KITP Exploration meeting on Novel Experiments for Fundamental Physics

Fundamental physics with atoms and molecules

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Department of Physics and Astronomy,
University of Delaware, Delaware, USA

thorium nuclear clock

https://thoriumclock.eu/

Q-SEnSE
An NSF Quantum Leap Challenge Institute

https://www.colorado.edu/research/qsense/

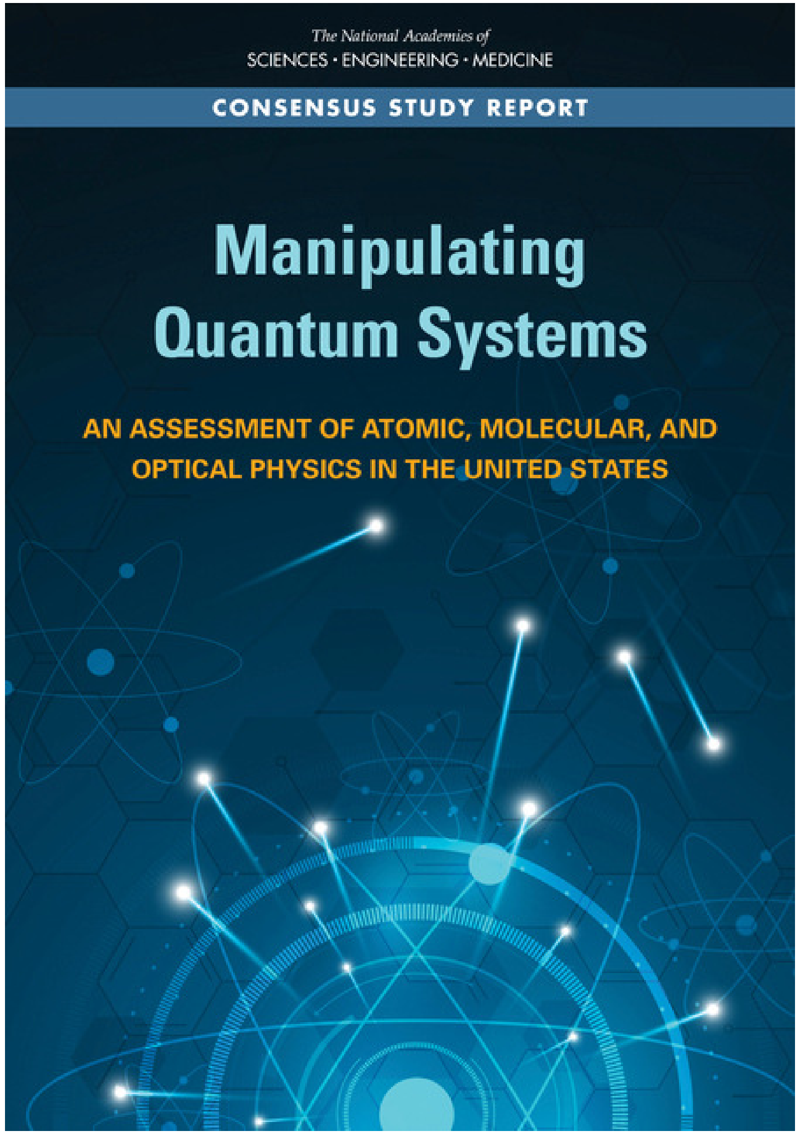
NSF

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

Office of Naval Research
ONR
Science & Technology

erc
European Research Council

2020 USA Decadal Assessment and Outlook Report on AMO Science and other recourses



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https://www.nationalacademies.org/amo

Chapter 6
PRECISION FRONTIER AND FUNDAMENTAL NATURE OF THE UNIVERSE

Recent review:
Search for new physics with atoms and molecules, M. S. Safronova, D. Budker, D. DeMille, Derek F. Jackson-Kimball, A. Derevianko, and Charles W. Clark, Rev. Mod. Phys. 90, 025008 (2018). **106 pages, over 1100 references**

Forthcoming Focus Issue in Quantum Science and Technology
Quantum Sensors for New-Physics Discoveries
Editors: Marianna Safronova and Dmitry Budker

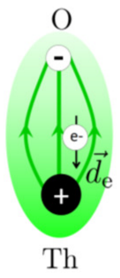
+18 articles will appear focusing on the future decade
https://iopscience.iop.org/journal/2058-9565/page/Focus-issues

Searches for BSM physics with Atomic, Molecular, and Optical (AMO) Physics

Fundamental symmetries with quantum science techniques

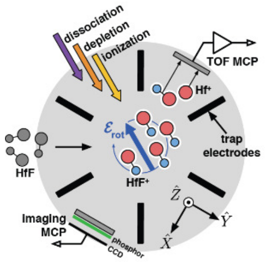
Searches for electron electric-dipole moment (eEDM)

Advanced ACME



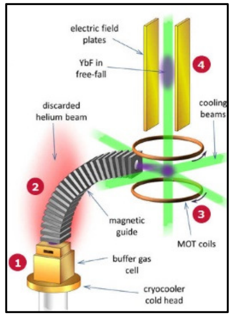
ThO

JILA eEDM



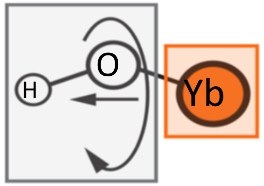
HfF^+, ThF^+

Imperial College



YbF

PolyEDM

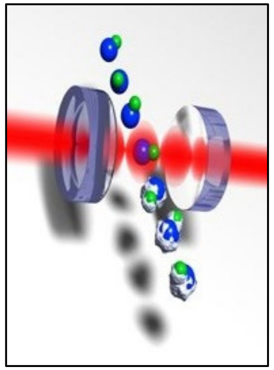


Also NMQM search

YbOH, …

Searches for hadronic EDMs

CeNTREX

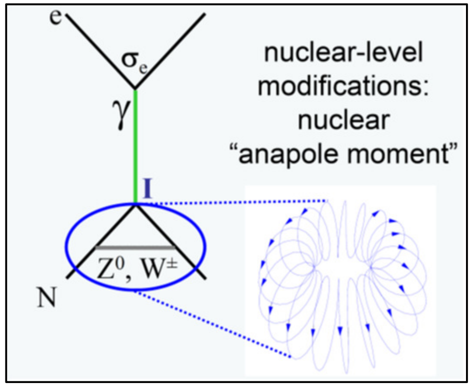


Hg
Xe
Ra
EDMs

TlF (proton EDM)

Enhanced parity violation

ZOMBIES



Also Yb (Mainz), Fr (FRIUMF & Japan)

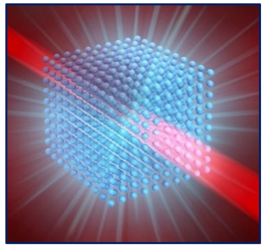
Rapid advances in ultracold molecule cooling and trapping; polyatomic molecules; future: molecules with Ra & “spin squeezed” entangled states

Atomic and Nuclear Clocks & Cavities

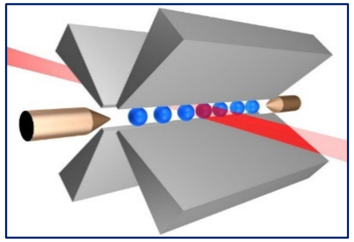
Major clock & cavities R&D efforts below, also molecular clocks, portable clocks and optical links

BSM searches with clocks

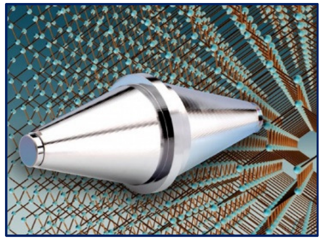
- Searches for variations of fundamental constants
- Ultralight scalar dark matter & relaxion searches
- Tests of general relativity
- Searches for violation of the equivalence principle
- Searches for the Lorentz violation



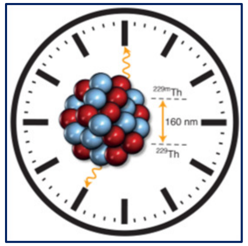
3D lattice clocks



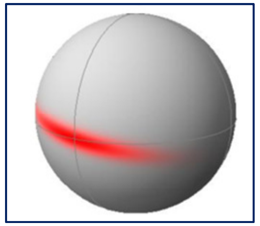
Multi-ion & entangled clocks



Ultrastable optical cavities



Nuclear & highly charge ion clocks



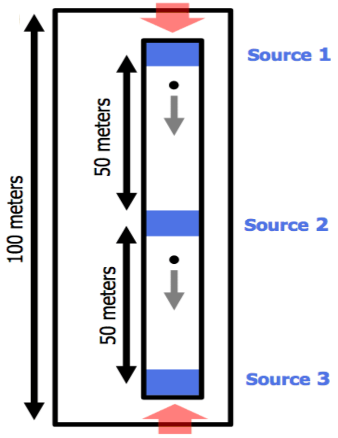
Measurements beyond the quantum limit

Atom interferometry

BSM searches:
Variation of fundamental constants
Ultralight scalar DM & relaxion searches
Violation of the equivalence principle

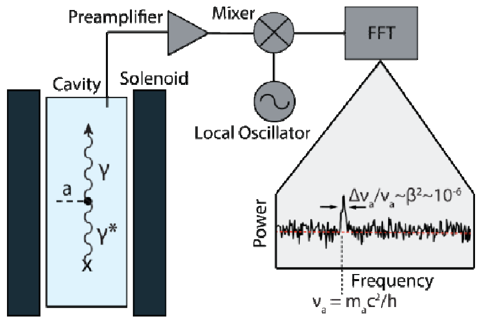
Prototype gravitational wave detectors

MAGIS-100 Fermilab



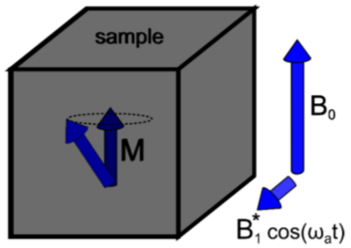
MIGA (France), 150 meters under construction
AION

Axion and ALPs searches



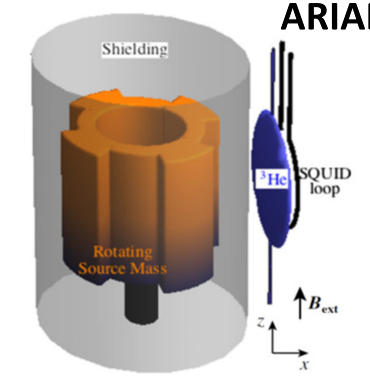
Microwave cavities: HAYSTAC
AMO: measurements beyond quantum limits

CASPEr-electric, solids
(coupling to gluons)



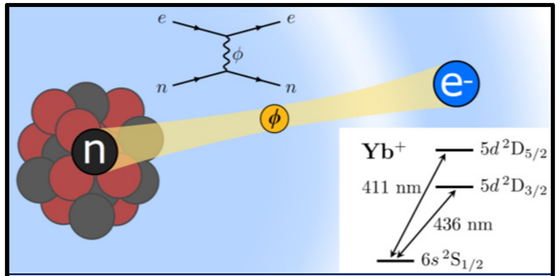
CASPEr-wind, Xe
(coupling to fermions)

ARIADNE



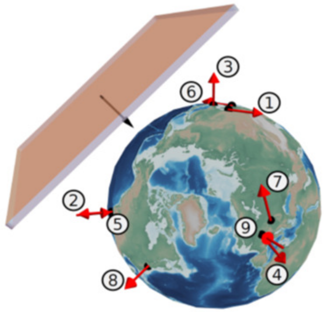
Resonantly detecting axion-mediated forces with NMR

Other dark matter & new force searches



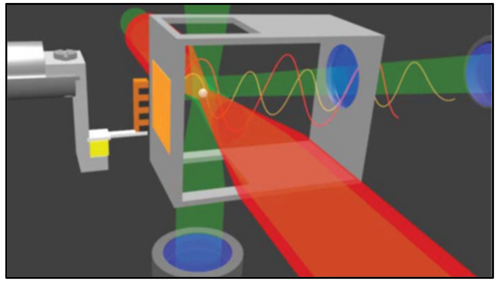
Fifth force searches with precision spectroscopy with atoms and ions

WReSL: Cs spectroscopy



GNOME: network of optical magnetometers for exotic physics

Levitated optomechanics



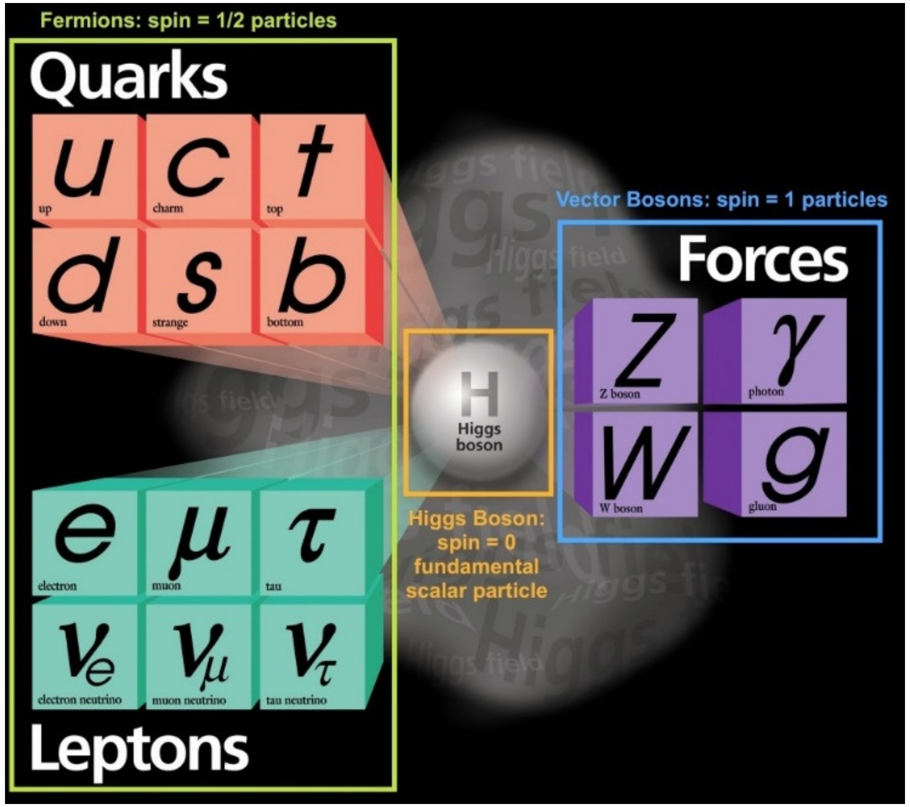
Also: gravitational wave detection and testing the Newtonian inverse square law

Many other current & future experiments: tests of the gravity-quantum interface, and HUNTER (AMO sterile neutrino search), SHAFT, ORGAN & UPLOAD (axions), solid-state directional detection with NV centers (WIMPs), doped cryocrystals for EDMs, Rydberg atoms, tests of QED, ...

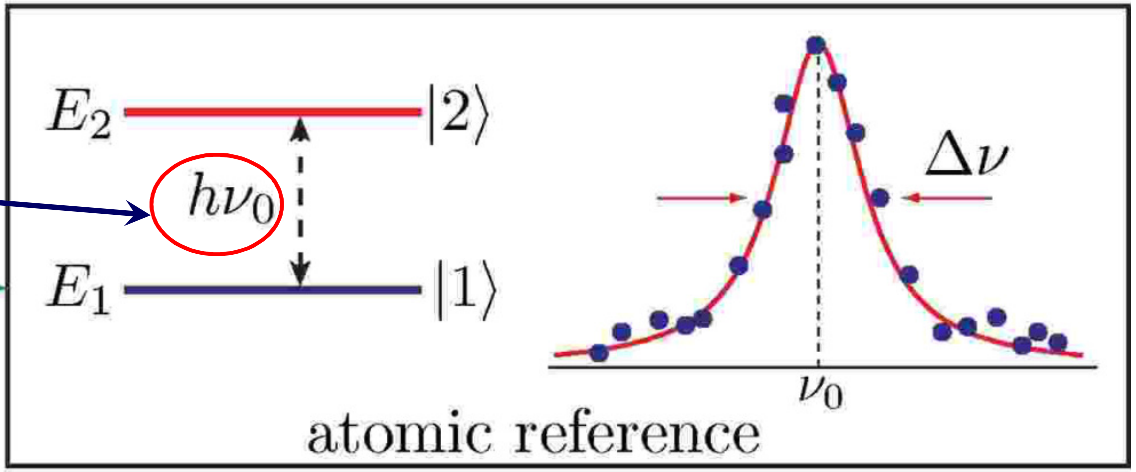
Search for physics beyond the standard model with atomic clocks

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.

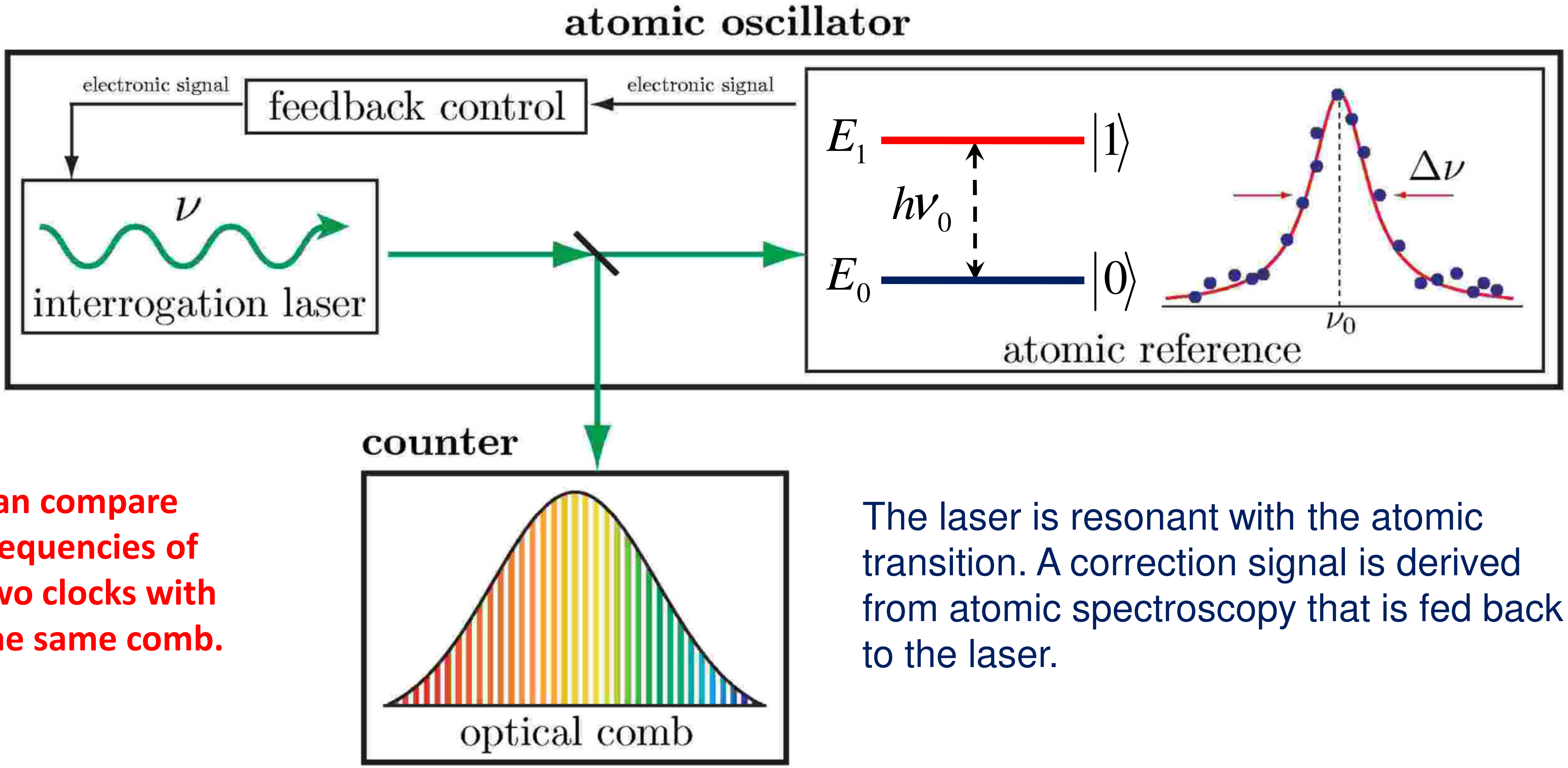


Frequency will change



BEYOND THE STANDARD MODEL?

How optical atomic clock works



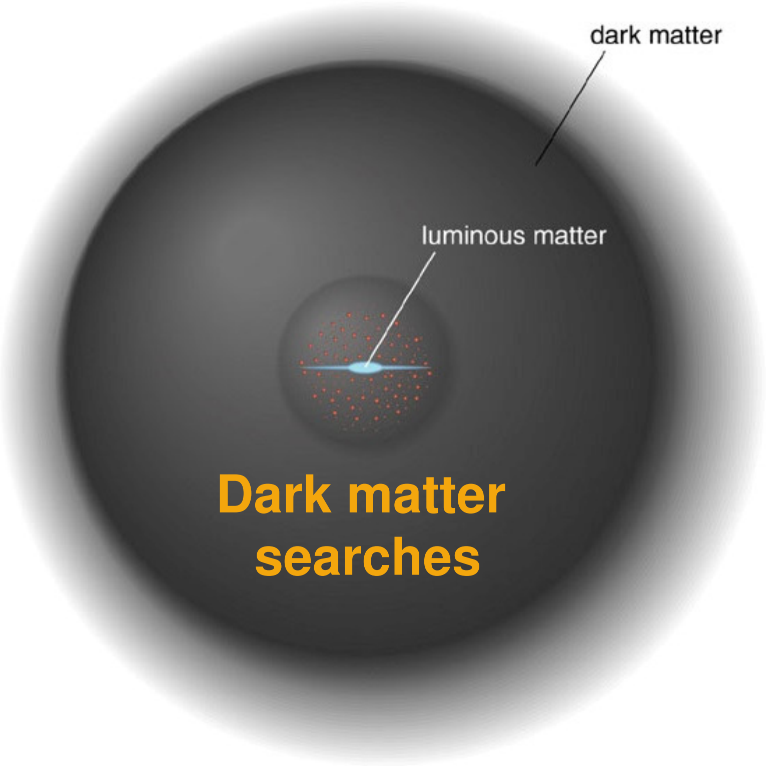
Can compare frequencies of two clocks with the same comb.

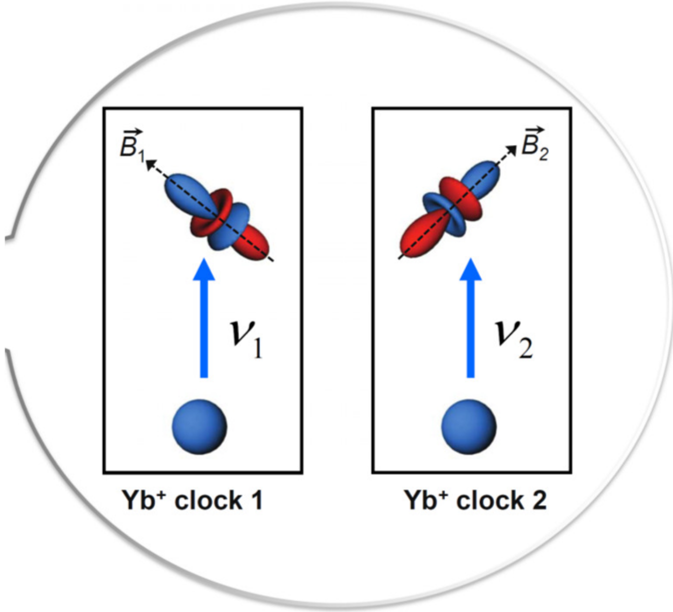
The laser is resonant with the atomic transition. A correction signal is derived from atomic spectroscopy that is fed back to the laser.

An optical frequency synthesizer (optical frequency comb) is used to divide the optical frequency down to countable microwave or radio frequency signals.

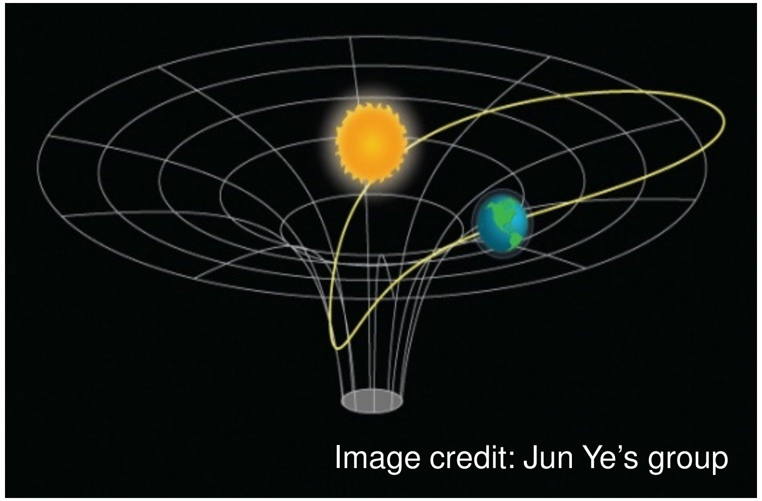
From: Poli et al. "Optical atomic clocks", La rivista del Nuovo Cimento 36, 555 (2018) arXiv:1401.2378v2

Search for physics beyond the Standard Model with atomic clocks





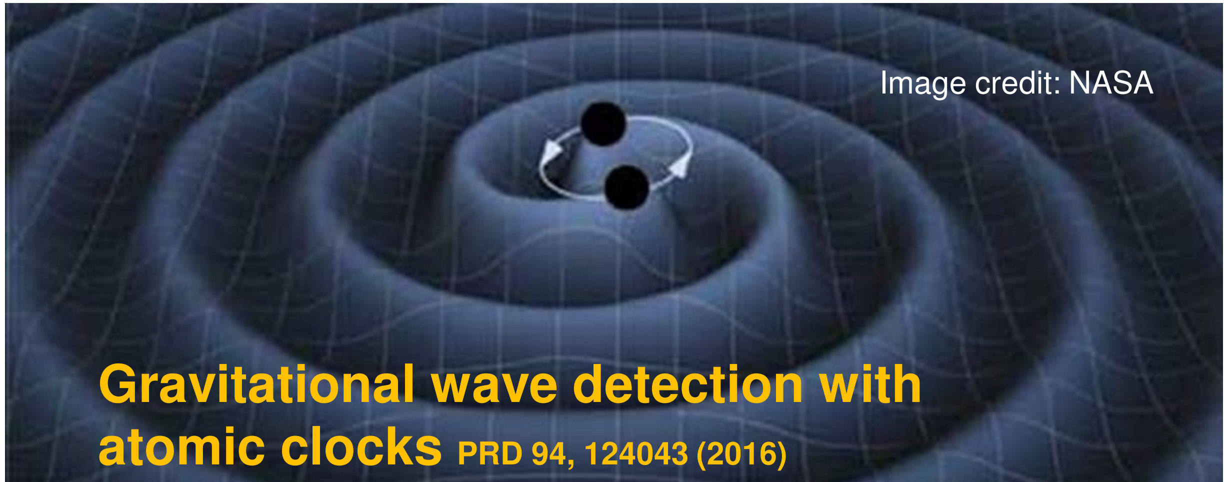
Search for the violation of Lorentz invariance



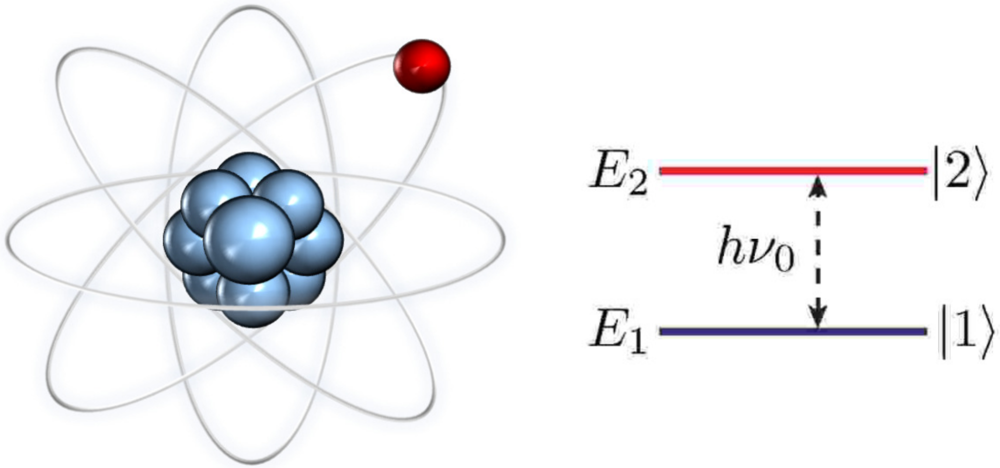
Tests of the equivalence principle

Are fundamental constants constant?

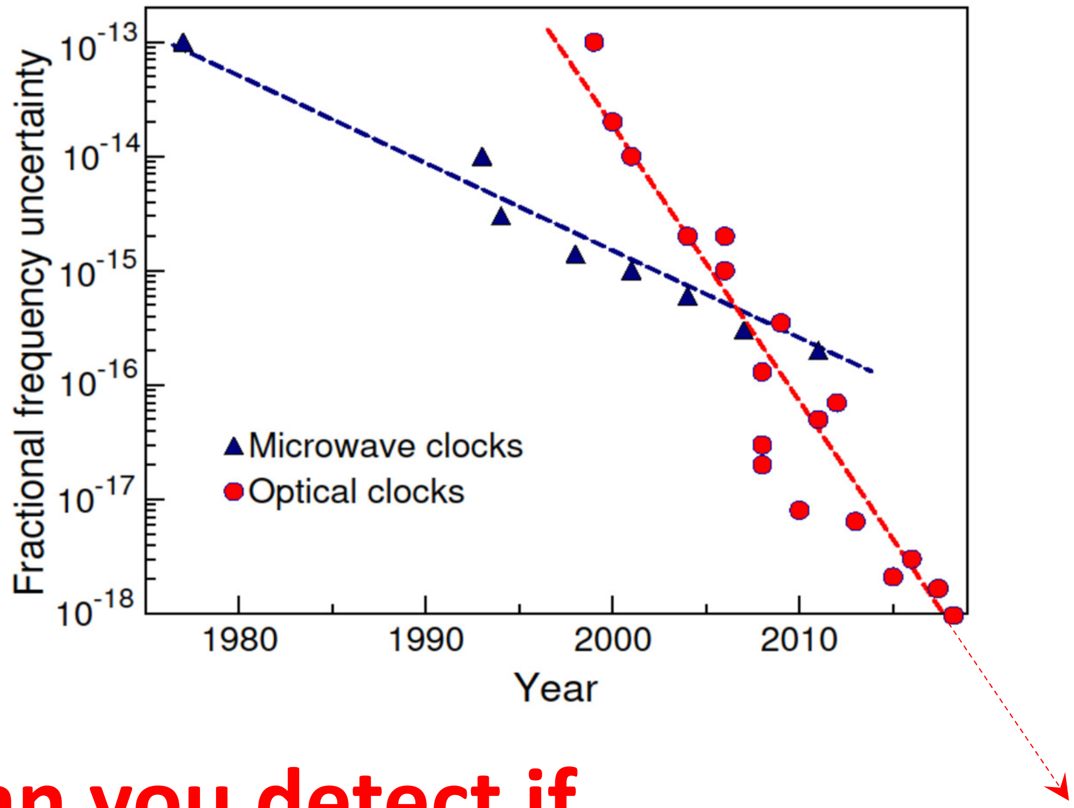
α



Dark matter can affects atomic energy levels

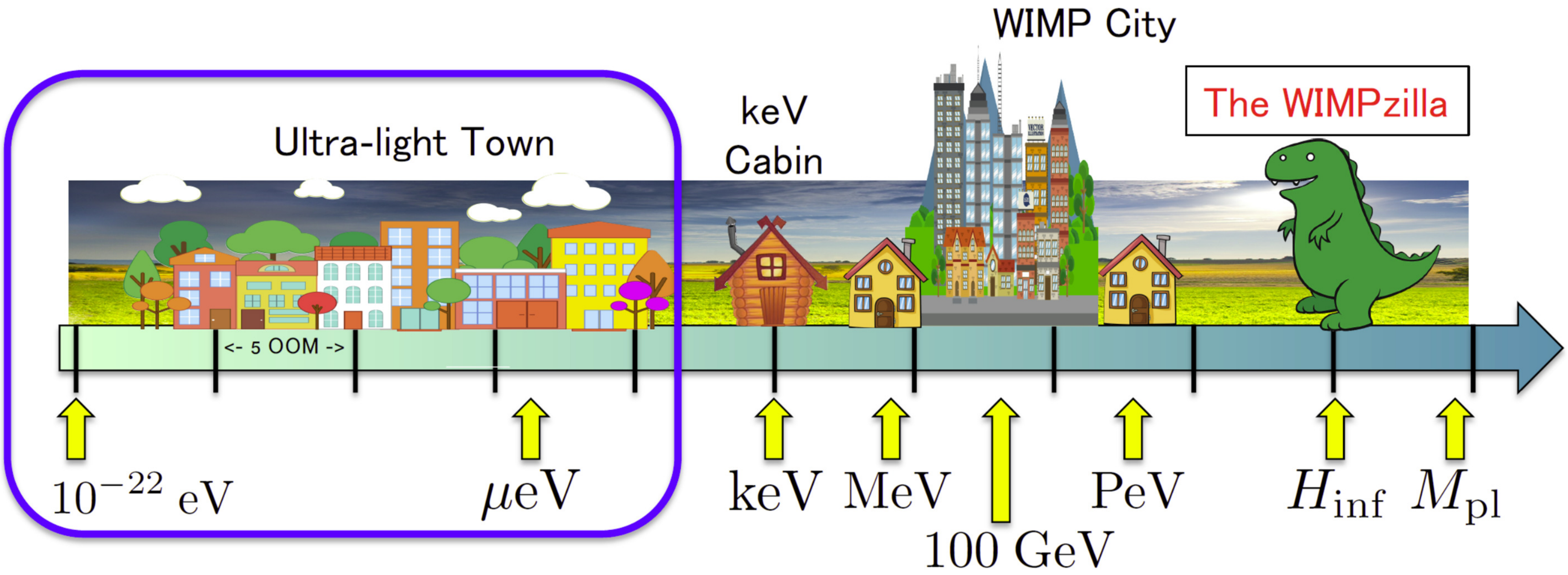


ν_0 is a clock frequency



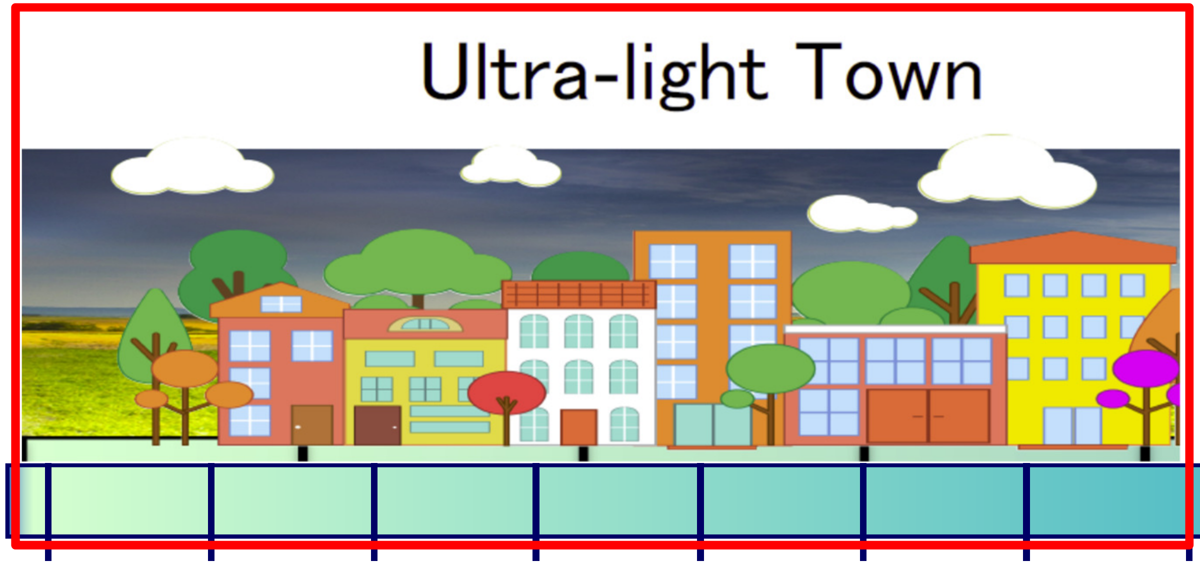
What dark matter can you detect if you can measure changes in atomic/nuclear frequencies to 19-20 digits?

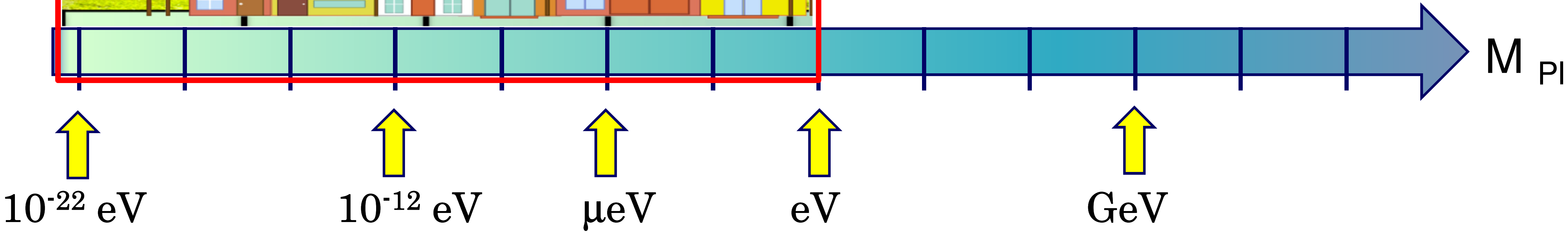
The landscape of dark matter masses



We do not know what dark matter particle mass is.

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

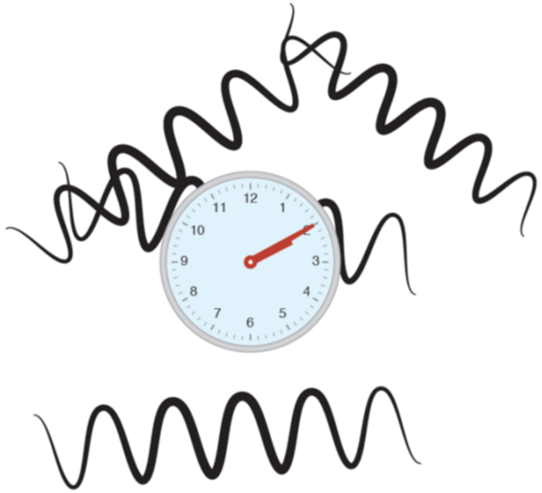




Dark matter density in our Galaxy > λ_{dB}^{-3}

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

Then, the scalar dark matter exhibits coherence and behaves like a wave $\phi(t) = \phi_0 \cos\left(m_\phi t + \bar{k}_\psi \times \bar{x} + \ldots\right)$



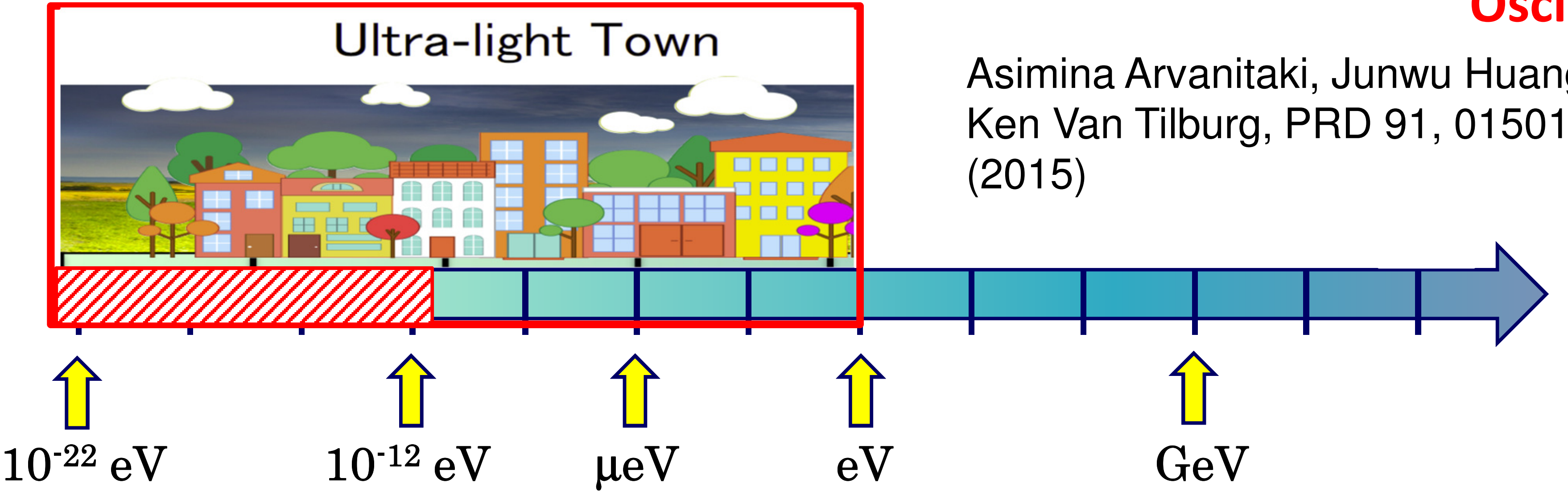
A. Arvanitaki et al., PRD 91, 015015 (2015)

Conf. Ser. **723** (2016) 012043

How to detect ultralight dark matter with clocks?

Oscillatory effects

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 & nuclear 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

$$\frac{\phi}{M^*}\mathcal{O}_{SM} \longrightarrow \mathcal{L}_\phi = \kappa\phi\left[+\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} \dots\right] \qquad \alpha = \alpha^{SM} + \delta\alpha$$

photons

Dark matter

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

Then, clock frequencies will oscillate!

DM virial velocities ~ 300 km/s

Measure clock frequency ratios: $\frac{\delta(\nu_2/\nu_1)}{(\nu_2/\nu_1)} \simeq d_e(K_2 - K_1)\kappa\phi(t)$

Sensitivity factors to α-variation

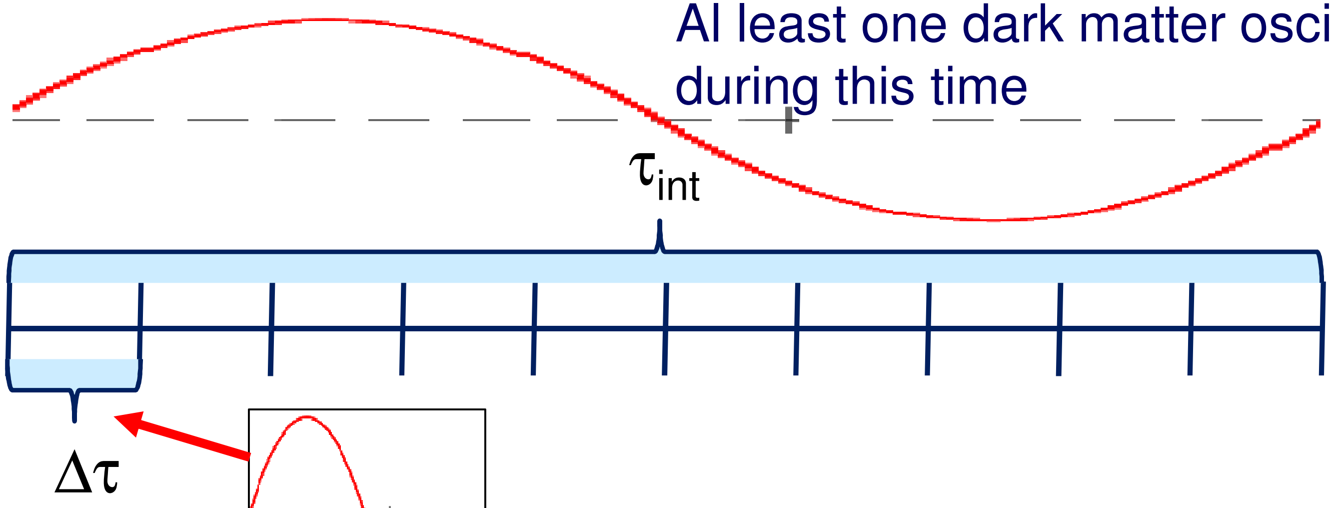
Result: plot couplings d_e vs. DM mass m_f

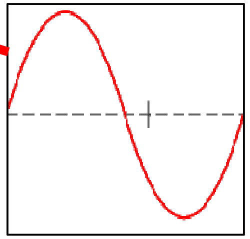
Clock measurement protocols for the dark matter detection

Single clock ratio measurement: averaging over time τ_1

Make N such measurements, preferably regularly spaced

Al least one dark matter oscillation during this time



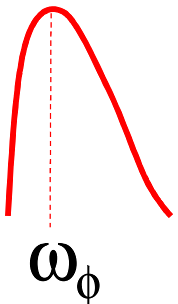


No more than one dark matter oscillation during this time or use extra pulse sequence

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}
1000	1 mHz	4×10^{-18}
10^{6}	10^{-6}	4×10^{-21}

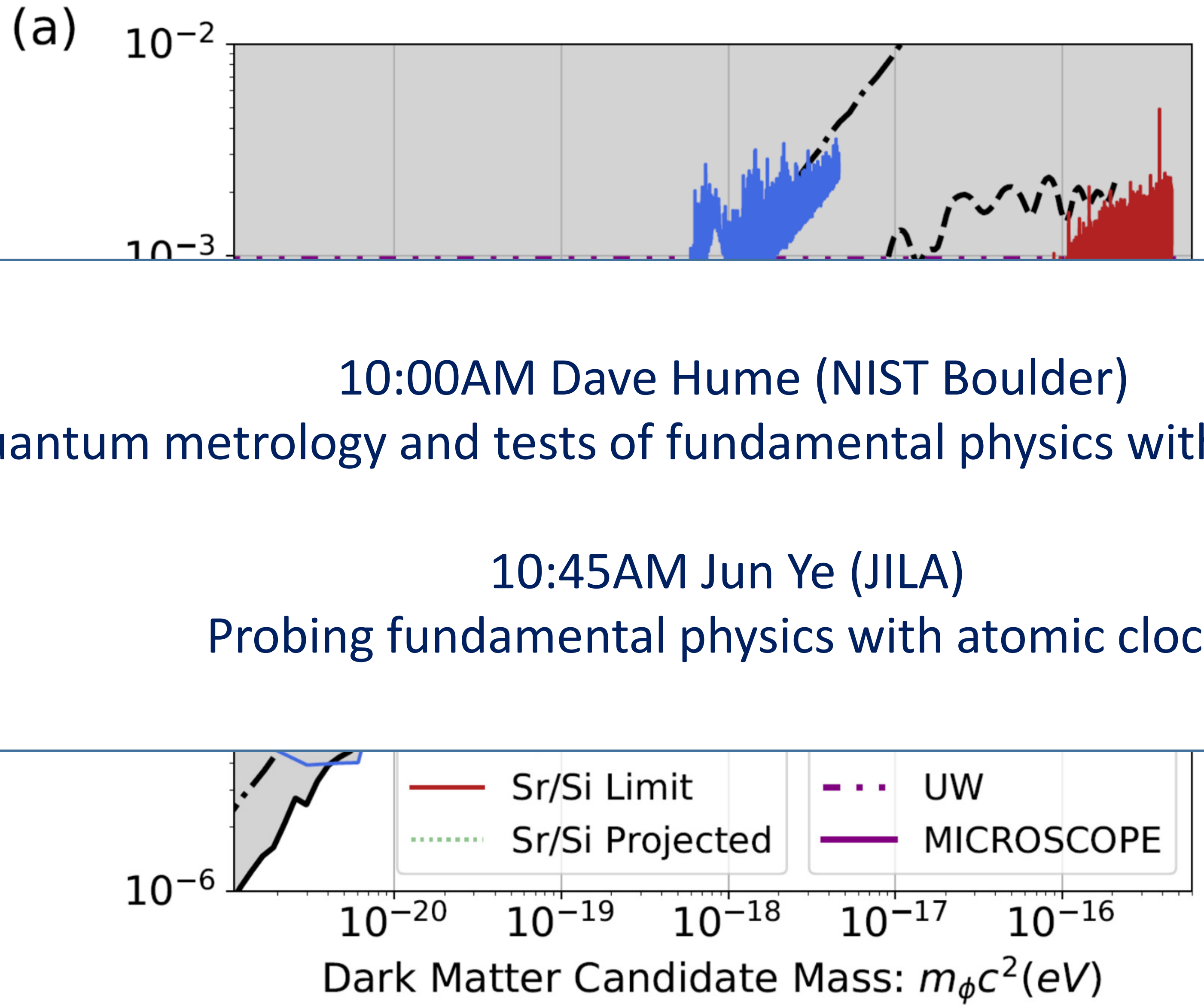
Detection signal:

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)

Dark Matter Exclusion (dilatonic coupling) Plot, Kennedy et al., Phys. Rev. Lett. 125, 201302 (2020)



Many improvements and new clocks are coming!

10:00AM Dave Hume (NIST Boulder)

Quantum metrology and tests of fundamental physics with trapped ions

10:45AM Jun Ye (JILA)

Probing fundamental physics with atomic clocks

Transient variations

nature physics

LETTERS

PUBLISHED ONLINE: 17 NOVEMBER 2014 | DOI: 10.1038/NPHYS3137

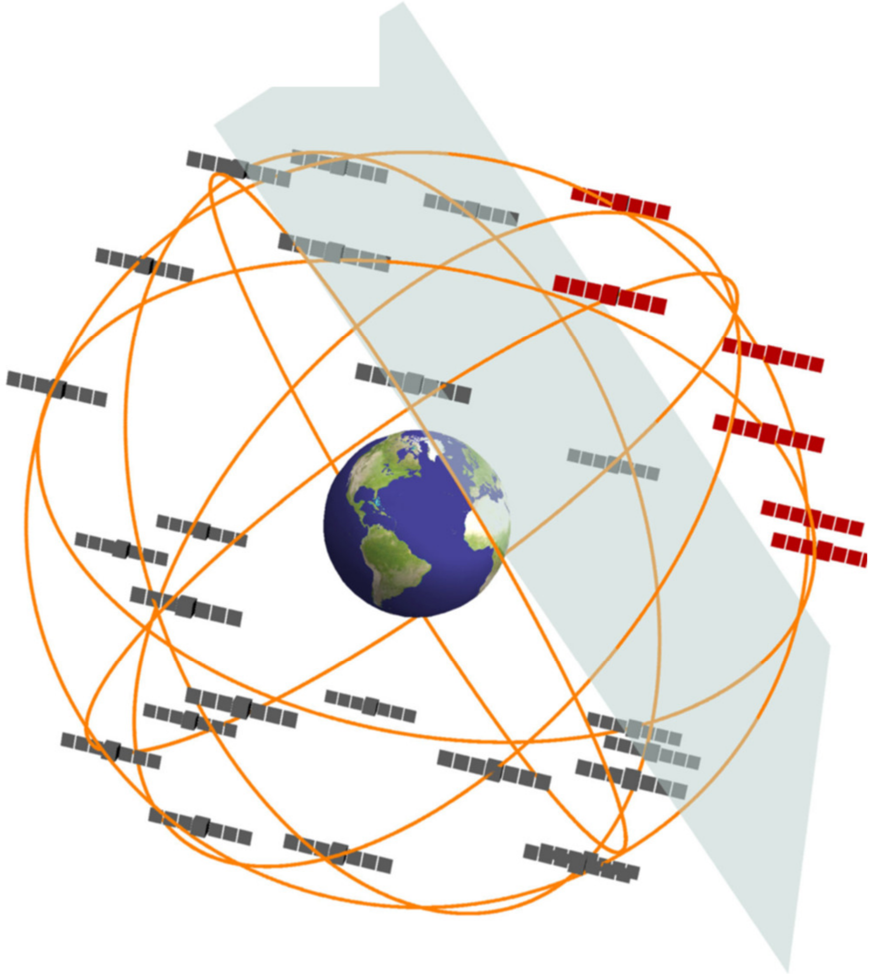
Hunting for topological dark matter with atomic clocks

Transient effects

A. Derevianko[1*] and M. Pospelov[2,3]

Dark matter clumps: point-like monopoles, one-dimensional strings or two-dimensional sheets (domain walls).

If they are large (size of the Earth) and frequent enough they may be detected by measuring changes in the synchronicity of a global network of atomic clocks, such as the Global Positioning System or networks of precision clocks on Earth.



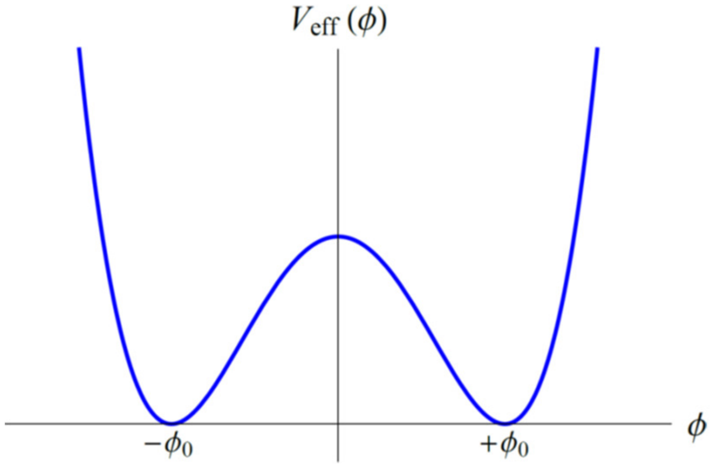
GPM.DM collaboration: Roberts at el., Nature Communications 8, 1195 (2017)

PHYSICAL REVIEW D **102,** 115016 (2020)

New bounds on macroscopic scalar-field topological defects from nontransient signatures due to environmental dependence and spatial variations of the fundamental constants

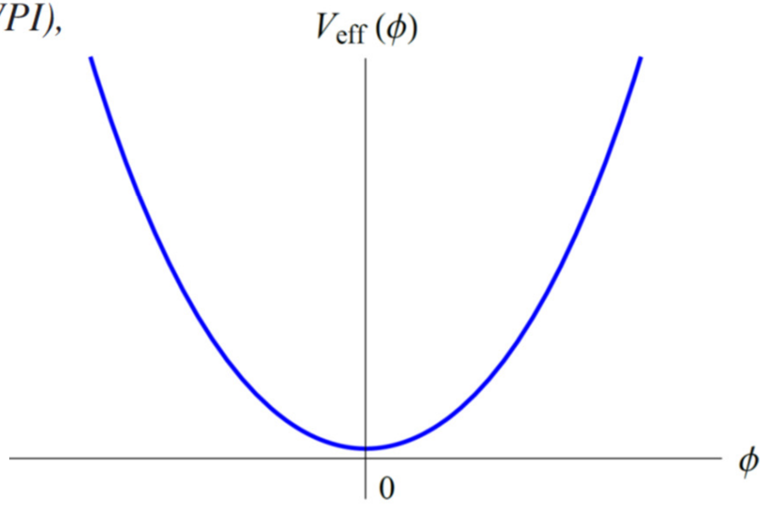
Yevgeny V. Stadnik

Kavli Institute for the Physics and Mathematics of the Universe (WPI),



Low-density environment

$$V_{\rm eff}(\phi) = \frac{\lambda}{4}\left(\phi^2 - \phi_0^2\right)^2 + \sum_{X=\gamma,e,N} \frac{\rho_X \phi^2}{(\Lambda'_X)^2}$$

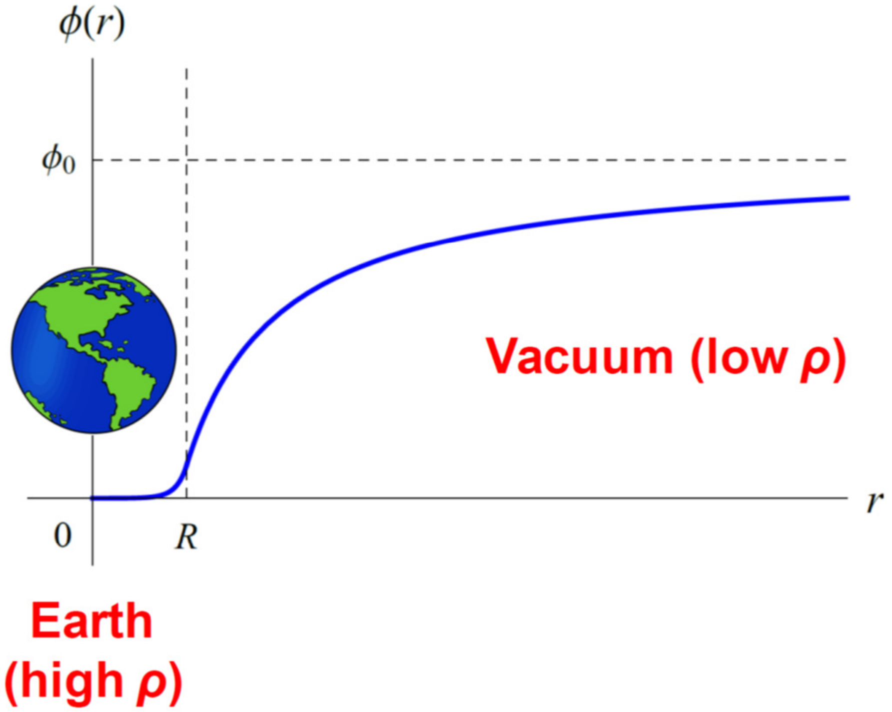


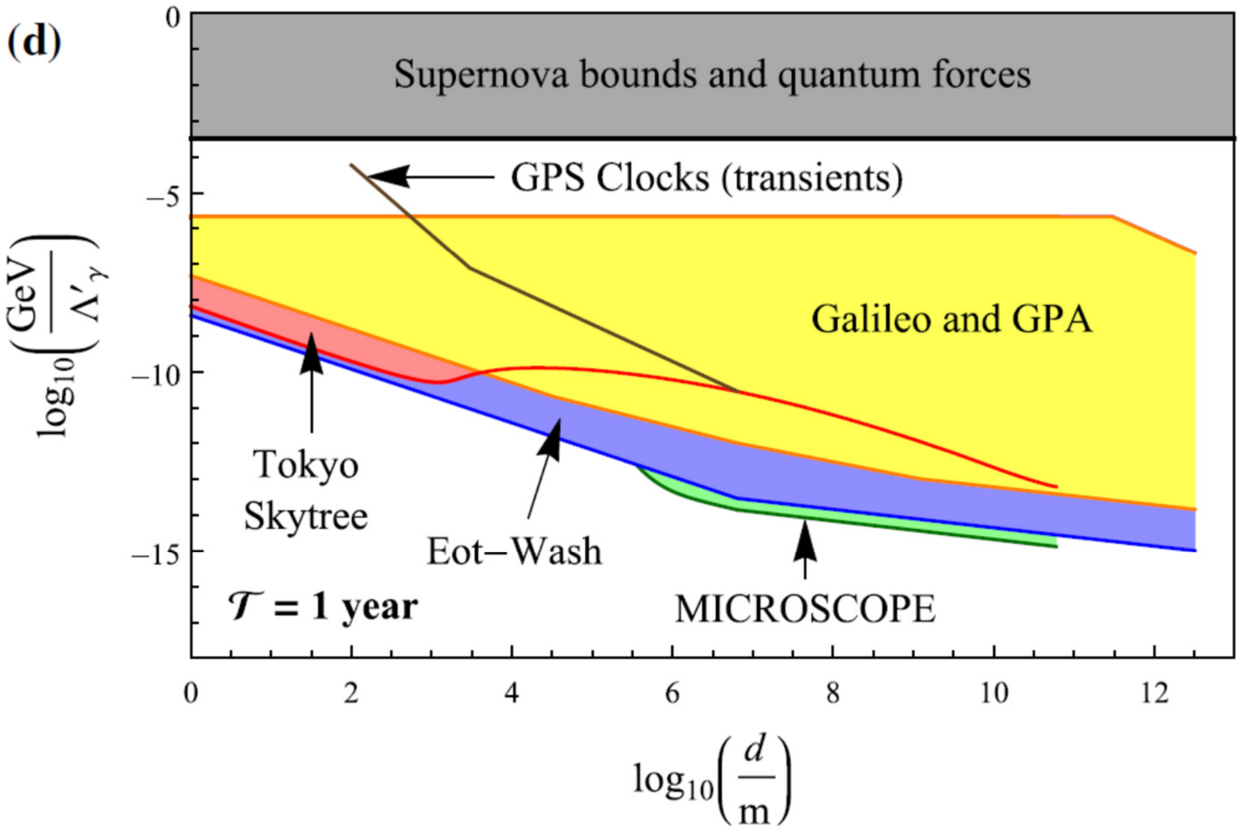
High-density environment

- Such scalar fields tends to be screened in dense environments
- All current experiments for topological defects were in the regime of strong screening (which was not accounted for)
- Environmental dependence of “constants”
- Must stronger constraints from such “non-transient effects

Slide credit: Yevgeny Stadnik

Environmental dependence of "constants" near Earth

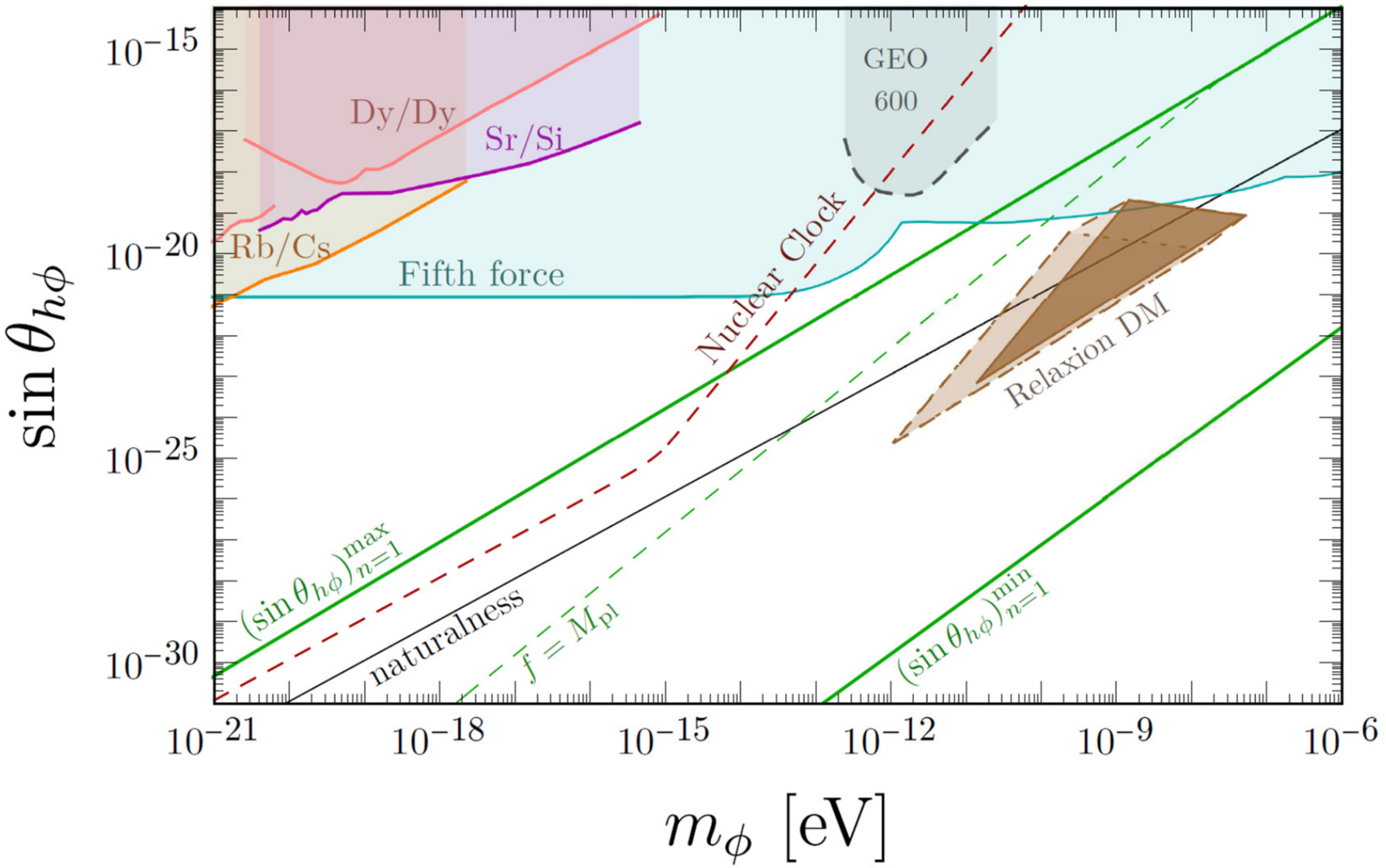




Picture credit: Yevgeny Stadnik

Probing the Relaxed Relaxion at the Luminosity and Precision Frontiers

Abhishek Banerjee, Hyungjin Kim, Oleksii Matsedonskyi, Gilad Perez, Marianna S. Safronova,
J. High Energ. Phys. 2020, 153 (2020).



Cosmological relaxation of the electroweak scale is an attractive scenario addressing the gauge hierarchy problem.

Its main actor, the relaxion, is a light spin-zero field which dynamically relaxes the Higgs mass with respect to its natural large value.

Continued collaboration with Gilad Perez' particle physics theory group.

Relaxion-Higgs mixing angle as a function of the relaxion mass.
A relaxion window and the available parameter space for the light relaxion, current and projected constraints.

Questions

- **What new physics can a network of clocks probe that two-clock or clock-cavity system in one place can not?**

- What new physics can we probe by sending clocks to space?
  What is the preferred orbit?

- Can network of clocks or Earth-space clock network probe the same new physics much better precision (beyond the statistics improvement)?

- What specific dark matter candidates can clocks probe?
  Relaxions? Possible dark matter transients besides domain walls?

- Clocks as part of the multi-messenger astronomy? Transient signals correlated with LIGO/VIRGO gravitational wave detection – what are their potential sources and detection strategy.

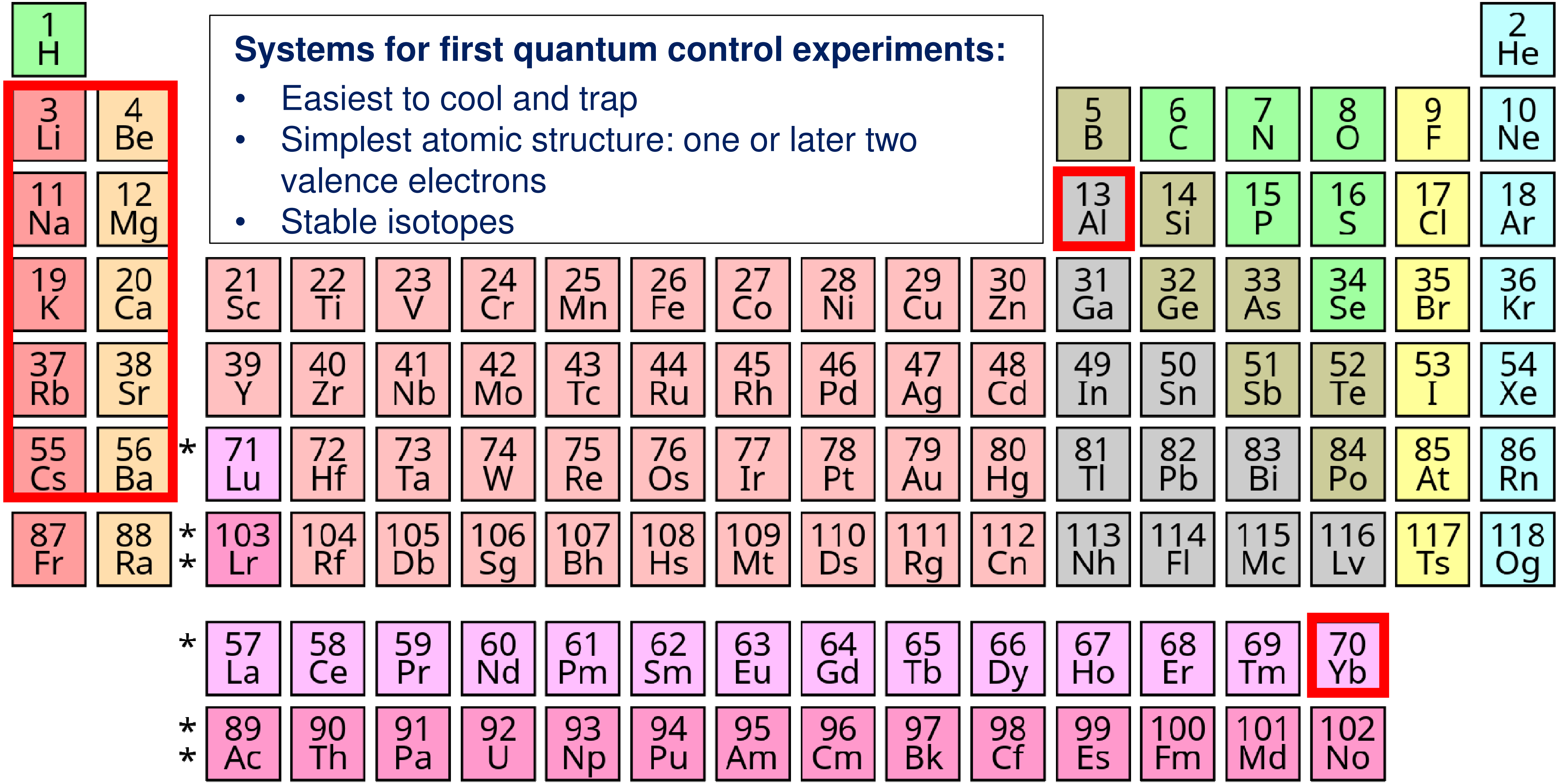
- Theory of dark matter clustering (i.e. can we have more dark matter to detect due to Earth/Sun gravitational wells?)

Fundamental physics with novel atomic and molecular systems

Why use novel systems?

Systems for first quantum control experiments:

- Easiest to cool and trap
- Simplest atomic structure: one or later two valence electrons
- Stable isotopes



Wikimedia Commons

Why use novel systems?

- **Much higher sensitivity for new physics or sensitivity to different new physics**

  Enhancements in heavy atoms, ions, and molecules with heavy atoms
  Relativistic effects
  Heavy nuclei (Z^3 or similar scaling)
  Octupole deformed nuclei
  Larger effective electric field (molecules for eEDM)

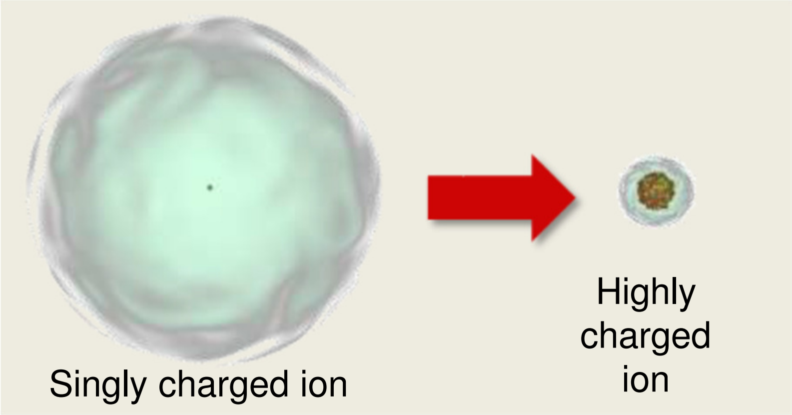
  Different types of transitions are available – sensitivity to different fundamental constants (molecules and molecular ions, highly-charged ions, nuclear clock)

  Need more isotopes or need a radioactive isotope

- **New systems have properties not available in currently used systems allowing for reduced systematics or better statistics**

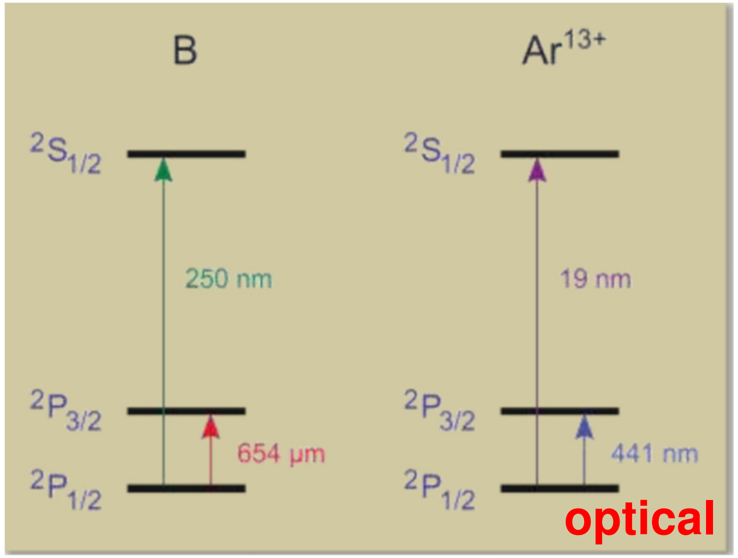
From building quantum sensors to dedicated new physics experiments

Novel systems: highly charged ions (HCIs)



Scaling with a nuclear charge Z

Binding energy	$\sim Z^2$
Hyperfine splitting	$\sim Z^3$
QED effects	$\sim Z^4$
Stark shifts	$\sim Z^{-6}$

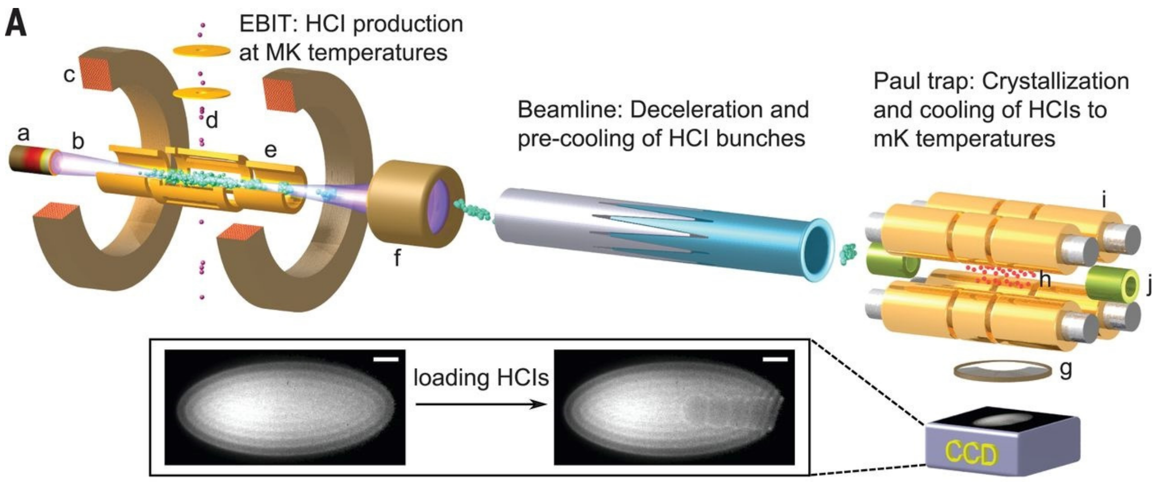


- Fine-structure, hyperfine-structure, and level-crossing transitions in range of table-top lasers
- Much higher sensitivity to new physics due to relativistic effects
- Rich variety of level structure not available in other systems
- Reduced systematics due to suppressed Stark shifts

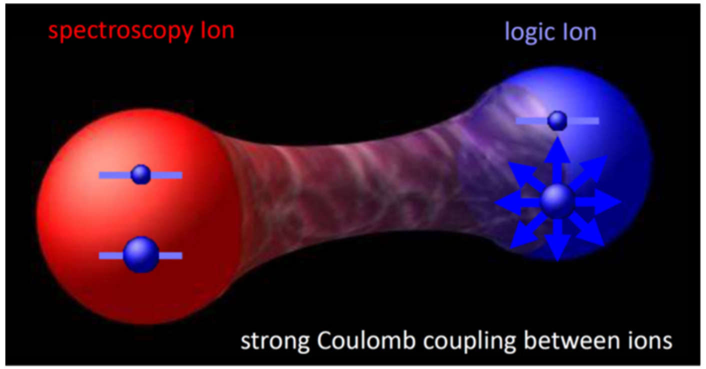
Review on HCIs for optical clocks: Kozlov *et al.*, Rev. Mod. Phy. **90**, 045005 (2018)

Picture credit: Piet Schmidt

HCIs for ultra-precise clocks (Paul traps): present status



No direct laser-cooling transitions: use sympathetic cooling with Be^+



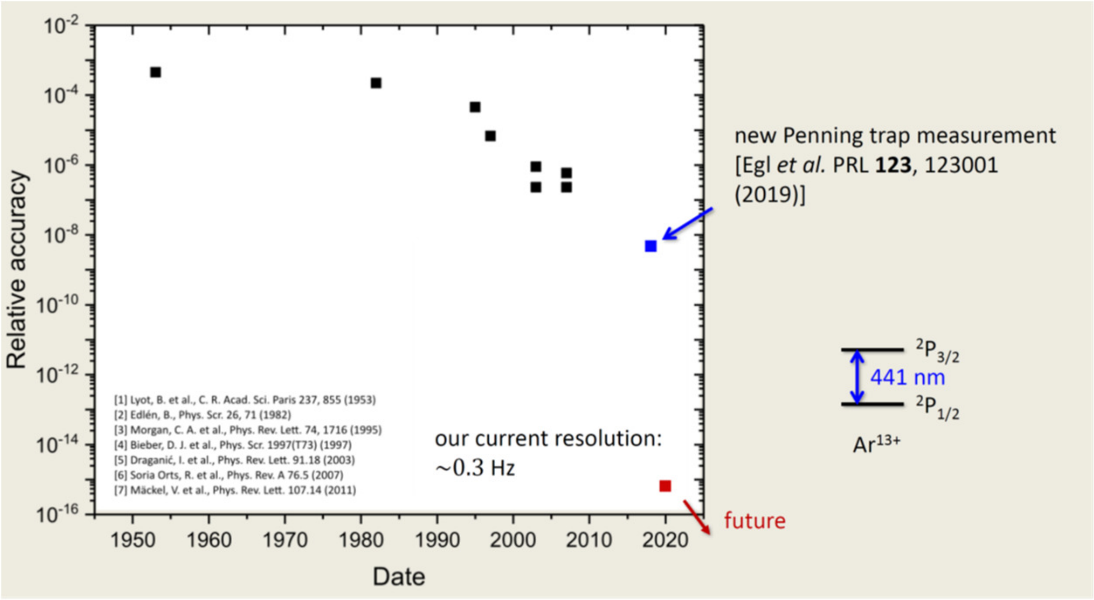
See Dave Hume's talk for more on quantum logic spectroscopy

2015: First sympathetic cooling of HCIs: L. Schmöger et al., Science 347, 1233 (2015), Heidelberg

2020: Coherent laser spectroscopy of highly charged ions using quantum logic, P. Micke et al., Nature 578, 60 (2020)

7 orders of magnitude improvement !!!

First prototype optical clock, PTB, Germany

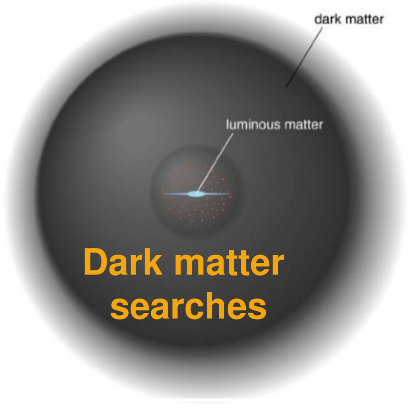


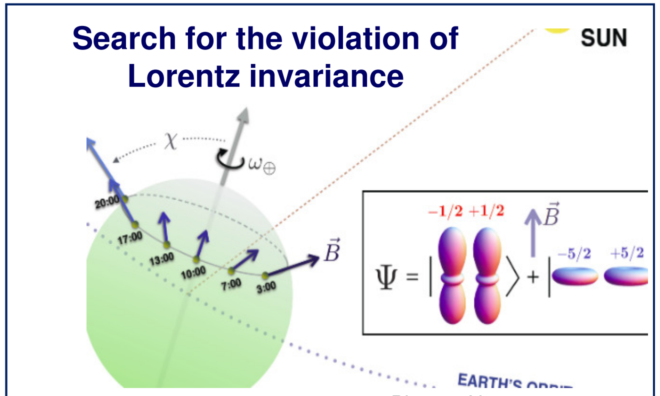
HCIs for ultra-precise clocks : applications & future

HCIs: **much larger** sensitivity to variation of α and dark matter searches then current clocks

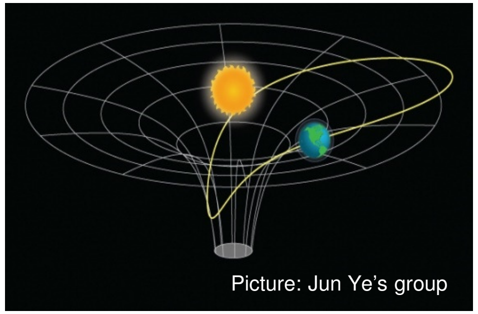
- Enhancement factor K>100, most of present clocks K<1, Yb^+ E3 K=6
- Hyperfine HCI clocks sensitive to m_e/m_p ratio and m_q/Λ_{QCD} ratio variation
- Additional enhancement to Lorentz violation searches

HCI review: Rev. Mod. Phys. 90, 45005 (2018)



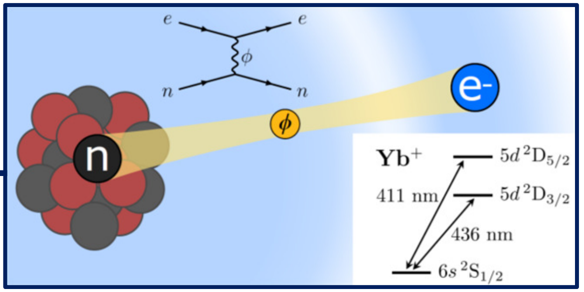


Picture: Nature 517, 592



Tests of the equivalence principle

- Searches for the variation of fundamental constants
- Tests of QED: precision spectroscopy
- Fifth force searches: precision measurements of isotope shifts with HCIs to study non-linearity of the King plot



5 years: Optical clocks with selected HCIs will reach 10^{-18} accuracy

10 years: Strongly α-sensitive transitions in HCIs will reach of 10^{-18} uncertainty, multi-ion HCI clocks

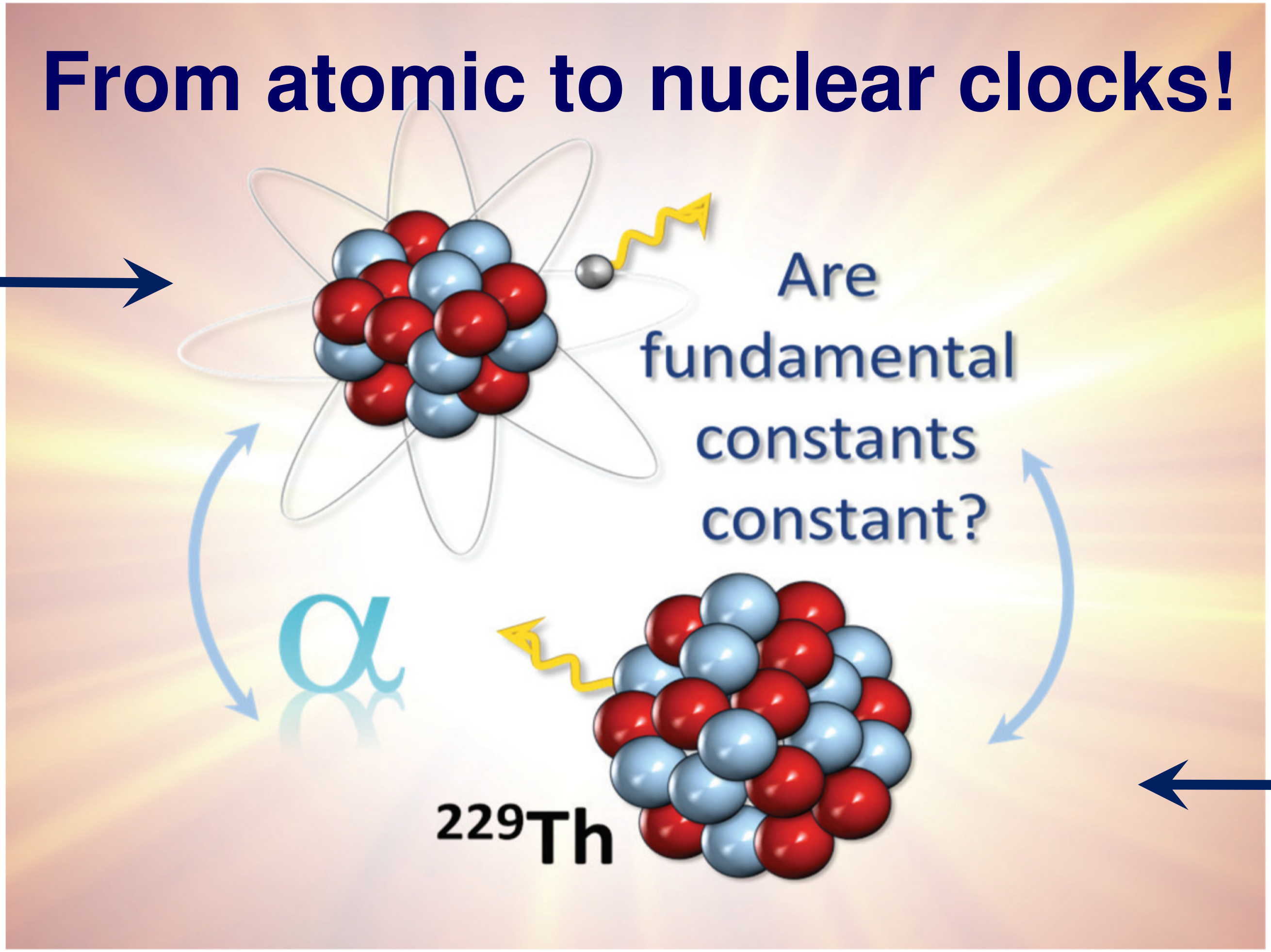
Thorium nuclear clocks for fundamental tests of physics

thorium
nuclear clock

https://thoriumclock.eu/

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

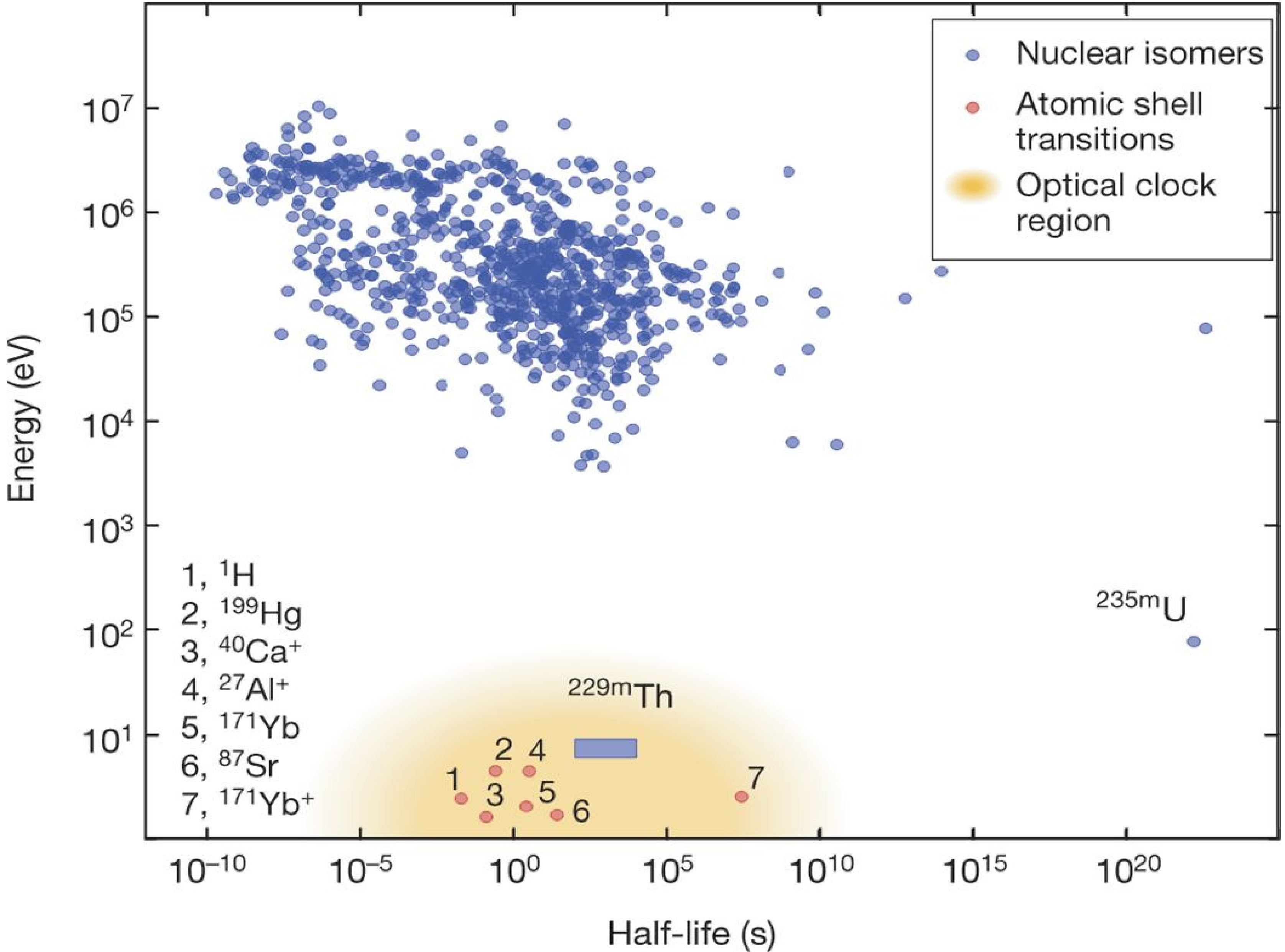
Clock based on transitions in atoms



Clock based on transitions in nuclei

Obvious problem: typical nuclear energy levels are in MeV

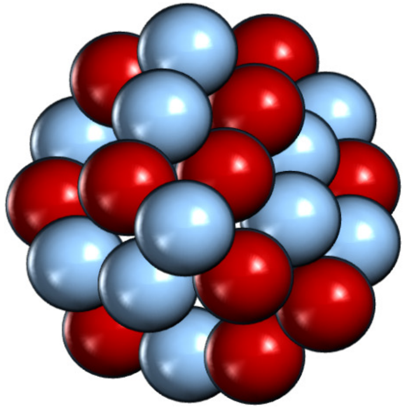
Six orders of magnitude from ~few eV we can access by lasers!

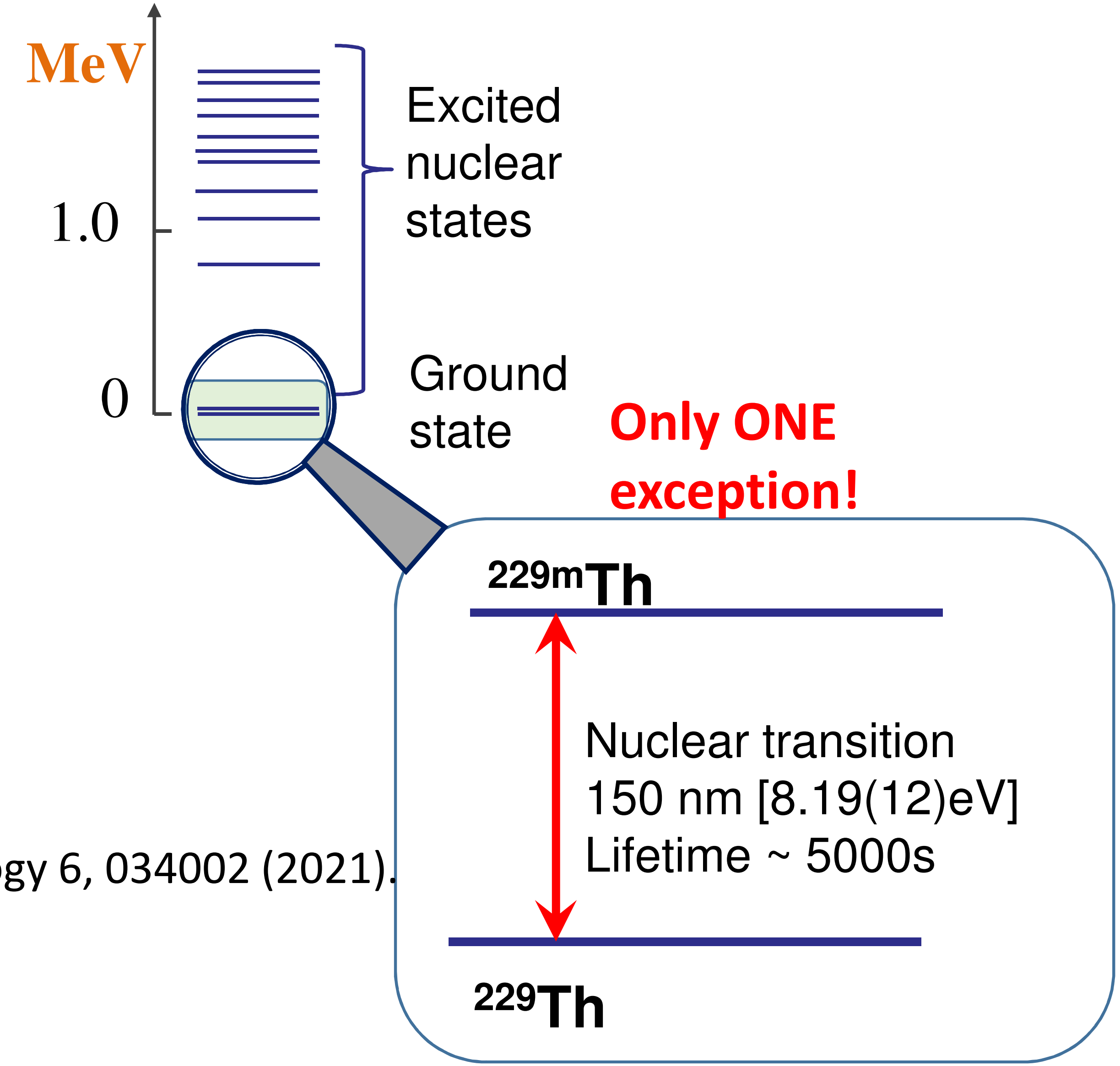


Nature 533, 47 (2016)

Th nuclear clock

Atomic Nucleus

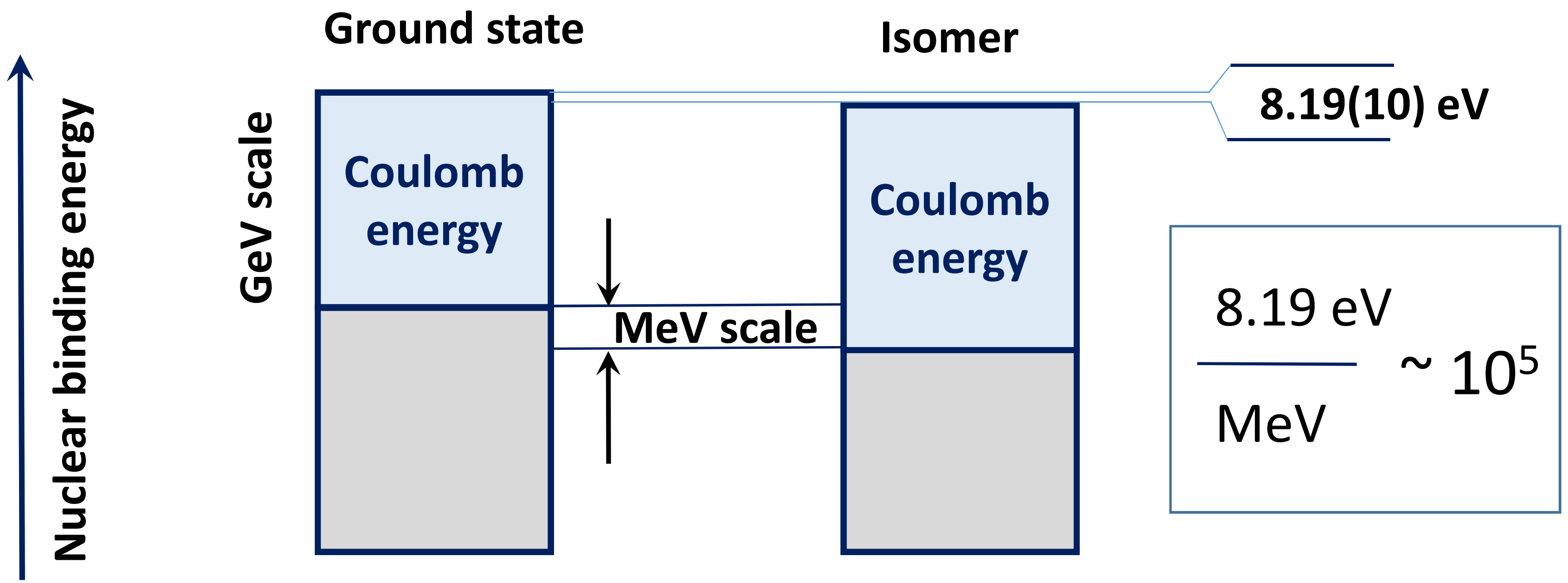




Energy of the ^{229}Th nuclear clock transition:
Seiferle *et al*., Nature 573, 243 (2019)
T. Sikorsky et al., Phys. Rev. Lett. 125, 142503 (2020).

Review: E. Peik, et al., Quantum Science and Technology 6, 034002 (2021).

Th nuclear clock: Exceptional sensitivity to new physics



Much higher predicted sensitivity (K = 10000-100000) to the variation of α and $\frac{m_q}{\Lambda_{QCD}}$.

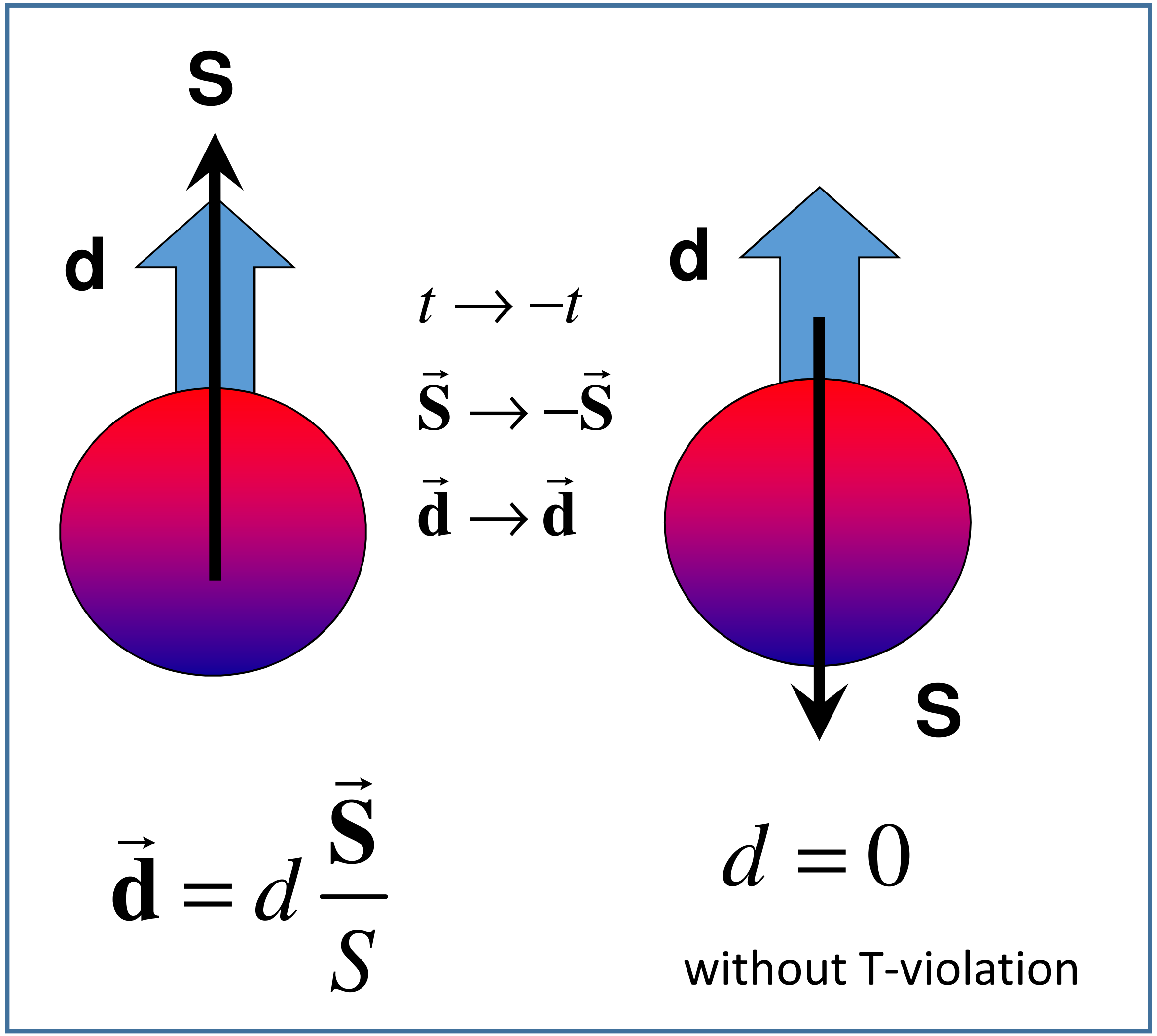
Nuclear clock is sensitive to coupling of dark matter to the nuclear sector of the standard model.

5 years: prototype nuclear clocks, based on both solid state and trapped ion technologies
Measure isomer properties to establish of sensitivity to new physics
Variation of fundamental constant and dark matter searches competitive with present clock

10 years: 10^{-18} – 10^{-19} nuclear clock, 5 - 6 orders improvement in current clock dark matter limits

Searches for the EDMs with novel systems

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



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

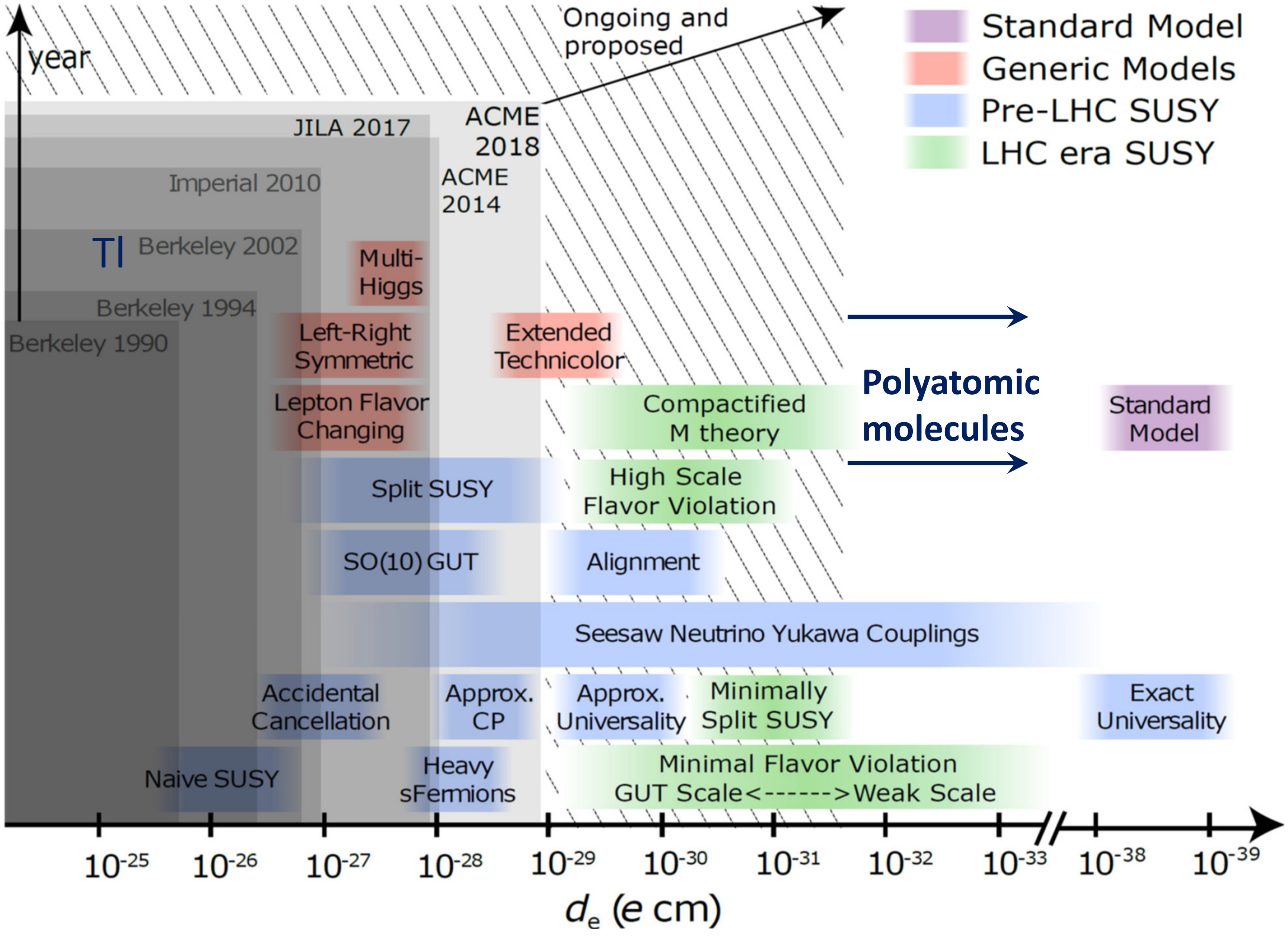


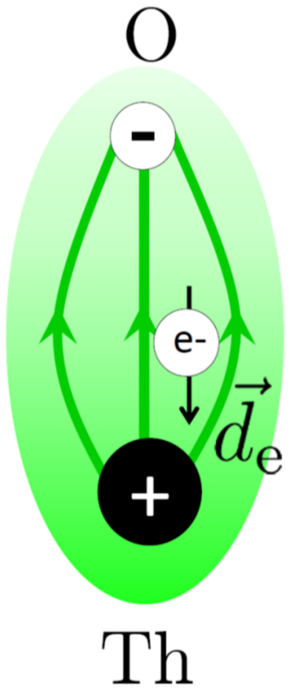
Figure is from 2020 USA AMO Decadal survey (Credit: Dave DeMille)

https://www.nationalacademies.org/amo

Searches for electron EDM with molecules

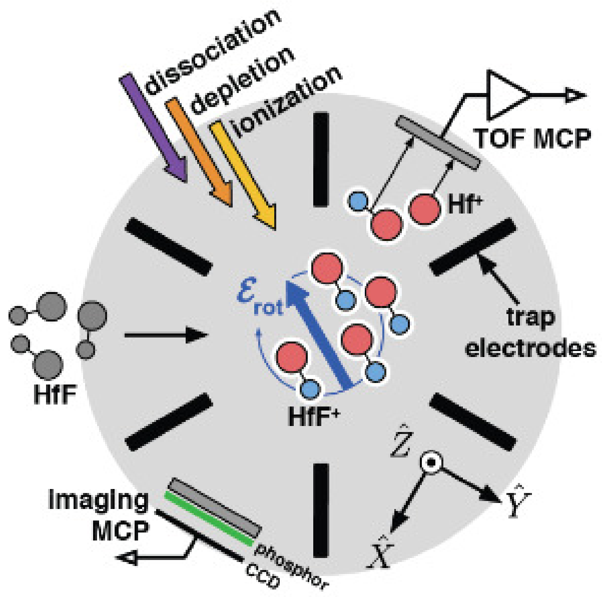
Present status: experiments with reported results

Advanced ACME



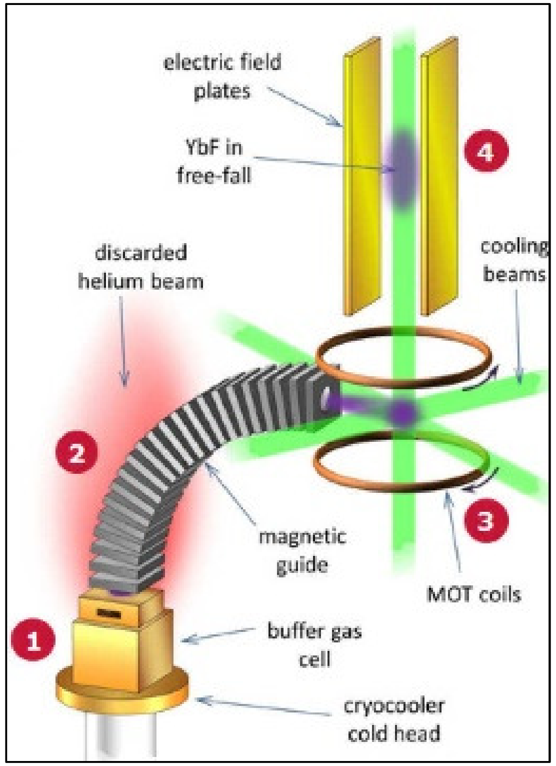
ThO

JILA eEDM



HfF^+, (now also ThF^+)

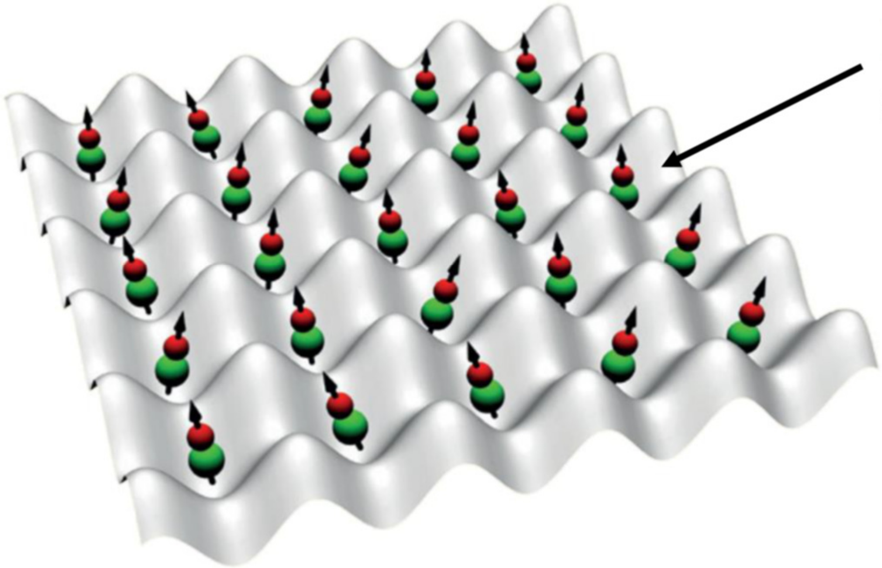
Imperial College



YbF

Expected an order or magnitude improvement in ~5 years

Electron EDM experiments: laser-cooled molecules



Need to trap at ultracold temperatures

Laser slowed, cooled, and trapped in 3D: SrF, CaF, and YO
Laser-cooled, but not yet trapped: YbF, BaH, SrOH, CaOH, YbOH, and $CaOCH_3$

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

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

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

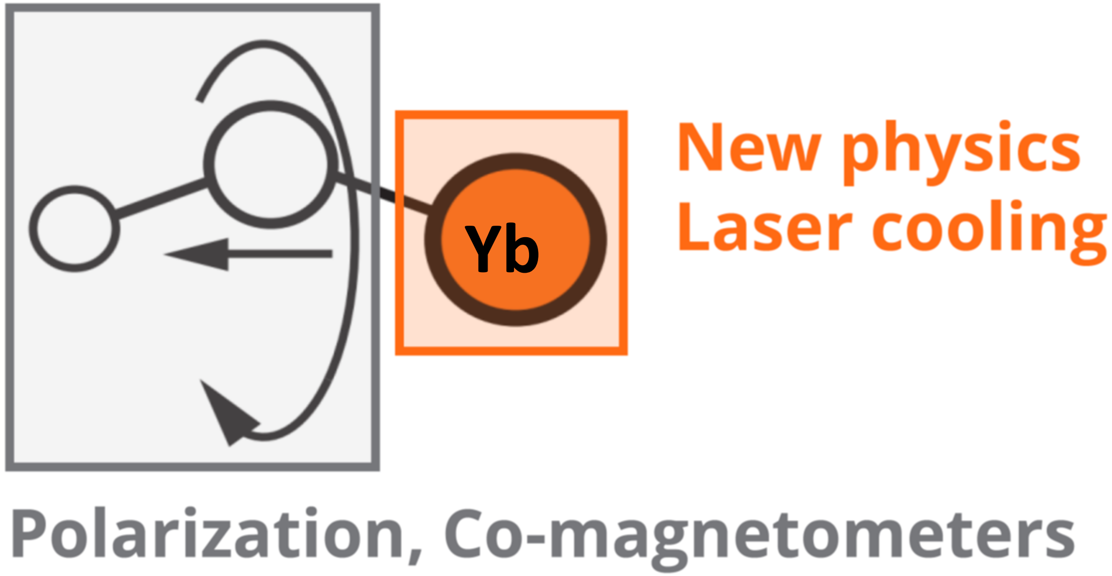
Slide from: Nick Hutzler

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

eEDM experiments with polyatomic laser-cooled

Caltech
Harvard

YbOH



Proposal: Ivan Kozyryev and N. R. Hutzler, Phys. Rev. Lett. **119**, 133002 (2017)
Review: N. R. Hutzler, *Quantum Sci. Technol.* **5** 044011 (2020)

5 years: An electron EDM result with trapped ultracold YbOH, initial goal 10^{-31} e cm

8 years: Improvements in coherence time and number trapped molecules: 10^{-32} e cm

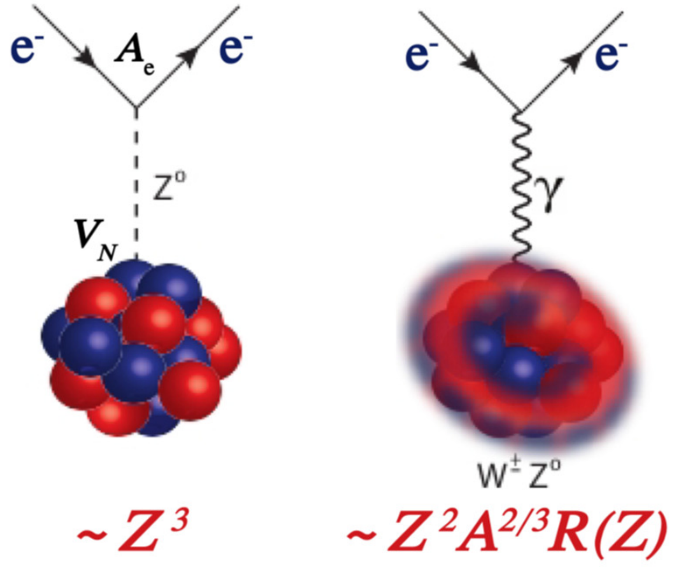
Also: YbOH nuclear MQM

Theory: J. Chem. Phys. 152, 084303 (2020)

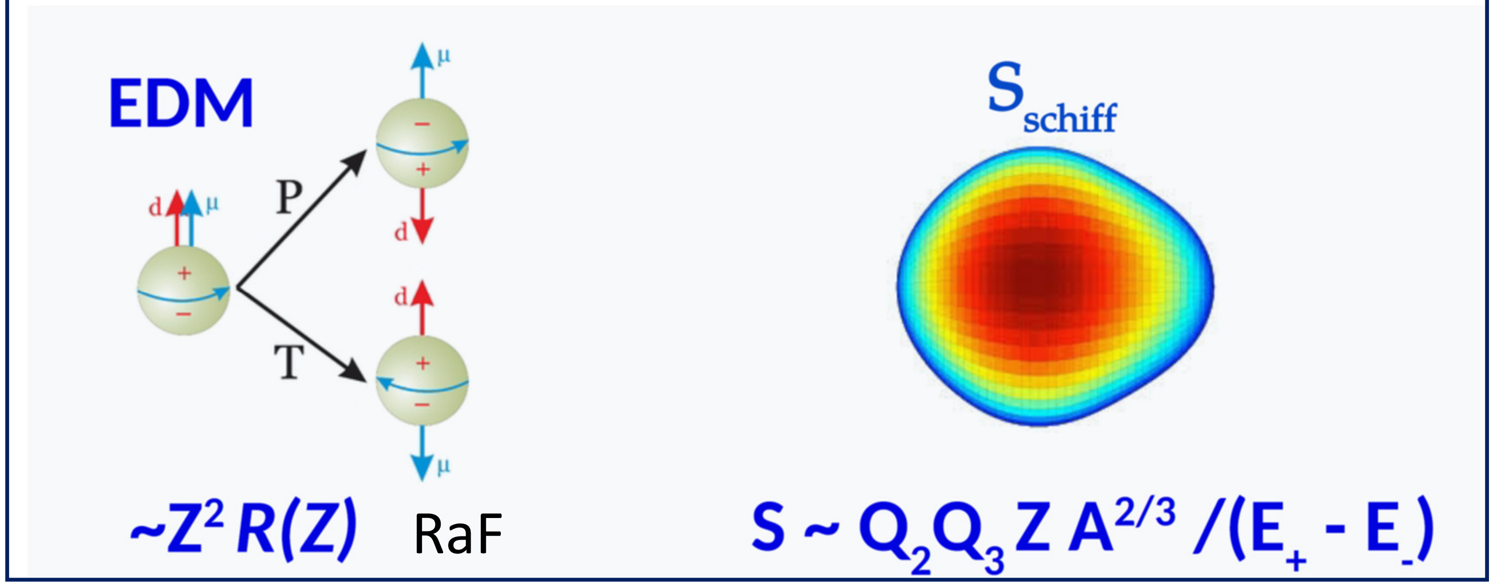
Picture & timeline from: Nick Hutzler

Fundamental symmetries: radioactive atoms and molecules

Parity violation



T-violation



ZOMBIES (Yale, BaF)
Yb (Mainz)

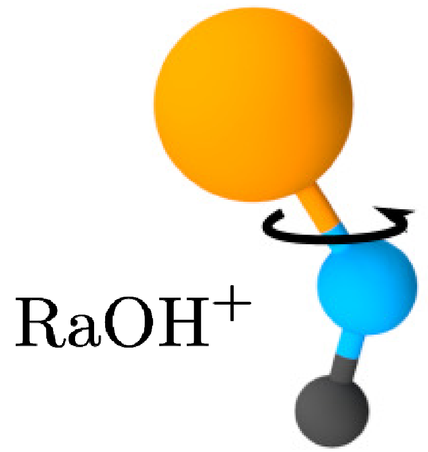
Fr (TRIUMF, Tokyo)
Ra^+ (UCSB)

Picture credits: Ronald Fernando Garcia Ruiz

Ra and Ra-based molecules have a further enhancement due to an octupole deformation of the ^{225}Ra nucleus: an intrinsic Schiff moment 1000 times larger than in spherical nuclei such as Hg.

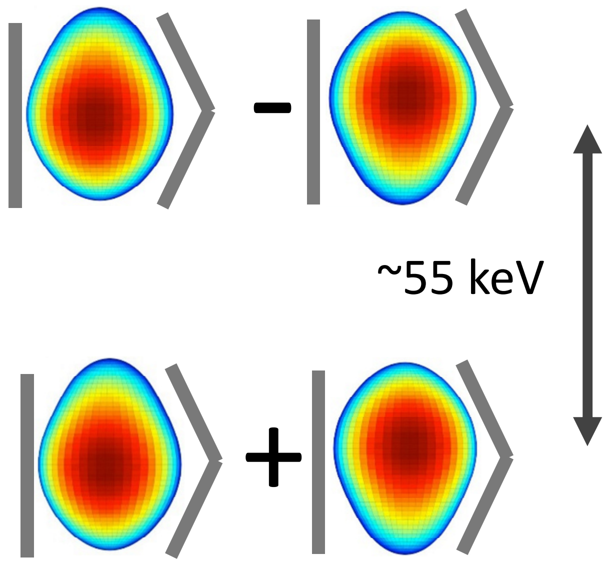
Collinear resonance ionization spectroscopy of RaF molecules
[Garcia Ruiz, Berger et al. CERN-INTC-2018-017 (2018)]

T-violation with radioactive molecular ions



Theory: nuclear Shiff moments sensitivity investigated for RaOH, RaOH+, ThOH$^+$, and $RaOCH_3^+$

RaOH$^+$ and $RaOCH_3^+$ having been recently created and cooled in an ion trap [UCSB, Fan et al., PRL 126, 023002 (2021)].



Octupole deformation ^{225}Ra

T- violating forces mix the states

Enhancement: ~1000x

from Andrew Jayich

Other candidate: ^{229}Pa, the splitting is 50(60) eV - we don't know if the state exists.

^{229}Pa may be 100,000 times more sensitive than ^{199}Hg.

Currently no significant source of ^{229}Pa (1.5 day half-life). Plans to harvest at the Facility for Rare Isotope Beams at Michigan State University.

J. T. Singh, Hyperfine Int. 240, 29 (2019)

UNIVERSITY OF DELAWARE

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Postdoc: Charles Cheng
Graduate students: Aung Naing, Adam Mars, Hani Zaheer

Online portal collaboration, Electrical & Computer Engineering:
Prof. Rudolf Eigenmann, graduate student: Parinaz Barakhshan
Prof. Bindiya Arora, GNDU, India

Another postdoc position will become available in summer of 2021

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Q-SEnSE
An NSF Quantum Leap Challenge Institute

erc Thorium nuclear clocks for fundamental tests of physics

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Ekkehard Peik, PTB
Peter Thirolf, LMU

Many thanks to Yevgeny Stadnik, José R. Crespo López-Urrutia, Nick Hutzler, Andrew Jayich, Piet Schmidt, and Ronald Fernando Garcia Ruiz for discussions and input for this talk!