QuantHEP 2024 - Quantum Technologies and Computation for High Energy Physics

September 6, 2024

Quantum sensors for high-energy physics

Marianna Safronova

Department of Physics and Astronomy
University of Delaware, Delaware

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
ONR
Science & Technology

erc
European Research Council

Advances in atom-based quantum technologies

1997 Nobel Prize
Laser cooling and trapping

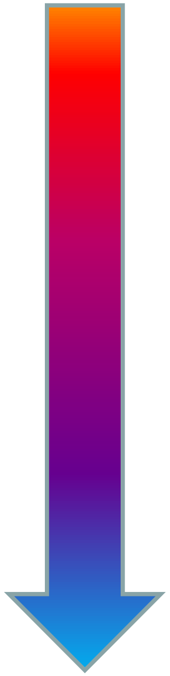
2001 Nobel Prize
Bose-Einstein Condensation

2005 Nobel Prize
Frequency combs

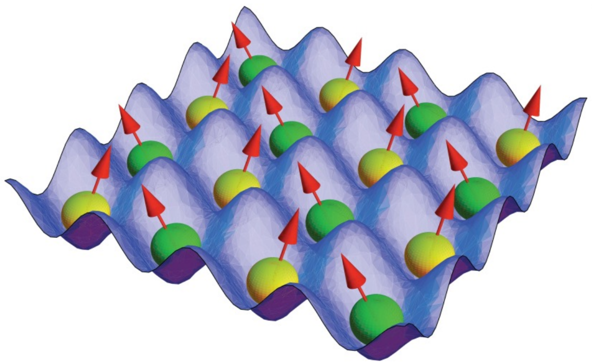
2012 Nobel prize
Quantum control

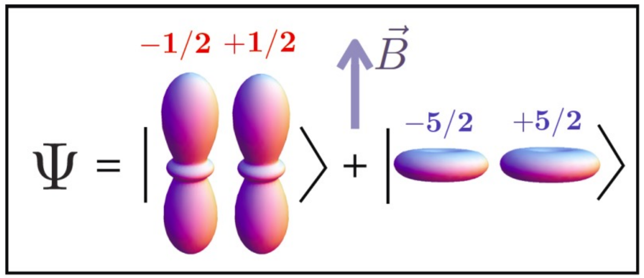
2022 Nobel prize
Bell inequalities, quantum information science

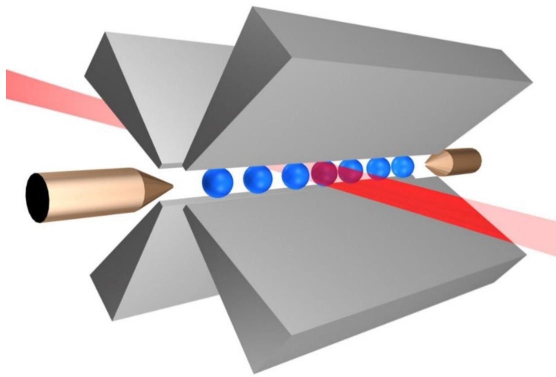
300K

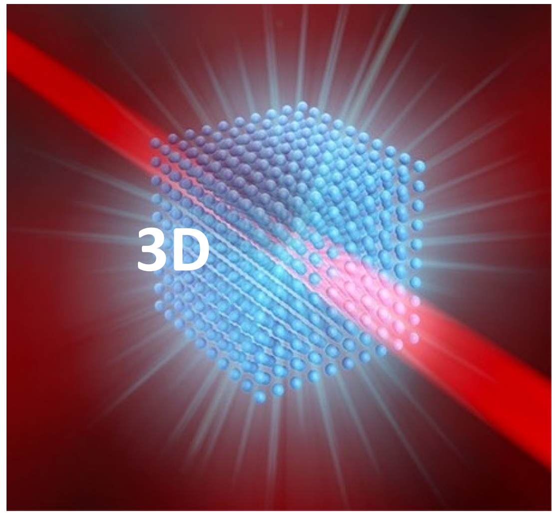


pK









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

Exceptional improvement in precision of quantum technologies

Enable orders of magnitude improvement of measurement precision

opens new ways to directly search for new physics

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)

What is a quantum sensor?

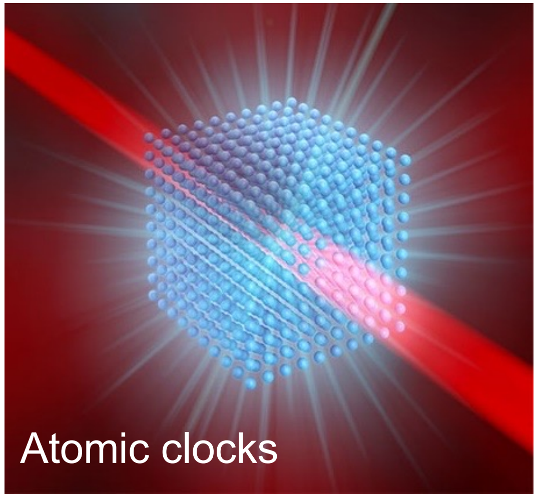
Focus Issue in Quantum Science and Technology (20 papers)
Quantum Sensors for New-Physics Discoveries
Editors: Marianna Safronova and Dmitry Budker

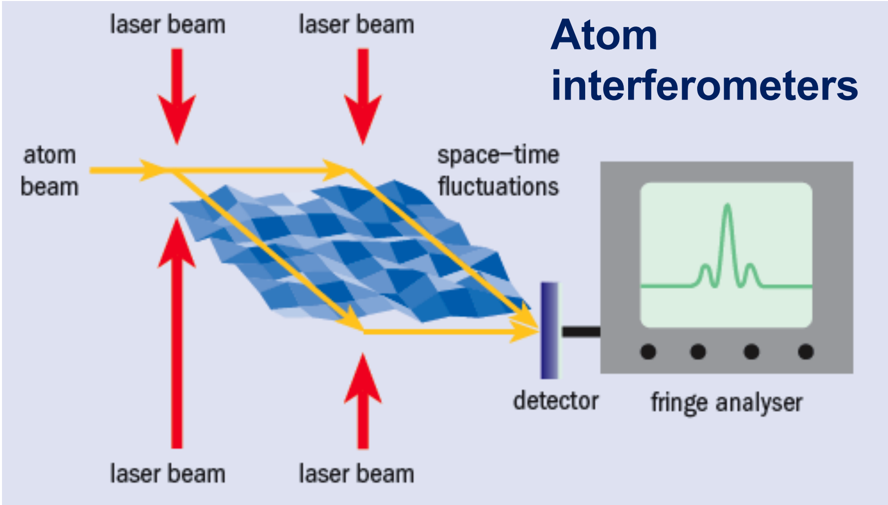
https://iopscience.iop.org/journal/2058-9565/page/Focus-on-Quantum-Sensors-for-New-Physics-Discoveries

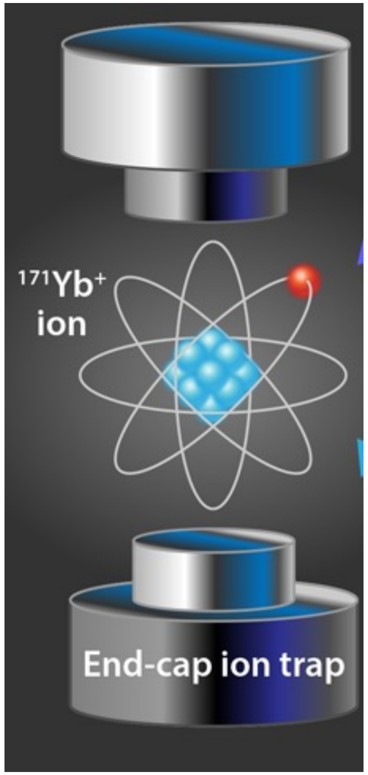
Editorial: Quantum technologies and the elephants, M. S Safronova and Dmitry Budker, Quantum Sci. Technol. 6, 040401 (2021).

“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***. “

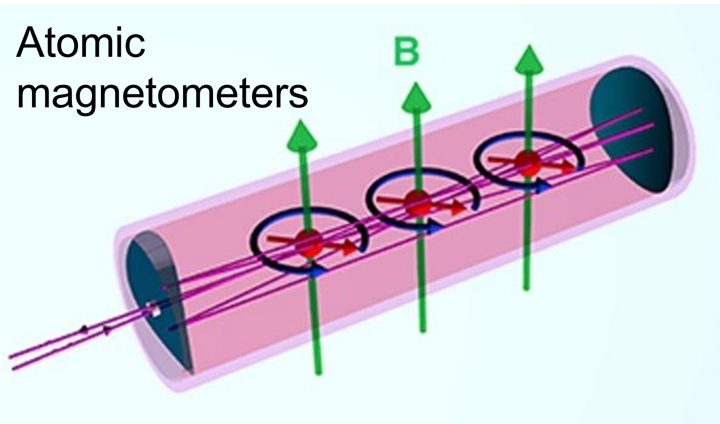
QUANTUM SENSORS







Trapped ions



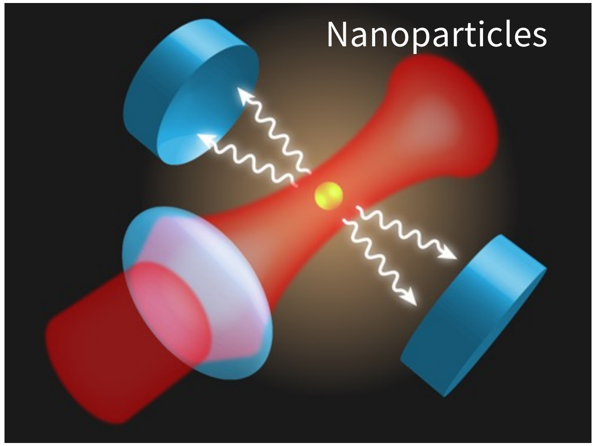
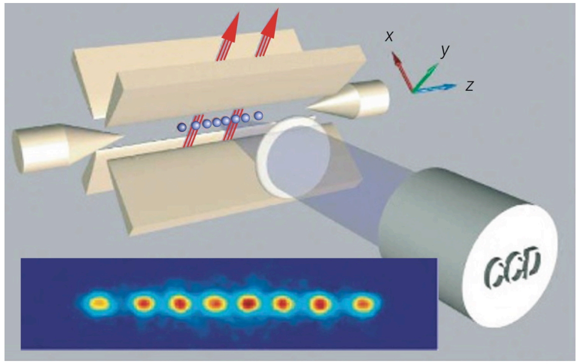
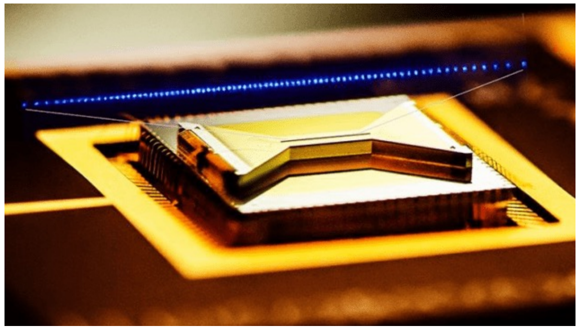


Image credit: JILA, APS/Alan Stonebraker, https://cerncourier.com/a/can-experiment-access-planck-scale-physics/, http://physicsworld.com/cws/article/news/2013/apr/24

QUANTUM SENSORS VS. QUANTUM COMPUTING AND SIMULATIONS

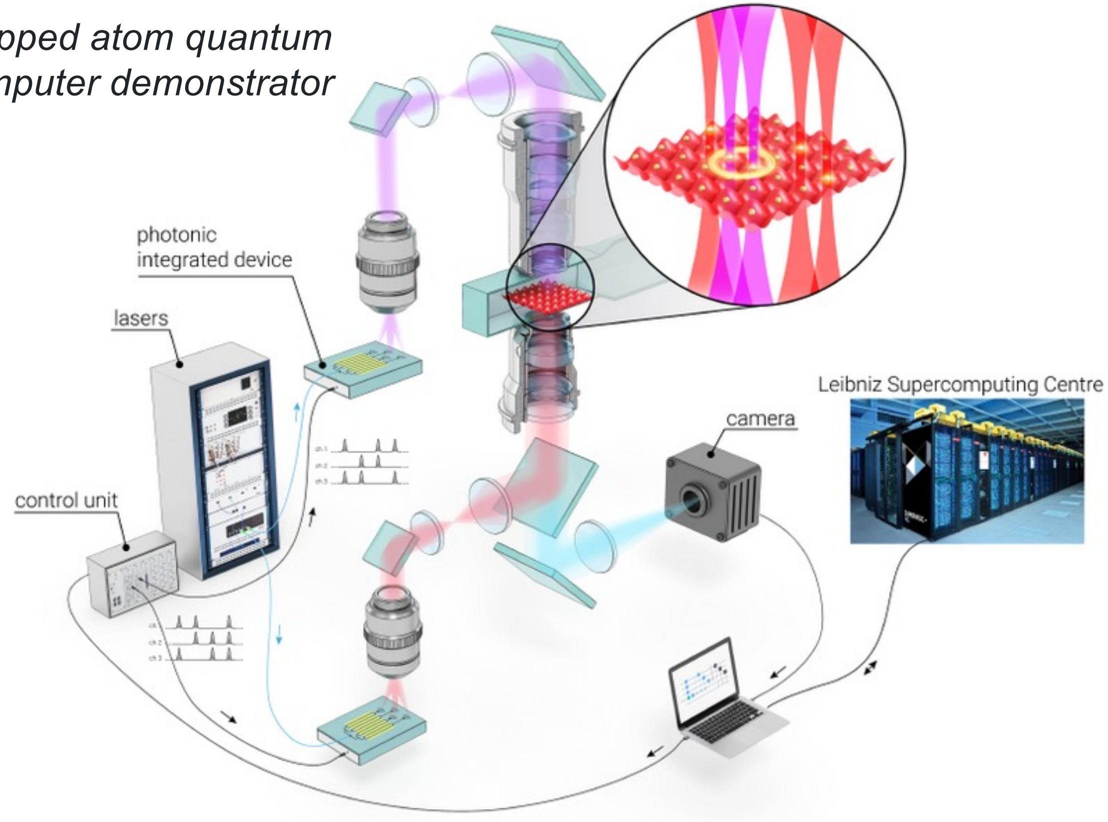
Based on the same cold atoms and ions, same or similar trapping and quantum control technologies





Trapped ions quantum computing

Trapped atom quantum computer demonstrator



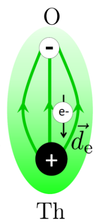
Nature 453, 1008 (2008), physicsworld.com/a/ion-based-commercial-quantum-computer-is-a-first,
https://www.munich-quantum-valley.de/research/research-areas/neutral-atom-qubits

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

Fundamental symmetries with quantum science techniques

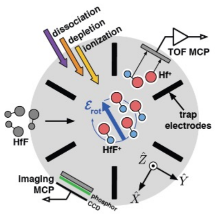
Searches for electron electric-dipole moment (eEDM)

Advanced ACME



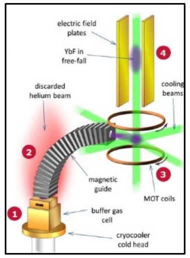
ThO

JILA eEDM



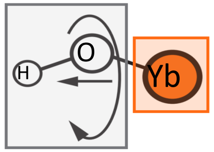
HfF^+, ThF^+

Imperial College



YbF

PolyEDM

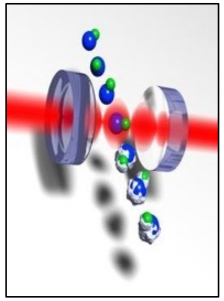


Also NMQM search

YbOH, …

Searches for hadronic EDMs

CeNTREX

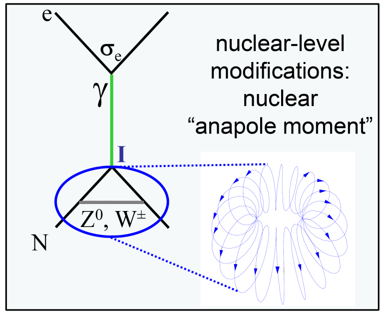


Hg
Xe
Ra
EDMs

TlF (proton EDM)

Enhanced parity violation

ZOMBIES



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

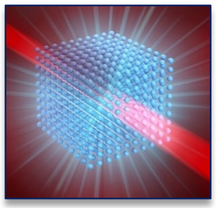
Rapid advances in ultracold molecule cooling and trapping; polyatomic molecules; future: molecules with Ra & "spin squeezed" entangled states

Atomic and Nuclear Clocks & Cavities

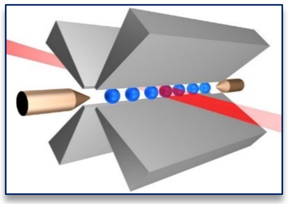
Major clock & cavities R&D efforts below, also molecular clocks, portable clocks and optical links

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

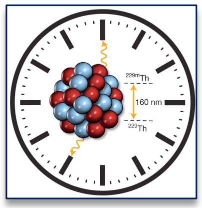


3D lattice clocks

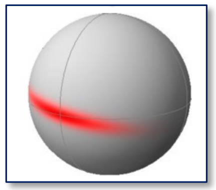


Multi-ion & entangled clocks

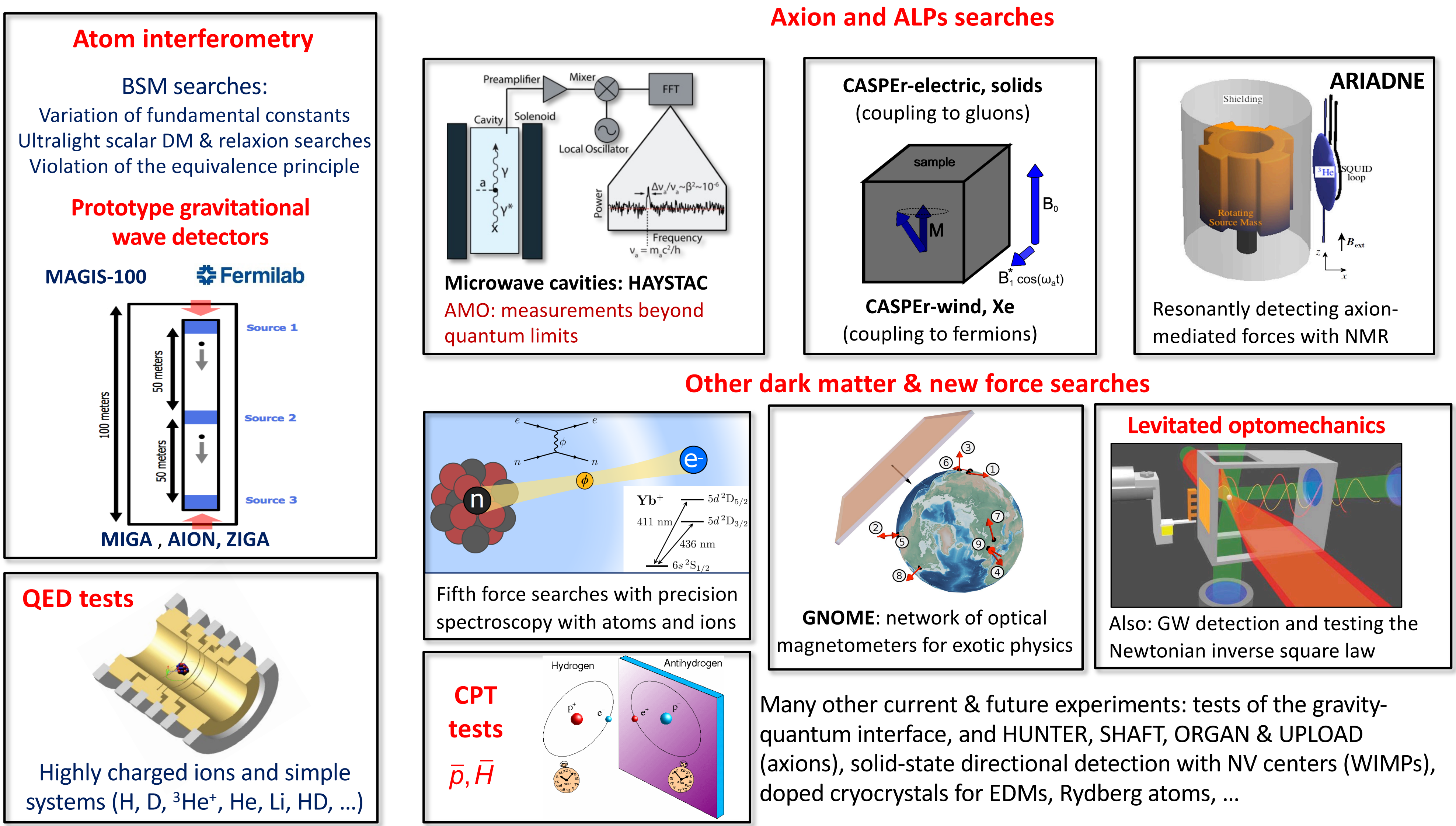
Ultrastable optical cavities



Nuclear & highly charge ion clocks

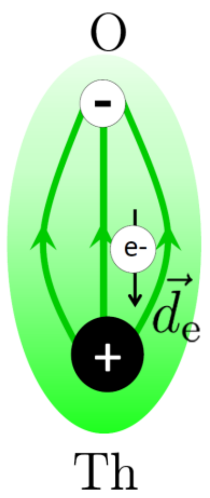


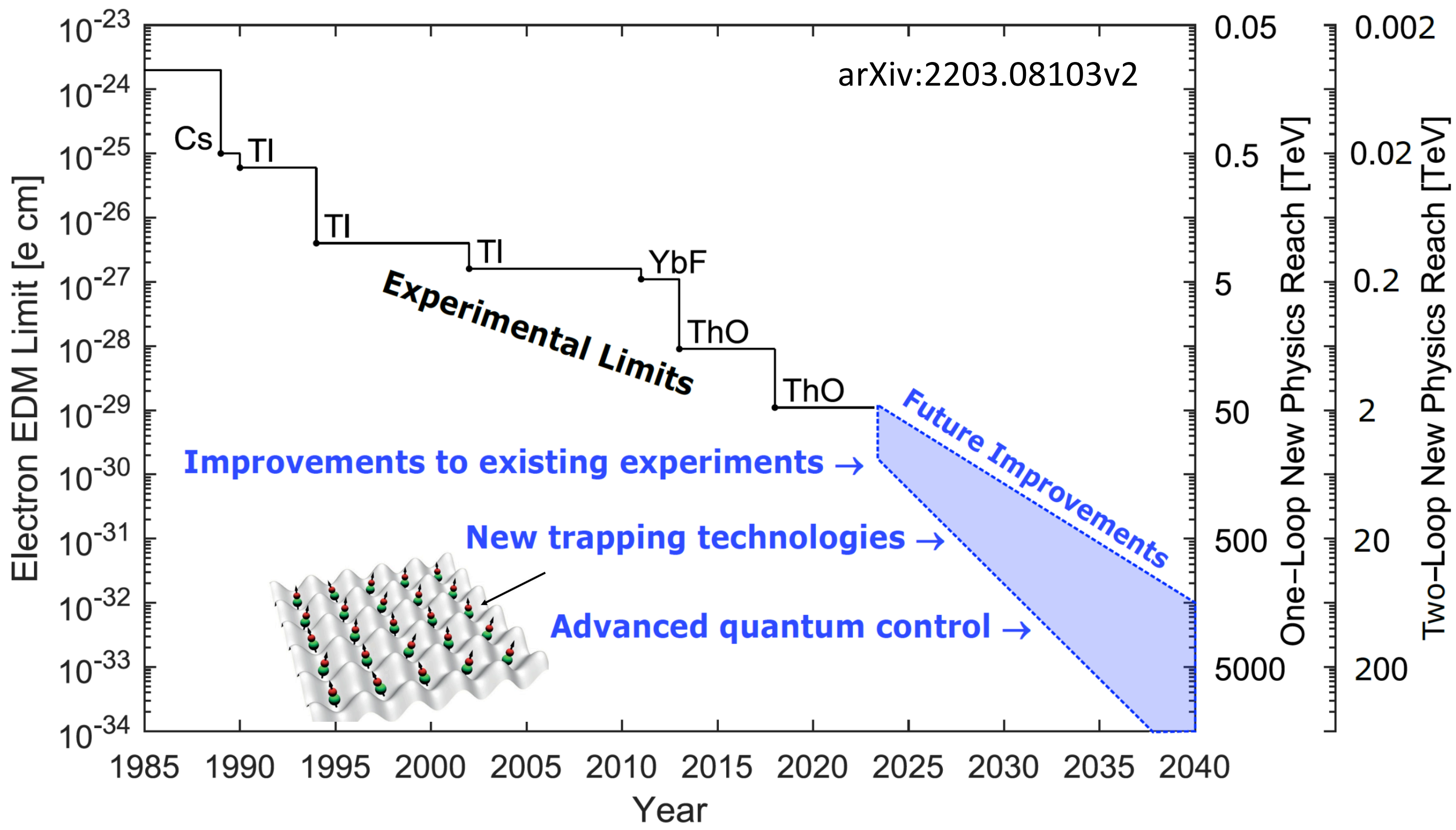
Measurements beyond the quantum limit


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
Source 1
Source 2
Source 3
50 meters
50 meters
100 meters
MIGA , AION, ZIGA
QED tests
Highly charged ions and simple systems (H, D, ³He⁺, He, Li, HD, ...)
Axion and ALPs searches
Preamplifier
Mixer
FFT
Cavity
Solenoid
Local Oscillator
Power
Frequency
Microwave cavities: HAYSTAC
AMO: measurements beyond quantum limits
CASPEr-electric, solids
(coupling to gluons)
sample
M
B₀
CASPEr-wind, Xe
(coupling to fermions)
ARIADNE
Shielding
SQUID loop
Rotating Source Mass
Resonantly detecting axion-mediated forces with NMR
Other dark matter & new force searches
e-
n
Yb⁺
411 nm
436 nm
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
p̄, H̄
Hydrogen
Antihydrogen
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, ...

QUANTUM TECHNOLOGIES FOR TEV SCALE PHYSICS: EDMs

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



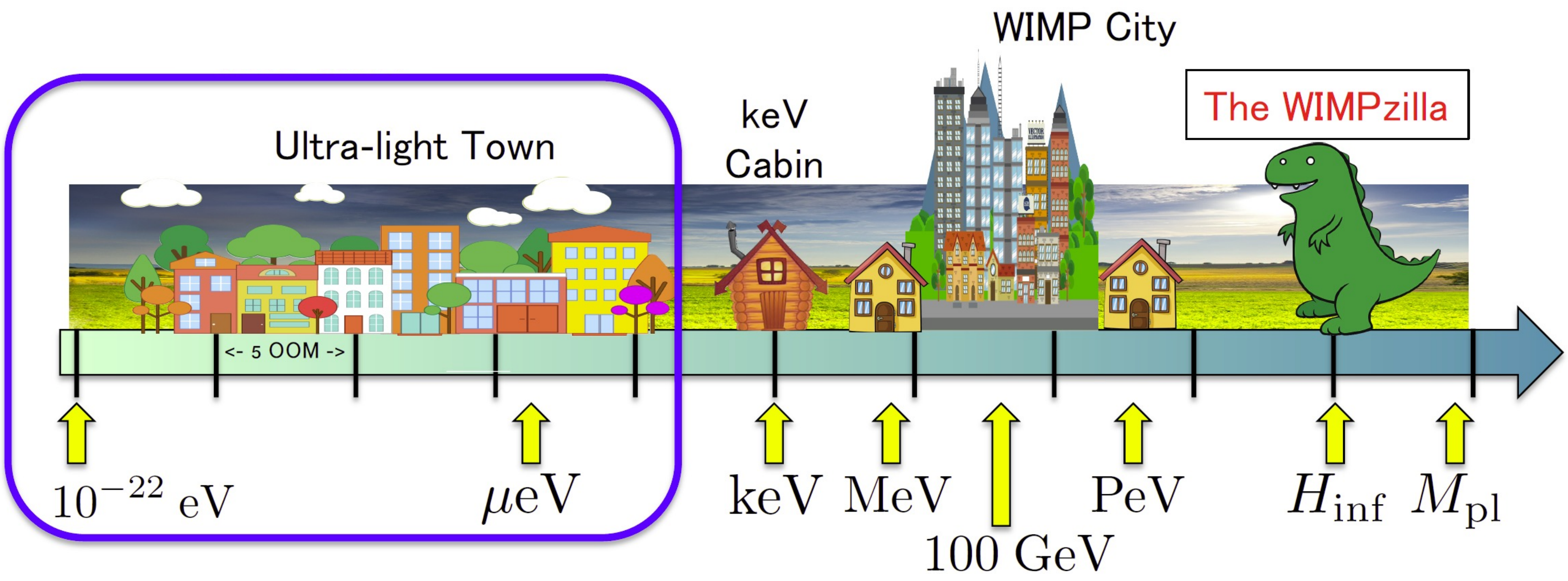


Electron EDM limits versus time, along with new physics reach for one-loop and two-loop effects

Slide from Andrew Long's 2018 LDW talk

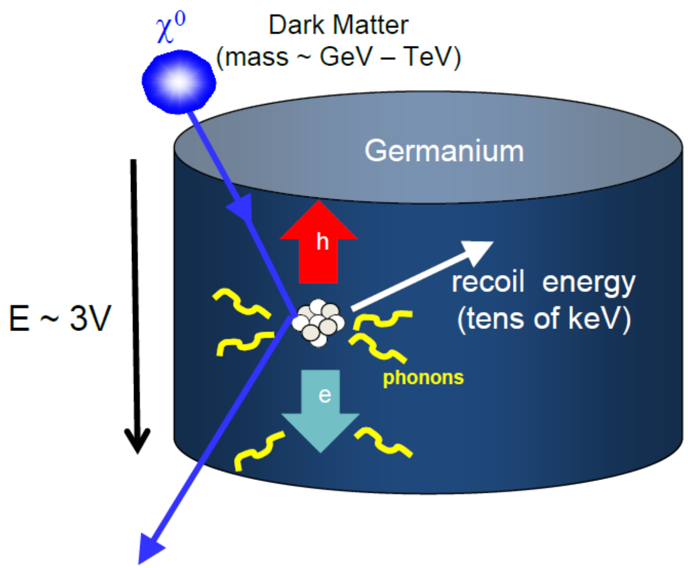
QUANTUM TECHNOLOGIES FOR DARK MATTER SEARCHES

The landscape of dark matter masses

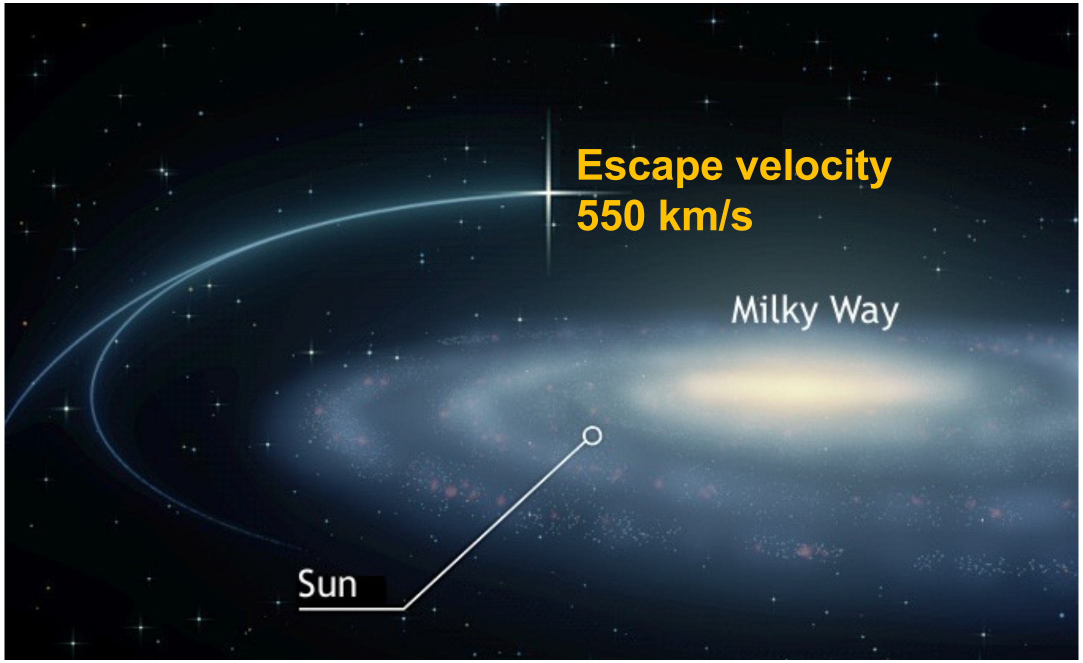


DARK MATTER DETECTION

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.

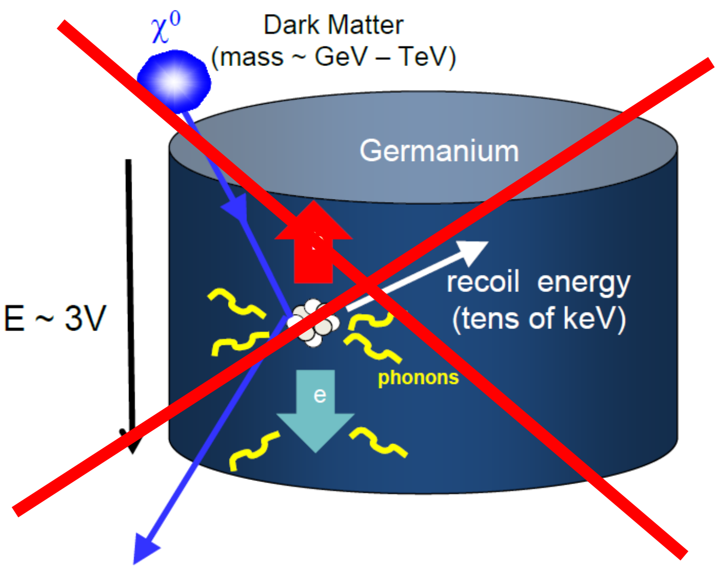


Ultralight dark matter has to be bosonic.

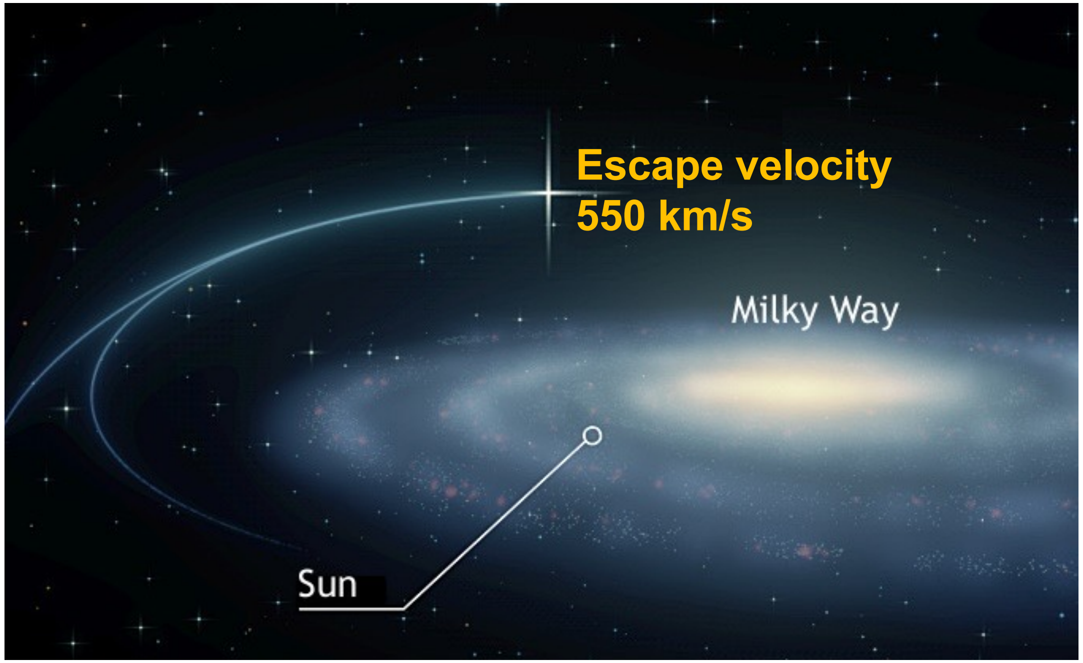
Image credits: CDMS: https://www.slac.stanford.edu/exp/cdms/
https://astronomynow.com/2016/04/14/speeding-binary-star-discovered-approaching-galactic-escape-velocity/

Ultralight 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/

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.

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

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

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

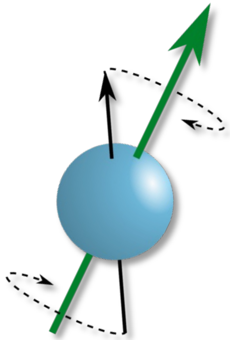
$$\phi_0 \sim \sqrt{2\rho_{\text{DM}}}/m_\phi$$

Dark matter field amplitude

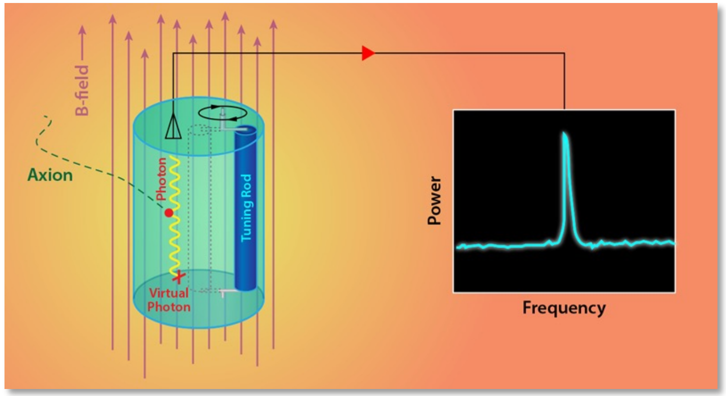
Dark matter density

Dark matter mass

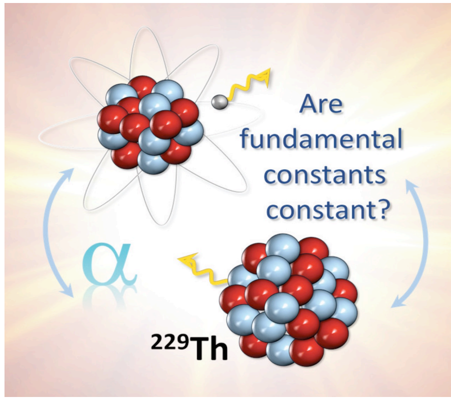
Observable effects of ultralight dark matter



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

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

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

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

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

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

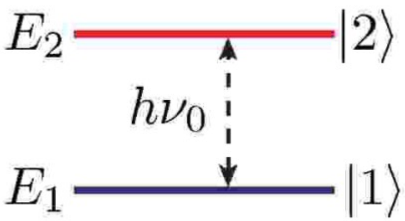
Key point: different (types) of clocks have different sensitivity to different constants

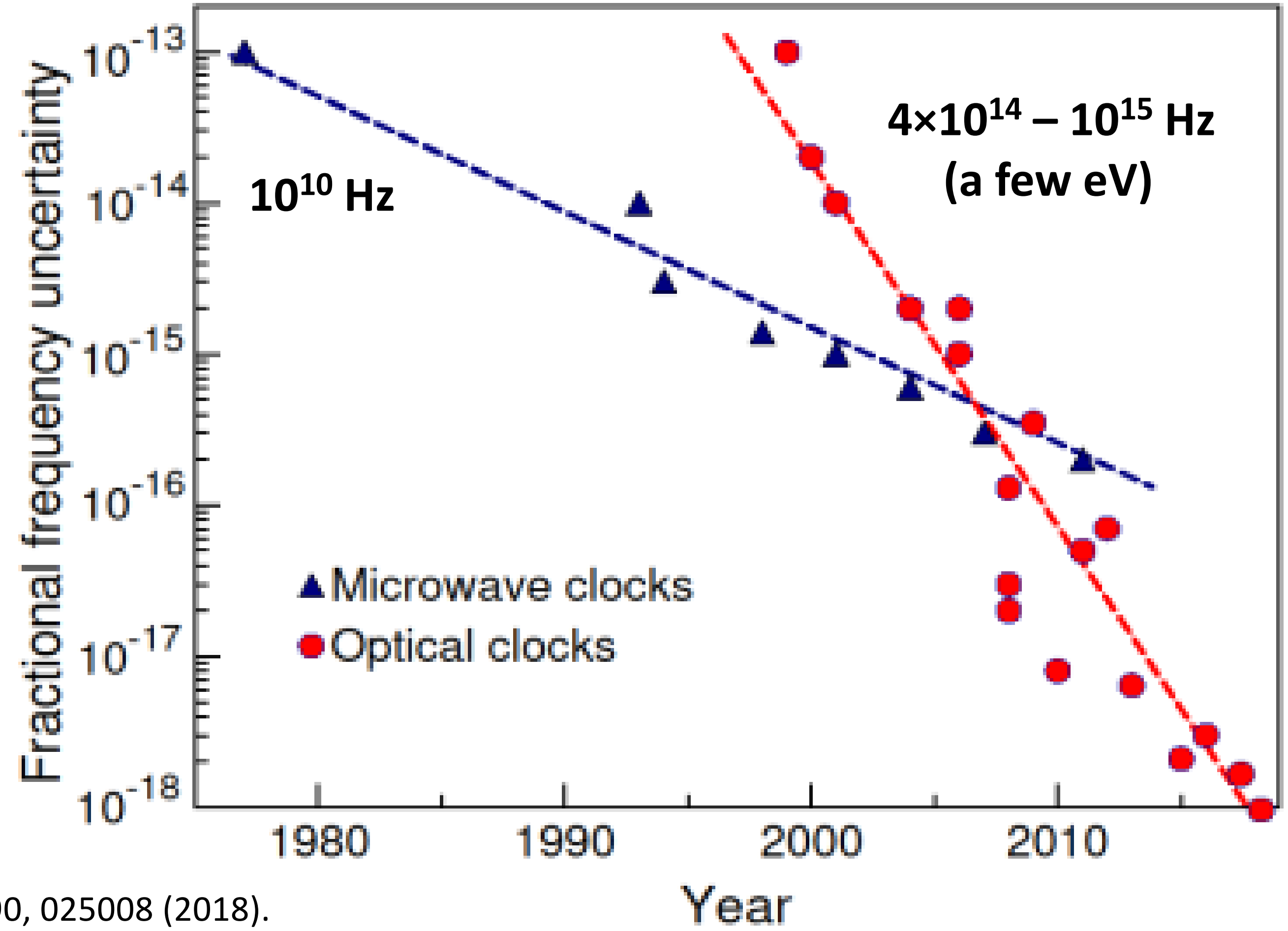
Observable: clock frequency ratios

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

airandspace.si.edu

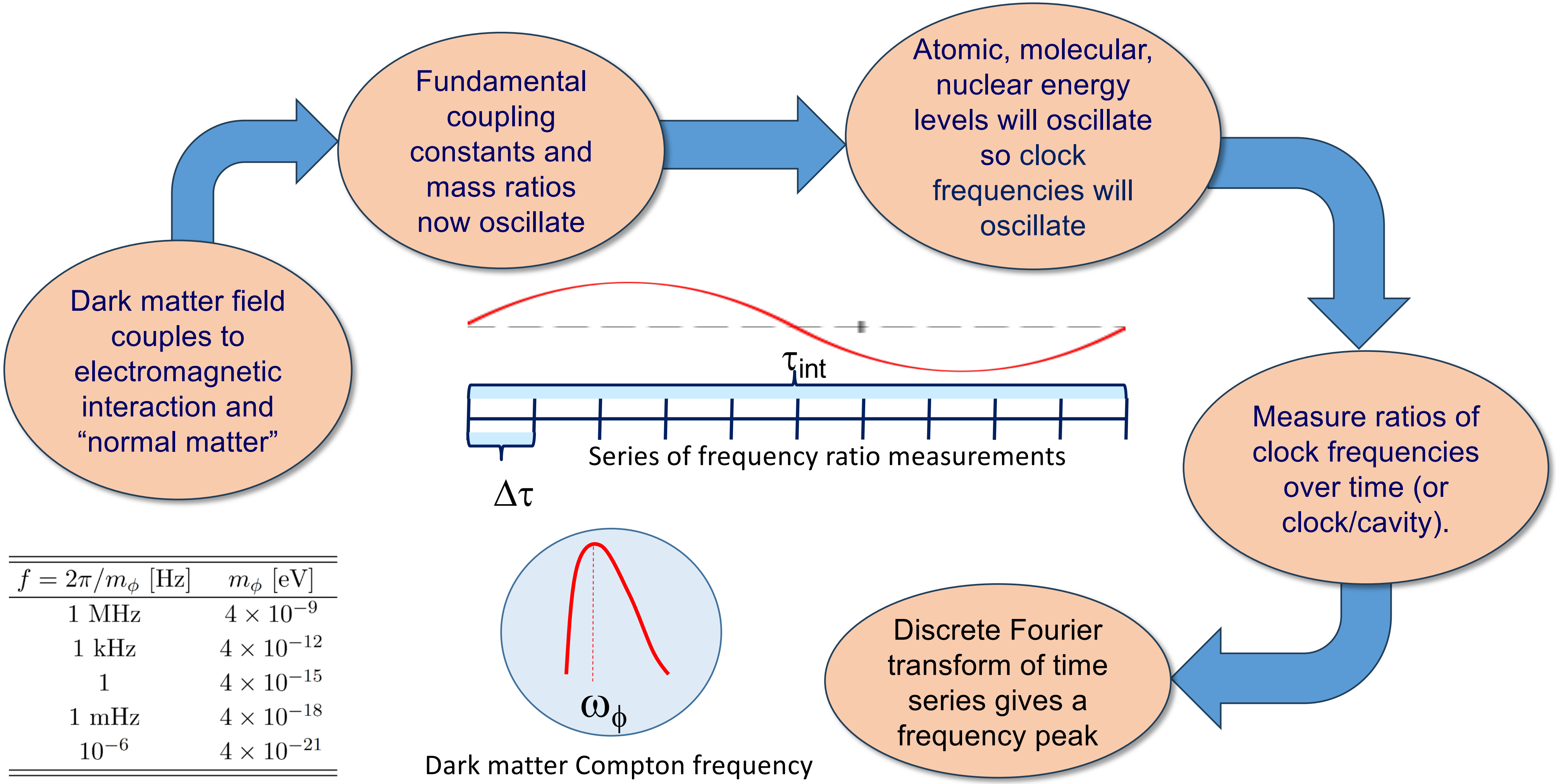
GPS satellites:
microwave
atomic clocks





M. S. Safronova et al., Rev. Mod. Phys. 90, 025008 (2018).

How to detect ULTRALIGHT dark matter with clocks?



$f = 2\pi/m_\phi$ [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}

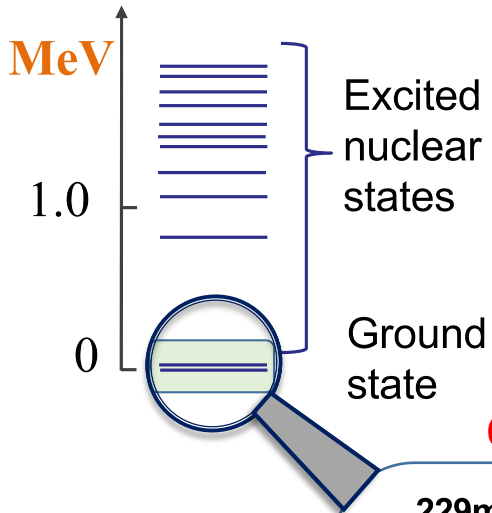
^{229}Th NUCLEAR CLOCK

Th^{3+} ion clock
Solid state clock

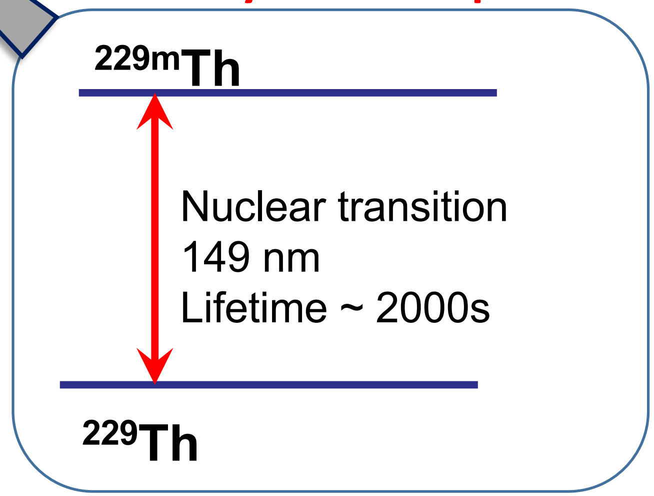
European Research Council

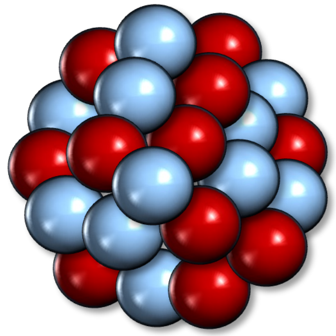
Thorsten Schumm, TU Wein
Ekkehard Peik, PTB
Peter Thirolf, LMU
Marianna Safronova, UD

Review & ERC Synergy project plan:
E. Peik, T. Schumm, M. S. Safronova, A. Pálffy, J. Weitenberg, and P. G. Thirolf, QST 6, 034002 (2021).



Only ONE exception!





Much higher predicted sensitivity to the variation of fine structure constant and $\frac{m_q}{\Lambda_{QCD}}$. K=5900(2500) arXiv:2407.17300.

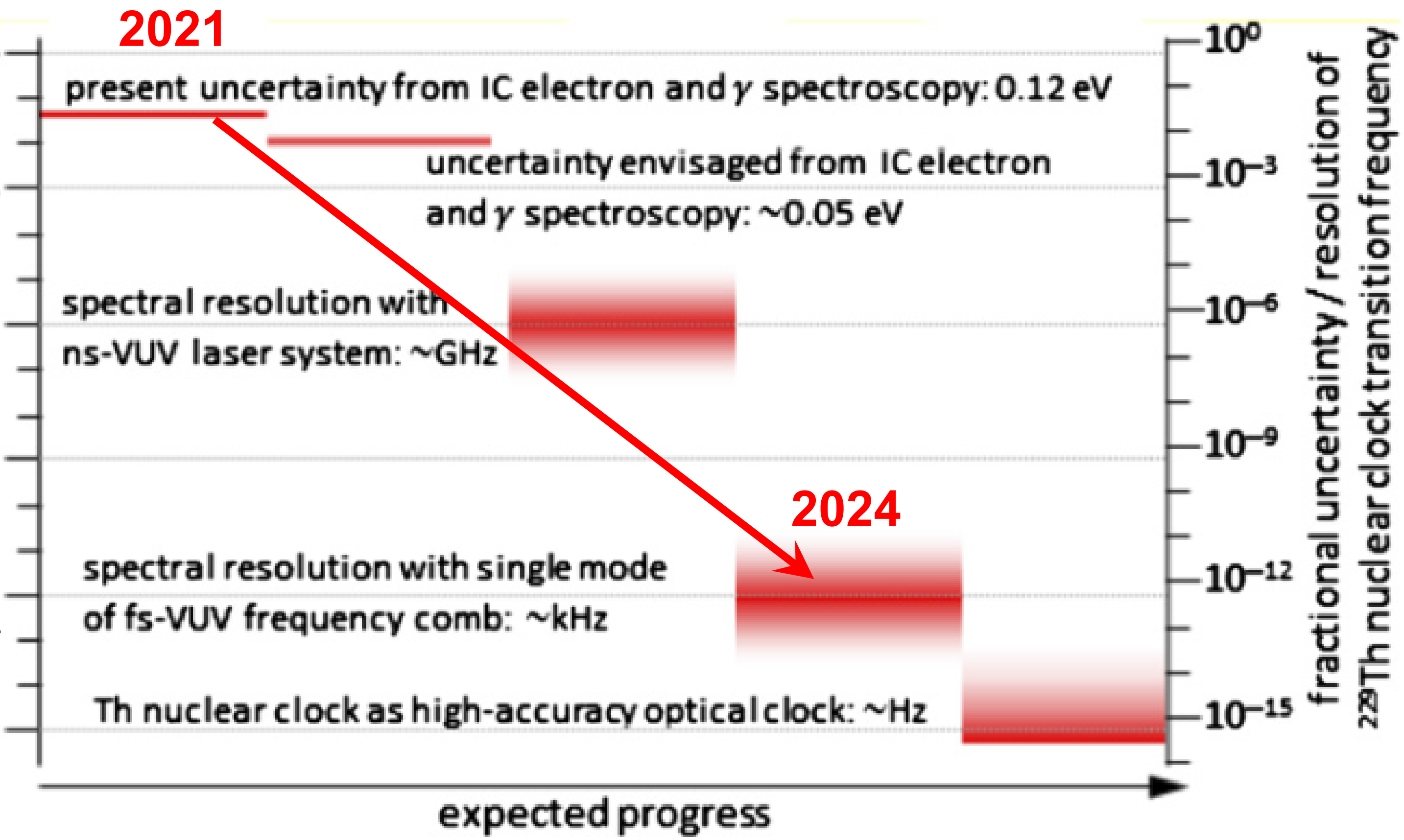
Nuclear clock is sensitive to coupling of dark matter to the nuclear sector of the standard model.

How to build a nuclear clock?

Nature 617, 706 (2023)

PRL 132, 182501 (2024)
PRL 133, 013201 (2024)

arXiv:2406.18719
2 020 407 384 335(2) kHz

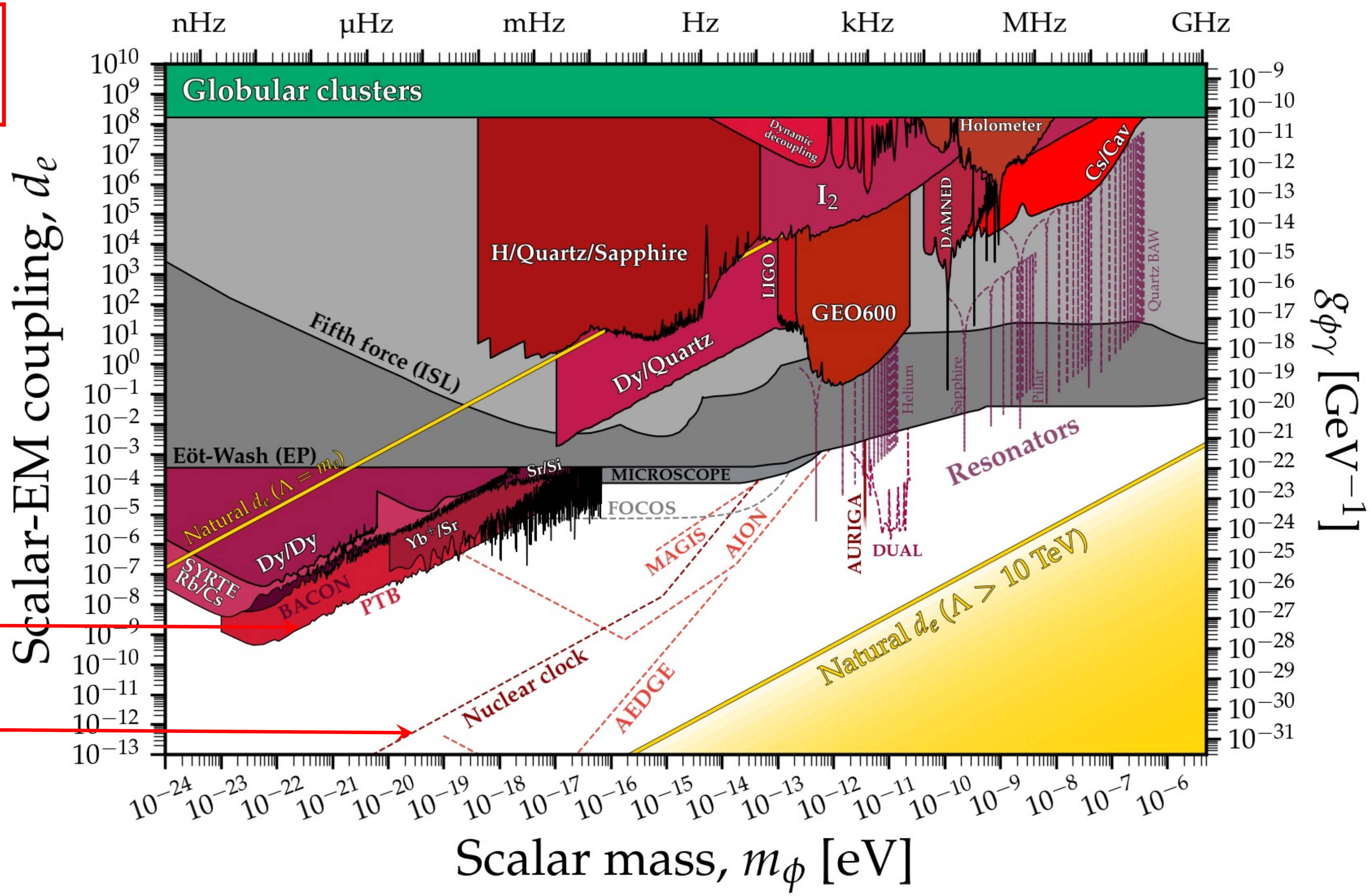


Quantum Science and Technology 6, 034002 (2021)

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

Present
clock limits

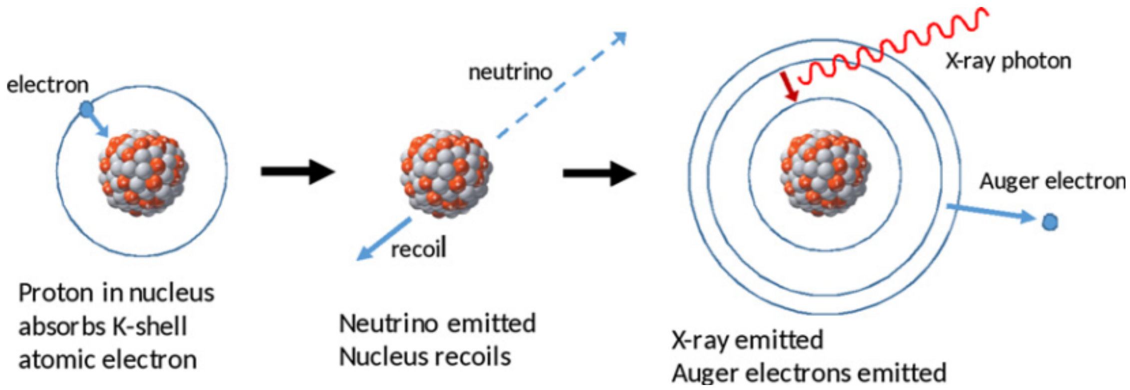
Projected
clock limits



arXiv:2203.14915

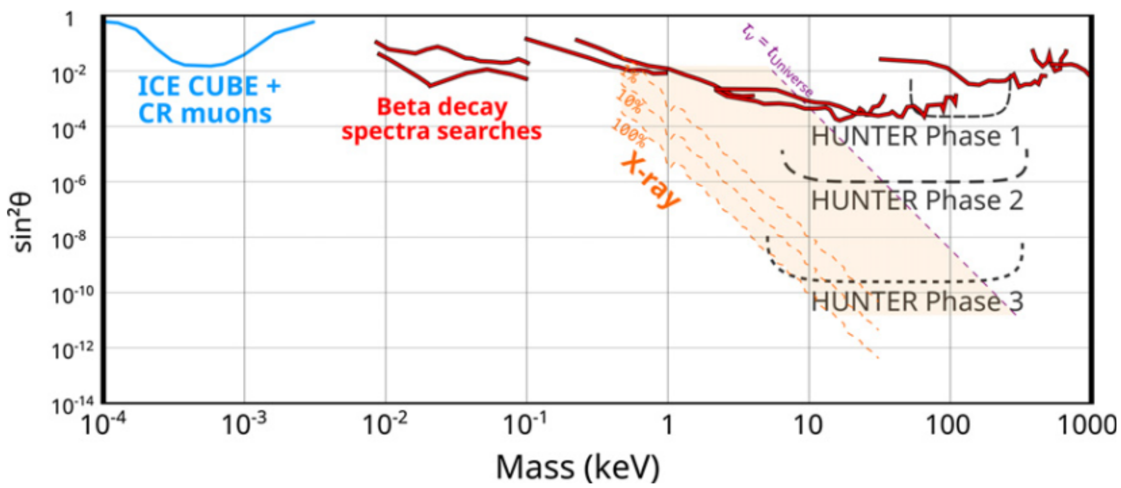
Ultralight DM limits: https://cajohare.github.io/AxionLimits/

HUNTER: Precision massive-neutrino search based on a laser cooled atomic source



$$^{131}\mathrm{Cs} \rightarrow {}^{131}\mathrm{Xe}^{*} + \nu_e$$

Cs atoms are trapped in a MOT. Complete kinematical reconstruction is possible, allowing the neutrino mass to be determined event-by-event.

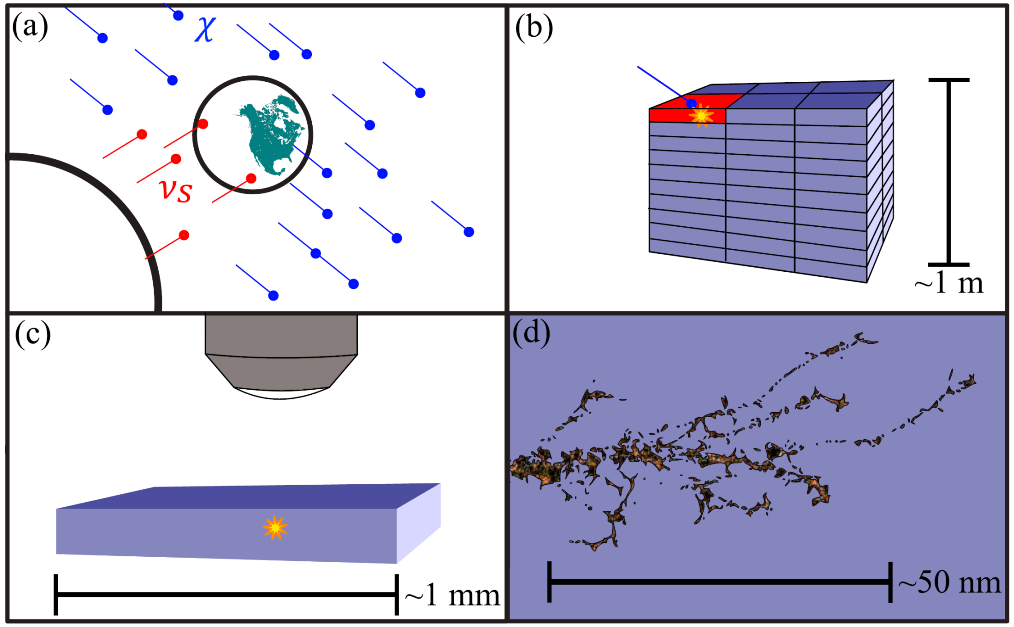


Limits on sterile neutrino coupling strength vs mass. Dashed lines (orange) show astrophysical limits permitting sterile neutrinos to be the galactic dark matter

From: C. J. Martoff *et al.*, *Quantum Sci. Technol.* **6** 024008 (2021)

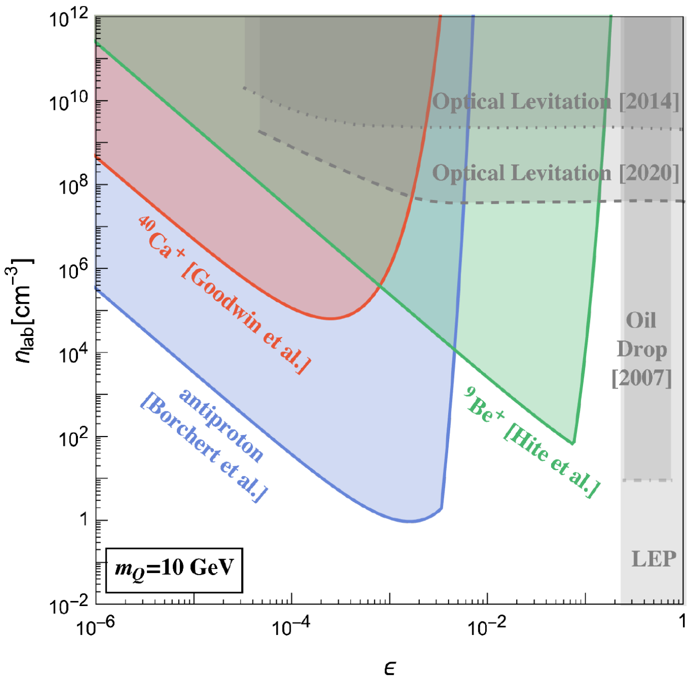
Searches for TeV dark matter: WIMPs and millicharged particles

Directional detection of WIMP dark matter with diamond



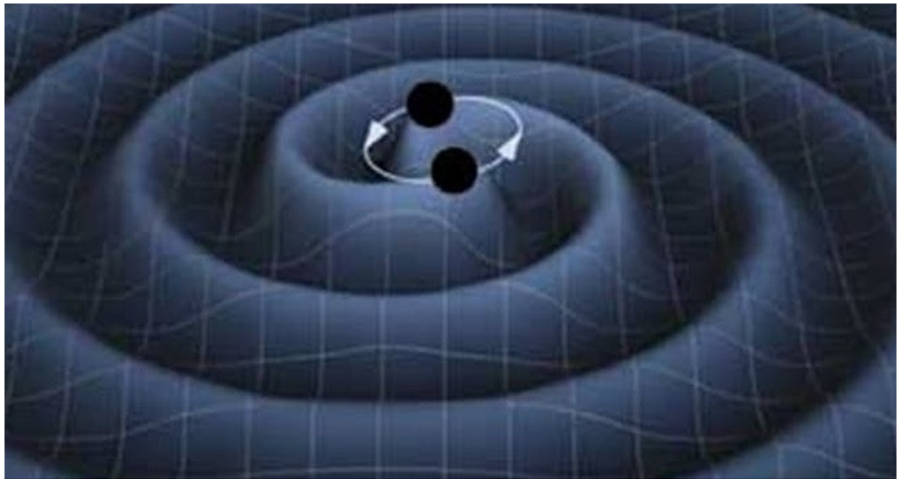
Quantum Sci. Technol. 6 (2021) 024011

Millicharged dark matter detection with ion traps

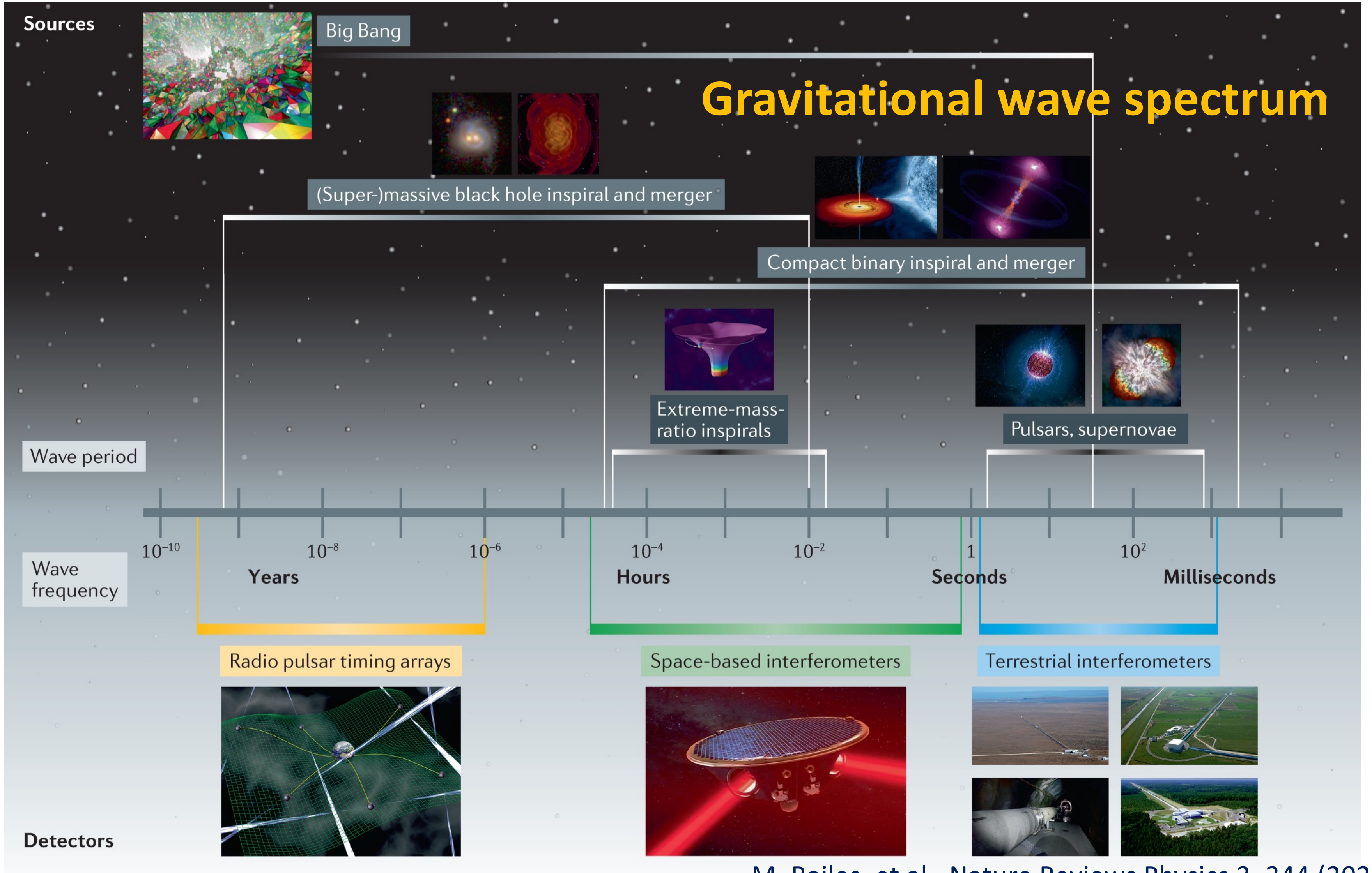


PRX Quantum 3, 010330 (2022)
Phys. Rev. Lett. 127, 061804 (2021)

New ideas in gravitational wave detection with atomic quantum sensors

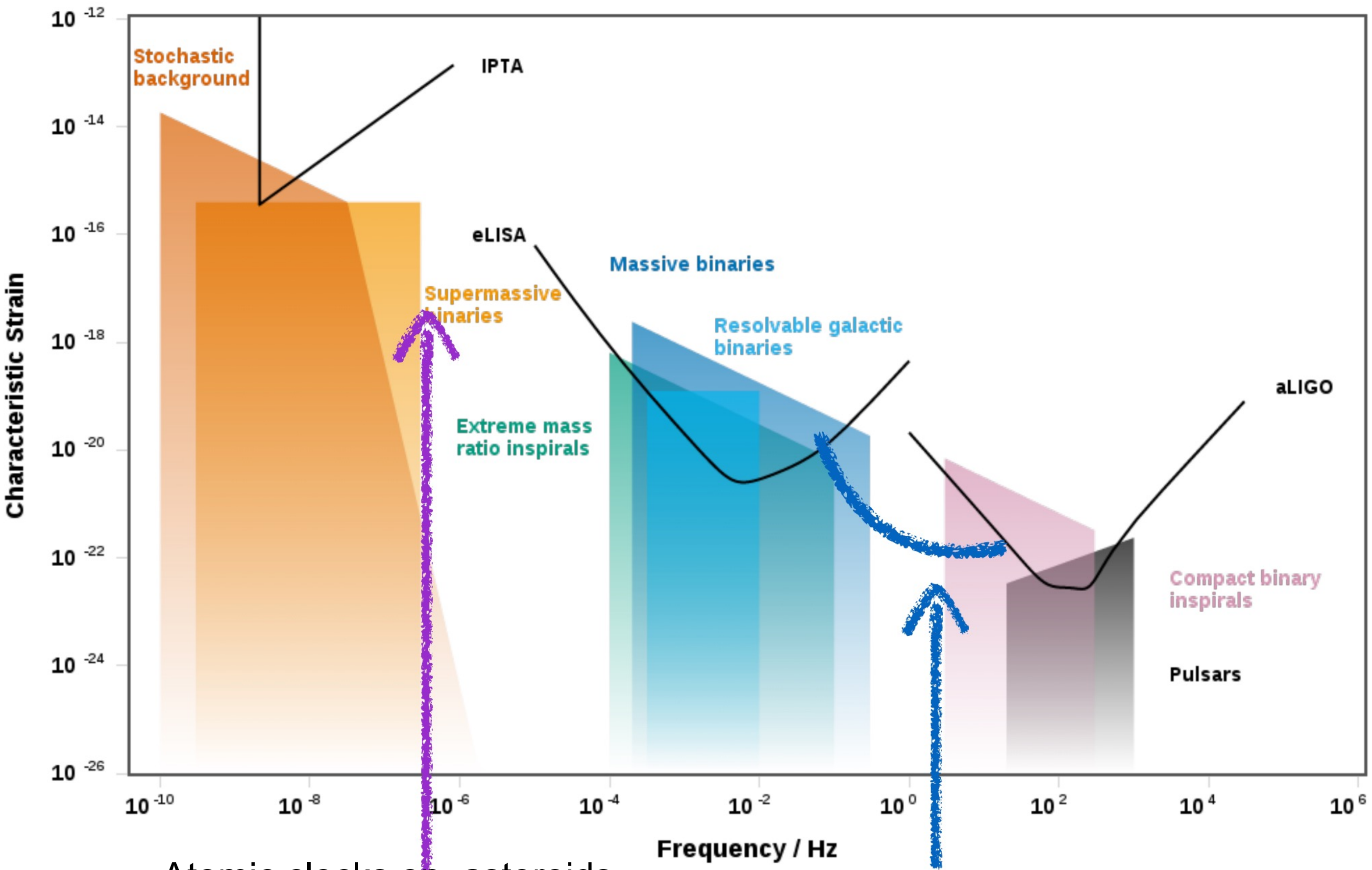


Gravitational wave spectrum



M. Bailes, et al., Nature Reviews Physics 3, 344 (2021)

Figure is from Peter Graham's talk at KITP 2021: https://online.kitp.ucsb.edu/online/novel-oc21/



Atomic clocks on asteroids

PRD 105, 103018 (2022)

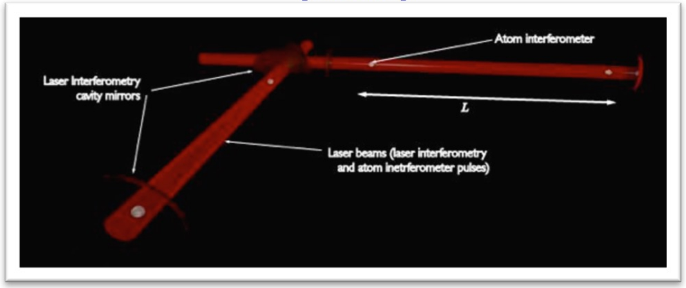
open band

~ 10^{-7} Hz - 10^{-4} Hz

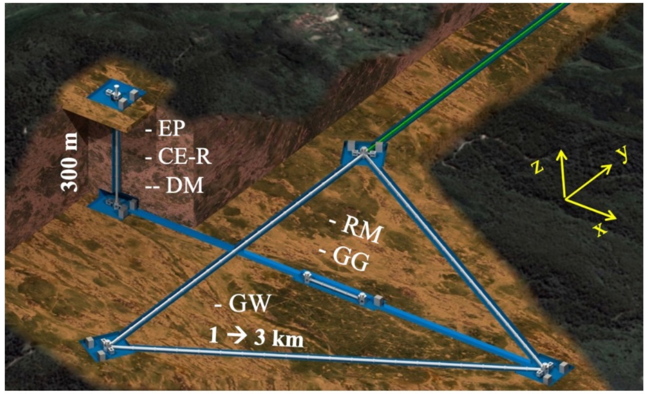
atoms (MAGIS, clocks, MIGA, AION...)

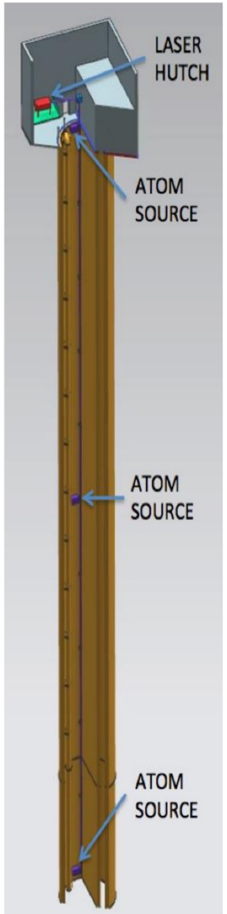
Atom interferometers: from 10 meters to 100 meters to 1km to space

MIGA: Terrestrial detector using atom interferometer at O(100m)
(France)

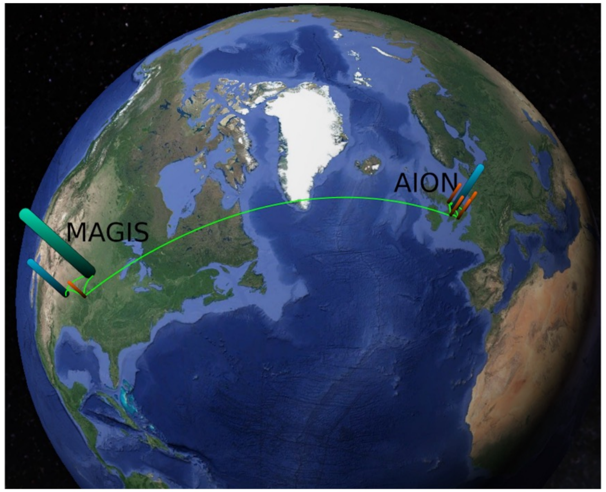


ZIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m)
(China)





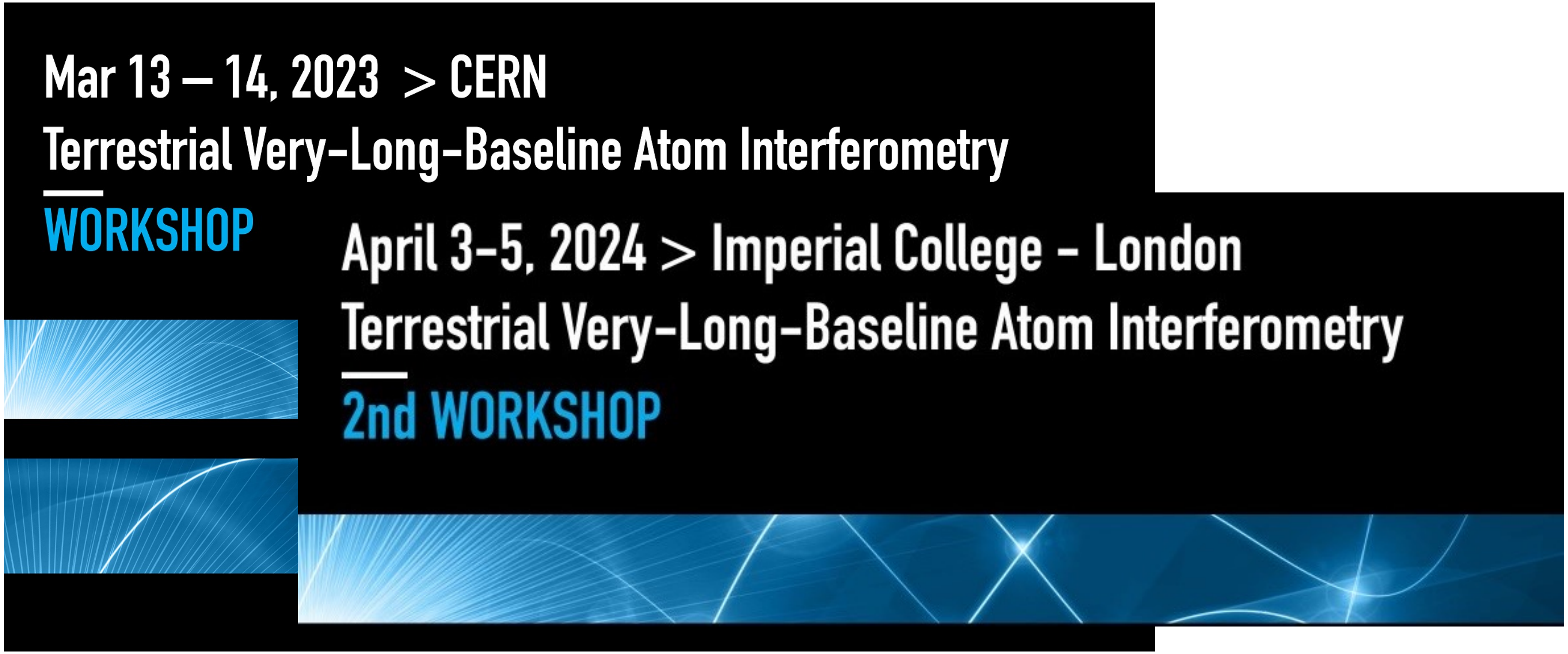
AION: Terrestrial shaft detector using atom interferometer at 10m – O(100m) planned
(UK)



MAGIS: Terrestrial shaft detector using atom interferometer at O(100m)
(US)

Planned network operation

Figures are from : talk by Oliver Buchmueller, Community Workshop on Cold Atoms in Space,https://indico.cern.ch/event/1064855/timetable/



https://indico.cern.ch/event/1208783, https://indico.cern.ch/event/1369392

Terrestrial Very-Long-Baseline Atom Interferometry: Workshop Summary, Sven Abend at al., AVS Quantum Sci. 6, 024701 (2024).

Proto collaboration is being formed for Terrestrial Very Long Baseline Atom Interferometer (TVLBAI) study. The main goals are to develop a Roadmap for the design and technology choices for one or several km-scale detectors to be ready for operation in the mid 2030s, which is supported by the cold atom community and the potential user communities interested in its science goals.

Future

- Quantum technologies presents fantastic opportunities for paradigm-changing discoveries
- Continuing fast development of quantum sensors is expected in the next decades
- Need strong collaboration between quantum science and particle physics communities
- Many more ideas to explore!

UD team and collaborators

Online portal team

Prof. Rudolf Eigenmann
UD (EECS)

Prof. Bindiya Arora
Guru Nanak Dev U., India

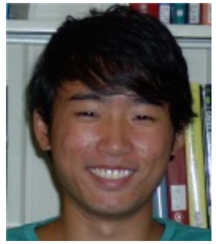
Parinaz Barakhshan
UD (CE)
Grad. St.

Adam Marrs
UD (Physics)
Graduated August 2021

Akshay Bhosale
UD (CE)
Grad. St.

Dr. Sergey Porsev
Research Associate III

Dr. Dmytro Filin
Research Associate III



Dr. Charles Cheung
Postdoc

Hani Zaheer
Grad. St.

Jason Arakawa
Postdoc

Aung Naing
Graduated August 2021

Collaborators:

ERC Synergy: Thorsten Schumm, TU Wein Ekkehard Peik, PTB, Peter Thirolf, LMU, Adriana Pálffy (FAU) Q-SEnSE: Jun Ye, Dave Leibrandt, Leo Hollberg, Nate Newbury

Particle physics: Josh Eby (IPMU, Tokyo), Volodymyr Takhistov (QUP, Tokyo), Gilad Perez' group (Weizmann Institute of Science, Israel), Yu-Dai Tsai (UC Irvine),

Dmitry Budker, Mainz and UC Berkeley, Andrew Jayich, UCSB, Murray Barrett, CQT, Singapore, José Crespo López-Urrutia, MPIK, Heidelberg , Piet Schmidt, PTB, University of Hannover, Nan Yu (JPL), Charles Clark, JQI, and many others!

Open postdoc position in Quantum Algorithms for New Physics Searches with Quantum Sensors