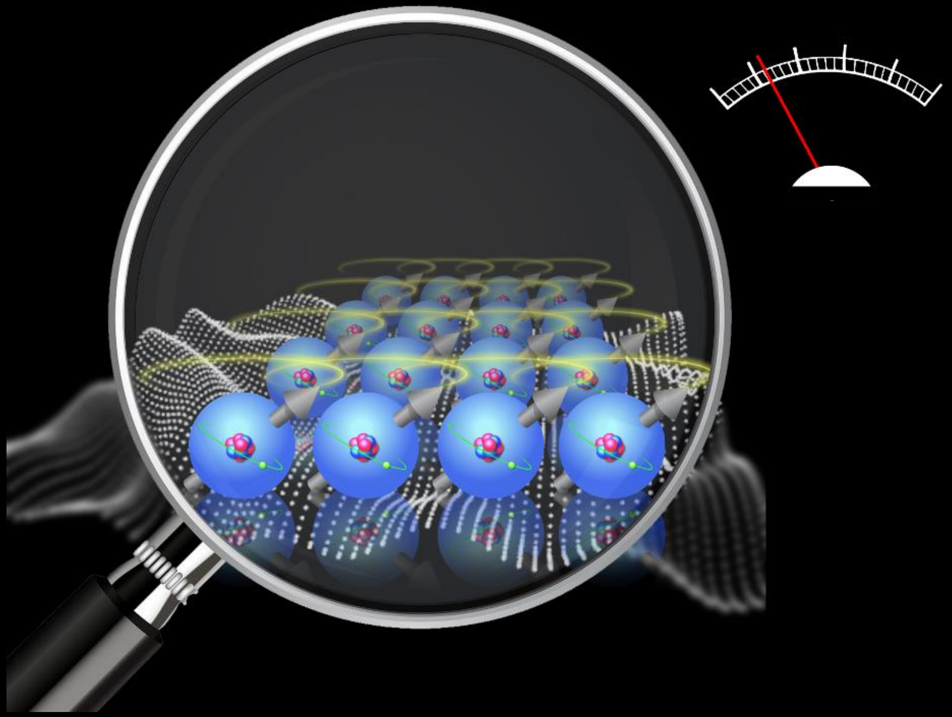

Quantum ensembles: spins and traps

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SnowMass2021

Spin-based searches for axions and ultra-light dark matter

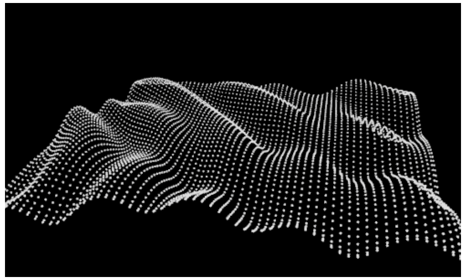
axion ⇔ strong CP problem

$\mathcal{L} \propto \theta_{\text{QCD}} G_{\mu\nu}\tilde{G}^{\mu\nu}$

axion-like dark matter $a(t) = a_0 \cos \omega_a t$

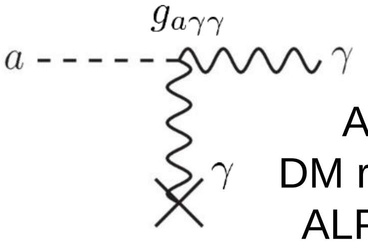
$\omega_a = m_a c^2/\hbar$ → ALP Compton frequency

$\rho_{\text{DM}} \propto a_0^2$ → dark matter density



axion field amplitude → $\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$ ← symmetry breaking scale

coupling to photons



ADMX, HAYSTAC, DM radio, ABRA, SHAFT, ALPS, CAST, IAXO, …

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

coupling to gluons

→ creates oscillating nucleon electric dipole moment (EDM)

→ spin to axion coupling:

$H \propto \vec{d} \cdot \vec{E}_{eff}$

$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$

coupling to fermions

→ creates axion "wind"

→ spin to axion "wind" coupling:

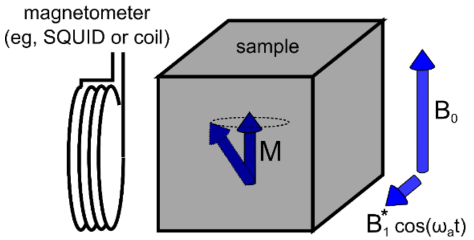
$H \propto \vec{\mu} \cdot \vec{B}_{eff}$

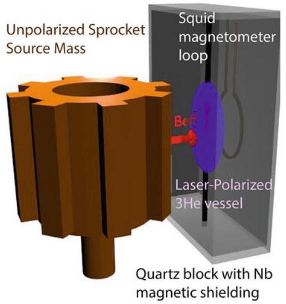
a figure of merit →

$\xi = xp\sqrt{N\tau}$

polarization, number of spins, coherence time

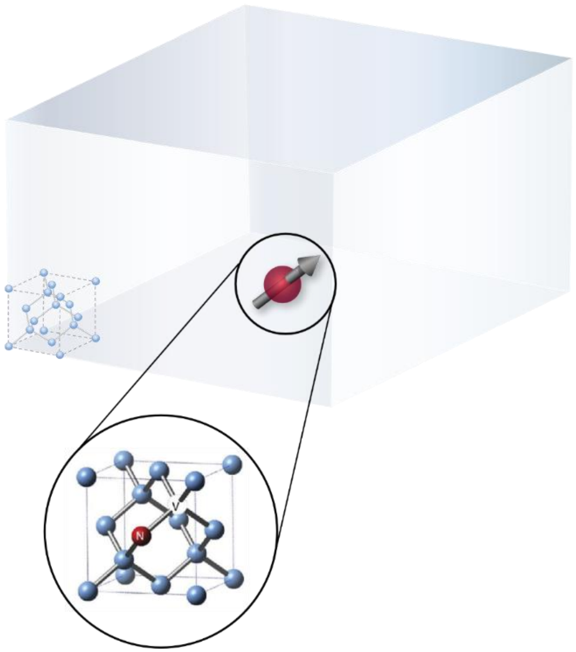
- CASPEr collaboration: g_d, g_{an} [D. Budker et al., *Phys. Rev. X* **4**, 021030 (2014)] [A. Garcon et al., *Science Adv.* **5**, eaax4539 (2019)]
- QUAX collaboration: g_{ae} [N. Crescini et al., *Phys. Rev. Lett.* **124**, 171801 (2020)]
- ARIADNE collaboration: g_{an} [A. Arvanitaki and A. Geraci, *Phys. Rev. Lett.* **113**, 161801 (2014)]



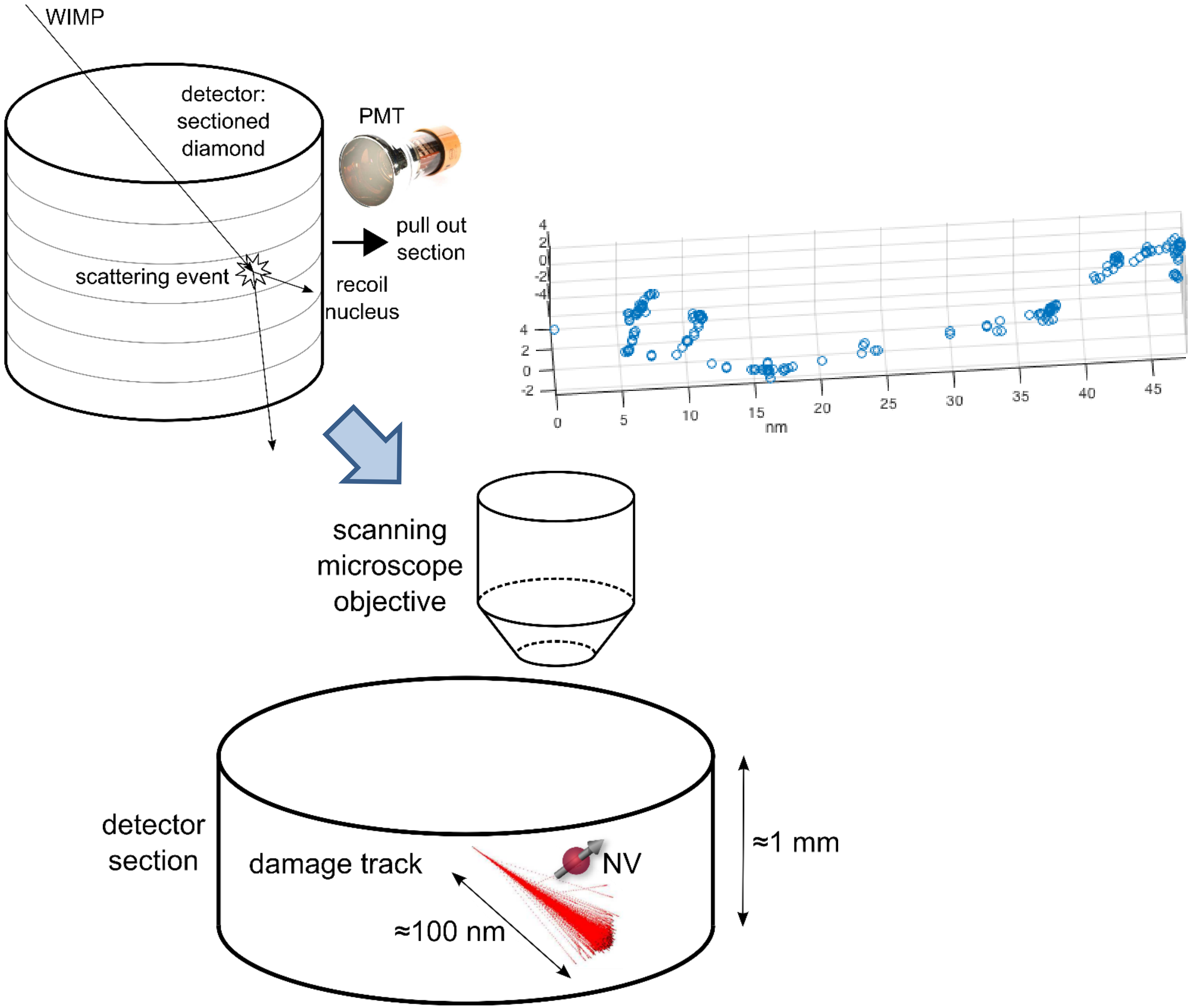


Spins as local quantum sensors

- a directional detector for WIMP dark matter using color centers in diamond
  [S. Rajendran, et al., *Phys. Rev. D* **96**, 035009 (2017)]

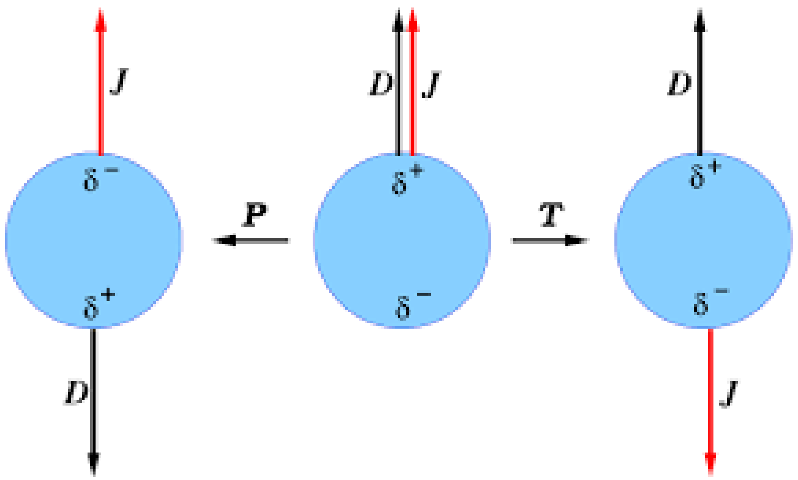


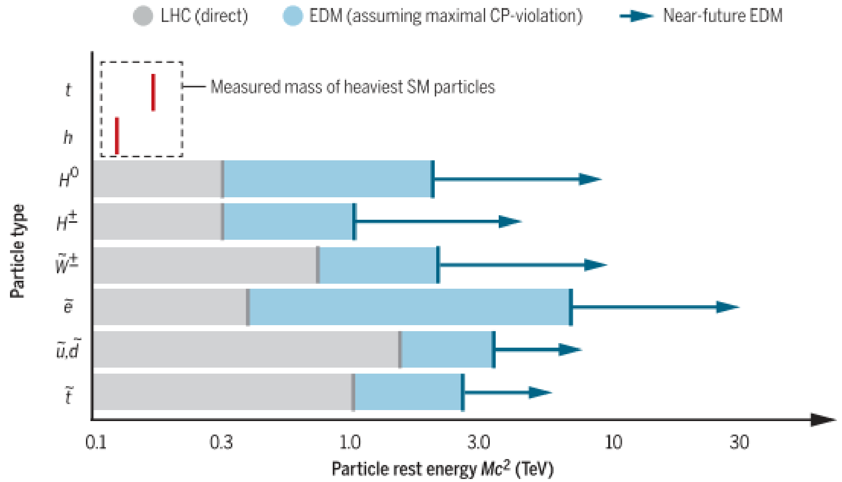
NV center



AMO searches for permanent electric dipole moments (EDM)

EDM experiments probe T-violating physics at high energies (eg, SUSY)

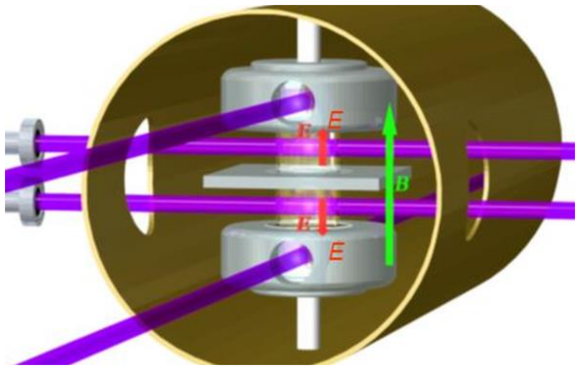




[D. DeMille, J. Doyle, A. Sushkov, *Science* **347**, 1100 (2015)]
[W. B. Cairncross, Jun Ye, *Nature Reviews Phys*. **1**, 510 (2019)]

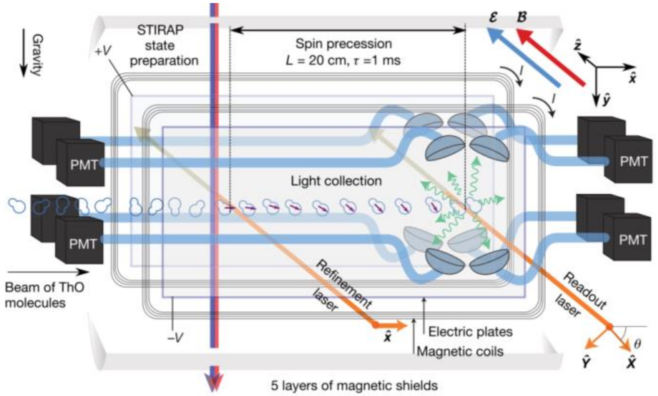
- ^{199}Hg EDM

[B. Graner, et al., *Phys. Rev. Lett*. **116**, 161601 (2016)]



- ACME collaboration: electron EDM with ThO

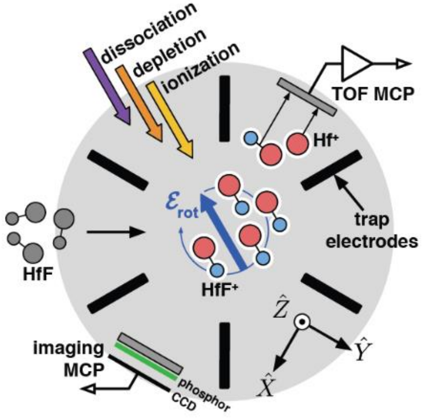
[J. Baron et al., *Science* **343**, 269 (2014)]
[V. Andreev et al., *Nature* **562**, 355 (2018)]



cold molecular beams

- HfF⁺ electron EDM experiment at JILA

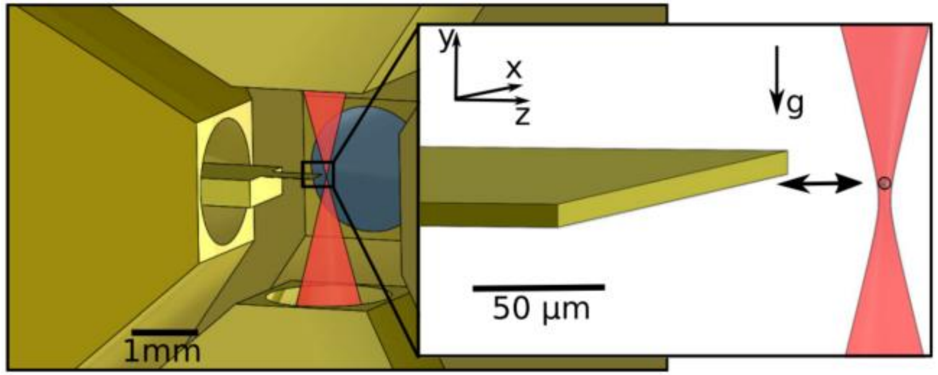
[W. B. Cairncross, et al., *Phys. Rev. Lett*. **119**, 153001 (2017)]

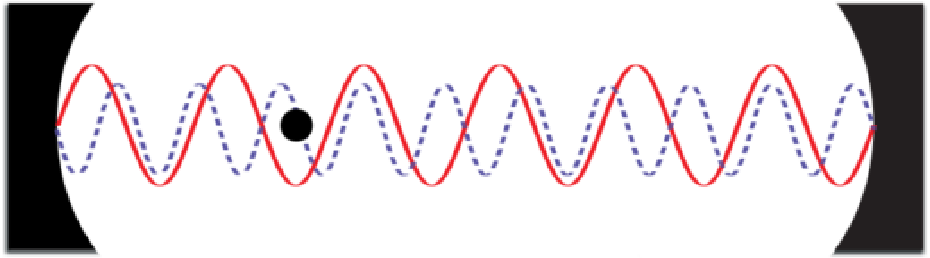


trapped molecular ions

5th force and dark matter searches with optomechanics

- 5th force, dark energy, and other new physics searches using levitated particles as test masses:

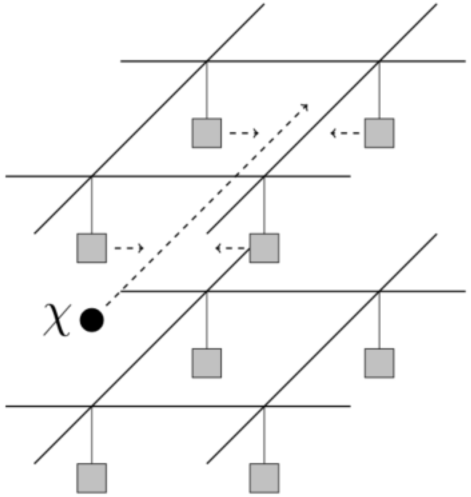




[A.D. Rider, et al., *Phys. Rev. Lett.* **117**, 101101 (2016)]
[A. Arvanitaki and A. Geraci, *Phys. Rev. Lett.* **101**, 071105 (2013)]
[D.C. Moore, et al., *Phys. Rev. Lett.* **113**, 251801 (2014)]

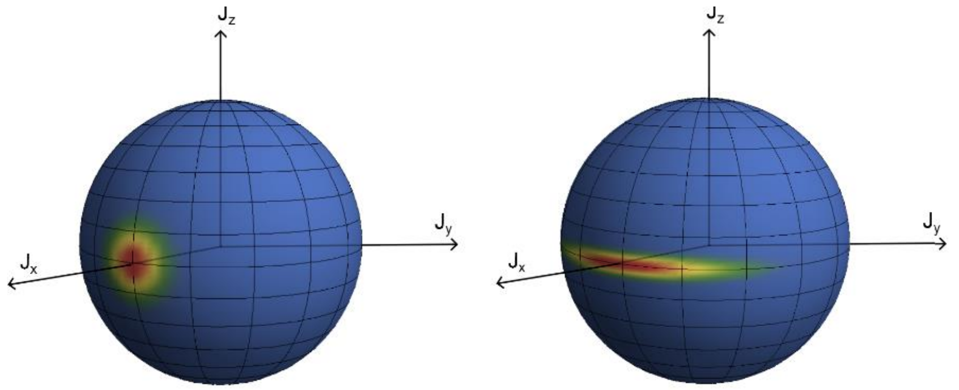
- dark matter coupling to mass

Physical device	Mass	Frequency	Temp.	Quantum limit	Sensitiv
Resonant acoustic wave:					
BAW/Weber bar [41]	1000 kg	1 kHz	4 K		$h_s \sim 10$
HBAR/phonon counting [76]	50 μg	10 GHz	10 mK	single phonon	$\sigma_E \sim 3$ $h_s \sim 10$ $(h_s \sim 1$
superfluid helium cavities [52]	1 ng	300 MHz	50 mK	single phonon	$\sigma_E \sim 1$
Resonant and below-resonance detectors:					
cantilever optomechanical accelerometer [77]	25 mg	10 kHz	300 K		$\sqrt{S_a} \sim$ $(\sqrt{S_a} \sim$
SiN-suspended test mass accelerometer [78, 79]	10 mg	10 kHz	300 K		$\sqrt{S_a} \sim$ $(\sqrt{S_a} \sim$
membrane optomechanics [80–86]	10 ng	1.5 MHz	100 mK	at SQL	$\sqrt{S_a} \sim$ $\sqrt{S_f} \sim$
crystalline cantilever for force sensing [87]	0.2 ng	1 kHz	200 mK		$\sqrt{S_a} \sim 3 \times 10^{-7}$g/$\sqrt{\text{Hz}}$ $\sqrt{S_f} \sim 10^{-18}$ N/$\sqrt{\text{Hz}}$
Pendula above resonance:					
LIGO mirror [88]	10 kg	10 Hz – 10 kHz	300 K	SN limited above 100 Hz	$\sqrt{S_a} \sim 4 \times 10^{-15}$ g/$\sqrt{\text{Hz}}$ at 100 Hz $\sqrt{S_x} \sim 10^{-19}$ m/$\sqrt{\text{Hz}}$
suspended mg mirror [89–91]	1 mg	1 – 10 kHz	300 K	factor of 20 in displacement from (off-resonant) SQL	$\sqrt{S_a} \sim 7 \times 10^{-11}$ g/$\sqrt{\text{Hz}}$ at 600 Hz $\sqrt{S_x} \sim 5 \times 10^{-17}$ m/$\sqrt{\text{Hz}}$
crystalline cantilever [92]	50 ng	10 – 100 kHz	300 K	at (off-resonant) SQL	$\sqrt{S_a} \sim 2 \times 10^{-7}$ g/$\sqrt{\text{Hz}}$ at 20 kHz $\sqrt{S_x} \sim 10^{-16}$ m/$\sqrt{\text{Hz}}$
Levitated and free-fall systems:					
LISA pathfinder [93]	15 kg	1 – 30 mHz	300 K		$\sqrt{S_a} \sim 10^{-15}$ g/$\sqrt{\text{Hz}}$
mm magnetically-levitated sphere [94]	4 mg	20 Hz	5 K		$\sqrt{S_a} \sim 2 \times 10^{-7}$ g/$\sqrt{\text{Hz}}$ $\sqrt{S_f} \sim 8 \times 10^{-12}$ N/$\sqrt{\text{Hz}}$
sub-mm magnetically-levitated sphere [95]	0.25 μg	1–20 Hz	laser cool to < 9 K		$\sqrt{S_a} \sim 10^{-7}$ g/$\sqrt{\text{Hz}}$ $\sqrt{S_f} \sim 2 \times 10^{-16}$ N/$\sqrt{\text{Hz}}$
optically trapped microsphere [96]	1 ng	10 – 100 Hz	laser cool to 50 μK	factor of 100 in displacement from (off-resonant) SQL	$\sqrt{S_a} \sim 10^{-7}$ g/$\sqrt{\text{Hz}}$ $\sqrt{S_f} \sim 10^{-18}$ N/$\sqrt{\text{Hz}}$
optically trapped nanosphere [97, 98] (rotational [99])	3 fg	300 kHz	laser cool to 12 μK	ground state	$\sqrt{S_a} \sim 7 \times 10^{-4}$ g/$\sqrt{\text{Hz}}$ $\sqrt{S_f} \sim 2 \times 10^{-20}$ N/$\sqrt{\text{Hz}}$ $\sqrt{S_\tau} \sim 10^{-27}$ Nm/$\sqrt{\text{Hz}}$
trapped ion crystal [18]	10^{-6} fg	1 MHz			$\sqrt{S_a} \sim 50$ g/$\sqrt{\text{Hz}}$ $\sqrt{S_f} \sim 4 \times 10^{-22}$ N/$\sqrt{\text{Hz}}$



[D. Carney, et al., arXiv:2008.06074]   [D. Carney, et al., arXiv:1903.00492]

Entanglement as a resource for HEP-relevant quantum sensors



detector figures of merit can sometimes be improved by making use of quantum correlations, such as entanglement, squeezing

- measurements beyond SQL

  [LIGO collab., *Nature Photon*. **7**, 613 (2013)]
  [O. Hosten, et al., *Nature* **529**, 505 (2016)]

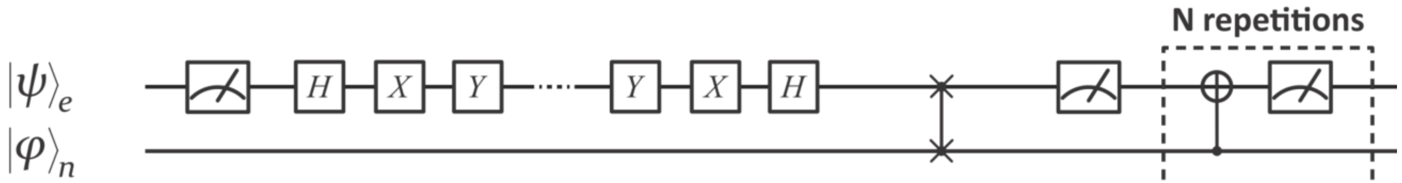
$\xi \propto \sqrt{N}$ (SQL)

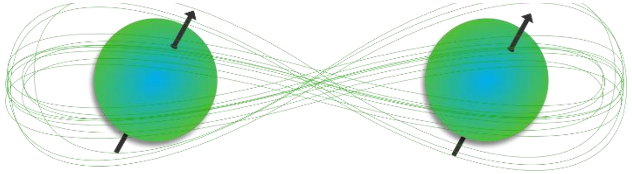
⇩

$\xi \propto N$ (Heisenberg)

- QND measurements, back-action evasion

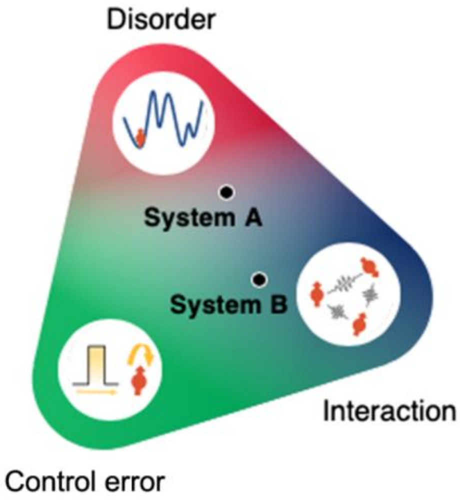
  [D. B. Hume, et al., *Phys. Rev. Lett*. **99**, 120502 (2007)]
  [I. Lovchinsky, et al., *Science* **351**, 836 (2016)]





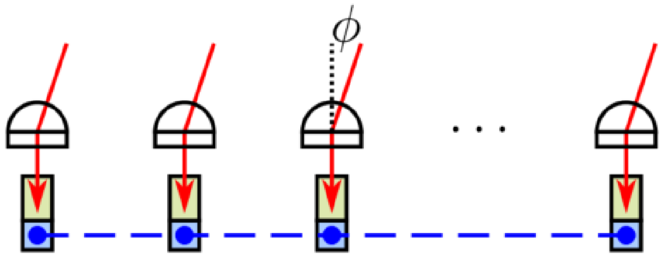
- dynamic hamiltonian engineering of many-body spin systems

  [J. Choi, et al., *Phys. Rev. X* **10**, 031002 (2020)]



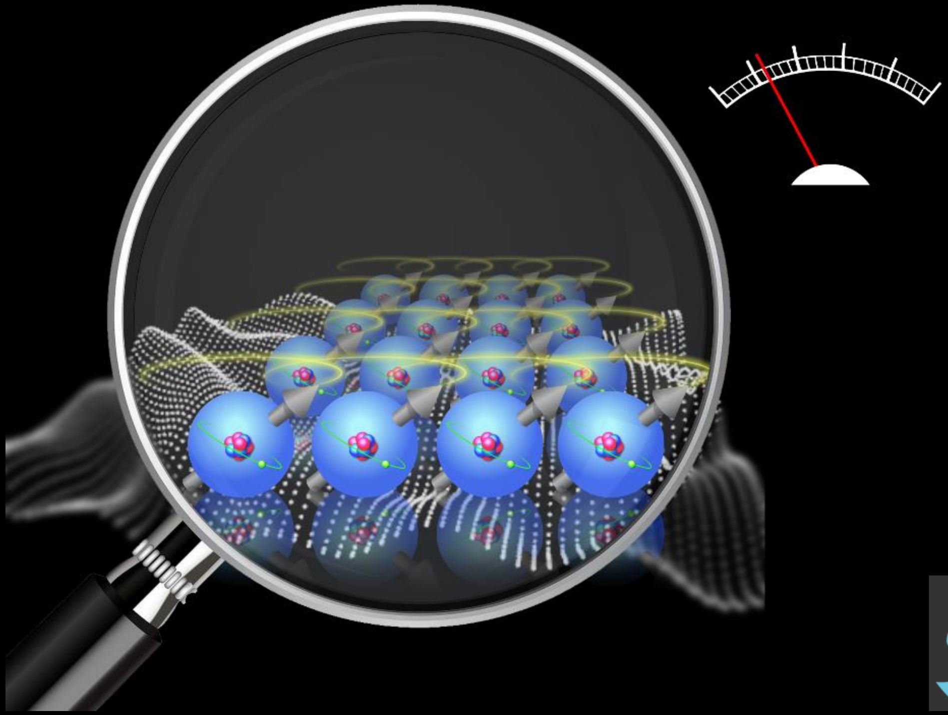
- quantum sensor networks

  [D. Gottesman, et al., *Phys. Rev. Lett*. **109**, 070503 (2012)]
  [E. Khabiboulline, et al., *Phys. Rev. Lett*. **123**, 070504 (2019)]



Alex Sushkov (BU): Quantum ensembles – spins and traps

Thank you!



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