GGI LECTURES ON THE THEORY OF
FUNDAMENTAL INTERACTIONS 2023

Tabletop experiments: Lecture 2

New physics searches with quantum technologies
Ultralight Dark matter

Marianna Safronova

Q-SEnSE
An NSF Quantum Leap Challenge Institute

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

thorium
nuclear clock

https://thoriumclock.eu/

UNIVERSITY OF DELAWARE®

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

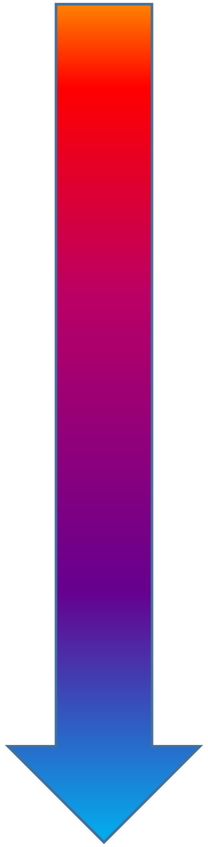
1997 Nobel Prize
Laser cooling and trapping

2001 Nobel Prize
Bose-Einstein Condensation

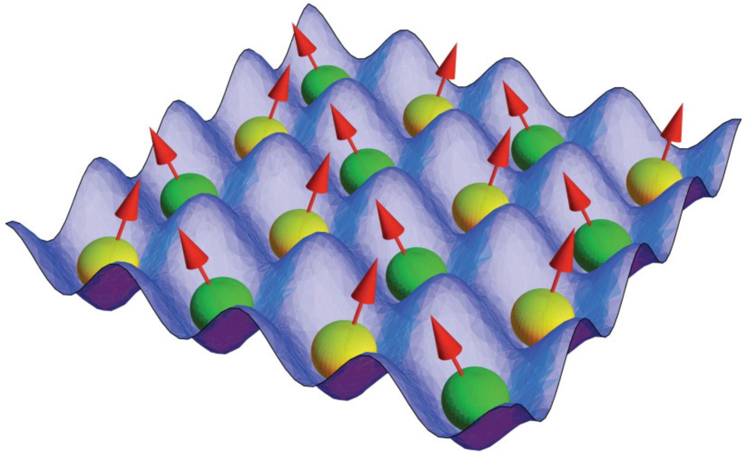
2005 Nobel Prize
Frequency combs

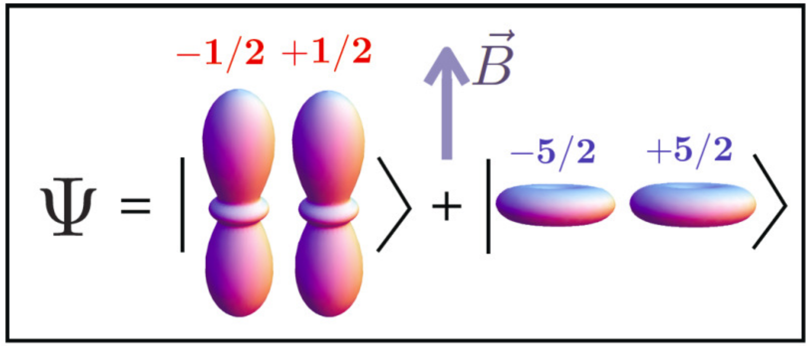
2012 Nobel prize
Quantum control

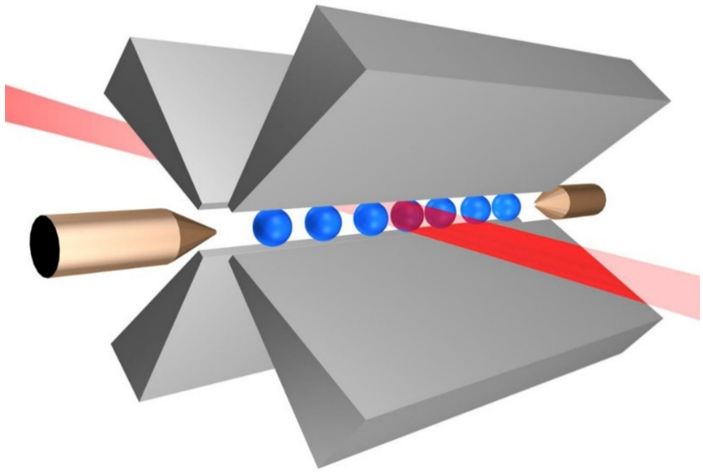
300K

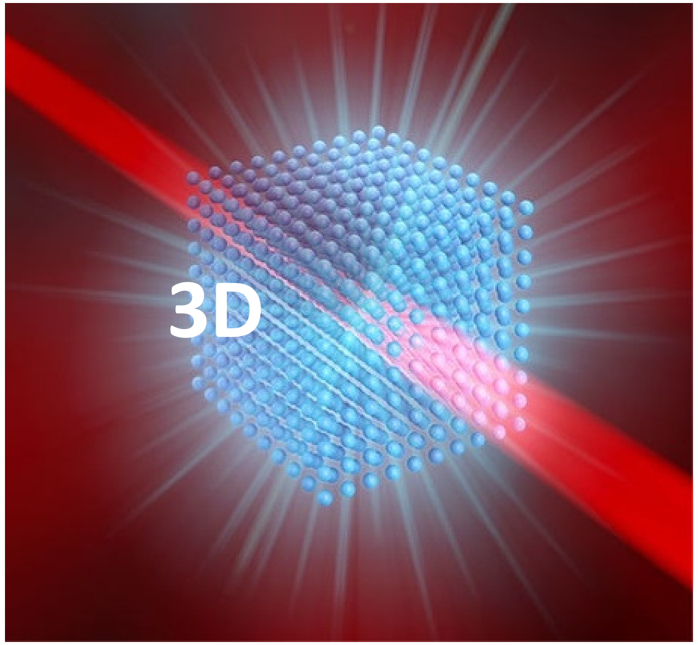


pK









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

Exceptional improvement in precision of

quantum technologies/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

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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

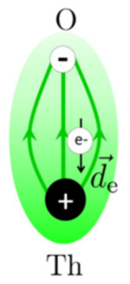
Search for violations of quantum statistics

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

Fundamental symmetries with quantum science techniques

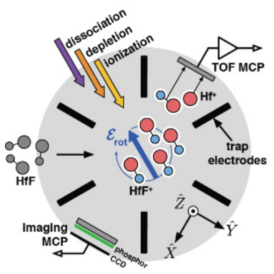
Searches for electron electric-dipole moment (eEDM)

Advanced ACME



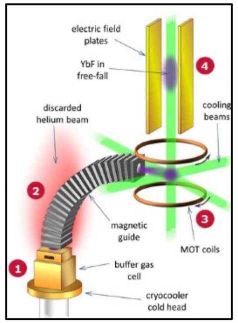
ThO

JILA eEDM



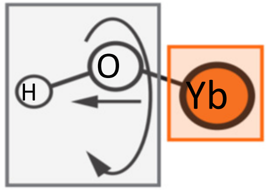
HfF^+, ThF^+

Imperial College



YbF

PolyEDM

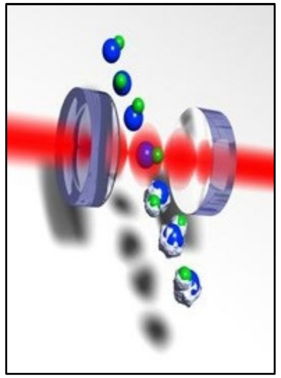


Also NMQM search

YbOH, …

Searches for hadronic EDMs

CeNTREX

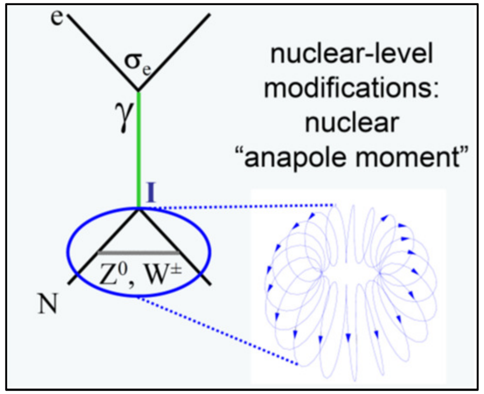


Hg
Xe
Ra
EDMs

TlF (proton EDM)

Enhanced parity violation

ZOMBIES



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

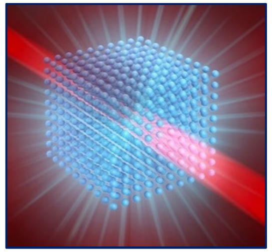
Rapid advances in ultracold molecule cooling and trapping; polyatomic molecules; future: molecules with Ra & "spin squeezed" entangled states

Atomic and Nuclear Clocks & Cavities

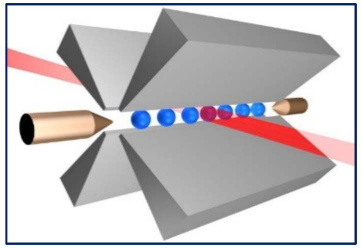
Major clock & cavities R&D efforts below, also molecular clocks, portable clocks and optical links

BSM searches with clocks

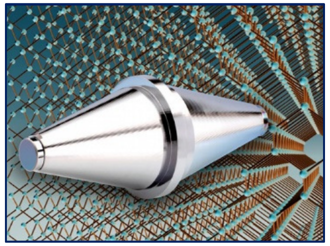
- Searches for variations of fundamental constants
- Ultralight scalar dark matter & relaxion searches
- Tests of general relativity
- Searches for violation of the equivalence principle
- Searches for the Lorentz violation



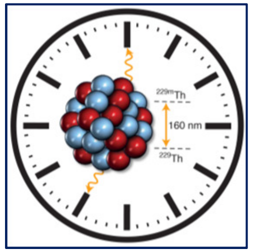
3D lattice clocks



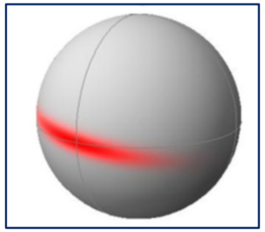
Multi-ion & entangled clocks



Ultrastable optical cavities



Nuclear & highly charge ion clocks



Measurements beyond the quantum limit

Atom interferometry

BSM searches:

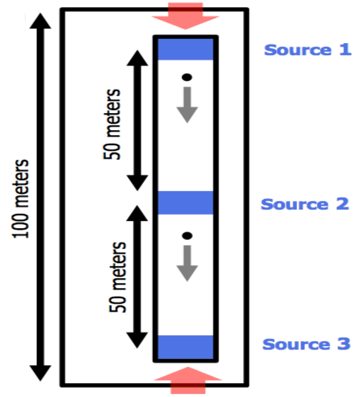
Variation of fundamental constants

Ultralight scalar DM & relaxion searches

Violation of the equivalence principle

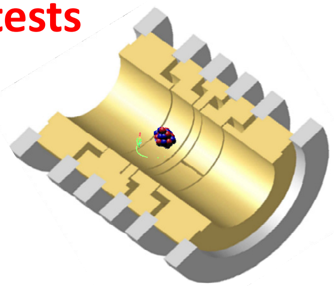
Prototype gravitational wave detectors

MAGIS-100 Fermilab



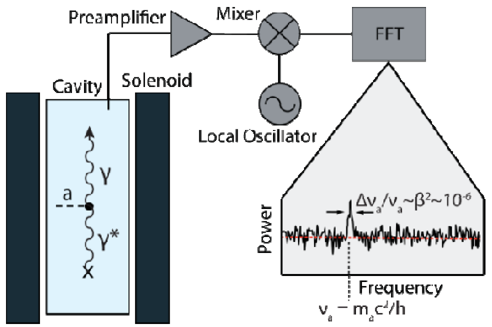
MIGA , AION, ZIGA

QED tests



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

Axion and ALPs searches

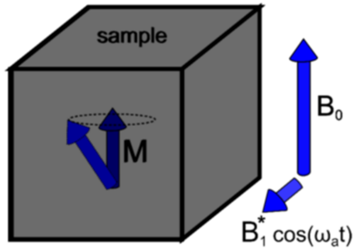


Microwave cavities: HAYSTAC

AMO: measurements beyond quantum limits

CASPEr-electric, solids

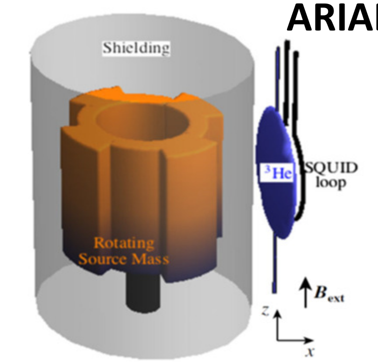
(coupling to gluons)



CASPEr-wind, Xe

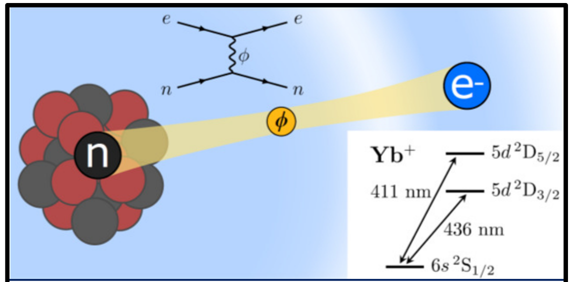
(coupling to fermions)

ARIADNE

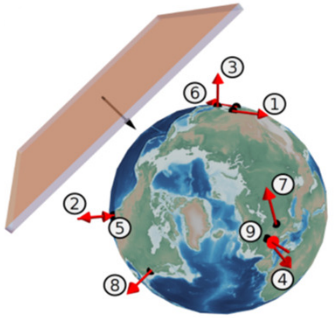


Resonantly detecting axion-mediated forces with NMR

Other dark matter & new force searches

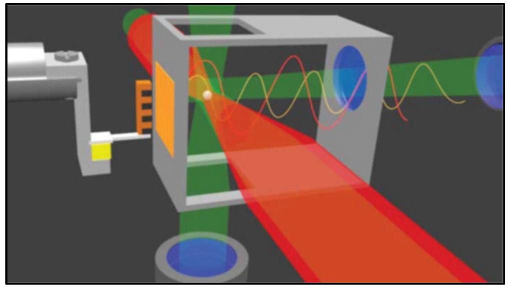


Fifth force searches with precision spectroscopy with atoms and ions



GNOME: network of optical magnetometers for exotic physics

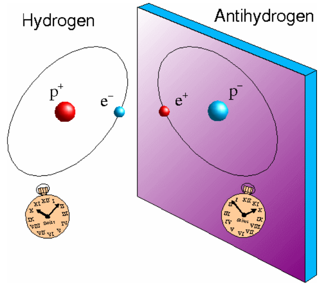
Levitated optomechanics



Also: GW detection and testing the Newtonian inverse square law

CPT tests

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

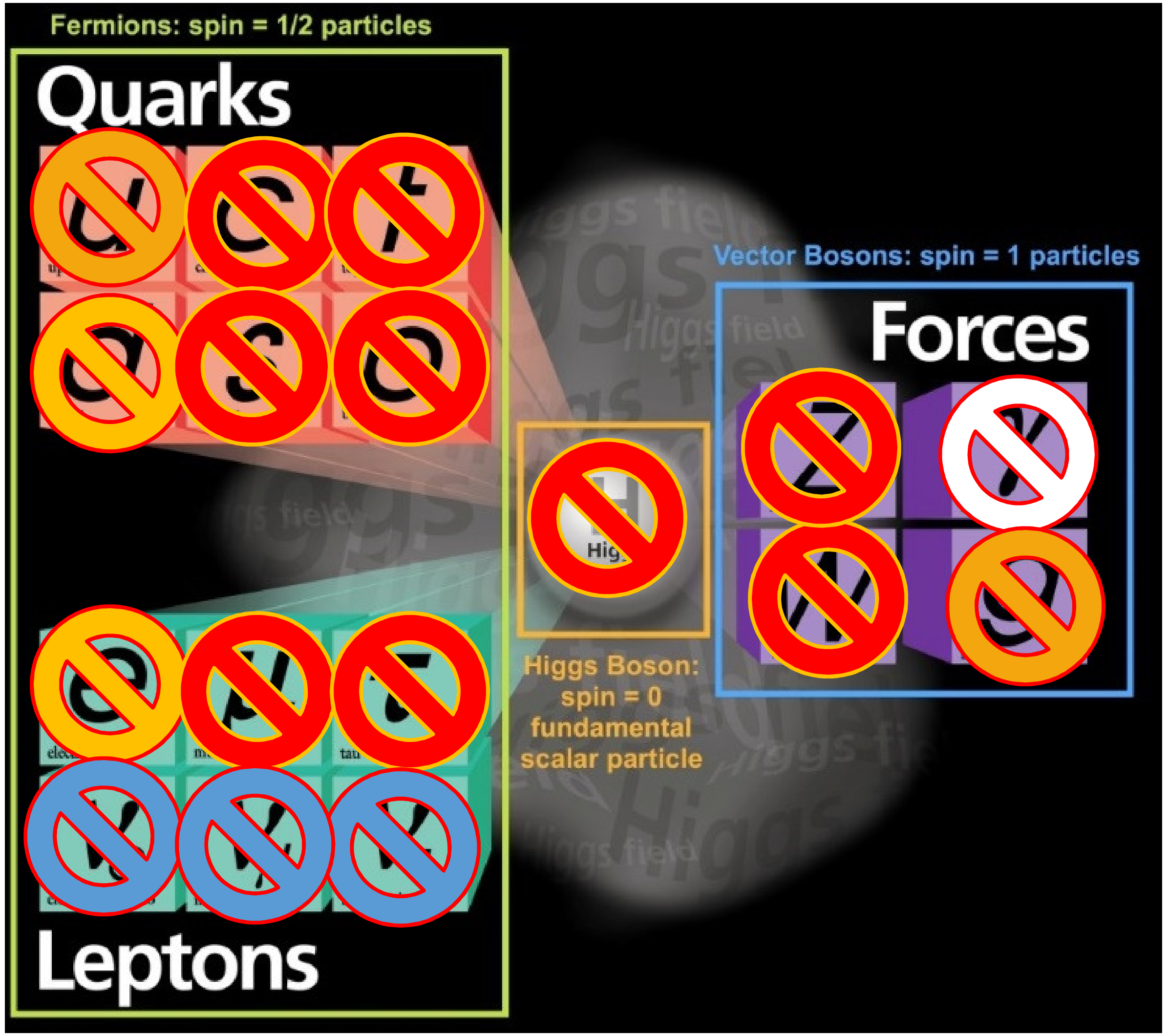


Many other current & future experiments: tests of the gravity-quantum interface, and HUNTER, SHAFT, ORGAN & UPLOAD (axions), solid-state directional detection with NV centers (WIMPs), doped cryocrystals for EDMs, Rydberg atoms, …

WHY SEARCH FOR DARK MATTER?


"Because it's there."
–George Mallory

Could elementary particles be cold dark matter?



Particle of light

Couple to plasma

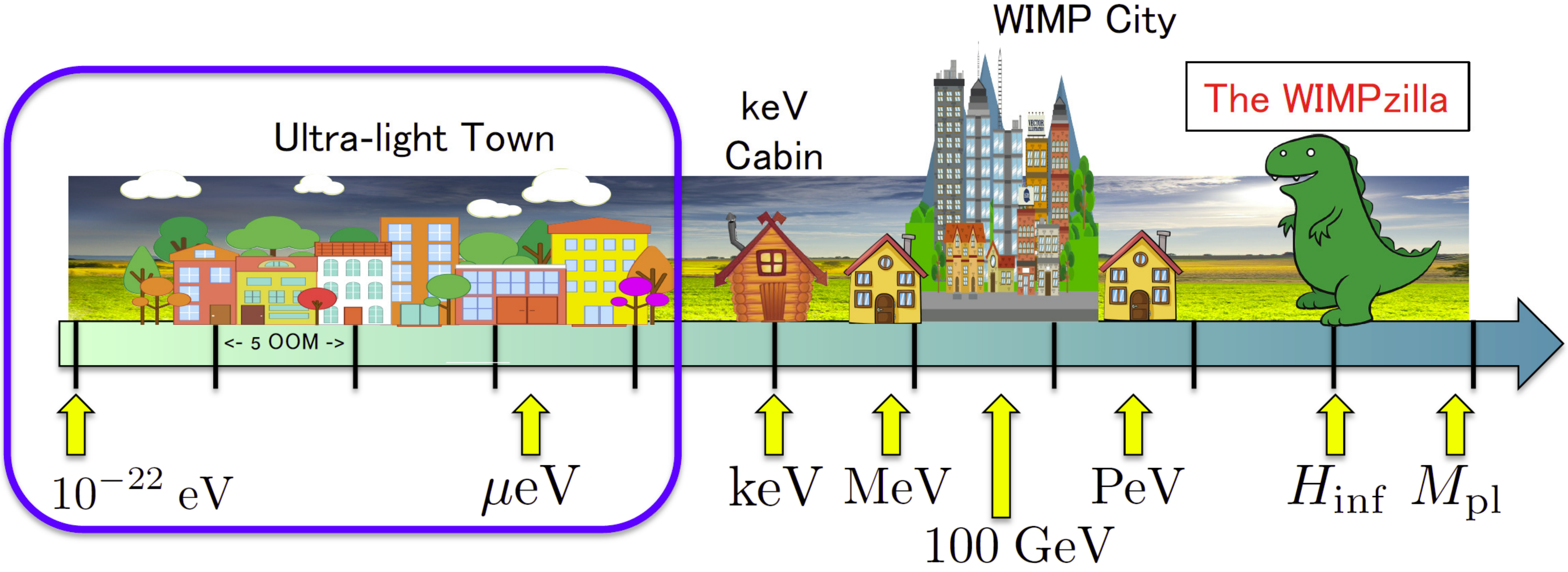
Decay quickly

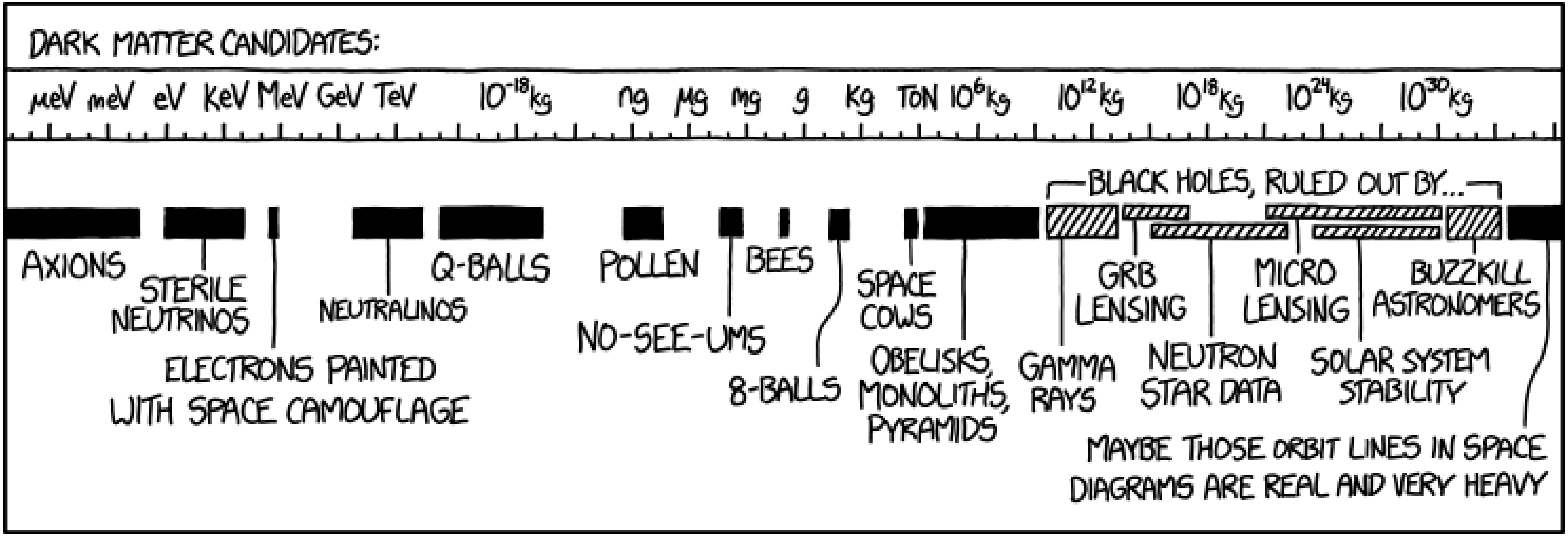
Hot dark matter

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

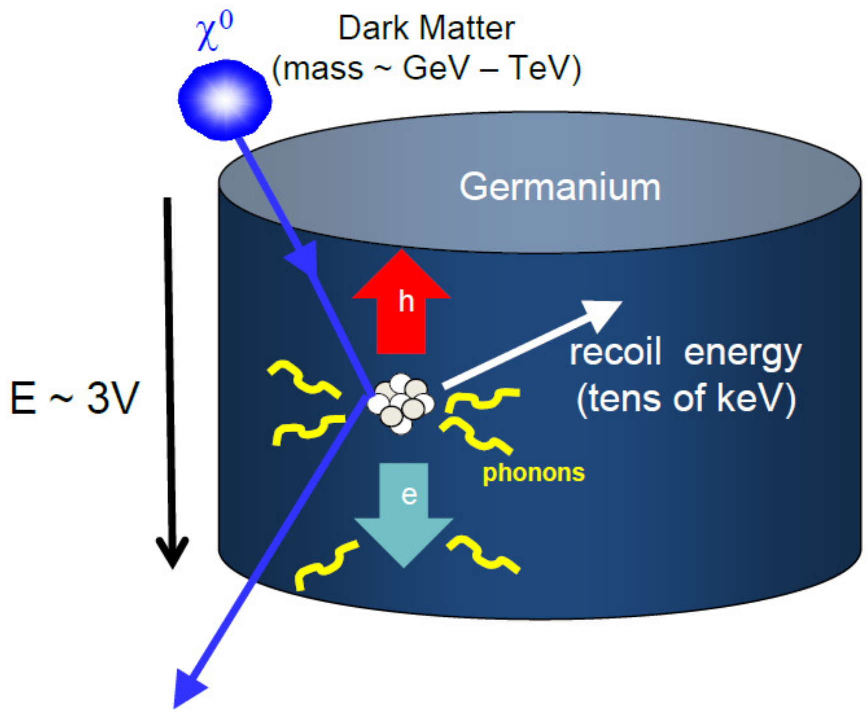




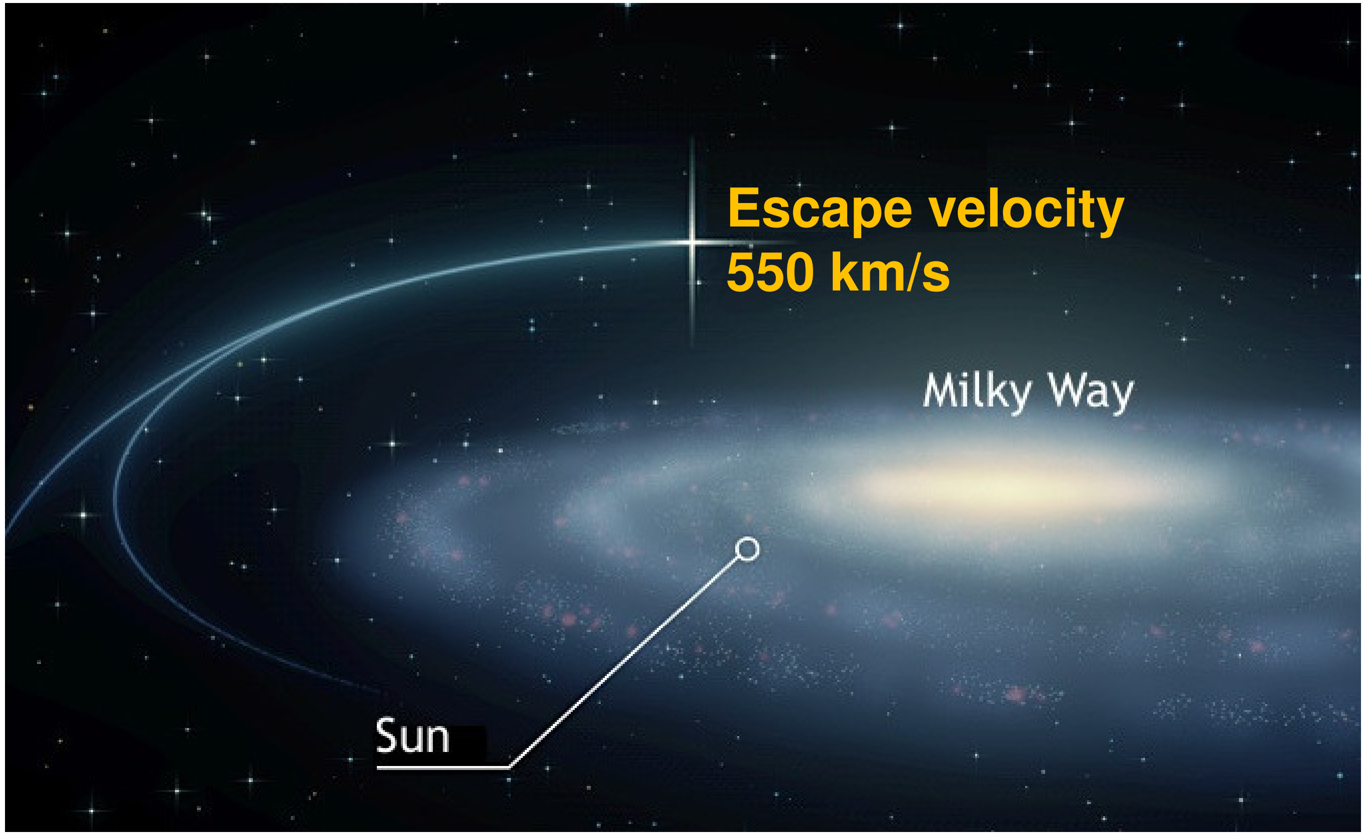
https://imgs.xkcd.com/comics/dark_matter_candidates.png

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

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



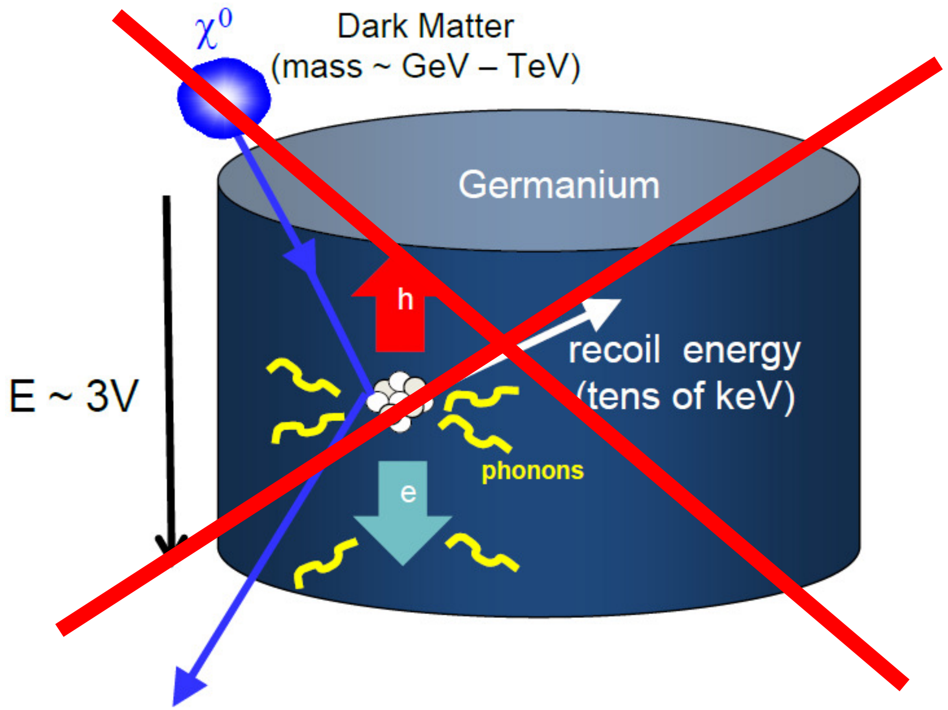
Fermi velocity for DM with mass <10 eV is higher than our Galaxy escape velocity.

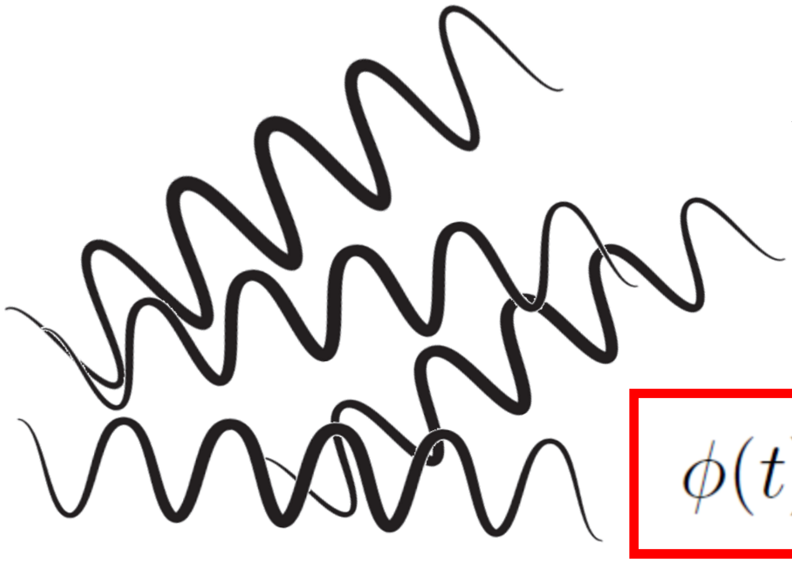


Ultralight dark matter has to be bosonic.

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

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





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

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

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

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

Dark matter field amplitude

Dark matter density

Dark matter mass

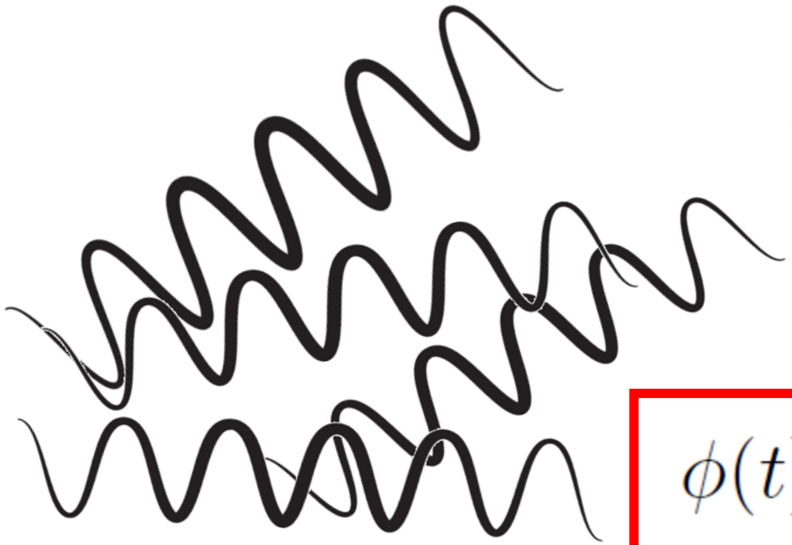
Image credits: CDMS: https://www.slac.stanford.edu/exp/cdms/

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

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.



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

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

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

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

Dark matter field amplitude

Dark matter density

Dark matter mass

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

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

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

$\phi_0 \sim \sqrt{2\rho_{\rm DM}}/m_\phi$ is the field oscillation amplitude and $\rho_{\rm DM}$ 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 $N_{\rm dB} = n_\phi \lambda_{\rm coh}^3$ larger than 1. $\lambda_{coh} \sim 10^3 (2\pi / m_\phi c)$

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

"Fuzzy" dark matter ($m_\phi \lesssim 10^{-18}$ 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!