GGI LECTURES ON THE THEORY OF FUNDAMENTAL INTERACTIONS 2023

Tabletop experiments: Lecture 5

Searches for new physics with space experiments
Detecting axions and APLs
Searches for electric dipole moment and CPT violation
Gravitational wave detection with atomic quantum sensors

Marianna Safronova

University of Delaware

Q-SEnSE
An NSF Quantum Leap Challenge Institute
https://www.colorado.edu/research/qsense/

thorium nuclear clock
https://thoriumclock.eu/

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.

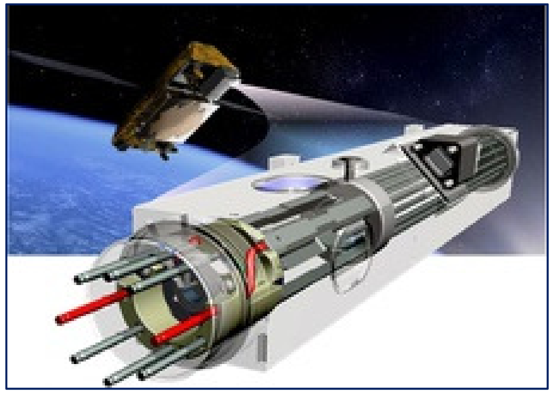
Cold Atoms in Space: Community Workshop Summary and Proposed Road-Map, Alonso et al., arXiv:2201.07789

Image credits: NASA, ESA

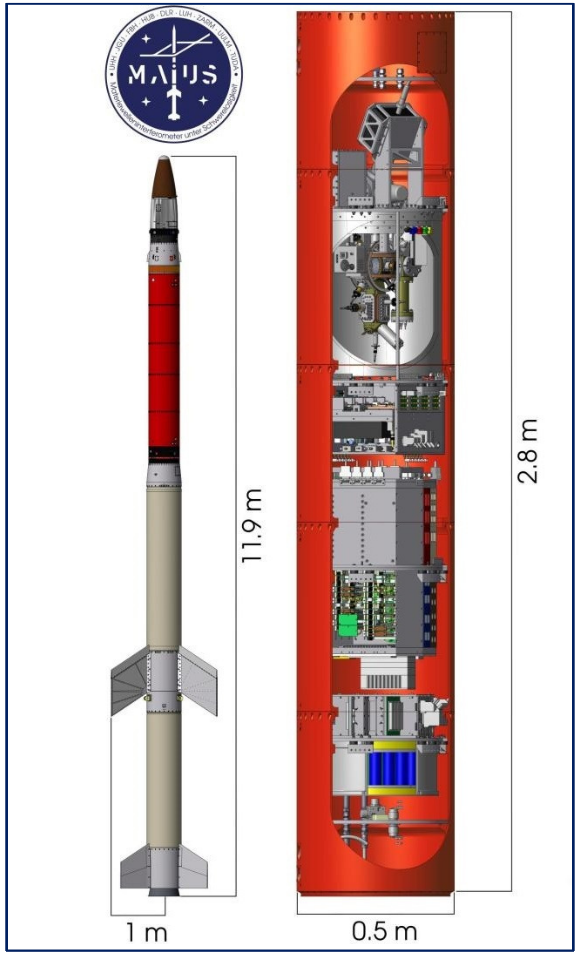
Quantum technologies in space

GPS, “hot” atoms, Microwave, Cs or Rb

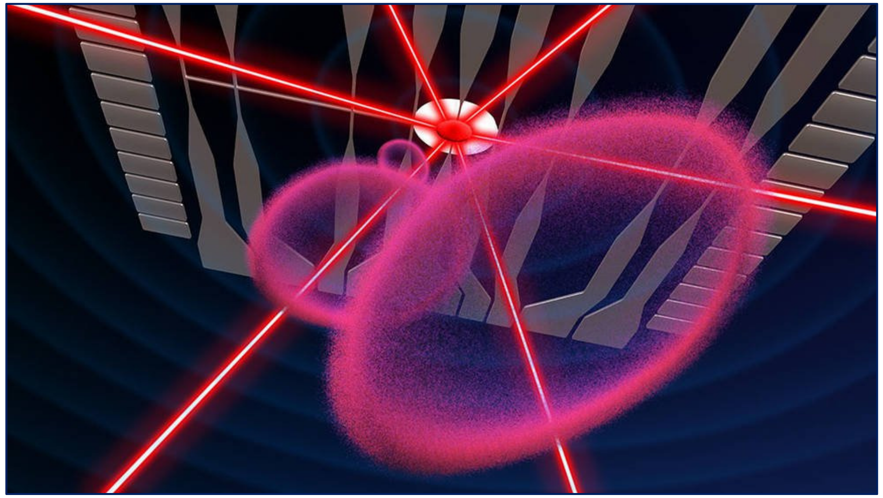
2017 CACES (Tiangong-2), China, microwave Rb cold atom clock



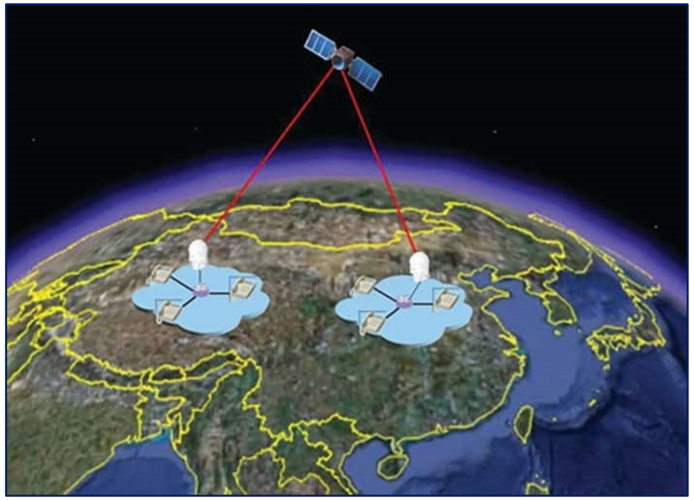
2019 NASA Deep Space Atomic Clock (DSAC), microwave, Hg^{+} ions



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



2018, Cold Atom Lab, ISS, NASA



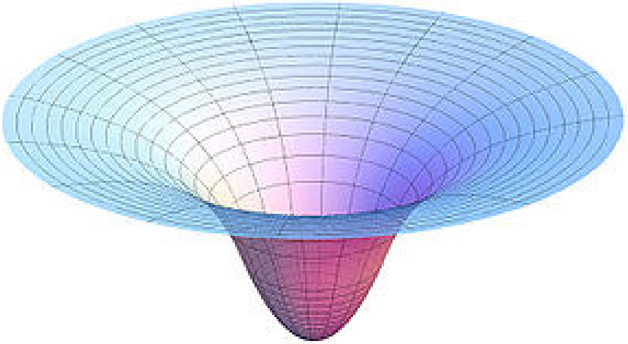
2016 QUESS, Entanglement distribution, China

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

Why to search for new physics in space?

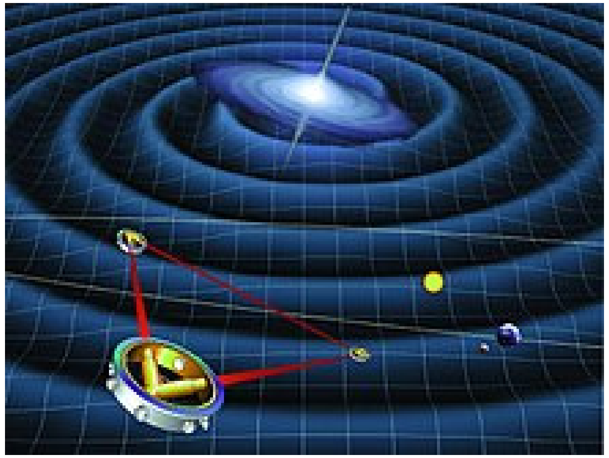
Quantum sensors in space enables discovery of new physics not possible on Earth
Many orders of magnitude improvements or principally different experiments are possible

Need to be away from Earth surface

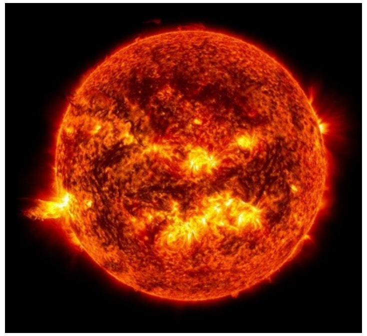


Tests of gravity are hindered by Earth gravity
Optical time transfer to link Earth clocks
Dark energy and some dark matter (screening)
Tests of fundamental postulates (WEP, LLI)

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

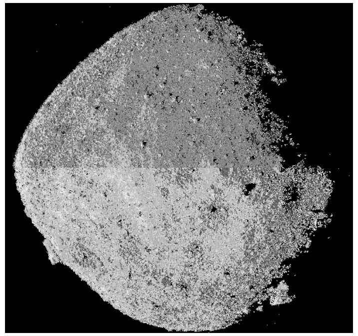


Image credits:
NASA, Wikipedia

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

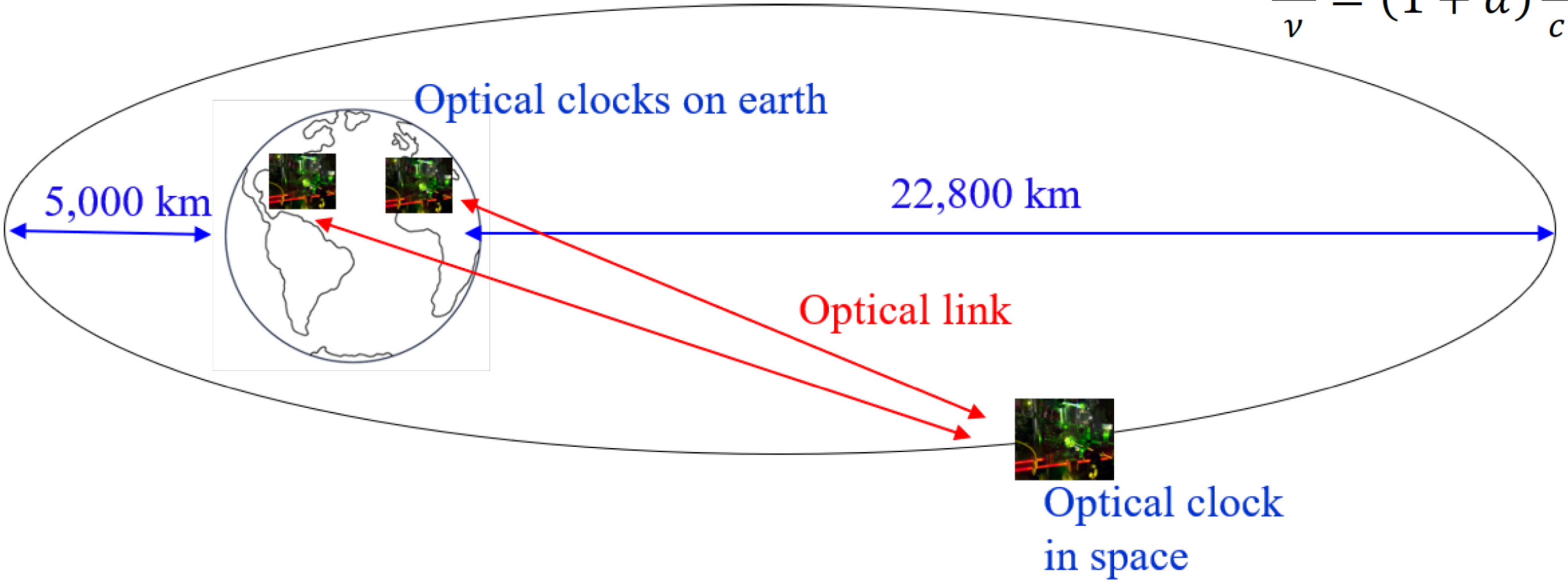
Asteroids for μHz gravitational-wave detection, Michael A. Fedderke, Peter W. Graham, Surjeet Rajendran, Phys. Rev. D 105, 103018 (2022)

New Constraints on Dark Matter and Cosmic Neutrino Profiles through Gravity, Yu-Dai Tsai, Joshua Eby, Jason Arakawa, Davide Farnocchia, Marianna S. Safronova, arXiv:2210.03749 (2022).

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

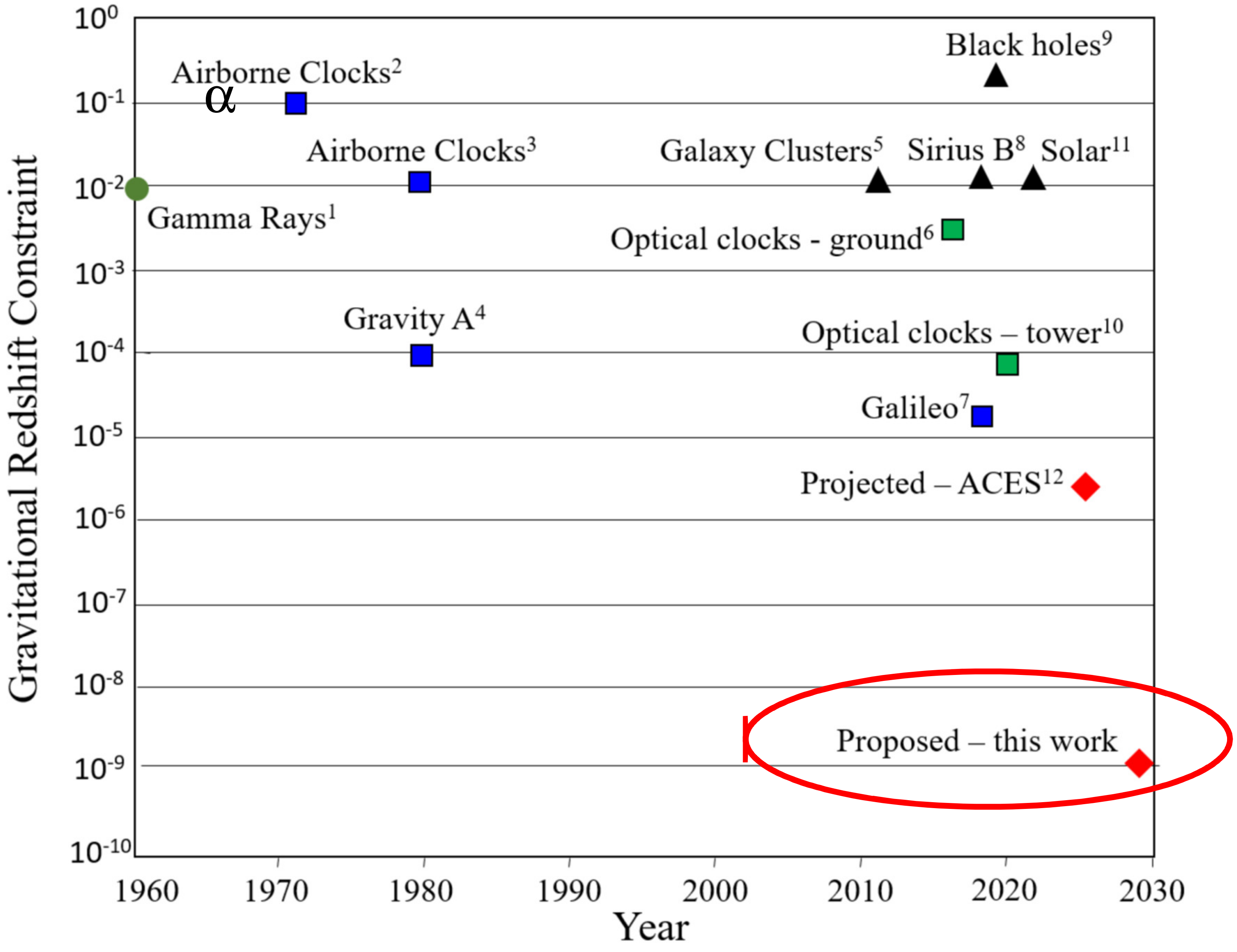
Andrei Derevianko, Kurt Gibble, Leo Hollberg, Nathan R. Newbury, Chris Oates, Marianna S. Safronova, Laura C. Sinclair, Nan Yu, Quantum Sci. Technol. 7, 044002 (2022)

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



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



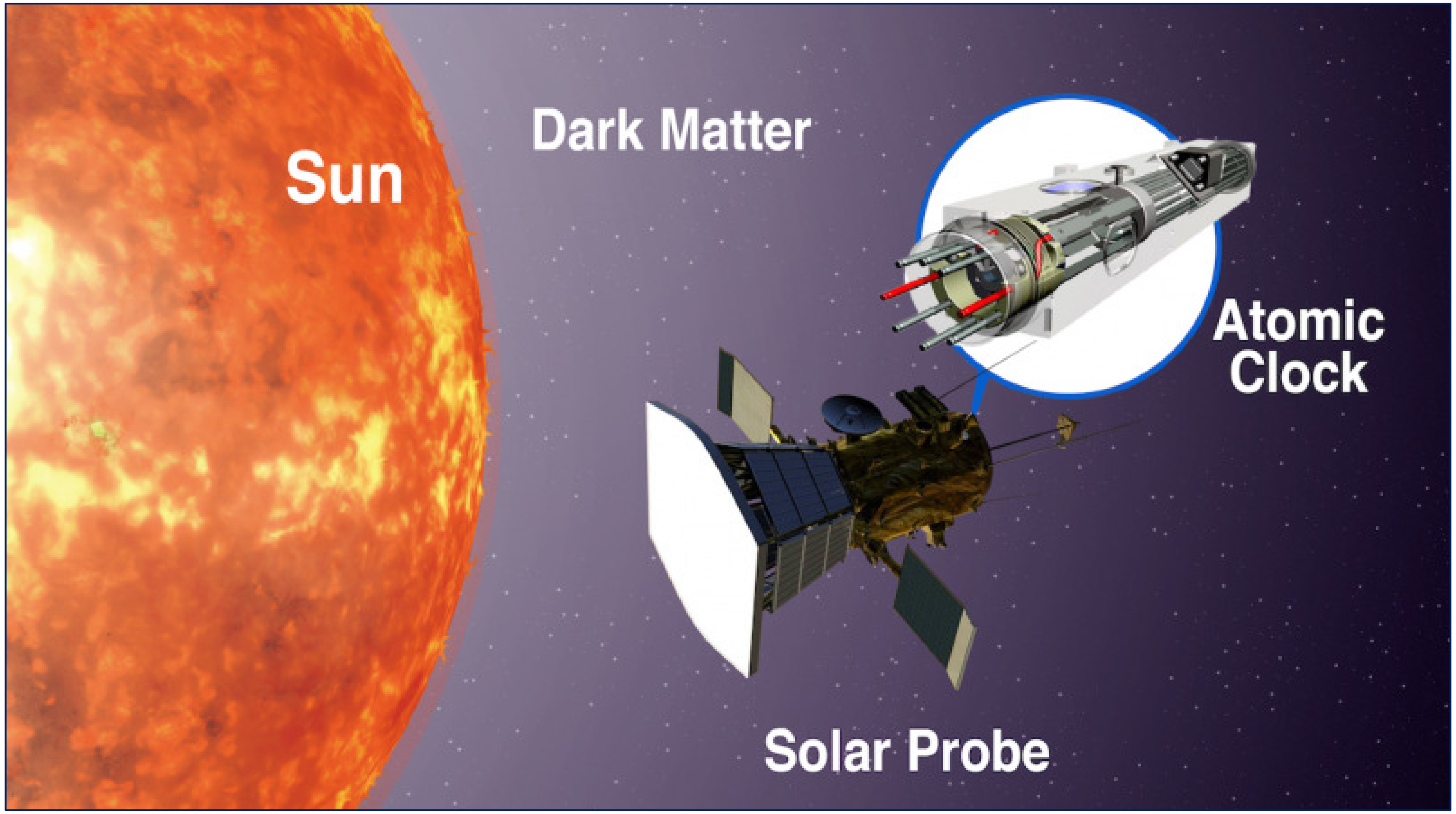
$$\frac{\Delta \nu}{\nu} = (1 + \alpha) \frac{\Delta U}{c^2}$$

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)

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



Yu-Dai Tsai, Joshua Eby, Marianna S. Safronova, Nature Astronomy, December 5 (2022)

Picture credit: Kavli IPMU

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

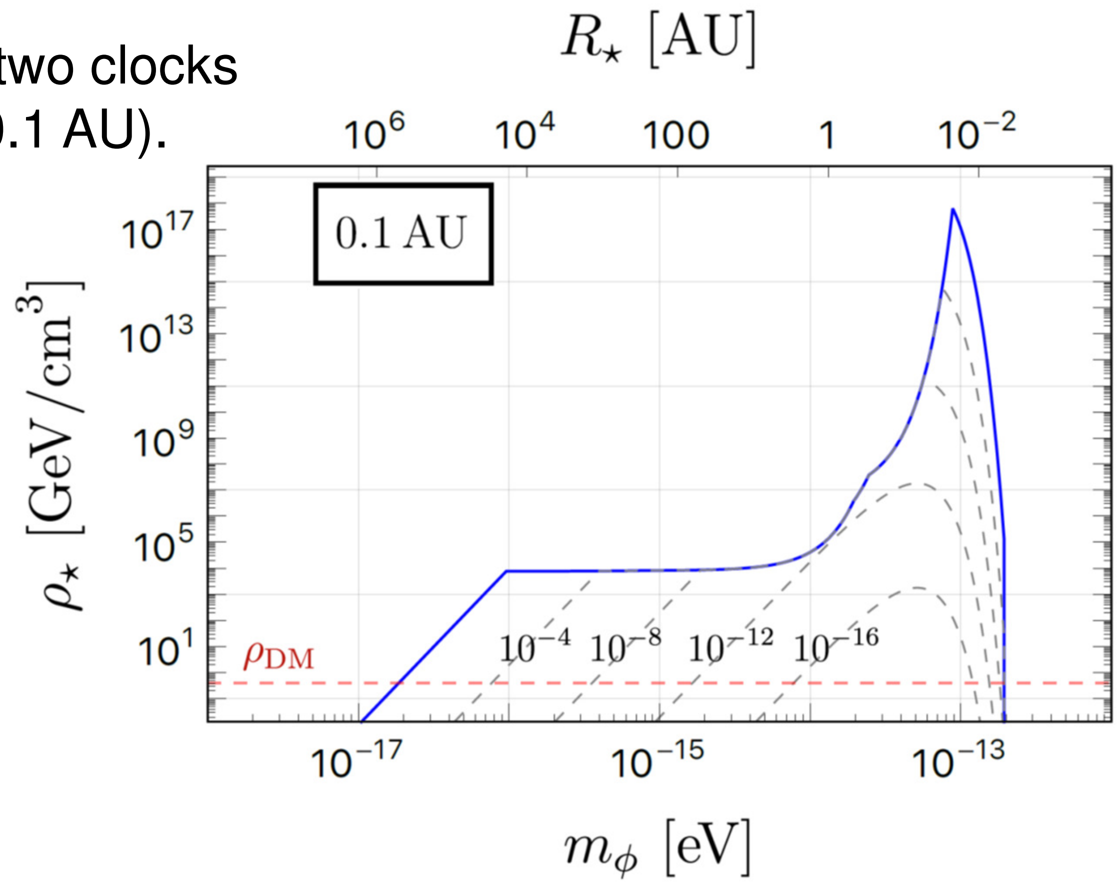
Yu-Dai Tsai, Joshua Eby, Marianna S. Safronova, Nature Astronomy, December 5 (2022)

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



nature physics

Transient variations

LETTERS

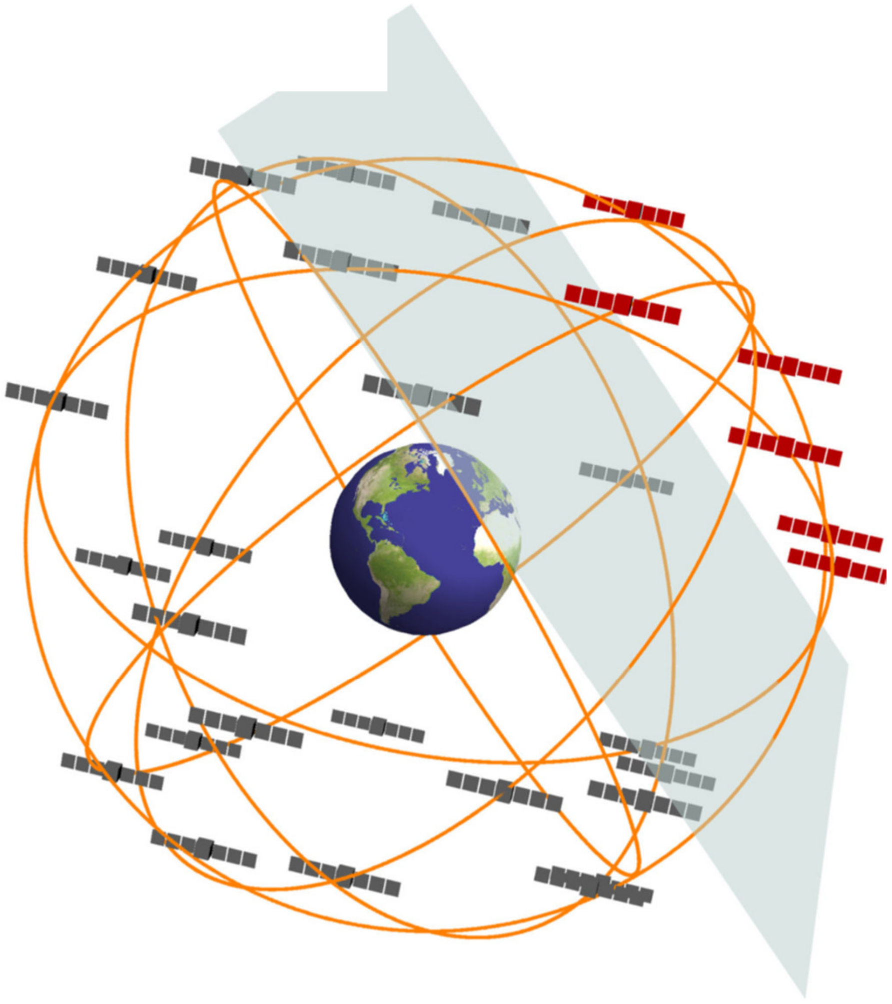
PUBLISHED ONLINE: 17 NOVEMBER 2014 | DOI: 10.1038/NPHYS3137

Hunting for topological dark matter with atomic clocks

Transient effects

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

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

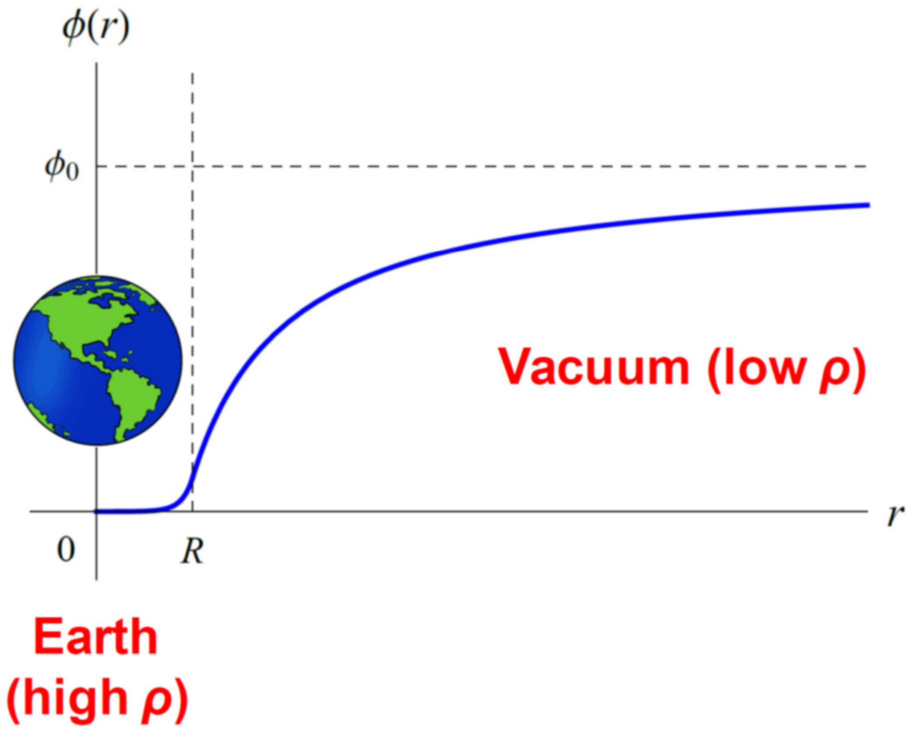


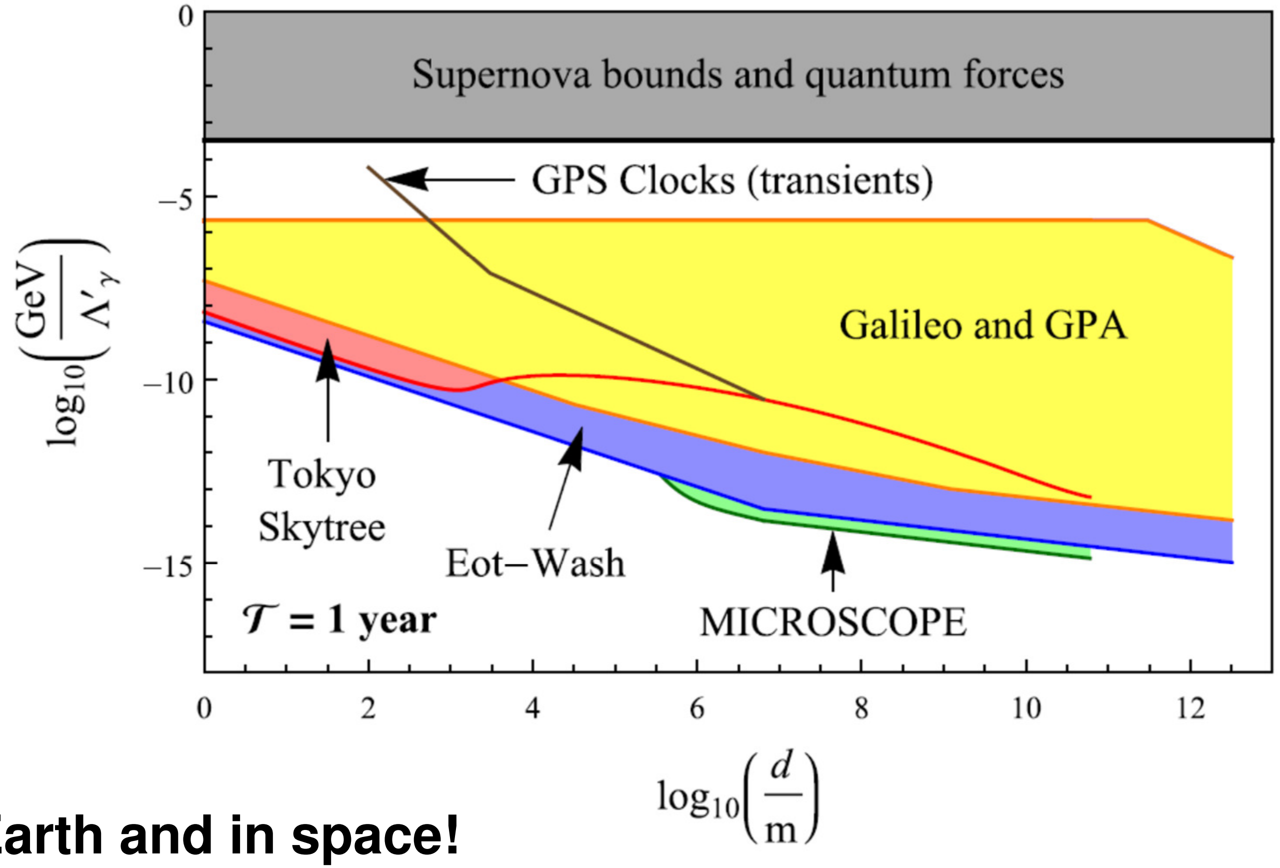
If they are large (size of the Earth) and frequent enough they may be detected by measuring changes in the synchronicity of a global network of atomic clocks, such as the Global Positioning System or networks of precision clocks on Earth.

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

Environmental dependence of fundamental “constants” near Earth

Screening of dark matter on Earth



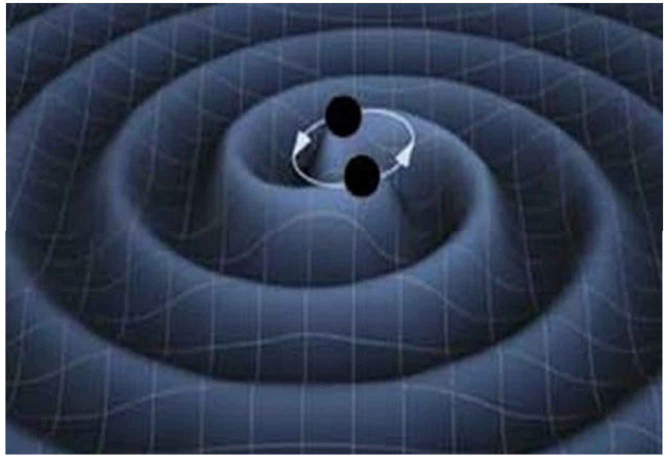


Fundamental constants can be different on Earth and in space!

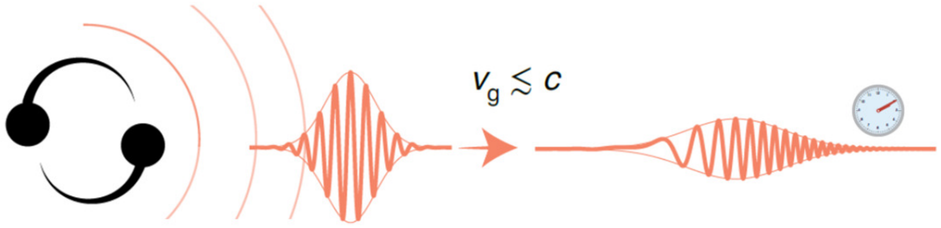
Picture credit: Yevgeny Stadnik

Yevgeny Stadnik, Phys. Rev. D 102, 115016 (2020)

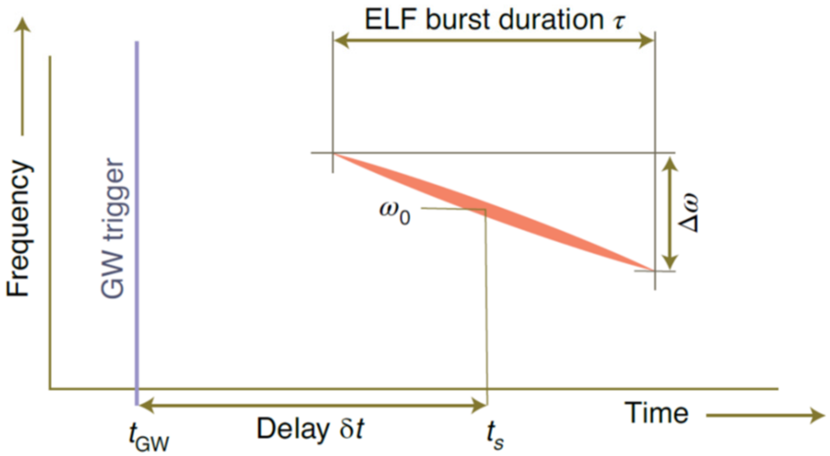
Quantum sensor networks as exotic field telescopes for multi-messenger astronomy



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.

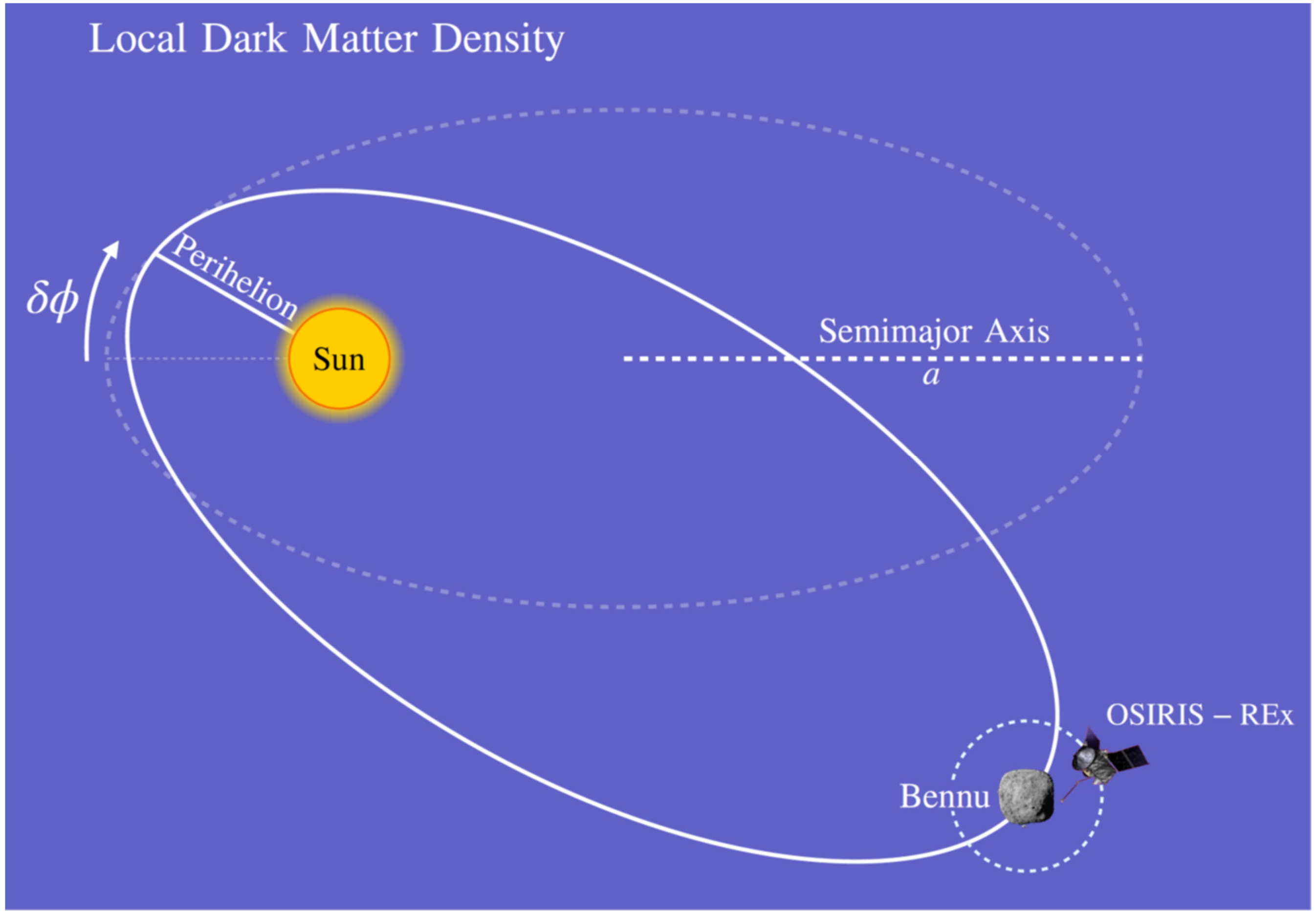


- The leading edge of an ultrarelativistic ELF burst would propagate across Earth in ~40 ms.
- Magnetometers: 1-10 ms temporal resolution.
- Need longer baseline for clocks.

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

Constraints on Dark Matter and Cosmic Neutrino Profiles through Gravity

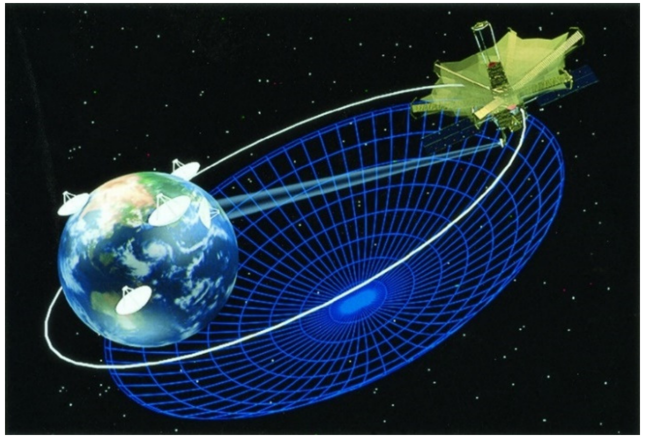
NASA mission to asteroid Bennu



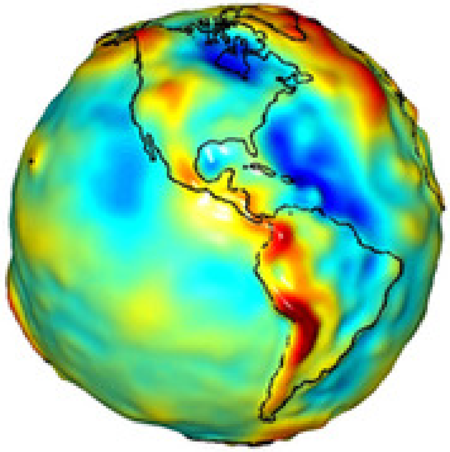
Yu-Dai Tsai, Joshua Eby, Jason Arakawa, Davide Farnocchia, and Marianna S. Safronova, arXiv:2210.03749, submitted to Nature Astronomy (2022)

Summary: space applications of atomic clocks

One way navigation

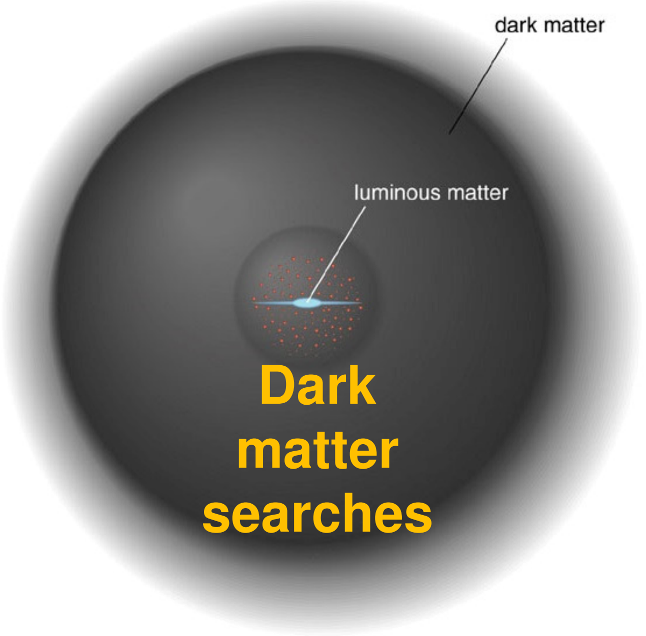


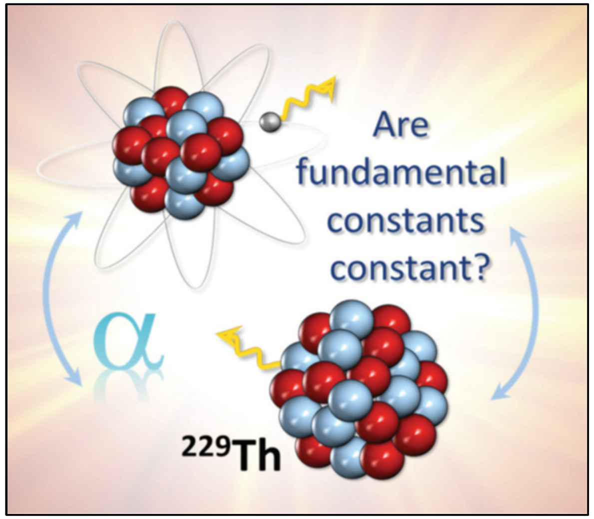
VLBI

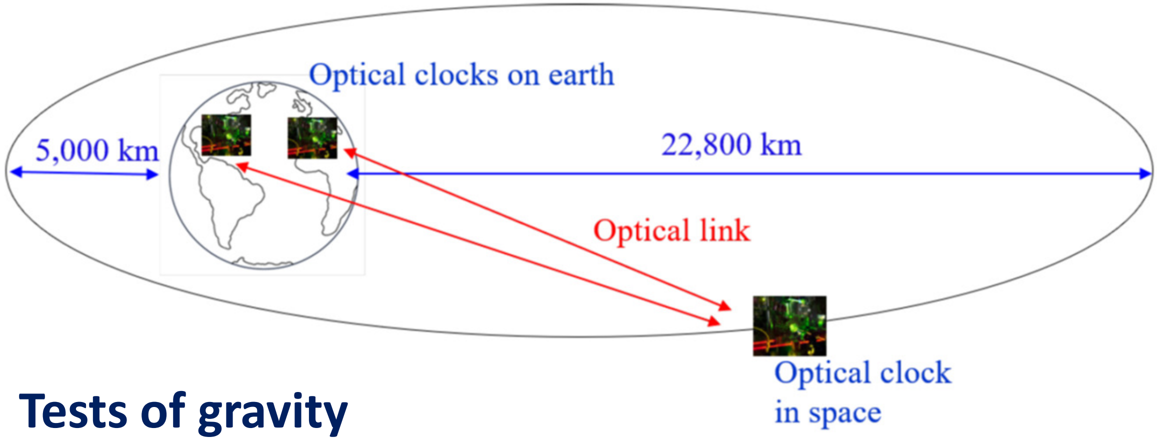


10^{-18}
1 cm
height

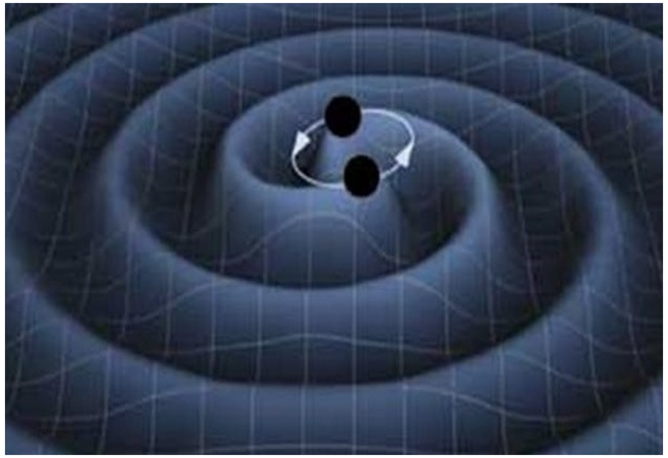
Earth sciences





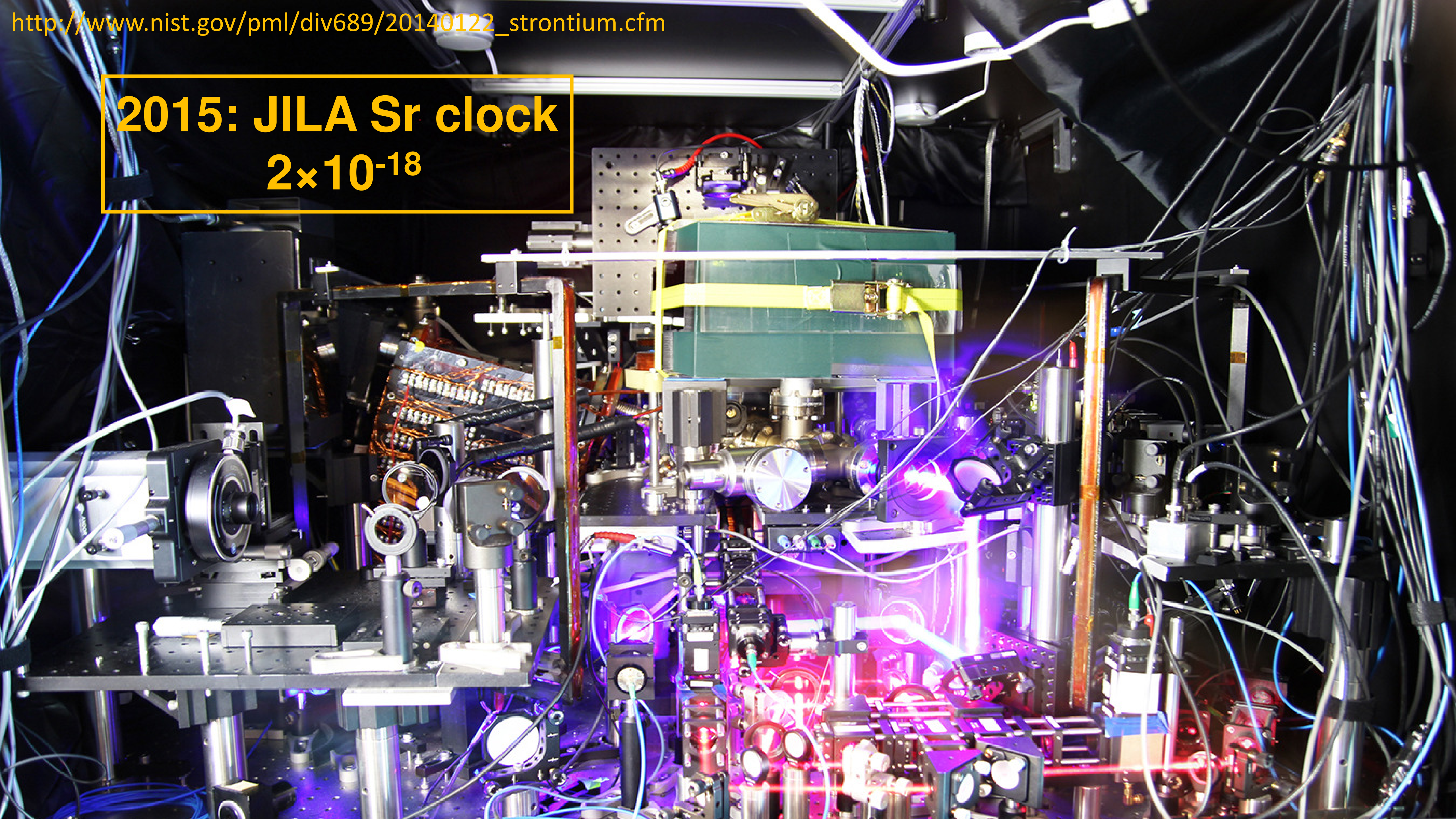


Tests of gravity
International time reference/compare Earth clocks
Searches of violation on Lorentz invariance
Tests of position invariance



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) .


http://www.nist.gov/pml/div689/20140122_strontium.cfm
2015: 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

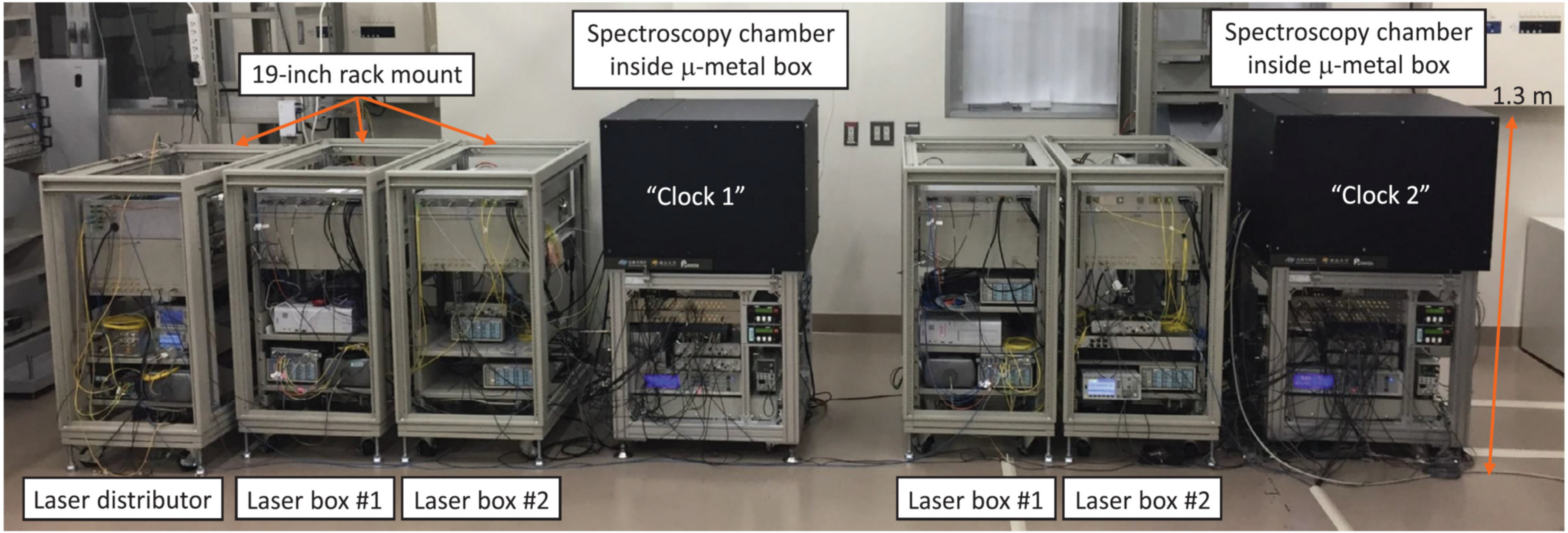


Figure 1. A pair of Sr optical lattice clocks placed at RIKEN laboratory.

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

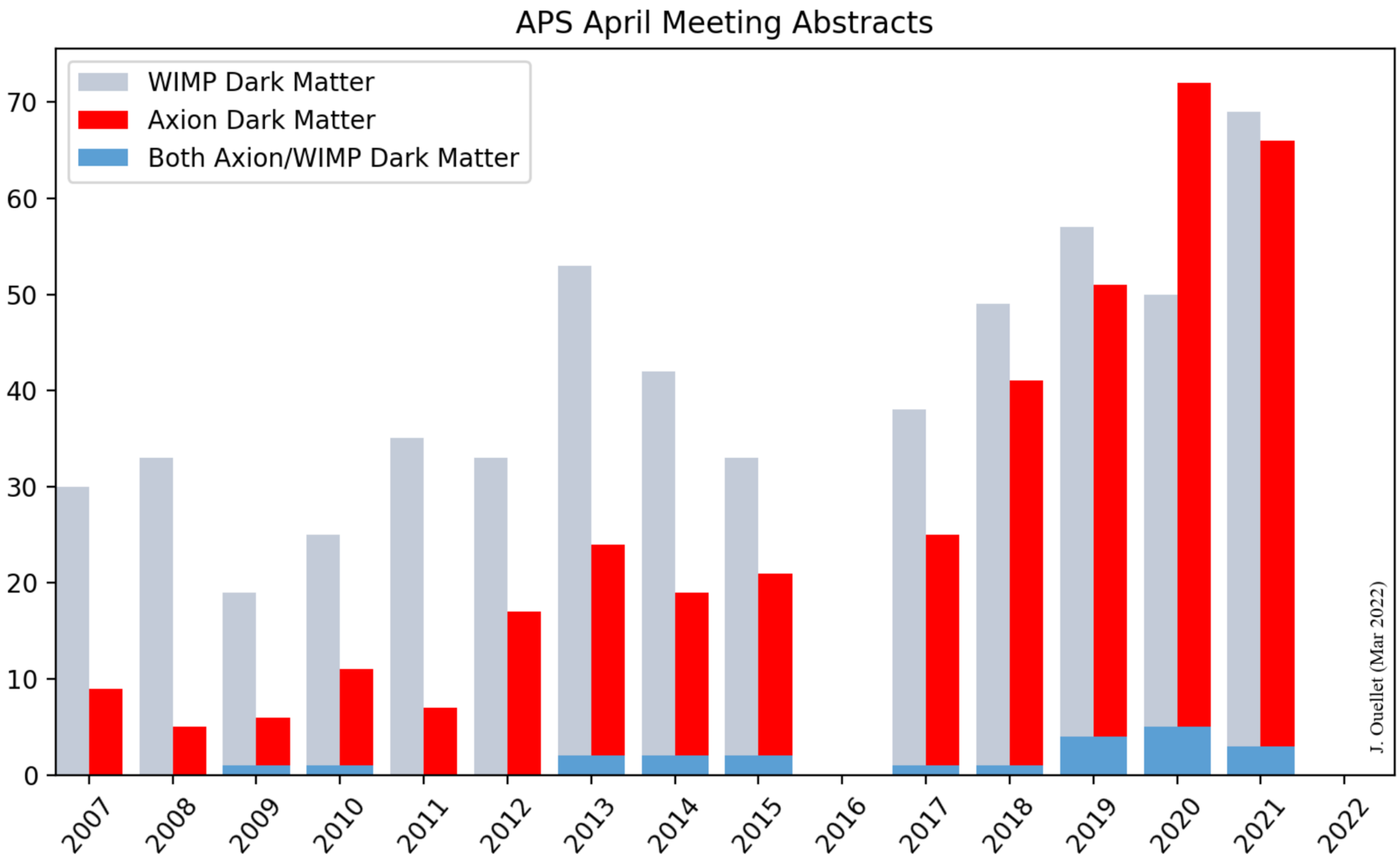
arXiv:2203.14923

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

Ultralight dark matter: fast growing community



J. Ouellet

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

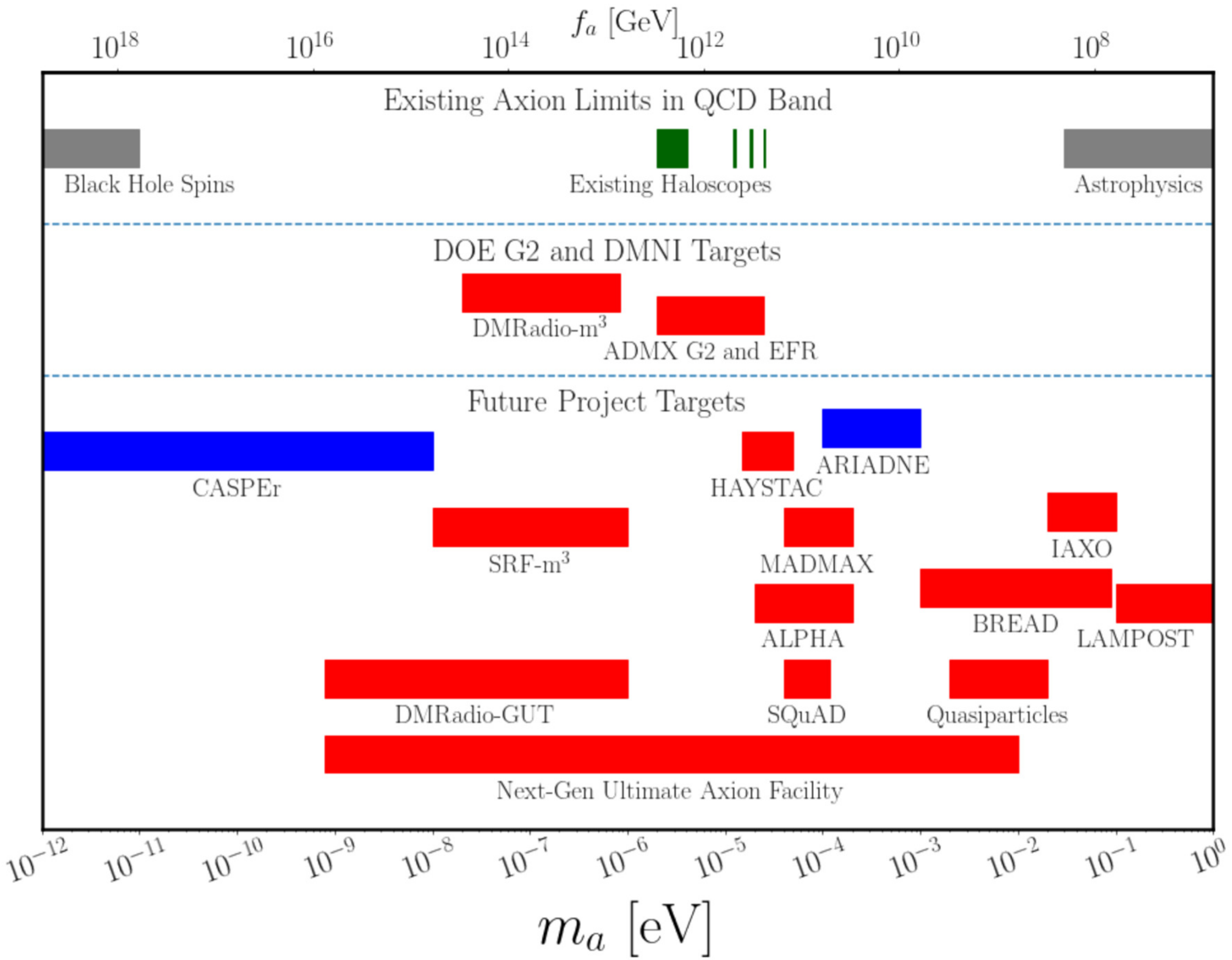
It minimally extends the SM with a new classically conserved global symmetry, the PQ symmetry $U(1)_{PQ}$, which is spontaneously broken at a scale fa. QCD axion is the low-energy consequence.

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

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

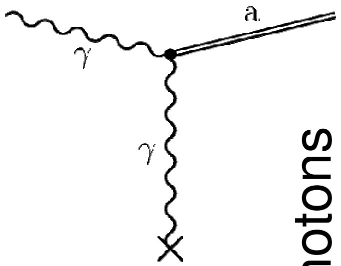
$$\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

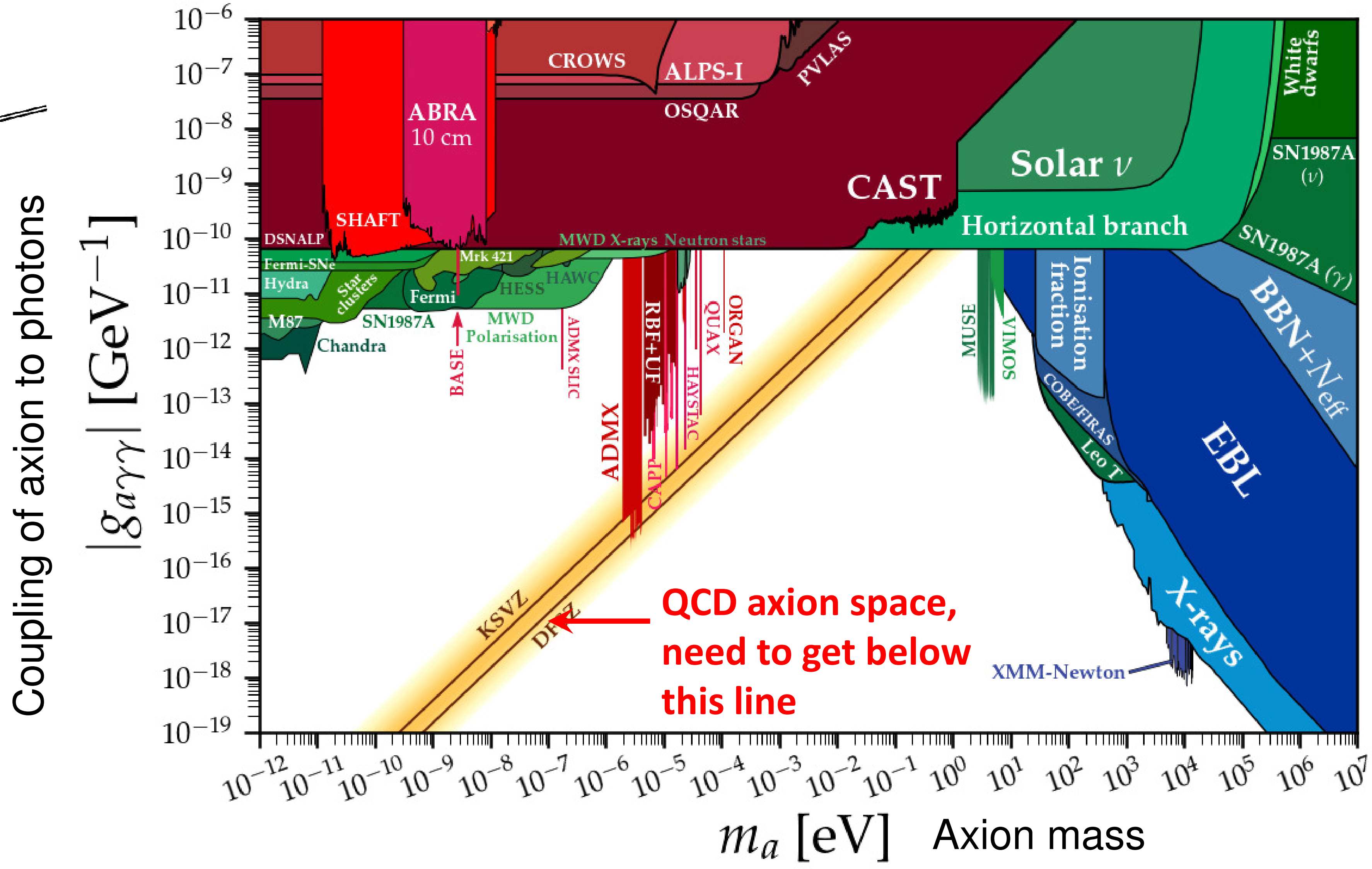
Blue indicates proposal utilizing alternative couplings.

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

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

Pseudoscalar dark matter: axions and APL

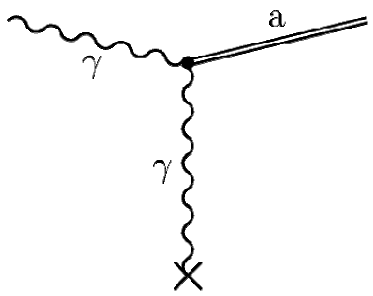




J. Jaeckel, G. Rybka, L. Winslow, for the Axion Prospects Collaboration. "Axion Dark Matter", arXiv:2203.14923

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

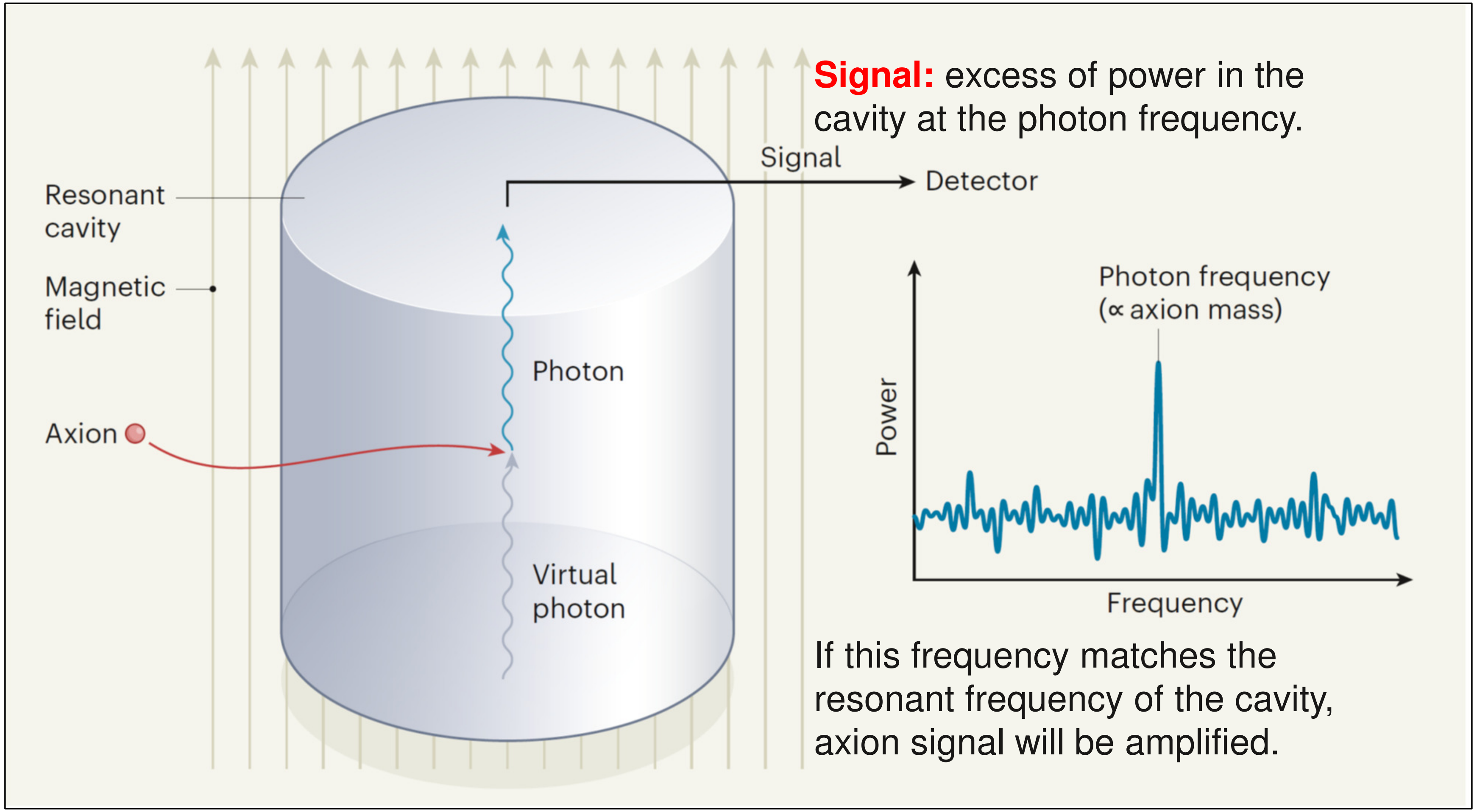
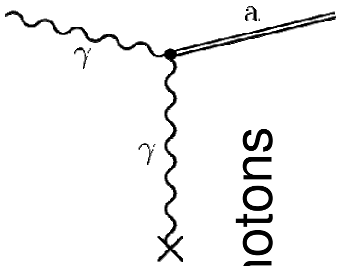
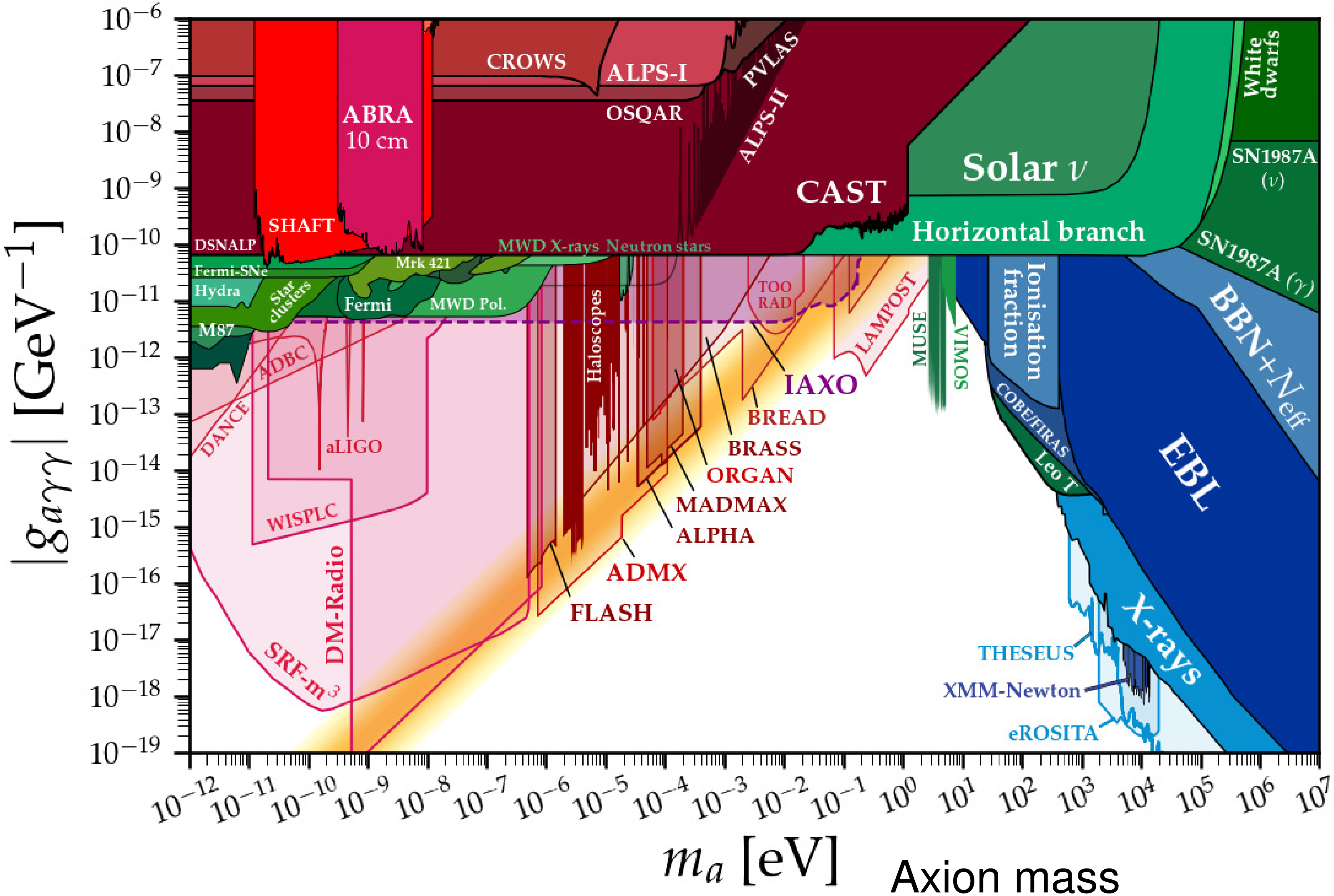


Image from: Nature 590, 226 (2021)

Axions and APLs: future prospects



Coupling of axion to photons



Axion mass

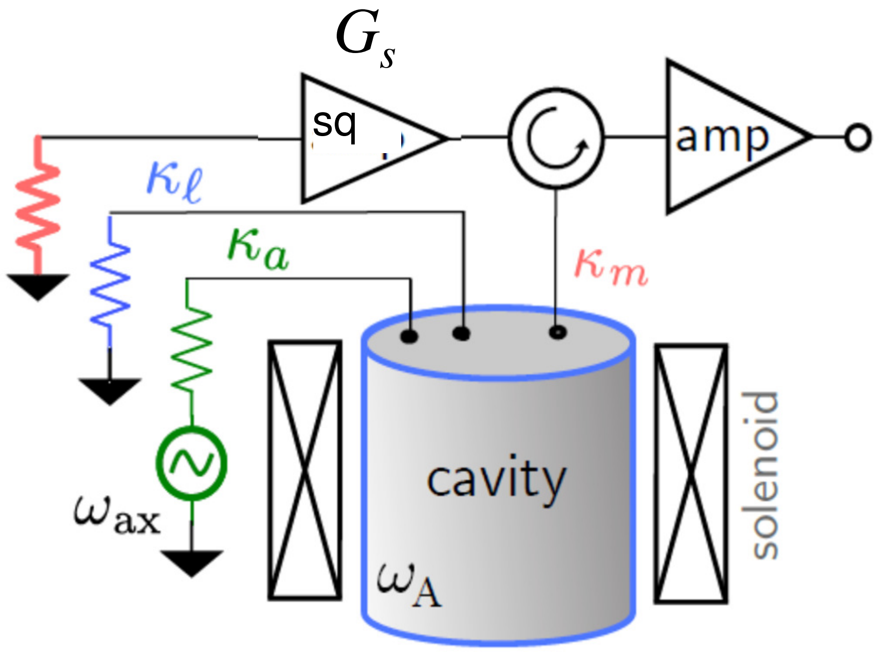
Need measurements beyond the standard quantum limit

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.**



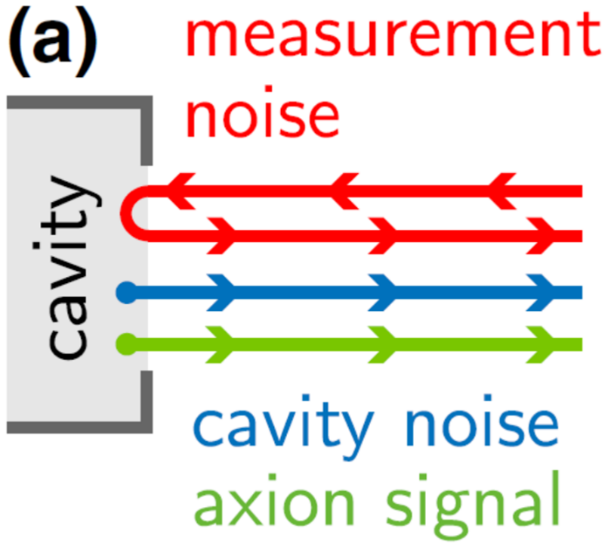


Figure credits: Konrad Lenhert & PRX Quantum **2**, 040350 (2021).

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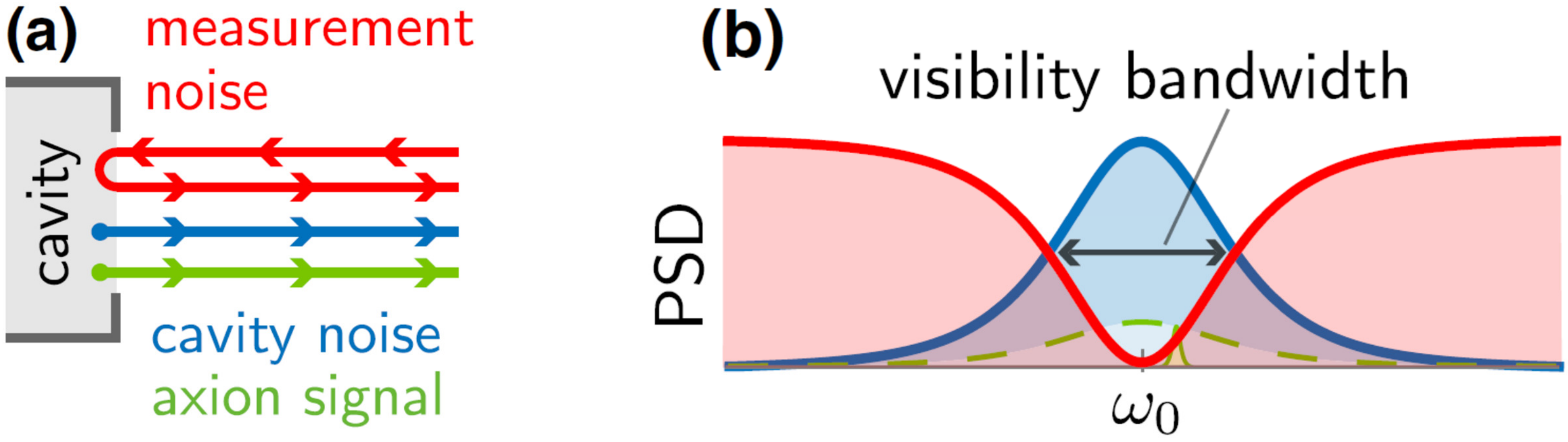
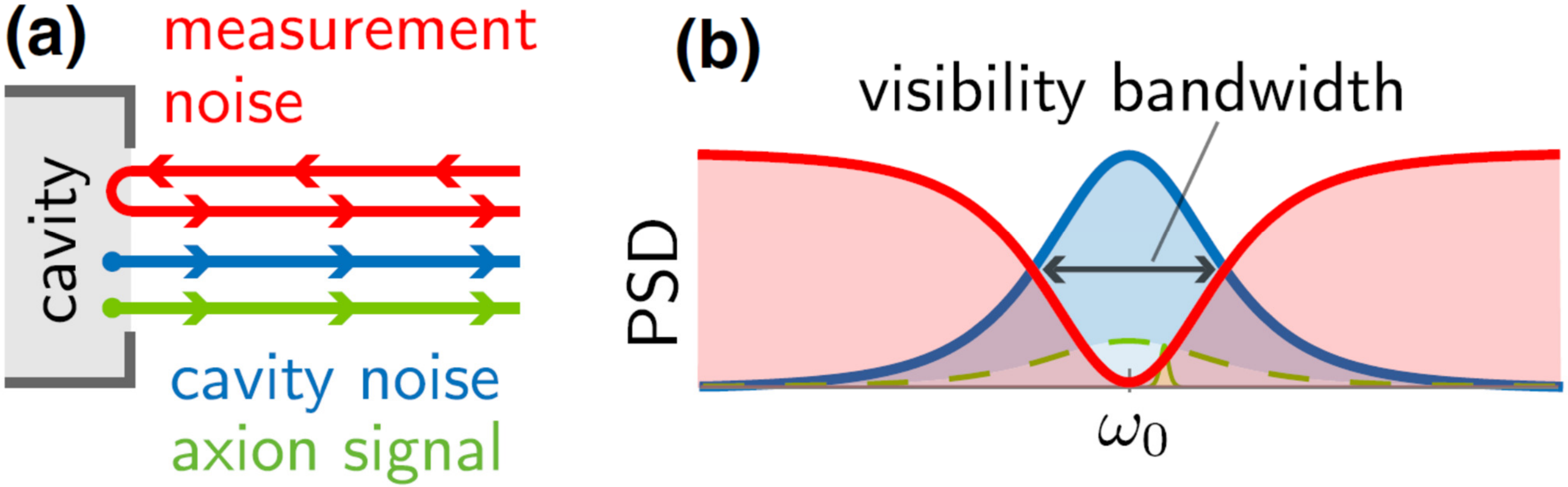
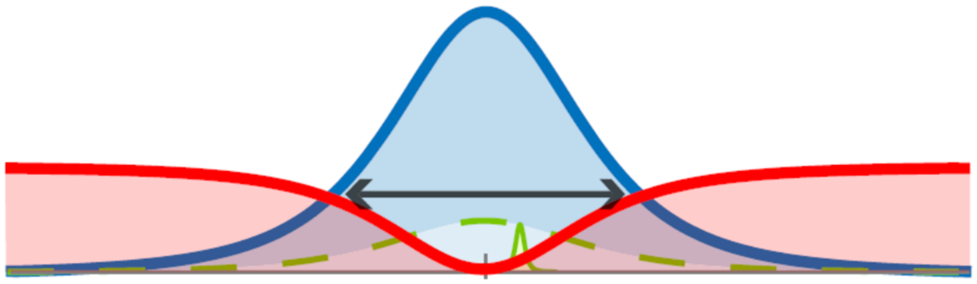


Figures: PRX Quantum **2**, 040350 (2021).

Quantum enhanced axion dark matter search



With quantum enhancement: version 1



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

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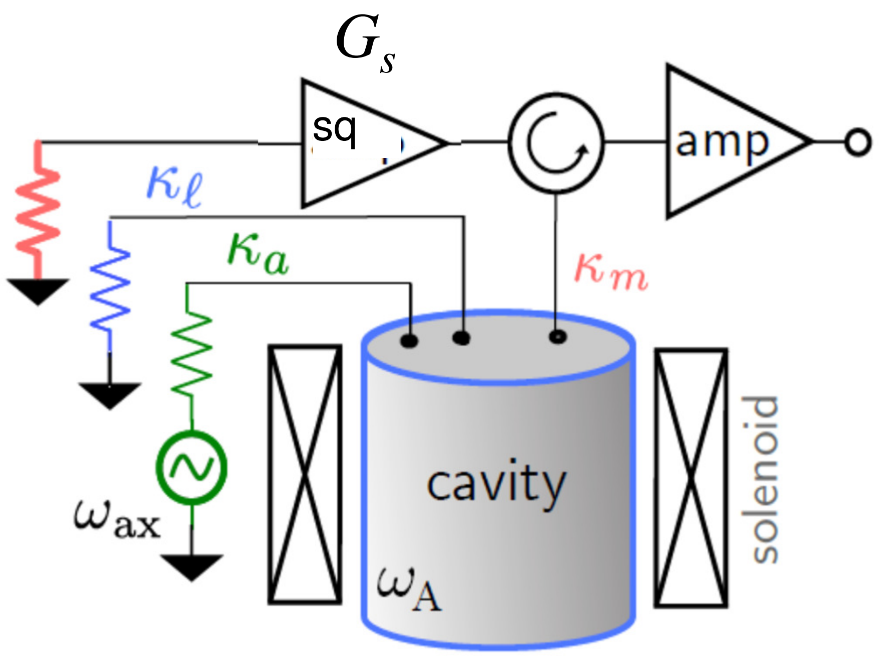
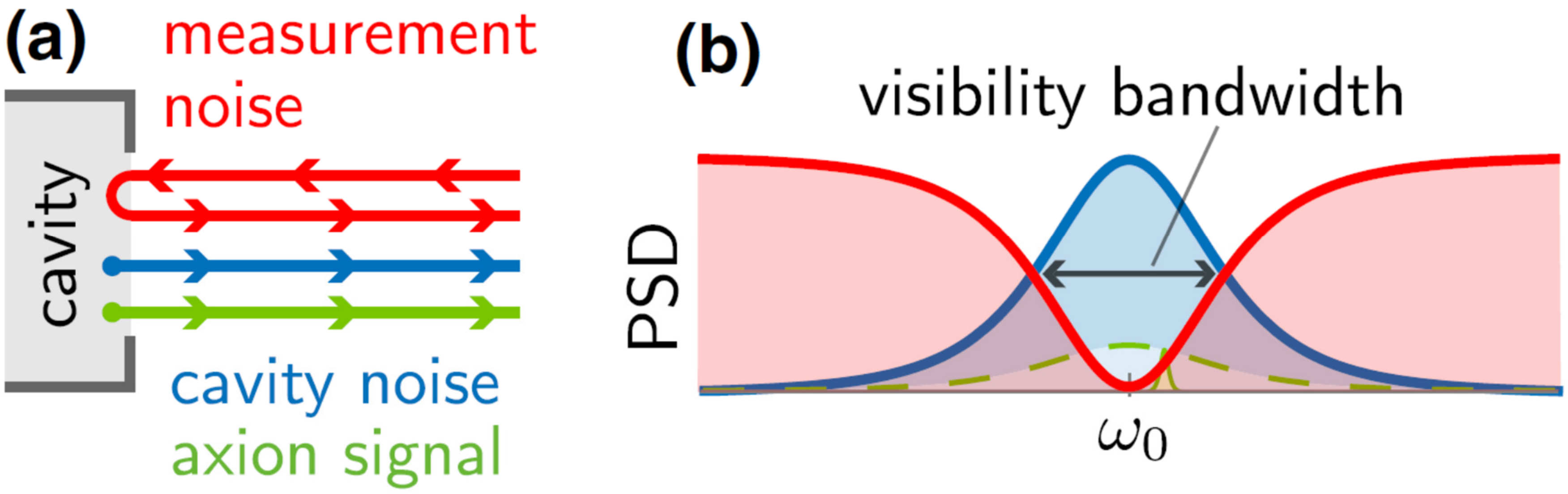


Quantum-enhanced measurement techniques can widen the visibility bandwidth by increasing noise that originates in the cavity (along with any signal present) relative to noise associated with measurement.

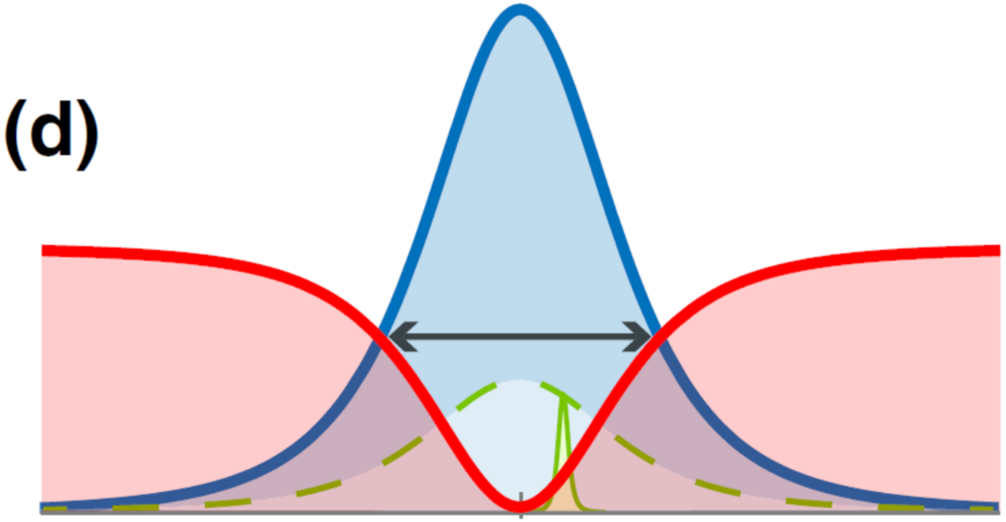
Two-fold speed in QCD axion search rate from squeezing was demonstrated in 2021 by coupling the HAYSTAC cavity to the squeezed-state receiver (Backes et al., Nature 590, 238).

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



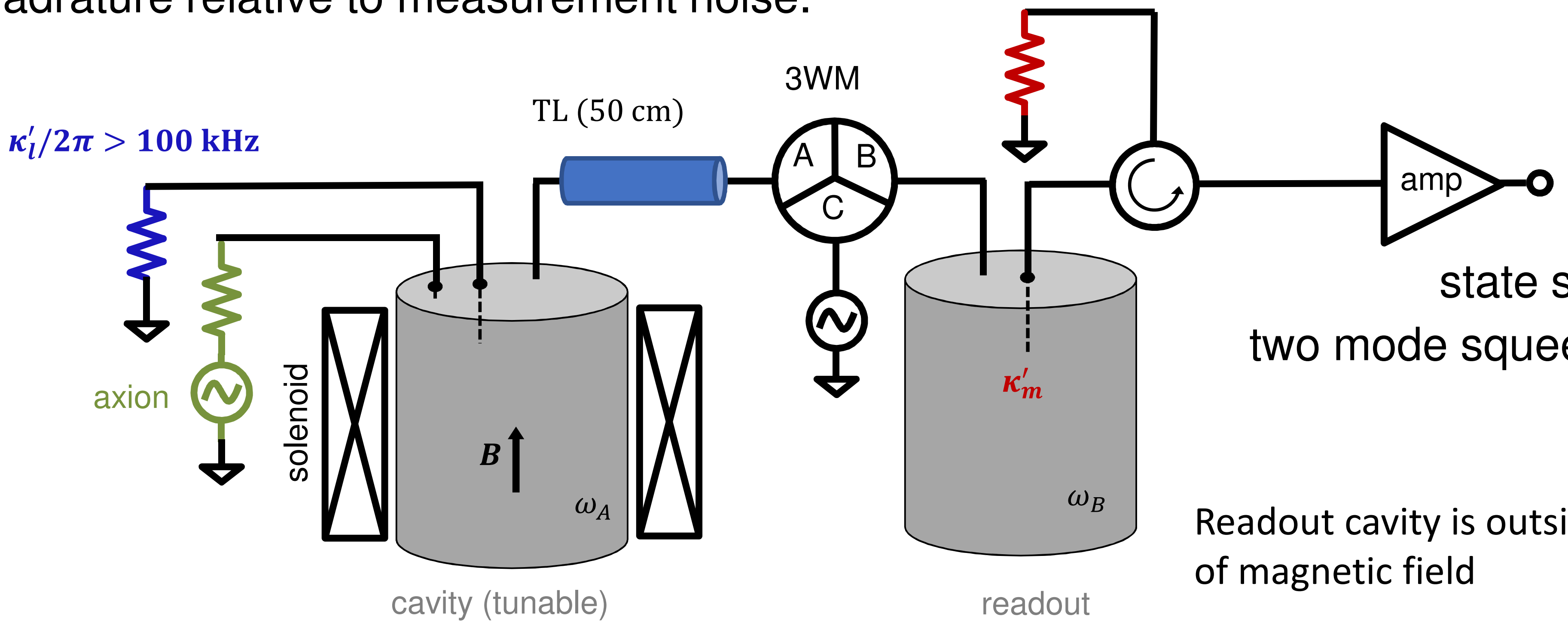
Noiseless amplification cannot be done in strong magnetic field

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): $\omega_B + \omega_A$

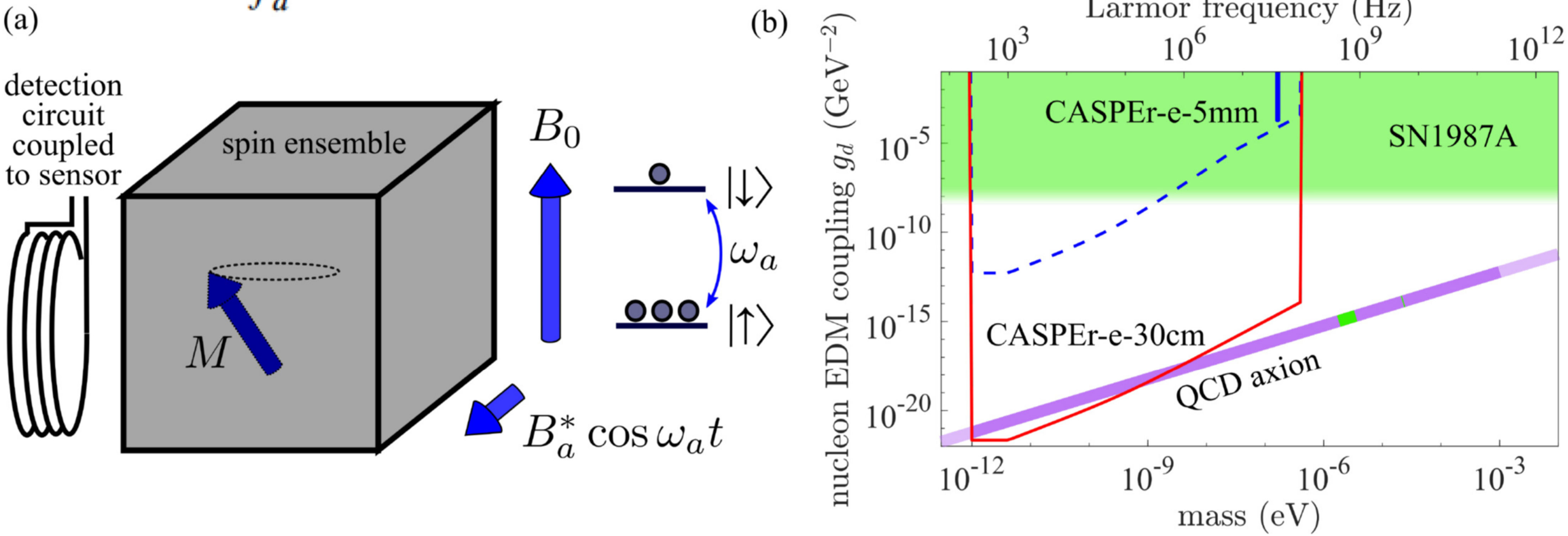
Readout cavity is outside of magnetic field

"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

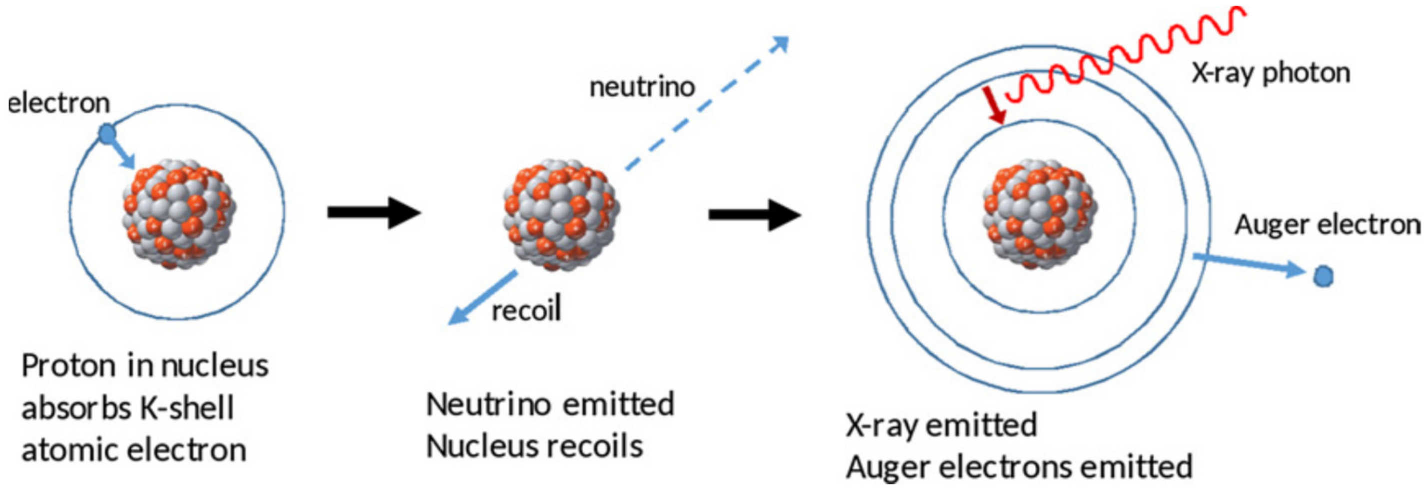
$$\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$



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.

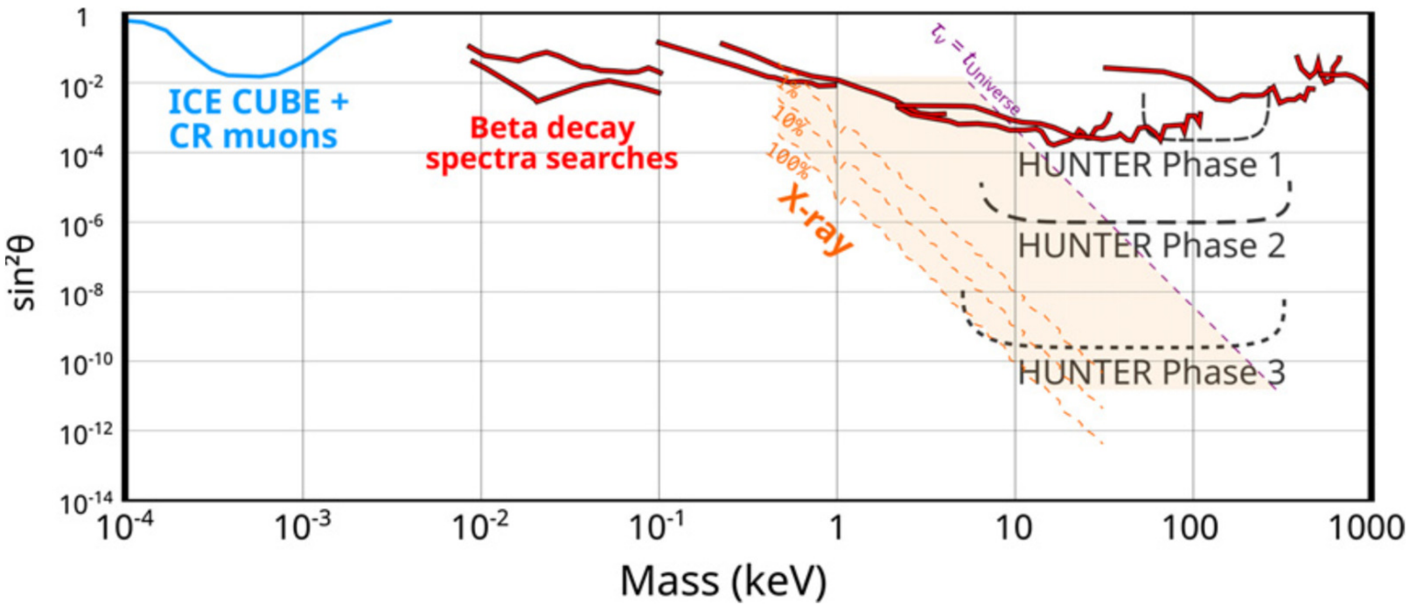
When this splitting is resonant with the axion-like dark matter Compton frequency ω_a, the ensemble magnetization M is tilted and undergoes precession that is detected by an inductively-coupled sensor.

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



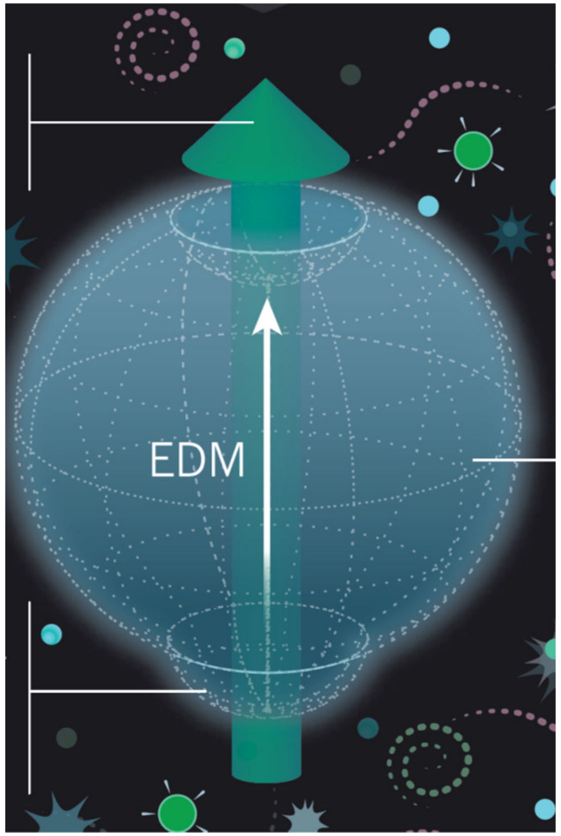
$$^{131}\mathrm{Cs} \rightarrow {}^{131}\mathrm{Xe}^{*} + \nu_e$$

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

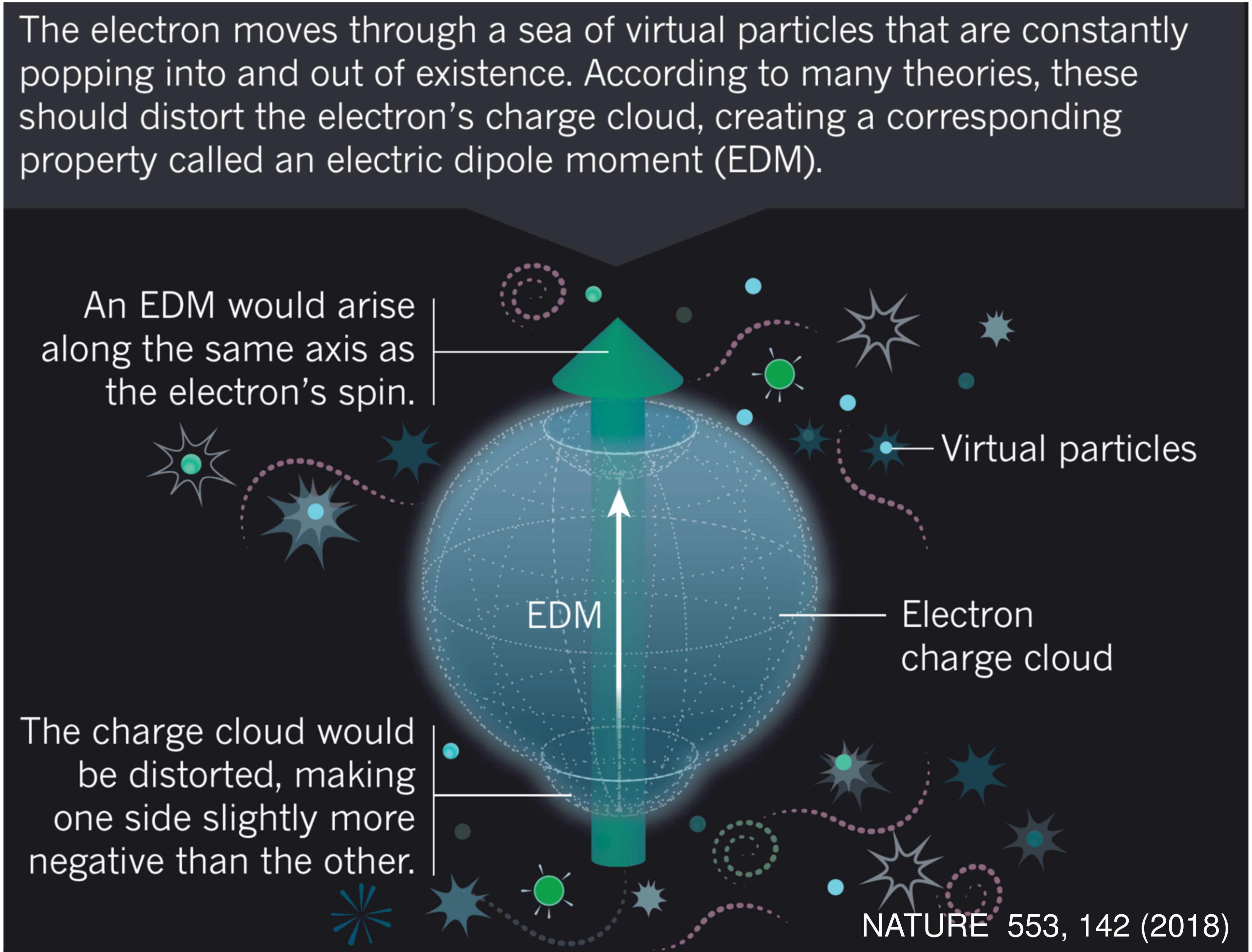


Limits on sterile neutrino coupling strength vs mass. Dashed lines (orange) show astrophysical limits permitting sterile neutrinos to be the galactic dark matter

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



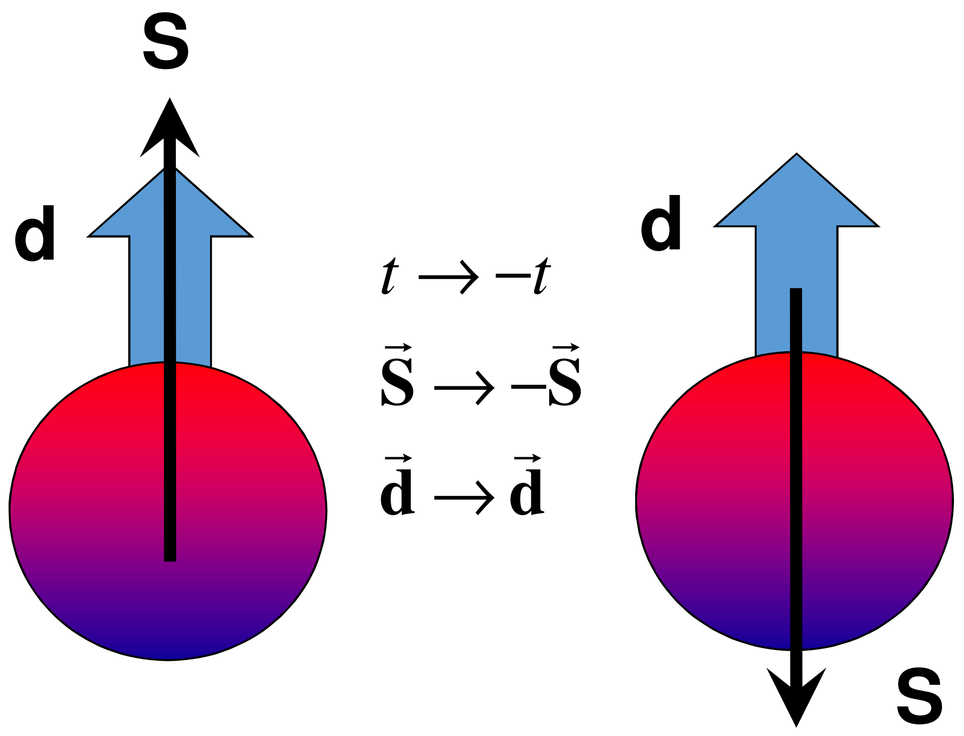
Searches for **permanent electric-dipole moments** that probe new TeV-scale physics


The electron moves through a sea of virtual particles that are constantly popping into and out of existence. According to many theories, these should distort the electron's charge cloud, creating a corresponding property called an electric dipole moment (EDM).
An EDM would arise along the same axis as the electron's spin.
Virtual particles
EDM
Electron charge cloud
The charge cloud would be distorted, making one side slightly more negative than the other.
NATURE 553, 142 (2018)

Permanent electric-dipole moment (EDM)

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

$t \rightarrow -t$



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

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

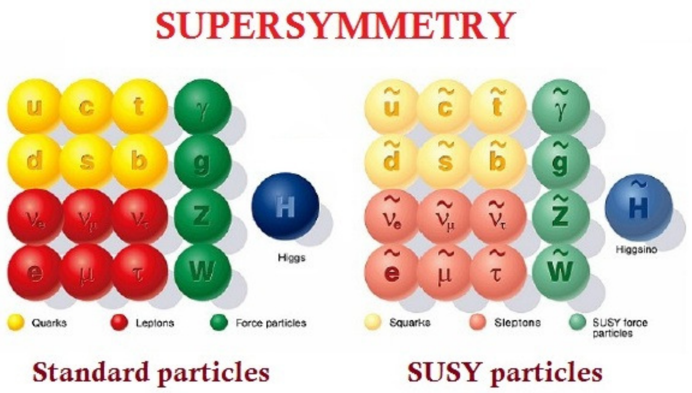
$$d = 0$$

without T-violation

Need new sources of T- (CP-) violation to explain matter-antimatter asymetry

Additional sources of CP-violation lead to much larger EDMs than standard model predicts.

Such EDMs should be observable with current experiments.

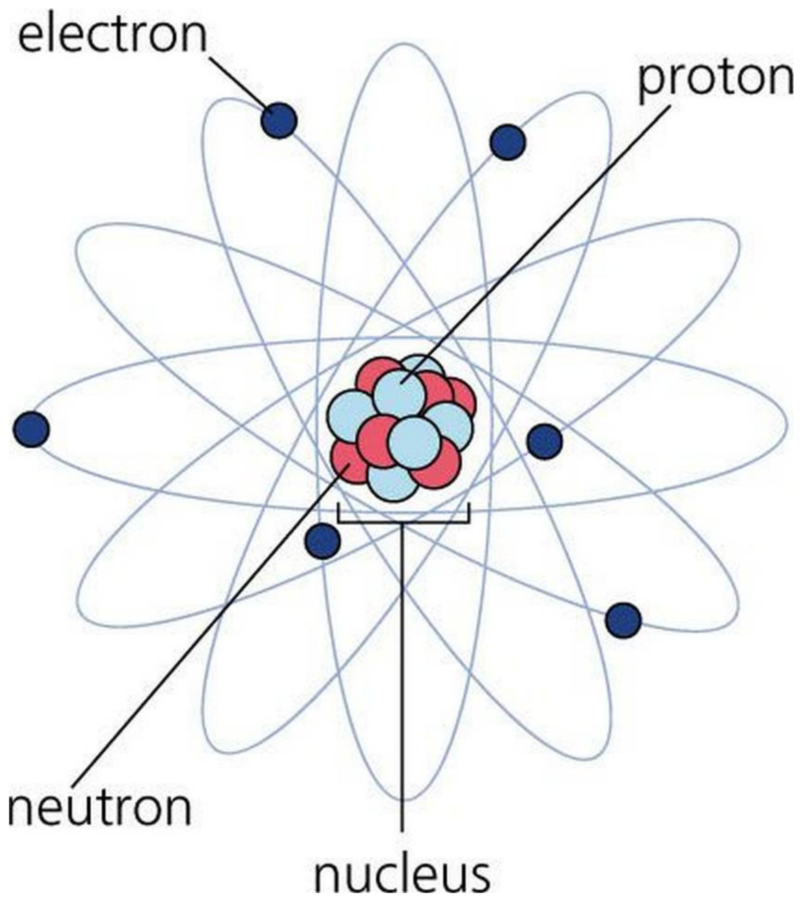


Sources of atomic and molecular EDMs

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

Electron EDM

P, T – violating electron-nucleon interaction



Neutron

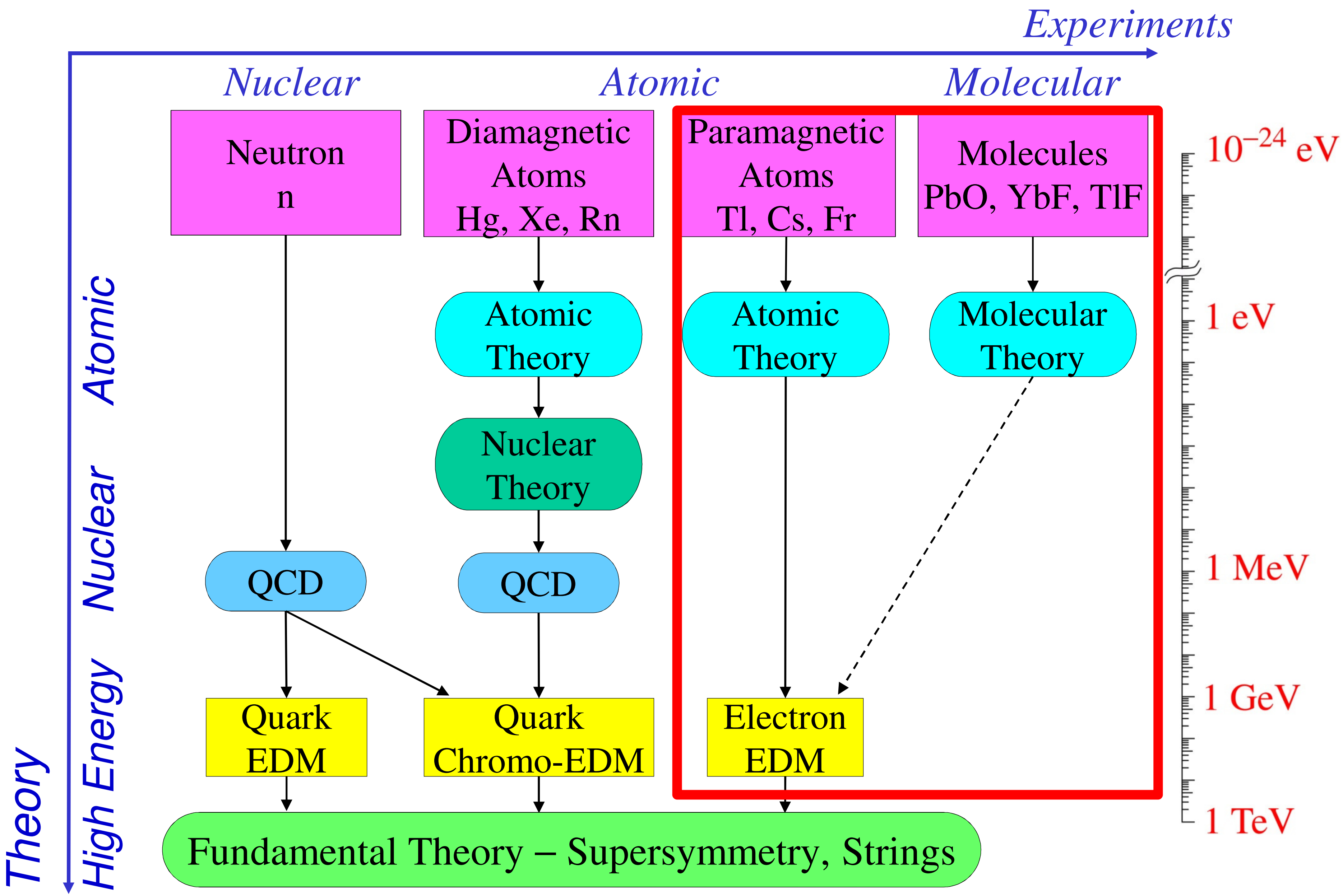
Diamagnetic atoms
Hg, Xe, **Ra, Rn**
Molecules
TlF

Nucleon EDM

P, T – violating nucleon- nucleon interaction

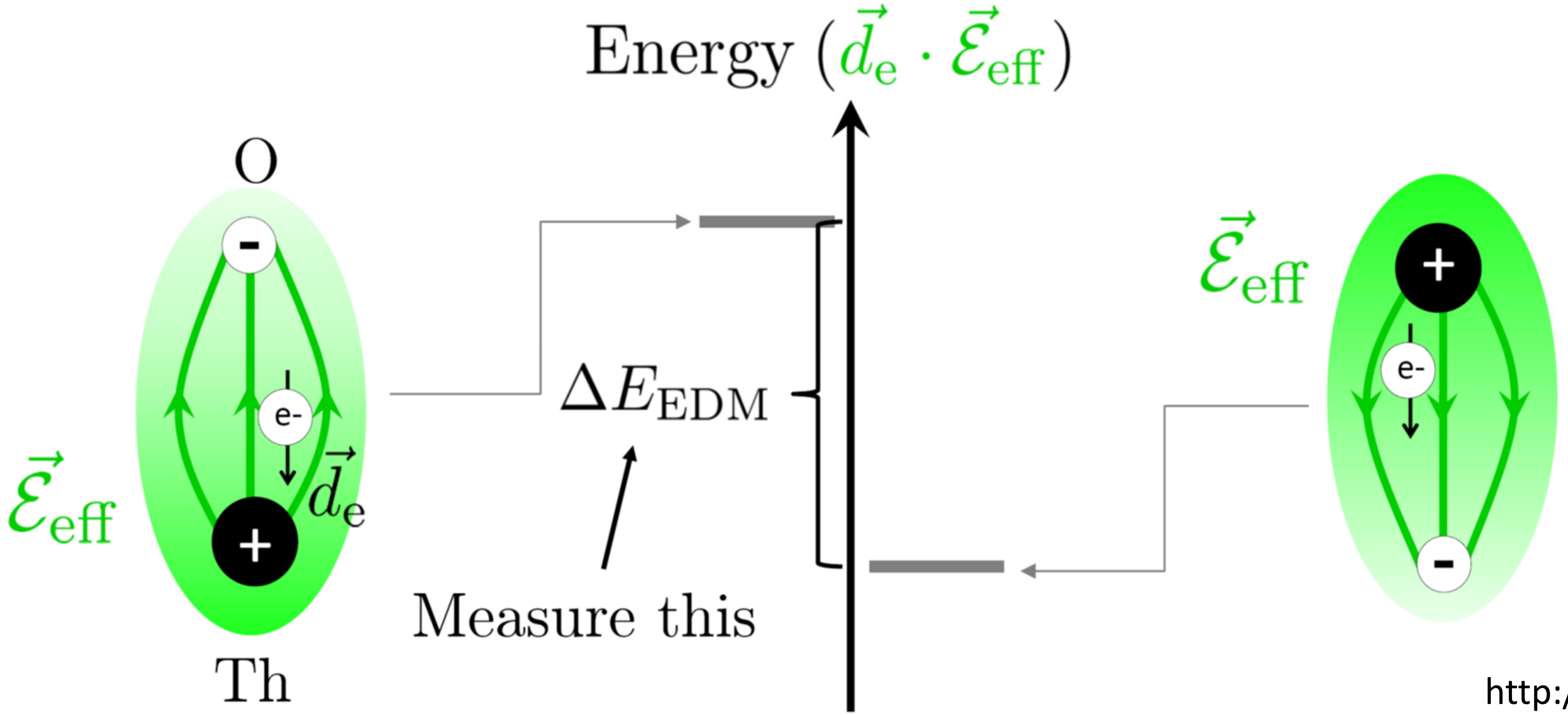
Need heavy atom or a molecule with a heavy atom for larger effect

Interpretation of EDM experiments



Mike Romalis, 2011 JLab talk (online)

Fundamental idea of electron EDM measurements



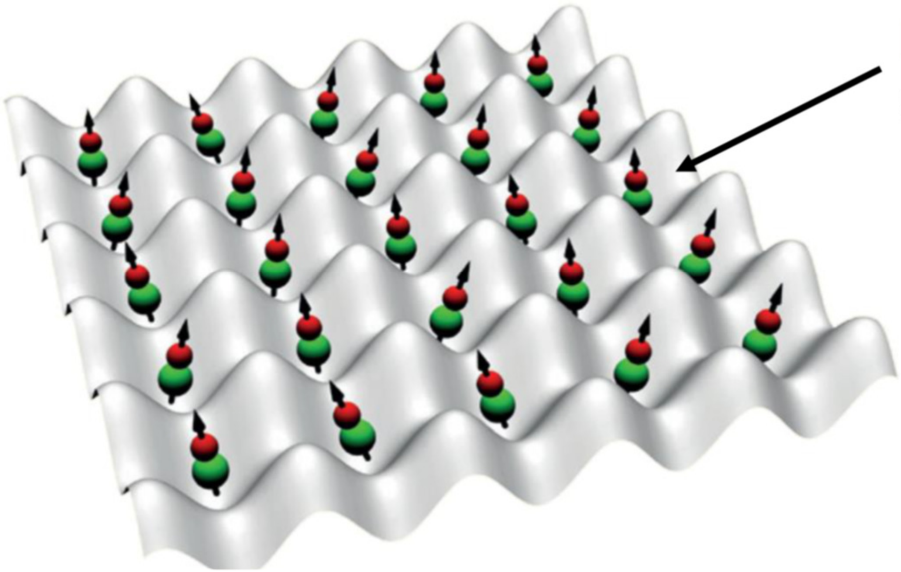
http://www.electronedm.org/

An electric dipole moment results in an energy shift in the presence of an electric field, such as the large E-fields present near heavy atomic nuclei.

Apply electric field, reverse, measure the energy splitting between electrons oppositely oriented relative to the effective molecular field in ThO (84 GV/cm): $\Delta E_{EDM}/2 = |\vec{d}_e \cdot \vec{\mathcal{E}}_{eff}|$

Such field is million times larger than any controlled field that can be created in a laboratory.

Electron EDM experiments: (1) laser-cooled molecules



Need to trap at ultracold temperatures

Laser slowed, cooled, and trapped in 3D: SrF, CaF, and YO
Laser-cooled, but not yet trapped: YbF, BaH, SrOH, CaOH, YbOH, and $CaOCH_3$

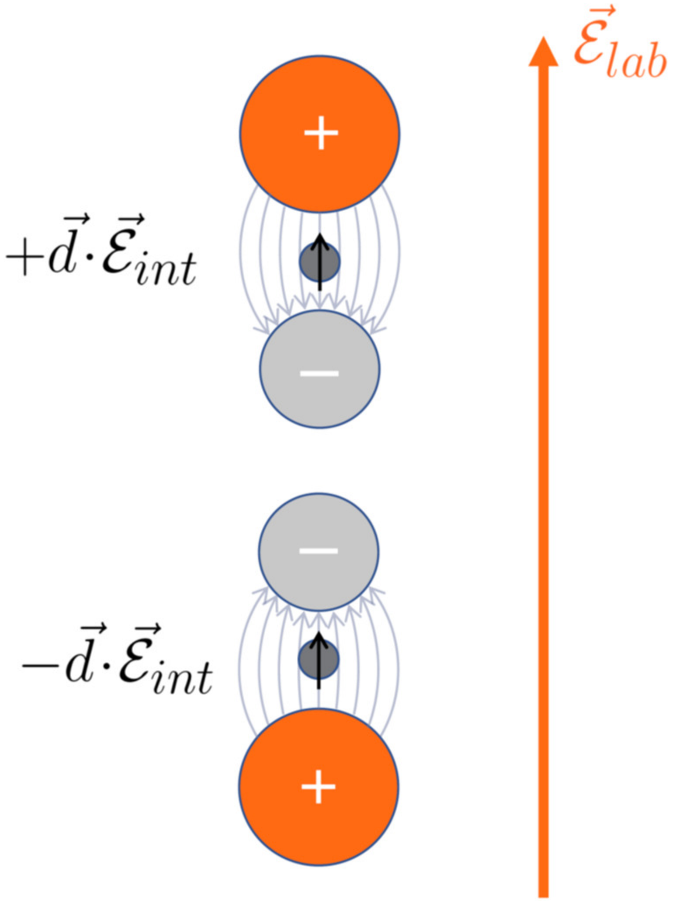
- 10^6 molecules
- 10 s coherence
- Large enhancement(s)
- Robust error rejection
- 1 week averaging

$M_{new\ phys}$ ~ 1,000 TeV

Even before implementing advanced quantum control, such as entanglement-based squeezing

Slide from: Nick Hutzler

Electron EDM experiments: (2) internal co-magnetometer



Need “internal co-magnetometer” states

No need to reverse electric field

ACME and JILA eEDM

ThO HfF$^+$

You can not laser cool any diatomic molecule with co-magnetometer states!

Numerous internal states give rise to many leakage channels out of a cycling transition.

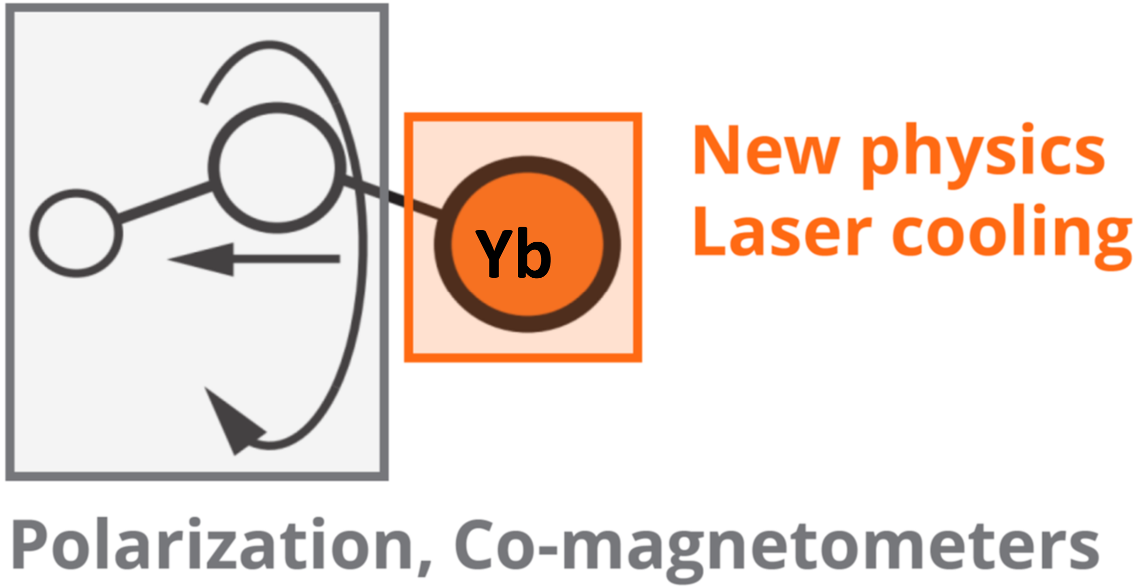
Note: there are other cooling methods besides laser cooling (sympathetic, evaporative, or optoelectrical) and trapped molecular ions enable very sensitive measurements without the need for laser cooling.

Picture from: Nick Hutzler

eEDM experiments with polyatomic laser-cooled

Caltech
Harvard

YbOH



Proposal: Ivan Kozyryev and N. R. Hutzler, Phys. Rev. Lett. **119**, 133002 (2017)
Review: N. R. Hutzler, *Quantum Sci. Technol.* **5** 044011 (2020)

5 years: An electron EDM result with trapped ultracold YbOH, initial goal 10^{-31} e cm

8 years: Improvements in coherence time and number trapped molecules: 10^{-32} e cm

12 years: Very large numbers of trapped molecules or many operating in parallel, 10^{-33} e cm

Further improvement with squeezing?

Picture & timeline from: Nick Hutzler

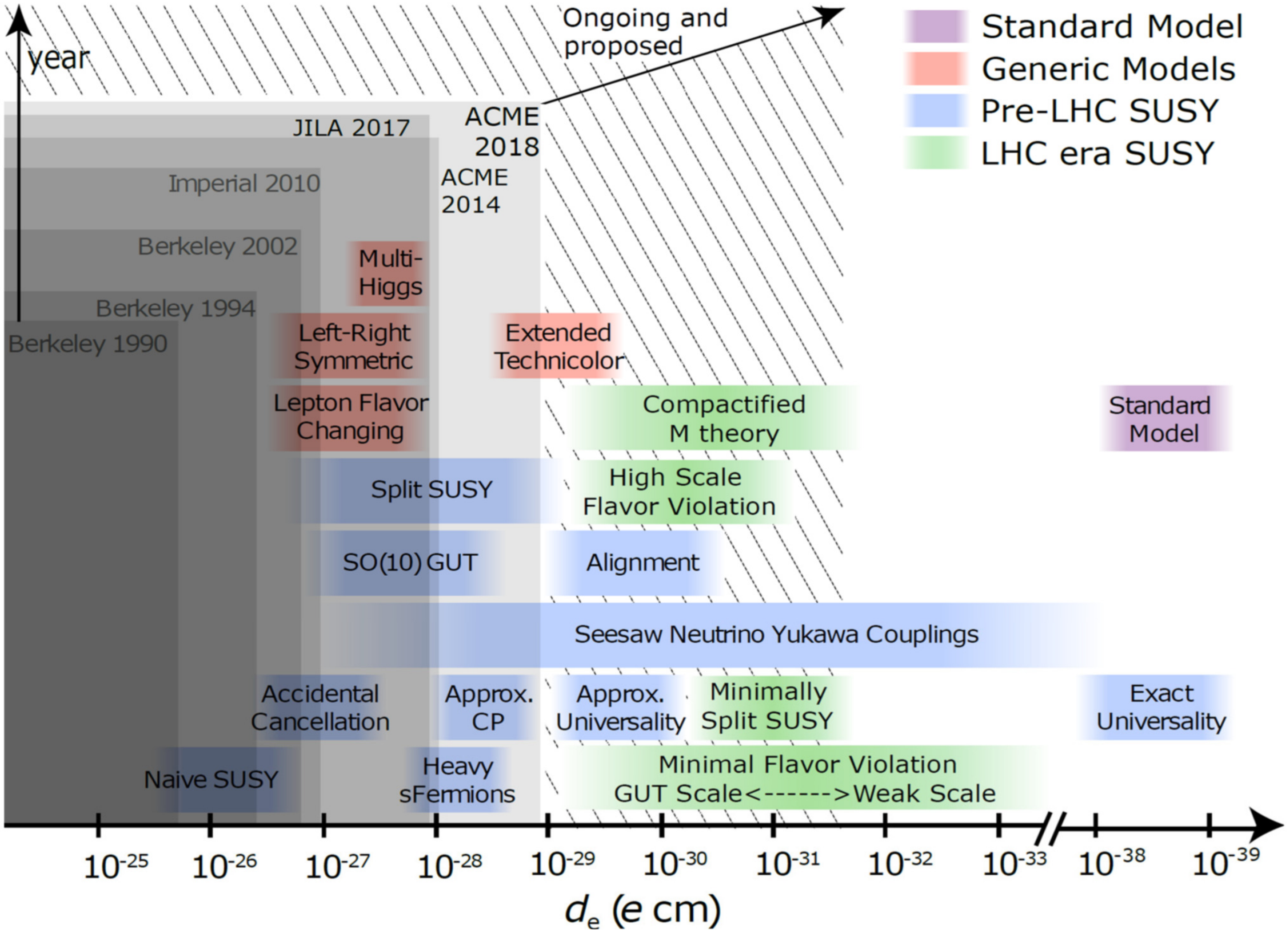
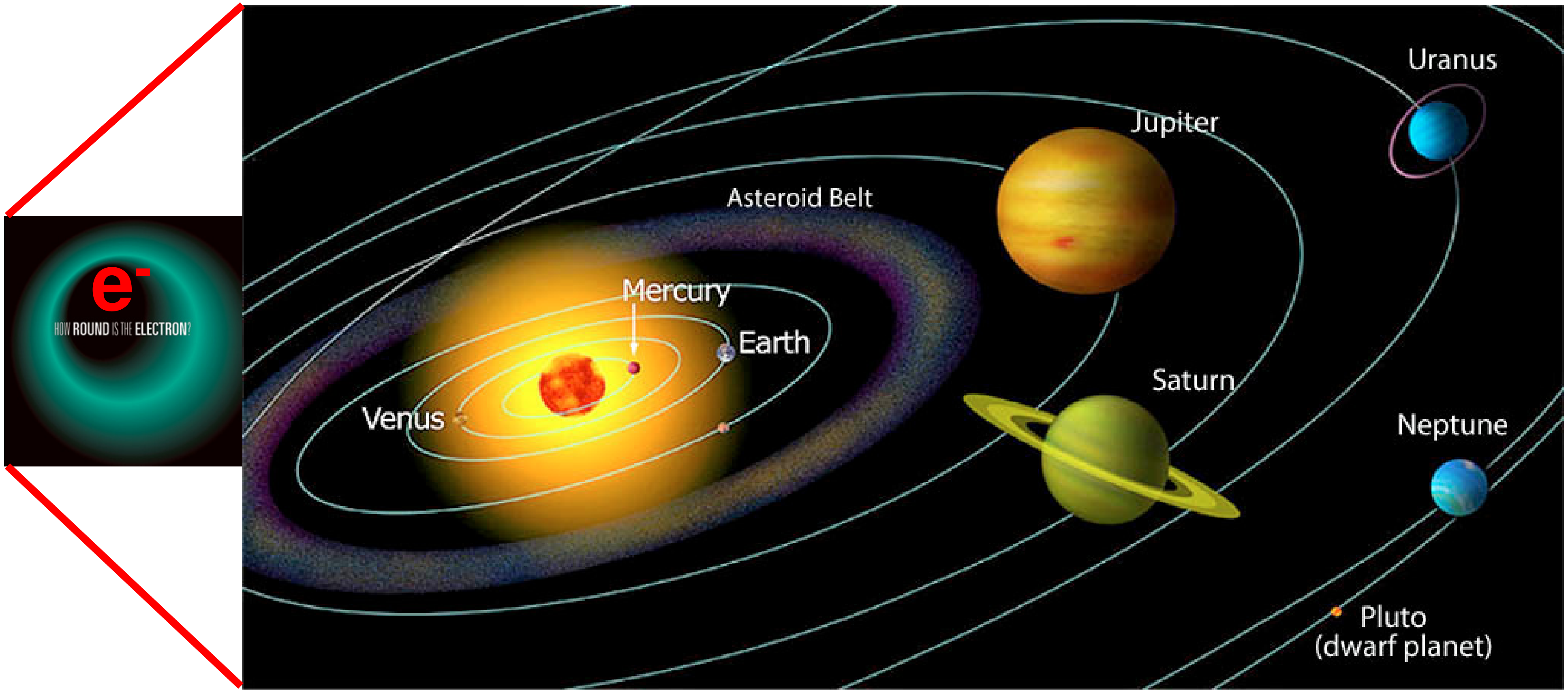


Figure is from 2020 USA AMO Decadal survey (Credit: Dave DeMille)

https://www.nationalacademies.org/our-work/decadal-assessment-and-outlook-report-on-atomic-molecular-and-optical-science

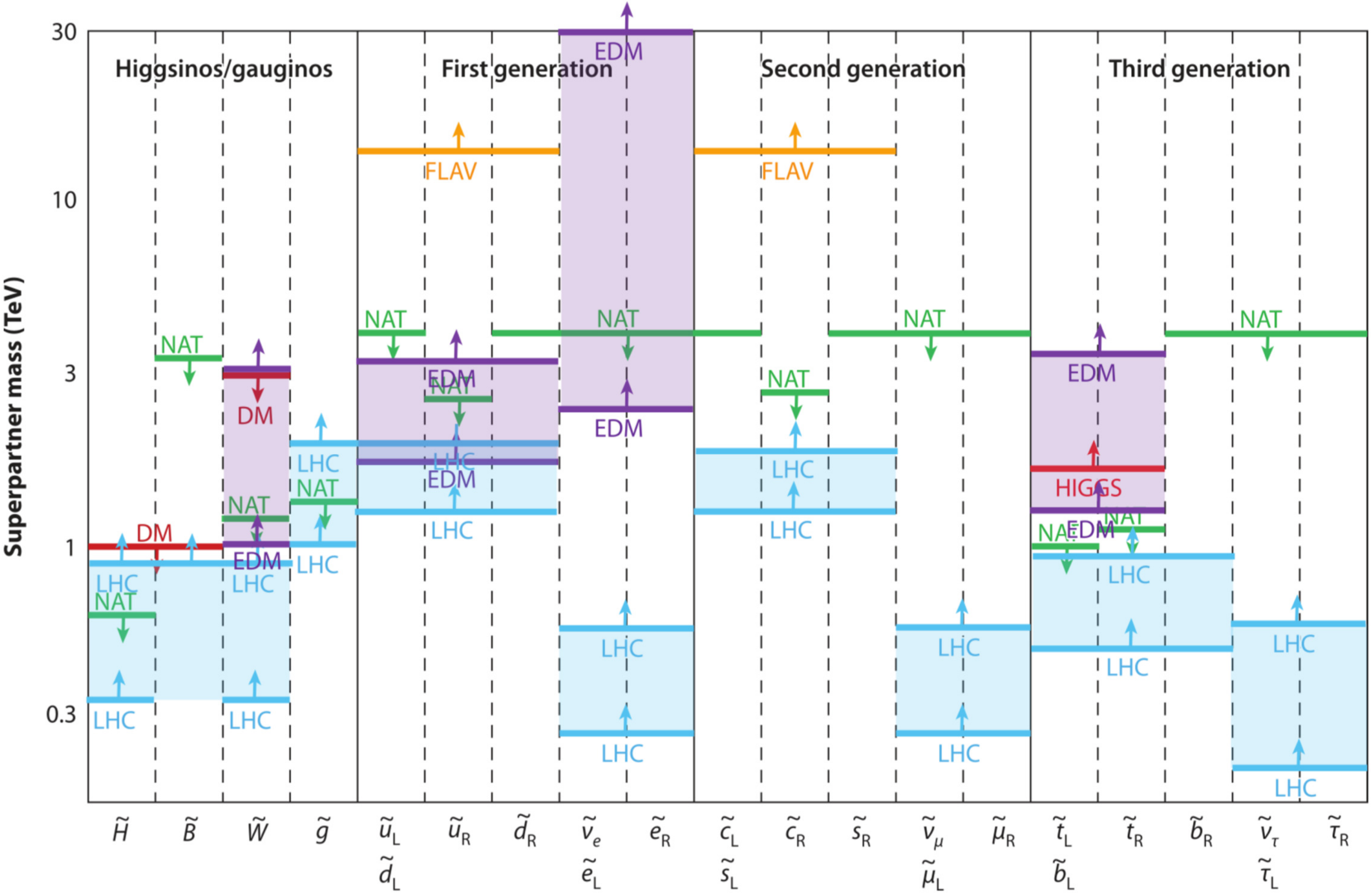
Electron EDM

Blow up the electron to the size of the Solar System



then it is spherical to within the *<u>width of a human hair.</u>*

Ed Hinds, http://www.scientificamerican.com



Slide from: Nick Hutzler

Adapted from J. Feng, Ann. Rev. Nuc. Part. Sci. 63, 351 (2019) with Dave DeMille

The BAD NEWS: Shiff theorem (1963)

Very simplified idea to detect atomic EDM: place atom in external electric filed and look for a linear Stark shift. **Immediate problem: atomic effect seem to be zero even if nucleon/electrons possesses EDM**.

Neither the atom nor any of its constituents is accelerated in the external electric field E, and in the nonrelativistic limit where atomic forces are electrostatic the average E field at the nucleus or at any electron must be zero.

The electronic and nuclear charges rearrange themselves to cancel the external E field.

The GOOD NEWS: Exceptions

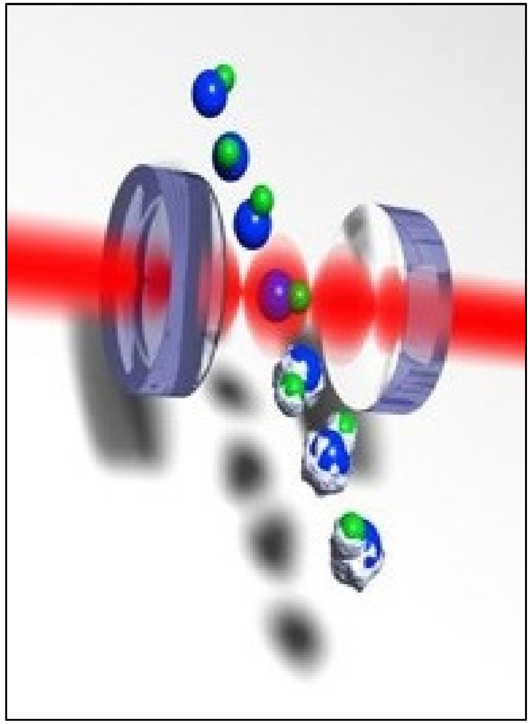
The screening is incomplete if one takes into account:

1) **Nucleus finite size** (if the nucleon electric dipole moment distribution is not the same as the nuclear charge distribution.)
2) **Relativistic effects**
3) **Magnetic effects**

Hadronic T-violation searches with molecules

CP-violation in the nucleus: manifest as a nuclear Schiff moment (NSM) or nuclear magnetic quadrupole moment (MQM). Arises from nucleon EDMs, new CP-violating nuclear forces, strong force CP-violation (θ).

CeNTREX: see arXiv:2010.01451



TlF (proton EDM)

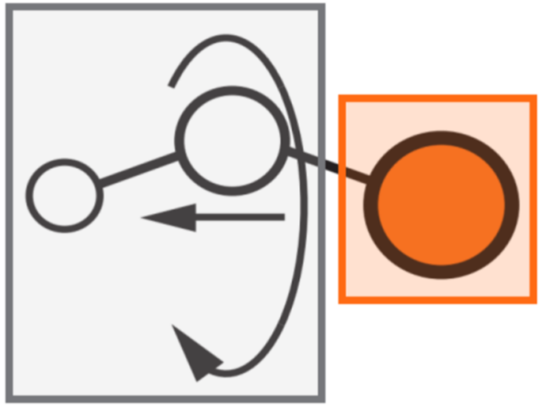
The observable signature of a Schiff moment will be a shift in the NMR frequency of ^{205}Tl nuclei when the molecules are polarized by a strong electric field.

First generation: a cryogenic molecular beam of TlF

Second generation: laser cool and trap the TlF molecules for increased sensitivity.

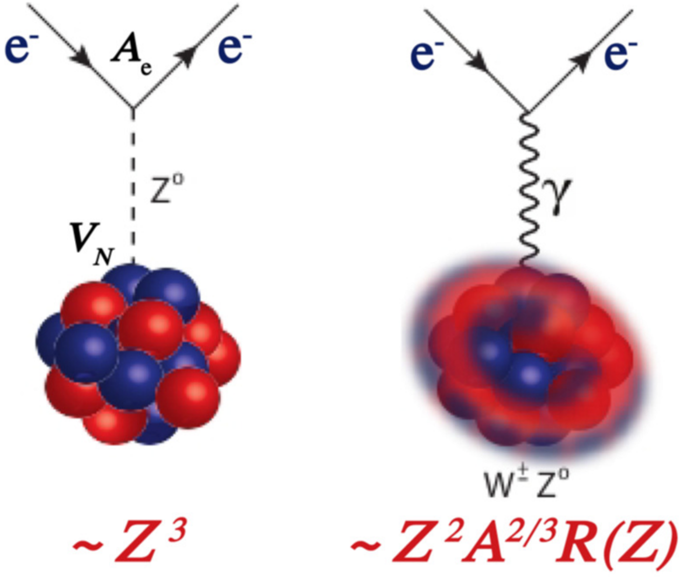
YbOH nuclear MQM

Theory: J. Chem. Phys. 152, 084303 (2020)

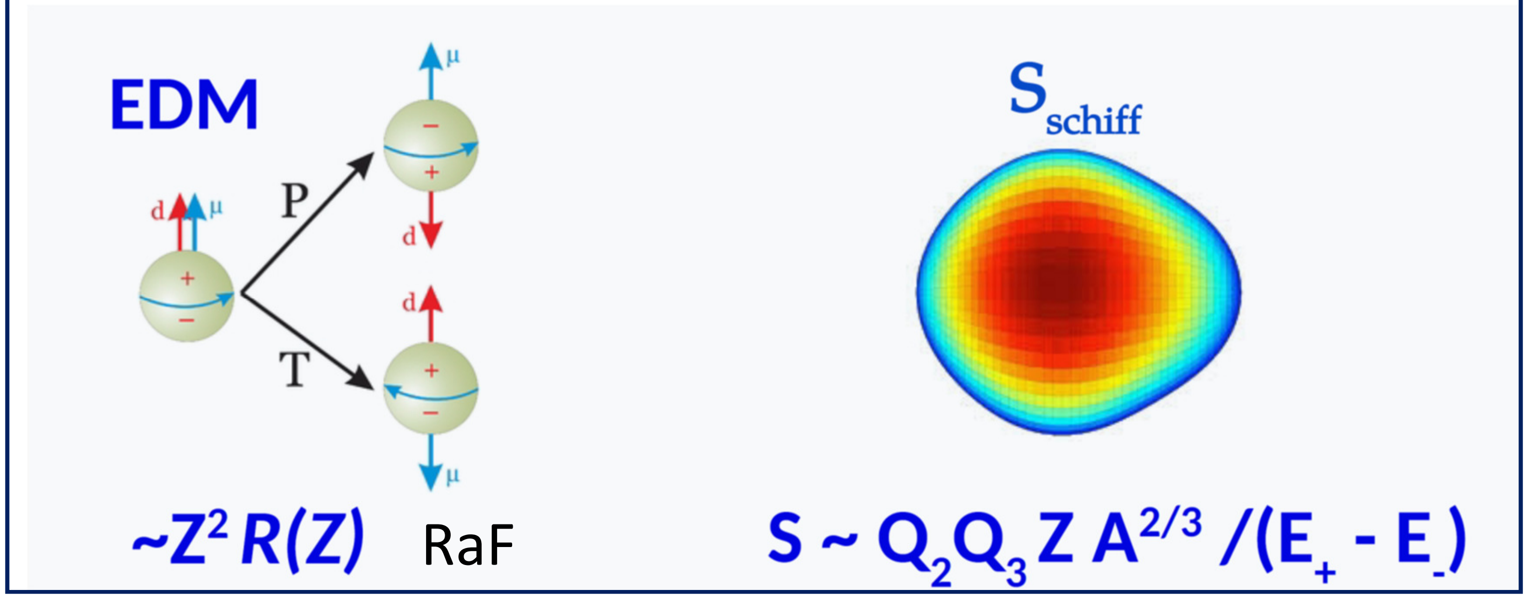


Fundamental symmetries: radioactive atoms and molecules

Parity violation



T-violation



ZOMBIES (Yale, BaF)
Yb (Mainz)

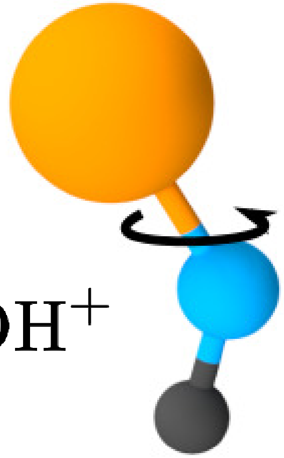
Fr (TRIUMF, Tokyo)
Ra^+ (UCSB)

Ra and Ra-based molecules have a further enhancement due to an octupole deformation of the ^{225}Ra nucleus: an intrinsic Schiff moment 1000 times larger than in spherical nuclei such as Hg.

Collinear resonance ionization spectroscopy of RaF molecules
[Garcia Ruiz, Berger et al. CERN-INTC-2018-017 (2018)]

Picture credits: Ronald Fernando Garcia Ruiz

T-violation with radioactive molecular ions

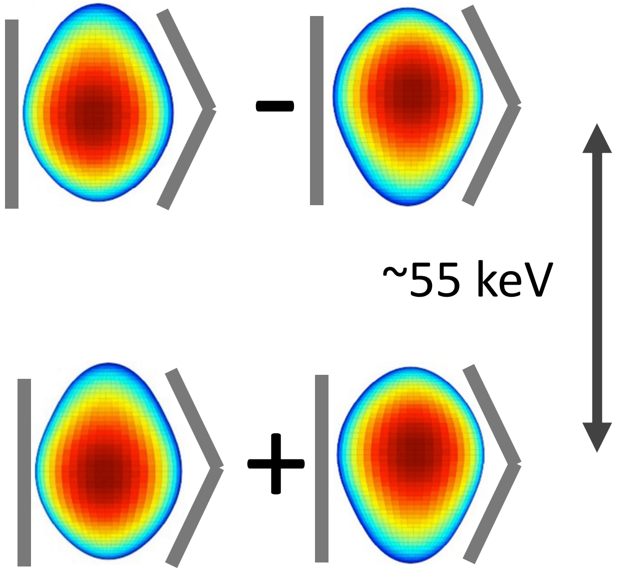


$RaOH^{+}$

Theory: nuclear Shiff moments sensitivity investigated for RaOH, RaOH+, $ThOH^{+}$, and $RaOCH_3^{+}$

$RaOH^{+}$ and $RaOCH_3^{+}$ having been recently created and cooled in an ion trap [UCSB, Fan et al., PRL 126, 023002 (2021)].

1st nuclear excited state



nuclear ground state

Octupole deformation ^{225}Ra

T- violating forces mix the states

Enhancement: ~1000x

from Andrew Jayich

Other candidate: ^{229}Pa, the splitting is 50(60) eV - we don't know if the state exists.

^{229}Pa may be 100,000 times more sensitive than ^{199}Hg.

Currently no significant source of ^{229}Pa (1.5 day half-life). Plans to harvest at the Facility for Rare Isotope Beams at Michigan State University.

J. T. Singh, Hyperfine Int. 240, 29 (2019)

Charge

$$q \to -q$$

Parity

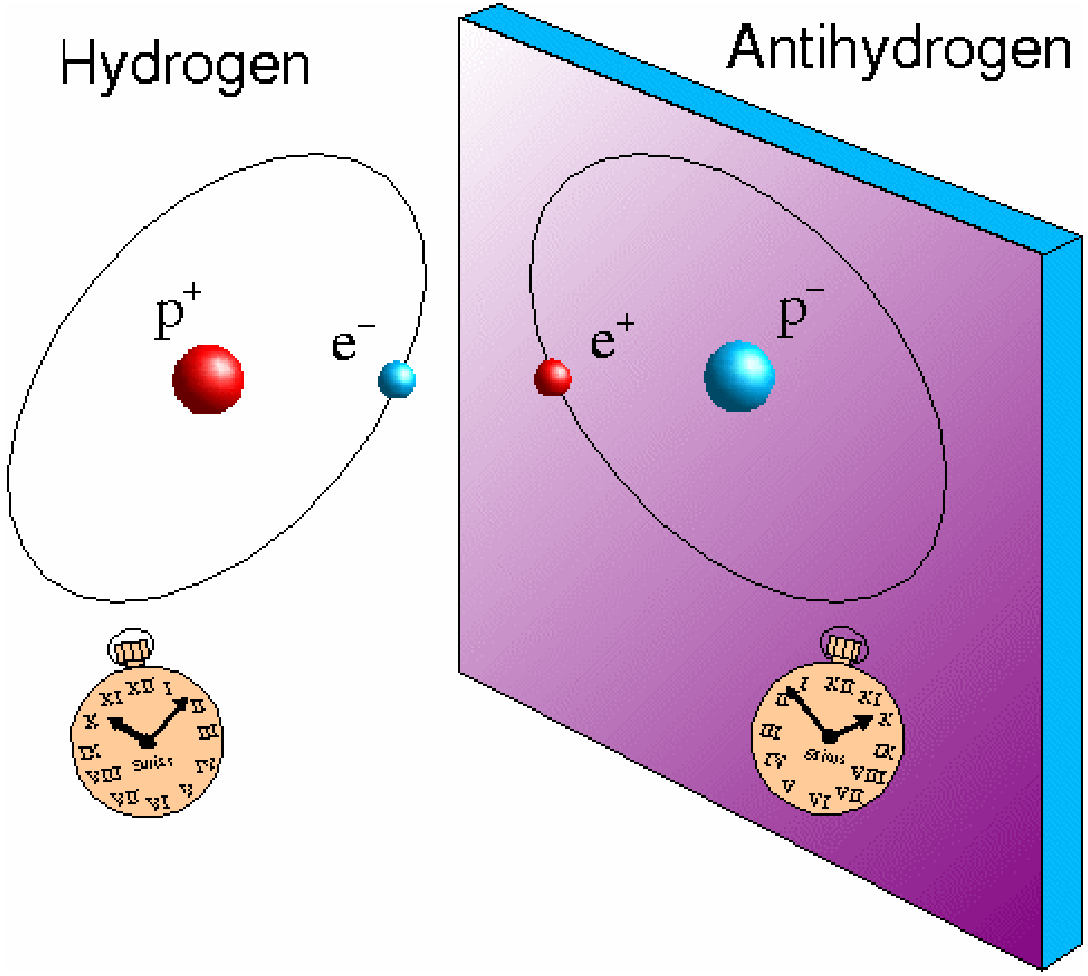
$$\vec{r} \to -\vec{r}$$

Time

$$t \to -t$$

Symmetries

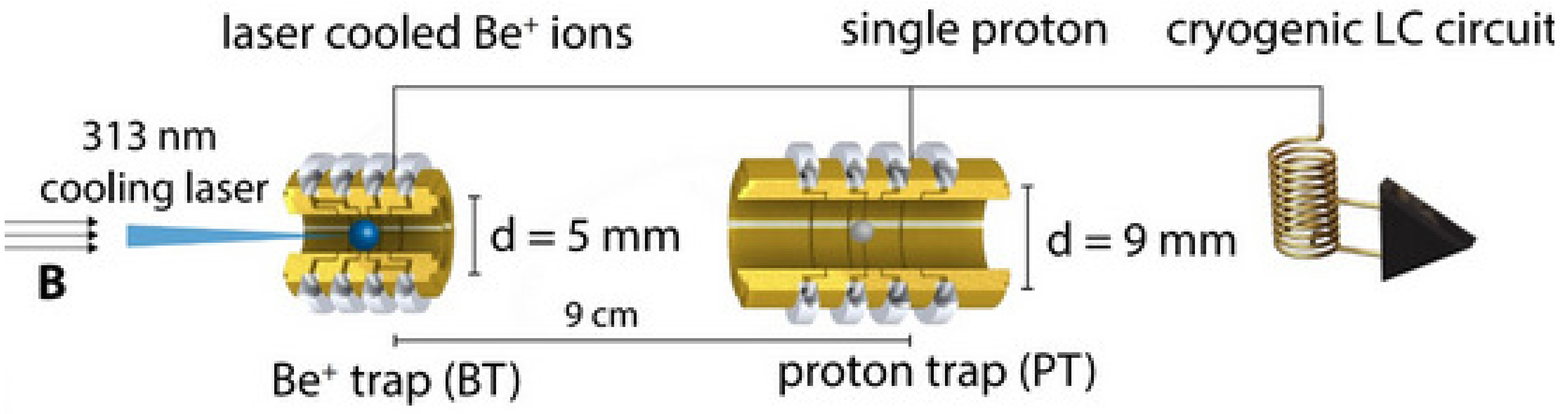
If **CPT** symmetry holds, then
T-violation → CP-violation



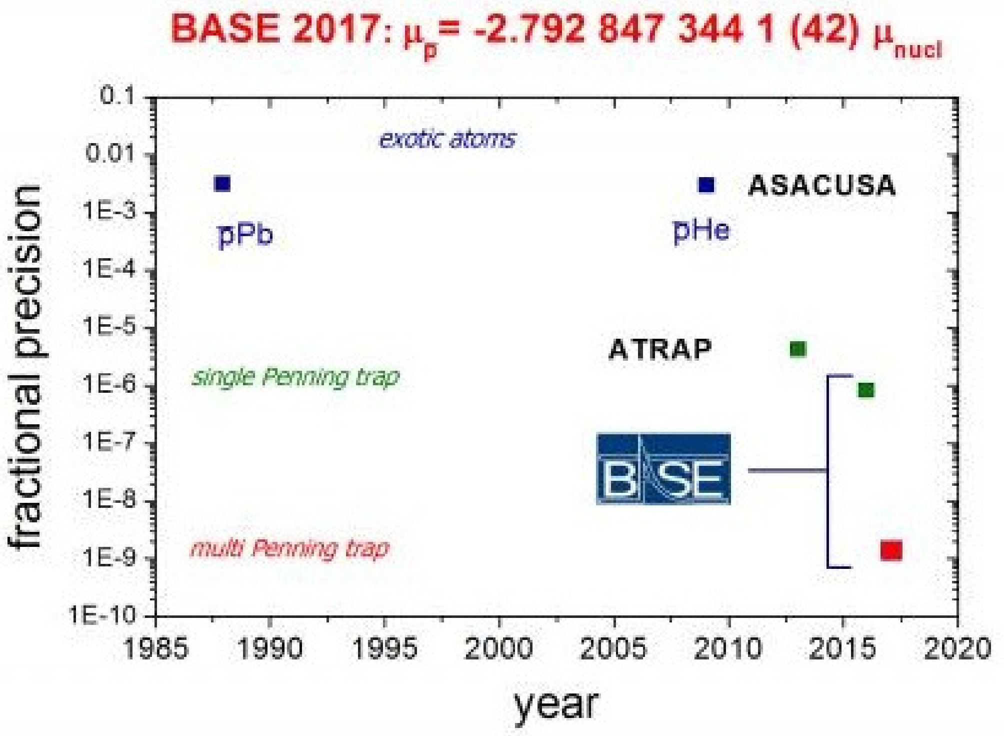
[BASE and ALPHA in the Top 10 of Physics Breakthroughs 2021]

www.mpq.mpg.de

BASE experiment: first demonstration of sympathetic cooling



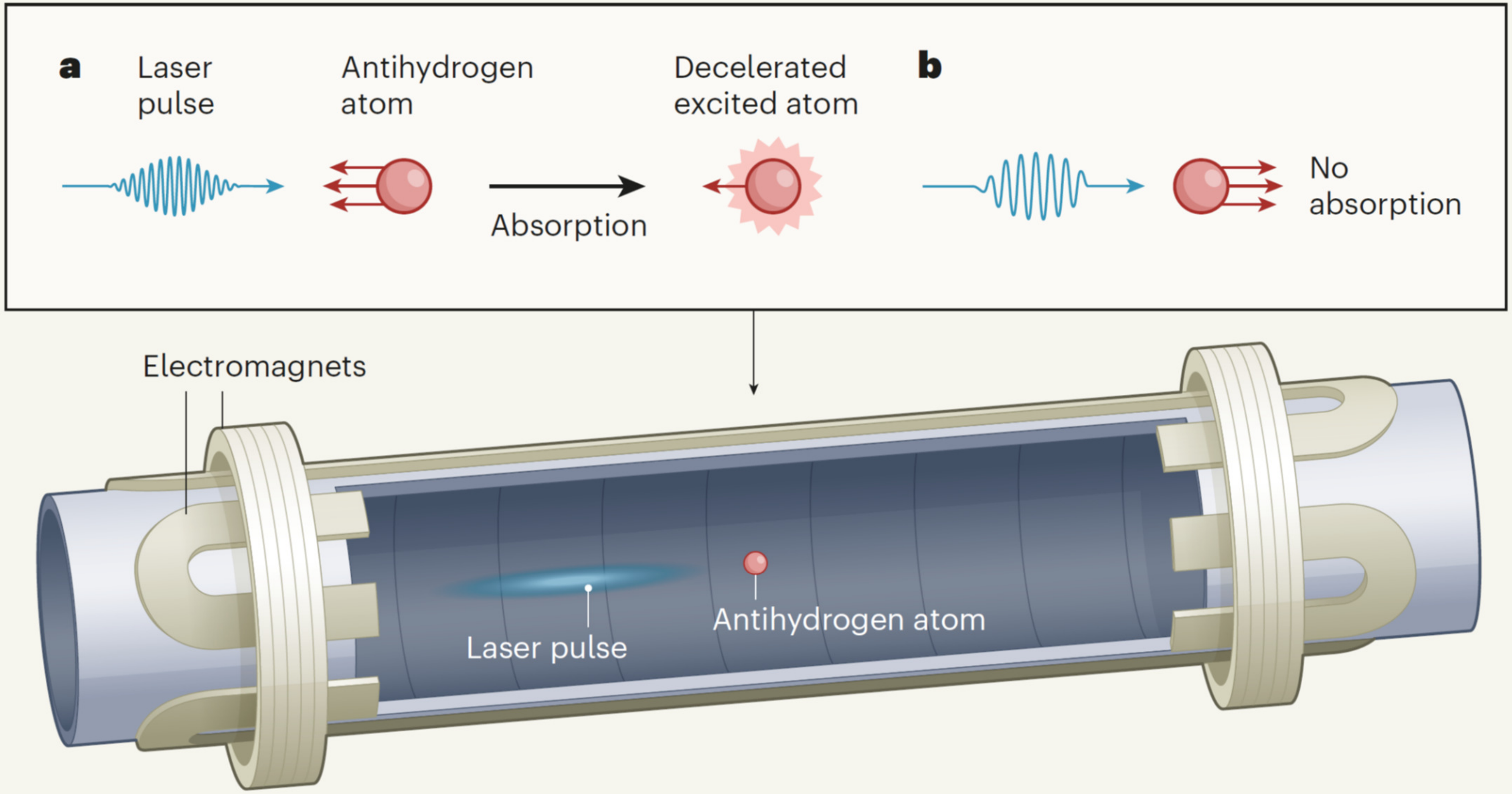
2021: Nature 596, 514 (2021)
The first sympathetic cooling of a single trapped proton, using laser-cooled beryllium ions stored in a spatially separated trap.



2022: Nature 601, 53 (2022)
The most precise comparison between a fundamental property of protons and antiprotons. The charge-to-mass ratios of protons and antiprotons are identical to within a record experimental uncertainty of 16 parts per trillion. The result for the ratio of antiproton to proton charge-to-mass ratios R=1.000 000 000 003 (16) corresponds to energy resolution of 2×10^{-27} GeV.

Antimatter cooled by laser light

Nature 592, 35 (2021)

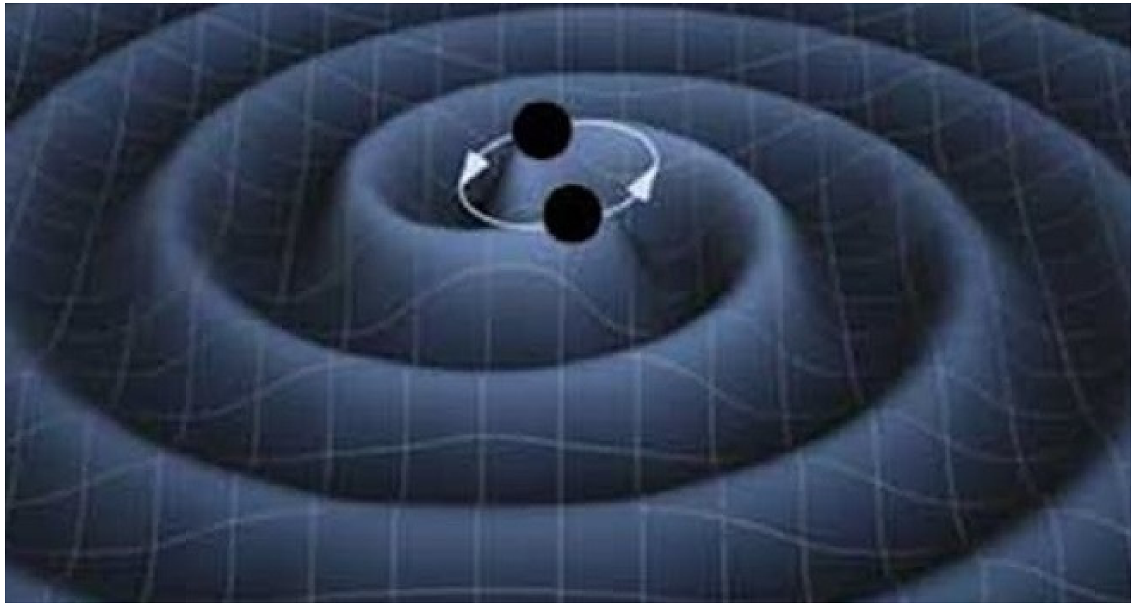


Nature **592**, 27 (2021)

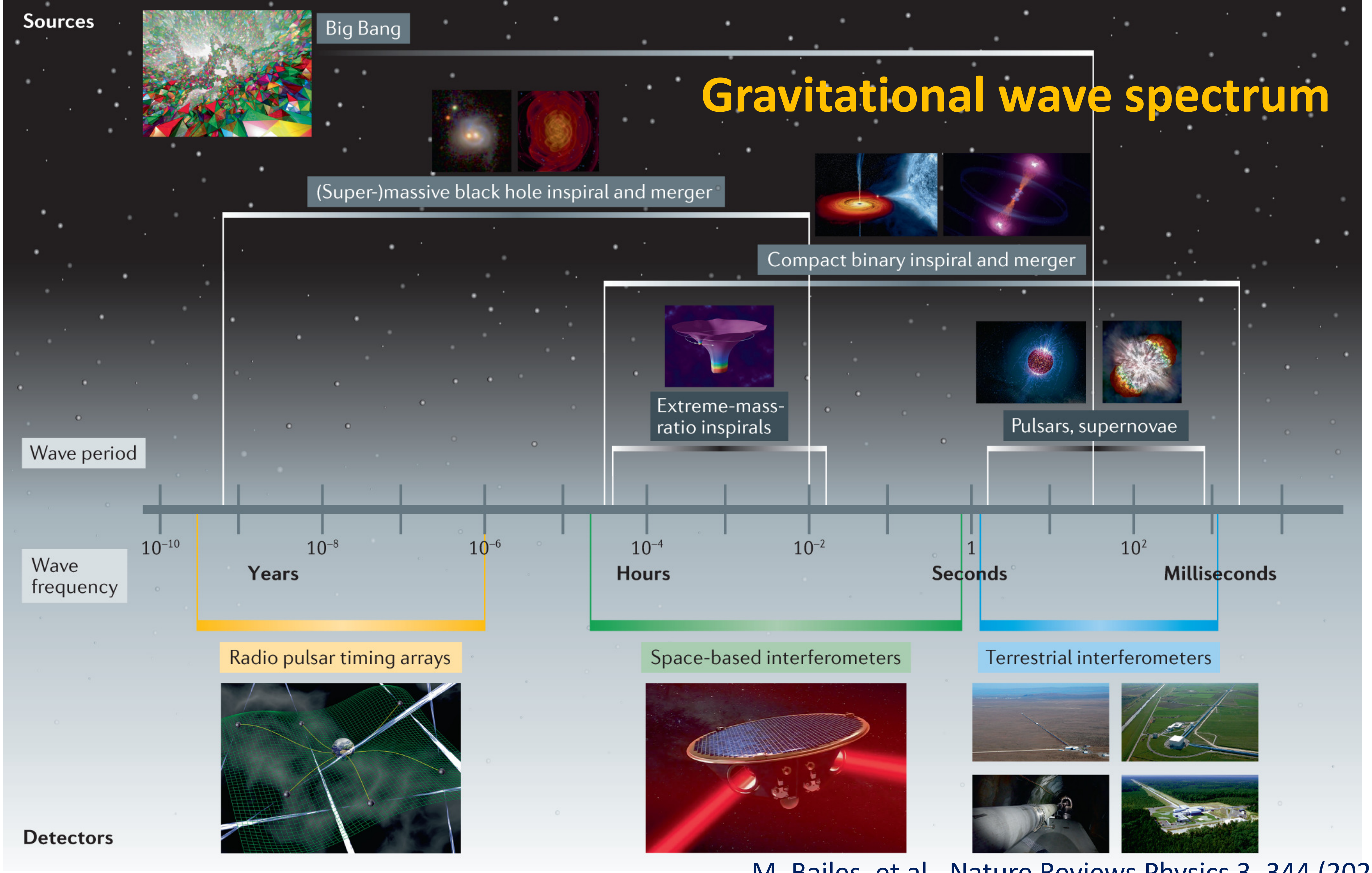
The 1S–2P transition was excited in magnetically trapped antihydrogen. The transition frequency agrees with the prediction for hydrogen to a precision of 5×10^{-8}.

Nature 561, 211 (2018)

New ideas in gravitational wave detection with atomic quantum sensors

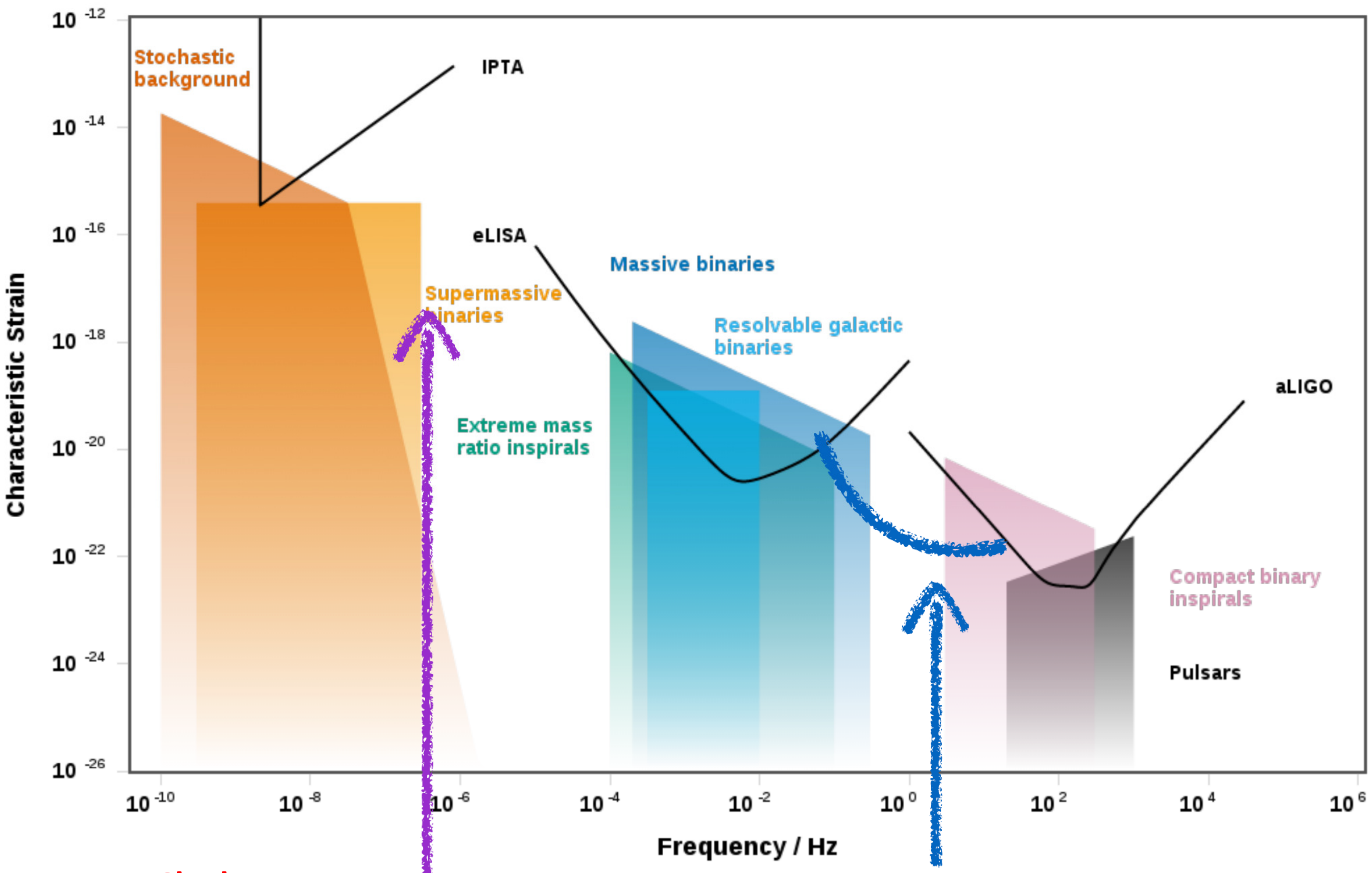


Gravitational wave spectrum



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/



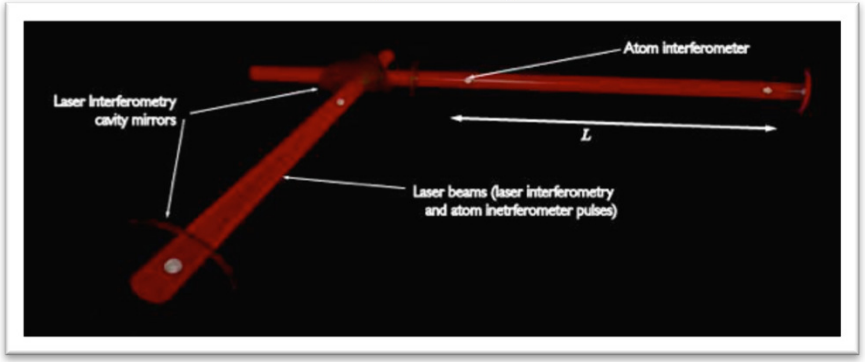
Clocks on asteroids open band

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

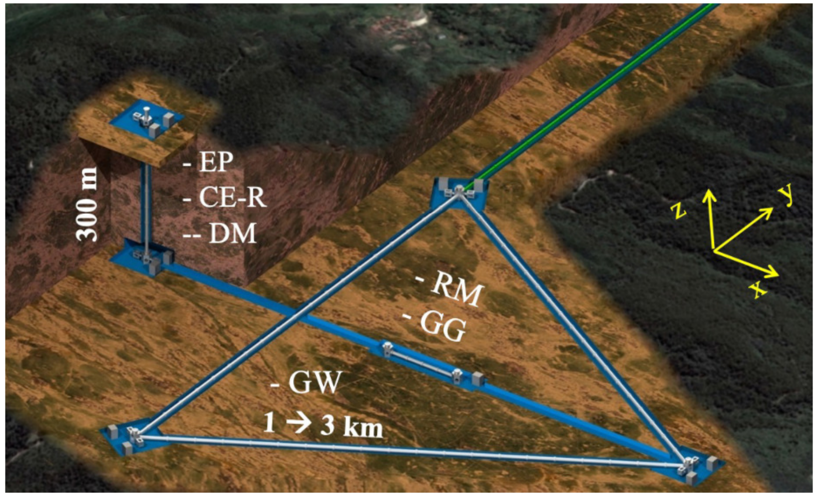
atoms (MAGIS, clocks, MIGA, AION…)

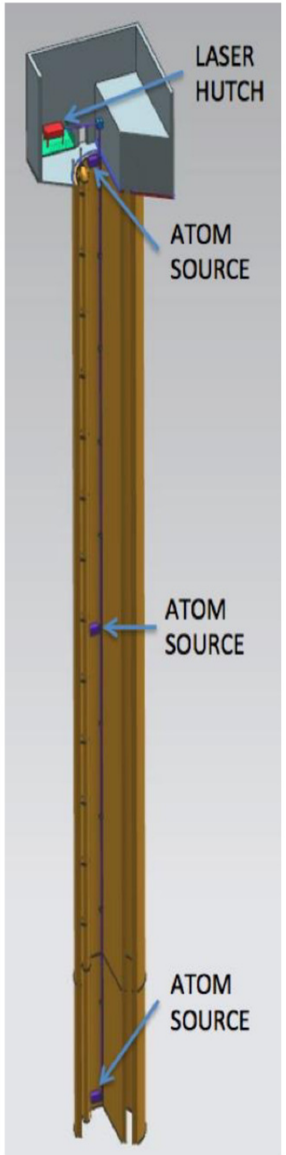
Atom interferometers: from 10 meters to 100 meters to 1km to space

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

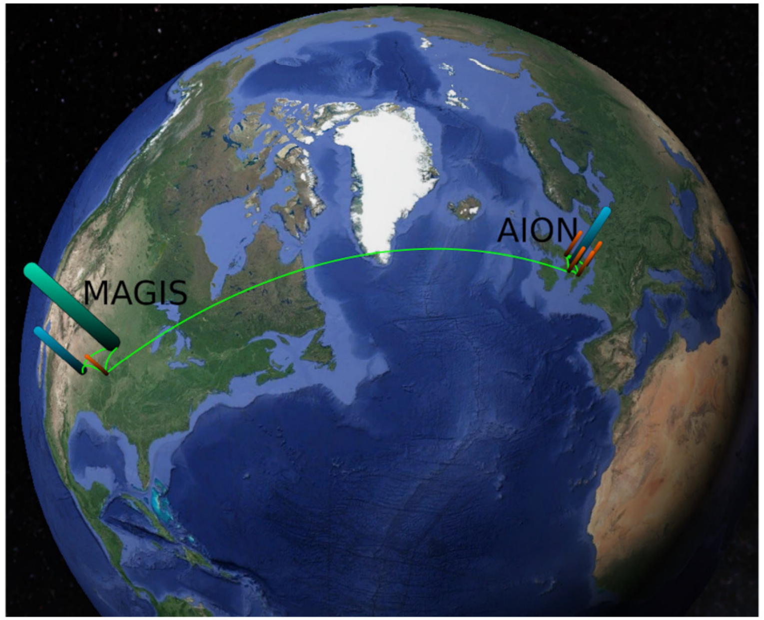


ZIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m)
(China)





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/

Searching for new physics with quantum sensors

Many new developments coming in the next 10 years!

Need more collaborations of particle physics and quantum science fields!

Many problems to solve and new ideas to look for!

2023

Solving physics problems of 1923 gave us quantum mechanics – a foundation of modern technology.

What new wonders discovery of new physics will bring?

2123