CERN AUTUMN SCHOOL
NOVEMBER 4, 2024

QUANTUM SENSORS FOR NEW-PHYSICS DISCOVERIES IN THE LABORATORY AND IN SPACE

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Q-SEnSE
An NSF Quantum Leap Challenge Institute

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

thorium nuclear clock

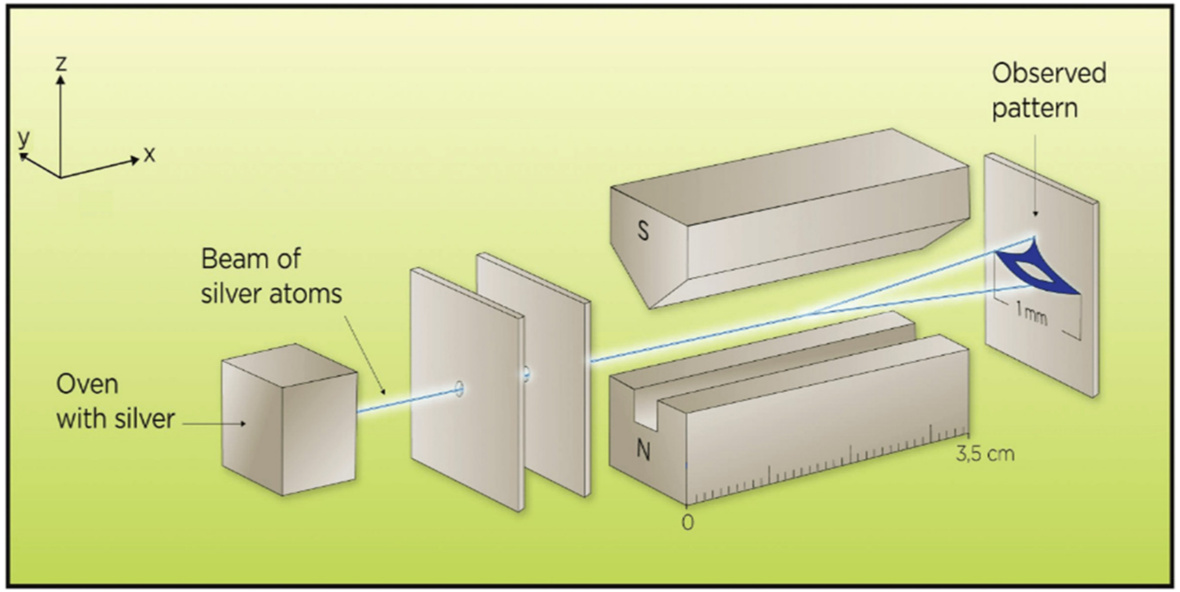
https://thoriumclock.eu/

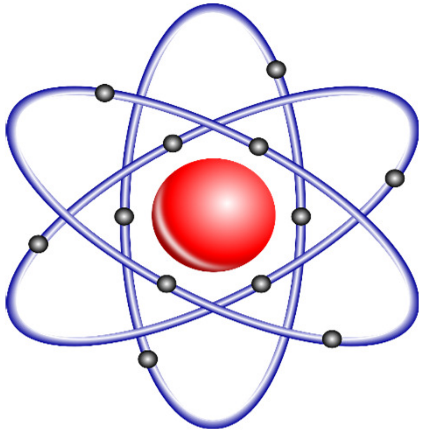
NSF
Office of Naval Research Science & Technology
European Research Council

1924

100 YEARS AGO

WE DID NOT KNOW WHAT ATOMS ARE MADE OF





Puzzles of atomic spectra

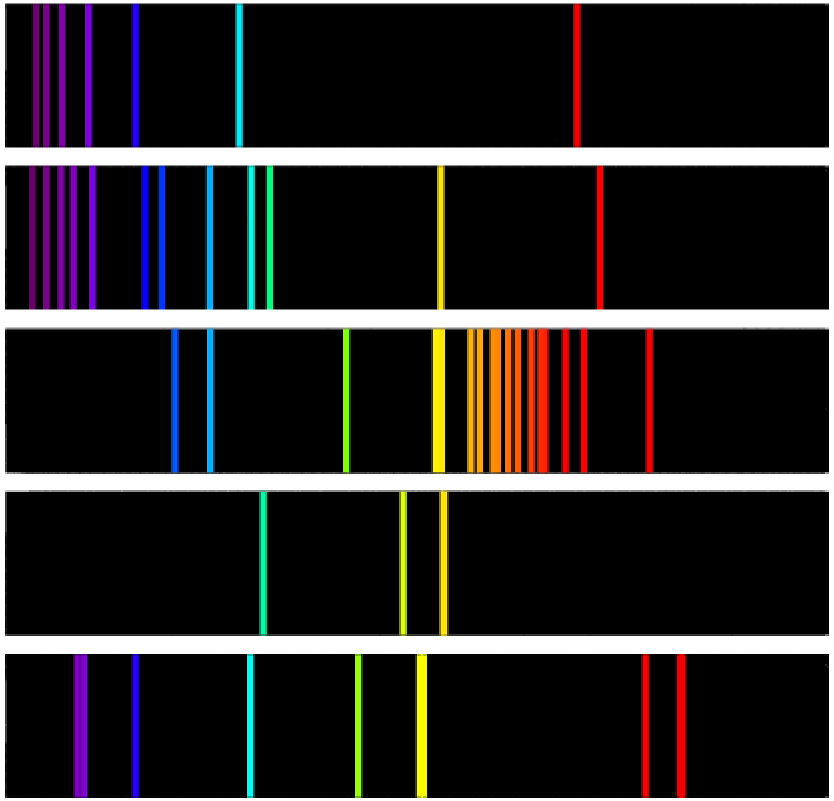
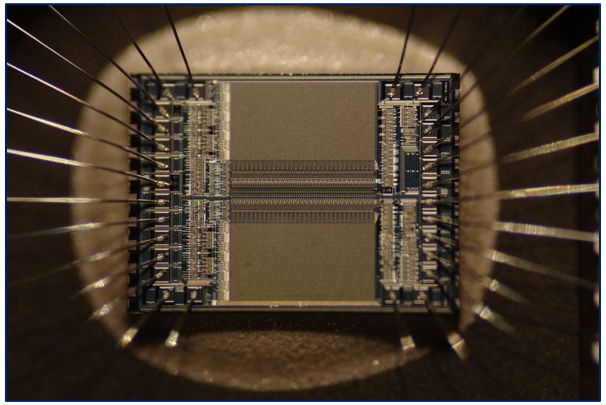


Figure credits: Entropy 2017, 19, 186, practical-chemistry.com

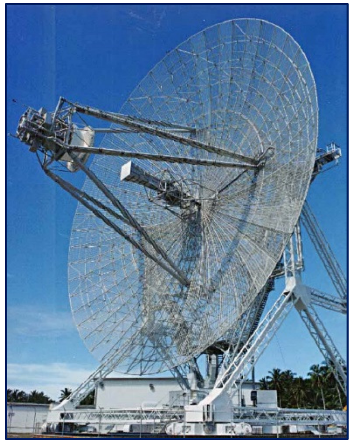
Solving physics puzzles: quantum mechanics



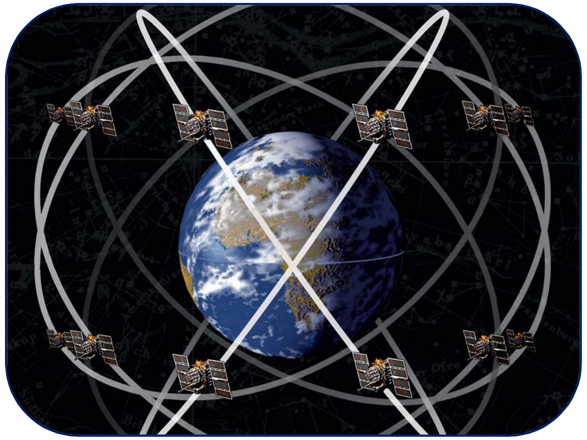
Computer technologies

Lasers

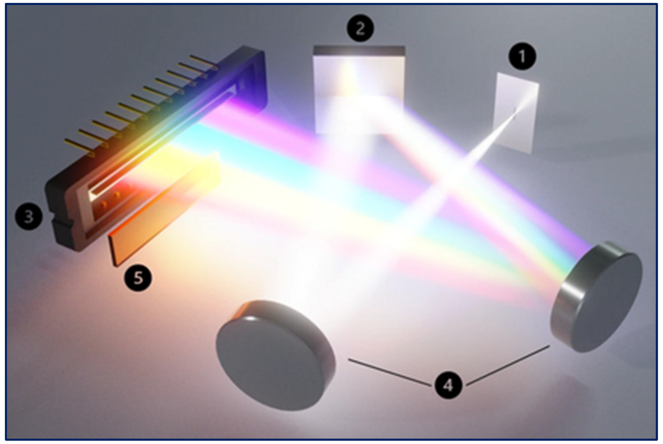
Solar cells



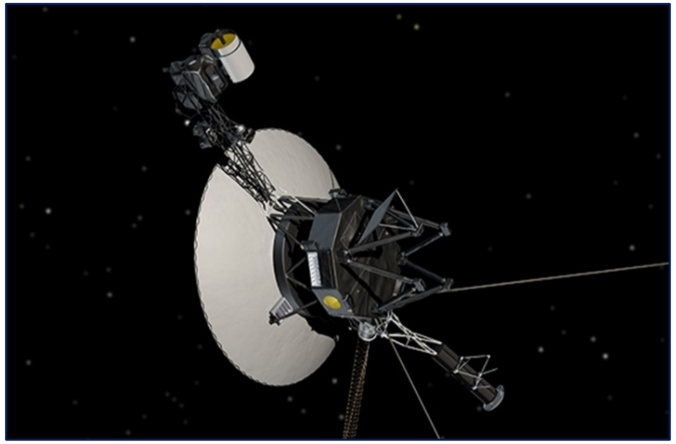
Radars



Navigation



Spectrometers, other detectors



Nuclear technologies

Image credits: Wiki, NASA, National Air and Space Museum

Extraordinary progress in the control of atoms, ions, and molecules

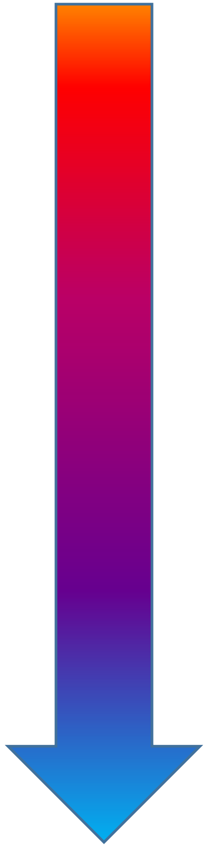
1997 Nobel Prize
Laser cooling and trapping

2001 Nobel Prize
Bose-Einstein Condensation

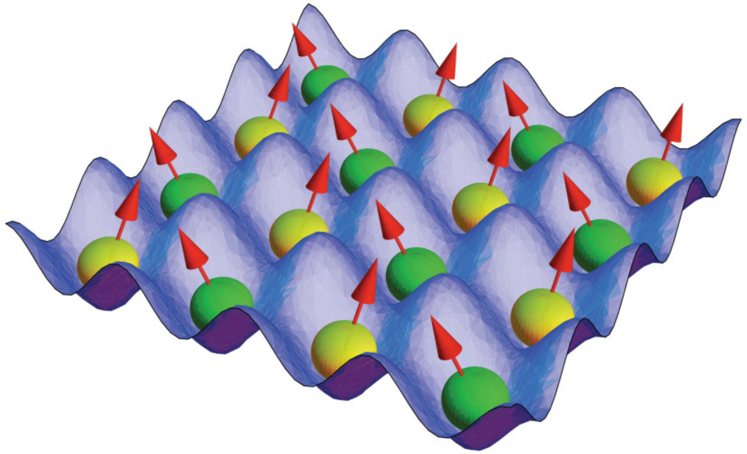
2005 Nobel Prize
Frequency combs

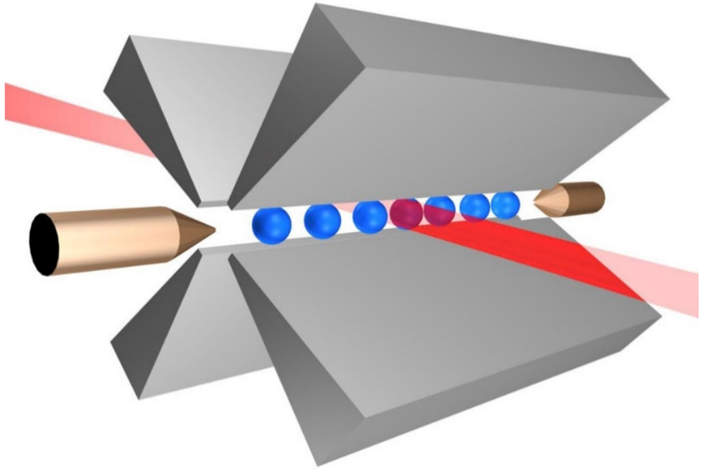
2012 Nobel prize
Quantum control

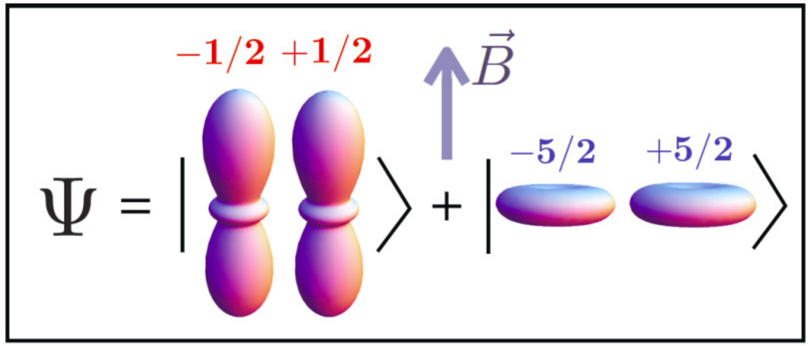
300K

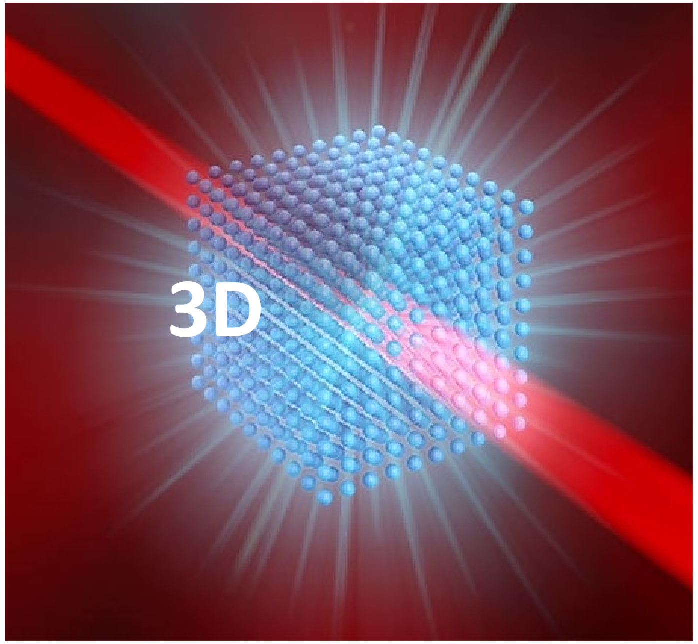


pK



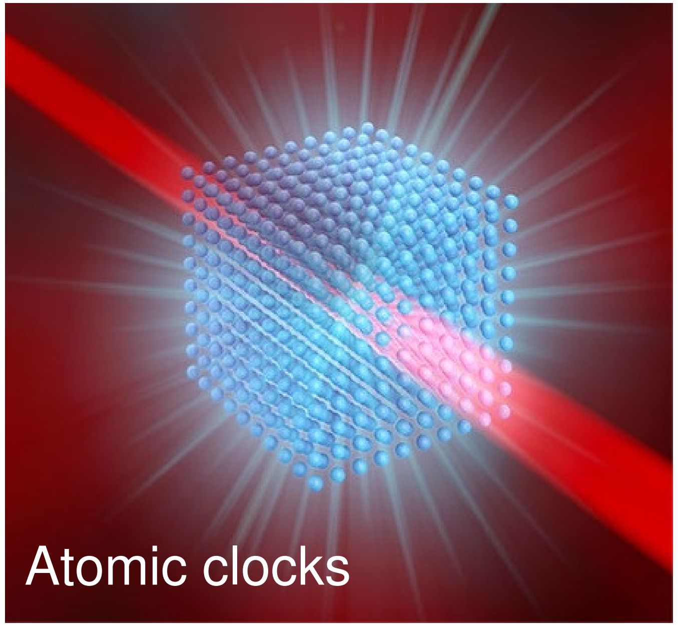


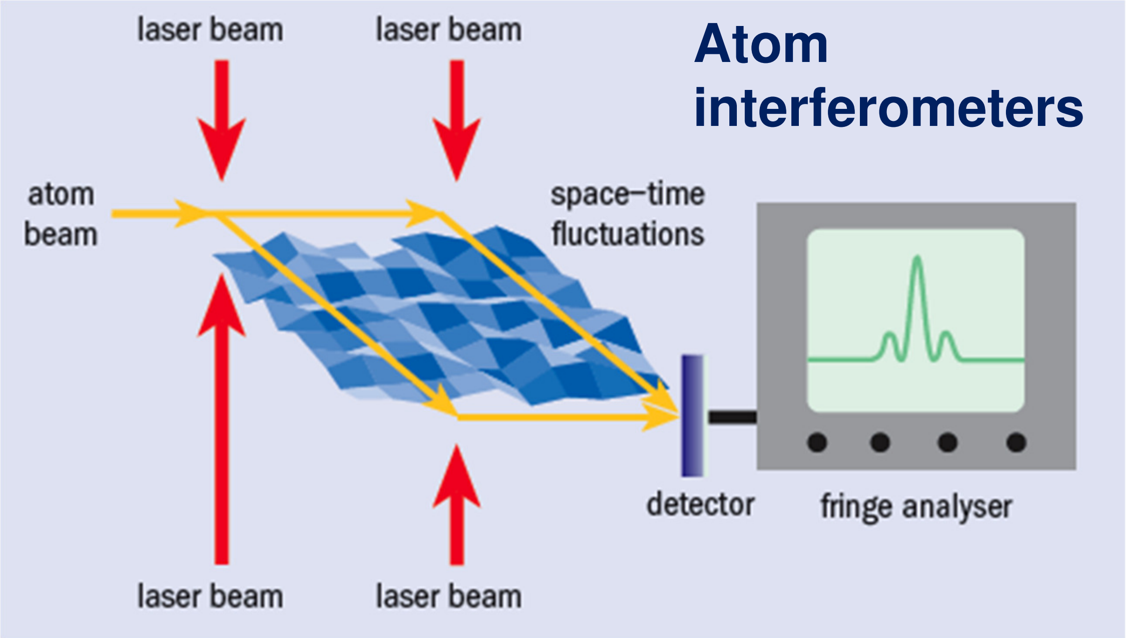


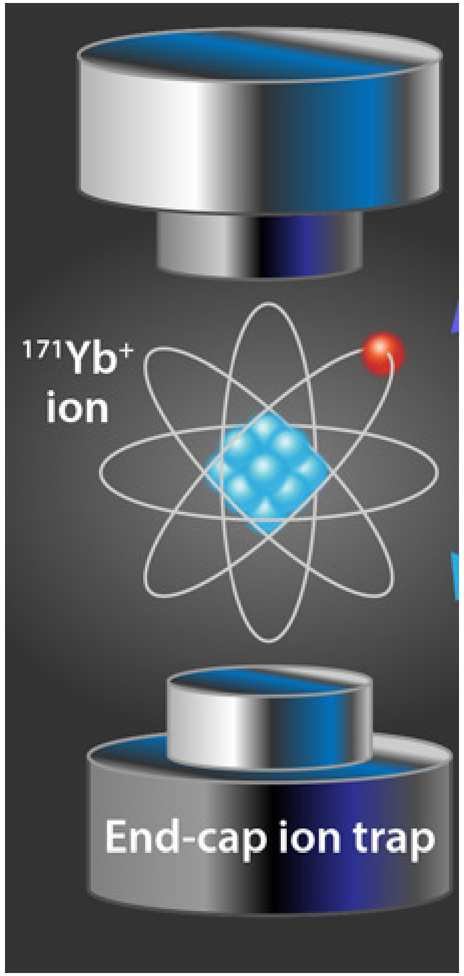


Atoms are now: **Ultracold** **Trapped** **Precisely controlled**

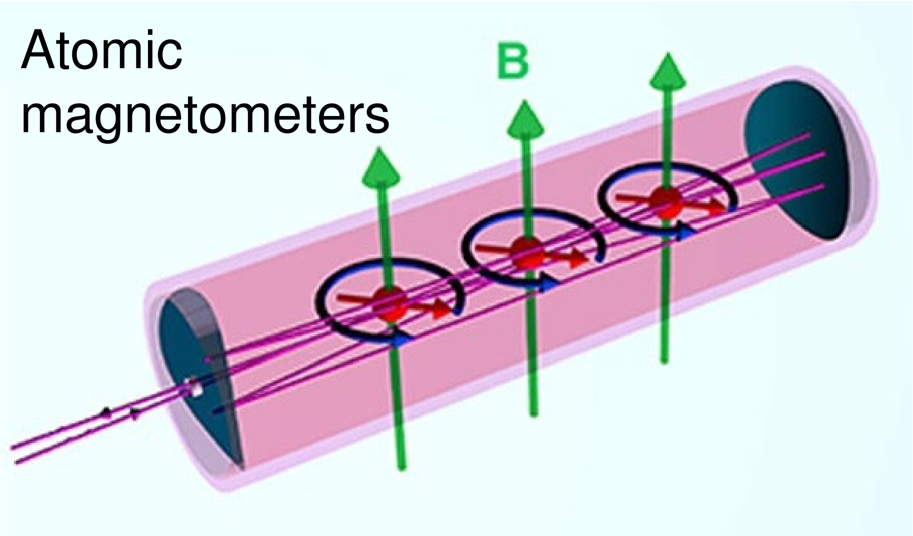
2024 100 YEARS LATER: QUANTUM SENSORS







Trapped ions



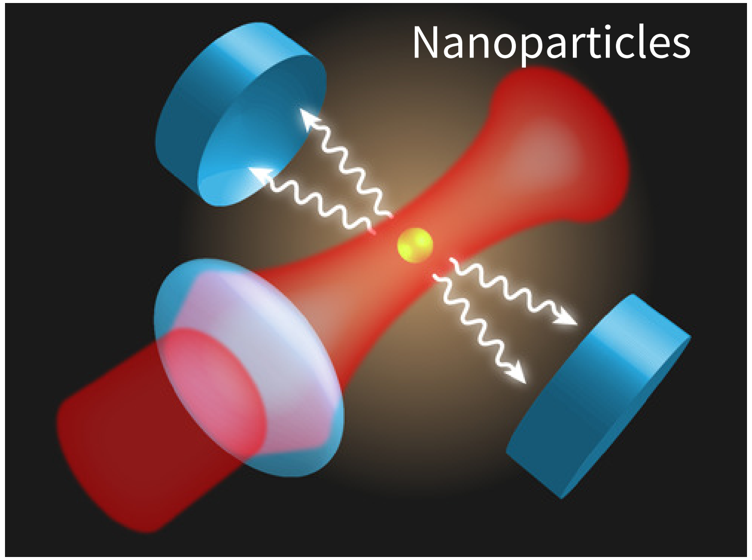
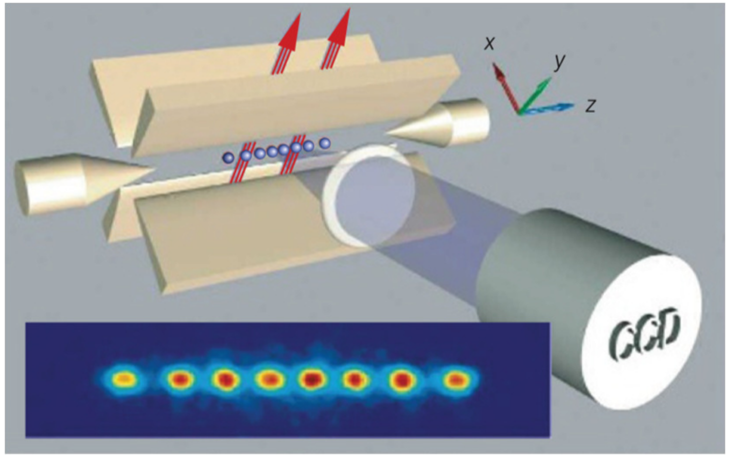
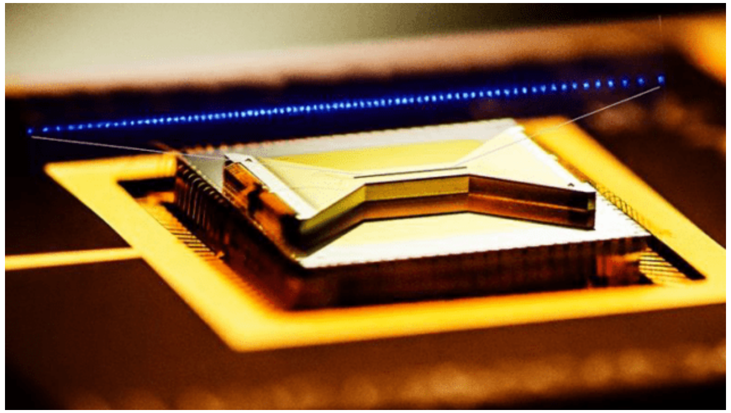


Image credit: JILA, APS/Alan Stonebraker, https://cerncourier.com/a/can-experiment-access-planck-scale-physics/, http://physicsworld.com/cws/article/news/2013/apr/24

QUANTUM SENSORS VS. QUANTUM COMPUTING AND SIMULATIONS

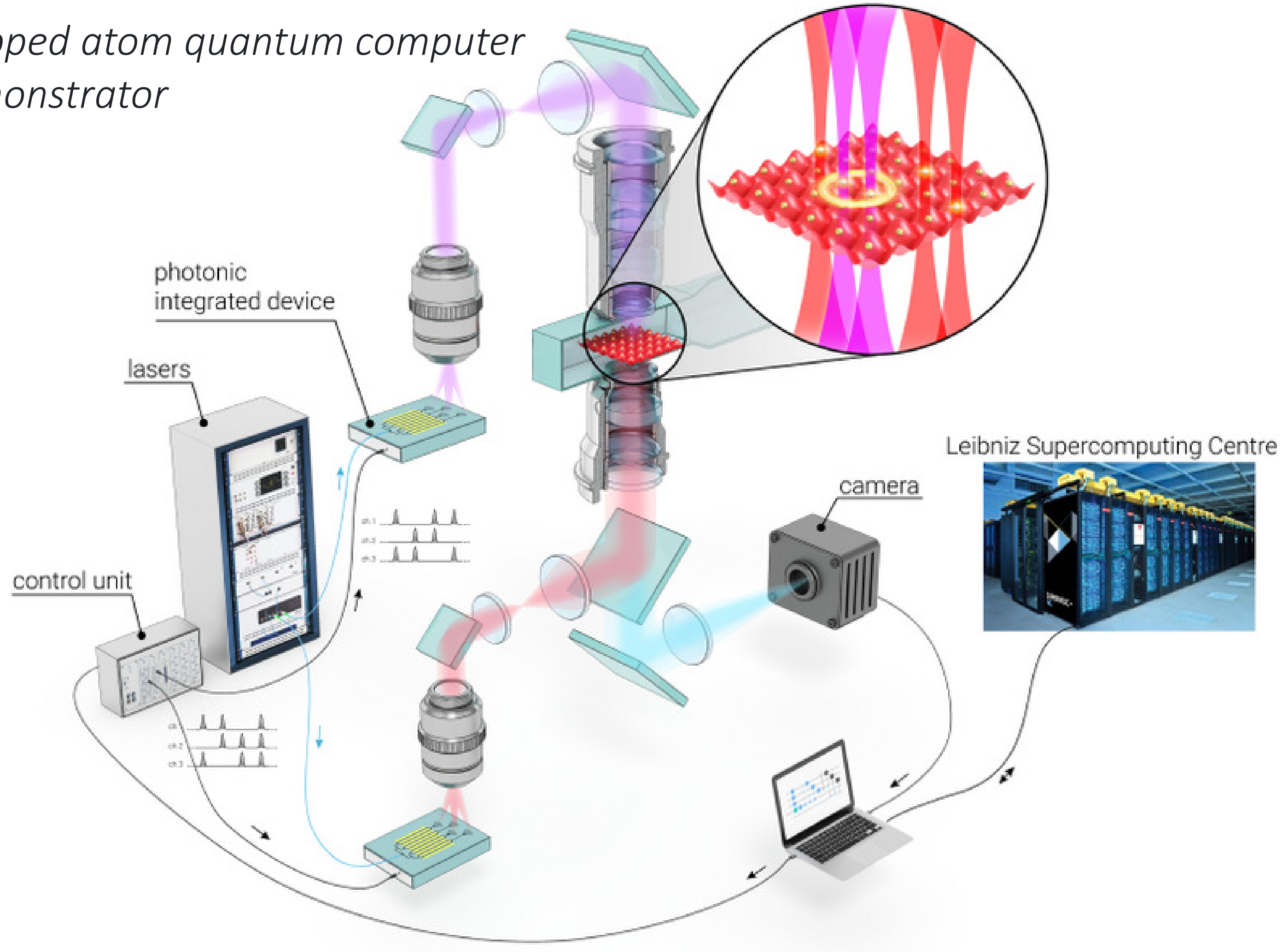
Based on the same cold atoms and ions, same or similar trapping and quantum control technologies





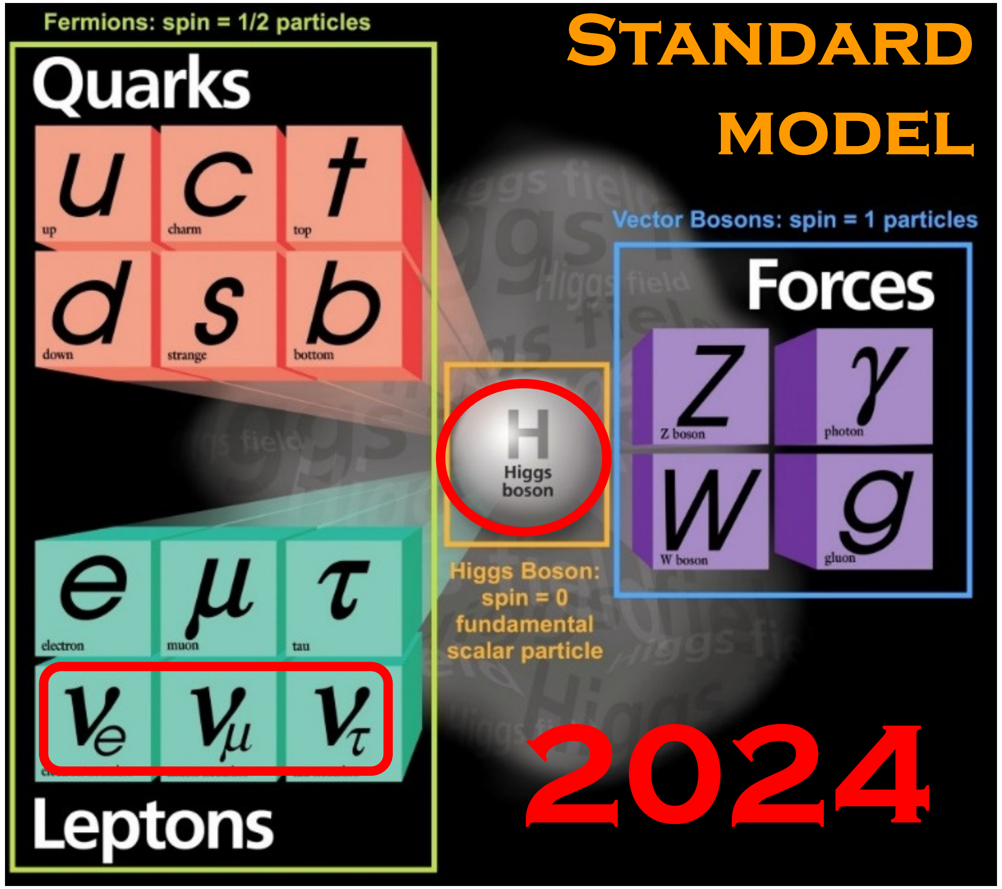
Trapped ions quantum computing

Trapped atom quantum computer demonstrator



Nature 453, 1008 (2008), physicsworld.com/a/ion-based-commercial-quantum-computer-is-a-first, https://www.munich-quantum-valley.de/research/research-areas/neutral-atom-qubits

2024: What we know now

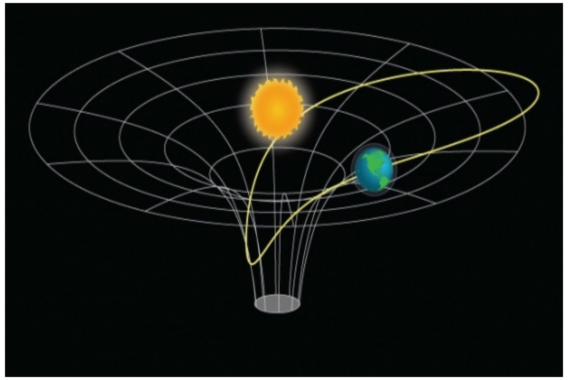


Quantum mechanics

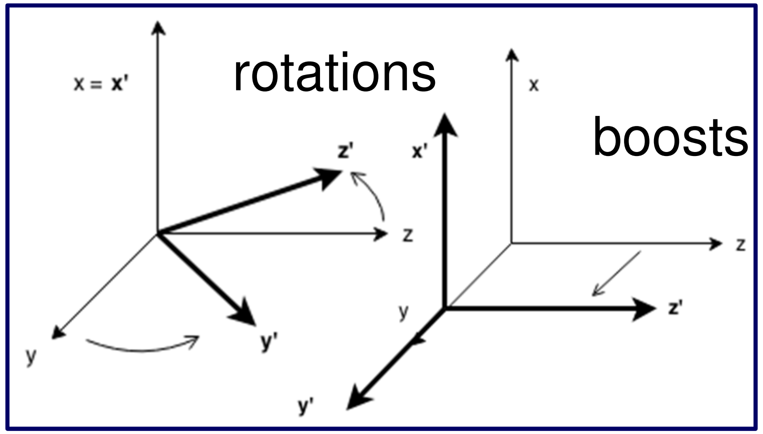
General relativity

Fundamental physics postulates

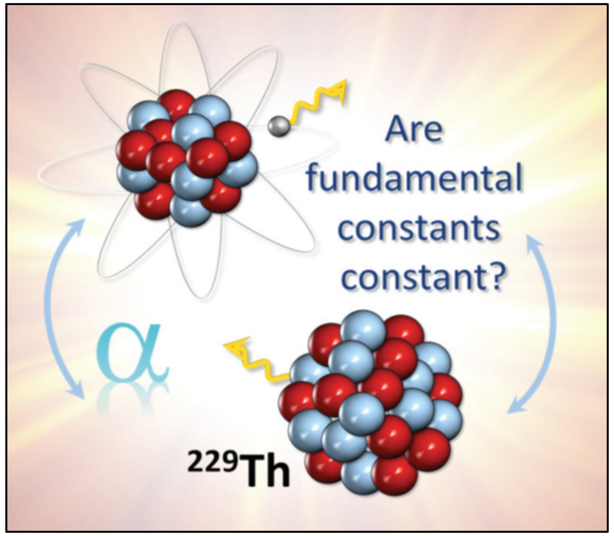
Position invariance



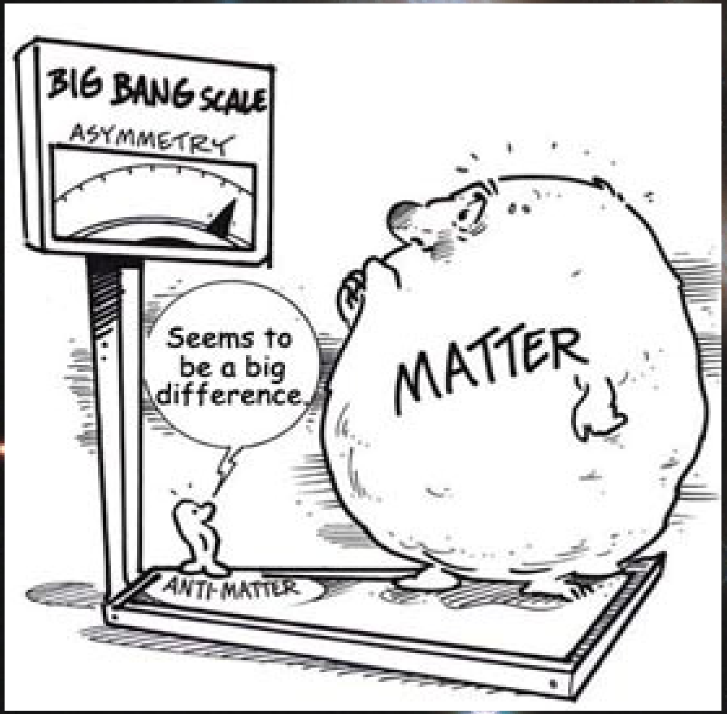
Lorentz invariance



Weak equivalence principle

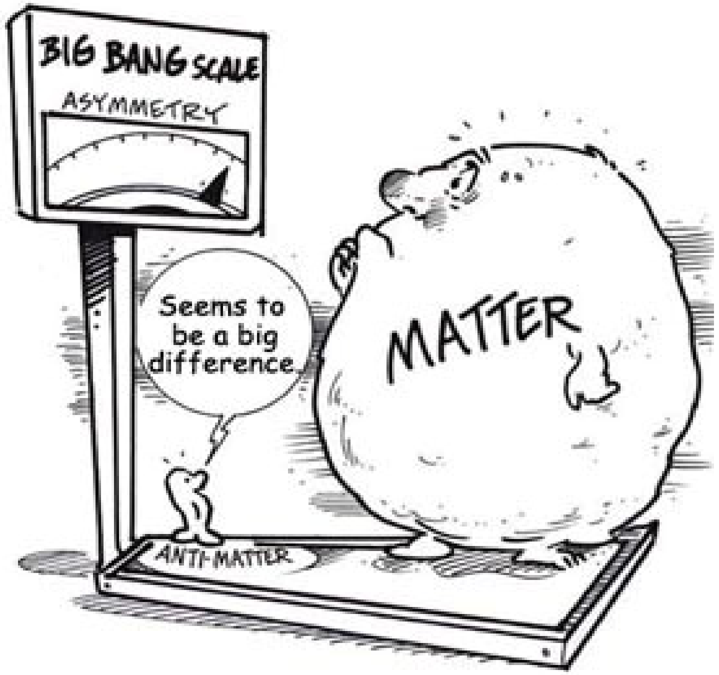


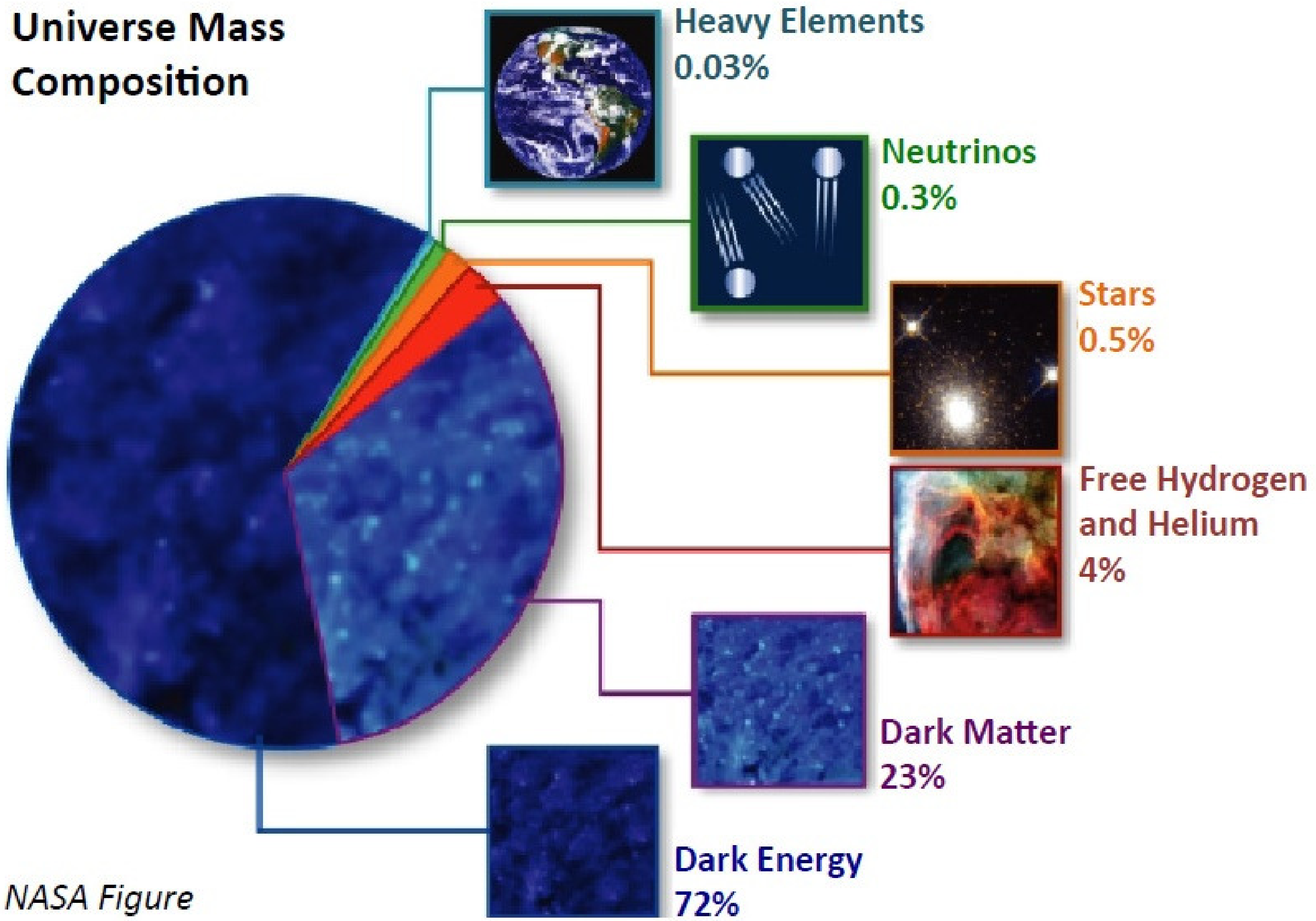
According to the Standard Model



Our Universe can not exist !

2024: New set of fundamental physics puzzles





NASA Figure

We do not know what Universe is made of

2024: Unanswered questions in particle physics
What we do not know about fundamental particle and interactions

Why to introduce Beyond the Standard Model (BSM) physics?

1. **Required by observations: Standard Model can not explain**
   - Dark matter
   - Matter-antimatter asymmetry
   - Accelerate expansion of the Universe (dark energy/cosmological constant?)
   - Neutrino masses

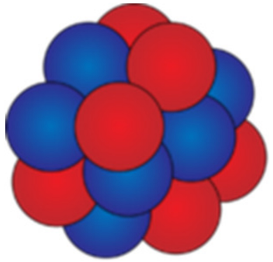
2. **"Unnatural" values of Standard Model parameters**
   - Cosmological constant
   - Higgs mass
   - Strong CP angle (from neutron EDM)
   - Masses of quark/leptons & numbers of families
   - Constants of fundamental interactions (fine-structure constant, strong coupling constant)

LIFE NEEDS VERY SPECIFIC FUNDAMENTAL CONSTANTS!

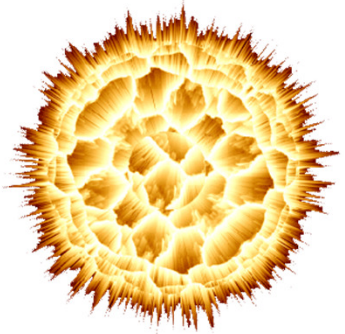
If α is too big → small nuclei can not exist

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

$\alpha \sim 1/137$



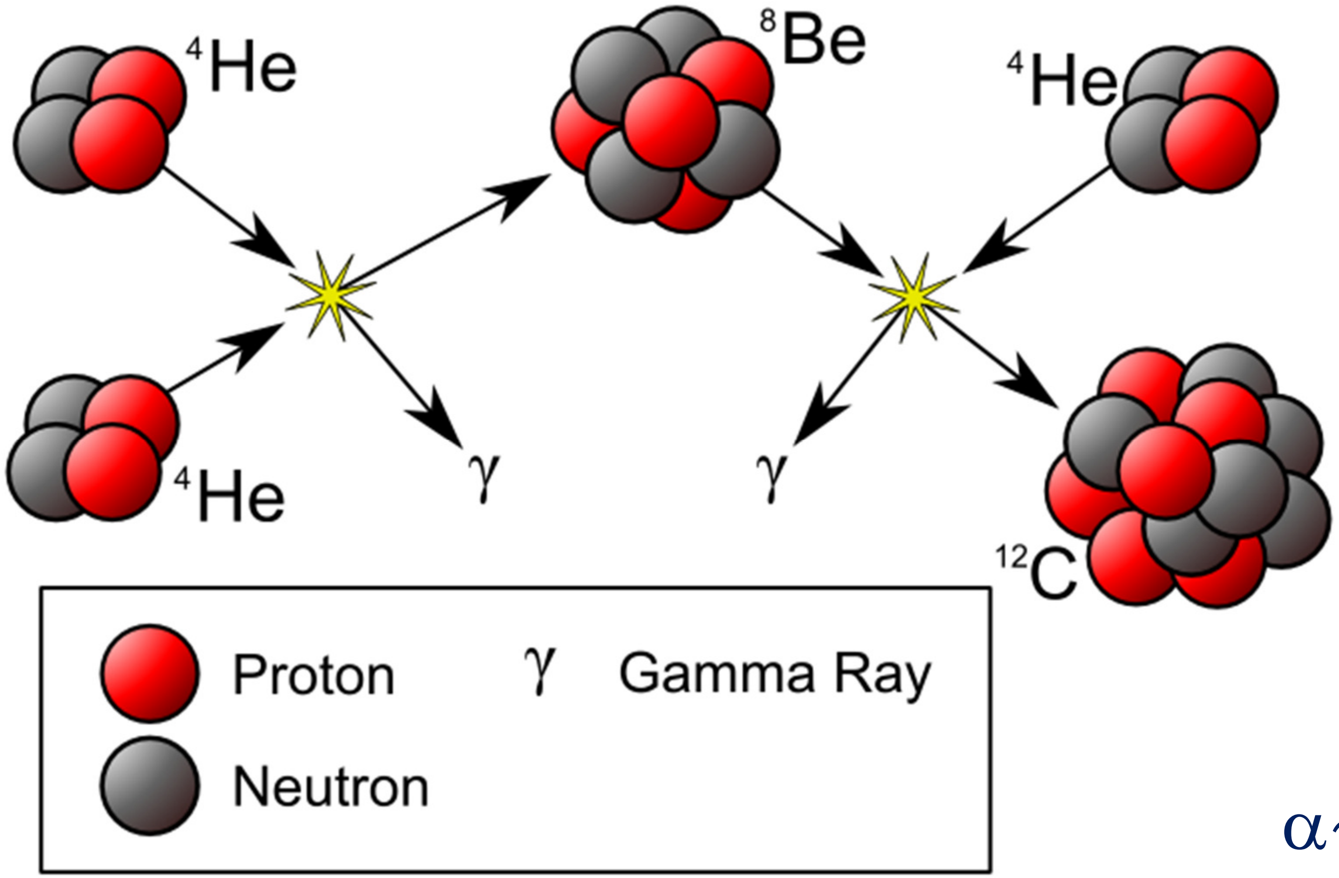
Carbon-12



$\alpha \sim 1/10$

will blow carbon apart

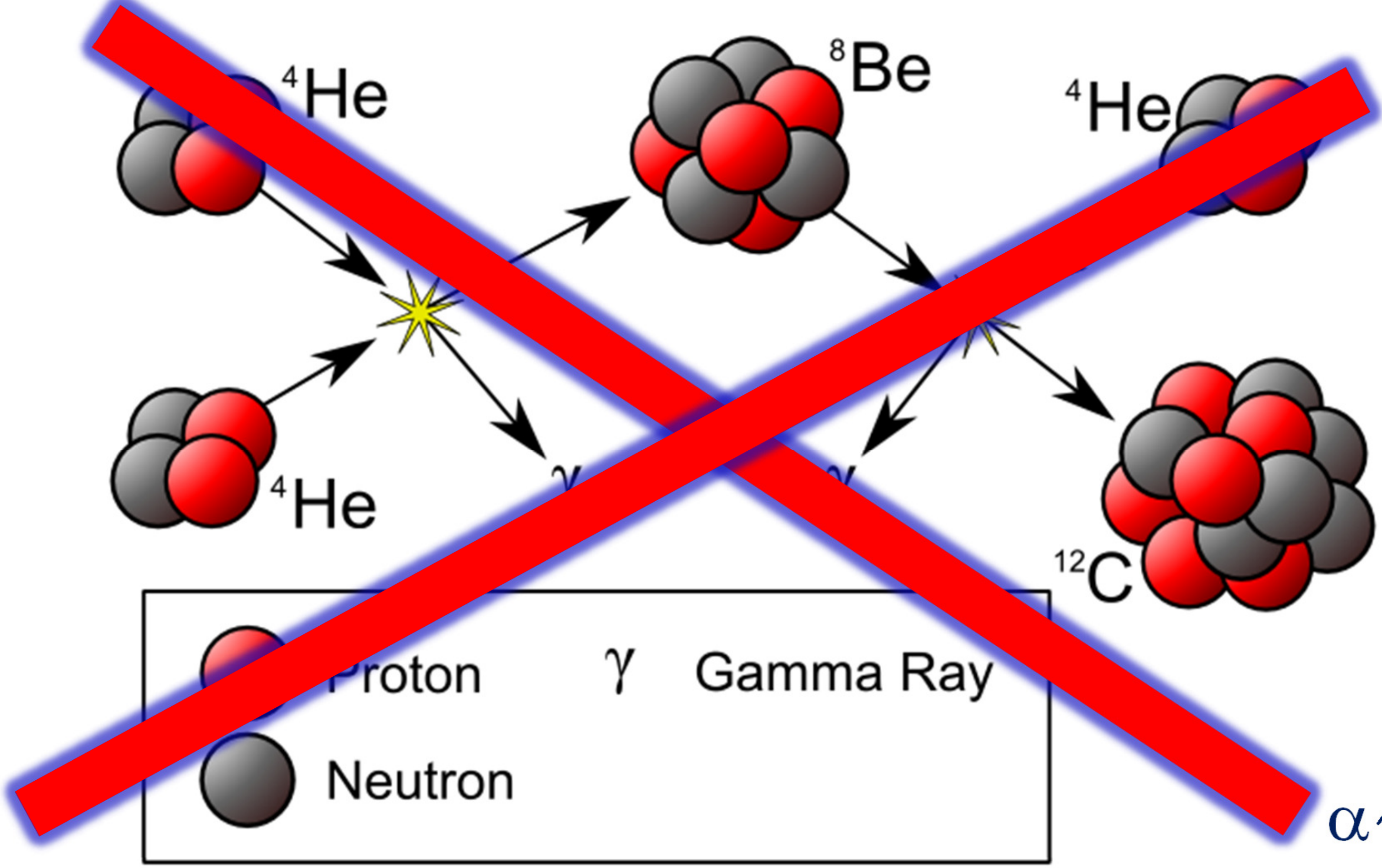
Life needs very specific fundamental constants!



$\alpha \sim 1/137$

Nuclear reaction in stars are particularly sensitive to α.
If α were different by 4%: **no carbon produced by stars**. No life.

Life needs very specific fundamental constants!



$\alpha \sim 1/132$

No carbon produced by stars:
No life in the Universe

2024: Unanswered questions in particle physics

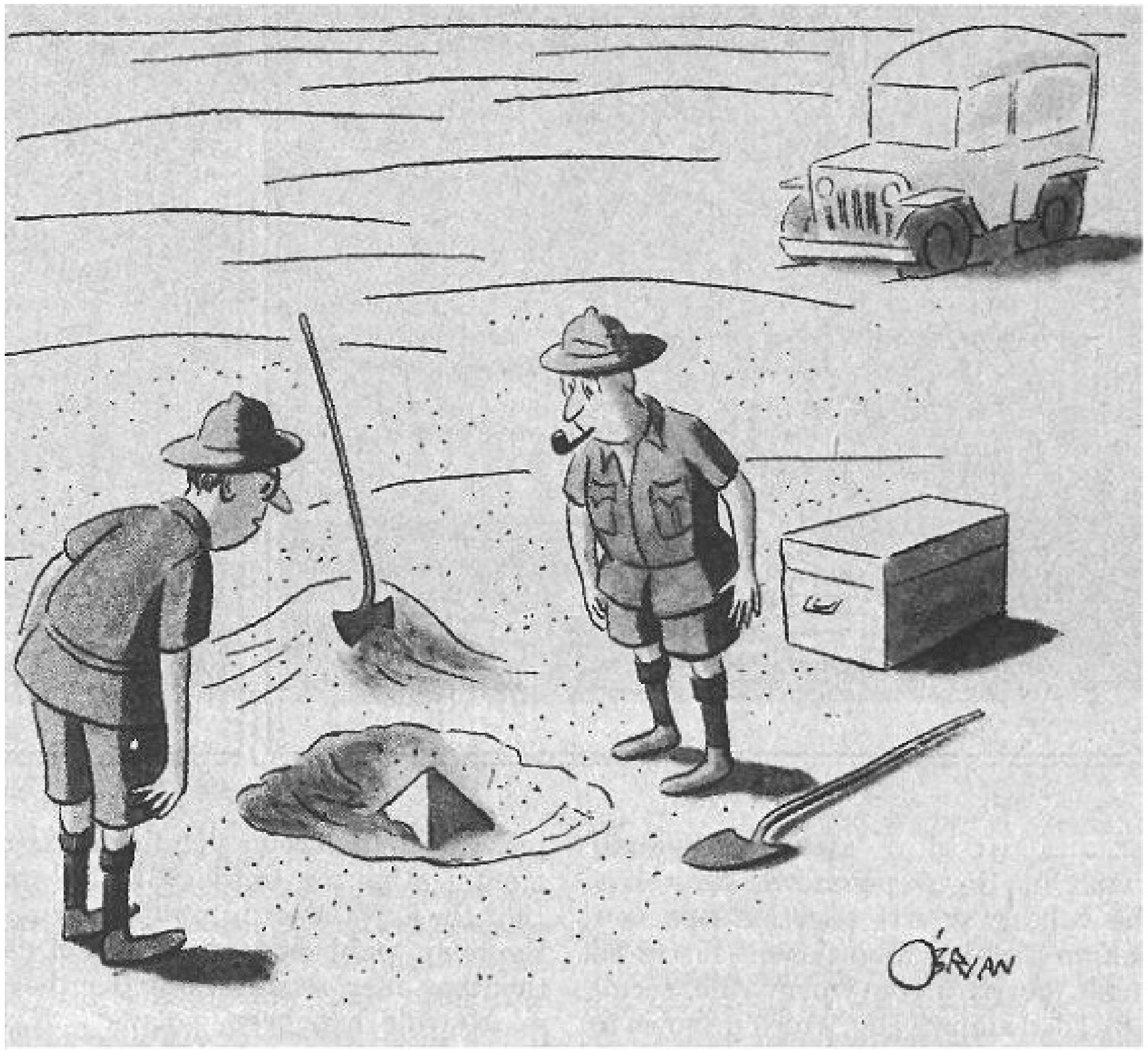
Other open questions

- How to connect gravity and quantum mechanics?
- Is there a limit on macroscopic quantum suppositions? Is quantum mechanics linear?
- Does general relativity hold in extreme regimes?
- Are fundamental constants actually constant?
- Are there violations of Einstein equivalence principle?
  - ✓ Universality of free fall
  - ✓ Position invariance
  - ✓ Local Lorentz invariance
- Are there violations of fundamental symmetries?
  - ✓ CPT (charge, parity, time)
  - ✓ Permutation symmetry for identical particles
  - ✓ The spin-statistics connection

Postulates of modern fundamental physics, experiments verify only to a certain precision

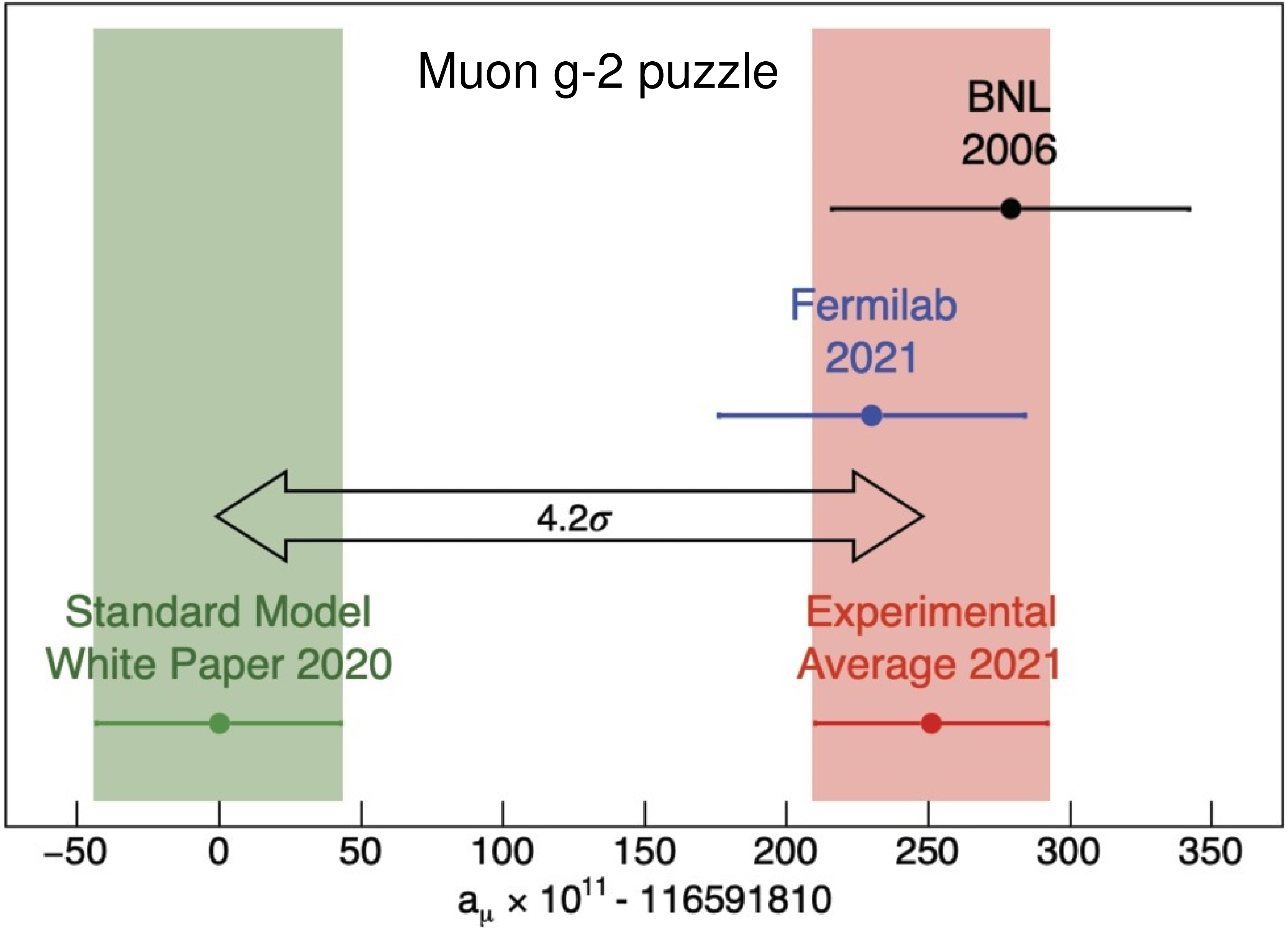
- New particles (many not contribute much for dark matter)?
- New fundamental interactions?
- Experimental/observational anomalies (could be SM): EDGES 21 cm anomaly, Hubble constant, too early quasars, muon g-2, gravitational constant G, neutron lifetime, neutrino experiment anomalies, many others

Experimental/observational anomalies

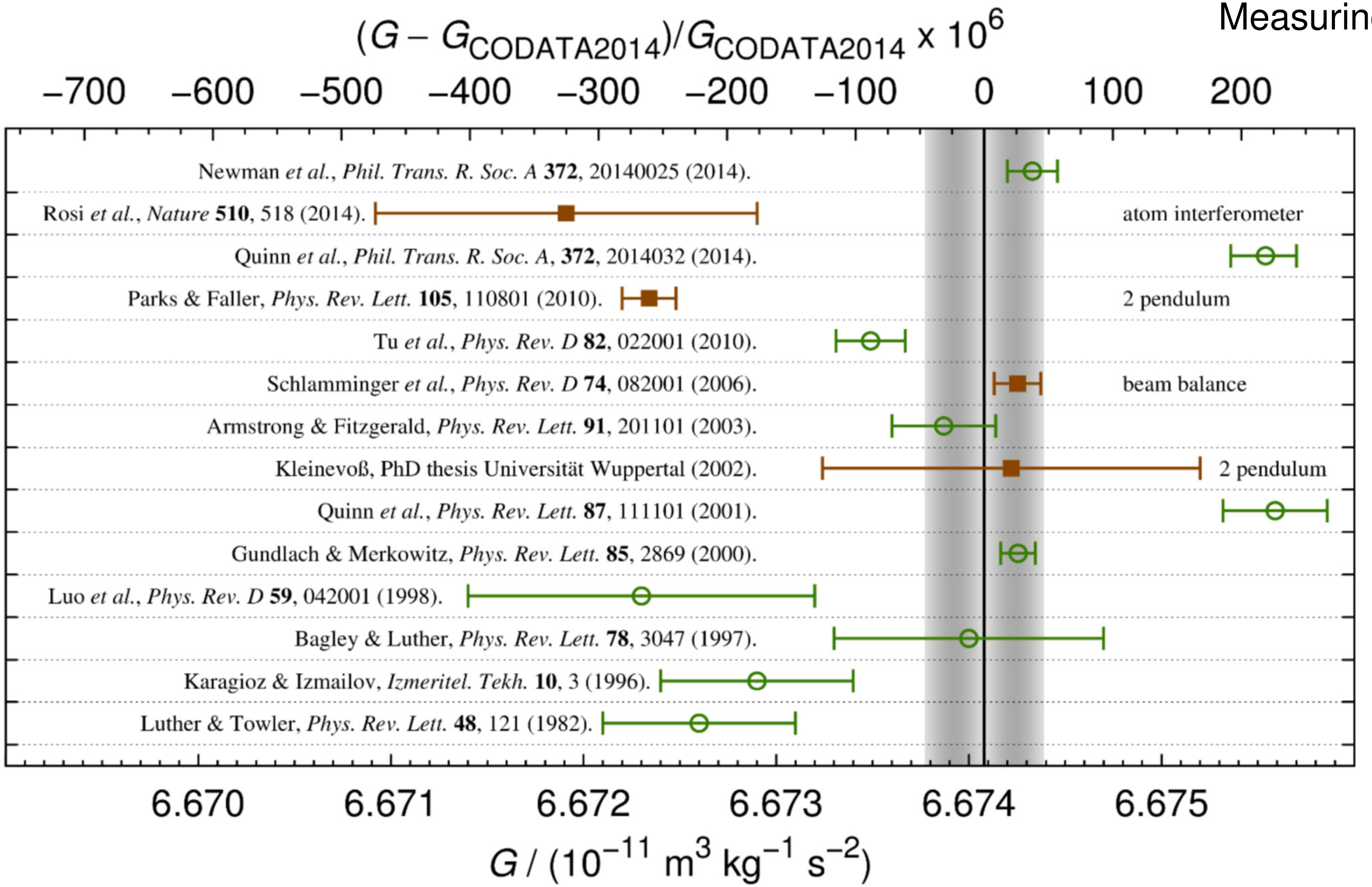


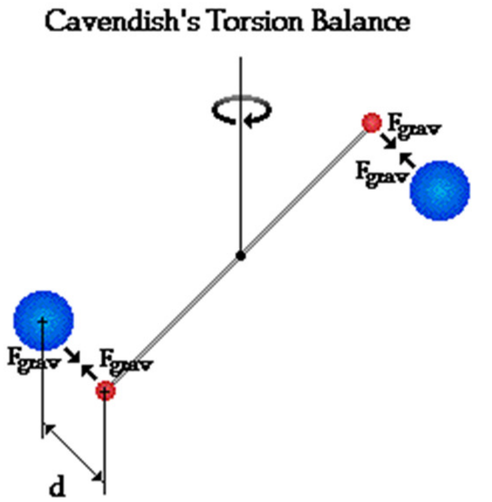
"This could be the discovery of the century. Depending, of course, on how far down it goes."

http://engent.blogspot.com



Review: Nuclear Physics B 975, 115675, 2022



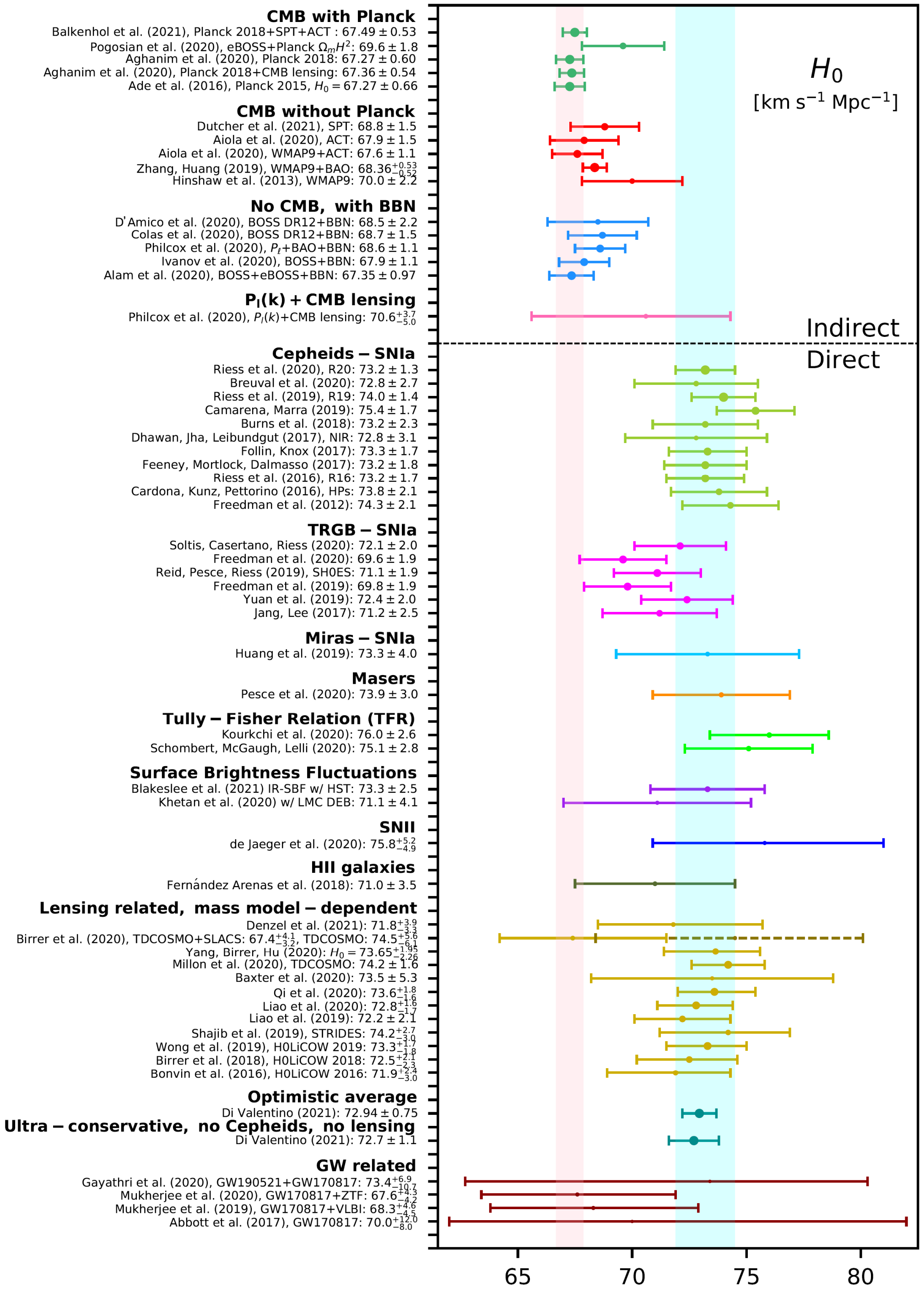


Measurements of the gravitational constant G. The points denoted with open circles were measured using a torsion balance, the solid points by other means. The black vertical line indicates the recommended value by CODATA. The grey area surrounding the black line denotes the 1-sigma uncertainty interval of the recommended value.
https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=921014

In the Realm of the Hubble tension – a Review of Solutions, E. Di Valentino et al., Class. Quantum Grav. 38, 153001 (2021), arXiv:2103.01183

The simplest ΛCDM model provides a good fit to a large span of cosmological data but harbors large areas of phenomenology and ignorance. With the improvement of the number and the accuracy of observations, discrepancies among key cosmological parameters of the model have emerged.

The most statistically significant tension is the 4σ to 6σ disagreement between predictions of the Hubble constant, H_0, made by the early time probes in concert with the “vanilla" ΛCDM Cosmological model, and a number of late time, model-independent determinations of H_0 from local measurements of distances and redshifts.



100 years ago: quantum mechanics was a solution to fundamental physics problems of that time (atomic spectra, etc.) revolutionizing our technology

Exceptional improvement in precision of quantum sensors opens new ways to solve new puzzles of the Universe

Our goal: search for new physics

What is a quantum sensor?

Focus Issue in Quantum Science and Technology (20 papers)

Quantum Sensors for New-Physics Discoveries

Editors: Marianna Safronova and Dmitry Budker

https://iopscience.iop.org/journal/2058-9565/page/Focus-on-Quantum-Sensors-for-New-Physics-Discoveries

Editorial:

Quantum technologies and the elephants, M. S Safronova and Dmitry Budker, Quantum Sci. Technol. 6, 040401 (2021).

"We take a broad view where any technology or device that is naturally described by quantum mechanics is considered ``quantum''. Then, ***a "quantum sensor" is a device, the measurement (sensing) capabilities of which are enabled by our ability to manipulate and read out its quantum states***. "

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 dark matter

Search for variation of fundamental constants

Searches for exotic forces

General relativity and gravitation

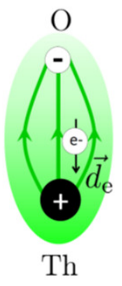
Search for violations of quantum statistics

Searches for BSM physics with Atomic, Molecular, and Optical Physics

Fundamental symmetries with quantum science techniques

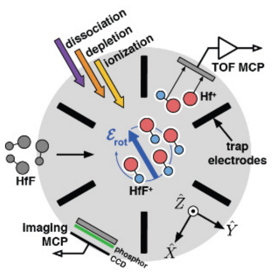
Searches for electron electric-dipole moment (eEDM)

Advanced ACME



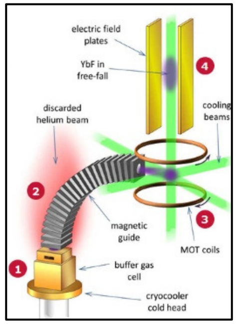
ThO

JILA eEDM



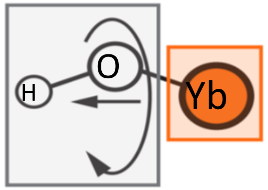
HfF^+, ThF^+

Imperial College



YbF

PolyEDM

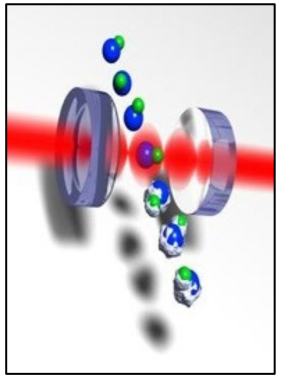


Also NMQM search

YbOH, …

Searches for hadronic EDMs

CeNTREX

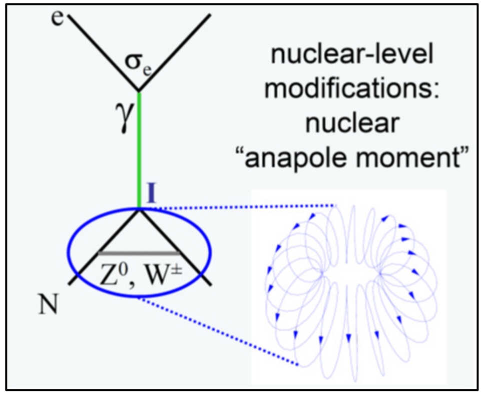


Hg
Xe
Ra
EDMs

TlF (proton EDM)

Enhanced parity violation

ZOMBIES



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

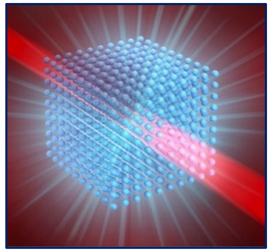
Rapid advances in ultracold molecule cooling and trapping; polyatomic molecules; future: molecules with Ra & "spin squeezed" entangled states

Atomic and Nuclear Clocks & Cavities

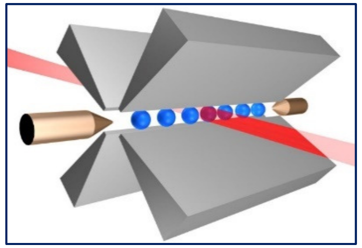
Major clock & cavities R&D efforts below, also molecular clocks, portable clocks and optical links

BSM searches with clocks

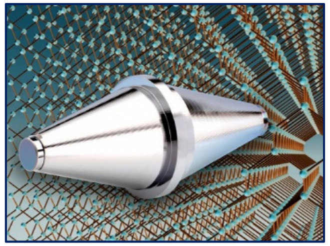
- Searches for variations of fundamental constants
- Ultralight scalar dark matter & relaxion searches
- Tests of general relativity
- Searches for violation of the equivalence principle
- Searches for the Lorentz violation



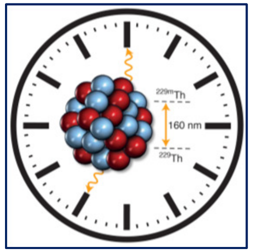
3D lattice clocks



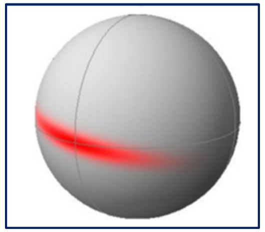
Multi-ion & entangled clocks



Ultrastable optical cavities



Nuclear & highly charge ion clocks



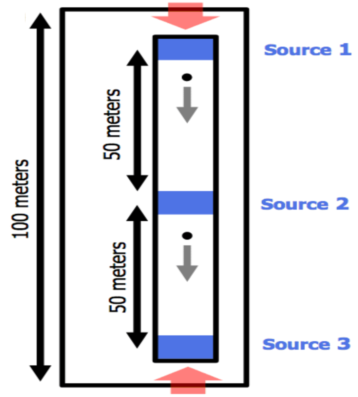
Measurements beyond the quantum limit

Atom interferometry

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

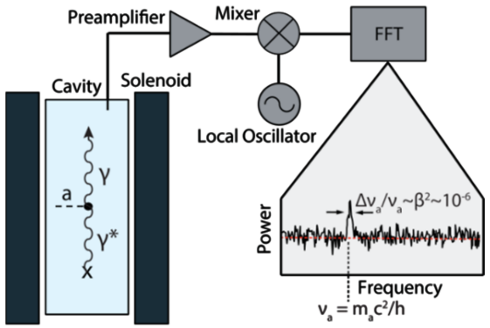
Prototype gravitational wave detectors

MAGIS-100 Fermilab



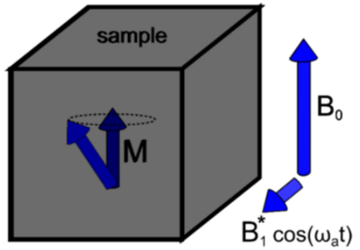
MIGA , AION, ZIGA

Axion and ALPs searches



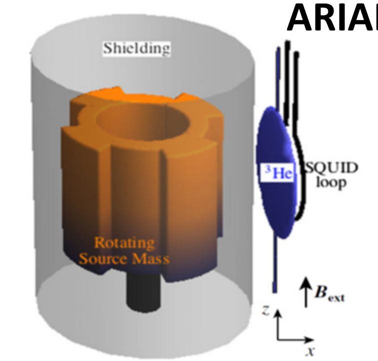
Microwave cavities: HAYSTAC
AMO: measurements beyond quantum limits

CASPEr-electric, solids
(coupling to gluons)



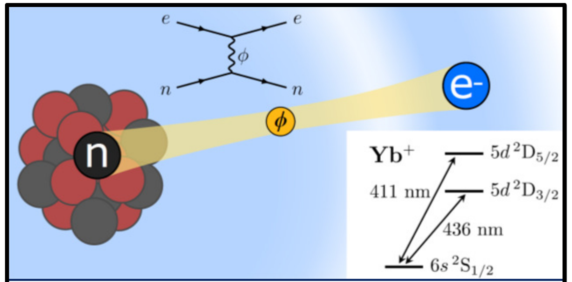
CASPEr-wind, Xe
(coupling to fermions)

ARIADNE

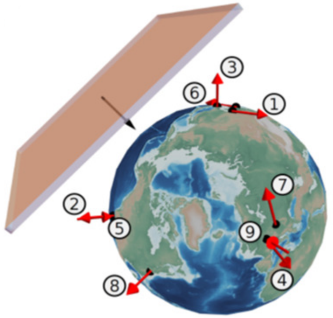


Resonantly detecting axion-mediated forces with NMR

Other dark matter & new force searches

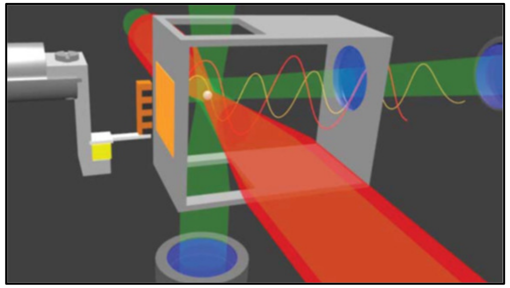


Fifth force searches with precision spectroscopy with atoms and ions



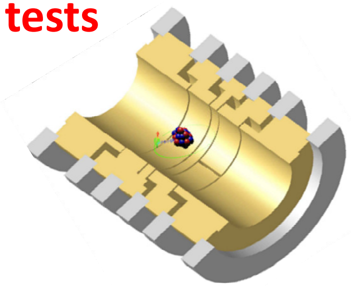
GNOME: network of optical magnetometers for exotic physics

Levitated optomechanics



Also: GW detection and testing the Newtonian inverse square law

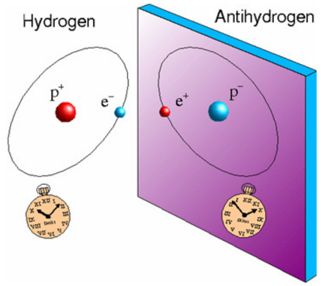
QED tests



Highly charged ions and simple systems (H, D, $^3He^+$, He, Li, HD, …)

CPT tests

$\bar{p}, \bar{H}$

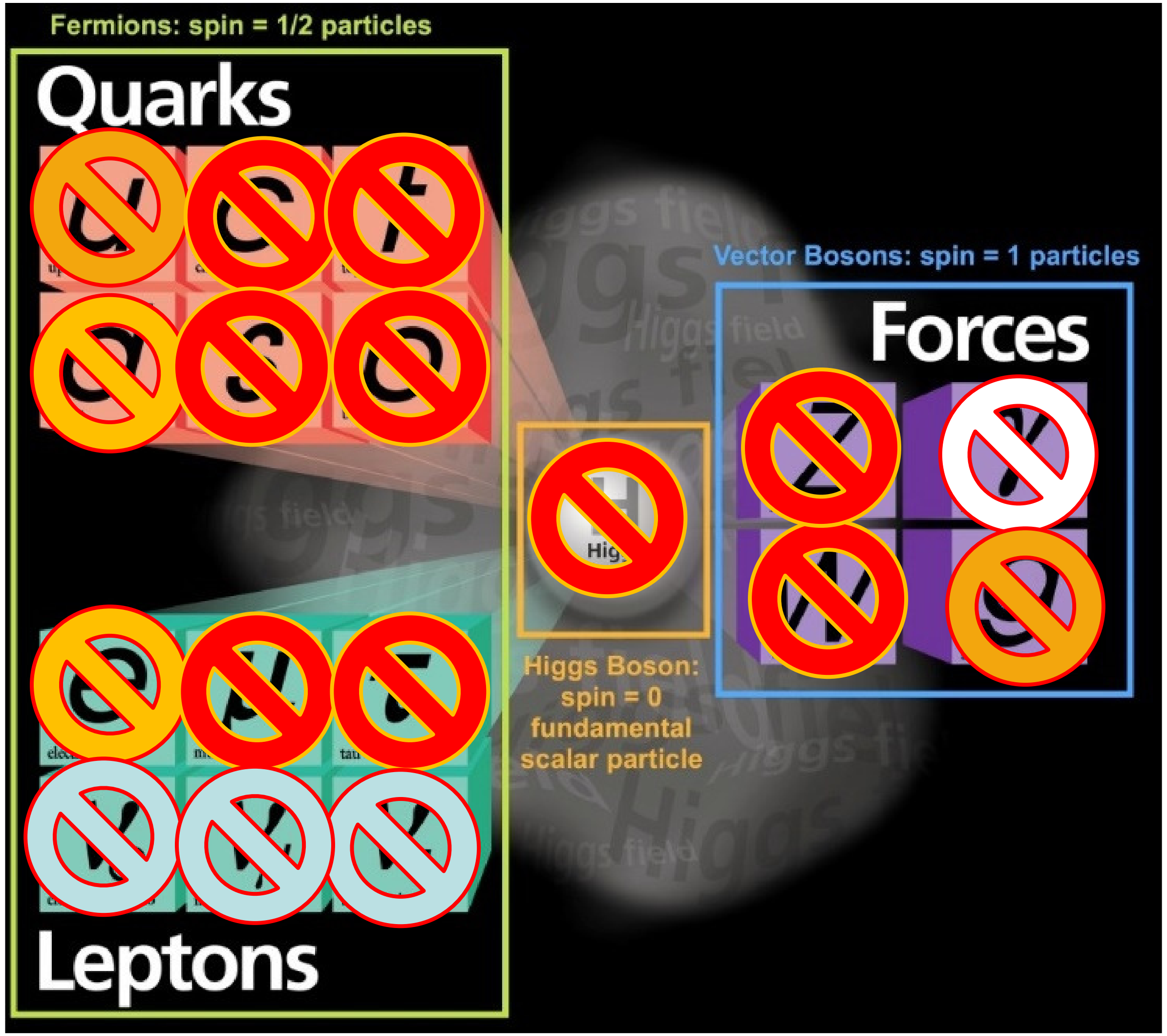


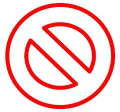
Many other current & future experiments: tests of the gravity-quantum interface, and HUNTER, SHAFT, ORGAN & UPLOAD (axions), solid-state directional detection with NV centers (WIMPs), doped cryocrystals for EDMs, Rydberg atoms, …

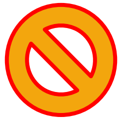
Why Search for Dark Matter?


"Because it's there."
–George Mallory

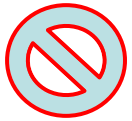
Could elementary particles be cold dark matter?




Particle of light


Couple to plasma

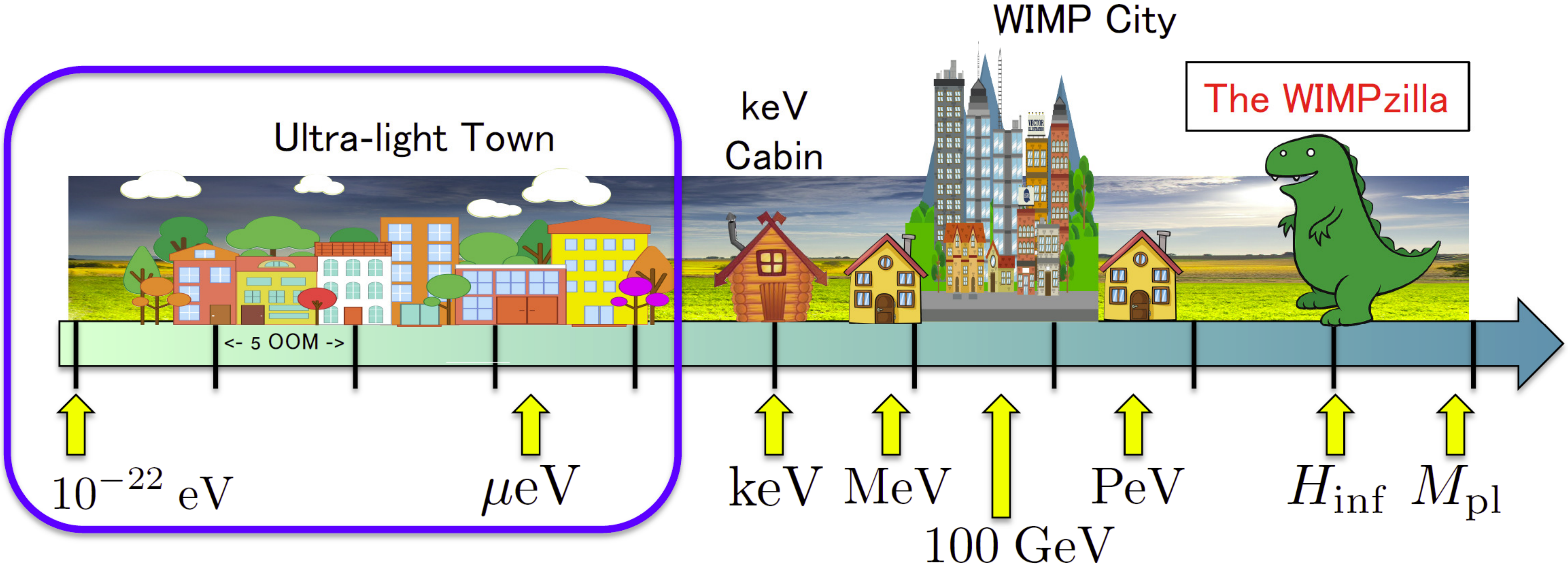

Decay quickly

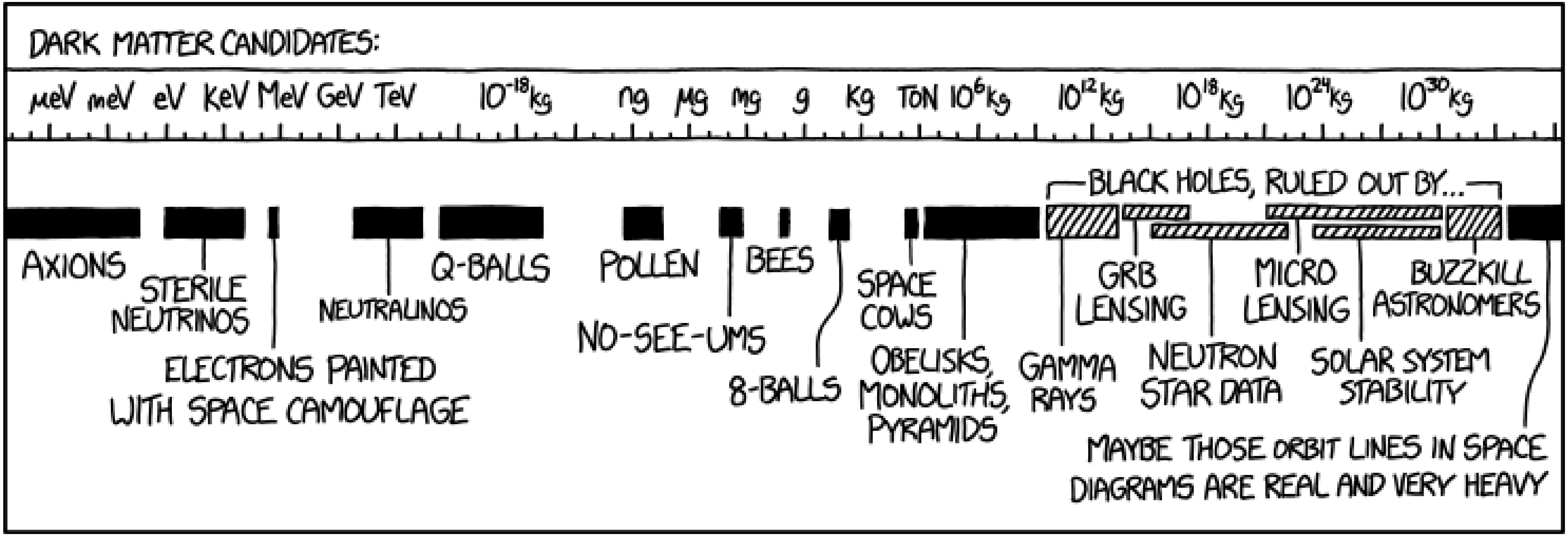

Hot dark matter

No known particle can be cold dark matter – Need to search for new particles.

Slide from Andrew Long's 2018 LDW talk

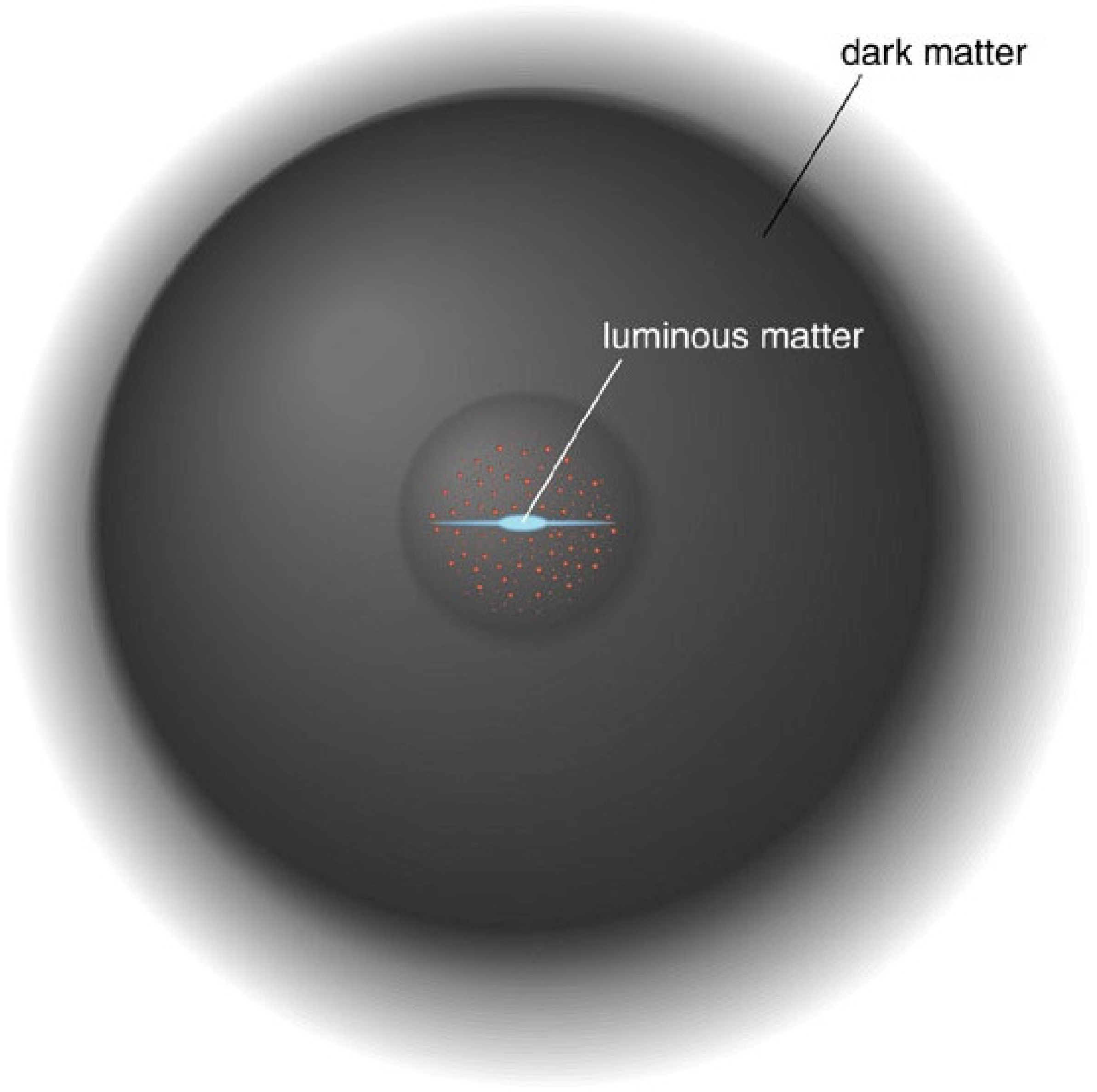
The landscape of dark matter masses



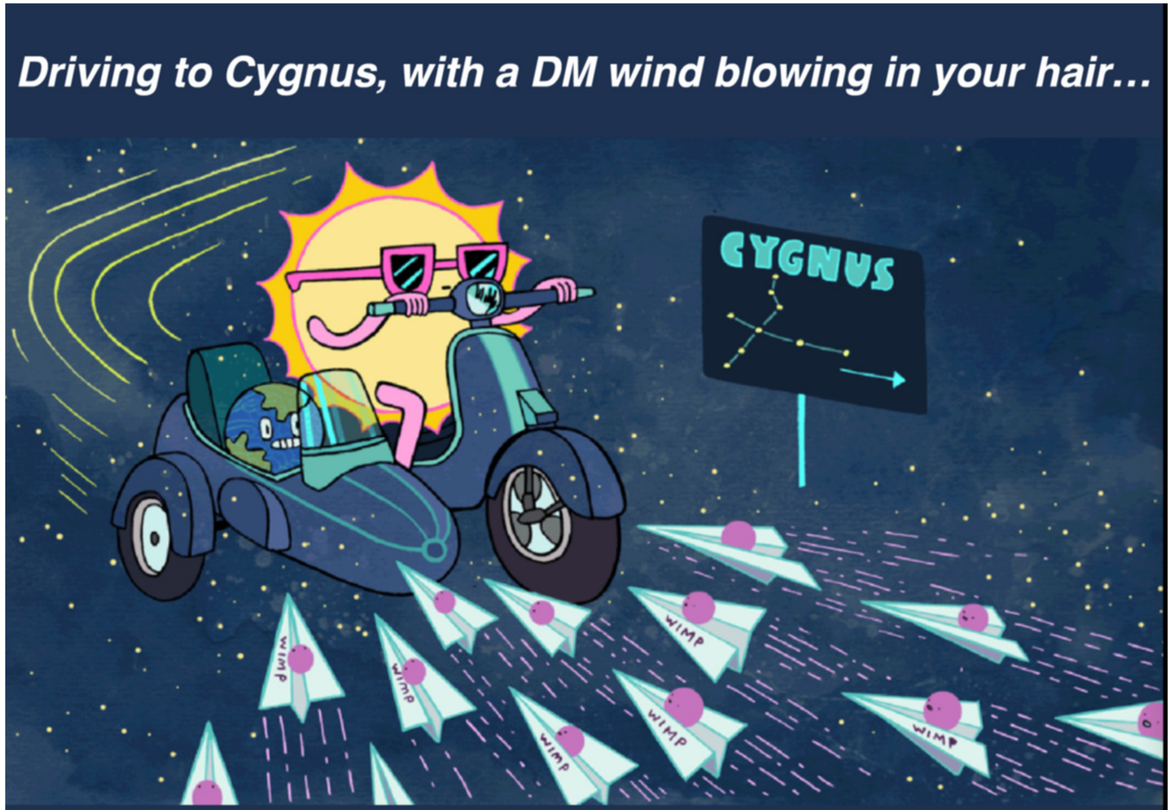


https://imgs.xkcd.com/comics/dark_matter_candidates.png

Where is dark matter?



Our visible galaxy is inside of a very large dark matter halo.

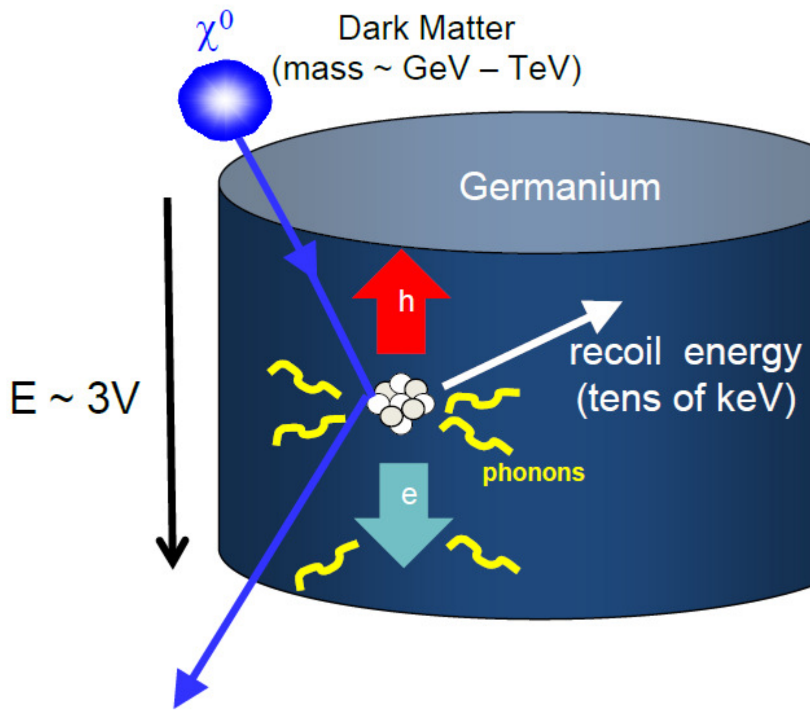


Picture from: Elisabetta Baracchini

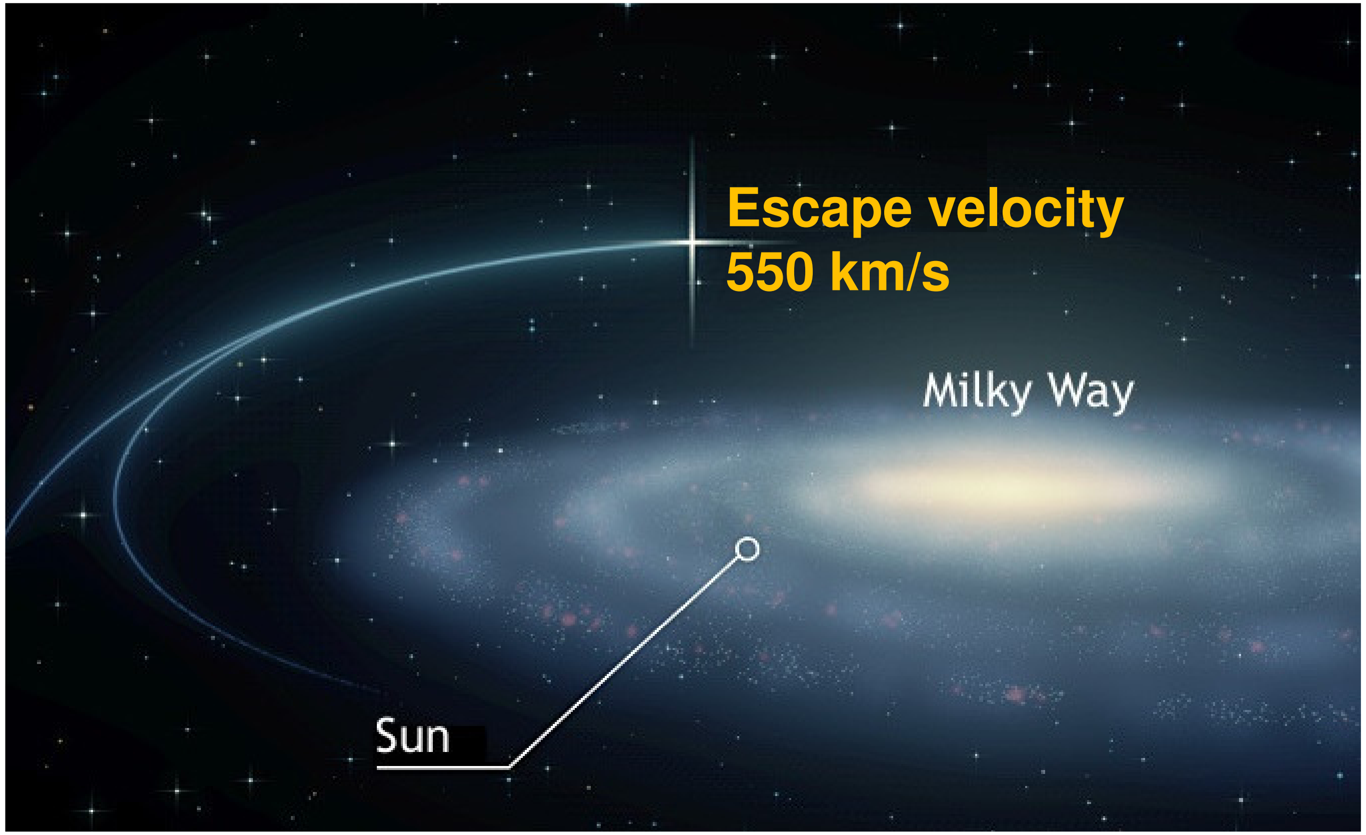
http://www.sjsu.edu/people/monika.kress/courses/sci255/

DARK MATTER DETECTION

Particle dark matter detection:
DM particle scatters and deposits energy
We detect this energy



Fermi velocity for DM with mass <10 eV is higher than our Galaxy escape velocity.



Ultralight dark matter has to be bosonic.

Image credits: CDMS: https://www.slac.stanford.edu/exp/cdms/
https://astronomynow.com/2016/04/14/speeding-binary-star-discovered-approaching-galactic-escape-velocity/

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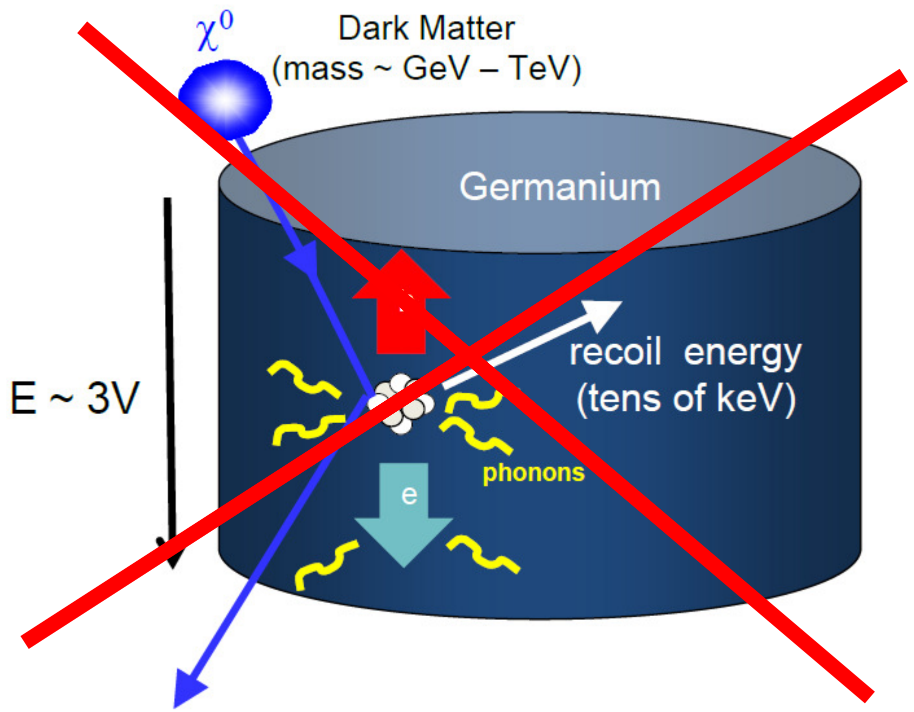

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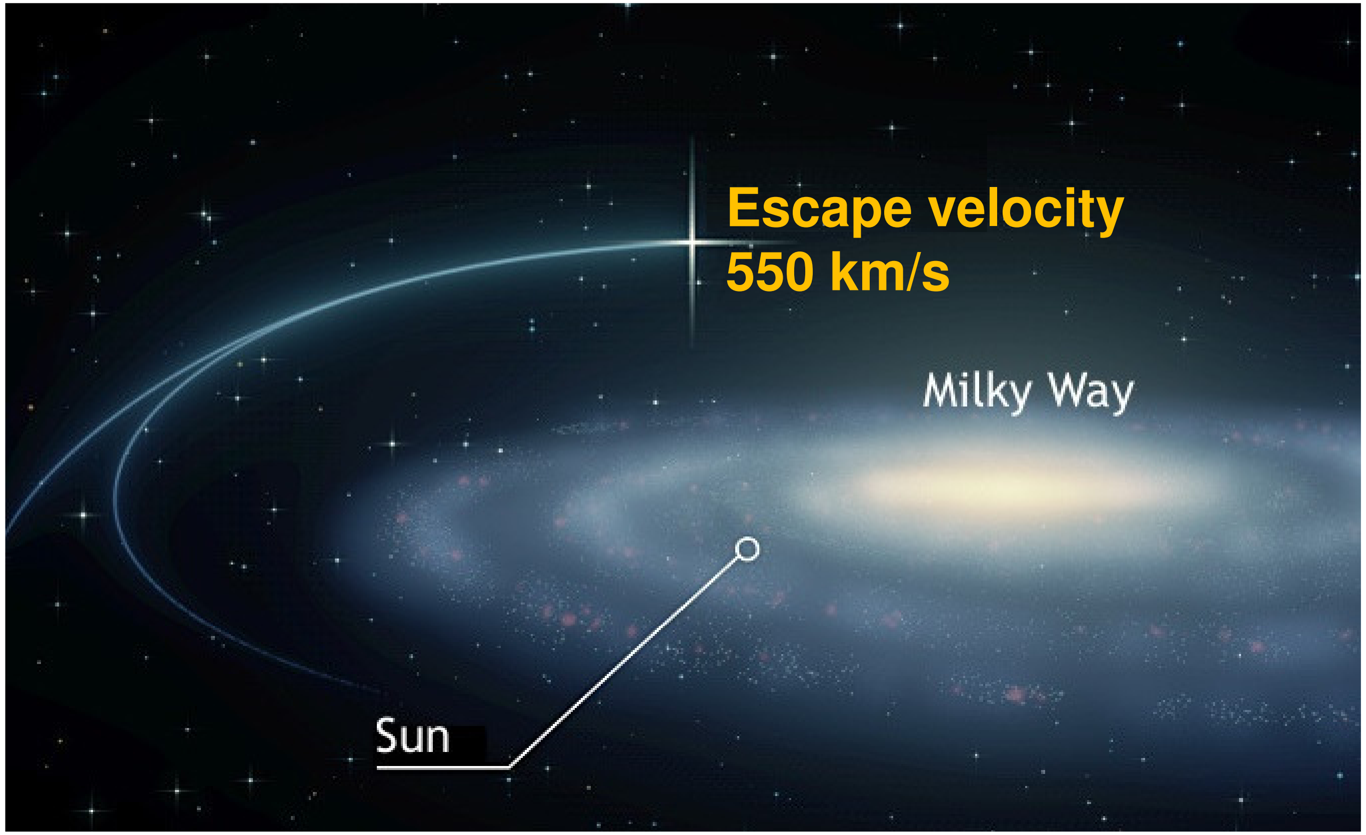

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https://astronomynow.com/2016/04/14/speeding-binary-star-discovered-approaching-galactic-escape-velocity/

Ultralight dark matter $(m_\phi \lesssim 10\ \mathrm{eV})$

The key idea: ultralight dark matter (UDM) particles behave in a "wave-like" manner.

UDM: coherent on the scale of detectors or networks of detectors.

Need different detection strategies from particle dark matter.

$$\phi(t) \approx \phi_0 \cos(m_\phi t)$$

$$\lambda_{\rm coh} \sim 10^3 (2\pi / m_\phi c)$$

$$N_{\rm dB} = n_\phi \lambda_{\rm coh}^3 \gg 1$$

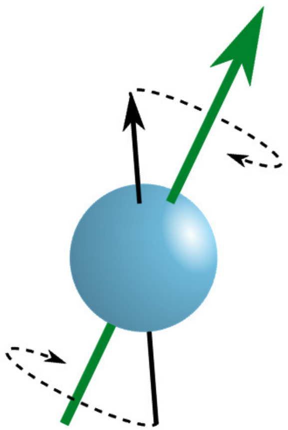
$$\phi_0 \sim \sqrt{2\rho_{\rm DM}}/m_\phi$$

Dark matter field amplitude

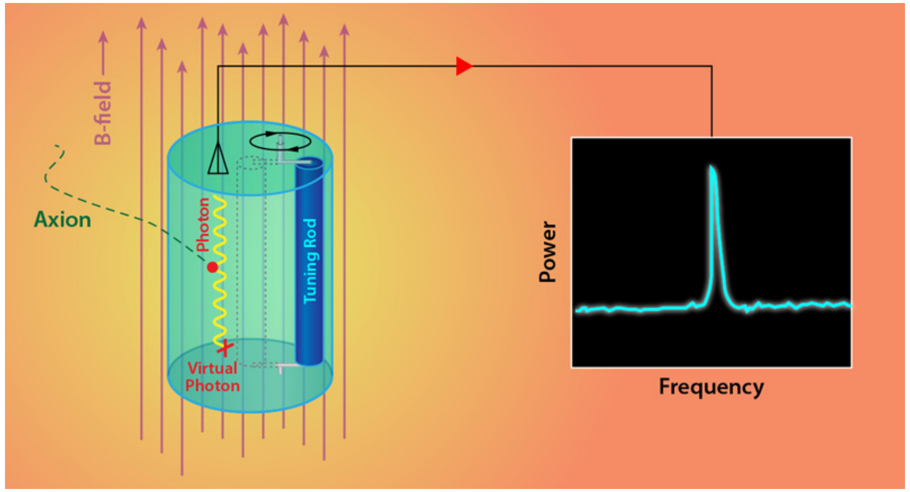
Dark matter density

Dark matter mass

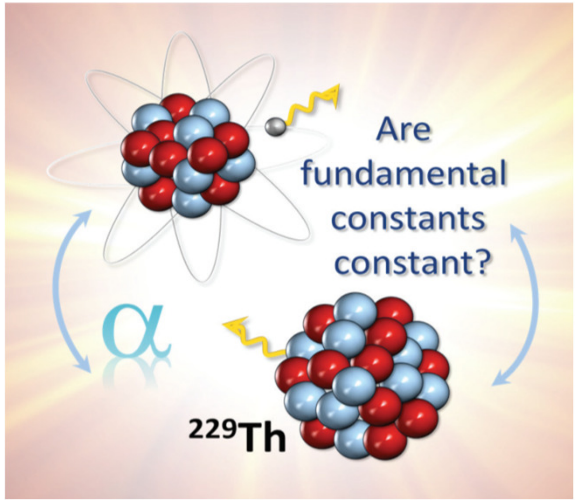
Observable effects of ultralight dark matter



Precession of nuclear or electron spins



Driving currents in electromagnetic systems, produce photons



Modulate the values of the fundamental "constants"

Induced equivalence principle-violating accelerations of matter

Detectors: Magnetometers, Microwave cavities, Trapped ions & other qubits, Atom interferometers, Laser interferometers (includes GW detectors), Optical cavities, Atomic, molecular, and nuclear clocks, Other precision spectroscopy

RMP 90, 025008 (2018)

Picture sources and credits: Wikipedia, Physics 11, 34 C. Boutan/Pacific Northwest National Laboratory; adapted by APS/Alan Stonebraker, modulate the values of the fundamental "constants" of nature

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

arXiv:2203.14923

Snowmass 2021 White Paper
Axion Dark Matter

J. Jaeckel[1], G. Rybka[2], L. Winslow[3], and the Wave-like Dark Matter Community [4]

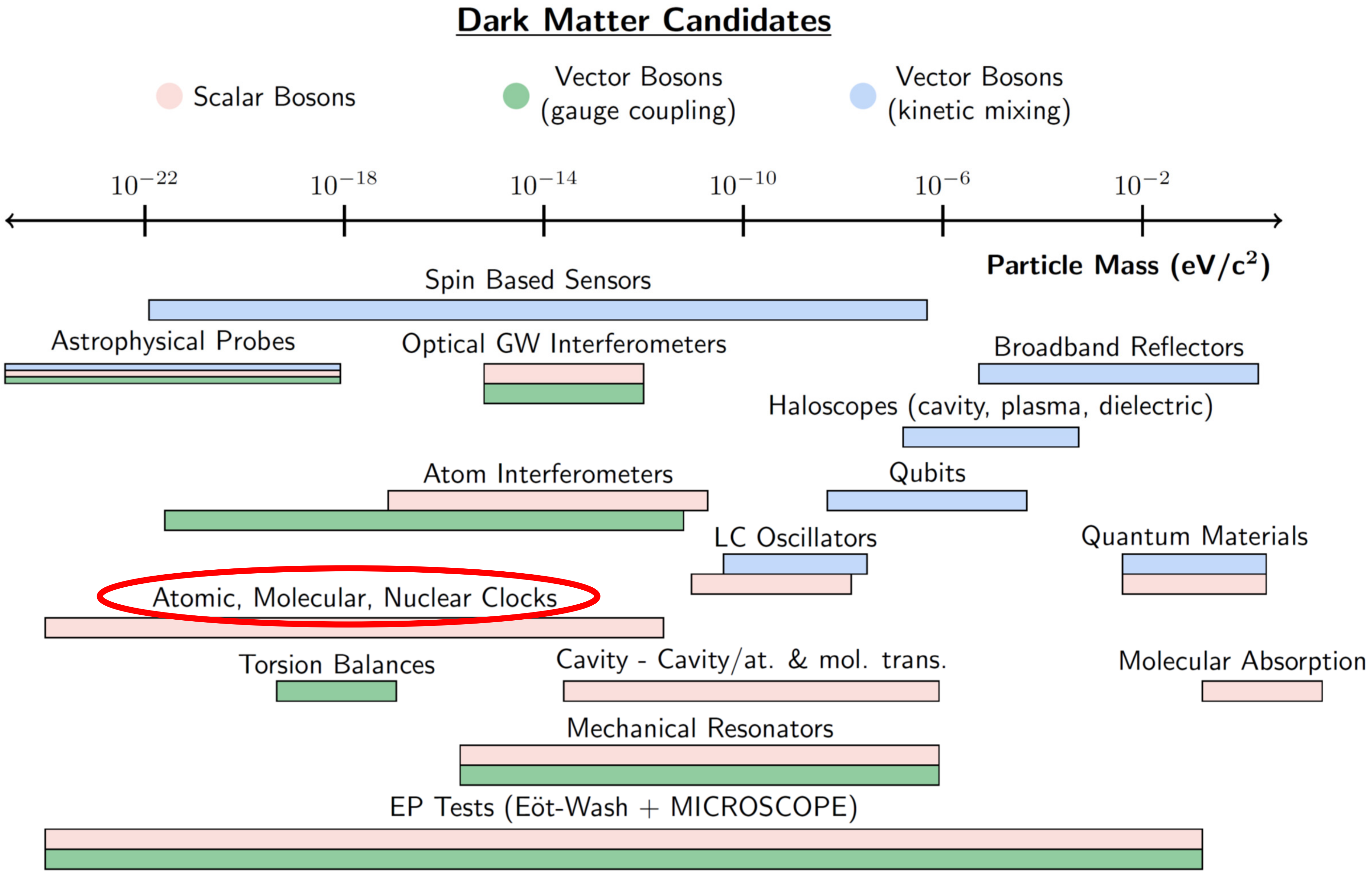
[1]Institut fuer theoretische Physik, Universitaet Heidelberg, Heidelberg, Germany
[2]University of Washington, Seattle, WA, USA
[3]Laboratory of Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA, USA
[4]Updated Author List Under Construction

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

arXiv:2203.14915

Snowmass 2021 CF2 Whitepaper
New Horizons: Scalar and Vector Ultralight Dark Matter

Dionysios Antypas,[1,2] Abhishek Banerjee,[3] Masha Baryakhtar,[4] Joey Betz,[5] John J. Bollinger,[6] Dmitry Budker,[1,2,7] Daniel Carney,[8] Sanha Cheong,[9,10] Mitul Dey Chowdhury,[11] José R. Crespo López-Urrutia,[12] Tejas Deshpande,[13] John M. Doyle,[14,15] Alex Drlica-Wagner,[16,17,18] Joshua Eby,[19] Gerrit S. Farren,[20] Nataniel L. Figueroa,[1,2] Susan Gardner,[21] Andrew Geraci,[13] Akshay Ghalsasi,[22] Sumita Ghosh,[23,24] Sinéad M. Griffin,[25,26] Daniel Grin,[27] Jens H. Gundlach,[4] David Hanneke,[28] Roni Harnik,[16] Joerg Jaeckel,[29] Dhruv Kedar,[30] Derek F. Jackson Kimball,[31] Shimon Kolkowitz,[32] Zack Lasner,[14,15] Ralf Lehnert,[33] David R. Leibrandt,[6,34] Erik W. Lentz,[35] Zhen Liu,[36] David J. E. Marsh,[37] Jack Manley,[38] Reina H. Maruyama,[23] Nathan Musoke,[39] Ciaran A. J. O'Hare,[40,41] Ekkehard Peik,[42] Gilad Perez,[3] Arran Phipps,[31] John M. Robinson,[30] Keir K. Rogers,[43] Murtaza Safdari,[9,10] Marianna S. Safronova,[5] Piet O. Schmidt,[42,44] Thorsten Schumm,[45] Maria Simanovskaia,[9] Swati Singh,[38,5] Yevgeny V. Stadnik,[40] Chen Sun,[46] Alexander O. Sushkov,[47,48,49] Volodymyr Takhistov,[19] Peter G. Thirolf,[50] Michael E. Tobar,[51,52] Oleg Tretiak,[1,2] Yu-Dai Tsai,[53] Sander Vermeulen,[54] Edoardo Vitagliano,[55] Zihui Wang,[56] Dalziel J. Wilson,[11] Jun Ye,[30] Muhammad Hani Zaheer,[5] Tanya Zelevinsky,[57] and Yue Zhao[58]



arXiv:2203.14915

Figure credit: Joey Betz, Swati Singh and many other authors

Scalar ultralight dark matter

Coupling of scalar UDM to the standard model:

$$\kappa = (\sqrt{2}M_{\rm Pl})^{-1}$$

$$\phi(t) \approx \phi_0 \cos(m_\phi t)$$

photons, electrons, gluons, quarks

$$\mathcal{L}_{\rm int}^{\rm lin} = \kappa\phi \left\{ \left[\frac{d_e F_{\mu\nu}F^{\mu\nu}}{4} - d_{m_e} m_e \bar{\psi}_e \psi_e \right] - \left[\frac{d_g \beta_3 G^a_{\mu\nu} G^{a\mu\nu}}{2g_3} + \sum_{q=u,d,s} \left(d_{m_q} + \gamma_m d_g\right) m_q \bar{\psi}_q \psi_q \right] \right\}$$

$$\alpha \rightarrow \frac{\alpha}{1-\kappa d_e \phi(t)} \approx \alpha\left(1+\kappa d_e \phi(t)\right) \qquad m_e \rightarrow m_e + \kappa m_e d_{m_e} \phi(t)$$

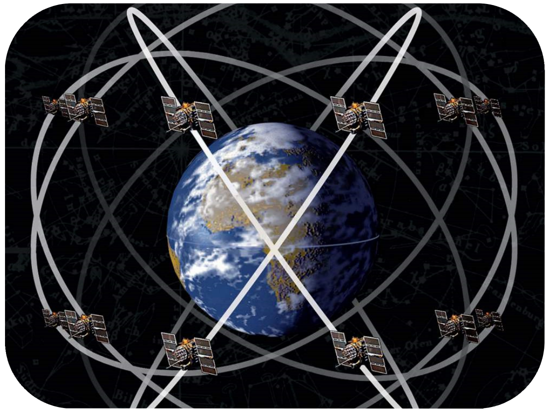
Scalar UDM will cause **oscillations** of the electromagnetic fine-structure constant α, strong interaction constant and fermion masses

Dimensionless constants: $\alpha, \frac{m_e}{m_p}, \frac{m_q}{\Lambda_{\rm QCD}}$

Key point: different (types) of clocks have different sensitivity to different constants

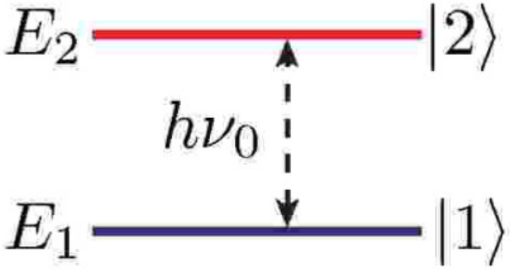
Observable: clock frequency ratios

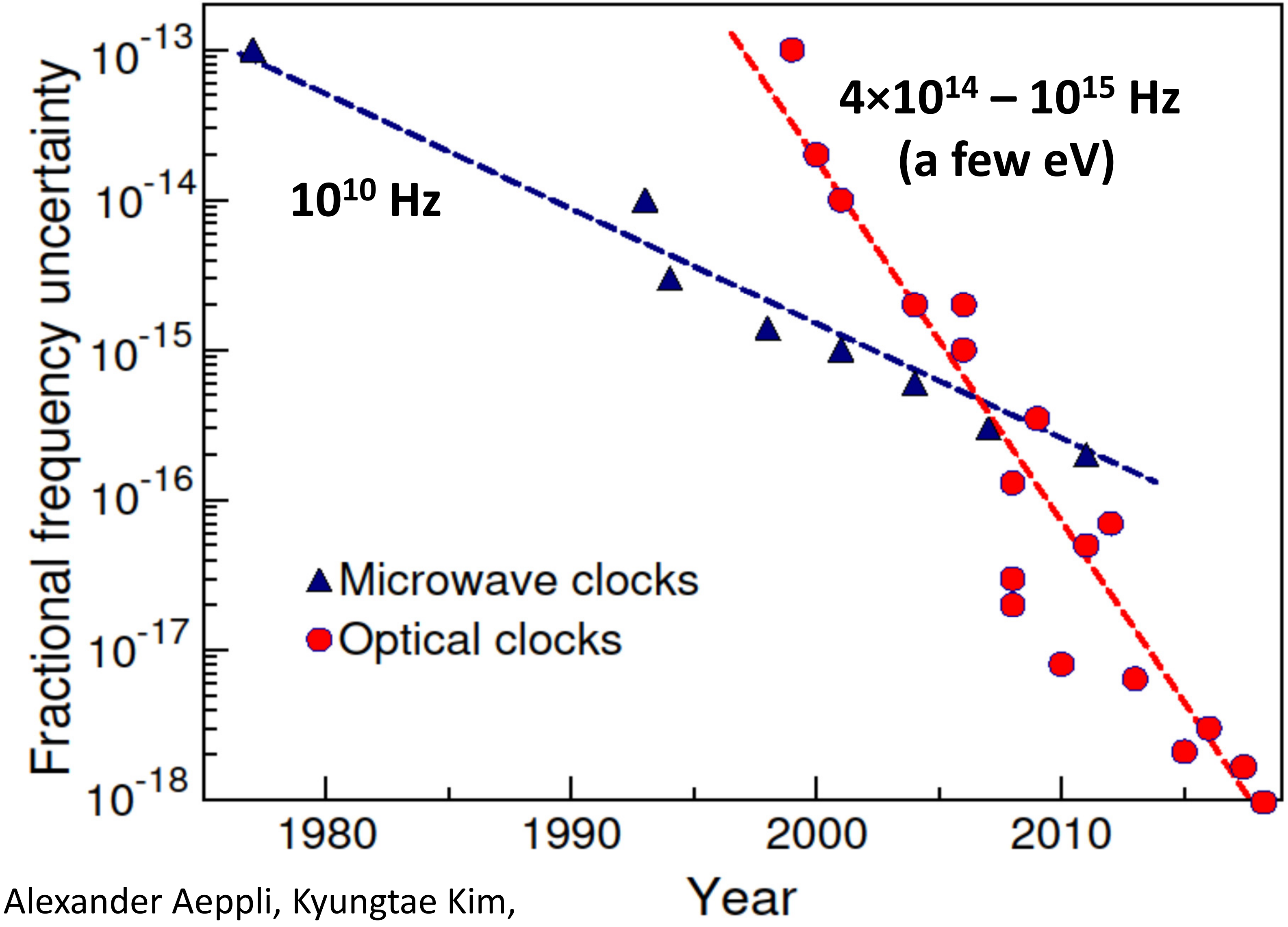
OPTICAL ATOMIC CLOCKS WILL NOT LOSE ONE SECOND IN 30 BILLION YEARS



airandspace.si.edu

GPS satellites: microwave atomic clocks





A clock with **8×10^{-19}** systematic uncertainty, Alexander Aeppli, Kyungtae Kim, William Warfield, Marianna S. Safronova, Jun Ye, Phys. Rev. Lett. 133, 023401 (2024)

Variation of which fundamental constants can we probe (or which dark matter couplings)

1. Frequency of optical transitions

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

$$\frac{d_e F_{\mu\nu}F^{\mu\nu}}{4}$$

$$\nu \simeq c R_\infty A F(\alpha)$$ **Depends only on α**

2. Frequency of hyperfine transitions

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

$$d_{m_e} m_e \bar{\psi}_e \psi_e$$

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

$$\frac{m_q}{\Lambda_{\rm QCD}}$$

$$\frac{d_g \beta_3 G^a_{\mu\nu} G^{a\mu\nu}}{2g_3}$$

Depends on α, μ, g-factors

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

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

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

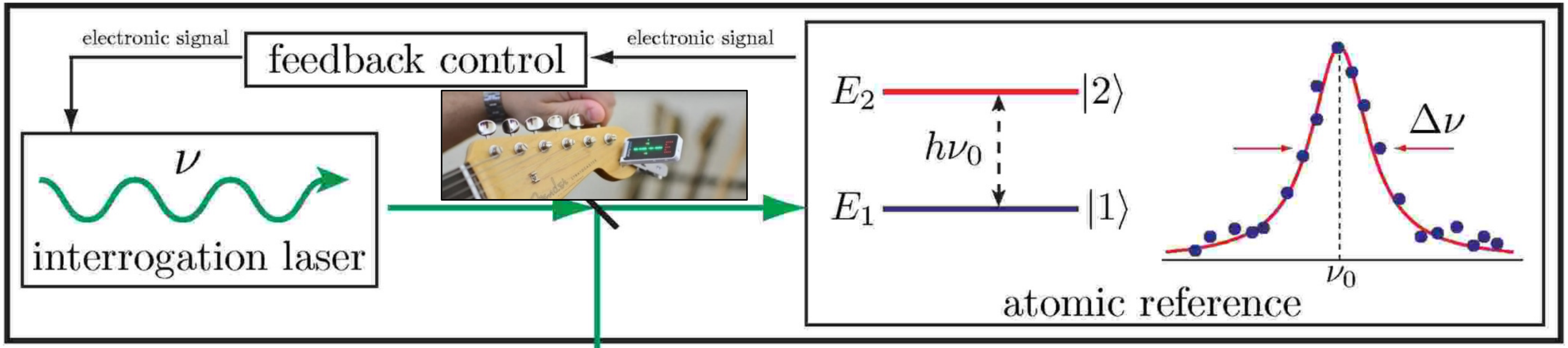
How optical atomic clock works ?

Ultrastable laser

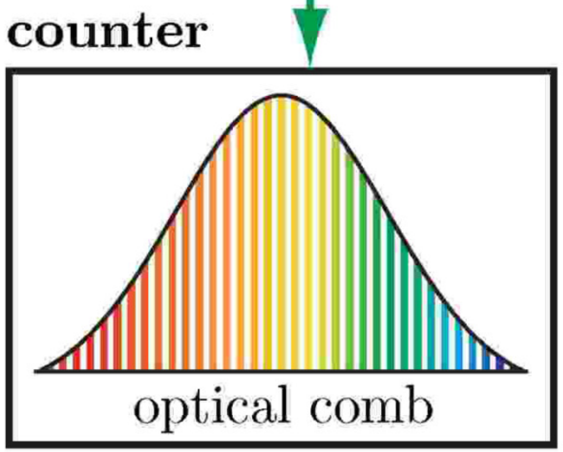
Atomic transition

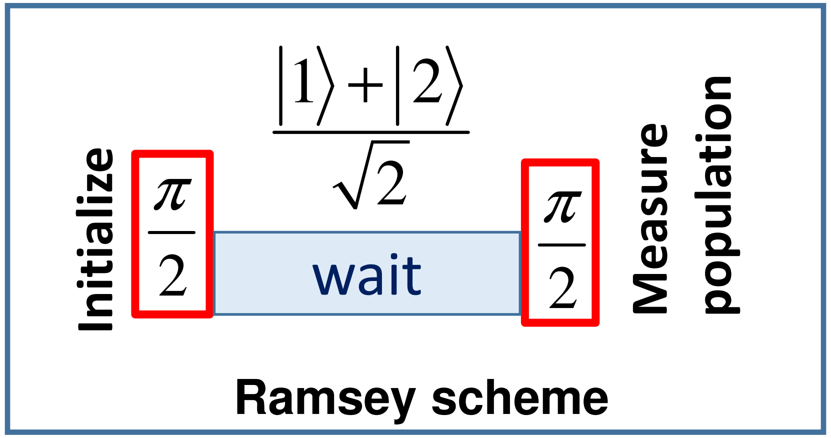
Basic idea: tune the laser to the frequency of the atomic transition

HOW OPTICAL ATOMIC CLOCK WORKS ?



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

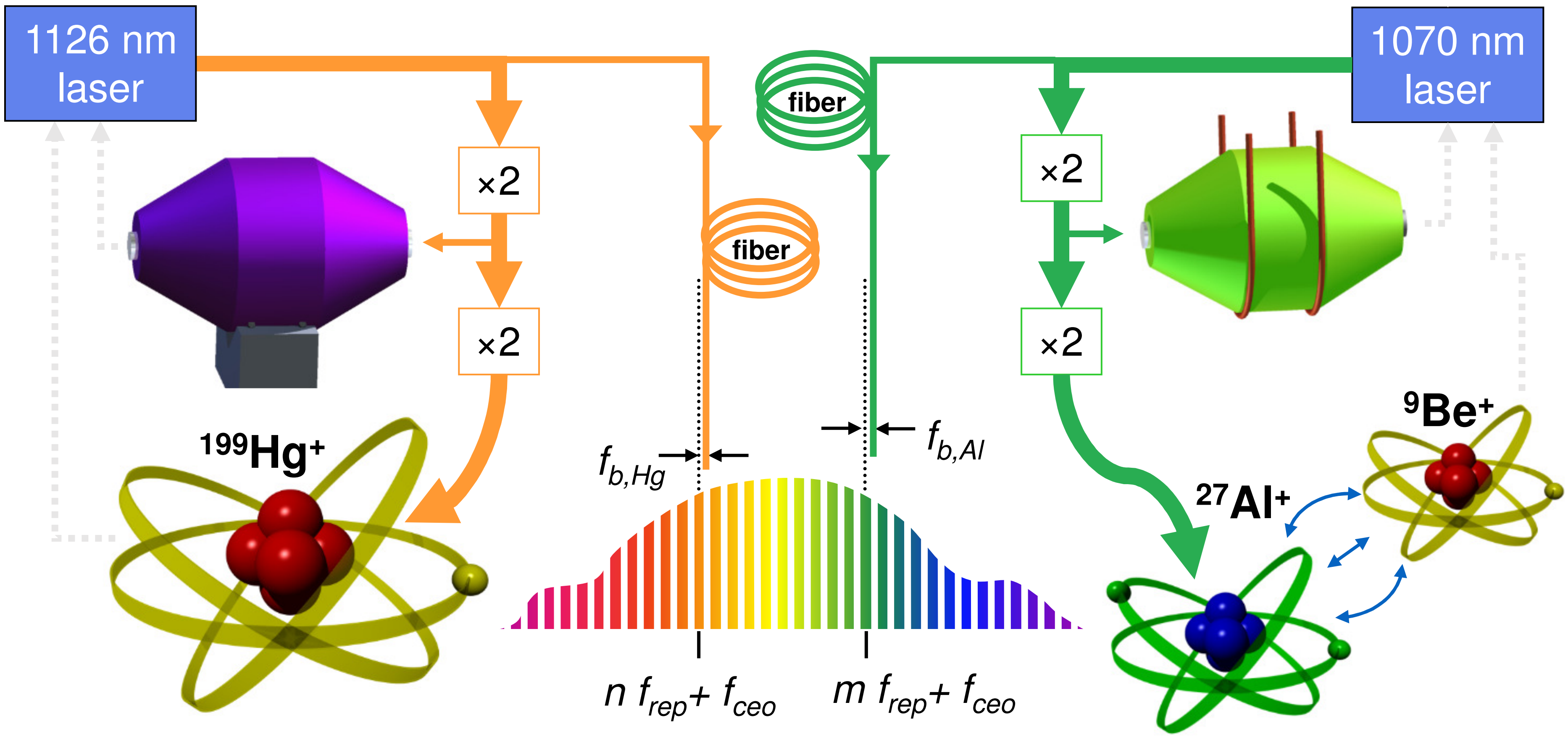
Observable: ratio of two clock frequencies

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

$$\frac{\nu\left(Hg^{+}\right)}{\nu\left(\mathrm{Al}^{+}\right)}$$

$K(Hg^{+}) = -2.9$ Sensitivity factors

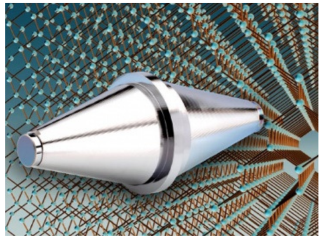
$K\left(Al^{+}\right) = 0.01$ Not sensitive to α-variation, used as reference



Picture credit: Jim Bergquist

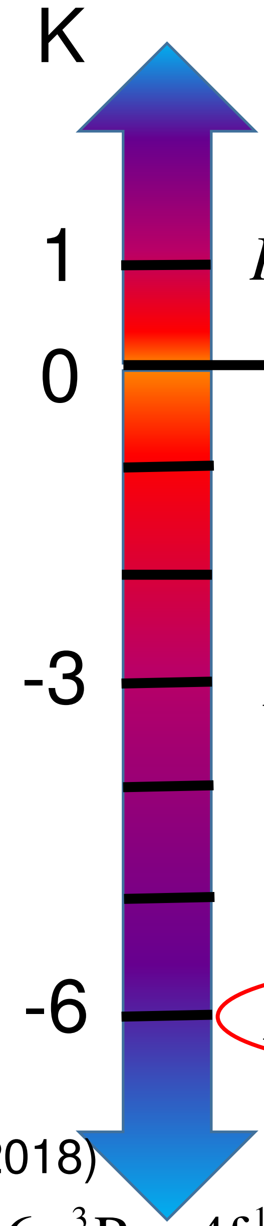
Science 319, 1808 (2008)

Enhancement (sensitivity) factor K for clocks



Cavity K=1

Effective Sr/cavity K=1



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

$K(Sr^+) = 0.4$

$K(Yb) = 0.3$

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

$K(Hg^+) = -2.9$

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

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

Future clocks:

$K(Cf^{15+} / Cf^{17+}) \approx 110$

Nuclear clock $K = ?$

Safronova et al., PRL120, 173001 (2018)

$K(Yb \ 4f^{14}6s6p\,^3P_0 - 4f^{13}6s^2 5d) = 15$

How to detect ULTRALIGHT dark matter with clocks?

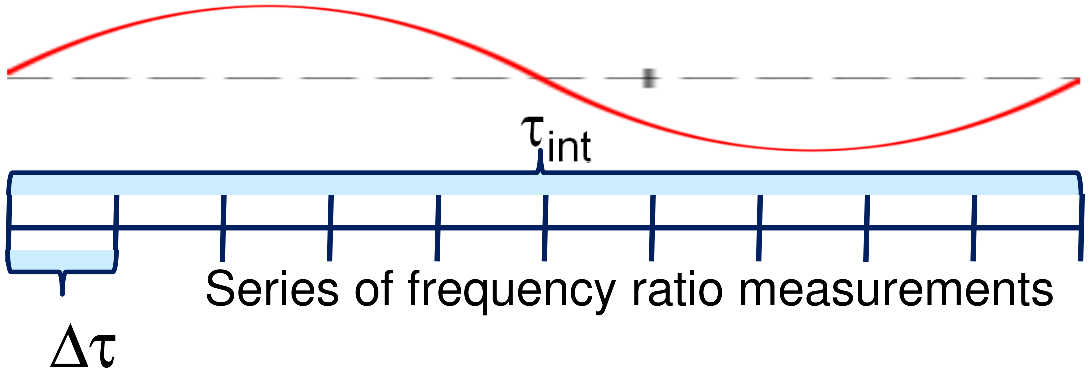
Dark matter field couples to electromagnetic interaction and "normal matter"

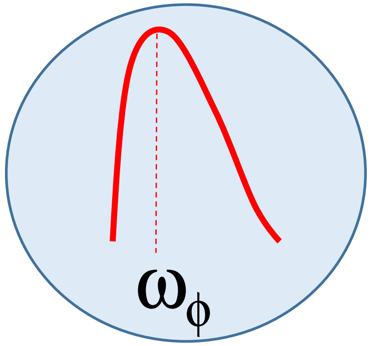
Fundamental coupling constants and mass ratios now oscillate

Atomic, molecular, nuclear energy levels will oscillate so clock frequencies will oscillate

Measure ratios of clock frequencies over time (or clock/cavity).

Discrete Fourier transform of time series gives a frequency peak





Dark matter Compton frequency

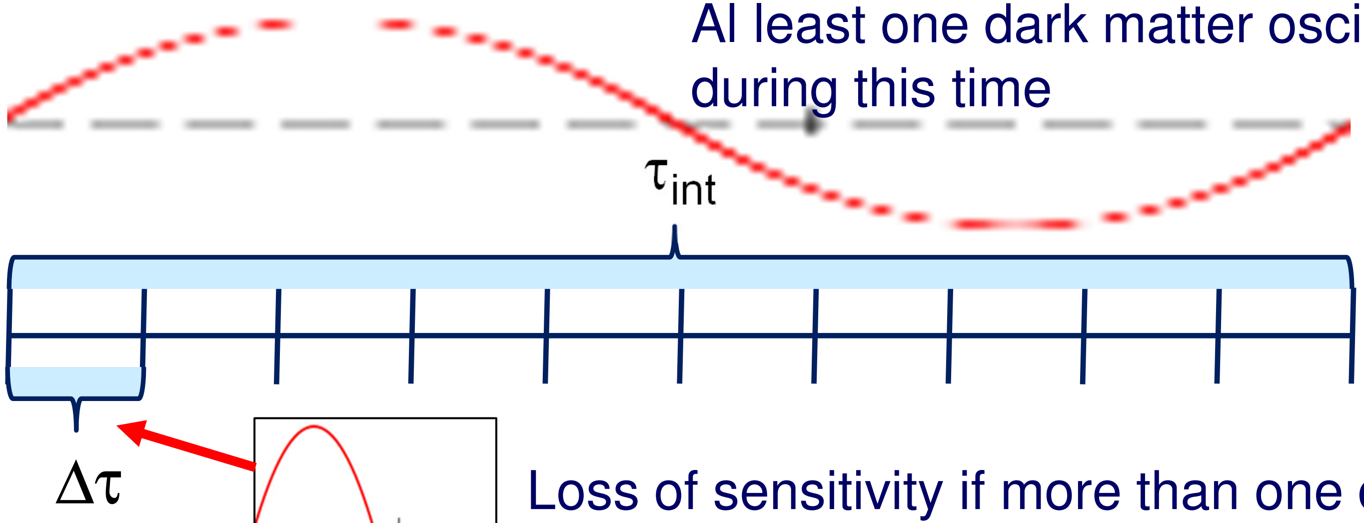
$f = 2\pi/m_\phi$ [Hz]	m_ϕ [eV]
1 MHz	4×10^{-9}
1 kHz	4×10^{-12}
1	4×10^{-15}
1 mHz	4×10^{-18}
10^{-6}	4×10^{-21}

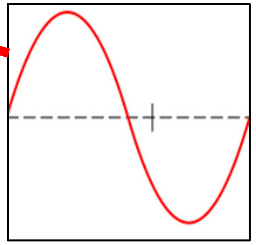
Clock measurement protocols for dark matter detection

Single clock ratio measurement: averaging over time $\Delta\tau$

Make N such measurements, preferably regularly spaced

Al least one dark matter oscillation during this time

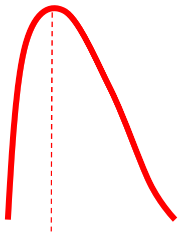




Loss of sensitivity if more than one dark matter oscillation during this time

Detection signal:

A peak with monochromatic frequency $f = 2\pi / m_\phi$ in the discrete Fourier transform of this time series.

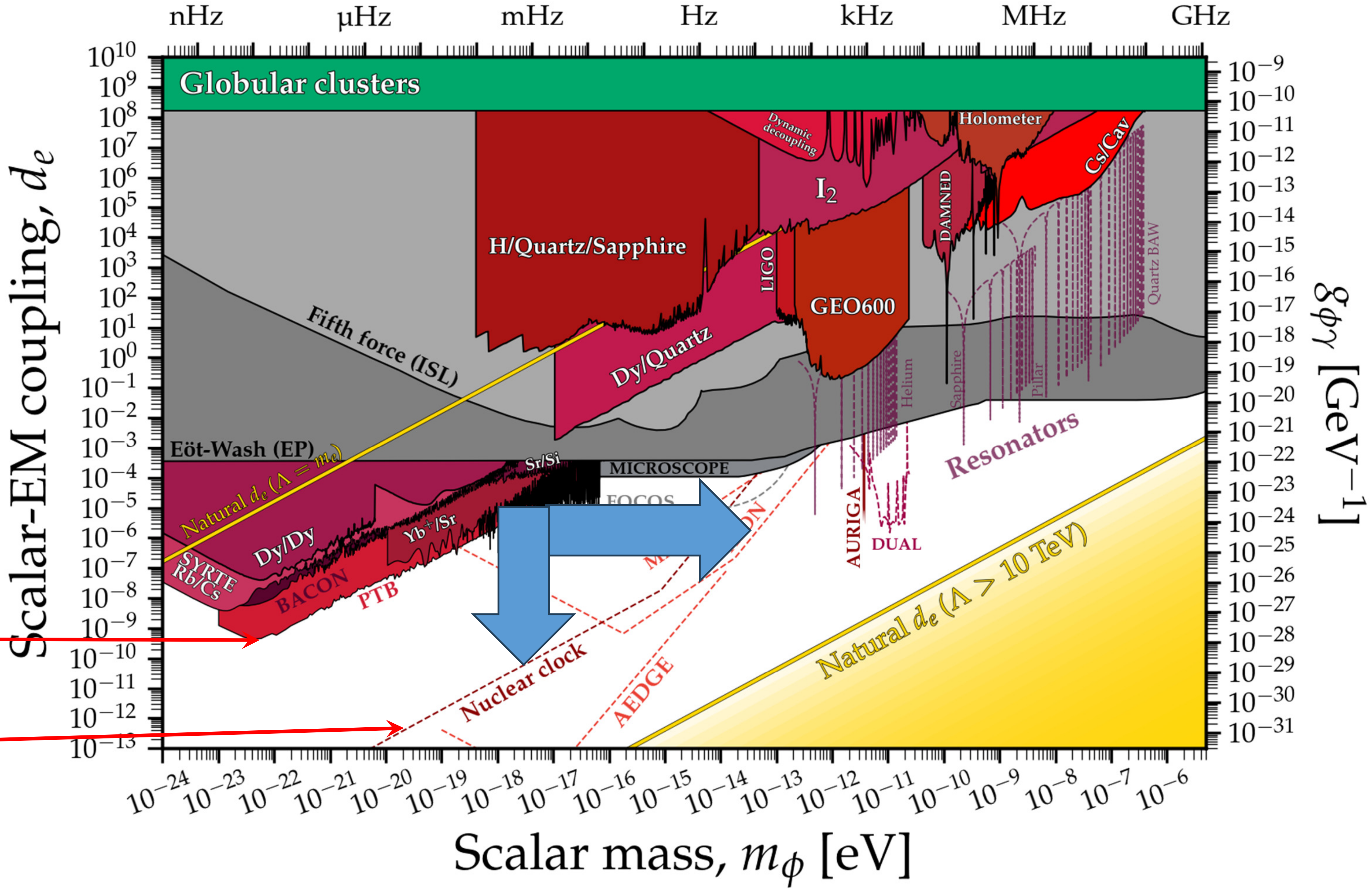


Solutions:

(1) Improve stability so shorter probe times are practical to use

(2) Use dynamic decoupling

$\phi F_{\mu\nu} F^{\mu\nu}$



Present clock limits

Projected clock limits

arXiv:2203.14915

Ultralight DM limits: https://cajohare.github.io/AxionLimits/