Search for New Physics with Atoms and Molecules

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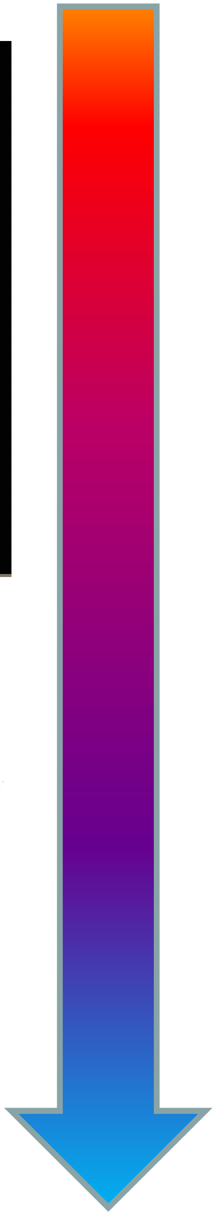
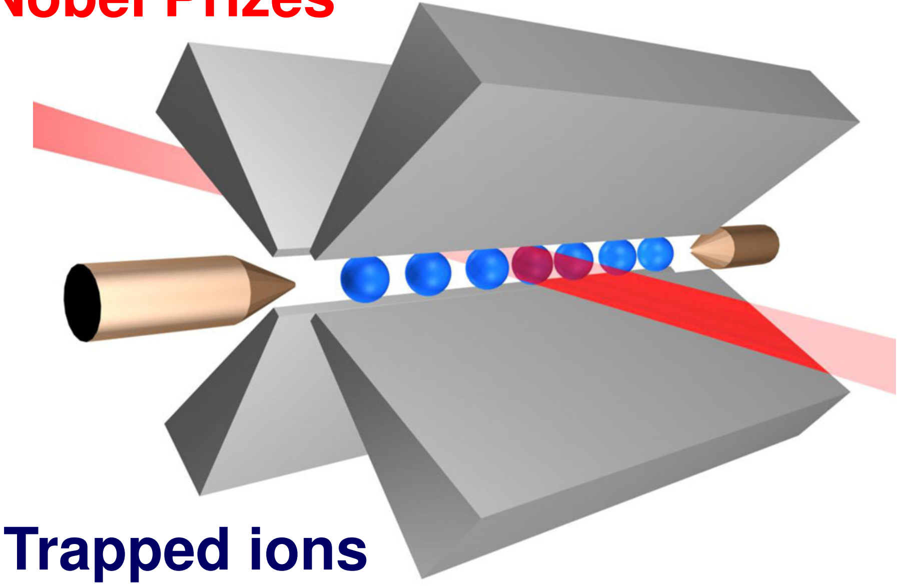
Outline

- General introduction: Why now is a good time to search for BSM physics with atoms and molecules? Atomic physics “tools”.
- Main classes of atomic and molecular BSM searches.
- Example 1: Electric-dipole moments (dedicated experiments)
- Example 2: BSM searches with atomic clocks
- Future
- Example 3: Proton radius puzzle – a few sigma discrepancy

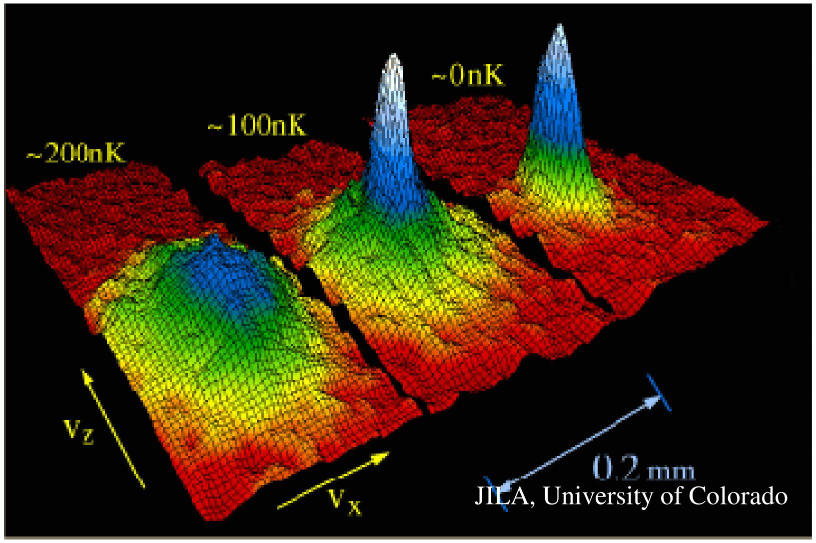
**1997, 2001
2005, 2012
Nobel Prizes**

Advances in AMO Physics





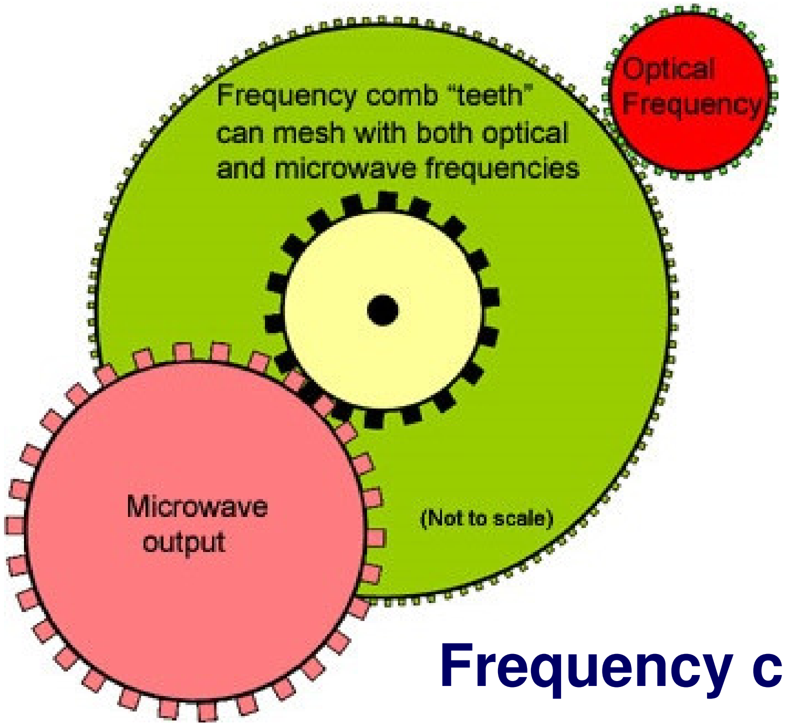
Trapped ions



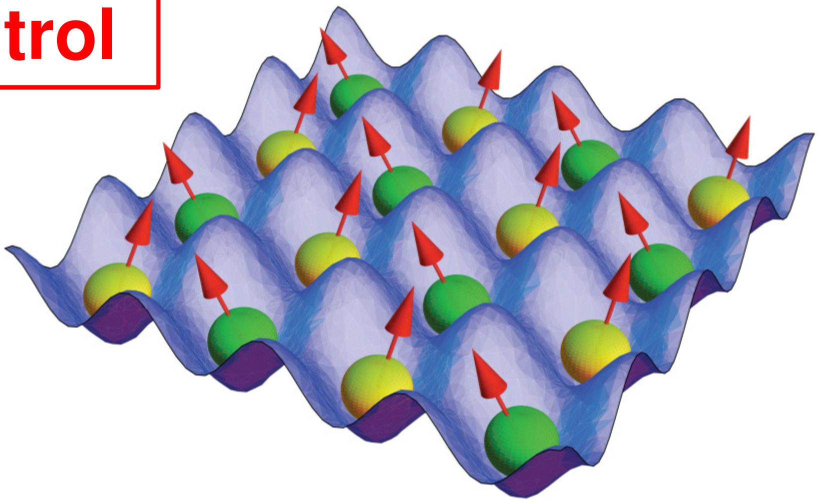
JILA, University of Colorado

New world of ultracold

Quantum control

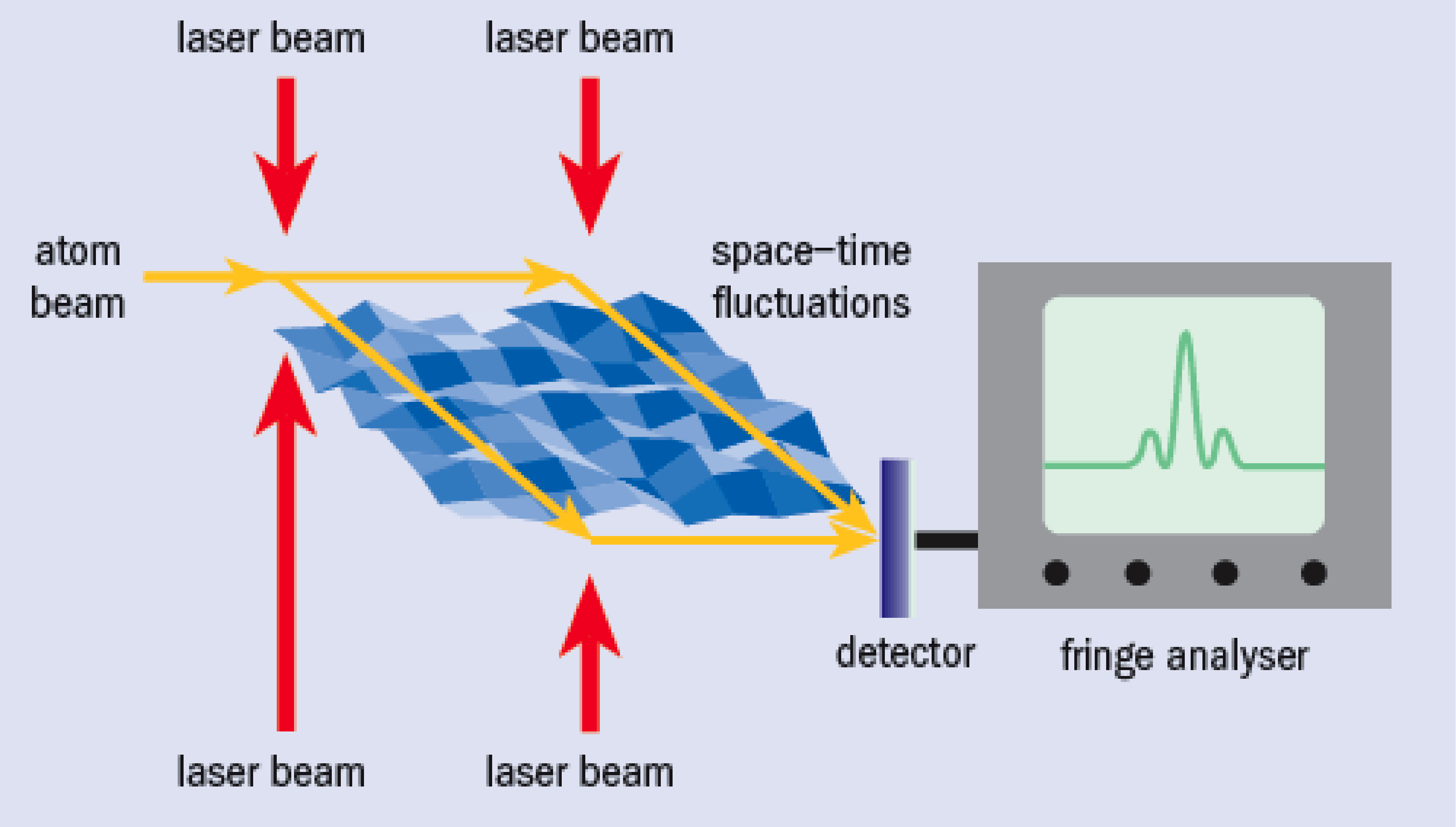


Frequency combs



Atoms in optical lattices

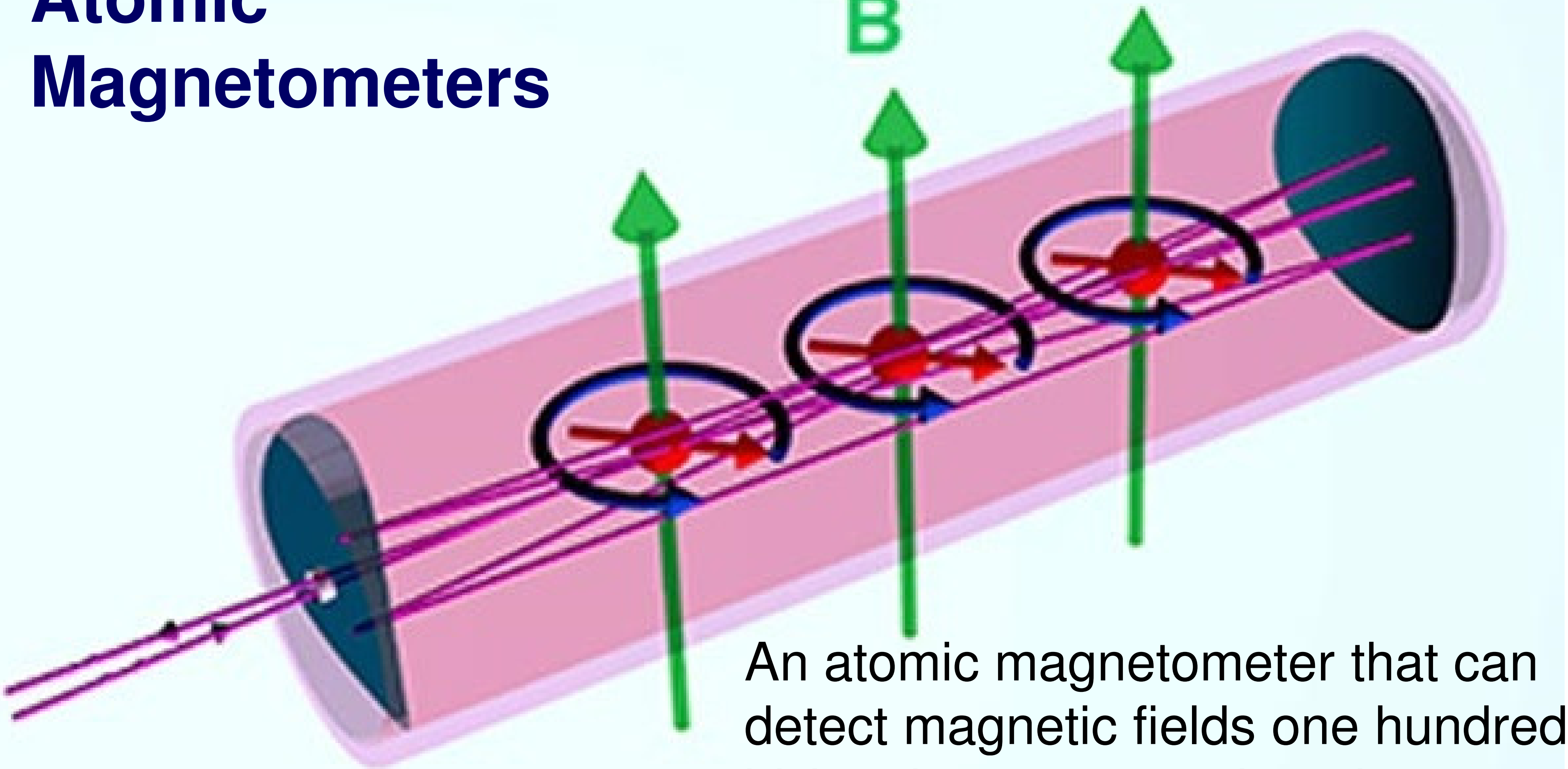
Atom Interferometers



Measure the phase difference to exceptional precision

http://images.iop.org/objects/ccr/cern/46/8/18/CCEcan1_10-06.gif

Atomic Magnetometers

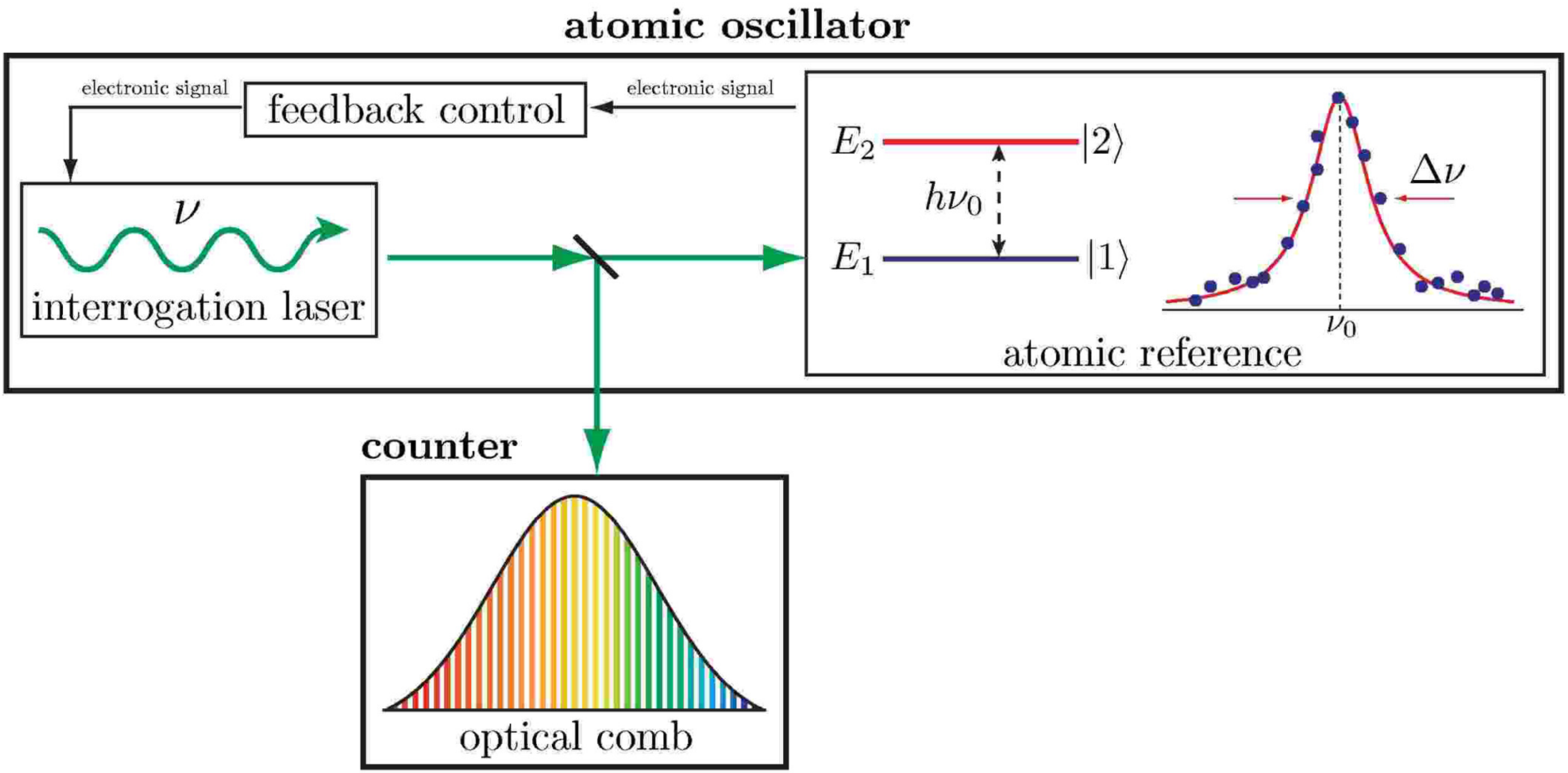


An atomic magnetometer that can detect magnetic fields one hundred billion times smaller than the Earth's!

Measure magnetic field to exceptional precision

http://physicsworld.com/cws/article/news/2013/apr/24/

Optical atomic clocks



Measure optical frequencies to exceptional precision: 10^{-18}

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

AMO and the Laws of Physics

- Precision atomic experiments (clocks, magnetometers, interferometers, quantum information, …):
  Do laws of physics hold within the experimental precision?

- Types of "search for new physics" experiments:

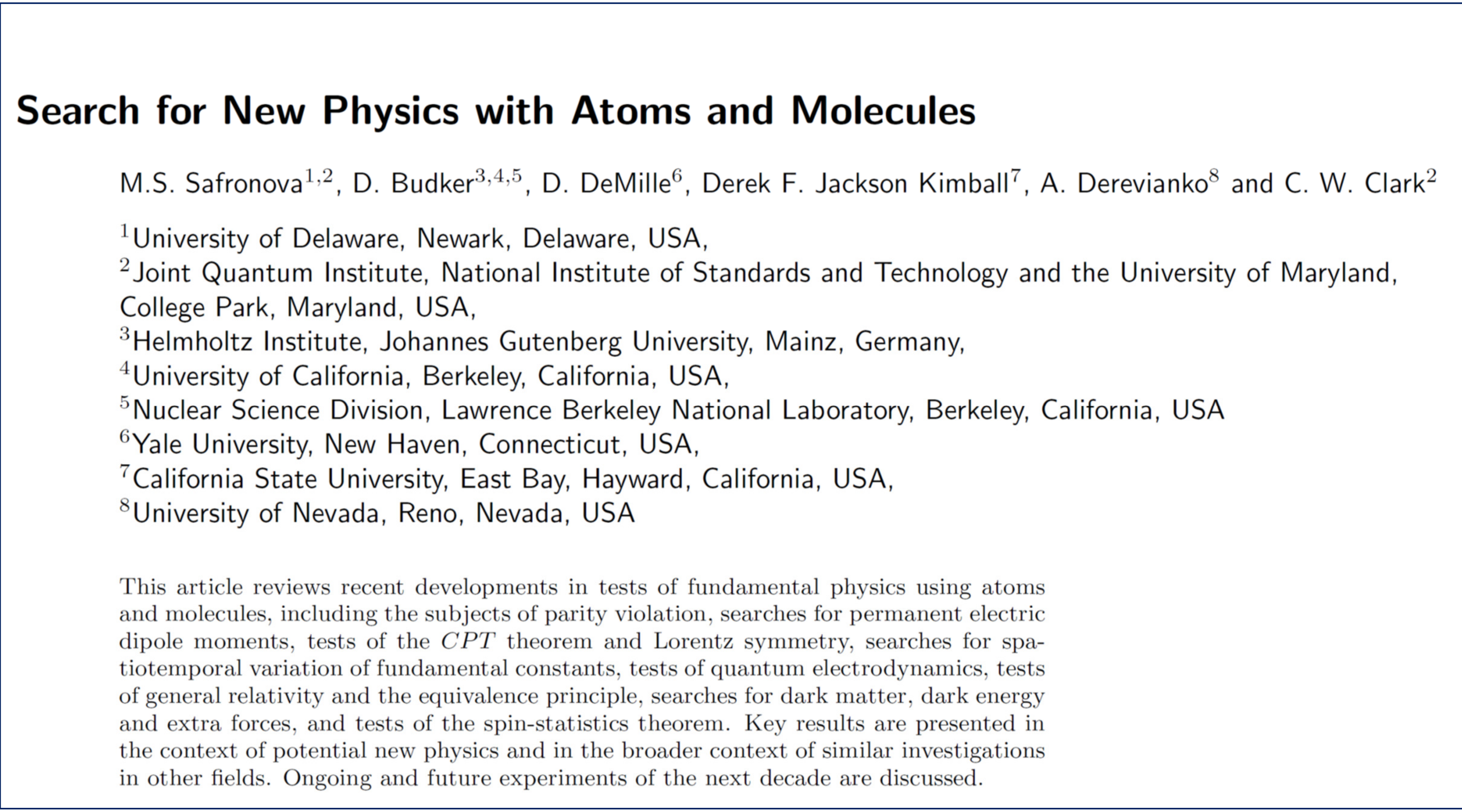
(1) Data already exist and just have to be interpreted.

(2) Experiments can be done with some modifications of existing set ups.

(3) New dedicated experiments.

play.google.com

Reviews of Modern Physics, in print, arXiv:1710.01833



Search for New Physics with Atoms and Molecules

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[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
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[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.

Review topics

1. Search for variation of fundamental constants
2. Precision tests of Quantum Electrodynamics
3. Atomic parity violation
4. Time-reversal violation: electric dipole moments and related phenomena
5. Tests of the CPT theorem, matter-antimatter comparisons
6. Searches for exotic spin-independent and spin-dependent interactions
7. Searches for light dark matter
8. General relativity and gravitation
9. Lorentz symmetry tests
10. Search for violations of quantum statistics

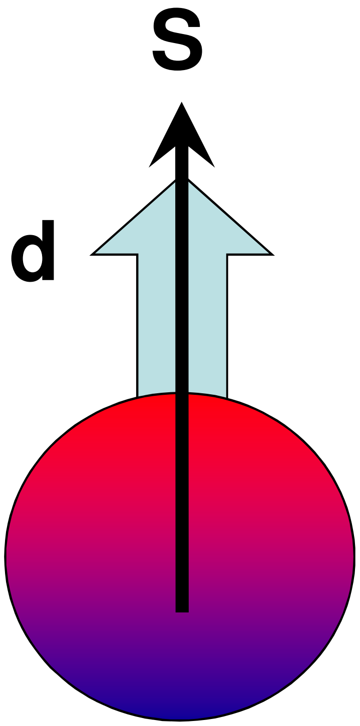
Example 1: EDM

The search for the electric-dipole moments

Dedicated experiments
Well-motivated theoretically
High discovery potential

Permanent electric-dipole moment (EDM)

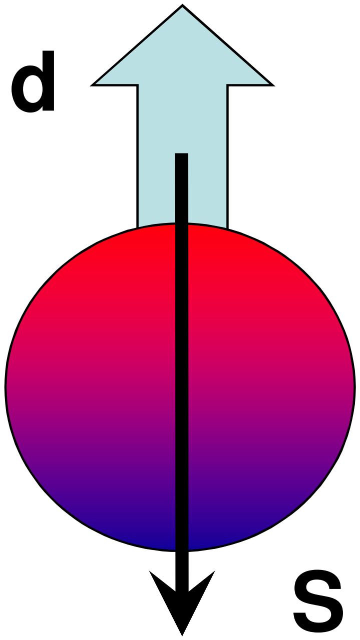
Time-reversal invariance must be violated for an elementary particle or atom to possess a **permanent EDM.**



$$t \rightarrow -t$$

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

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



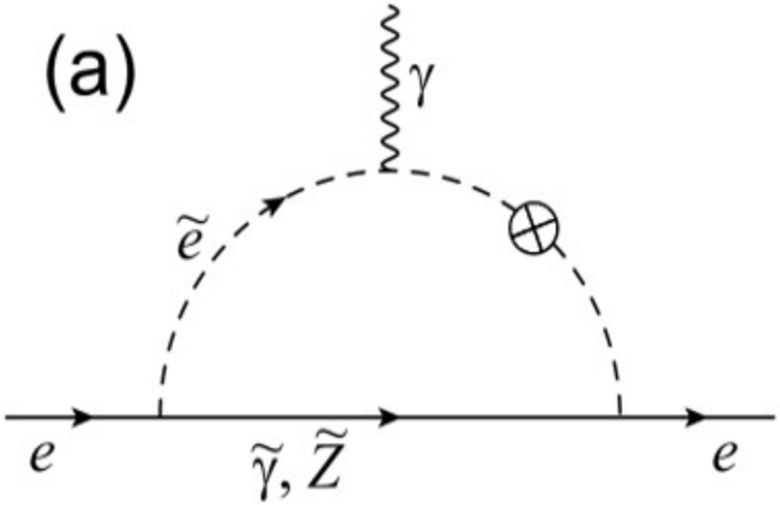
$$\boxed{\begin{gathered}\vec{\mathbf{d}} = d\,\frac{\vec{\mathbf{S}}}{S} \\ d = 0\end{gathered}}$$

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/ near future experiments.

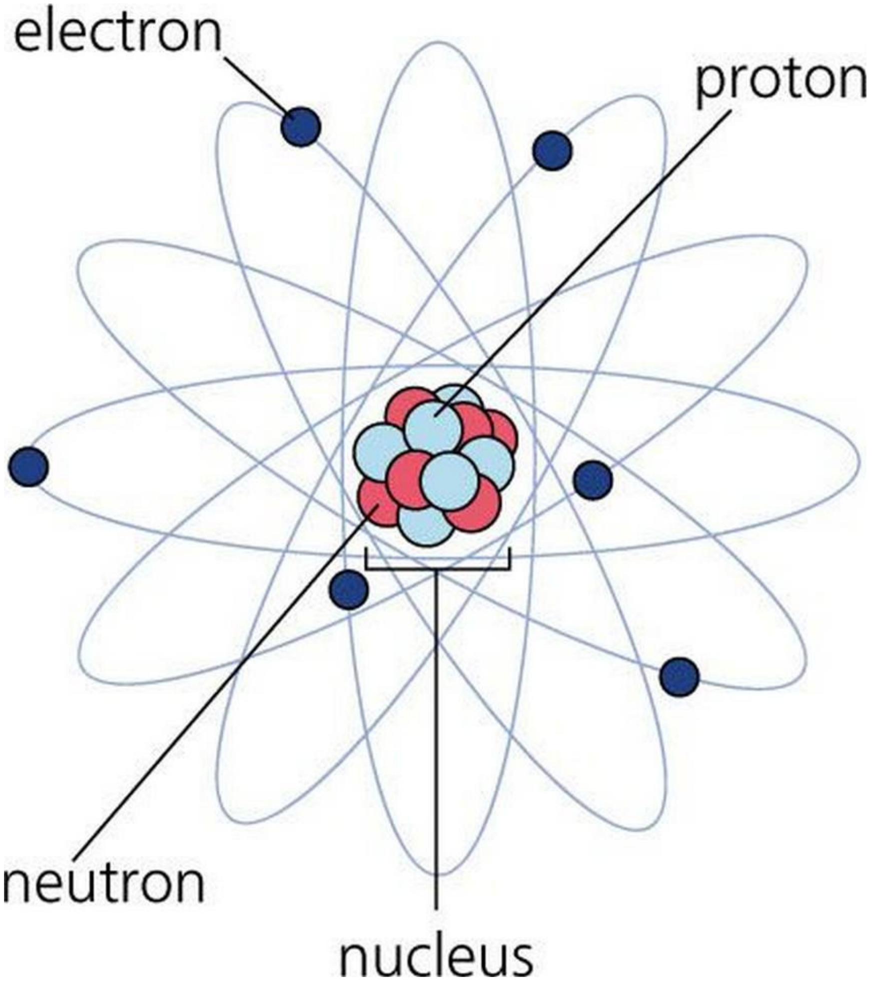


J. Engel et al., Progress in Particle and Nuclear Physics 71 (2013) 21

Sources of atomic and molecular EDMs

P, T – violating electron-nucleon interaction

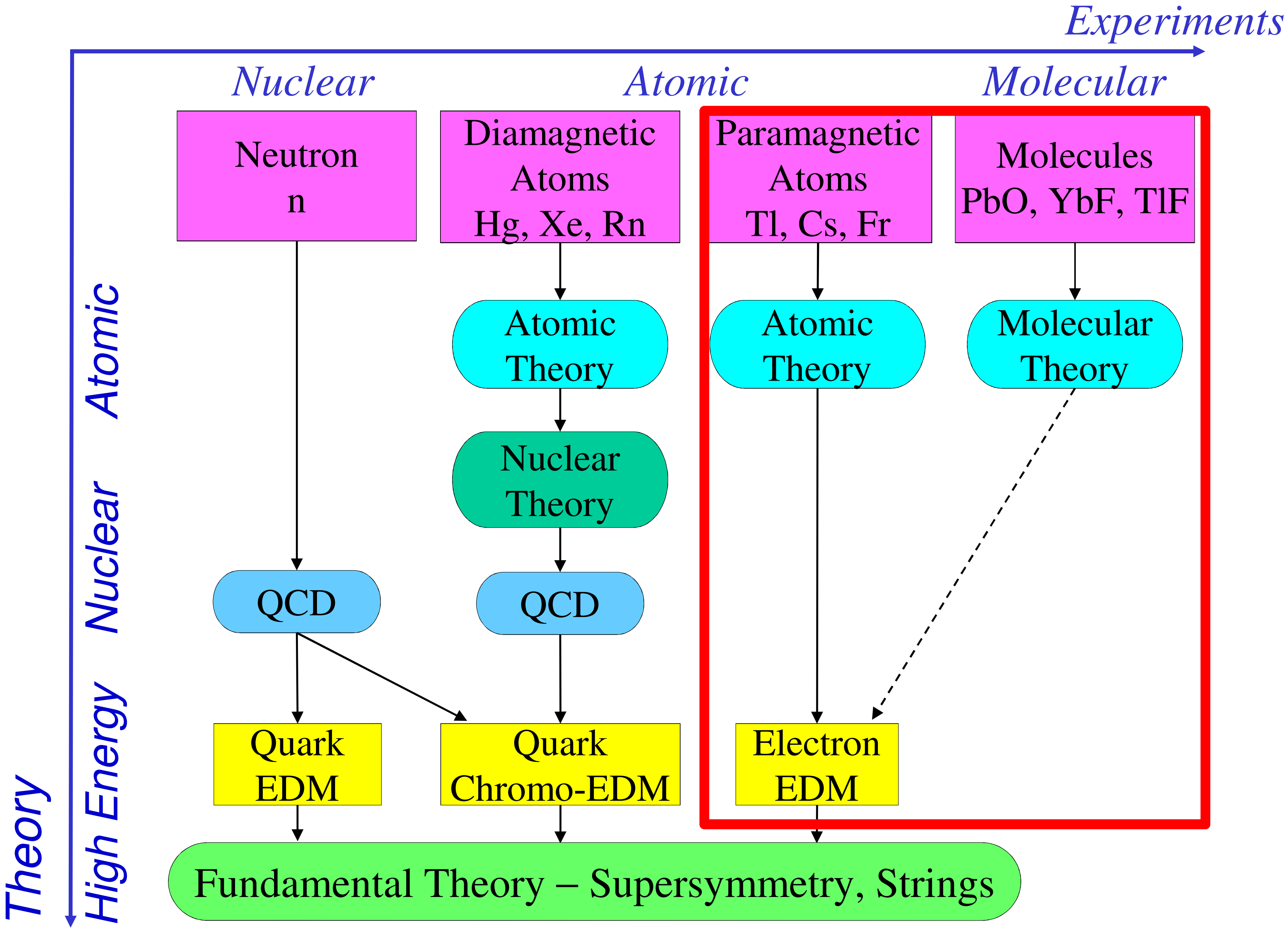
Electron EDM



P, T – violating nucleon- nucleon interaction

Nucleon EDM

Interpretation of EDM experiments



Experiments

Nuclear

Atomic

Molecular

Neutron
n

Diamagnetic
Atoms
Hg, Xe, Rn

Paramagnetic
Atoms
Tl, Cs, Fr

Molecules
PbO, YbF, TlF

Atomic
Theory

Atomic
Theory

Molecular
Theory

Nuclear
Theory

QCD

QCD

Quark
EDM

Quark
Chromo-EDM

Electron
EDM

Fundamental Theory – Supersymmetry, Strings

Theory

High Energy

Nuclear

Atomic

Mike Romalis, 2011 JLab talk (online)

Limits on electron EDM

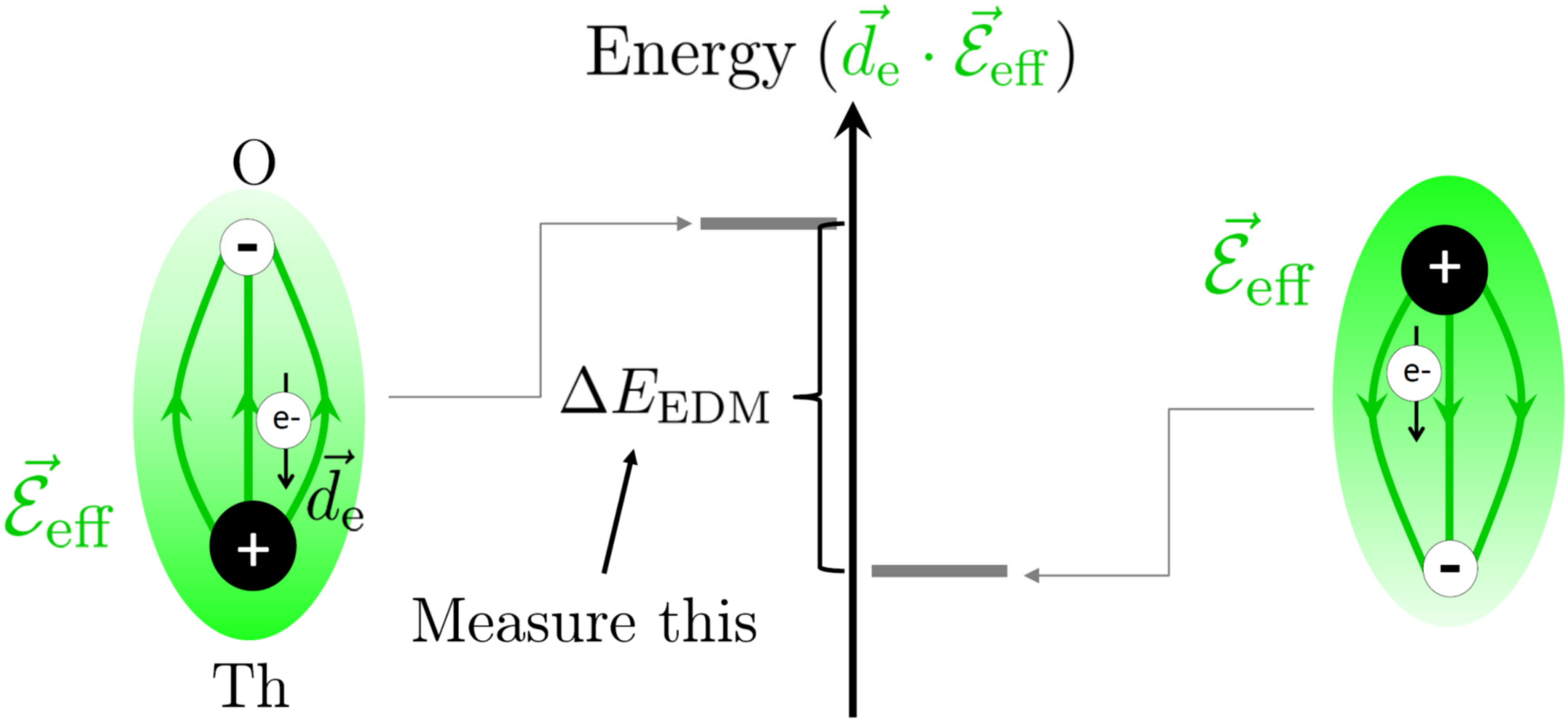
2014: ORDER OF MAGNITUDE IMPROVEMENT

Tl atom
$|d_e| < 1.6 \times 10^{-27}\ e\ \mathrm{cm}$
PRL 88, 071805 (2002)

YbF molecule
Ed Hinds group, ICL
$|d_e| < 1.05 \times 10^{-27}\ e\ \mathrm{cm}$
Nature 473, 493 (2011)

ThO molecule
$|d_e| < 8.7 \times 10^{-29}\ e\ \mathrm{cm}$
The ACME Collaboration
Harvard/Yale
Science 343, 269 (2014)

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.

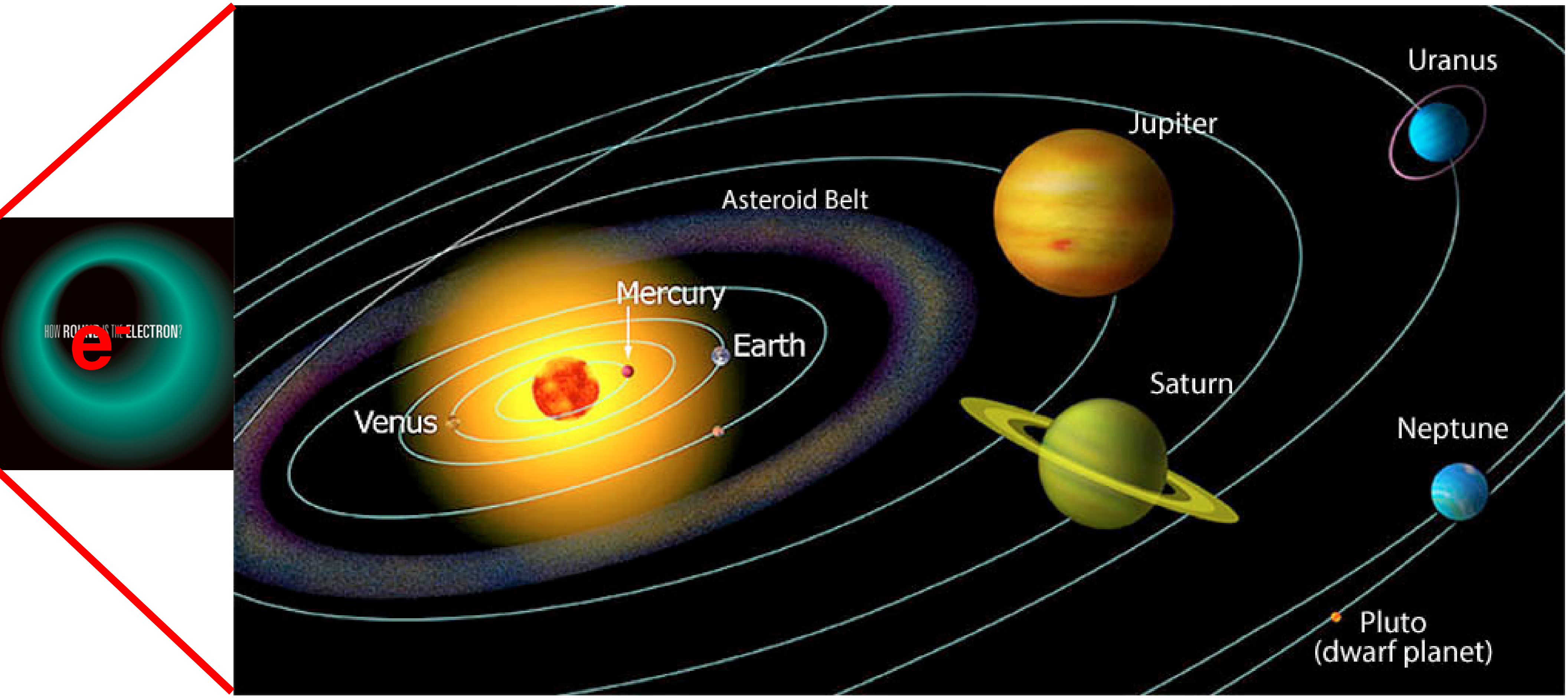
Apply electric field, reverse, measure the energy splitting between electrons oppositely oriented relative to the effective molecular field in ThO (84 GV/cm):

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

http://www.electronedm.org/

Electron EDM

Blow up the electron to the size of the Solar System

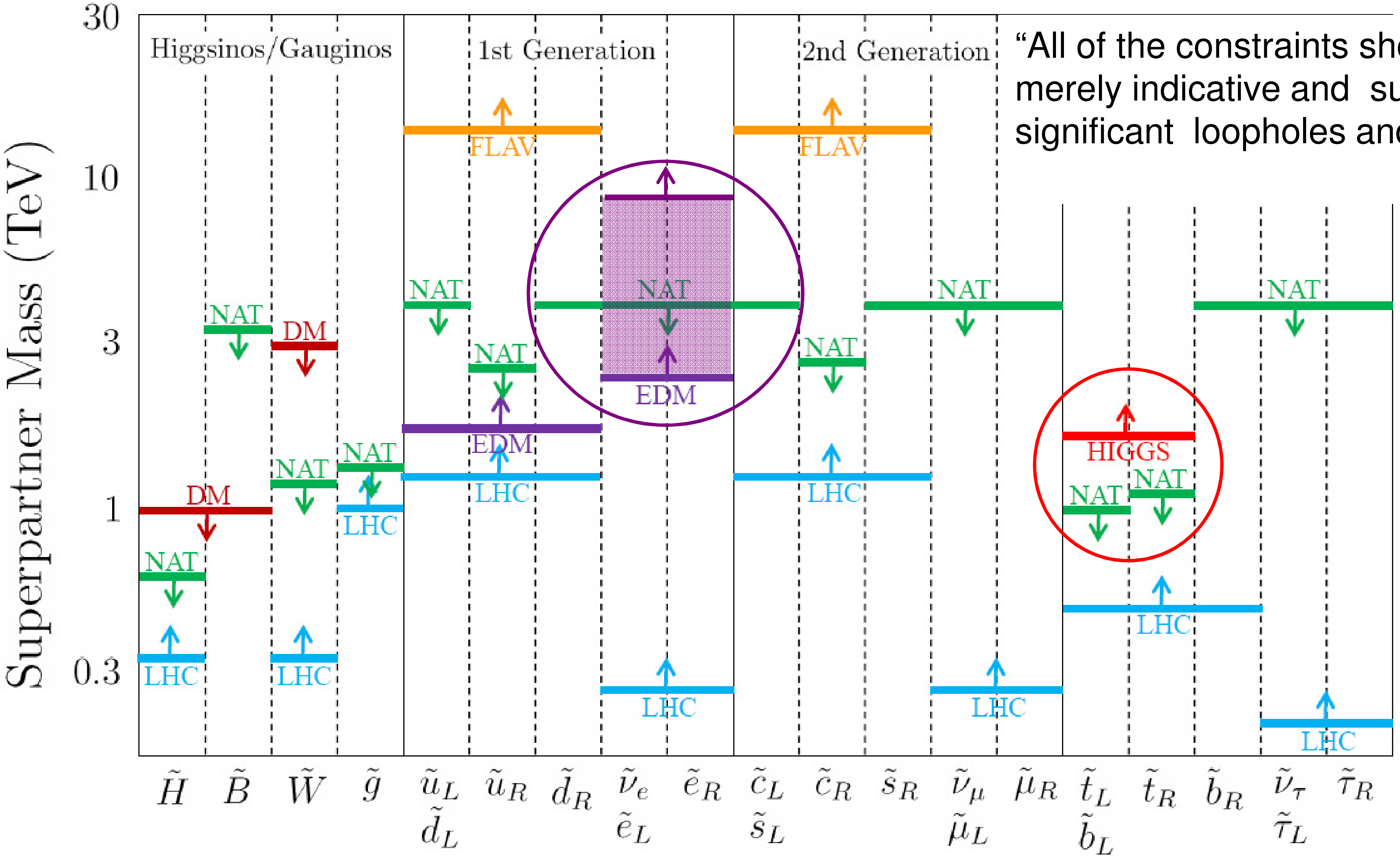


then it is spherical to within the ***width of a human hair.***

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

Implications for BSM physics

Jonathan Feng: "Naturalness and the status of SUSY", arXiv 1302.6587

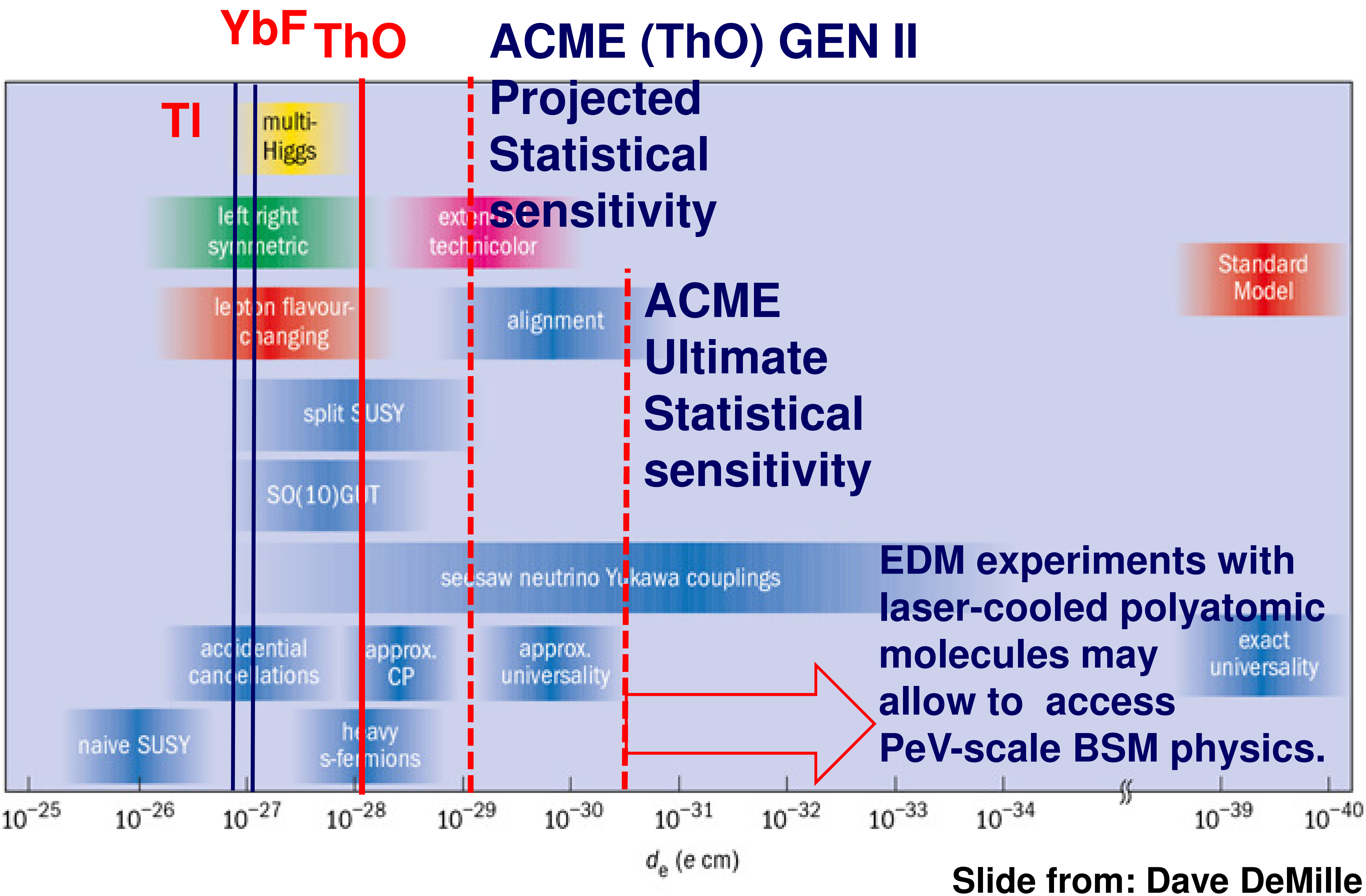


"All of the constraints shown are merely indicative and subject to significant loopholes and caveats"

ACME (like Higgs mass) pushes SUSY into "unnatural" region

Slide from: Dave DeMille

Electron EDM limits



EDM experiments with laser-cooled polyatomic molecules may allow to access PeV-scale BSM physics.

Slide from: Dave DeMille

Example 2:
BSM searches with atomic clocks

Search for the variation of fundamental constants
Dark matter searches
Search for the violation of the Lorentz invariance
Future: searches for the gravitational waves

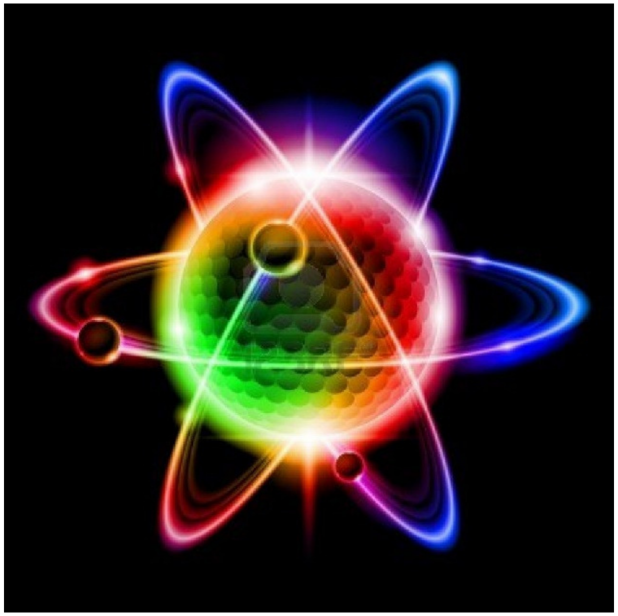
Ingredients for an atomic clock

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

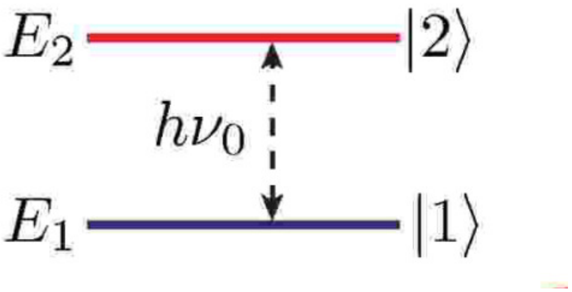
2. Take a sample of atoms (or just one)

3. Build a device that produces oscillatory signal in resonance with atomic frequency

4. Count cycles of this signal

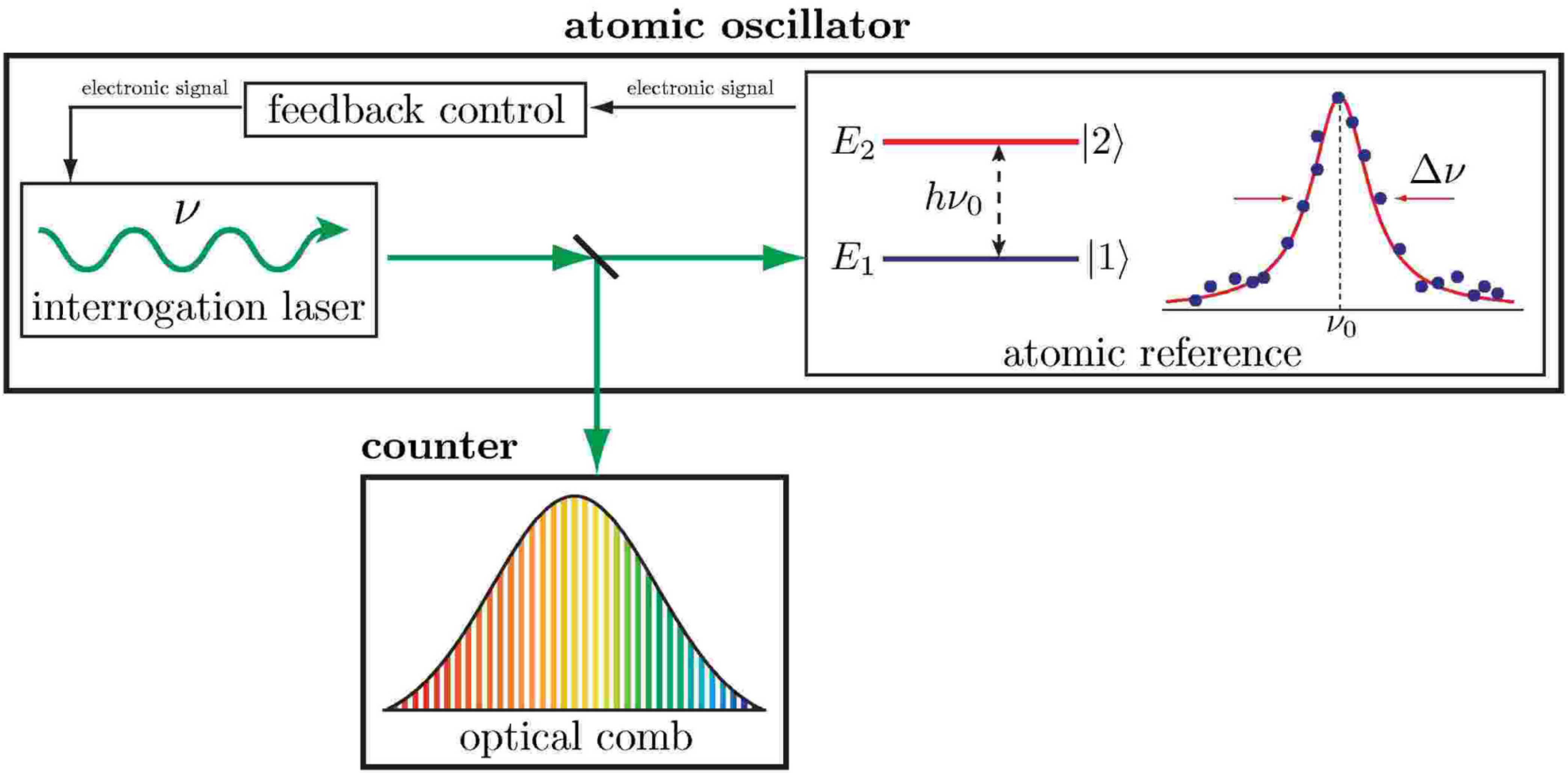


valentinagurarie.wordpress.com/tag/atom/



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

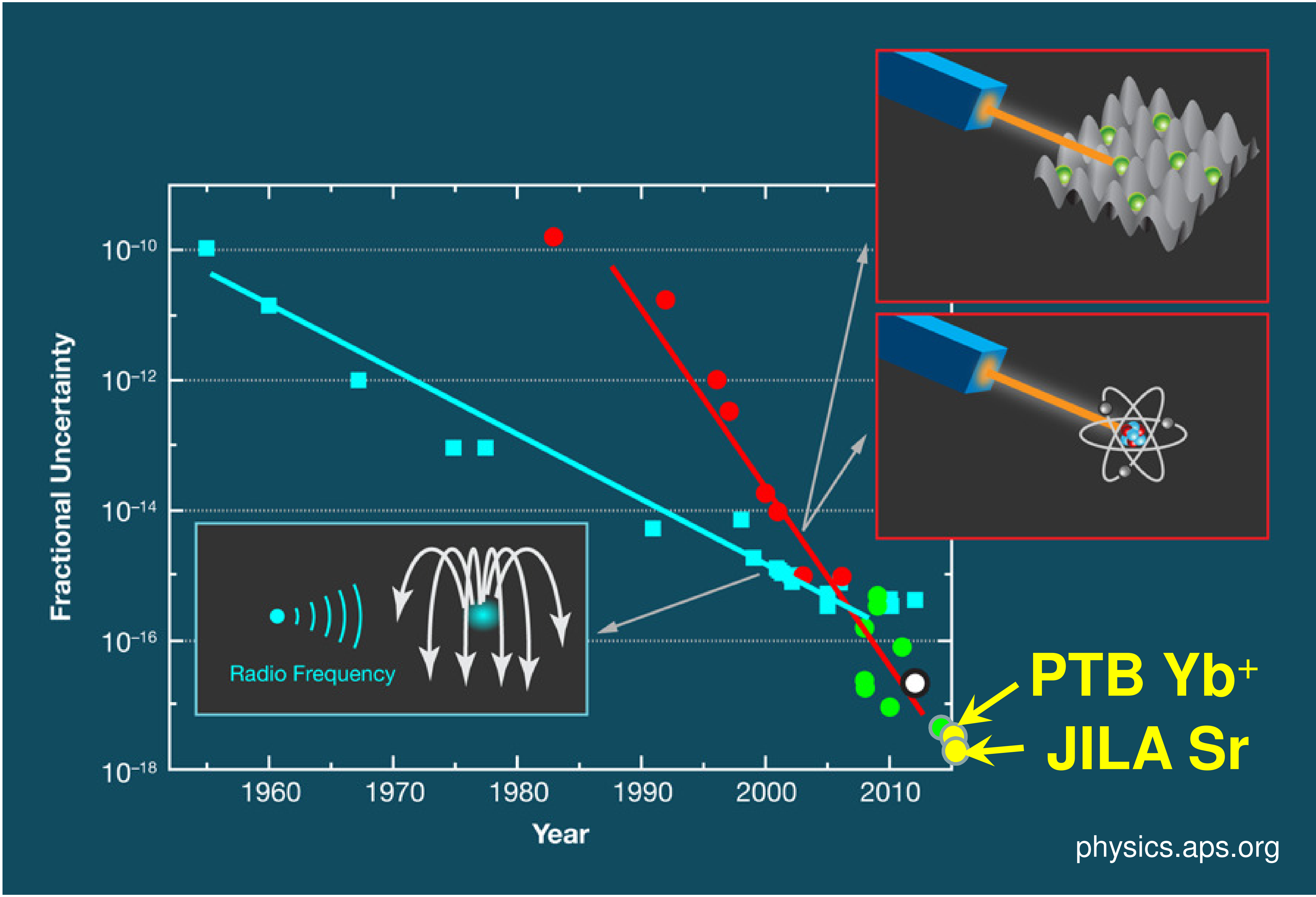
Optical atomic clocks



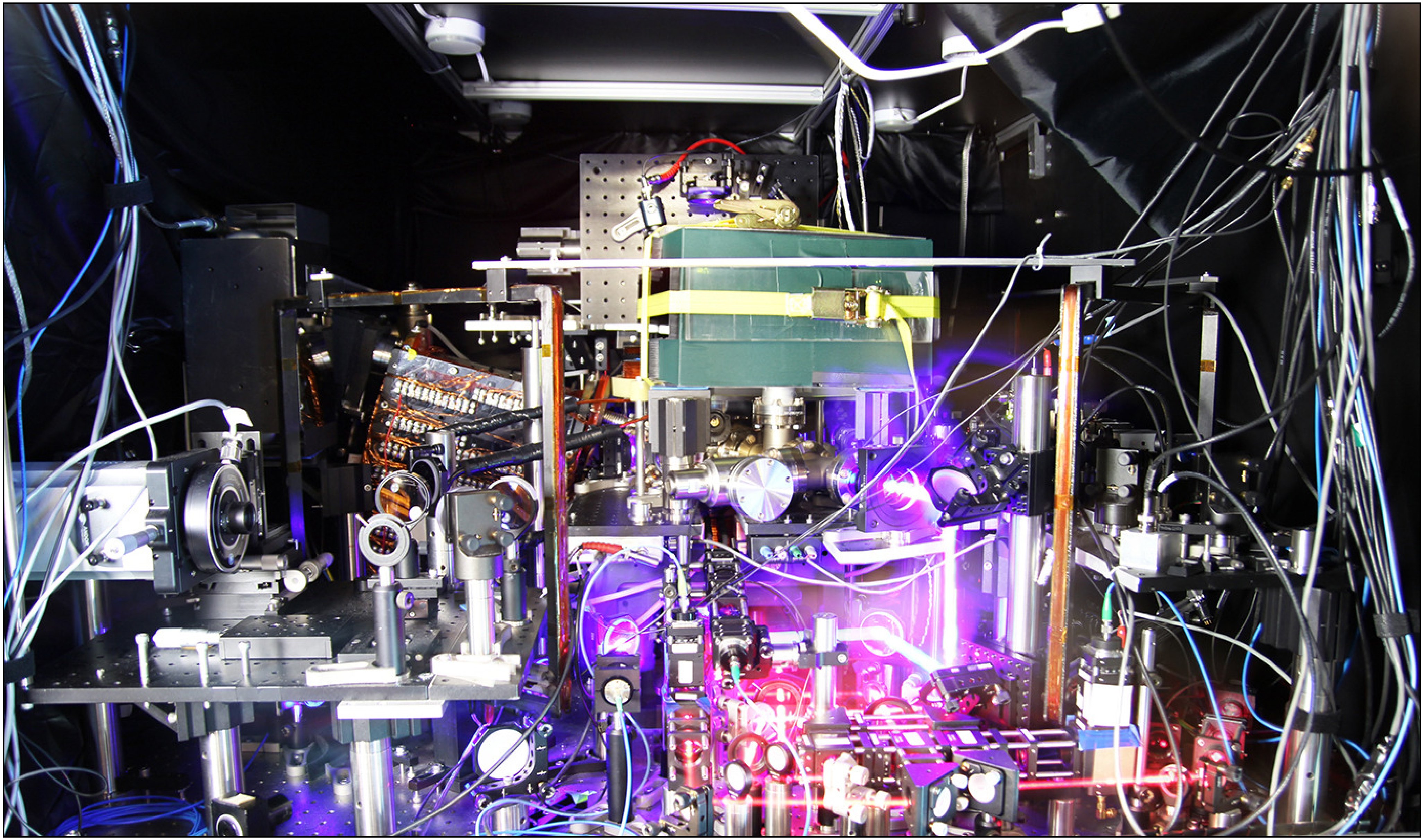
Measure optical frequencies to exceptional precision: 10^{-18}

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

Optical vs. microwave clocks



Sr clock will lose 1 second in 15 billion years !



Nicholson et al., Nature Comm. 6, 6896 (2015) **Sr: 2×10^{-18}**

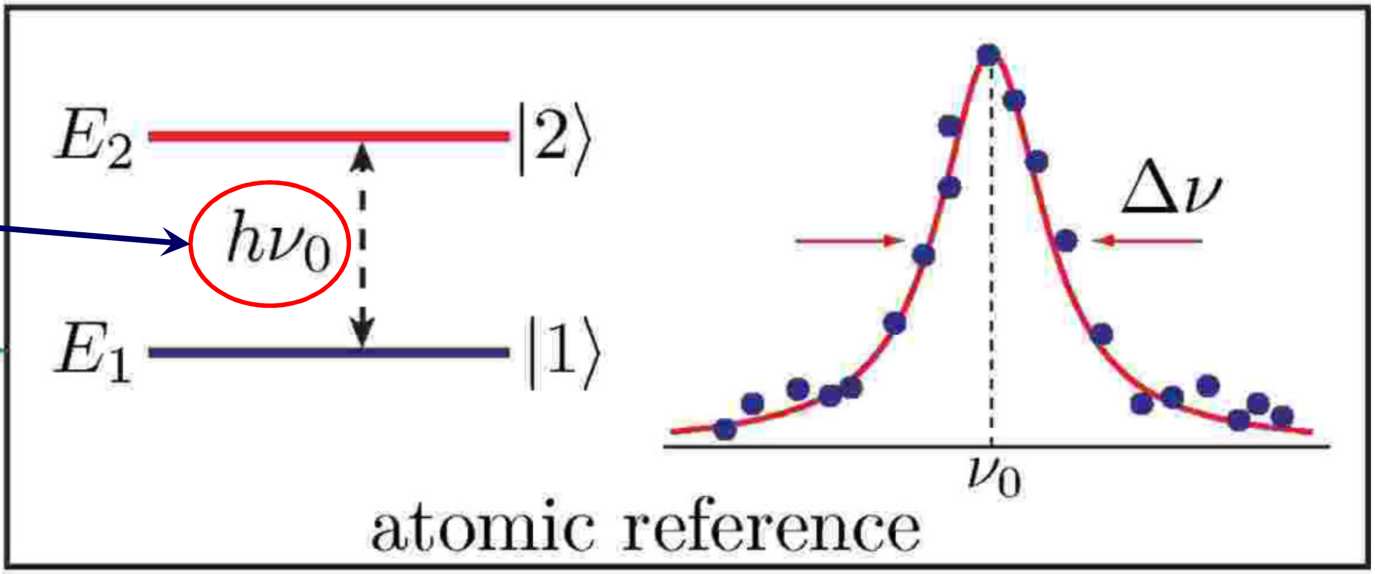
http://www.nist.gov/pml/div689/20140122_strontium.cfm

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

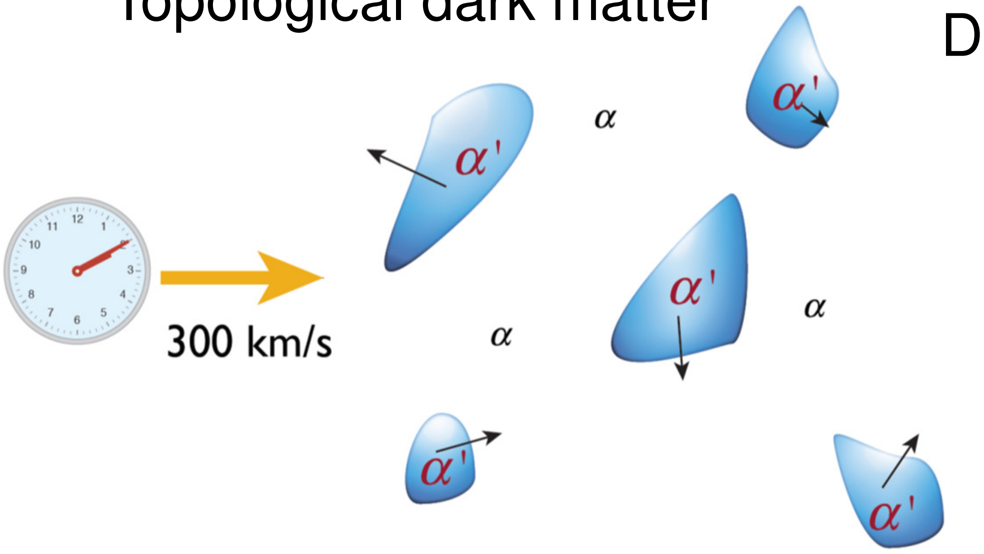


Time-variation of fundamental constants

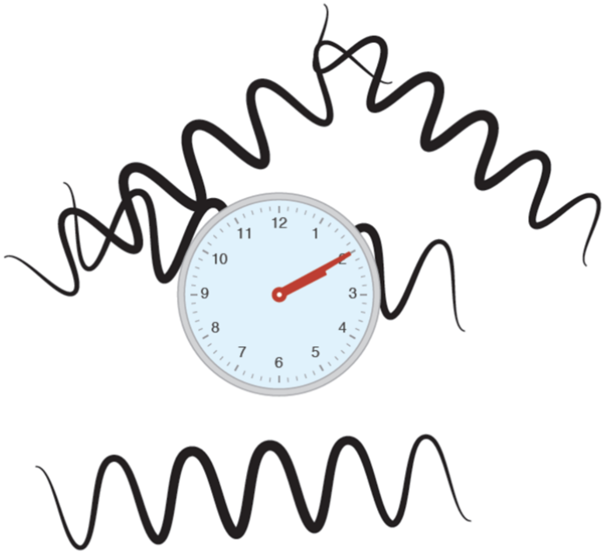
- Slow drifts
- Transient variations
- Oscillations
- Stochastic

Dark energy?

Topological dark matter



Dilaton dark matter or axion-like particles

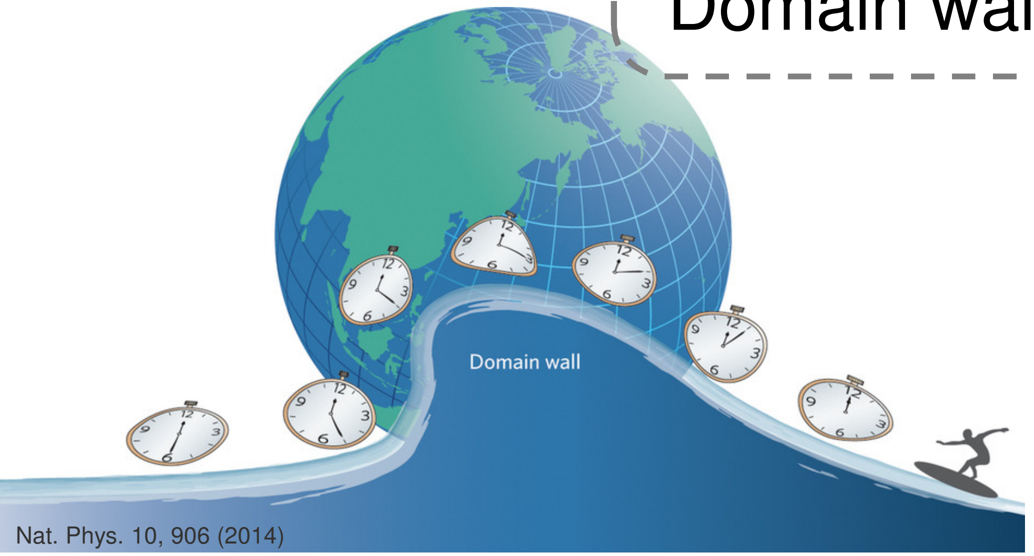


A. Derevianko, Conf. Ser. **723** (2016) 012043

Spatial variations of fundamental constants

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

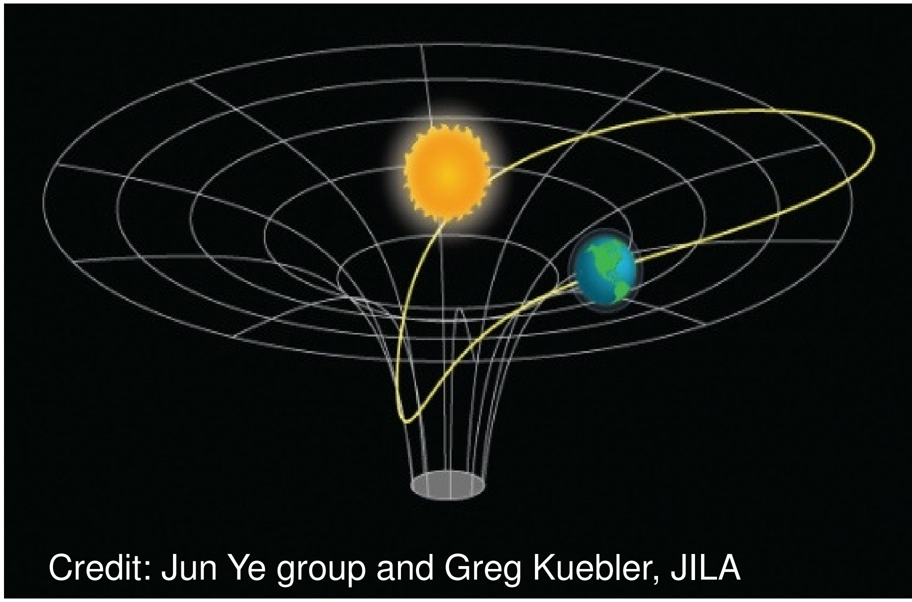
Cosmological spatial variation Domain walls



Nat. Phys. 10, 906 (2014)

Dependence on matter density: Chameleons

Dependence on gravity



Credit: Jun Ye group and Greg Kuebler, JILA

Laboratory searches for variation of fundamental constants and dark matter

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

1. Frequency of optical transitions

$$\nu \simeq cR_\infty A F(\alpha)$$ Depends only on α

2. Frequency of hyperfine transitions

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

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

Depends on α, μ, g-factors (quark masses to QCD scale)

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

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

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

4. Laser cavities L ~ α

Comparing different types of transitions probes different constants and DM/SM couplings

(1) Measure the ratio R of optical to hyperfine (Cs) clock frequencies:

sensitive α, μ, g-factors (quark masses)

(2) Measure the ratio R of two optical clock frequencies:

sensitive only to α-variation and DM coupling to SM via Fμν

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

Calculate with good precision

Sensitivity of optical clocks to α-variation

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

Enhancement factor

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

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

$$\frac{\partial}{\partial t} \ln \frac{\nu_2}{\nu_1} = \underbrace{(K_2 - K_1)}_{100} \frac{1}{\alpha} \frac{\partial \alpha}{\partial t}$$

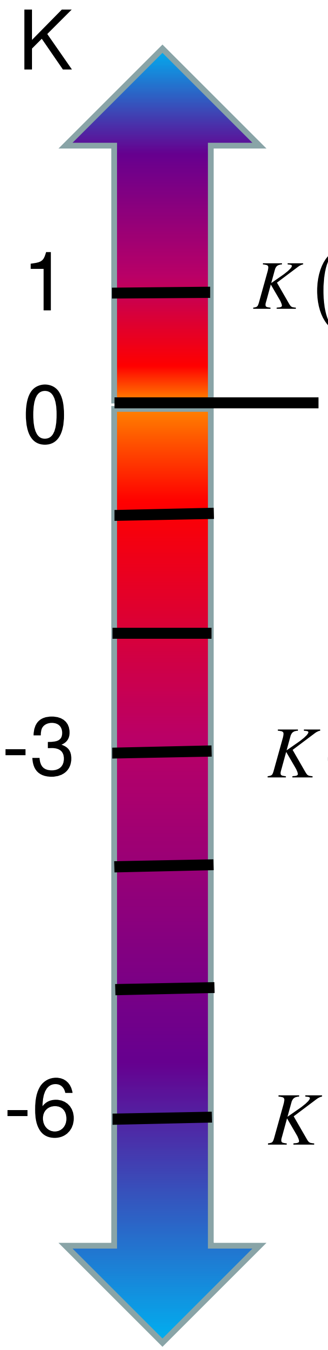
Test of α-variation

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

Easier to measure large effects!

Enhancement factors for current clocks

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



$K(Sr^+) = 0.4$

$K(Yb) = 0.3$

Neutral atoms
Superb stability

$K(Hg) = 0.8, \ K(Yb^+ E2) \ = \ 1$

$K(Al^+) = 0.01, \ K(Sr) = 0.06, \ K(Ca^+) = 0.1$

Neutral atoms
Superb stability

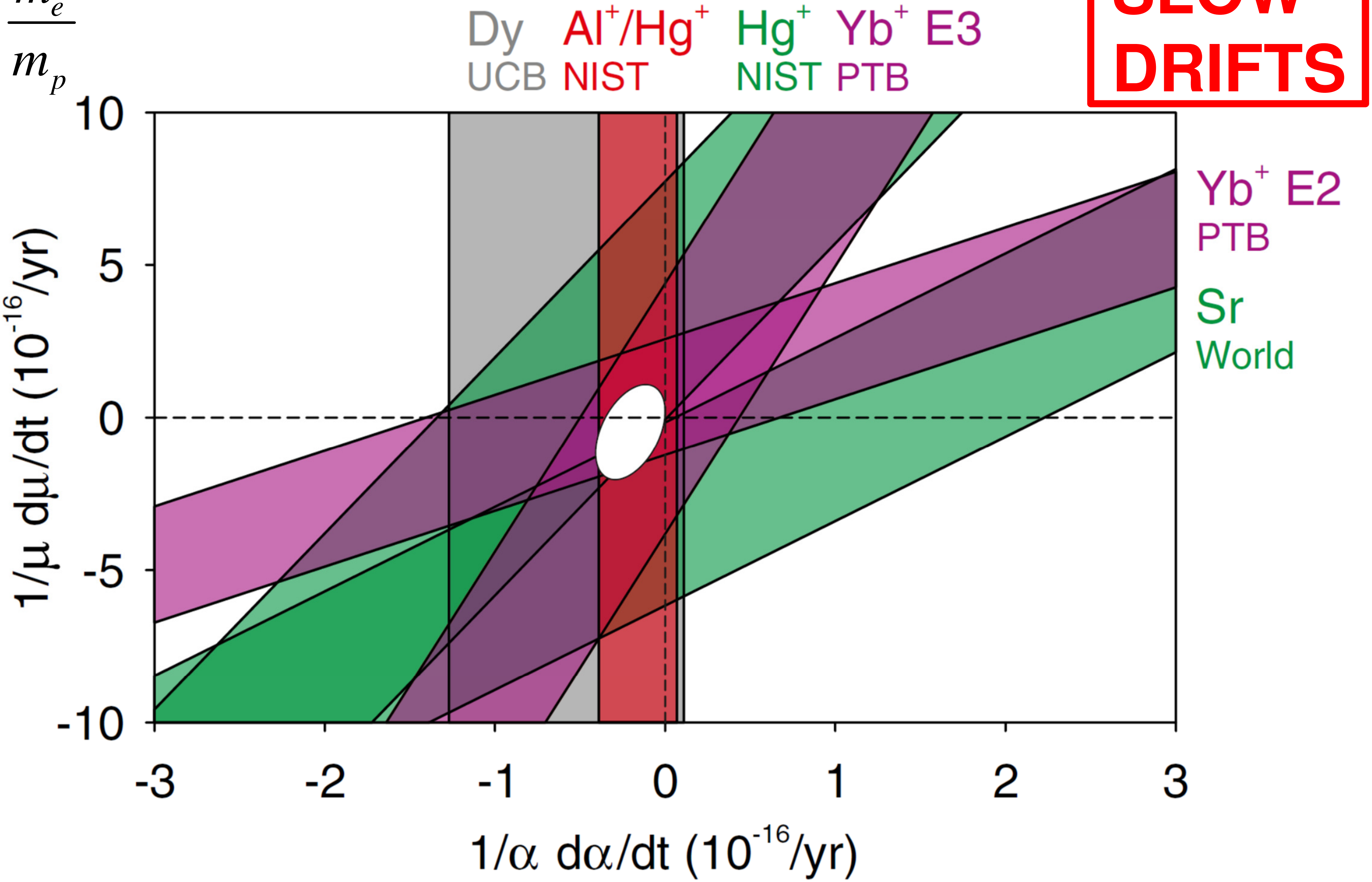
$K(Hg^+) = -2.9$

Current stability
limitations with ion
clocks (N=1)

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

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

SLOW DRIFTS



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

Ultralight dark matter

Bosonic dark matter (DM) with mass $m_\phi < 1\text{eV}$

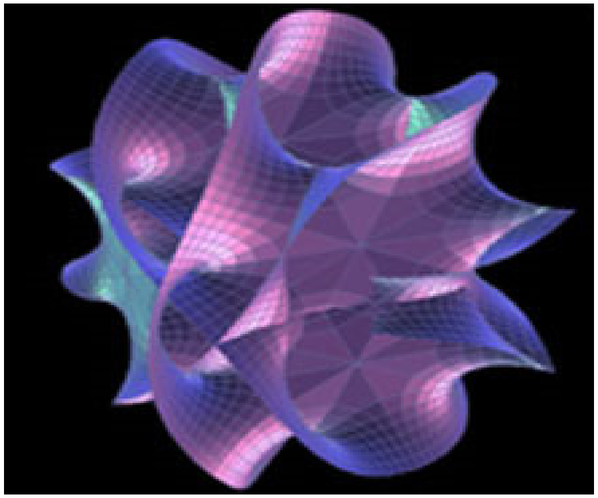
Dark matter density in our Galaxy > λ_{dB}^{-3}

λ_{dB} is the de Broglie wavelength of the particle.

Then, the scalar dark matter exhibits coherence and behaves like a wave.

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

Dilatons: appears in theories with extra dimensions when the volume of the compactified dimensions is allowed to vary.



Dilatonic couplings to the Standard Model

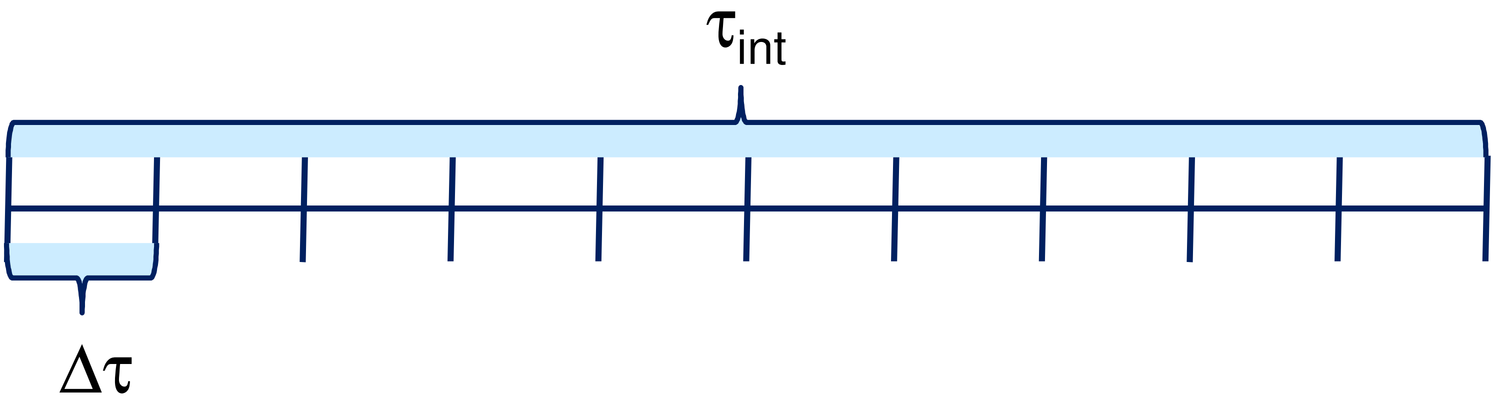
$$\frac{\phi}{M^*}\mathcal{O}_{\rm SM}$$

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

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)

Ultralight dark matter

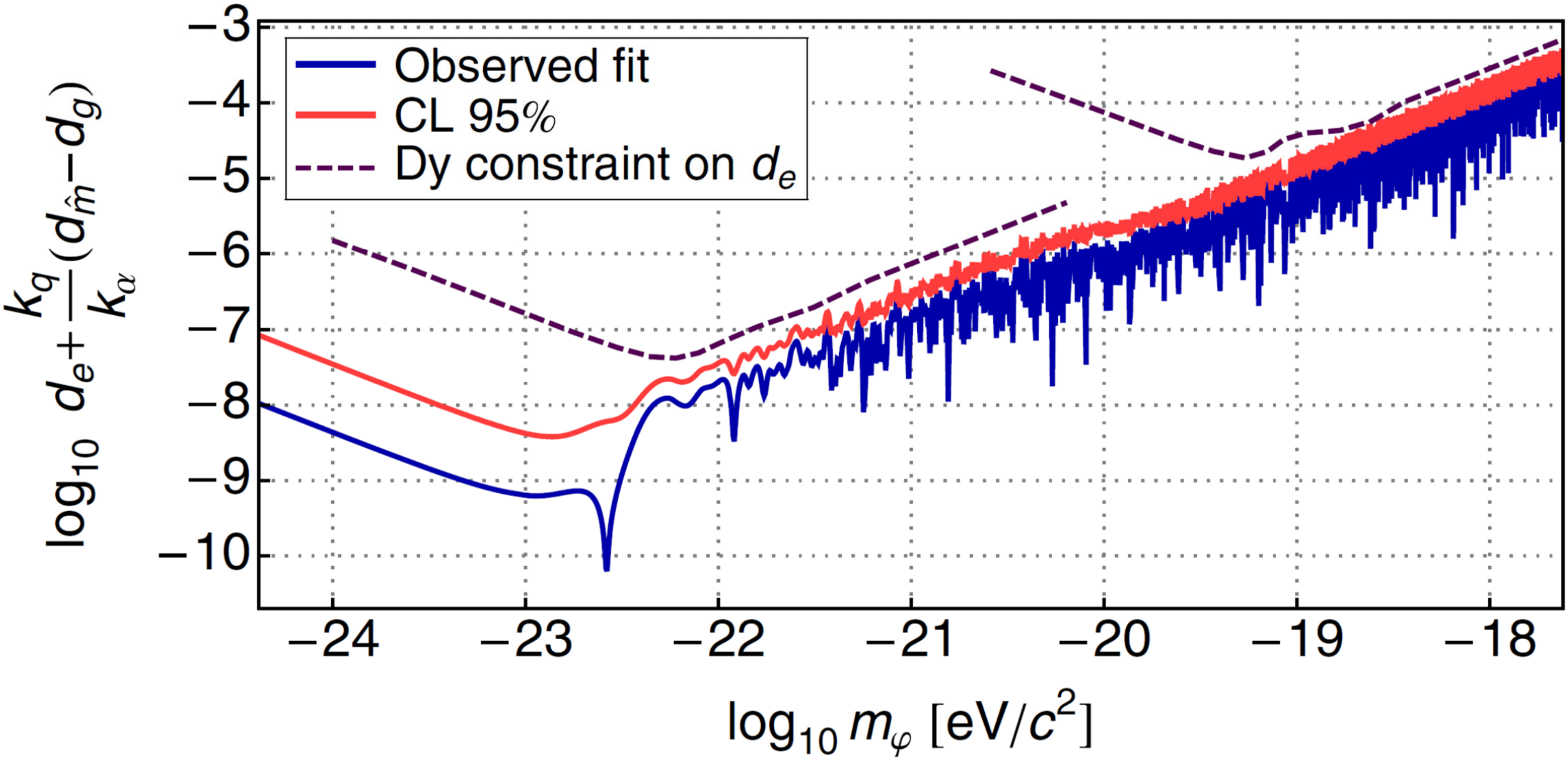
$$\phi(t) = \phi_0 \cos\left(m_\phi t + \bar{k}_\phi \times \bar{x} + \ldots\right)$$

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

Experimental results



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

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

How to improve BSM clock searches?

1. Improve current clocks – **two (?)** more orders.

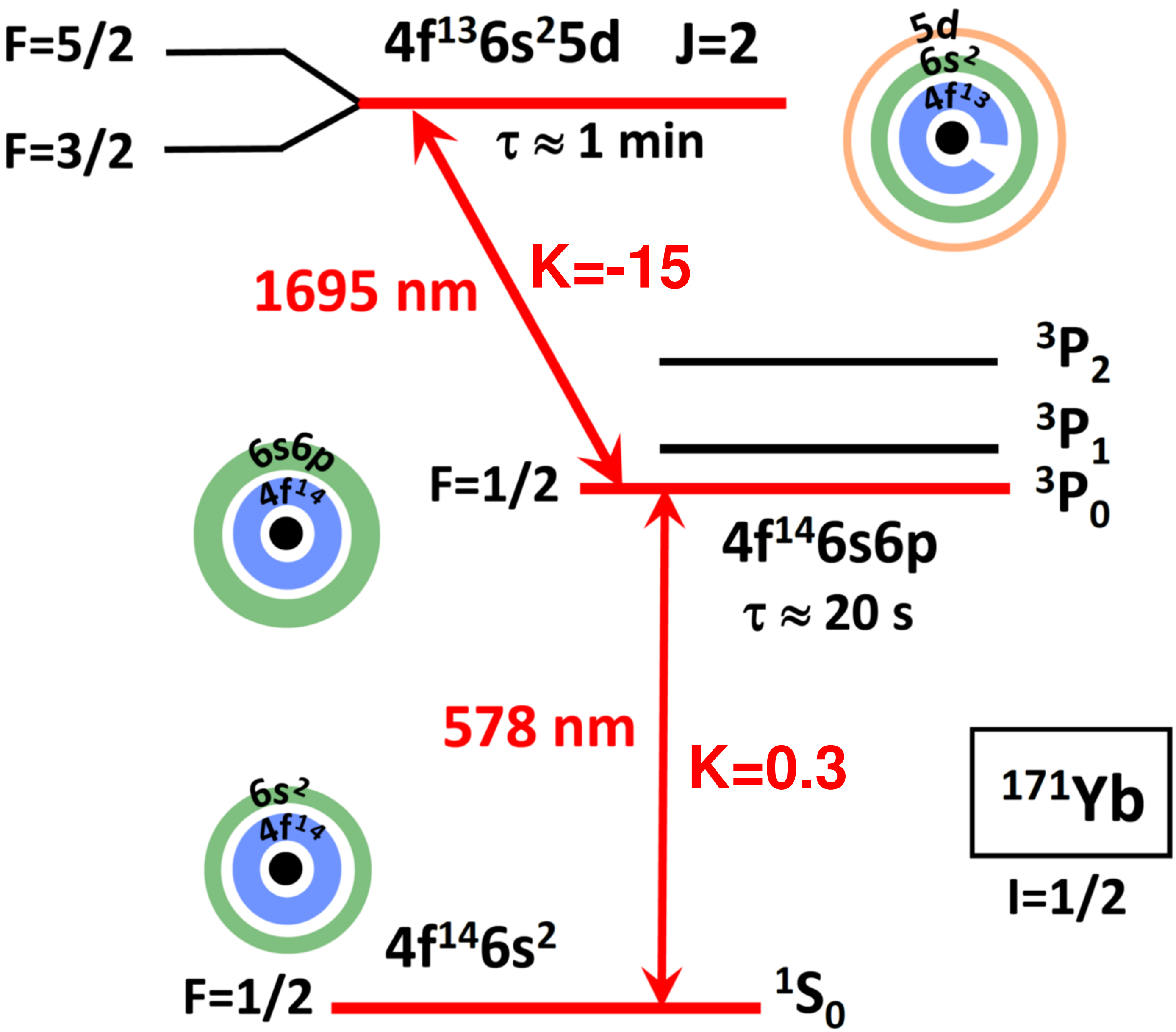
2. Resolve stability issue of the trapped ion clocks (need N>1).

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

Two clock transitions in neutral Yb



F=5/2

F=3/2

$4f^{13}6s^25d$ J=2

$\tau \approx 1$ min

1695 nm

K=-15

$^3P_2$

$^3P_1$

F=1/2

$^3P_0$

$4f^{14}6s6p$

$\tau \approx 20$ s

578 nm

K=0.3

^{171}Yb

I=1/2

$4f^{14}6s^2$

F=1/2

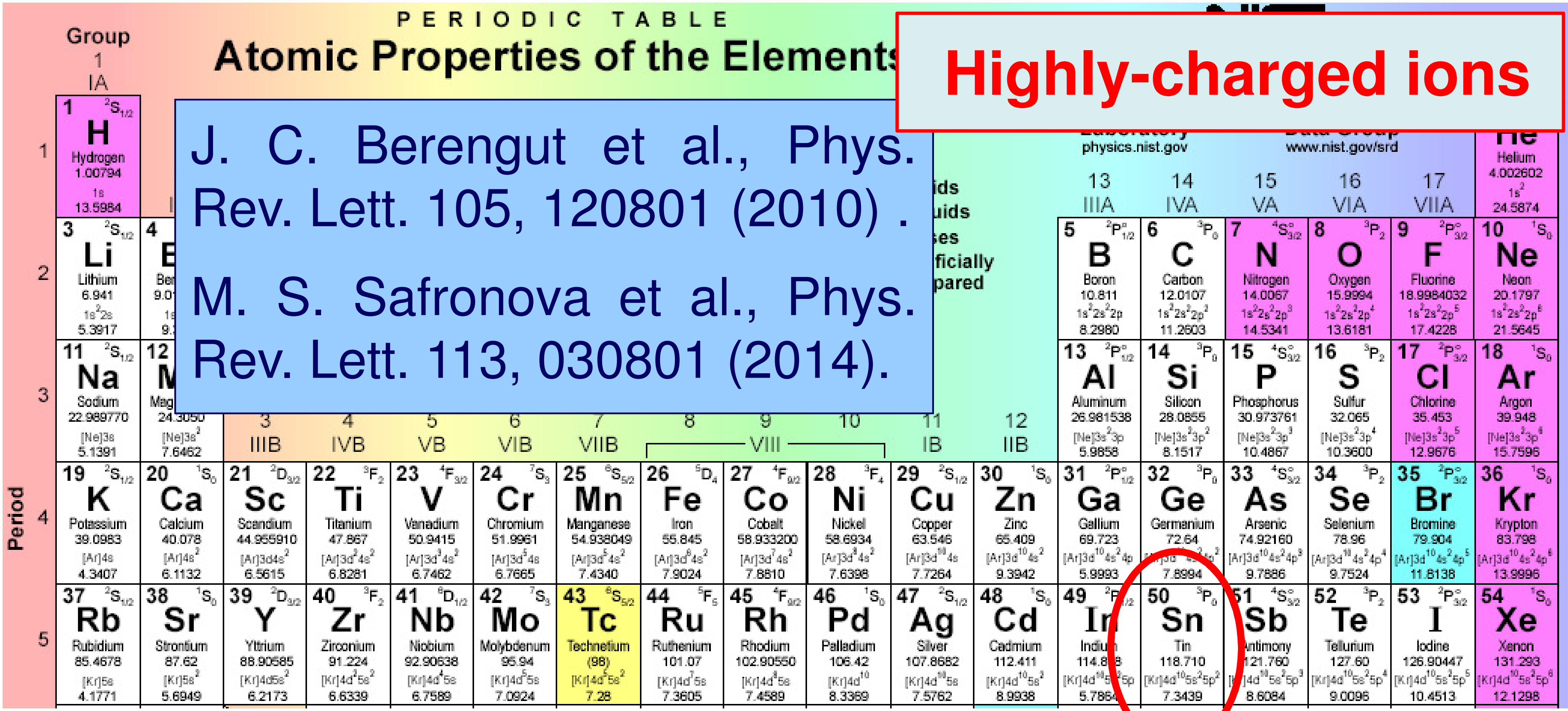
$^1S_0$

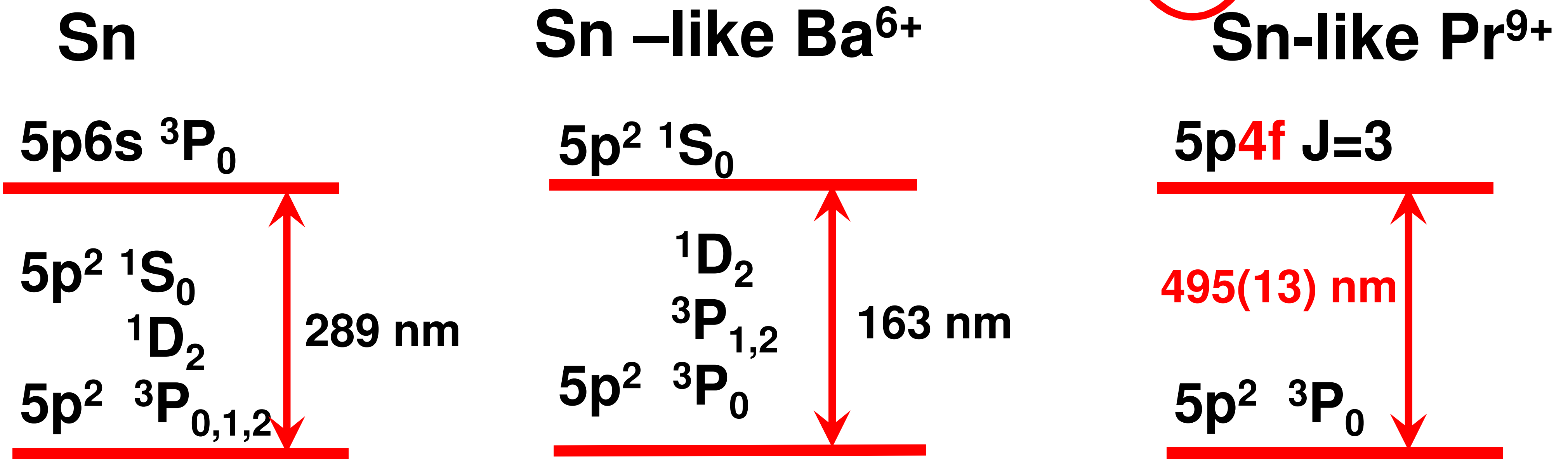
M. S. Safronova, S. G. Porsev, Christian Sanner, and Jun Ye, arxiv:1801.06239, in press, Phys. Rev. Lett. (2018).

Highly-charged ions

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

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





Sn

5p6s $^3P_0$

5p^2 $^1S_0$

$^1D_2$

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

289 nm

Sn –like Ba^{6+}

5p^2 $^1S_0$

$^1D_2$

$^3P_{1,2}$

5p^2 $^3P_0$

163 nm

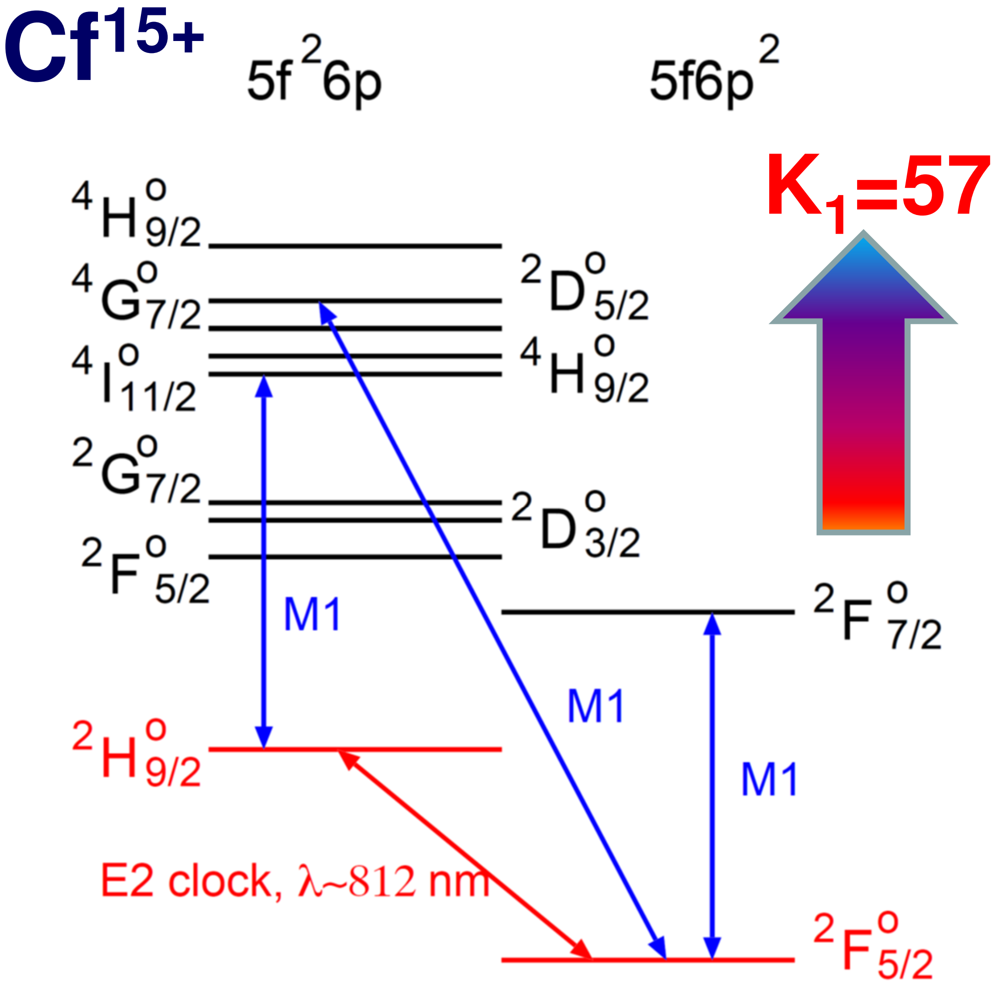
Sn-like Pr^{9+}

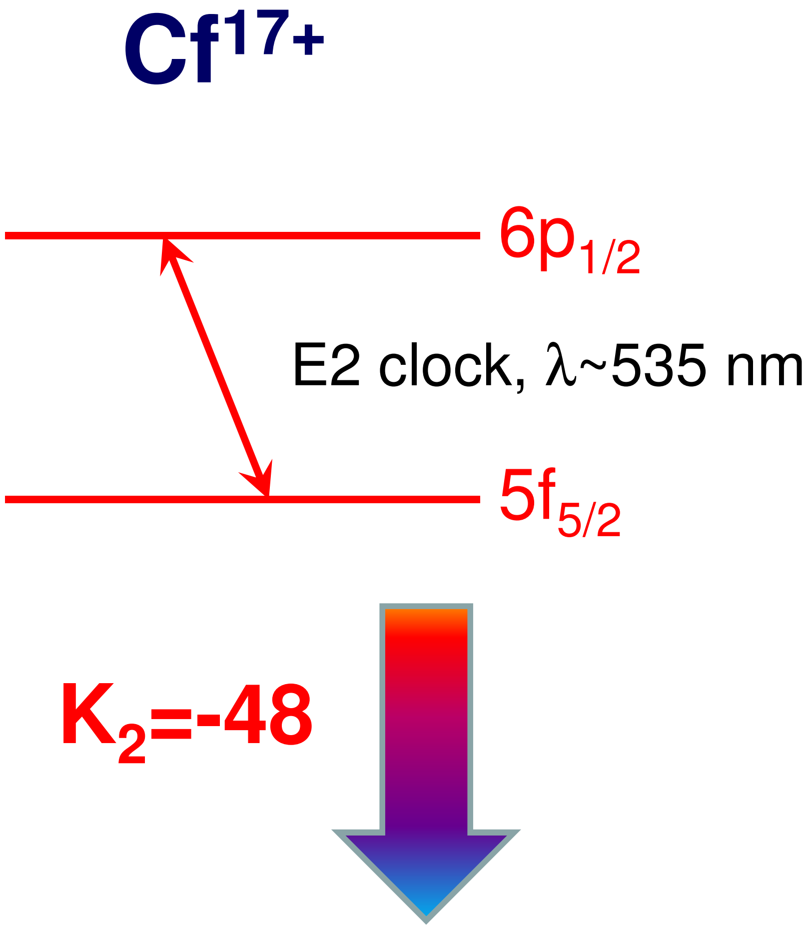
5p4f J=3

495(13) nm

5p^2 $^3P_0$

Factor of 100 enhancement for α-variation!





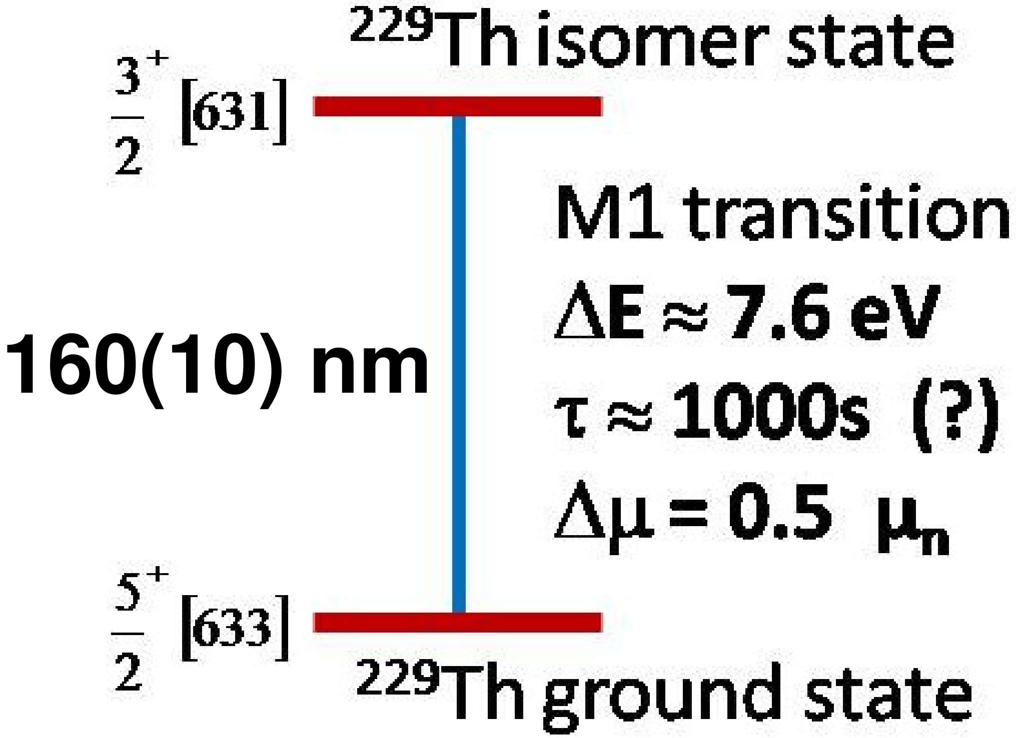
Review of all HCI proposals: **M. G. Kozlov, M. S. Safronova, J. R. Crespo López-Urrutia, P. O. Schmidt, arxiv:1803.06532, submitted to RMP (2018).**

HCI for tests of Lorentz invariance:

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).

Th ion nuclear clock

Th nuclear clock:
Nuclear isomer transition in 229 Thorium has been suggested as an etalon transition in a new type of optical frequency standard.



M1 transition
$\Delta E \approx 7.6$ eV
$\tau \approx 1000$s (?)
$\Delta\mu = 0.5\ \mu_n$

Possible orders of magnitude enhancement to the variation of α and $\frac{m_q}{\Lambda_{QCD}}$ but orders of magnitude uncertainty in the enhancement factors.

AMO precision experiments will continue to improve in coming decades

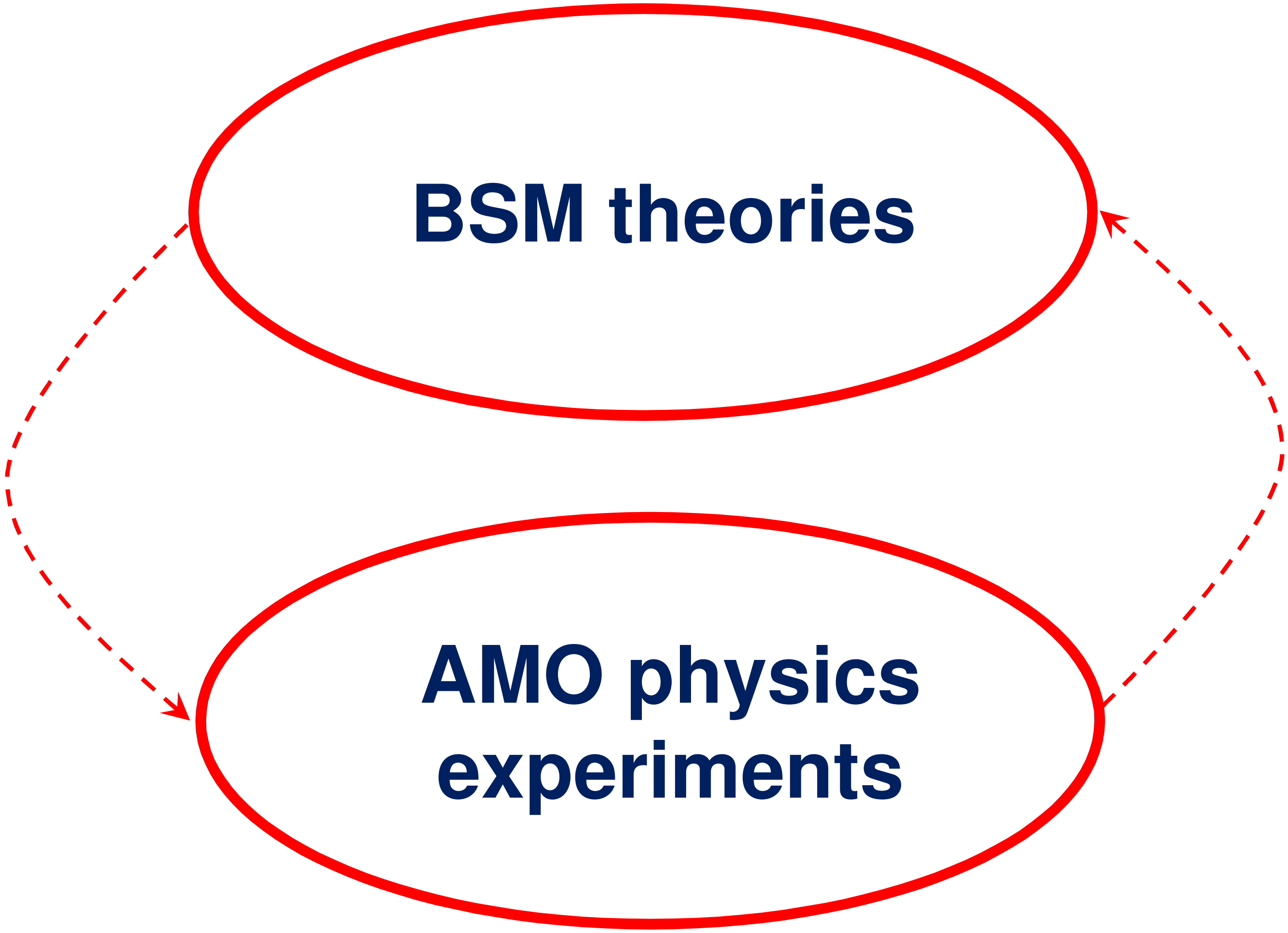
1. Laser cooling of molecules
2. Molecules in optical lattices & precision control
3. Ultracold highly-charged ions
4. Improved other quantum sensing techniques
5. Improved laser technologies
6. Measurements beyond the quantum limit
7. Quantum information tools and materials for DM searches
8. Ultra intense laser pulses

……

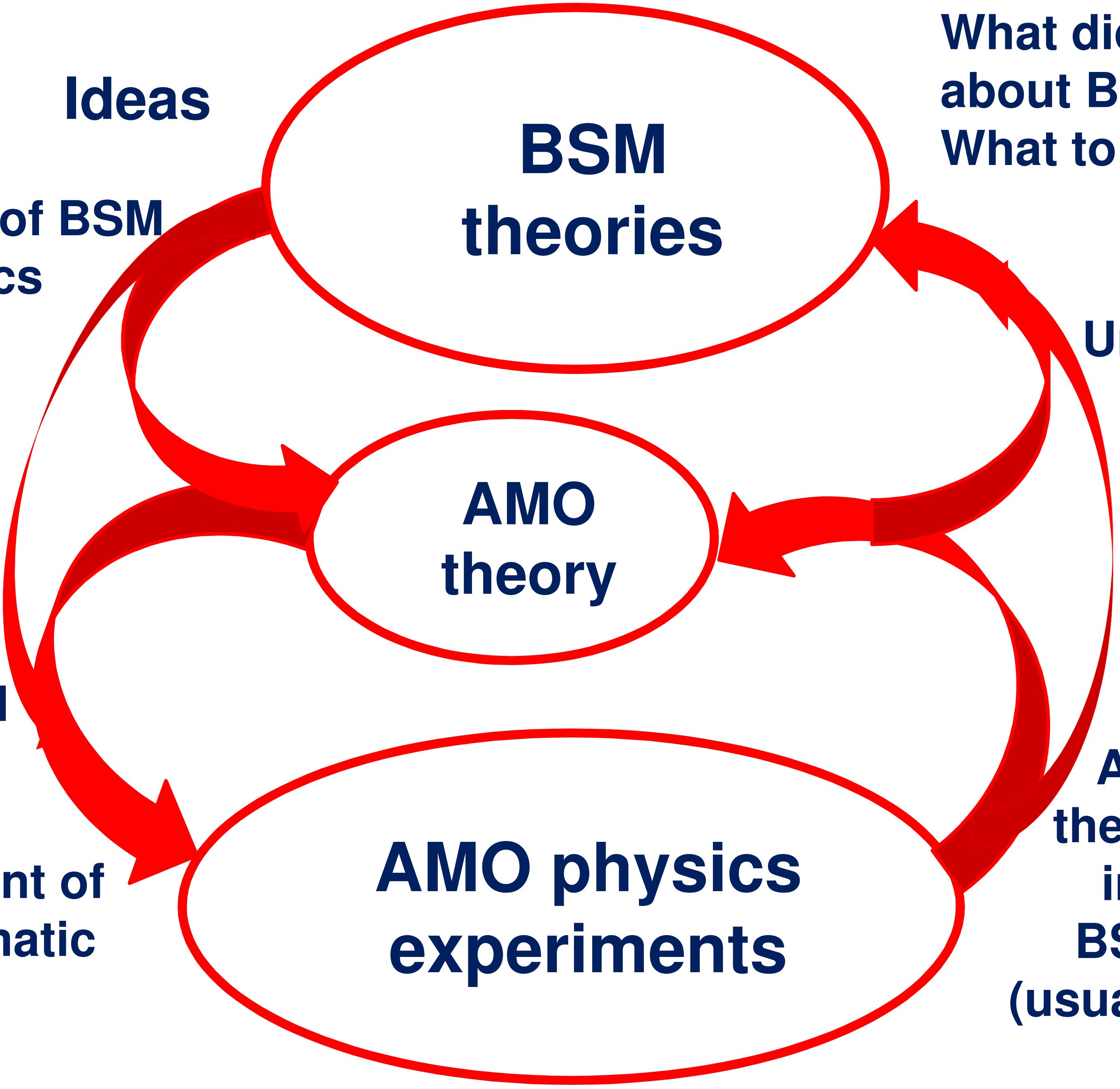
AMO theory expertise for future dark matter searches

Structure, collisional and ionization effects in atoms and molecules

New calculation on WIMP scattering on electrons: B. M. Roberts, V. V. Flambaum, G. F. Gribakin; Phys. Rev. Lett. 116, 023201 (2016); B. M. Roberts, V. A. Dzuba, V. V. Flambaum, M. Pospelov, Y. V. Stadnik, Phys. Rev. D 93, 115037 (2016)


BSM theories
AMO physics experiments

Need to build much stronger connections!



BSM theories

AMO theory

AMO physics experiments

Ideas

Connection of BSM
to SM physics

Resulting
AMO
Hamiltonian

Experimental
Signal

Assessment of
SM systematic
effects

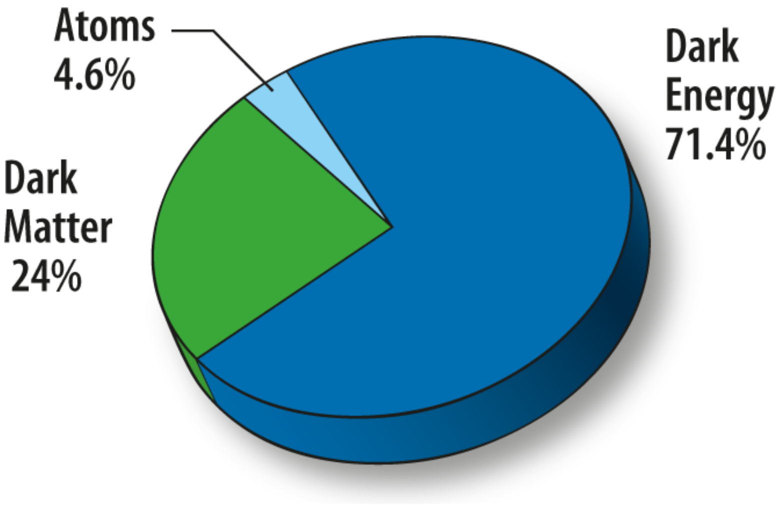
What did we learn
about BSM physics?
What to do next?

Understanding
experimental
capabilities
for future
ideas

Analysis of
the experiment
in terms of
BSM physics
(usually need AMO
theory)

Conclusion

Great potential for discovery of new physics



NEED

BSM PHYSICS

AMO THEORY AND EXPERIMENTS

Future:
New Systems
New Experiments
New Physics?

Topical Group on Precision Measurement & Fundamental Constants (GPMFC) annual workshop

Even years – day before DAMOP
Odd years – day before the April meeting

2015 Tests of Fundamental Symmetries (April meeting)

2017 Ultralight Dark Matter (April meeting)

2018 Precision-measurement Searches for New Physics (May 28, DAMOP)
https://www.aps.org/units/damop/meetings/annual/gpmfc-workshop.cfm

2019 New Ideas in Dark Matter searches (April meeting)