THE 2022 TRI-INSTITUTE SUMMER SCHOOL ON ELEMENTARY PARTICLES

Ultralight New Physics: part 1

Dark matter searches with quantum sensors

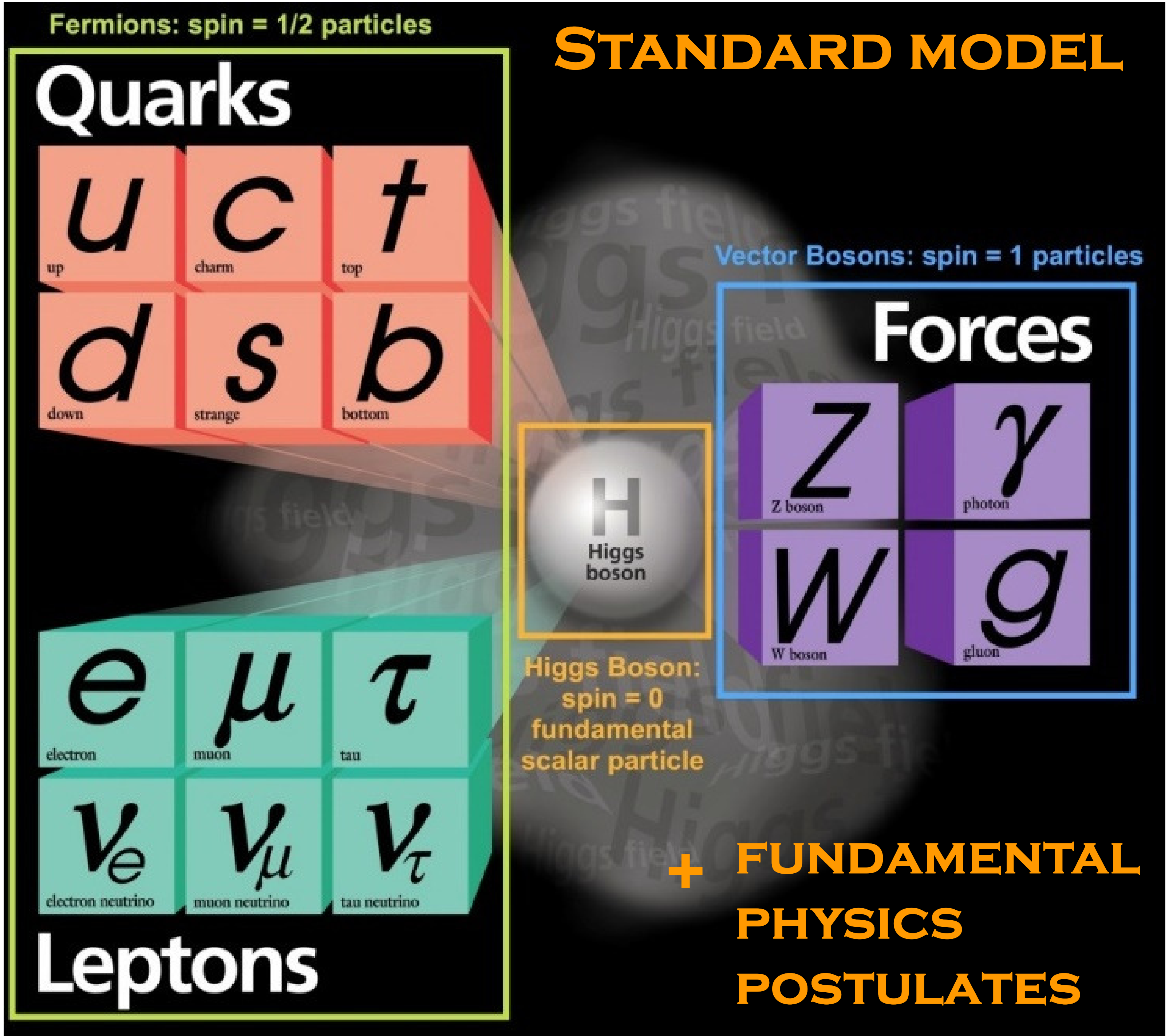
Marianna Safronova

University of Delaware

Q-SEnSE
An NSF Quantum Leap Challenge Institute
https://www.colorado.edu/research/qsense/

thorium nuclear clock
https://thoriumclock.eu/

2022



Fermions: spin = 1/2 particles
STANDARD MODEL
Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Vector Bosons: spin = 1 particles
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
Higgs Boson: spin = 0 fundamental scalar particle
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Leptons
+ FUNDAMENTAL PHYSICS POSTULATES

1922

100 years ago

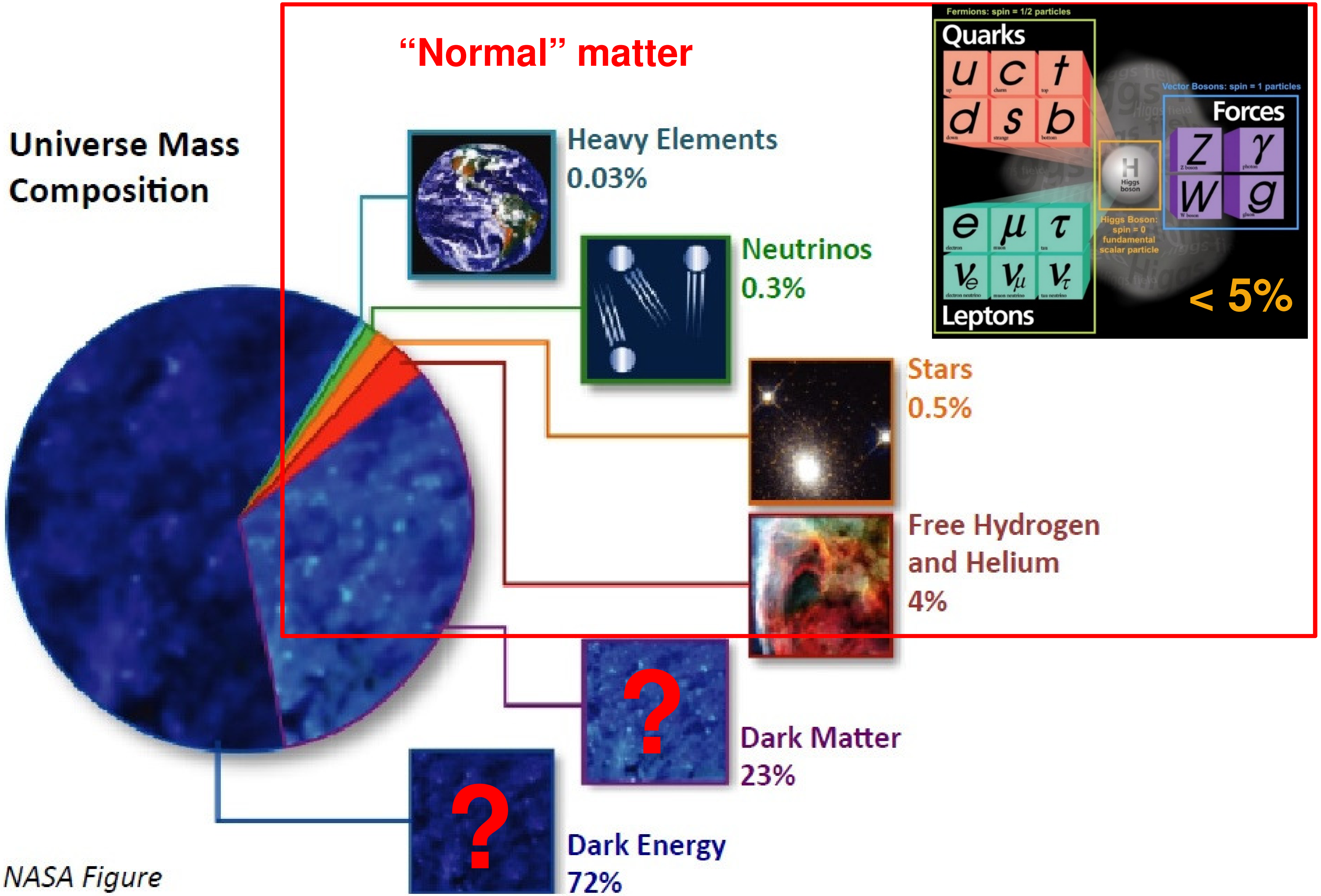
We though we knew everything about the Universe

1897 Electron
1919 Proton

According to the Standard Model

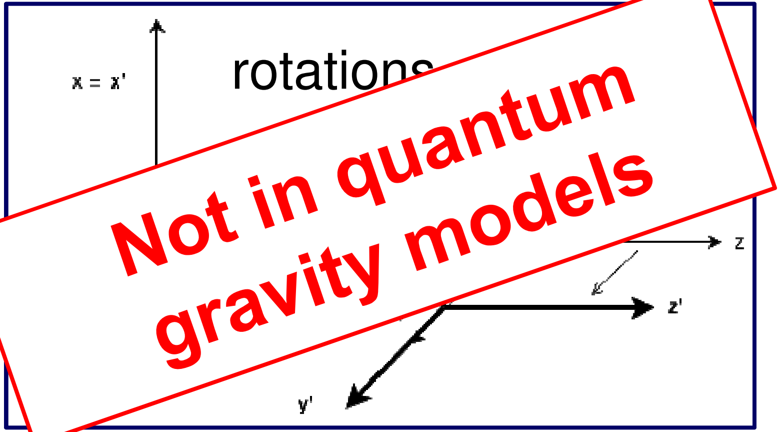
Our Universe can not exist !

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



When we compare experiments, what do we assume?

Lorentz invariance



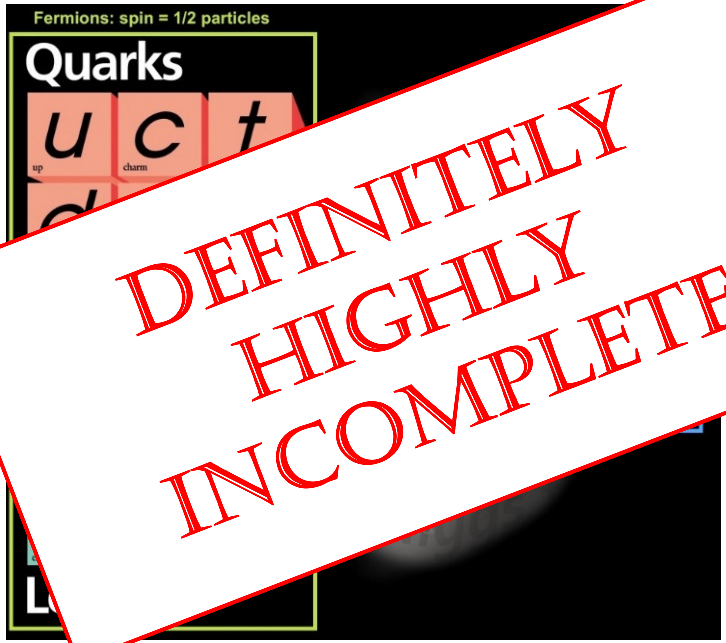
Not in quantum gravity models

Position invariance

Weak equivalence principle

Not in many dark matter scenarios or other BSM models

"Constants" are not constant in most BSM models



DEFINITELY HIGHLY INCOMPLETE

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

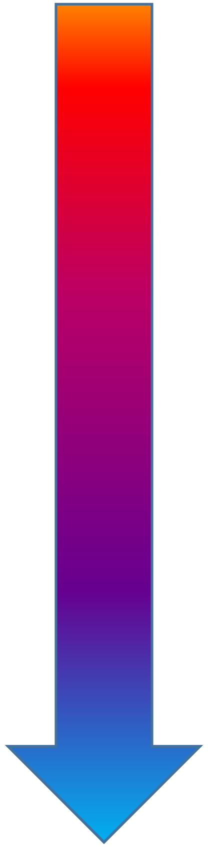
1997 Nobel Prize
Laser cooling and trapping

2001 Nobel Prize
Bose-Einstein Condensation

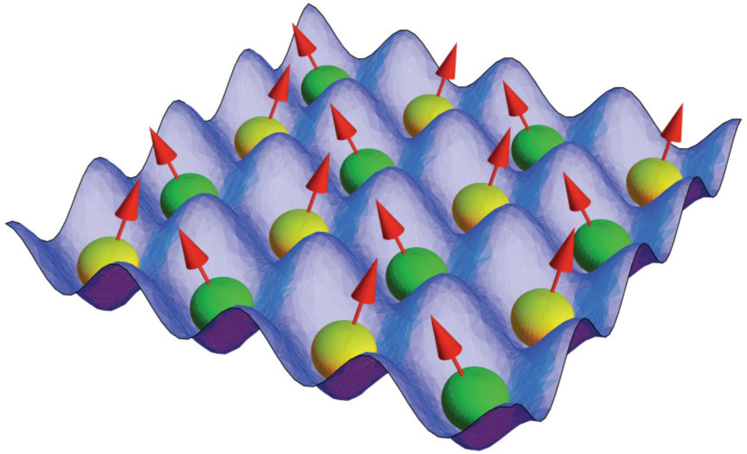
2005 Nobel Prize
Frequency combs

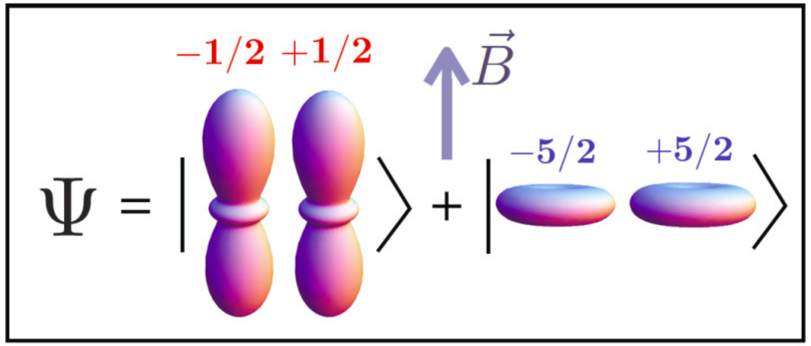
2012 Nobel prize
Quantum control

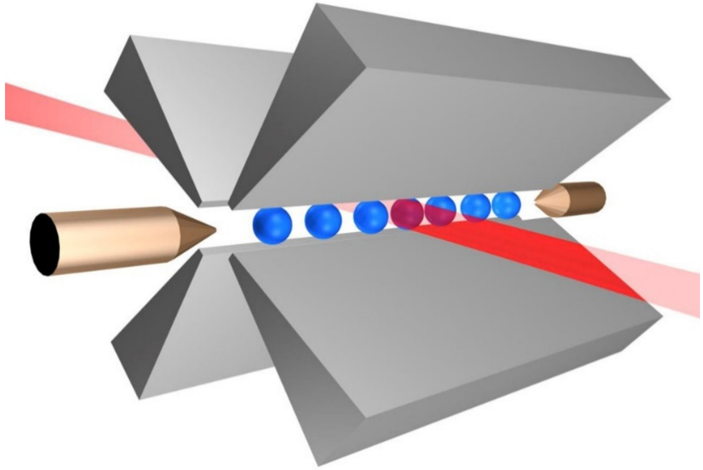
300K

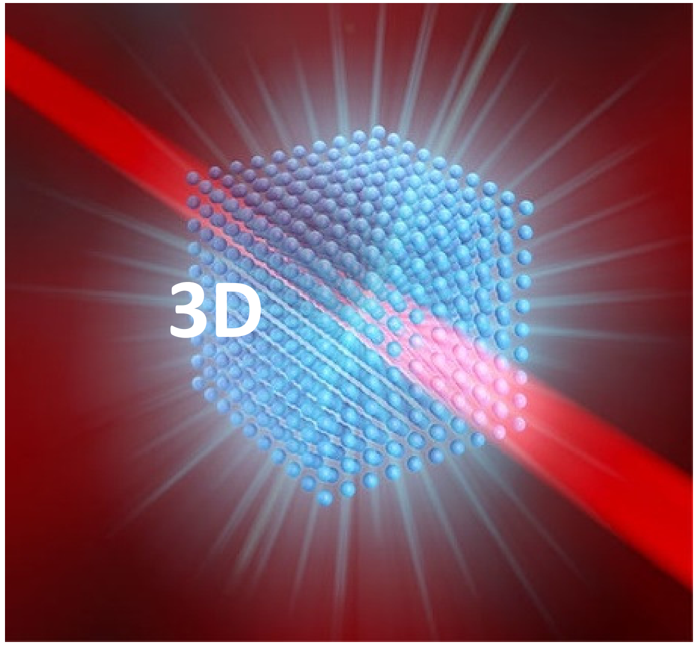


pK









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

Exceptional improvement in precision of

QUANTUM SENSORS

opens new ways to search for new physics and test fundamental physics postulates

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 light dark matter

Search for variation of fundamental constants

Searches for exotic forces

General relativity and gravitation

Search for violations of quantum statistics

(All) high-precision AMO quantum sensors can search for ultralight new physics

Not all new physics AMO quantum sensors are searching for is ultralight

Very wide scope of AMO new physics searches

Precision tests of Quantum Electrodynamics

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Atomic parity violation

Search for variation of fundamental constants

Time-reversal violation:
electric dipole moments and related phenomena

Searches for exotic forces

Tests of the CPT theorem:
matter-antimatter comparisons

General relativity and gravitation

Lorentz symmetry tests

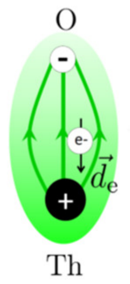
Search for violations of quantum statistics

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

Fundamental symmetries with quantum science techniques

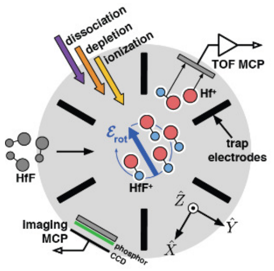
Searches for electron electric-dipole moment (eEDM)

Advanced ACME



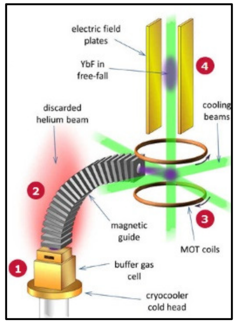
ThO

JILA eEDM



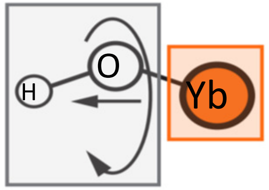
HfF⁺, ThF⁺

Imperial College



YbF

PolyEDM

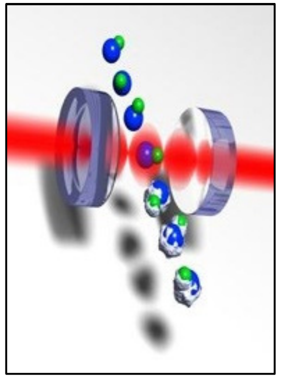


Also NMQM search

YbOH, …

Searches for hadronic EDMs

CeNTREX

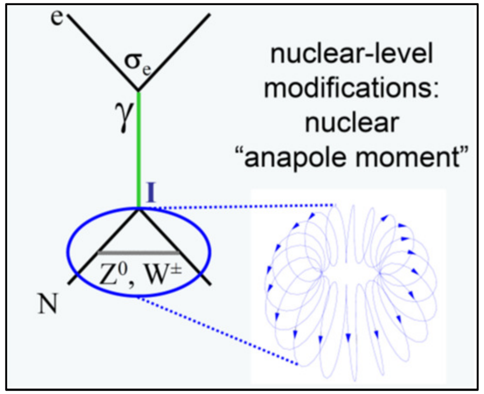


Hg
Xe
Ra
EDMs

TlF (proton EDM)

Enhanced parity violation

ZOMBIES



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

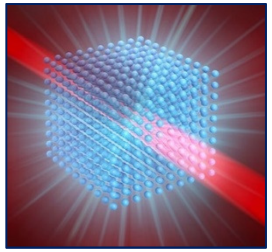
Rapid advances in ultracold molecule cooling and trapping; polyatomic molecules; future: molecules with Ra & "spin squeezed" entangled states

Atomic and Nuclear Clocks & Cavities

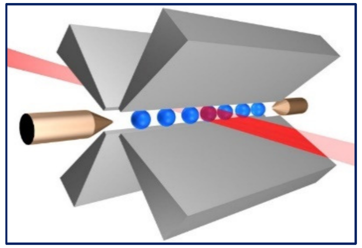
Major clock & cavities R&D efforts below, also molecular clocks, portable clocks and optical links

BSM searches with clocks

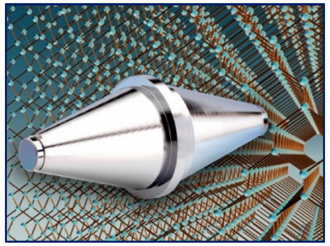
- Searches for variations of fundamental constants
- Ultralight scalar dark matter & relaxion searches
- Tests of general relativity
- Searches for violation of the equivalence principle
- Searches for the Lorentz violation



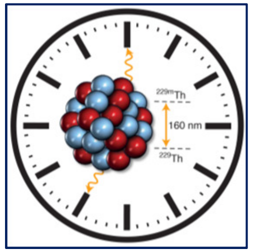
3D lattice clocks



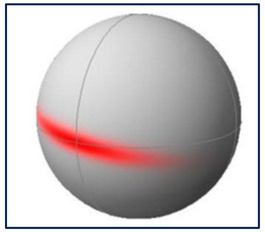
Multi-ion & entangled clocks



Ultrastable optical cavities



Nuclear & highly charge ion clocks



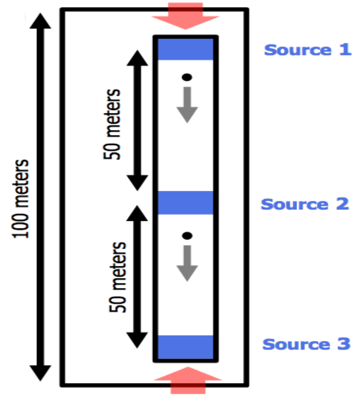
Measurements beyond the quantum limit

Atom interferometry

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

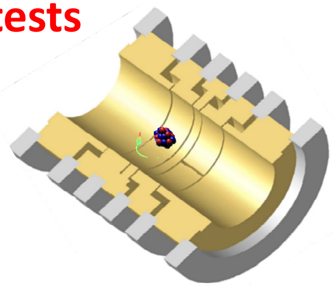
Prototype gravitational wave detectors

MAGIS-100 Fermilab



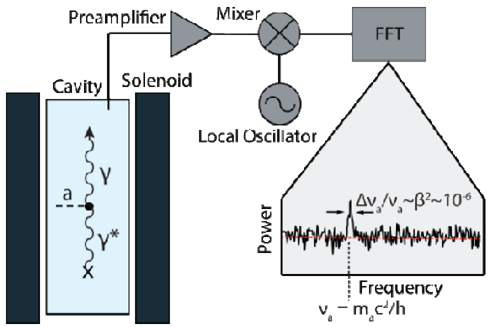
MIGA , AION, ZIGA

QED tests



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

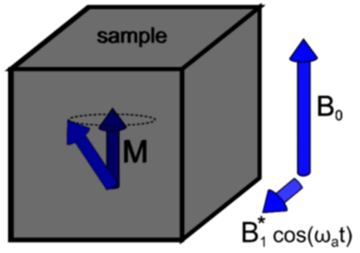
Axion and ALPs searches



Microwave cavities: HAYSTAC

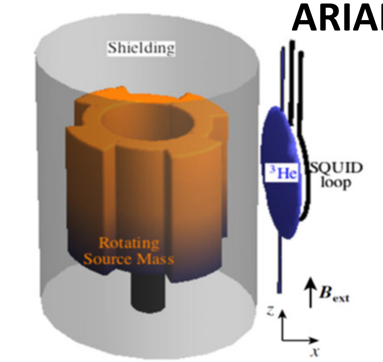
AMO: measurements beyond quantum limits

CASPEr-electric, solids
(coupling to gluons)



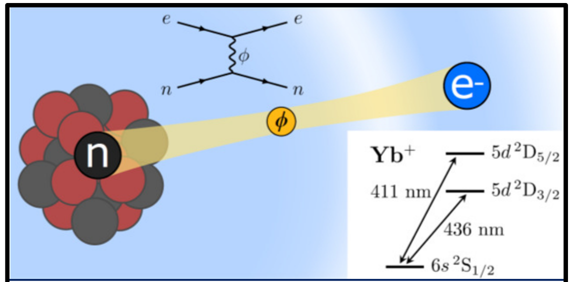
CASPEr-wind, Xe
(coupling to fermions)

ARIADNE

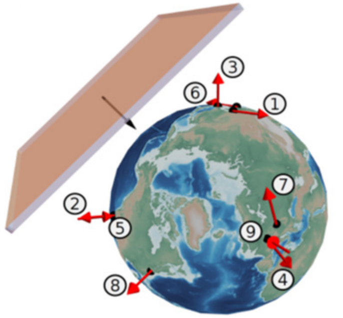


Resonantly detecting axion-mediated forces with NMR

Other dark matter & new force searches

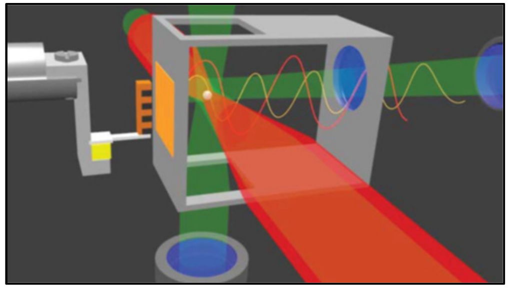


Fifth force searches with precision spectroscopy with atoms and ions



GNOME: network of optical magnetometers for exotic physics

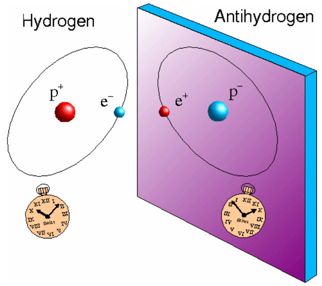
Levitated optomechanics



Also: GW detection and testing the Newtonian inverse square law

CPT tests

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

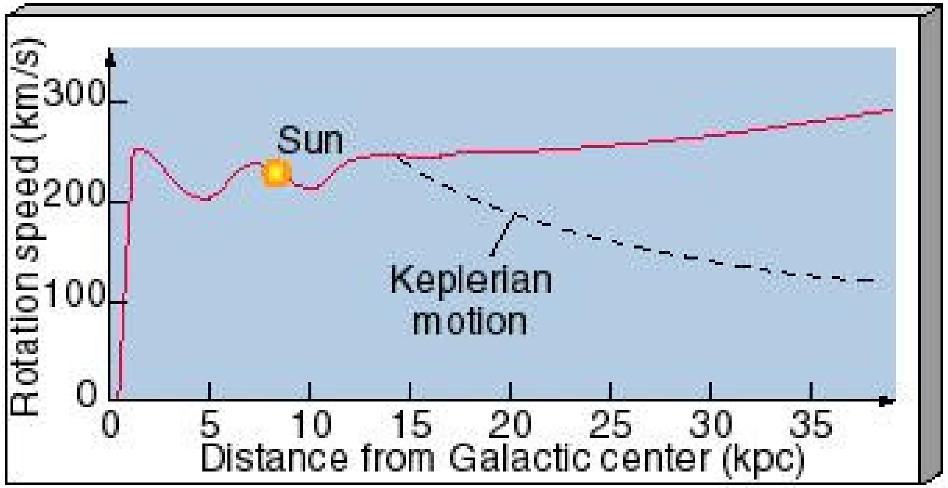


Many other current & future experiments: tests of the gravity-quantum interface, and HUNTER, SHAFT, ORGAN & UPLOAD (axions), solid-state directional detection with NV centers (WIMPs), doped cryocrystals for EDMs, Rydberg atoms, …

WHY SEARCH FOR DARK MATTER?


"Because it's there."
–George Mallory

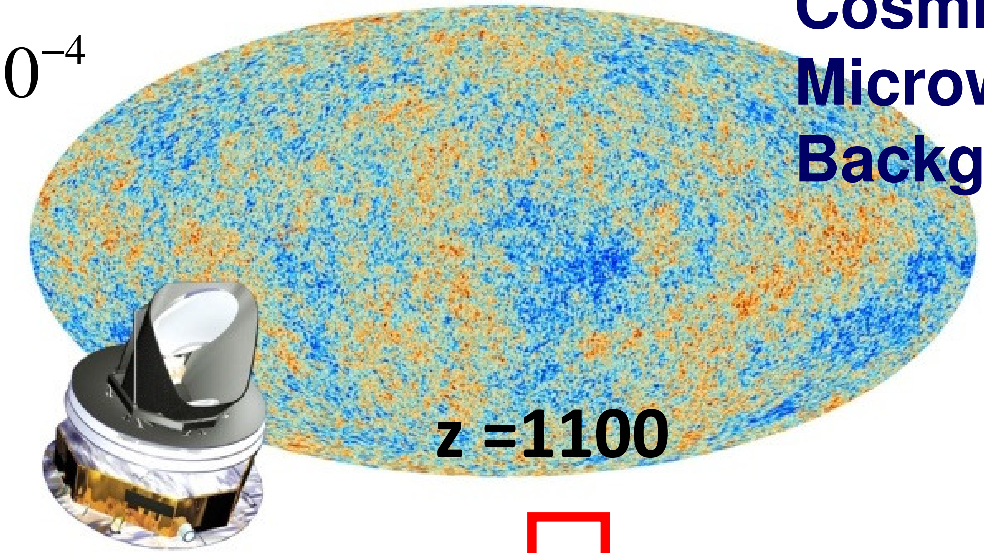
What is the experimental evidence for dark matter?



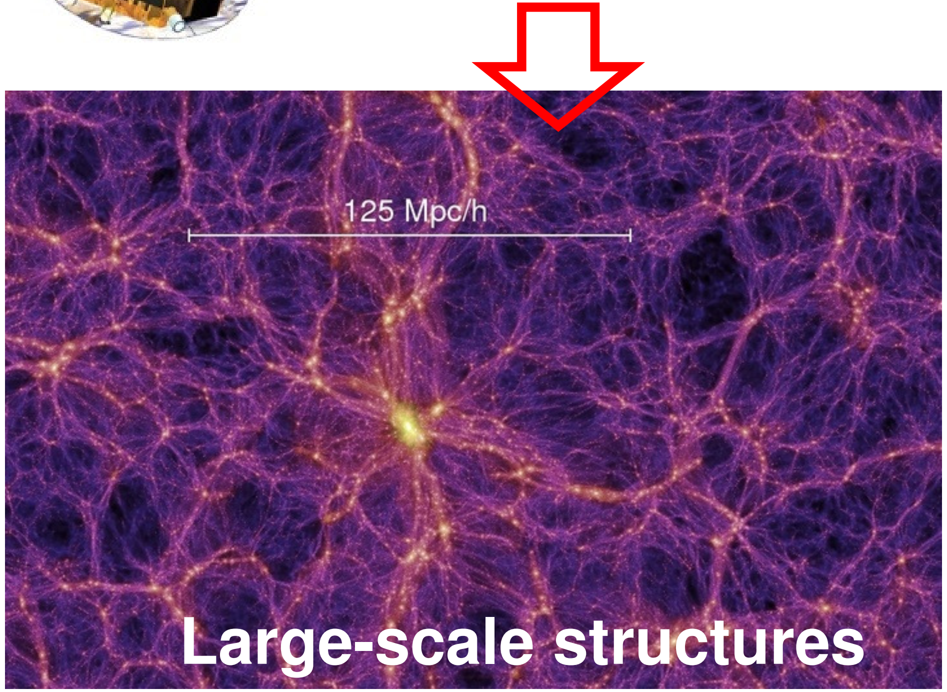
Rotation curves

$$\frac{\delta\rho}{\rho} \approx 10^{-4}$$

Cosmic Microwave Background

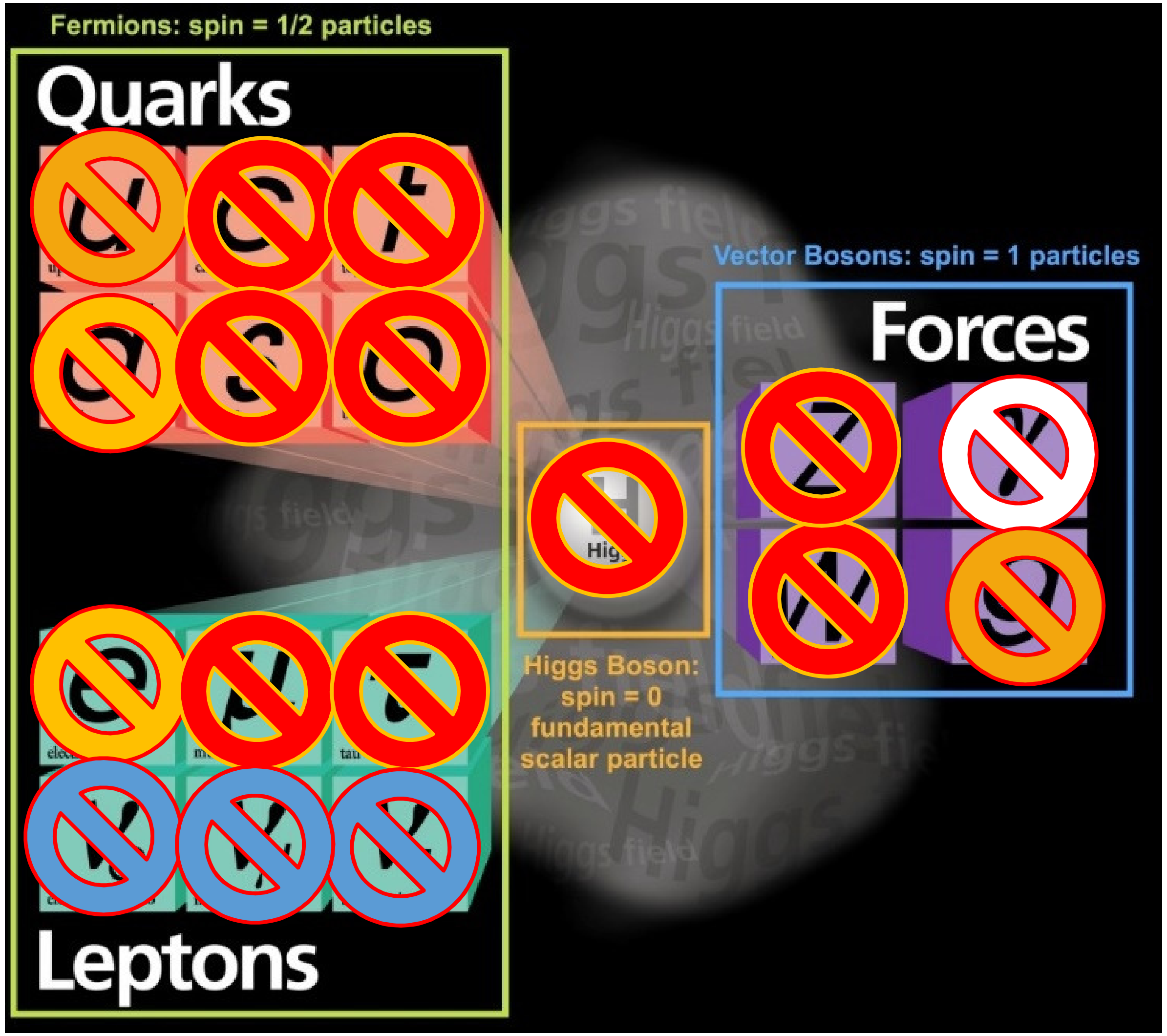


Gravitational lensing



Large-scale structures

Could elementary particles be cold dark matter?



Particle of light

Couple to plasma

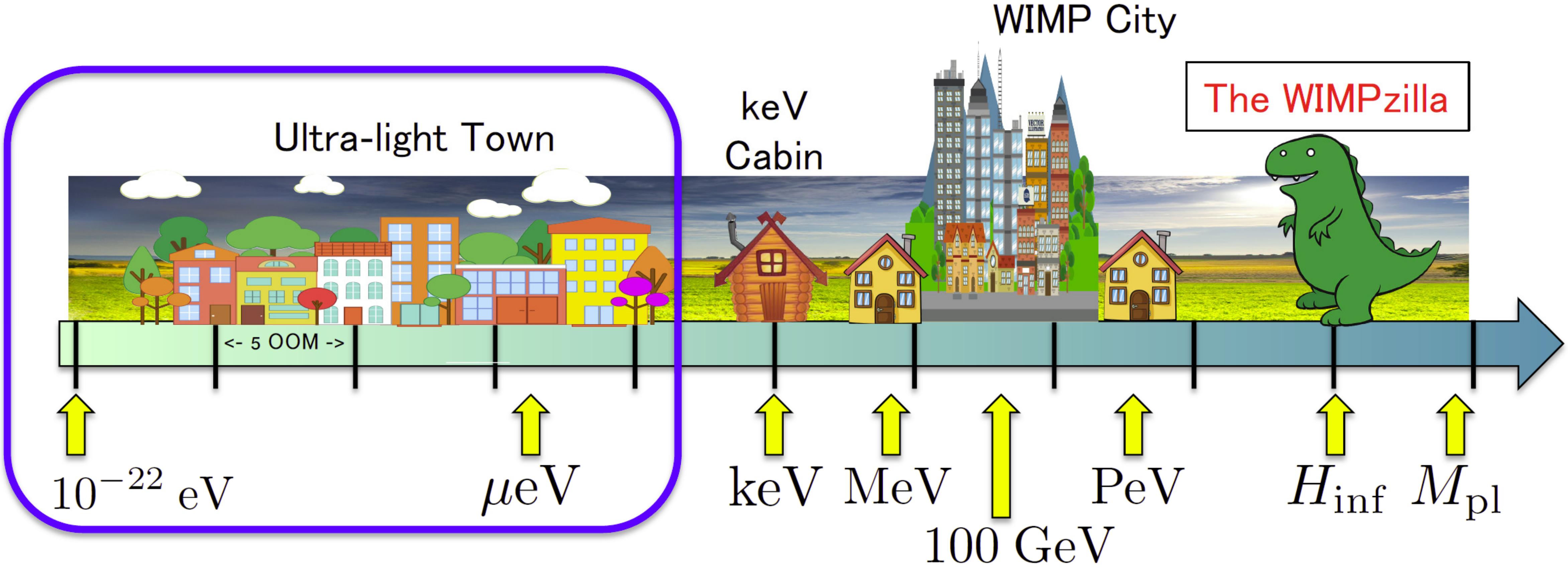
Decay quickly

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



ULTRALIGHT DARK MATTER $(m_\phi \lesssim 10 \;\; \mathrm{eV})$

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

1. UDM phenomenology is described by an oscillating classical field: $\phi(t) \approx \phi_0 \cos(m_\phi t)$

$\phi_0 \sim \sqrt{2\rho_{\mathrm{DM}}}/m_\phi$ is the field oscillation amplitude and ρ_{DM} is the local DM density.

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

3. Typical occupation numbers $N_{\mathrm{dB}} = n_\phi \lambda_{\mathrm{coh}}^3$ larger than 1. $\lambda_{\mathrm{coh}} \sim 10^3 (2\pi / m_\phi c)$

4. We can classify UDM by spin and intrinsic parity:
scalar, pseudoscalar (axion and ALPs), vector (dark photons)

"Fuzzy" dark matter ($m_\phi \lesssim 10^{-18} \;\; \mathrm{eV}$) affect large-scale structures and produce other astrophysical signatures.

Ultralight dark matter signatures

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

Different detection paradigm from particle dark matter.

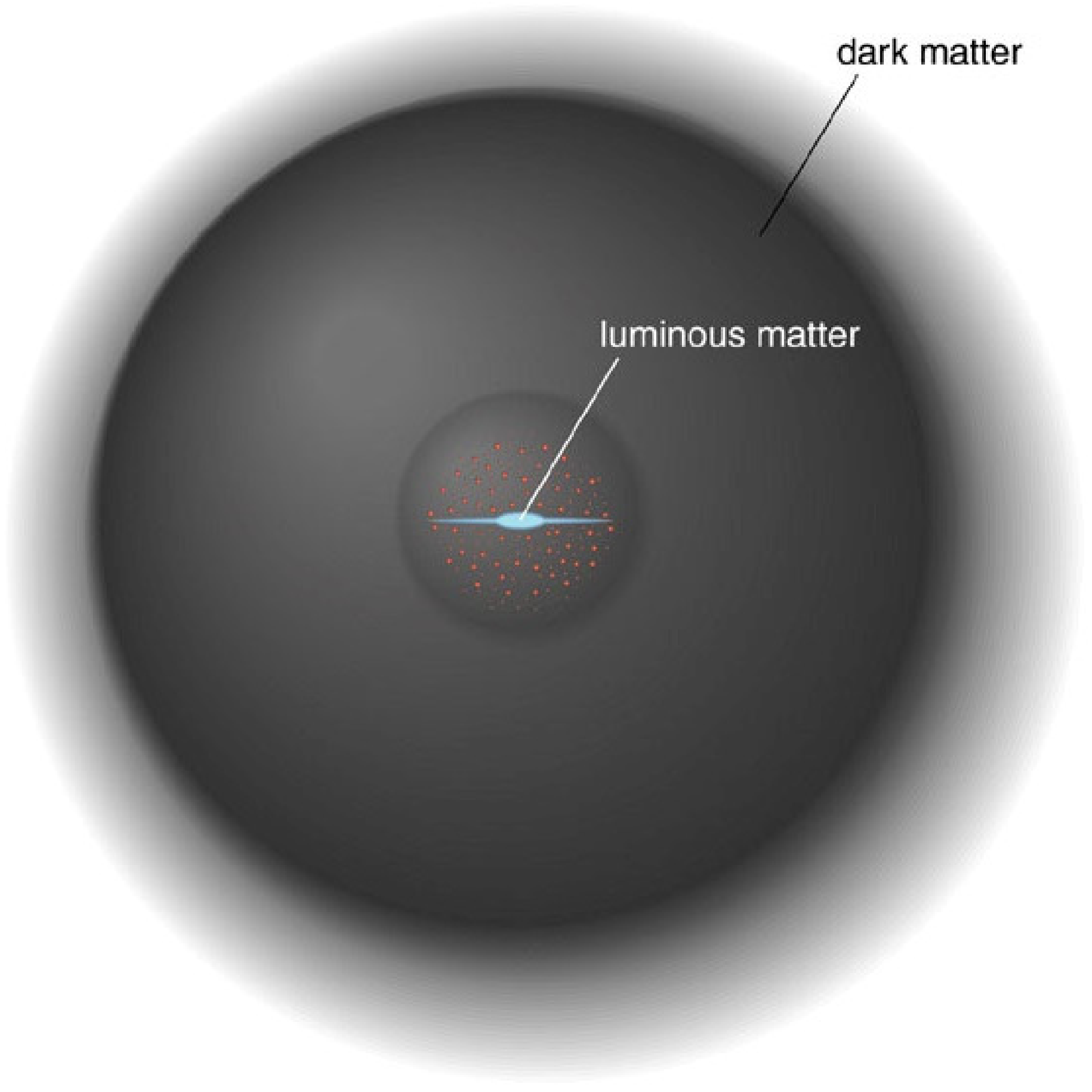
UDM fields may cause:

- ✓ precession of nuclear or electron spins
- ✓ drive currents in electromagnetic systems, produce photons
- ✓ induce equivalence principle-violating accelerations of matter
- ✓ modulate the values of the fundamental “constants” of nature
  - induce changes in atomic transition frequencies and local gravitational field
  - affect the length of macroscopic bodies

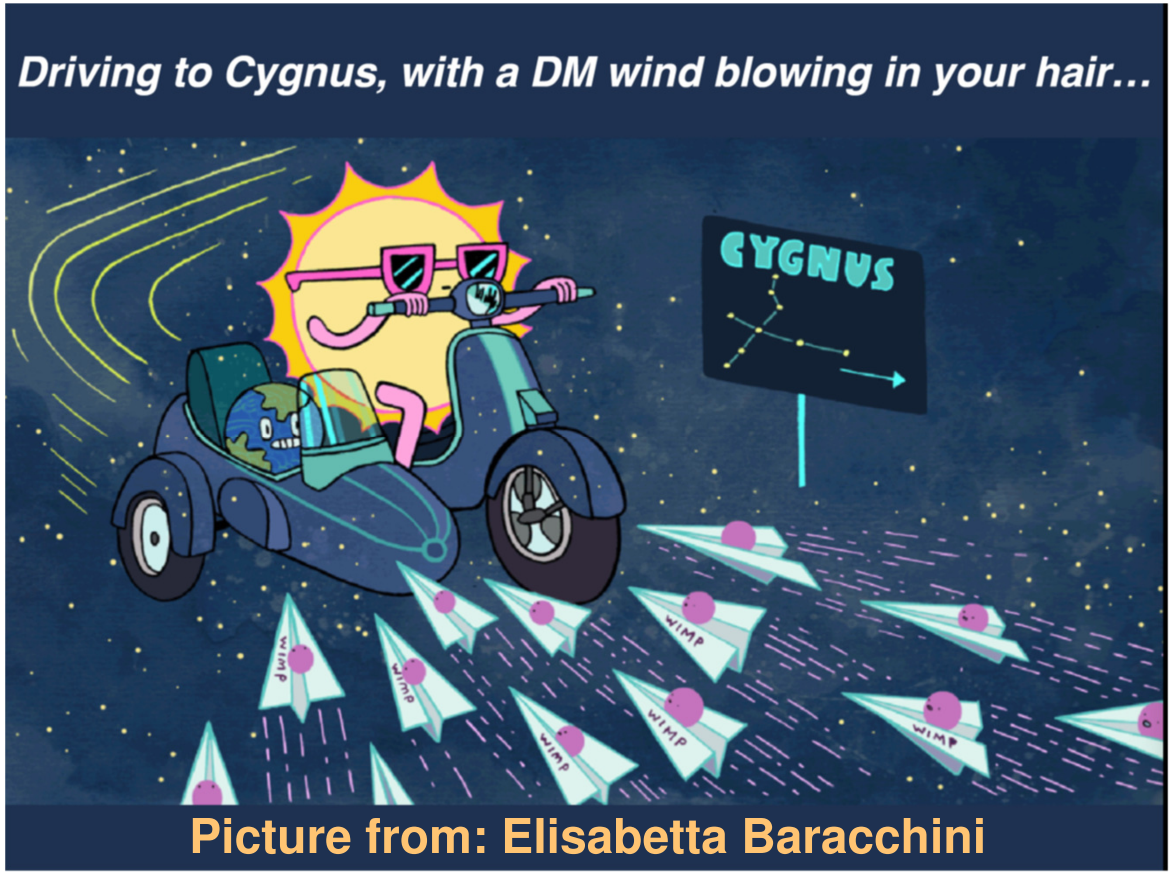
Magnetometers
Microwave cavities
Trapped ions & other qubits
Atom interferometers
Laser interferometers
Optical cavities
Atomic, molecular, and nuclear clocks
Other precision spectroscopy

Various quantum sensors are very sensitive to UDM!

Where is dark matter?



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



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

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]

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

Scalar ultralight dark matter

Coupling of scalar UDM to the standard model:

Linear coupling $\frac{\phi}{M^*}\mathcal{O}_{SM}$ $\kappa = (\sqrt{2}M_{Pl})^{-1}$

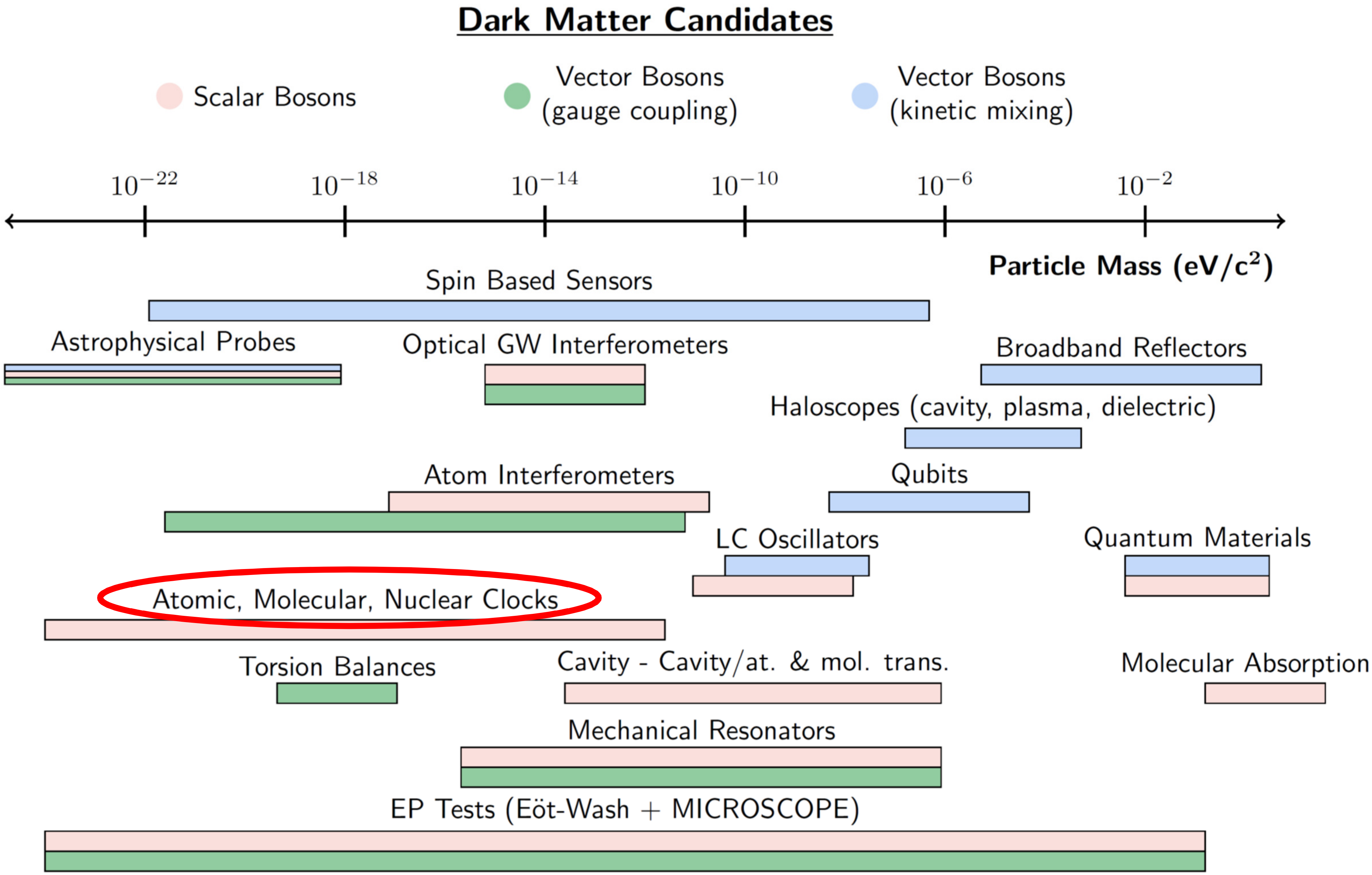
photons electrons gluons quarks

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

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

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

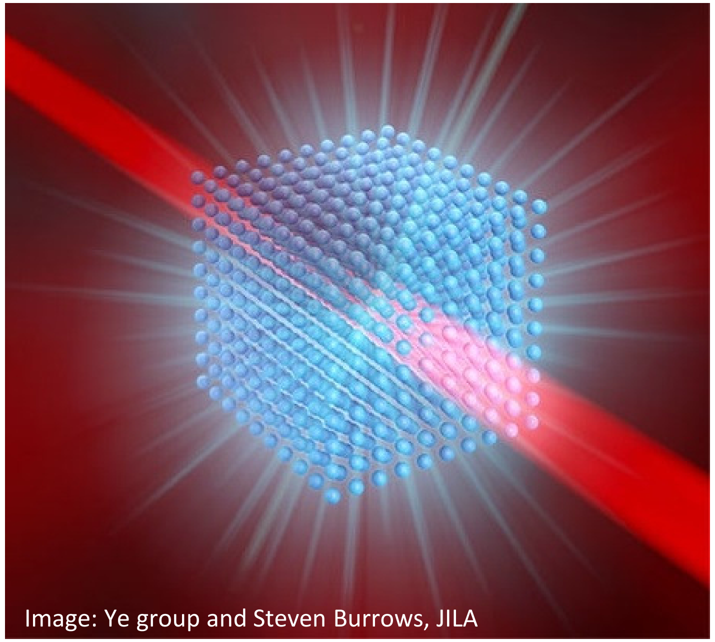
$$\alpha \to \frac{\alpha}{1 - g_\gamma \phi} \approx \alpha(1 + g_\gamma \phi)\,, \quad m_\psi \to m_\psi + g_\psi \phi$$

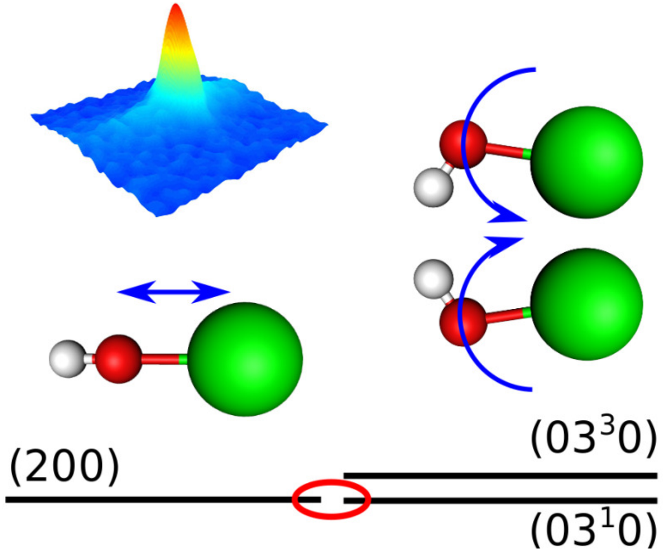


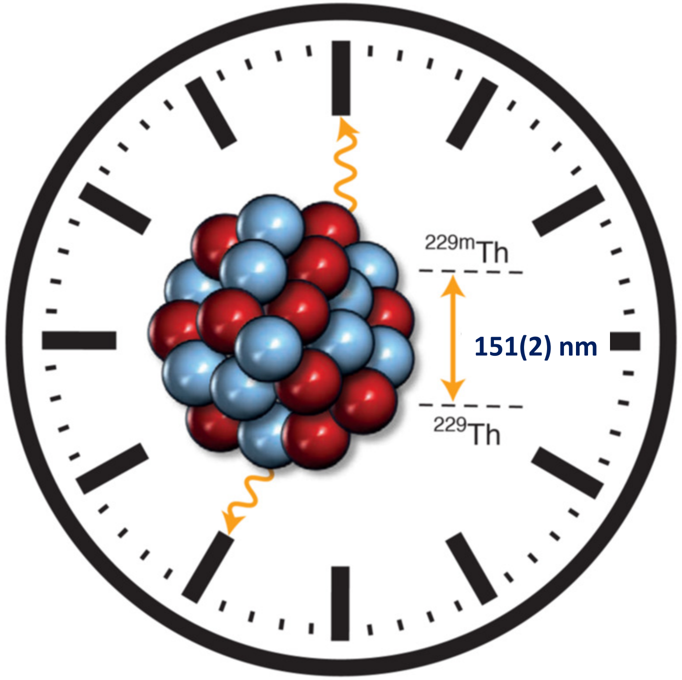
arXiv:2203.14915

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

Dark matter searches with atomic, molecular, and nuclear clocks

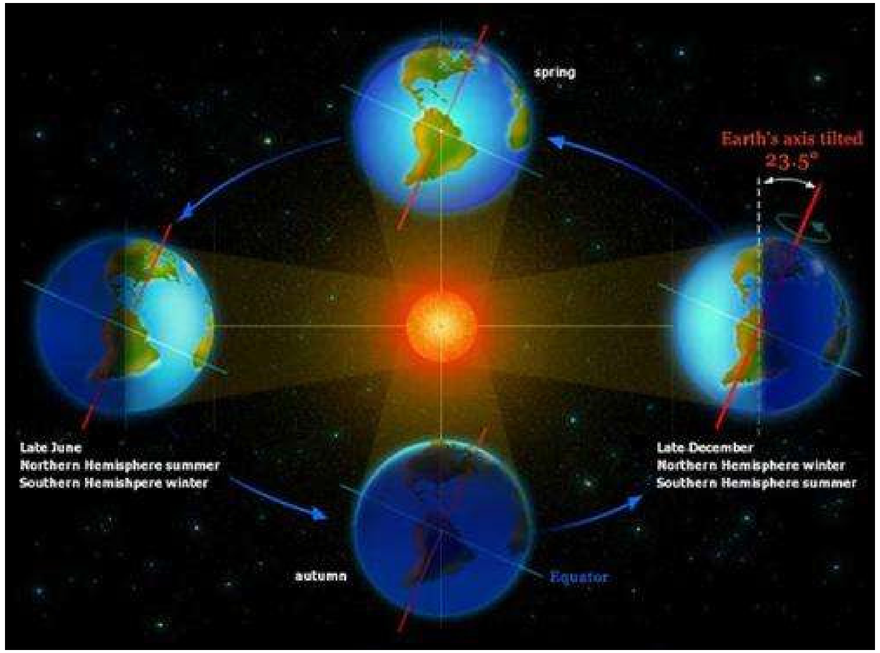






Ingredients for a clock

1. Need a system with **periodic behavior**:
   it cycles occur at constant frequency



2. Count the cycles to produce time interval
3. Agree on the origin of time to generate a time scale

NOAA/Thomas G. Andrews

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

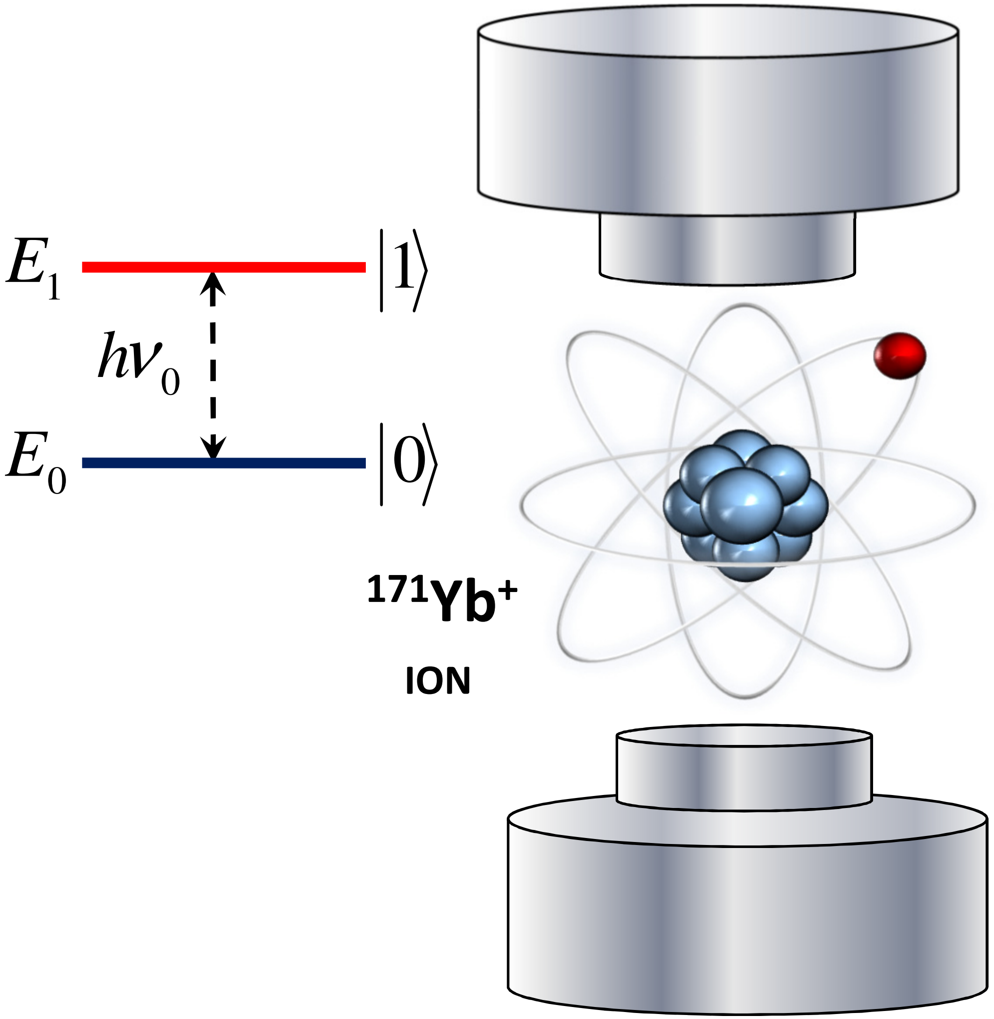
Ingredients for an atomic clock

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)

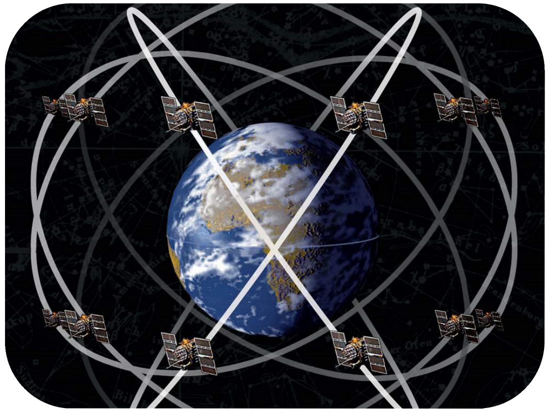
3. Build a laser in resonance with this atomic frequency

4. Count cycles of this signal



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

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



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GPS satellites: microwave atomic clocks