PANEL ON HELIOPHYSICS, PHYSICS, AND PHYSICAL SCIENCE

June 11, Keck Center

Quantum Technologies in Space for New Physics Discoveries

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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

1925

2025

100 YEARS AGO

WE DID NOT KNOW WHAT ATOMS ARE MADE OF

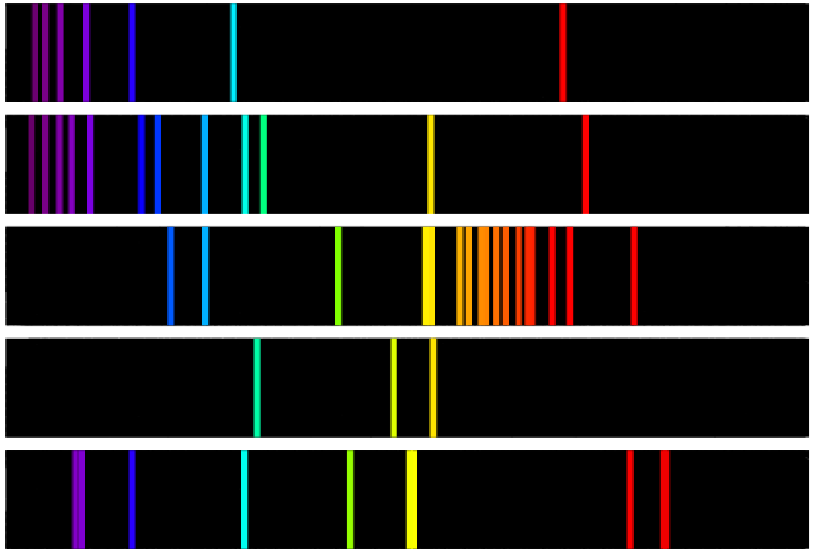
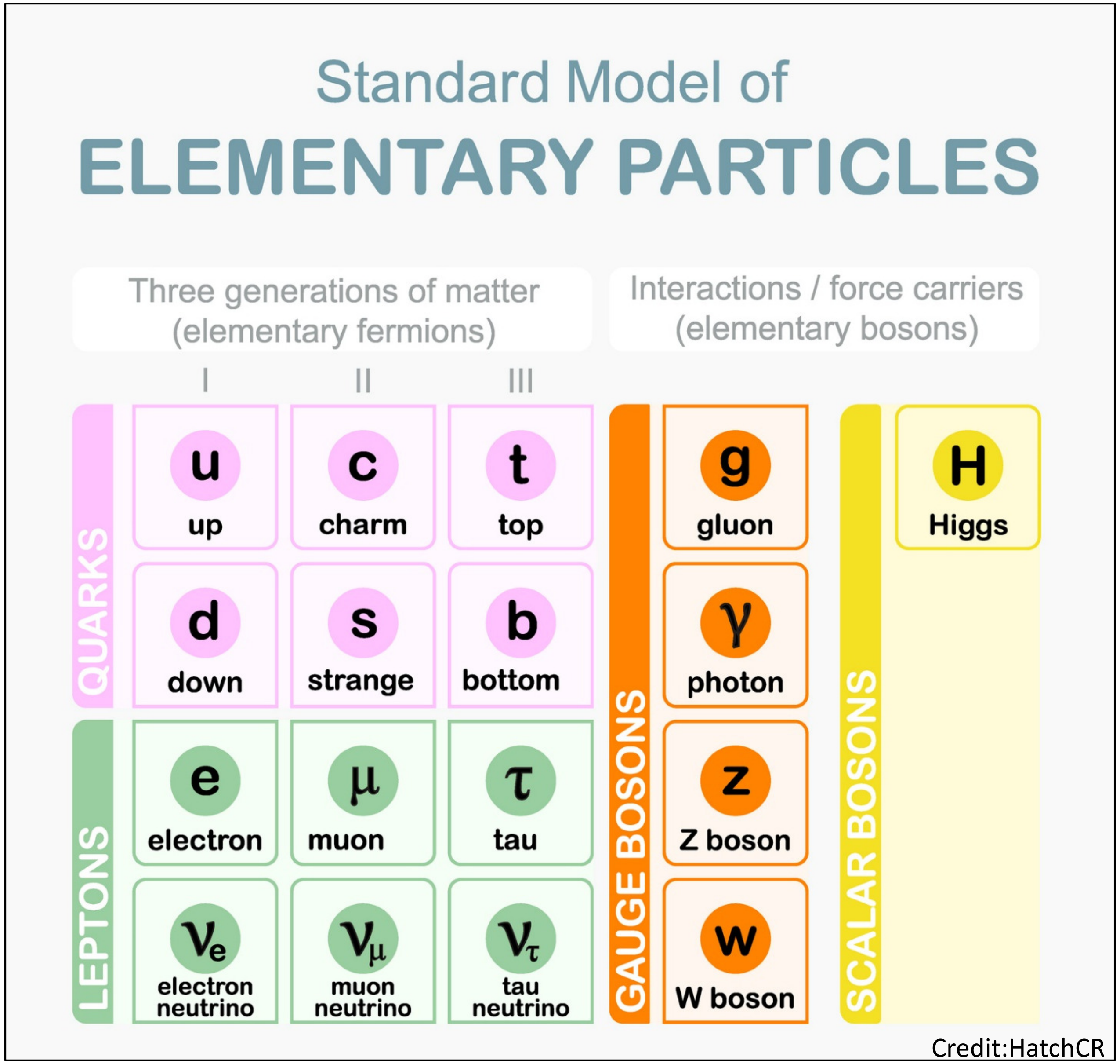


Figure credits: Entropy 2017, 19, 186, practical-chemistry.com



2025: Problems with the standard model

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

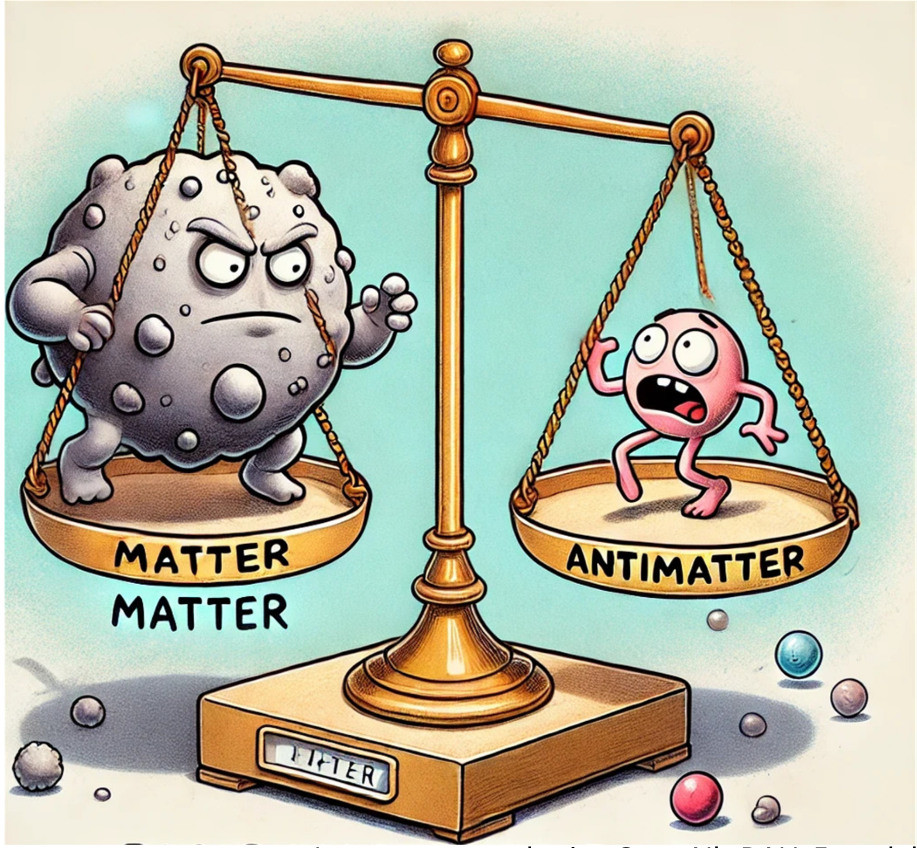
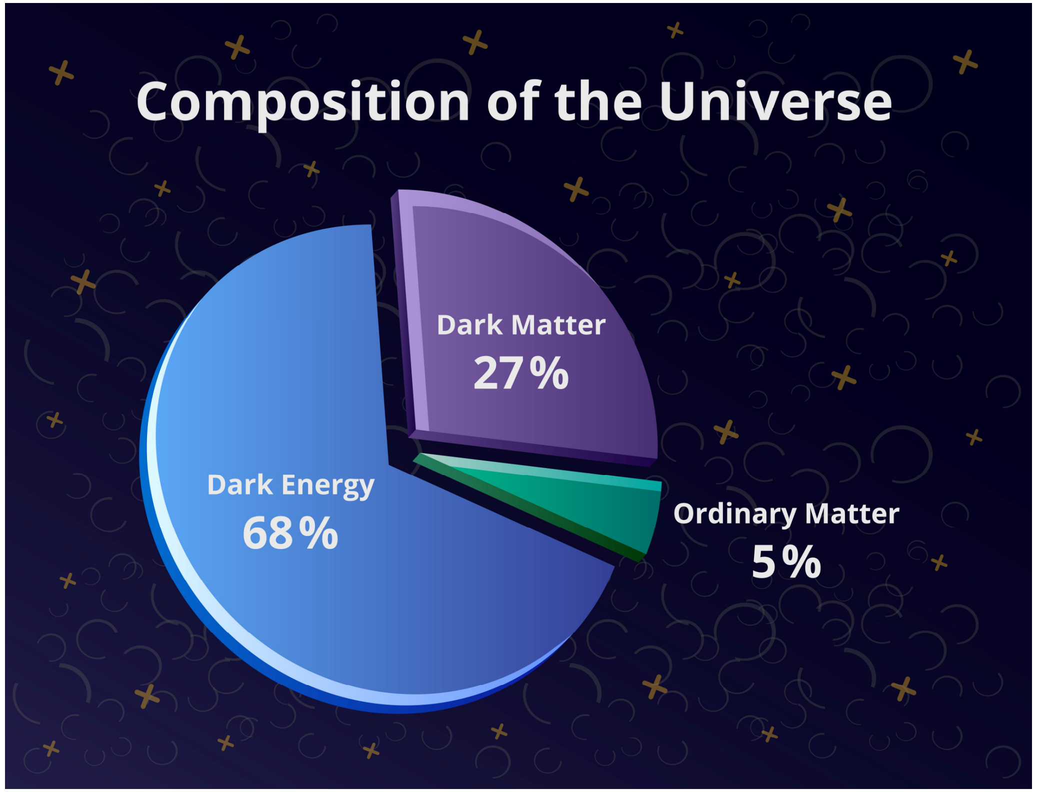


Image generated using OpenAI's DALL·E model



- 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

Revolution in atomic physics: the path to quantum sensors

1997 Nobel Prize
Laser cooling and trapping

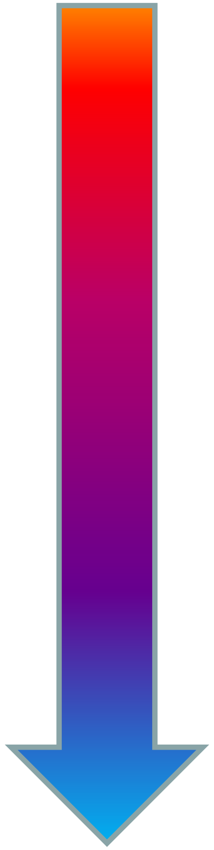
2001 Nobel Prize
Bose-Einstein Condensation

2005 Nobel Prize
Frequency combs

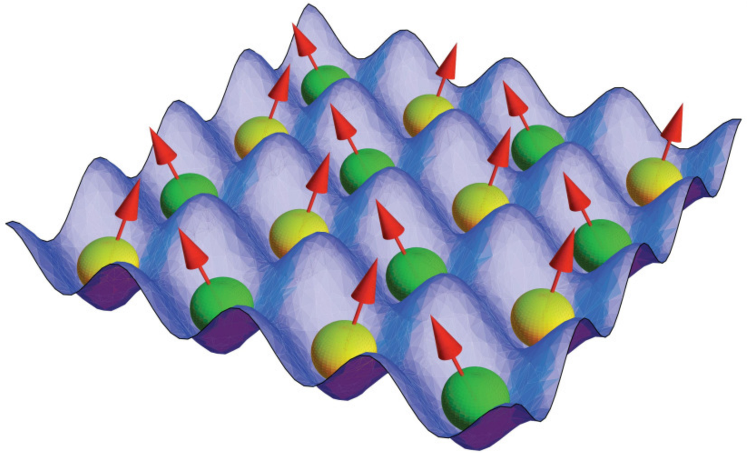
2012 Nobel prize
Quantum control

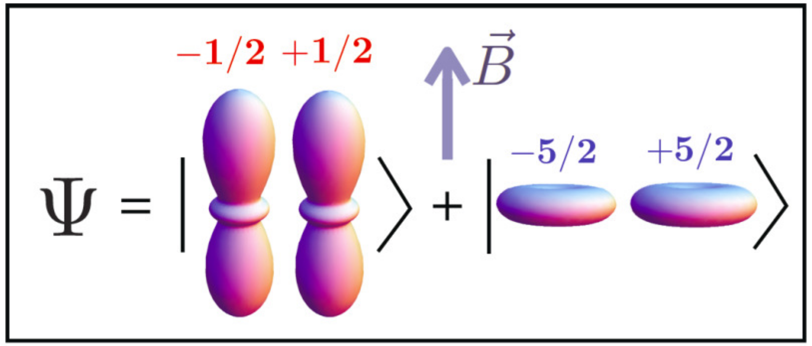
2022 Nobel prize
Bell inequalities, quantum information science

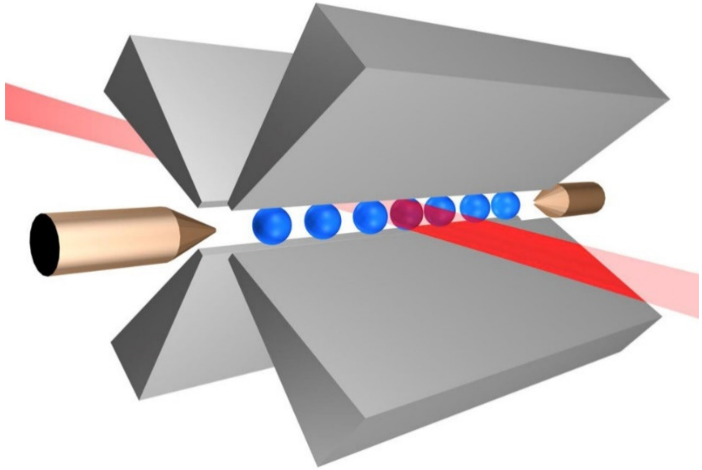
300K

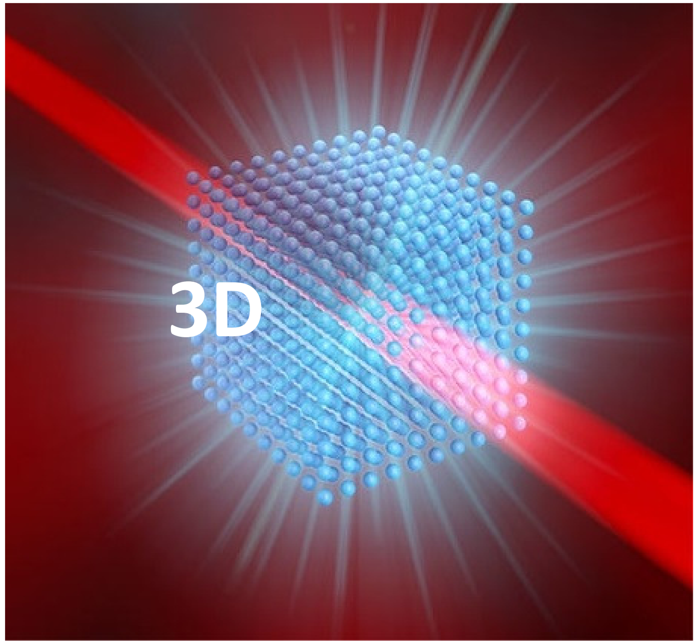


pK









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

Image credits: JILA, U. Innsbruck

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

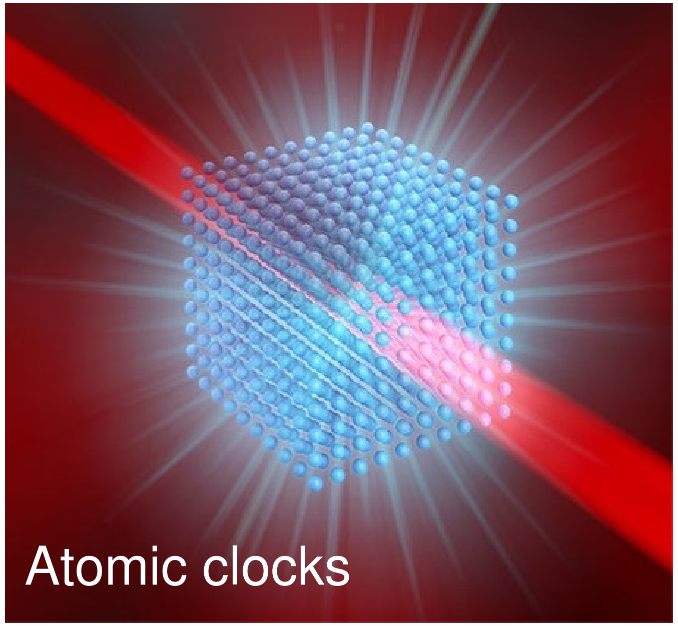
https://iopscience.iop.org/journal/2058-9565/page/Focus-on-Quantum-Sensors-for-New-Physics-Discoveries

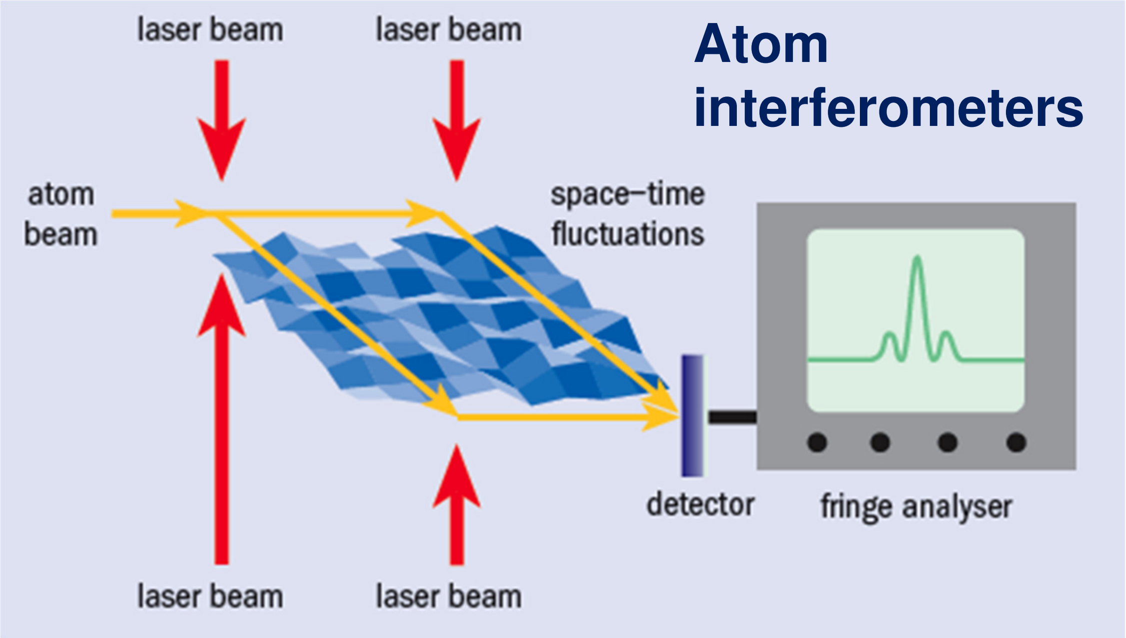
Editorial:

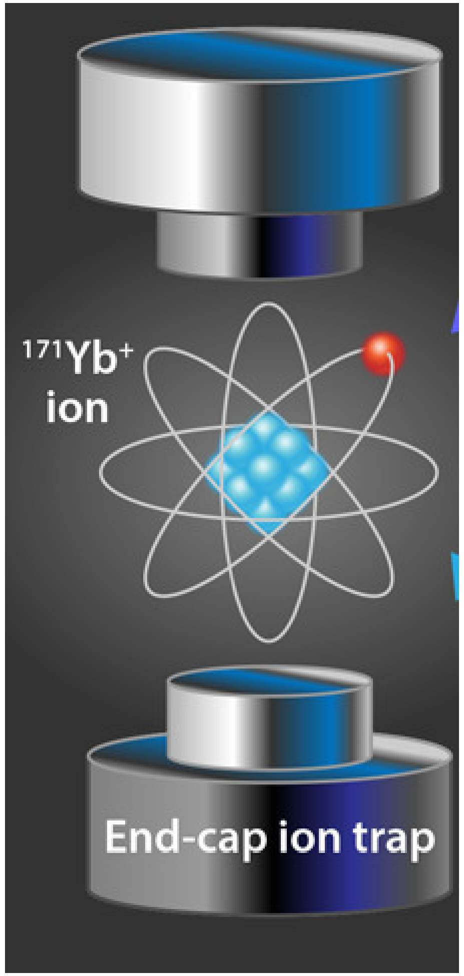
Quantum technologies and the elephants, M. S Safronova and Dmitry Budker, Quantum Sci. Technol. 6, 040401 (2021).

"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***. "

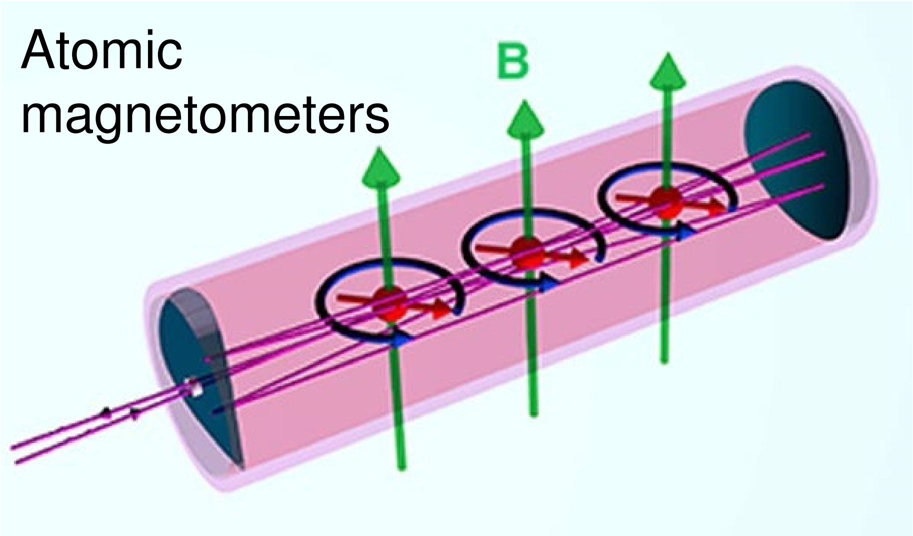
2025 100 YEARS LATER: QUANTUM SENSORS







Trapped ions



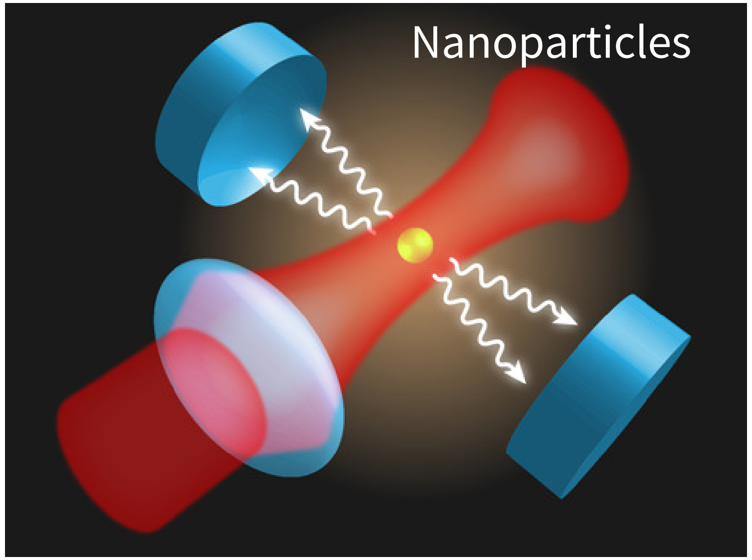
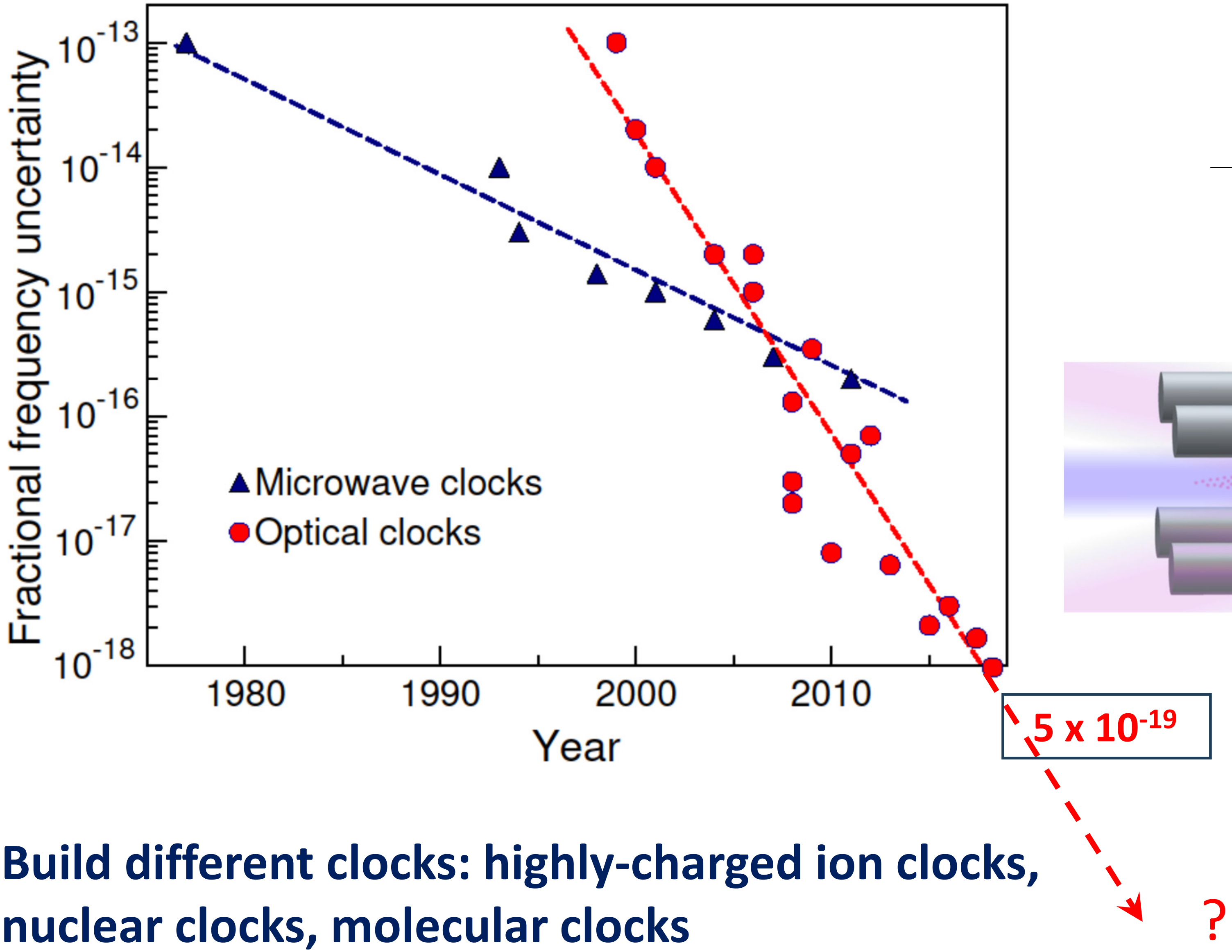
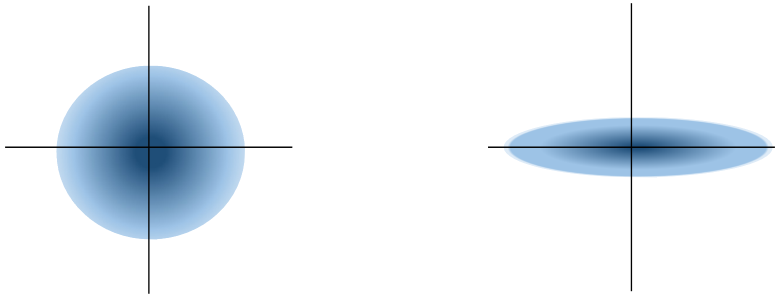


Image credit: JILA, APS/Alan Stonebraker, https://cerncourier.com/a/can-experiment-access-planck-scale-physics/, http://physicsworld.com/cws/article/news/2013/apr/24

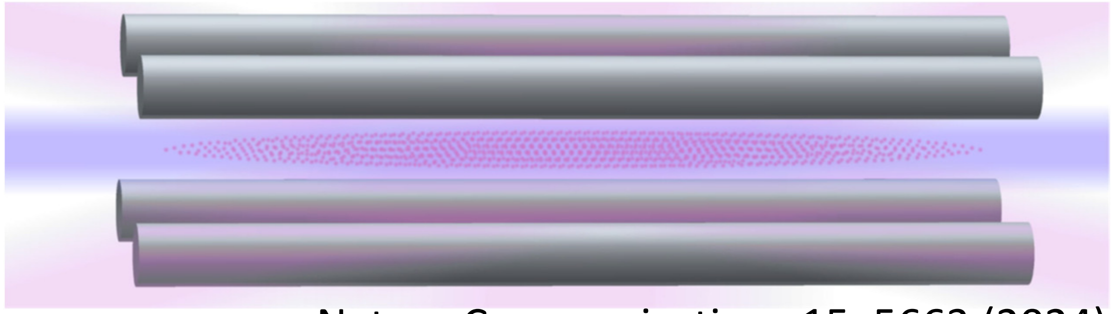
Advances in optical atomic clocks



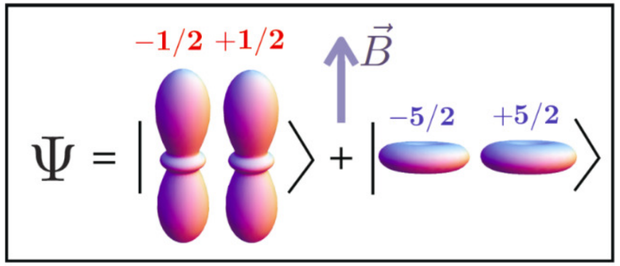
Measurements beyond the quantum limit



Large ion crystals



Nature Communications 15, 5663 (2024)



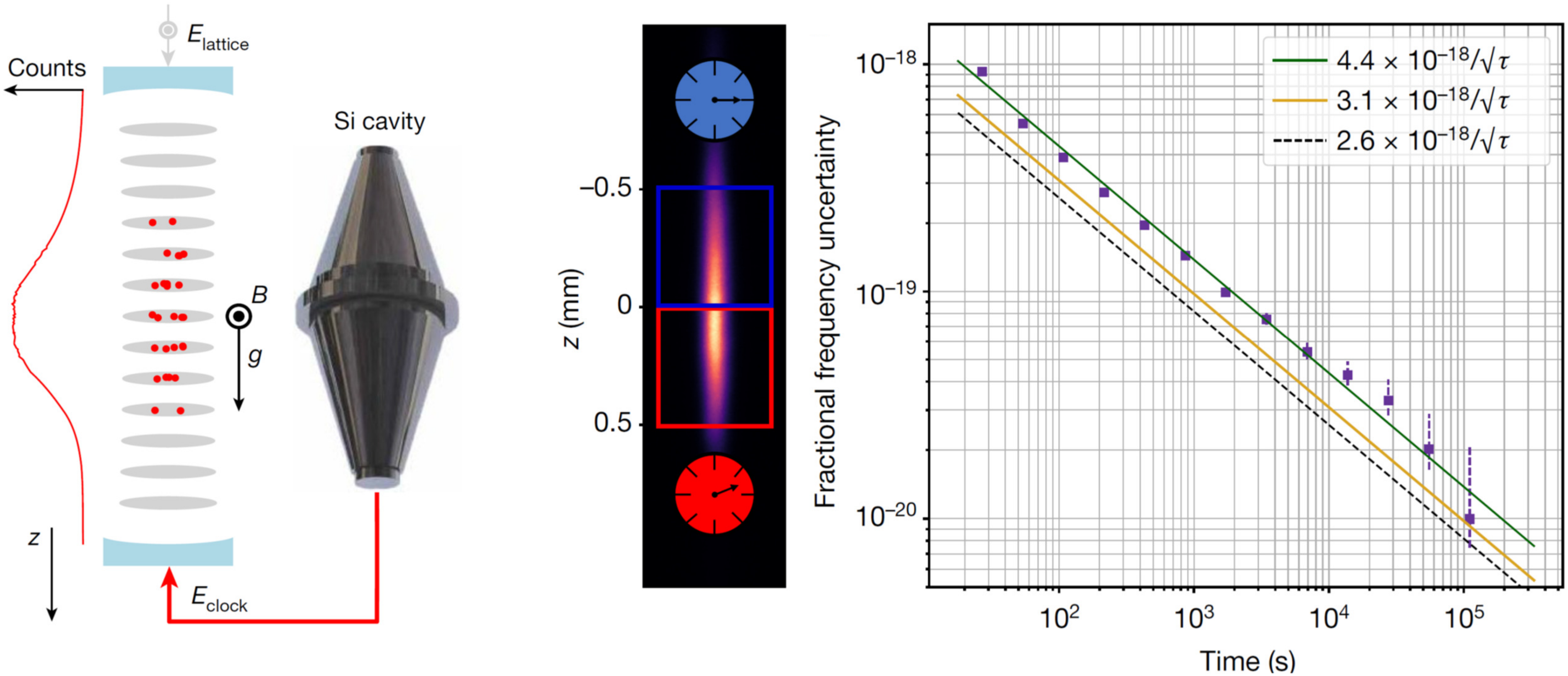
Entangled clocks

Build different clocks: highly-charged ion clocks, nuclear clocks, molecular clocks

Fantastic progress in optical clock stability

Resolving the gravitational redshift across a millimetre-scale atomic sample,

T. Bothwell, Kennedy, C., Aeppli, A., Kedar, D., Robinson, J., Oelker, E., Staron, A., and Ye, J., Nature 602, 420 (2022).



10^{-18} was reached in a few seconds!

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.

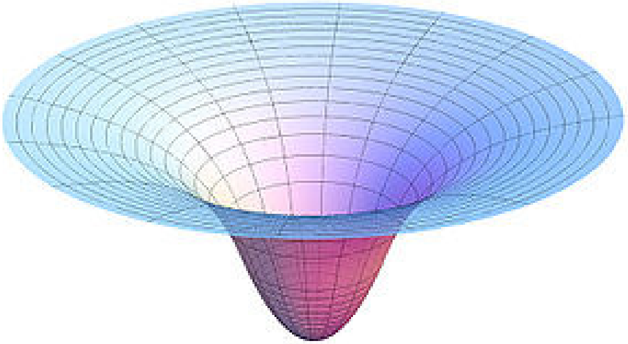
Goals: testing relativistic gravity, searching for violations of fundamental symmetries, searching for additional fundamental forces, and searching for time-variations of the fundamental constants. Probing the hidden nature of the universe by searching for dark matter and dark energy and other exotic 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 launched April 2025

Why to search for new physics in space?

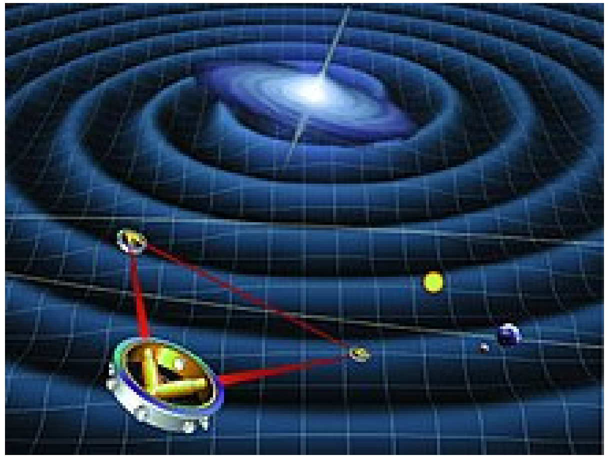
Quantum sensors in space enables discovery of new physics not possible on Earth
Many orders of magnitude improvements or principally different experiments are possible

Need to be away from Earth surface

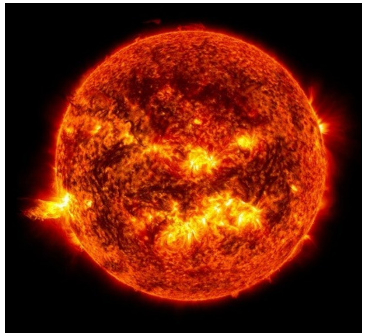


Tests of gravity are hindered by Earth gravity
Optical time transfer to link Earth clocks
Dark energy and some dark matter (screening)
Tests of fundamental postulates (WEP, LLI)

Need access to **variable gravitational potentials**



Long baselines: gravitational waves, dark matter (especially transients), dark energy



Sun: Dark matter halo bound to the Sun? Extreme overdensities possible
Moon: laser ranging, low seismic activity, permanent cryogenic environment
Asteroids: test masses

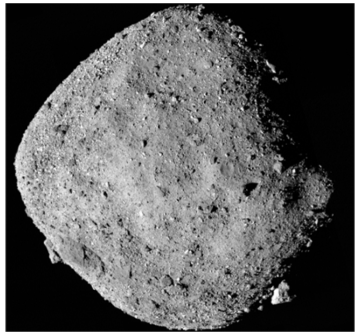
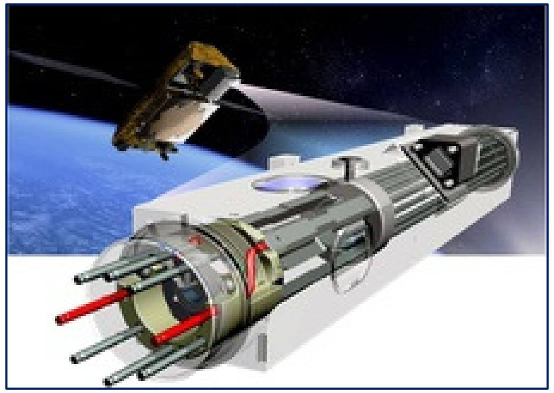


Image credits: NASA, Wikipedia

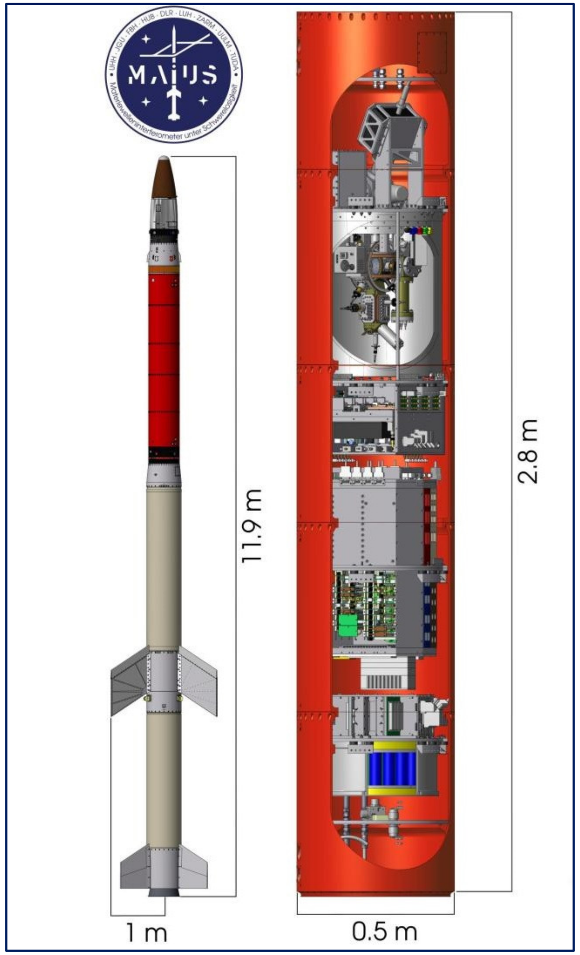
Quantum technologies in space

GPS, “hot” atoms, Microwave, Cs or Rb

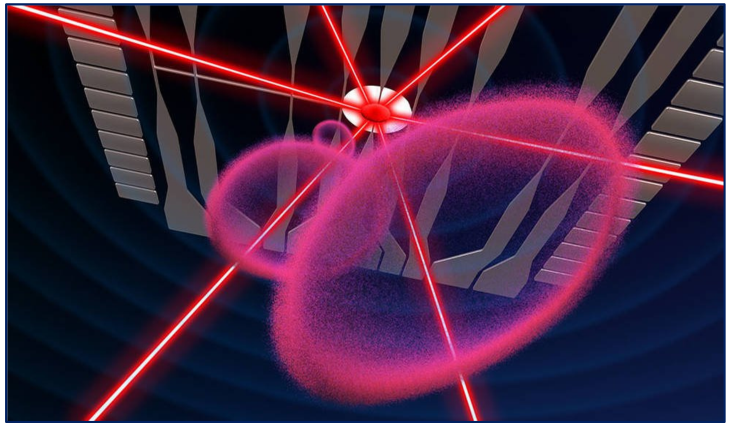
2017 CACES (Tiangong-2), China, microwave Rb cold atom clock



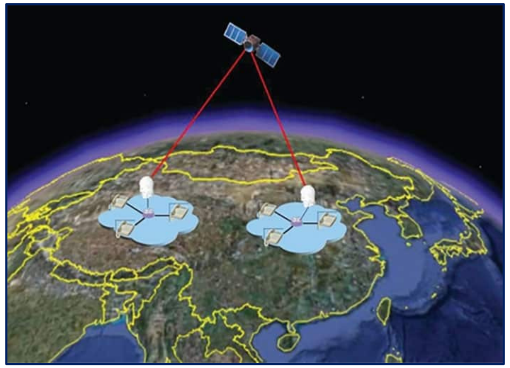
2019 NASA Deep Space Atomic Clock (DSAC), microwave, Hg^+ ions



2016 MAUS-1 sounding rocket, cold Rb atoms, BEC, atom interferometry, DLR



2018, Cold Atom Lab, ISS, NASA



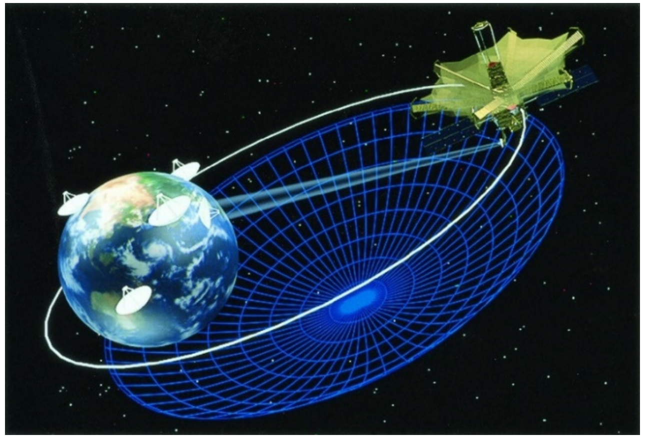
2016 QUESS, Entanglement distribution, China

2025 ACES, cold atom microwave clock, ESA

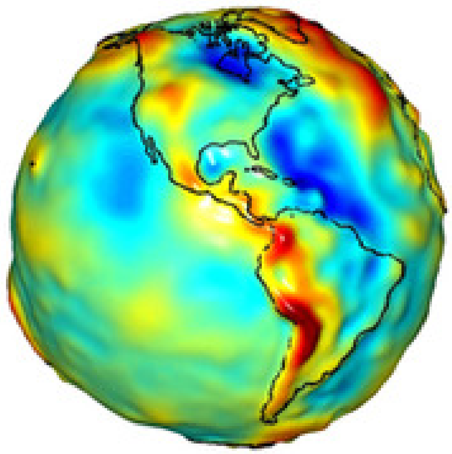
Image credits: JPL, NASA, ESA, CMSE, NSSC, DLR/Leibnitz, University of Hannover

SPACE APPLICATIONS OF ATOMIC CLOCKS

One way navigation

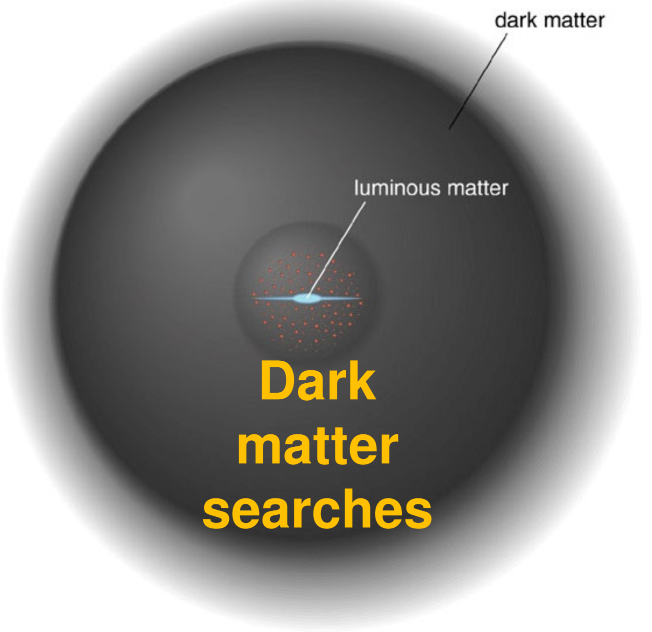


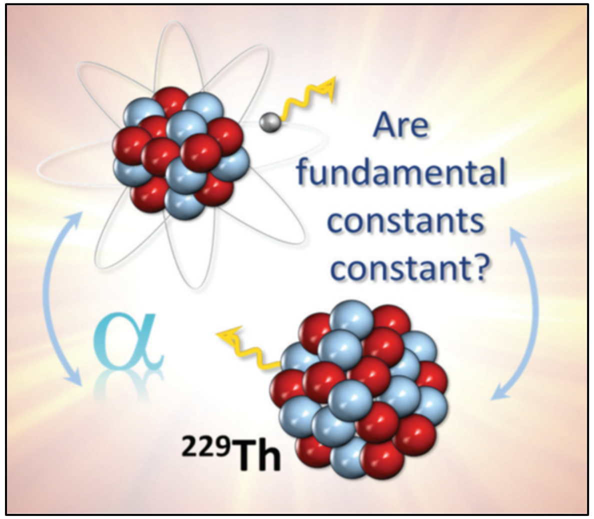
VLBI

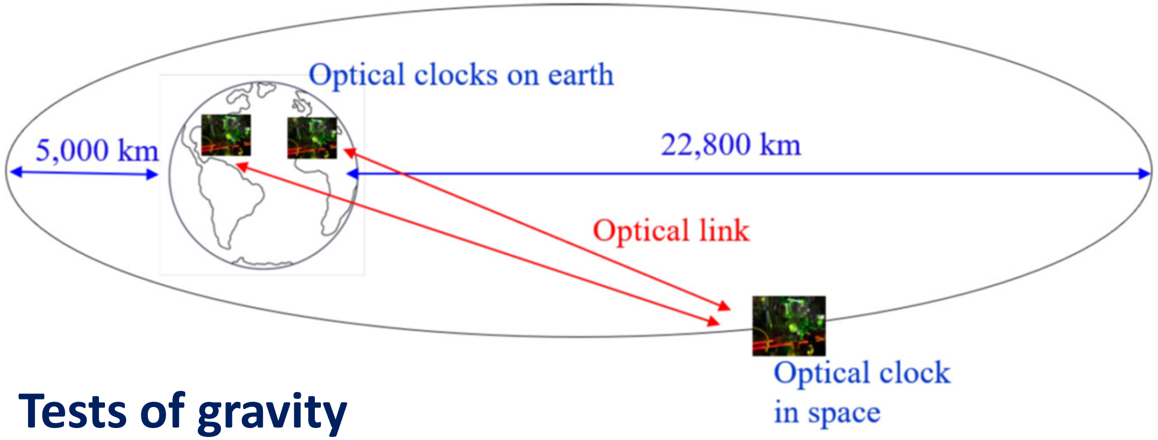


10^{-18}
1 cm
height

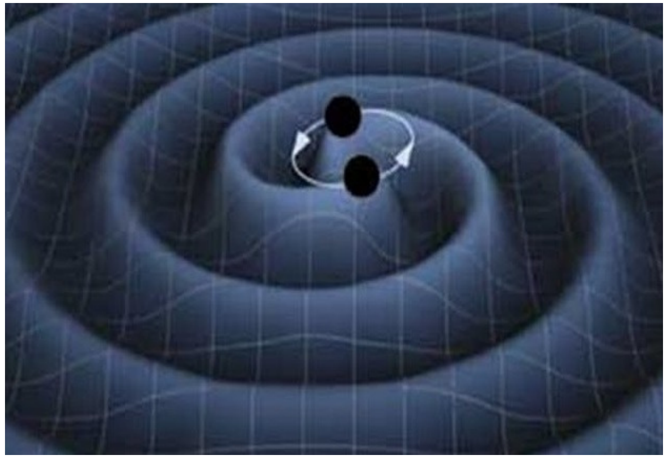
Earth sciences







Tests of gravity
International time reference/compare Earth clocks
Searches of violation on Lorentz invariance
Tests of position invariance



Detection of gravitational waves (different frequencies) and correlated ultralight fields signal

Image Credits: NASA, NOAA, Science 281,1825; 346, 1467, University of Hannover, PTB, PRD 94, 124043, ADP 531, 1800364 (2019) .

Quantum sensors for navigation

One way navigation with atomic clocks

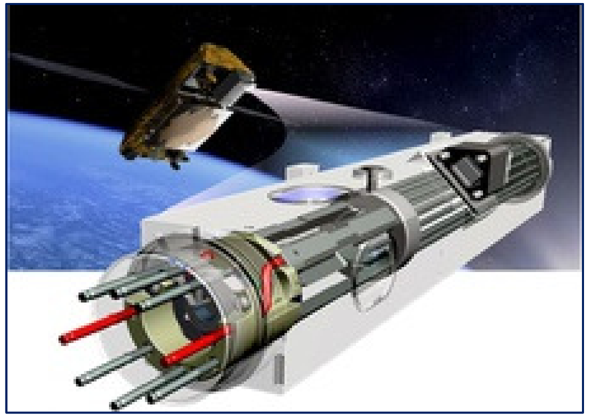


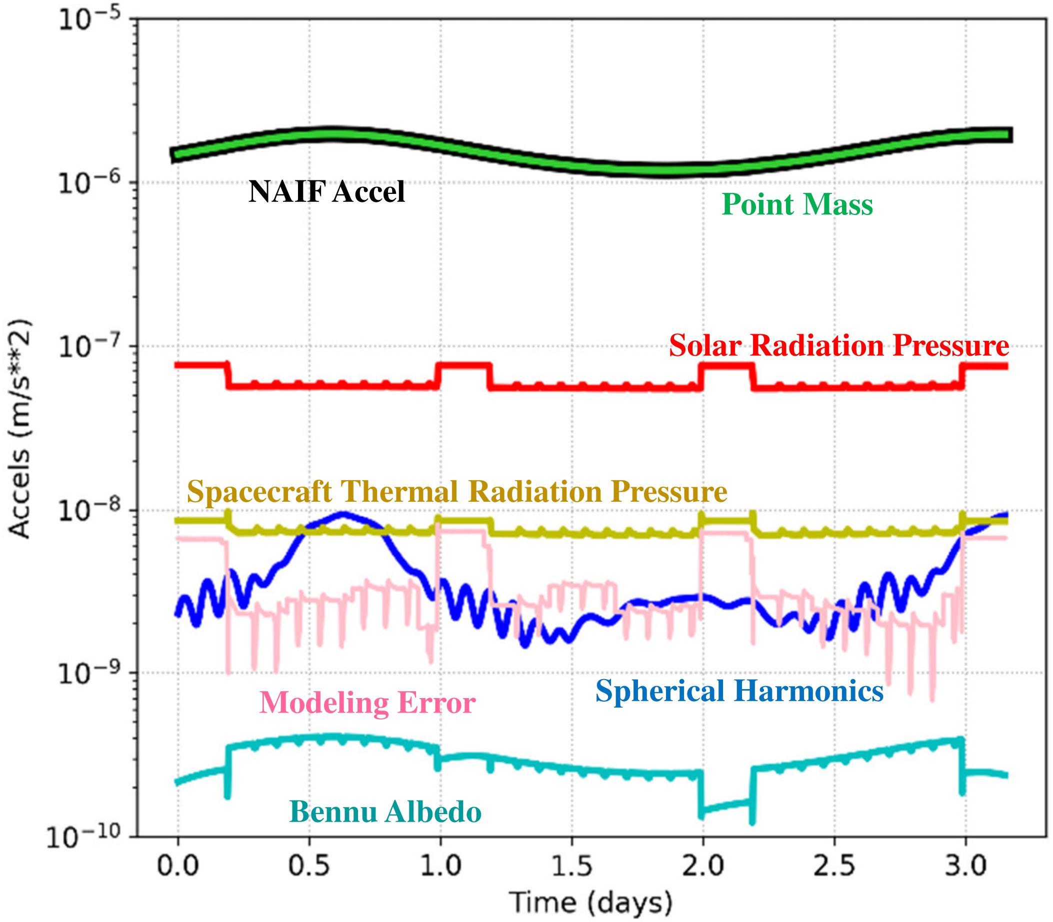
Image credits: NASA

Sensors based on shaken lattice interferometry for space navigation

Accelerometer in development by Dana Anderson Group, UC

Weak gravity of Bennu => motion sensitive to non-gravitational accelerations

Highly-sensitive accelerometer measuring non-gravitational force on spacecraft

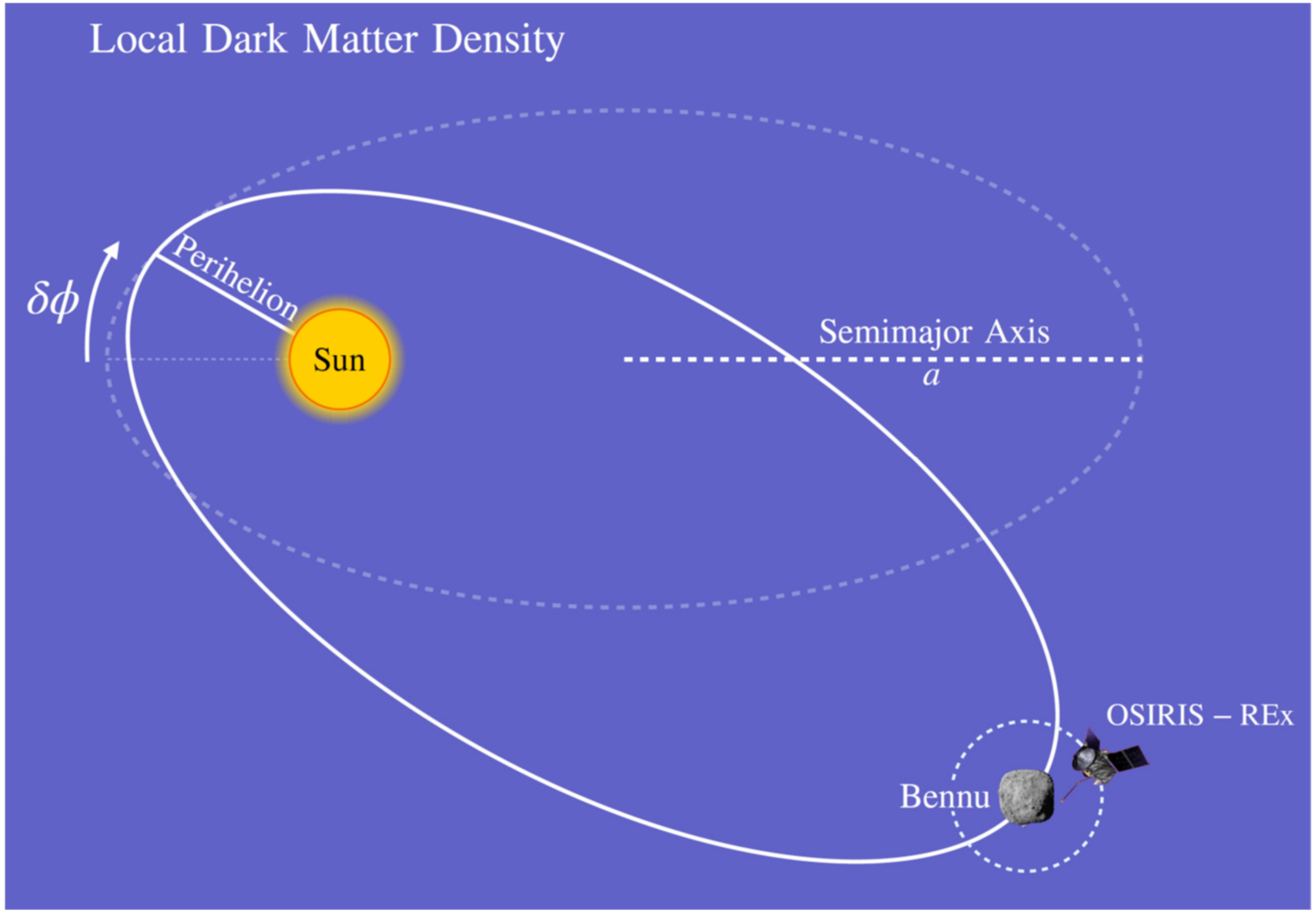


Application of Shaken Lattice Interferometry Based Sensors to Space Navigation, M. R. Rybak, P. Axelrad, C. LeDesma, Dana Z. Anderson, Todd Ely, arXiv:2207.06453 (2022)

Constraints on dark matter from orbital data

NASA mission to asteroid Bennu

Use orbit precession data to set limits on dark matter density in the Solar system

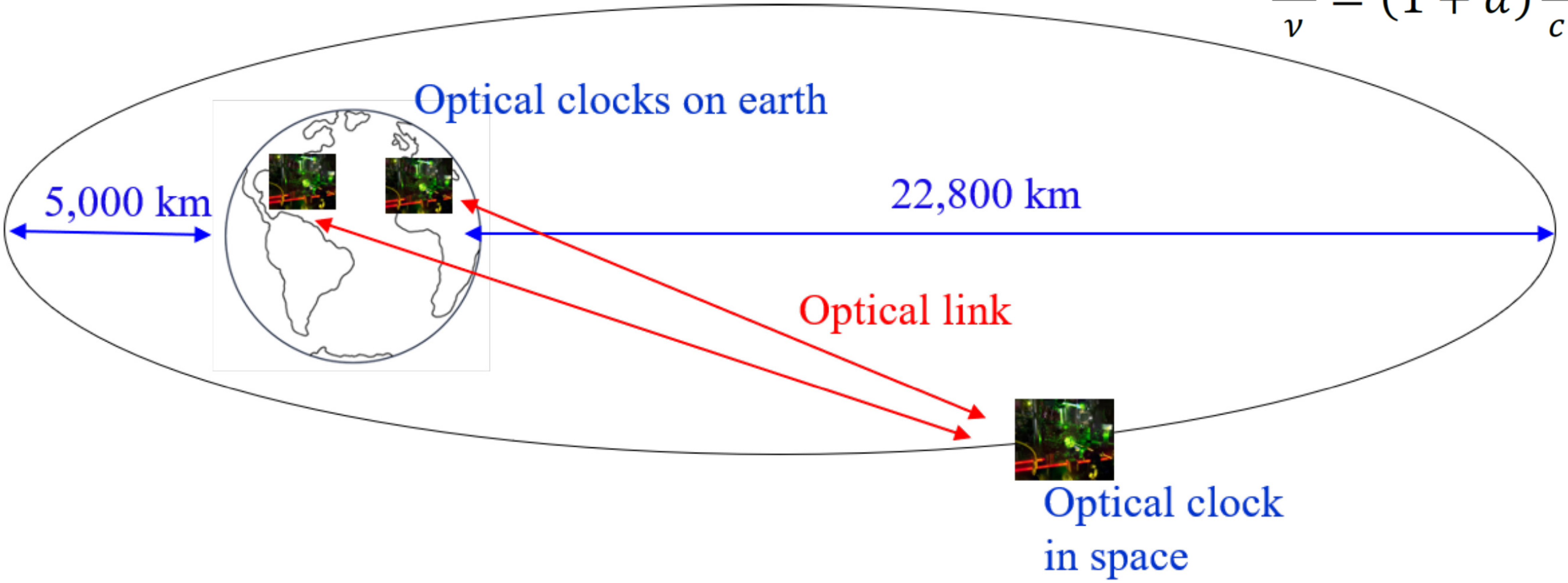


Yu-Dai Tsai, Joshua Eby, Jason Arakawa, Davide Farnocchia, and Marianna S. Safronova, JCAP 02, 029 (2024)

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

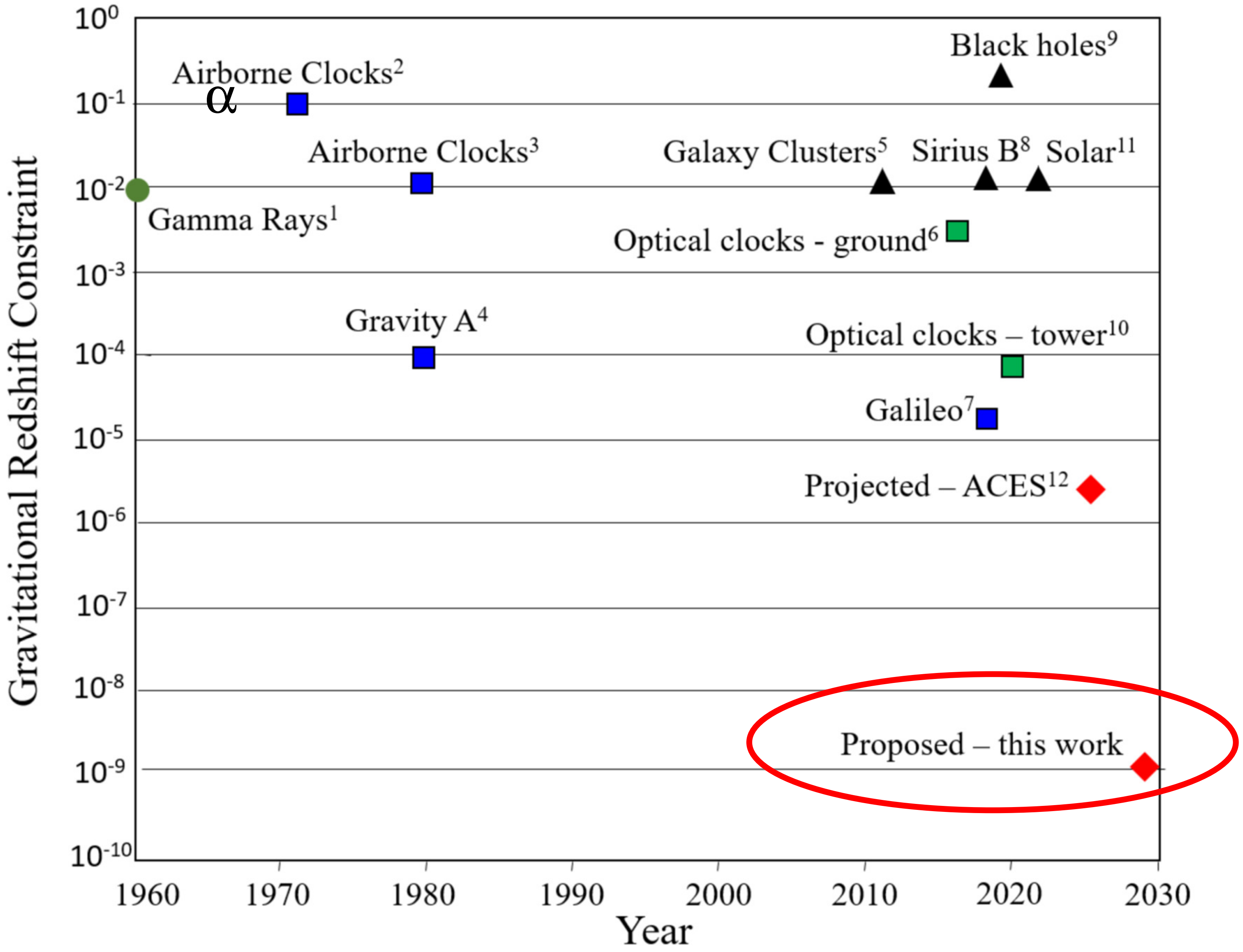
Andrei Derevianko, Kurt Gibble, Leo Hollberg, Nathan R. Newbury, Chris Oates, Marianna S. Safronova, Laura C. Sinclair, Nan Yu, Quantum Sci. Technol. 7, 044002 (2022)

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



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

Projected bound for gravitational redshift constraint for FOCOS mission



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

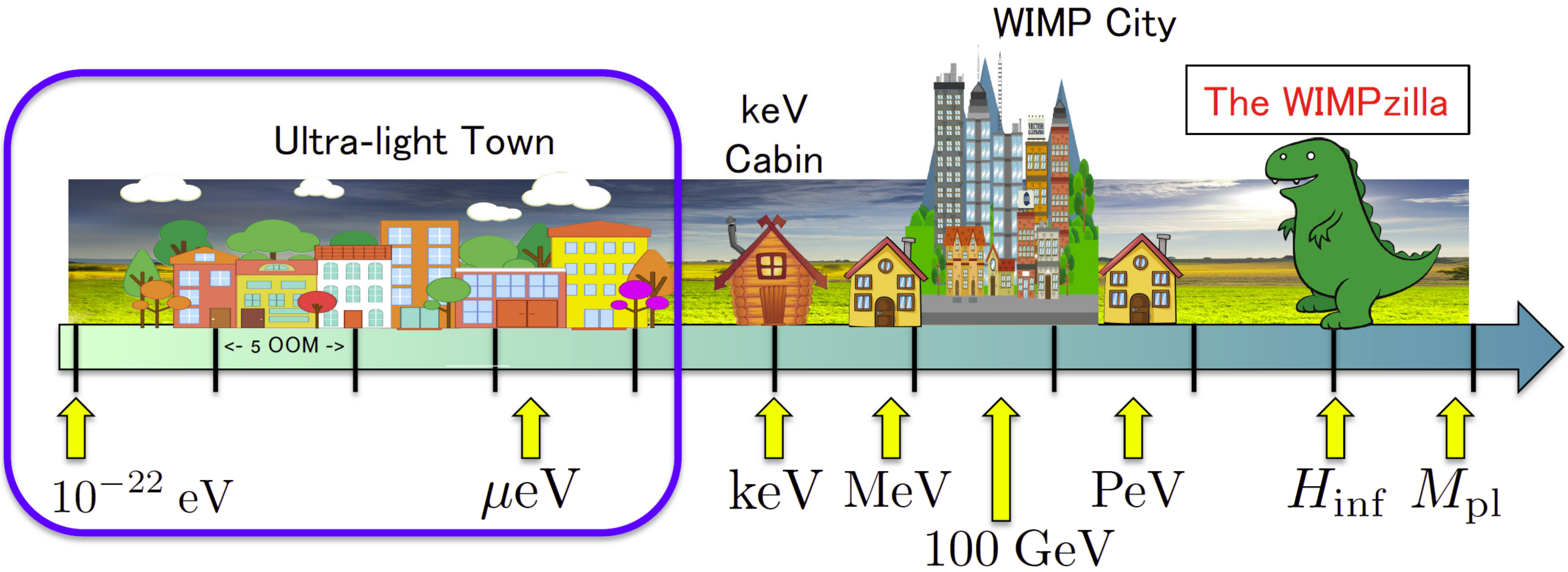
The primary goal for this mission would be to test the gravitational redshift, a classical test of general relativity, **with a sensitivity 30,000 times beyond current limits.**

Additional science objectives:

- Other tests of relativity
- Enhanced searches for dark matter and drifts in fundamental constants
- **Establishing a high accuracy international time/geodesic reference (linking Earth clocks)**

Dark matter searches with clocks/atom interferometers

The landscape of dark matter masses



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

How to detect ULTRALIGHT dark matter with clocks?

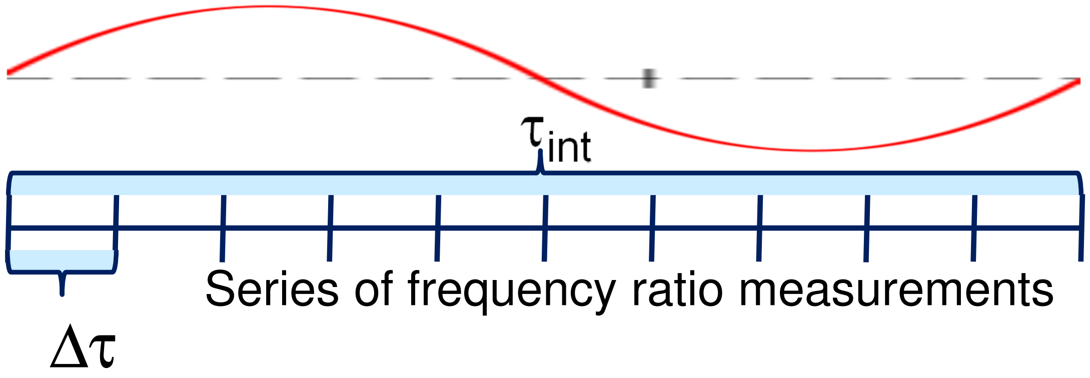
Dark matter field couples to electromagnetic interaction and “normal matter”

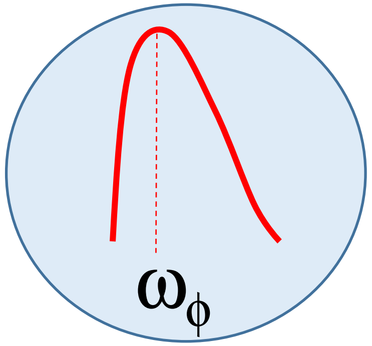
Fundamental coupling constants and mass ratios now oscillate

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

Measure ratios of clock frequencies over time (or clock to 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}

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

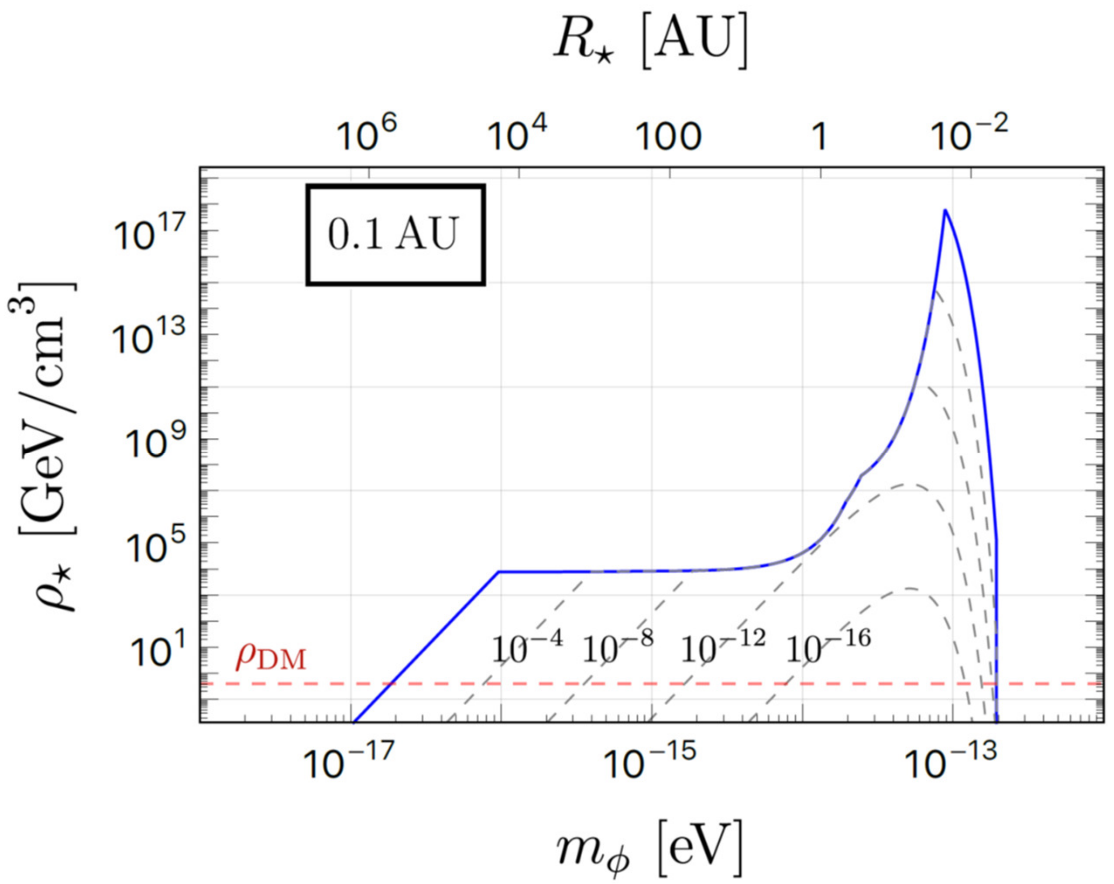
Yu-Dai Tsai, Joshua Eby, Marianna S. Safronova, Nature Astronomy 7, 113 (2023).
Dmitry Budker, Joshua Eby, Marianna S. Safronova & Oleg Tretiak EPJ Quantum Technology 12, 39 (2025)

We do not know how much dark matter there is in the Solar system.

We propose a clock-comparison satellite mission with two clocks onboard, to the inner reaches of the solar system (0.1 AU).

Science goals:

- Search for the dark matter halo bound to the Sun
- Probe natural relaxion (solves hierarchy problem and can be dark matter) parameter space
- Look for the spatial variation of the fundamental constants associated with a change in the gravitation potential



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nature physics

LETTERS

PUBLISHED ONLINE: 17 NOVEMBER 2014 | DOI: 10.1038/NPHYS3137

Transient variations

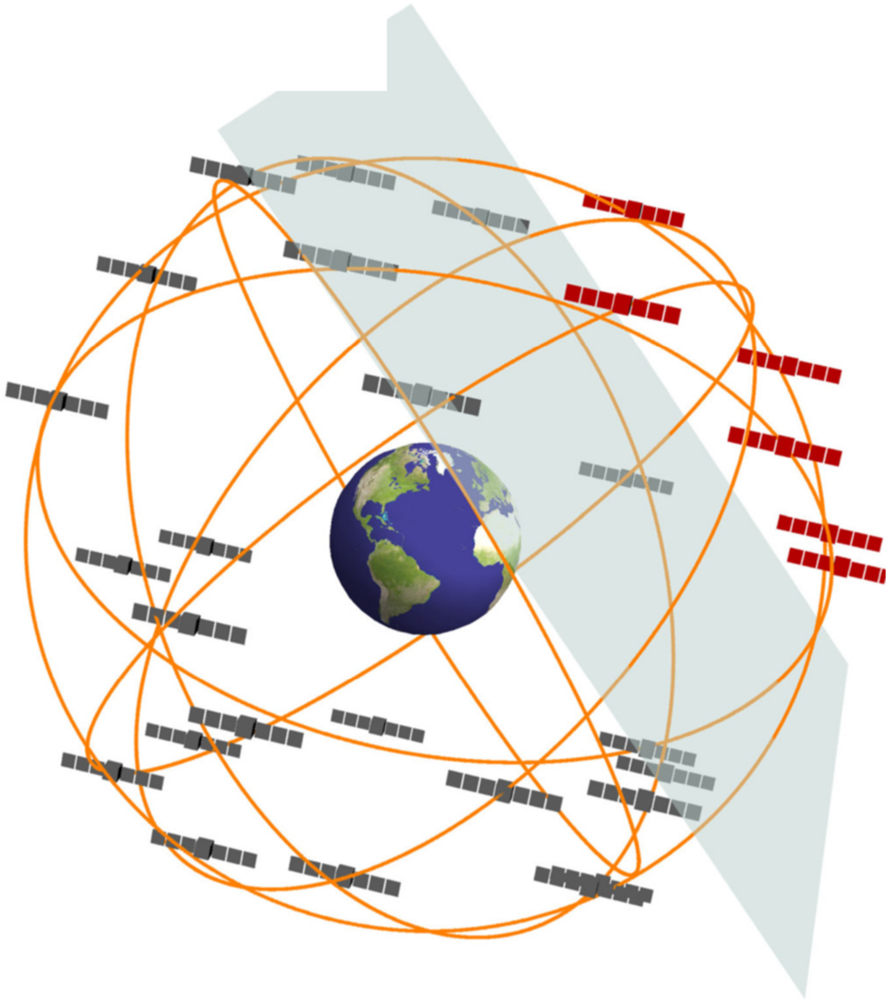
Hunting for topological dark matter with atomic clocks

A. Derevianko[1]* and M. Pospelov[2,3]

Transient effects

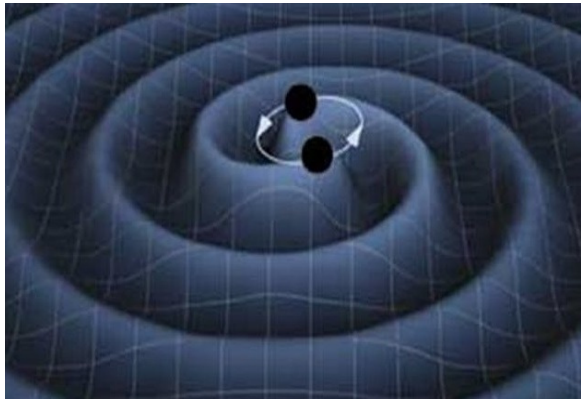
Dark matter clumps: point-like monopoles, one-dimensional strings or two-dimensional sheets (domain walls).

If they are large (size of the Earth) and frequent enough they may be detected by measuring changes in the synchronicity of a global network of atomic clocks, such as the Global Positioning System or networks of precision clocks on Earth.

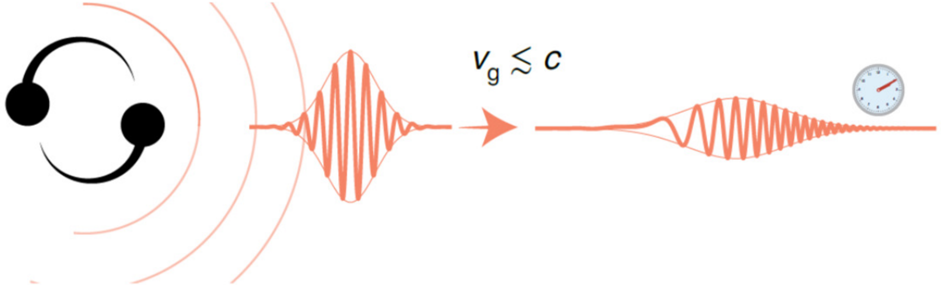


GPM.DM collaboration: Roberts at el., Nature Communications 8, 1195 (2017)

Quantum sensor networks as exotic field telescopes for multi-messenger astronomy



Bursts of exotic low-mass fields (ELFs) could be generated by cataclysmic astrophysical events, such as black-hole or neutron-star mergers, supernovae or the processes that produce fast radio bursts.

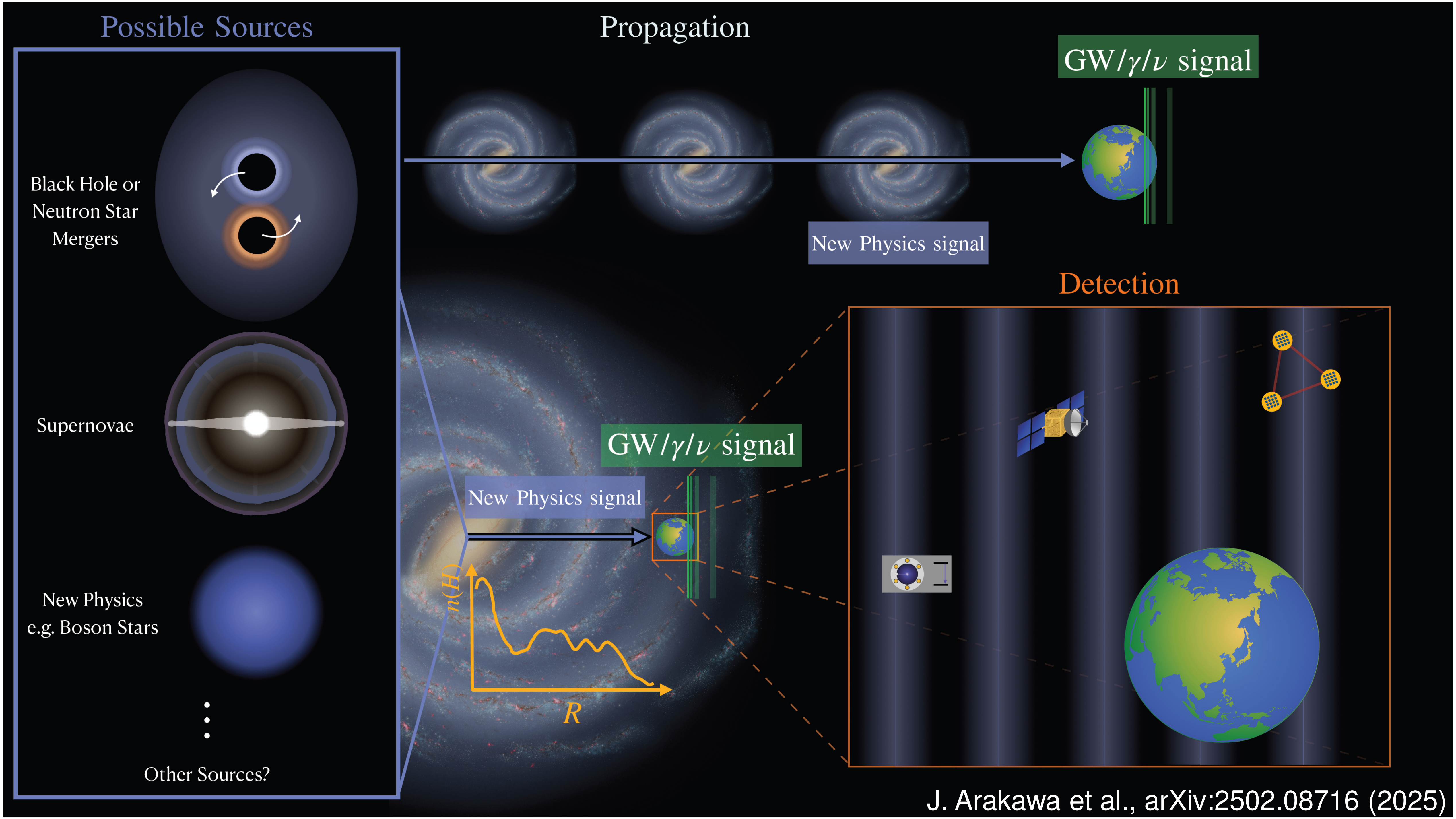


Effect of dispersion on the expected ELF signal at a precision quantum sensor.

- The leading edge of an ultrarelativistic ELF burst would propagate across Earth in ~40 ms.
- Magnetometers: 1-10 ms temporal resolution.
- Need longer baseline for clocks.

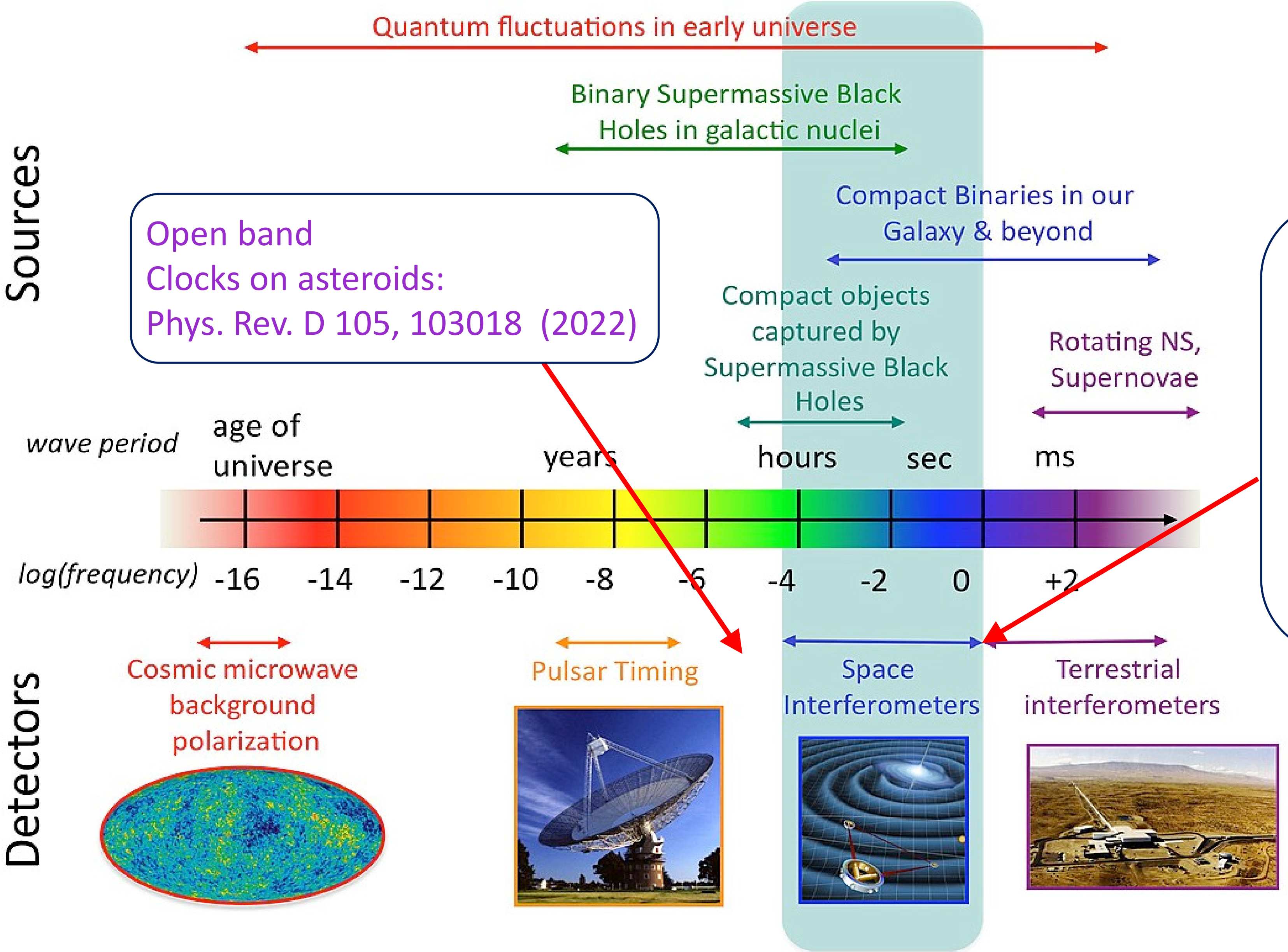
Conner Dailey, Colin Bradley, Derek F. Jackson Kimball, Ibrahim A. Sulai, Szymon Pustelny, Arne Wickenbrock and Andrei Derevianko, Nature Astronomy 5, 150 (2021)

Multimessenger Astronomy Beyond the Standard Model: New Window from Quantum Sensors, Jason Arakawa, Muhammad H. Zaheer, Volodymyr Takhistov, Marianna S. Safronova, Joshua Eby, arXiv:2502.08716 (2025).


Possible Sources
Propagation
GW/γ/ν signal
Black Hole or
Neutron Star
Mergers
New Physics signal
Detection
Supernovae
GW/γ/ν signal
New Physics signal
n(H)
R
New Physics
e.g. Boson Stars
Other Sources?
J. Arakawa et al., arXiv:2502.08716 (2025)

Towards probing the entire gravitational wave spectrum

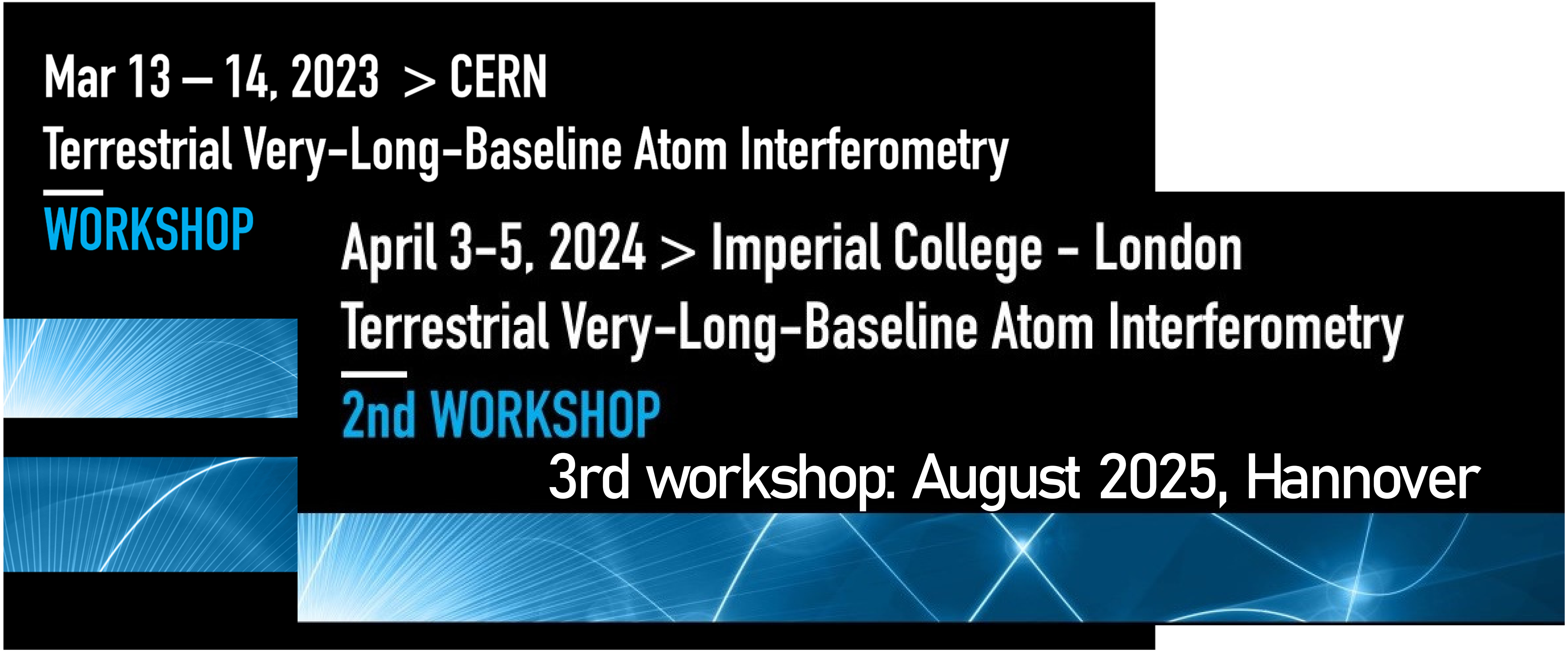
Open band
Clocks on asteroids:
Phys. Rev. D 105, 103018 (2022)



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); Second workshop: EPJ Quantum Technology 12, 42 (2025).

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.

Moon, planets, asteroids & quantum sensors

Looking for ideas: Moon, planets and asteroids for new physics searches with quantum sensors

- Moon: low seismic noise, cryogenic & vacuum environment
- Moon time and navigation?
- Can clocks on the Moon improve lunar laser ranging?
- Dark matter and gravitational detection with the Moon

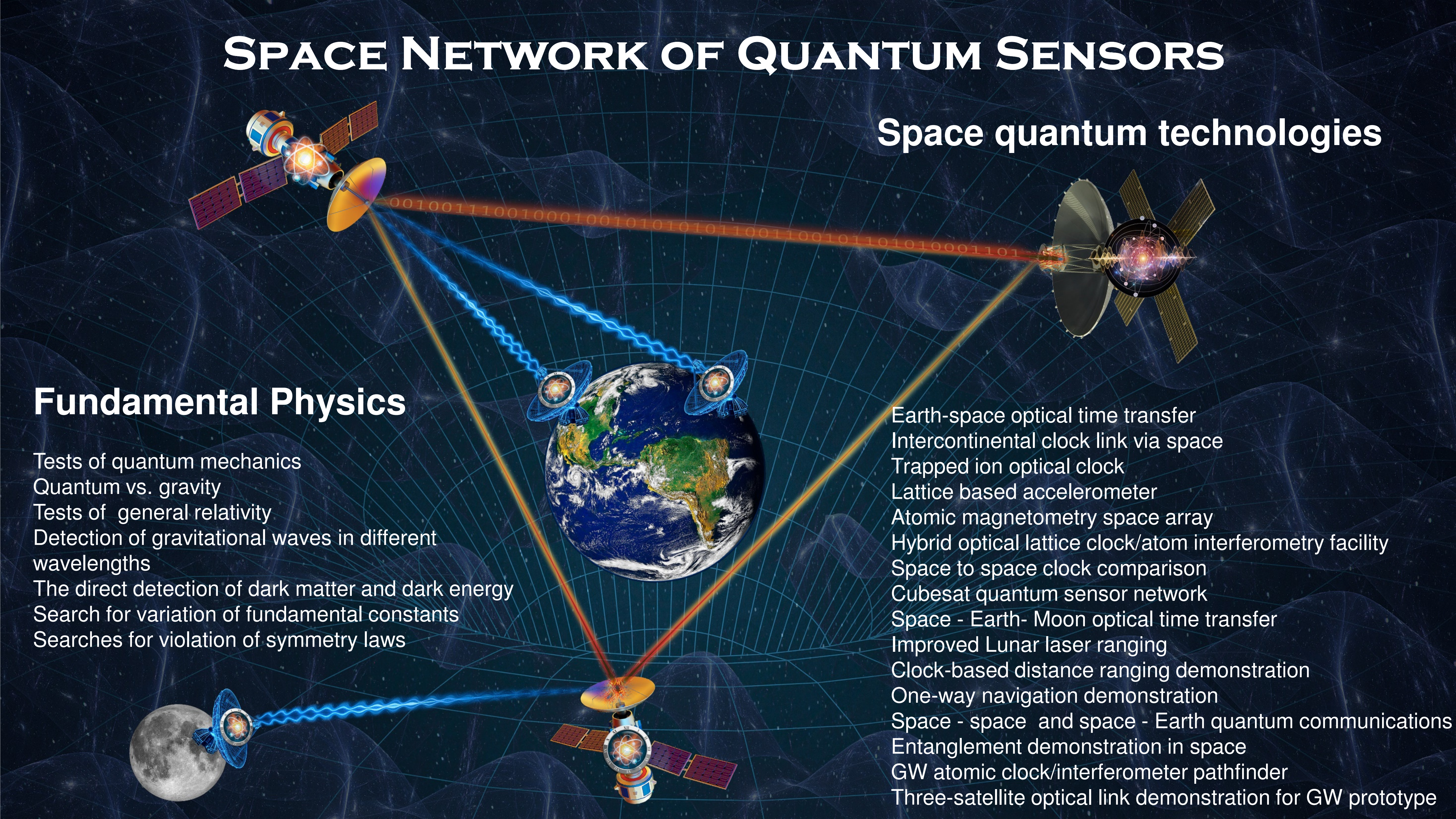
  Lunar seismic and gravitational antenna (LSGA)
- Can we use quantum sensors to track asteroids for better orbital determination?
- How to we use clocks to monitor distance between asteroids?

OSIRIS-REx constraints on local dark matter and cosmic neutrino profiles, Yu-Dai Tsai, Joshua Eby, Jason Arakawa, Davide Farnocchia, Marianna S. Safronova, JCAP 02, 029 (2024).

Asteroid astrometry as a fifth-force and ultralight dark sector probe, Yu-Dai Tsai, Youjia Wu, Sunny Vagnozzi, Luca Visinelli, JCAP 2304 (2023) 031

Asteroids for μHz gravitational-wave detection, Michael A. Fedderke, Peter W. Graham, Surjeet Rajendran, Phys. Rev. D 105, 103018 (2022)

Image credit: NASA


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

Future

- Deployment of quantum sensors in space presents fantastic opportunities for paradigm-changing discoveries and enable exploration

- Continuing fast development of quantum sensors is expected in the next decades

- NASA has a window of opportunity to establish efficient pathways for fast deployment of quantum sensors in space to advance its key missions and lead the field

- New opportunities for fundamental physics with quantum technologies on the Moon?

UD team and collaborators

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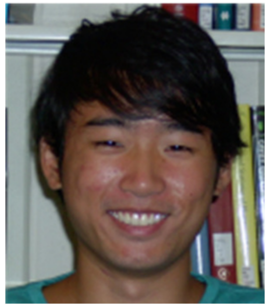
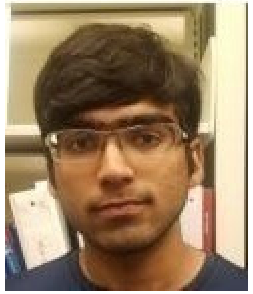


Dr. Charles Cheung
Scientist



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