THE 2022 TRI-INSTITUTE SUMMER SCHOOL ON ELEMENTARY PARTICLES

Ultralight New Physics: part 2

Dark matter searches with quantum sensors

Q-SEnSE
An NSF Quantum Leap Challenge Institute

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

Marianna Safronova

University of Delaware

thorium
nuclear clock

https://thoriumclock.eu/

Dark matter searches with atomic, molecular, and nuclear clocks

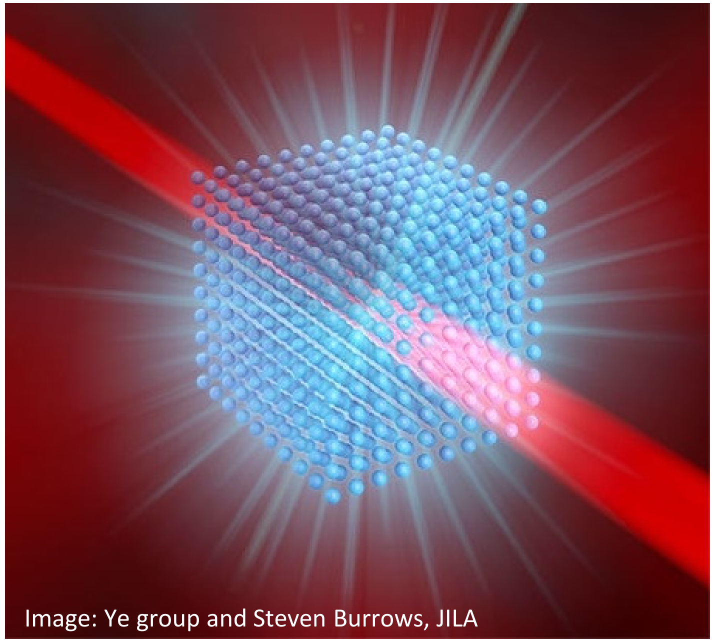
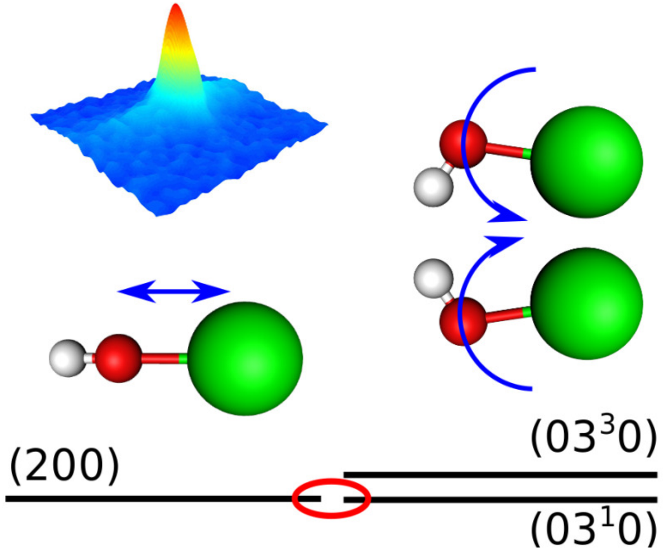
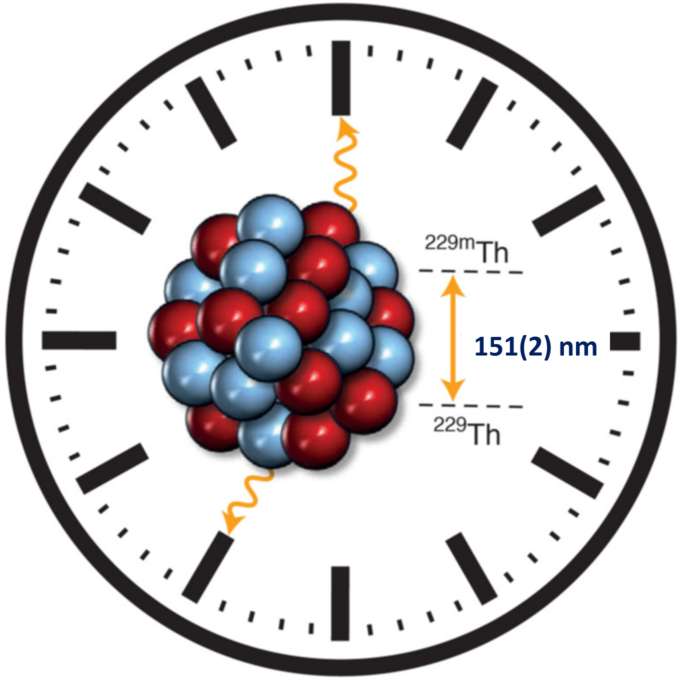


Image: Ye group and Steven Burrows, JILA

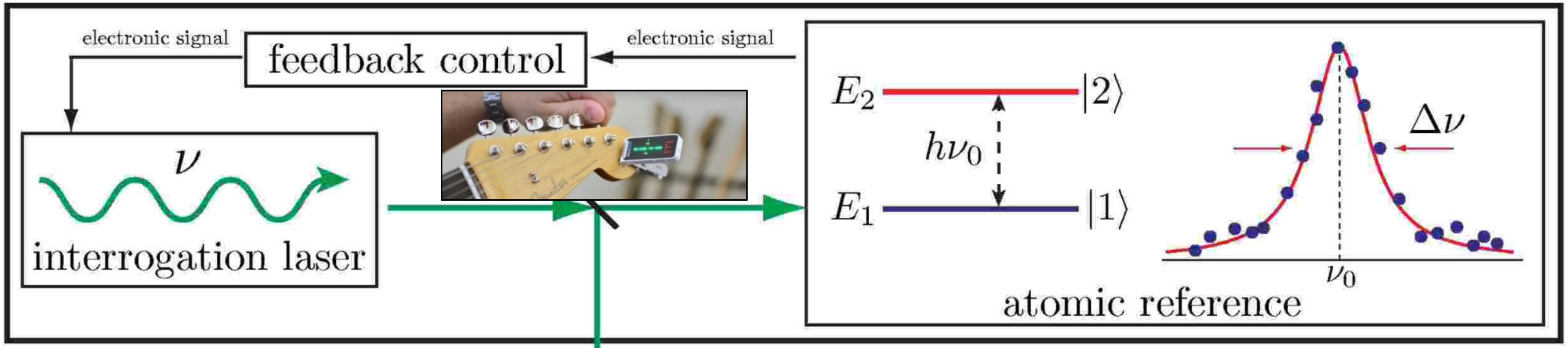




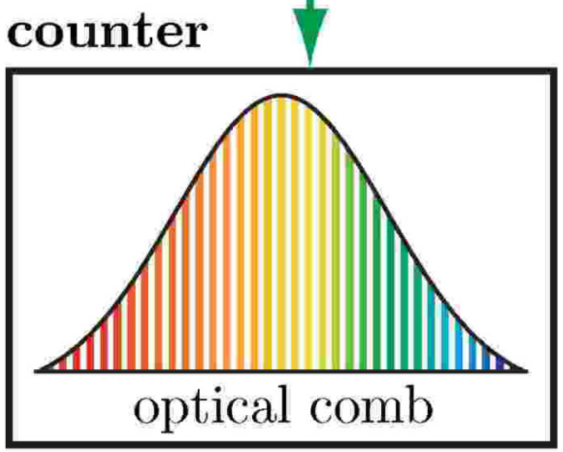
HOW OPTICAL ATOMIC CLOCK WORKS ?

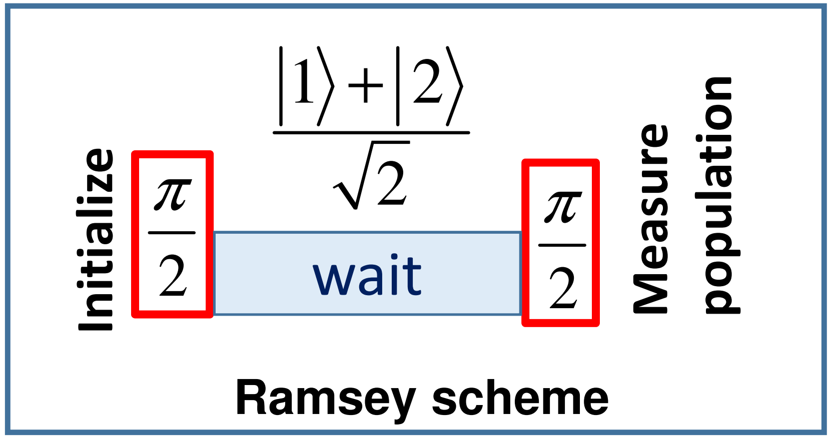
BASIC IDEA: TUNE THE LASER TO THE FREQUENCY OF THE ATOMIC TRANSITION

HOW OPTICAL ATOMIC CLOCK WORKS ?



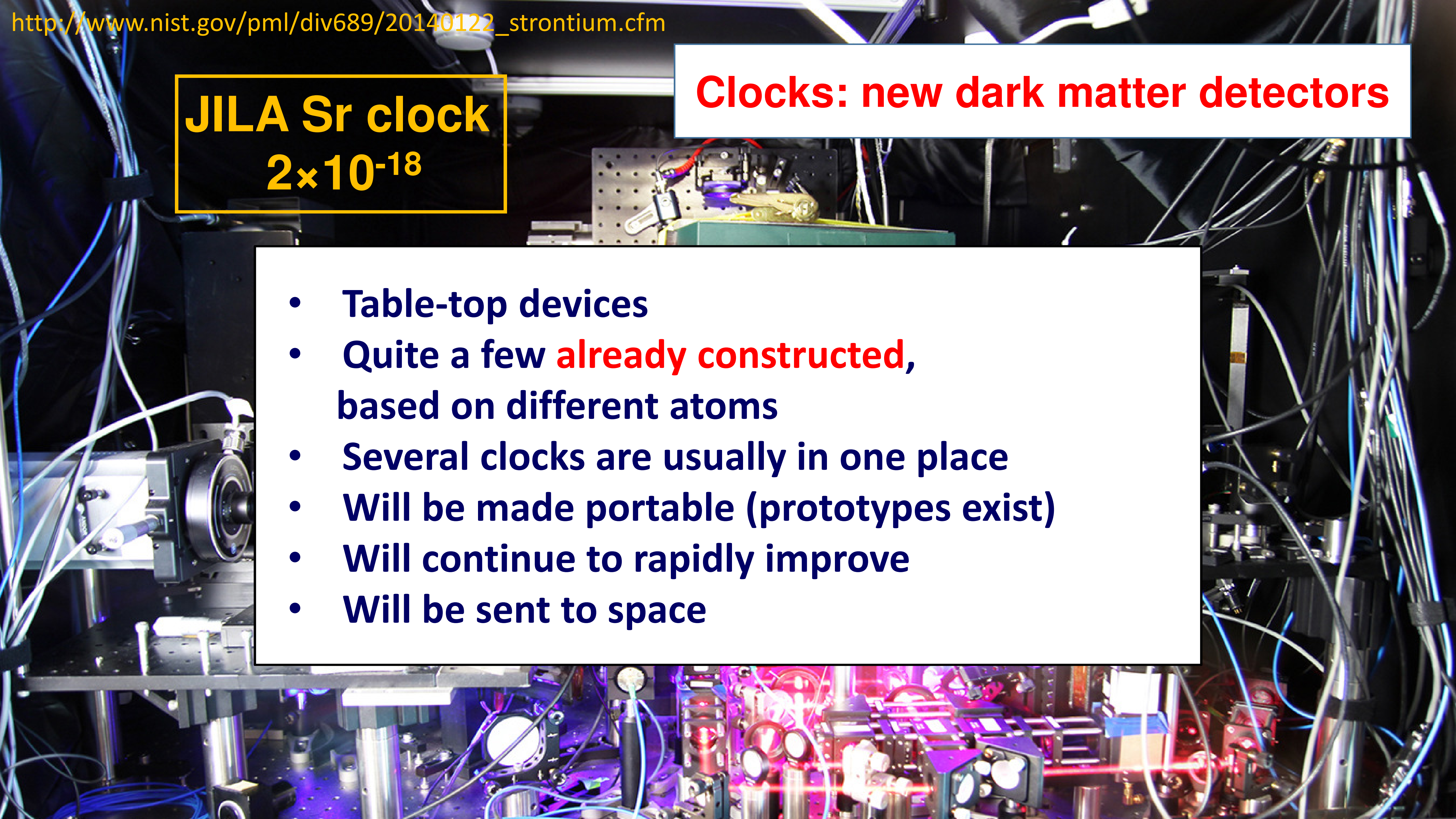
The laser is resonant with the atomic transition. A correction signal is derived from atomic spectroscopy that is fed back to the laser.





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

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



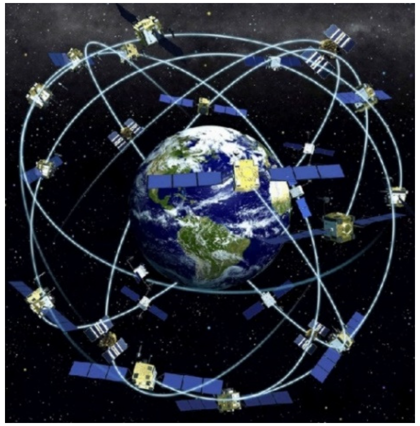
http://www.nist.gov/pml/div689/20140122_strontium.cfm

Clocks: new dark matter detectors

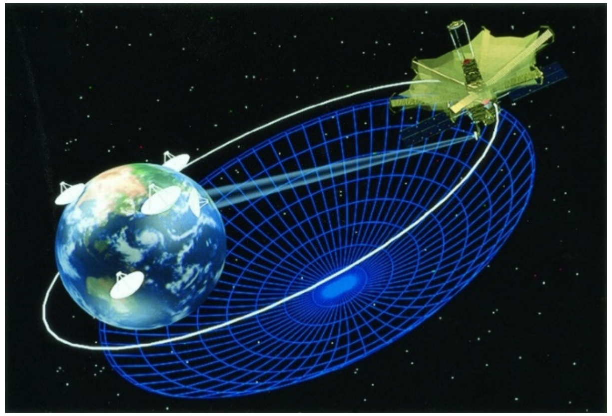
JILA Sr clock
2×10^{-18}

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

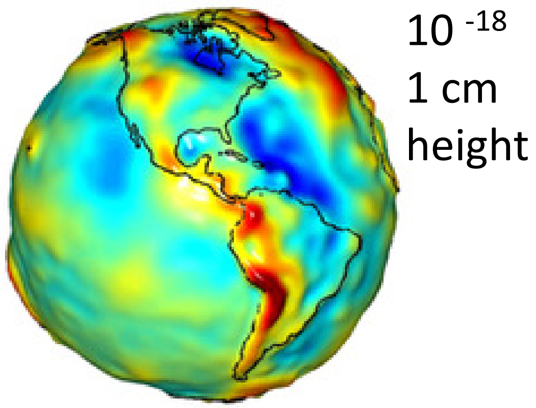
APPLICATIONS OF ATOMIC CLOCKS



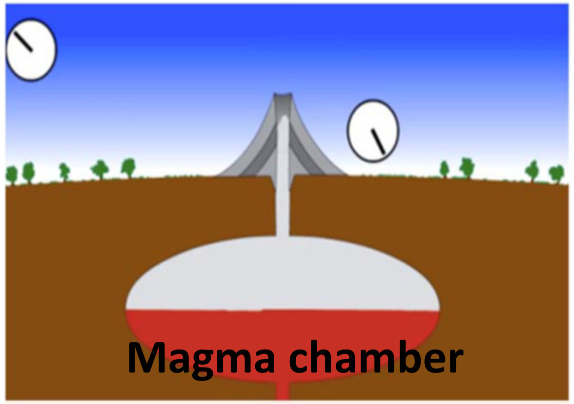
GPS, deep space navigation



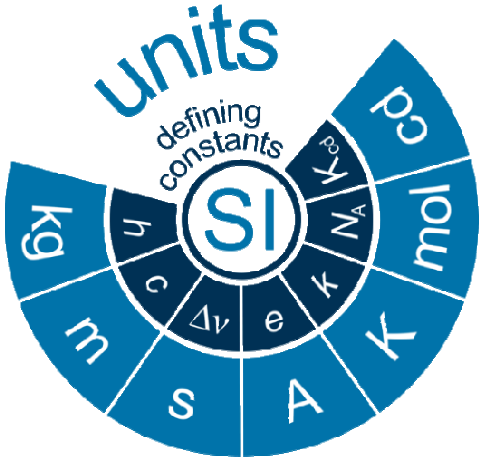
Very Long Baseline Interferometry



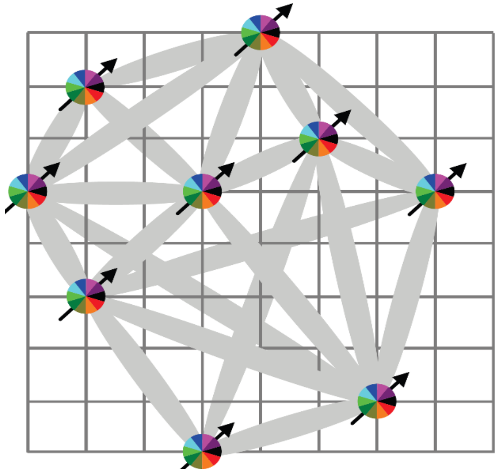
Relativistic geodesy



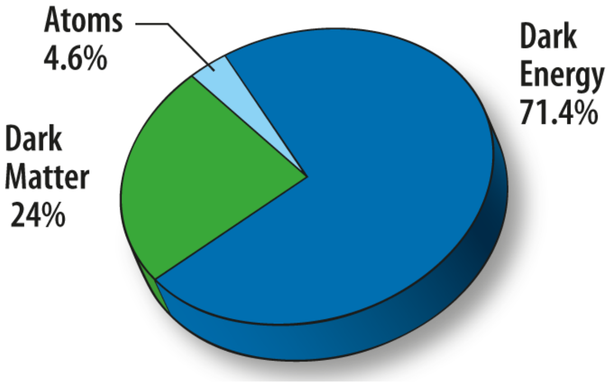
Gravity Sensor

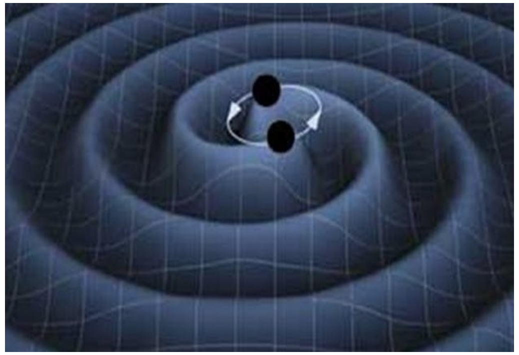


Definition of the second



Quantum simulation



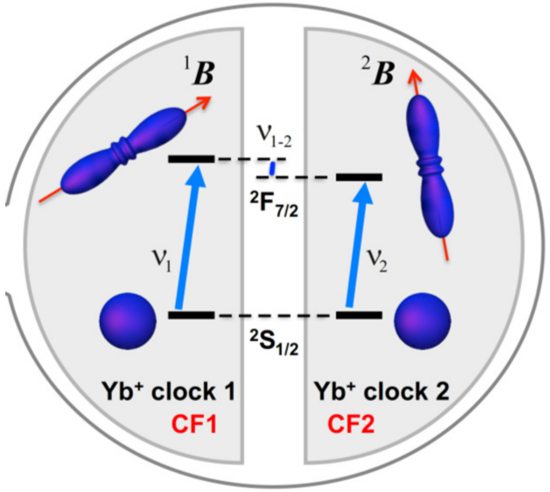


Searches for physics beyond the Standard Model

Image Credits: NOAA, Science 281,1825; 346, 1467, University of Hannover, PTB, PRD 94, 124043, Eur. Phys. J. Web Conf. 95 04009

SEARCH FOR PHYSICS BEYOND THE STANDARD MODEL WITH ATOMIC CLOCKS

Dark matter searches



Search for the violation of Lorentz invariance

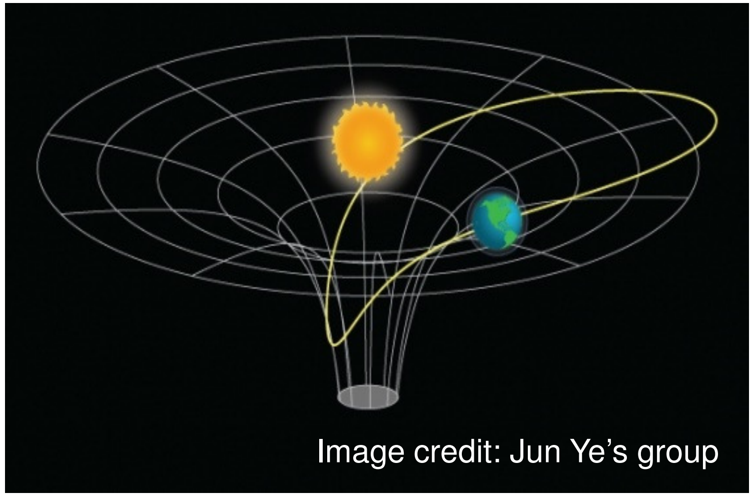


Image credit: Jun Ye's group

Tests of the position invariance

Are fundamental constants constant?

α

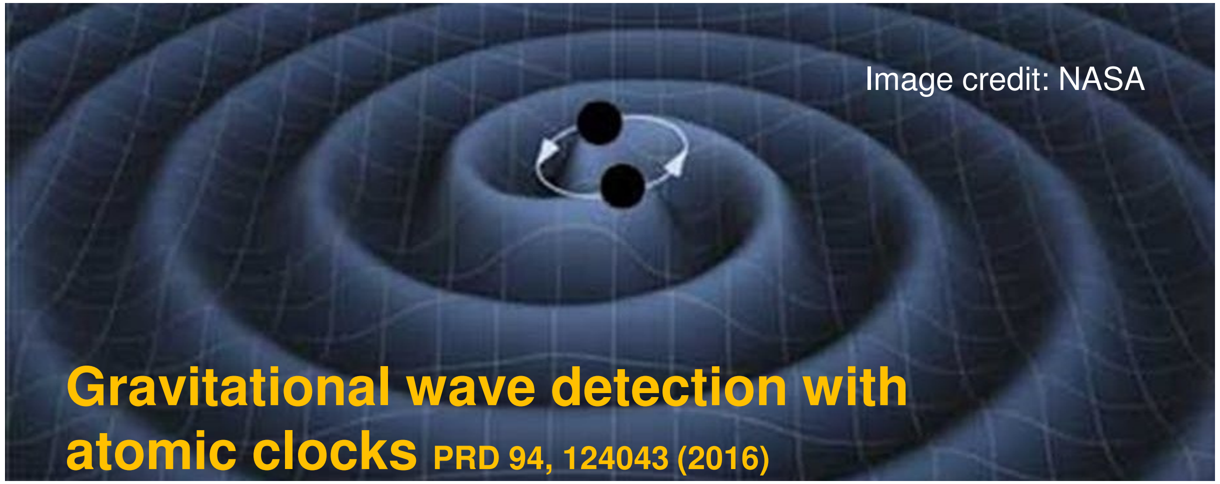


Image credit: NASA

Gravitational wave detection with atomic clocks PRD 94, 124043 (2016)

How to detect ultralight dark matter with clocks & cavities?

Oscillatory DM effects

Least exotic idea

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, molecular, and nuclear energy levels will oscillate so clock frequencies will oscillate. **Strength of the effect depends on the transition.** Cavity length will oscillate.

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

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}

Clocks are broadband dark matter detectors but can be made resonant

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

Variation of which fundamental constants can we probe (or which dark matter couplings)

1. Frequency of optical transitions

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c}$$

$$\frac{d_e F_{\mu\nu}F^{\mu\nu}}{4}$$

$$\nu \simeq cR_\infty AF(\alpha)$$

Depends only on α

2. Frequency of hyperfine transitions

$$\mu = \frac{m_p}{m_e}$$

$$d_{m_e} m_e \bar{\psi}_e \psi_e$$

$$\nu_{\text{hfs}} \simeq cR_\infty A_{\text{hfs}} \times g_i \times \frac{m_e}{m_p} \times \alpha^2 F_{\text{hfs}}(\alpha)$$

$$\frac{m_q}{\Lambda_{\text{QCD}}}$$

$$\frac{d_g \beta_3 G^a_{\mu\nu} G^{a\mu\nu}}{2g_3}$$

Depends on α, μ, g-factors

2. Transitions in molecules: μ only, μ and α, or all three

$$E_{\text{el}} : E_{\text{vib}} : E_{\text{rot}} \sim 1 : \bar{\mu}^{1/2} : \bar{\mu}$$

$$\bar{\mu} = 1/\mu$$

Sensitivity of optical clocks to α-variation

$$E = E_0 + q\left(\frac{\alpha^2}{\alpha_0^2} - 1\right)$$

Enhancement factor

$$\boxed{K = \frac{2q}{E_0}}$$

Need: large K for at least one for the clocks

Best case: large K_2 and K_1 of opposite sign for clocks 1 and 2

$$\frac{\partial}{\partial t}\ln\frac{\nu_2}{\nu_1} = (K_2 - K_1)\frac{1}{\alpha}\frac{\partial \alpha}{\partial t}$$

↑

Test of α-variation

Frequency ratio accuracy 10^{-18} 100 10^{-20}

Easier to measure large effects!

Observable: ratio of two clock frequencies

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

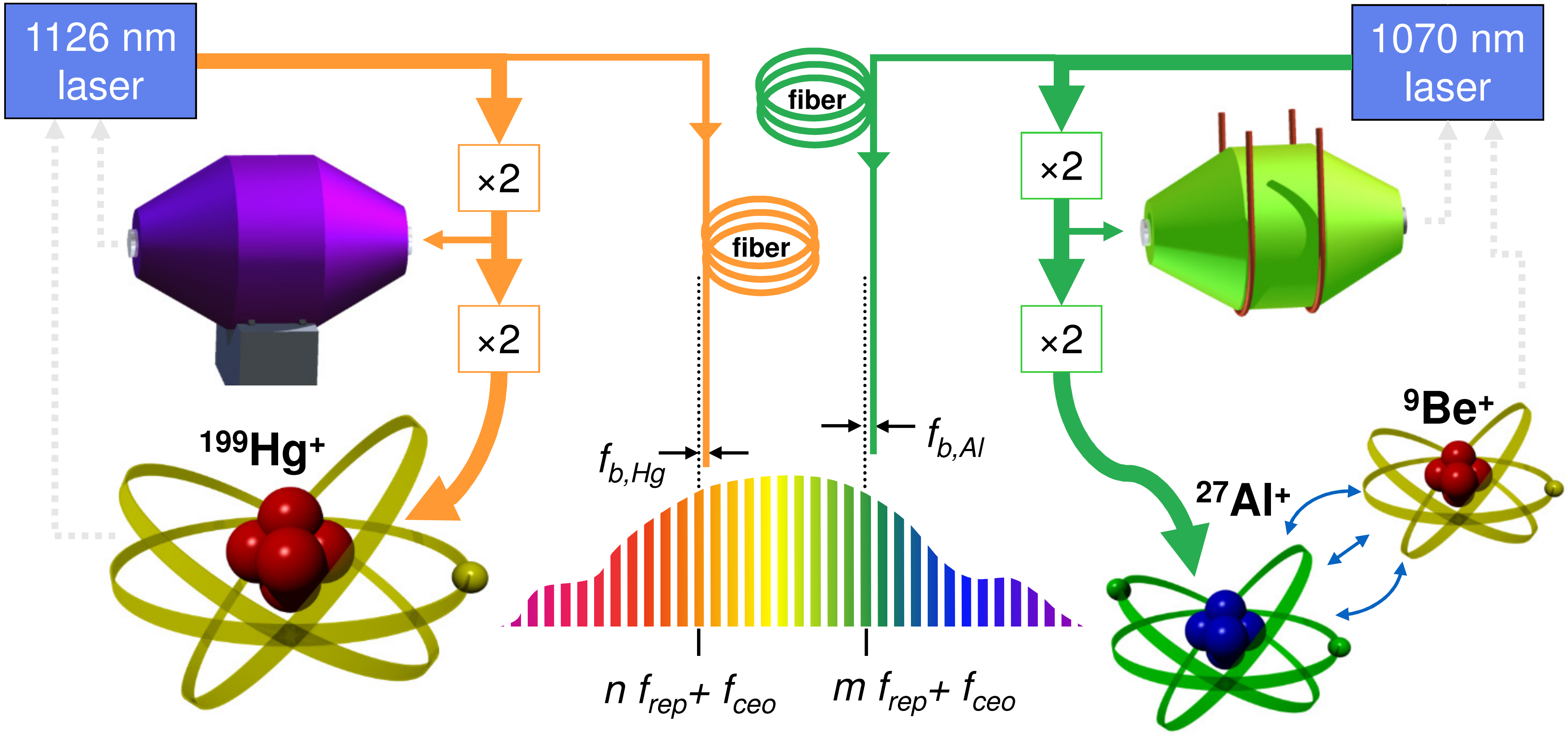
$$\frac{\nu\left(Hg^{+}\right)}{\nu\left(\mathrm{Al}^{+}\right)}$$

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

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

Sensitivity factors

Not sensitive to α-variation, used as reference



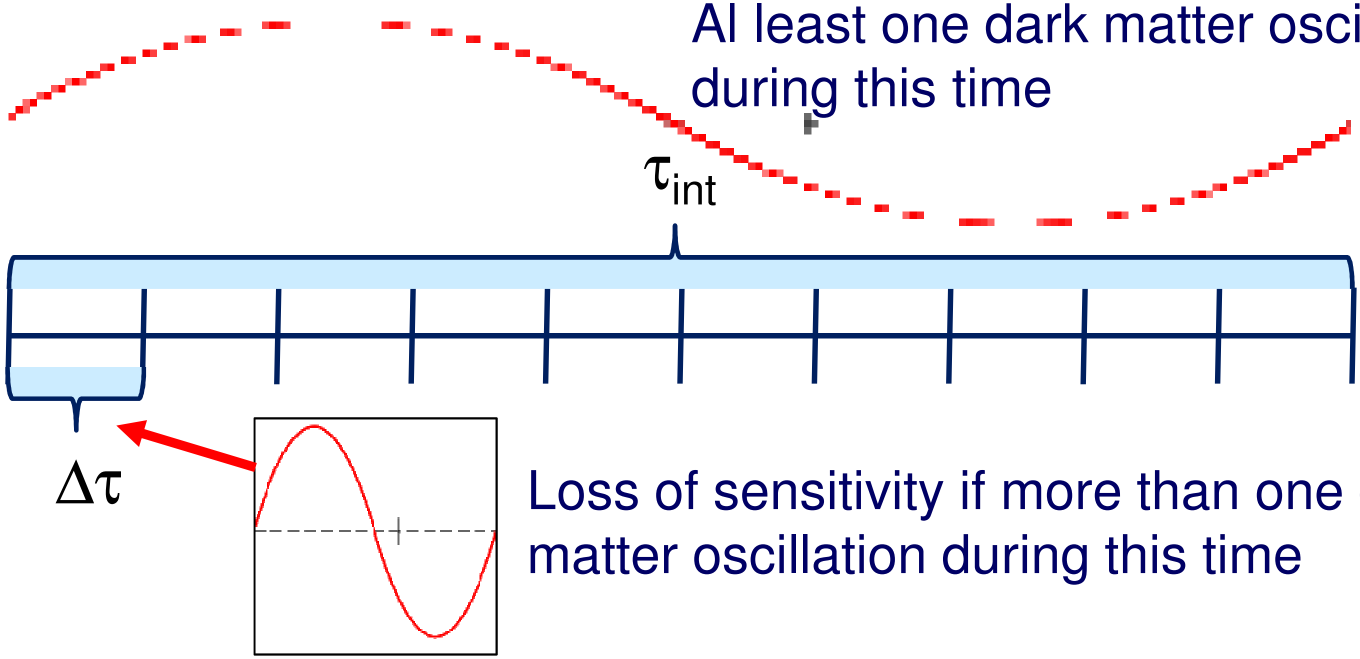
Picture credit: Jim Bergquist

Science 319, 1808 (2008)

Clock measurement protocols for dark matter detection

Single clock ratio measurement: averaging over time Δτ

Make N such measurements, preferably regularly spaced

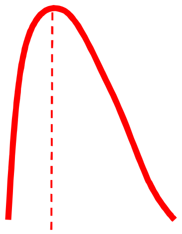


Al least one dark matter oscillation during this time

Loss of sensitivity if more than one dark matter oscillation during this time

Detection signal:

A peak with monochromatic frequency $f = 2\pi/m_\phi$ in the discrete Fourier transform of this time series.



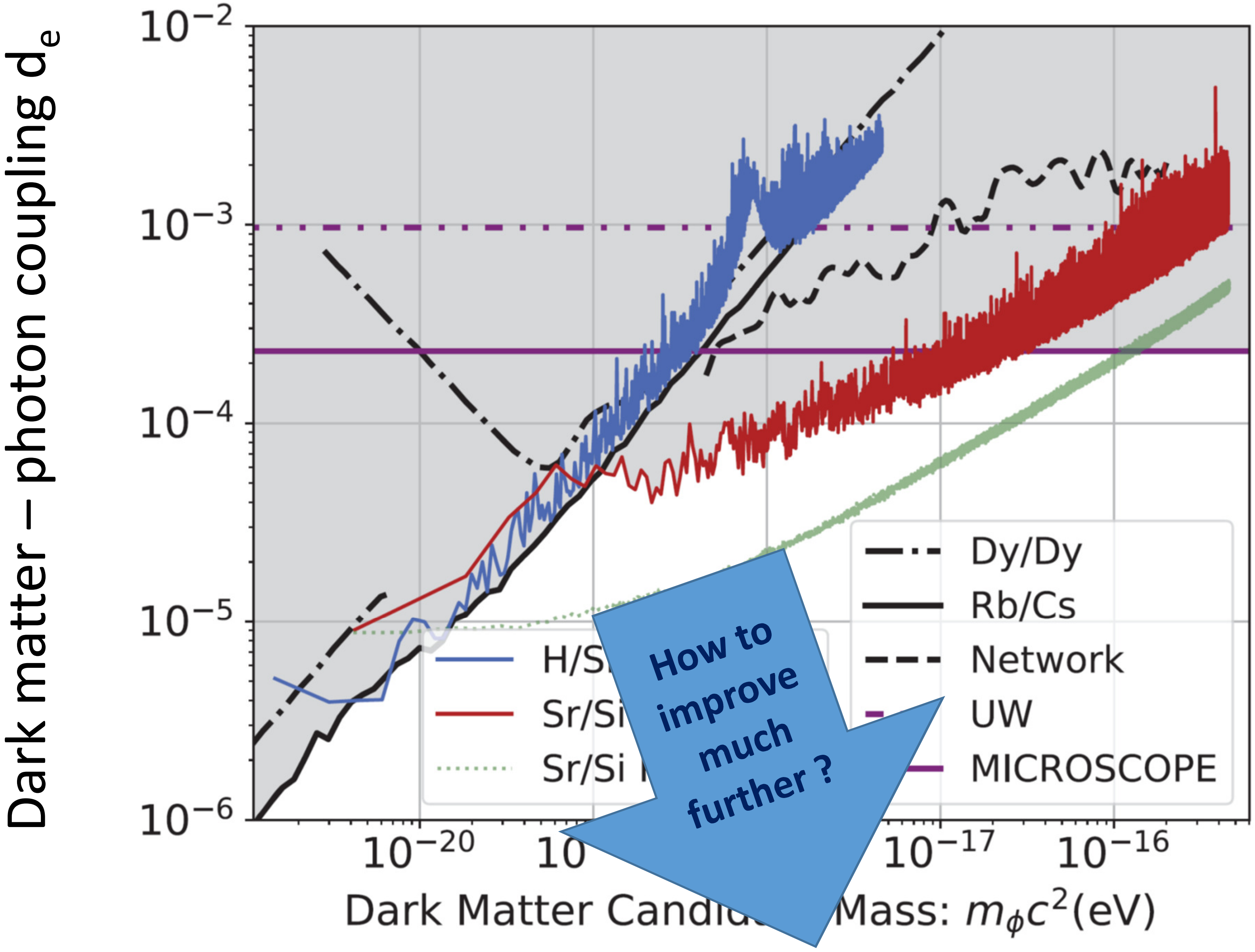
Solutions:

(1) Improve stability so shorter probe times are practical to use

(2) Use dynamic decoupling

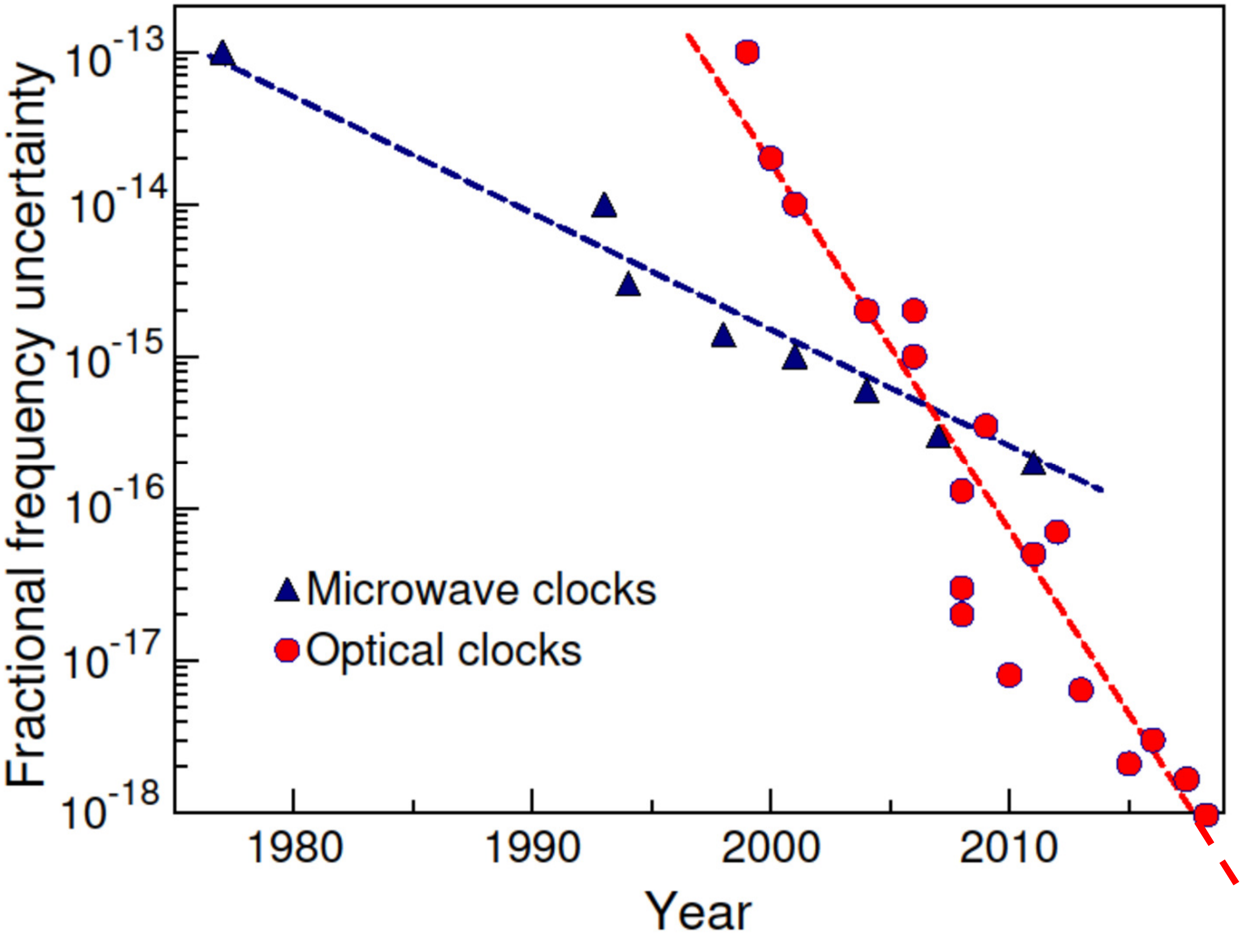
JILA Sr clock-cavity comparison C. Kennedy et al., PRL 125, 201302 (2020)

Oscillating dark matter bounds



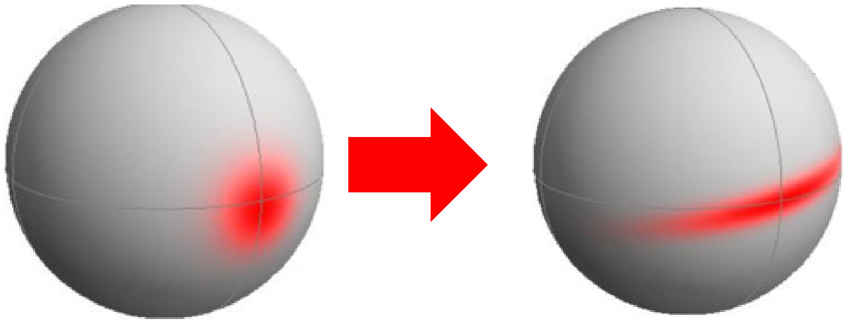
How to improve much further ?

IMPROVE CLOCKS!

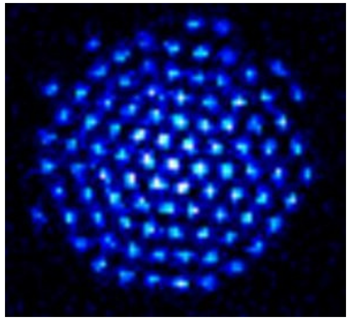


?

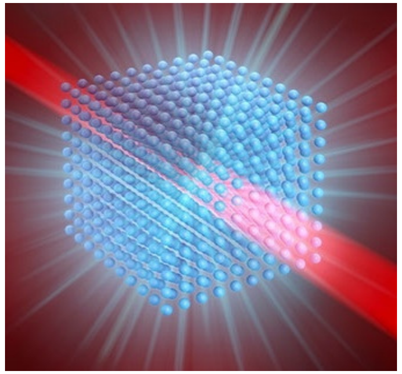
M. S. Safronova, D. Budker, D. DeMille, Derek F. Jackson-Kimball, A. Derevianko, and Charles W. Clark, Rev. Mod. Phys. 90, 025008 (2018).



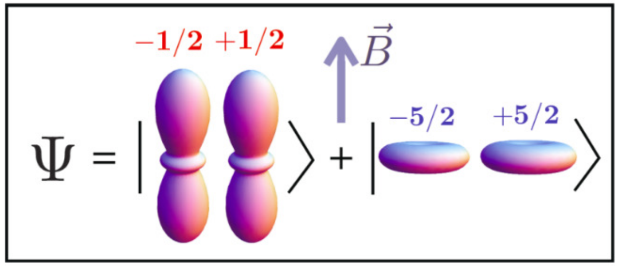
Measurements beyond the quantum limit



Large ion crystals



New designs for lattice clocks



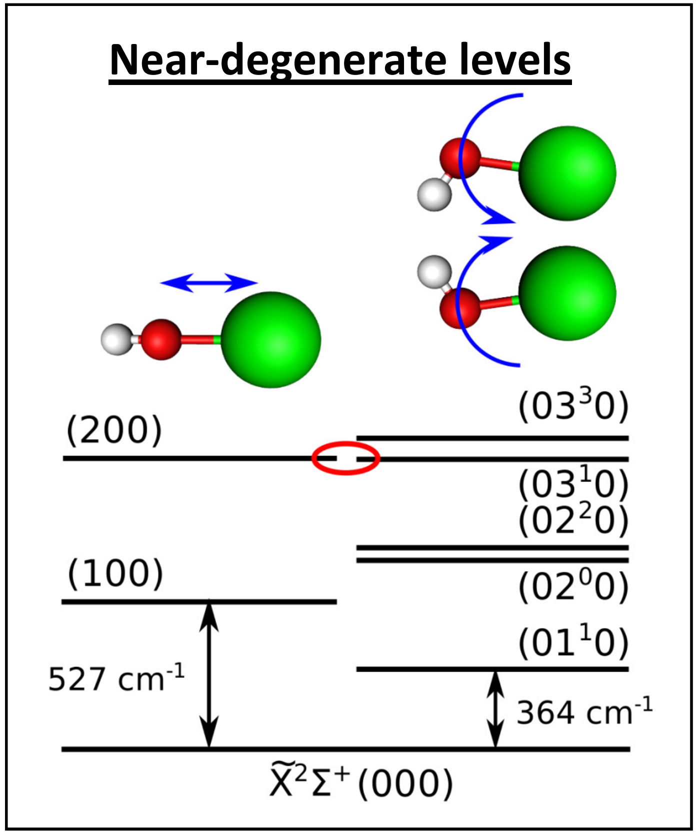
Entangled clocks

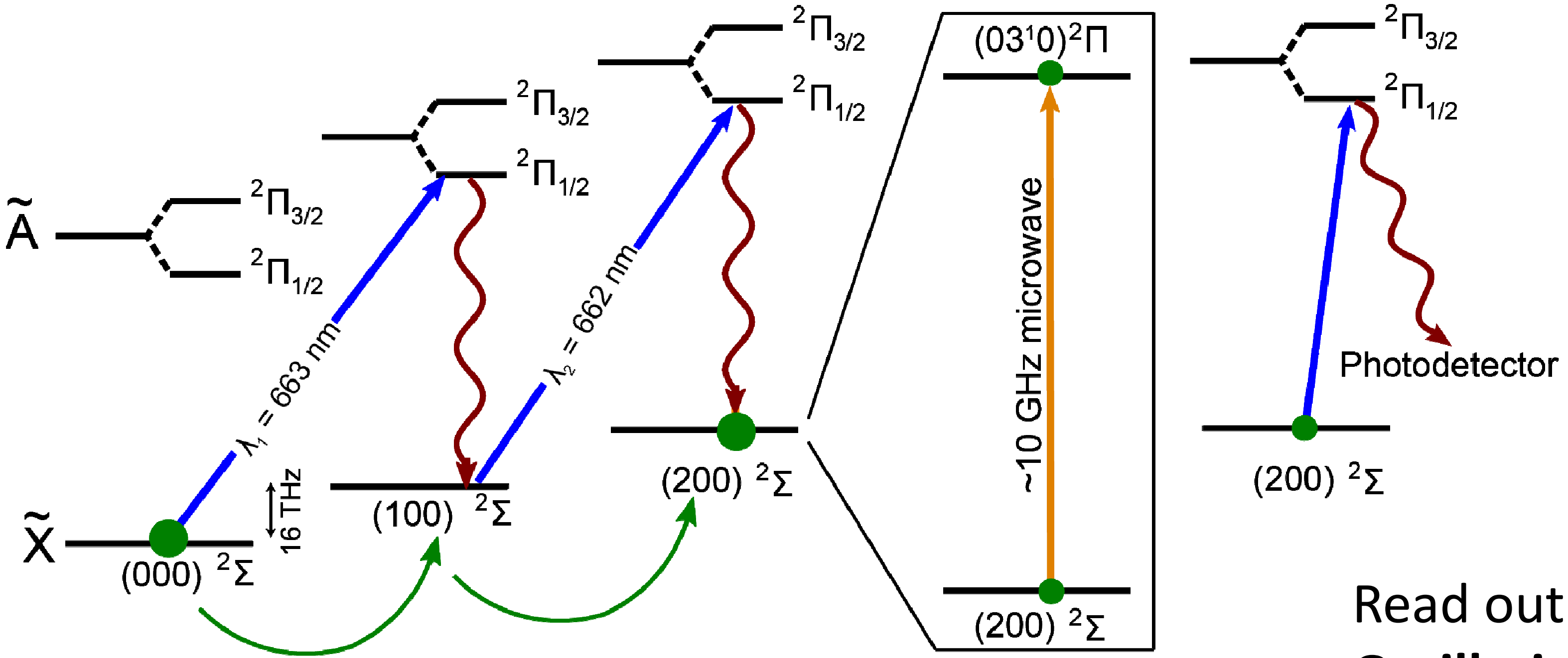
Build different clocks

(1) Enhanced sensitivity to variation of fine-structure constants (photon-DM coupling)
(2) Sensitive to variation of different fundamental constants

Scalar DM search with ultracold SrOH

- Use molecular spectroscopy to search for variation of $\mu = \dfrac{m_e}{m_p}$
- Ultralight dark matter has different effects on excited states
- Can take advantage of fortuitous near-degeneracies
- $\sim\ 10^{-17}/\sqrt{\text{day}}$ fractional uncertainty in $\delta\mu/\mu$





Optically pump into "science state"

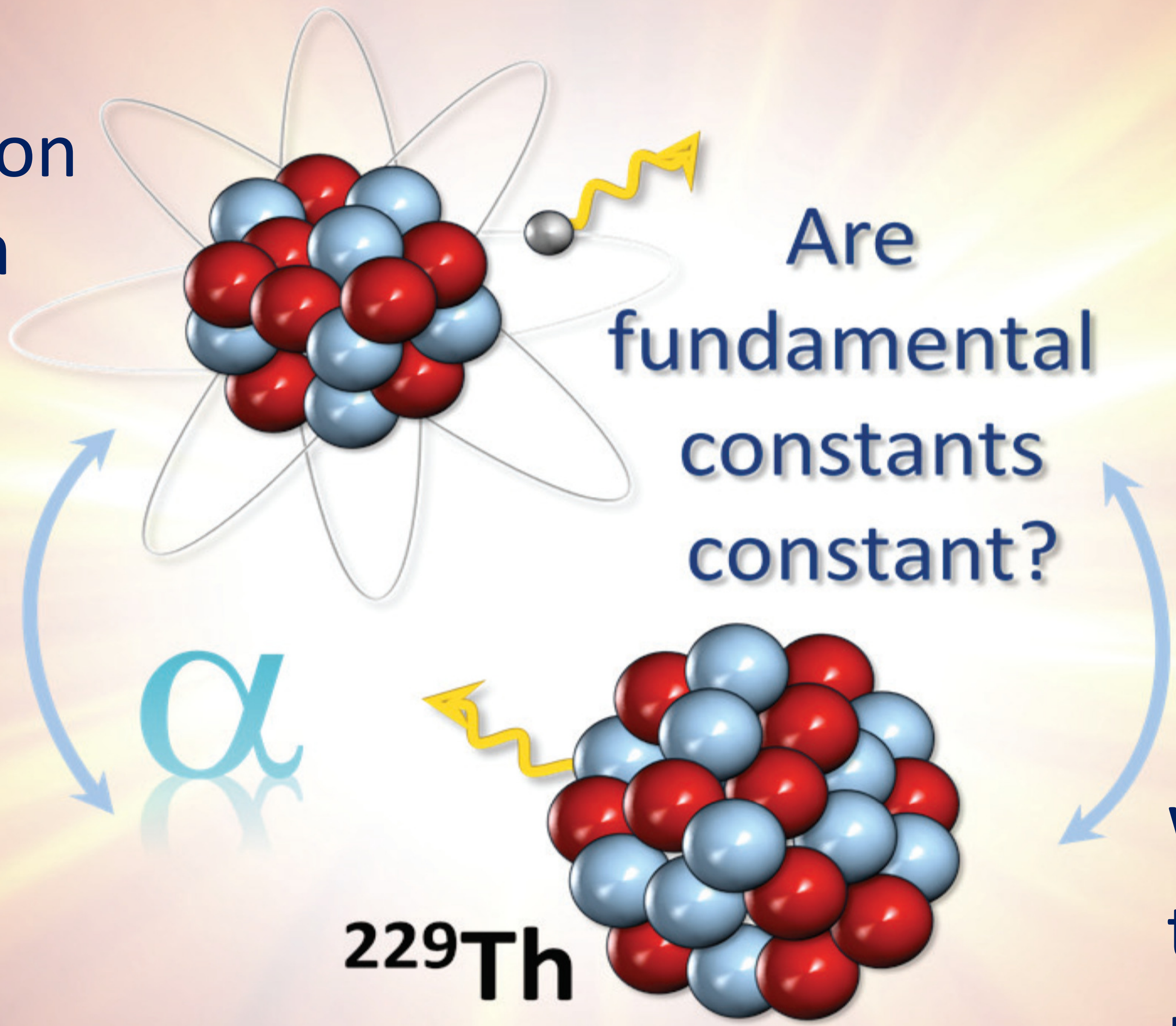
Transfer to near-degenerate vibrational state via microwaves

Read out transferred population

Oscillating resonance is a signature of dark matter

FROM ATOMIC TO NUCLEAR CLOCKS!

Clock based on transitions in atoms



Are fundamental constants constant?

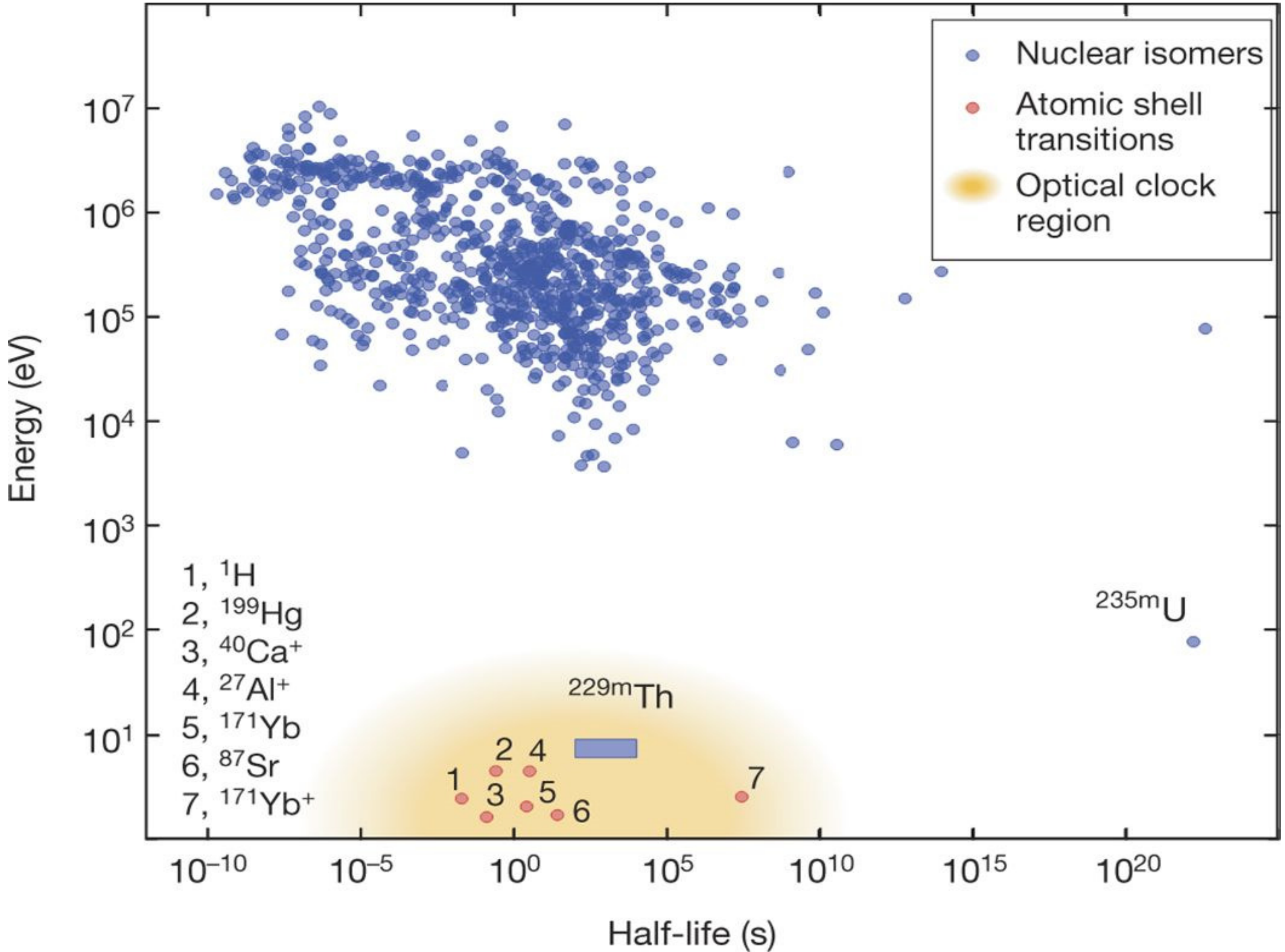
What about transitions in nuclei?

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?

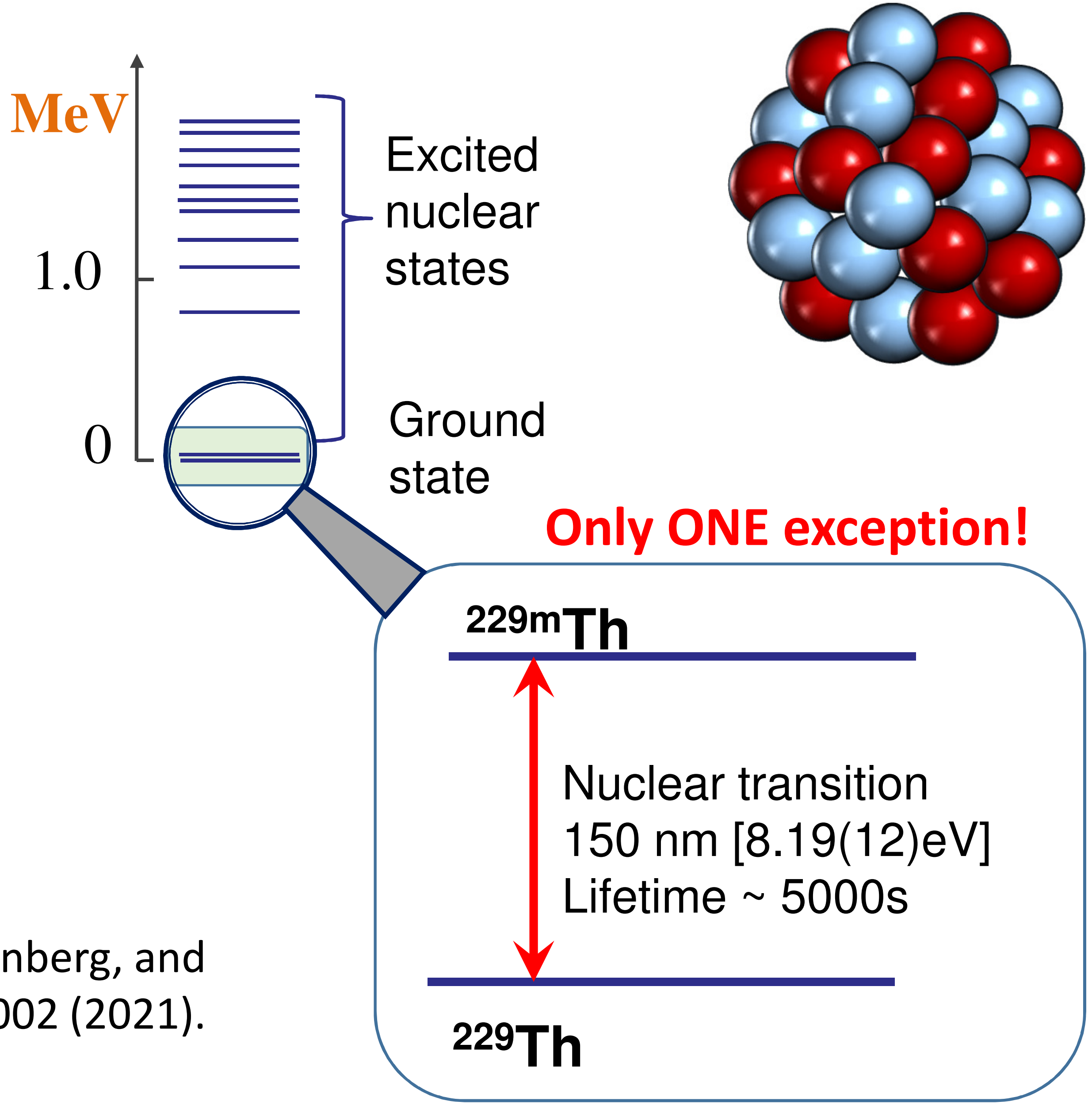


Nature 533, 47 (2016)

^{229}Th NUCLEAR CLOCK

European Research Council

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



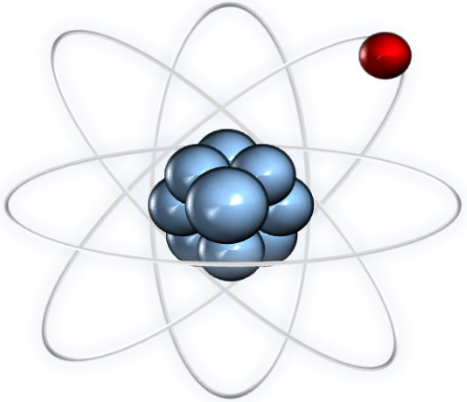
Only ONE exception!

Nuclear transition
150 nm [8.19(12)eV]
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).

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^{3+} ion



What is different for the nuclear clock?

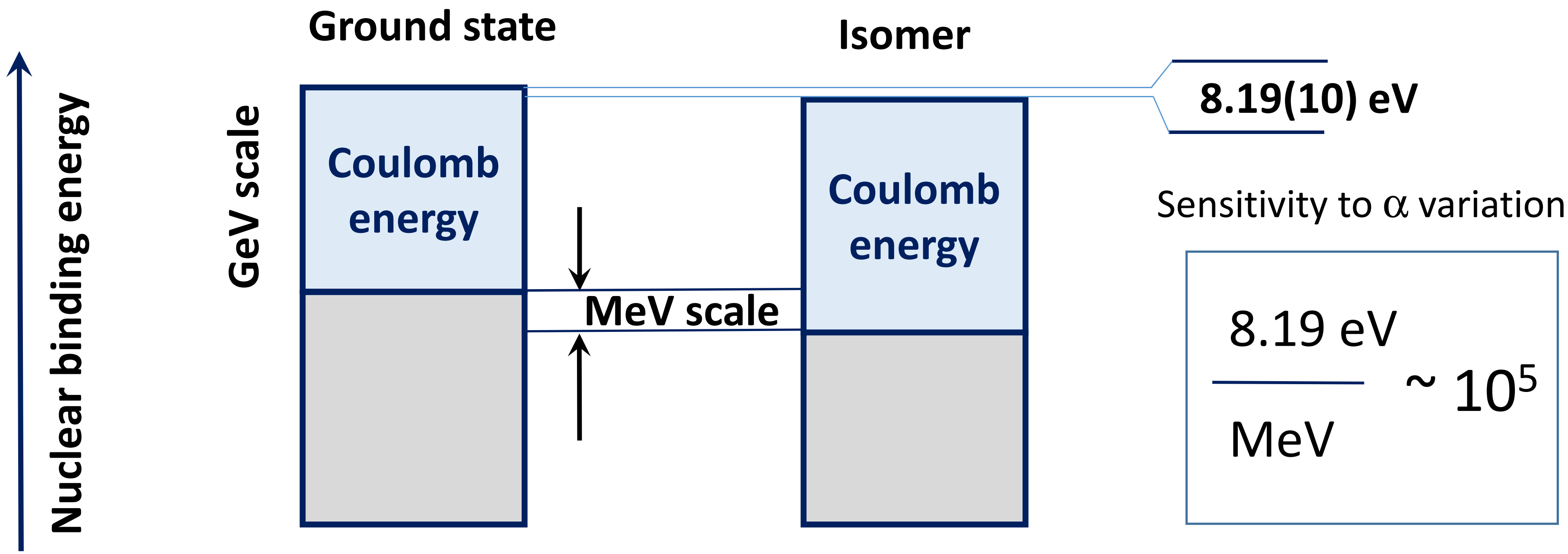
(1) **Much higher sensitivity to the variation of α**

(2) **Nuclear clock is sensitive to other fundamental constants**

(3) **Nuclear clock is sensitive to coupling of dark matter to both electromagnetic and the nuclear sector of the standard model**

Another possibility:
solid state nuclear
clock

Th nuclear clock: Exceptional sensitivity to new physics



Nuclear binding energy

GeV scale

Ground state

Isomer

Coulomb energy

Coulomb energy

MeV scale

8.19(10) eV

Sensitivity to α variation

$$\frac{8.19\ \text{eV}}{\text{MeV}} \sim 10^5$$

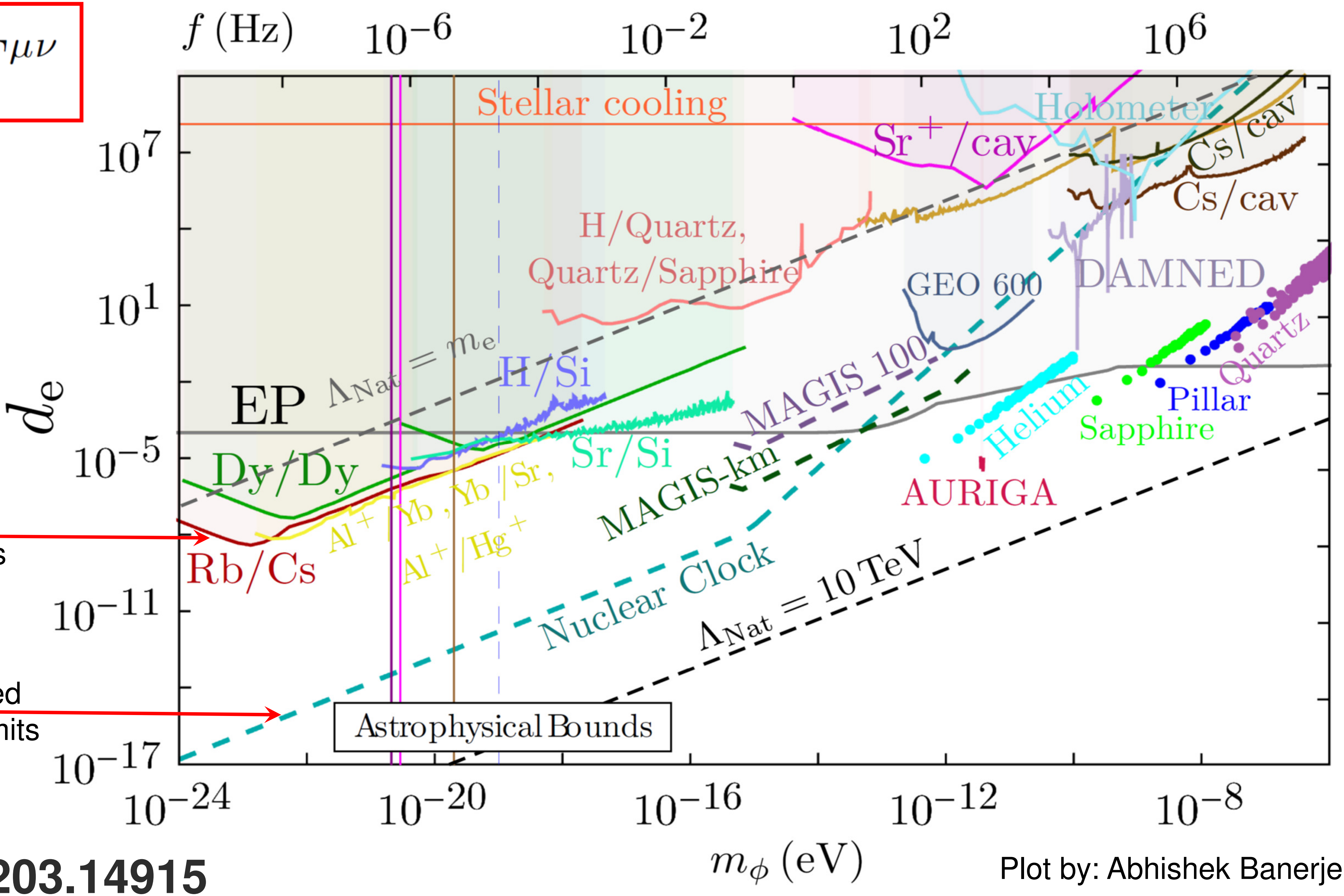
Much higher predicted sensitivity (K = 10000-100000) to the variation of α and $\frac{m_q}{\Lambda_{QCD}}$.

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

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



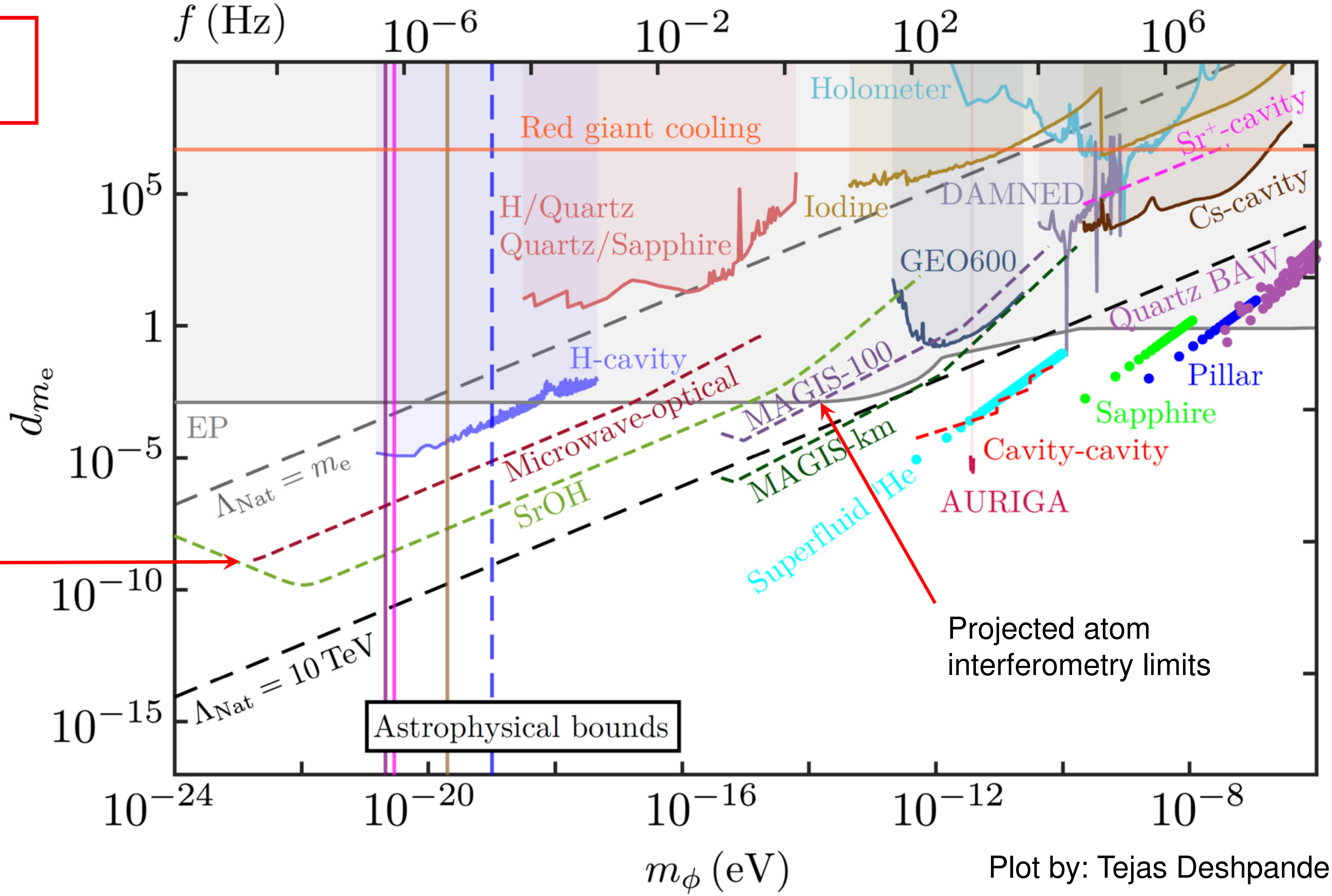
Present
clock limits

Projected
clock limits

arXiv:2203.14915

Plot by: Abhishek Banerjee

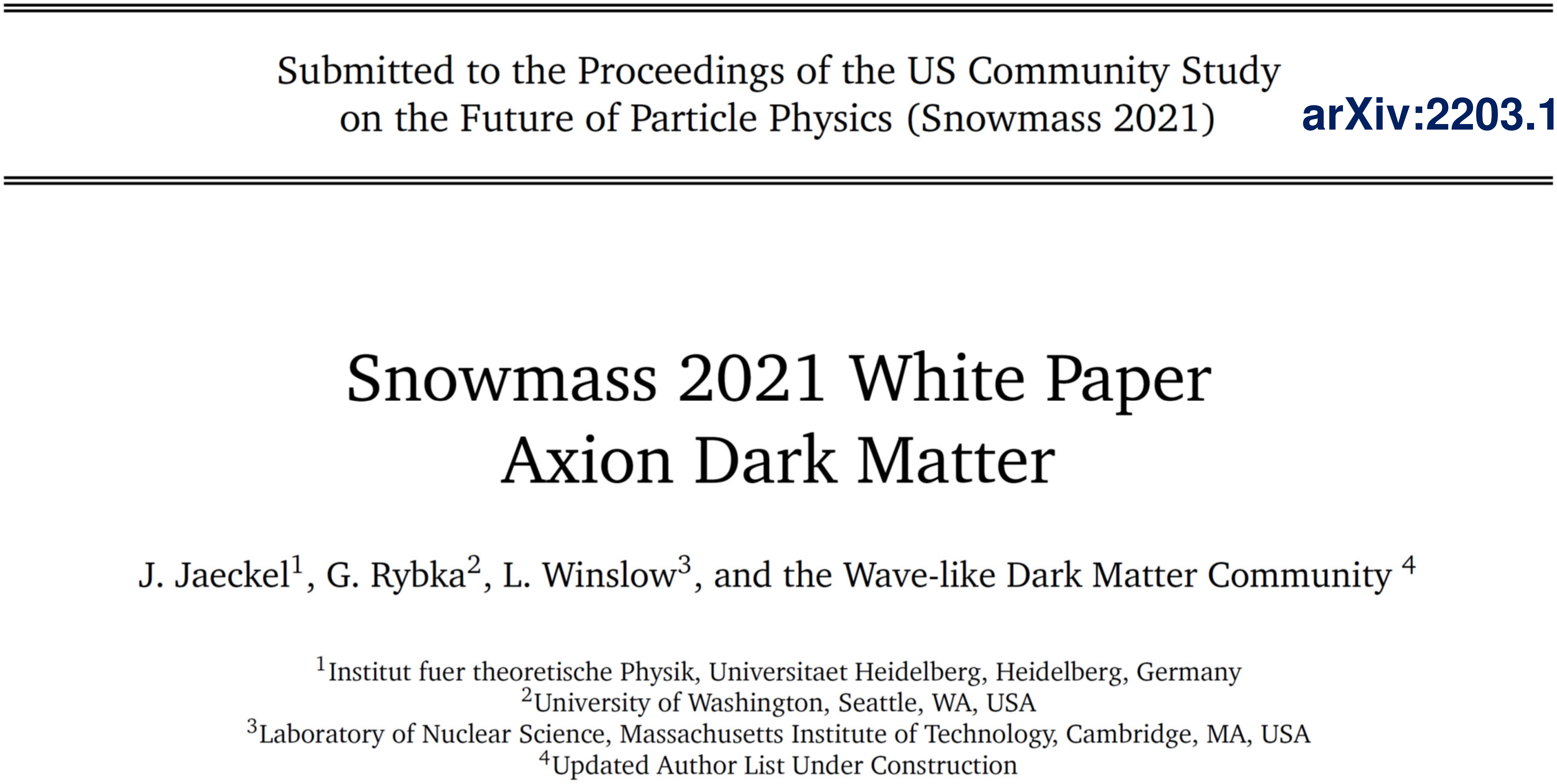
$\phi \bar{e} e$



Projected clock limits

Projected atom interferometry limits

Plot by: Tejas Deshpande



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

arXiv:2203.14923

Snowmass 2021 White Paper
Axion Dark Matter

J. Jaeckel[1], G. Rybka[2], L. Winslow[3], and the Wave-like Dark Matter Community [4]

[1]Institut fuer theoretische Physik, Universitaet Heidelberg, Heidelberg, Germany
[2]University of Washington, Seattle, WA, USA
[3]Laboratory of Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA, USA
[4]Updated Author List Under Construction

Pseudoscalar dark matter: QCD axion

Extremely well motivated dark matter candidate: QCD axion solves strong CP problem, parameter space is known

QCD $\mathcal{L}_\theta \sim \bar{\theta}\, G\widetilde{G}$ generically break the CP symmetry

G is the gluon field strength tensor

$\bar{\theta} \leq 10^{-10}$

From non-observation of neutron EDM

Strong CP problem

C: charge
P: parity

Strong interaction could violate CP but does not as of present experimental accuracy defined by limit on neutron EDM. **Serious fine-tuning problem.**

Solution: Peccei-Quinn (PQ) mechanism

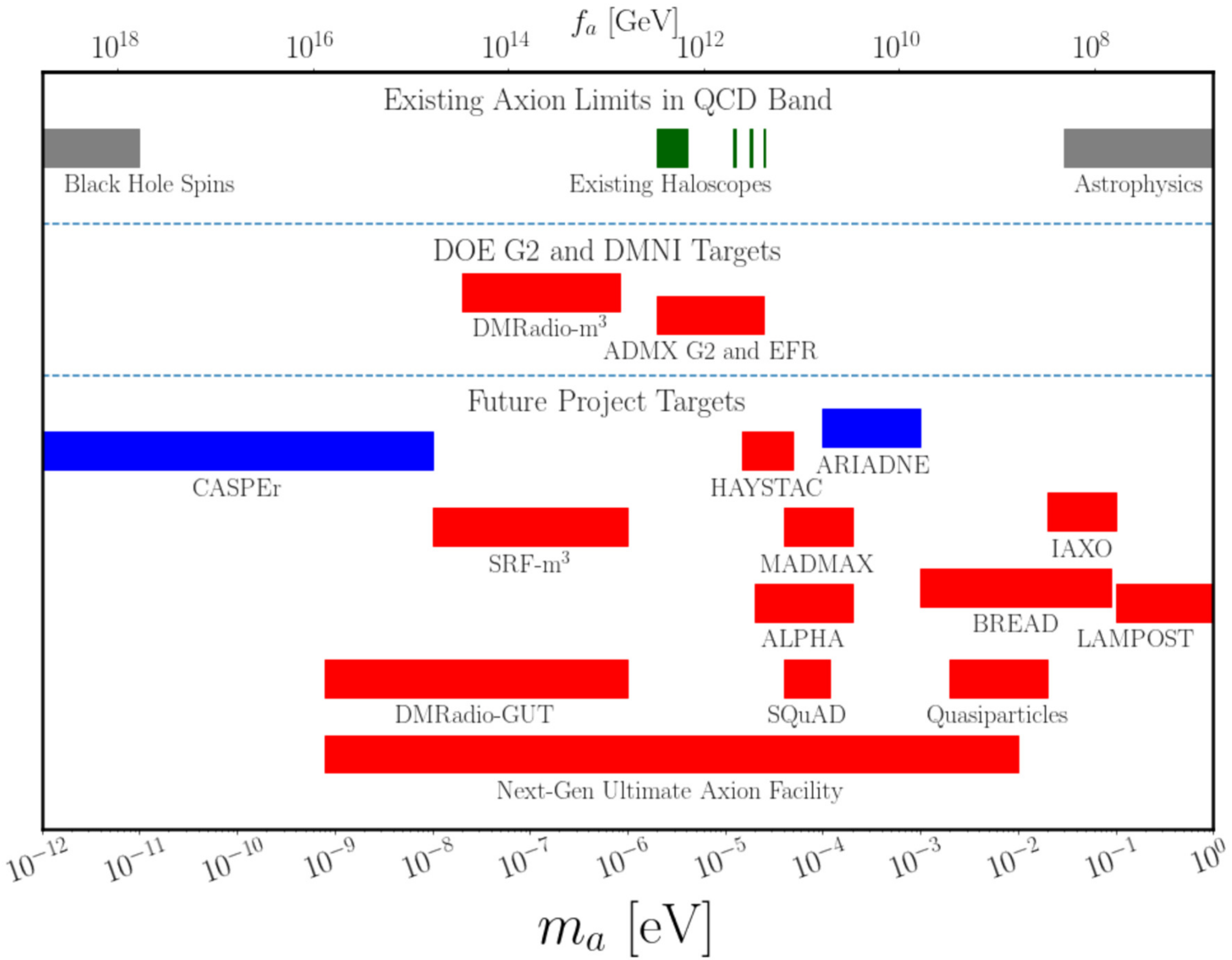
It minimally extends the SM with a new classically conserved global symmetry, the PQ symmetry $U(1)_{PQ}$, which is spontaneously broken at a scale f_a. QCD axion is the low-energy consequence.

$$\mathcal{L} = \left(\frac{a}{f_a} - \bar{\theta}\right)\frac{\alpha_s}{8\pi} G^{\mu\nu a}\tilde{G}^a_{\mu\nu}$$

The axion dynamically relaxes the value of $\bar{\theta}_{\text{eff}} \equiv \langle a\rangle / f_a - \bar{\theta}$ to zero.

From chiral perturbation theory: $m_a = 5.691(51)\mu\text{eV}(10^{12}\text{GeV}/f_a)$

Axions and APL searches



The green bars indicate running experiments in the QCD region.

Red indicate proposals that utilize the axion-photon coupling.

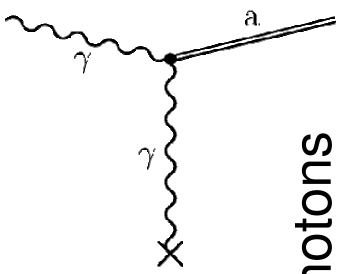
$$\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

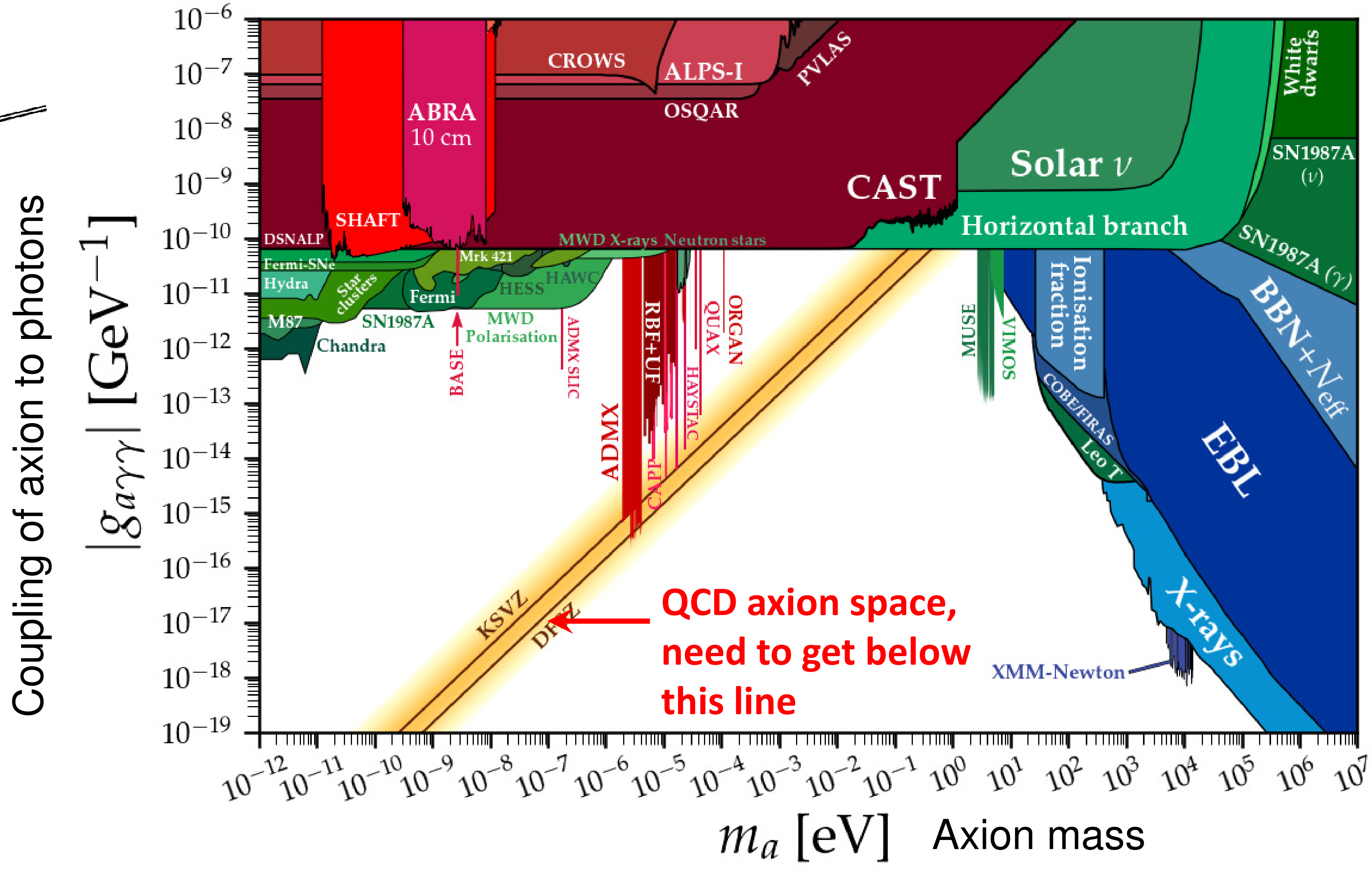
Blue indicates proposal utilizing alternative couplings.

$$\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu} \qquad \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

J. Jaeckel, G. Rybka, L. Winslow, for the Axion Prospects Collaboration. “Axion Dark Matter”, arXiv:2203.14923

Pseudoscalar dark matter: axions and APL



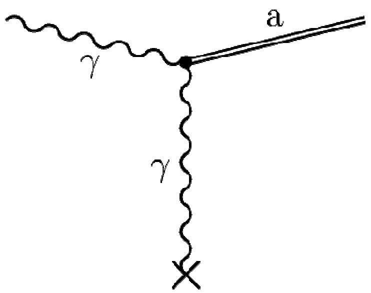


QCD axion space, need to get below this line

J. Jaeckel, G. Rybka, L. Winslow, for the Axion Prospects Collaboration. “Axion Dark Matter”, arXiv:2203.14923

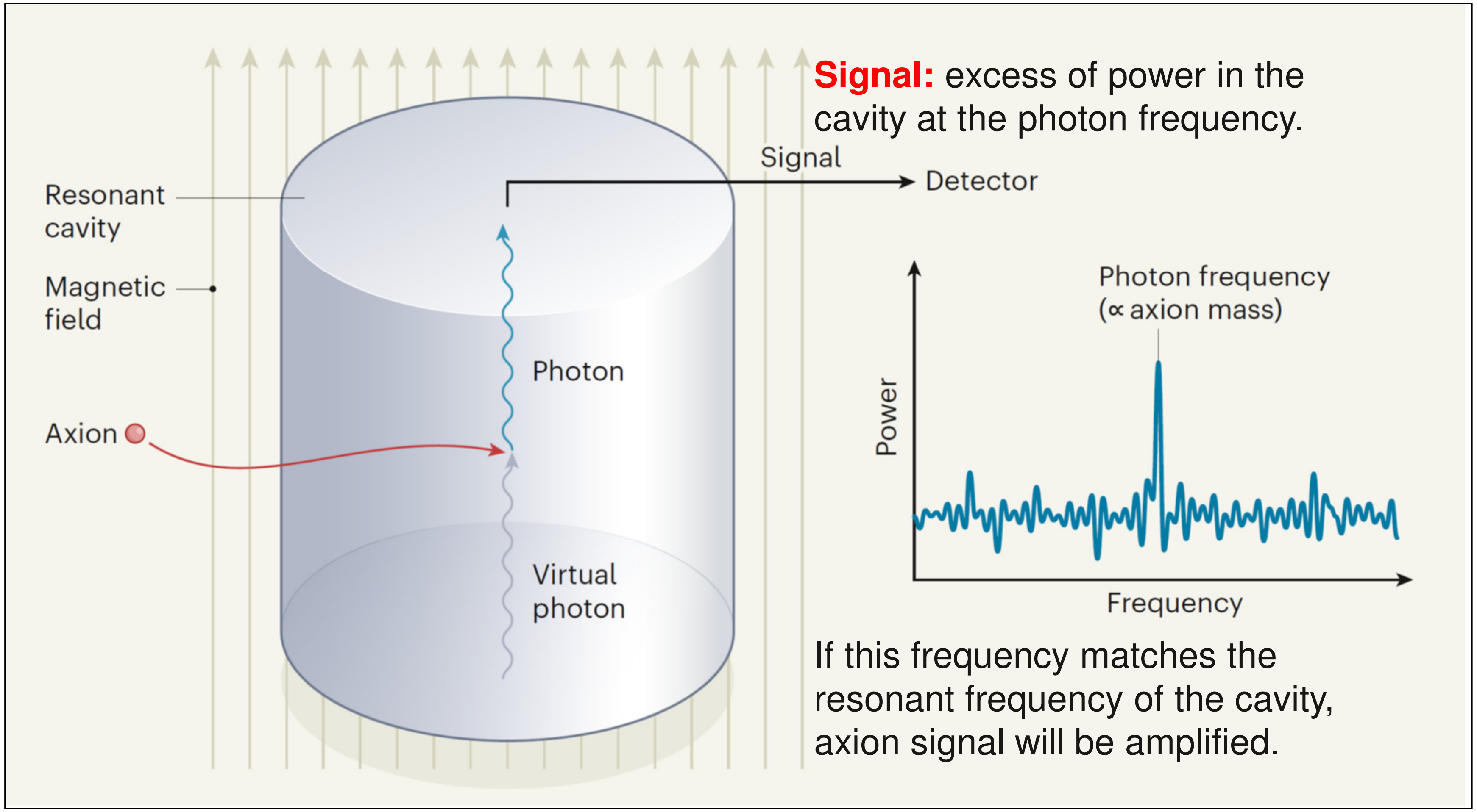
The resonant cavity haloscopes

$$\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



Basic idea:
The electromagnetic fields (one of the γ) created by an axion (a) in a large static magnetic field B (second γ) are resonantly amplified in a microwave cavity.

ADMX: Axion Dark Matter eXperiment (ADMX)
HAYSTAC: The **H**aloscope **A**t **Y**ale **S**ensitive **T**o **A**xion **C**DM
Tunable microwave cavity searches for axions

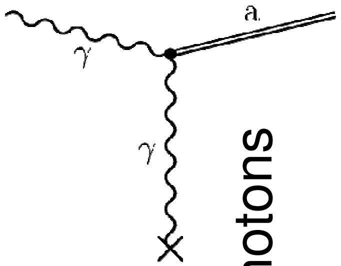


Signal: excess of power in the cavity at the photon frequency.

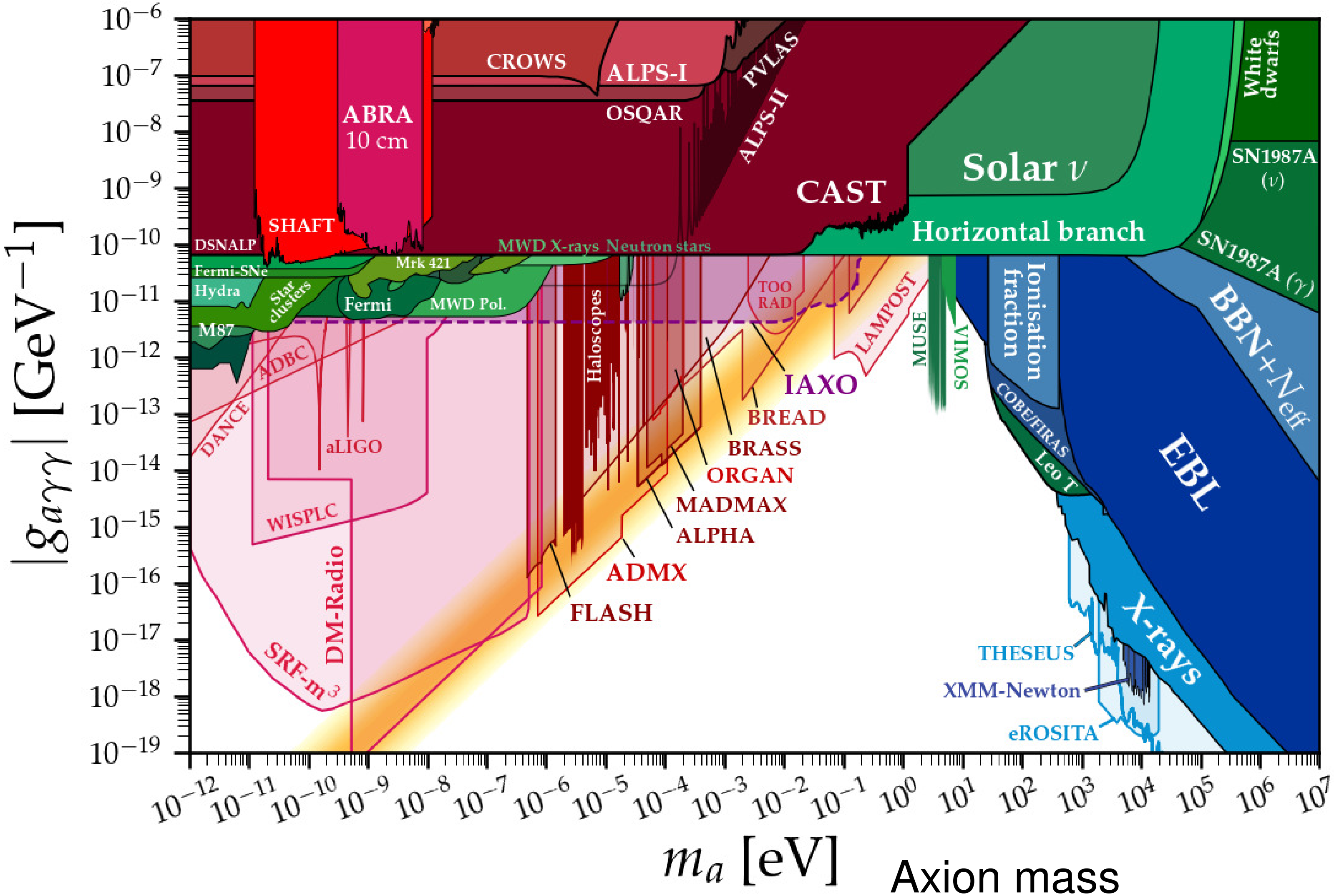
If this frequency matches the resonant frequency of the cavity, axion signal will be amplified.

Image from: Nature 590, 226 (2021)

Axions and APLs: future prospects



Coupling of axion to photons



Axion mass

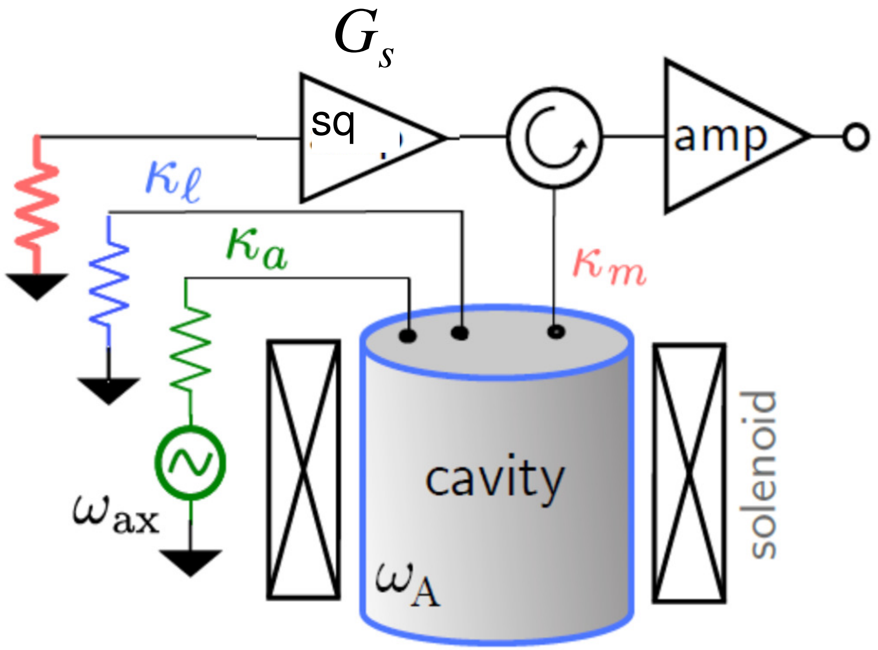
Need measurements beyond the standard quantum limit

Q-SEnSE
An NSF Quantum Leap Challenge Institute

J. Jaeckel, G. Rybka, L. Winslow, for the Axion Prospects Collaboration. “Axion Dark Matter”, arXiv:2203.14923

Quantum enhanced axion dark matter search

- The size of a simple haloscope cavity must scale with the axion Compton wavelength $1/m_a$.
- The scan rate scales as $R \sim \nu_a^{-14/3}$ so scanning is too slow for higher masses **(20,000 years).**
- **One solution: compensate for this using quantum metrology techniques, decreasing the noise beyond the standard quantum limit.**



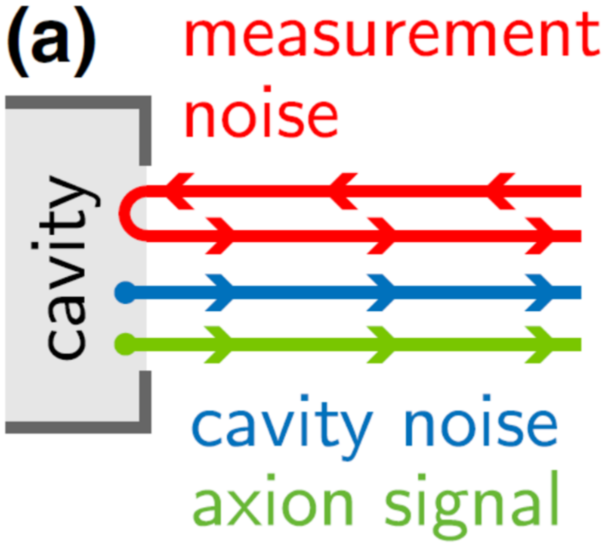


Figure credits: Konrad Lenhert & PRX Quantum **2**, 040350 (2021).

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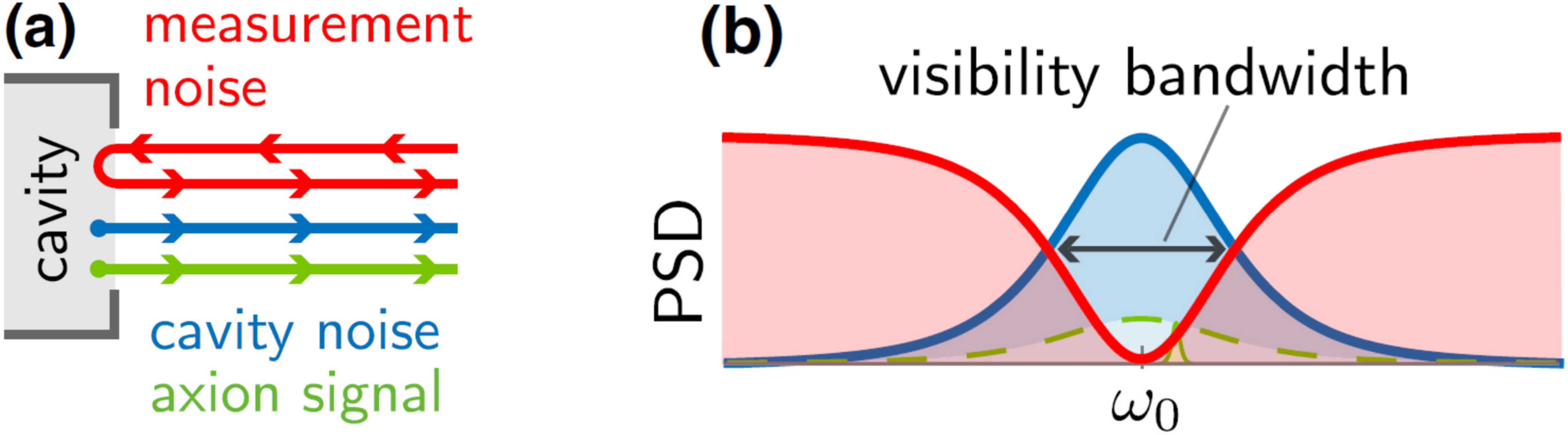
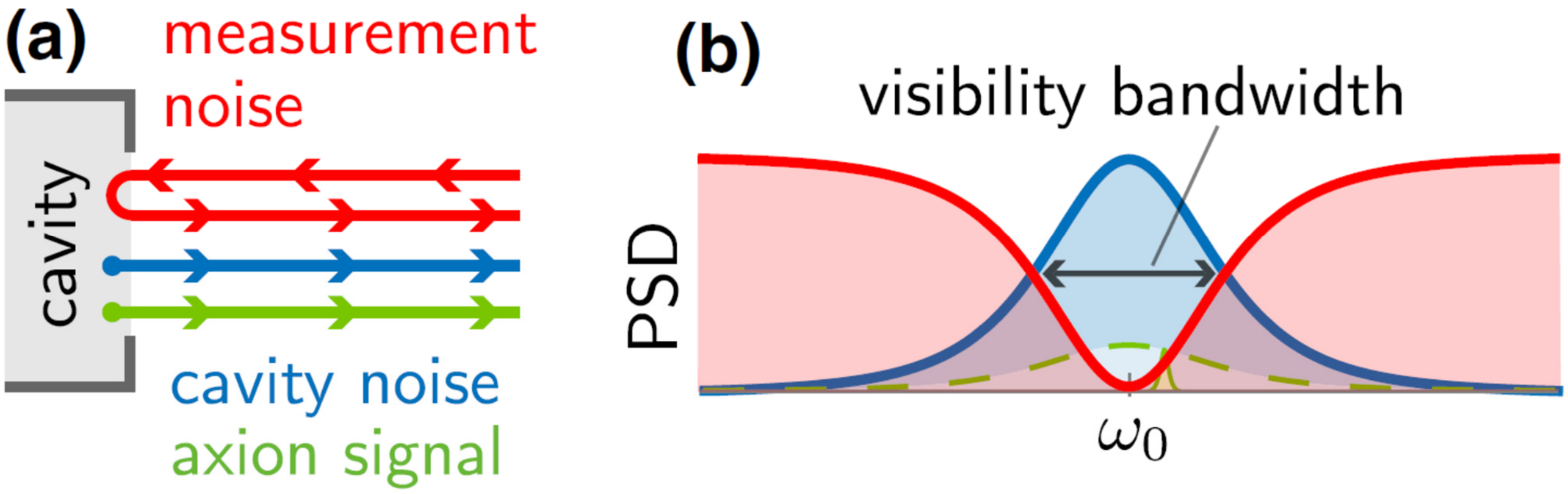
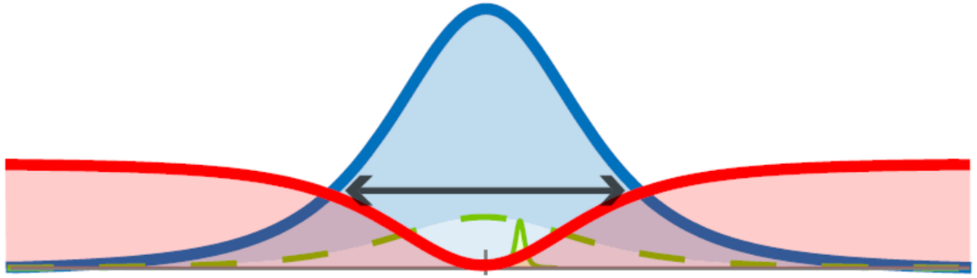


Figures: PRX Quantum **2**, 040350 (2021).

Quantum enhanced axion dark matter search



With quantum enhancement: version 1



Figures: PRX Quantum **2**, 040350 (2021).

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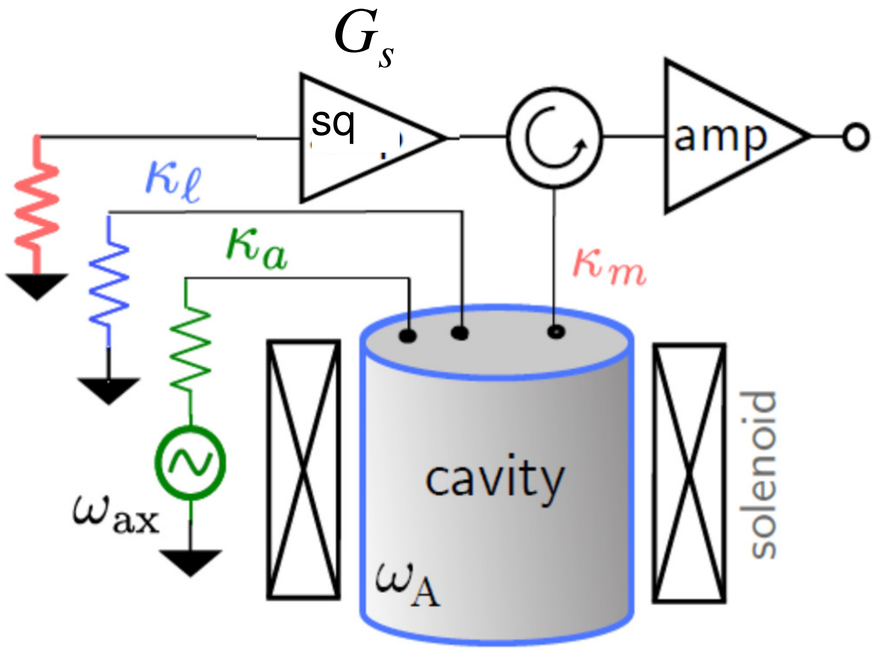
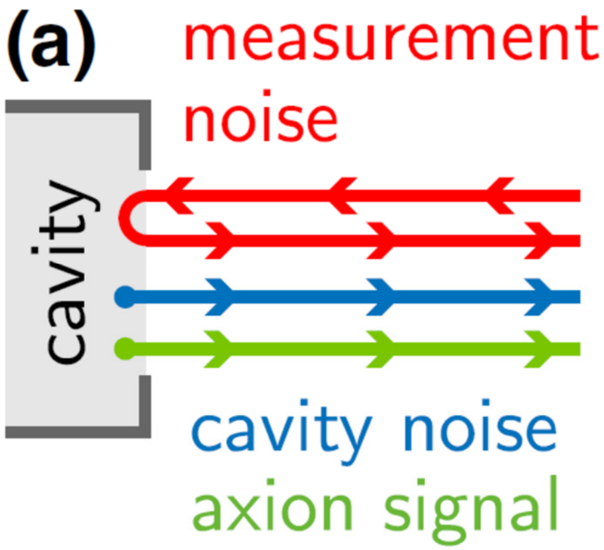


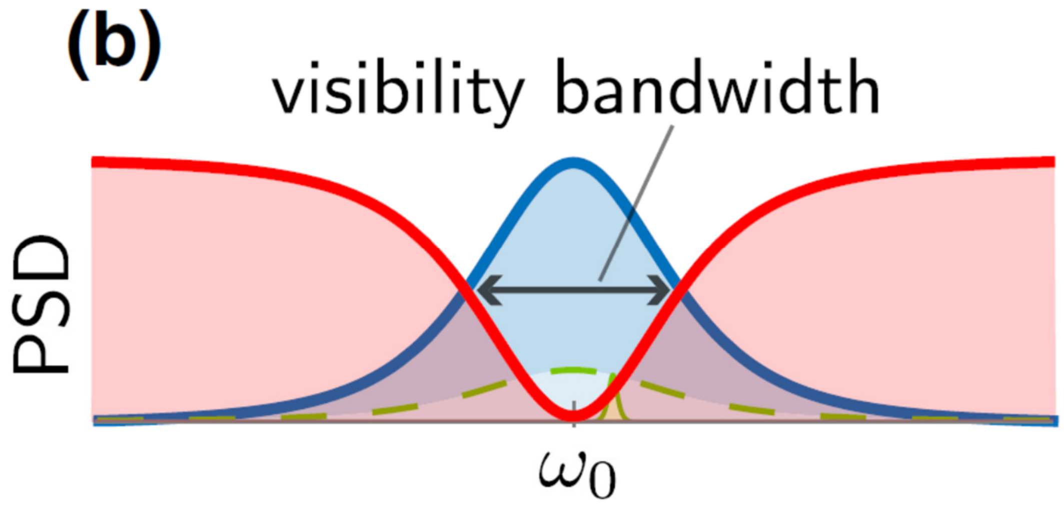
Quantum-enhanced measurement techniques can widen the visibility bandwidth by increasing noise that originates in the cavity (along with any signal present) relative to noise associated with measurement.

Two-fold speed in QCD axion search rate from squeezing was demonstrated in 2021 by coupling the HAYSTAC cavity to the squeezed-state receiver (Backes et al., Nature 590, 238).

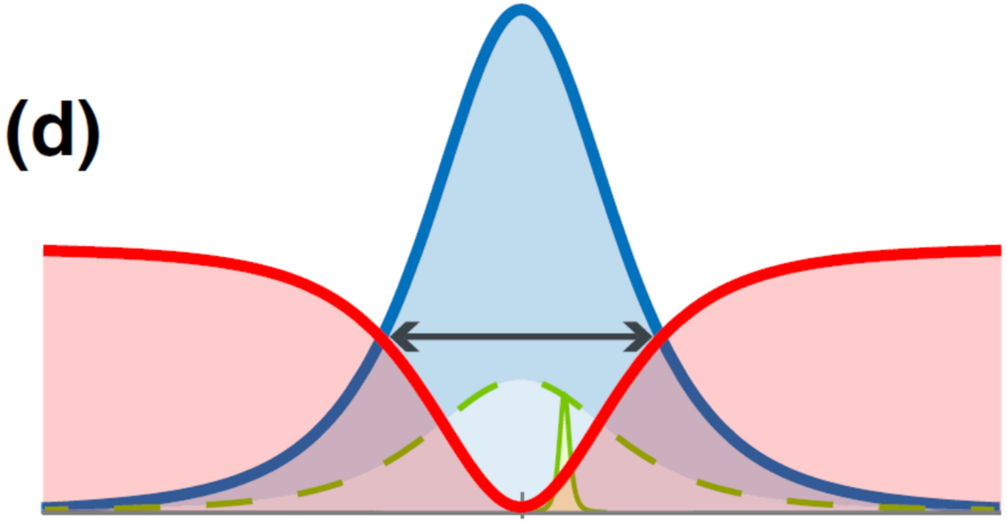
Quantum enhancement was limited by the loss associated with transporting microwave squeezed states through a cascaded microwave network.

Quantum enhanced axion dark matter search





With quantum enhancement: version 2



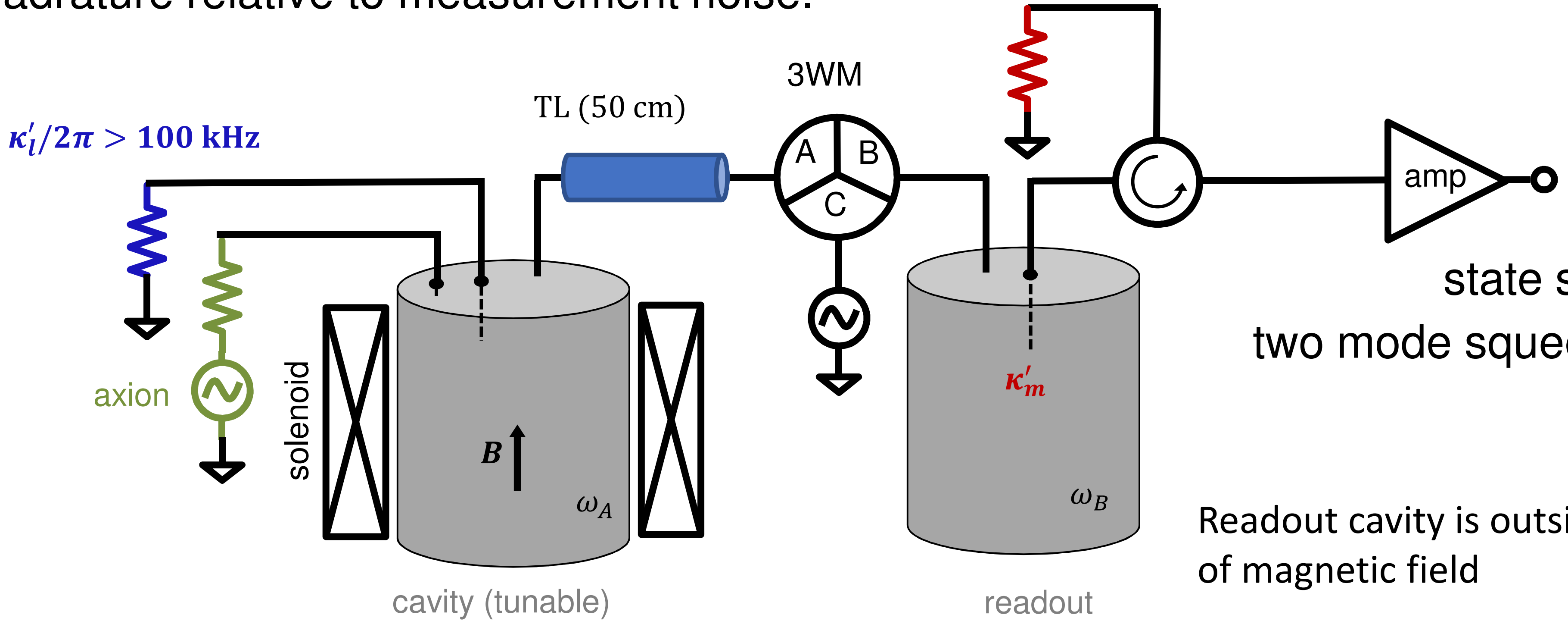
Noiseless amplification cannot be done in strong magnetic field

More enhancement from embedded entanglement

Proposal for 15 fold speedup

Circumvent the loss using two cavities with an embedded three-wave mixing element that simultaneously preparing the cavities in entangled states and swapping those states.

Widen the visibility bandwidth by amplifying the cavity noise and axion signal together in a single quadrature relative to measurement noise.



state swap (g): $\omega_B - \omega_A$

two mode squeezing (h): $\omega_B + \omega_A$

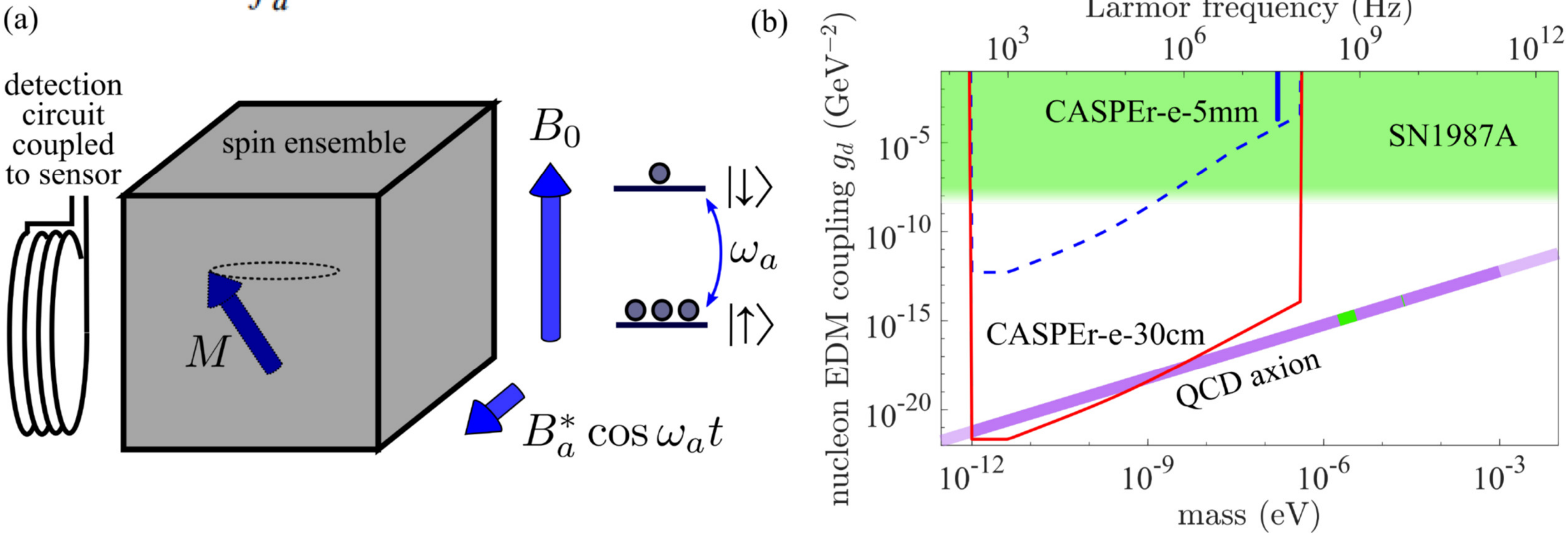
Readout cavity is outside
of magnetic field

"Cavity Entanglement and State Swapping to Accelerate the Search for Axion Dark Matter," K. Wurtz, et al., KWL, *PRX Quantum* **2**, 040350 (2021).

The Cosmic Axion Spin Precession Experiment

CASPEr-e

$$\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$



The CASPEr experimental schematic (a) and CASPEr-e projected sensitivity (b)
Spin states of a nuclear spin ensemble are split by the applied bias field B_0.

When this splitting is resonant with the axion-like dark matter Compton frequency ω_a, the ensemble magnetization M is tilted and undergoes precession that is detected by an inductively-coupled sensor.

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

Image credits: NASA, ESA

Why to search for new physics in space?

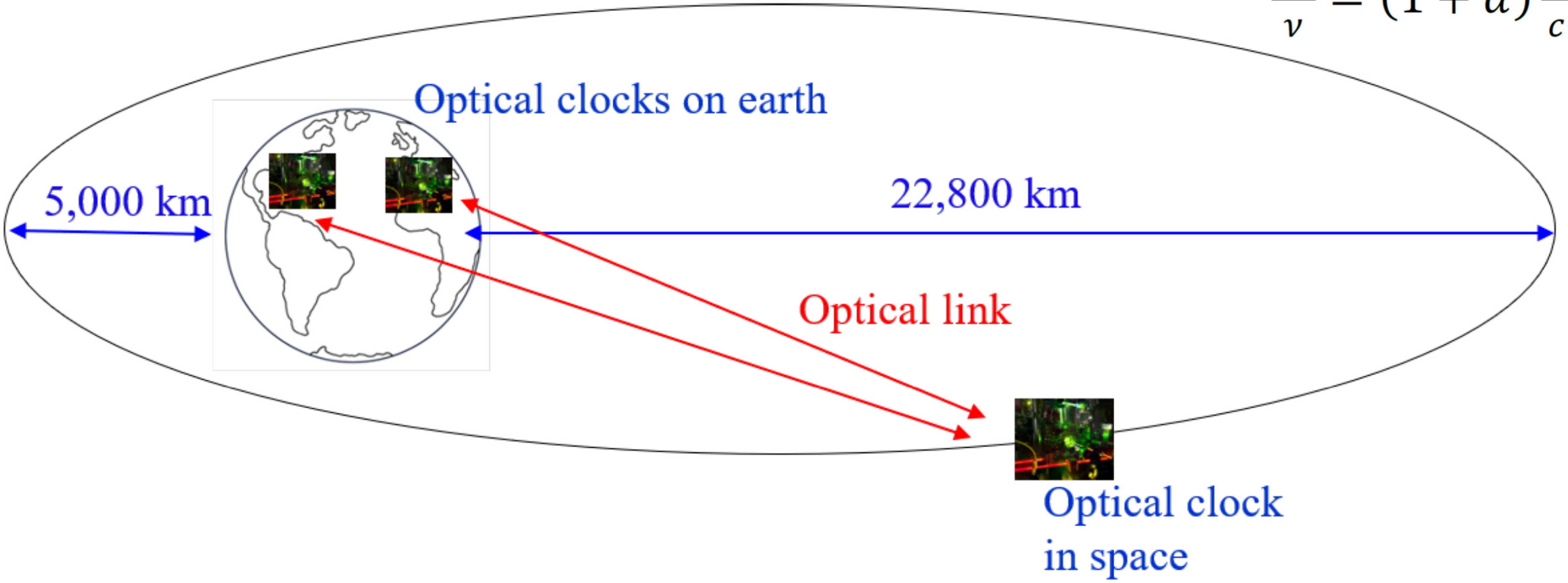
Many orders of magnitude improvements or principally different experiments are possible

- Effects may be screened on Earth (DM with quadratic coupling to SM, dark energy)
- Variable gravitational potential: elliptical orbits around the Earth and the Sun
- Many other opportunities for tests of gravity, dark energy searches
- Constrain DM distribution in the Solar system
- Ability to link optical Earth-bound clocks
- Long baseline (for gravitational wave detection), moon & asteroids as test masses
- Different range of gravitational wave frequencies accessible & no seismic noise
- Being able to direct access of all spatial components of the basic coefficients for Lorentz and CPT violation, matter-gravity coupling, different boosts than available on Earth
- Microgravity
- …

FUNDAMENTAL PHYSICS WITH A STATE-OF-THE-ART OPTICAL CLOCK IN SPACE

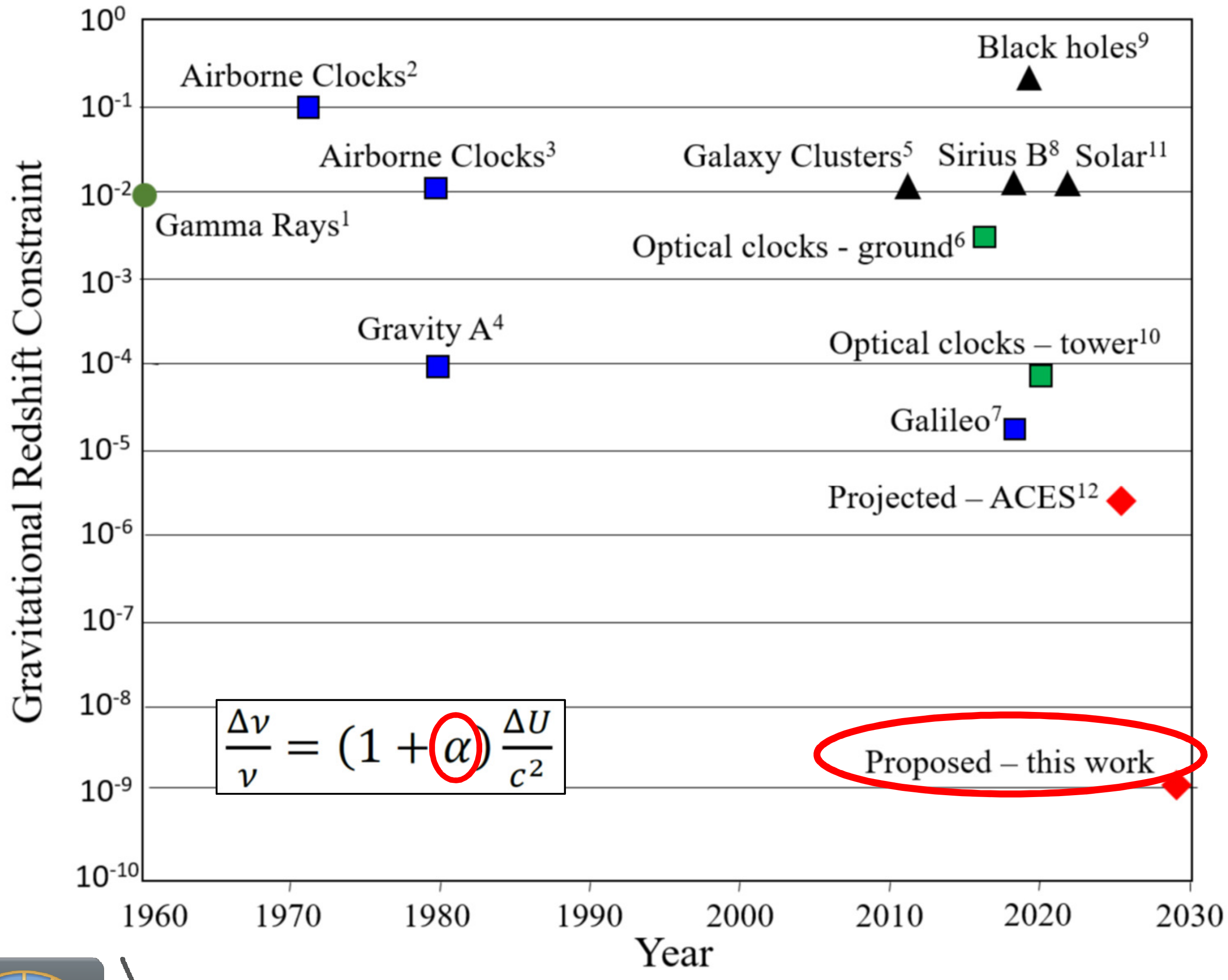
Andrei Derevianko, Kurt Gibble, Leo Hollberg, Nathan R. Newbury, Chris Oates,
Marianna S. Safronova, Laura C. Sinclair, Nan Yu, arXiv:2112.10817

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



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

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



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

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

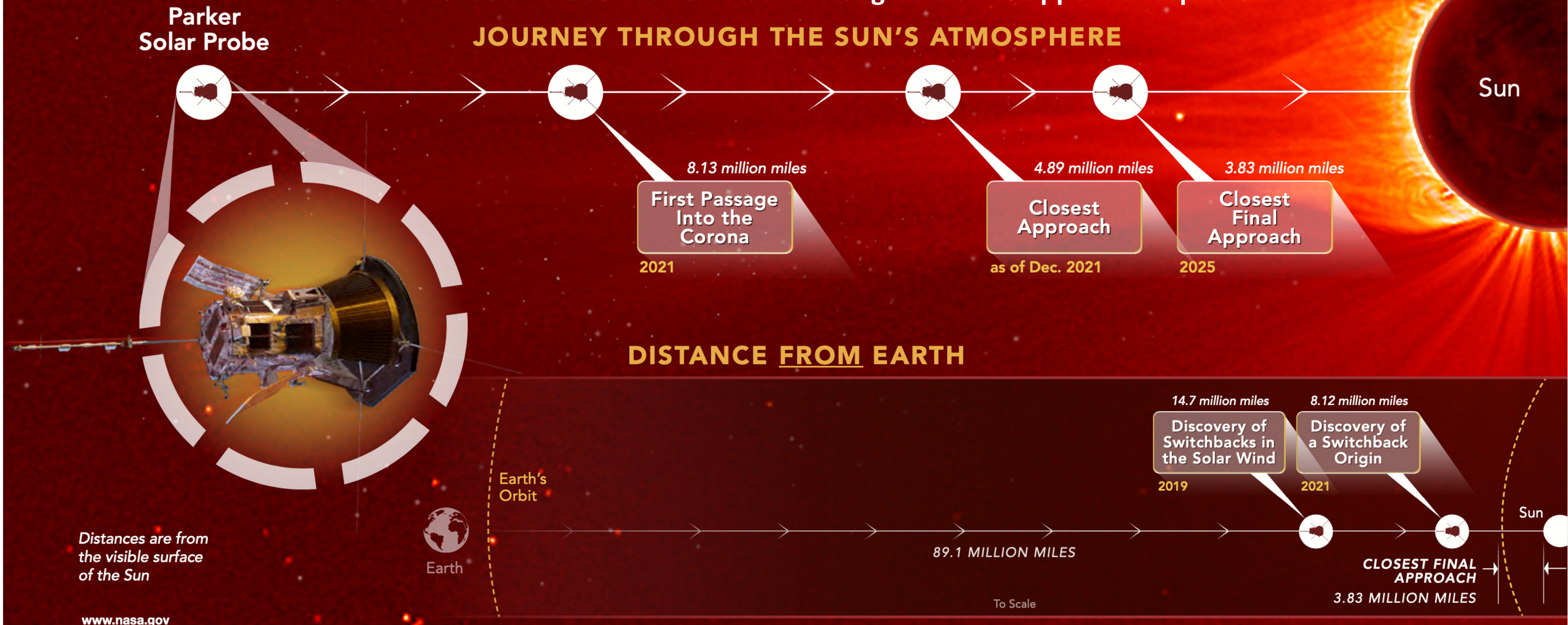
Image credit: NASA's Goddard Space Flight Center/Mary P. Hrybyk-Keith

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



DISTANCE FROM EARTH

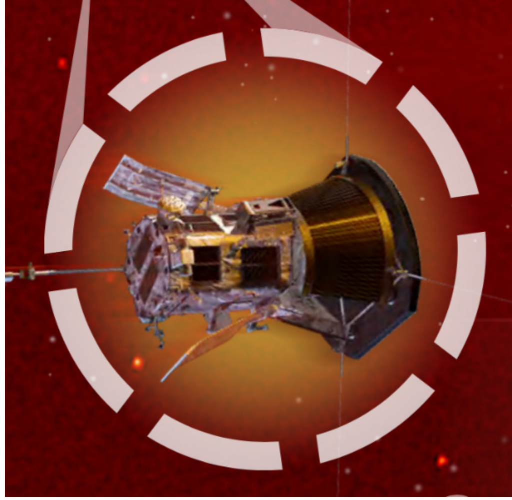
Distances are from the visible surface of the Sun

www.nasa.gov

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

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

SpaceQ -- Direct Detection of Ultralight Dark Matter with Space Quantum Sensors

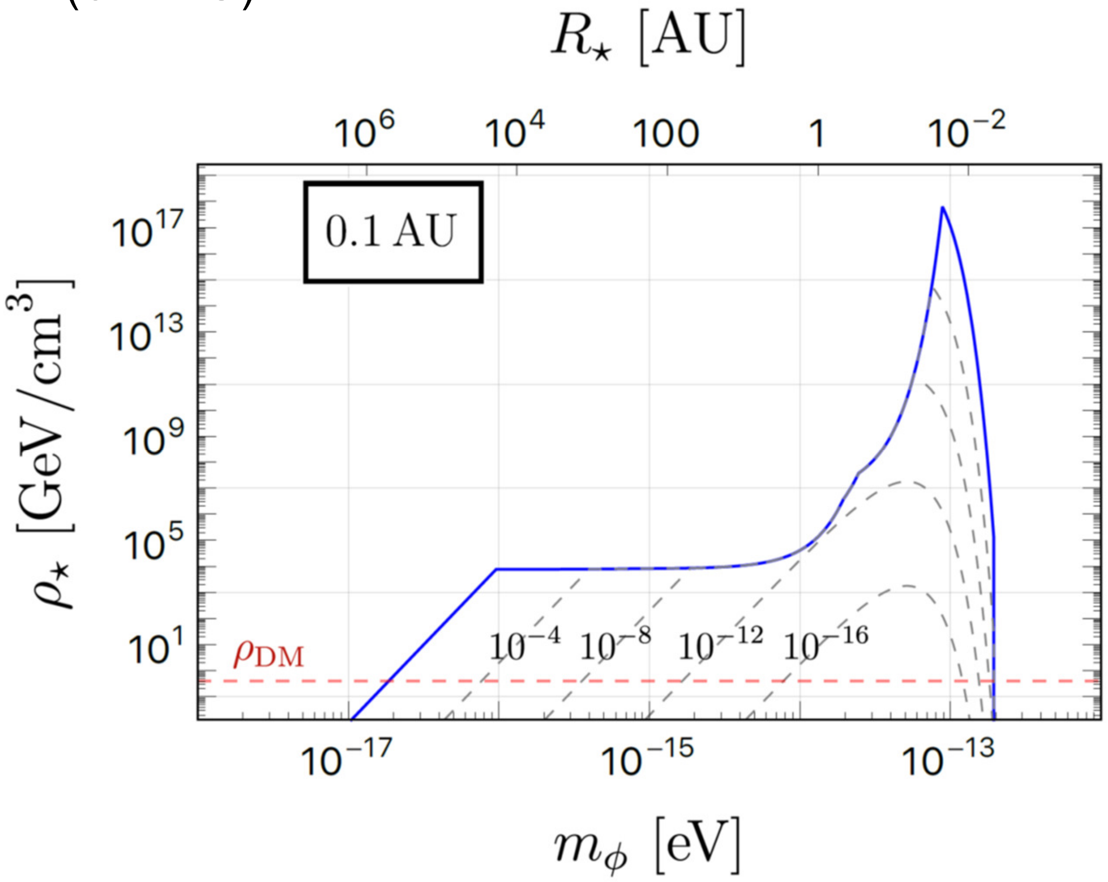


Yu-Dai Tsai, Joshua Eby, Marianna S. Safronova, arXiv:2112.07674

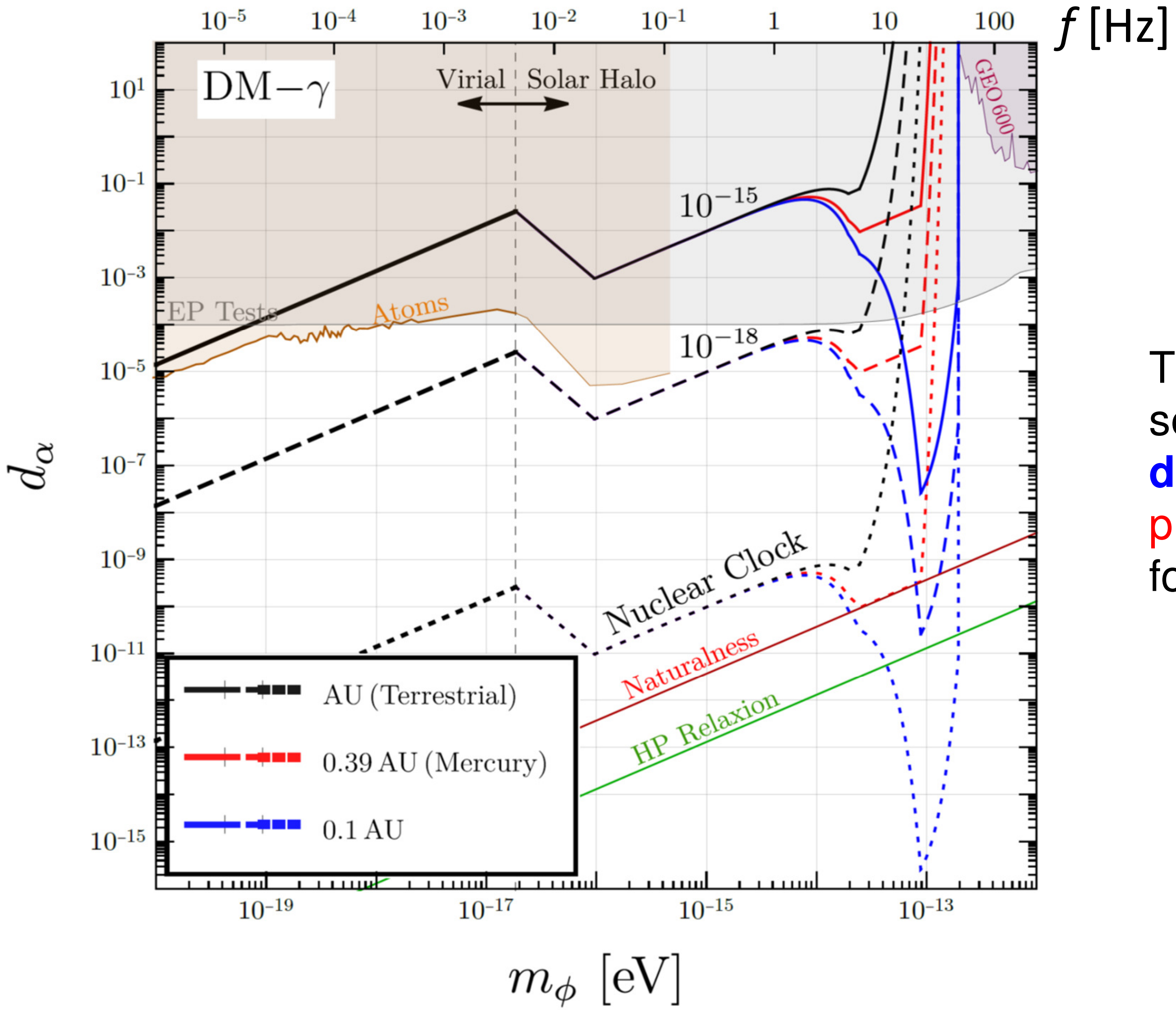
We propose a clock-comparison satellite mission with two clocks onboard, to the inner reaches of the solar system (0.1 AU).

Science goals:

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



ESTIMATED SENSITIVITY REACHES FOR DARK MATTER 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

Moon, planets, asteroids & quantum sensors

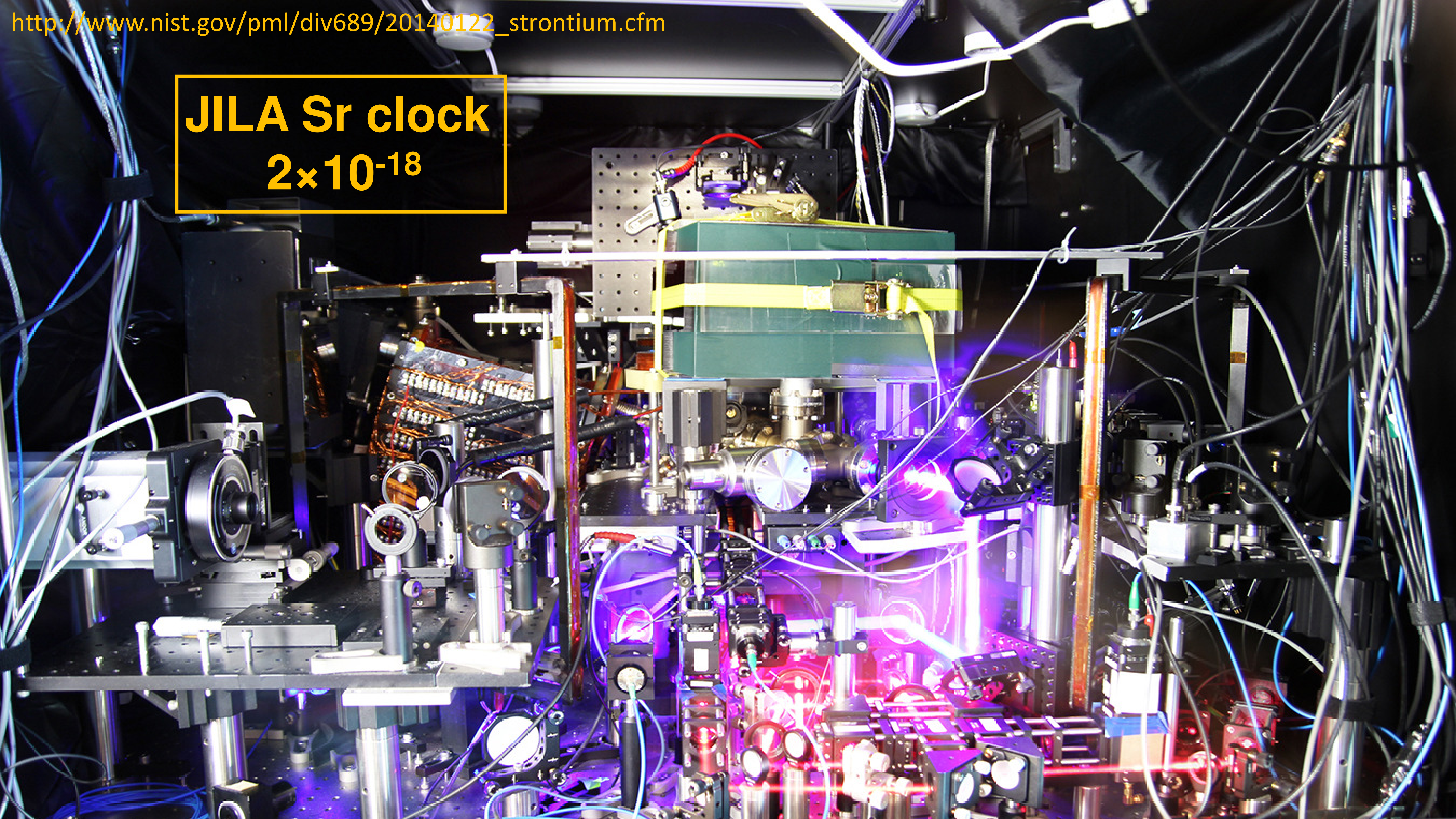
Looking for ideas: Moon, planets and asteroids for new physics searches with quantum sensors

OSIRIS-Rex: NASA mission to asteroid Bennu

- Moon: low seismic noise, free permanent cryogenic & vacuum environment
- Can QS on the Moon further improve Lunar Laser Ranging?
- 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)



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

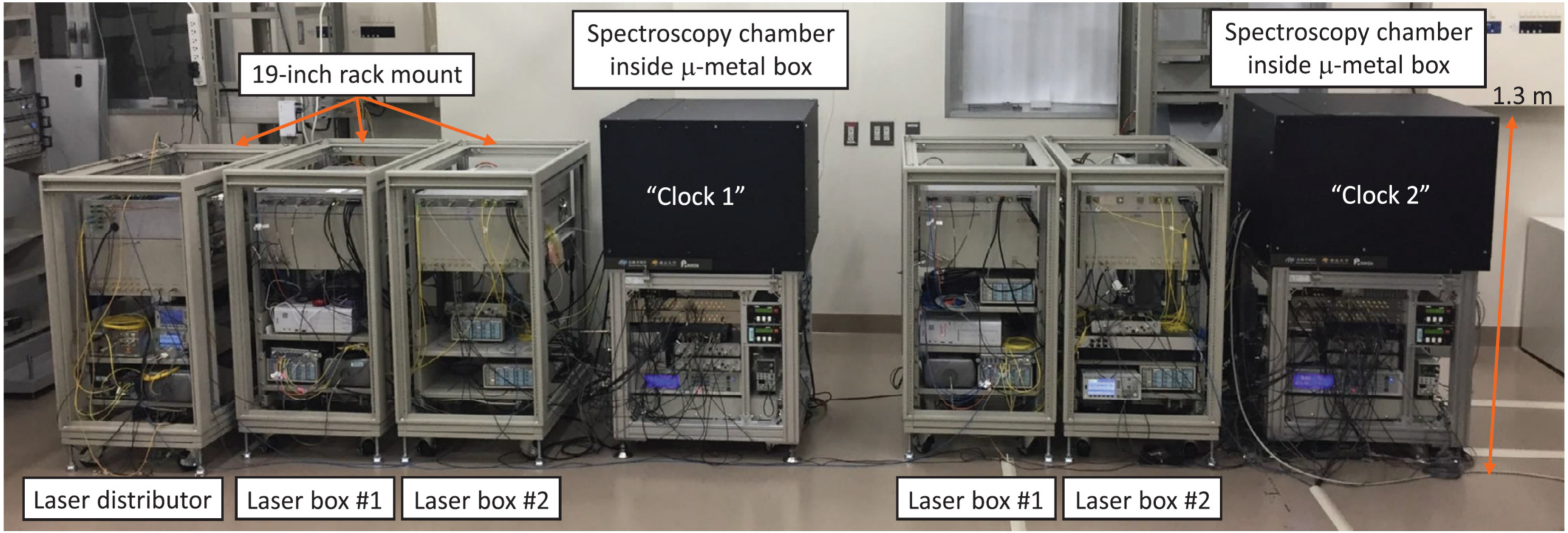
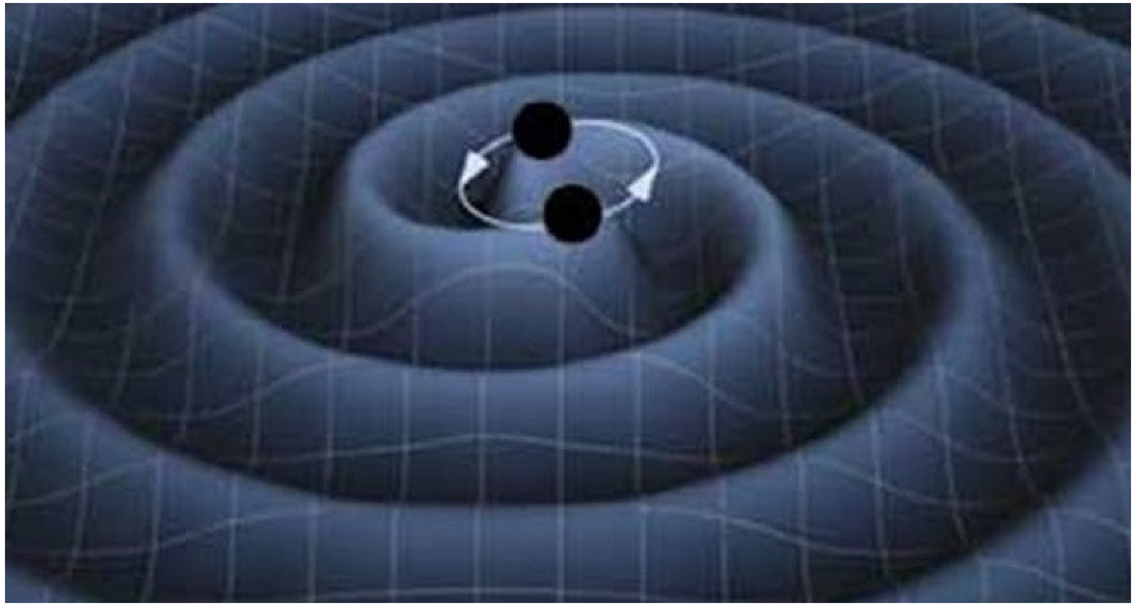
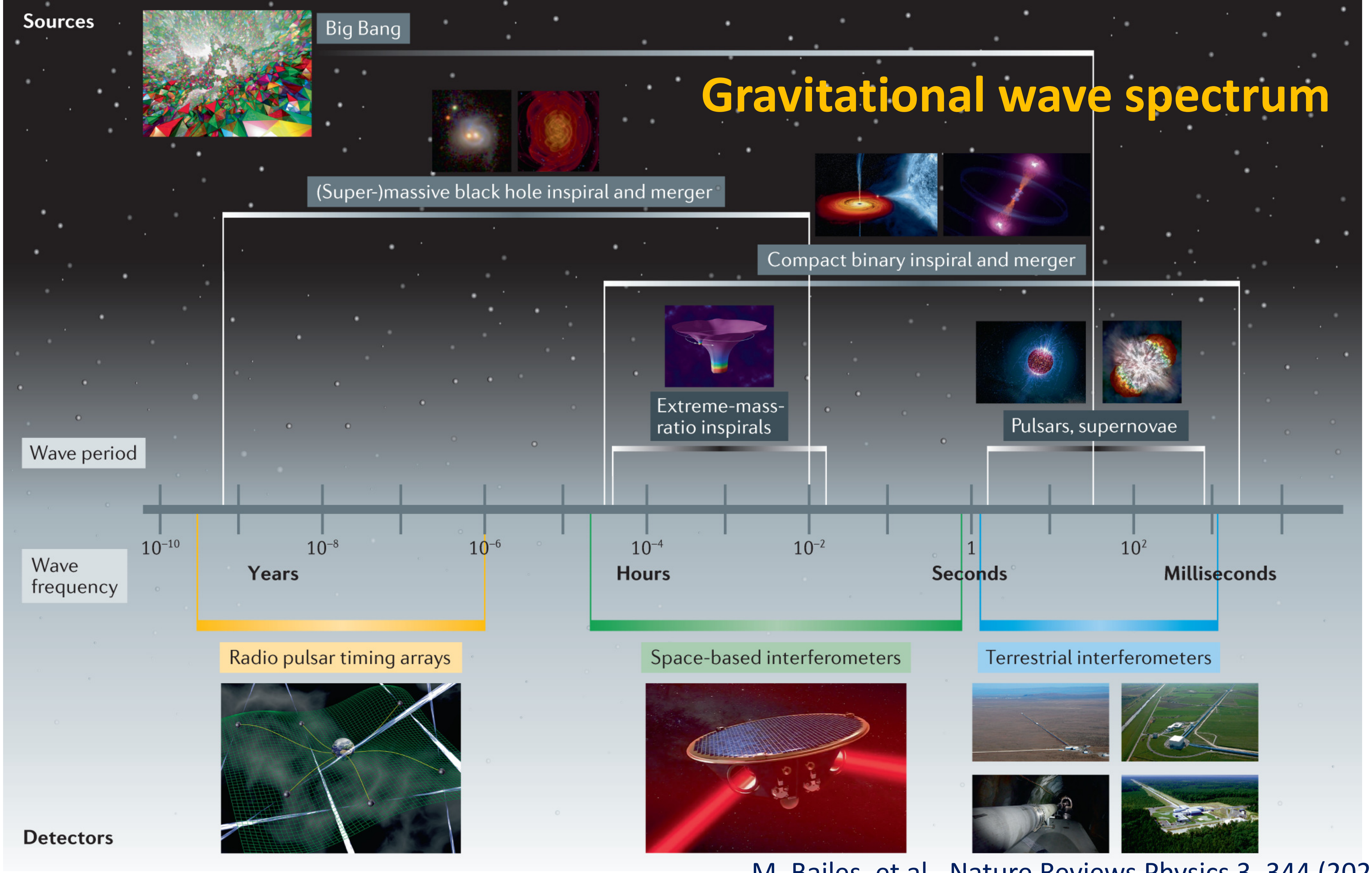


Figure 1. A pair of Sr optical lattice clocks placed at RIKEN laboratory.

New ideas in gravitational wave detection with atomic quantum sensors

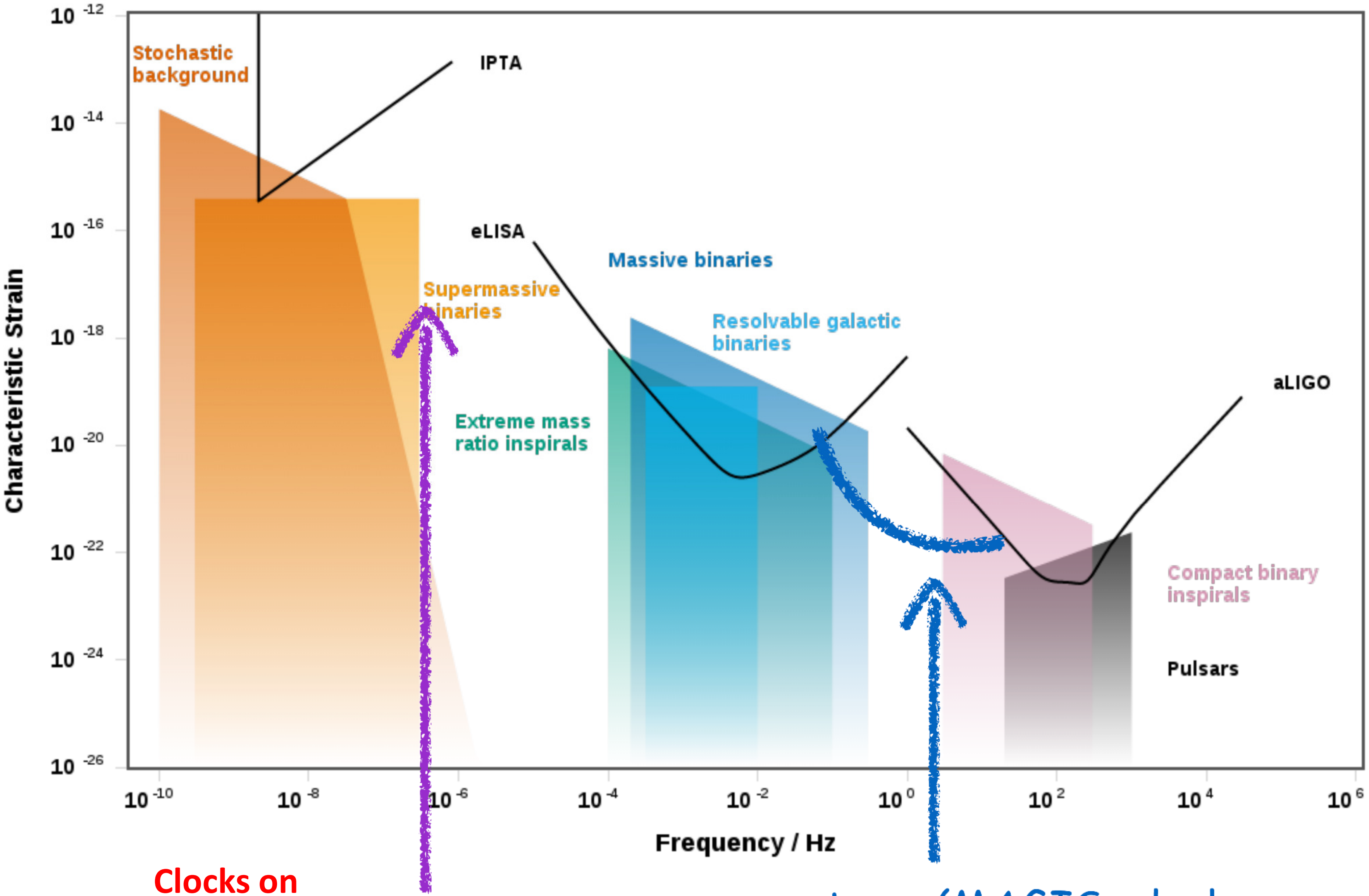


Gravitational wave spectrum



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/



Clocks on asteroids open band

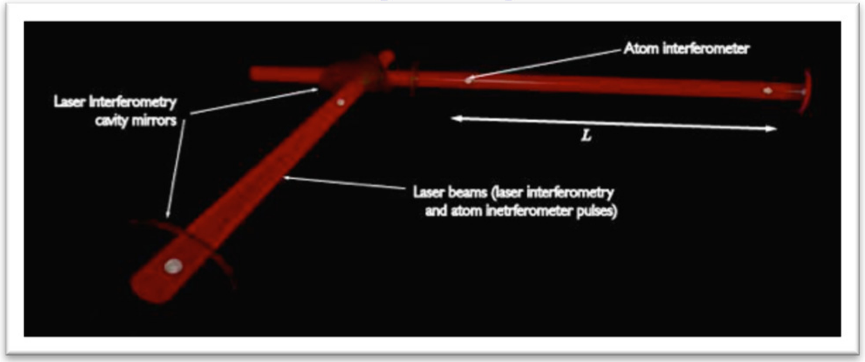
PRD **105**, 103018 ~ 10^{-7} Hz - 10^{-4} Hz

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

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

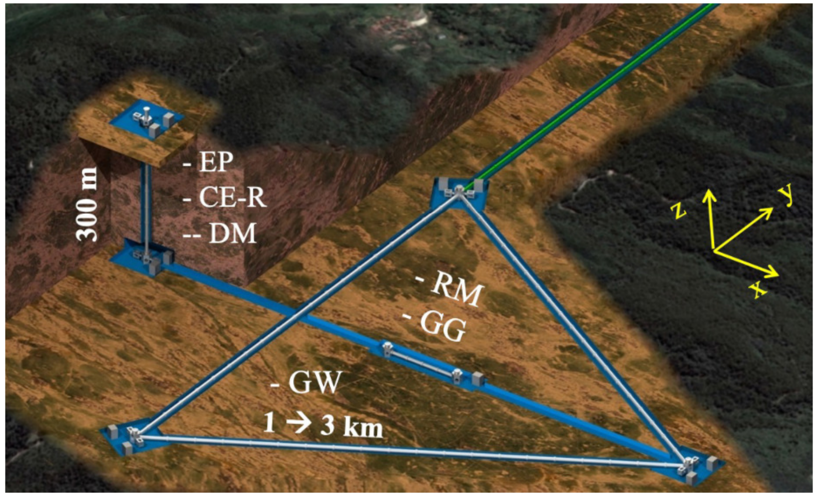
MIGA: **Terrestrial detector using atom interferometer at O(100m)**

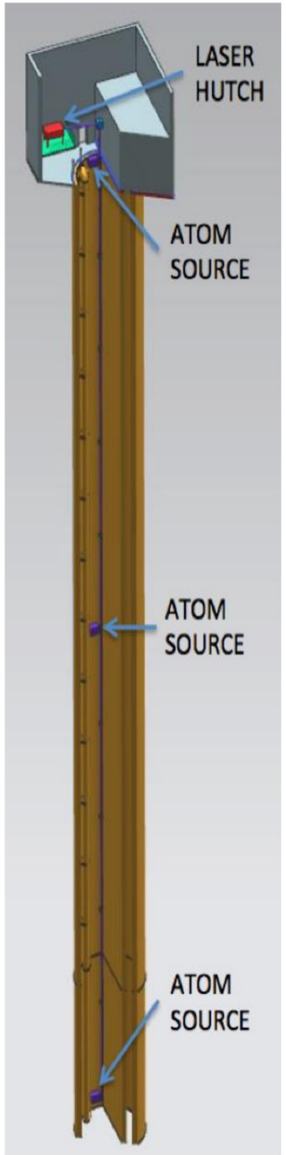
(France)



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

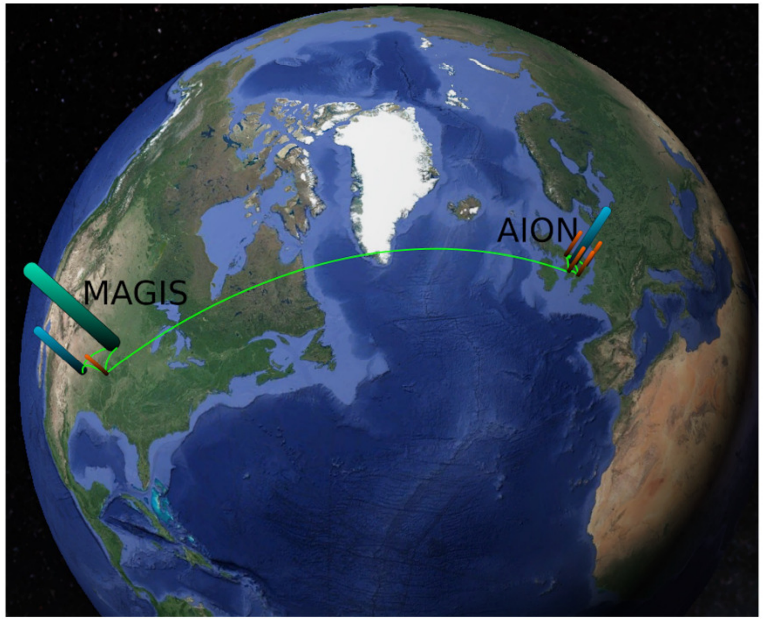
(China)





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/

2022

Solving physics problems of 1922 gave us quantum mechanics – a foundation of modern technology.

What new wonders discovery of new physics will bring?

2122