FALL MEETING OF THE BOARD ON PHYSICS AND ASTRONOMY

November 21-22, 2024

Update on Entanglement, Dark, and Normal Matter

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 Science & Technology

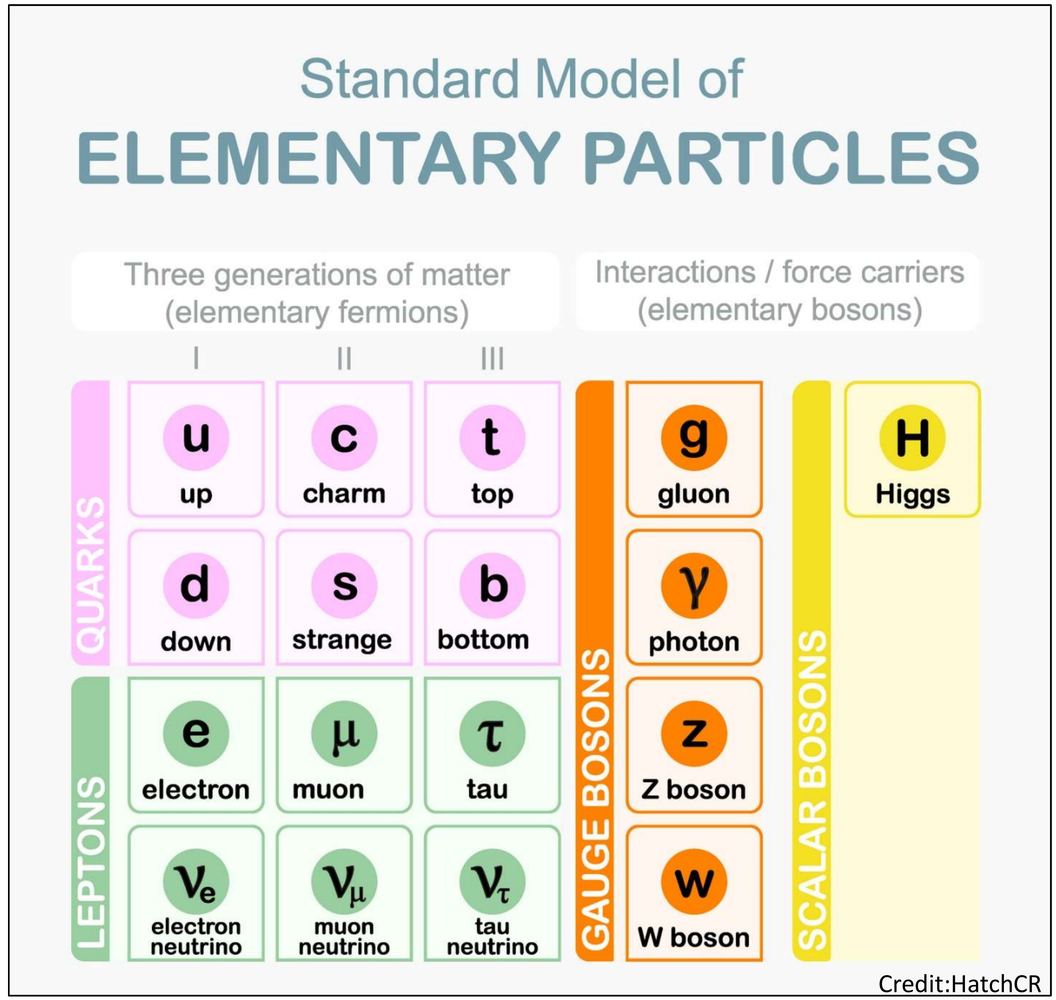
European Research Council

1924

2024

100 YEARS AGO

WE DID NOT KNOW WHAT ATOMS ARE MADE OF



2024: Problems with the standard model

New physics is required due to observations: no Standard Model explanation

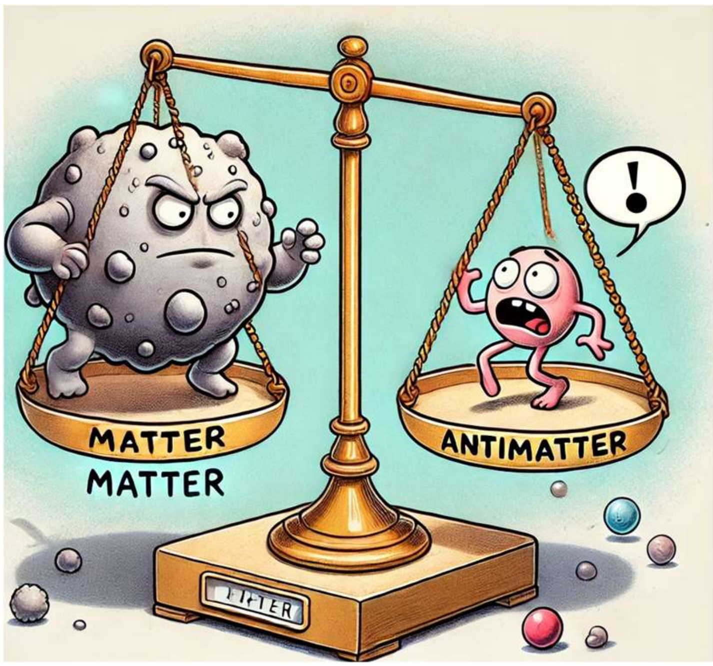
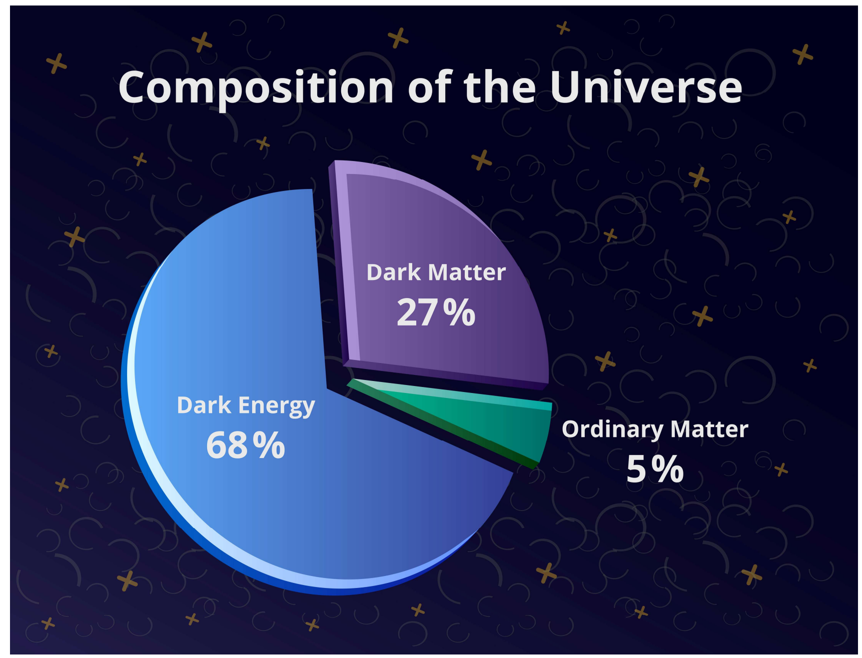


Image generated using OpenAI's DALL·E model



- Dark matter
- Matter-antimatter asymmetry
- Neutrino masses
- Accelerate expansion of the Universe (dark energy/cosmological constant?)

We do not know what the universe is made of

2024: Other unanswered questions in Fundamental physics

- 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

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 ATOMIC AND MOLECULAR QUANTUM TECHNOLOGIES OPENS NEW WAYS TO SOLVE THE PUZZLES OF THE UNIVERSE

Atomic, molecular, and nuclear clocks, atom interferometers, atom magnetometers, trapped ions & other qubits, ultracold atoms and molecules, optical cavities, levitated optomechanics, and other

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)
Over 1500 citations

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

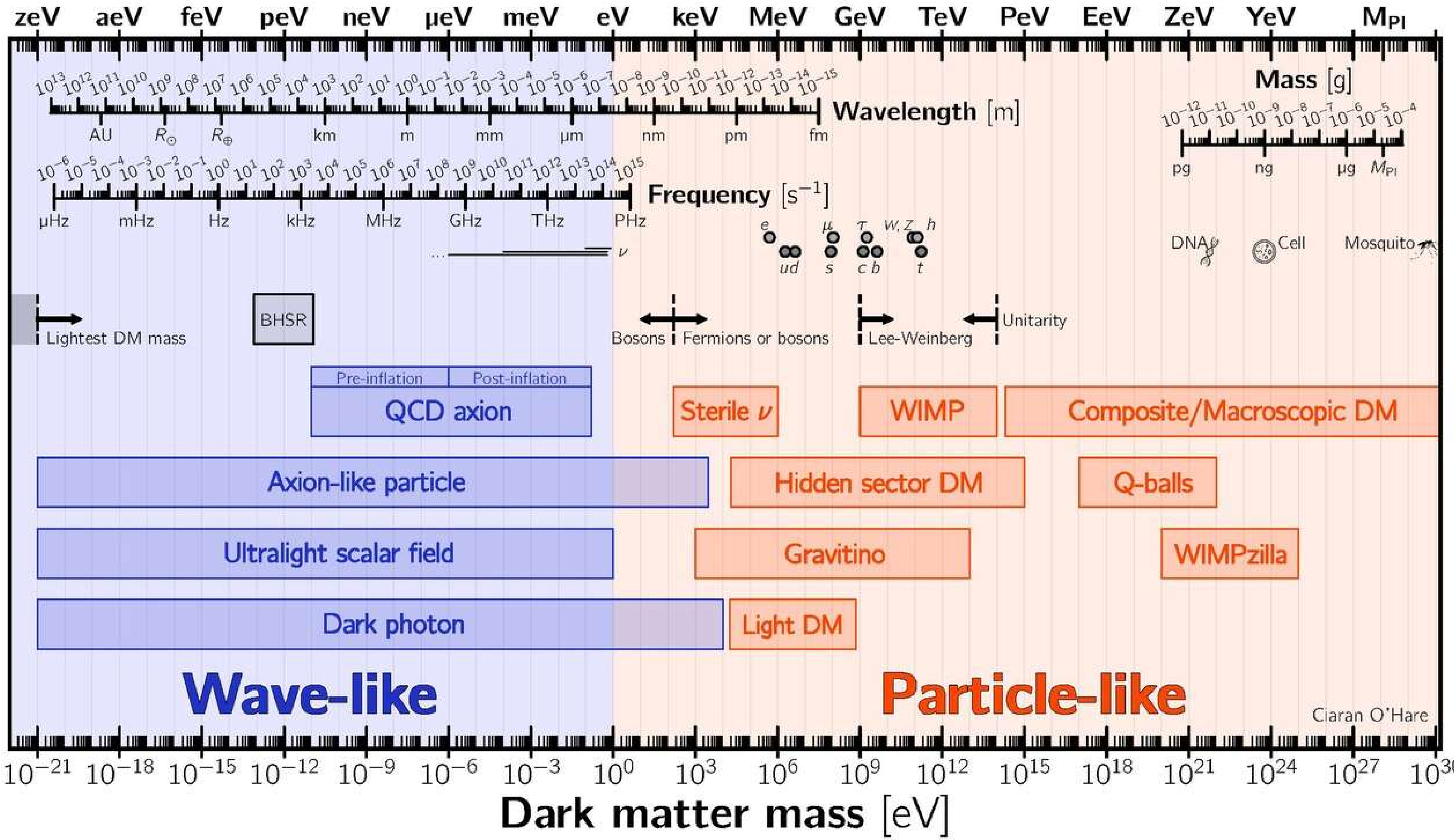
Searches for dark matter

Search for variation of fundamental constants

Searches for exotic forces

General relativity and gravitation

Search for violations of quantum statistics



Picture credit: Ciaran O'Hare. https://en.wikipedia.org/wiki/File:Dark_matter_candidates.pdf

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.

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

Need different detection strategies from particle dark matter.

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

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

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

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

Dark matter field amplitude (ϕ_0)

Dark matter density (ρ_{DM})

Dark matter mass (m_ϕ)

Ultralight dark matter signatures

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

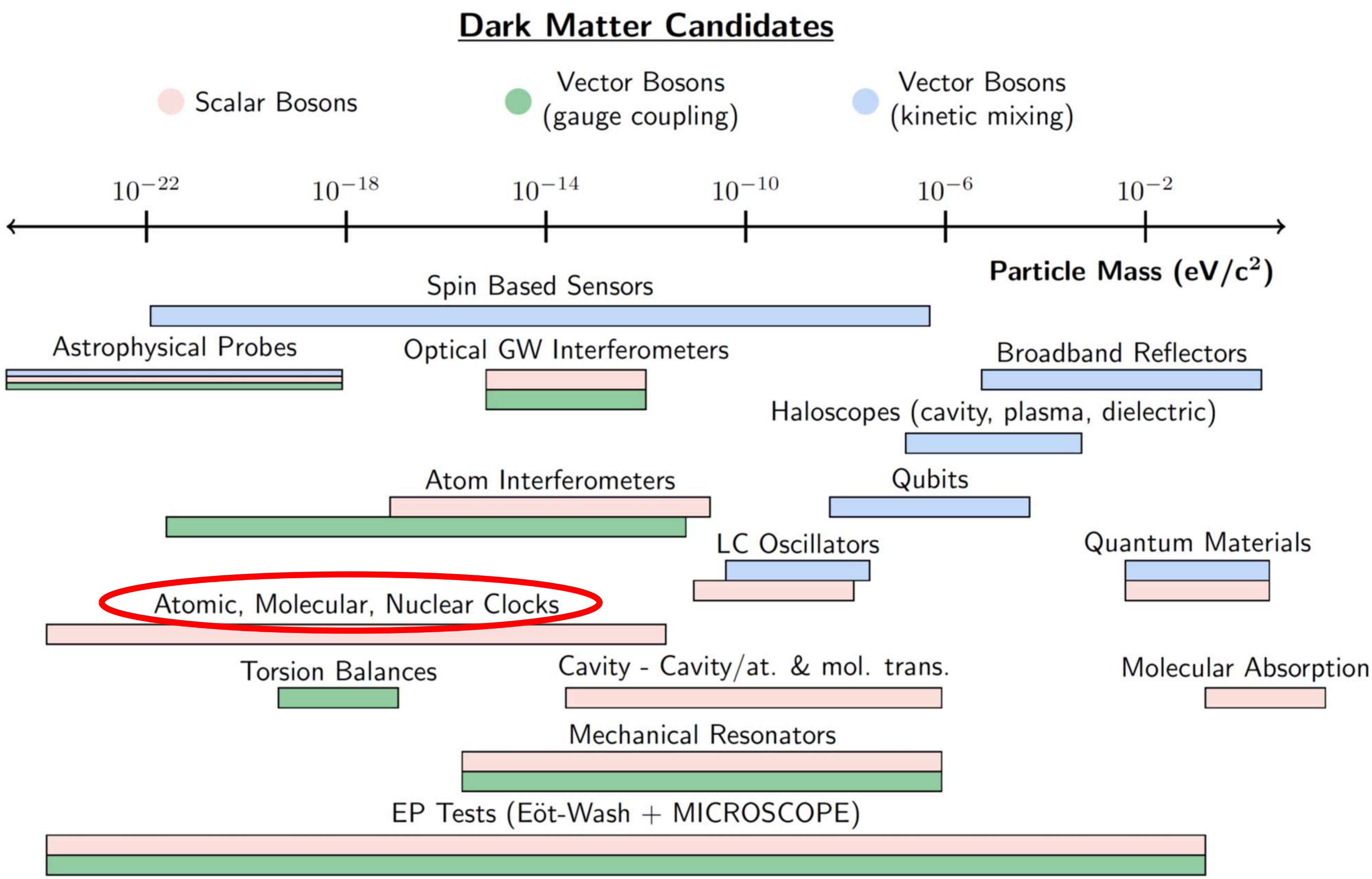
Different detection paradigm from particle dark matter.

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!

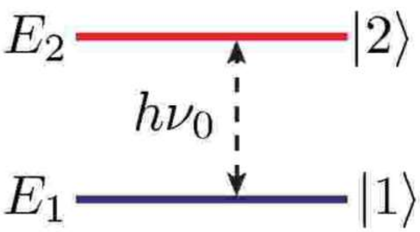


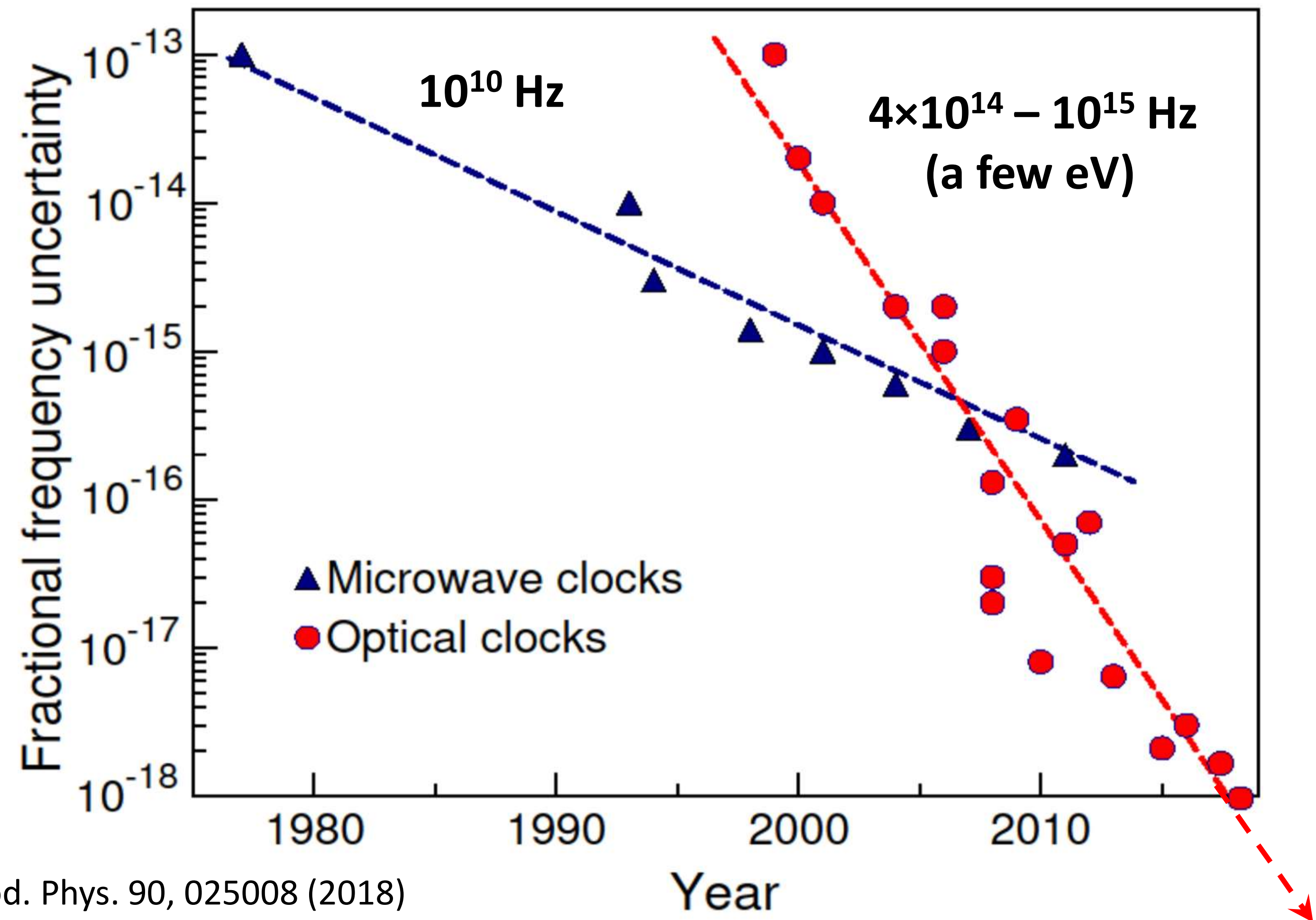
Snowmass, arXiv:2203.14915

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

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

GPS satellites:
microwave
atomic clocks





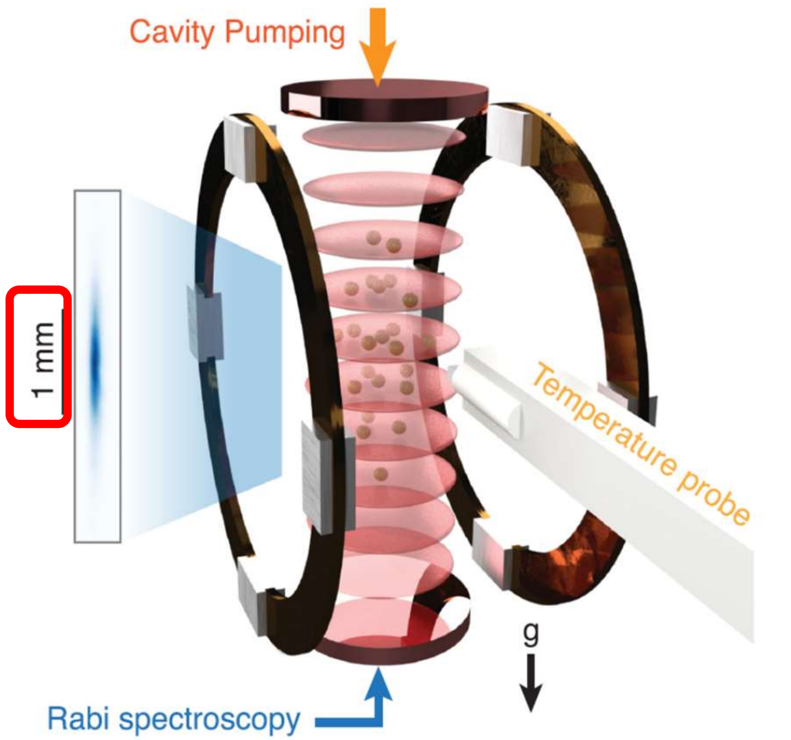
M. S. Safronova et al., Rev. Mod. Phys. 90, 025008 (2018)

PHYSICAL REVIEW LETTERS 133, 023401 (2024)

Editors' Suggestion | Featured in Physics

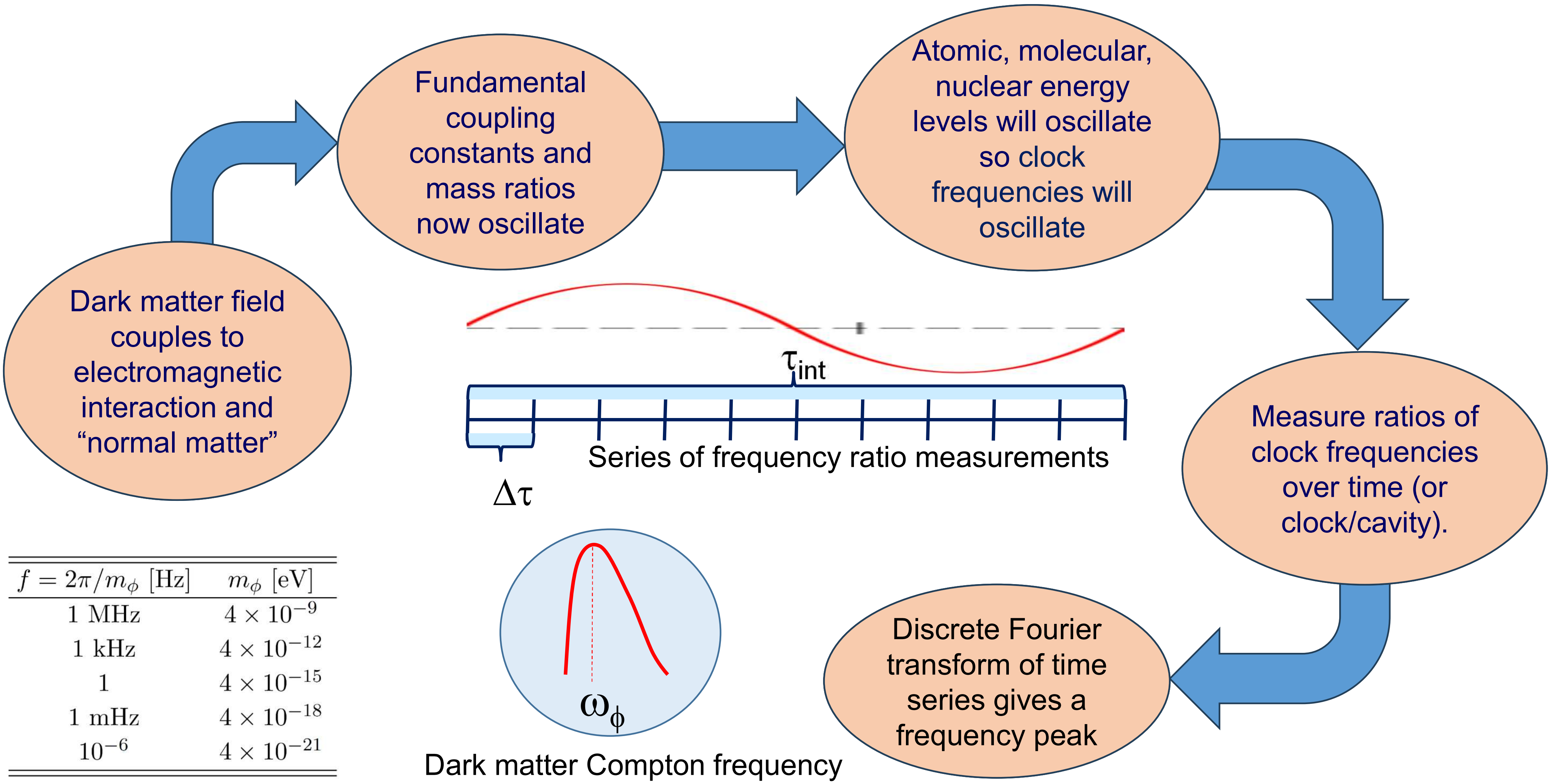
Clock with 8×10^{-19} Systematic Uncertainty

Alexander Aeppli,[1,*] Kyungtae Kim,[1] William Warfield,[1] Marianna S. Safronova,[2] and Jun Ye[1,†]



Future: (entangled) clocks on curved space time

How to detect ultralight dark matter with clocks?

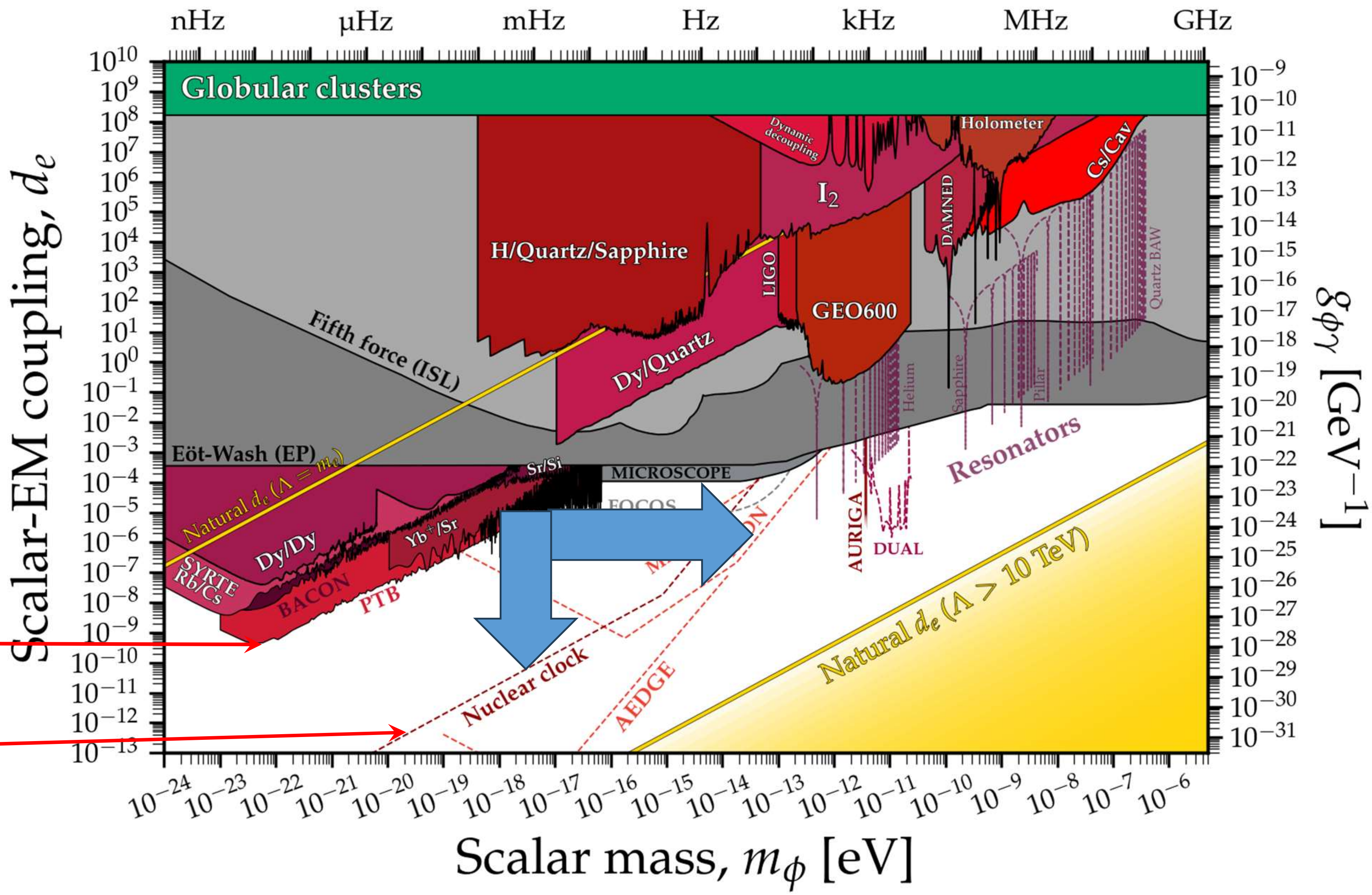


$f = 2\pi/m_\phi$ [Hz]	m_ϕ [eV]
1 MHz	4×10^{-9}
1 kHz	4×10^{-12}
1	4×10^{-15}
1 mHz	4×10^{-18}
10^{-6}	4×10^{-21}

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

Present
clock limits

Projected
clock limits

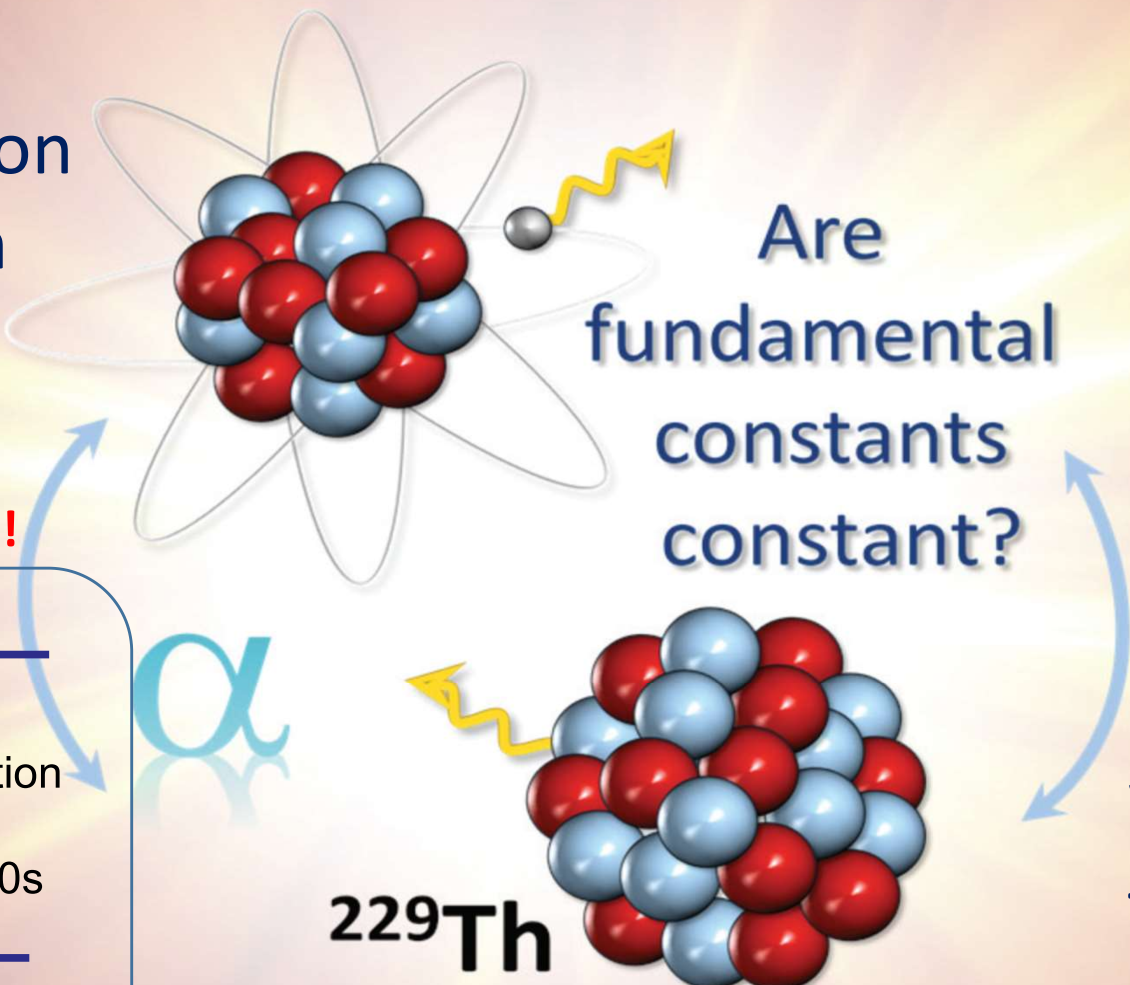


arXiv:2203.14915

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

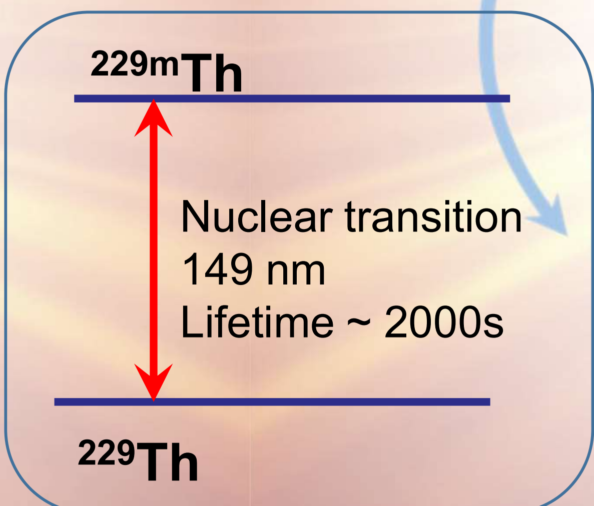
From atomic to nuclear clocks!

Clock based on transitions in atoms



Are fundamental constants constant?

Only ONE exception!



What about transitions in nuclei?

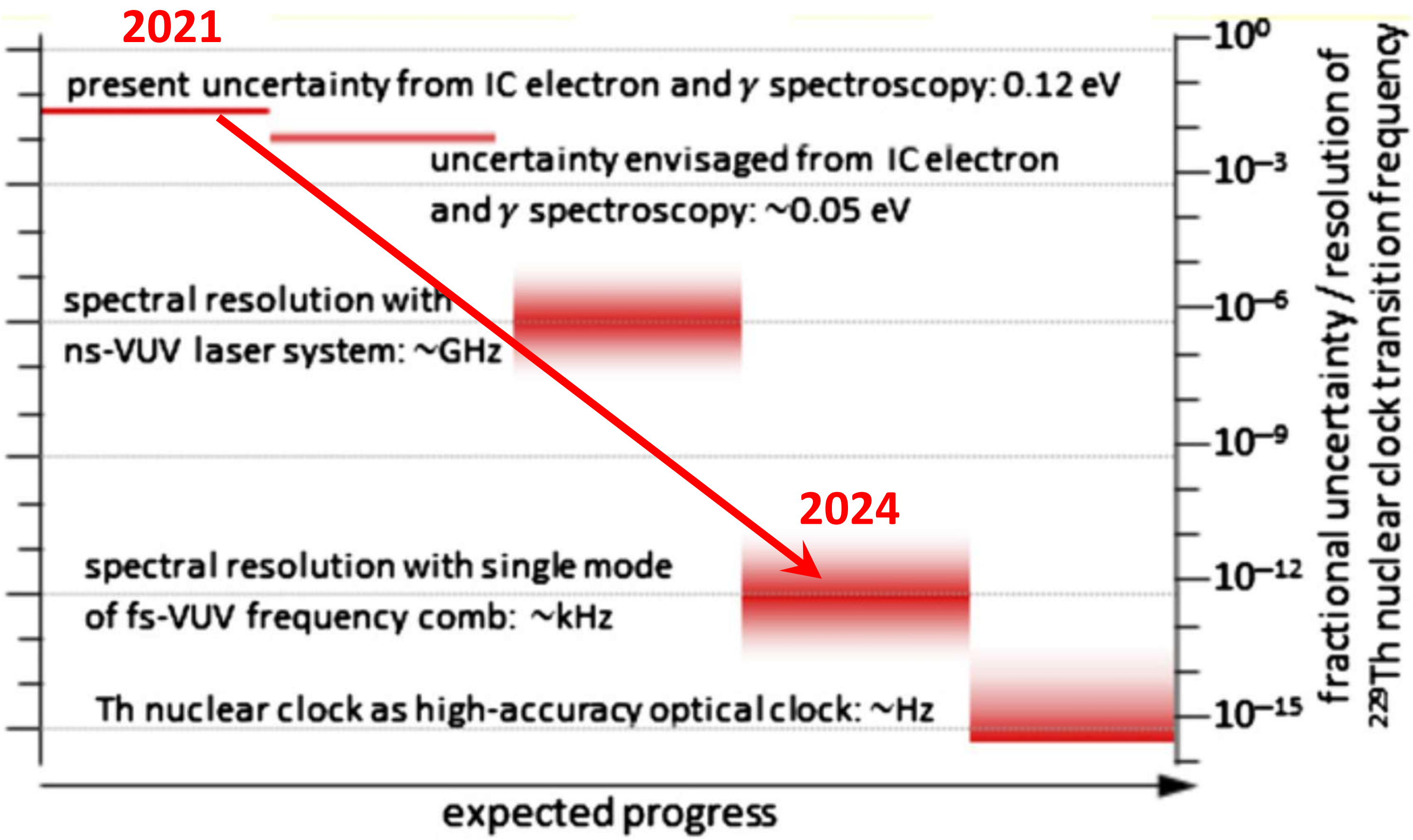
Picture from: M. S. Safronova, Annalen der Physik 531, 1800364 (2019)

How to build a nuclear clock?

Nature 617, 706 (2023)

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

Nature 633, 63 (2024)
2 020 407 384 335(2) kHz

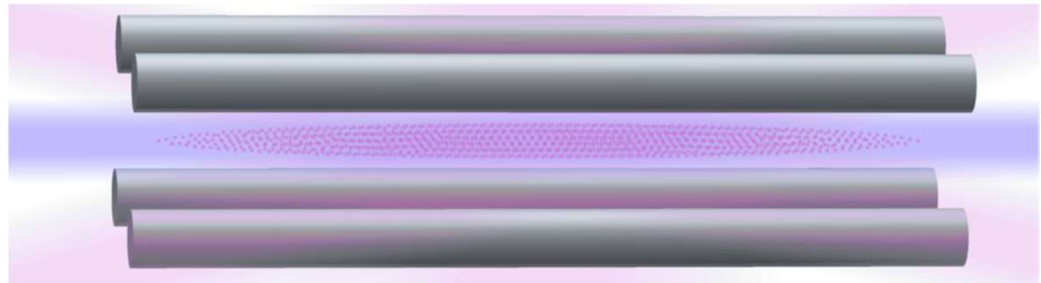


Quantum Science and Technology 6, 034002 (2021)

Stability, entanglement, and fundamental physics

Clocks with large scale ion Coulomb crystals

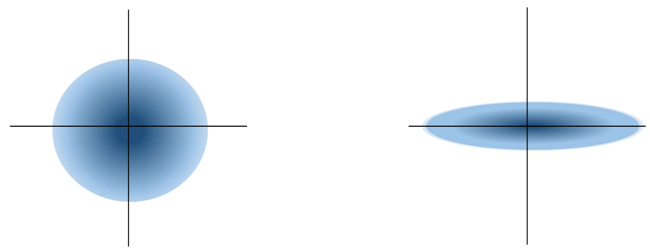
$$\frac{1}{\sqrt{\text{number of atoms}}}$$



From Nature Communications 15, 5663 (2024)

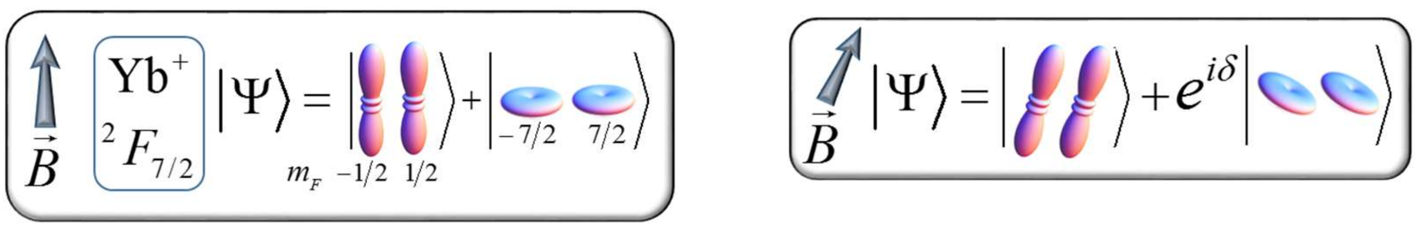
Measurements beyond the standard quantum limit

LIGO, HAYSTAC (axion search, improve scan rate)



Entangled ions

$$\frac{1}{\text{number of atoms}}$$



Example: Searching for Lorentz violation: Nature Physics 12, 465 (2016)

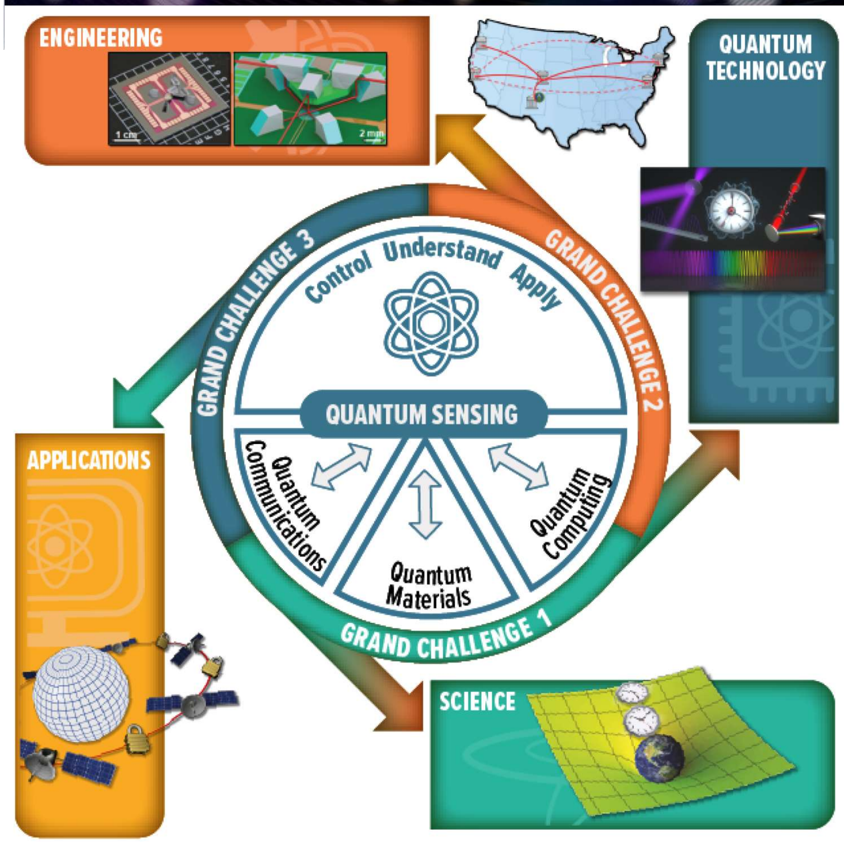
Future: using entanglement as a new resource for fundamental physics (for tests of gravity/quantum interface)

Q-SEnSE: Quantum Systems through Entangled Science and Engineering

An NSF Quantum Leap Challenge Institute

Spooky Quantum to Solve Real-world Problems

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



In the Q-SEnSE institute, prominent quantum researchers in experiment and theory, science and engineering, from around the U.S. and internationally, collaborate to explore how advanced quantum sensing can discover new fundamental physics, develop and apply novel quantum technologies, provide tools for a national infrastructure in quantum sensing, and train a quantum savvy workforce.

41 PIs and Senior Investigators,
15 Institutions and National Labs

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

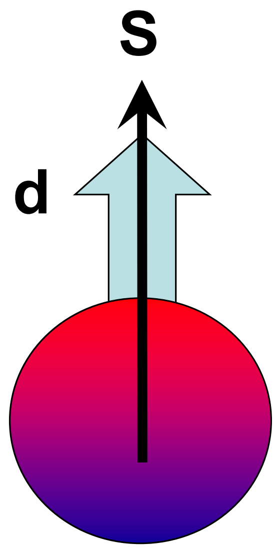
Searches for exotic forces

General relativity and gravitation

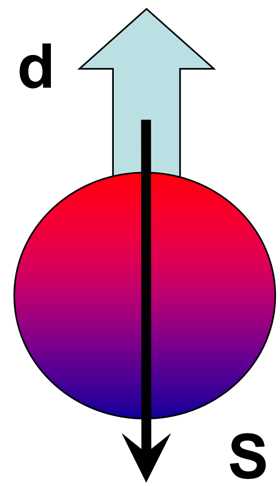
Search for violations of quantum statistics

Permanent electric-dipole moment (EDM)

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



$$t \rightarrow -t$$
$$\vec{\mathbf{S}} \rightarrow -\vec{\mathbf{S}}$$
$$\vec{\mathbf{d}} \rightarrow \vec{\mathbf{d}}$$



$$\vec{\mathbf{d}} = d\,\frac{\vec{\mathbf{S}}}{S}$$
$$d = 0$$

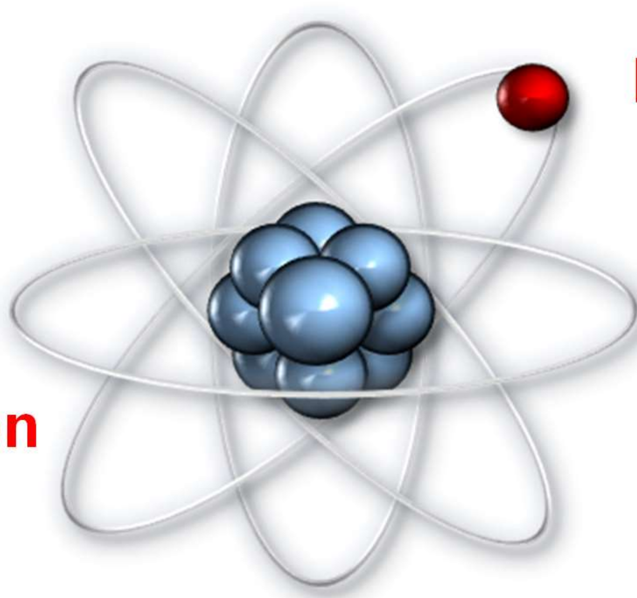
Matter – antimatter asymmetry: need new sources of CP- (T-) violation

Look for EDMs as a signature of TeV scale physics (supersymmetry, etc.)

Sources of atomic and molecular EDMs

Paramagnetic atoms
Cs, Tl, **Fr**
Molecules
YbF, ThO, HfF^+, ThF^+,**RaF**
YbOH, **RaOH**

P, T – violating electron-nucleon interaction



Electron EDM

Nucleon EDM

P, T – violating nucleon- nucleon interaction

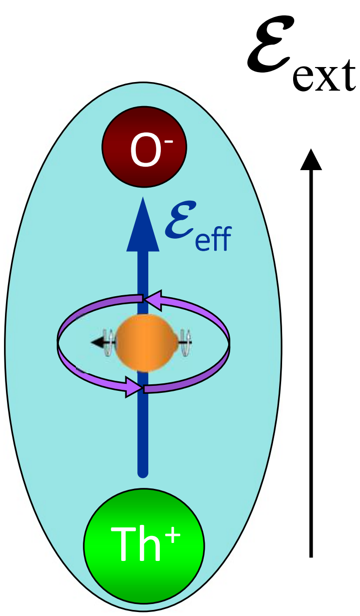
Neutron

Diamagnetic atoms
Hg, Xe, **Ra, Rn**
Molecules
TlF

Need heavy atom or a molecule with a heavy atom for larger effect

Pathway to probing extreme energy scales

$$\Delta E_{\mathrm{EDM}}/2 = |\vec{d}_e \cdot \vec{\mathcal{E}}_{\mathrm{eff}}|$$



Picture courtesy of Dave DeMille

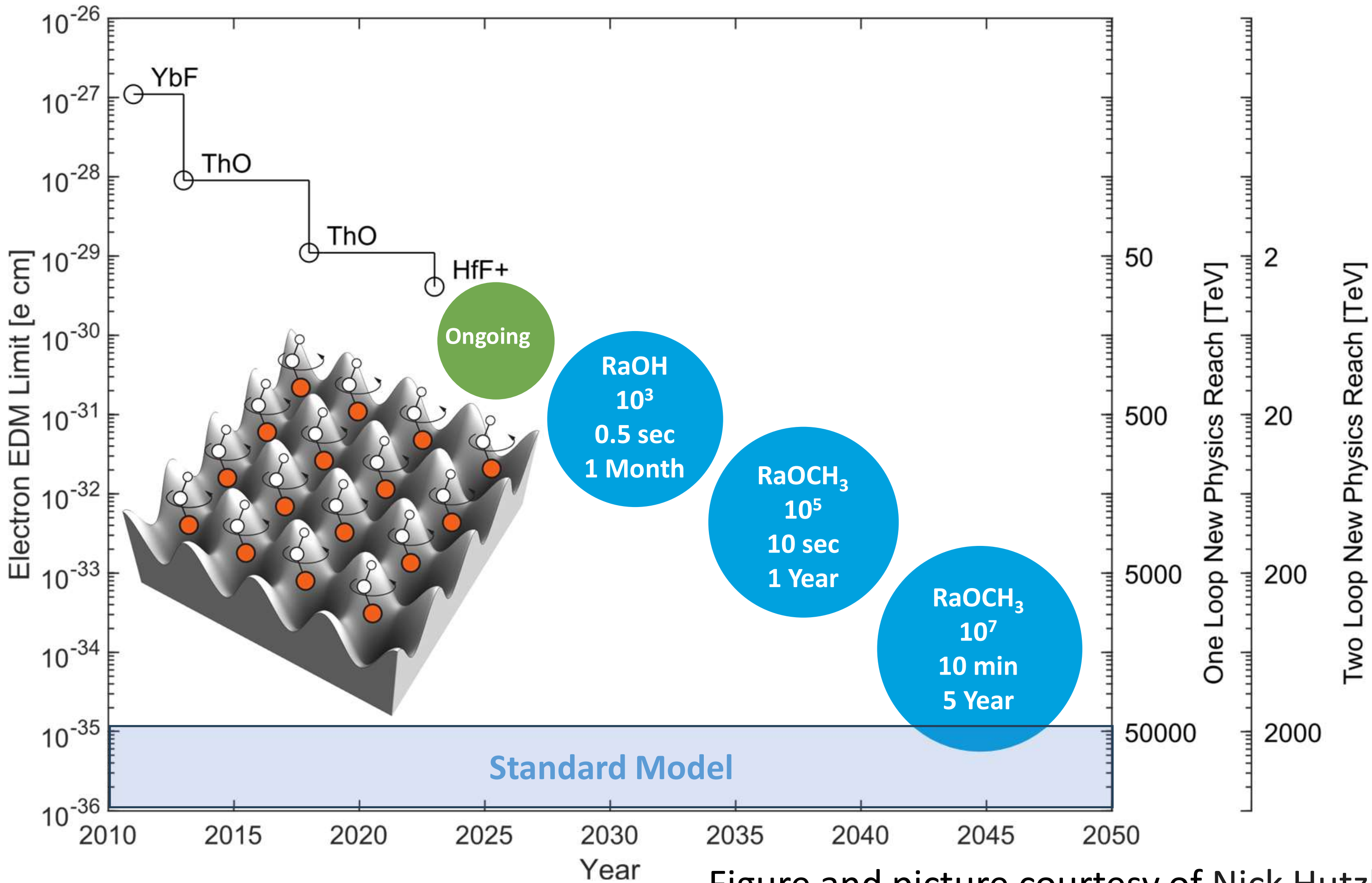
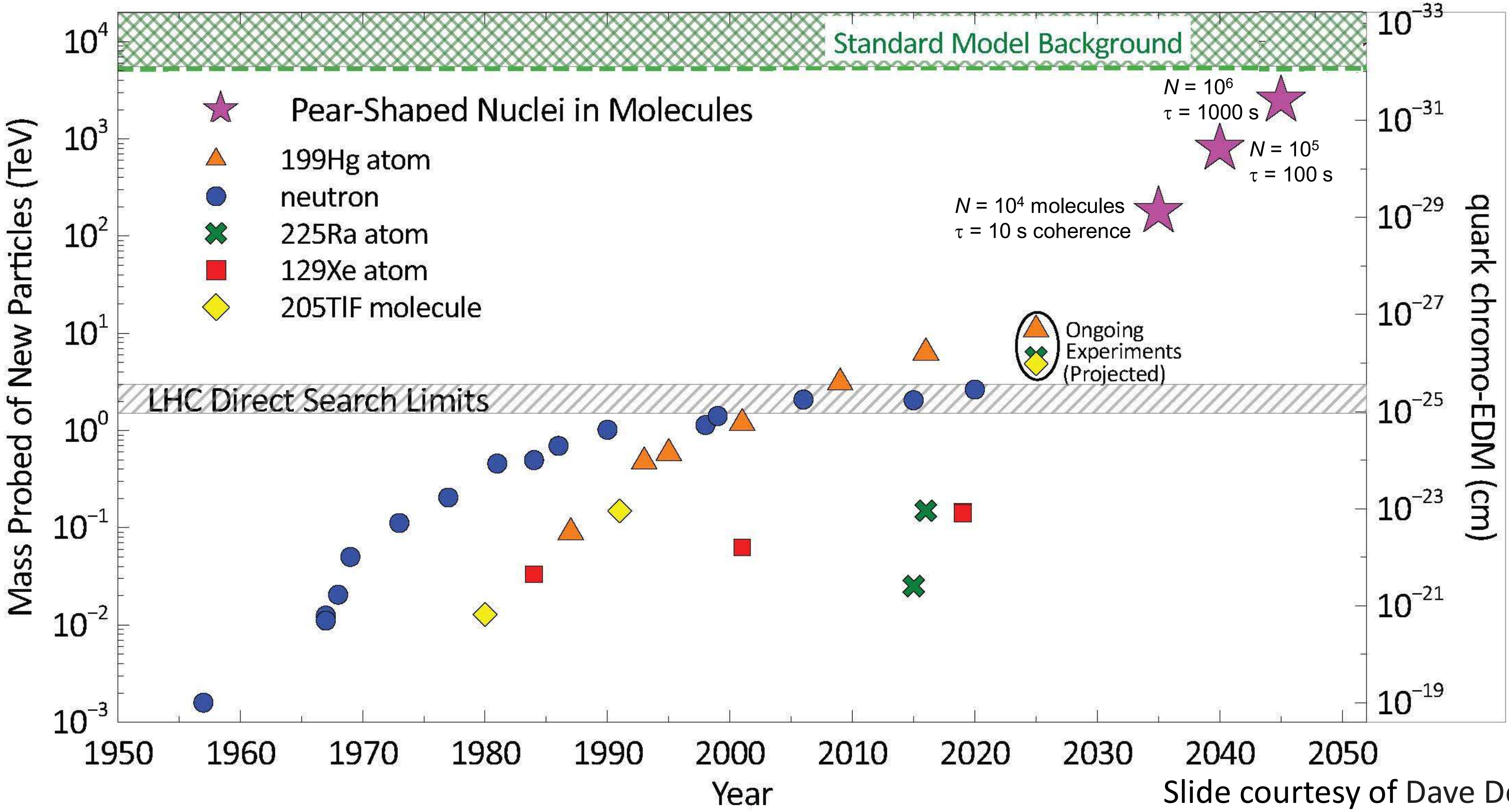


Figure and picture courtesy of Nick Hutzler

Trajectory: probing >1000 TeV with chromo-EDMs



Slide courtesy of Dave DeMille

Quantum technologies for space research

What quantum technologies will be sent to space?
What new physics can one search for in space better then on Earth?

Key Science question: What new physics, including particle physics, general relativity, and quantum mechanics, can be discovered with experiments that can only be carried out in space?

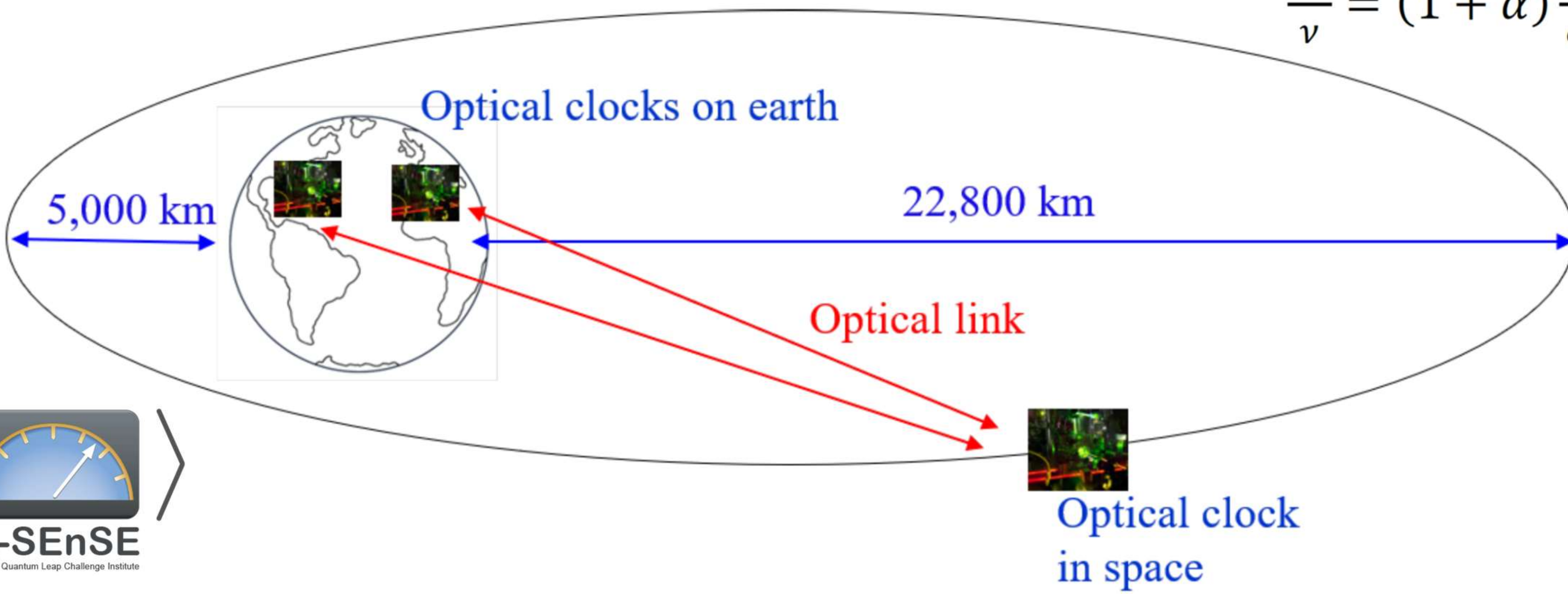
MULTI-AGENCY OPPORTUNITY: PROBING THE FABRIC OF SPACETIME
Initial R&D thrusts are to develop space-rated, quantum technology optical lattice clocks.
Goals: testing relativistic gravity, searching for violations of fundamental symmetries, searching for additional fundamental forces, and searching for time-variations of the fundamental constants. Probing the hidden nature of the universe by searching for dark matter and dark energy and other exotic low-mass fields. Testing whether the gravitational field has quantum aspects.

- May 2023: Establishment of NASA Fundamental Physics Analysis group https://www.jpl.nasa.gov/go/funpag
- MS will lead Review of Modern Physics (approved) on Opportunities for fundamental physics discovery in space with quantum sensors
- European efforts: Cold Atoms in Space: Community Workshop Summary and Proposed Road-Map, Ivan Alonso et al., EPJ Quantum Technol. 9, 30 (2022)
- ESA ACES (cold microwave clock on ISS) mission expected launch April 2, 2025

Fundamental Physics with a State-of-the-Art Optical Clock in Space

Andrei Derevianko, Kurt Gibble, Leo Hollberg, Nathan R. Newbury, Chris Oates, Marianna S. Safronova, Laura C. Sinclair, Nan Yu, Quantum Sci. Technol. 7, 044002 (2022)

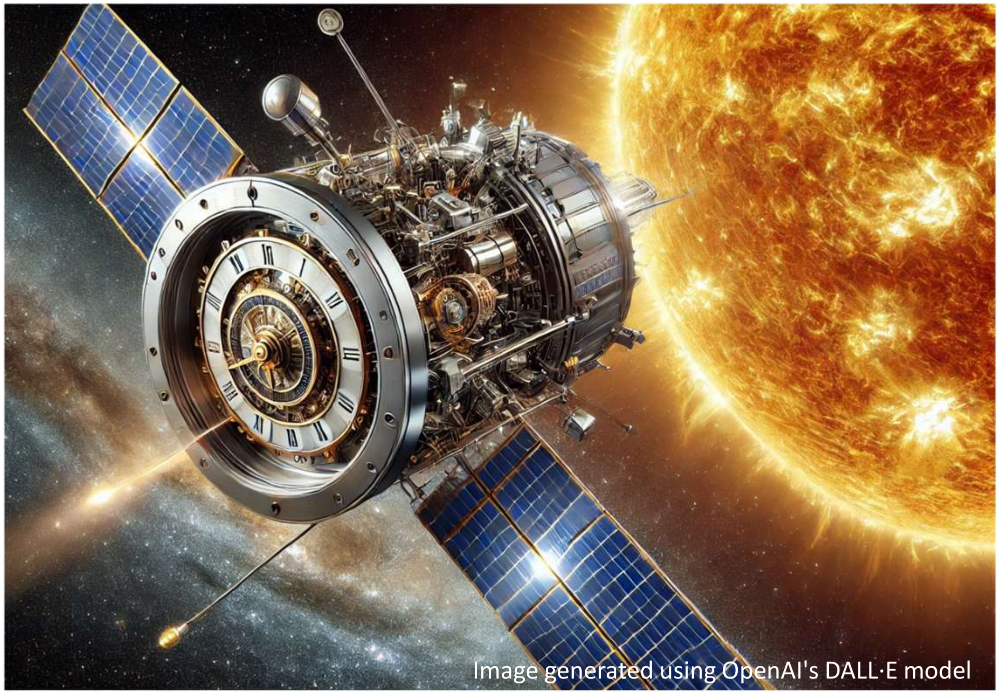
$$\frac{\Delta\nu}{\nu} = (1+\alpha)\frac{\Delta U}{c^2}$$

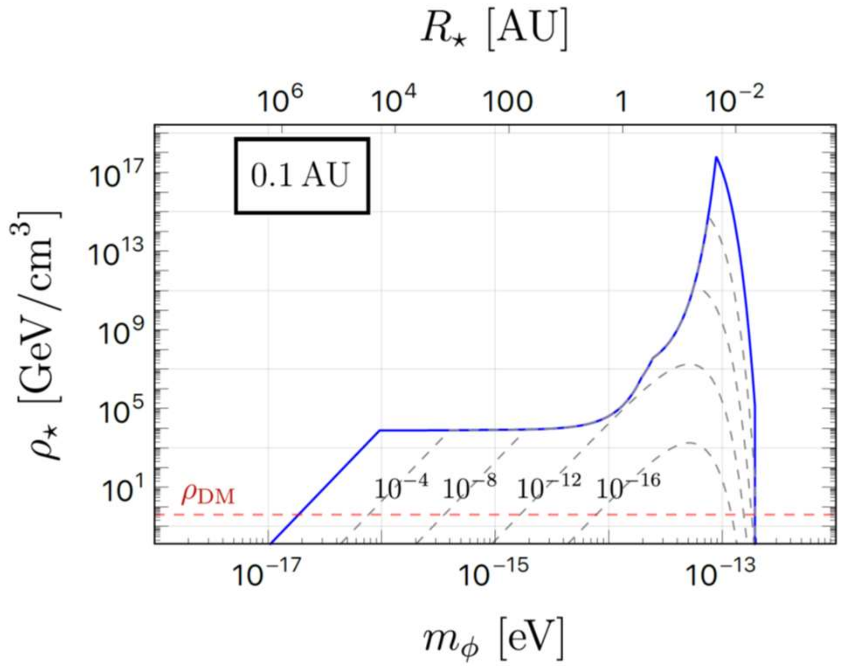


Q-SEnSE
An NSF Quantum Leap Challenge Institute

Schematic of the proposed mission to test Fundamental physics with an Optical Clock Orbiting in Space (FOCOS)

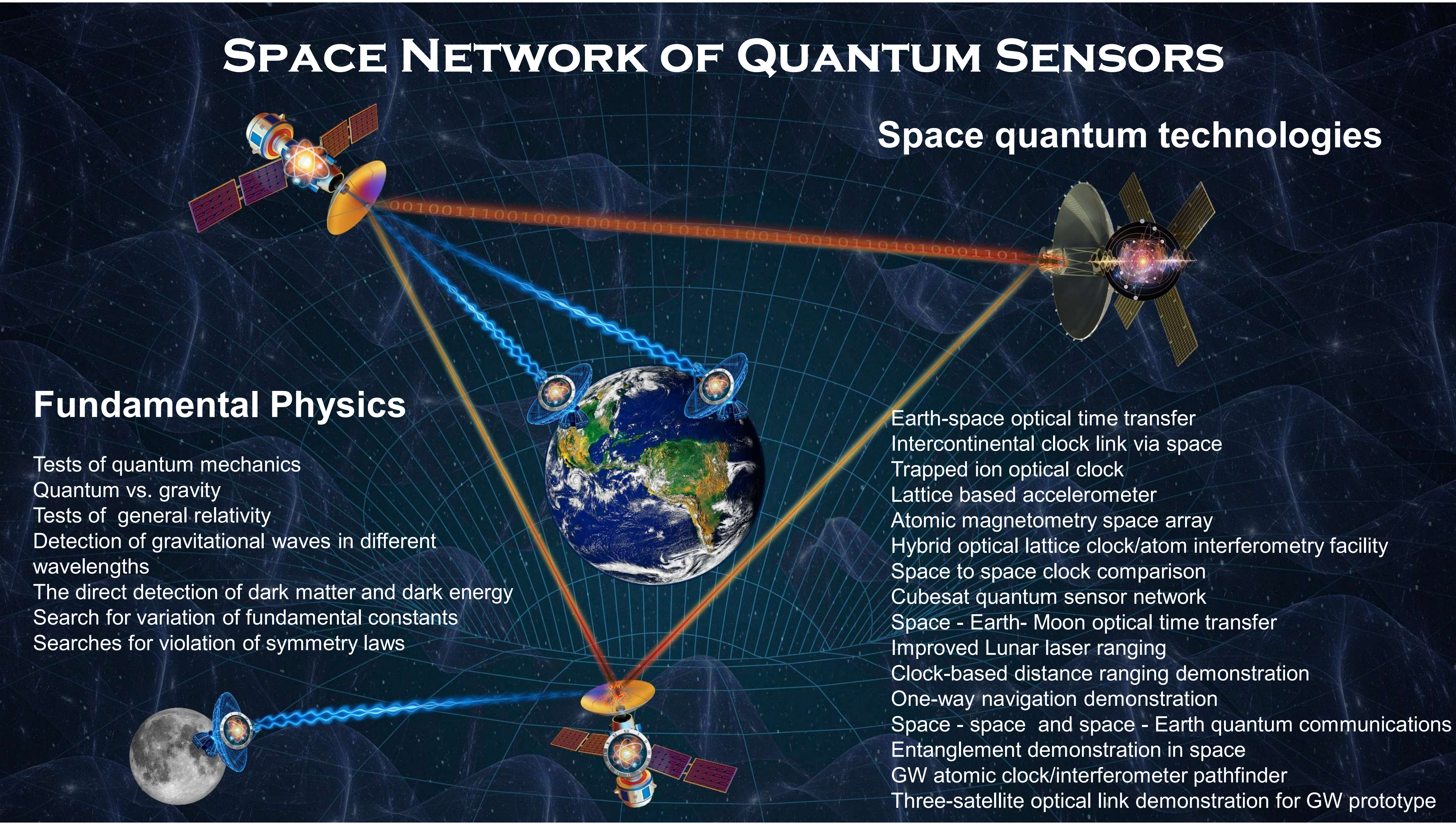
Direct detection of ultralight dark matter bound to the Sun and Jupiter with space quantum sensors





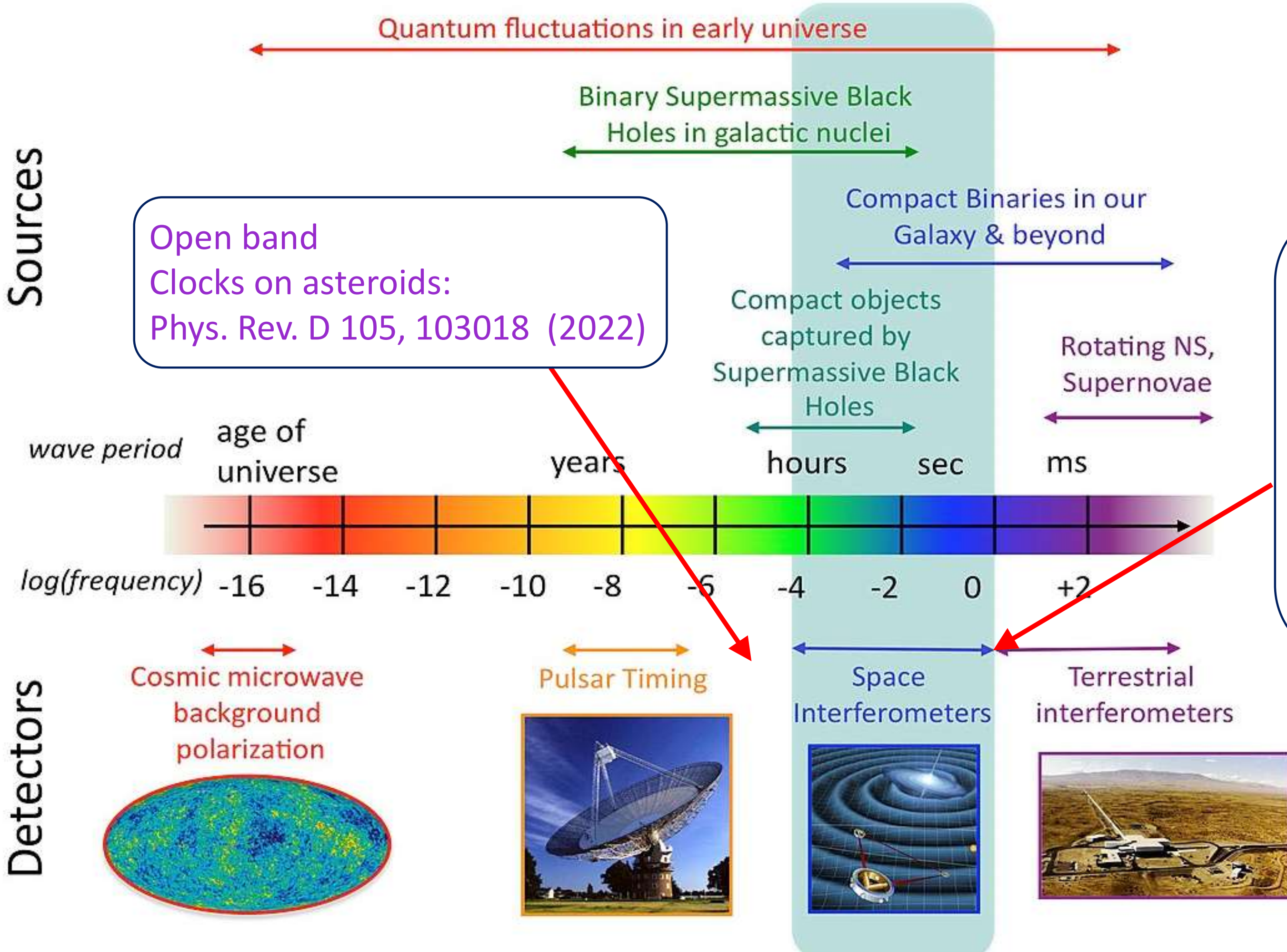
We propose a clock-comparison satellite mission with two clocks onboard, to the inner reaches of the solar system (0.1 AU) to search for the dark matter halo bound to the Sun.

Yu-Dai Tsai, Joshua Eby, M. S. Safronova, Nature Astronomy 7, 113 (2023).
Dmitry Budker, Joshua Eby, M. S. Safronova, Oleg Tretiak, arXiv:2408.10324 (2024).


Space Network of Quantum Sensors
Space quantum technologies
Fundamental Physics
Tests of quantum mechanics
Quantum vs. gravity
Tests of general relativity
Detection of gravitational waves in different wavelengths
The direct detection of dark matter and dark energy
Search for variation of fundamental constants
Searches for violation of symmetry laws
Earth-space optical time transfer
Intercontinental clock link via space
Trapped ion optical clock
Lattice based accelerometer
Atomic magnetometry space array
Hybrid optical lattice clock/atom interferometry facility
Space to space clock comparison
Cubesat quantum sensor network
Space - Earth- Moon optical time transfer
Improved Lunar laser ranging
Clock-based distance ranging demonstration
One-way navigation demonstration
Space - space and space - Earth quantum communications
Entanglement demonstration in space
GW atomic clock/interferometer pathfinder
Three-satellite optical link demonstration for GW prototype

Towards probing the entire gravitational wave spectrum

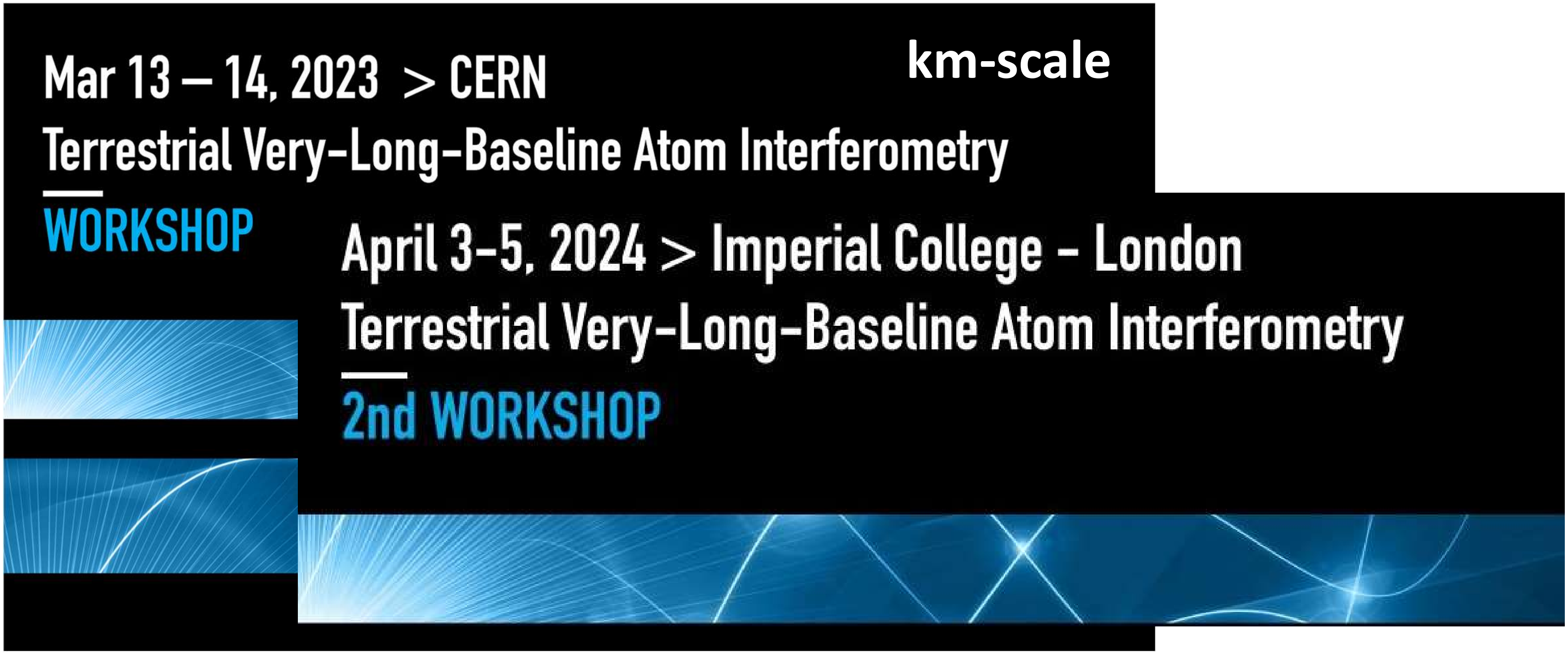
Open band
Clocks on asteroids:
Phys. Rev. D 105, 103018 (2022)



Atomic interferometry
(MAGIS, clocks, MIGA, AION…)
Terrestrial and space-based

MAGIS-100 is a 100 meter atom interferometry gravitation wave detector prototype is under construction at Ferrmlab

Picture credit: NASA Goddard Space Flight Center - http://science.gsfc.nasa.gov/663/research/index.html



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).

University of Delaware is member of the Proto collaboration 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.

2024

SOLVING PHYSICS PROBLEMS OF 1924 GAVE US QUANTUM MECHANICS – A FOUNDATION OF MODERN TECHNOLOGY.

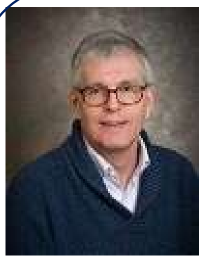
QUANTUM TECHNOLOGIES WILL CONTINUE RAPIDLY IMPROVE OPENING NEW PATHWAYS TO FUNDAMENTAL PHYSICS PARADIGM-SHIFTING DISCOVERIES.

WHAT NEW TECHNOLOGIES DISCOVERY OF NEW PHYSICS WILL BRING?

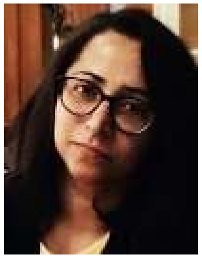
2124 … ?

UD team and collaborators

Online portal team



Prof. Rudolf Eigenmann
UD (EECS)



Prof. Bindiya Arora
Perimeter Institute

Parinaz Barakhshan
UD (CE)
Grad. St.

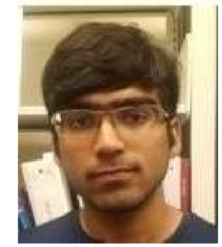
Adam Marrs
UD (Physics)
Graduated August 2021

Akshay Bhosale
UD (CE)
Grad. St.

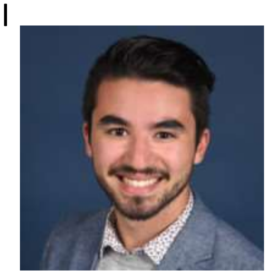
Dr. Sergey Porsev
Research Associate III

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!