PIKIMO 13, NOVEMBER 12, 2022

QUANTUM SENSORS IN SPACE FOR DARK MATTER DETECTION

Q-SEnSE
An NSF Quantum Leap Challenge Institute

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

Marianna Safronova

Department of Physics and Astronomy
University of Delaware, Delaware

thorium
nuclear clock

https://thoriumclock.eu/

NSF

Office of Naval Research
ONR
Science & Technology

erc
European Research Council

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

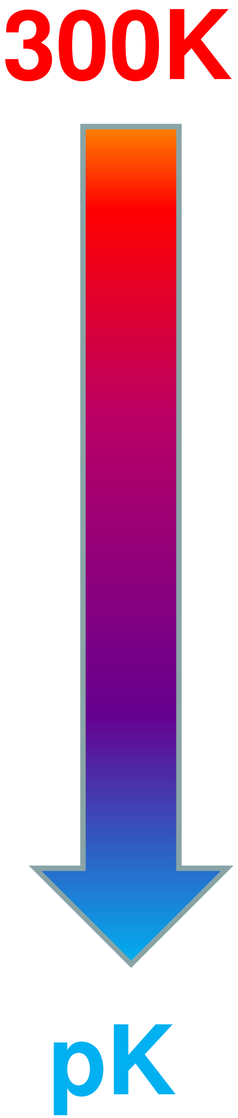
1997 Nobel Prize
Laser cooling and trapping

2001 Nobel Prize
Bose-Einstein Condensation

2005 Nobel Prize
Frequency combs

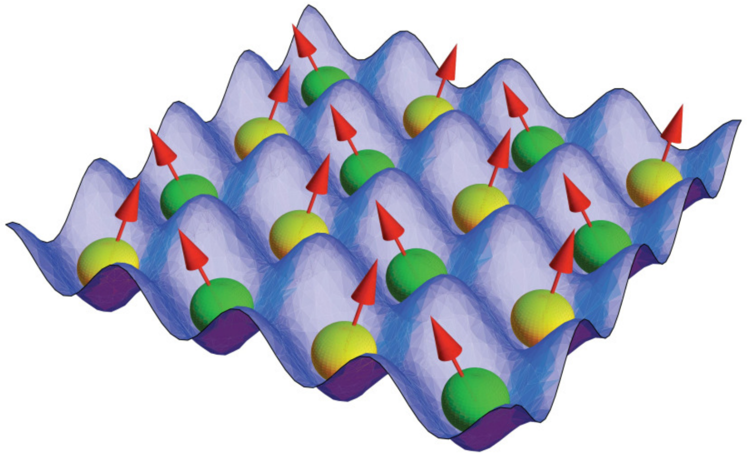
2012 Nobel prize
Quantum control

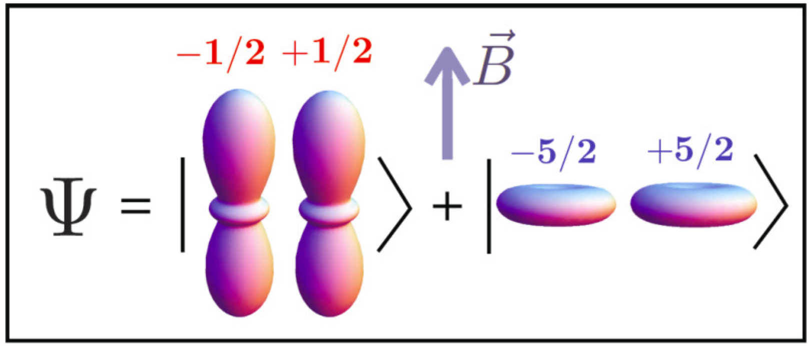
2022 Nobel prize
Bell inequalities, quantum information science

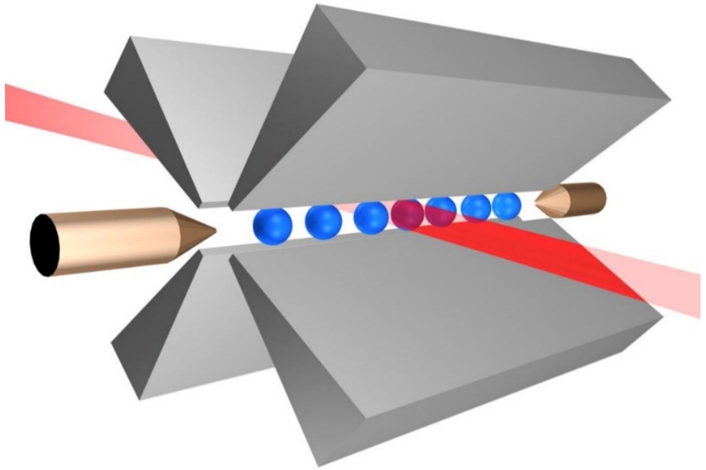


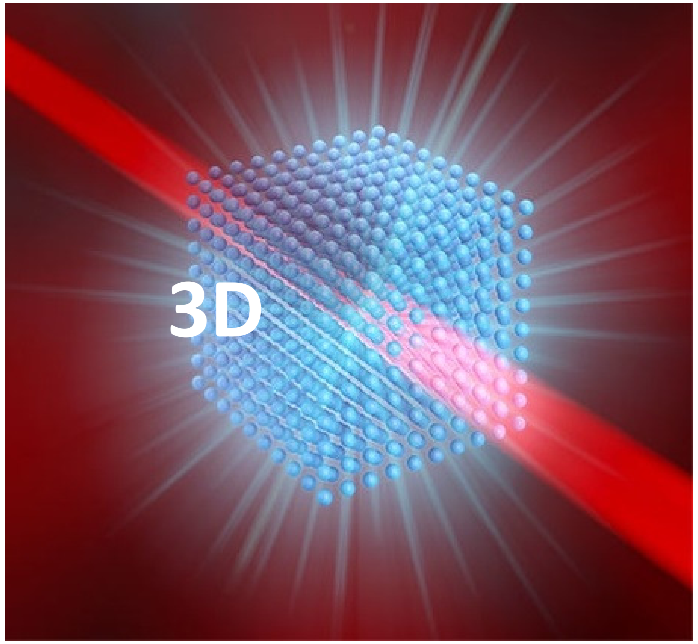
300K

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

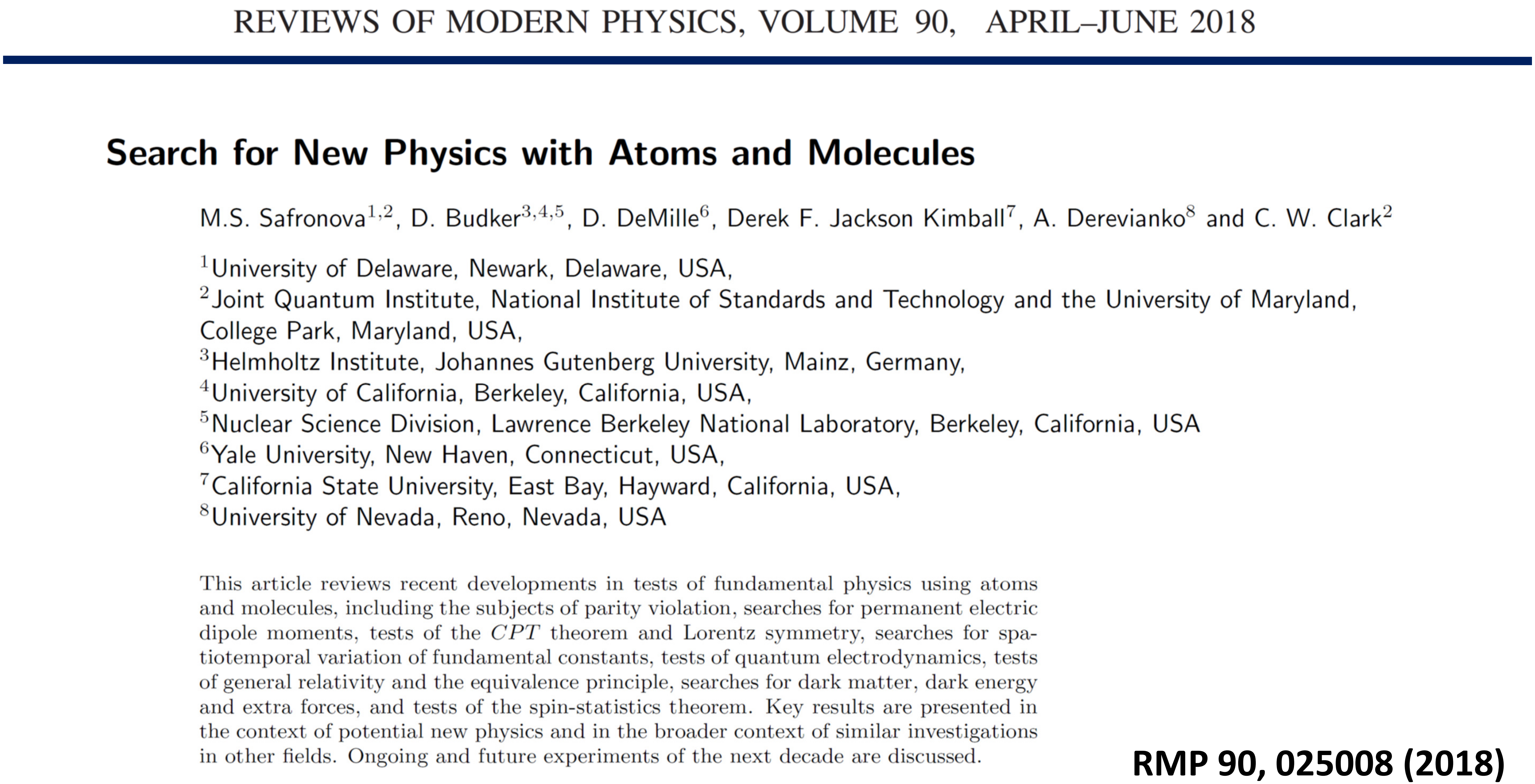
Editors: Marianna Safronova and Dmitry Budker

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.

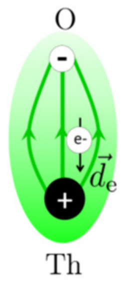
RMP 90, 025008 (2018)

SEARCHES FOR BSM PHYSICS WITH ATOMIC, MOLECULAR, AND OPTICAL PHYSICS

Fundamental symmetries with quantum science techniques

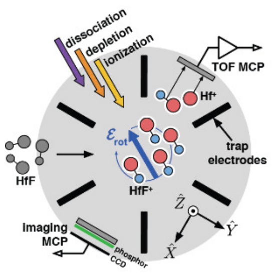
Searches for electron electric-dipole moment (eEDM)

Advanced ACME



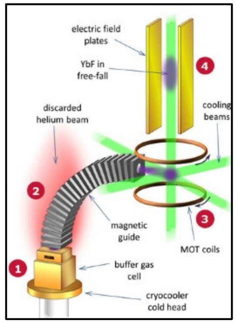
ThO

JILA eEDM



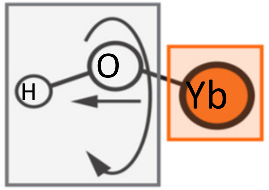
HfF⁺, ThF⁺

Imperial College



YbF

PolyEDM

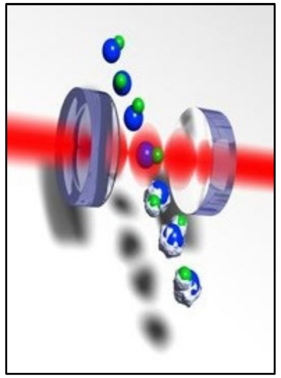


Also NMQM search

YbOH, …

Searches for hadronic EDMs

CeNTREX

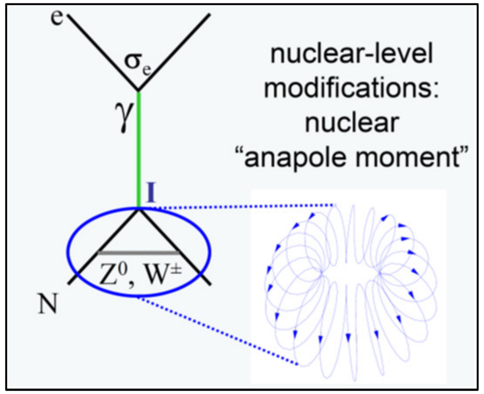


Hg
Xe
Ra
EDMs

TlF (proton EDM)

Enhanced parity violation

ZOMBIES



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

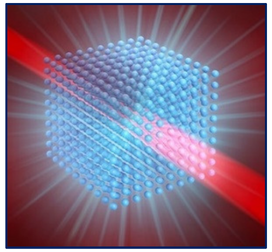
Rapid advances in ultracold molecule cooling and trapping; polyatomic molecules; future: molecules with Ra & "spin squeezed" entangled states

Atomic and Nuclear Clocks & Cavities

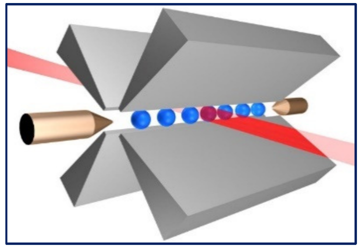
Major clock & cavities R&D efforts below, also molecular clocks, portable clocks and optical links

BSM searches with clocks

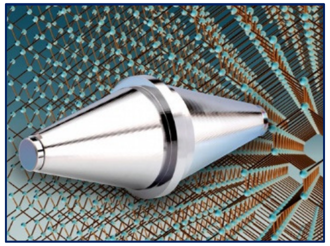
- Searches for variations of fundamental constants
- Ultralight scalar dark matter & relaxion searches
- Tests of general relativity
- Searches for violation of the equivalence principle
- Searches for the Lorentz violation



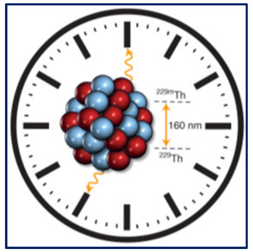
3D lattice clocks



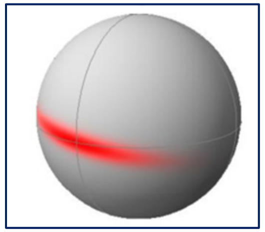
Multi-ion & entangled clocks



Ultrastable optical cavities



Nuclear & highly charge ion clocks



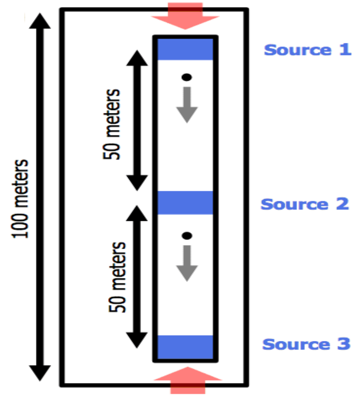
Measurements beyond the quantum limit

Atom interferometry

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

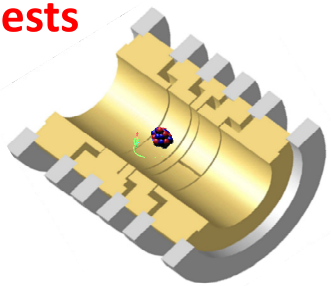
Prototype gravitational wave detectors

MAGIS-100 Fermilab



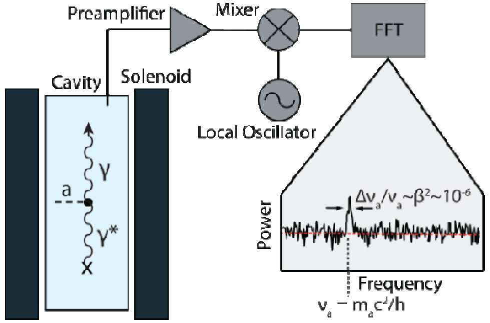
MIGA , AION, ZIGA

QED tests



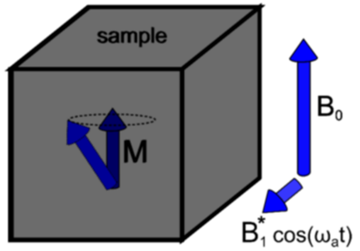
Highly charged ions and simple systems (H, D, ^{3}He$^+$, He, Li, HD, …)

Axion and ALPs searches



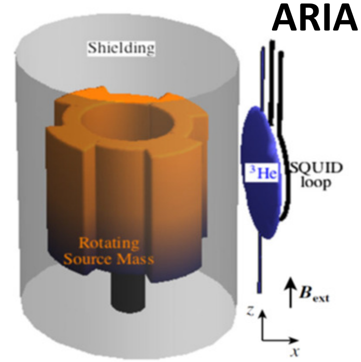
Microwave cavities: HAYSTAC
AMO: measurements beyond quantum limits

CASPEr-electric, solids
(coupling to gluons)



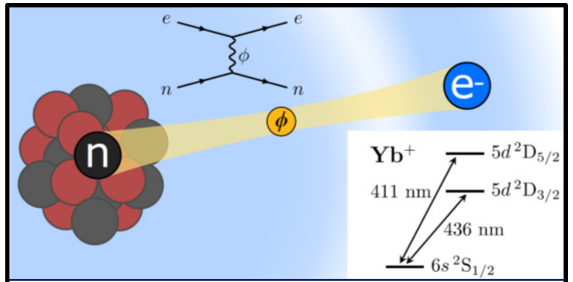
CASPEr-wind, Xe
(coupling to fermions)

ARIADNE

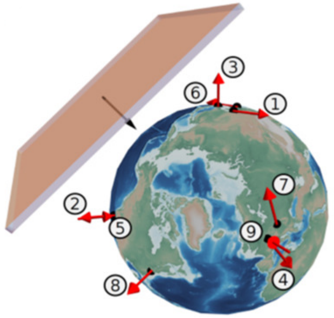


Resonantly detecting axion-mediated forces with NMR

Other dark matter & new force searches

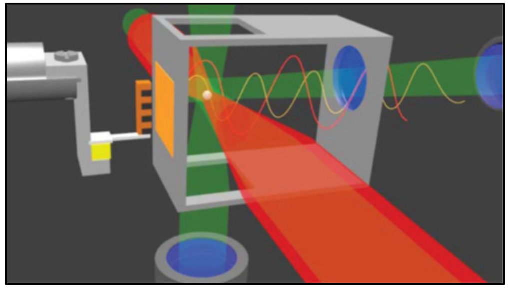


Fifth force searches with precision spectroscopy with atoms and ions



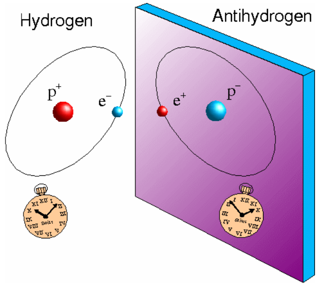
GNOME: network of optical magnetometers for exotic physics

Levitated optomechanics



Also: GW detection and testing the Newtonian inverse square law

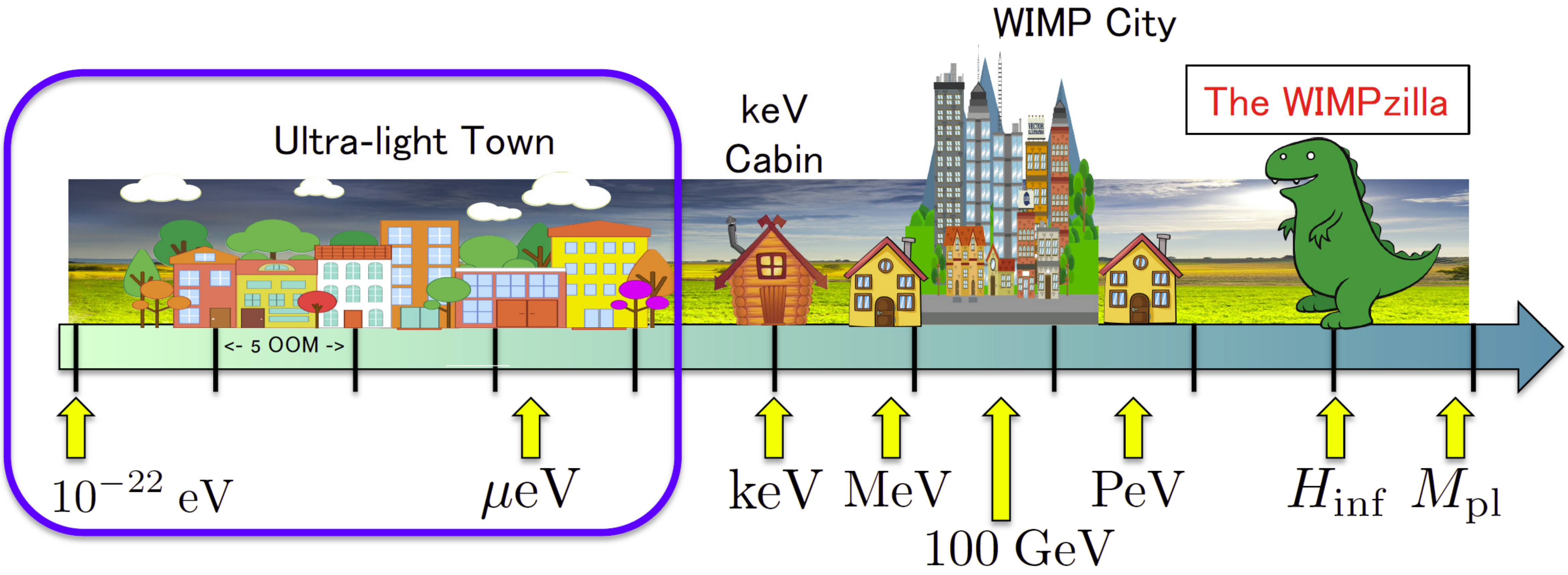
CPT tests
$\overline{p}, \overline{H}$



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, …

Slide from Andrew Long's 2018 LDW talk

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.

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

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

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

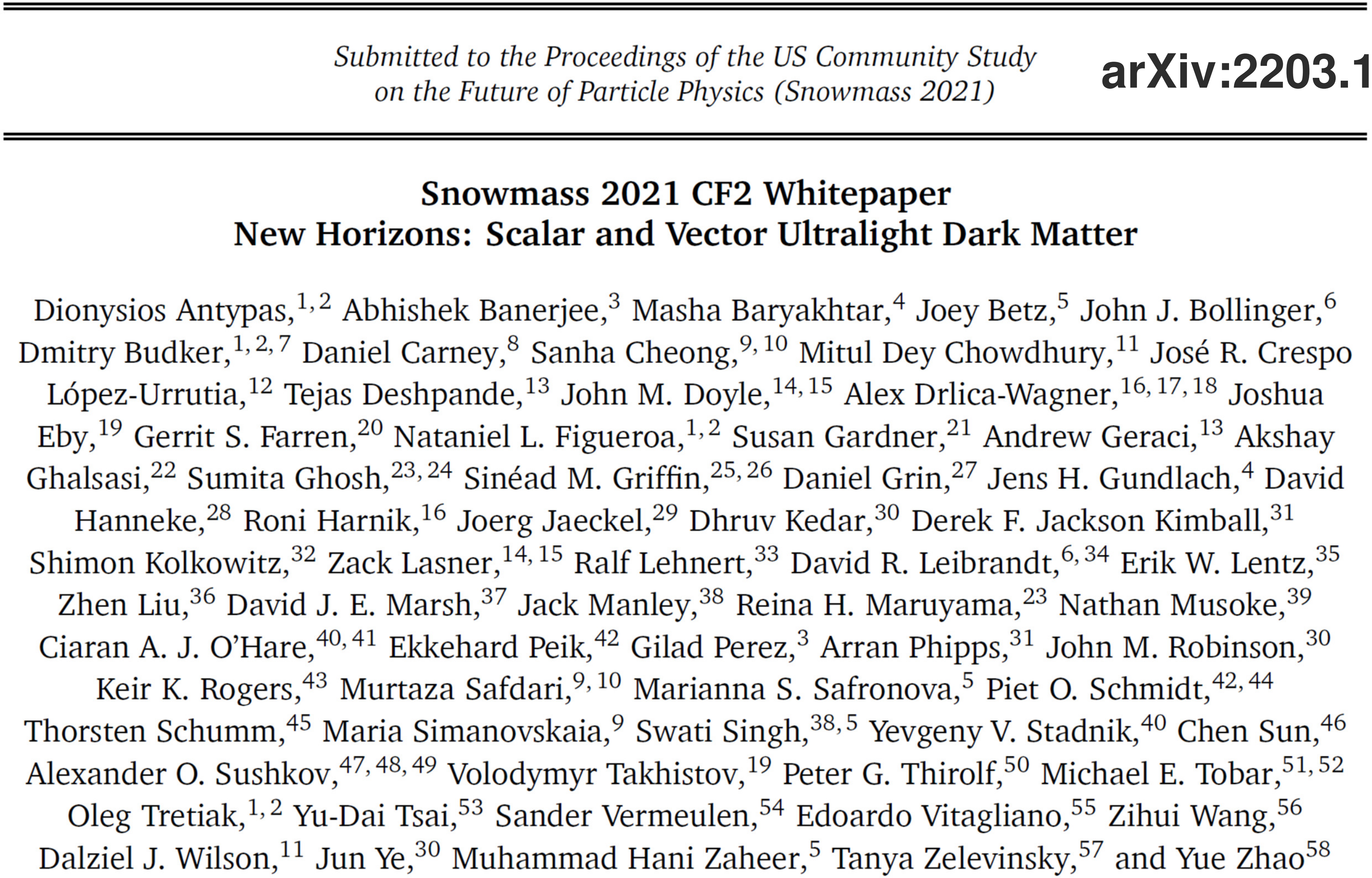
Different detection paradigm from particle dark matter.

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!



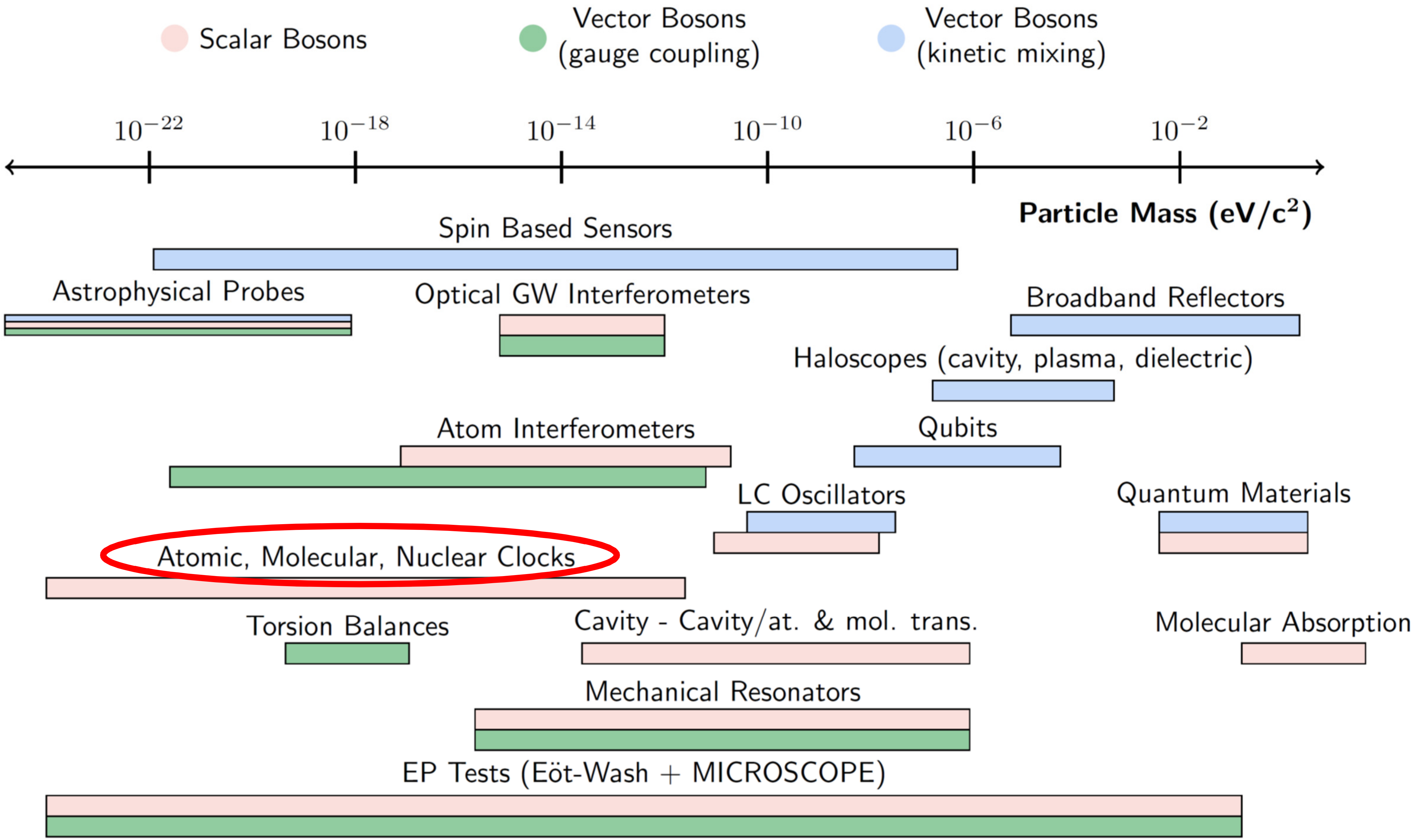
Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

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]

arXiv:2203.14915

Dark Matter Candidates



🟥 Scalar Bosons

🟩 Vector Bosons (gauge coupling)

🟦 Vector Bosons (kinetic mixing)

10^{-22} 10^{-18} 10^{-14} 10^{-10} 10^{-6} 10^{-2}

Particle Mass ($\mathrm{eV/c^2}$)

Spin Based Sensors

Astrophysical Probes

Optical GW Interferometers

Broadband Reflectors

Haloscopes (cavity, plasma, dielectric)

Atom Interferometers

Qubits

LC Oscillators

Quantum Materials

Atomic, Molecular, Nuclear Clocks

Torsion Balances

Cavity - Cavity/at. & mol. trans.

Molecular Absorption

Mechanical Resonators

EP Tests (Eöt-Wash + MICROSCOPE)

arXiv:2203.14915

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

DARK MATTER SEARCHES WITH ATOMIC AND NUCLEAR CLOCKS

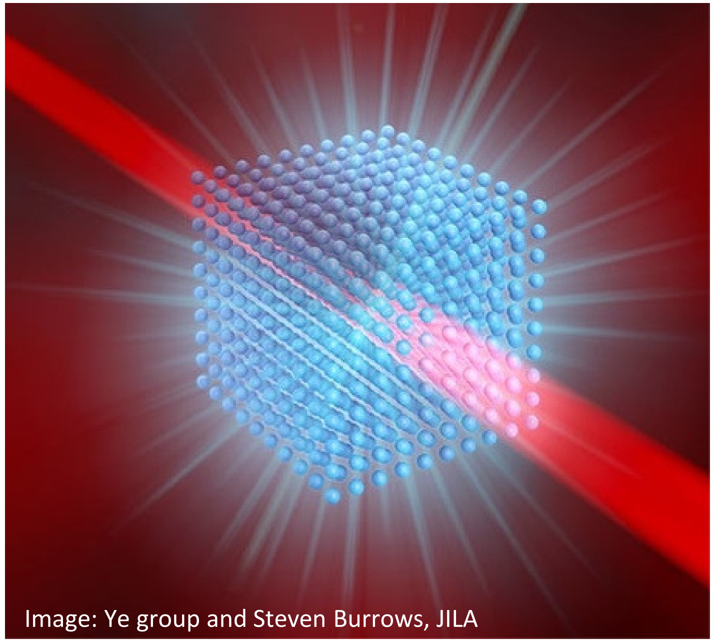
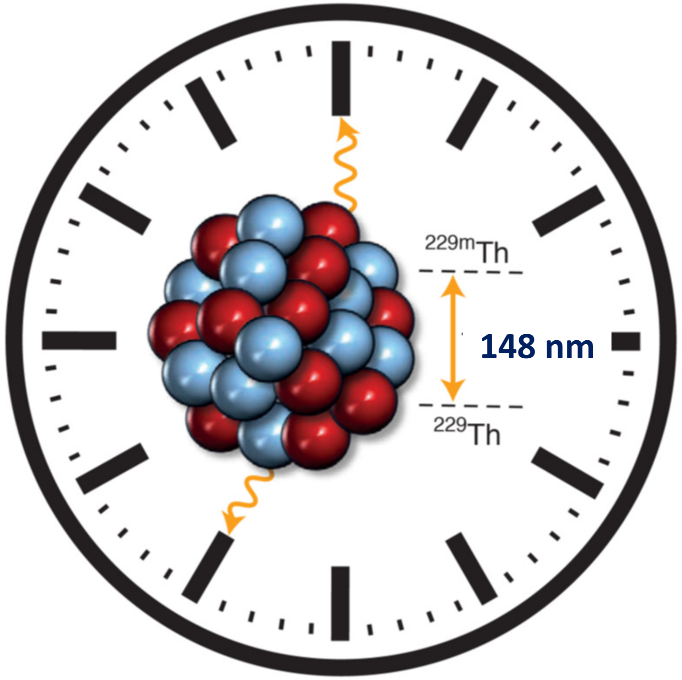
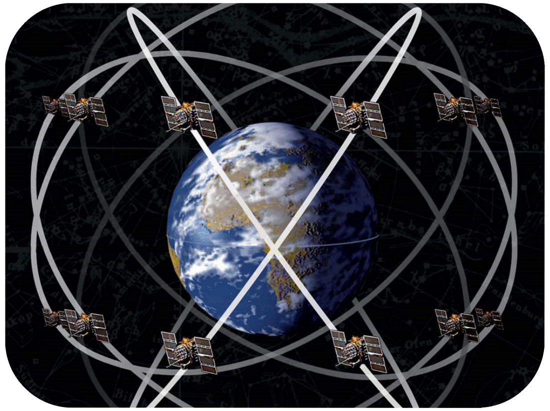


Image: Ye group and Steven Burrows, JILA

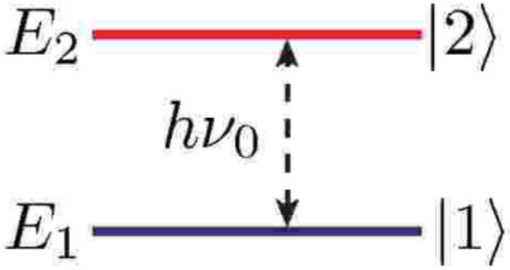


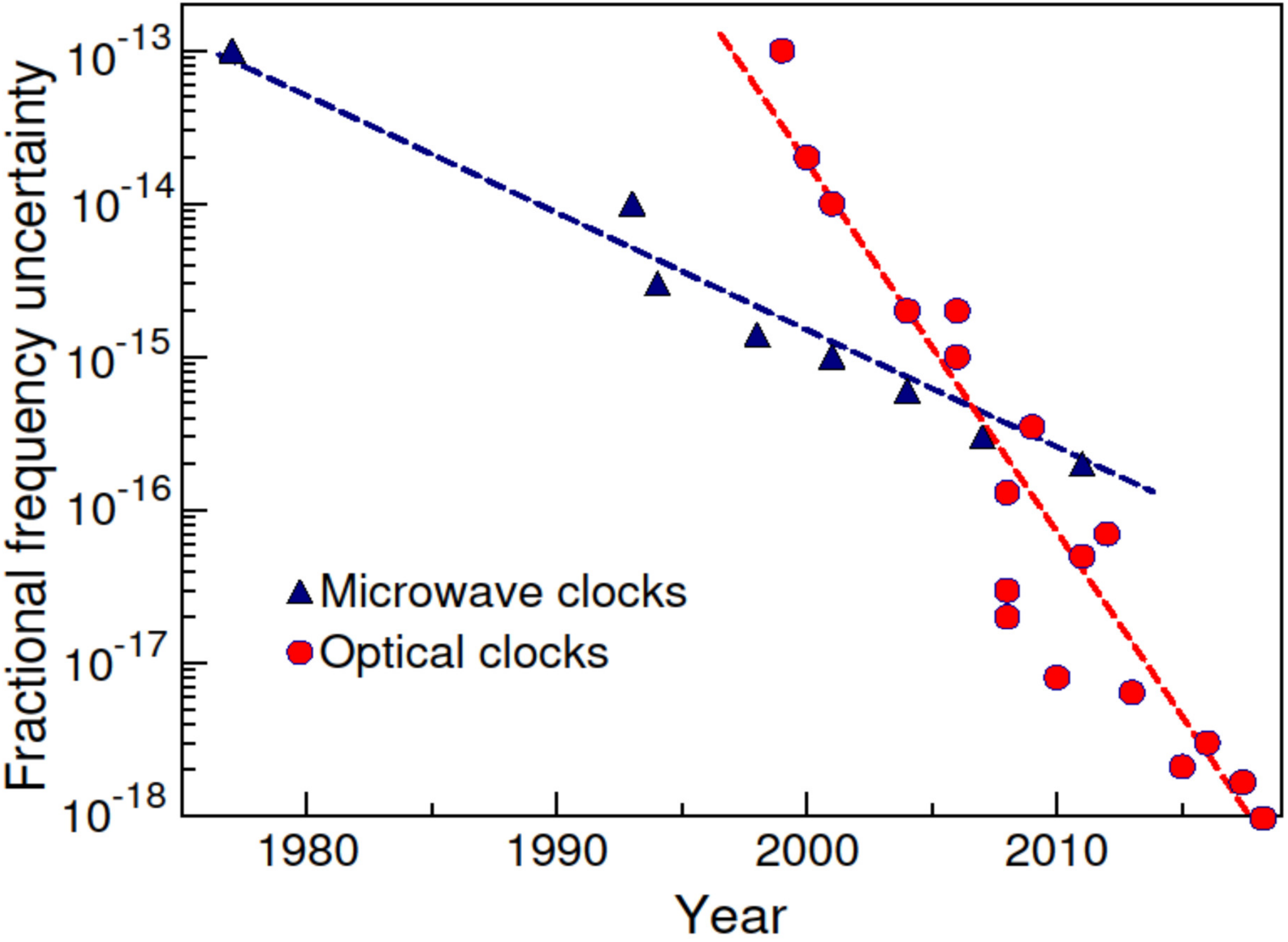
OPTICAL ATOMIC CLOCKS WILL NOT LOSE ONE SECOND IN 30 BILLION YEARS !



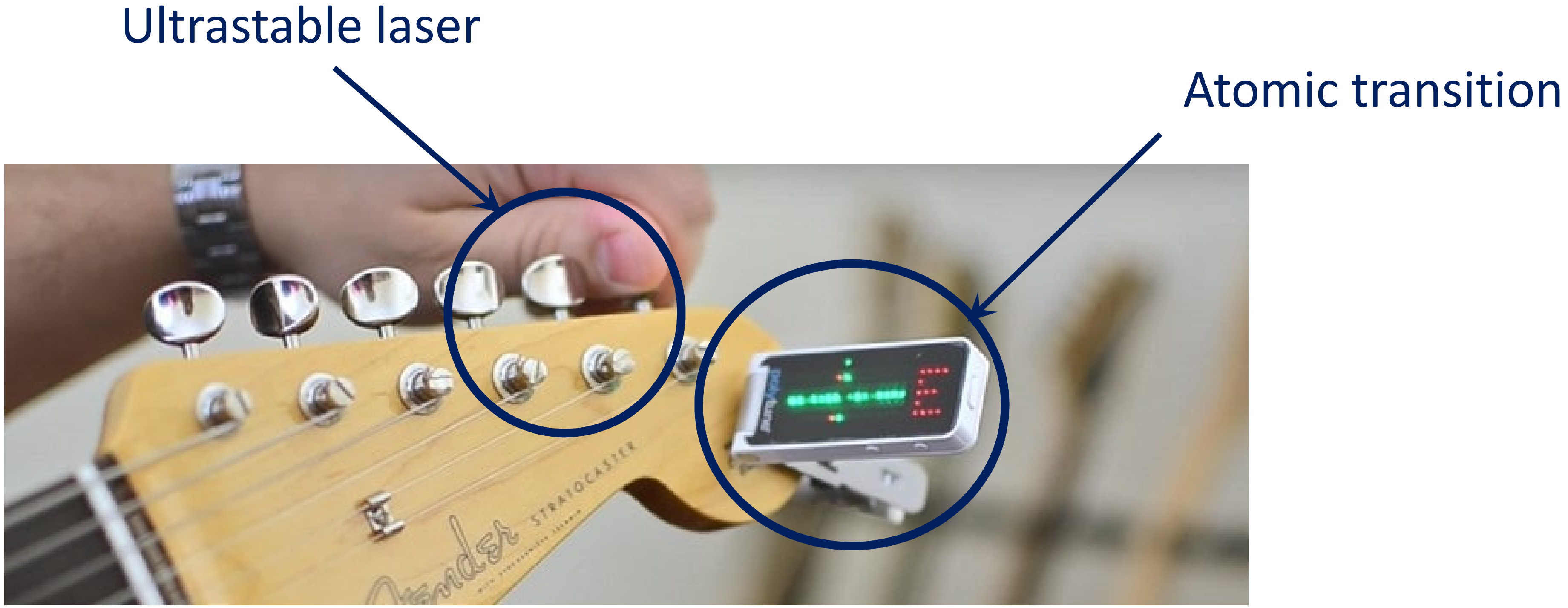
airandspace.si.edu

GPS satellites:
microwave
atomic clocks





HOW OPTICAL ATOMIC CLOCK WORKS ?

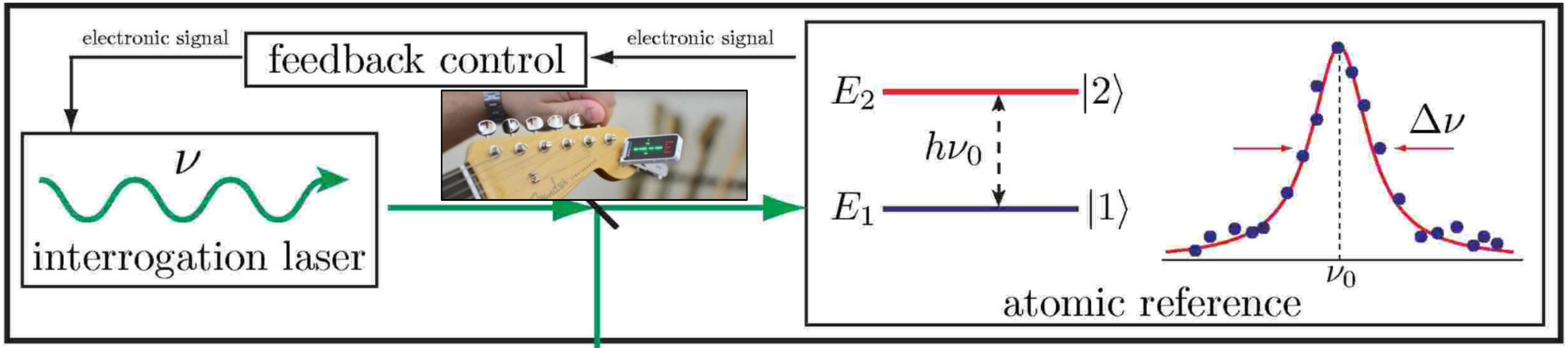


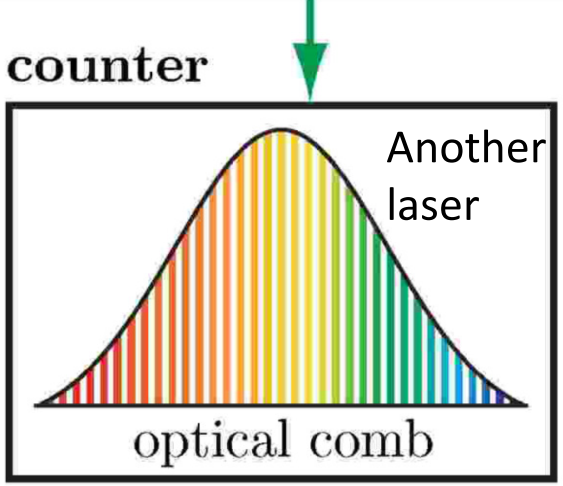
BASIC IDEA: TUNE THE LASER TO THE FREQUENCY OF THE ATOMIC TRANSITION

How optical atomic clock works ?

Laser cooled and trapped atoms or ions

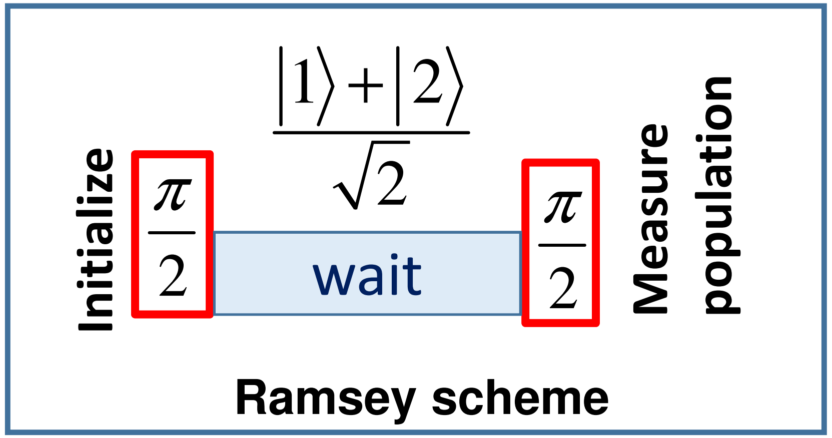
Ultrastable laser





Another laser

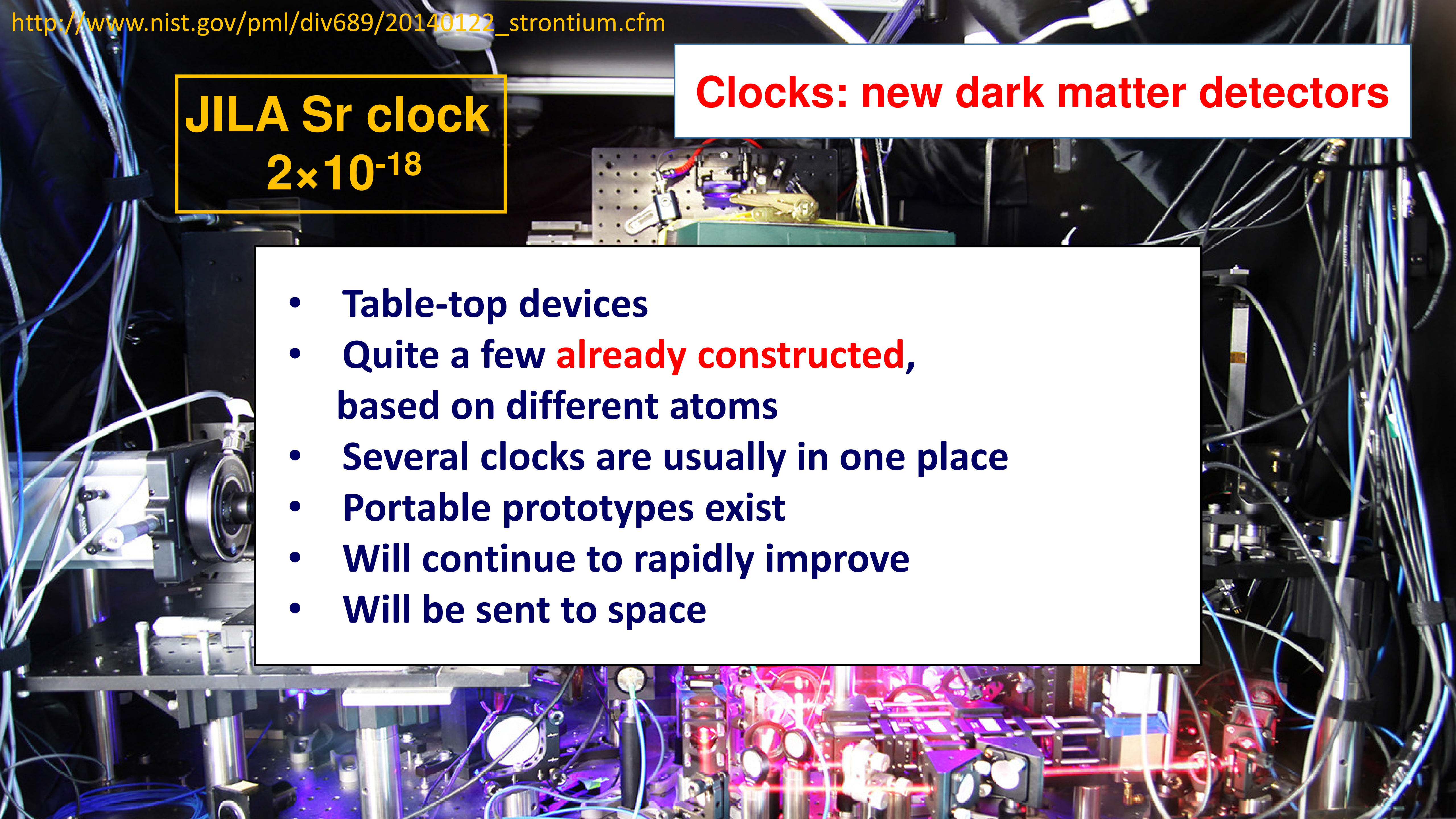
The laser is resonant with the atomic transition. A correction signal is derived from atomic spectroscopy that is fed back to the laser.



An optical frequency synthesizer (optical frequency comb) is used to divide the optical frequency down to countable microwave or radio frequency signals.

Poli et al. “Optical atomic clocks”, La rivista del Nuovo Cimento 36, 555 (2018) arXiv:1401.2378v2

Clocks: new dark matter detectors



http://www.nist.gov/pml/div689/20140122_strontium.cfm

JILA Sr clock
2×10^{-18}

- Table-top devices
- Quite a few already constructed, based on different atoms
- Several clocks are usually in one place
- Portable prototypes exist
- Will continue to rapidly improve
- Will be sent to space

SCALAR ULTRALIGHT DARK MATTER

Coupling of scalar UDM to the standard model:

$$\kappa = (\sqrt{2}M_{\mathrm{Pl}})^{-1}$$

photons **electrons** **gluons** **quarks**

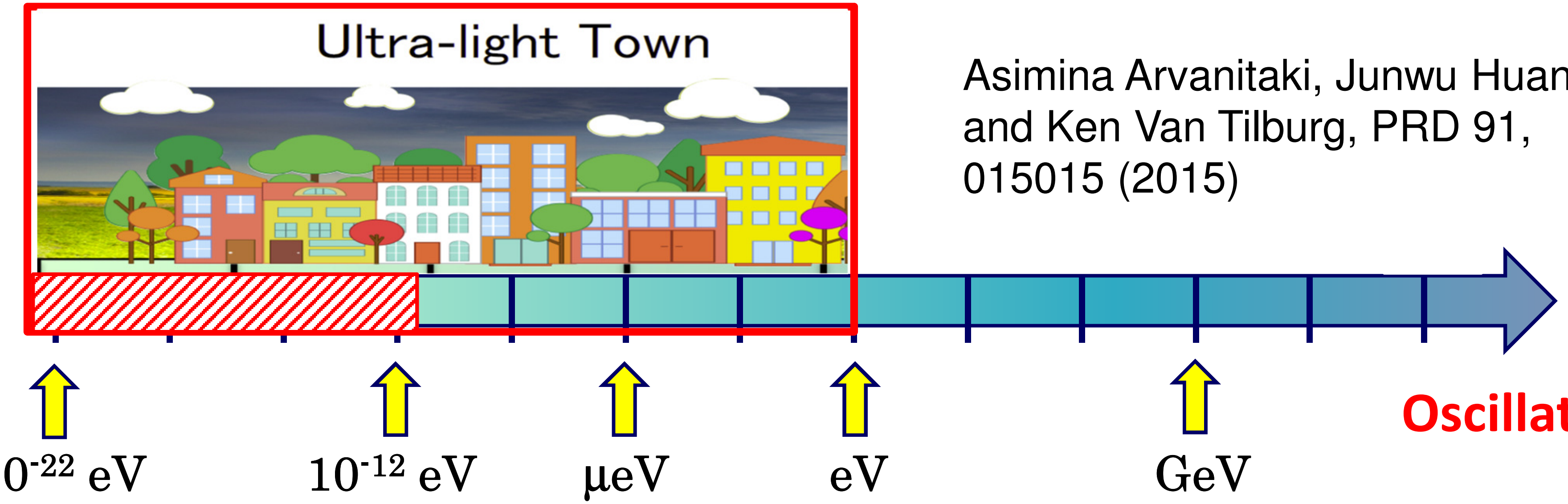
$$\mathcal{L}^{\mathrm{lin}}_{\mathrm{int}} = \kappa\phi \left\{ \left[\frac{d_e F_{\mu\nu}F^{\mu\nu}}{4} - d_{m_e} m_e \bar{\psi}_e \psi_e \right] - \left[\frac{d_g \beta_3 G^a_{\mu\nu} G^{a\mu\nu}}{2g_3} + \sum_{q=u,d,s} \left(d_{m_q} + \gamma_m d_g\right) m_q \bar{\psi}_q \psi_q \right] \right\}$$

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

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

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

HOW TO DETECT ULTRALIGHT DARK MATTER WITH CLOCKS?



Asimina Arvanitaki, Junwu Huang, and Ken Van Tilburg, PRD 91, 015015 (2015)

Oscillatory effects

Dark matter field $\phi(t) = \phi_0 \cos\left(m_\phi t + \bar{k}_\phi \times \bar{x} + \ldots\right)$ couples to electromagnetic interaction and “normal matter”

$$\boxed{\frac{\phi}{M^*}\mathcal{O}_{\mathrm{SM}}}$$

It will make fundamental coupling constants and mass ratios oscillate

Atomic & nuclear energy levels will oscillate so clock frequencies will oscillate

Can be detected with monitoring ratios of clock frequencies over time (or clock/cavity).

OBSERVABLE: RATIO OF TWO CLOCK FREQUENCIES

Measure a ratio of Al$^+$ clock frequency to Hg$^+$ clock frequency

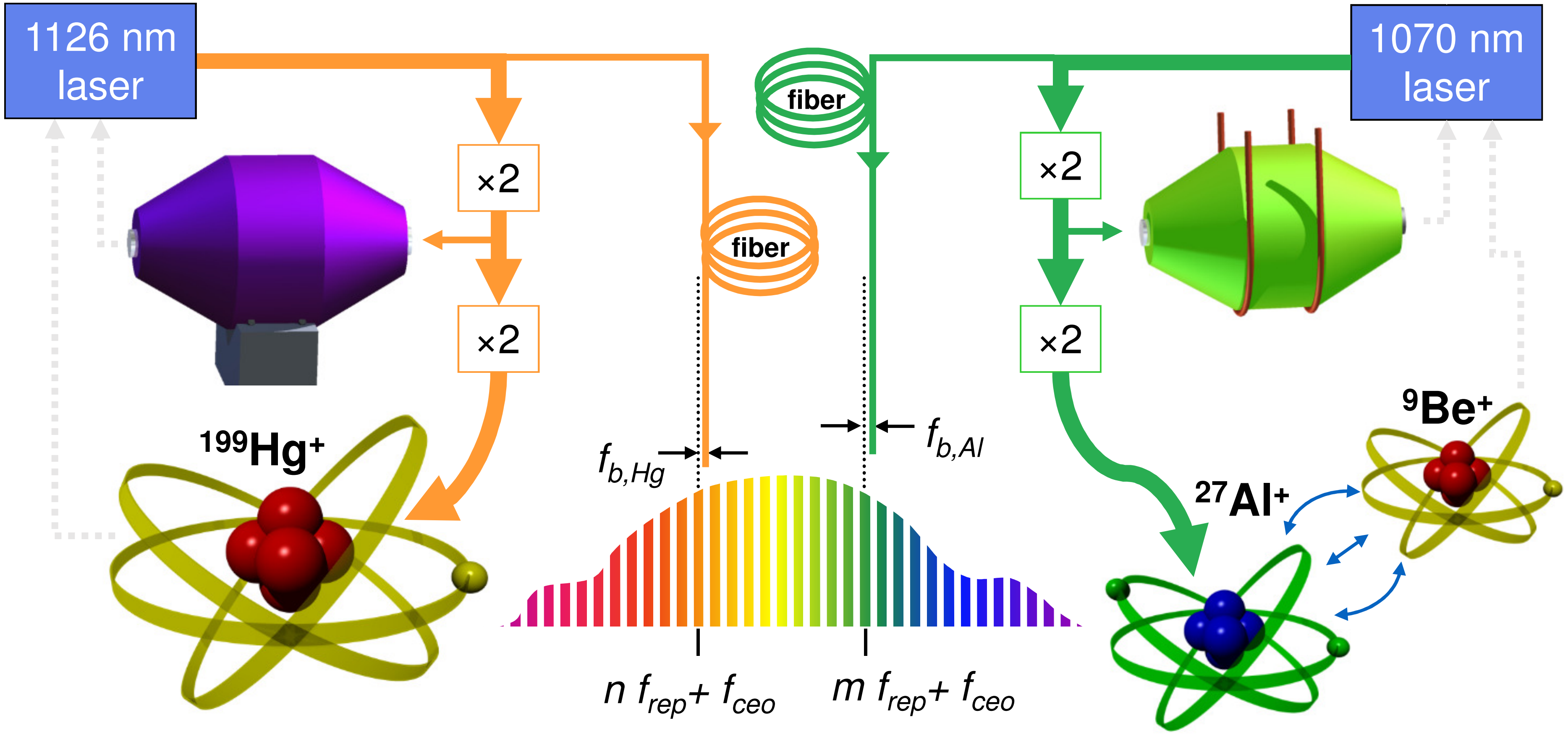
$$\frac{\nu\left(Hg^+\right)}{\nu\left(\mathrm{Al}^+\right)}$$

$$K(Hg^+) = -2.9$$

$$K\left(Al^+\right) = 0.01$$

Sensitivity factors

Not sensitive to α-variation, used as reference



Picture credit: Jim Bergquist

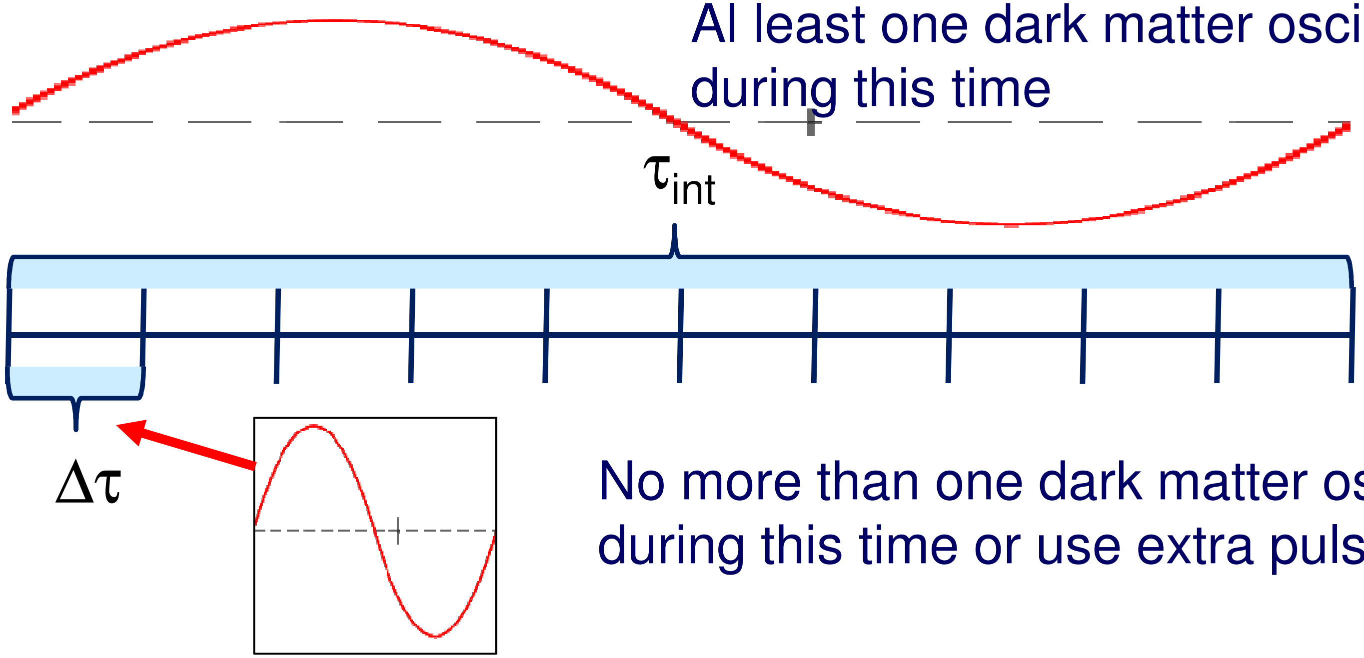
Science 319, 1808 (2008)

CLOCK MEASUREMENT PROTOCOLS FOR THE DARK MATTER DETECTION

Single clock ratio measurement: averaging over time τ_1

Make N such measurements, preferably regularly spaced

Clocks are broadband UDM detectors but can be made resonant



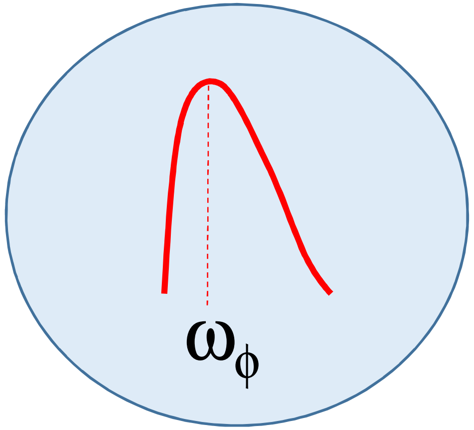
Al least one dark matter oscillation during this time

No more than one dark matter oscillation during this time or use extra pulse sequence

τ [s]	$f = 2\pi/m_\phi$ [Hz]	m_ϕ [eV]
10^{-6}	1 MHz	4×10^{-9}
10^{-3}	1 kHz	4×10^{-12}
1	1	4×10^{-15}
1000	1 mHz	4×10^{-18}
10^{6}	10^{-6}	4×10^{-21}

Detection signal:

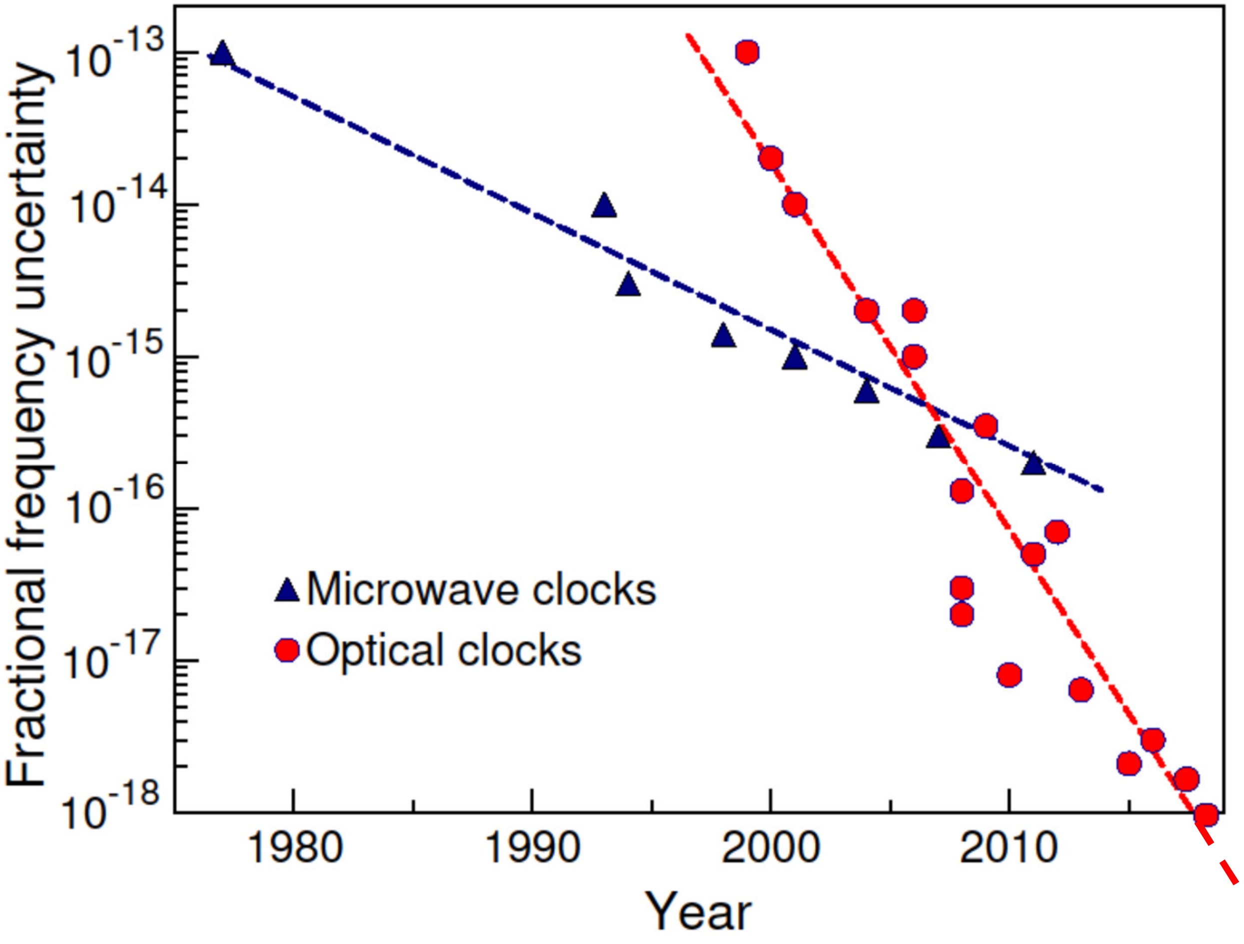
A peak with monochromatic frequency
in the discrete Fourier transform of this time series.



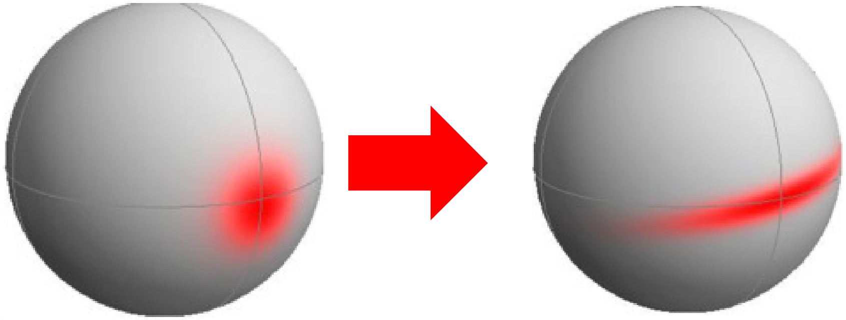
$$f = 2\pi/m_\phi$$

A. Arvanitaki et al., PRD 91, 015015 (2015)

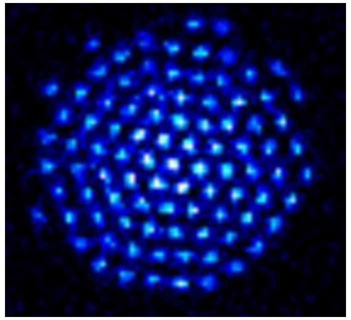
OPTICAL CLOCKS WILL CONTINUE TO IMPROVE



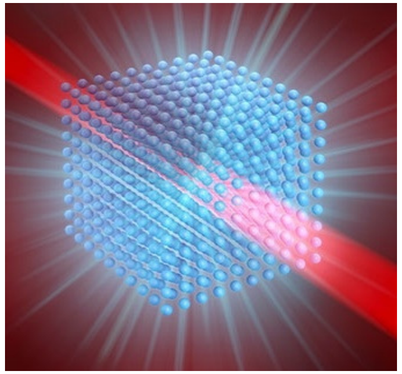
?



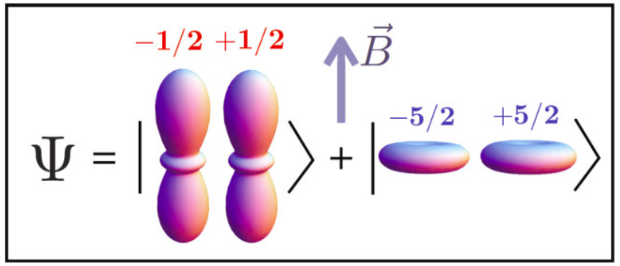
Measurements beyond the quantum limit



Large ion crystals



New designs for lattice clocks

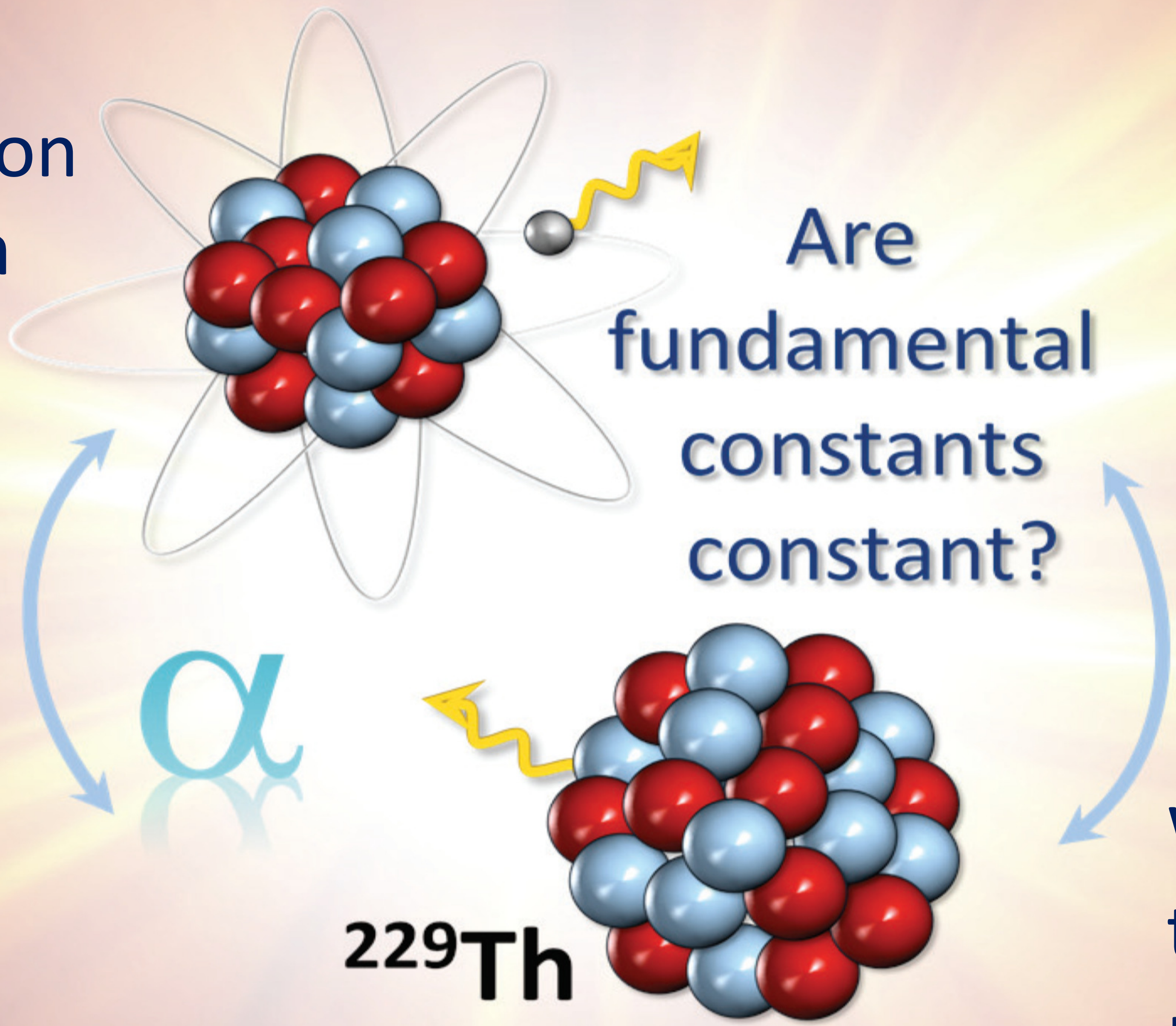


Entangled clocks

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

From atomic to nuclear clocks!

Clock based on transitions in atoms



Are fundamental constants constant?

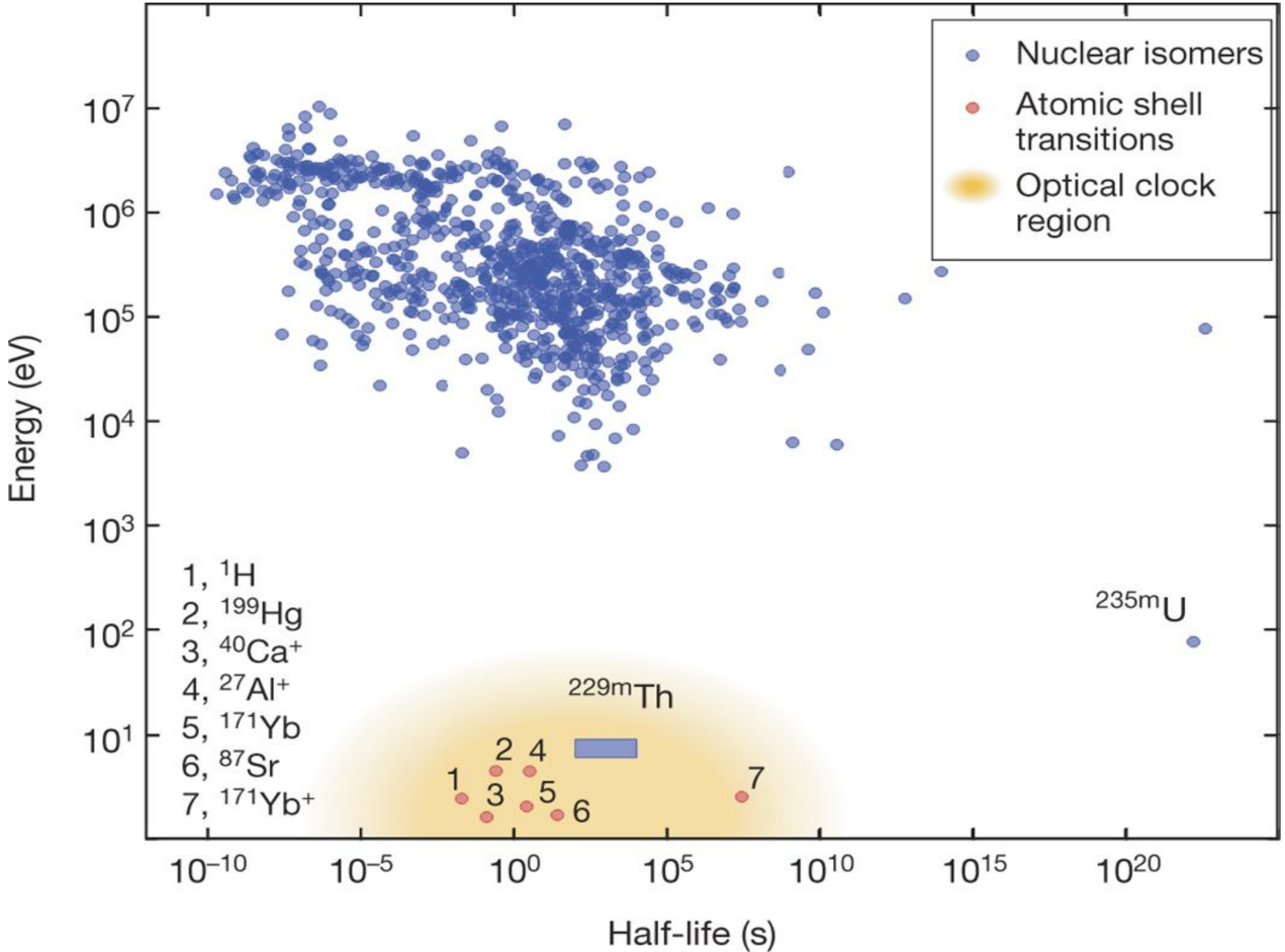
What about transitions in nuclei?

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

OBVIOUS PROBLEM: TYPICAL NUCLEAR ENERGY LEVELS ARE IN MEV

Six orders of magnitude from ~few eV we can access by lasers!

Nuclear clocks?

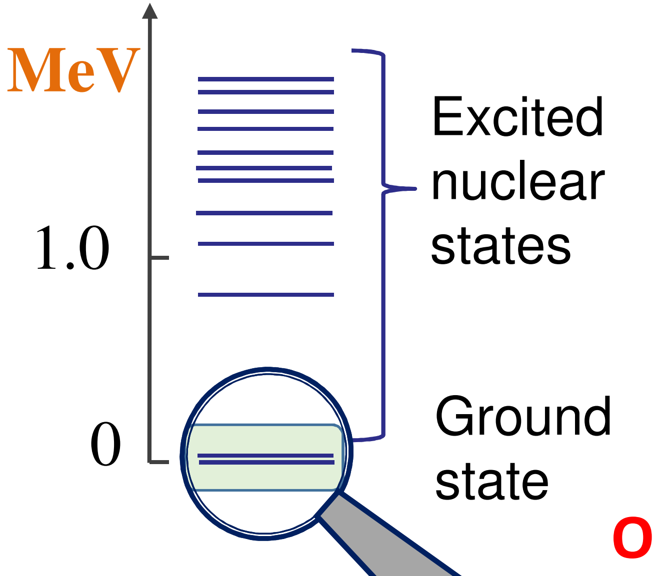


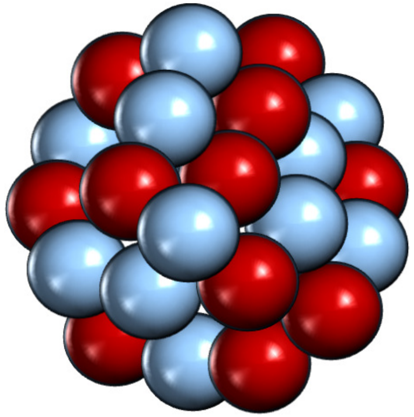
Nature 533, 47 (2016)

^{229}Th NUCLEAR CLOCK

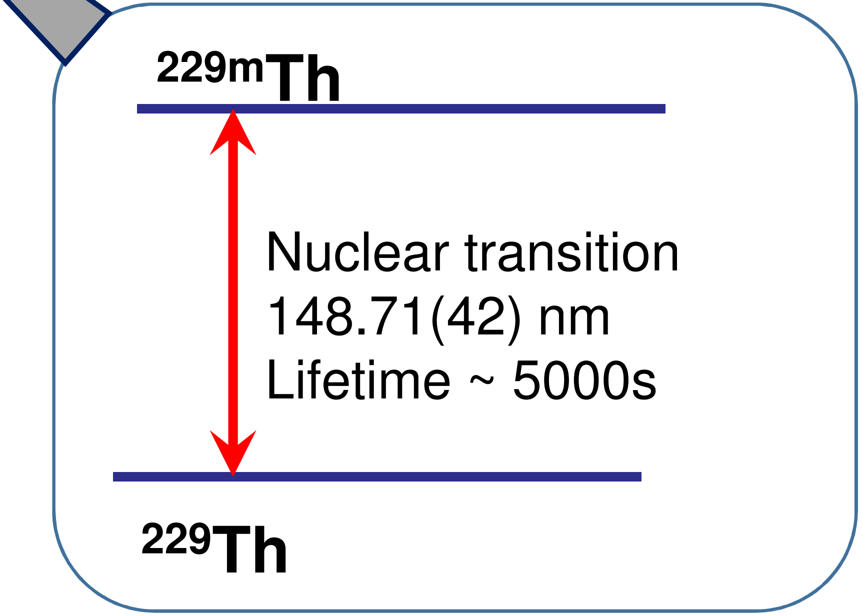
European Research Council

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





Only ONE exception!

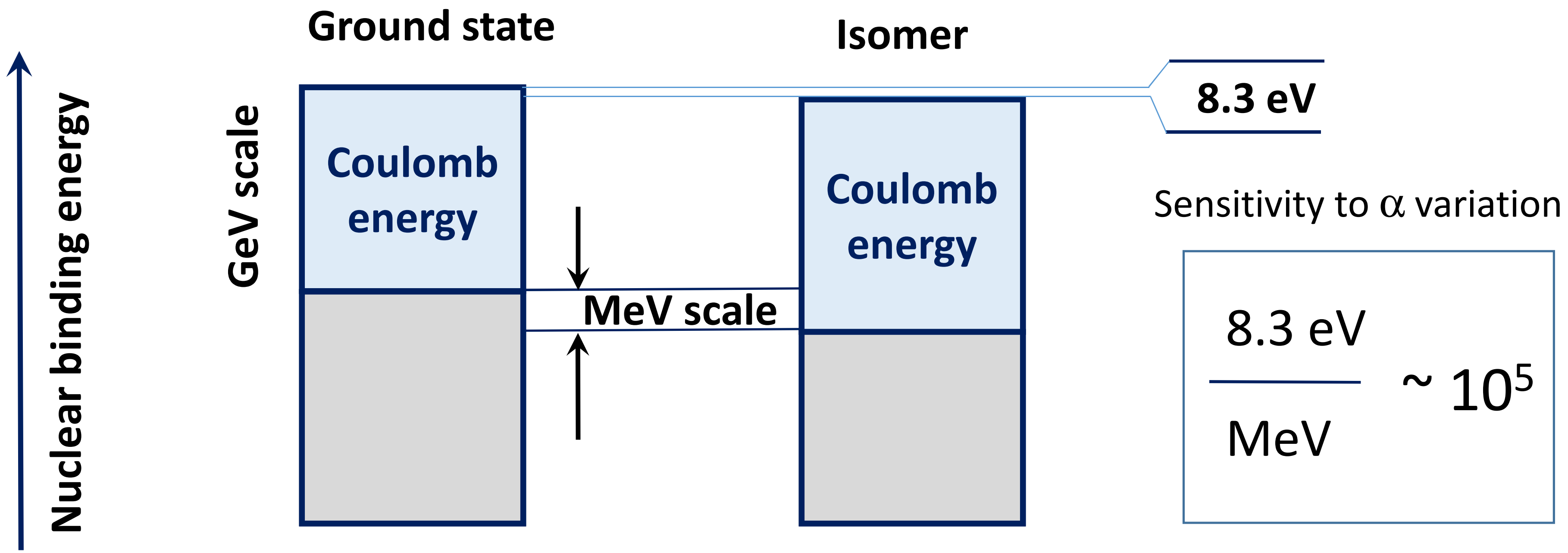


Nuclear transition
148.71(42) nm
Lifetime ~ 5000s

Energy of the ^{229}Th nuclear clock transition:
Seiferle *et al*., Nature 573, 243 (2019)
T. Sikorsky et al., Phys. Rev. Lett. 125, 142503 (2020).
S. Kraemer et al., arXiv:2209.10276 (2022)

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

Th nuclear clock: Exceptional sensitivity to new physics



Sensitivity to α variation

$$\boxed{\frac{8.3\ \text{eV}}{\text{MeV}} \sim 10^5}$$

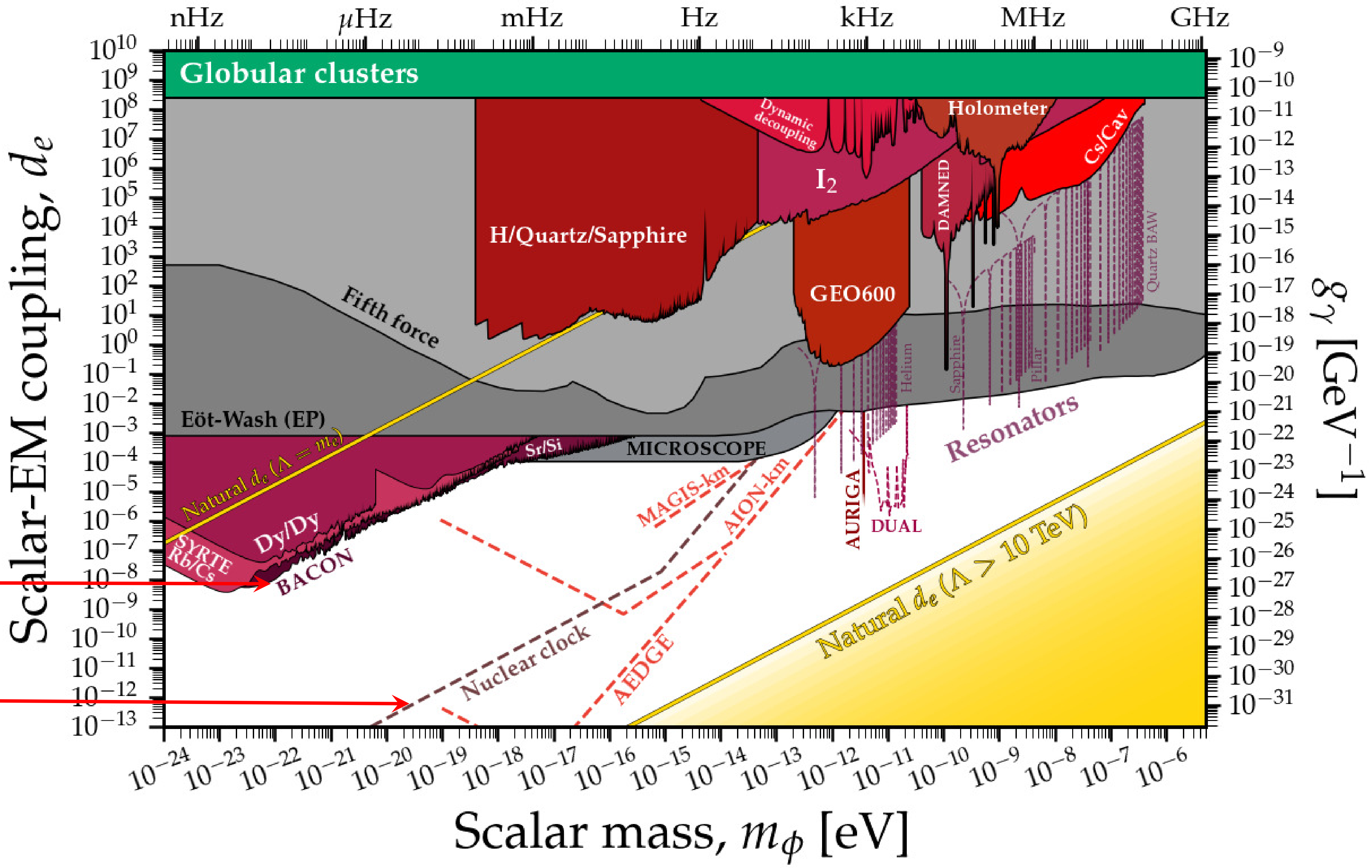
Much higher predicted sensitivity (K = 10000-100000) to the variation of α and $\frac{m_q}{\Lambda_{QCD}}$.

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

5 years: prototype nuclear clocks, based on both solid state and trapped ion technologies
Variation of fundamental constant and dark matter searches competitive with present clock

10 years: 10^{-18} – 10^{-19} nuclear clock, 5 - 6 orders improvement in current clock dark matter limits

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



Present
clock limits

Projected
clock limits

arXiv:2203.14915
Ultralight DM limits: https://cajohare.github.io/AxionLimits/

NEXT DECADE OF SPACE RESEARCH

What quantum technologies will be sent to space?

What new physics can one search for in space better then on Earth?

Ongoing NASA Decadal Survey: Biological and Physical Sciences in Space
https://science.nasa.gov/biological-physical/decadal-survey

Europe: Community workshop on cold atoms in space (September 2021)
https://indico.cern.ch/event/1064855/
Goal: develop a community roadmap and milestones to demonstrate the readiness of cold atom technologies in space, as proposed in the Voyage 2050 recommendations.

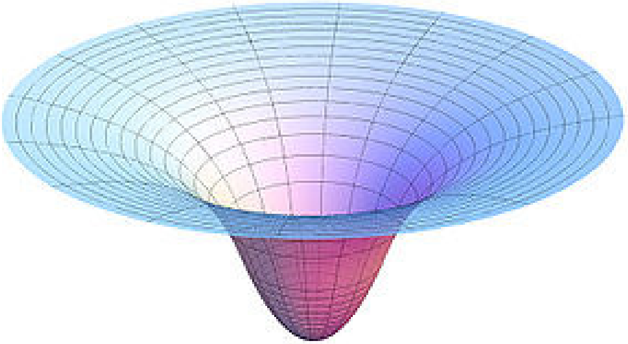
Cold Atoms in Space: Community Workshop Summary and Proposed Road-Map, Alonso et al., arXiv:2201.07789, EPJ Quantum, in press (2022)

Image credits: NASA, ESA

WHY TO SEARCH FOR NEW PHYSICS IN SPACE?

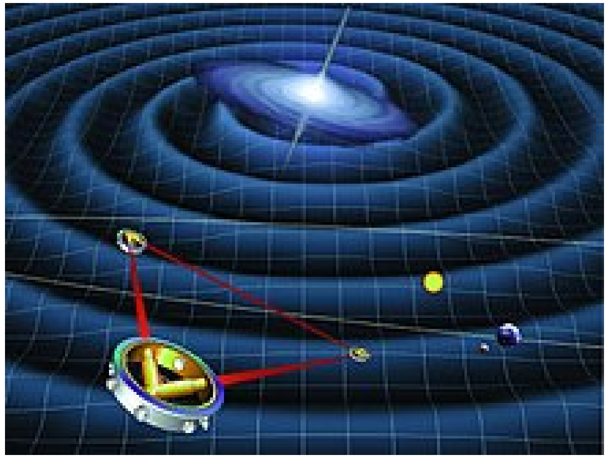
Quantum sensors in space enables discovery of new physics not possible on Earth
Many orders of magnitude improvements or principally different experiments are possible

Need to be away from Earth surface

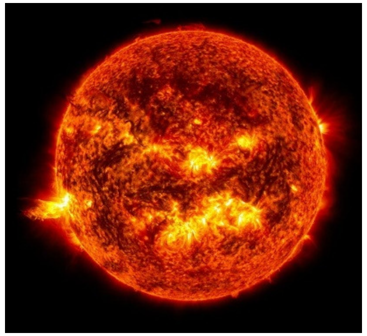


Tests of gravity are hindered by Earth gravity
Optical time transfer to link Earth clocks
Dark energy and some dark matter (screening)
Tests of fundamental postulates (WEP, LLI)

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

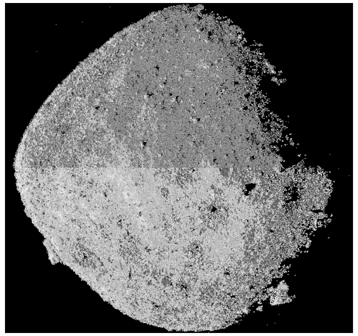
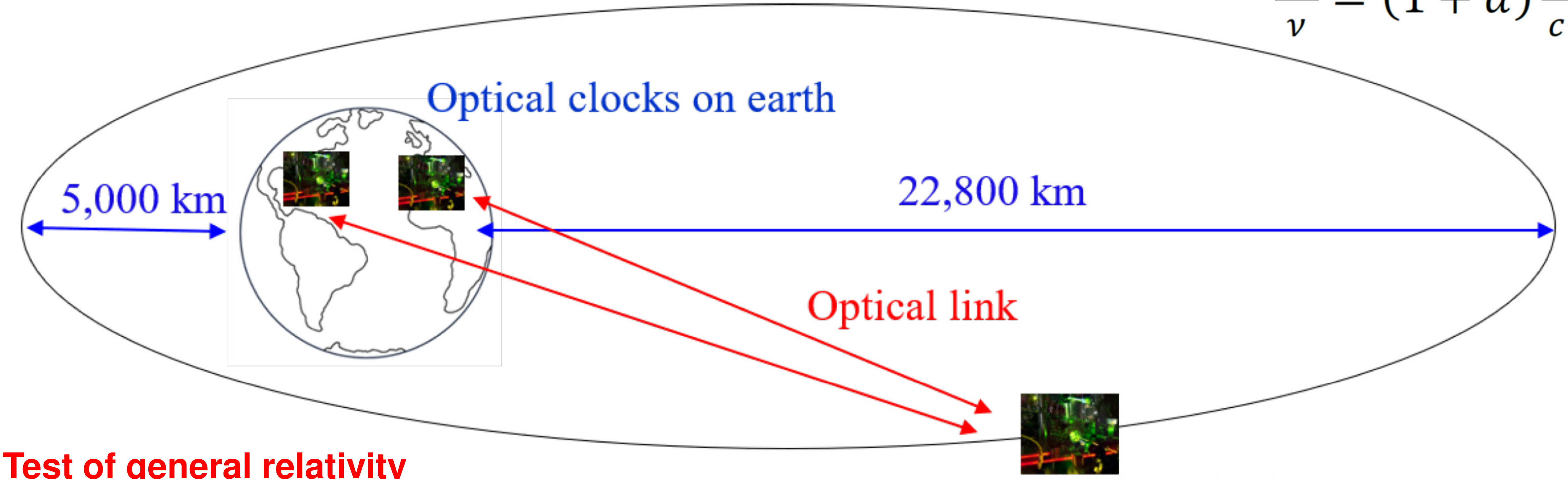


Image credits:
NASA, Wikipedia

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)

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

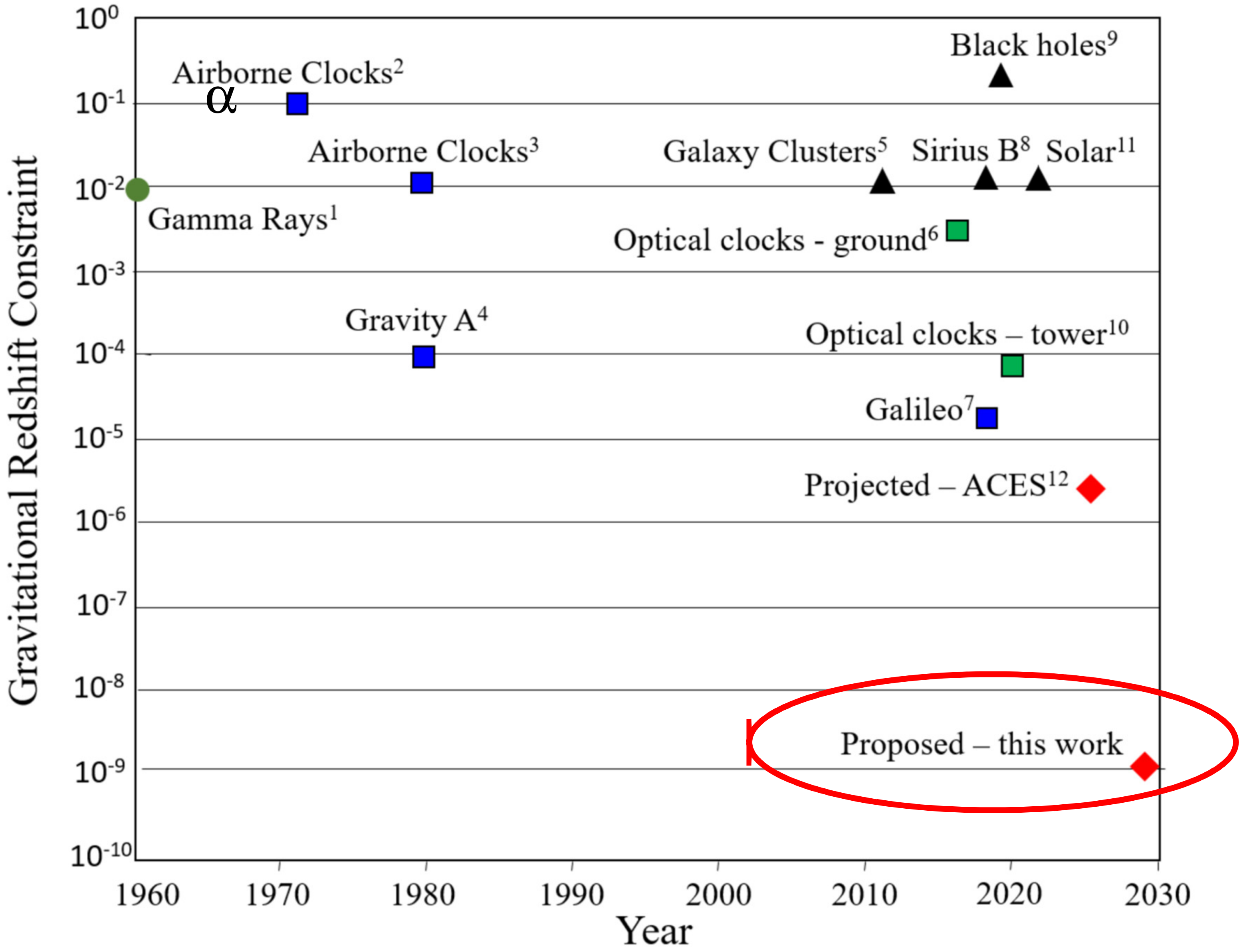


Optical clock
in space

Test of general relativity

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)

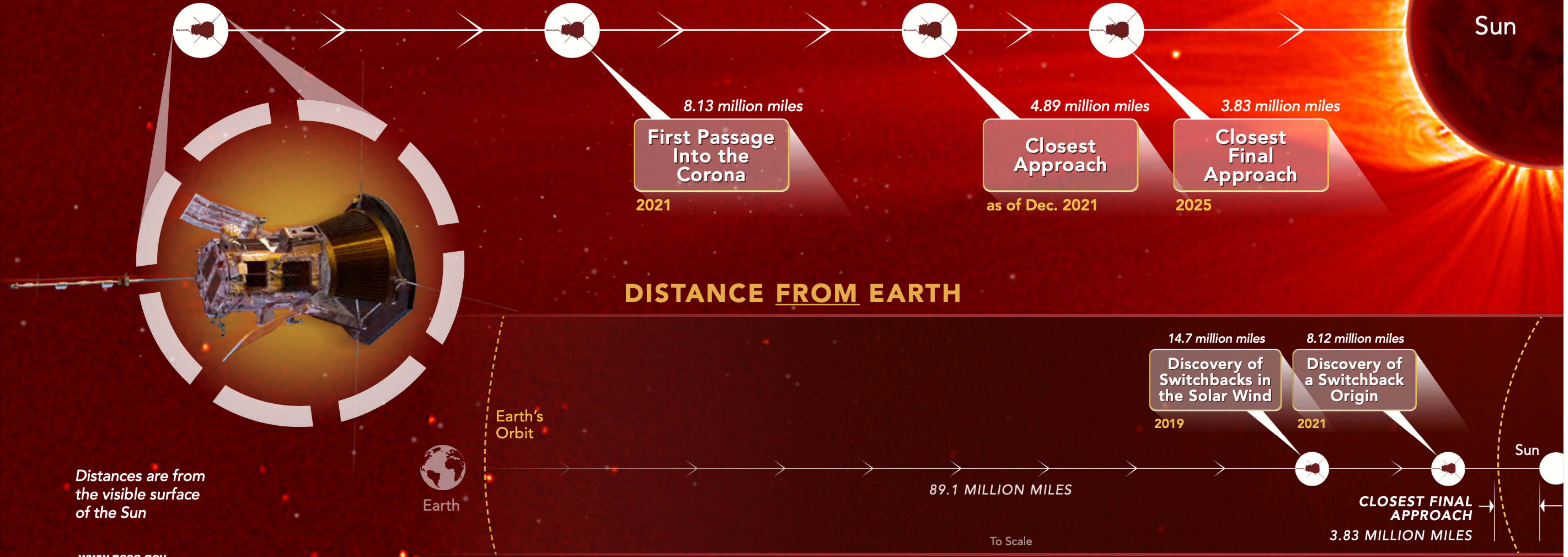
Image credit: NASA's Goddard Space Flight Center/Mary P. Hrybyk-Keith

National Aeronautics and Space Administration

PARKER SOLAR PROBE

NASA’s Parker Solar Probe has now flown through the Sun’s upper atmosphere – the corona

JOURNEY THROUGH THE SUN’S ATMOSPHERE



Parker Solar Probe

Sun

8.13 million miles
First Passage Into the Corona
2021

4.89 million miles
Closest Approach
as of Dec. 2021

3.83 million miles
Closest Final Approach
2025

DISTANCE FROM EARTH

14.7 million miles
Discovery of Switchbacks in the Solar Wind
2019

8.12 million miles
Discovery of a Switchback Origin
2021

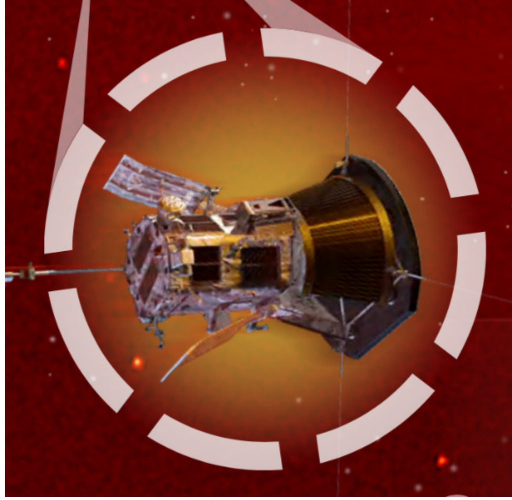
Distances are from the visible surface of the Sun

www.nasa.gov

For more information, please visit: *nasa.gov/sunearth*

Sun Image Credit: M. Druckmüller, P. Aniol, Vojtech Rusin

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



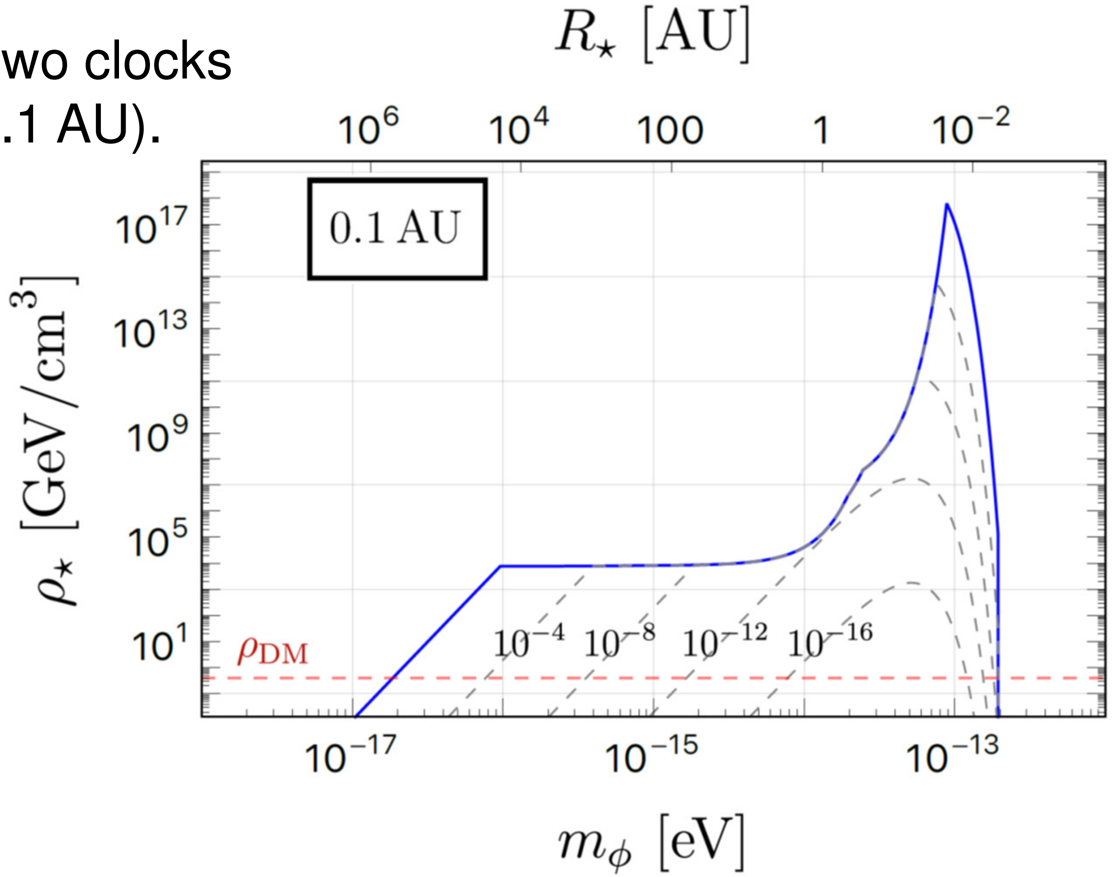
Yu-Dai Tsai, Joshua Eby, Marianna S. Safronova, arXiv:2112.07674,
in press, Nature Astronomy (2022)

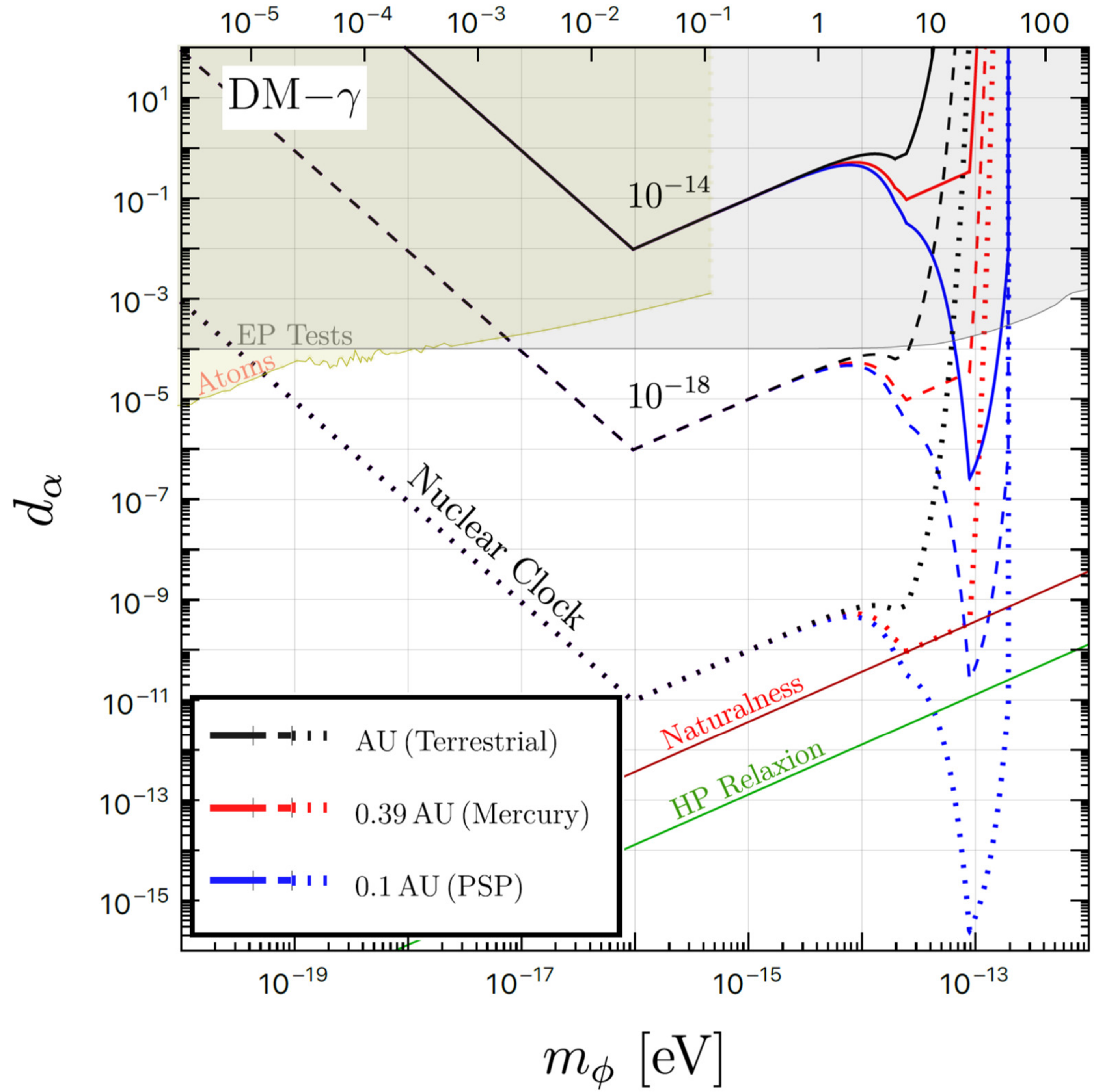
We do not know how much dark matter there is in the Solar system.

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



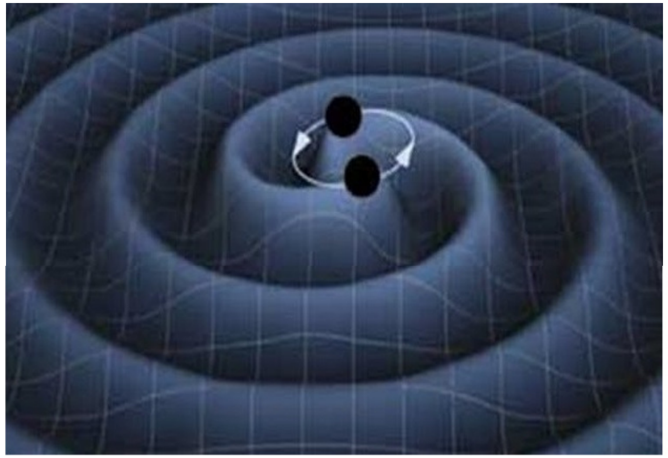


Estimated sensitivity reaches for ultralight dark matter (linear coupling) and bound to the Sun.

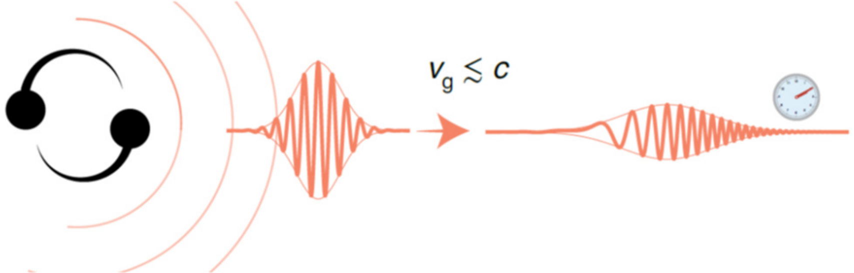
The blue, red, and black denote sensitivity for probes at the **distance of 0.1 AU**, probes at the orbit of Mercury, and for terrestrial clocks, respectively

Yu-Dai Tsai, Joshua Eby, Marianna S. Safronova, arXiv:2112.07674, in press, Nature Astronomy (2022)

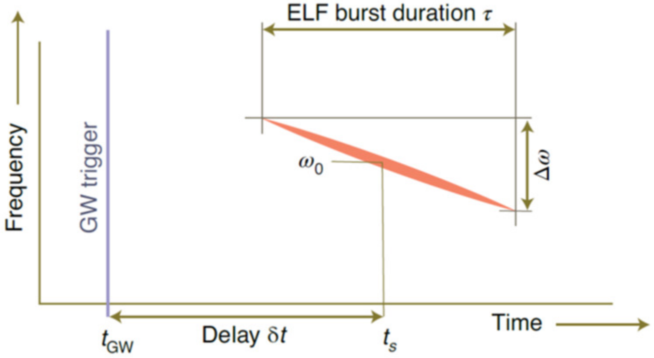
Quantum sensor networks as exotic field telescopes for multi-messenger astronomy



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)

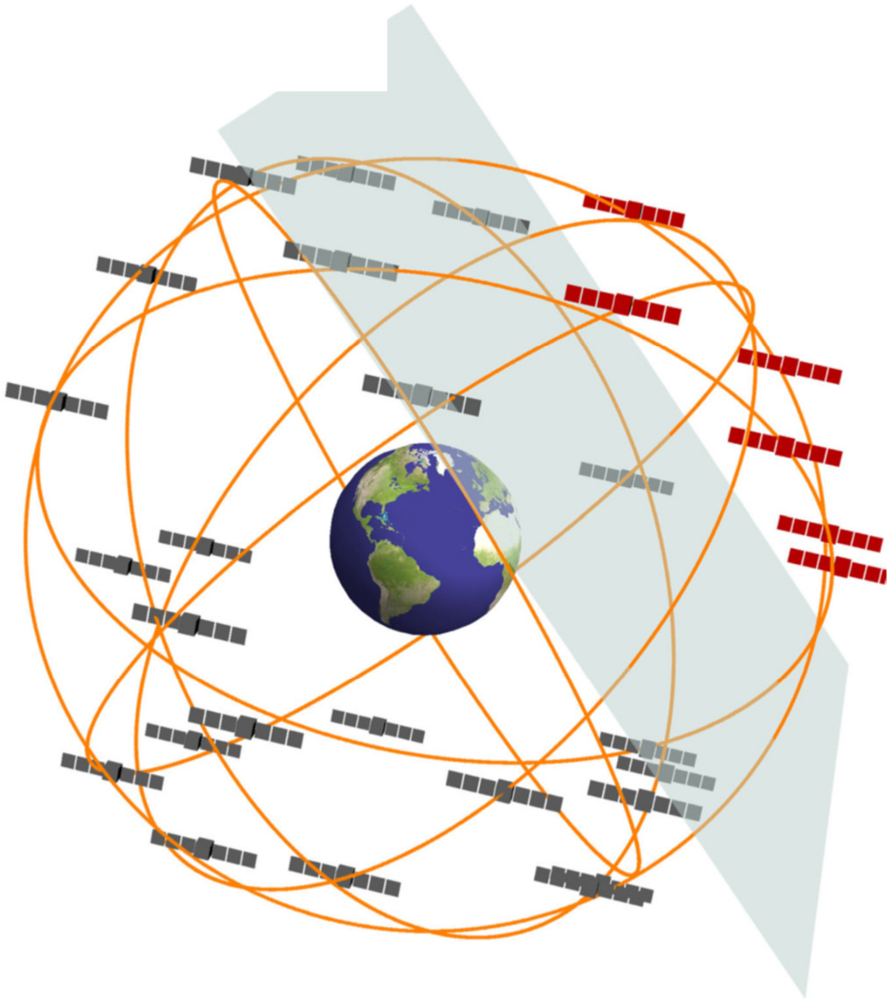
nature
physics
LETTERS
PUBLISHED ONLINE: 17 NOVEMBER 2014 | DOI: 10.1038/NPHYS3137

Transient variations

Hunting for topological dark matter with atomic clocks

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

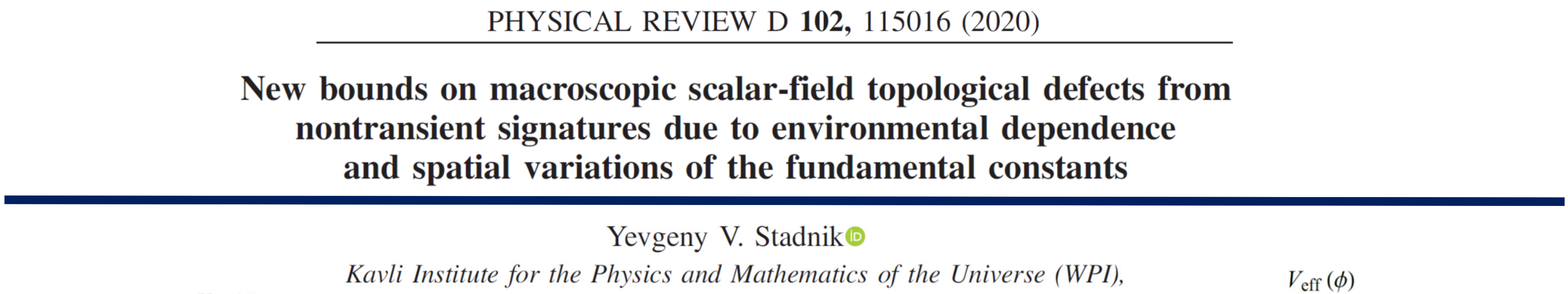
Transient effects



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)

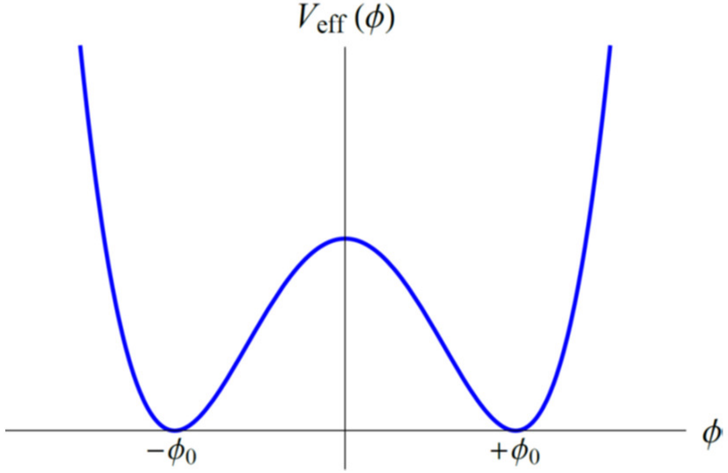


PHYSICAL REVIEW D **102,** 115016 (2020)

New bounds on macroscopic scalar-field topological defects from nontransient signatures due to environmental dependence and spatial variations of the fundamental constants

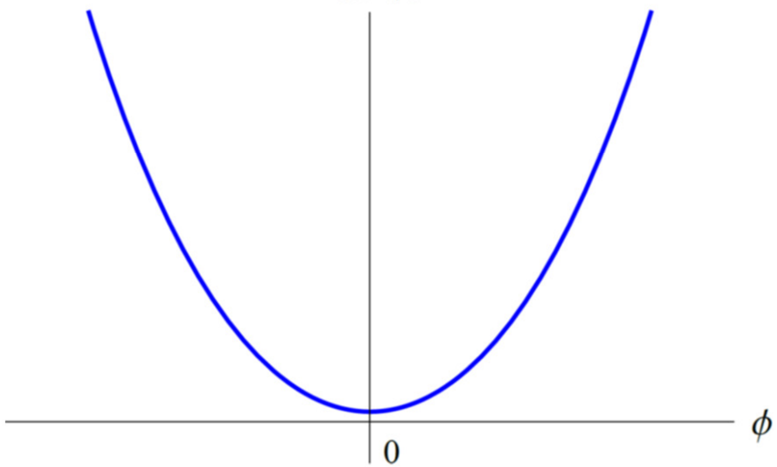
Yevgeny V. Stadnik

Kavli Institute for the Physics and Mathematics of the Universe (WPI),



Low-density environment

$$V_{\mathrm{eff}}(\phi) = \frac{\lambda}{4}\left(\phi^2 - \phi_0^2\right)^2 + \sum_{X=\gamma,e,N} \frac{\rho_X \phi^2}{\left(\Lambda'_X\right)^2}$$



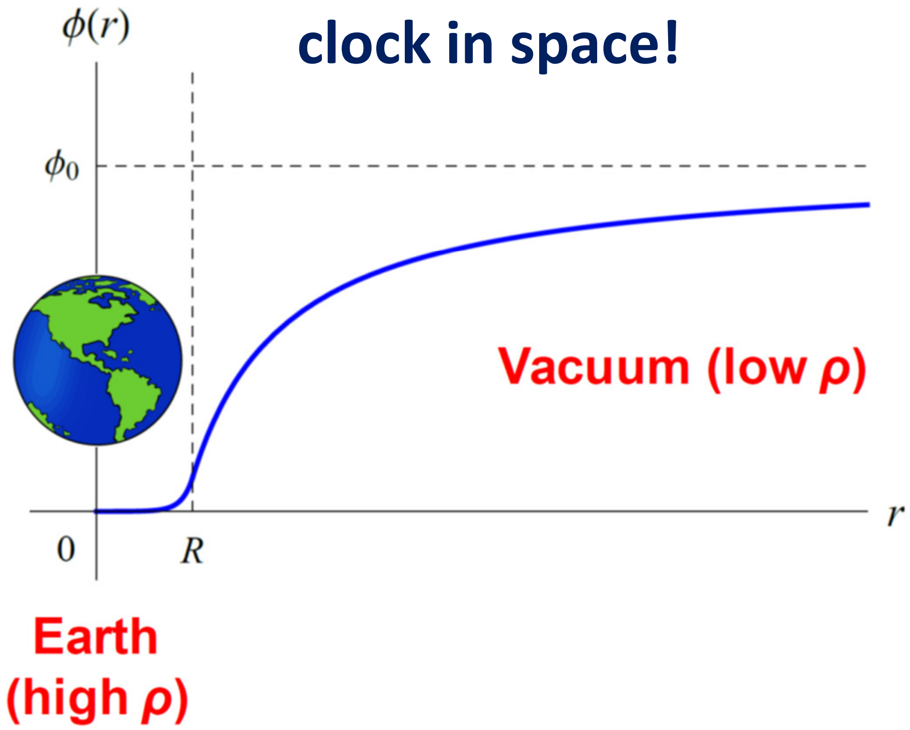
High-density environment

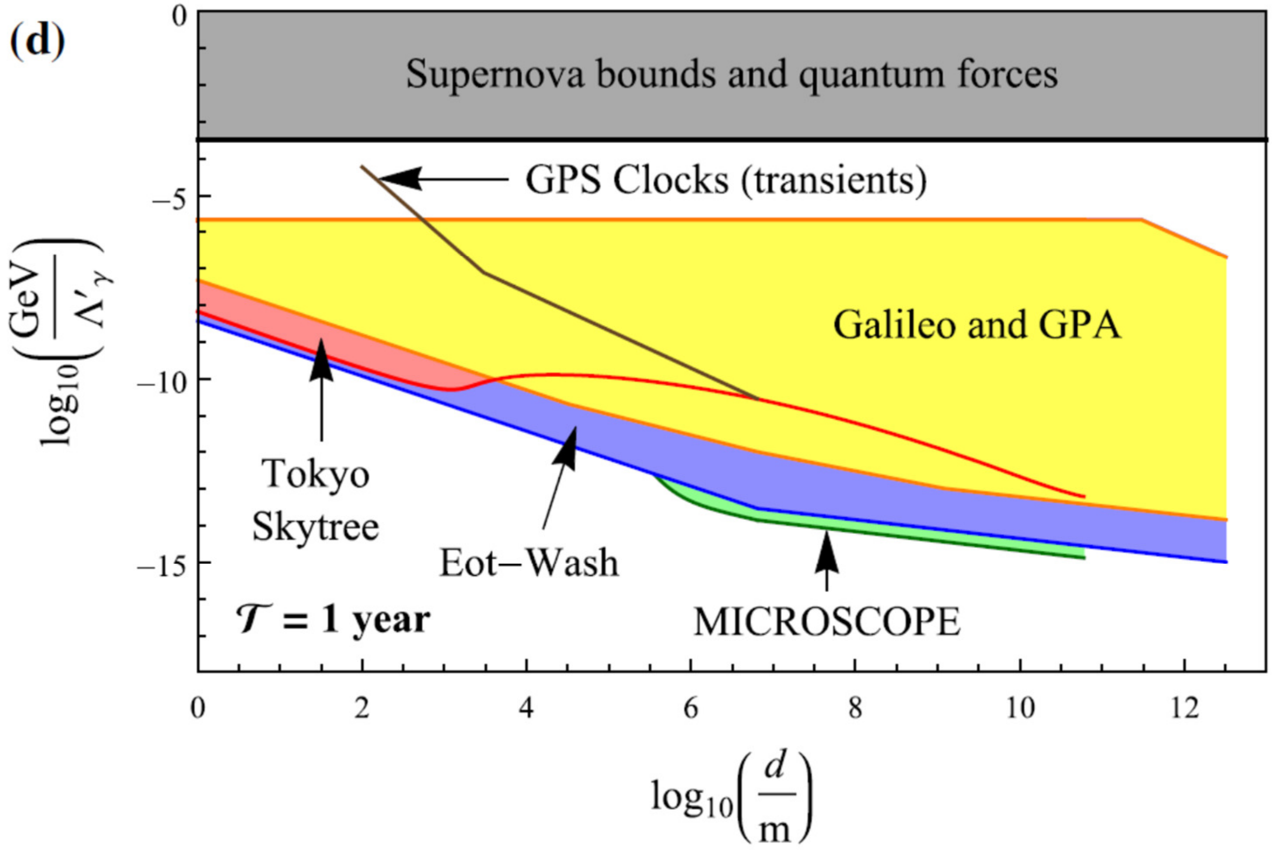
- Such scalar fields tends to be screened in dense environments
- All current experiments for topological defects were in the regime of strong screening (which was not accounted for)
- Environmental dependence of “constants”
- Must stronger constraints from such “non-transient effects

Slide credit: Yevgeny Stadnik

Environmental dependence of “constants” near Earth

Need to have a precision clock in space!





Picture credit: Yevgeny Stadnik

Moon, planets, asteroids & quantum sensors

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

- Moon: low seismic noise, free permanent cryogenic & vacuum environment
- Dark matter and gravitational detection with the Moon

Lunar seismic and gravitational antenna (LSGA)

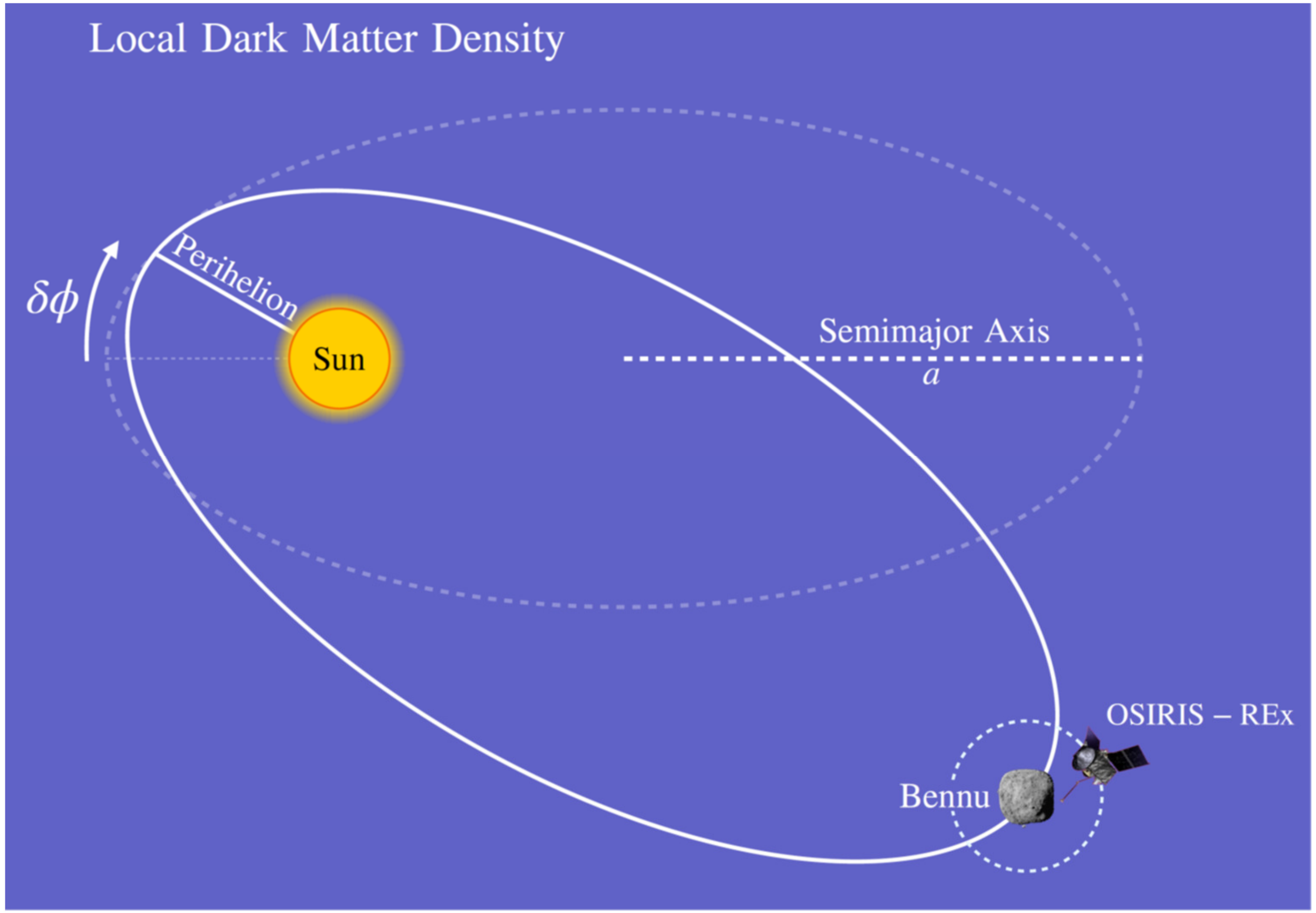
- How can quantum sensors can aid navigation in missions to planets and asteroids?
- Can we use quantum sensors to track asteroids?
- How to we use clocks to monitor distance between asteroids?

Asteroid astrometry as a fifth-force and ultralight dark sector probe, Yu-Dai Tsai, Youjia Wu, Sunny Vagnozzi, Luca Visinelli, arXiv:2107.04038

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

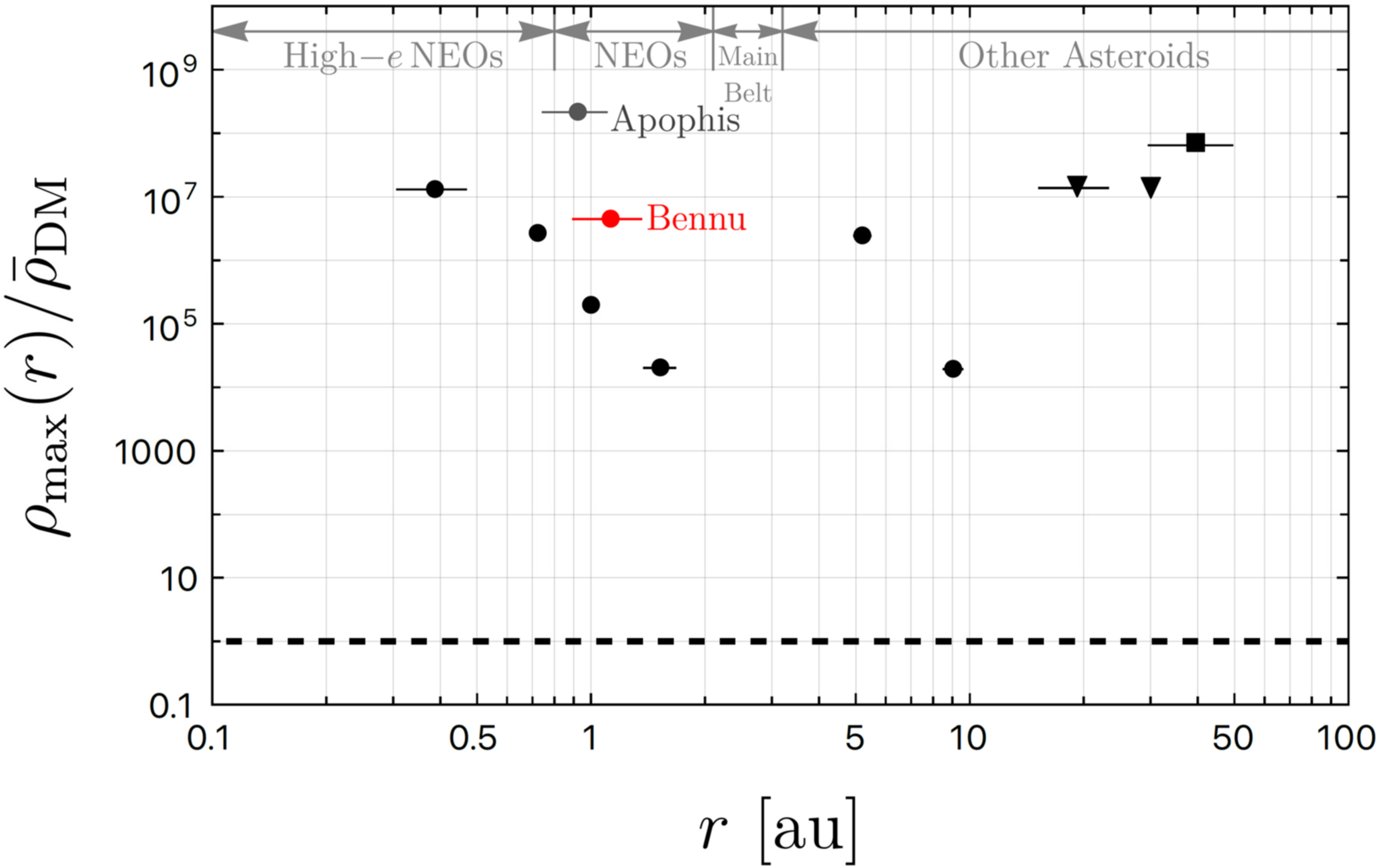
Constraints on Dark Matter and Cosmic Neutrino Profiles through Gravity

NASA mission to asteroid Bennu



Yu-Dai Tsai, Joshua Eby, Jason Arakawa, Davide Farnocchia, and Marianna S. Safronova, arXiv:2210.03749, submitted to Nature Astronomy (2022)

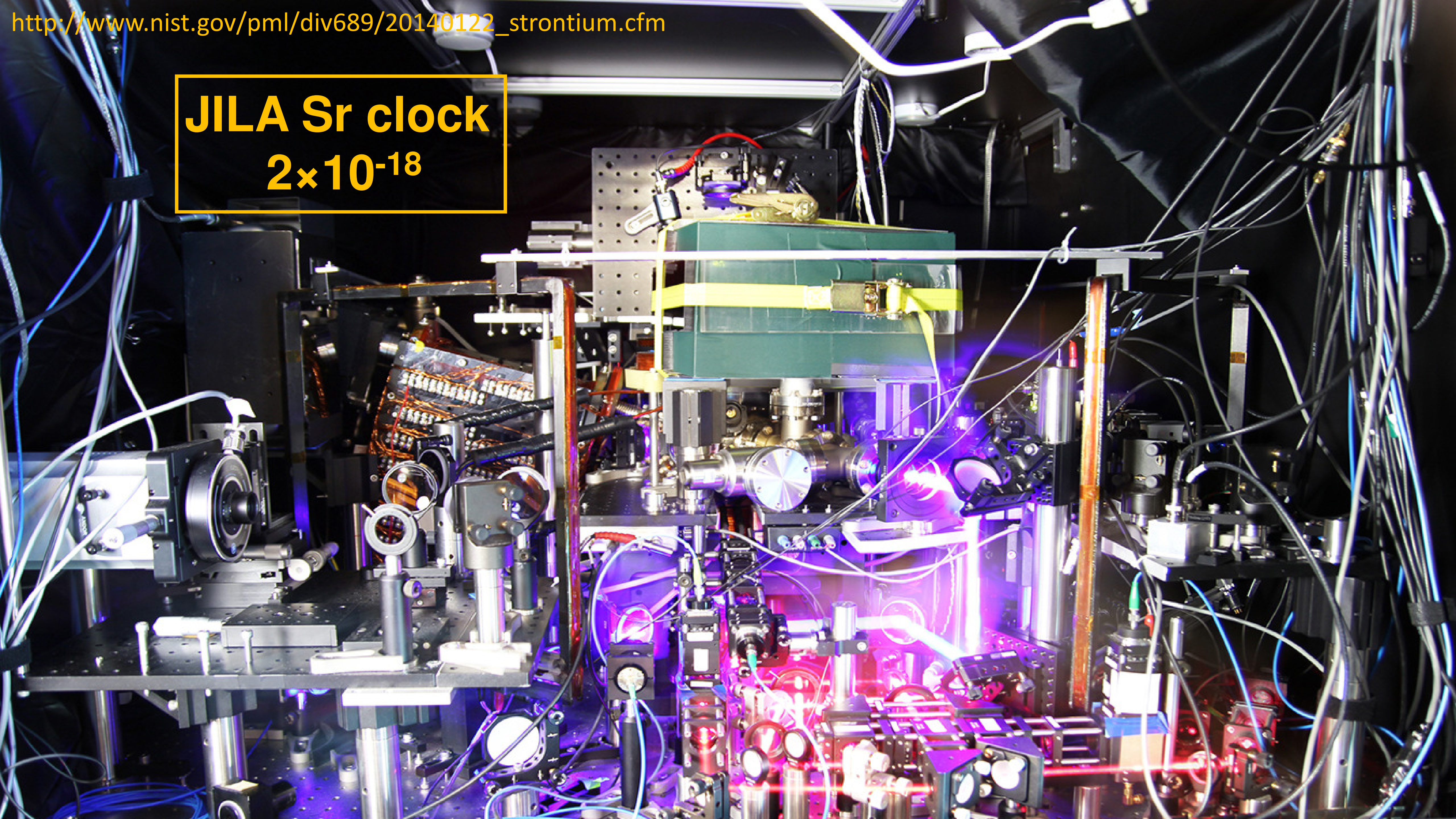
Constraints on Dark Matter and Cosmic Neutrino Profiles through Gravity



http://www.nist.gov/pml/div689/20140122_strontium.cfm

JILA Sr clock

2×10^{-18}



RESEARCH ARTICLE

ADVANCED QUANTUM TECHNOLOGIES
www.advquantumtech.com

Transportable Strontium Optical Lattice Clocks Operated Outside Laboratory at the Level of 10^{-18} Uncertainty

Adv. Quantum Technol. **2021**, 4, 2100015

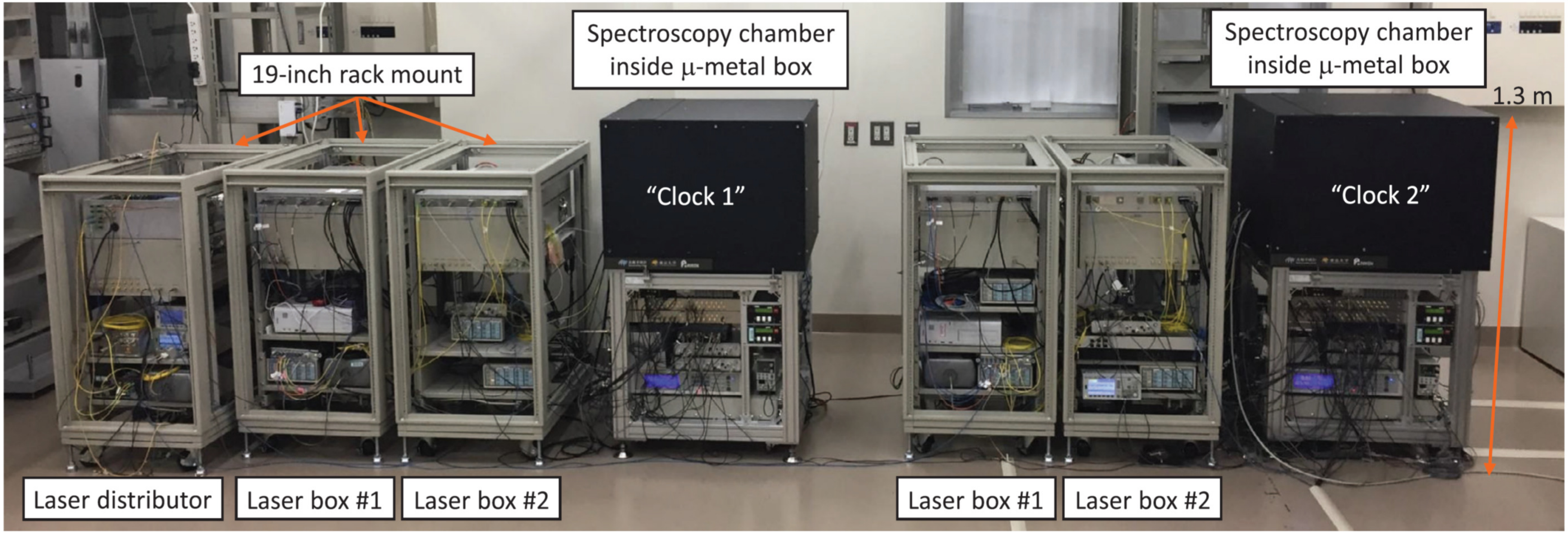
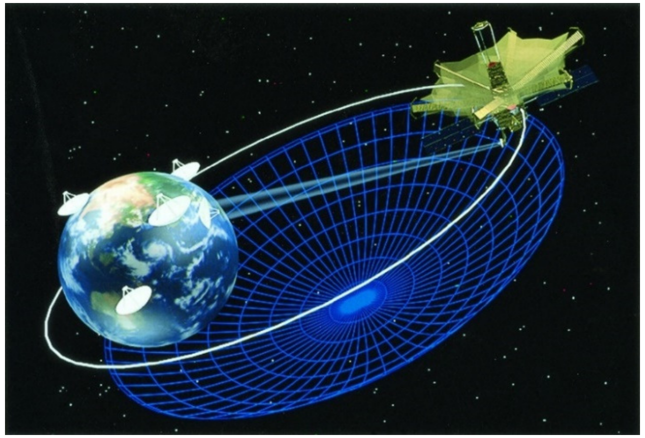


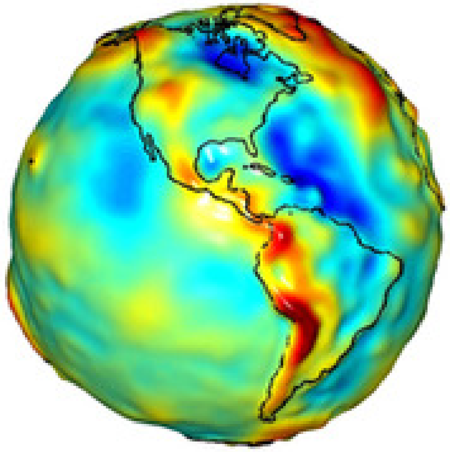
Figure 1. A pair of Sr optical lattice clocks placed at RIKEN laboratory.

Space applications of atomic clocks

One way navigation



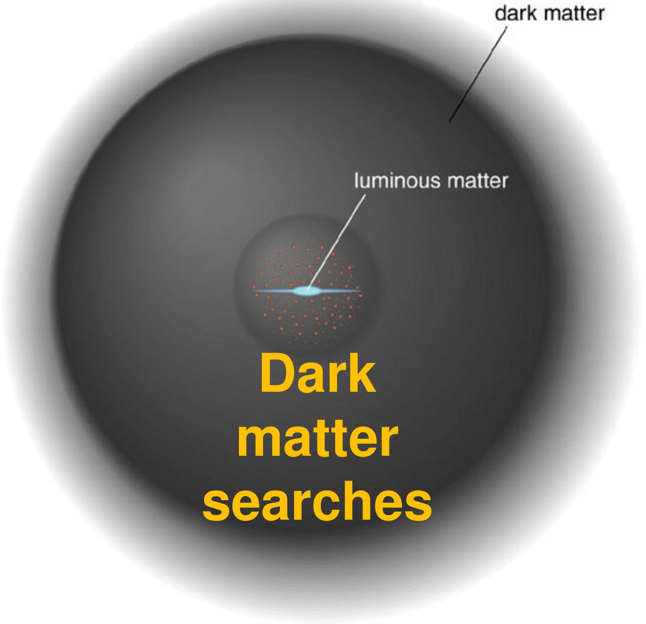
VLBI



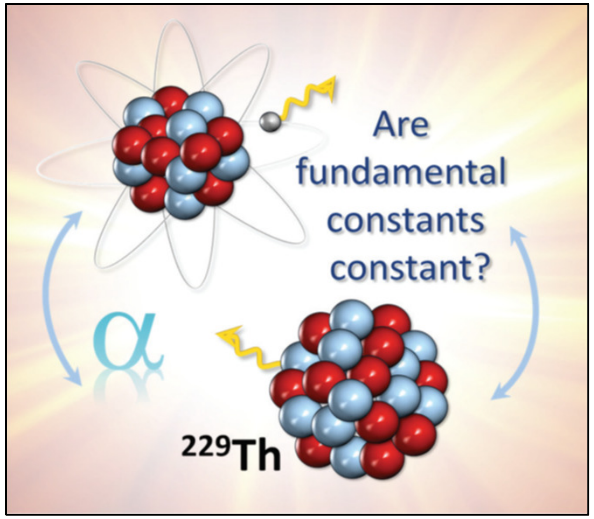
10^{-18}

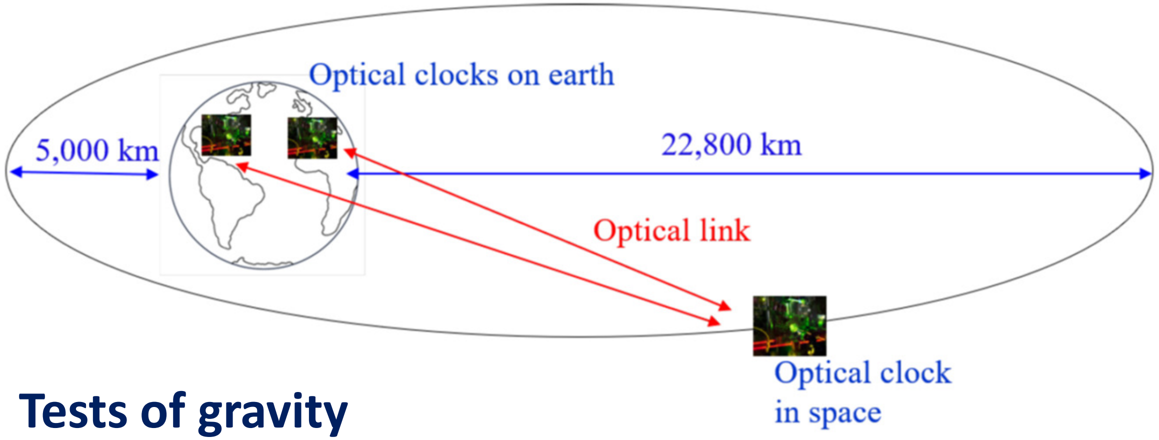
1 cm height

Relativistic geodesy



Dark matter searches



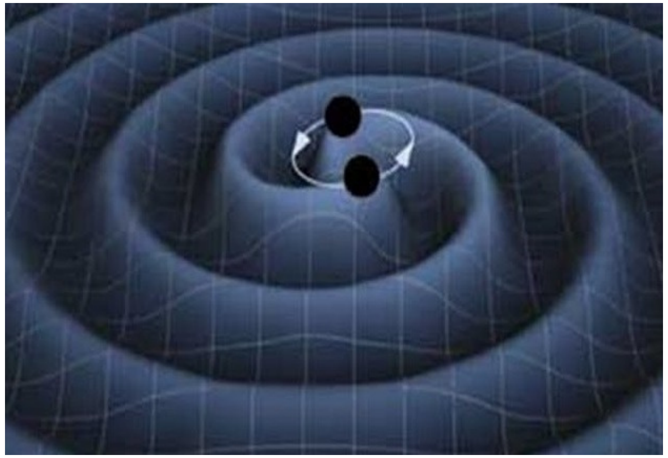


Tests of gravity

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) .

Challenges of deploying quantum sensors in space

Quantum sensors are extremely rapidly developing

Ideas of how to use quantum sensor in space for fundamental physics are rapidly developing

We NEED MODERN quantum sensors in space to advance fundamental physics

Need to find new efficient pathways of getting current quantum sensors to space within a decade.

Efforts of reduced SWaP & automation already started for portable quantum applications.

Establish collaborative projects of interdisciplinary academia teams/national labs/industry and NASA with theory participation (AMO, gravity, particle physics, earth sciences, astrophysics, etc.)

Need to answer many particle physics questions:
designing space missions to maximize science results

Transient signals for networks of quantum sensors, mechanisms for ELF bursts, propagation of ELF fields, mechanism of formation of DM halos bound to the Sun, Earth, etc., mechanism of formation, explosion, and detection of bosonic DM stars, how to use networks of quantum sensors on asteroids to probe DM and exotic forces, phenomenology of scalar models, DM screening effects, probing dark matter distribution in solar system, new ideas?

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 decade

- 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

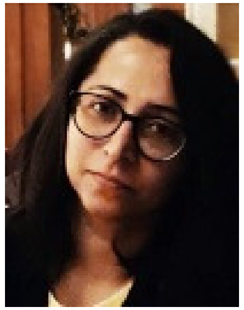
- Need to answer many particle physics questions for designing space missions to maximize science results

- Need more ideas on new physics searches with quantum sensors

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

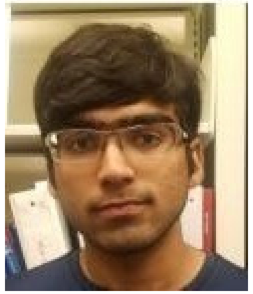

Akshay Bhosale
UD (CE)
Grad. St.


Dr. Sergey Porsev
Research Associate III


Dr. Dmytro Filin
Research Associate III


Dr. Charles Cheung
Postdoc


Jason Arakawa
postdoc


Hani Zaheer
Grad. St.


Aung Naing
Graduated August 2021

Collaborators:

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

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

Code development: Mikhail Kozlov (PNPI, LETI), Ilya Tupitsyn (St. Petersburg University), Andrey Bondarev (St. Petersburg Polytechnic Univ.)

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!