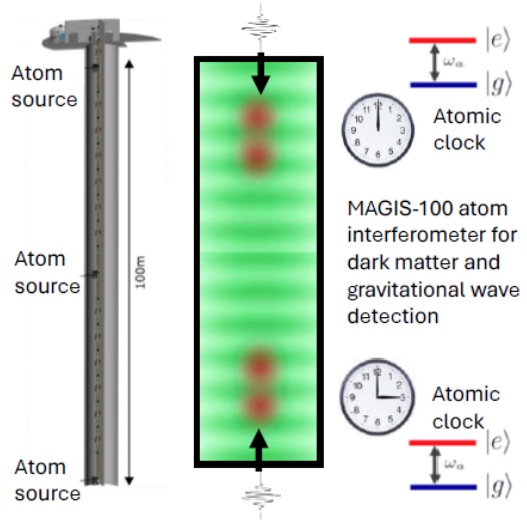
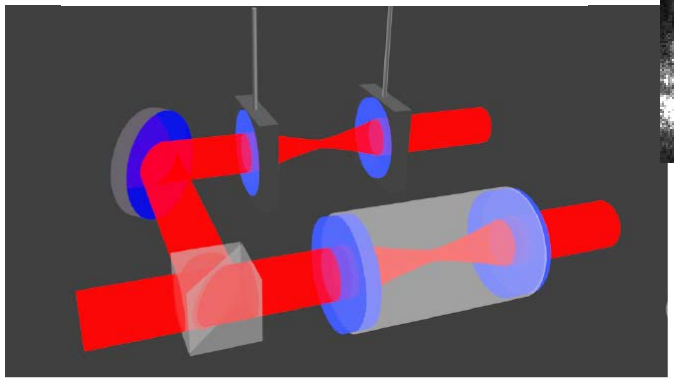
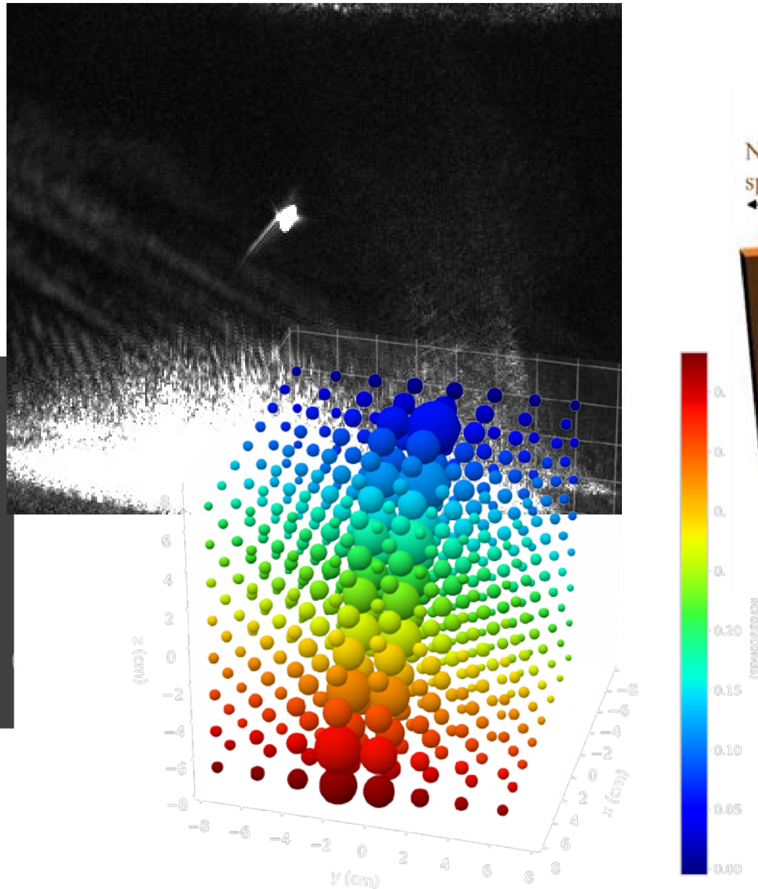
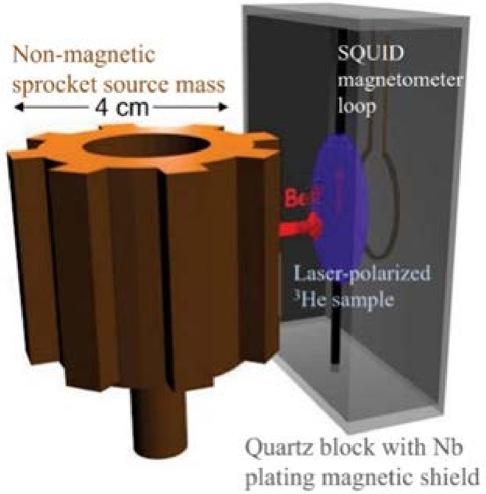
AMO, clocks, interferometry, NMR, Optomechanical Sensors (RDC-8 overview)









A.Geraci,
with S. Singh, T. Kovachy

Center for Fundamental Physics (CFP)

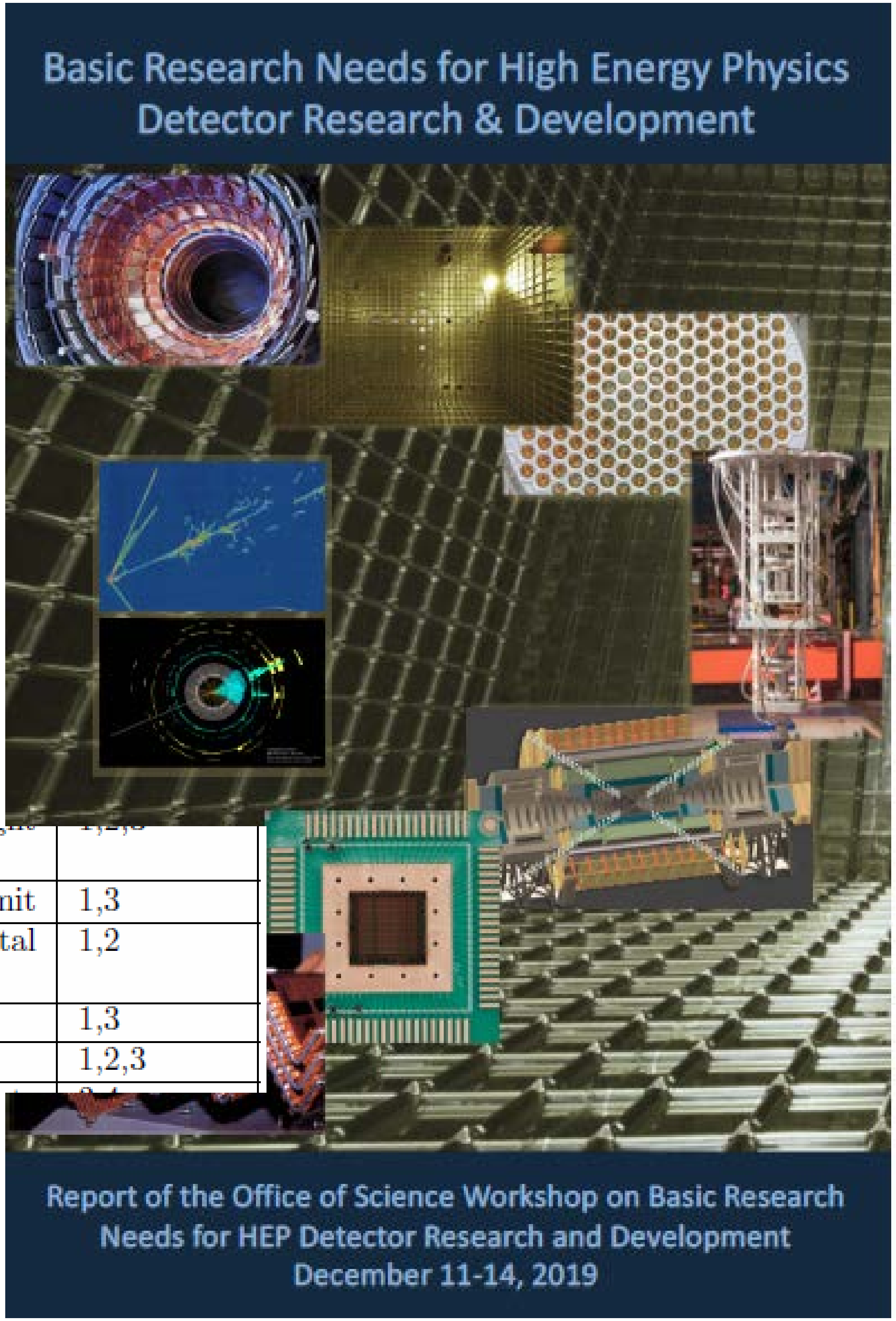
CPAD, Nov 19-22 2024, Knoxville, TN

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



RDC-8 Quantum Sensing methods:

This subcategory includes, but is not limited to, techniques and devices such as

- AMO methods, including clocks, interferometry, neutral atoms and molecules, trapped ions
- NMR, magnetometers, spin precession
- optomechanical sensors: optomechanical devices, optical-RF-magnetic levitation, cantilevers etc.
- entangled probes to beat the SQL with optical readout etc.

RDC-8 Goals and Work Packages:

RDC8-WP3a: Optimizing detector sensitivity, scalability, readout and control

Example ensemble-based quantum sensors: include atomic clocks, atomic interferometers, and spin-polarized samples, while device-based quantum sensors involve platforms such as optomechanical sensors or optical cavities.

It is of interest to improve the signal-to-noise of these sensing platforms:

including optimization of device design (e.g. by using larger volumes, higher density and/or polarization),

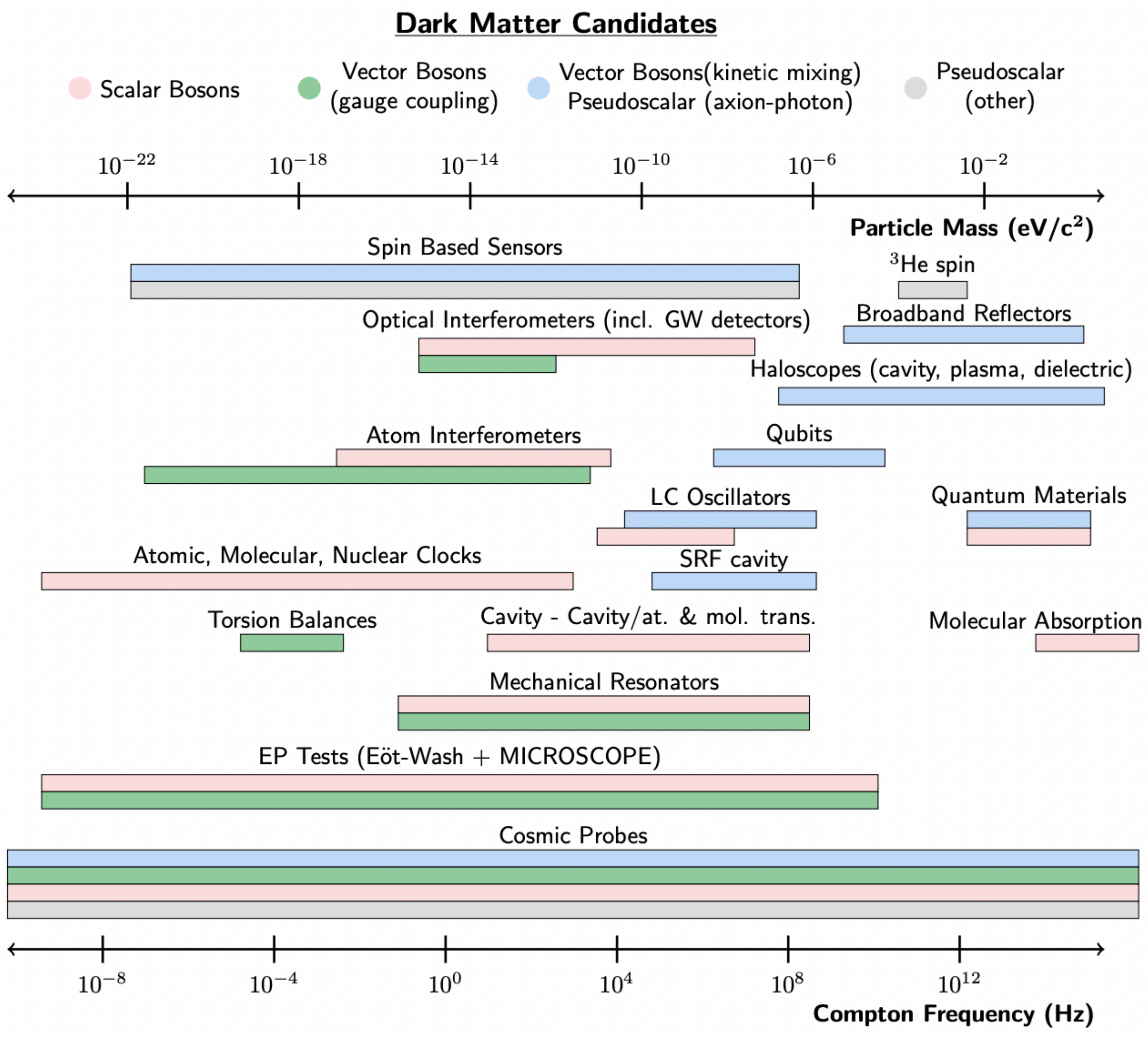
readout (e.g.via quantum measurement, control and parameter estimation techniques),

overcoming noise (e.g. spin projection noise).

→ Optimized sensors for:

- **dark matter and dark energy,**
- **tests of fundamental symmetries (e.g. CP violation),**
- **relativistic physics (e.g. gravitational wave detection)**
- **foundations of quantum mechanics.**

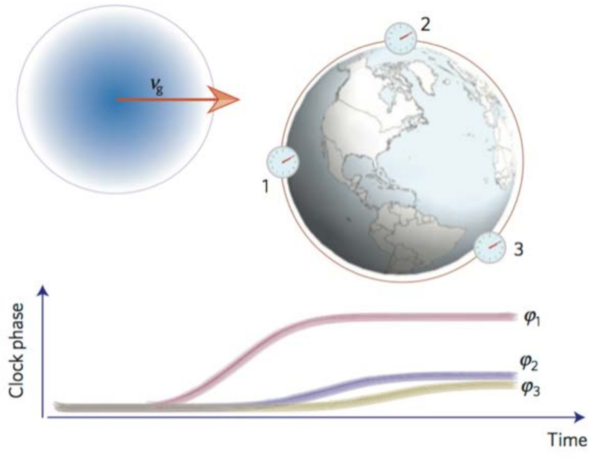
Diverse types of quantum sensors for ultralight DM searches



Similar figure made for: “New Horizons: Scalar and Vector ultralight dark matter”
Snowmass Proceedings of the US community study on the Future of Particle Physics (arXiv:2203.14915)

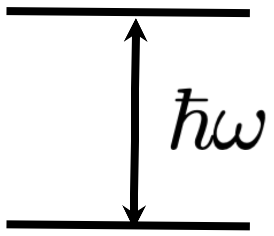
Example: Atomic Clocks

Constrain Transient DM candidates

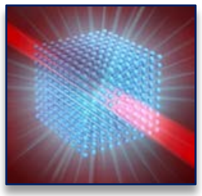


Dereviako & Pospelov, *Nature Physics* (2014)

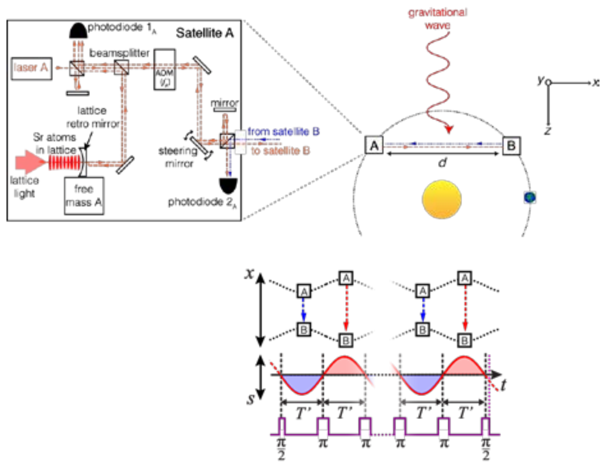
- Measure the qubit transition energy very well.



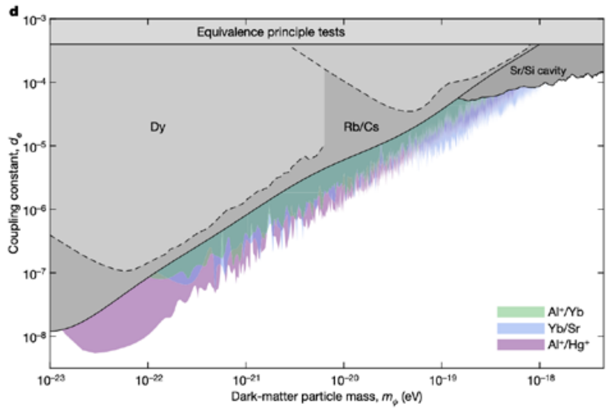
~1 part in 10^19

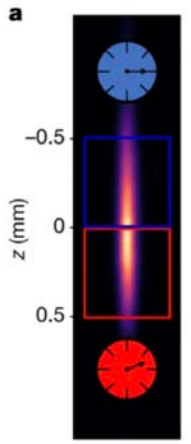


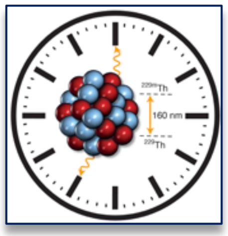
GW detection



- HEP-related applications:







Nuclear & highly charged ion clocks

Constrain Fuzzy DM candidates

Plot: BACON Collaboration, Nature **564** 591 (2021).

Measure GR time dilation (over mm scale)

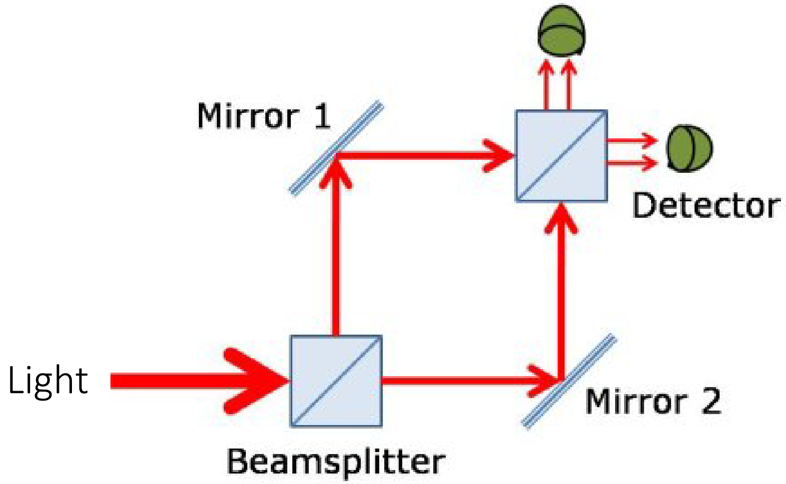
Figure: Bothwell et. al, Nature **602** 420 (2022).

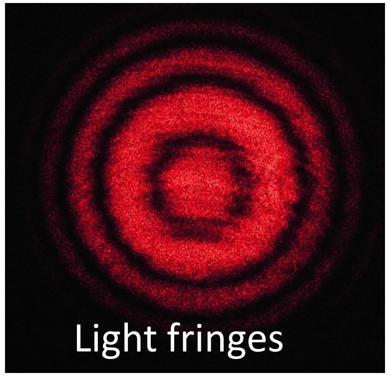
Lorentz invariance tests, etc.

Kolkowitz *et al. PRD* (2016)

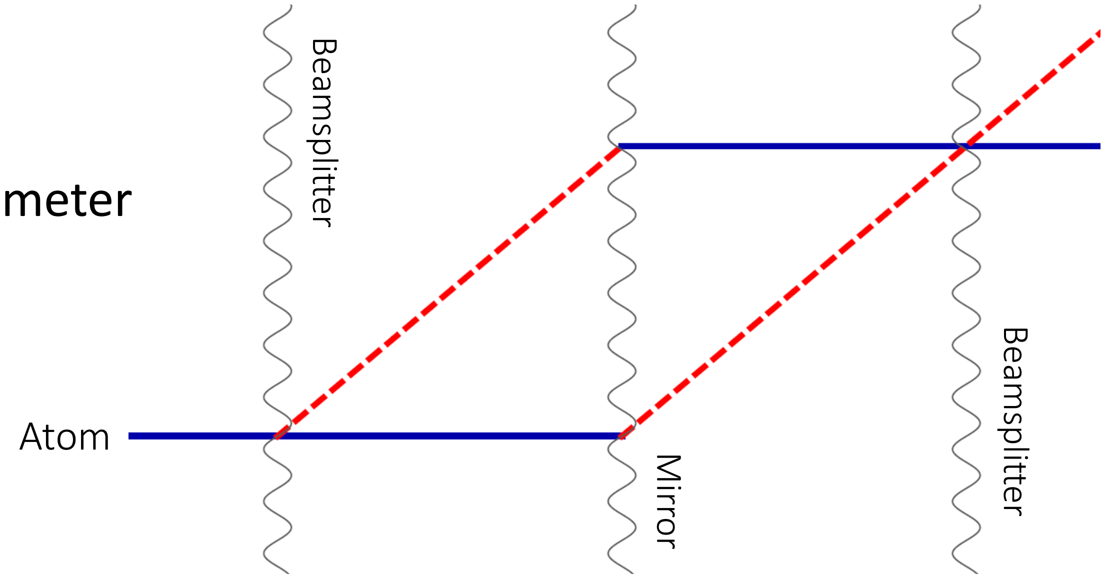
Example: Atom Interferometry

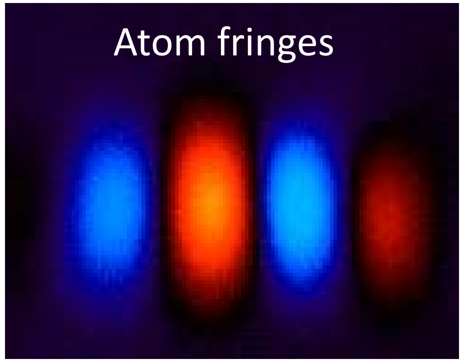
Light interferometer





Atom interferometer

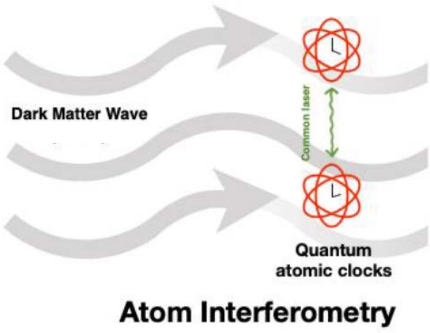




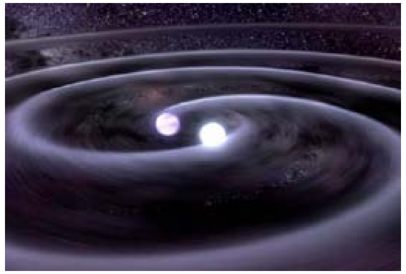
http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

Long-Baseline (100 m or longer) Atom Interferometry: Science Motivation

- Search for wavelike dark matter
  - Oscillating atomic transition frequencies
  - Oscillating species-dependent accelerations
  - Spin precession

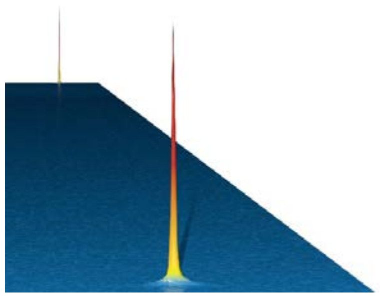


- Search for new fundamental interactions
  - Fifth forces



- Gravitational wave detection in new, mid-band frequency range (0.03 – 3 Hz)
  - Complementary to program of laser interferometer detectors
  - Promising to detect GWs generated during the early Universe, probe of high energy physics

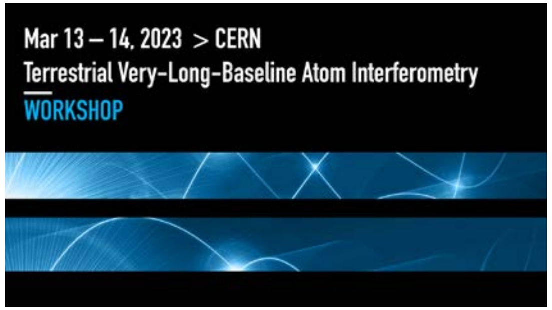
- Fundamental tests of quantum mechanics at macroscopic scales
  - Delocalizations >1 m for multiple seconds
  - Test fundamental decoherence mechanisms, non-linear quantum mechanics



Global Efforts in Long-Baseline Atom Interferometry

- Rapidly growing global community in this area, instruments being built around the world

- Example: CERN Very-Long-Baseline Terrestrial Atom Interferometry Workshop, March 13-14 (2023): ~200 registered participants. https://indico.cern.ch/event/1208783/



MAGIS-100 in US (Abe et al., QST 6, 044003 (2021))

AION in UK (Badurina et al., J. of Cosmology and Astrophysics 05 (2020) 011)

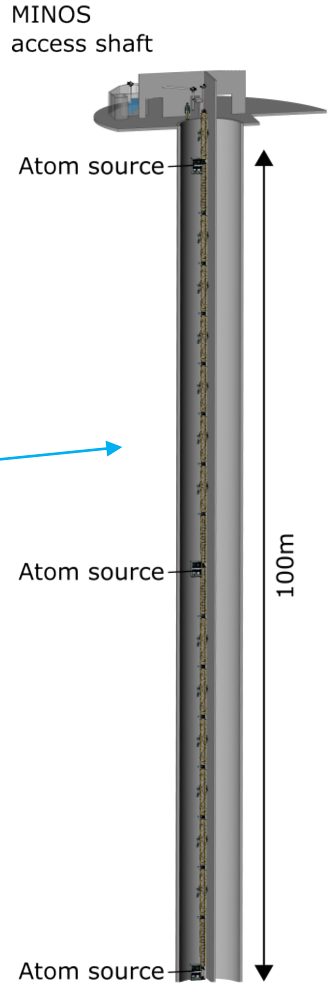
MIGA in France (Canuel et al., Scientific Reports 8, 14064 (2018))

ZAIGA in China (Zhan et al., International Journal of Modern Physics D 29, 1940005 (2020))

VLBAI in Germany (Hartwig et al., New Journal of Physics 17, 035011 (2015))

Naval Postgraduate School in US

- Community is also studying prospects for future space-based detectors (Abou El-Neaj et al., EPJ Quantum Technology 7, 6 (2020)); synergies with related proposals using optical lattice clocks in space (Kolkowitz et al., PRD 94, 124043 (2016))



Atom Interferometry R&D Needs

- Advanced quantum control techniques to enhance sensitivity and suppress influence of noise backgrounds, e.g. enabling the application of more “atom mirror” operations to increase signal amplification

- High-flux and spin-squeezed atom sources to improve phase resolution

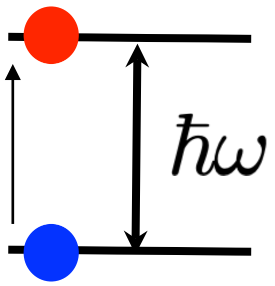
- Developing spatially and temporally multiplexed atom interferometry sensor arrays to reject backgrounds, improve measurement bandwidth, and detect transient signals

- Develop an international network of long-baseline atom interferometers—possibly with entanglement between different nodes

- Leverage artificial intelligence, machine learning, and simulation expertise from HEP community to develop improved control protocols and optimal data analysis strategies

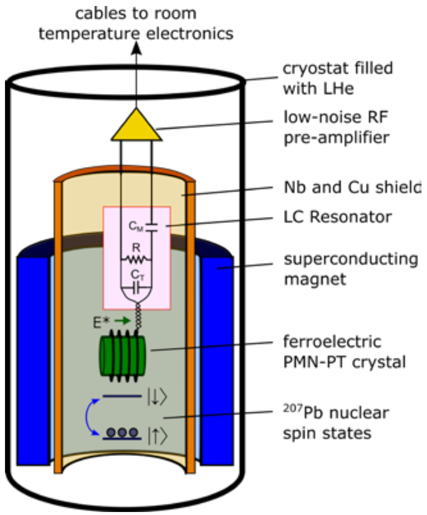
Examples: Nuclear Magnetic Resonance based sensors

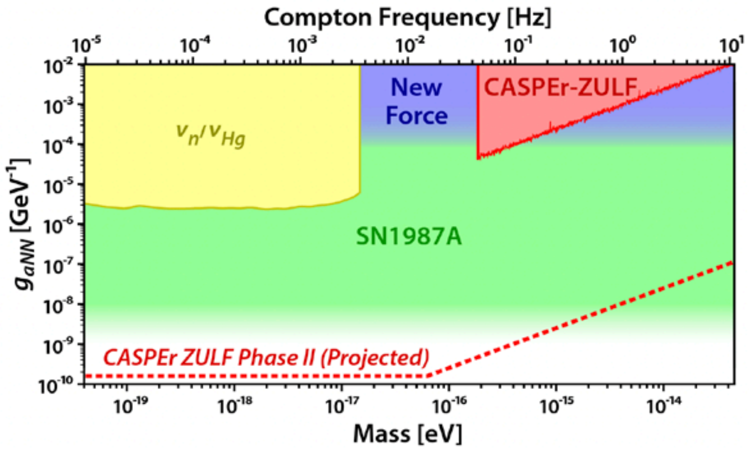
- Drive the qubit transition (sometimes by unknown fields, e.g axions).



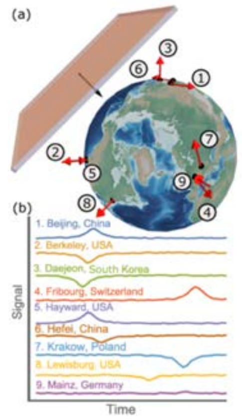
- HEP-related applications:

CASPER



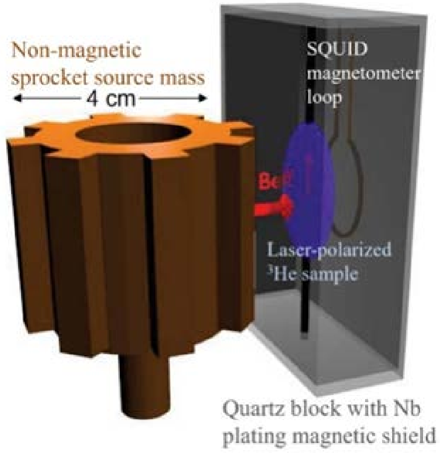


Garcon *et al.* , *Sci. Adv.* **5**,4539(2019)



From GNOME collaboration

ARIADNE



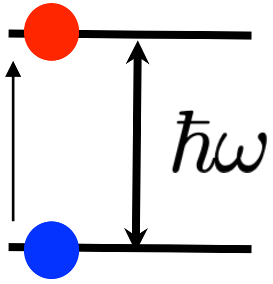
→ larger volumes, higher spin density and/or polarization

Fifth forces from axions

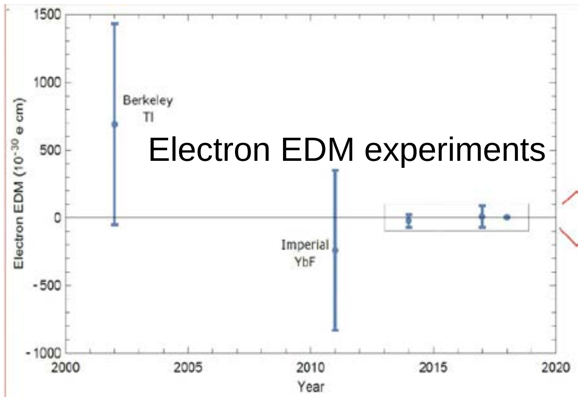
Spin-based sensor for BSM Review: PRA **108**, 010101 (2023).

Examples: Molecule Based sensors

- EDM searches

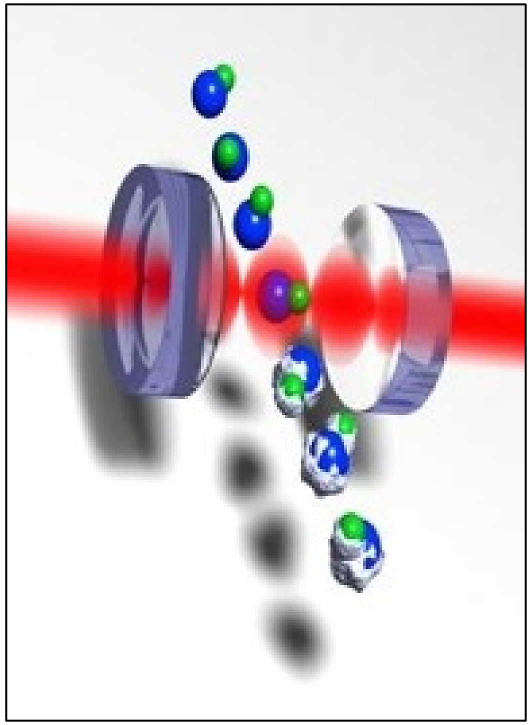


- HEP-related applications:



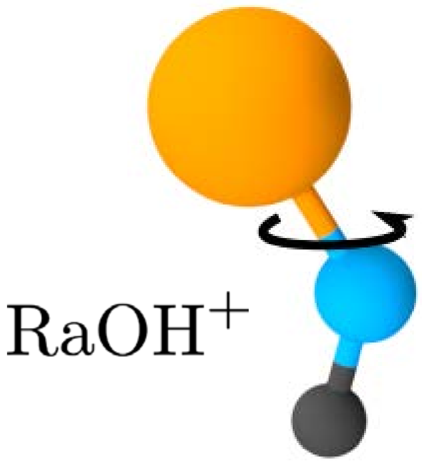
Plot: ACME at Northwestern Website (references therein)

CeNTREX: see arXiv:2010.01451



TlF (proton EDM)

T-violation with radioactive molecular ions

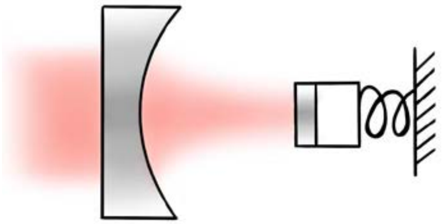


UCSB, Fan et al., PRL 126, 023002 (2021)

Spin-based sensor for BSM Review: PRA **108**, 010101 (2023).

Optomechanical sensors

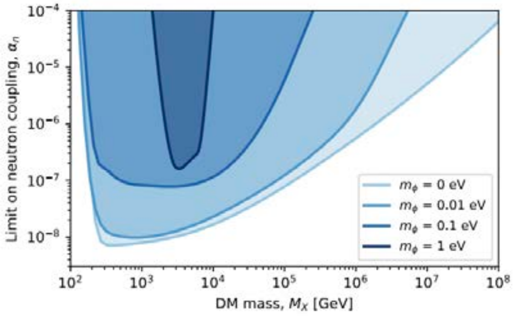
- Measure weak force/displacement very well.



LIGO

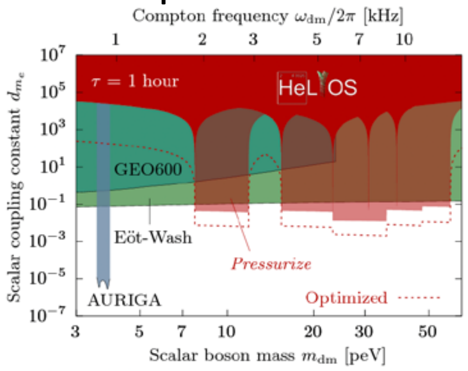
- HEP-related applications:

Levitated microspheres



Monteiro et al. PRL **125**, 181102 (2020).

Liquid He detectors



Hirschel et. al, arXiv 2309.07995 (2023).

High-freq. GW detection

Neutrino scattering

Quintessence-style fields…

Review: *Mechanical quantum sensing in the search for dark matter*,
Carney et. al, Quantum Sci. Technol. **6** 024002 (2021) .

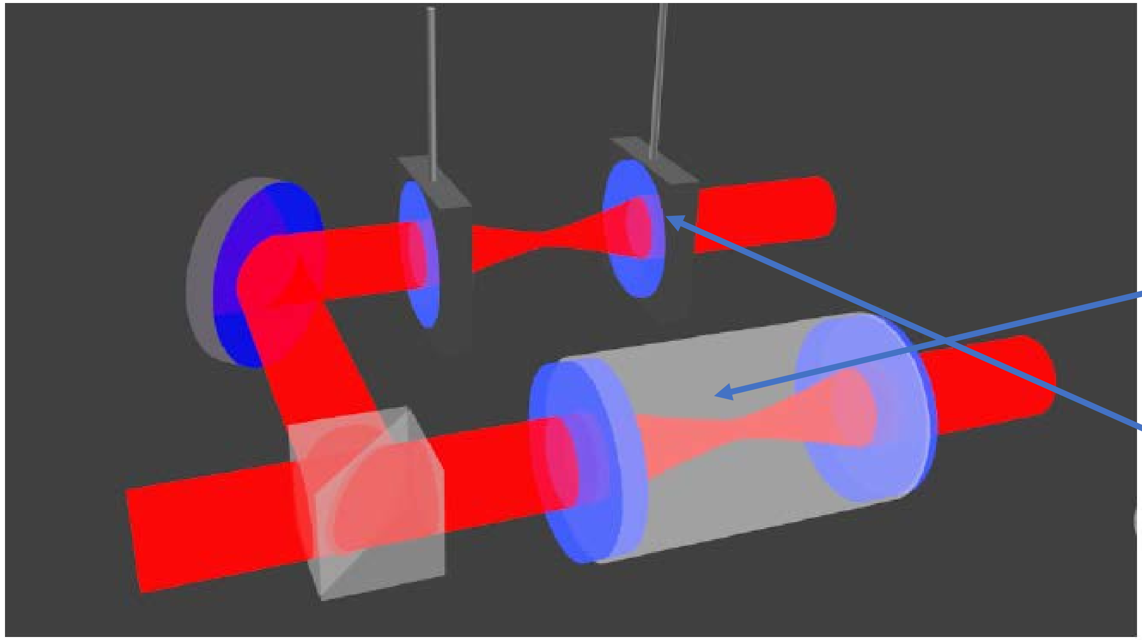
Example: Detecting ultra-light scalar dark matter with optical cavities

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

$$\frac{\delta m_e(t,\mathbf{r})}{m_{e,0}} = d_{m_e}\sqrt{4\pi\hbar c}E_P^{-1}\phi(t,\mathbf{r})$$

$$\frac{\delta\alpha(t,\mathbf{r})}{\alpha_0} = d_e\sqrt{4\pi\hbar c}E_P^{-1}\phi(t,\mathbf{r})$$

oscillations in size of atoms (and strain in material objects)

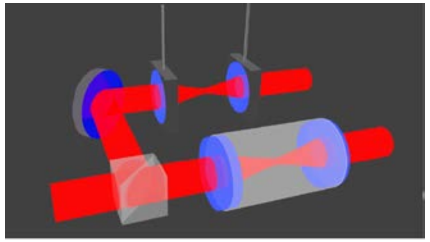


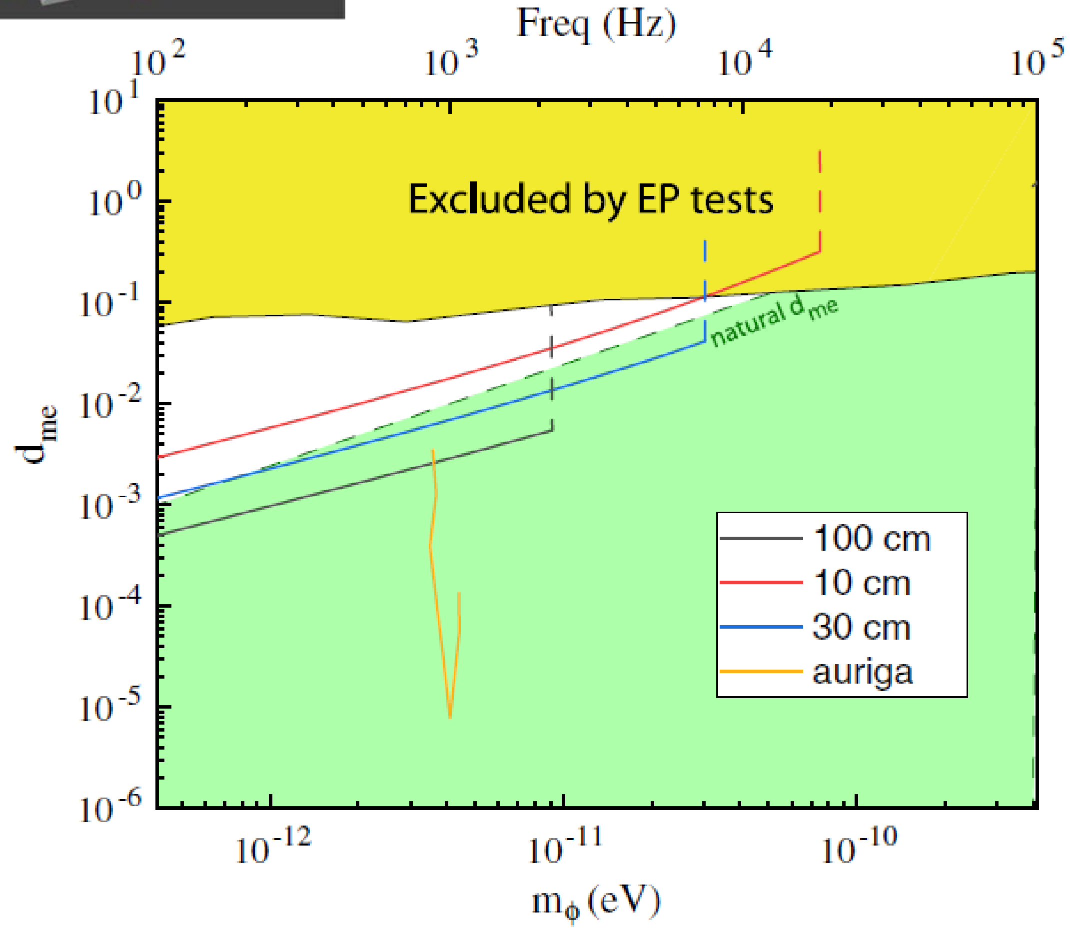
Dark matter field causes strain in rigid cavity at f_ϕ

Suspended cavity cannot respond quickly enough for f_ϕ in audio-band (100 Hz- 100 kHz)

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

Reach for variation of electron mass d_{me}

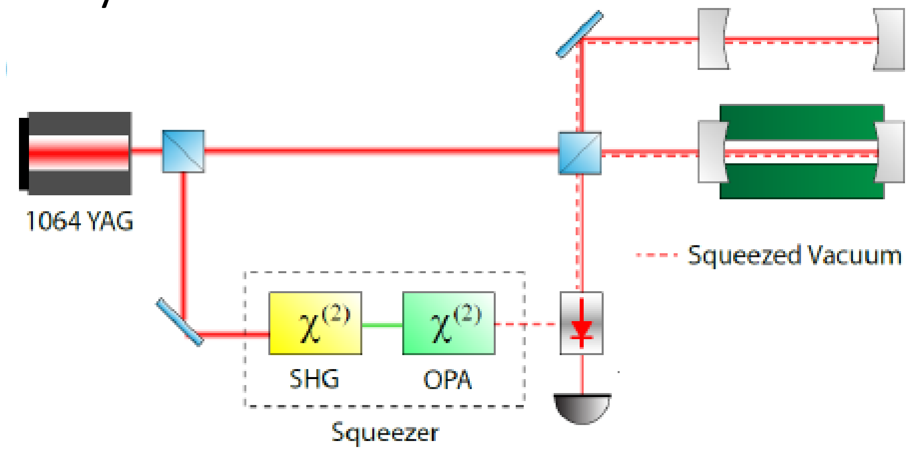




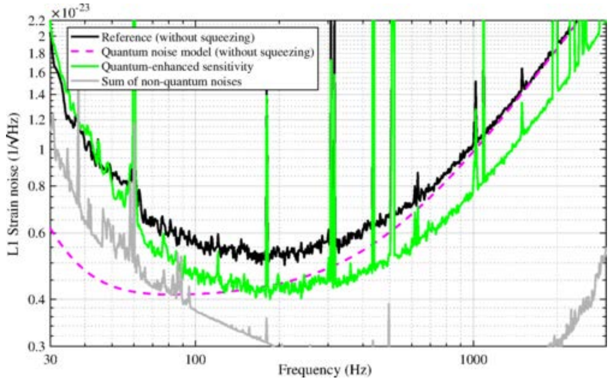
AG, C. Bradley, W. Gao, J. Weinstein, A. Derevianko, PRL (2019)

-Cryogenic experiment for low thermal noise to reach the shot noise limit

- quantum squeezing techniques can improve sensitivity >1 kHz

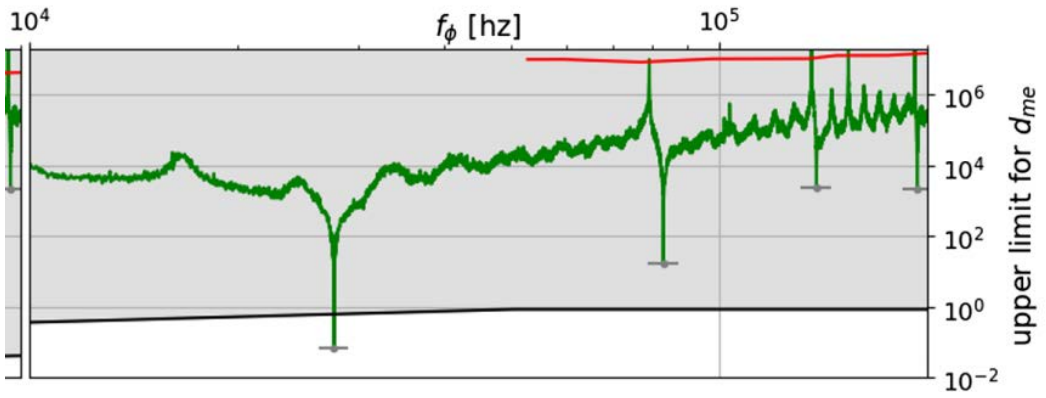


Borrow proven methods from GW community (LIGO, VIRGO):

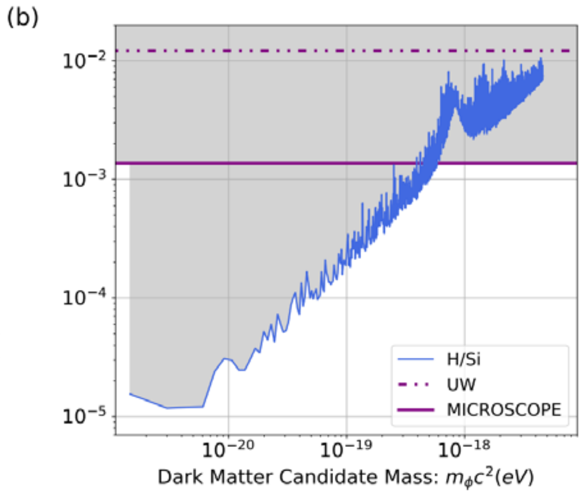


Recent DM limits from other cavity experiments

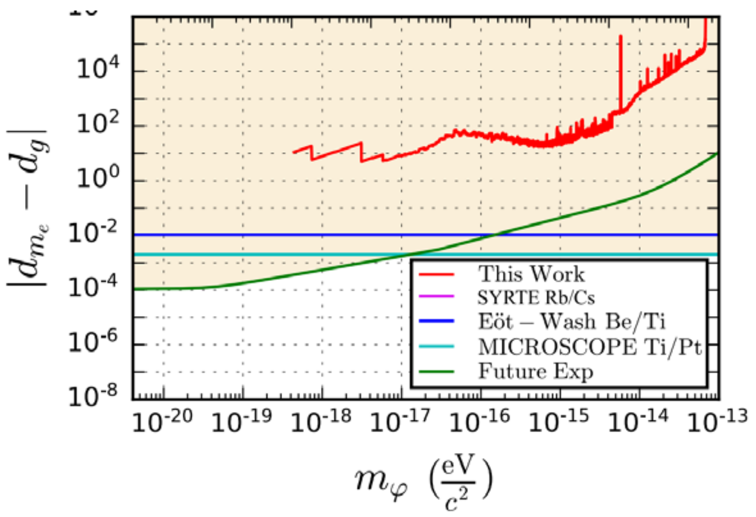
Experiments are **already** constraining scalar dark matter!



Savalle et al. PRL **126**, 051301 (2021).

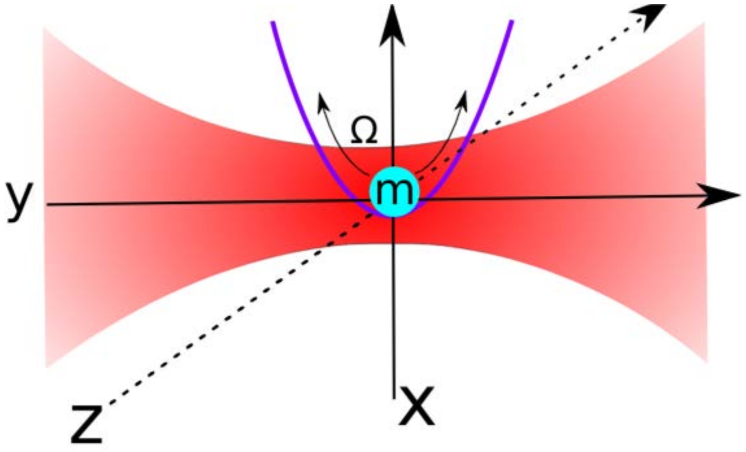


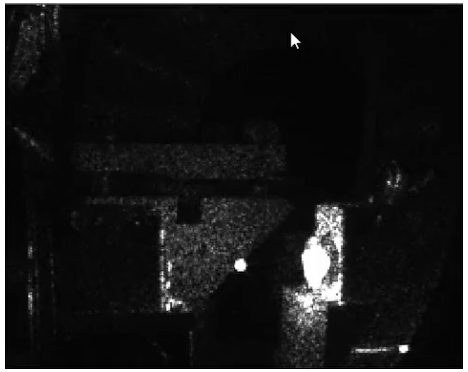
Kennedy et al. PRL **125**, 201302 (2020).



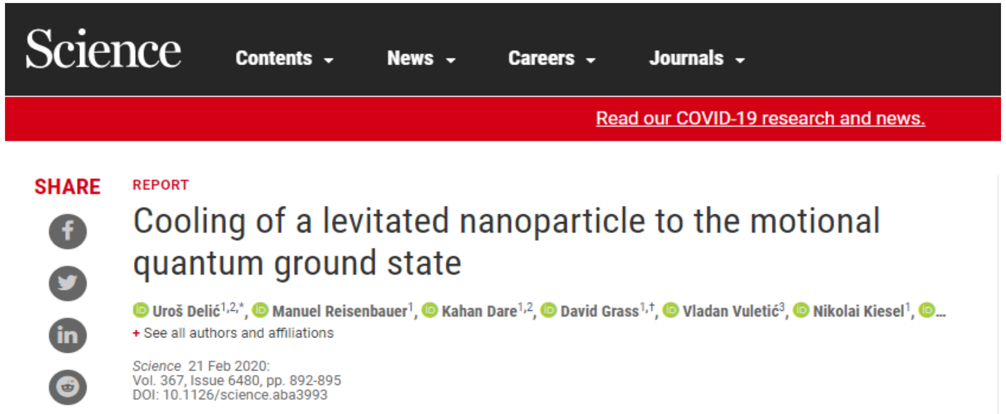
Campbell et al. PRL **126**, 071301 (2021)

Example: Levitated optomechanical sensors





- Neutral glass particles trapped in laser focus
- High Q factors ~ 10^12 → excellent force sensors
- Can reduce the effective motional 'temperature' to quantum ground state of vibration!



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REPORT

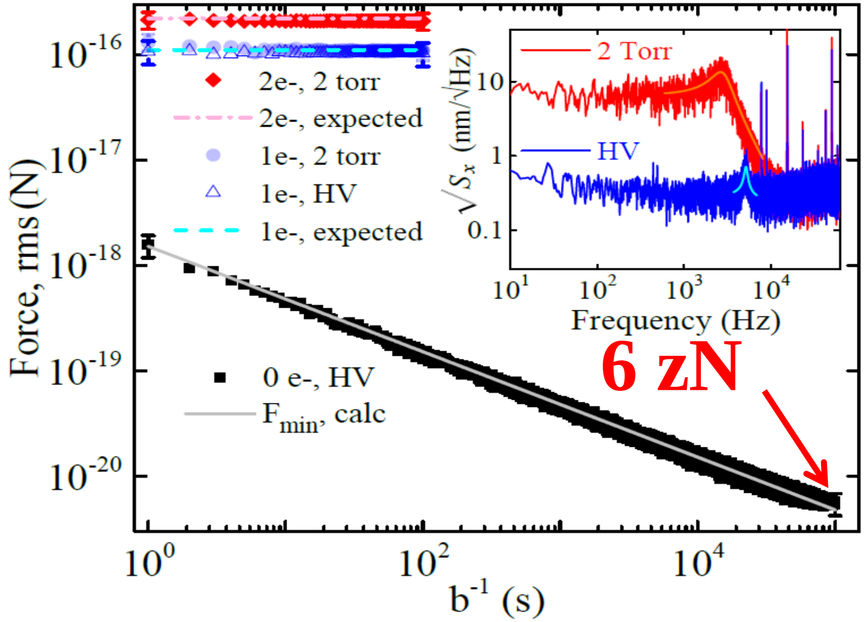
Cooling of a levitated nanoparticle to the motional quantum ground state

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

zeptonewton sensing

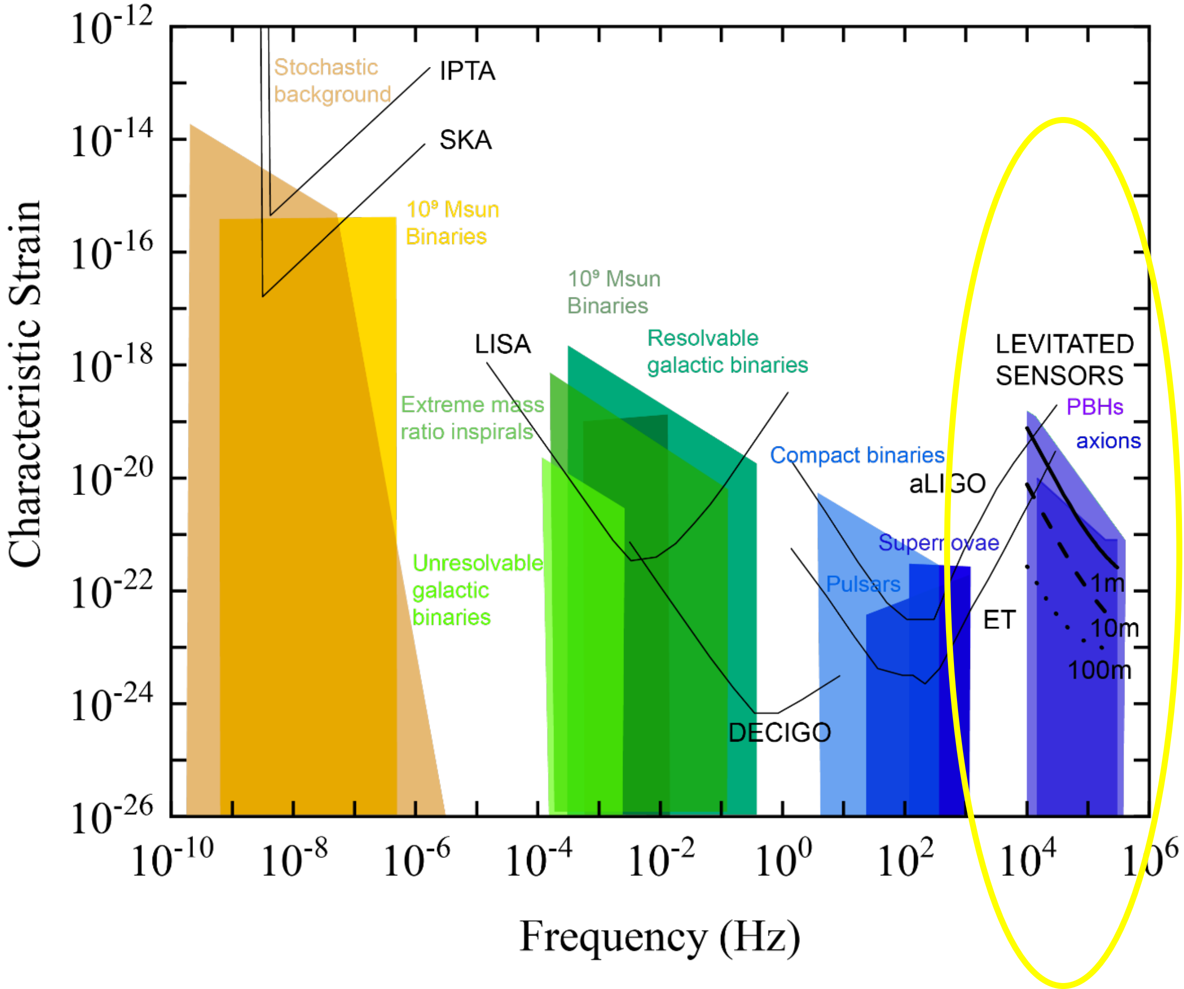


$$S_{F,x} = 1.63 \pm .37 \ \mathrm{aN}/\sqrt{\mathrm{Hz}}$$

G. Ranjit, et.al. , *Phys. Rev. A*, 93, 053801 (2016)

GW detectors as a probe of the dark sector

→Axions, Primordial Black holes (PBHs)



Primordial black hole dark matter and the LIGO/Virgo observations

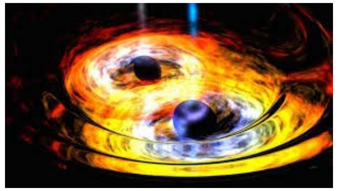
Karsten Jedamzik[1]

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

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

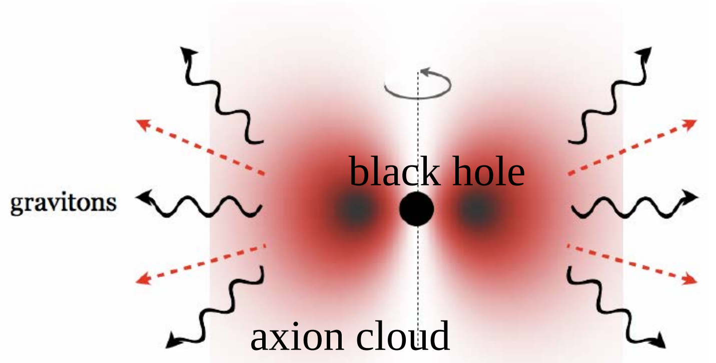
Citation Karsten Jedamzik JCAP09(2020)022

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, arxiv:2010.13157 (2020)

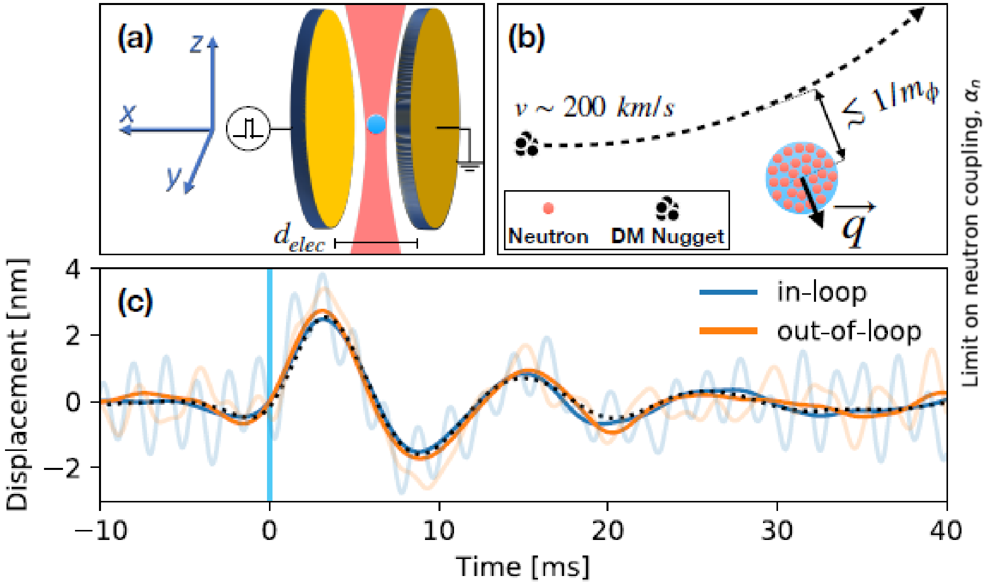
D.C. Moore and AG, Quantum Sci. Technol. 6 014008 (2021)

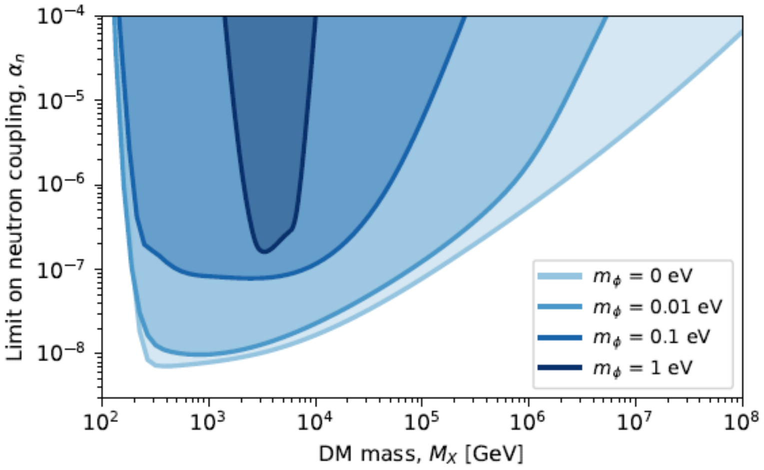
Composite DM search with Levitated microspheres

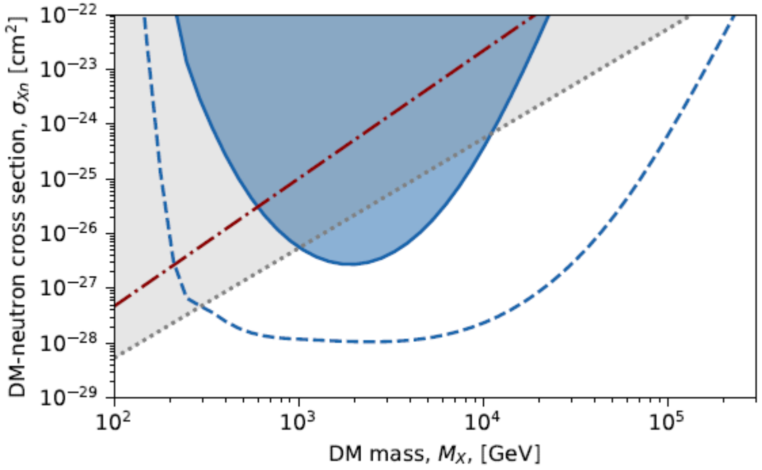
Search for Composite Dark Matter with Optically Levitated Sensors

Fernando Monteiro, Gadi Afek, Daniel Carney, Gordan Krnjaic, Jiaxiang Wang, and David C. Moore

Phys. Rev. Lett. **125**, 181102 – Published 28 October 2020



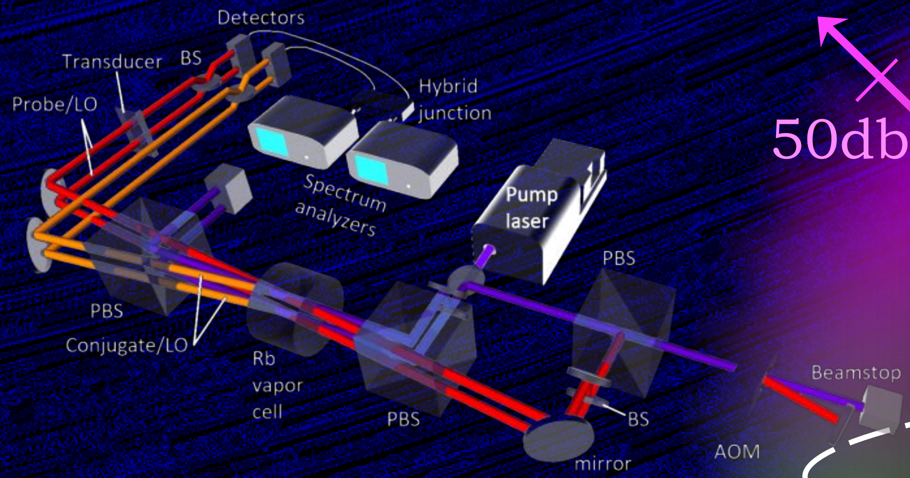


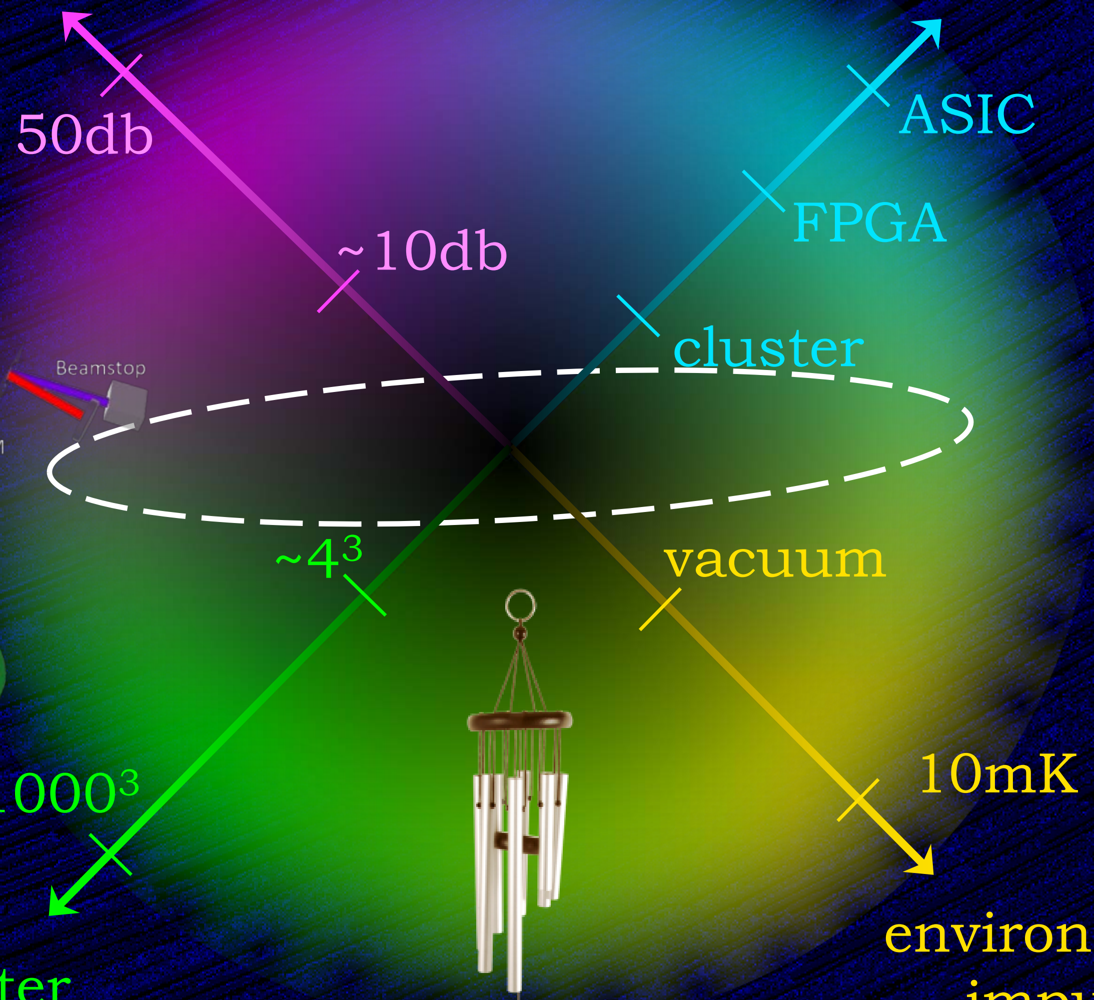


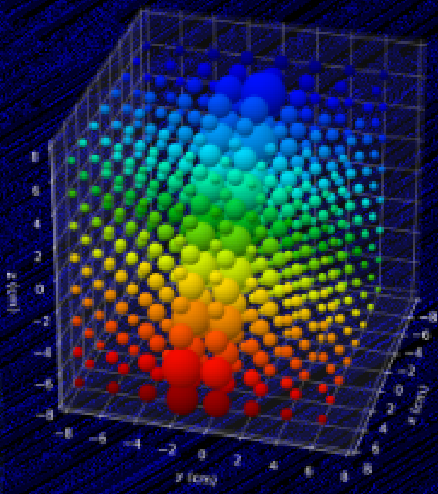
Windchime: Gravitational Detection of Planck-Mass Dark Matter

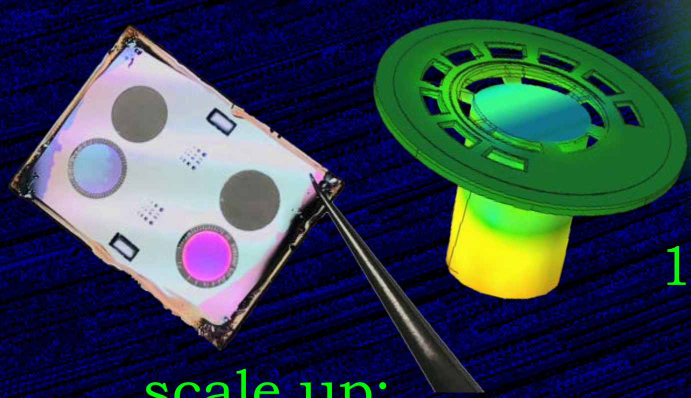
quantum noise suppression:
short signals (neutrinos/sub-GeV)

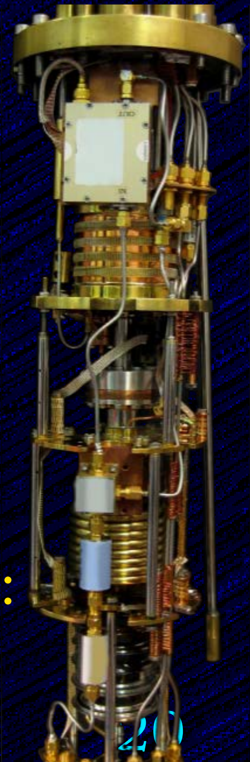
computing:
streaming analysis, ML-based design









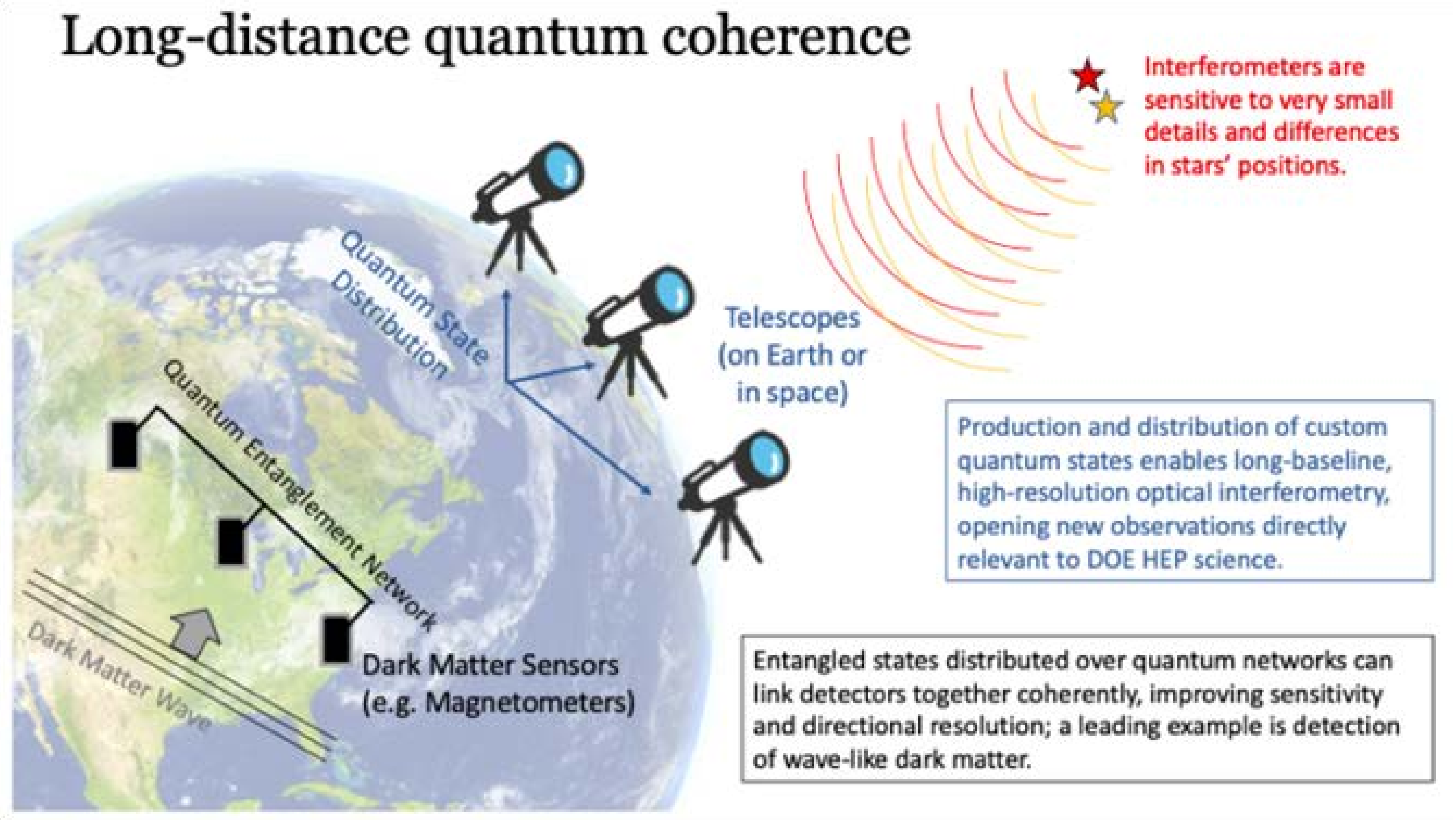


scale up:
ultralight dark matter

environmental isolation:
impulse metrology

Windchime

Quantum networks



Summary

- Several precision quantum sensing techniques well suited for future advances in HEP science. 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, NMR spin ensembles)
- Technical limiting factors in many (e.g. 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)
- Exciting road ahead in the coming decade!