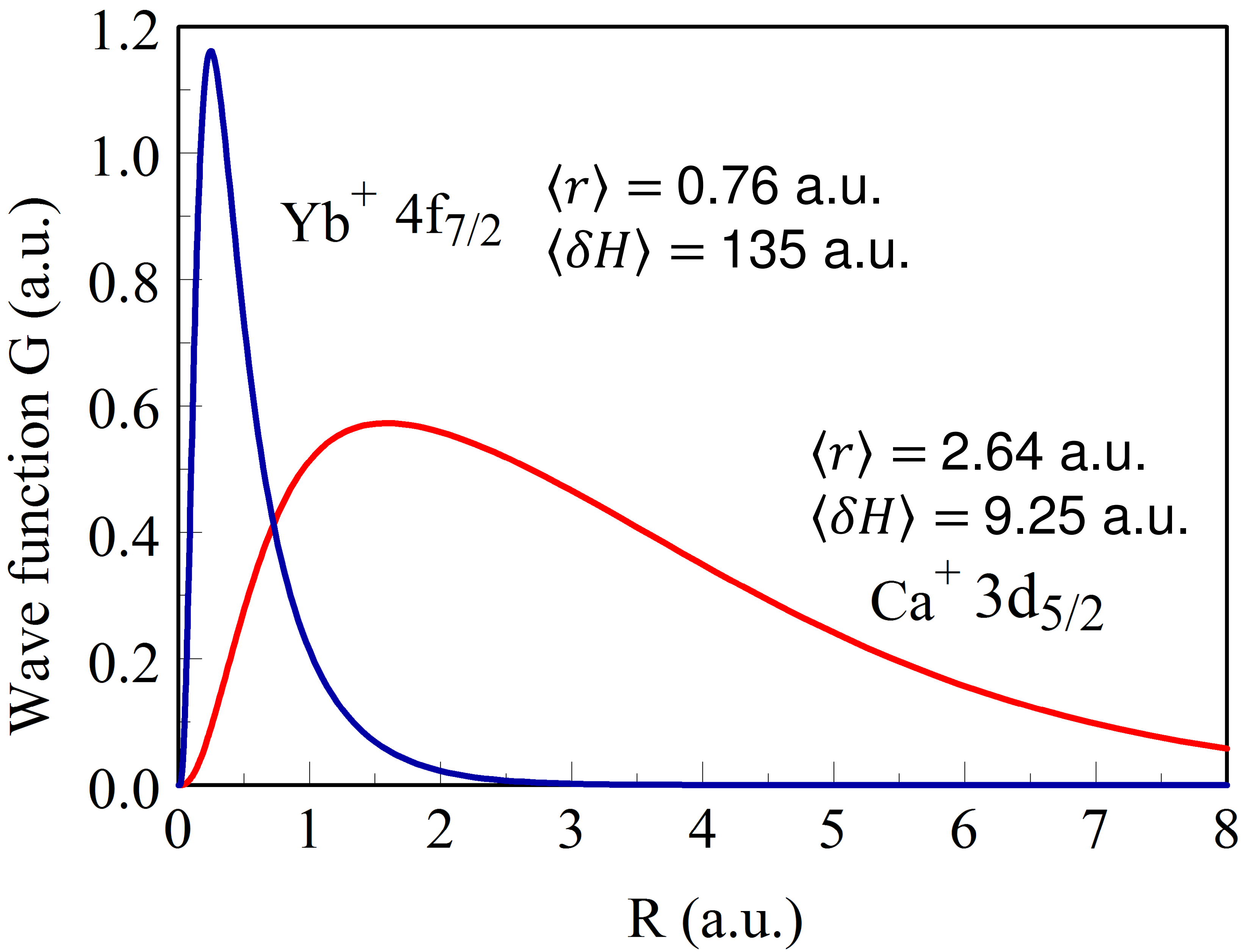
Need the largest matrix element of Lorentz violating Hamiltonian:

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

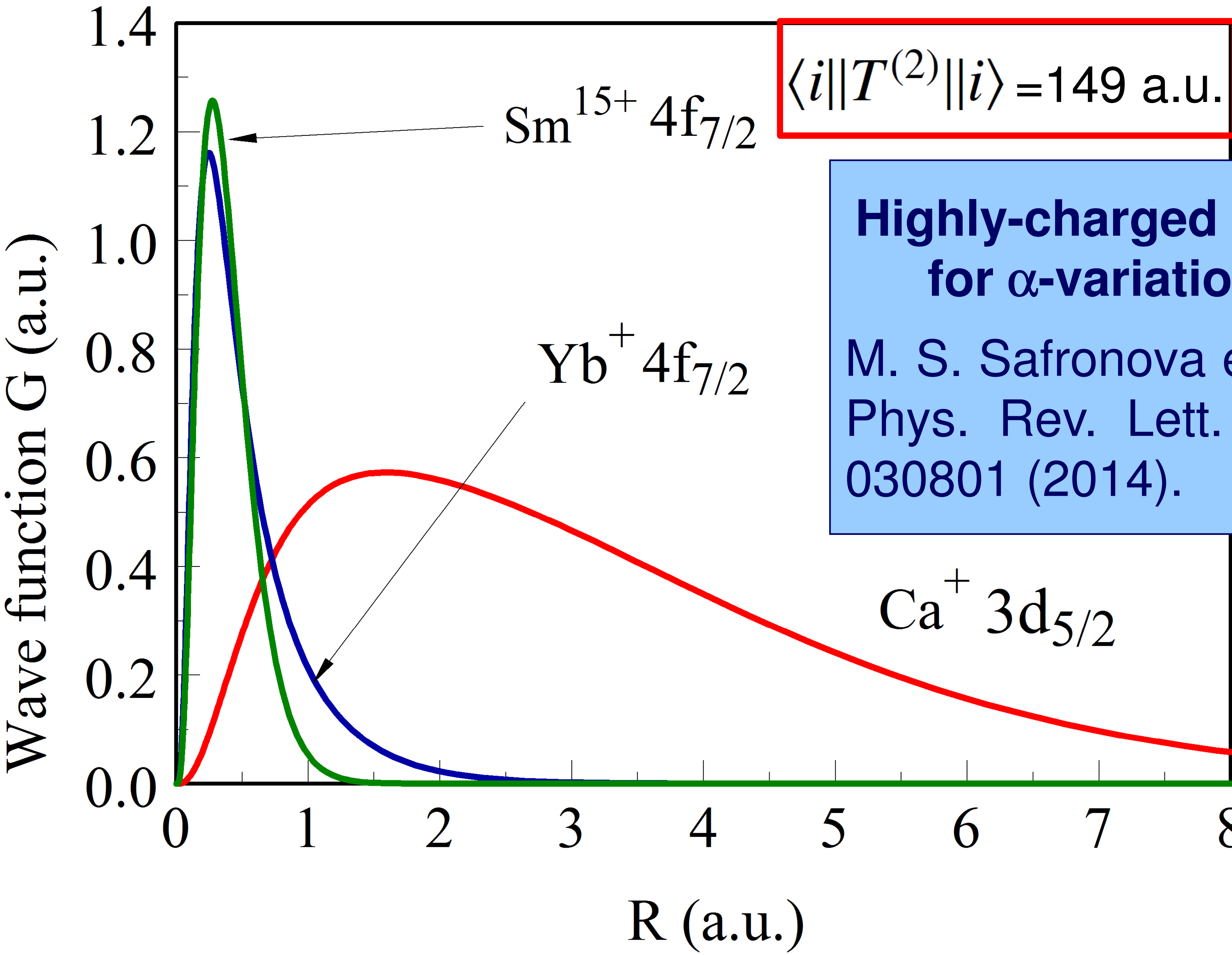


Need the largest matrix element of Lorentz violating Hamiltonian:

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



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



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	$\lvert\langle J \Vert T^{(2)} \Vert J\rangle\rvert$	$\lvert \Delta E/(hC_0^{(2)})\rvert$
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	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}

CLOCK!

Strongly enhanced effects of Lorentz symmetry violation in entangled Yb^+ and highly-charged ions

Possible factor of 27000 improvement in Lorentz symmetry test comparing to Ca^+!

Sensitivity (larger matrix element)	x 15 (Yb^+), >50 (HCI)
Longer probe time (to 60 seconds):	x 45
Year-long measurement:	x 20
Pure state preparation:	x 2

Yb^+: V. A. Dzuba, V. V. Flambaum, M. S. Safronova, S. G. Porsev, T. Pruttivarasin, M. A. Hohensee, H. Häffner, Nature Physics 12, 465 (2016).

Better scheme: R. Shaniv, R. Ozeri, M. S. Safronova, S. G. Porsev, V. A. Dzuba, V. V. Flambaum and H. Häffner, Phys. Rev. Lett. 120, 103202 (2018).

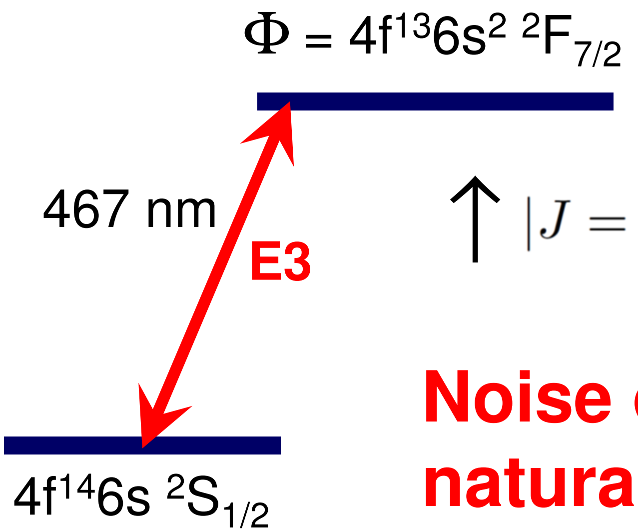
Optical clock comparison for Lorentz symmetry testing
Hundredfold improved LV bounds

Christian Sanner, Nils Huntemann, Richard Lange,
Christian Tamm, Ekkehard Peik,
Marianna S. Safronova, and Sergey G. Porsev

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

Nature 567, 204 (2019)

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



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

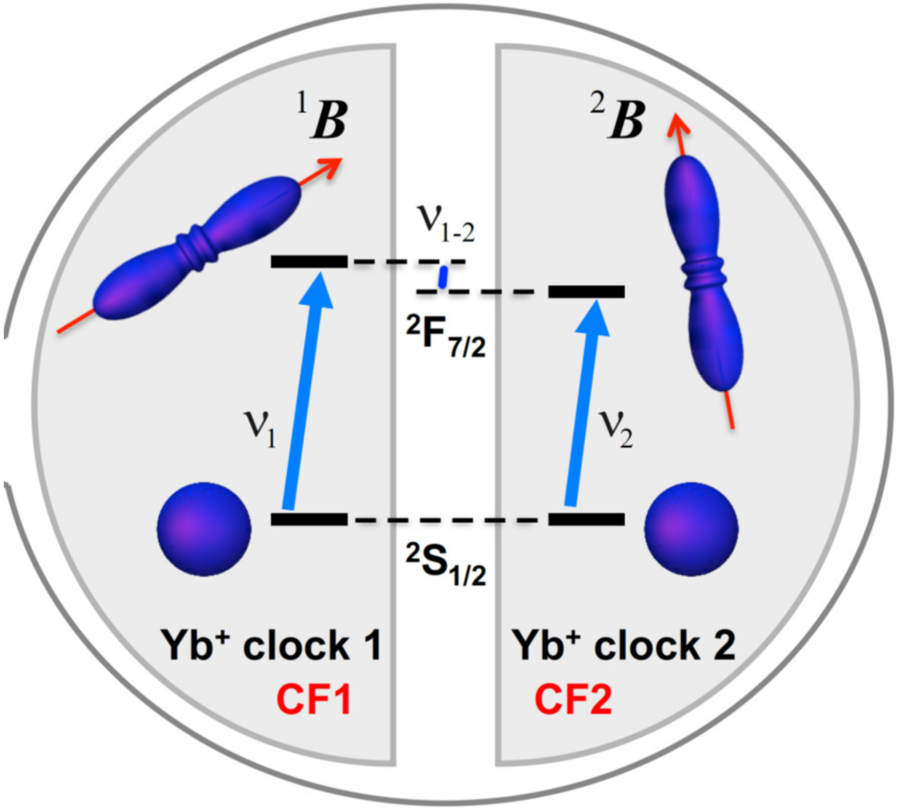
Extremely small quadrupole moment

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

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

Calculate expectation value of δH to determine how much clock state shifts

$$\delta H = -\frac{1}{6} C_0^{(2)} T_0^{(2)} \longleftarrow \boxed{T_0^{(2)} \equiv p^2 - 3{p_3}^2} \qquad \langle \Phi | T_0^{(2)} | \Phi \rangle \approx 23.3 \text{ a.u.}$$



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

$$C_0^{(2)} = C_0^{(2)}[\mathrm{Yb1}] - \dot{C}_0^{(2)}[\mathrm{Yb2}]$$

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

MEASURE

CALCULATE

EXTRACT LORENTZ VIOLATING COEFFICIENT

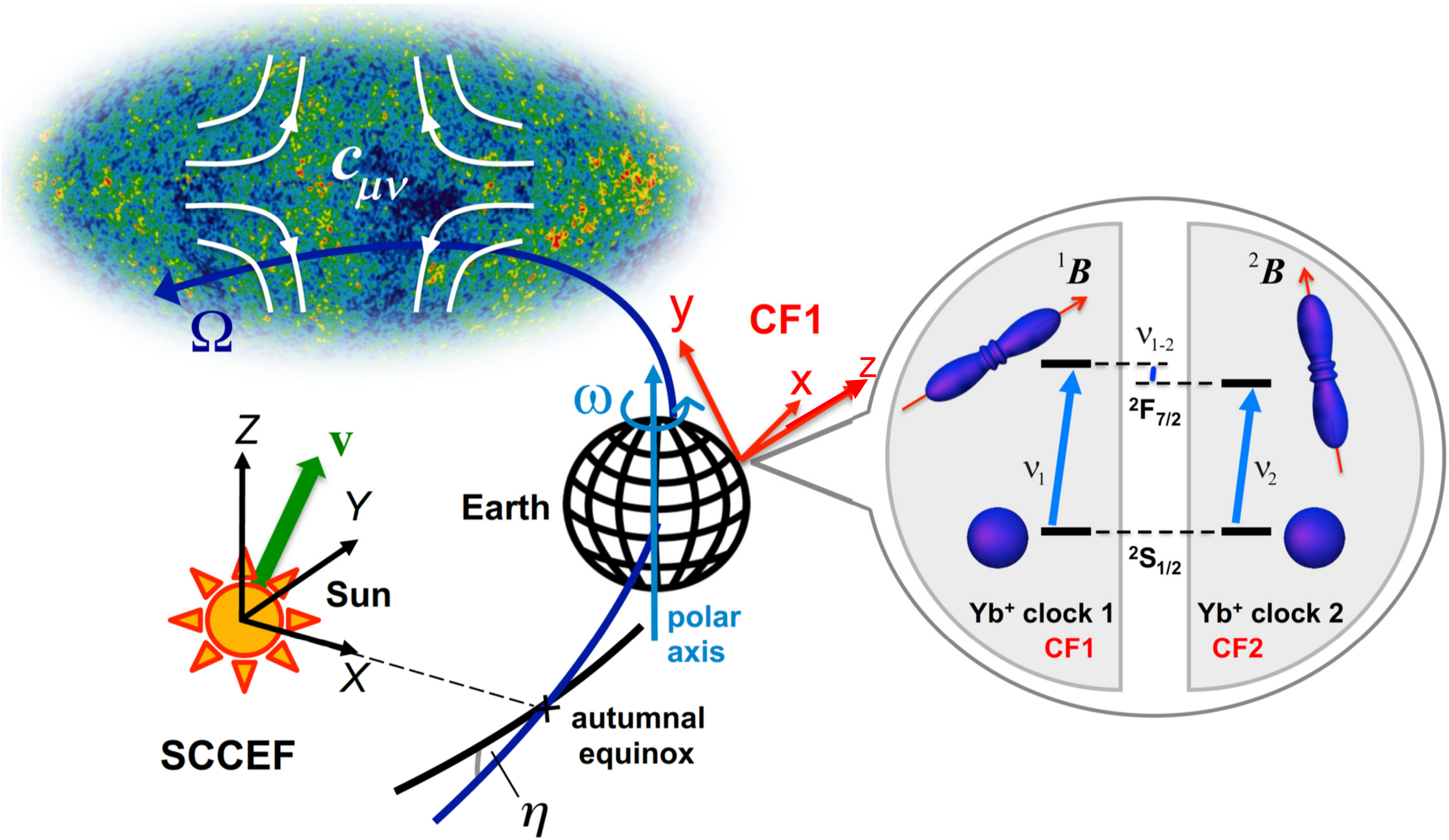


Image credit: Christian Sanner, JILA

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, Nature 567, 204 (2019).

(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).

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.

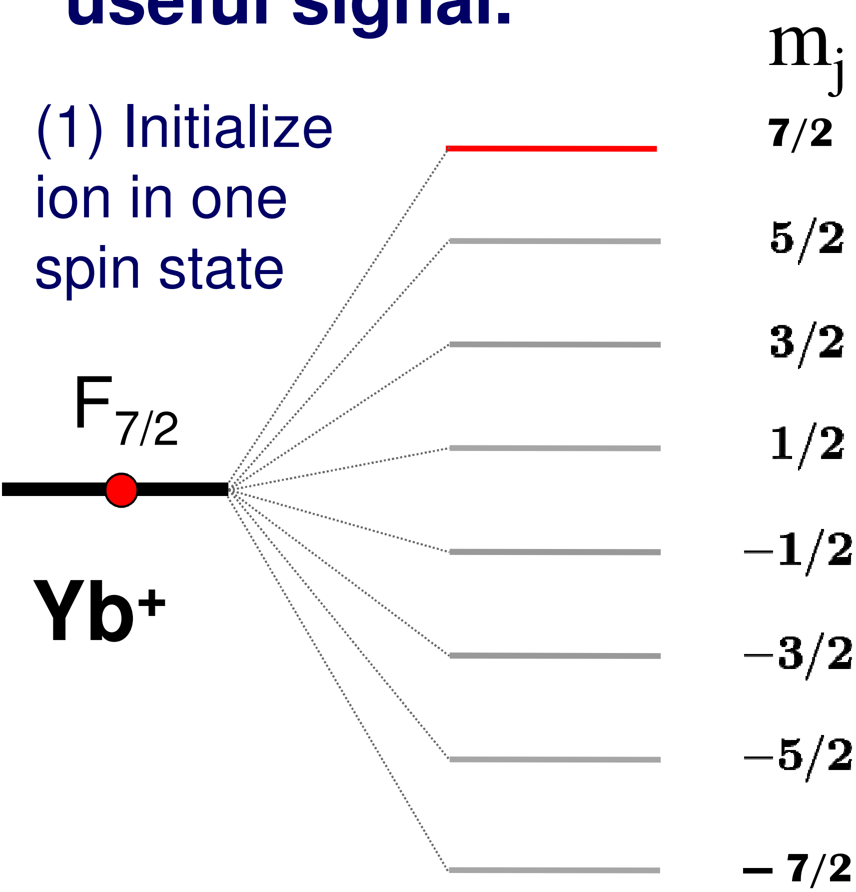
Moreover, the scheme can be performed on systems with no optical transitions, and therefore it is also applicable to highly charged ions which exhibit particularly high sensitivity to Lorentz invariance violation.

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:

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

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

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.

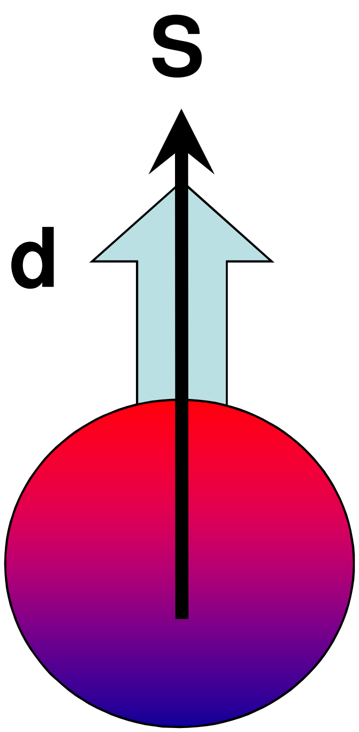
(3) Repeat n times, measure population in the initial state to extract the LV signal

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

THE SEARCH FOR THE ELECTRON ELECTRIC DIPOLE MOMENT

Permanent electric-dipole moment (EDM)

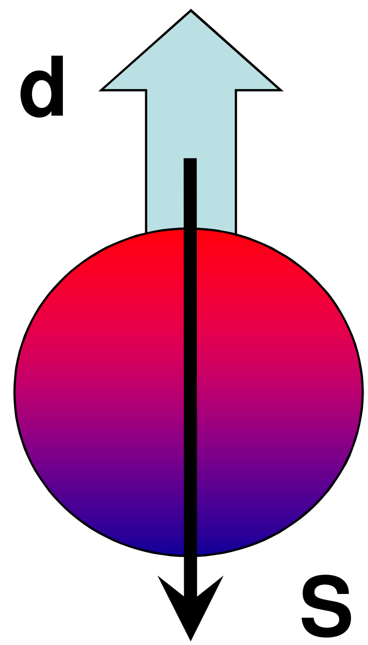
Time-reversal invariance must be violated for an elementary particle or atom to possess a **permanent EDM.**



$$t \rightarrow -t$$

$$\vec{\mathbf{S}} \rightarrow -\vec{\mathbf{S}}$$

$$\vec{\mathbf{d}} \rightarrow \vec{\mathbf{d}}$$



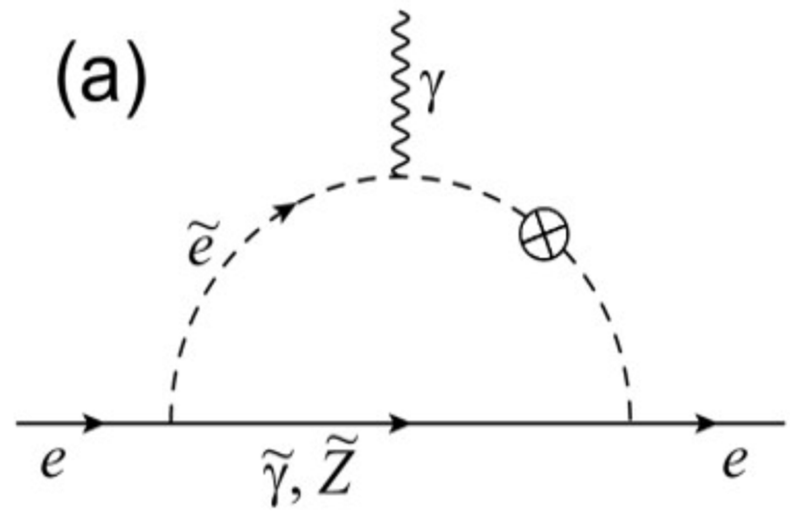
$$\boxed{\begin{array}{l} \vec{\mathbf{d}} = d\,\dfrac{\vec{\mathbf{S}}}{S} \\ d = 0 \end{array}}$$

Classical physics: t → -t, Δt → -Δt, v → -v, L= r × mv, L → -L

Matter – Antimatter asymmetry: Need new sources of CP- (T-) violation

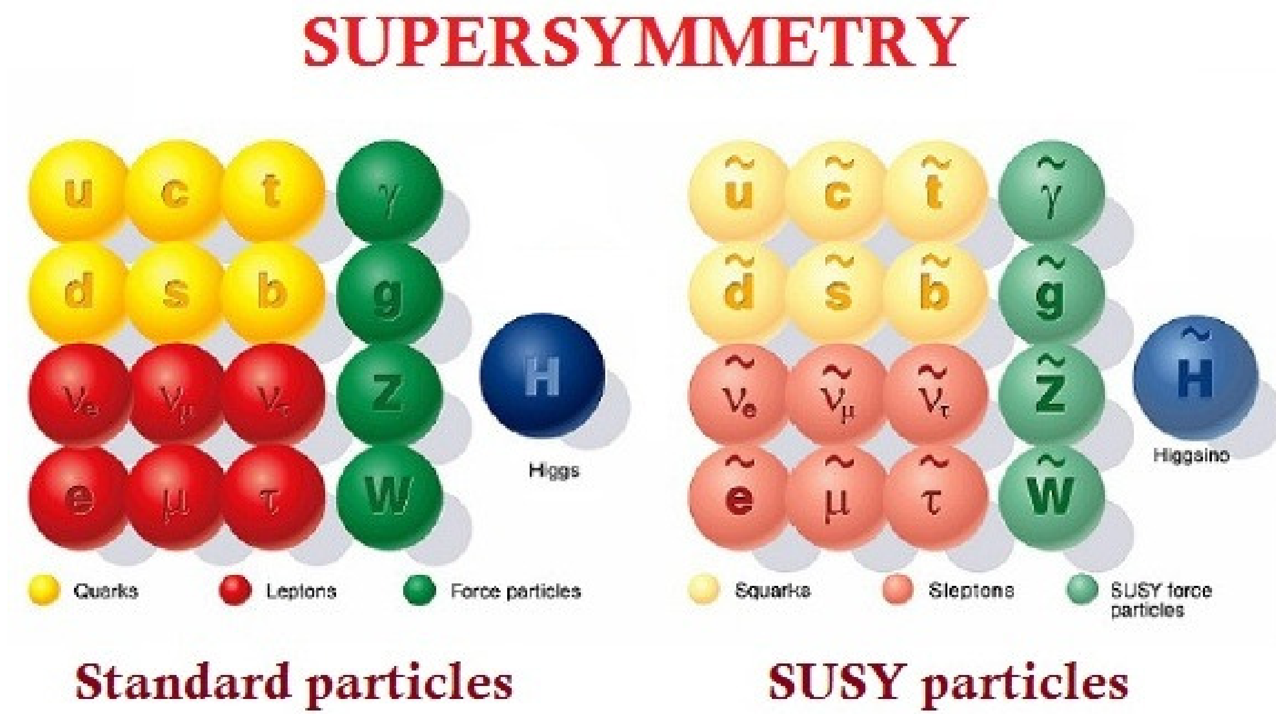
Additional sources of CP-violation lead to much larger EDMs than SM predicts.

Such EDMs should be observable with current experiments.



J. Engel et al., Progress in Particle and Nuclear Physics 71 (2013) 21

Matter – Antimatter asymmetry:
Need new sources of CP- (T-) violation



BONUS: The lightest supersymmetric particle is stable and make a perfect candidate for dark matter (WIMP)

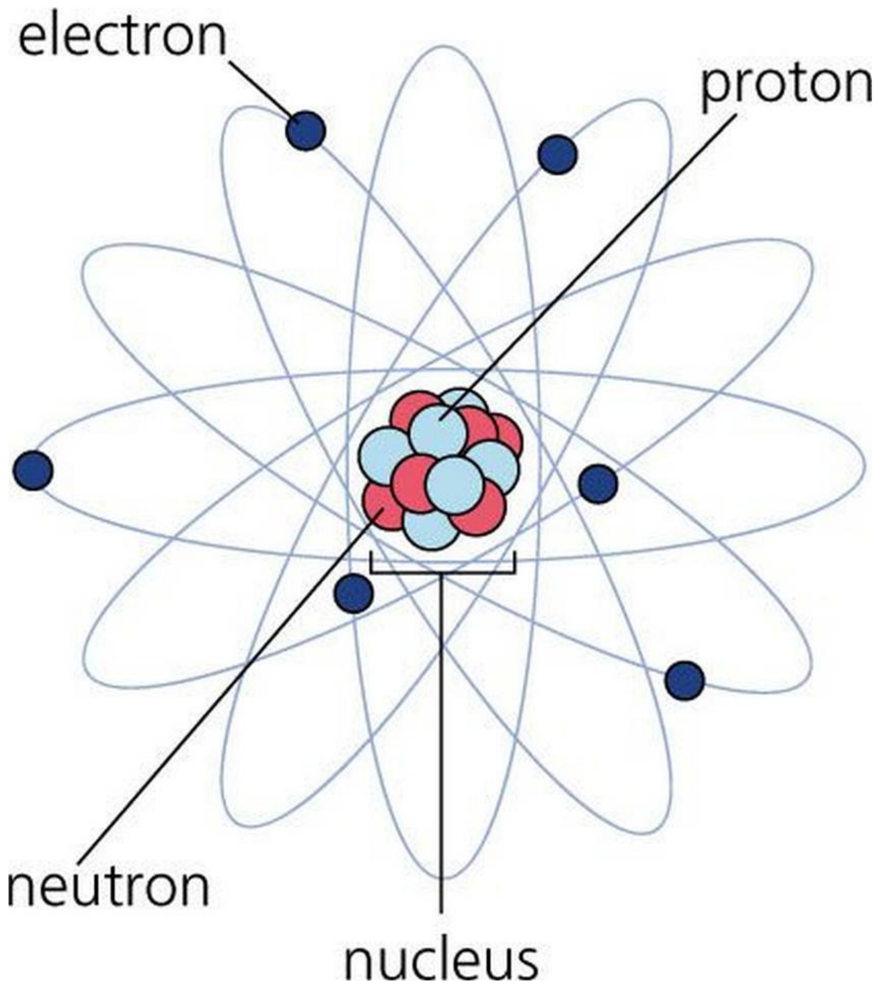
Look for electron EDM as a signature of supersymmetry!

www.simonsfoundation.org

Sources of atomic and molecular EDMs

P, T – violating
electron-nucleon interaction

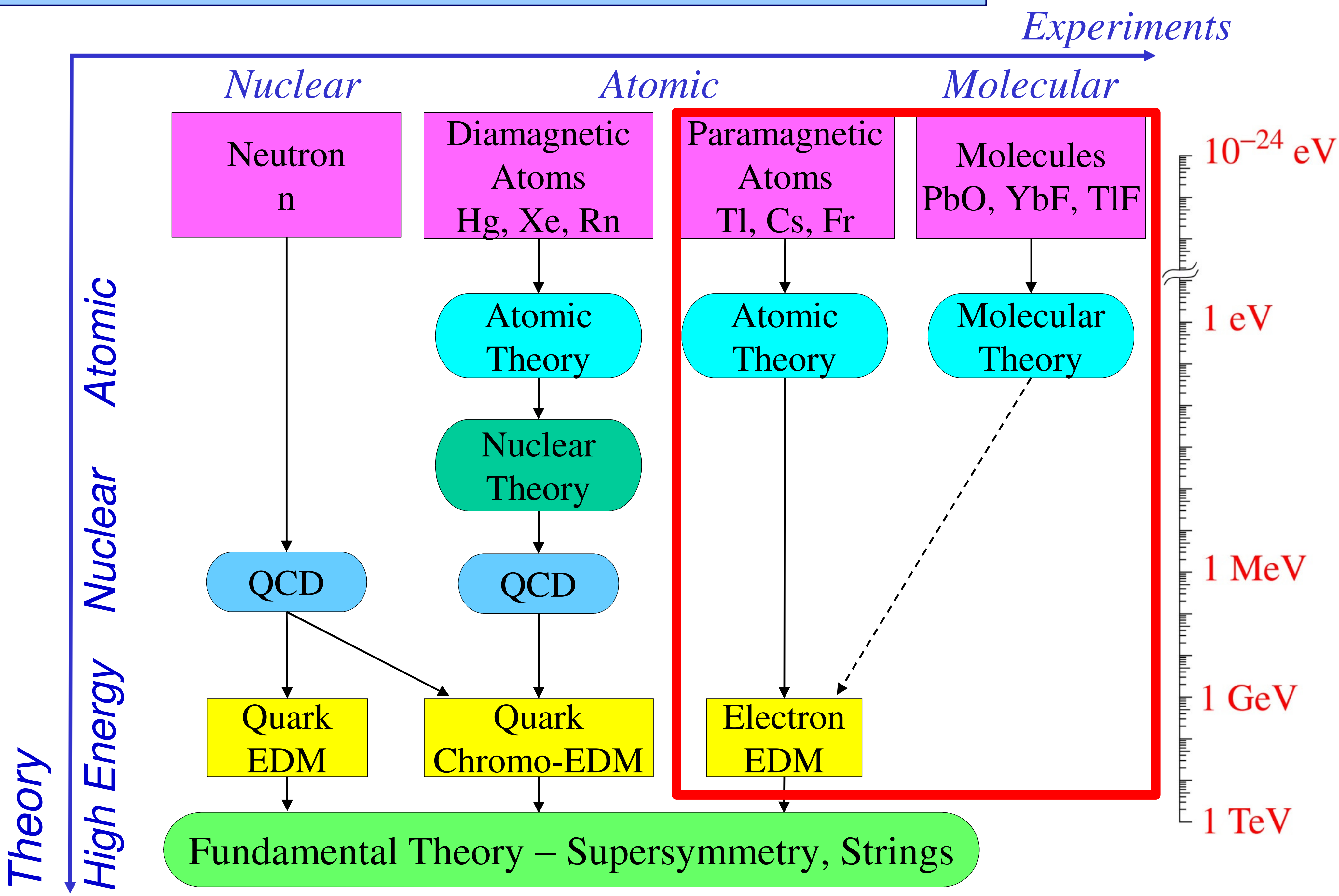
Electron EDM



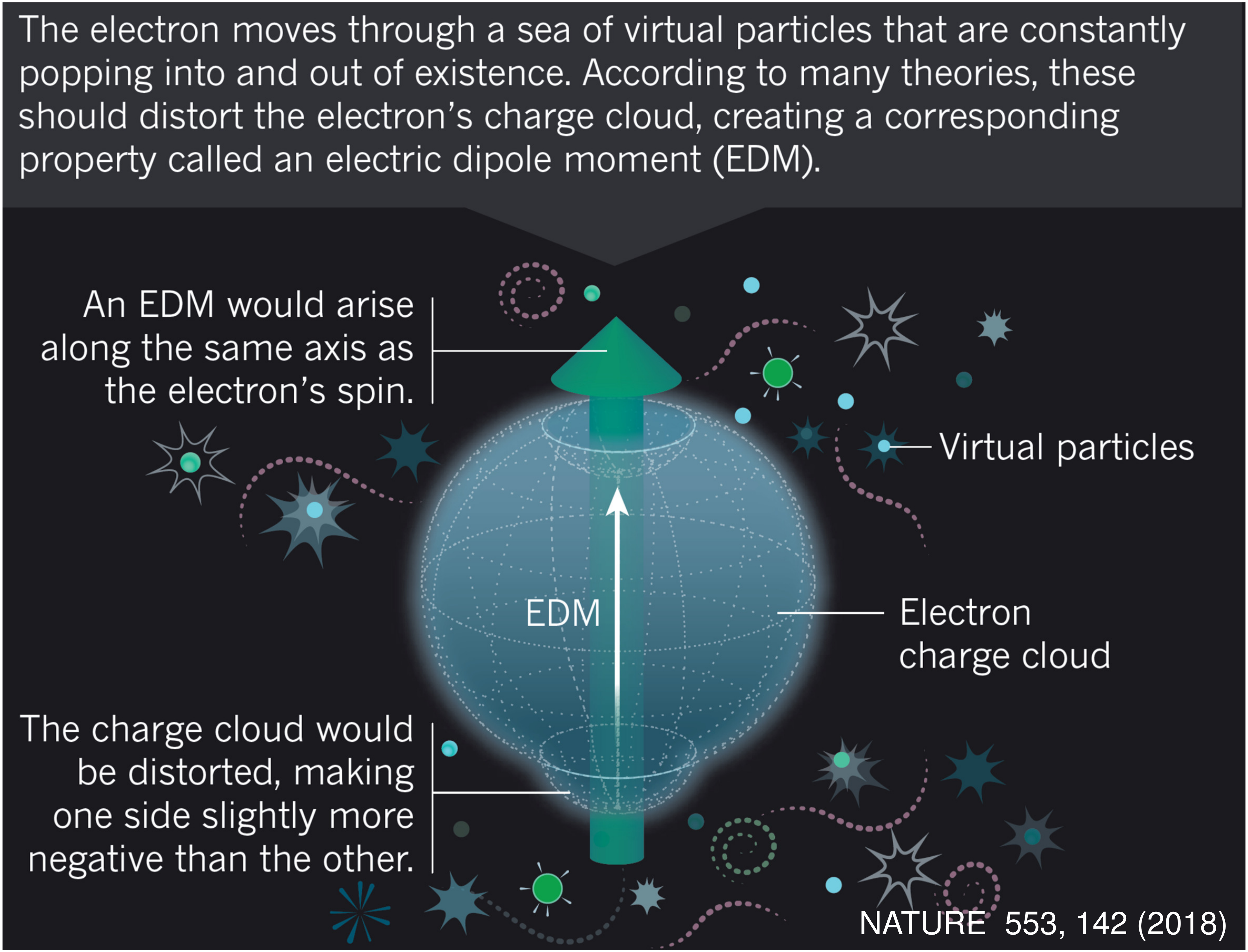
P, T – violating
nucleon- nucleon
interaction

Nucleon
EDM

Interpretation of EDM experiments



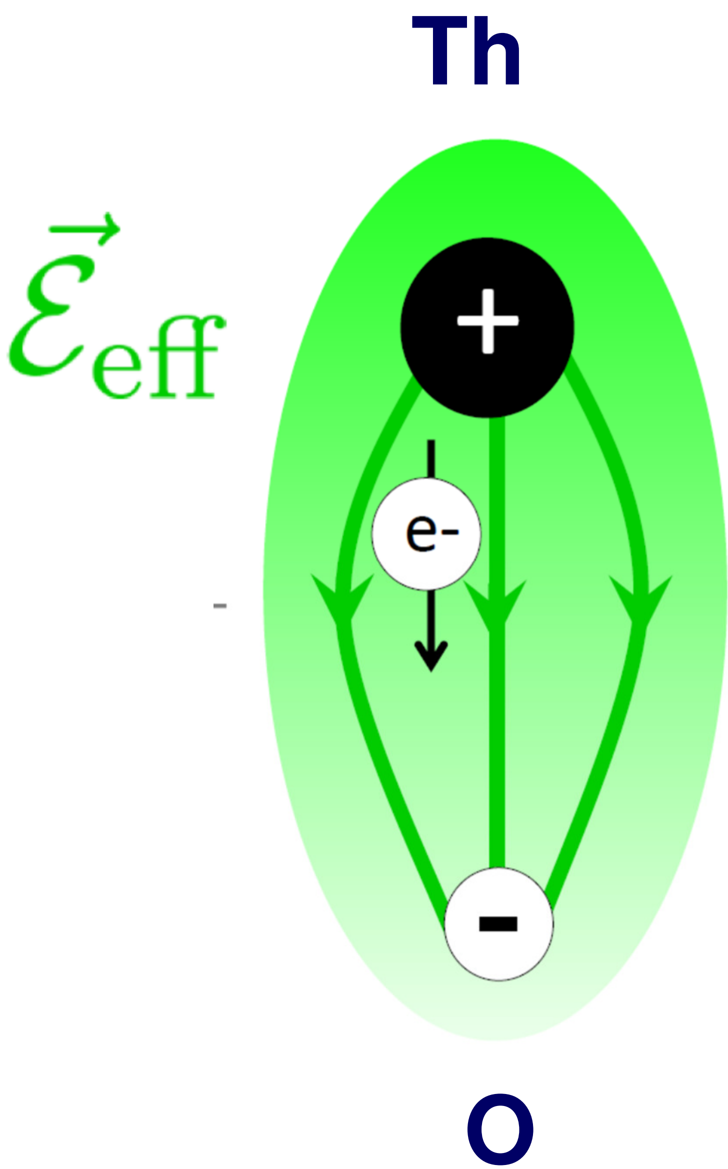
Mike Romalis, 2011 JLab talk (online)


The electron moves through a sea of virtual particles that are constantly popping into and out of existence. According to many theories, these should distort the electron's charge cloud, creating a corresponding property called an electric dipole moment (EDM).
An EDM would arise along the same axis as the electron's spin.
Virtual particles
EDM
Electron charge cloud
The charge cloud would be distorted, making one side slightly more negative than the other.
NATURE 553, 142 (2018)

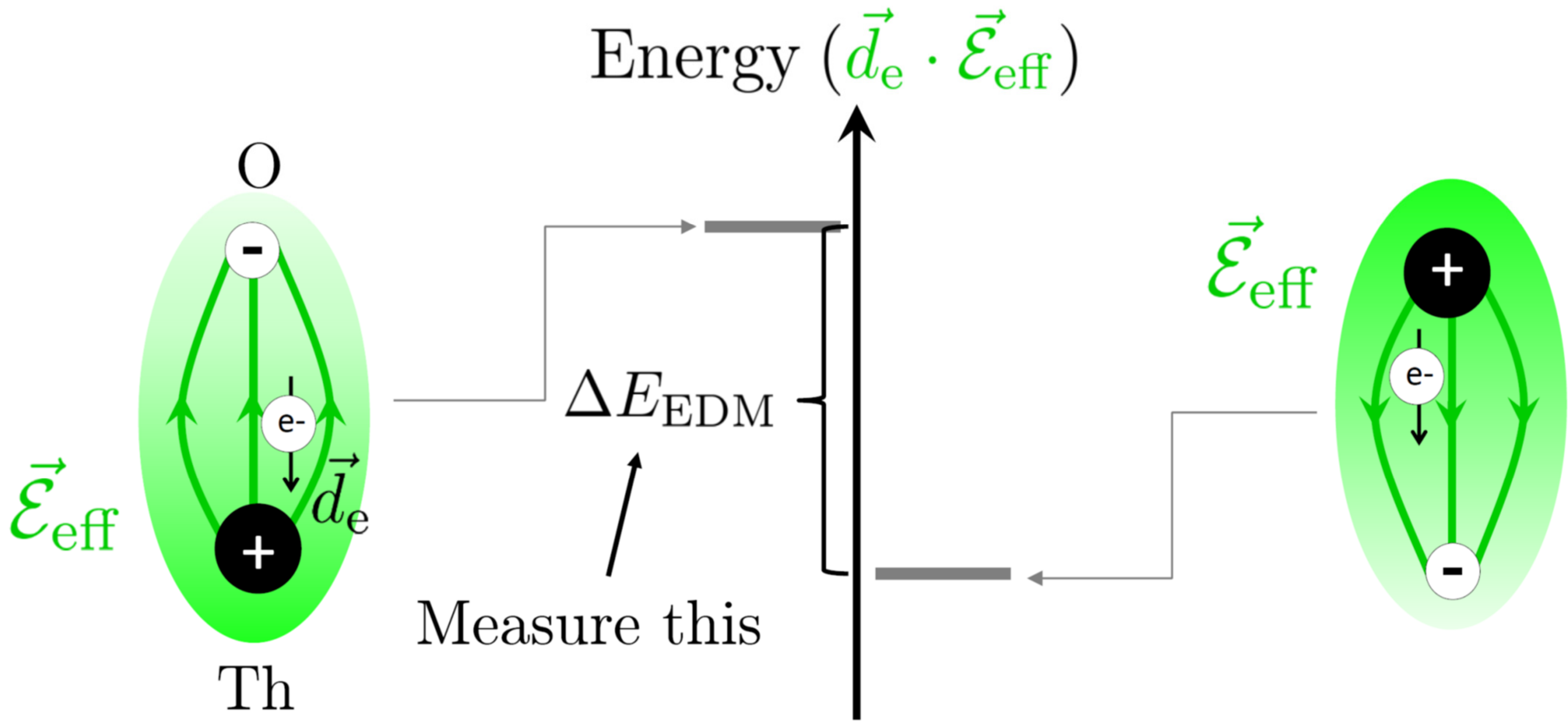
Fundamental idea of electron EDM measurements

Put electron in strong electric field

Energy $(\vec{d}_e \cdot \vec{\mathcal{E}}_{\text{eff}})$



Fundamental idea of electron EDM measurements

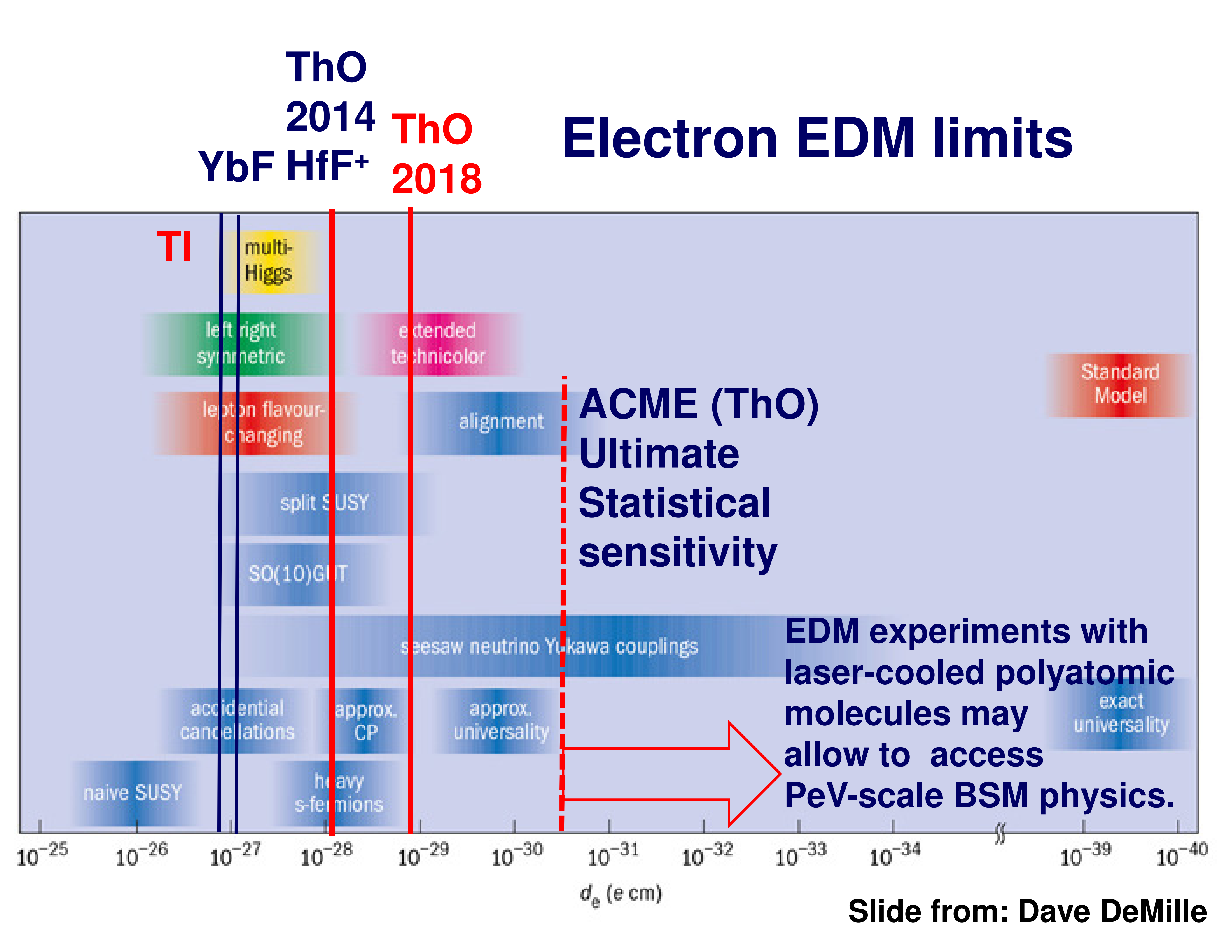


An electric dipole moment results in an energy shift in the presence of an electric field, such as the large E-fields present near heavy atomic nuclei.

Apply electric field, reverse, measure the energy splitting between electrons oppositely oriented relative to the effective molecular field in ThO (84 GV/cm):

$$\Delta E_{EDM}/2 = |\vec{d}_e \cdot \vec{\mathcal{E}}_{eff}|$$

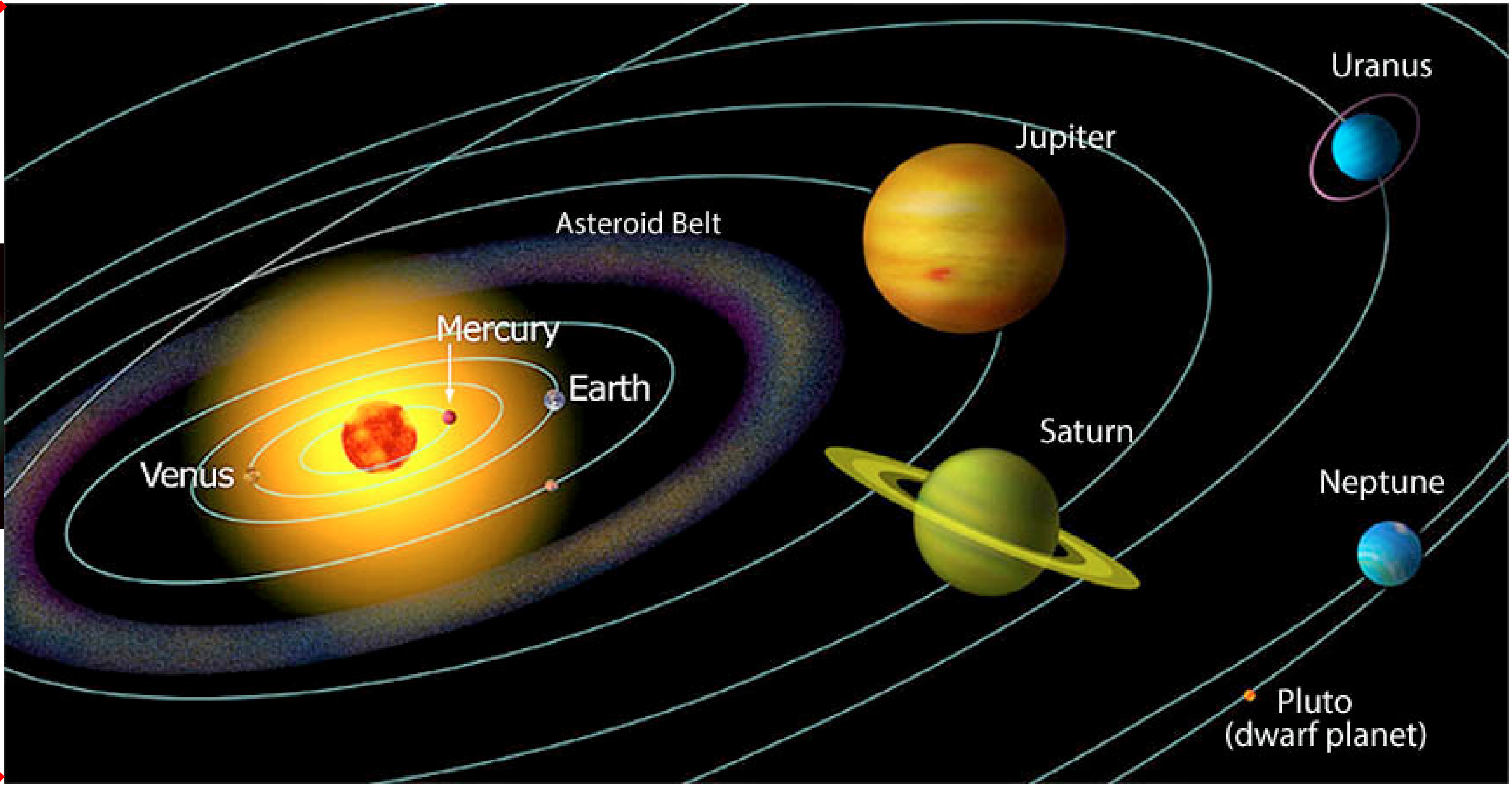
http://www.electronedm.org/



ThO 2014
YbF HfF+
ThO 2018
Electron EDM limits
Tl
multi-Higgs
left right symmetric
extended technicolor
Standard Model
lepton flavour-changing
alignment
ACME (ThO) Ultimate Statistical sensitivity
split SUSY
SO(10)GUT
seesaw neutrino Yukawa couplings
EDM experiments with laser-cooled polyatomic molecules may allow to access PeV-scale BSM physics.
accidental cancellations
approx. CP
approx. universality
exact universality
naive SUSY
heavy s-fermions
10^{-25} 10^{-26} 10^{-27} 10^{-28} 10^{-29} 10^{-30} 10^{-31} 10^{-32} 10^{-33} 10^{-34} 10^{-39} 10^{-40}
d_e (e cm)
Slide from: Dave DeMille

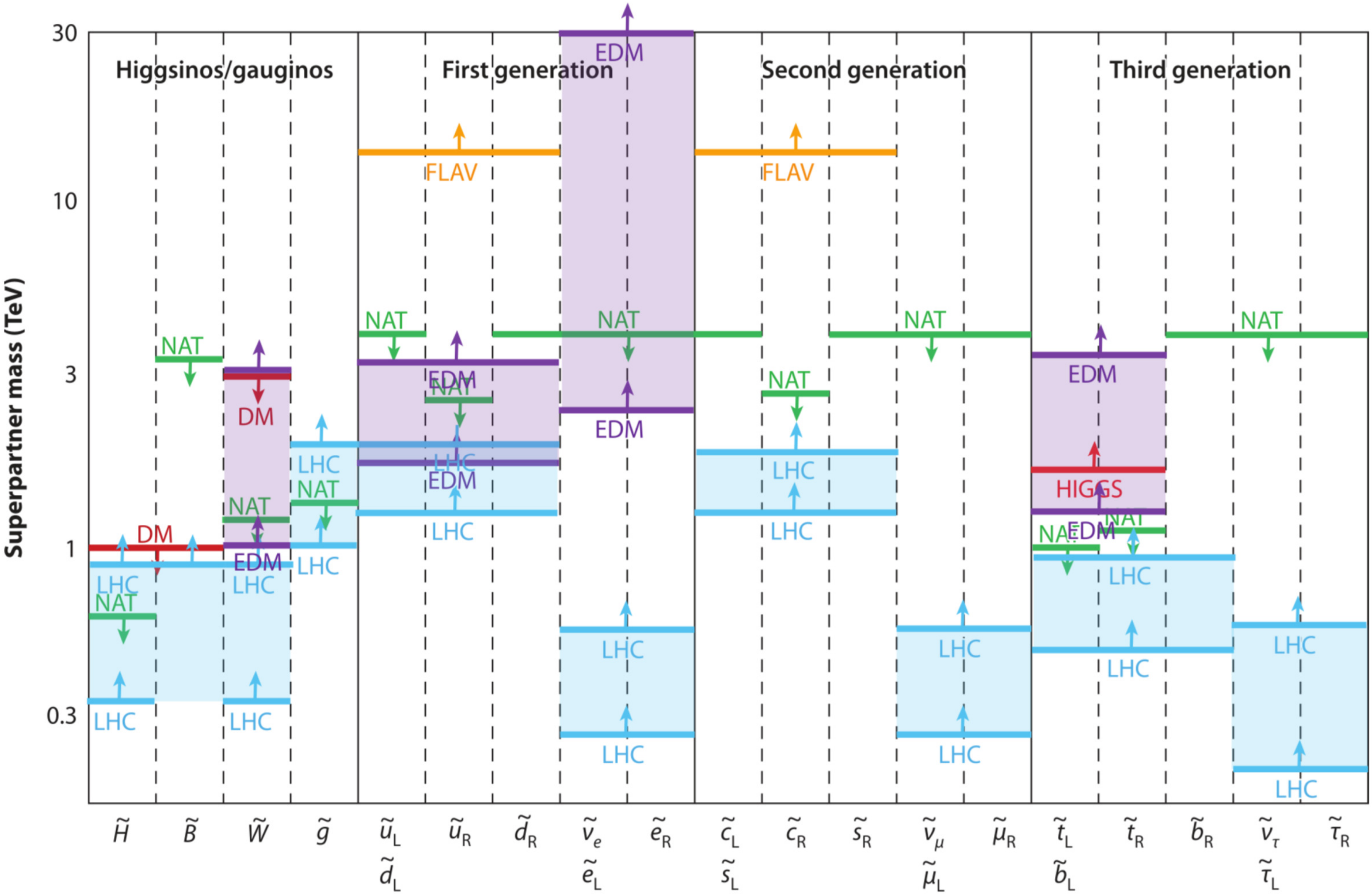
Electron EDM

Blow up the electron to the size of the Solar System



then it is spherical to within the *width of a human hair.*

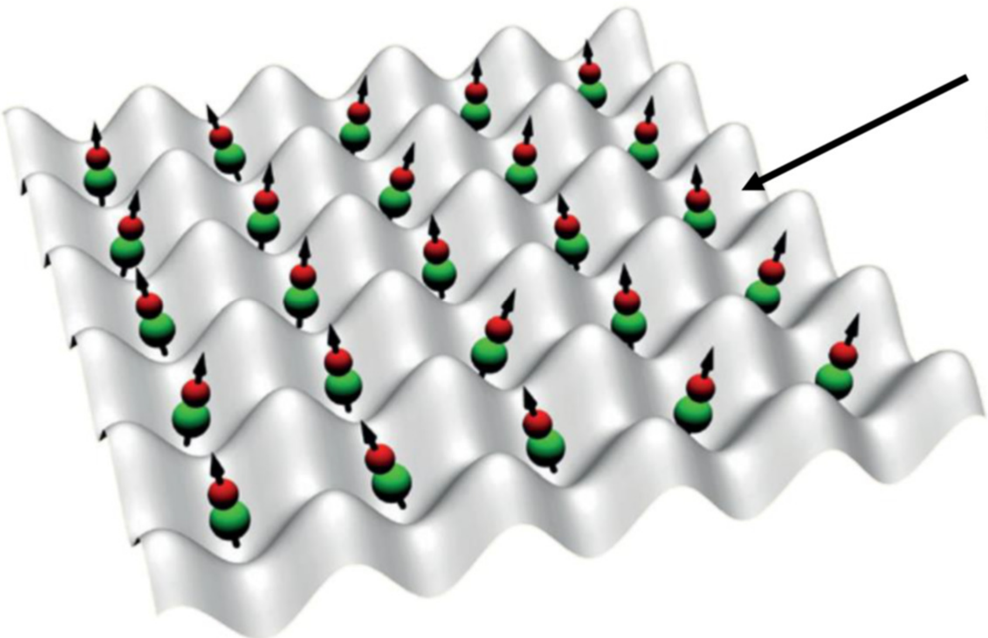
Ed Hinds, http://www.scientificamerican.com



Slide from: Nick Hutzler

Adapted from J. Feng, Ann. Rev. Nuc. Part. Sci. 63, 351 (2019) with Dave DeMille

Electron EDM experiments with laser-cooled molecules



Heavy, polar molecule sensitive to new physics

Need to trap at ultracold temperatures

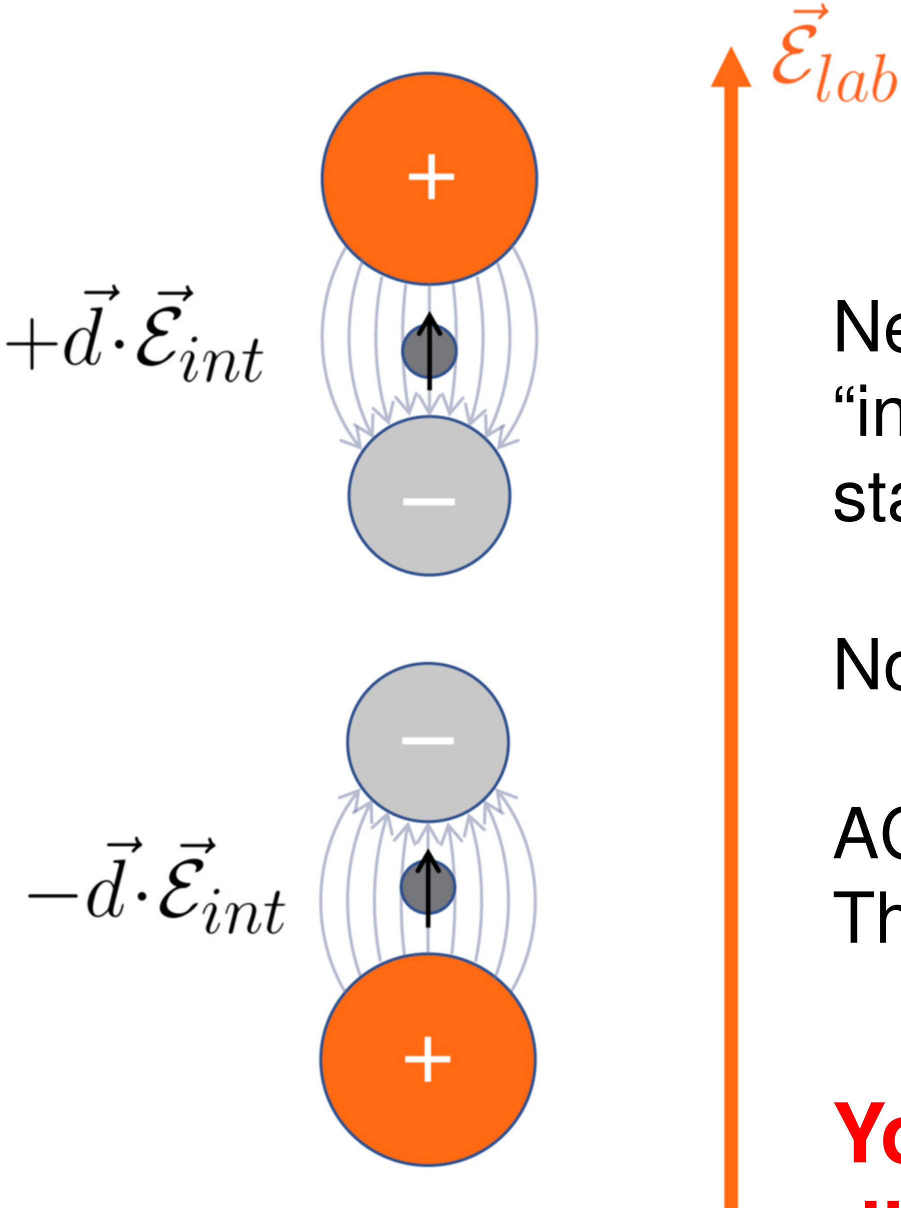
- 10^6 molecules
- 10 s coherence
- Large enhancement(s)
- Robust error rejection
- 1 week averaging

$M_{\text{new phys}} \sim$ 1,000 TeV

Even before implementing advanced quantum control, such as entanglement-based squeezing

Slide from: Nick Hutzler

Electron EDM experiments with laser-cooled molecules



Need
“internal co-magnetometer”
states

No need to reverse electric field

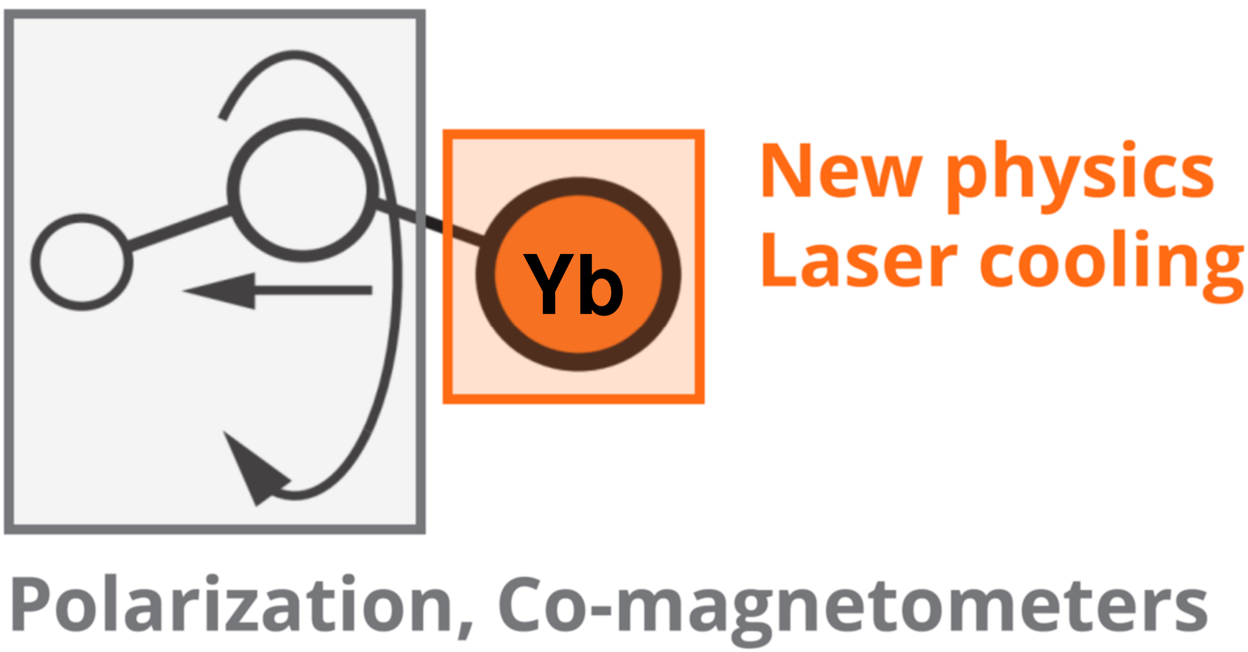
ACME and JILA eEDM
ThO HfF+

You can not laser cool any diatomic molecule with co-magnetometer states!

Picture from: Nick Hutzler

Electron EDM experiments with polyatomic laser-cooled molecules

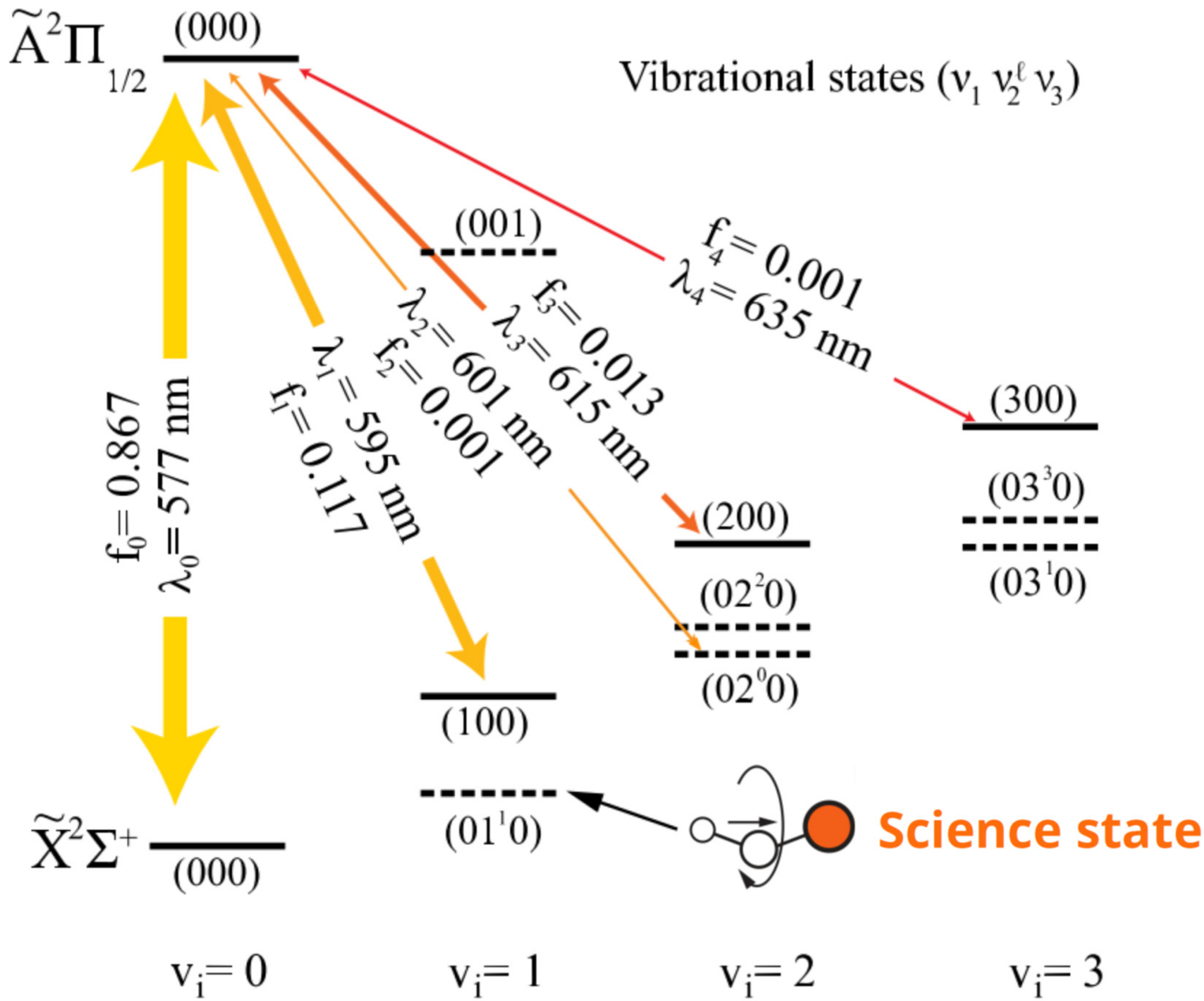
YbOH



Ivan Kozyryev and N. R. Hutzler, Phys. Rev. Lett. **119**, 133002 (2017)

Picture from: Nick Hutzler

Need molecular theory support!



Picture from: Nick Hutzler

Conclusion

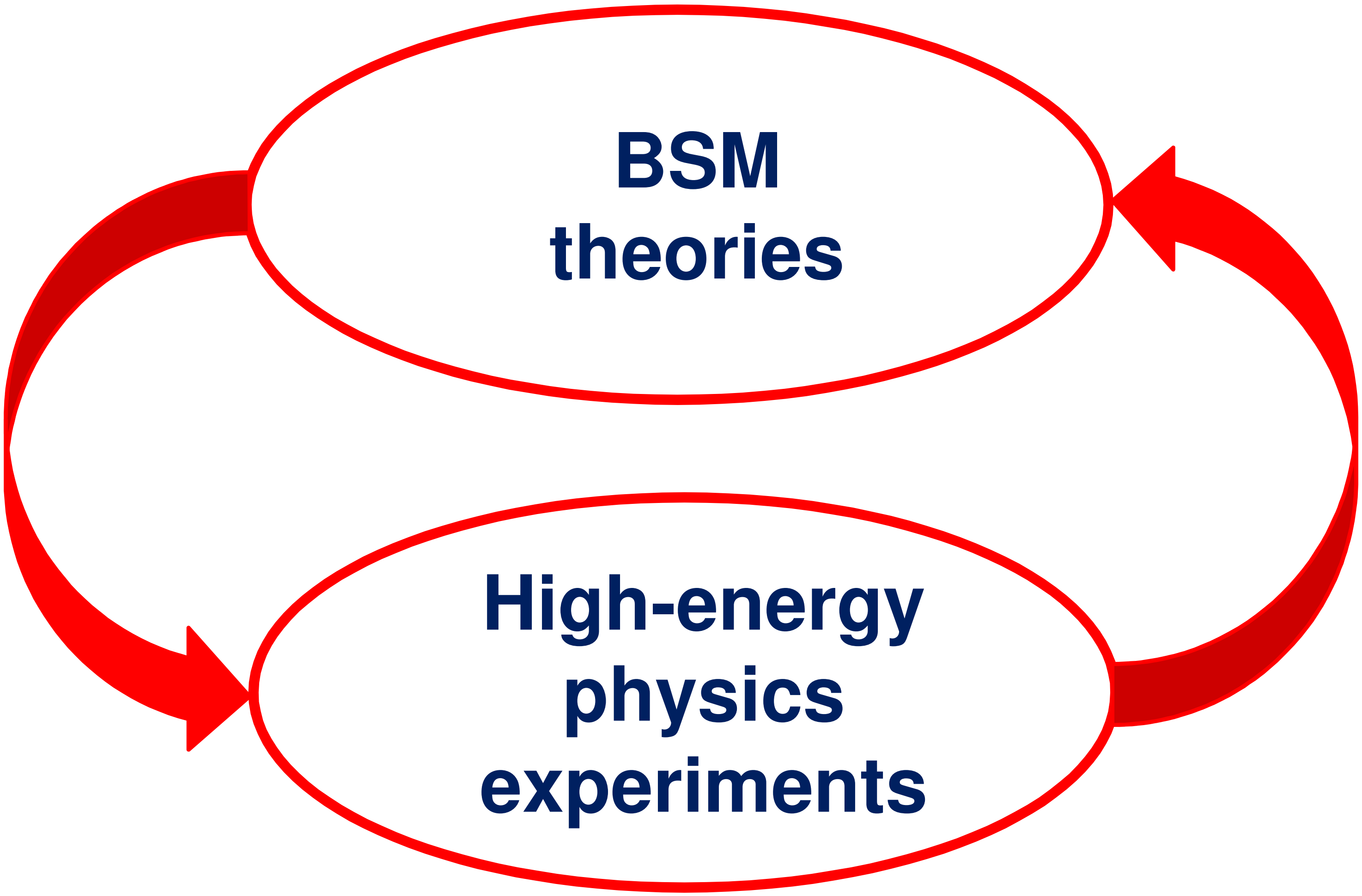
Quantum Sensors for Fundamental Physics:

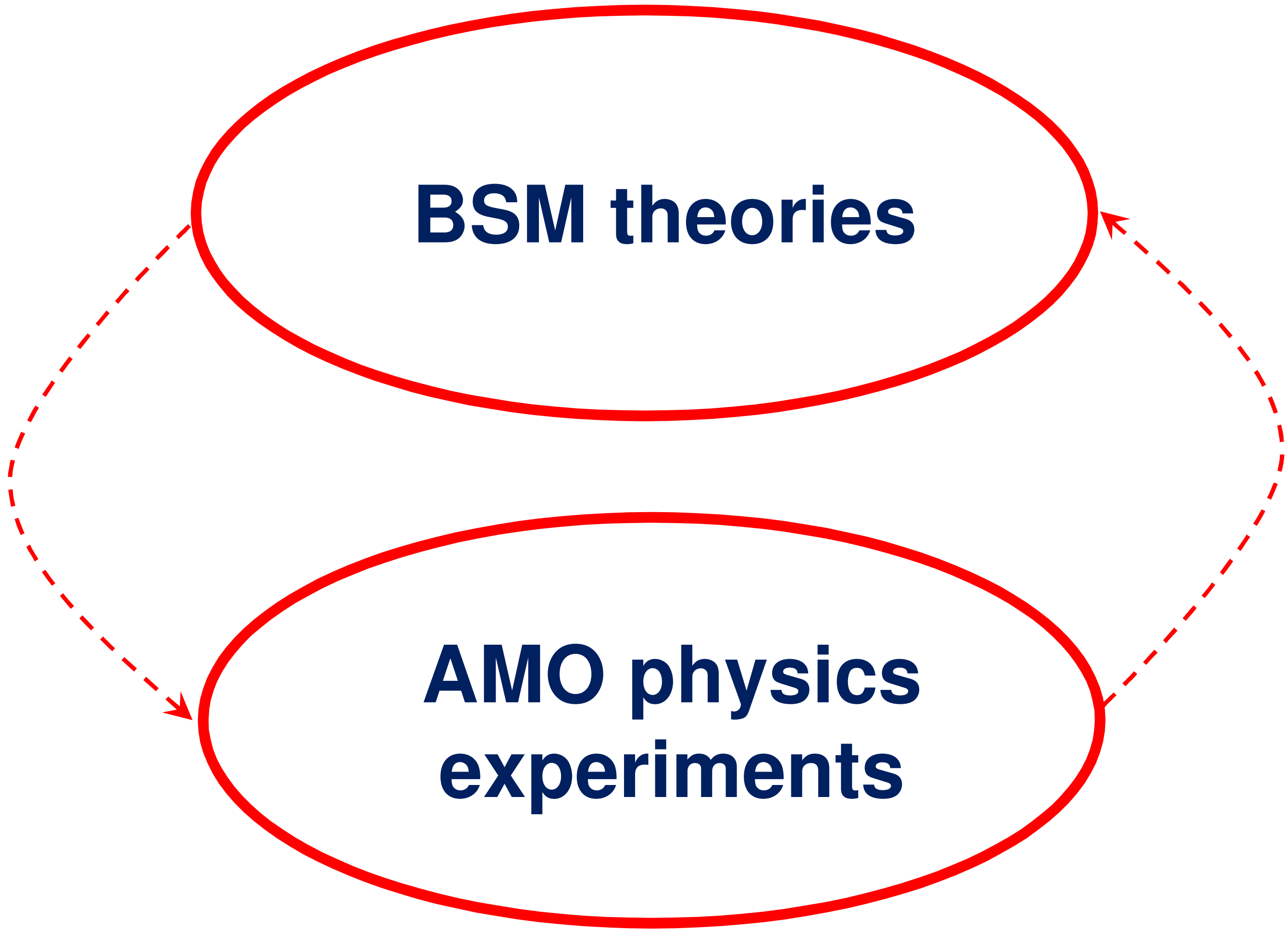
What do we need to increase discovery potential?

Better quantum sensors

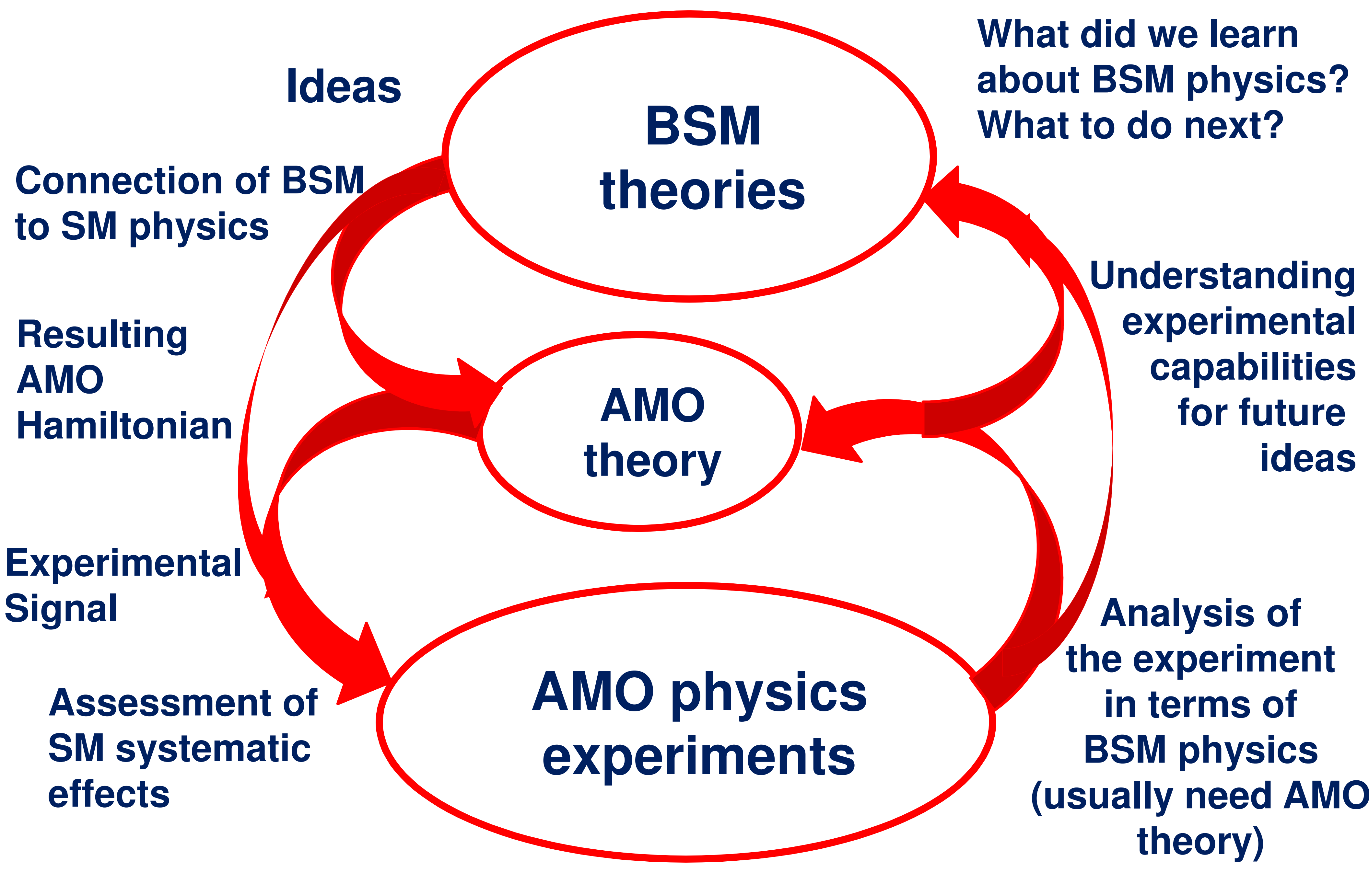
More new quantum sensors

Stronger connections between particle physics and AMO


BSM
theories
High-energy
physics
experiments


BSM theories
AMO physics experiments

Need to build much stronger connections!



Need new ideas!

More DM candidates?

What are the best motivated scalar candidates?

Detection goals … naturalness line?

How to motivate/produce topological defects?

How to detect various other transient

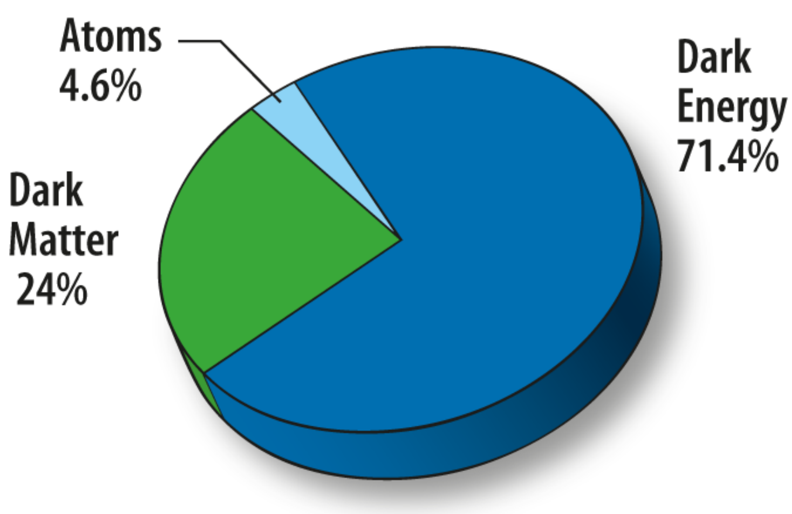
DM “clumps” with clock networks?

How to use clocks for measure “heavier” ultralight DM?

New ideas for DM searches with other AMO technologies?

Quantum Sensors:

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!