Quantum sensors for HEP science – Interferometers, Mechanics, Traps, and Clocks

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

Snowmass 2021: Quantum Sensors for HEP Science - Interferometers, Mechanics, Traps, and Clocks

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A. Geraci, Northwestern University
Center for Fundamental Physics (CFP)

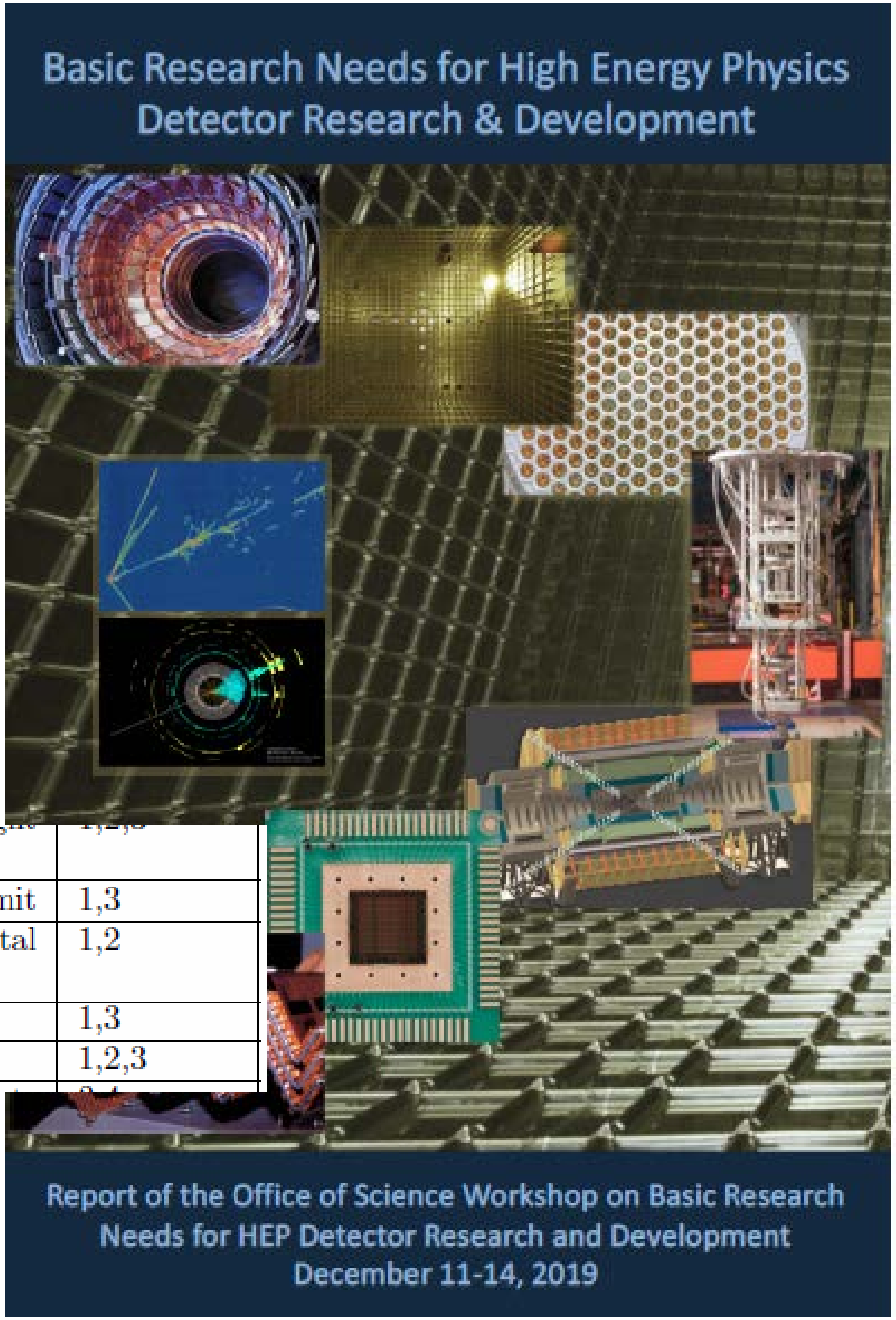
RF3: Fundamental Physics in Small Experiments
Snowmass Rare Processes and Precision Frontier Meeting
Cincinnati, OH, May 16-19, 2022

Quantum sensors for HEP science

BRN: Report Date: Aug 2020

Priority research directions include new quantum technologies:

	collection	
Quantum	PRD 12: Advance quantum devices to meet and surpass the Standard Quantum Limit	1,3
	PRD 13: Enable the use of quantum ensembles and sensor networks for fundamental physics	1,2
	PRD 14: Advance the state of the art in low-threshhold quantum calorimeters	1,3
	PRD 15: Advance enabling technologies for quantum sensing	1,2,3



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).

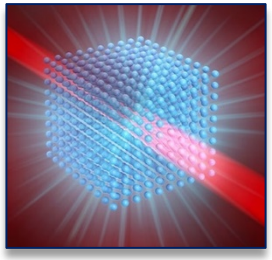
“We take a broad view where any technology or device that is naturally described by quantum mechanics is considered ``quantum''. Then, ***a "quantum sensor" is a device, the measurement (sensing) capabilities of which are enabled by our ability to manipulate and read out its quantum states***. “

Atomic and Nuclear Clocks & Cavities

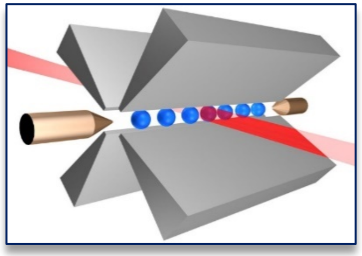
Major clock & cavities R&D efforts below, also molecular clocks, portable clocks and optical links

BSM searches with clocks

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

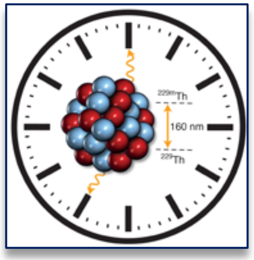


3D lattice clocks

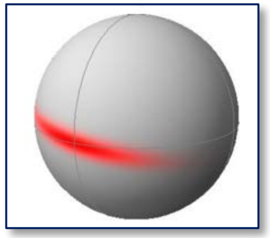


Multi-ion & entangled clocks

Ultrastable optical cavities



Nuclear & highly charge ion clocks



Measurements beyond the quantum limit

Atom interferometry

BSM searches:

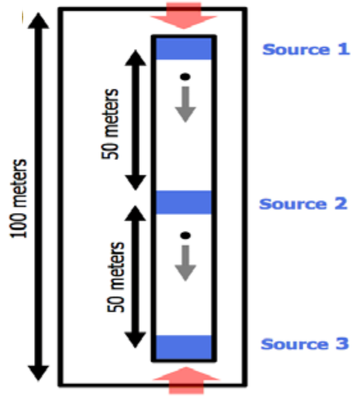
Variation of fundamental constants

Ultralight scalar DM & relaxion searches

Violation of the equivalence principle

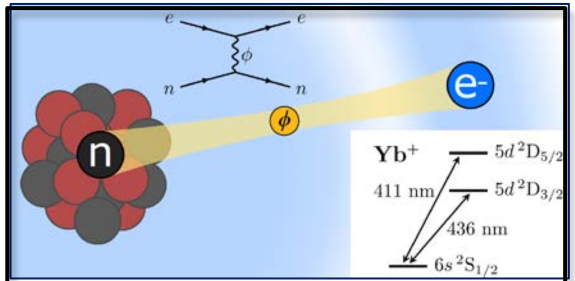
Prototype gravitational wave detectors

MAGIS-100 **Fermilab**



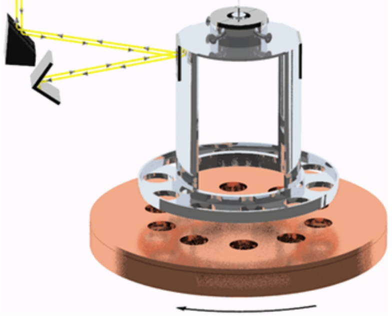
MIGA , AION, ZIGA

Other new force searches



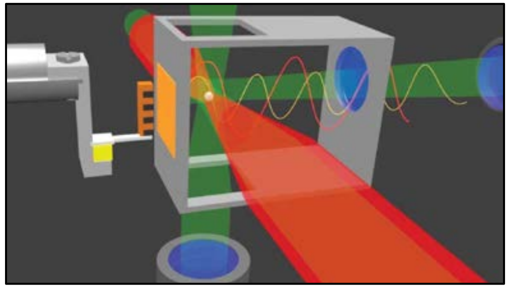
Fifth force searches with precision spectroscopy with atoms and ions

Torsion balances



EP violation tests, big G, Newtonian inverse square law

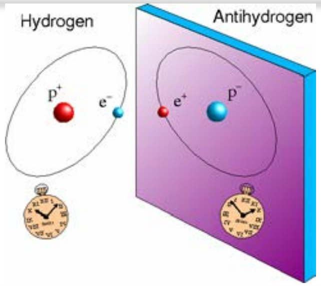
Levitated optomechanics



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, doped cryocrystals for EDMs, Rydberg atoms, …

Topics discussed in white paper

https://arxiv.org/abs/2203.07250

III. Atom Interferometers
- A. Overview of the technique
- B. Science with tabletop atom interferometers
- C. Science with long baseline atomic sensors
- D. Detector development

IV. Optomechanical sensors

V. Atomic, nuclear, and molecular clocks & precision spectroscopy
- A. Clock R&D
- B. Isotope shift precision measurements
- C. Clock-based gravitational wave detection

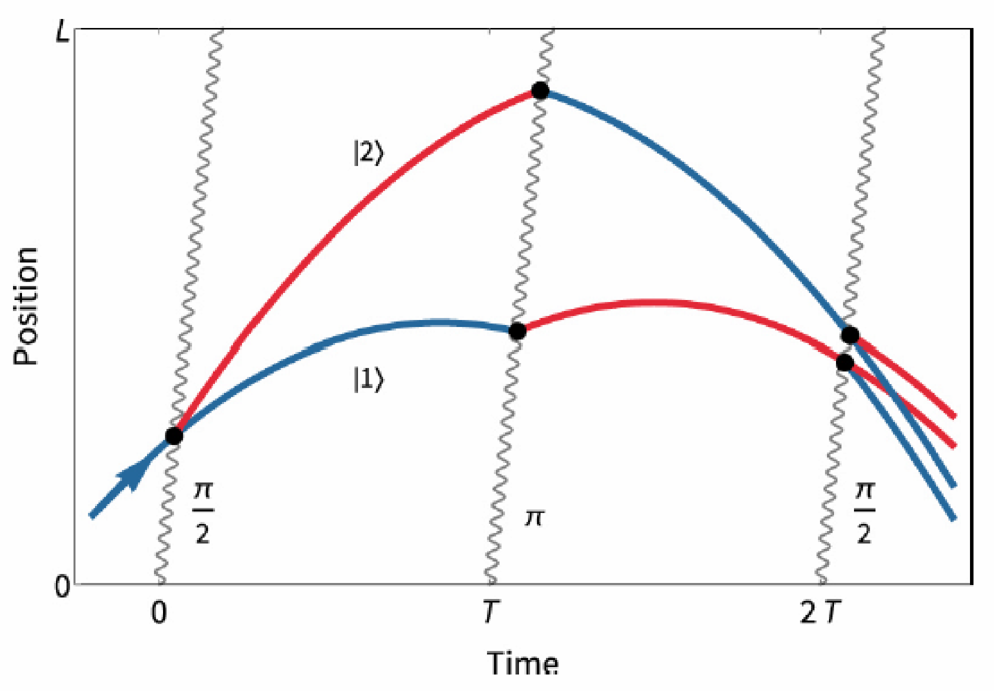
VI. Fundamental physics with radioactive atoms and molecules

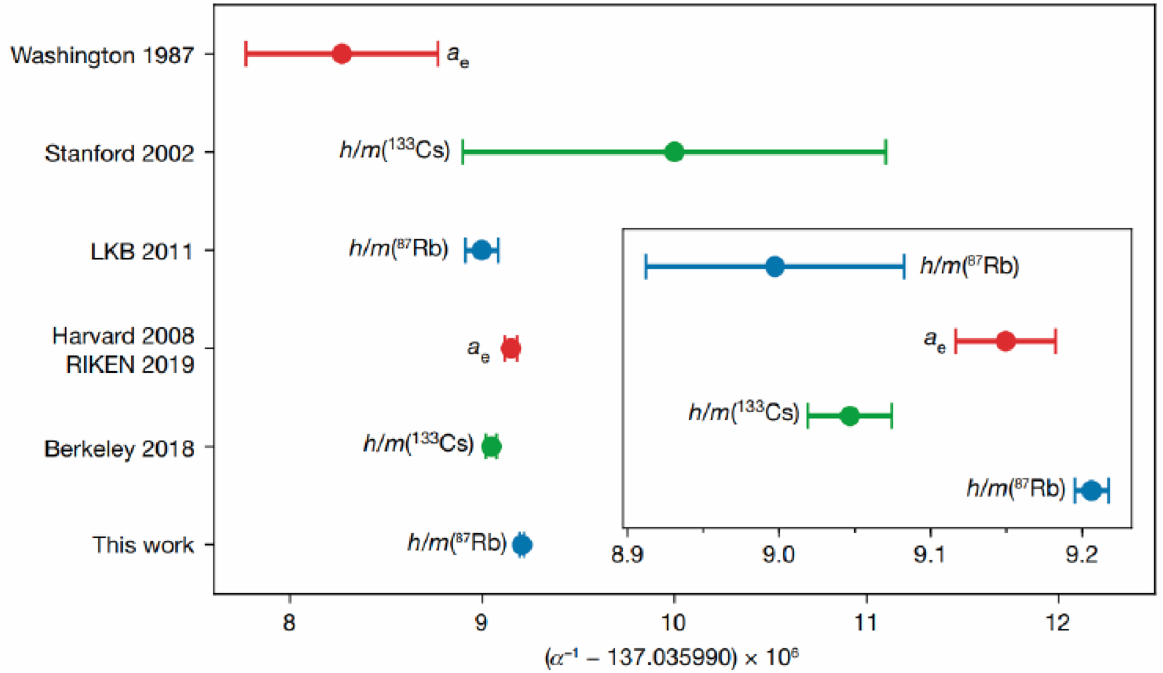
Other relevant white papers:

Snowmass White Paper: Precision Studies of Spacetime Symmetries and Gravitational Physics
https://arxiv.org/abs/2203.09691
(see also talk yesterday by Ralf)

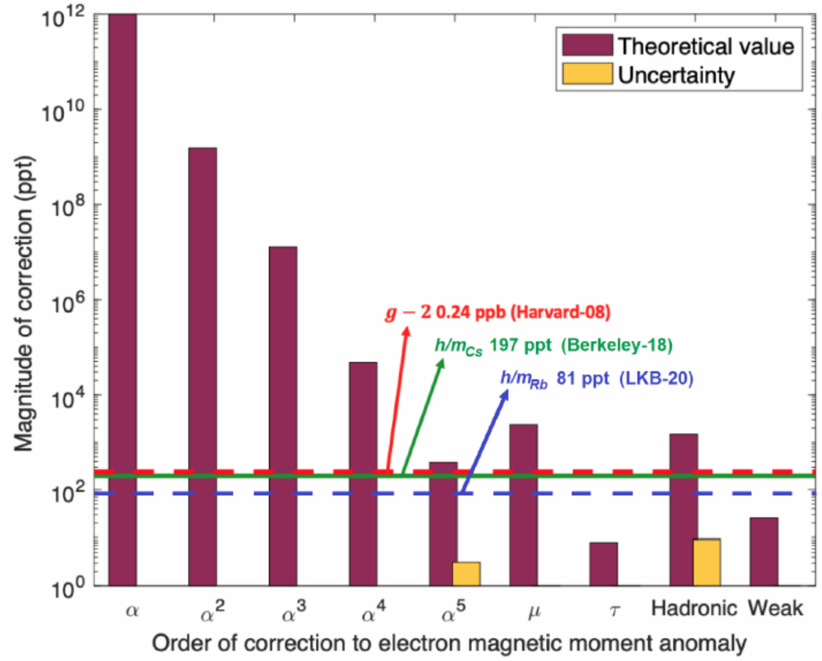
New Horizons: Scalar and Vector Ultralight Dark Matter
https://arxiv.org/abs/2203.14915

III. Atom interferometry



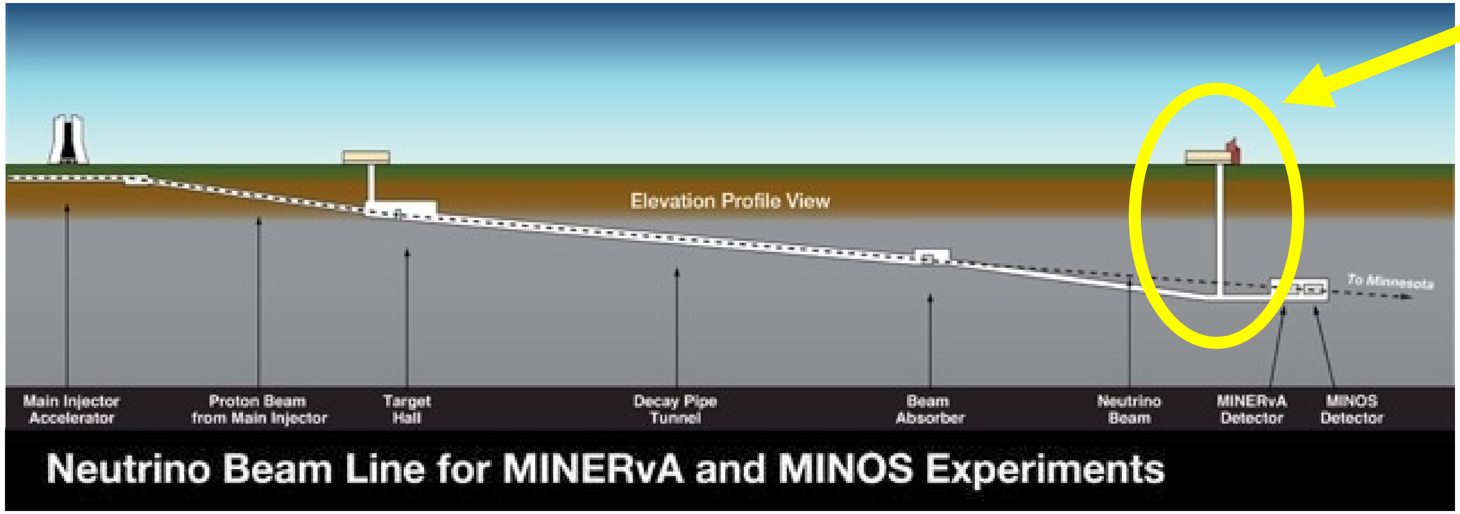


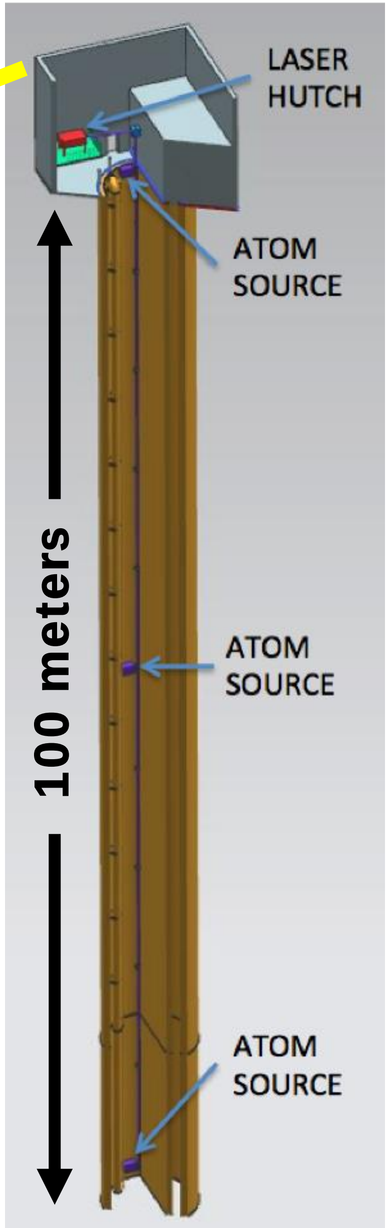
Precision measurement of fine structure constant



MAGIS-100: Detector prototype at Fermilab

Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor





- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum superposition states: >meter wavepacket separation, up to 9 seconds duration

STANFORD · JOHNS HOPKINS UNIVERSITY · Northwestern University · Fermilab · SLAC · THE UNIVERSITY OF CHICAGO · UNIVERSITY OF CAMBRIDGE · Northern Illinois University · UNIVERSITY OF OXFORD · UNIVERSITY OF LIVERPOOL

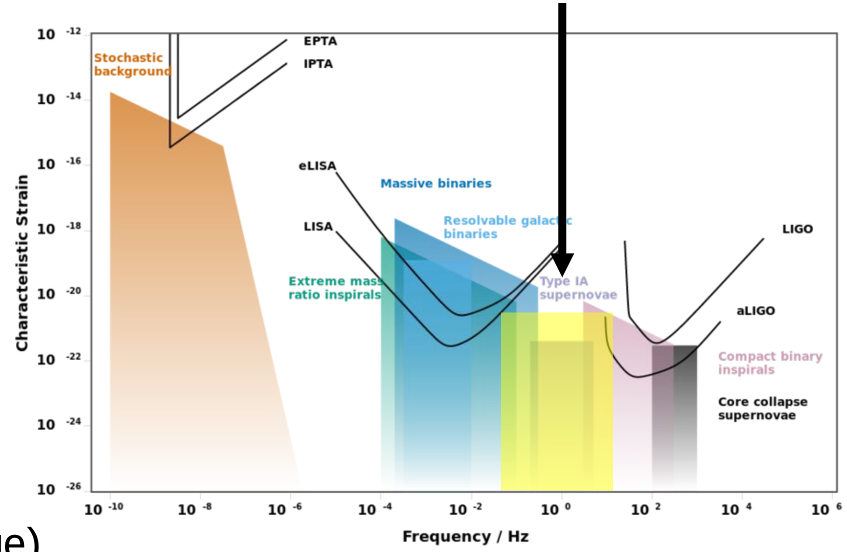
Slide: Jason Hogan

Long baseline atom interferometry science

Mid-band: 0.03 Hz to 3 Hz

Mid-band gravitational wave detection

- LIGO sources before they reach LIGO ban
- Multi-messenger astronomy: optimal band for sky localization
- Cosmological sources

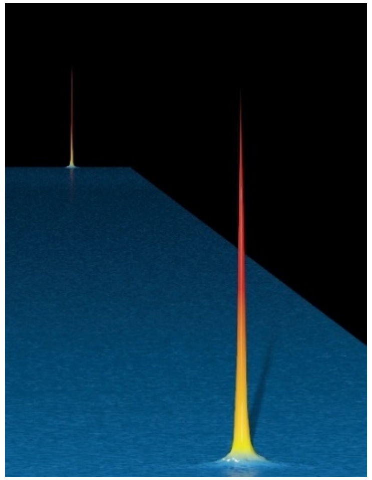


Ultralight wave-like dark matter probe

- Mass $<10^{-14}$ eV (Compton frequency in ~Hz range)
- Scalar- and vector-coupled DM candidates
- Time-varying energy shifts, EP-violating new forces, spin-coupled effects

Tests of quantum mechanics at macroscopic scales

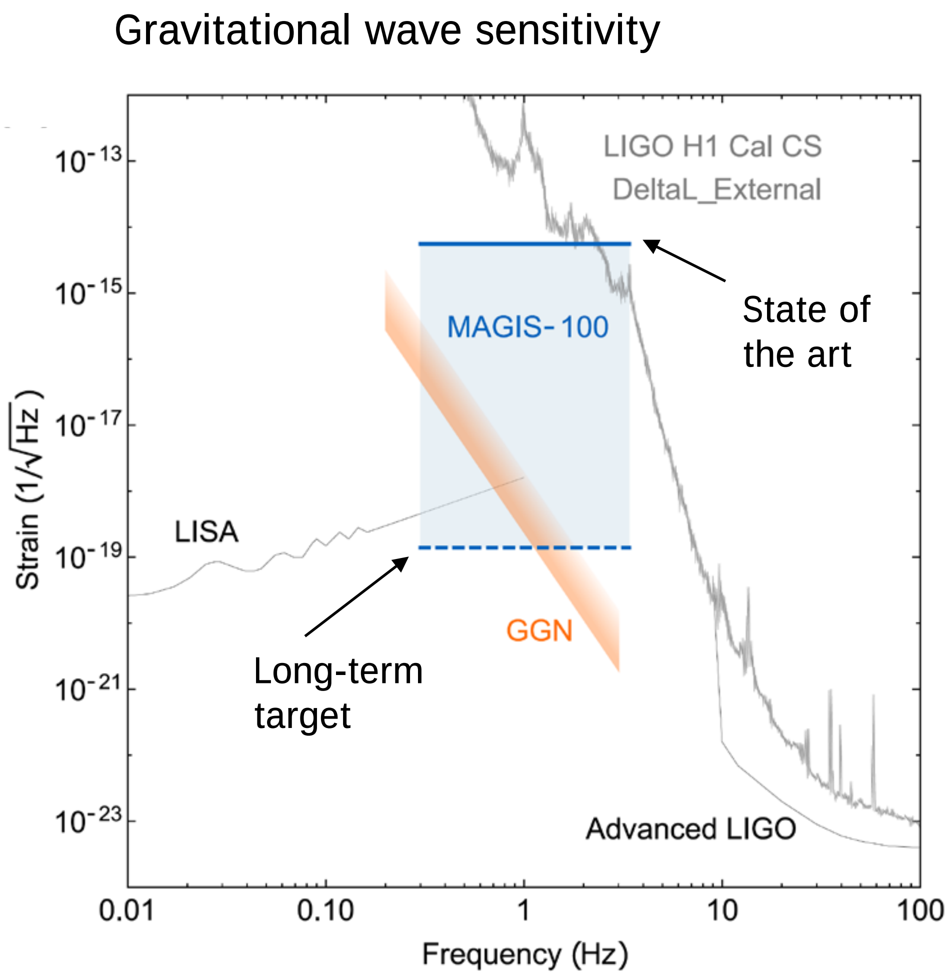
- Meter-scale wavepacket separation, duration of seconds
- Decoherence, spontaneous localization, non-linear QM, ...

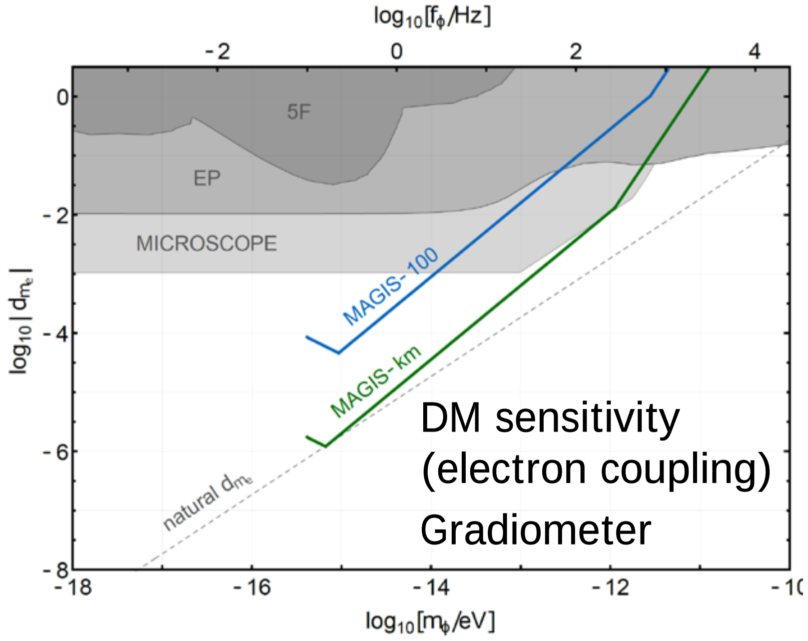


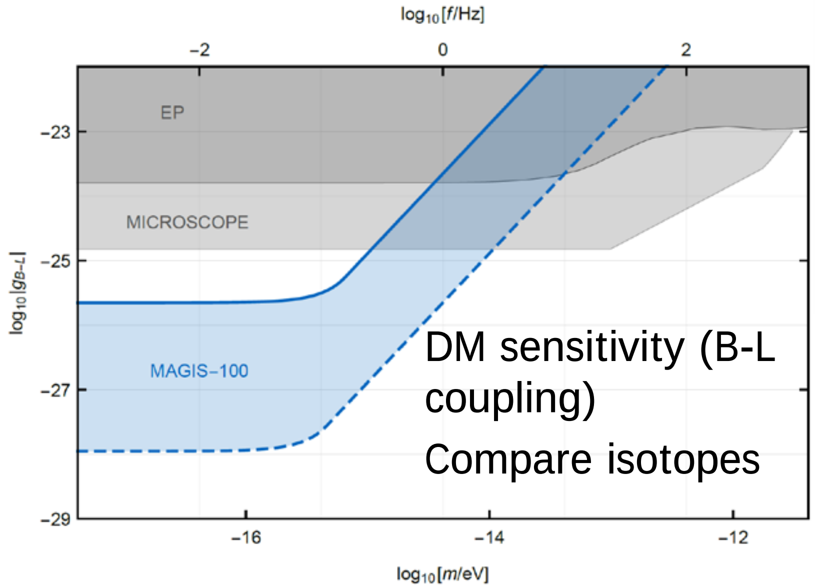
Rb wavepackets separated by 54 cm

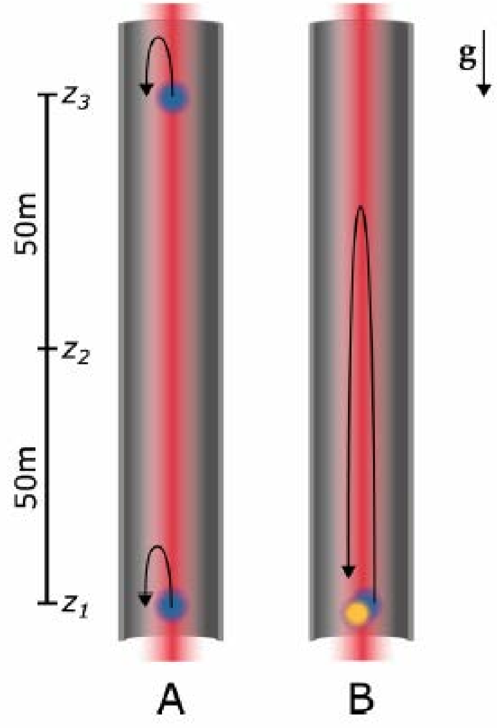
Slide: Jason Hogan

MAGIS-100 projected sensitivity









Slide: Jason Hogan

IV. (Opto-)mechanical sensors

- Torsion balances

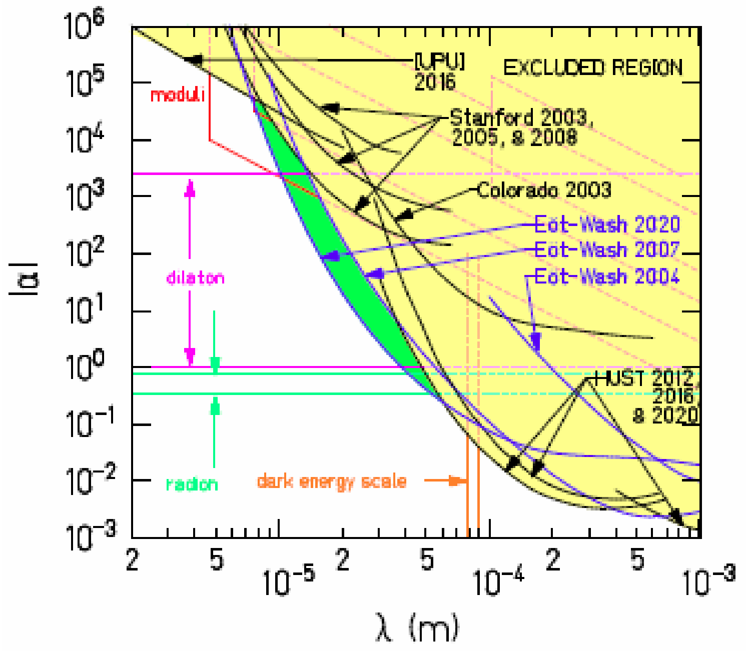
exotic short-range gravity
equivalence-principle violation
novel spin-dependent interactions

Limiting factors:

1) environmental vibrations
(particularly in short-range tests where patch charges couple to the spurious modes producing noise that dominates at small separations and limits the minimum attainable separation.)

2) time-varying environmental gravity-gradients limit equivalence-principle tests.

Both of these technical limiting factors could be addressed by a development of a suitable underground facility that was open to outside users.

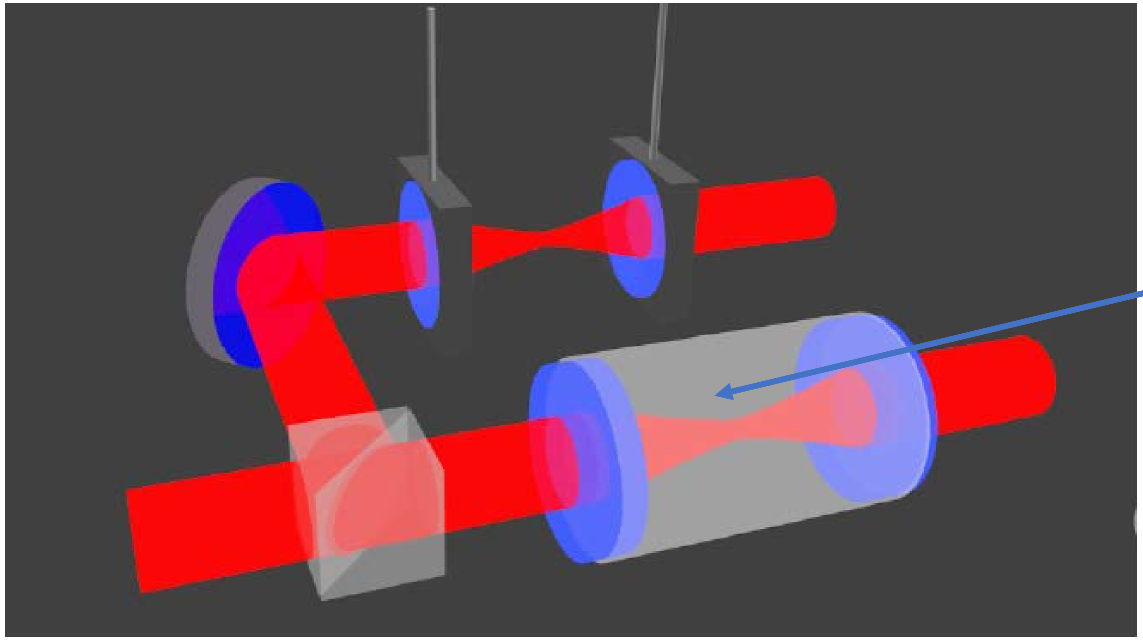


J.G. Lee, E.G. Adelberger, T.S. Cook, S.M. Fleischer, B.R. Heckel. Physical Review Letters, (124), 101101 (2020)

Optical cavity detectors for Dark Matter

$$\phi(t,\mathbf{r}) \approx \frac{\hbar}{m_\phi c}\sqrt{2\rho_{\rm DM}}\cos\left[2\pi f_\phi t - \mathbf{k}_\phi\cdot\mathbf{r} + ...\right]$$

$$\boxed{\begin{aligned} \frac{\delta m_e(t,\mathbf{r})}{m_{e,0}} &= d_{m_e}\sqrt{4\pi\hbar c}E_P^{-1}\phi(t,\mathbf{r}) \\ \frac{\delta\alpha(t,\mathbf{r})}{\alpha_0} &= d_e\sqrt{4\pi\hbar c}E_P^{-1}\phi(t,\mathbf{r}) \end{aligned}}$$

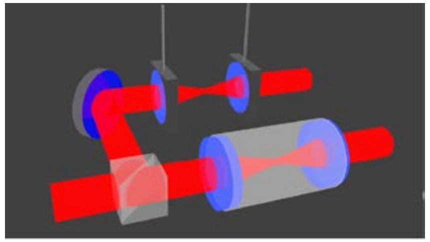


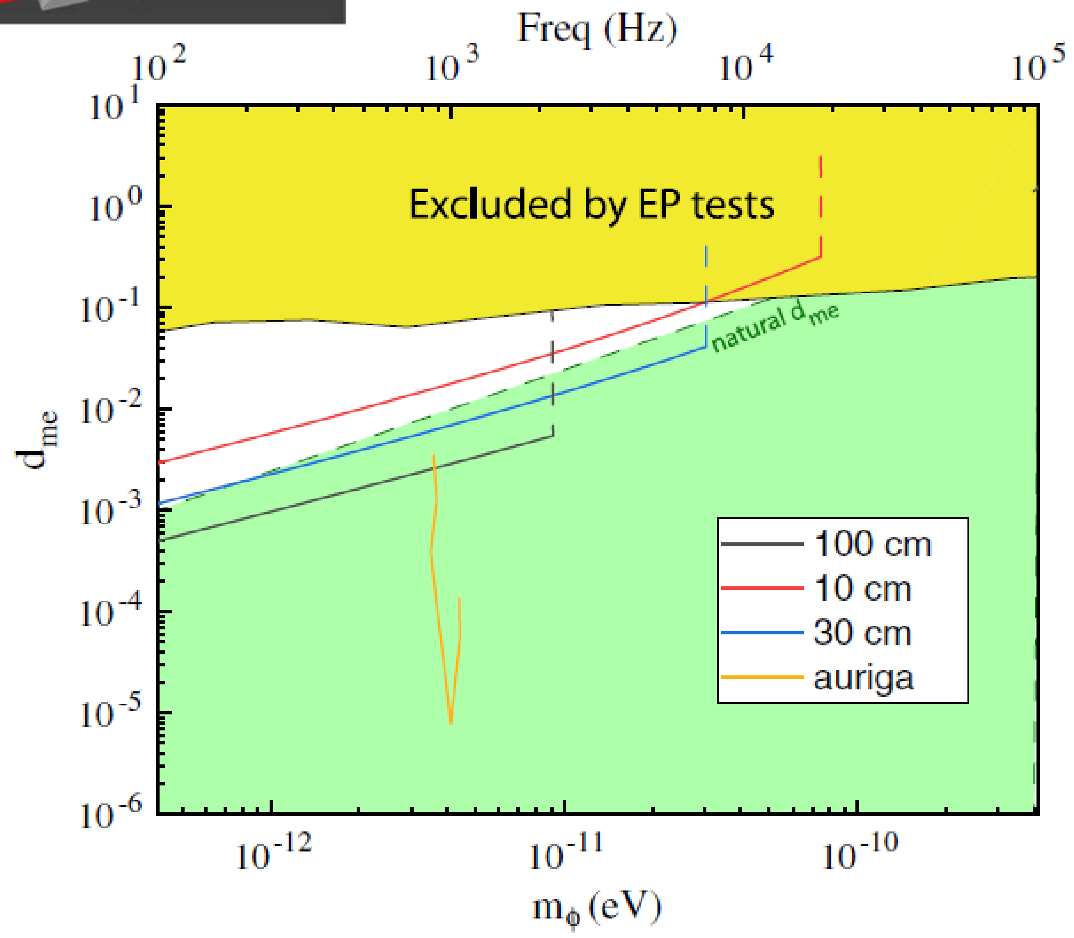
Dark matter field causes strain in rigid cavity at f_ϕ

Suspended cavity cannot respond quickly enough for f

AG, C. Bradley, W. Gao, J. Weinstein, A. Derevianko, PRL (2019)

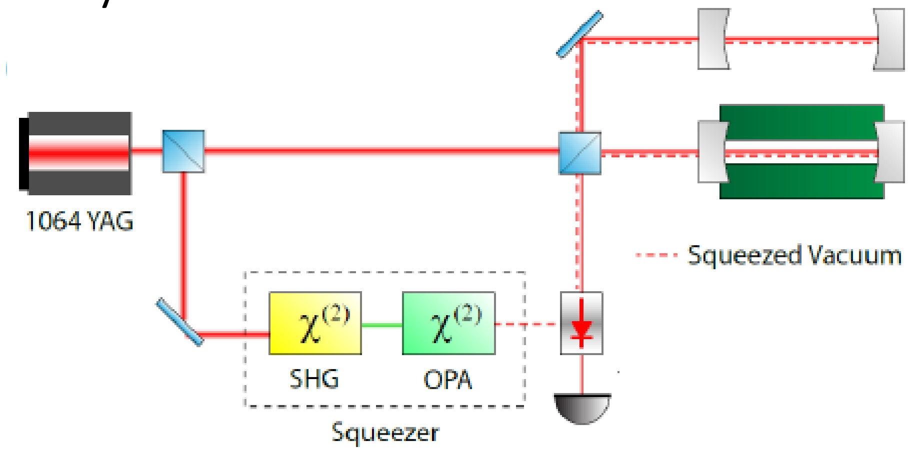
Reach for variation of electron mass d_{me}



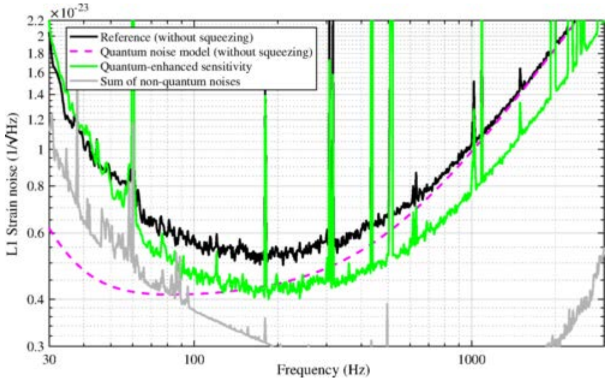


AG, C. Bradley, W. Gao, J. Weinstein, A. Derevianko, PRL (2019)

-Cryogenic experiment for low thermal noise to reach the shot noise limit
- quantum squeezing techniques can improve sensitivity >1 kHz

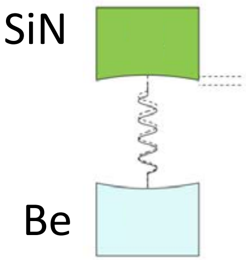


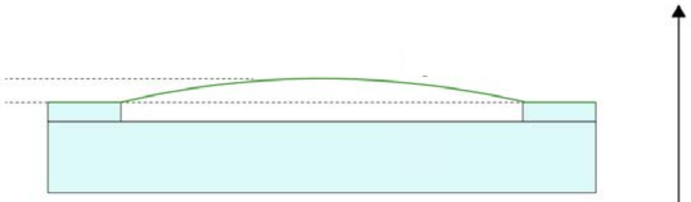
Borrow proven methods from GW community (LIGO, VIRGO):

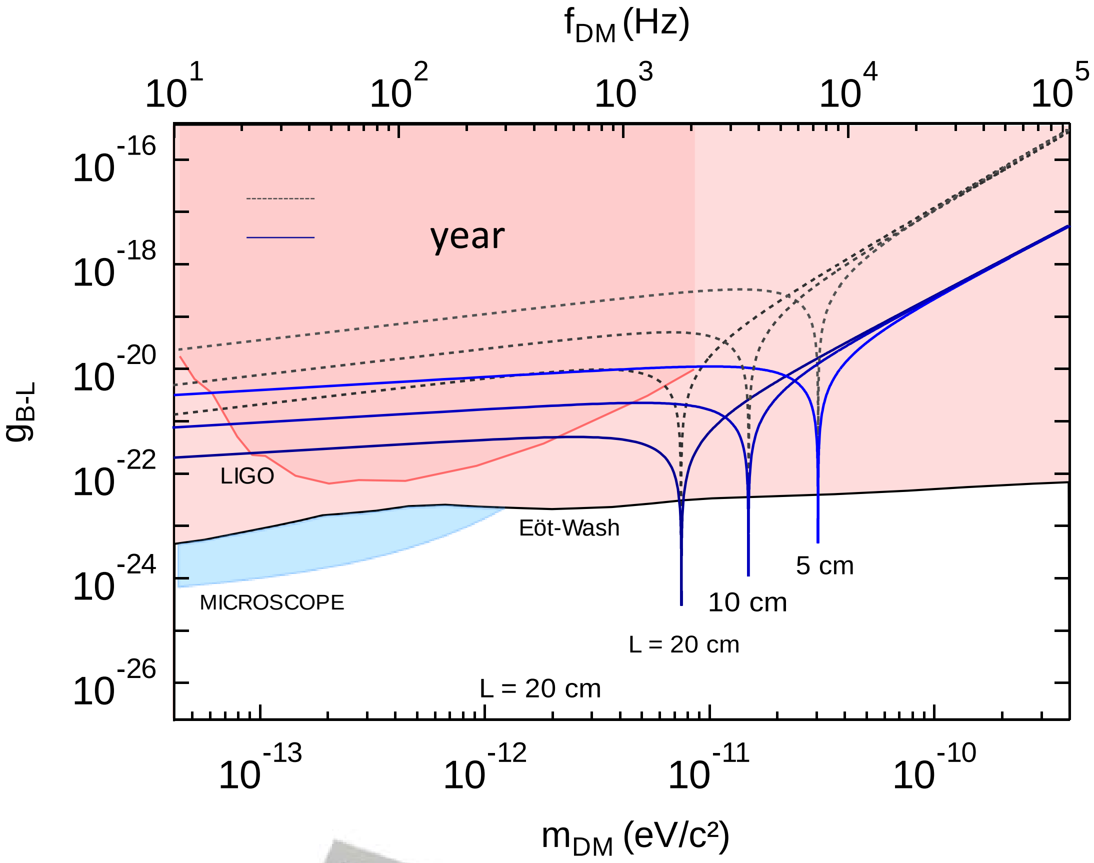


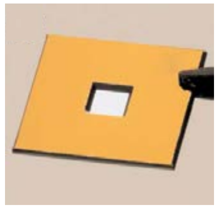
A membrane-based dark photon detector

Differential acceleration between materials (e.g. if coupled to B-L)









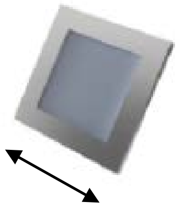
membrane
(

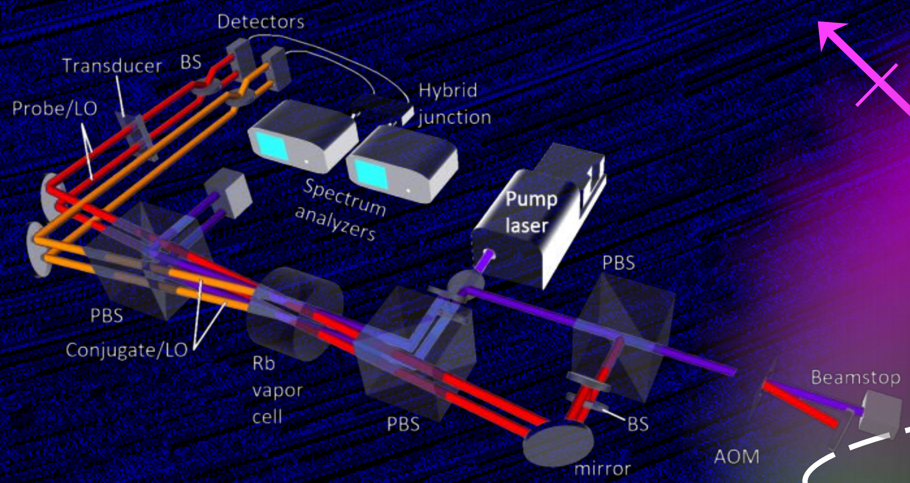
+

Be Mirror
(Webb telescope)

+

Cryogenics
(100 mK)




Detectors
Transducer
BS
Hybrid
junction
Probe/LO
Spectrum
analyzers
Pump
laser
PBS
PBS
Conjugate/LO
Rb
vapor
cell
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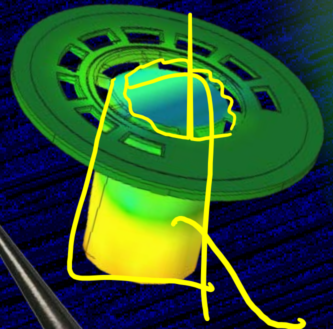
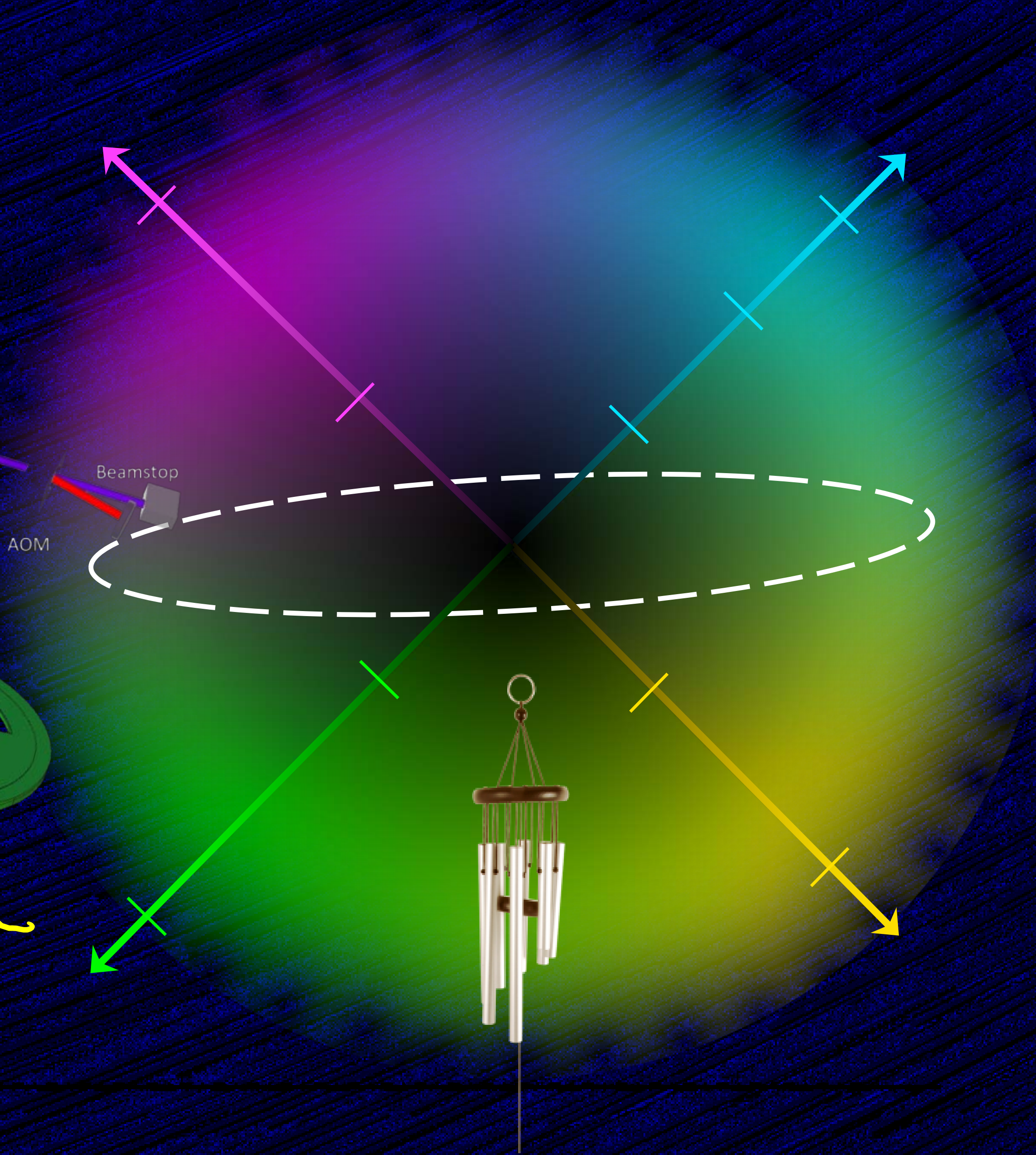
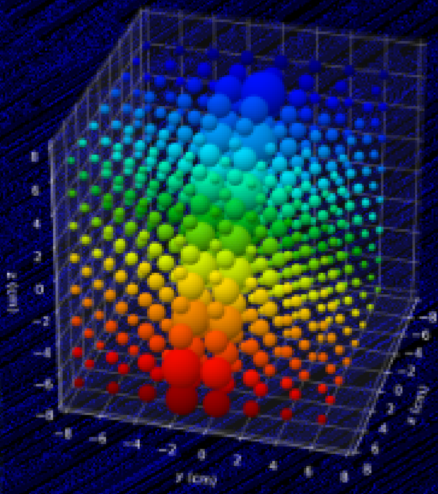
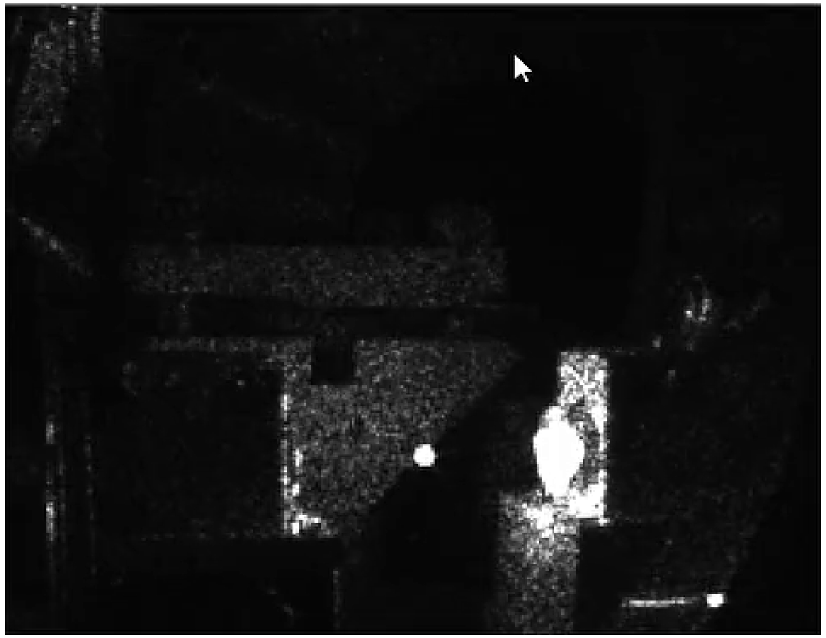
BS
mirror
AOM
Beamstop

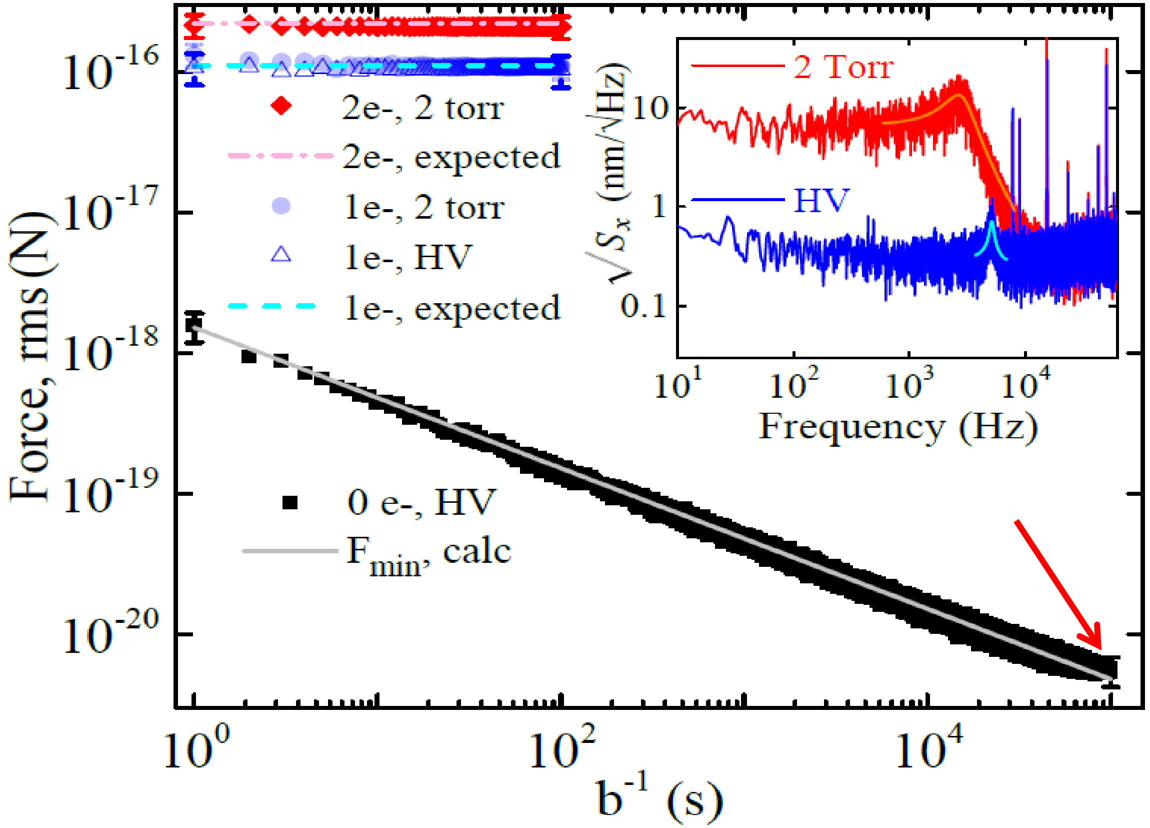






Levitated optomechanical sensors

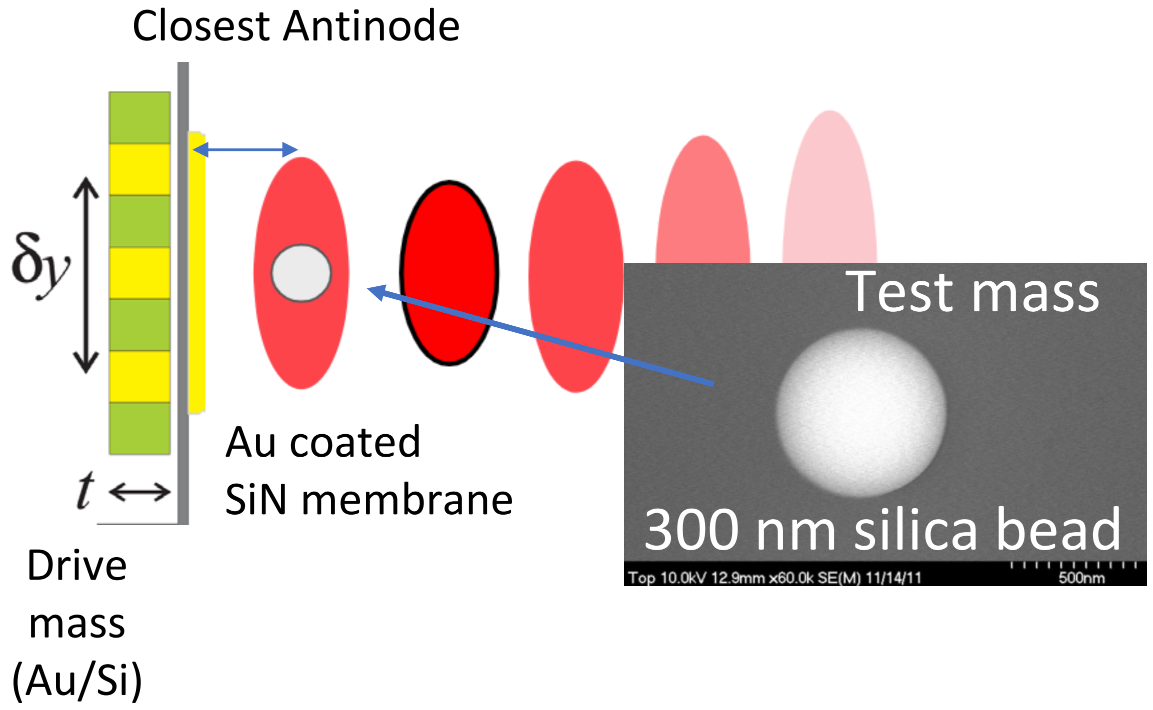


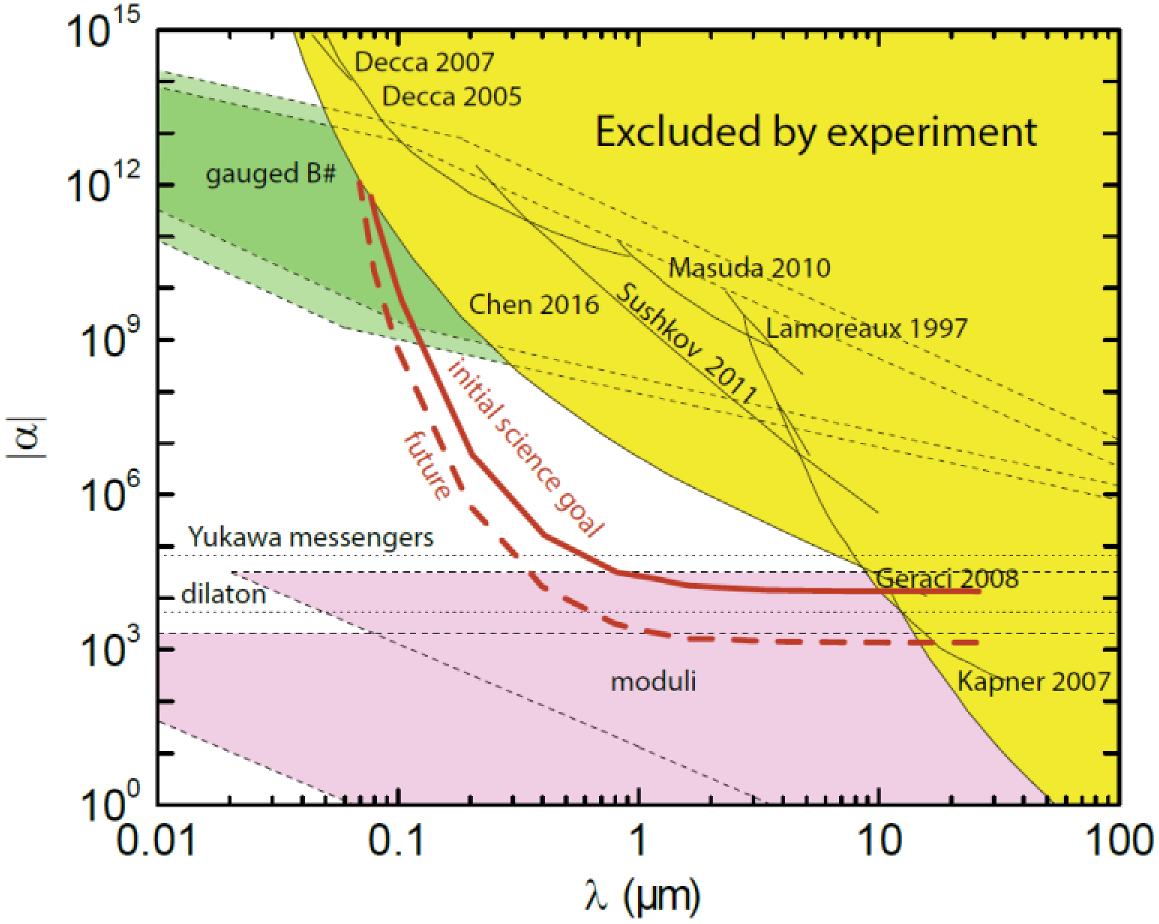


zeptonewton sensitivity in a standing wave trap

G. Ranjit, et.al. , *Phys. Rev. A*, 93, 053801 (2016), C. Montoya et. al. Appl.Opt. (2022)

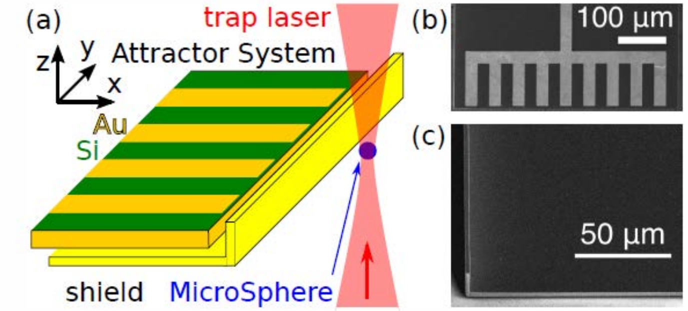
Projected sensitivity – fifth force tests





$$=-\qquad \frac{}{}\left(+\alpha \quad ^{-\ \lambda}\right)$$

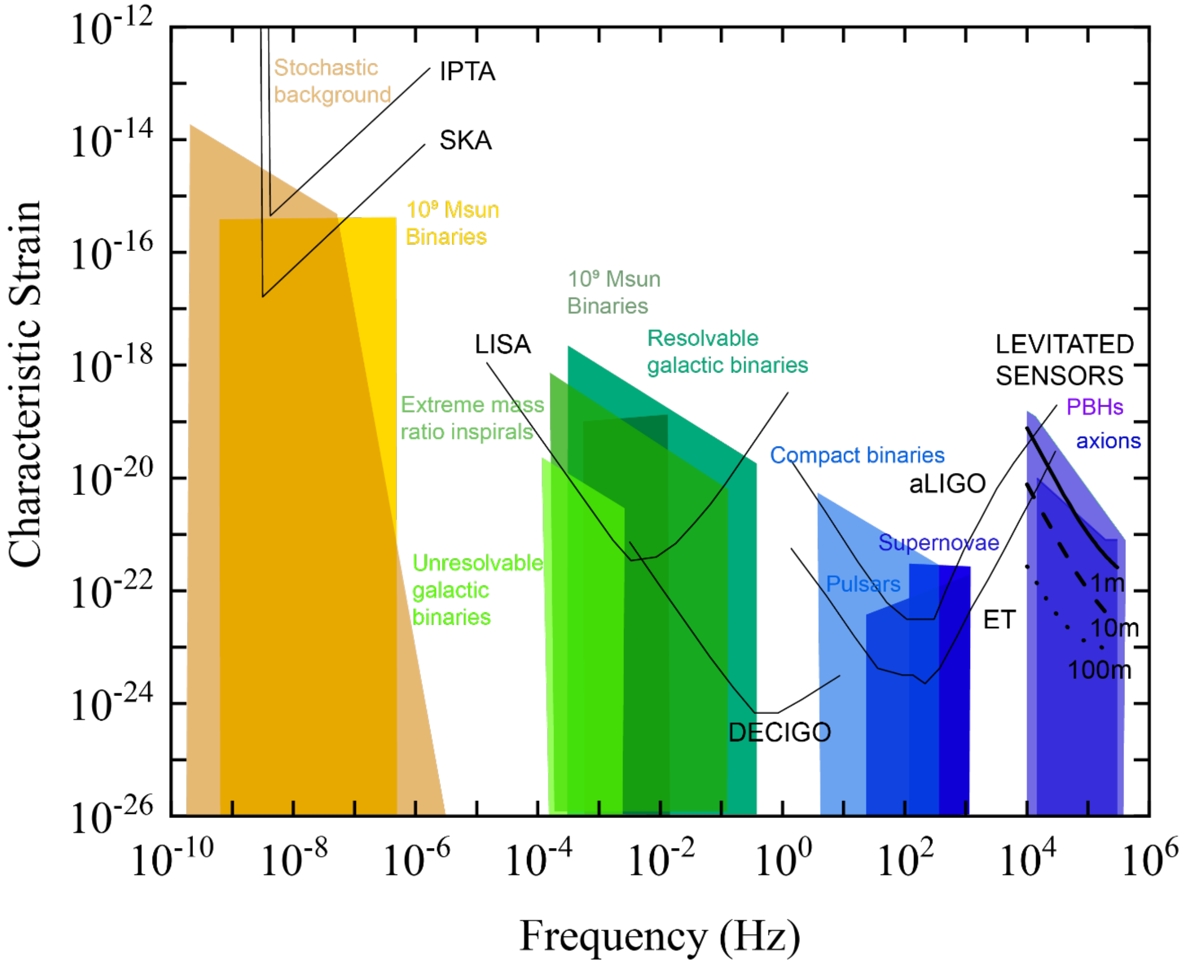
Also work at
Stanford,Yale



AG, S.B. Papp, and J. Kitching, . **105**, 101101 (2010)

GW detectors as a probe of the dark sector

Axions, Primordial Black holes (PBHs)



Primordial black hole dark matter and the LIGO/Virgo observations

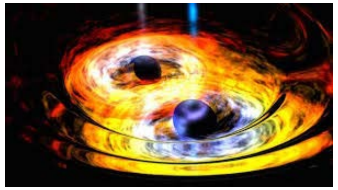
Karsten Jedamzik[1]

Published 14 September 2020 • © 2020 IOP Publishing Ltd and Sissa Medialab

Journal of Cosmology and Astroparticle Physics, Volume 2020, September 2020

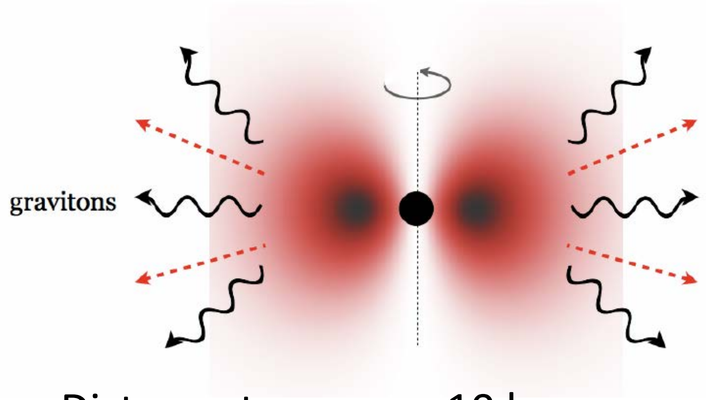
Citation Karsten Jedamzik JCAP09(2020)022

PBHs:



Distance to source: 1 kpc (within our galaxy)

Axions:



Distance to source: 10 kpc (within our galaxy)

Integration time: 10^6 sec

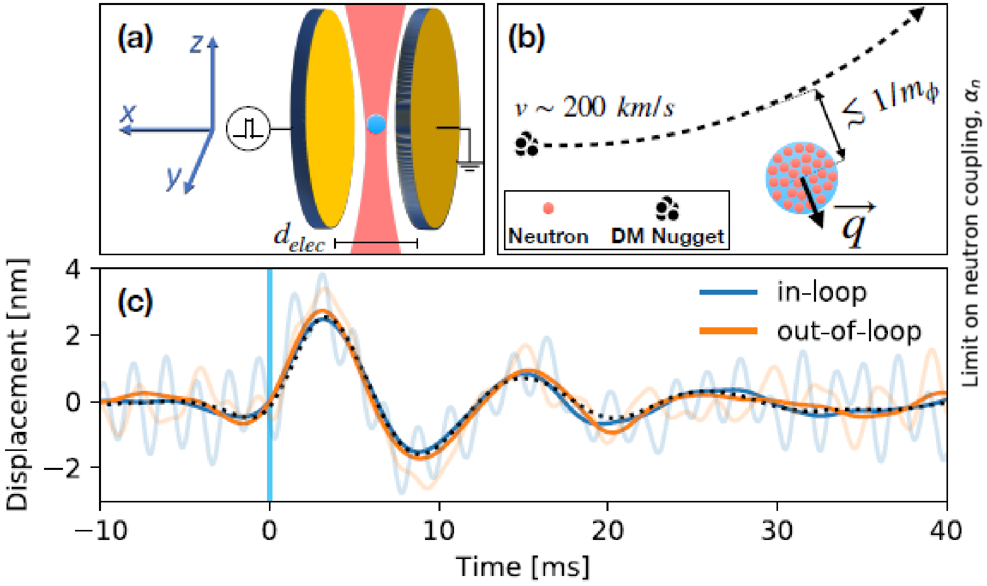
N. Aggarwal, G. Winstone, M. Baryakhtar, M.H. Teo, S. Larson, V. Kalogera, AG, PRL (2022)

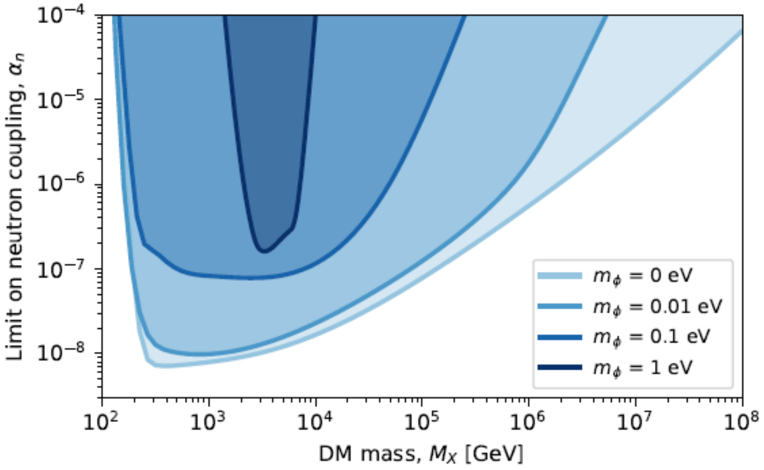
D.C. Moore and AG, Quantum Sci. Technol. 6 014008 (2021)

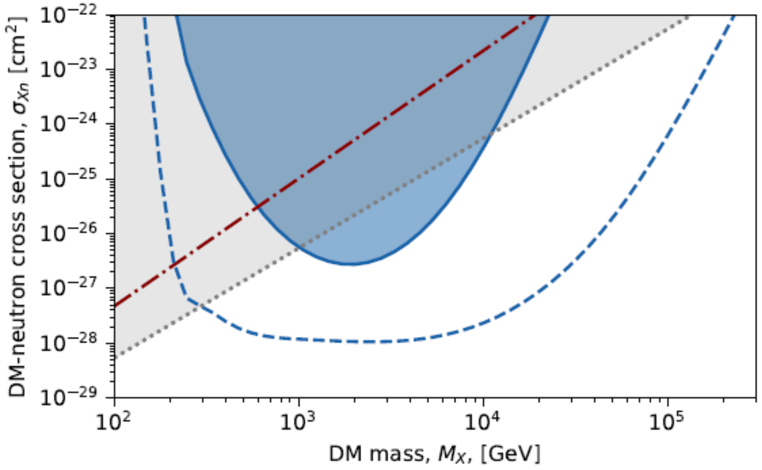
Composite DM search with Levitated microspheres

Search for Composite Dark Matter with Optically Levitated Sensors

Fernando Monteiro, Gadi Afek, Daniel Carney, Gordan Krnjaic, Jiaxiang Wang, and David C. Moore
Phys. Rev. Lett. **125**, 181102 – Published 28 October 2020







(Ground) state of the art:

Dynamical backaction:

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REPORT

Cooling of a levitated nanoparticle to the motional quantum ground state

Uroš Delić[1,2,*], Manuel Reisenbauer[1], Kahan Dare[1,2], David Grass[1,†], Vladan Vuletić[3], Nikolai Kiesel[1], ...

+ See all authors and affiliations

Science 21 Feb 2020:
Vol. 367, Issue 6480, pp. 892-895
DOI: 10.1126/science.aba3993

Article | Figures & Data | Info & Metrics | eLetters | PDF

A nanoparticle trapped and cooled

Cooling massive particles to the quantum ground state allows fundamental tests of quantum mechanics to be made; it would provide an experimental probe of the boundary between the classical and quantum worlds. Delić *et al.* laser-cooled an optically trapped solid-state object (a ~150-nanometer-diameter silic a nanoparticle) into its quantum ground state of motion starting from room temperature. Because the object is levitated using optical forces, the experimental configuration can be switched to free fall, thereby providing a test bed for several macroscopic quantum experiments.

Science, this issue p. 892

Measurement based cooling:

nature

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nature > articles > article

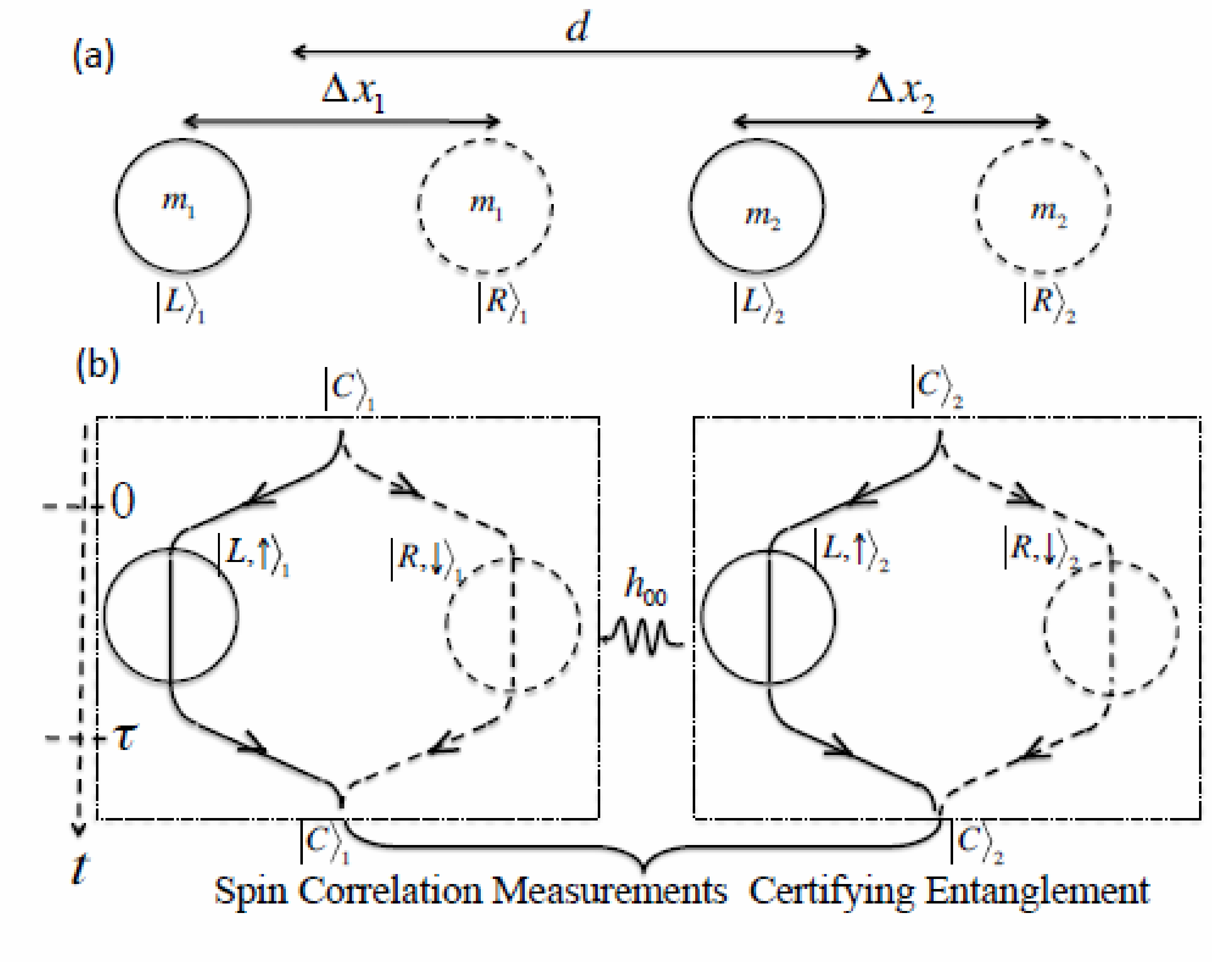
Article | Published: 14 July 2021

Quantum control of a nanoparticle optically levitated in cryogenic free space

Felix Tebbenjohanns, M. Luisa Mattana, Massimiliano Rossi, Martin Frimmer & Lukas Novotny

Nature **595**, 378–382 (2021) | Cite this article

Does gravity participate in quantum entanglement?

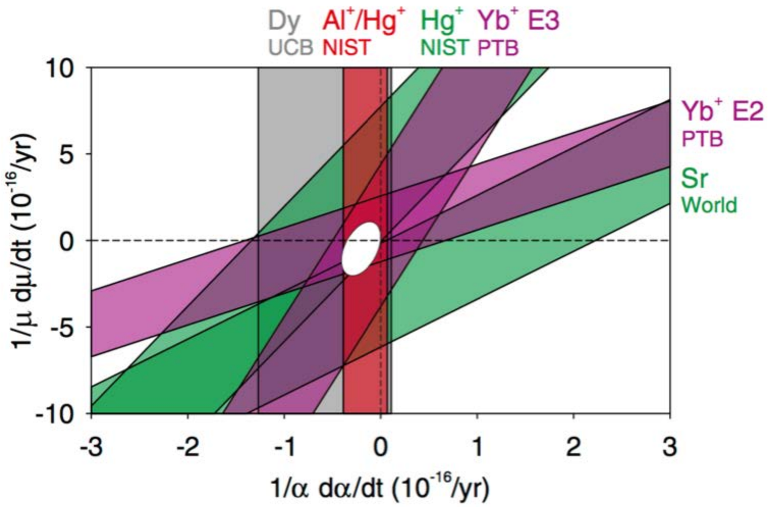


Challenges:

- Production of large superpositions
- Technical decoherence of large superpositions (e.g. Blackbody)
- Gas collisions
- Magnetic backgrounds
- Background vibrations, GG noise
- Surface interactions e.g. Casimir, Patch

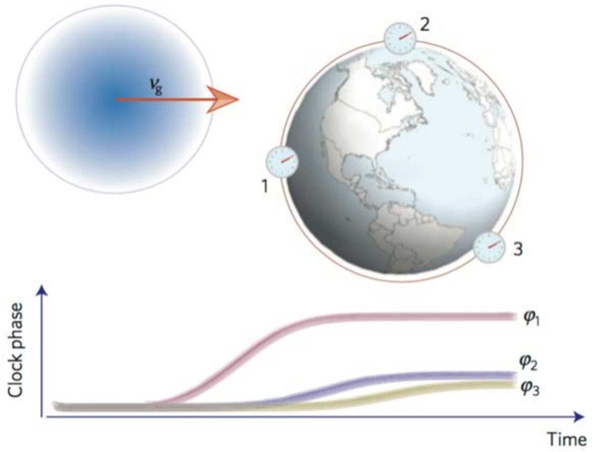
S. Bose, A. Mazumdar, G. W. Morley, H. Ulbricht, M. Toroš, M. Paternostro, AG, P. F. Barker, M. S. Kim, and G. Milburn., Phys. Rev. Lett. **119**, 240401 (2017)

Variations of fundamental constants



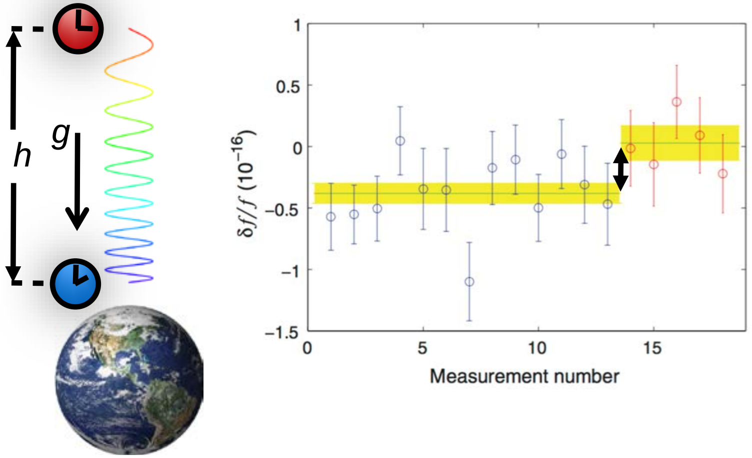
Huntemann *et al.* *PRL* (2014)

Dark matter searches



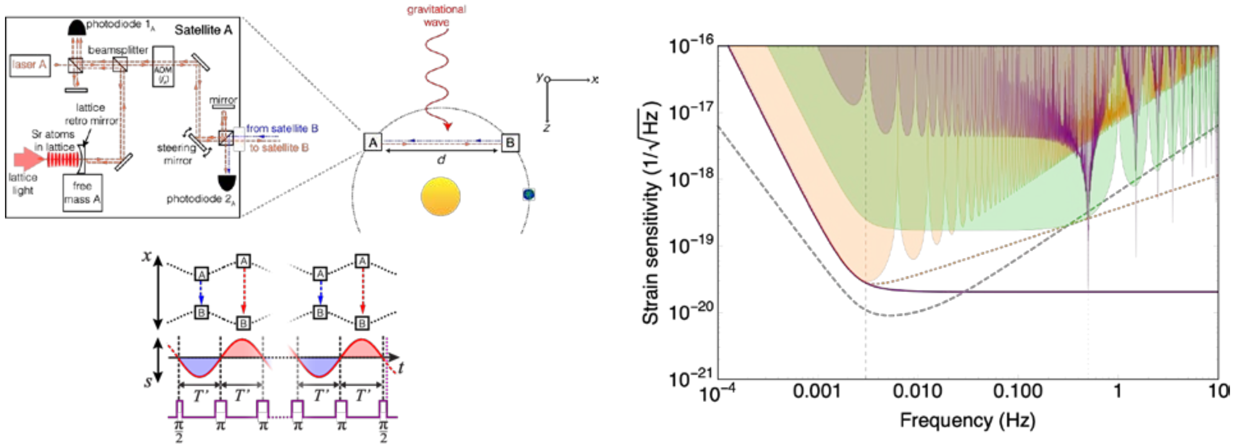
Dereviako & Pospelov, *Nature Physics* (2014)

Tests of relativity



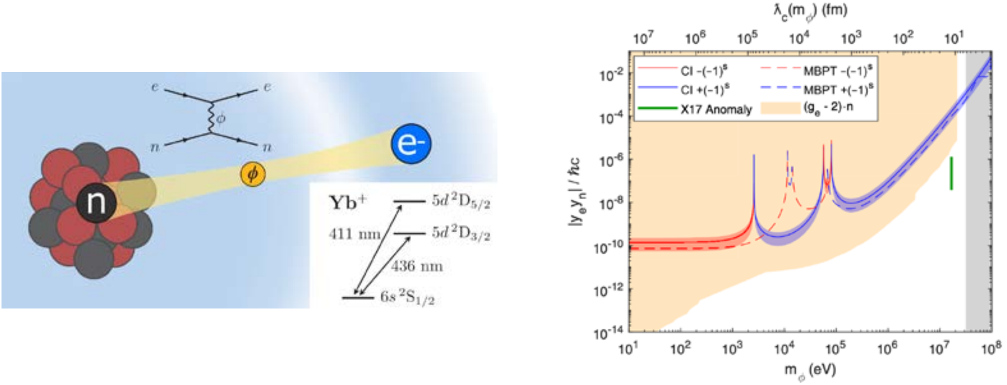
Chou *et al.* *Science* (2010)

GW detection



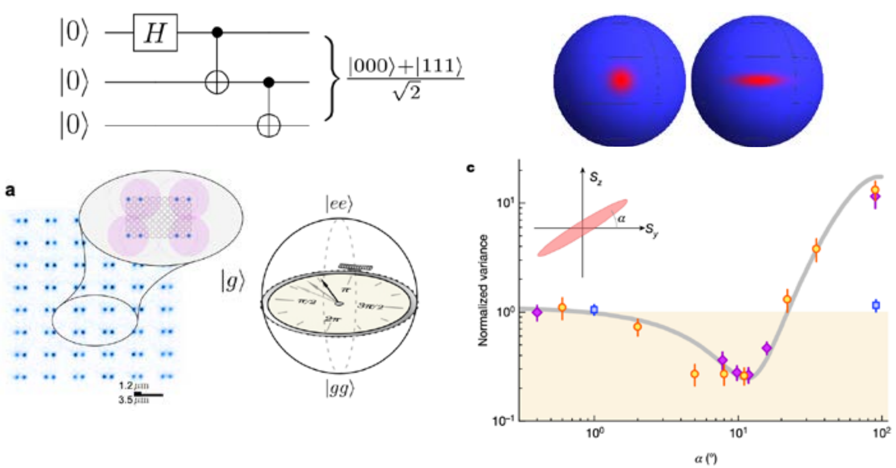
Kolkowitz *et al.* *PRD* (2016)

Fifth force searches



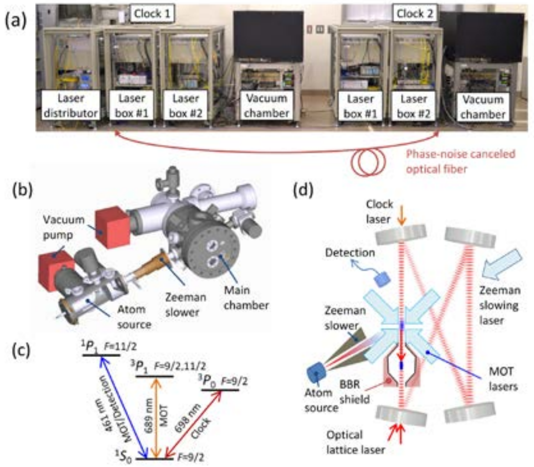
Counts *et al.* *PRL* (2020)

Quantum entanglement enhanced clocks



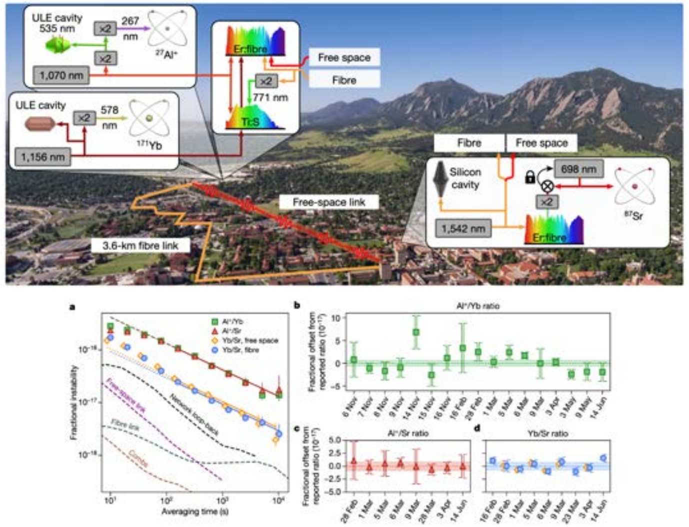
Schine *et al.* *arXiv* (2021), Pedrozo-Peñafiel *et al.* *Nature* (2020)

Portable clocks



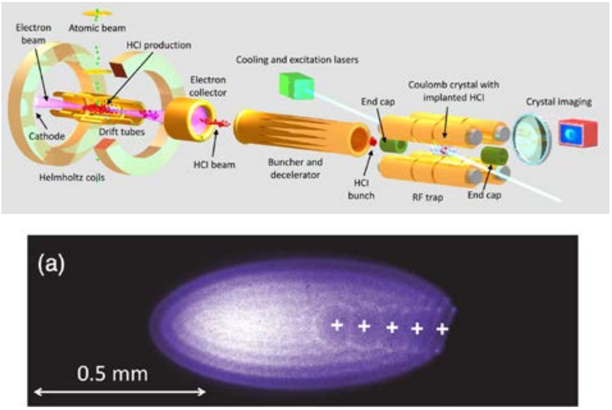
Takamoto *et al.* *APL*, (2022)

Clock networks



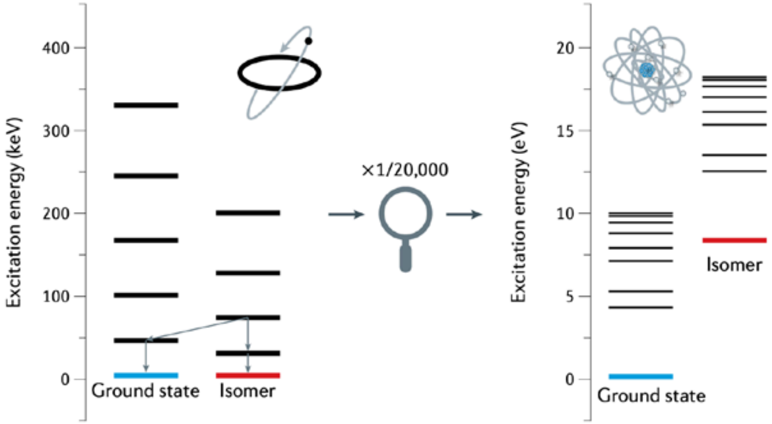
BACON collaboration, *Nature* (2021)

Highly charged ion clocks



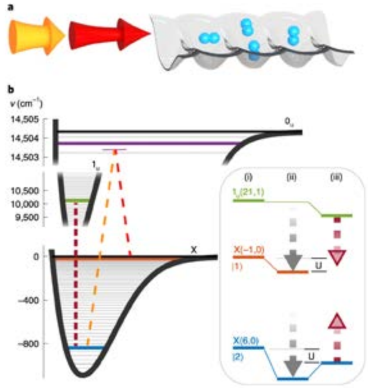
Schmöger *et al.* *Science* (2015)

Nuclear clocks



Beeks *et al.* *Nature Review Physics* (2021)

Molecular clocks



Kondov *et al.* *Nature Physics* (2019)

Search for short-range fifth forces with isotope shift spectroscopy

King plot of Isotope Shifts

Mass shift (MS) Field shift (FS)

$$\nu_i^{AA'} \equiv \nu_i^A - \nu_i^{A'} = K_i\,\mu_{AA'} + F_i\,\delta\langle r^2\rangle_{AA'}$$

electronic
nuclear

Poorly known
nuclear charge
radius

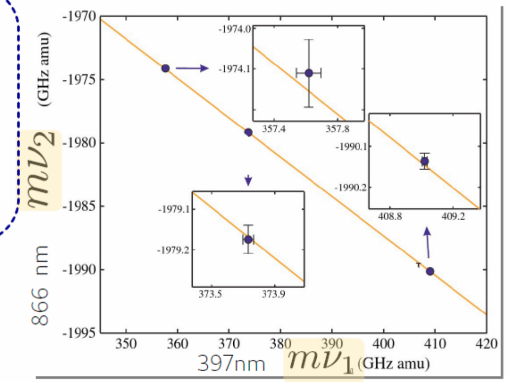
$i = 1, 2$

2nd transition to eliminate charge radius

Linear King relation (at leading order):

$$m\nu_2 = F_{21} m\nu_1 + K_{21}$$

[King '63]



[Gebert, Wan, Wolf, Angstmann, Berengut, Schmidt; PRL 115, 053003 (2015)]

check if 3 points (= 3 isotope pairs) on straight line

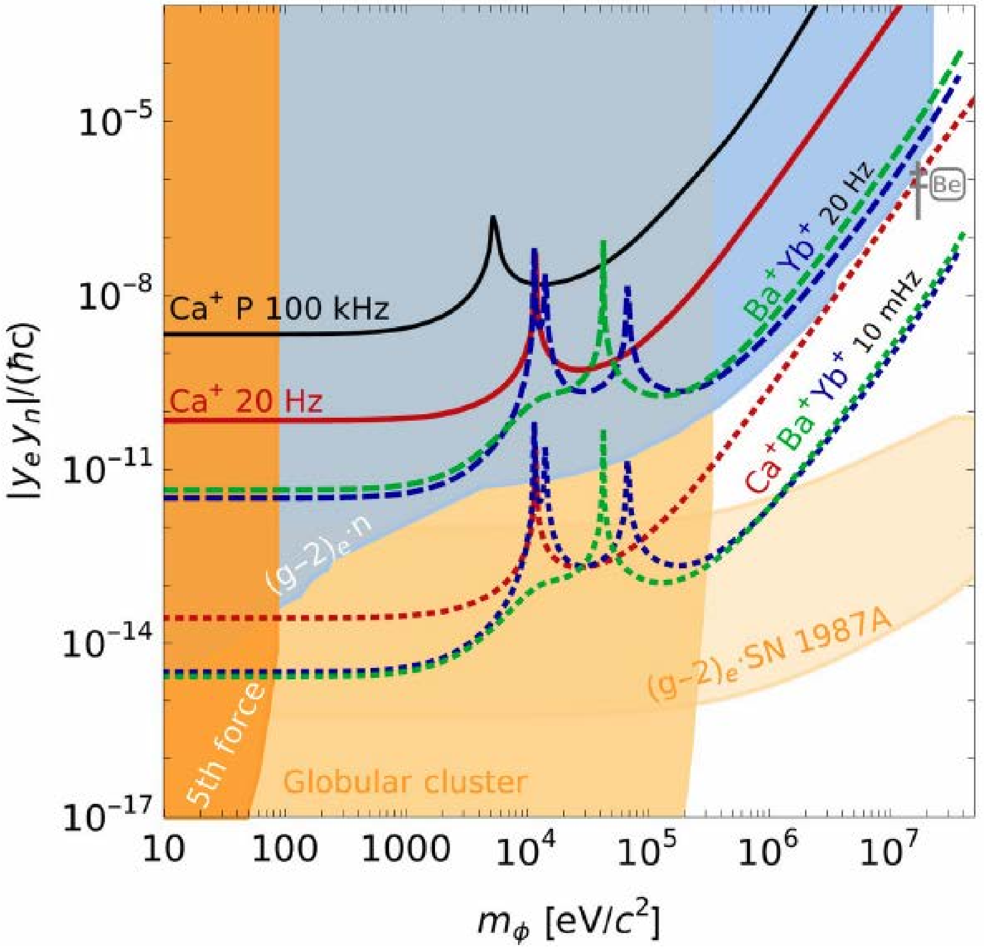
Energy shift due to new long-range interaction

$$V_{\rm NP} = \frac{y_e y_n}{4\pi r} e^{-m_\phi r}$$

$$m\nu_2 = F_{21} m\nu_1 + K_{21} - y_e y_n AA'(X_2 - X_1 F_{21})$$

NP ϕ coupling to electrons and neutrons

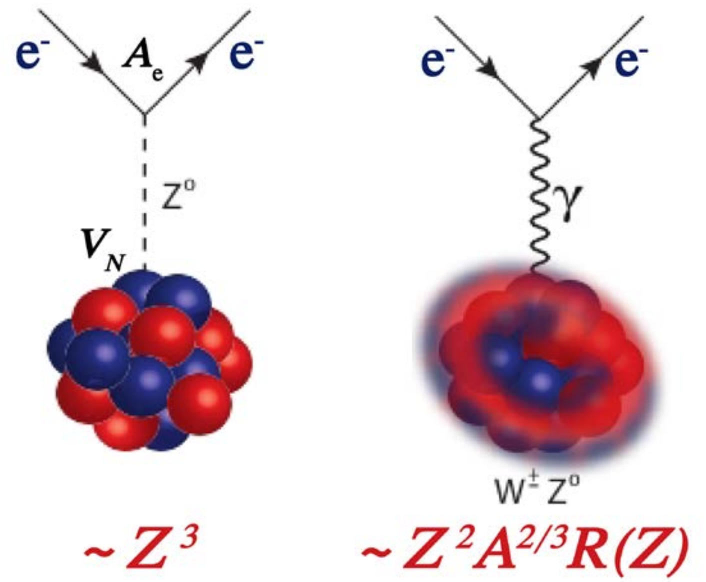
theory input: NP electronic coefficients
overlap of wavefunctions with NP potential
$X_i = X_i(m_\phi)$



Solaro et.al. Phys. Rev. Lett. **125**, 123003 (2020)

VI: Fundamental symmetries: radioactive atoms and molecules

Parity violation

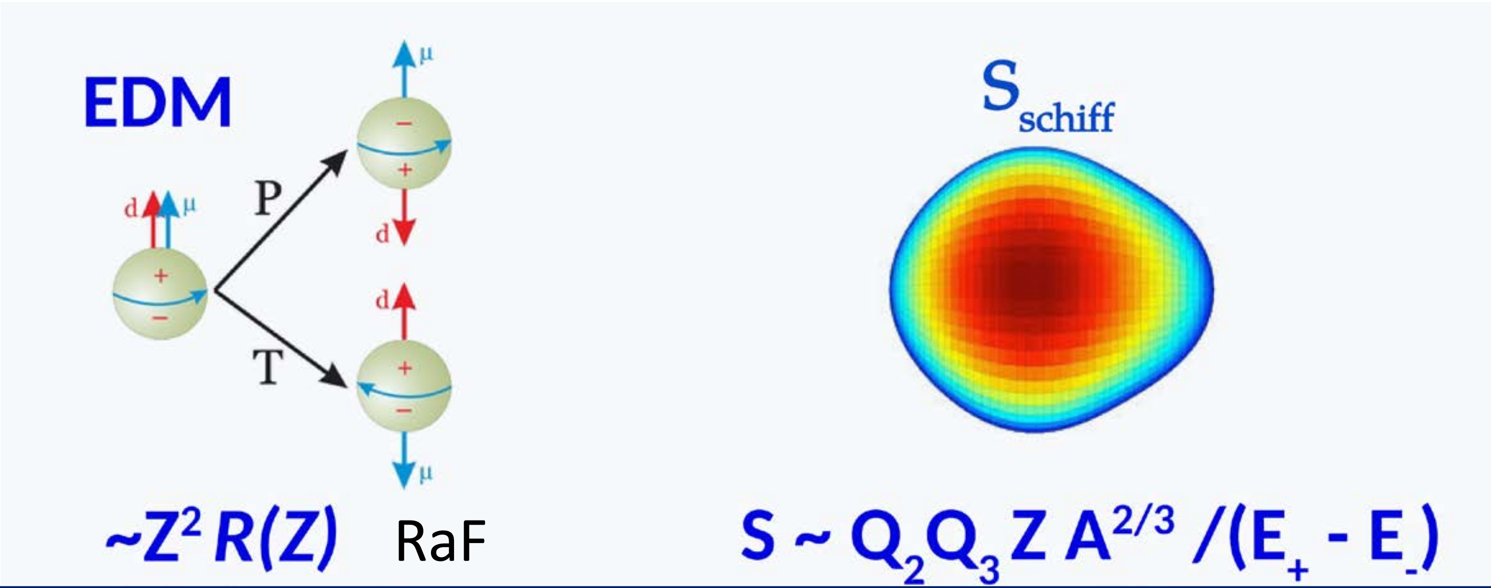


ZOMBIES (Yale, BaF)
Yb (Mainz)

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

Picture credits: Ronald Fernando Garcia Ruiz

T-violation



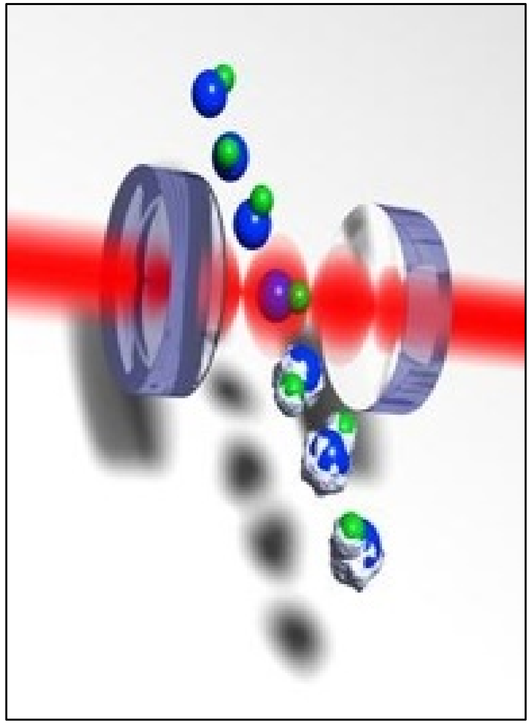
Ra and Ra-based molecules have a further enhancement due to an octupole deformation of the ^{225}Ra nucleus: an intrinsic Schiff moment 1000 times larger than in spherical nuclei such as Hg.

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

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)

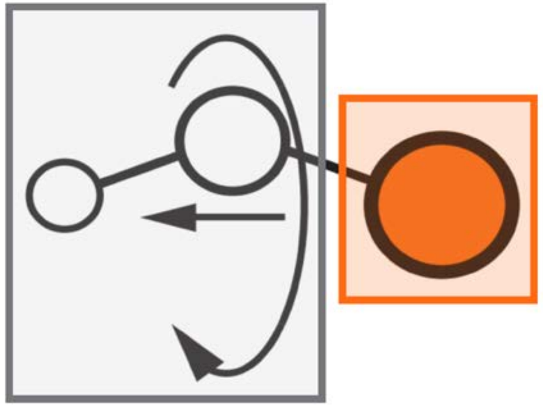
The observable signature of a Schiff moment will be a shift in the NMR frequency of ^{205}Tl nuclei when the molecules are polarized by a strong electric field.

First generation: a cryogenic molecular beam of TlF

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

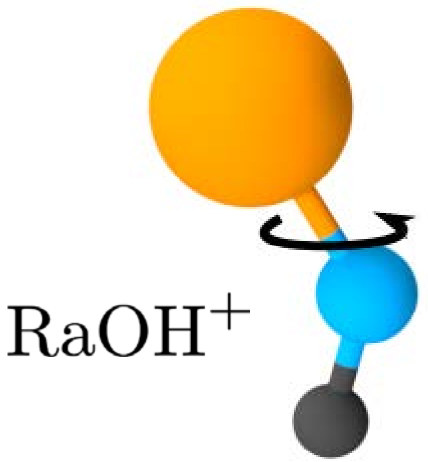
YbOH nuclear MQM

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



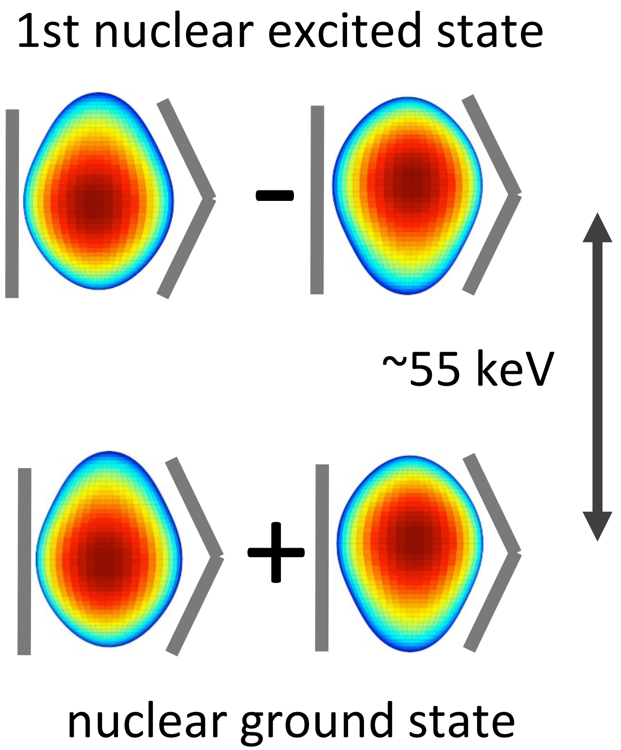
3 years:
beam-based measurements

T-violation with radioactive molecular ions



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)].



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)

T-violation with radioactive atoms and molecules: timeline

From Andrew Jayich and Ronald Fernando Garcia Ruiz

1-2 years : Laser cooling of $^{225}Ra^{+}$, measurements of Ra^{+} properties, Ac^{2+} with radium quantum logic
Investigate RaOH, RaOH+, other polyatomic molecules containing Ra, ^{229}ThO, $^{229}ThF^{+}$ at ISOLDE
RaF: Precision experiments: rotational and hyperfine structure

3 years: First quantum logic spectroscopy (QLS) of radioactive molecules using Ra+ as the logic qubit
QLS of radium-based triatomic molecules: RaOH+, RaSH+, RaCN+
RaF: Deacceleration and trapping

5 years: First QLS-based single molecular ion EDM measurement with Ra
Measure the nuclear energy level structure of ^{229}Pa
RaF: first laser cooling tests and systematic studies, symmetry-violating measurements

8 years: New θ_{QCD} bounds

10-15 years: If ^{229}Pa enhancement as predicted new θ_{QCD} bounds pushing the low few 10^{-13} range

Summary

- Several precision quantum sensing techniques well suited for future advances in HEP science (Interferometers, Mechanics, Traps, Clocks)
- Mid-scale efforts already launching at DOE labs (e.g. MAGIS)
- Many existing and developing small-scale experiments (precision torsion balance experiments, opto-mechanics, levitated sensors, optical interferometers, clocks, trapped atoms and molecules)
- Technical limiting factors in many (opto)-mechanical experiments (external vibration, gravity gradient noise) could be addressed by a development of a suitable underground facility that was open to outside users (cavity experiments, torsion balances, matter wave interferometers)