TRIUMF SCIENCE WEEK 2020

SEARCHES FOR NEW PHYSICS WITH ATOMS AND MOLECULES

Marianna Safronova

Department of Physics and Astronomy, University of Delaware, Delaware
Joint Quantum Institute, NIST and the University of Maryland, College Park, Maryland

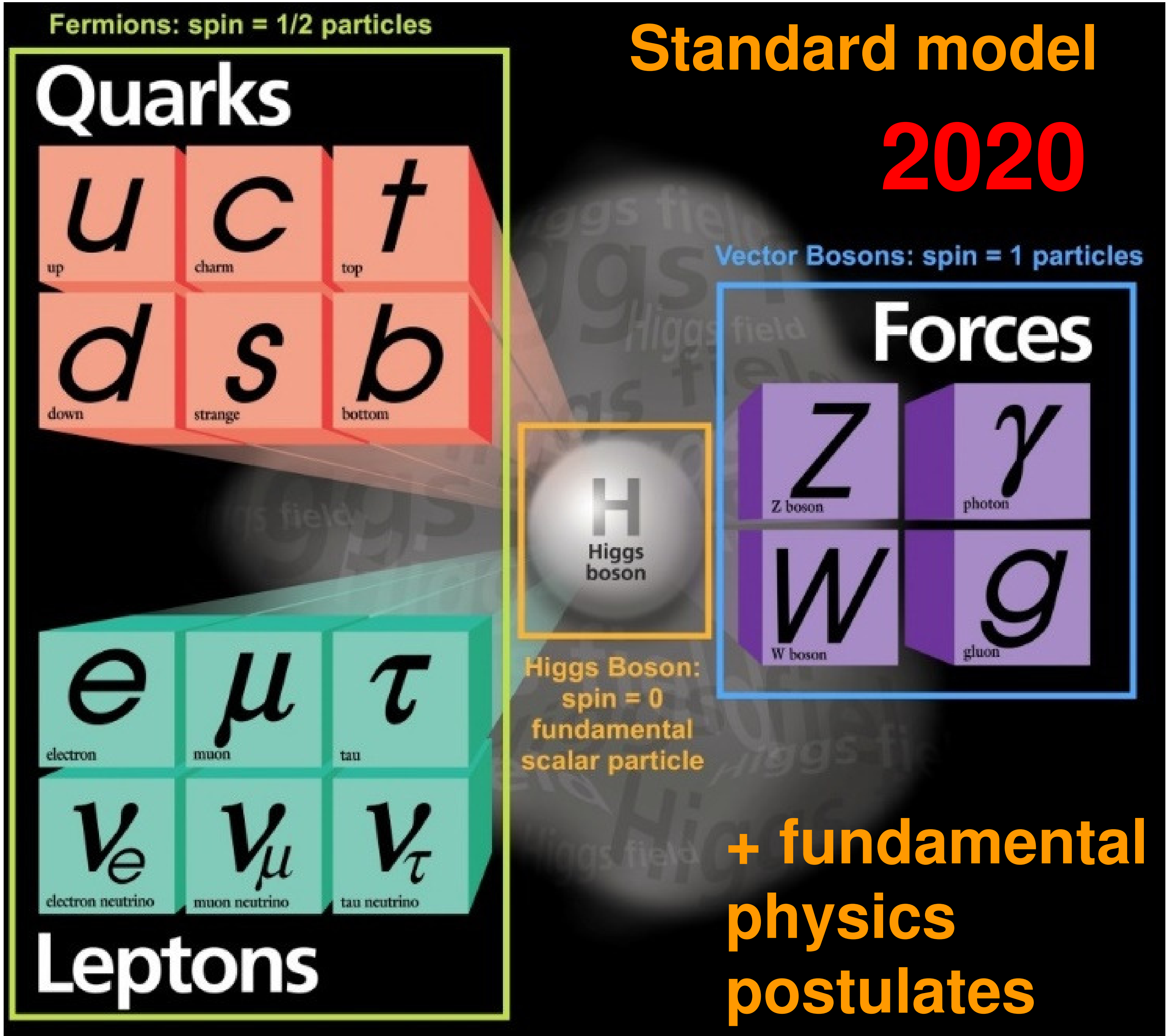
NSF

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Office of Naval Research
USN ONR
Science & Technology

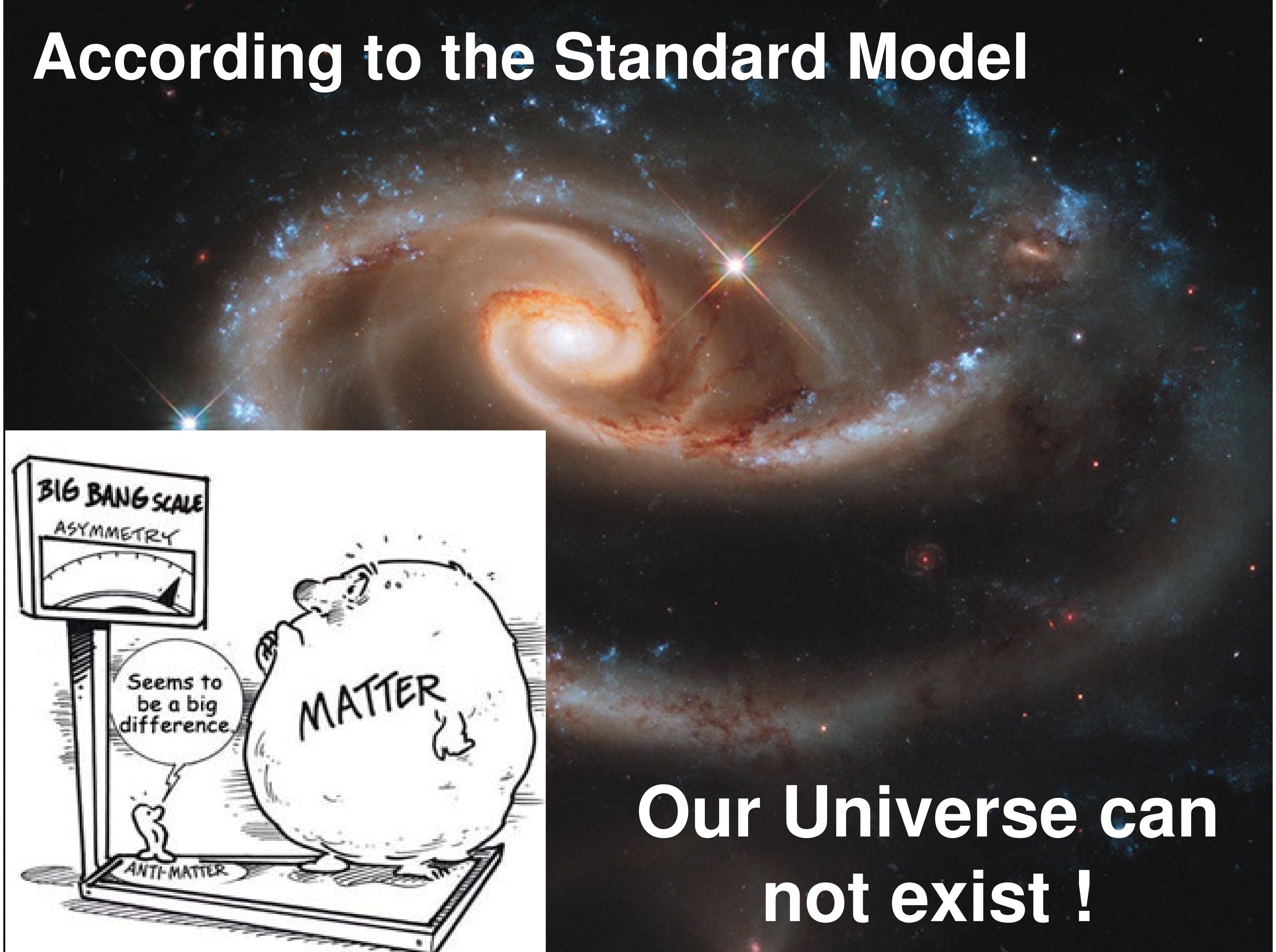
erc
European Research Council

Standard model 2020



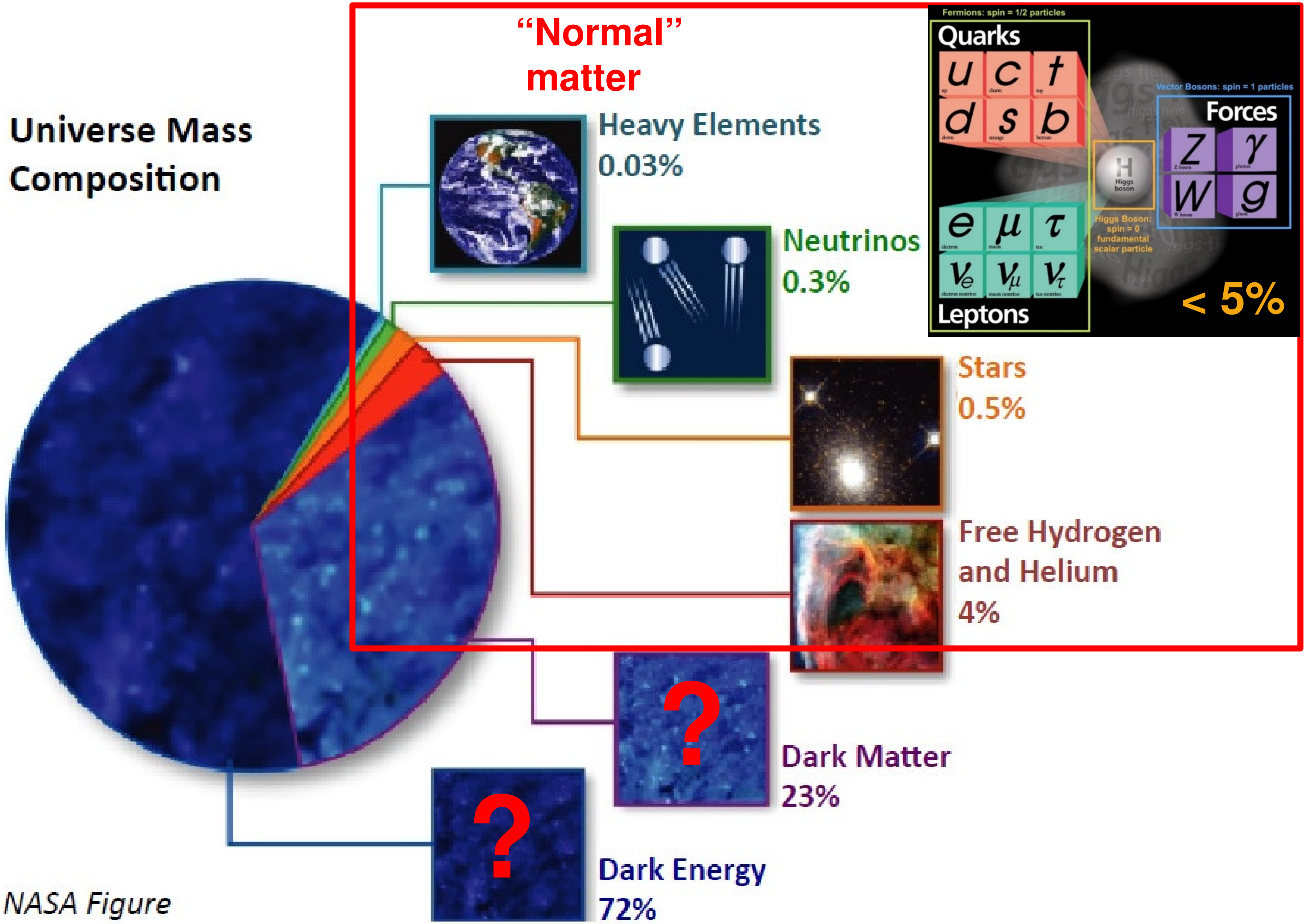
+ fundamental physics postulates

According to the Standard Model



Our Universe can not exist !

We don’t know what most (95%) of the Universe is!



Extraordinary progress in the control of atoms and ions

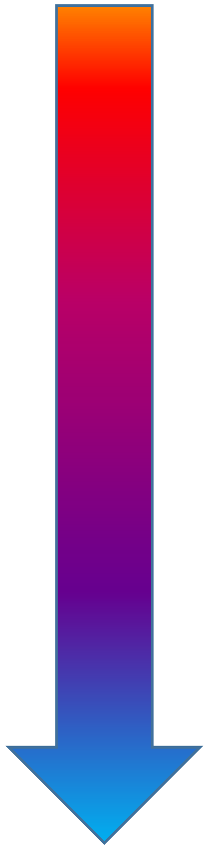
1997 Nobel Prize
Laser cooling and trapping

2001 Nobel Prize
Bose-Einstein Condensation

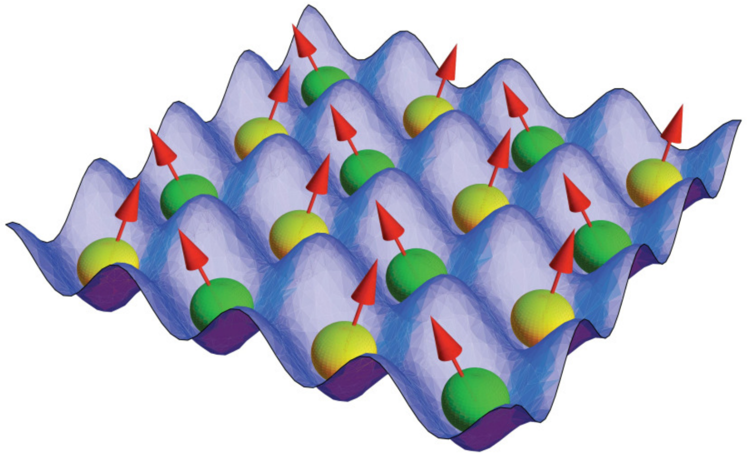
2005 Nobel Prize
Frequency combs

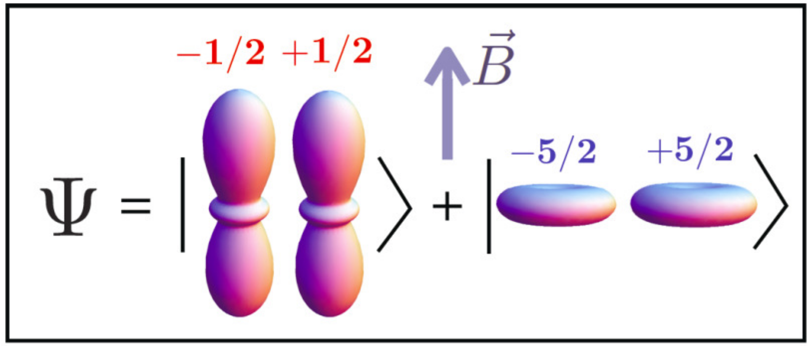
2012 Nobel prize
Quantum control

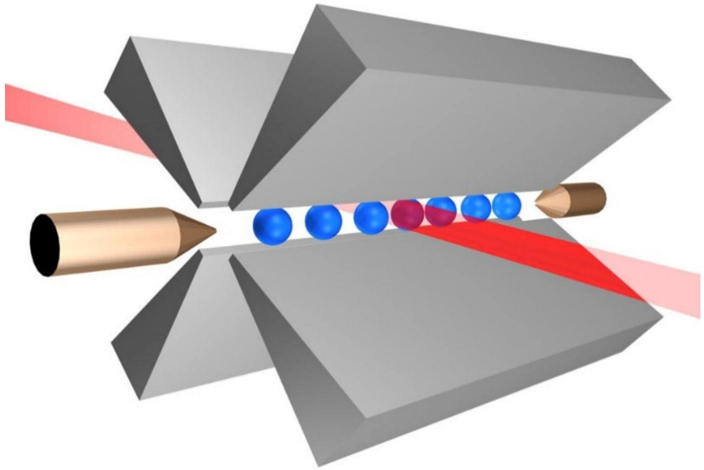
300K

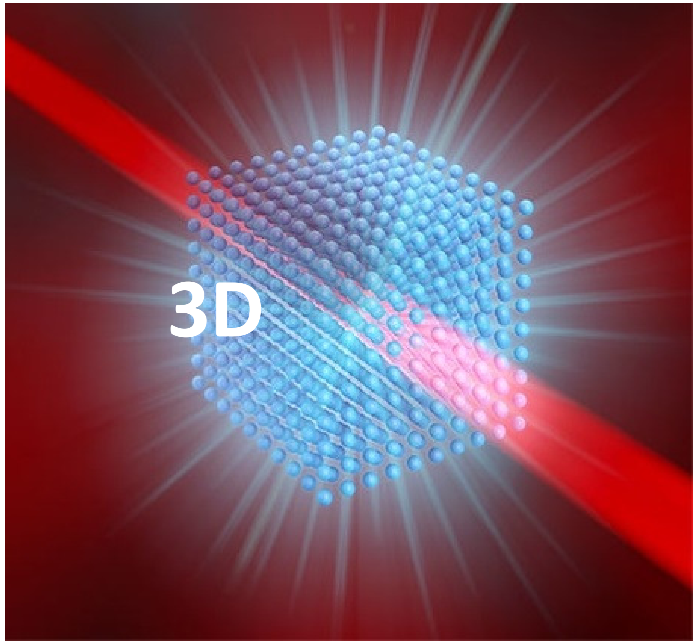


pK

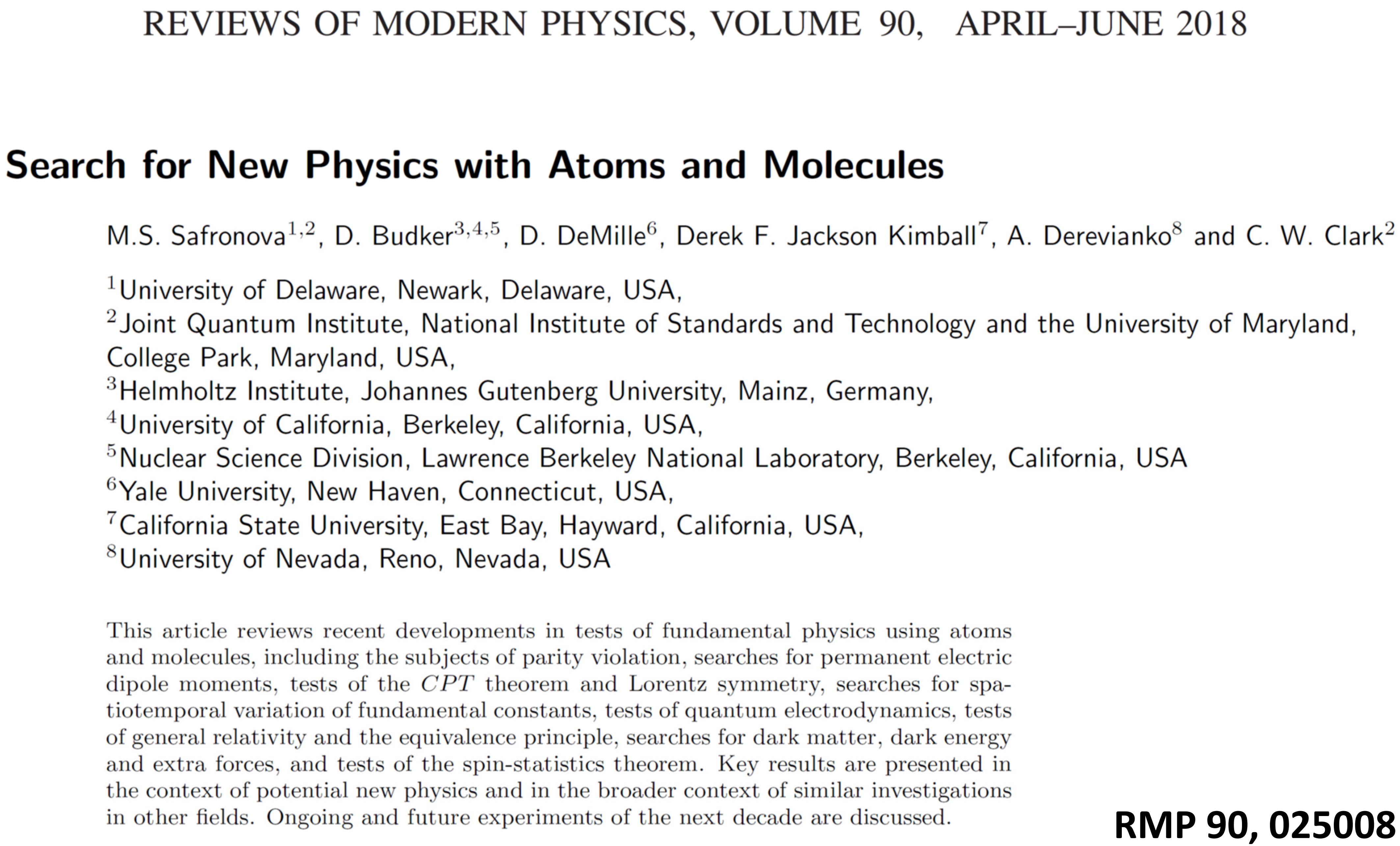








Atoms are now: **Ultracold** **Trapped** **Precisely controlled**



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)

Very wide scope of AMO new physics searches

Precision tests of Quantum Electrodynamics

Atomic parity violation

Time-reversal violation:
electric dipole moments and related phenomena

Tests of the CPT theorem:
matter-antimatter comparisons

Lorentz symmetry tests

Searches for light dark matter

Search for variation of fundamental constants

Searches for exotic forces

General relativity and gravitation

Search for violations of quantum statistics

Many searches need or will benefit from the use of radioactive isotopes

Precision tests of Quantum Electrodynamics

Atomic parity

Monday:
TRIUMF at the Precision Frontier
Beatrice Franke

e CPT theorem:
tter-antimatter comparisons

Lorentz symmetry tests

Searches for light dark matter

Search for variation of fundamental constants

Searches for exotic forces

General relativity and gravitation

Search for violations of quantum statistics

TRIUMF

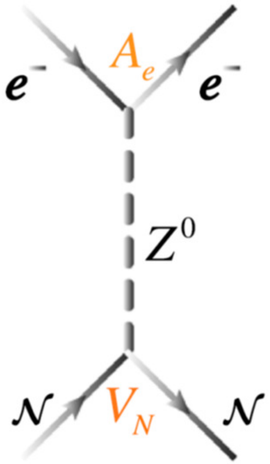
FrPNC

Atomic parity violation with laser trapped francium

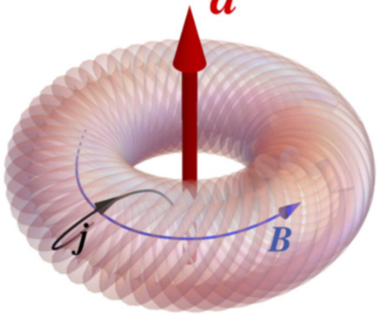
$\vec{r} \rightarrow -\vec{r}$

Z^3 enhancement

Ra^+ at UCSB, Cs, Yb



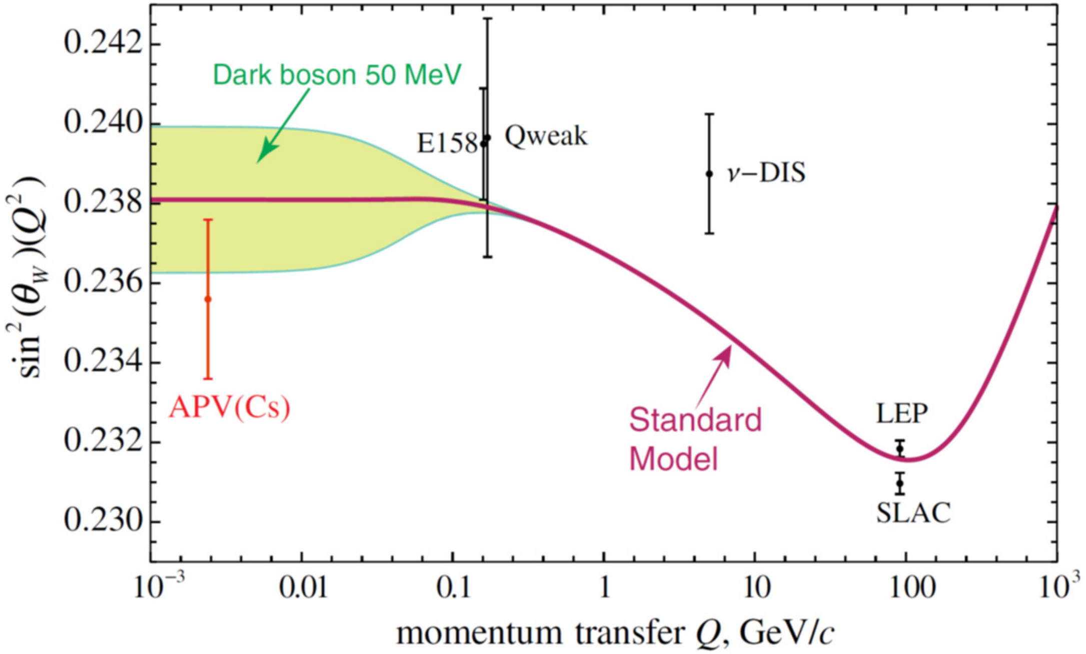
Z-boson exchange



Nuclear anapole moment

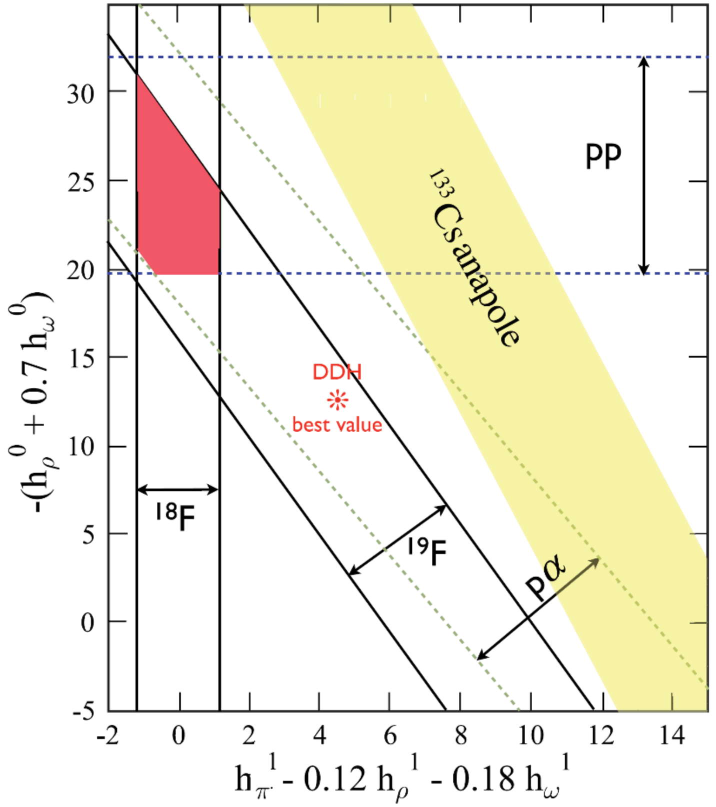
Forbidden electronic transitions become very weakly allowed due to parity violation

Optical transition scheme: 7s-8s in Fr
Microwave transition scheme: 7s hyperfine



Testing standard model and searching for dark matter

Study parity violation in the nuclei



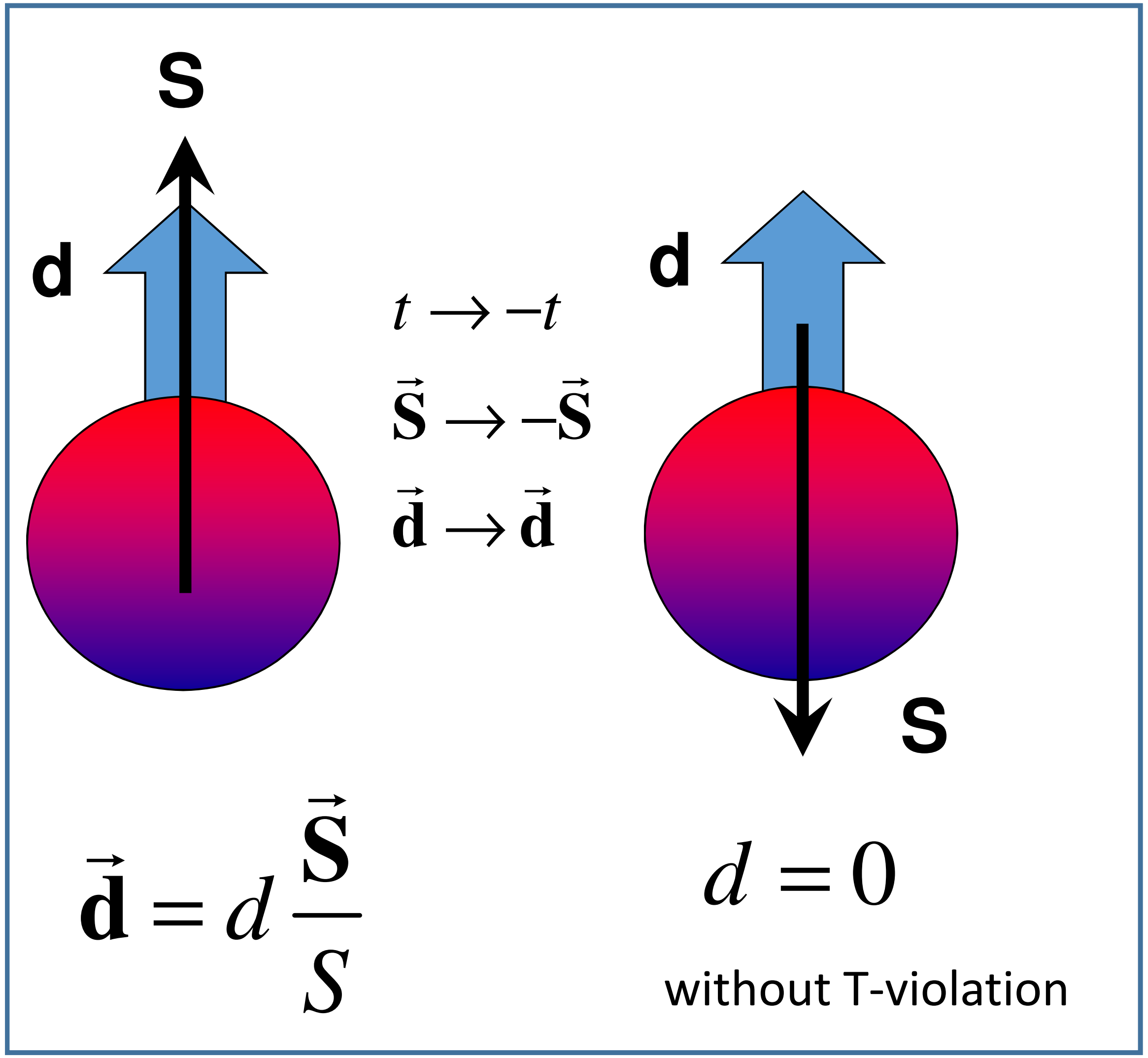
Constraints on combinations of parity-violating meson couplings

Rev. Mod. Phys. 90, 025008 (2018)

Permanent electric-dipole moment (EDM)

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

$t \to -t$



$$t \to -t$$
$$\vec{\mathbf{S}} \to -\vec{\mathbf{S}}$$
$$\vec{\mathbf{d}} \to \vec{\mathbf{d}}$$

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

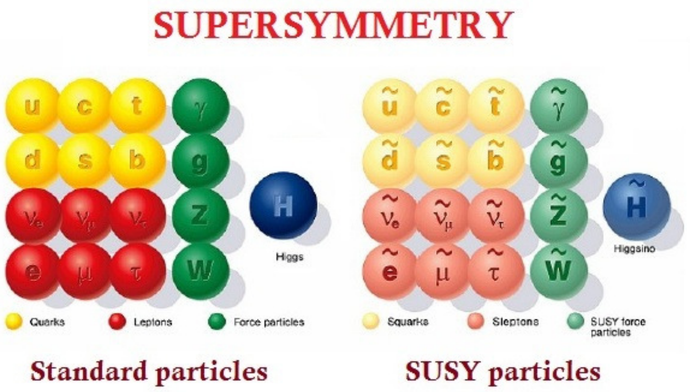
$$d = 0$$

without T-violation

Need new sources of T- (CP-) violation to explain matter-antimatter asymetry

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

Such EDMs should be observable with current experiments.



Sources of atomic and molecular EDMs

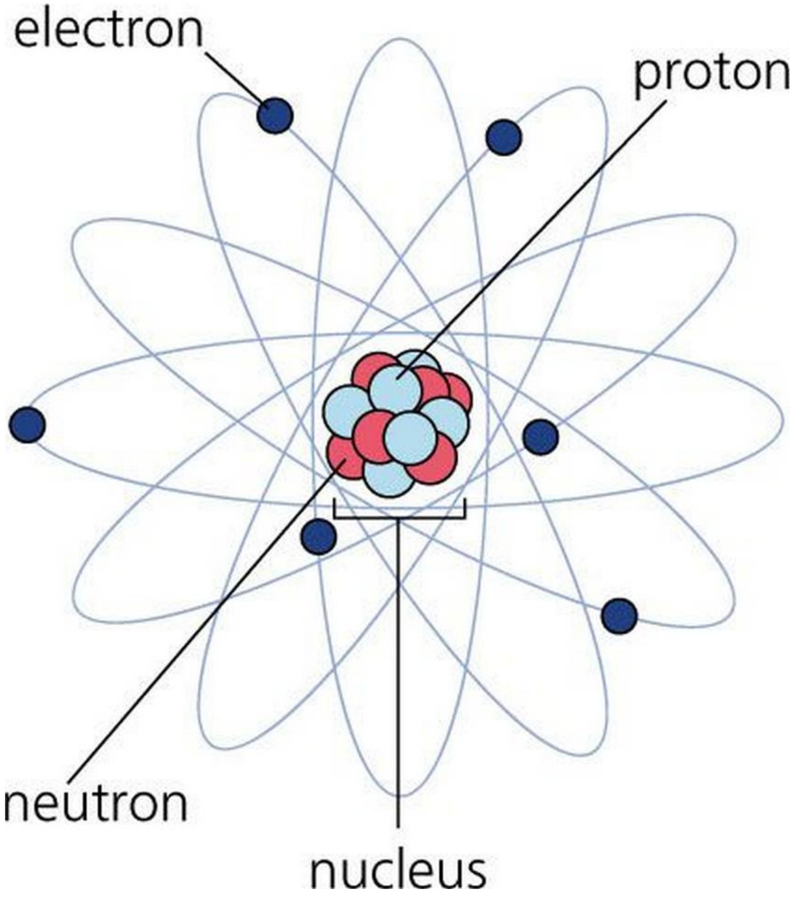
Paramagnetic atoms
Cs, Tl, **Fr** (eedm.info)
Molecules
YbF, ThO, HfF$^+$, ThF$^+$,**RaF**
YbOH, **RaOH**

Ronald Fernando GARCIA RUIZ
Radioactive molecules as laboratories for fundamental physics (Friday)

Diamagnetic atoms
Hg, Xe, **Ra, Rn**
Molecules
TlF

Electron EDM

P, T – violating electron-nucleon interaction

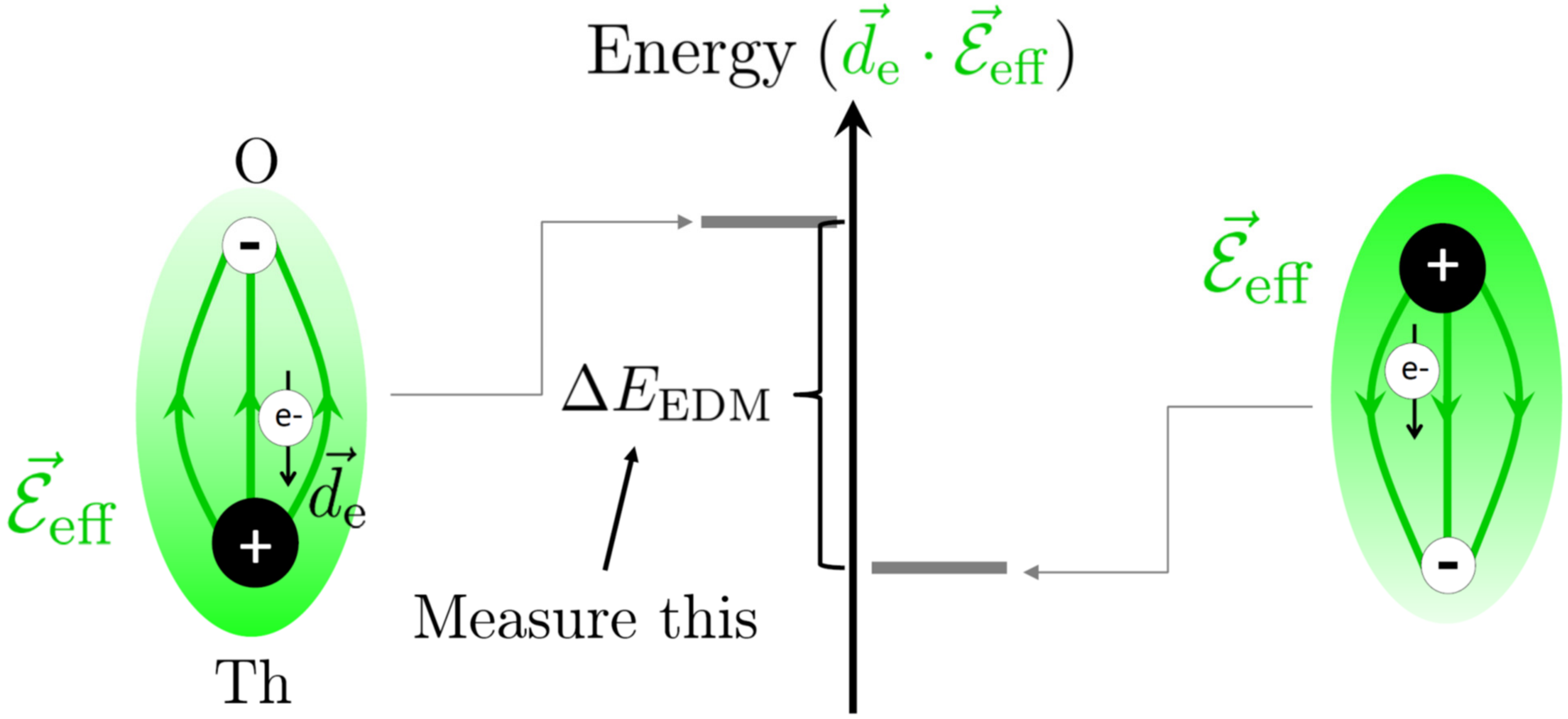


Nucleon EDM

P, T – violating nucleon- nucleon interaction

Need heavy atom or a molecule with a heavy atom for larger effect

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

http://www.electronedm.org/

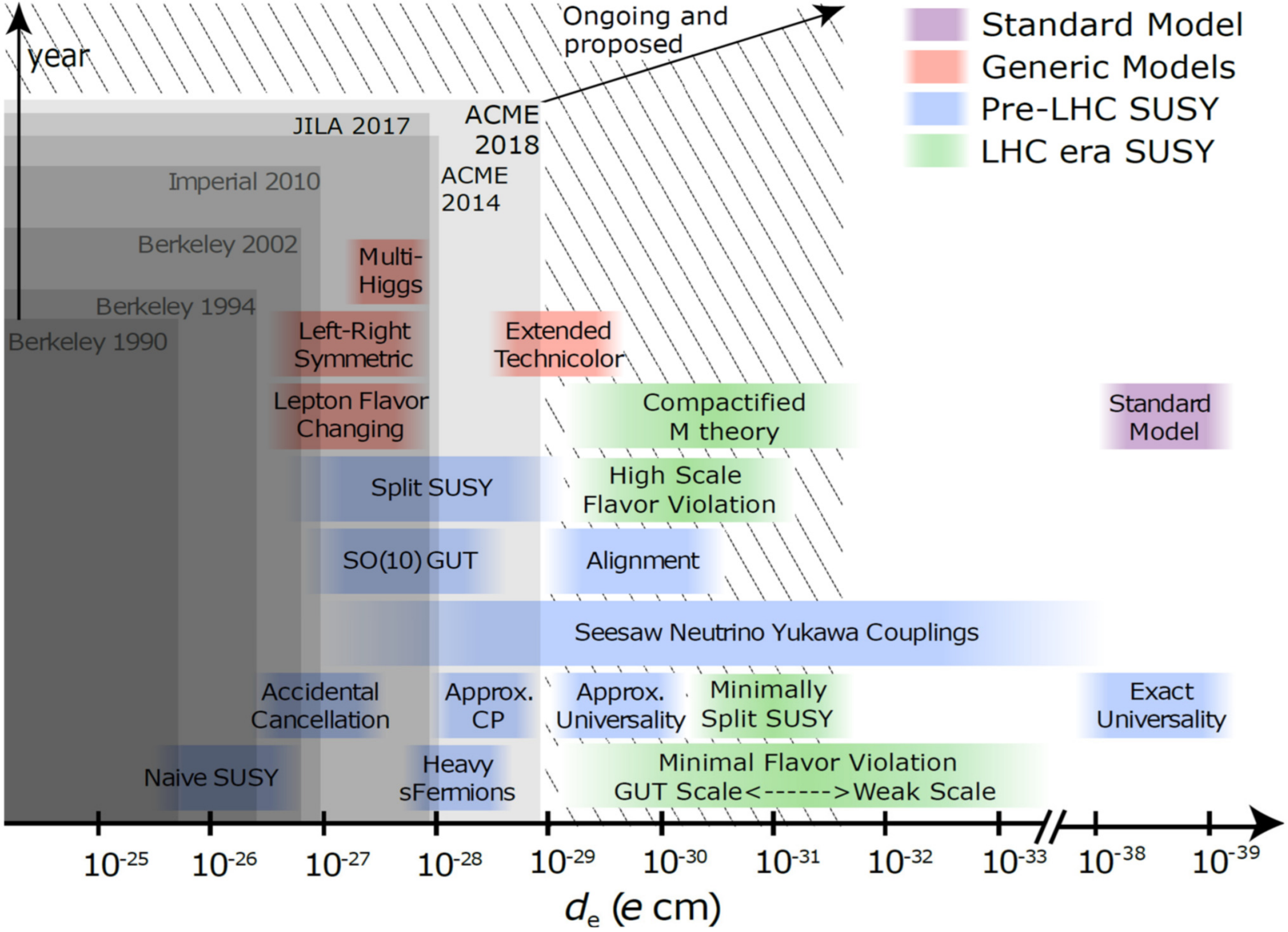
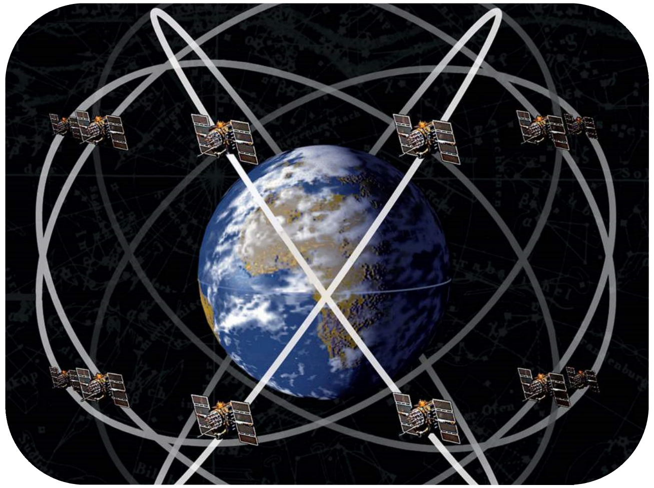


Figure is from 2020 USA AMO Decadal survey (Credit: Dave DeMille)

https://www.nationalacademies.org/our-work/decadal-assessment-and-outlook-report-on-atomic-molecular-and-optical-science

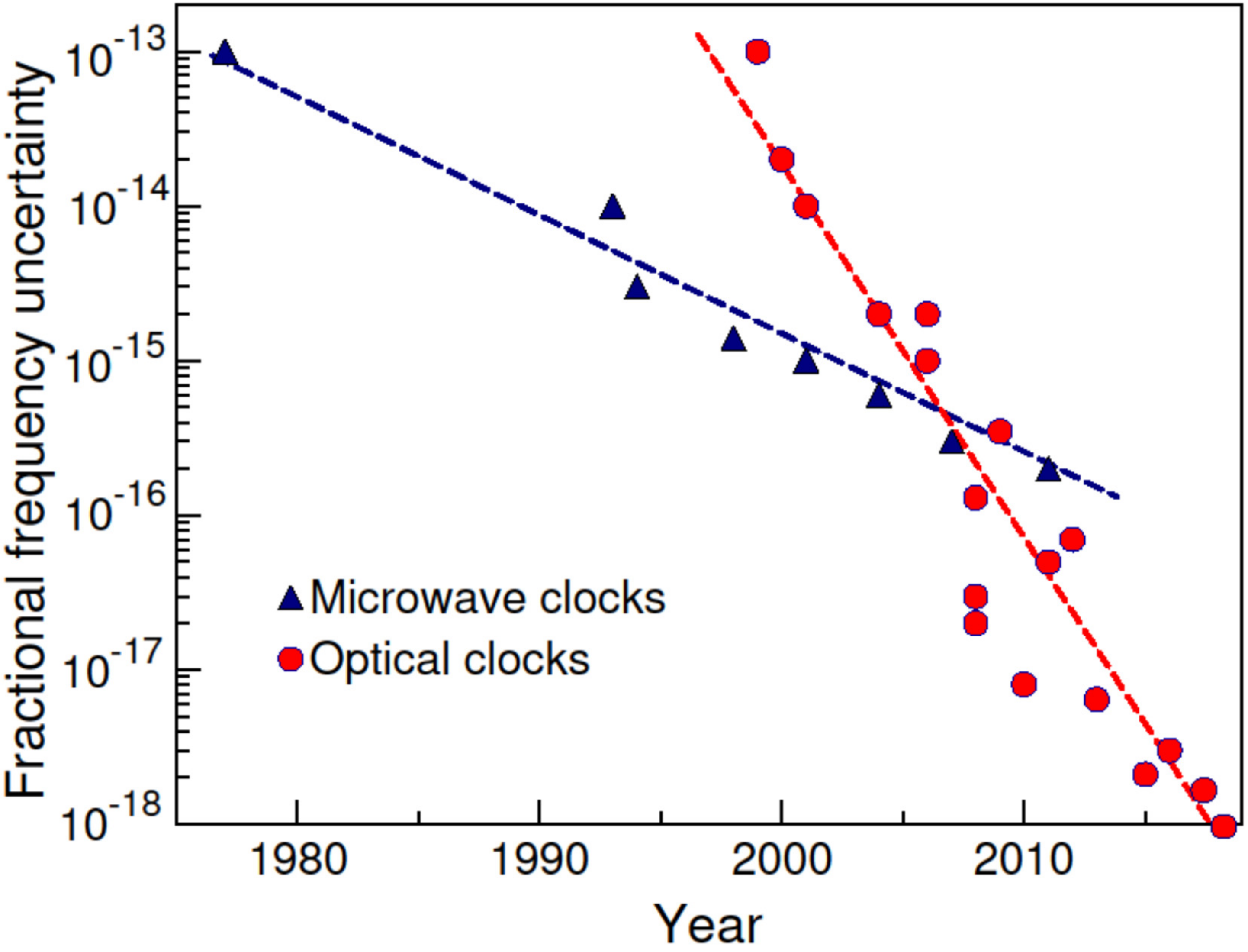
NEW PHYSICS SEARCHES WITH ATOMIC CLOCKS

GPS satellites:
microwave
atomic clocks



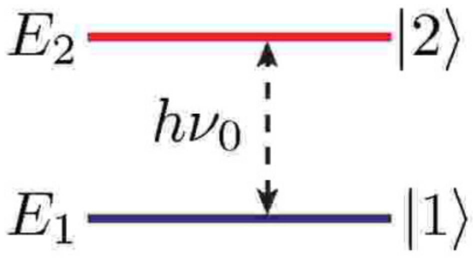
airandspace.si.edu

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



Ingredients for an atomic clock

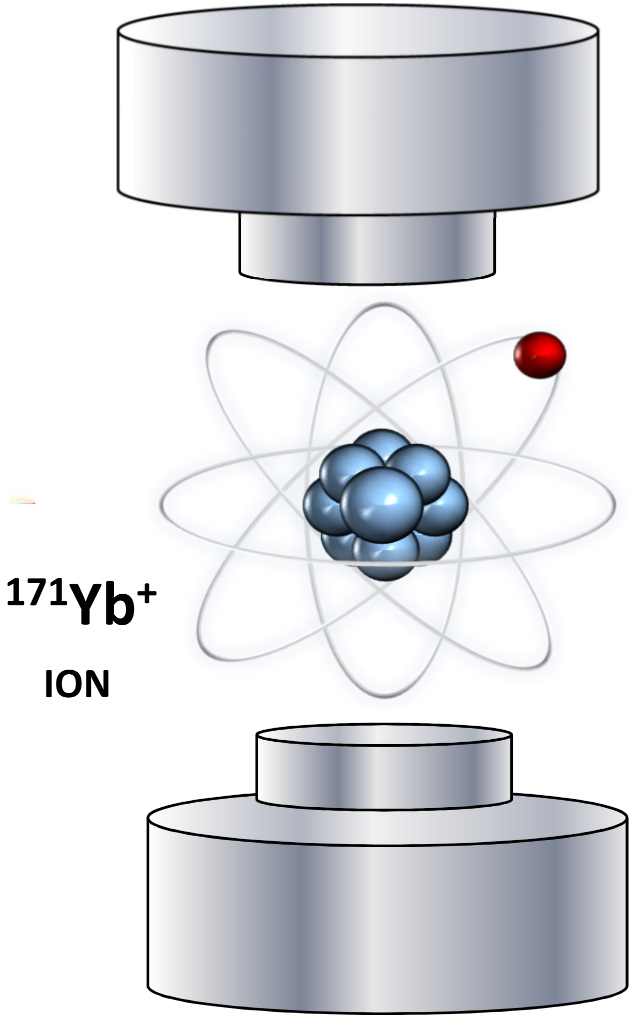
1. Atoms are all the same and will oscillate at exactly the same frequency (in the same environment): **you now have a perfect oscillator!**



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

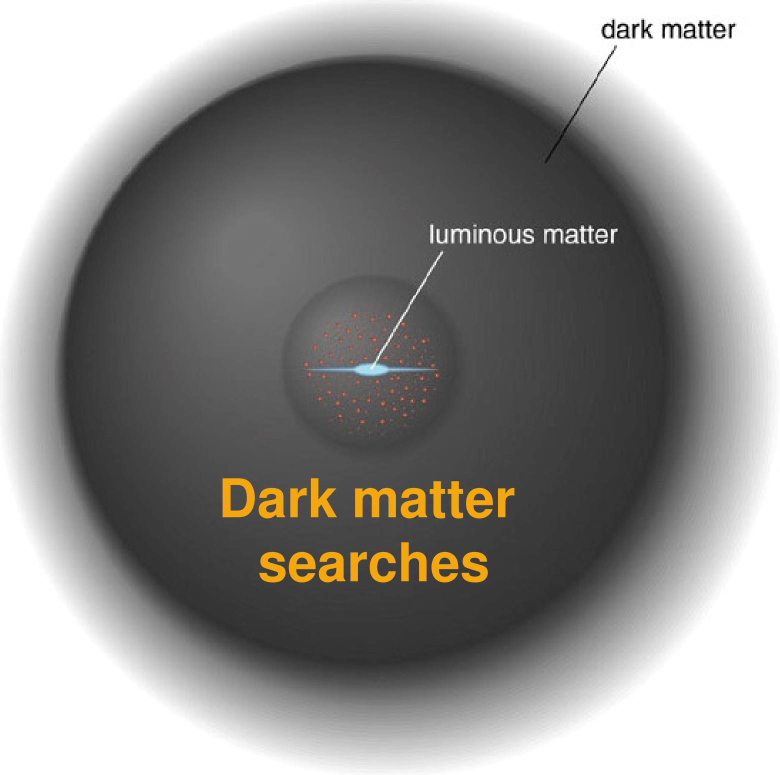
3. Build a laser and tune it to be in resonance with this atomic frequency

4. Count cycles of this signal

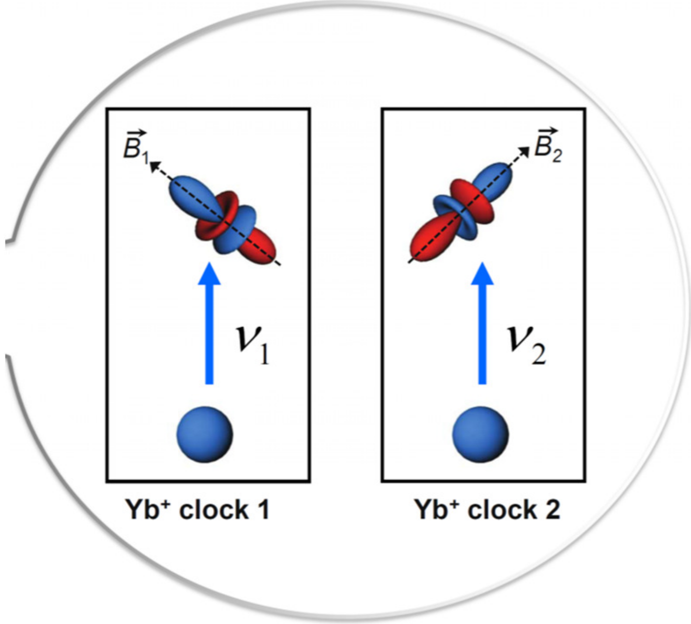


Ludlow et al., RMP 87, 637 (2015)

Search for physics beyond the Standard Model with atomic clocks



Dark matter searches



Search for the violation of Lorentz invariance

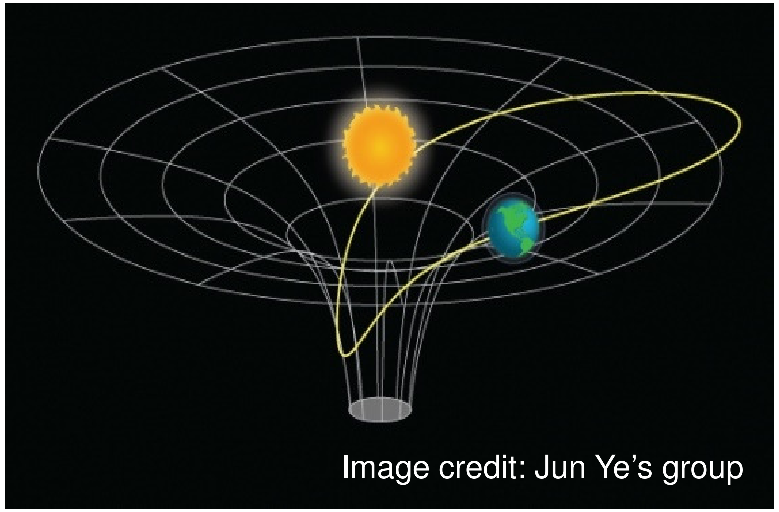


Image credit: Jun Ye's group

Tests of the equivalence principle

Are fundamental constants constant?

α

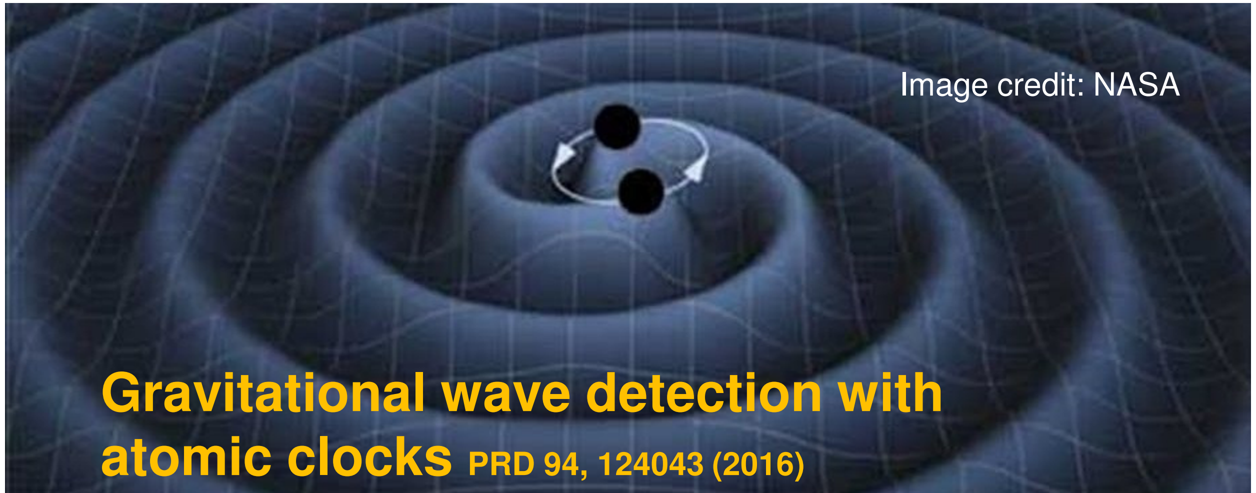


Image credit: NASA

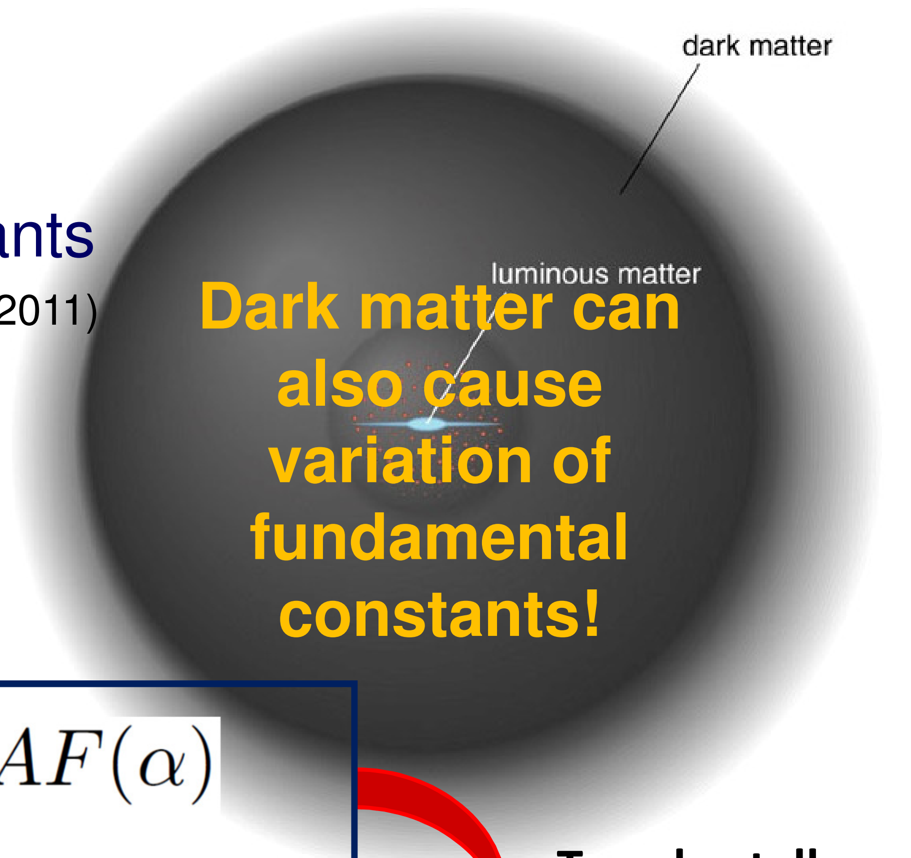
Gravitational wave detection with atomic clocks PRD 94, 124043 (2016)

Variation of fundamental constants

Theories with varying dimensionless fundamental constants

J.-P. Uzan, Living Rev. Relativity 14, 2 (2011)

- String theories
- Other theories with extra dimensions
- Loop quantum gravity
- Dark energy theories: chameleon and quintessence models
- …many others



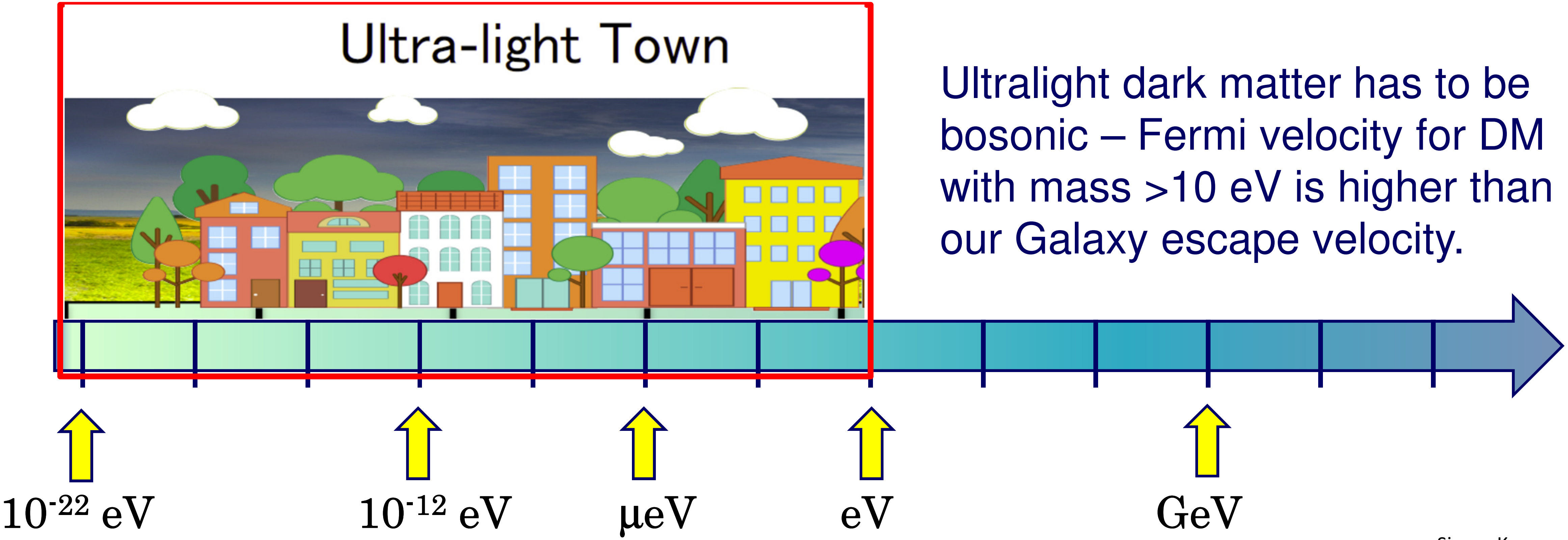
Dark matter can also cause variation of fundamental constants!

Frequency of optical transitions $\nu \simeq cR_\infty AF(\alpha)$ **depends on the fine-structure constant α.**

Some clocks are more sensitive to this effect than others

Measure the ratio of two optical clock frequencies to search for the variation of α. Keep doing this for a while.

Tuesday talk
Particle Physics Beyond Colliders: A theory perspective
Asimina Arvanitaki



Ultralight dark matter has to be bosonic – Fermi velocity for DM with mass >10 eV is higher than our Galaxy escape velocity.

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

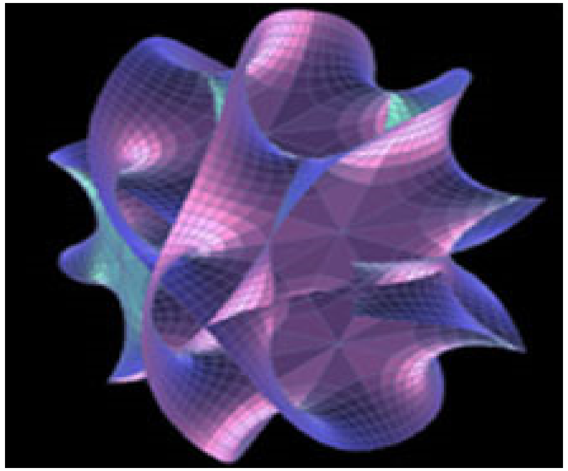
λ_{dB} is the de Broglie wavelength of the particle.

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

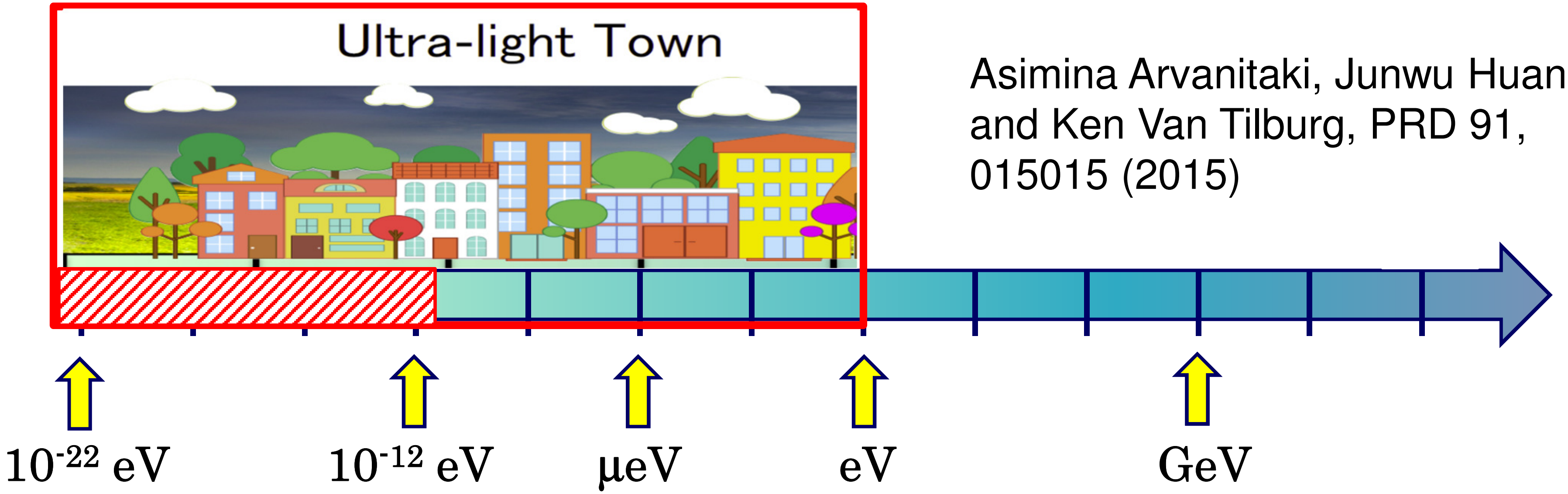
$$\frac{\phi}{M^*}\mathcal{O}_{\mathrm{SM}}$$

Simon Knapen, 2018 KITP



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

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).

Sensitivity of optical clocks to α-variation/dark matter

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

Enhancement factor

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

Can calculate
with high accuracy

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

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

↑

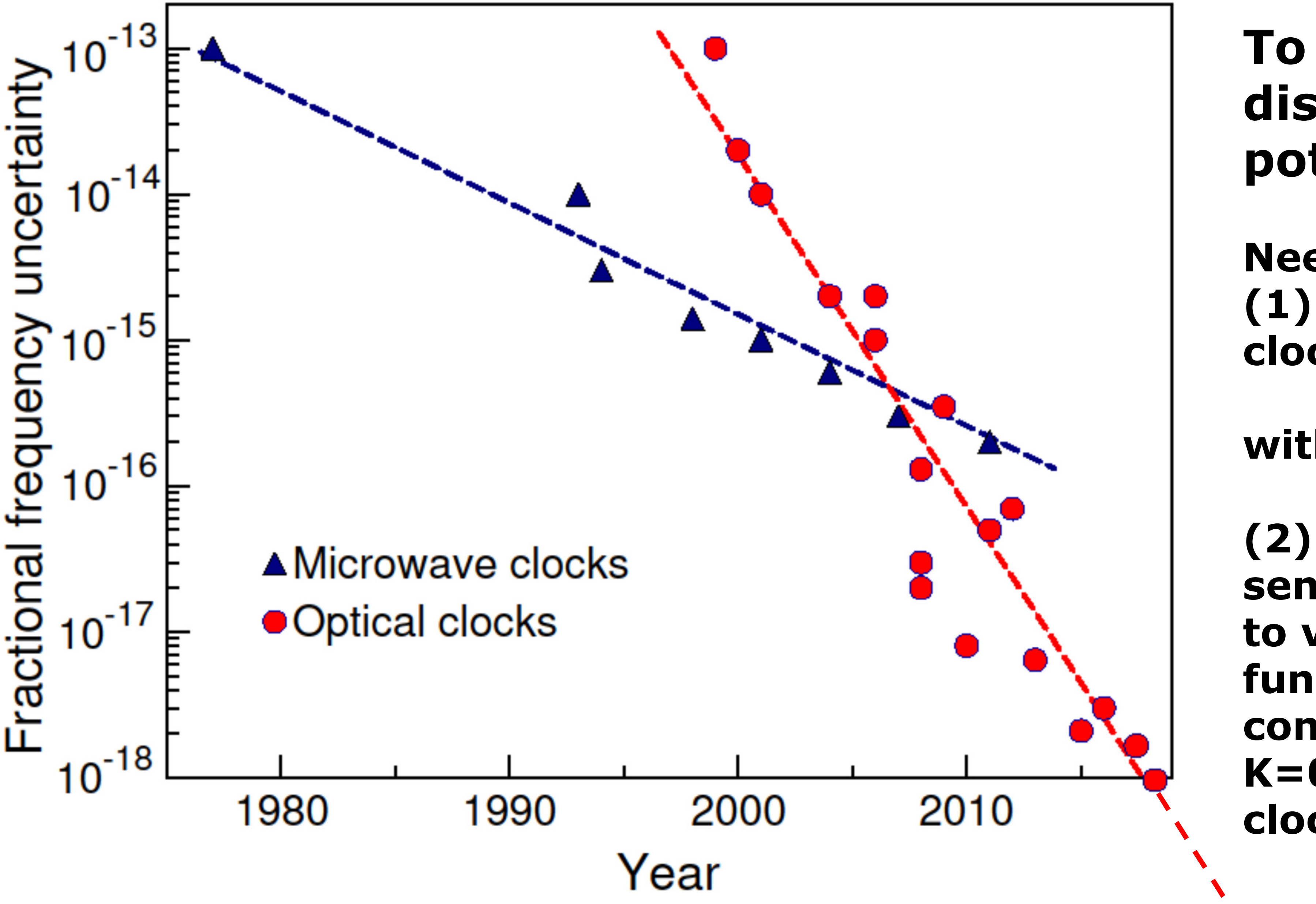
Frequency ratio
accuracy 10^{-18}

100

Test of α-variation

10^{-20}

Easier to measure large effects!



To maximize the discovery potential

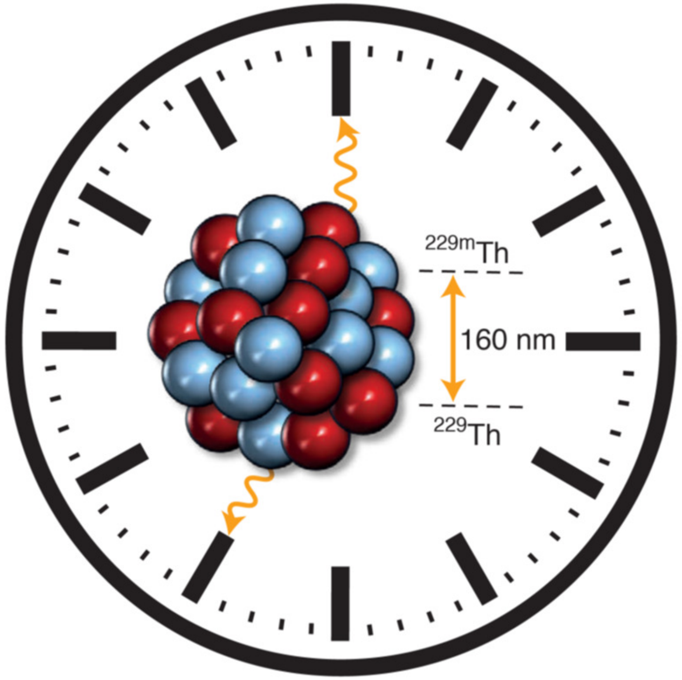
Need:
(1)most precise clocks

with

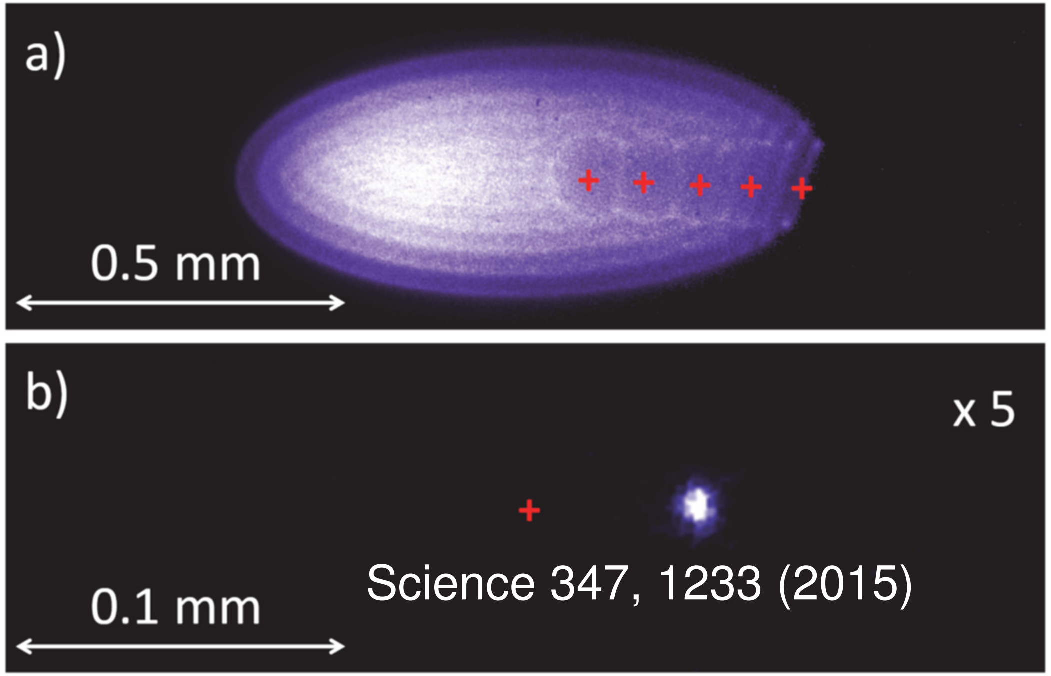
(2) largest possible sensitivity factors K to variation of fundamental constants
K=0-6 for present clocks

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

The Future: New Clocks



Nuclear clock



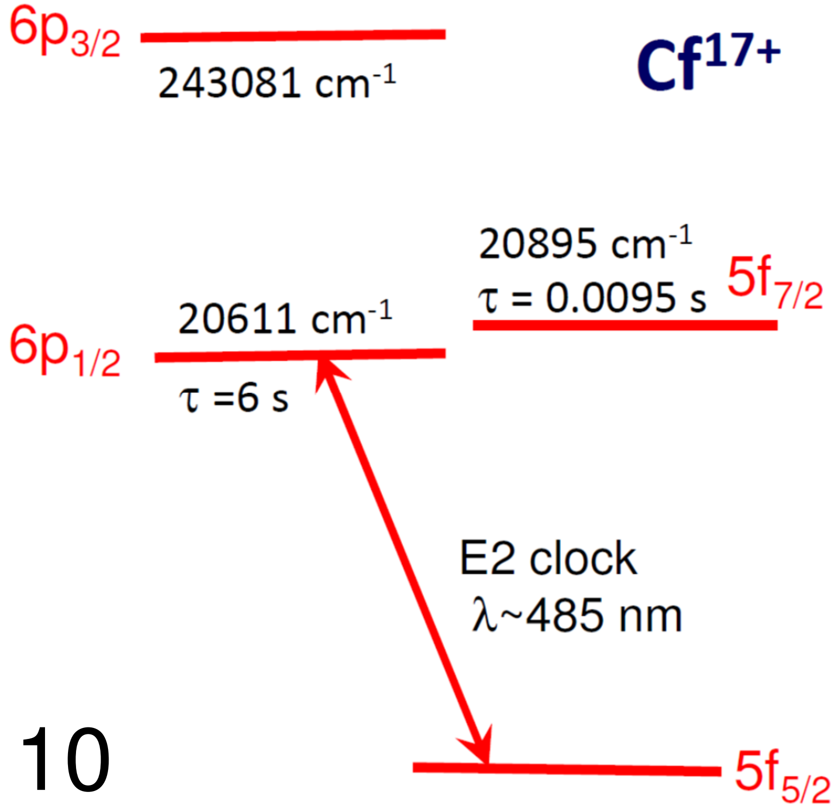
Science 347, 1233 (2015)

Clocks with ultracold highly charged ions

First demonstration of quantum logic spectroscopy at PTB, Germany
Nature 578 (7793), 60 (2020)

Optical clocks based on the Cf^{15+} and Cf^{17+} ions

^{249}Cf I = 9/2 (351 y)
^{250}Cf I = 0 (13.1 y)
^{251}Cf I = 1/2 (898 y)


Cf^{17+}

$6p_{3/2}$ 243081 cm^{-1}

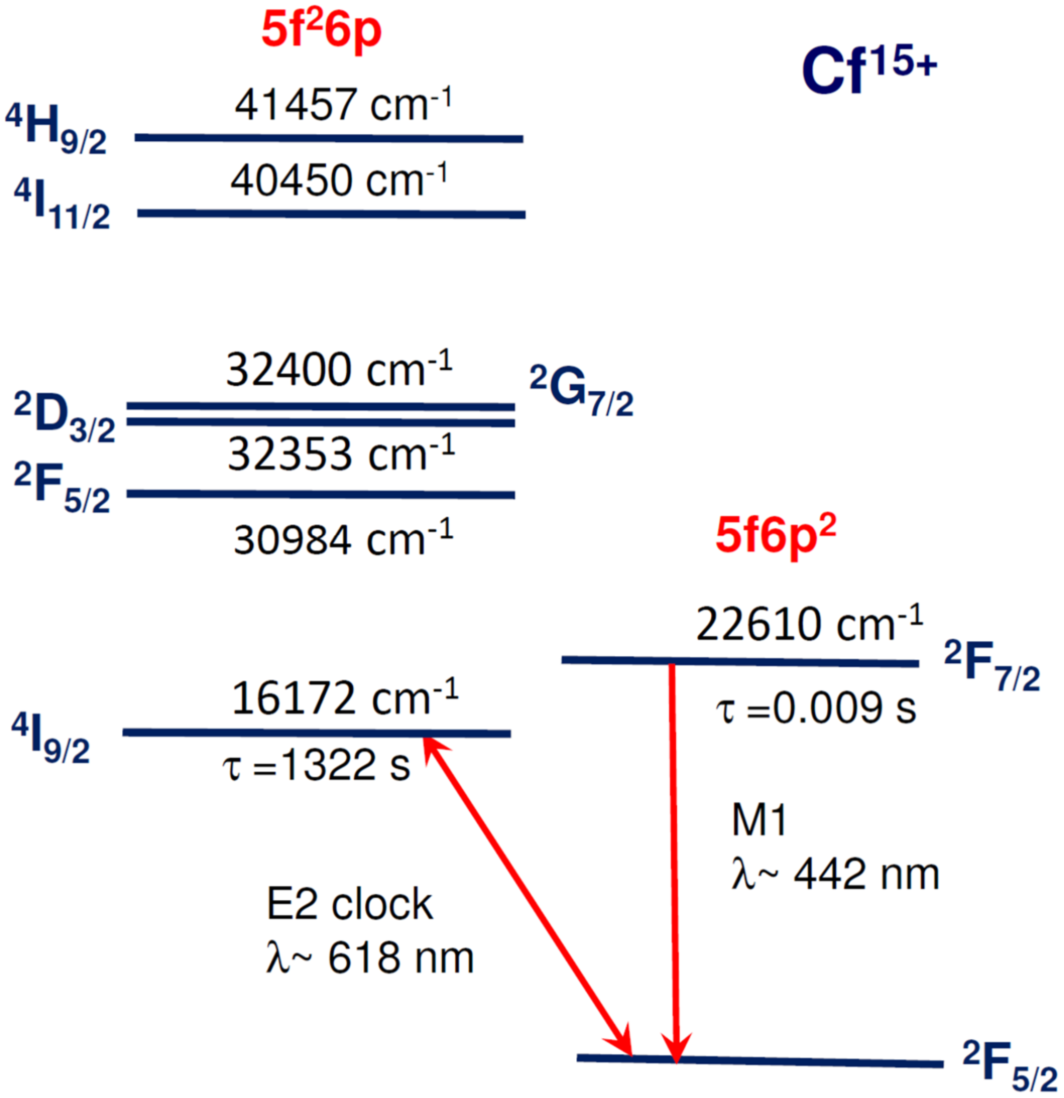
$5f_{7/2}$ 20895 cm^{-1} τ = 0.0095 s

$6p_{1/2}$ 20611 cm^{-1} τ =6 s

E2 clock
λ~485 nm

$5f_{5/2}$

$\Delta K \approx 110$


Cf^{15+}

5f^{2}6p

$^4H_{9/2}$ 41457 cm^{-1}

$^4I_{11/2}$ 40450 cm^{-1}

$^2G_{7/2}$ 32400 cm^{-1}

$^2D_{3/2}$ 32353 cm^{-1}

$^2F_{5/2}$ 30984 cm^{-1}

5f6p^2

$^2F_{7/2}$ 22610 cm^{-1} τ =0.009 s

$^4I_{9/2}$ 16172 cm^{-1} τ =1322 s

E2 clock
λ~ 618 nm

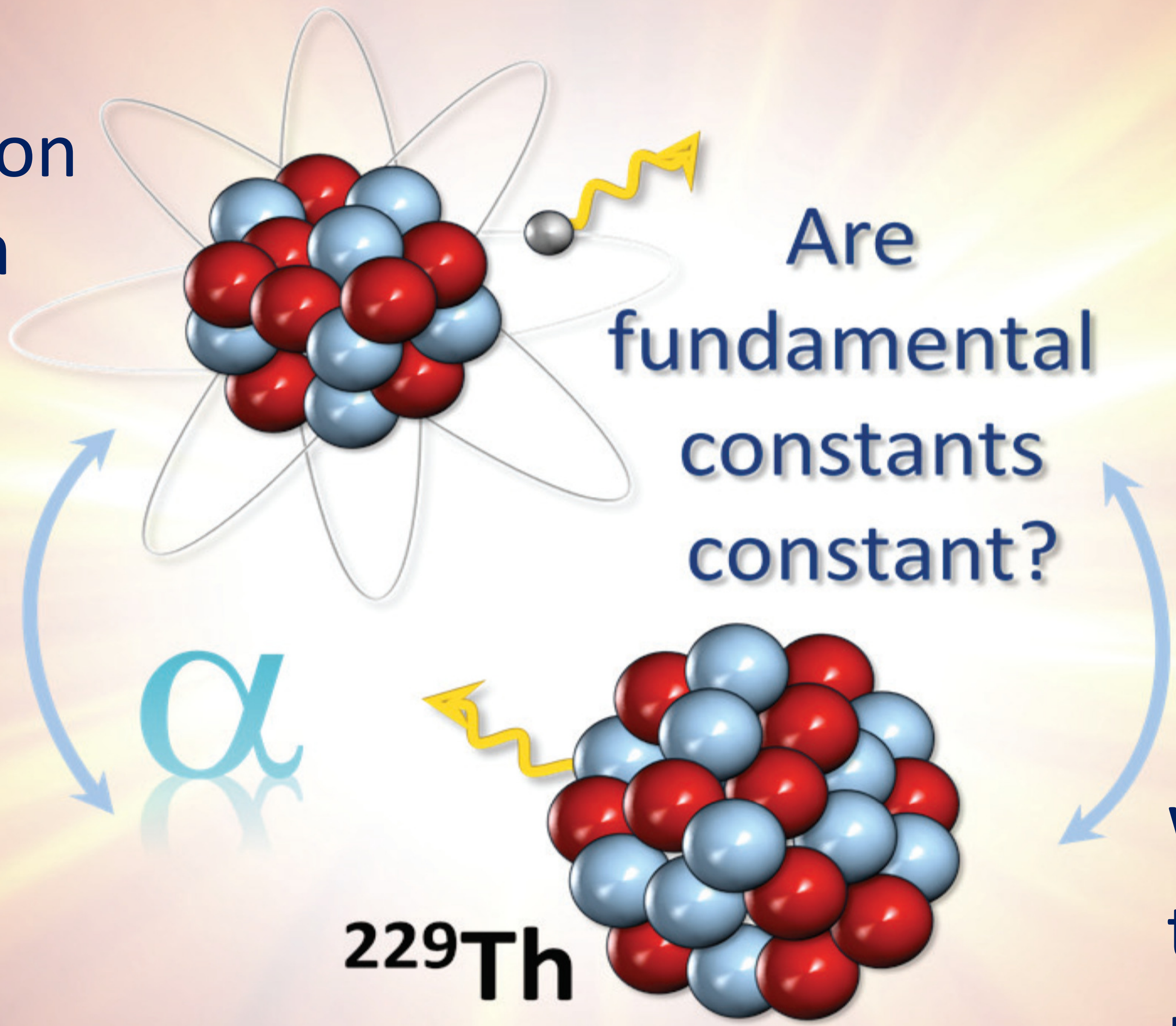
M1
λ~ 442 nm

$^2F_{5/2}$

S. G. Porsev, U. I. Safronova, M. S. Safronova, P. O. Schmidt, A. I. Bondarev, M. G. Kozlov, I. I. Tupitsyn, PRA 102, 012802 (2020)

From atomic to nuclear clocks!

Clock based on transitions in atoms

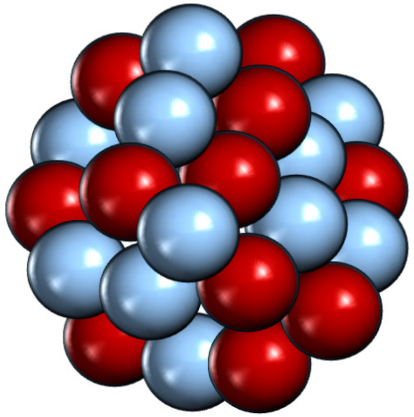


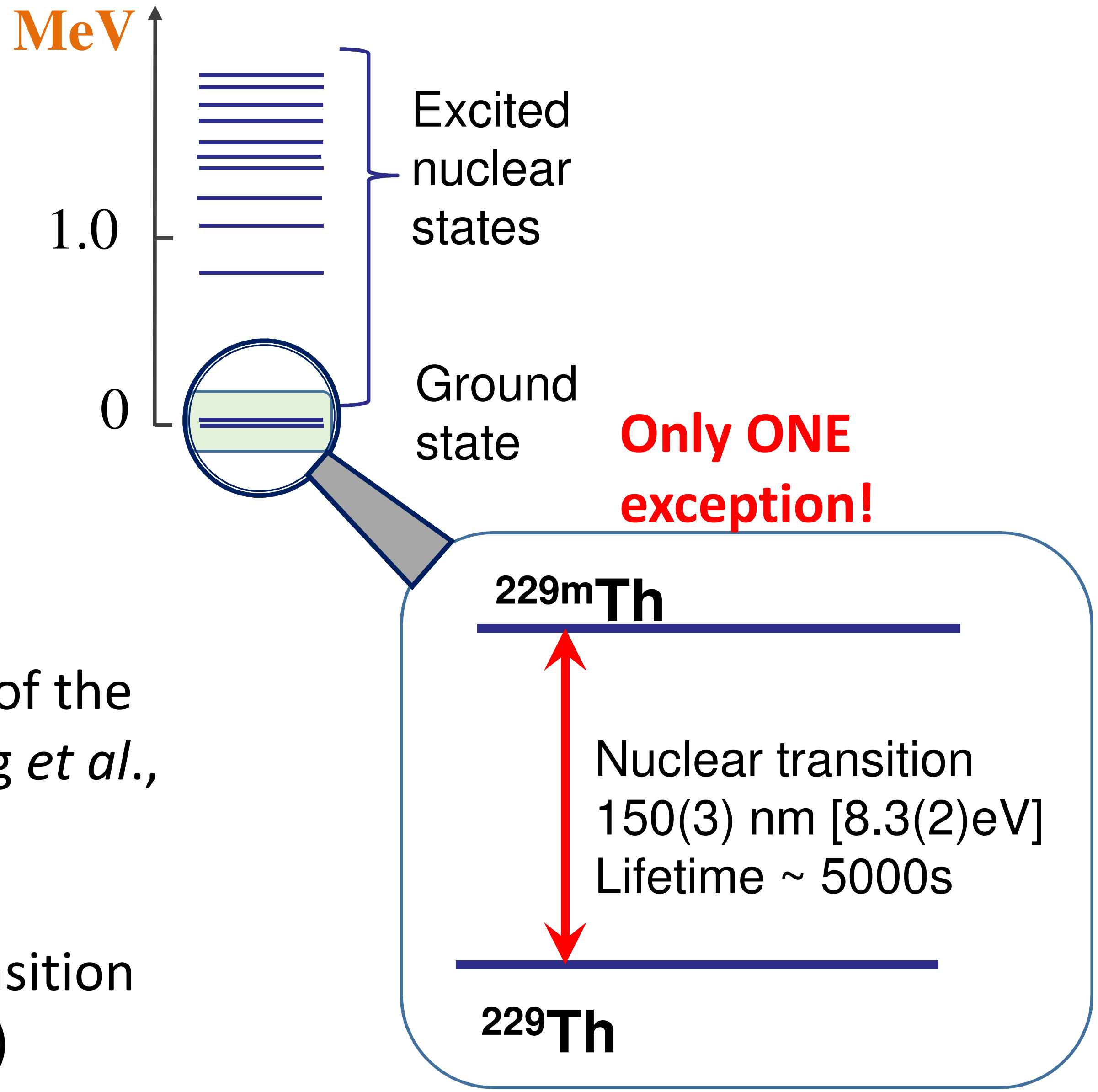
What about transitions in nuclei?

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

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

Atomic
Nucleus





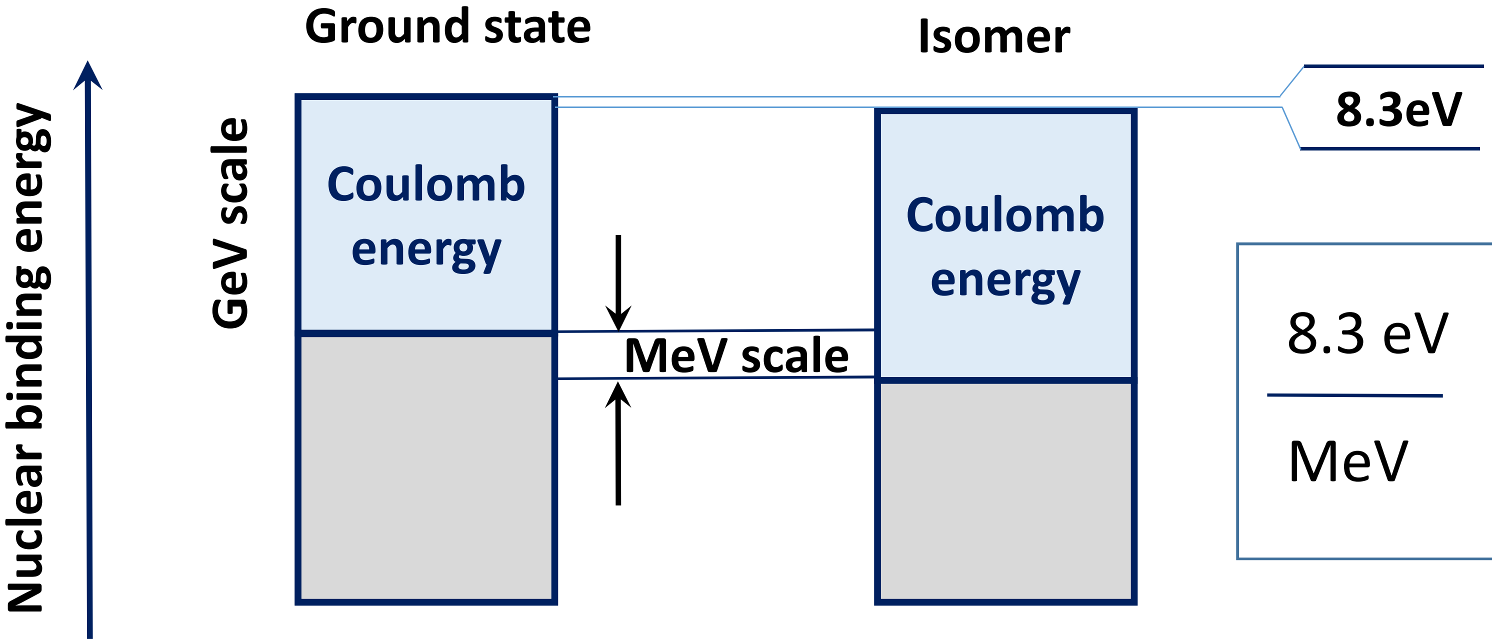
Only ONE exception!

Nuclear transition
150(3) nm [8.3(2)eV]
Lifetime ~ 5000s

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



$$\frac{8.3\ \text{eV}}{\text{MeV}} \sim 10^5$$

Thorium nuclear clocks for fundamental tests of physics

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

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!

Great potential for discovery of new physics

Many new physics searches with atoms and molecules need or will benefit from the use of radioactive isotopes

- Large enhancements of new physics signals
- Unique sensitivities (such as in a nuclear clock)
- Need more isotopes (4 or more even isotopes) for new force searches
- Unique experimental opportunities (search for sterile neutrinos with trapped radioactive atoms)
- Other applications: quantum information with radioactive qubits (need I=1/2)

Significant recent improvements in atomic theory & precision laser spectroscopy for the extraction of nuclear properties (nuclear moments, nucleir radii changes, etc.)