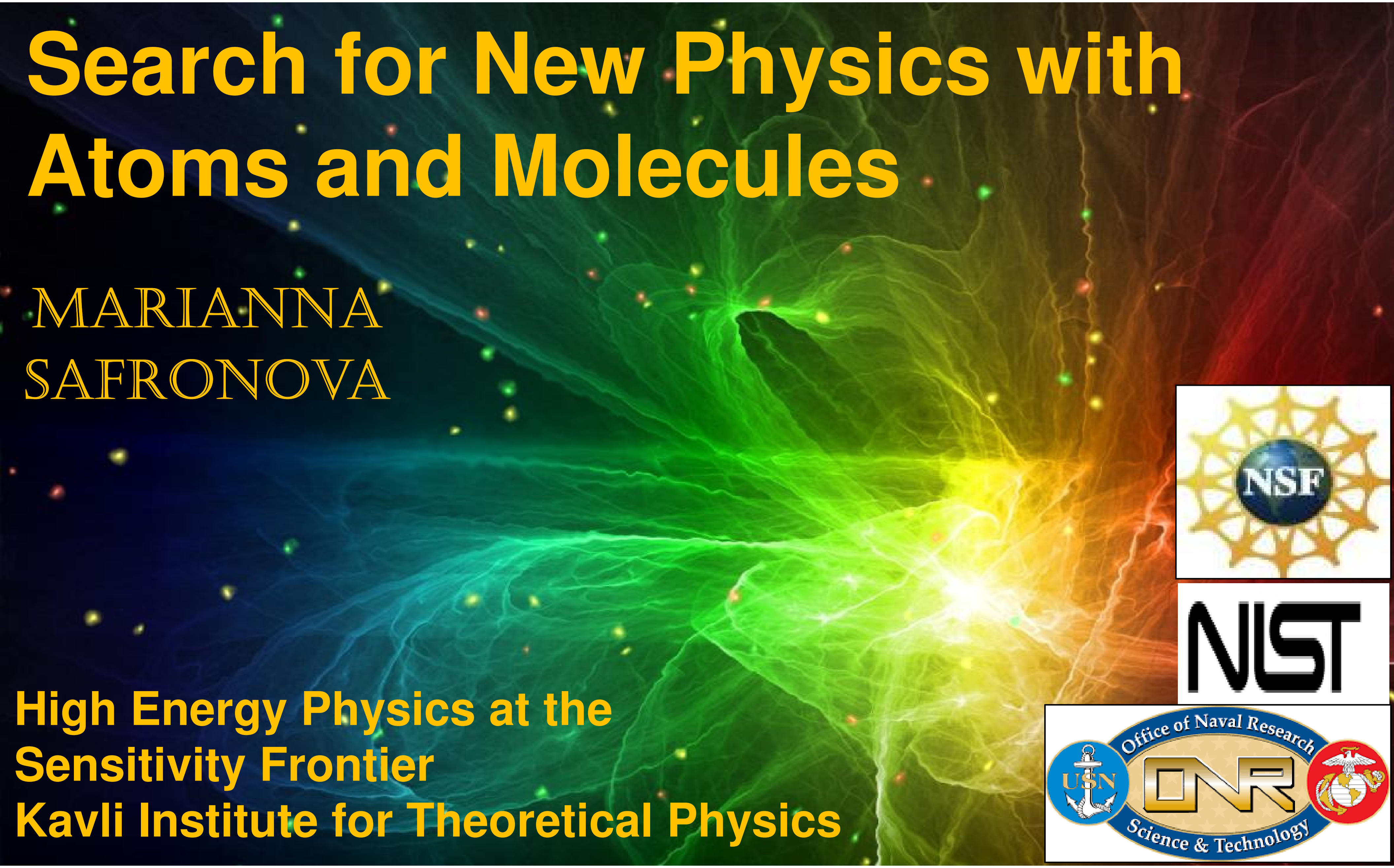


Search for New Physics with Atoms and Molecules

MARIANNA
SAFRONOVA

High Energy Physics at the
Sensitivity Frontier
Kavli Institute for Theoretical Physics

NSF

NIST

Office of Naval Research
USN
ONR
Science & Technology

UNIVERSITY OF DELAWARE

jqi Joint
Quantum
Institute

Outline

- Introduction: BSM searches with atomic, molecular and optical (AMO) physics: advantages and challenges

- General introduction: Why now is a good time to search for BSM physics with atoms and molecules? Main “tools”.

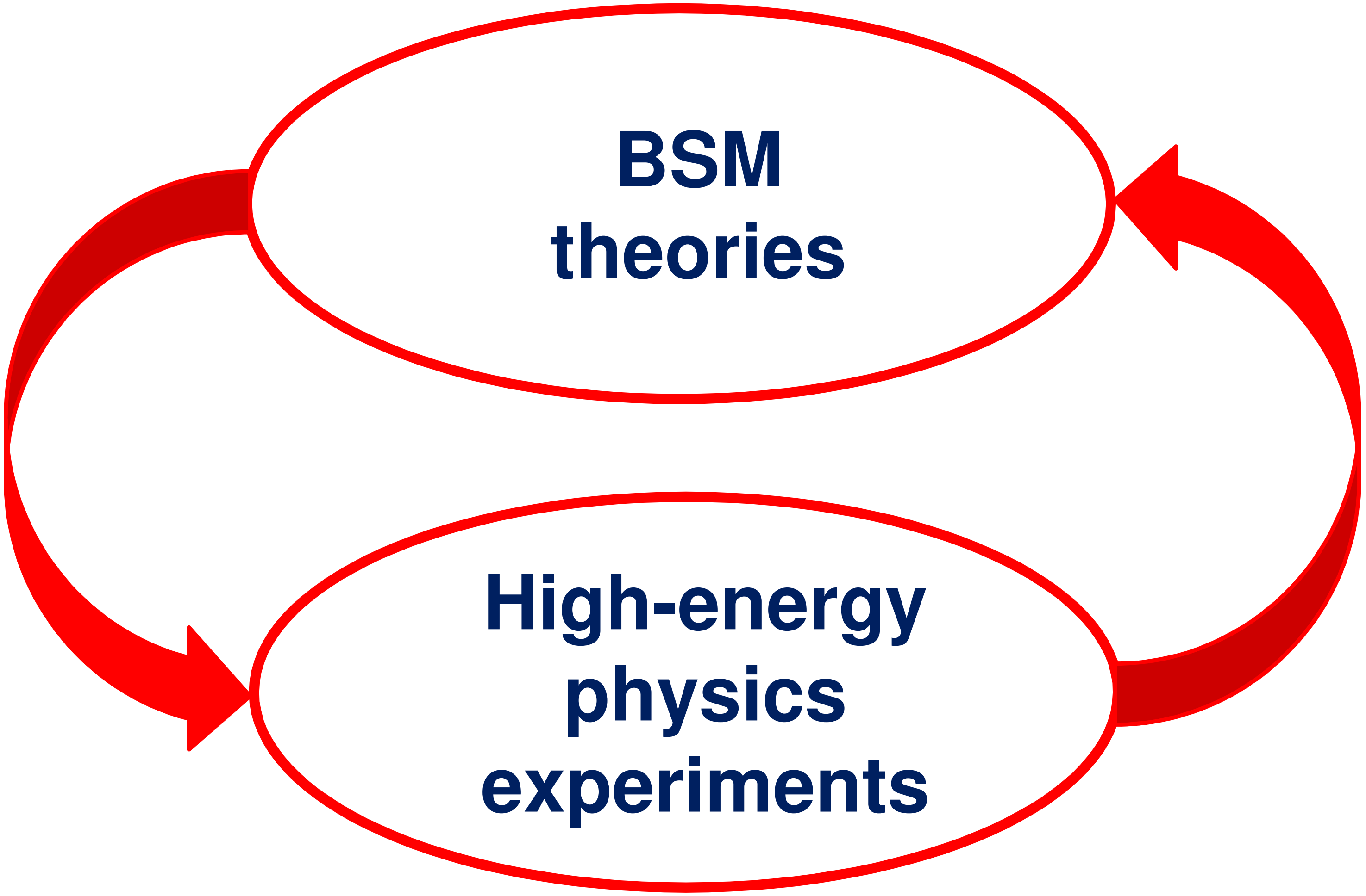
- Main classes of AMO BSM searches.

- Example 1: Electric-dipole moments (dedicated experiments)

- Example 2: Search for the violation of Lorentz invariance (not all are dedicated experiments)

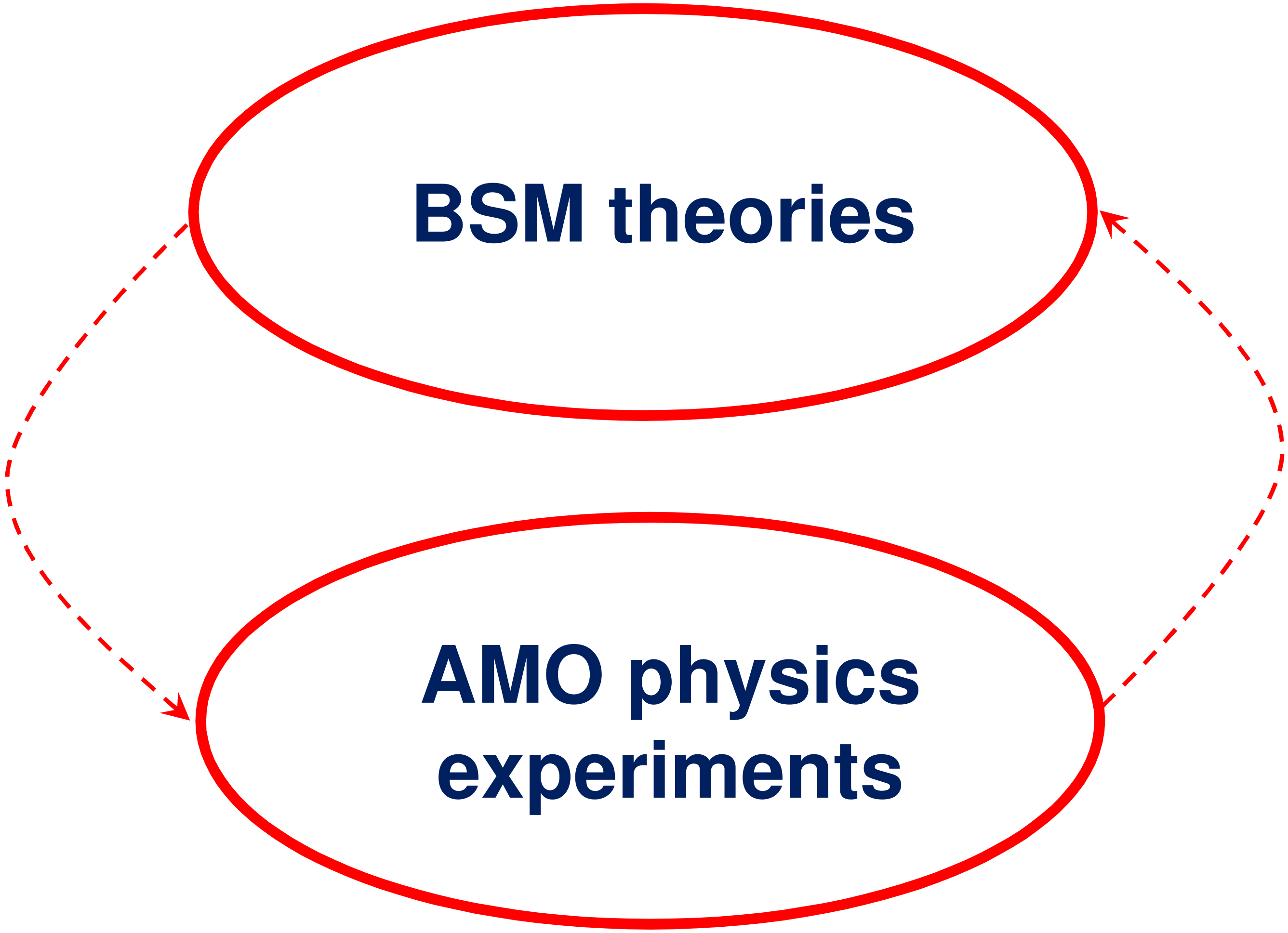
- Example 3: Proton radius puzzle – a few sigma discrepancy

- Future

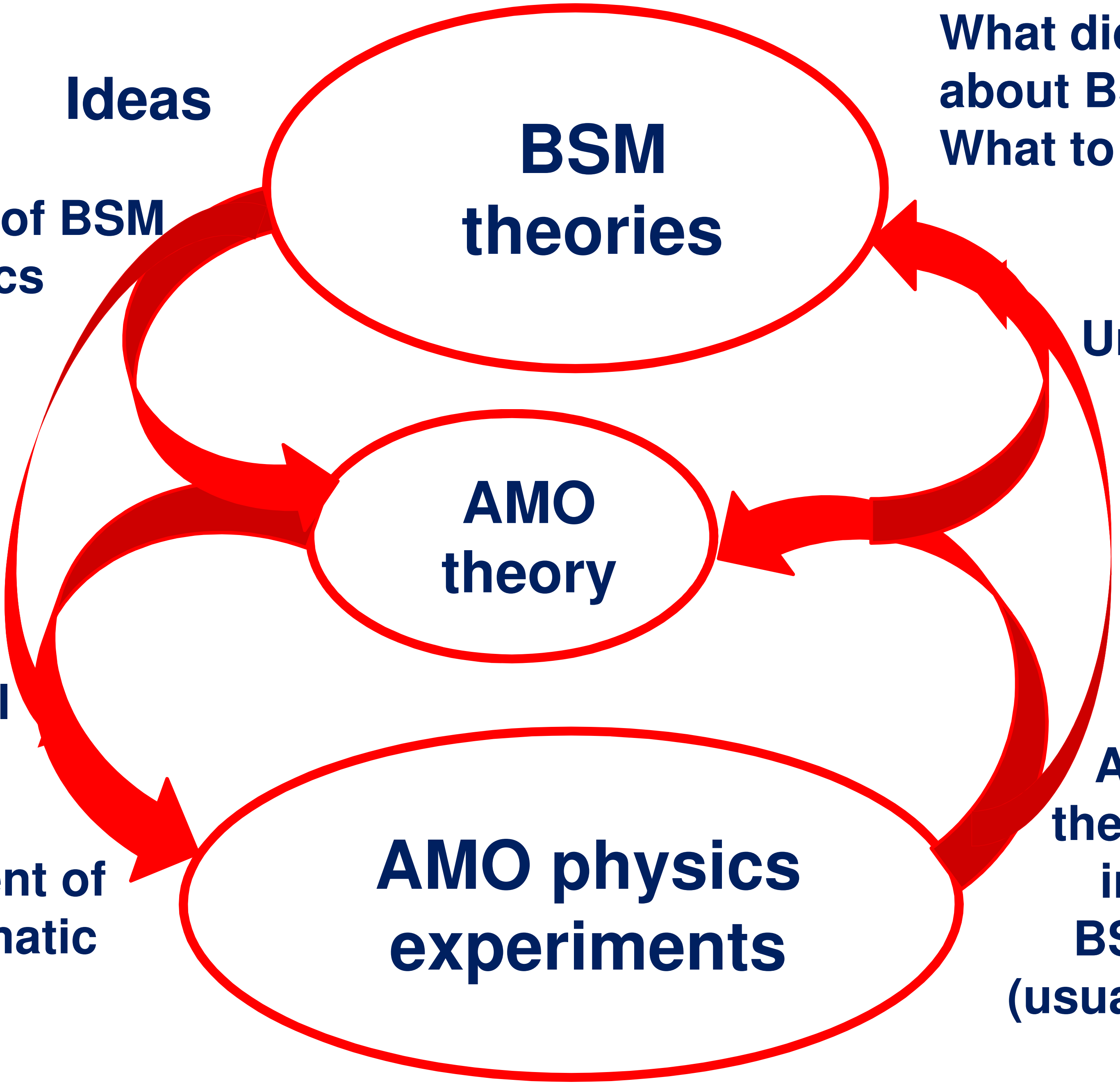


BSM theories

High-energy physics experiments


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

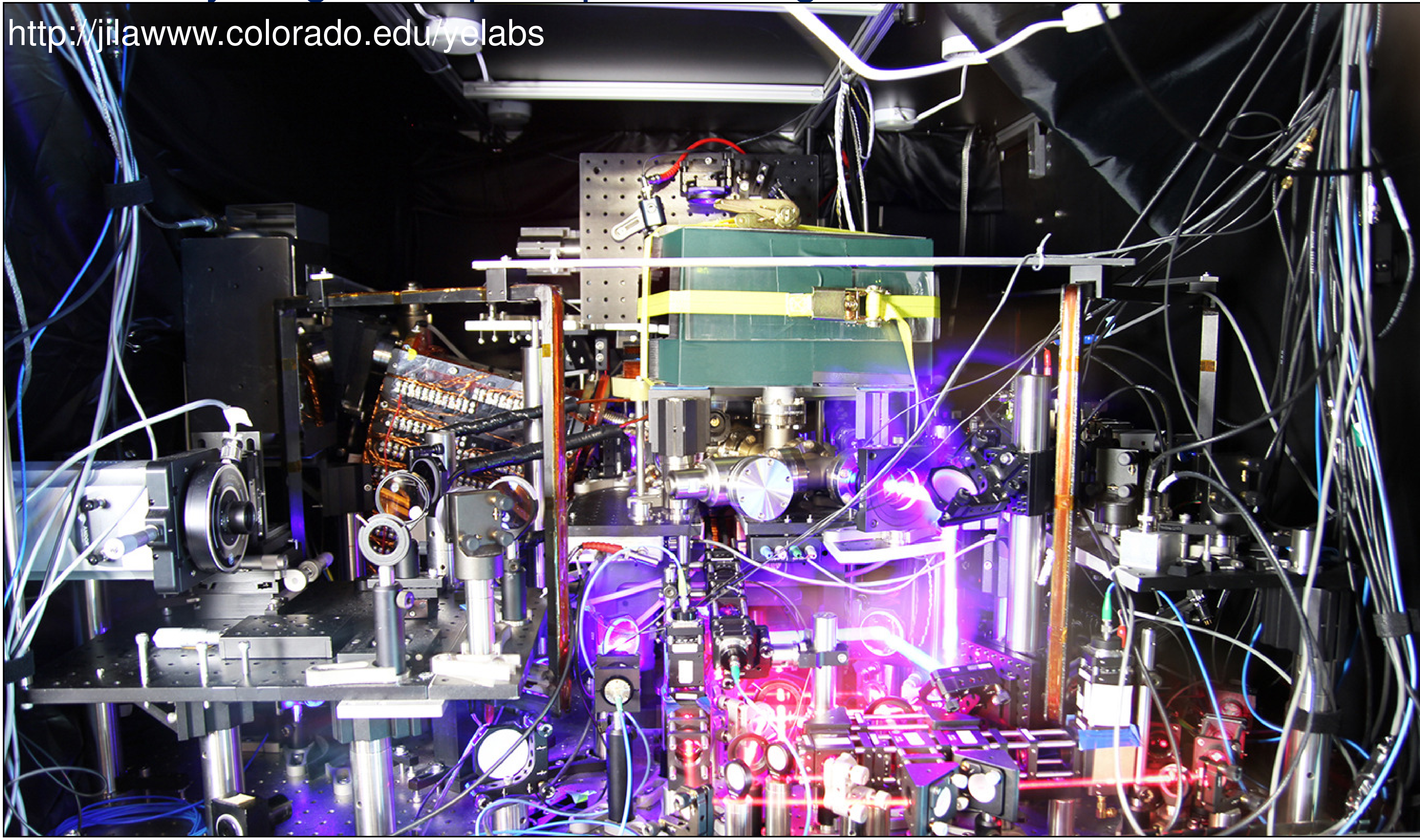
What did we learn
about BSM physics?
What to do next?

Understanding
experimental
capabilities
for future
ideas

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

AMO searches for BSM physics: advantages

1. Experiments are (mostly) table-top. Can be build in University labs by single/few principle investigators.


http://jilawww.colorado.edu/yelabs

AMO searches for BSM physics: advantages

1. Experiments are (mostly) table-top. Can be build in University labs by single/few principle investigators.

2. In many cases, **experimental set up are already designed** for other applications.

3. In some cases, experiments can be done very quickly.

4. Experimental techniques are rapidly evolving, very strongly driven by other applications, with potential for quick significant improvements.

5. AMO field is growing with many new postdocs looking for interesting new projects to do as a faculty.

Community is interested in BSM physics research and scientists in other AMO subfields may be willing to do new experiments.

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

Need atomic and molecular theory to search for new physics!

- **New ideas:** what other fundamental tests can be done with atoms and molecules?
- **Propose new experiments**: select systems with the largest enhancements of effects of interest
- **Calculate properties** of systems
- Analyze experiments to **extract possible new physics**
- Propose **new tools for precision measurements**
  New clock proposals: Th nuclear clock, highly-charged ions?

AMO searches for BSM physics: problems

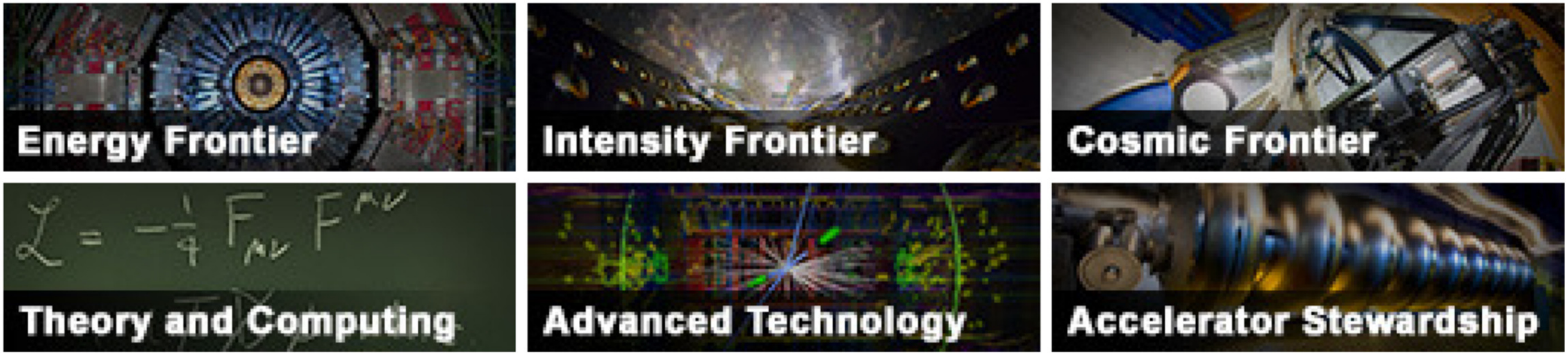
1. Lack of connection to BSM theories

2. “Measuring zero” – what do we learn from negative results?

   “Reducing parameter space” idea is mostly alien to AMO experiment.

3. Division of experimental effort by the measurement signal or by a specific interpretation. Lack of cross-interpretation of the results from various experiments.

4. US finding dilemma – DOE does not have a “Precision Frontier”



Why now?

It is a great time to use AMO experiments for BSM physics searches!

Advances in AMO Physics:
New world of ultracold

Steve Chu

Claude Cohen-Tannoudji

Bill Phillips

1997
Nobel Prize
Laser cooling
and trapping

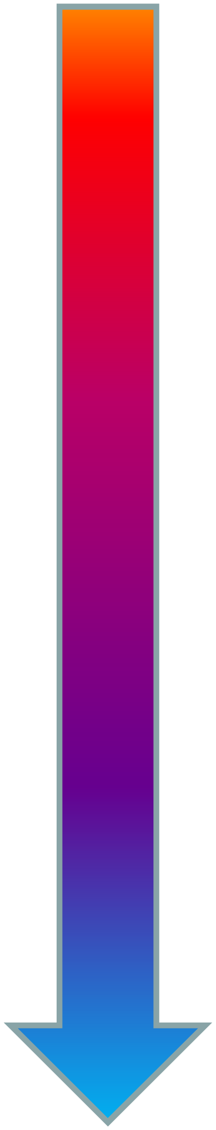
Eric Cornell

Wolfgang Ketterle

Carl Wieman

2001
Nobel Prize
Bose-Einstein
Condensation

300K

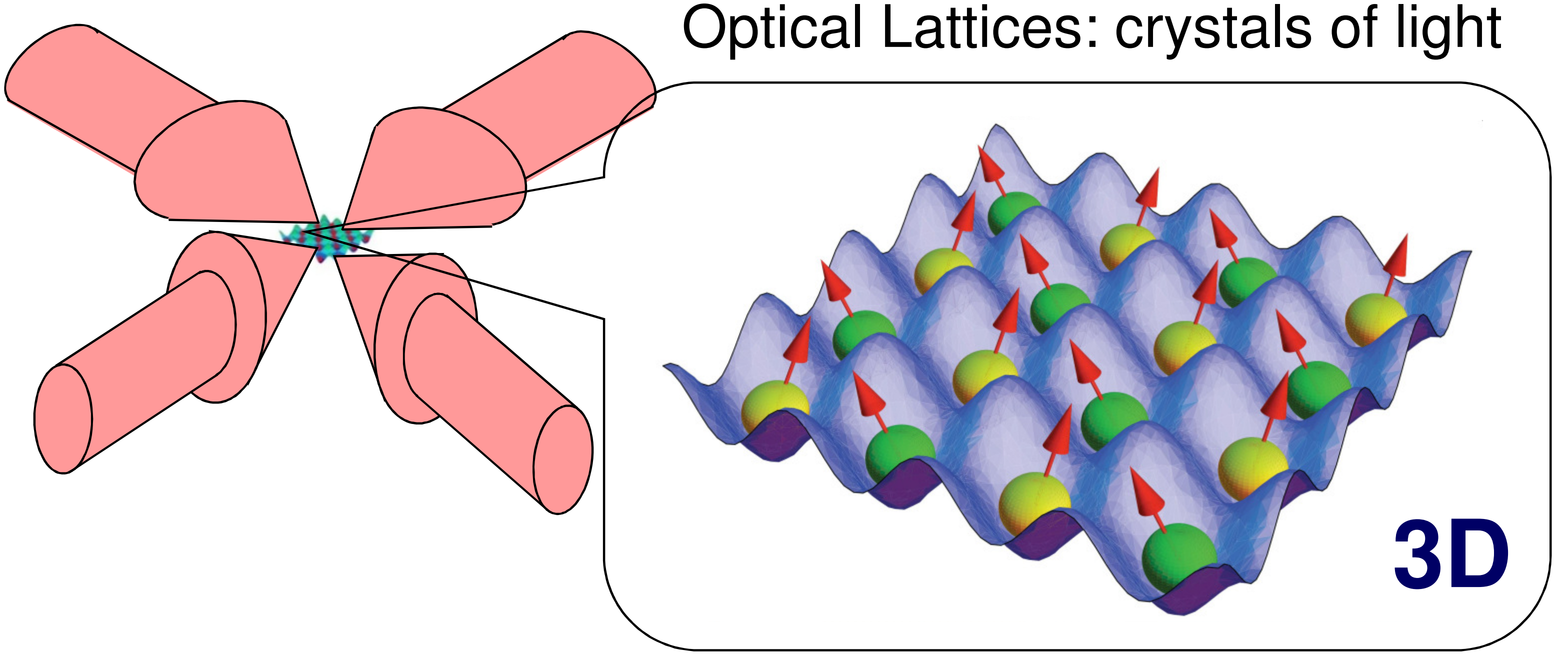


500nK

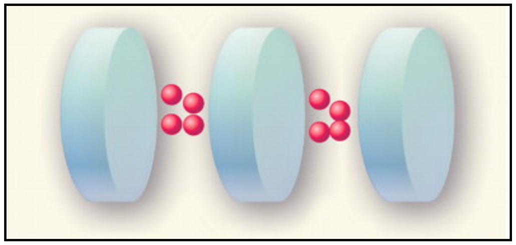
nobel.org

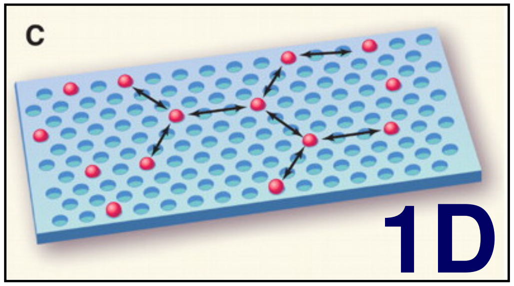
Trapping neutral atoms and ions

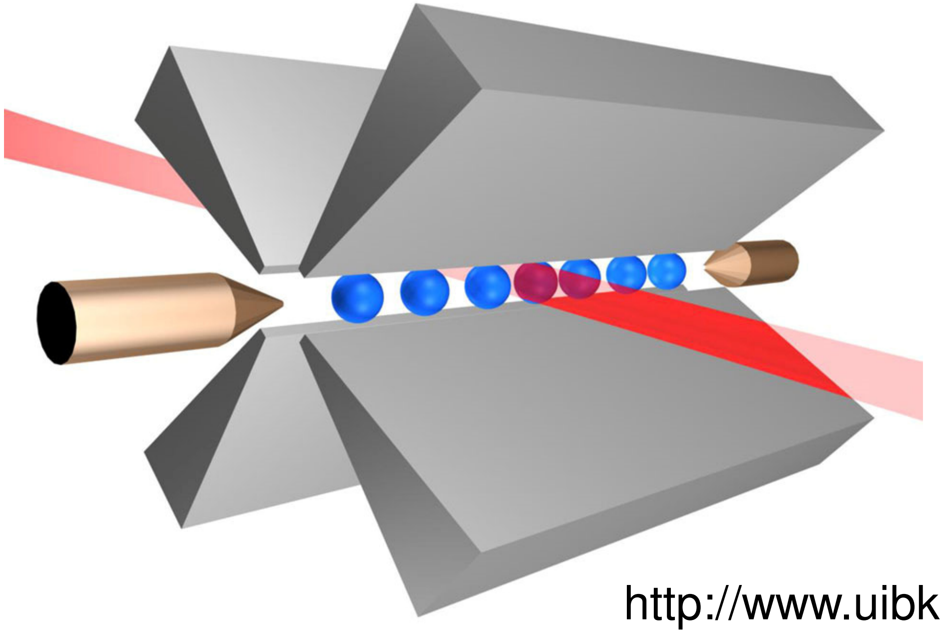
Optical Lattices: crystals of light



2D







Trapped ion chains

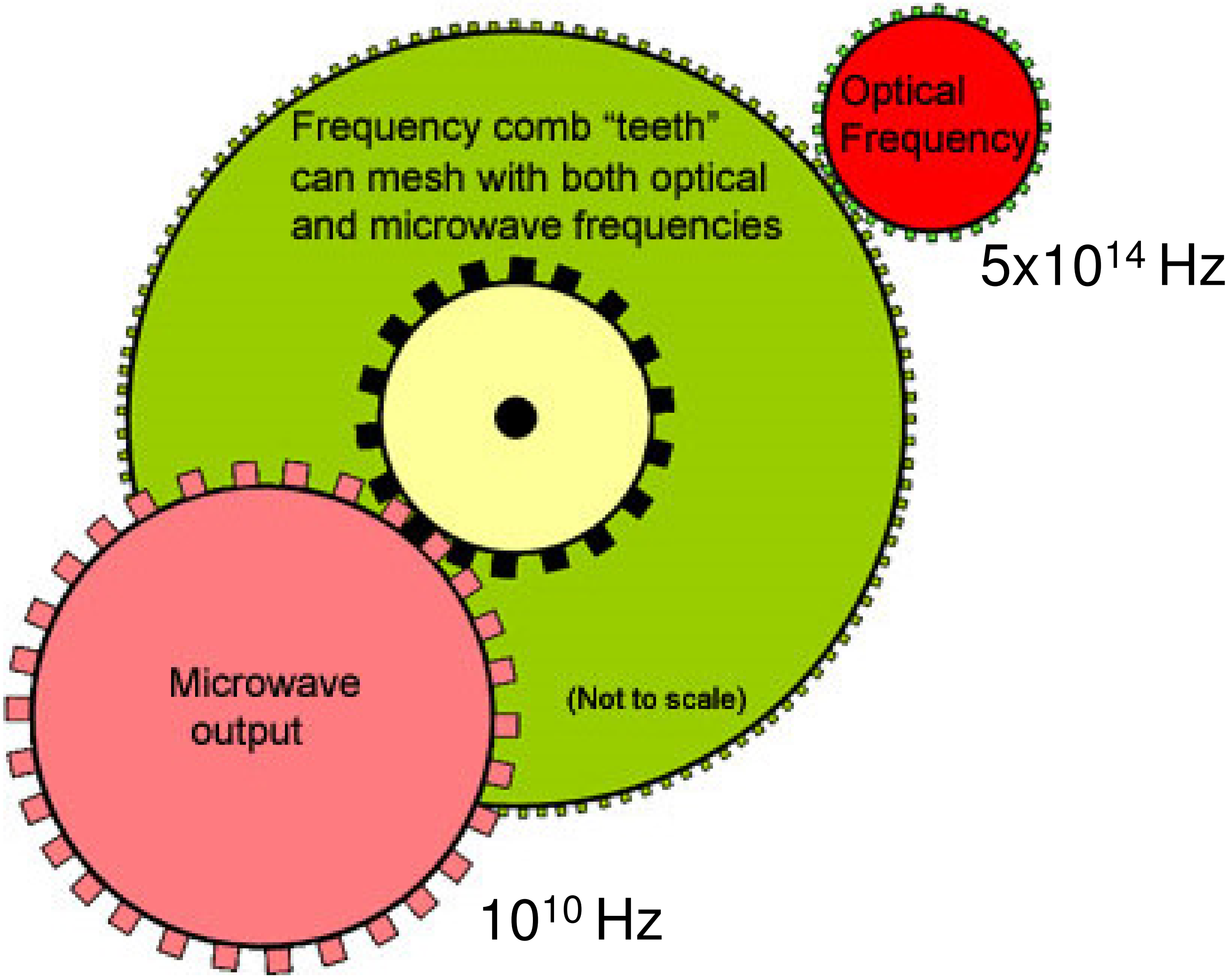
http://www.uibk.ac.at/th-physik/qo/research/trappedions.html

How to “count” optical frequencies

2005 Nobel Prize

Theodor Hänsch

John Hall

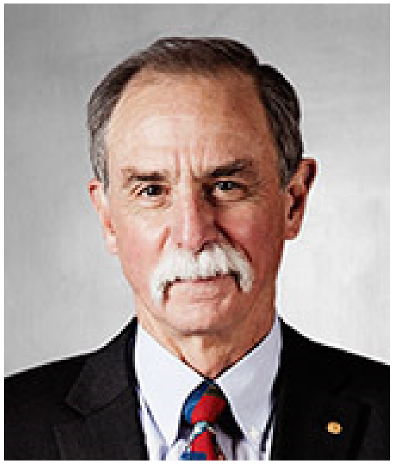


Laser-based precision spectroscopy and the optical frequency comb technique

nist.gov

Quantum Control: measuring and manipulation of individual quantum systems

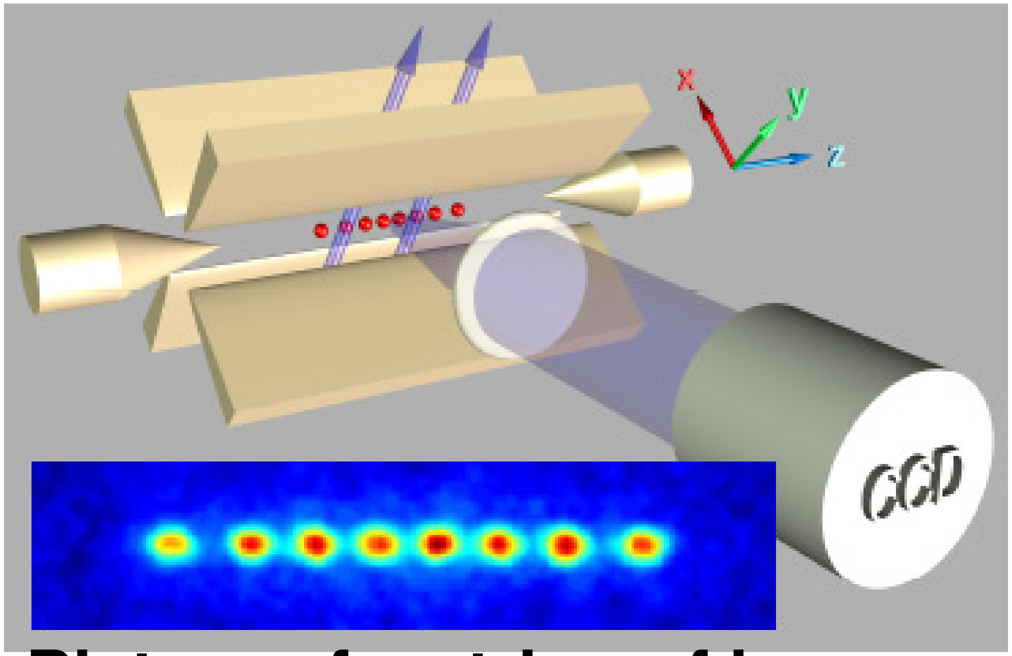
2012 Nobel prize



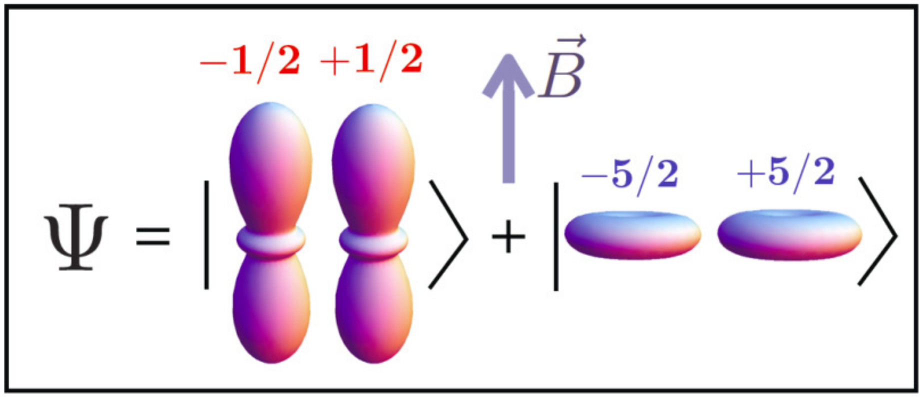
David Wineland

Serge Haroche

nobel.org



Picture of a string of ions



Ca^+
$3d_{5/2}$

Making quantum superposition of two ions

Advances in Precision Atomic physics tools

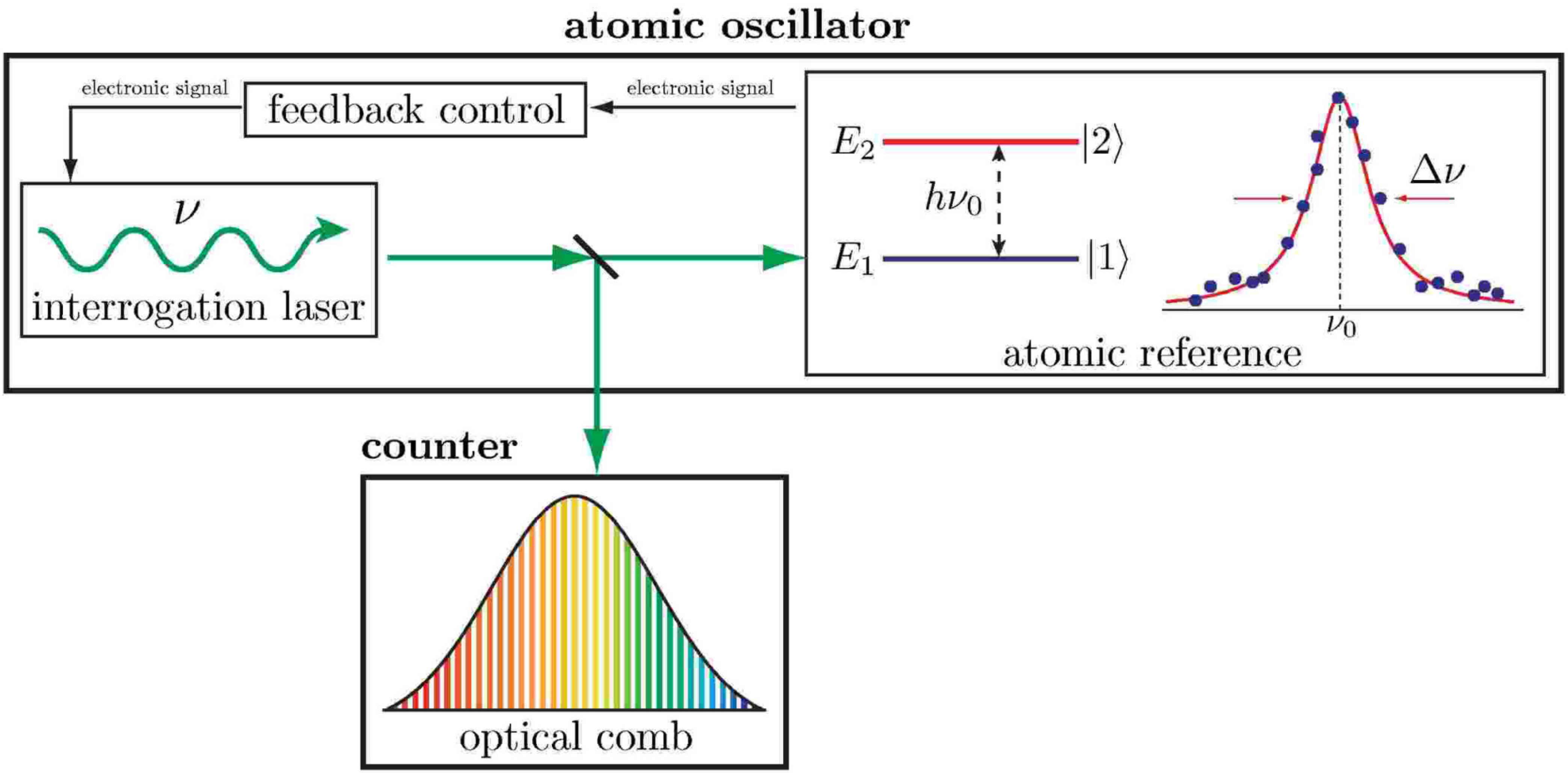
- Atomic clocks
- Atom and Light interferometers

  Matter Waves!
- Atomic magnetometers

- Ultracold and trapped atoms and ions
- Cold molecular beams
- Quantum information technologies

- New: Cooling of highly-charged ions
- New: UV frequency combs
- In progress: laser cooling of molecules

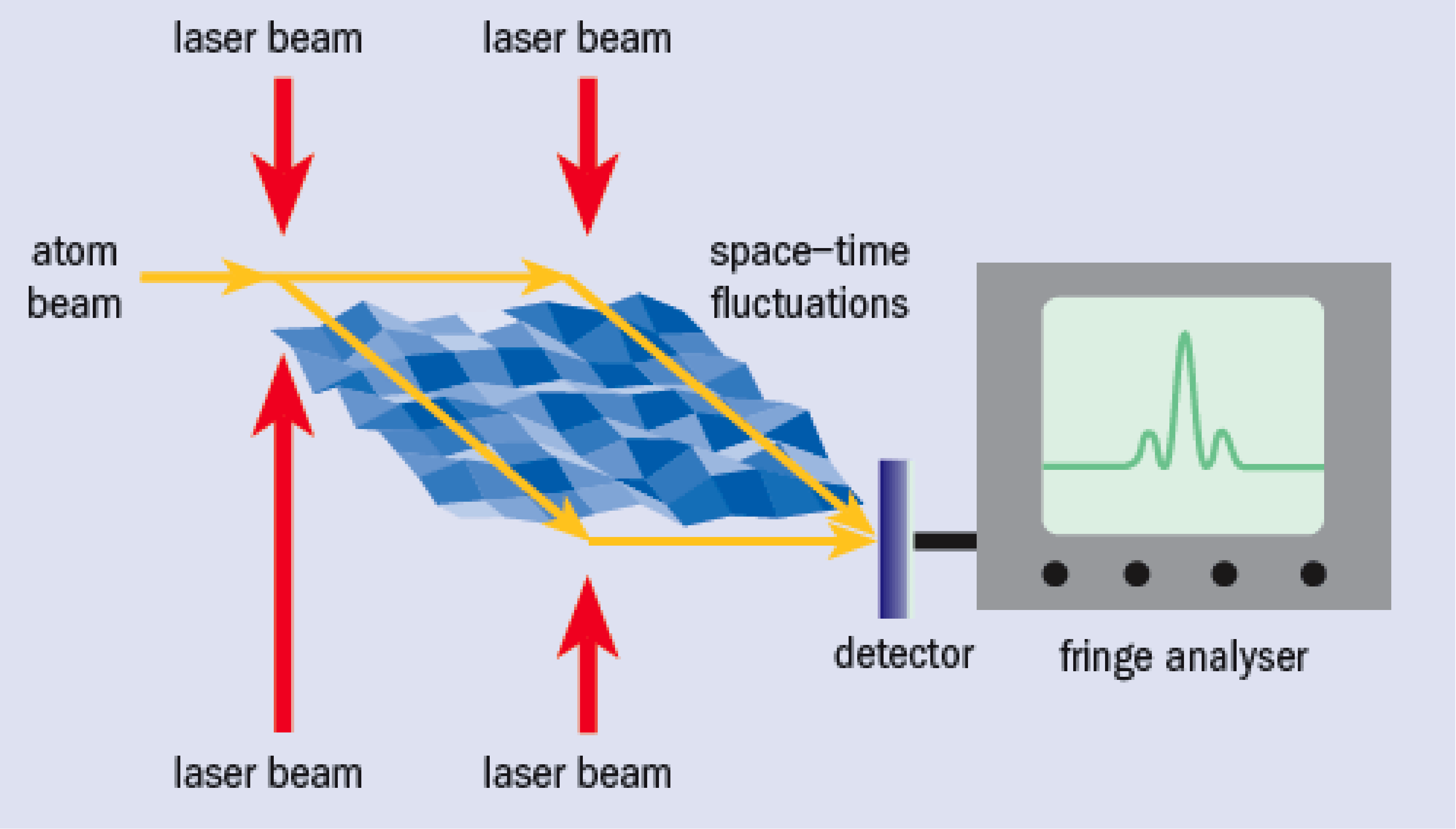
Optical atomic clock



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

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

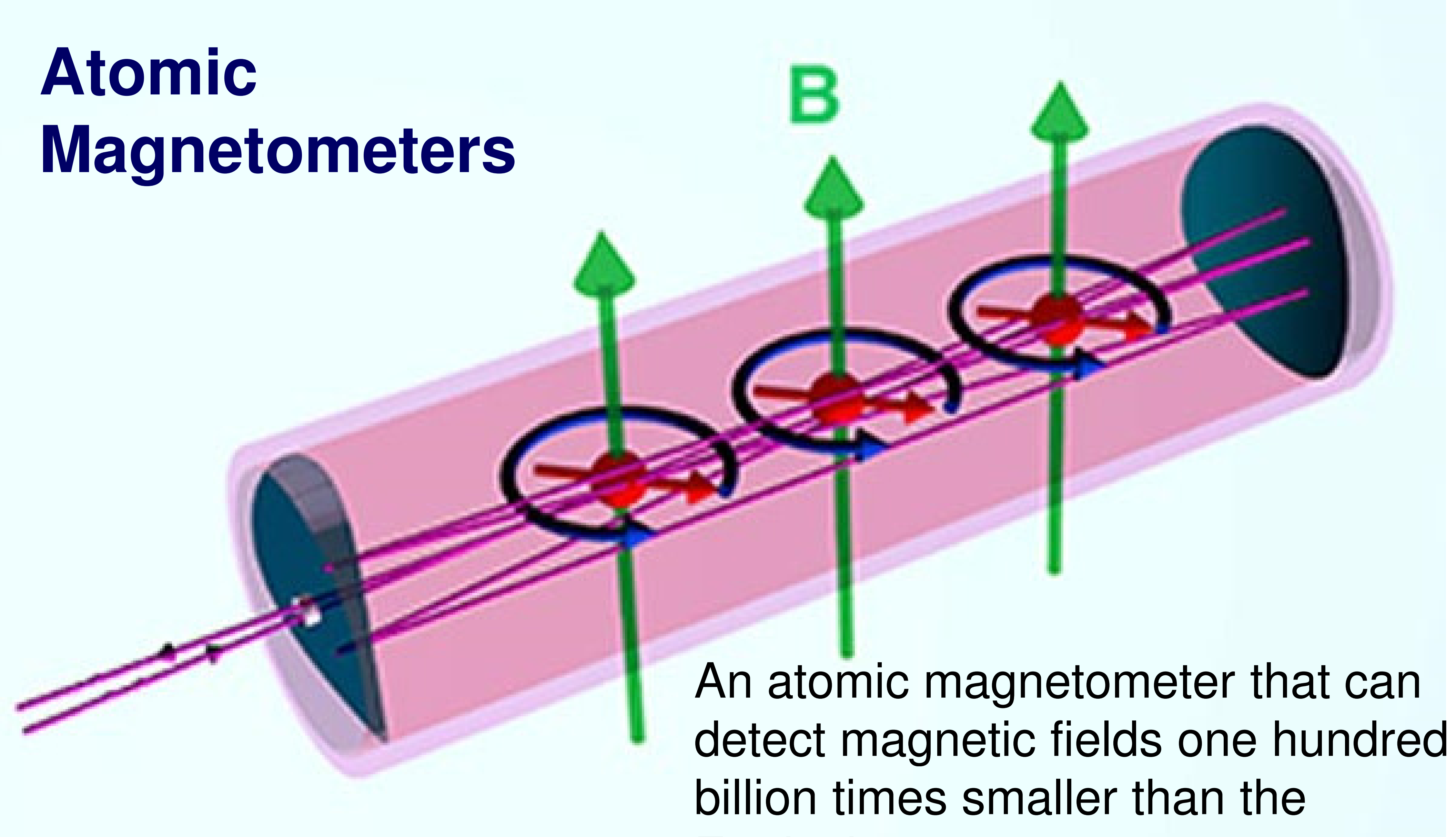
Atom Interferometers



Measure the phase difference to exceptional precision

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

Atomic Magnetometers

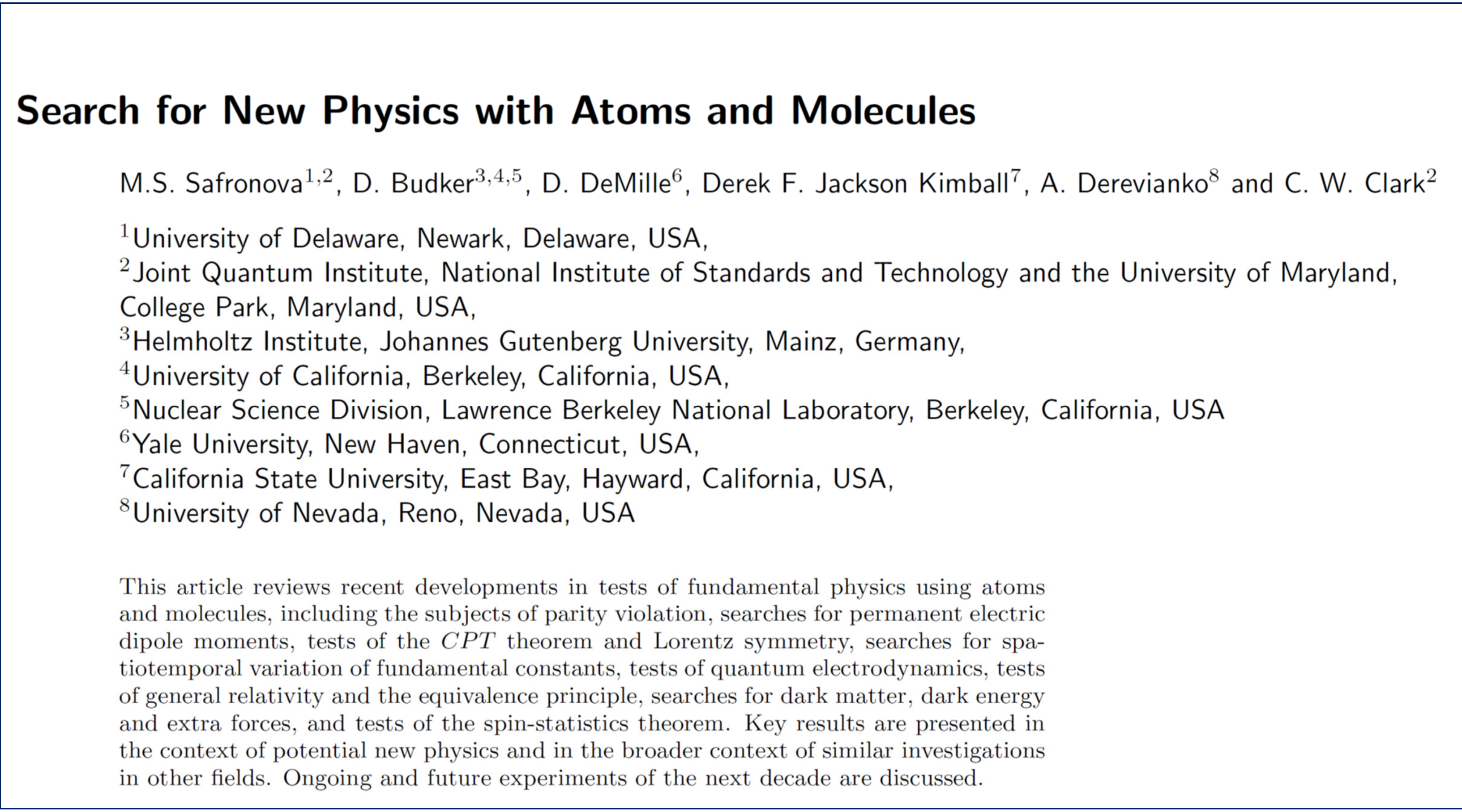


An atomic magnetometer that can detect magnetic fields one hundred billion times smaller than the Earth's!

Measure magnetic field to exceptional precision

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

Reviews of Modern Physics, in print,
arXiv:1710.01833



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]

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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
[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.

Review chapters:

1. **Search for variation of fundamental constants (next week)**

   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 (next week)**

   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) (next week)

- 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

Example 1: EDM

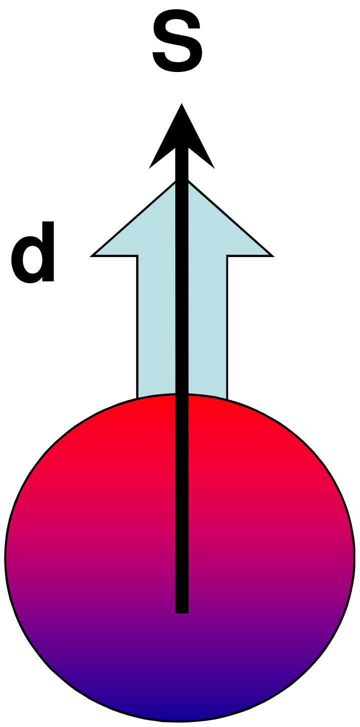
The search for the electron electric-dipole moment

Dedicated experiments
Well-motivated theoretically
High discovery potential

EDM review: arXiv:1710.02504

Permanent electric-dipole moment (EDM)

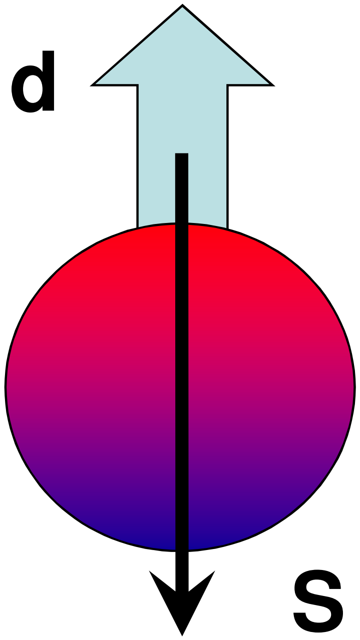
Time-reversal invariance must be violated for an elementary particle or atom to possess a **permanent EDM.**



$$t \rightarrow -t$$

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

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



$$\vec{\mathbf{d}} = d\,\frac{\vec{\mathbf{S}}}{S}$$

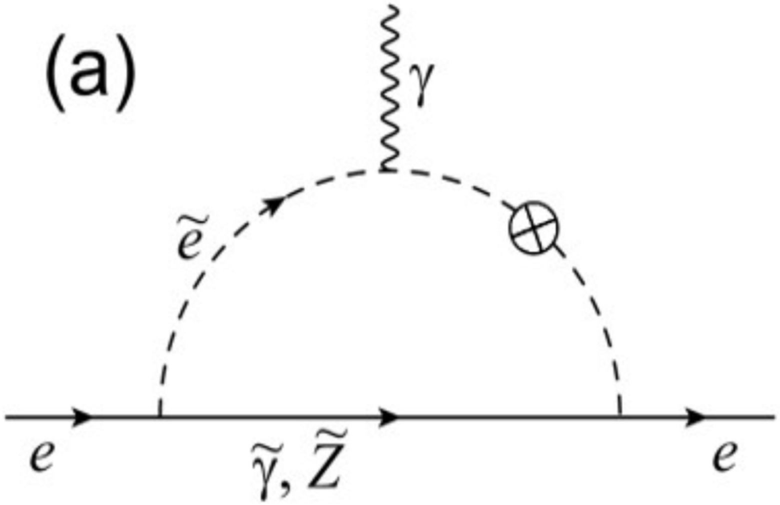
$$d = 0$$

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.

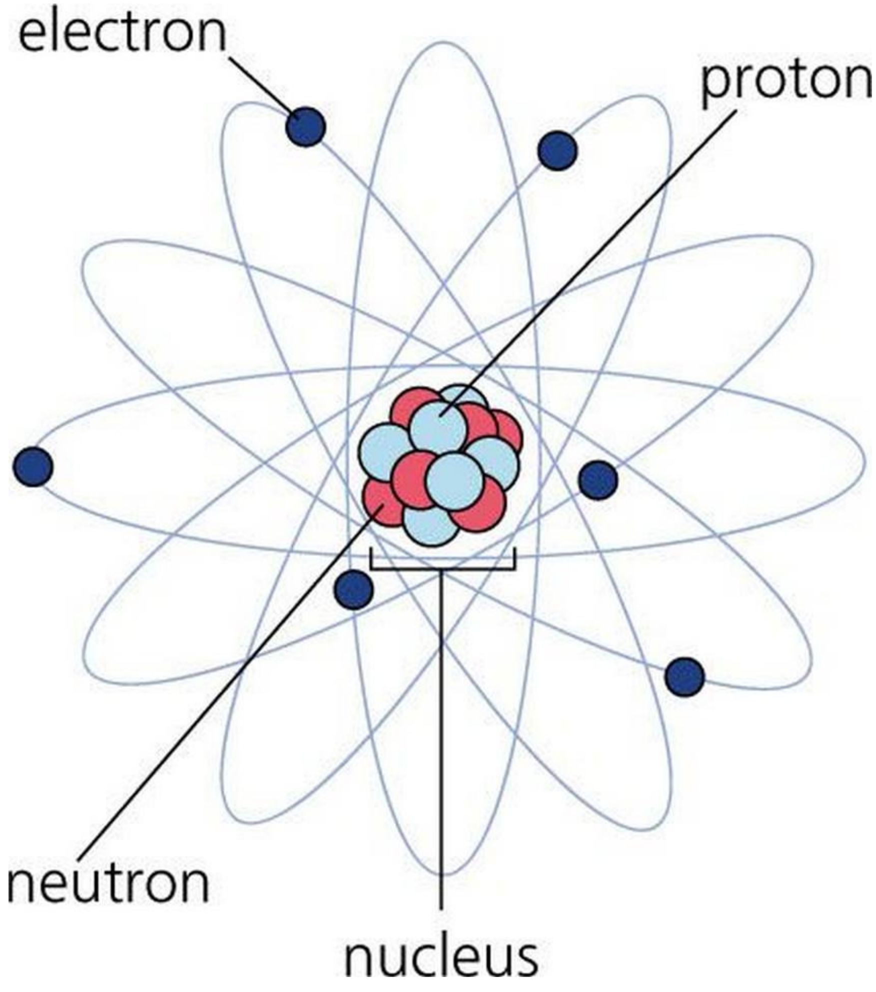


J. Engel et al., Progress in Particle and Nuclear Physics 71 (2013) 21

Sources of atomic and molecular EDMs

Electron EDM

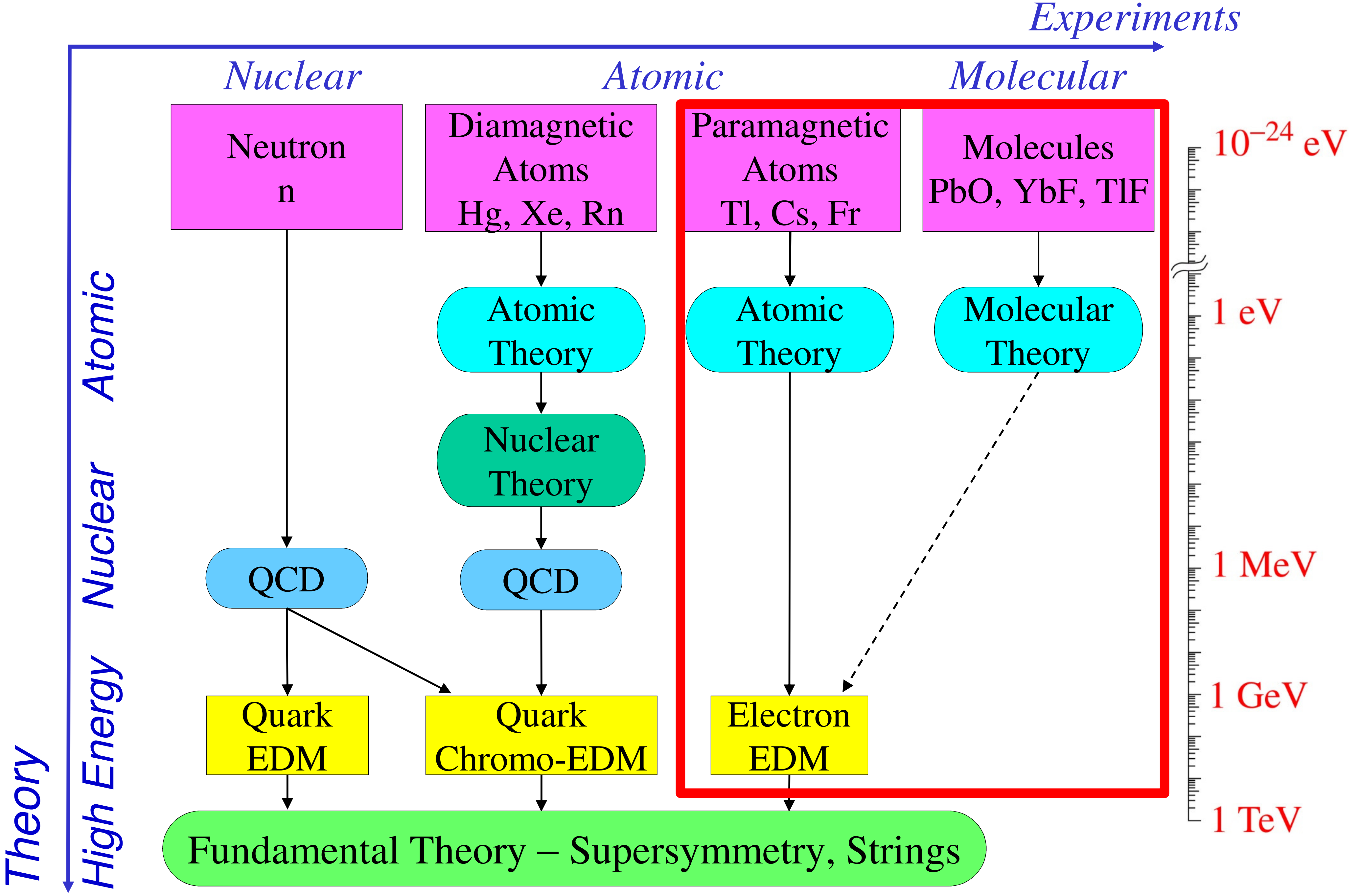
P, T – violating electron-nucleon interaction



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*

10^{-24} eV

1 eV

1 MeV

1 GeV

1 TeV

Mike Romalis, 2011 JLab talk (online)

Limits on electron EDM

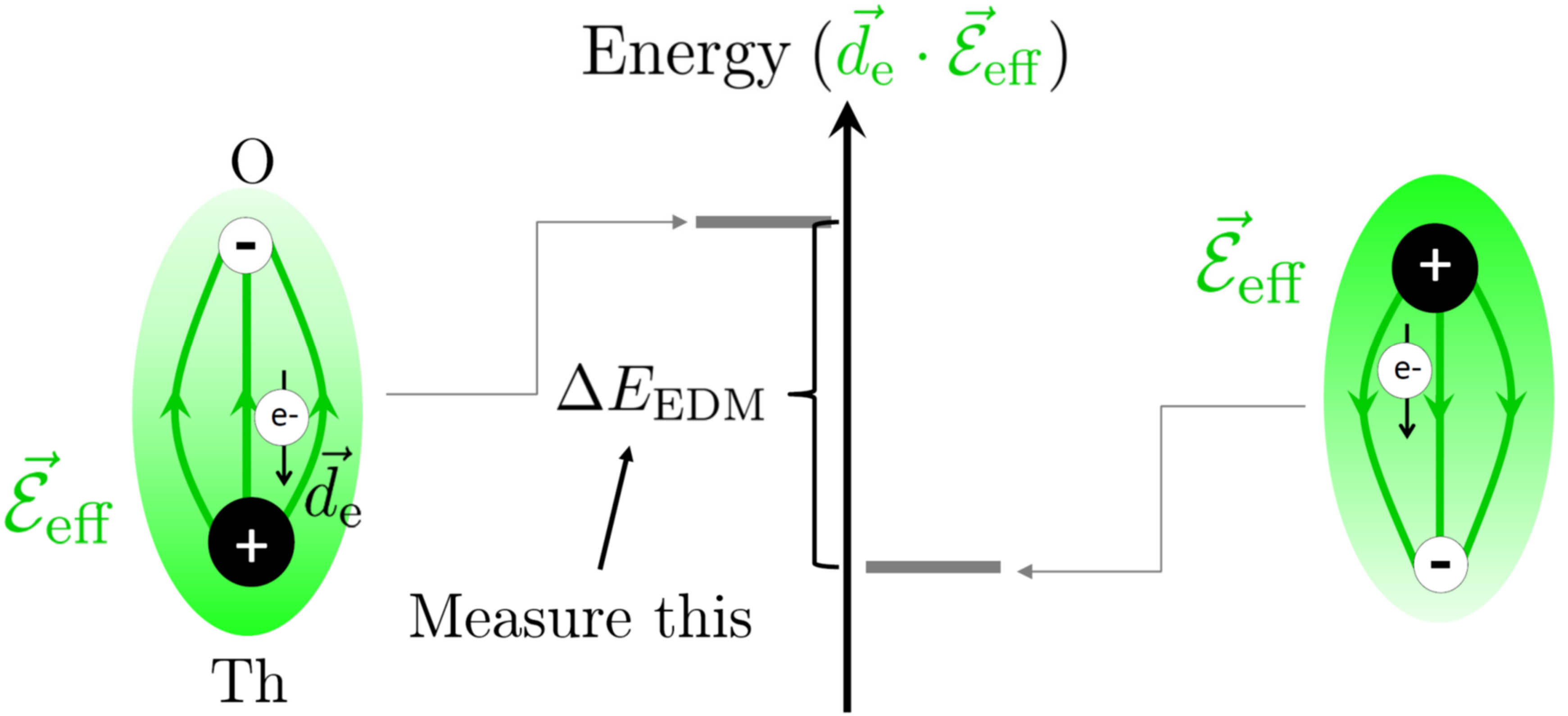
2014: ORDER OF MAGNITUDE IMPROVEMENT

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

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

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

Fundamental idea of electron EDM measurements



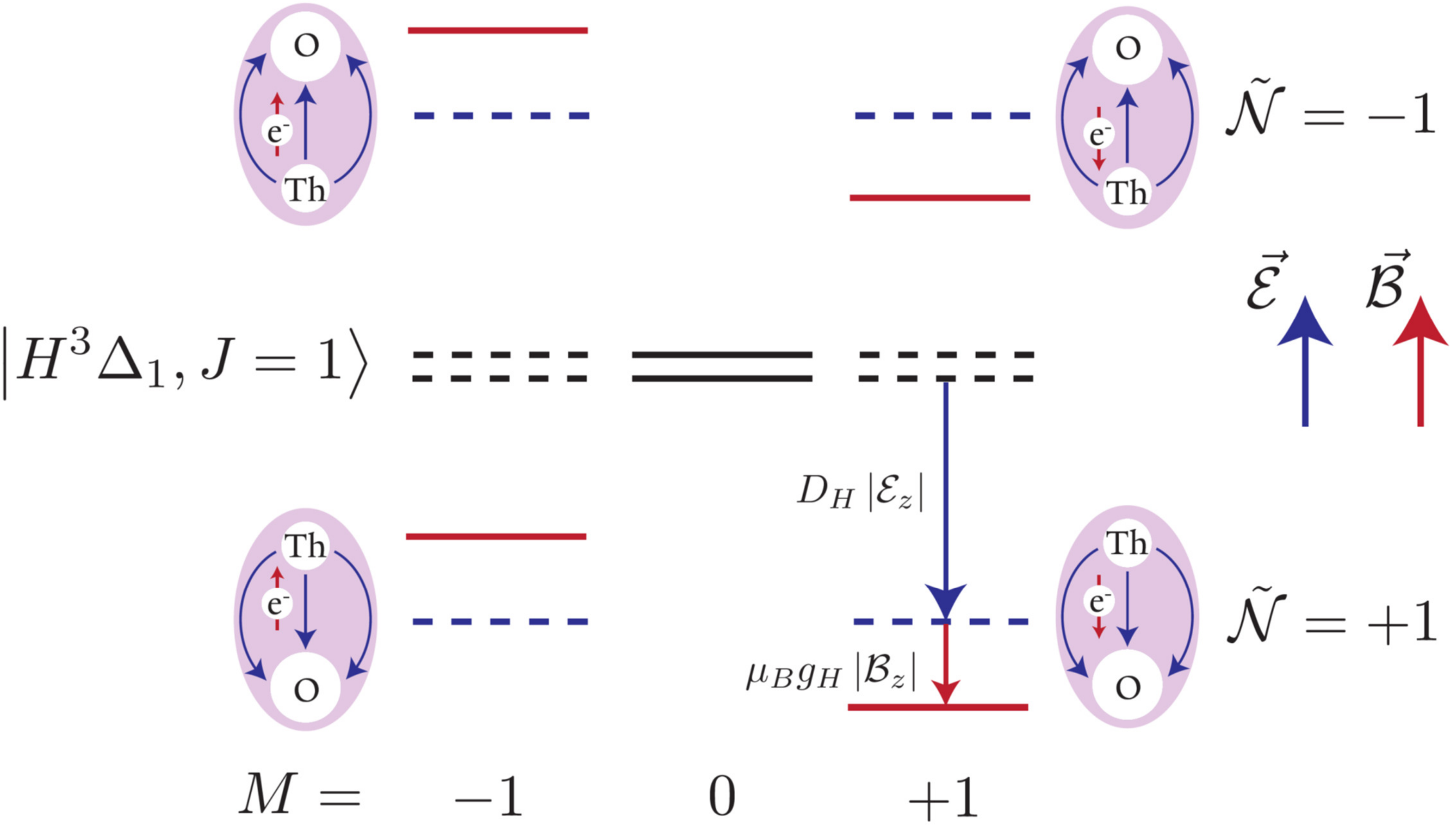
An electric dipole moment results in an energy shift in the presence of an electric field, such as the large E-fields present near heavy atomic nuclei.

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

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

http://www.electronedm.org/

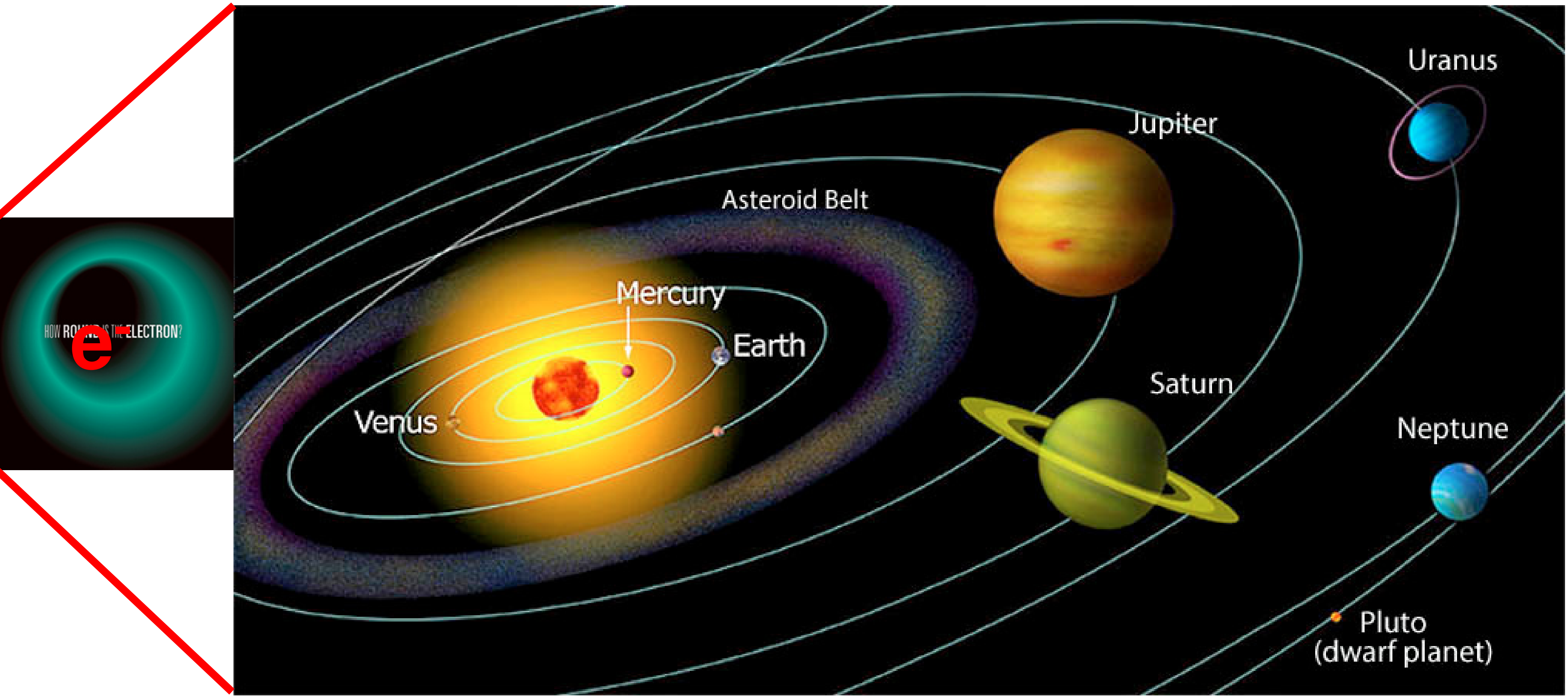
$$E\left(M,\tilde{\mathcal{N}},\tilde{\mathcal{E}},\tilde{\mathcal{B}}\right) = -\tilde{\mathcal{N}} D_H \left|\mathcal{E}_z\right| - M \mu_B g_H \tilde{\mathcal{B}} \left|\mathcal{B}_z\right|$$



Slide from: Brendon Oleary

Electron EDM

Blow up the electron to the size of the Solar System

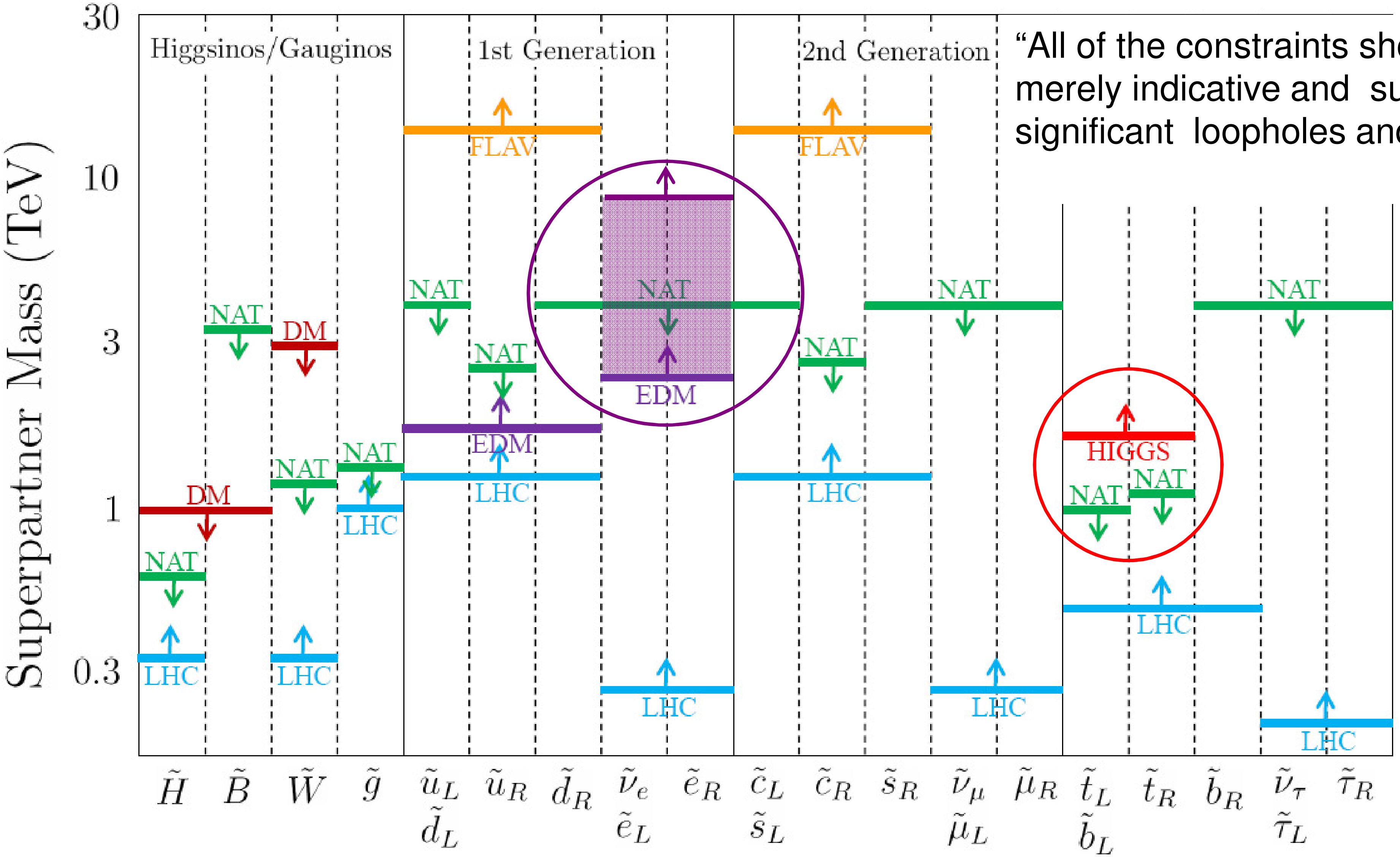


then it is spherical to within the *<u>width of a human hair.</u>*

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

Implications for BSM physics

J. Feng, UC Irvine: “Naturalness and the status of SUSY”, arXiv 1302.6587

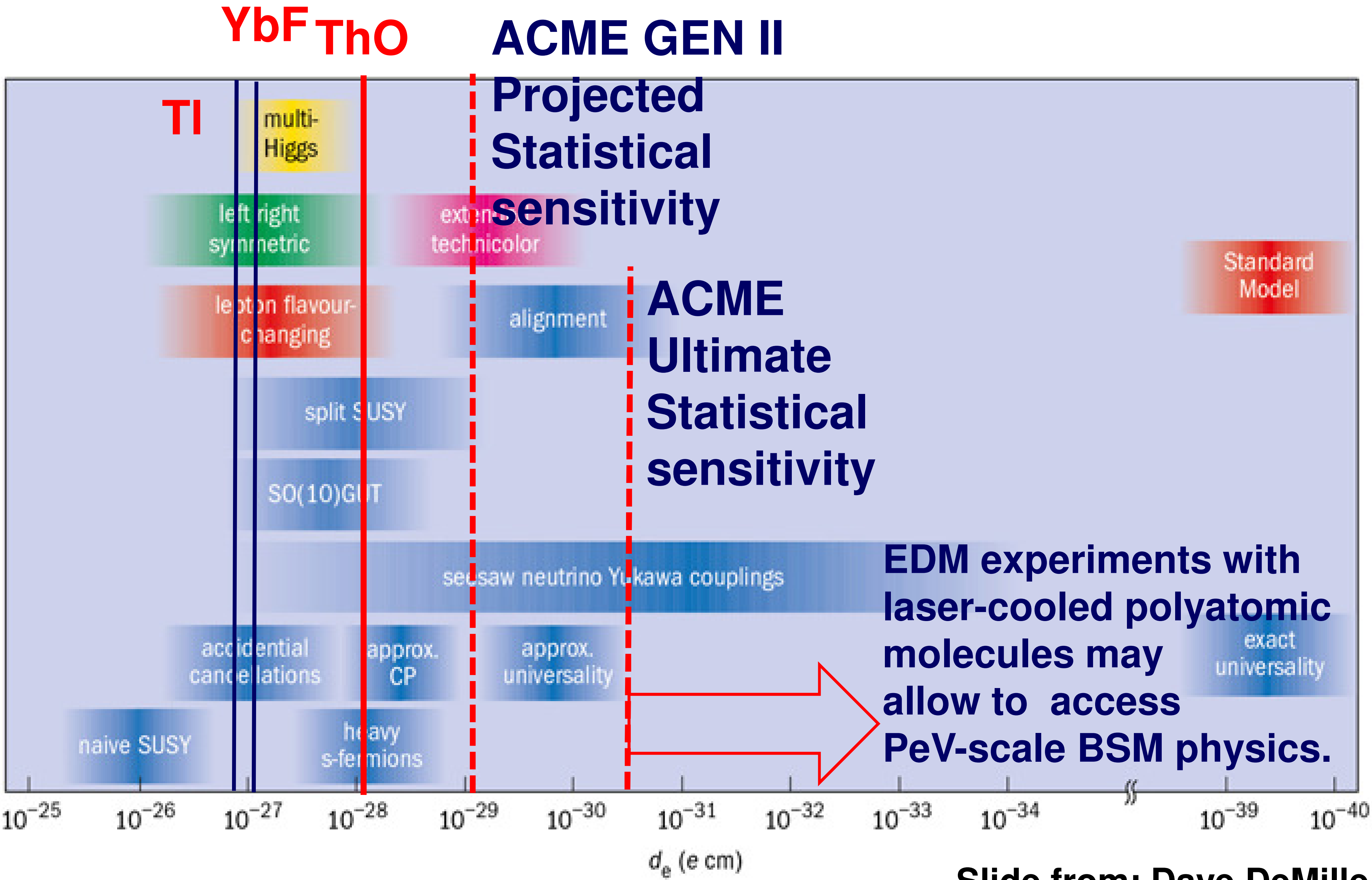


“All of the constraints shown are merely indicative and subject to significant loopholes and caveats”

ACME (like Higgs mass) pushes SUSY into “unnatural” region

Slide from: Dave DeMille

Electron EDM limits



ACME GEN II Projected Statistical sensitivity

ACME Ultimate Statistical sensitivity

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

Slide from: Dave DeMille

Example 2:
Search for Lorentz invariance violation

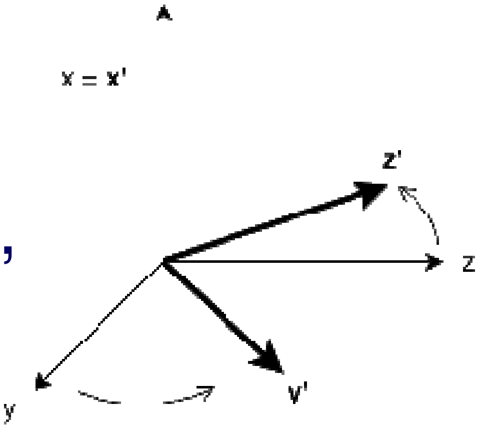
A framework developed for the analysis of completely different experiments:
Standard Model Extension

Both dedicated and “already have the set up” experiments.

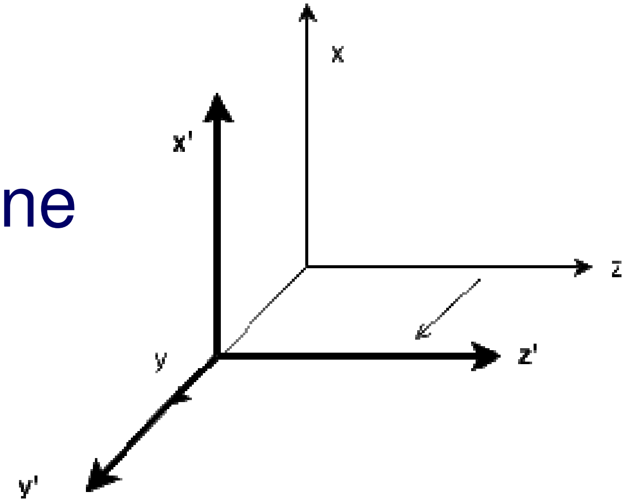
Quantum-information techniques

Lorentz transformations:

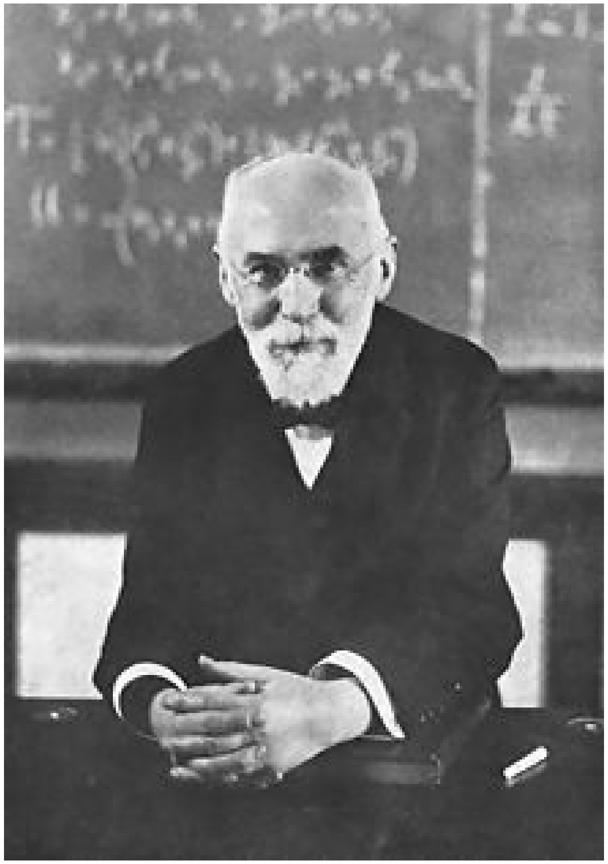
Rotations and Boosts



Three basic types of rotation, one about each of the three spatial directions.



Three types of boosts (changes of velocity), one along each of the three spatial directions.

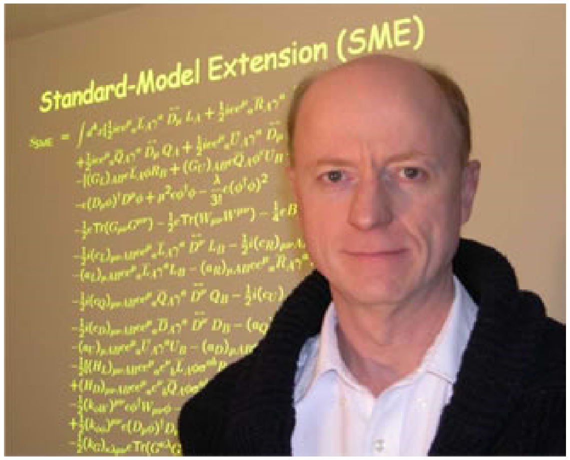


Hendrik Antoon Lorentz

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

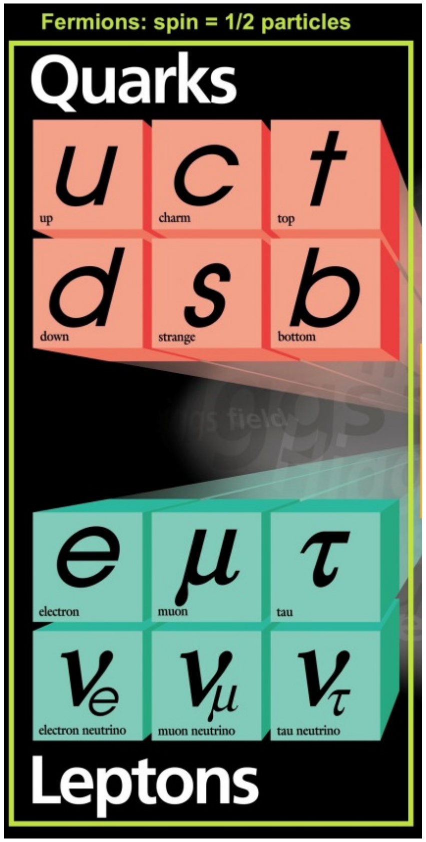
http://www.physics.indiana.edu/~kostelec/faq.htm

Alan Kostelecky



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

$$\gamma_\nu \downarrow \qquad m \downarrow$$

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

Standard Model Extension

$$\bar{\psi} \, \overleftrightarrow{\partial}^\nu \, \psi \equiv \bar{\psi} \, \partial^\nu \, \psi - \psi \, \partial^\nu \, \bar{\psi}$$

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

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

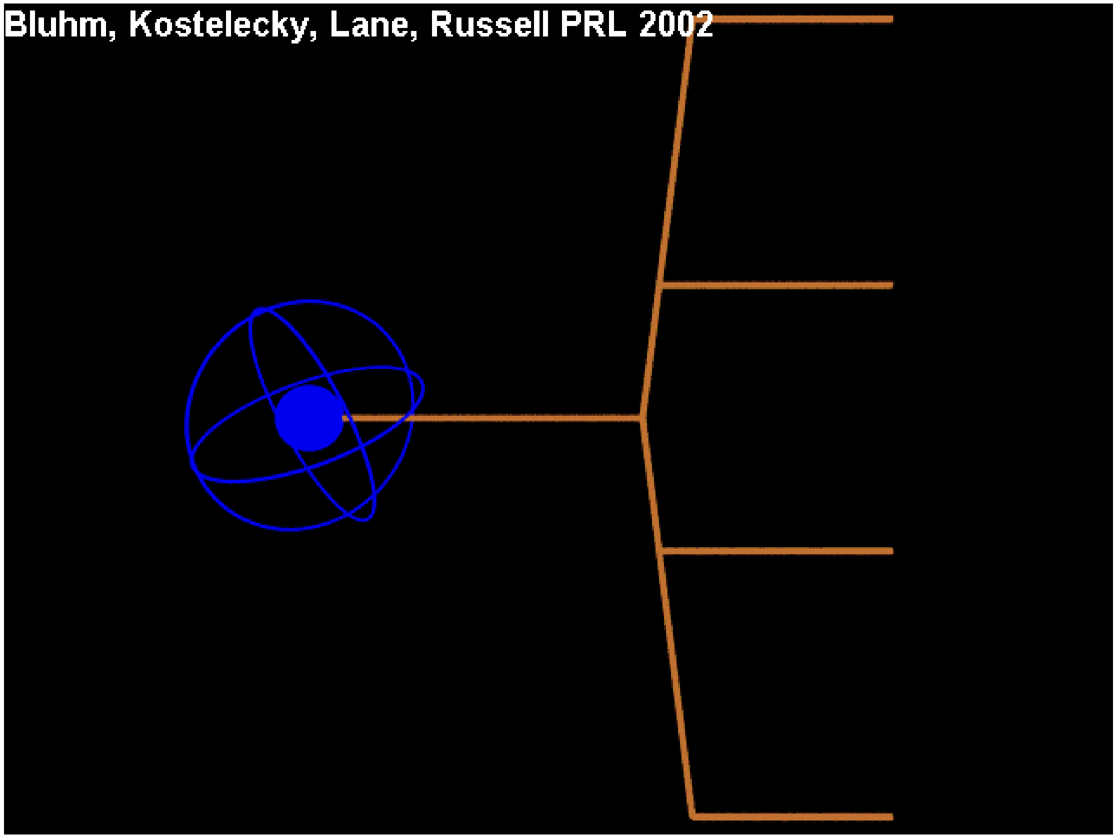
$$M := \boxed{m} + \underbrace{a_{\mu} \gamma^{\mu} + b_{\mu} \gamma_5 \gamma^{\mu}}_{\text{CPT-violating}} + \frac{1}{2} H_{\mu\nu} \sigma^{\mu\nu}$$

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**

The basic idea of atomic physics tests of Lorentz invariance:

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



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

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!

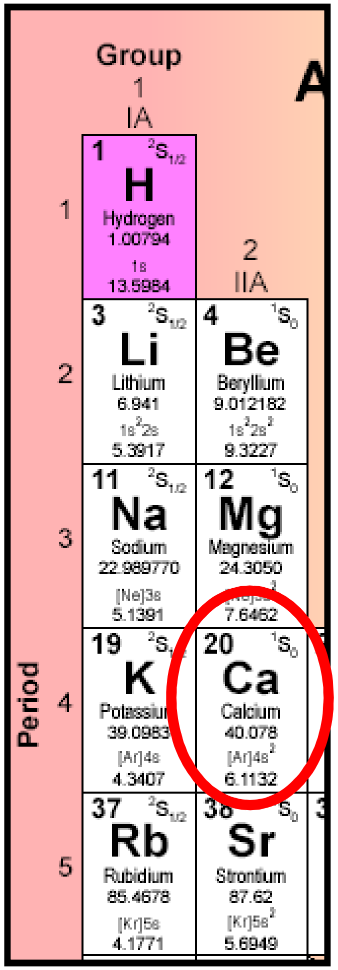
$$\delta H = -\left(C_0^{(0)} - \frac{2U}{3c^2}c_{00}\right)\frac{\mathbf{p}^2}{2} - \frac{1}{6}C_0^{(2)}T_0^{(2)}$$

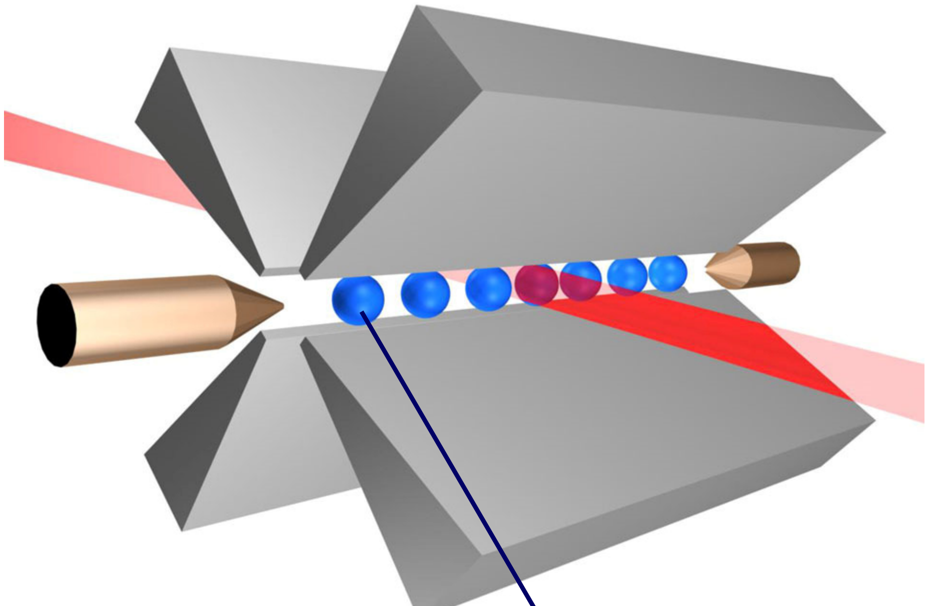
U is the Newtonian potential $-MG/r$

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

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

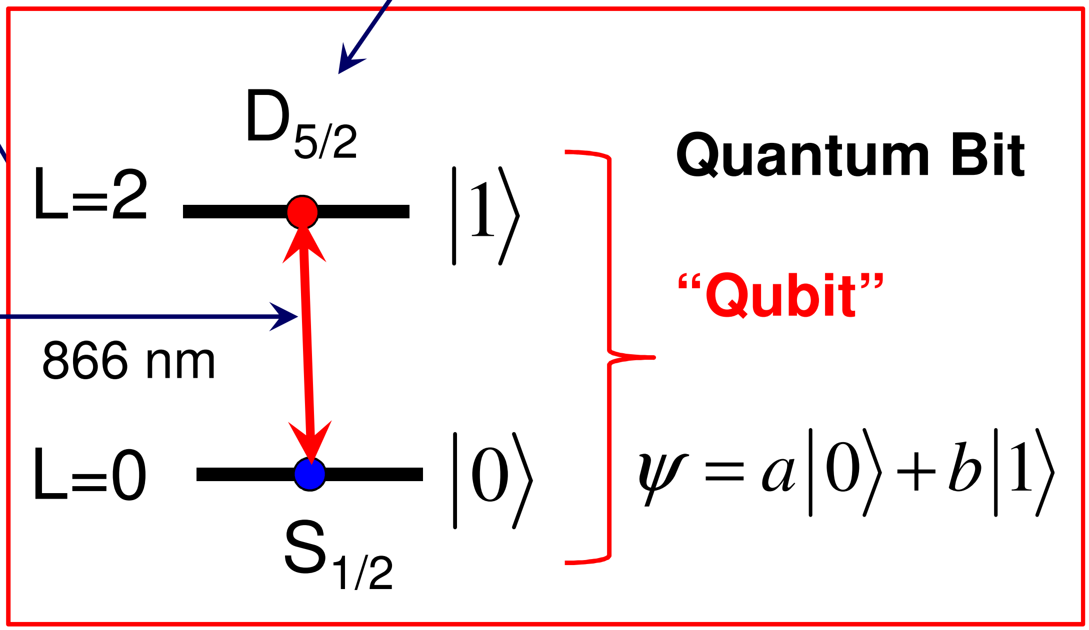
Ca⁺ ion: building quantum computers





Long-lived state
1.2 second lifetime

Electric-dipole
transition
forbidden



Quantum Bit

"Qubit"

$$\psi = a|0\rangle + b|1\rangle$$

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

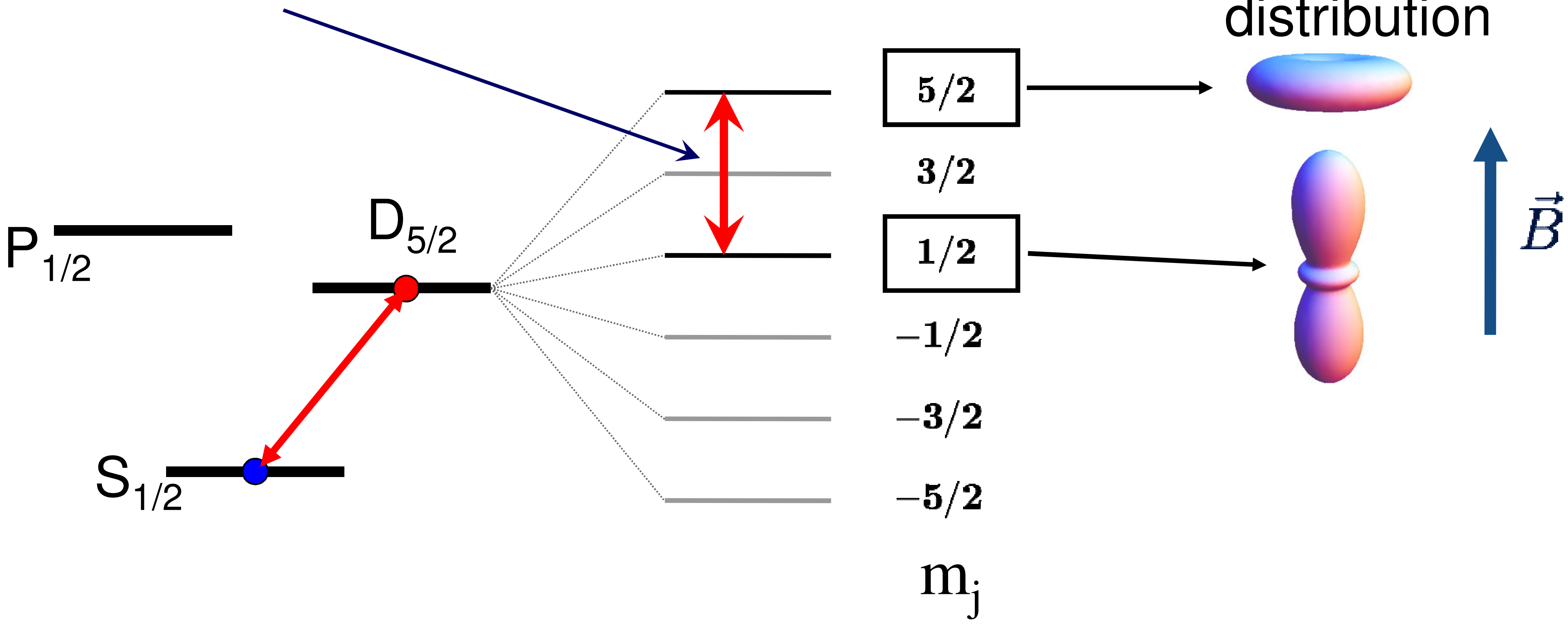
The frequency difference (in Hz) for a pair of Ca+ ions used is given by

$$\frac{2}{h}\left(E_{m_J=5/2}-E_{m_J=1/2}\right)=(-1.484\times 10^{15}\ \mathrm{Hz})\times\left((5/2)^2-(1/2)^2\right)C_0^{(2)}$$

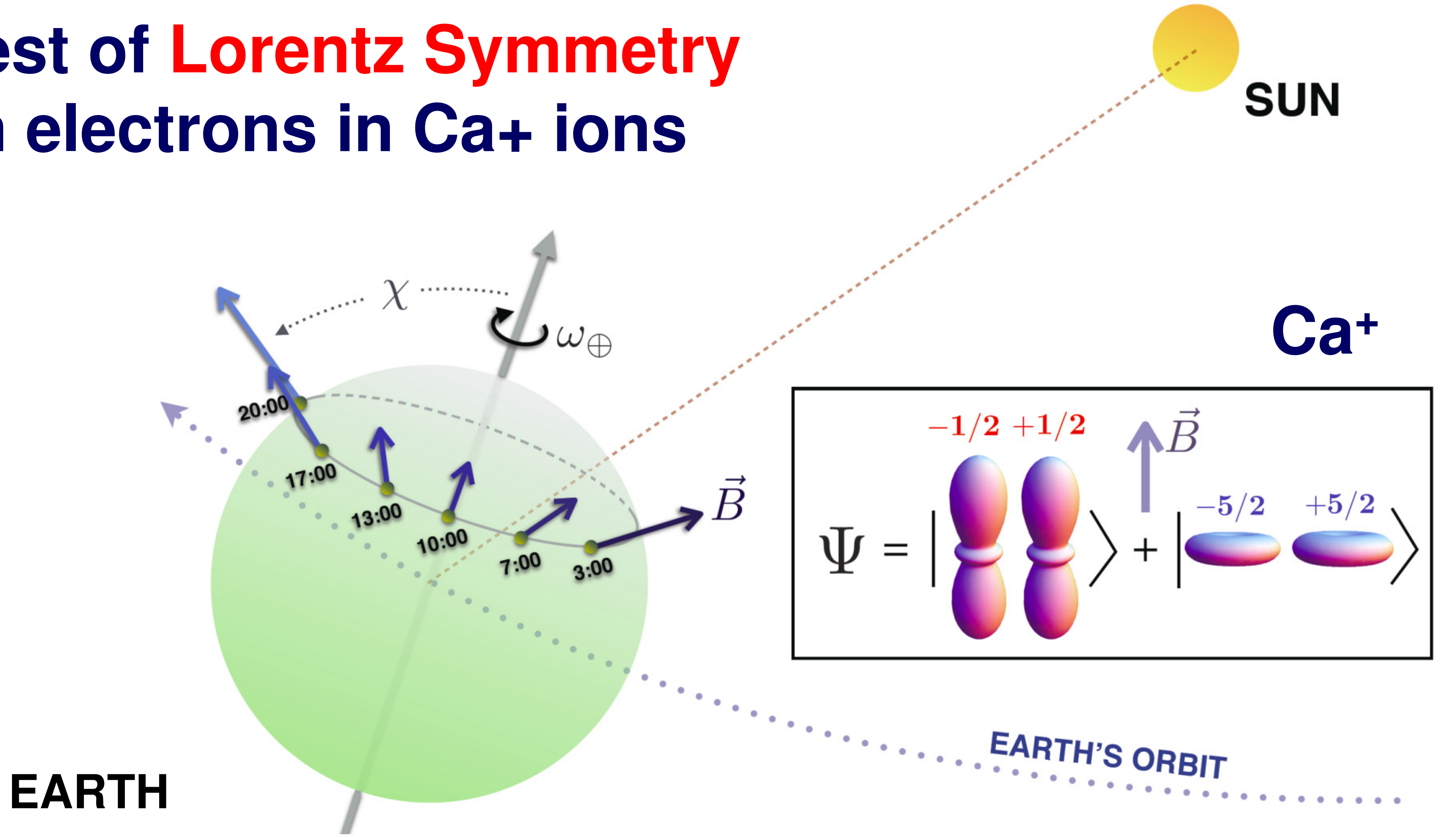
$$=(-8.9(2)\times 10^{15}\ \mathrm{Hz})\times C_0^{(2)}$$

Measure Zeeman splitting

Electron distribution



A Test of Lorentz Symmetry with electrons in Ca+ ions



As the Earth rotates, the direction of the electron motion changes and any violation of local Lorentz invariance will give rise to variations in the electron's energy.

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

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).

Limits to Lorentz violation

Lorentz violating effects are suppressed by some power of R

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

Present limits for electron sector

[1] $c_{JK} < 10^{-18}$

[2] $c_{TJ} < 10^{-13} - 10^{-15}$

Yb+ projected limit [3]

$$c_{JK} < 10^{-23}$$
$$c_{TJ} < 10^{-19}$$

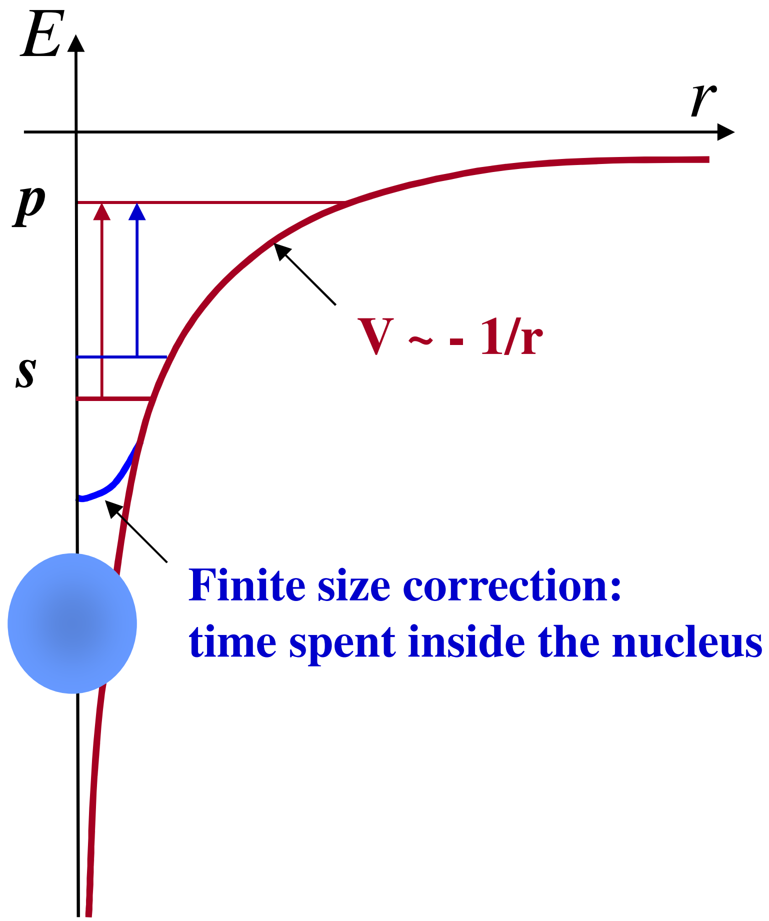
Yb+ experiment sensitivity will be significantly below O(1) suppression limit.

Ref. [1] T. Pruttivarasin, M. Ramm, S. G. Porsev, I. I. Tupitsyn, M. S. Safronova, M. A. Hohensee & H. Häffner, Nature 517, 592–595 (2015)
Ref. [2] B. Altschul, Phys. Rev. D 82, 016002 (2010)
Ref. [3] V. A. Dzuba, V. V. Flambaum, M. S. Safronova, S. G. Porsev, T. Pruttivarasin, M. A. Hohensee, H. Häffner, Nature Physics 12, 465 (2016).

Example 3:
Proton radius puzzle

Finite radius of the proton → H energy level shifts

Measurement of transitions → measure nuclear size



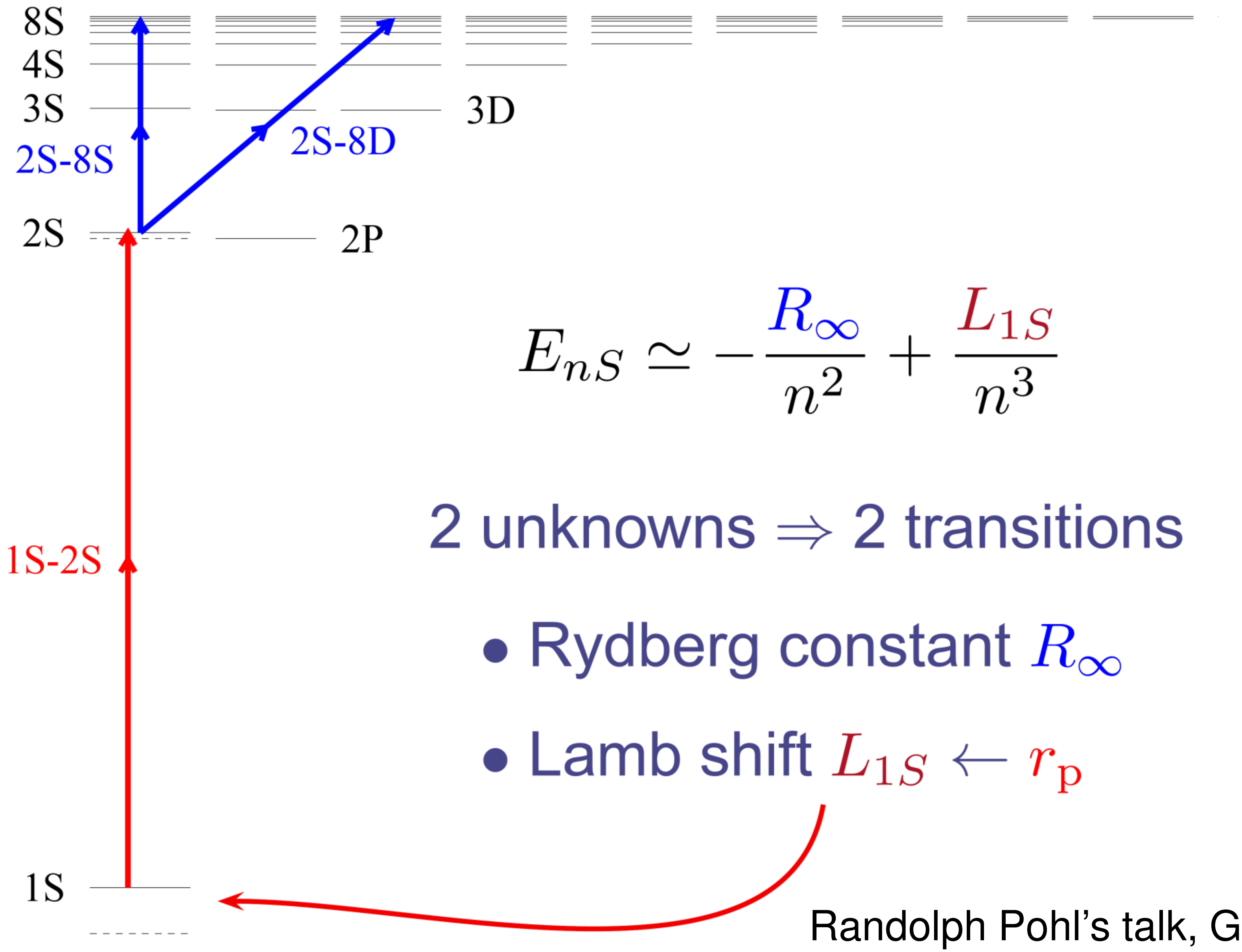
1. Measure the transition energies between different levels
2. Calculate all corrections to these energies (need to calculated QED really well)
3. Extract the corrections to the energies due to a proton radius

   $\sim (Z\alpha)\, R_p^2\, |\Psi(0)|^2$

4. Extract the rms radius
5. Repeat for many transitions and average

Hydrogen spectroscopy (Lamb shift):

$$L_{1S}(r_\mathrm{p}) = 8171.636(4) + 1.5645\,\langle r_\mathrm{p}^2\rangle \quad \text{MHz}$$



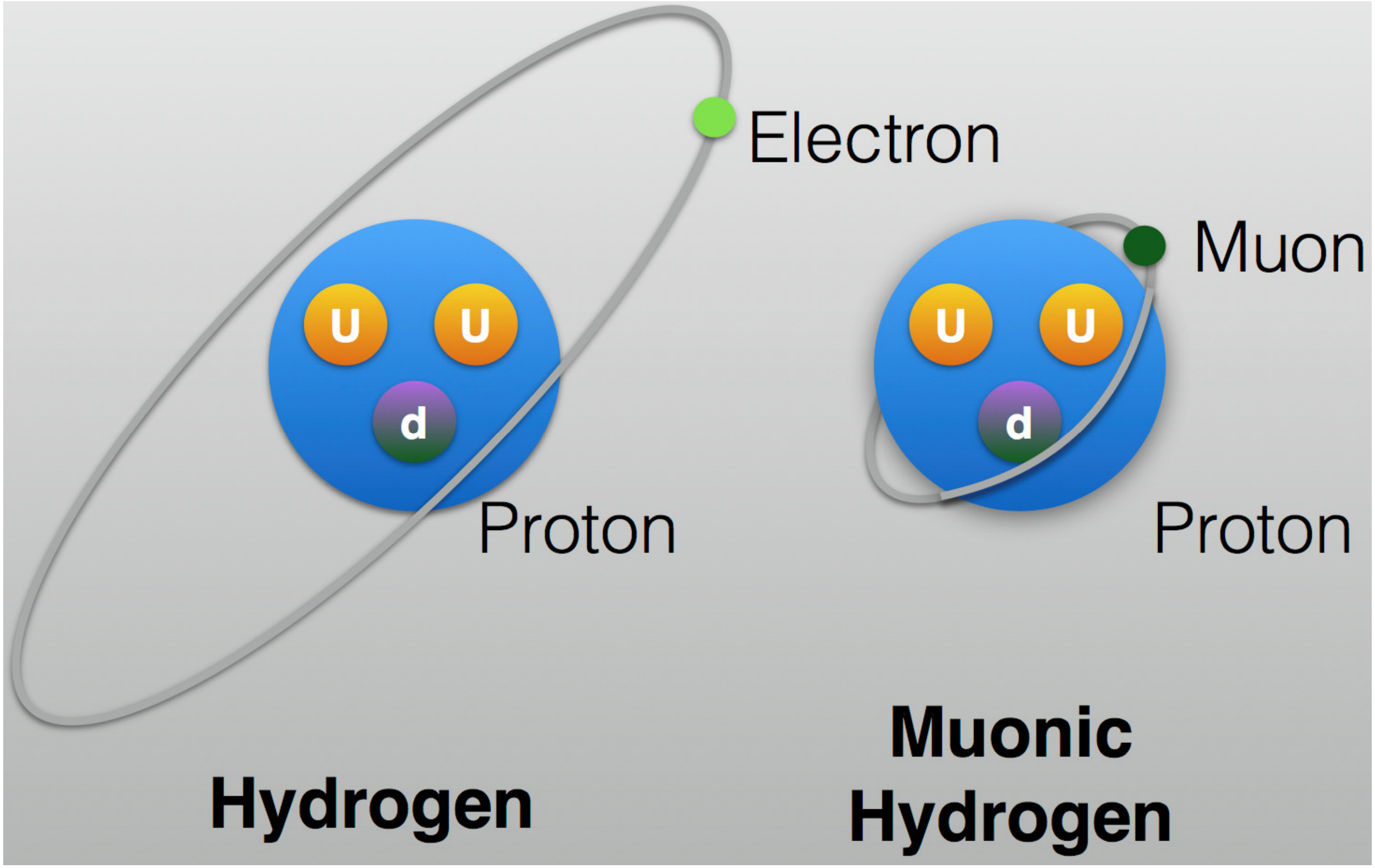
$$E_{nS} \simeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

2 unknowns $\Rightarrow$ 2 transitions

- Rydberg constant R_∞
- Lamb shift $L_{1S} \leftarrow r_\mathrm{p}$

Randolph Pohl's talk, GHP, April 2013

Even better way to measure the proton radius

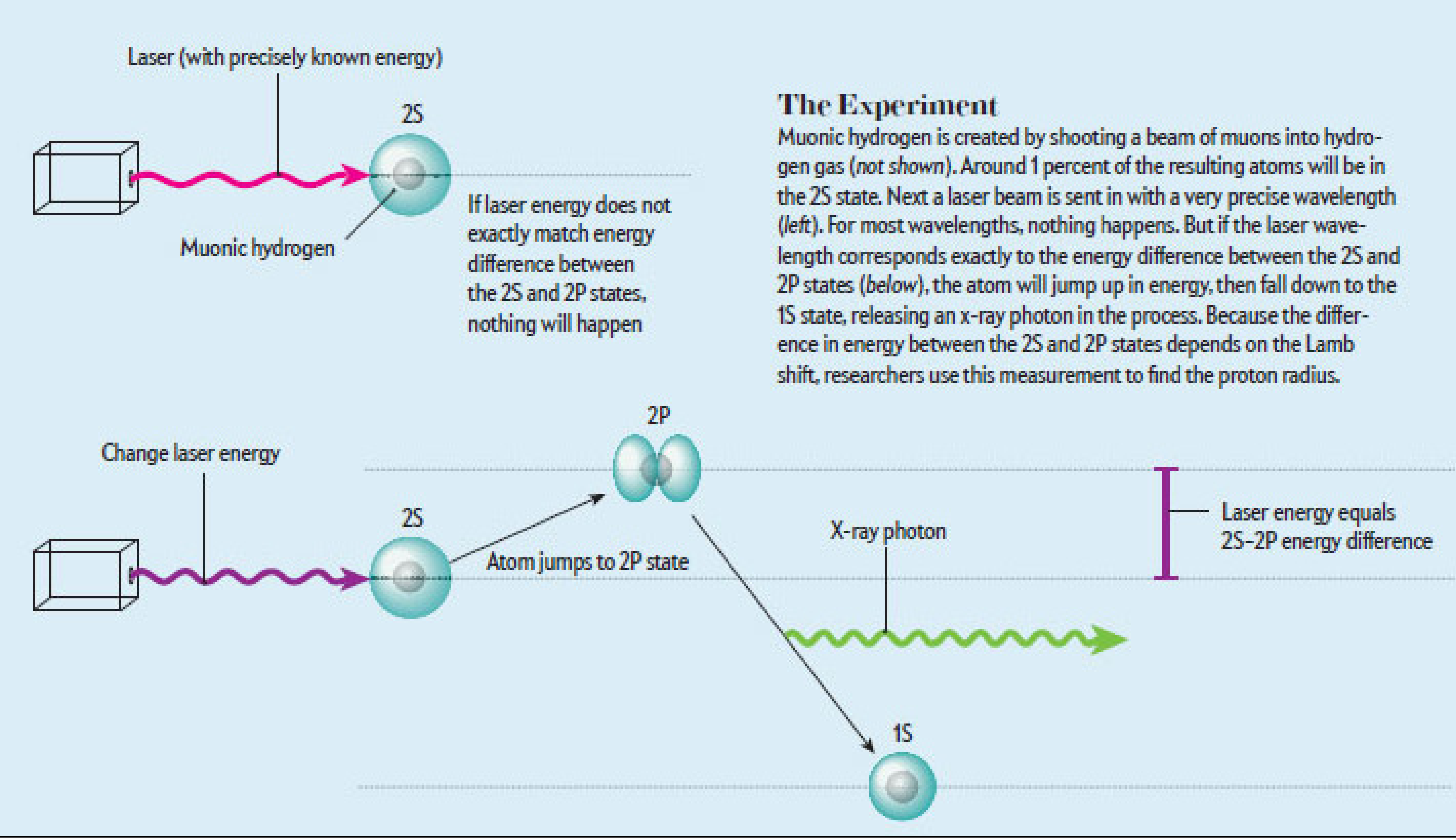


Probability for a lepton to be inside the proton $\propto$ to its mass cubed, $(207)^3 = 8\,869\,743$ enhancement for a muon !

http://www.ust.edu.tw/

Muonic hydrogen experiment

Paul Scherrer Institute (Switzerland)

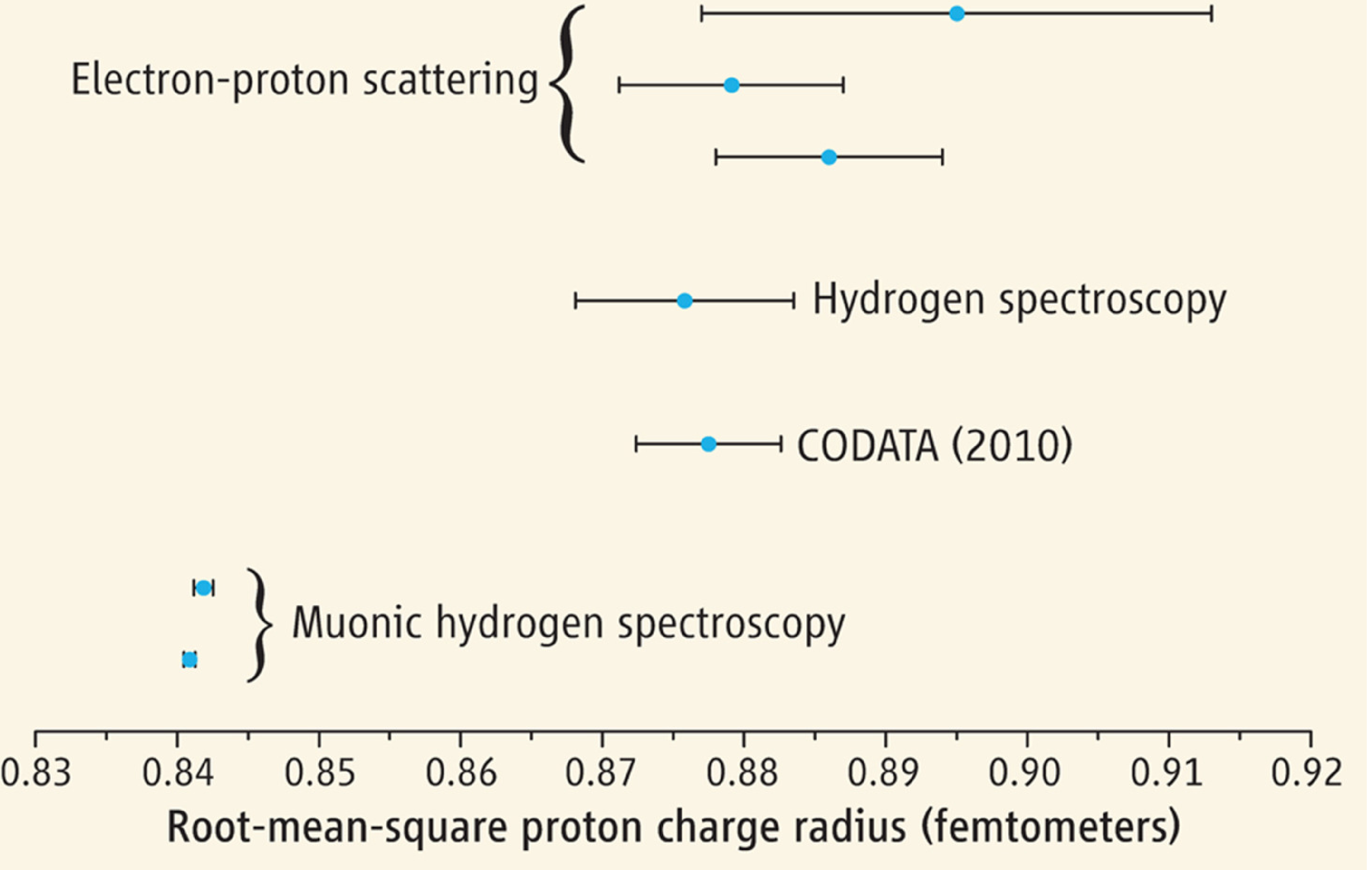


The Experiment

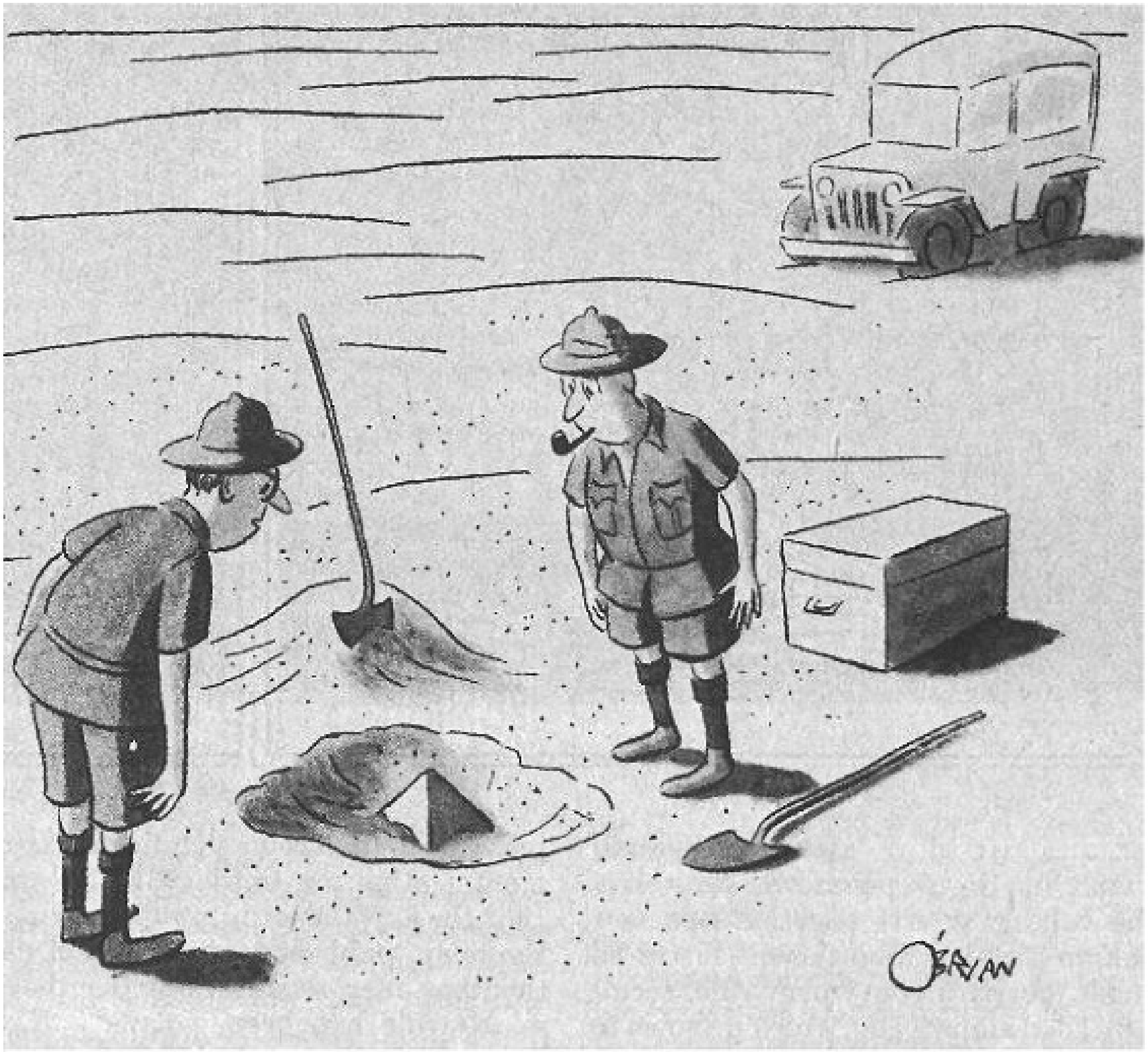
Muonic hydrogen is created by shooting a beam of muons into hydrogen gas (*not shown*). Around 1 percent of the resulting atoms will be in the 2S state. Next a laser beam is sent in with a very precise wavelength (*left*). For most wavelengths, nothing happens. But if the laser wavelength corresponds exactly to the energy difference between the 2S and 2P states (*below*), the atom will jump up in energy, then fall down to the 1S state, releasing an x-ray photon in the process. Because the difference in energy between the 2S and 2P states depends on the Lamb shift, researchers use this measurement to find the proton radius.

Scientific American **310**, 32 - 39 (2014)

Proton radius puzzle

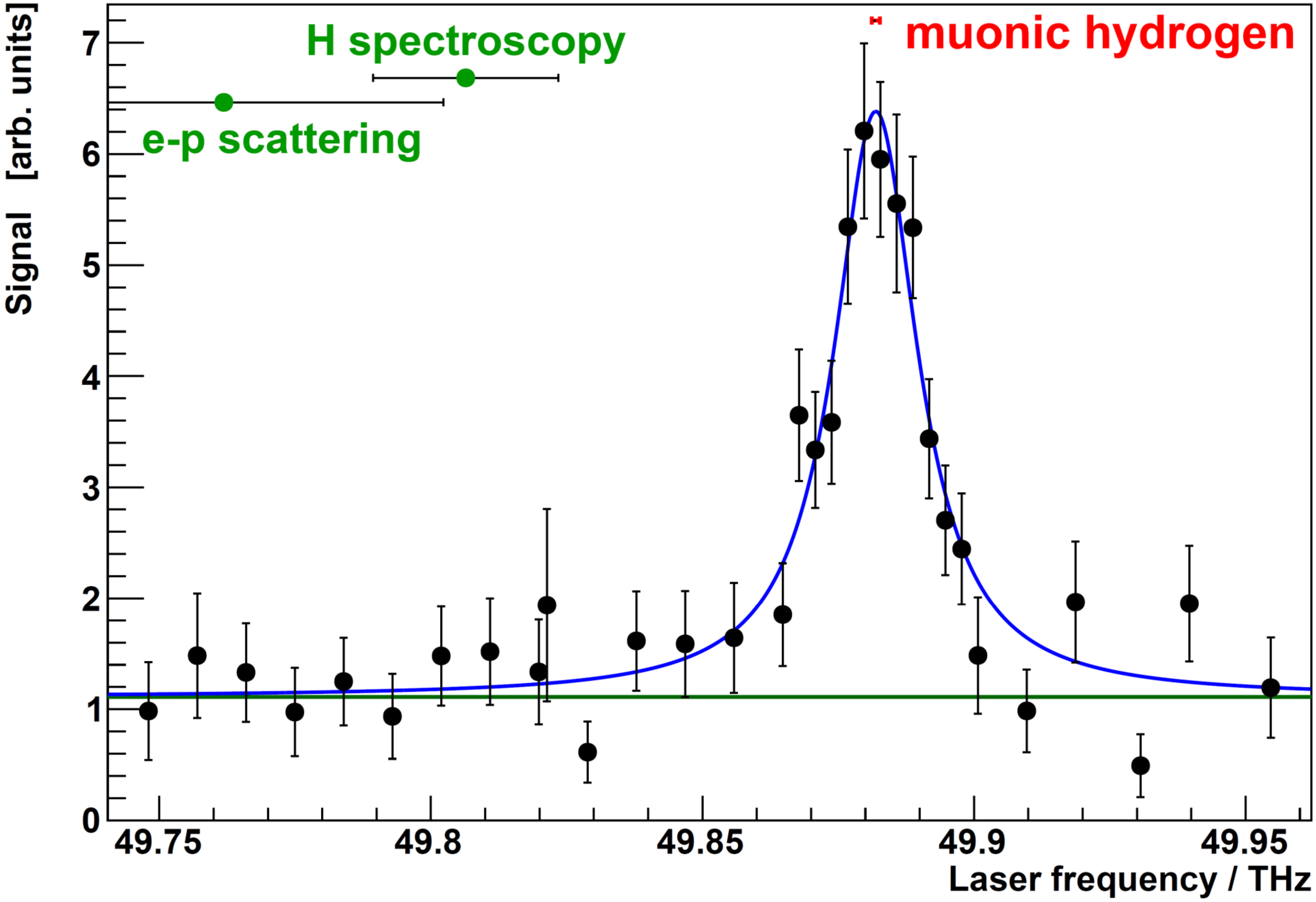


Science 339, 405 (2013)



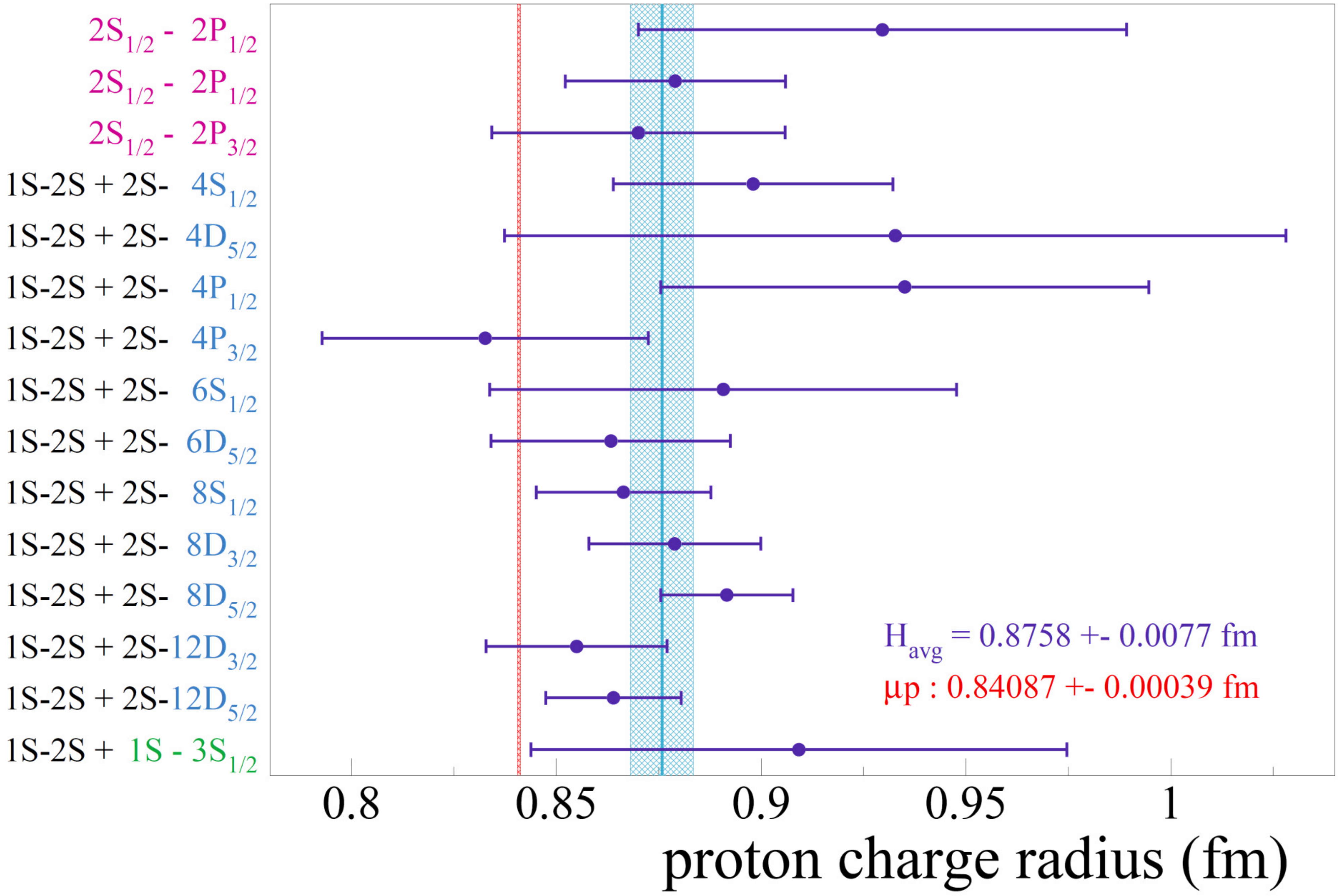
"This could be the discovery of the century. Depending, of course, on how far down it goes."

The discrepancy is 4 linewidths!



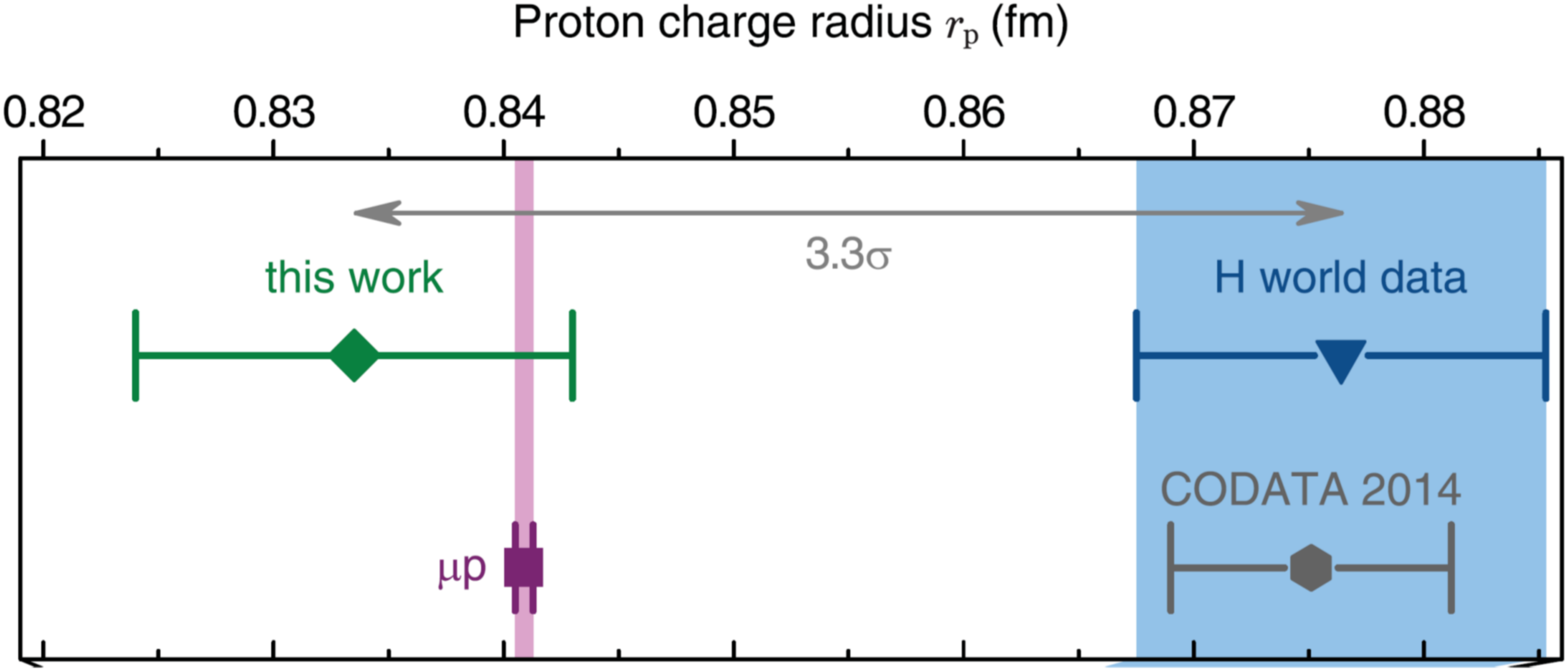
R. Pohl et al., Annu. Rev. Nucl. Part. Sci. 63, 175 (2013)

Hydrogen Spectroscopy

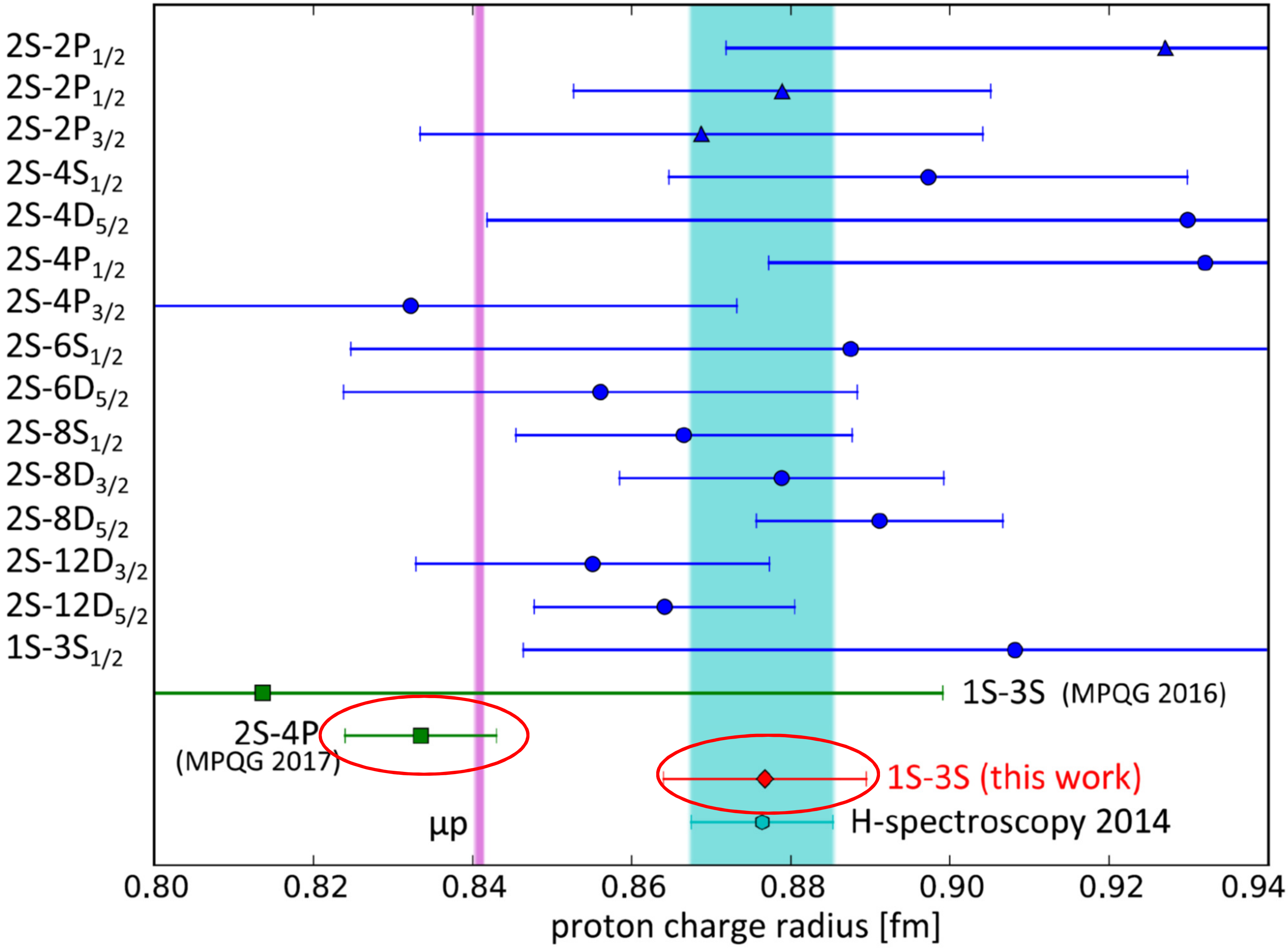


R. Pohl et al., Annu. Rev. Nucl. Part. Sci. 63, 175 (2013)

New measurements of the 2S-4P transition frequency in H
Beyer et al., Science 358, 79 (2017)

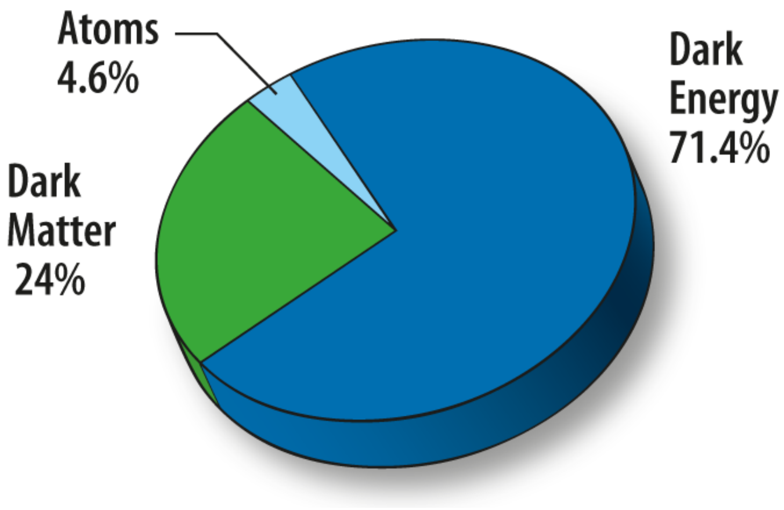


New measurement of the 1S – 3S transition frequency of hydrogen: contribution to the proton charge radius puzzle, arXiv:1801.08816 (2018)



Conclusion

Great potential for discovery of new physics



NEED

BSM PHYSICS

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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

2017 Ultralight Dark Matter

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)