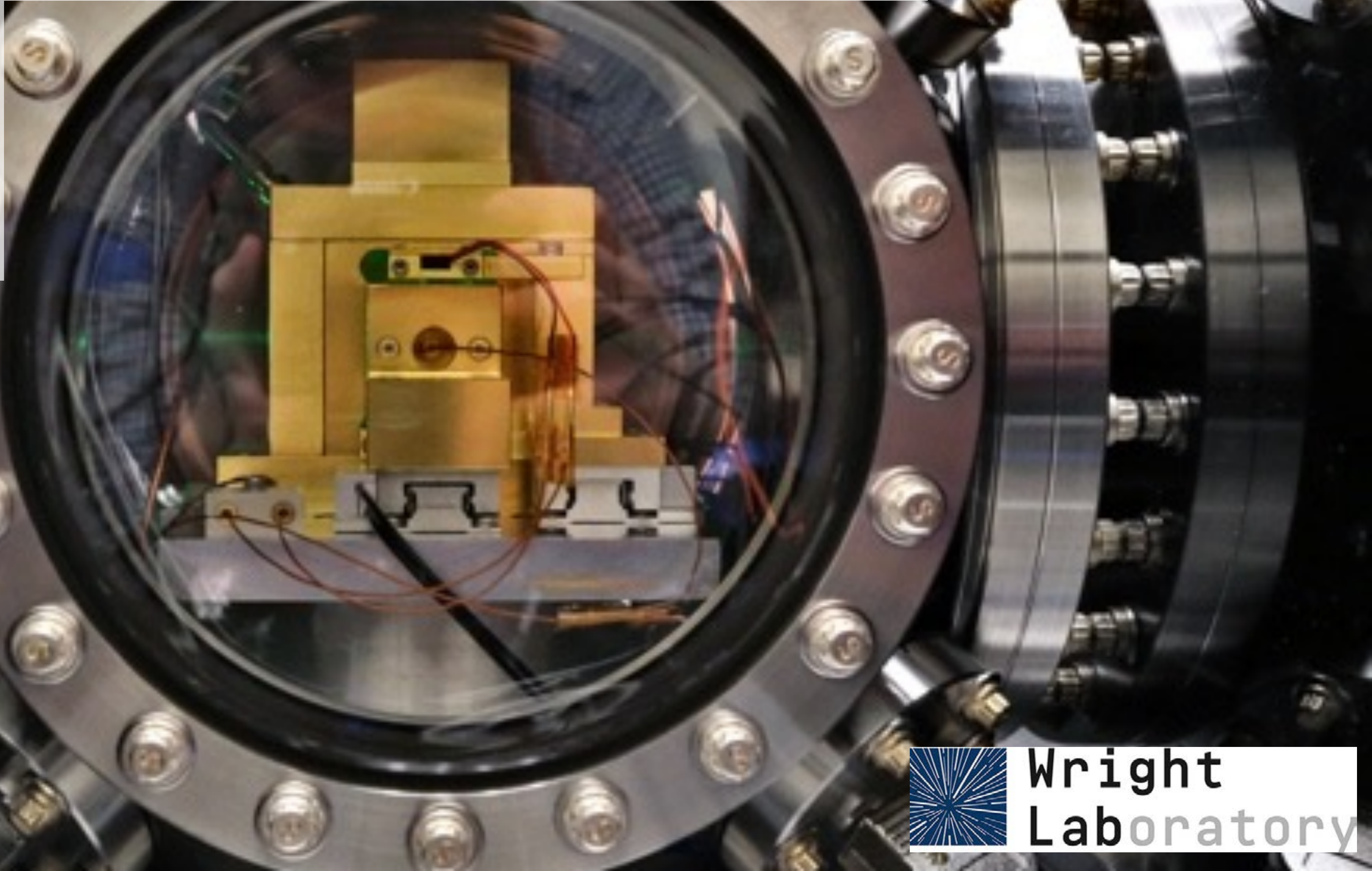
Searches for dark matter with quantum optomechanical sensors

David Moore

WL Quantum Sensing Workshop

April 8, 2022



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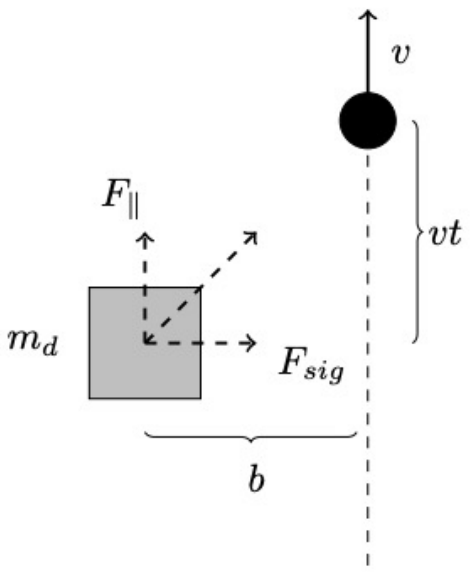
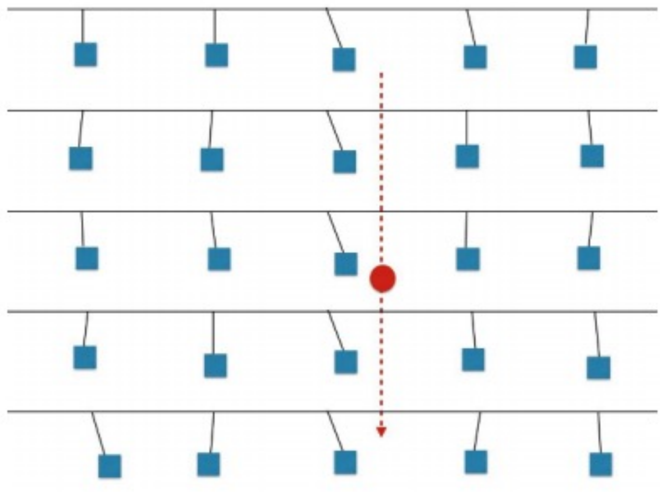
Model independent search for dark matter

- Thinking big, one can at least imagine what a model-independent terrestrial search for dark matter might look like

Gravitational impulse:



Array of sensors:

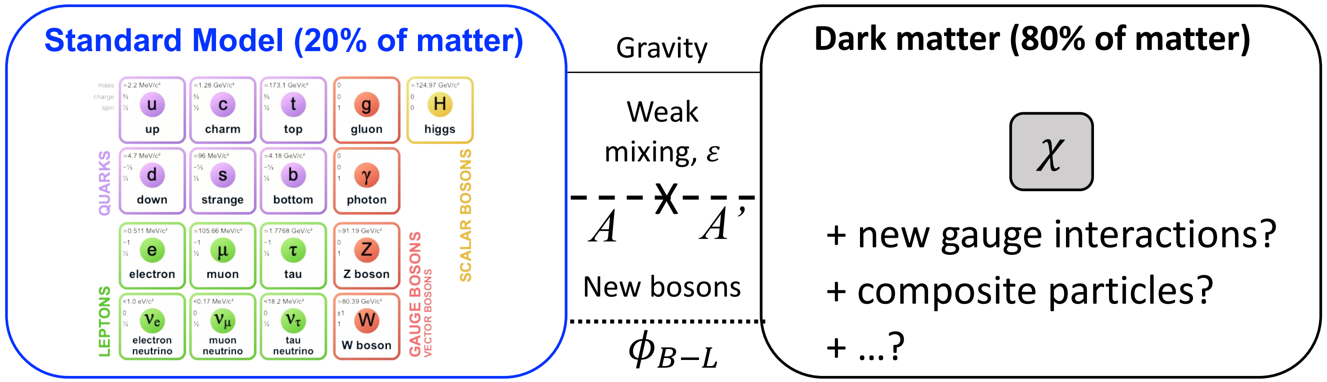


Carney et al., "Proposal for gravitational direct detection of dark matter," PRD 102, 072003 (2020), arXiv:1903.00492

- For sufficiently heavy dark matter ($m_\chi \gtrsim m_{Pl}$) this *might* be possible, at least in principle
  - Measurement limits are a key issue → need >30 dB beyond the SQL!!!

Optomechanical systems

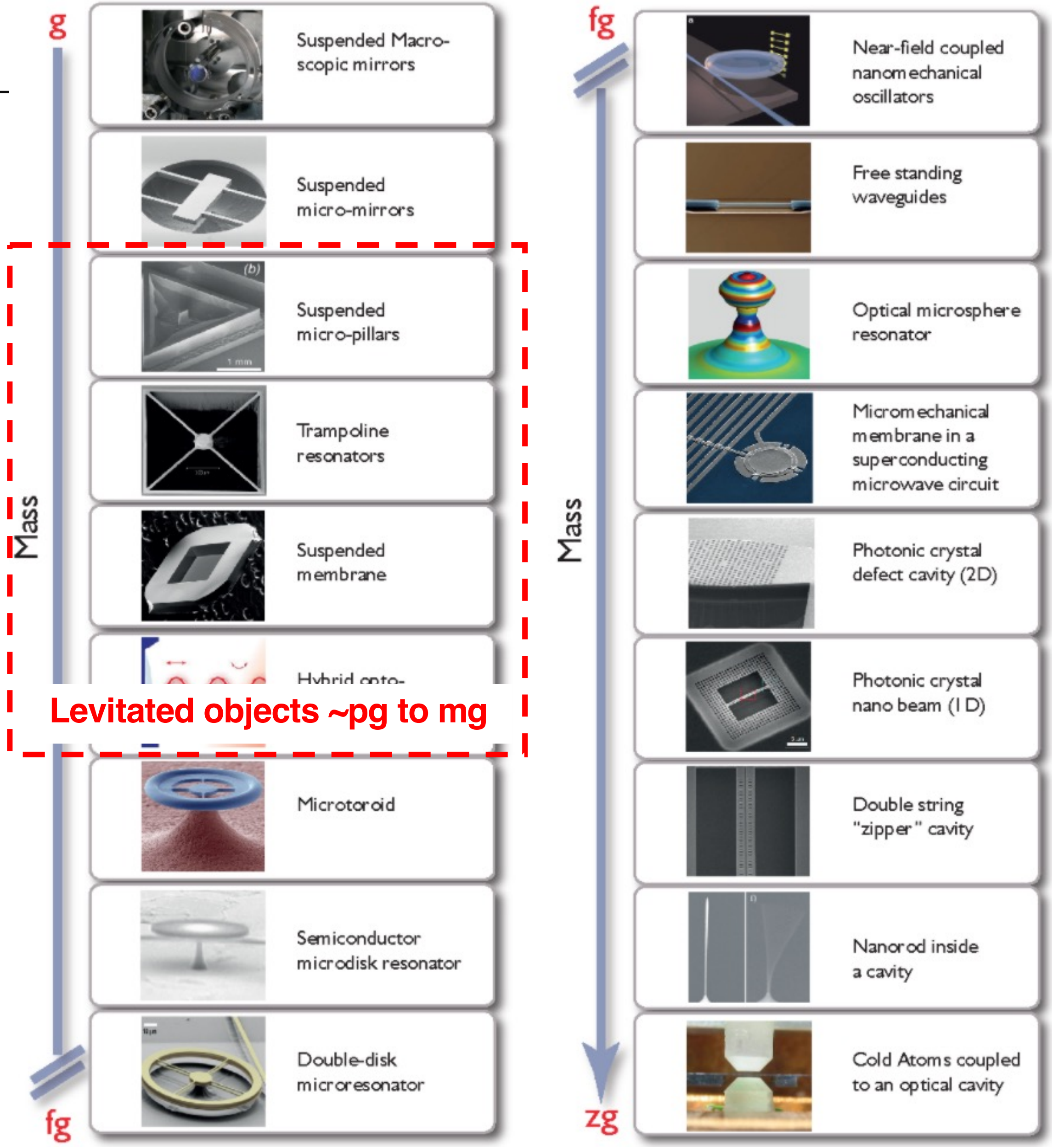
- Gravitational detection itself (if possible) requires substantial advances beyond the current state-of-the-art



- Existing optomechanical systems can already search for dark matter coupling to matter via stronger forces

- Although here I will focus on optically levitated nanogram mass spheres, many options!

For more details: "Mechanical Quantum Sensing in the Search for Dark Matter," Quant. Sci. Tech. 6 024002 (2021), arXiv:2008.06074

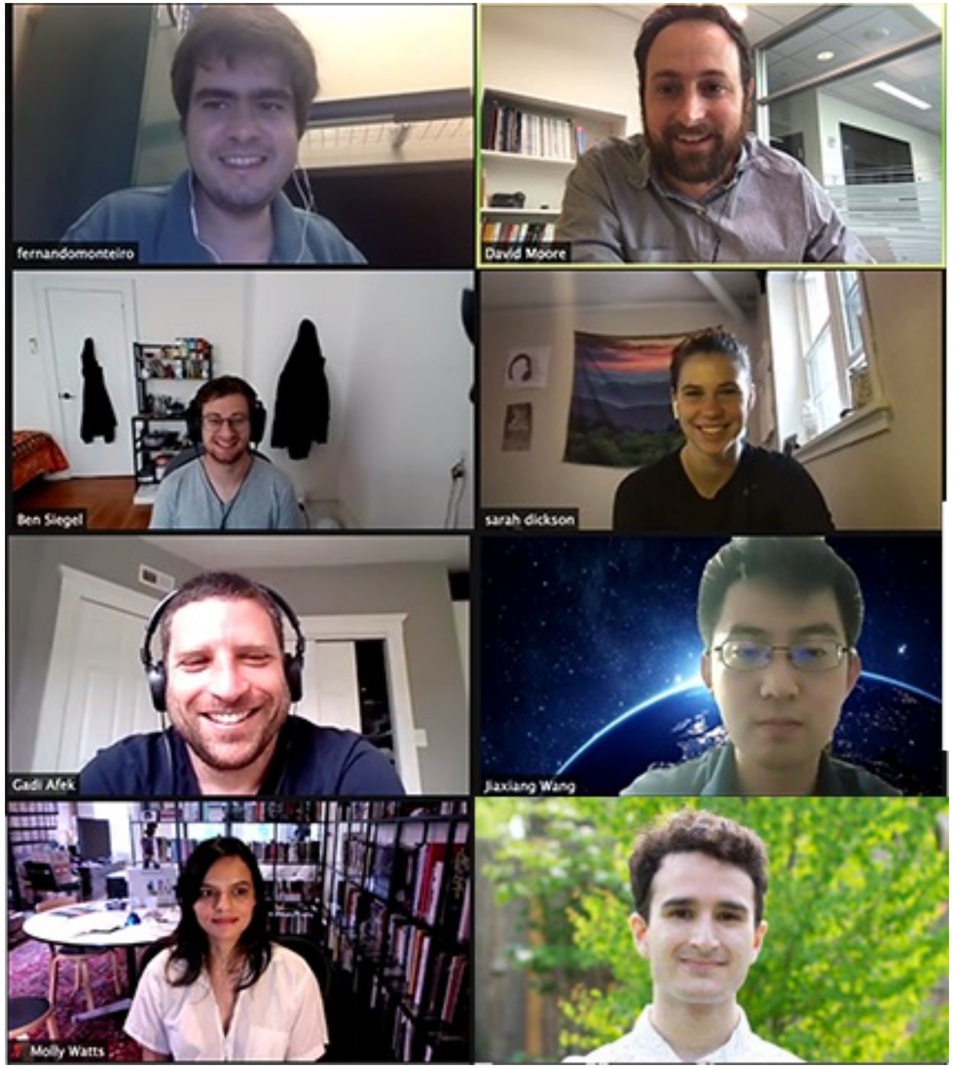


Aspelmeyer et al., Rev. Mod. Phys. 86, 1391 (2014)

The SIMPLE team at Yale:

(Search for new Interactions in a Microsphere Precision Levitation Experiment)

- Gadi Afek
- David Moore
- Luke Mozarsky
- Emily Peng
- Tom Penny
- Juan Recoaro
- Ben Siegel
- Yu-Han Tseng
- Jiaxiang Wang
- Molly Watts



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Levitated microspheres

- Micron-sized dielectric masses can be levitated with ~few mW of laser power

- Optical tweezers are a common tool in biophysics to measure ~pN forces

- At high vacuum, extremely low dissipation is possible, e.g. at "standard quantum limit (SQL)" for 10 μm sphere:

$\sigma_F \sim 10^{-19}$ N Hz$^{-1/2}$ at 10^{-10} mbar

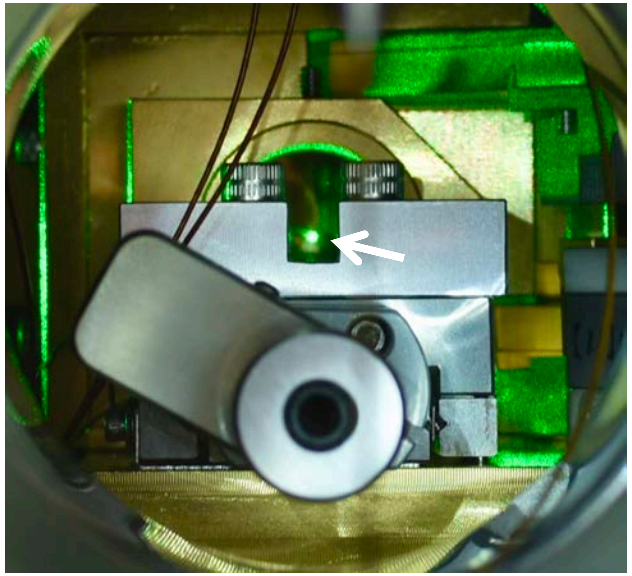
$\sigma_a \sim 10^{-9}\, g$ Hz$^{-1/2}$

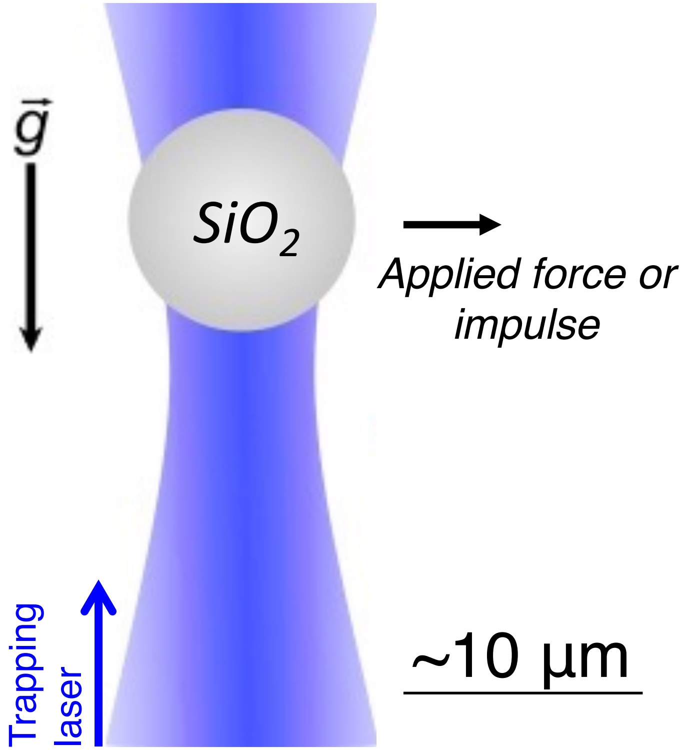
$\sigma_p \sim 10^{-22}$ kg m/s (~1 MeV/c)

Ashkin & Dziedzic, Appl. Phys. Lett. ***19****, 283 (1971)*

- Levitated masses are isolated both electrically and thermally

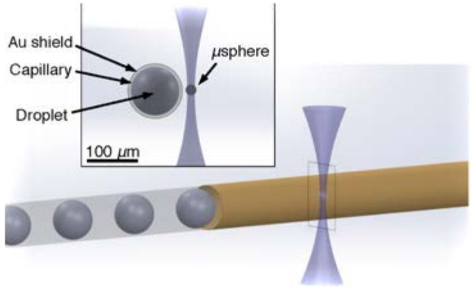
Photograph of trapped microsphere:

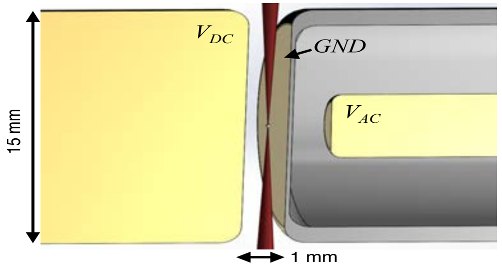




Applications to fundamental physics

- **Searches for “fifth forces”:**
  - Tests of Newton’s law
  - Tests of Coulomb’s law

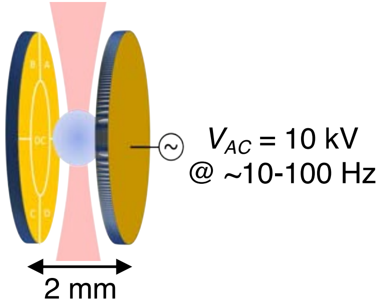


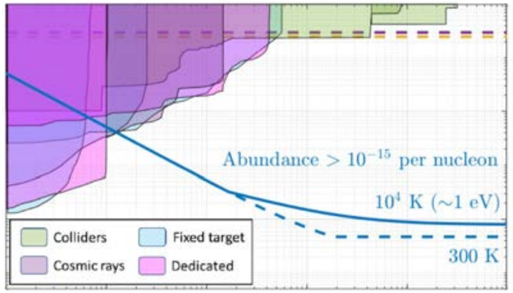


See also: PRL 117, 101101, arXiv:1604.04908 (2016)

- **Neutrality of matter**:
  - Millicharged dark matter particles

    Afek et al., Phys. Rev. D 104, 012004 (2021), arXiv:2012.08169
  - Charge quantization

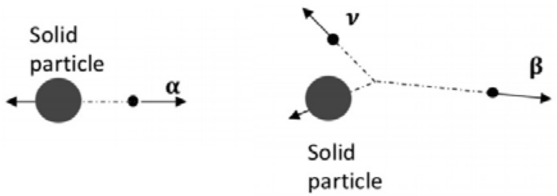




*Afek et al., arXiv:2012.08169 (2021), DCM et al., PRL **113** 251801, arXiv:1408:4396 (2014)*

- **Detection of small impulses:**
  - Nuclear recoils from α/β decays
  - Kinematic detection of dark matter

    Monteiro et al., Phys. Rev. Lett. 125, 181102 (2020), arXiv:2007.12067
    Carney et al., Phys. Rev. Lett. 127, 061804 (2021), arXiv:2104.05737
    Afek et al., Phys. Rev. Lett. 128, 101301 (2022) ,arXiv:2111.03597

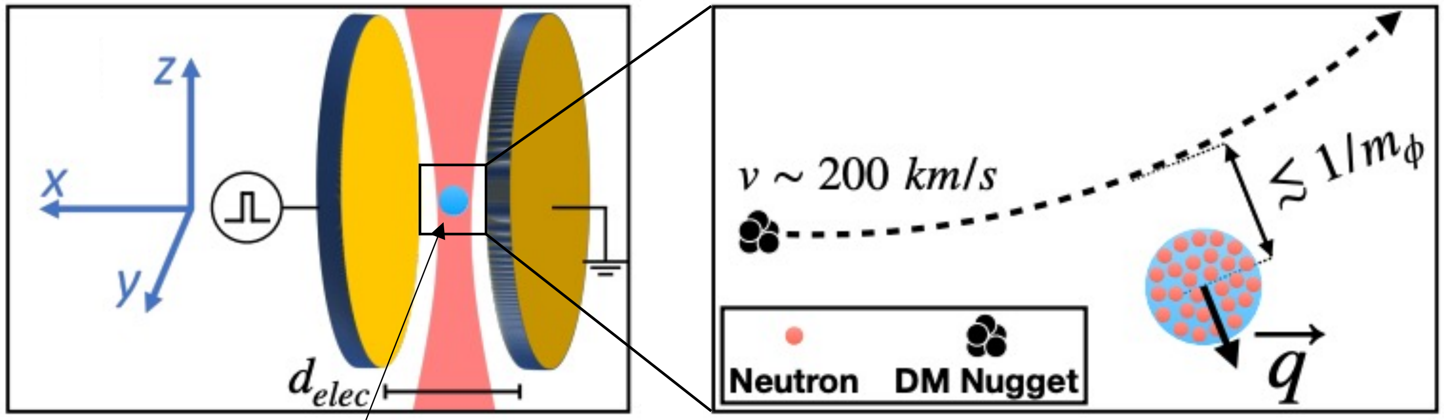


*Malyzhenkov et al., PRA **98**, 052103 (2018)*

Kinematic detection of dark matter

- Levitated microspheres can already search for certain classes of heavy DM that could interact with matter via a new long-range force
- Cool microsphere's motion and search for impulses from passing DM particles

Schematic of measurement principle:



Trapped, cooled, spin-stabilized ng sphere ($k_b T_{cm} \sim 20$ neV)

Monteiro et al., PRL 125, 181102 (2020), arXiv:2007.12067

Assume dark matter interacts with matter via some generic new force:

Coupling to a single neutron — *Number of neutrons*

$$V = \alpha_n N_n \frac{e^{-m_\phi r}}{r}$$

(Yukawa potential for boson ϕ with mass m_ϕ)

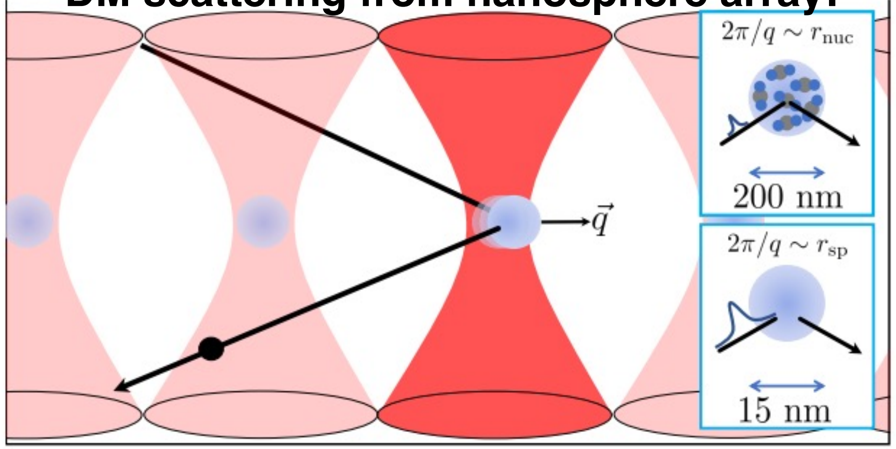
Huge enhancement in the coherent scattering cross section:

$$\sigma \propto N_n^2 \sim 10^{29}!$$

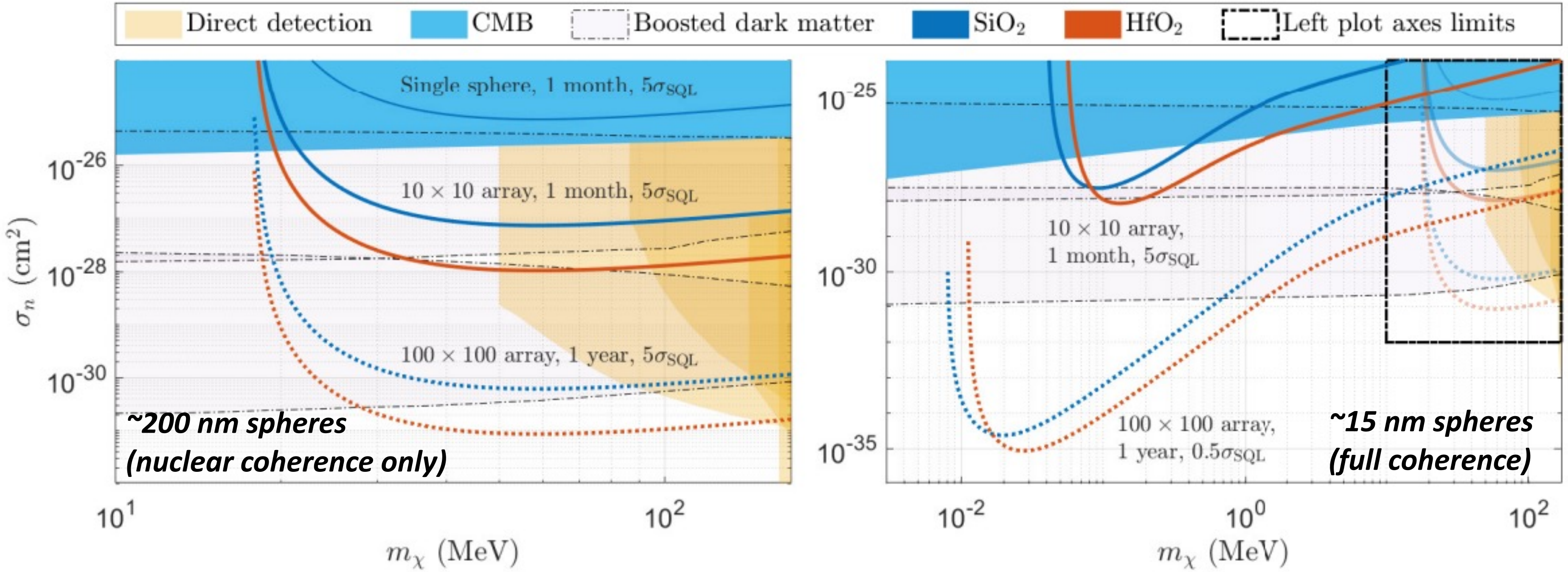
Coherent scattering from nanospheres

- For smaller spheres, much lower recoil thresholds can be obtained (at the cost of reduced target mass)
- Coherence over entire sphere possible even for short-range interactions for ~15 nm spheres

DM scattering from nanosphere array:



Projected low-mass DM sensitivity:



Afek et al., Phys. Rev. Lett. 128, 101301 (2022) ,arXiv:2111.03597

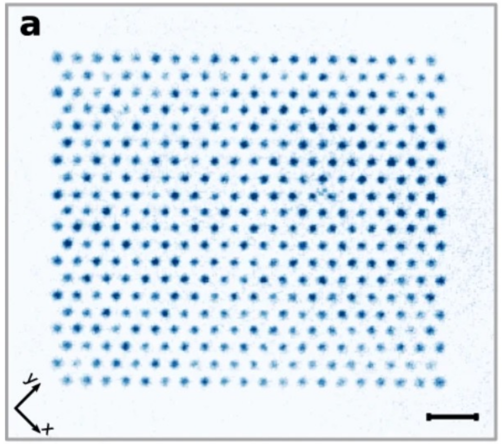
Physics "Viewpoint":
https://physics.aps.org/articles/v15/32

Future sensitivity

- The first proof-of-principle search for DM with mechanical detectors can already explore well beyond existing searches for certain classes of models
- Next steps:
  - Continue to push towards SQL (and possibly beyond)
  - Develop large arrays of sensors, and longer exposures

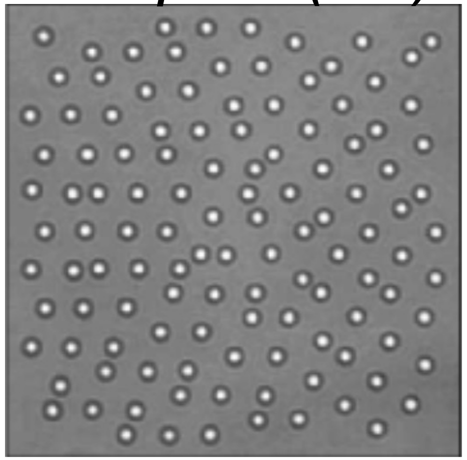
Tweezer arrays:

Atoms:



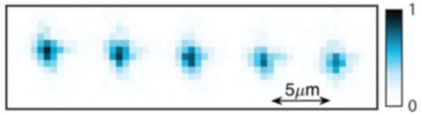
Wang et al. npj Quantum Inf 6, 54 (2020)

Microspheres (fluid):



D. Grier and Y. Roichman Appl. Optics 45, 880 (2006)

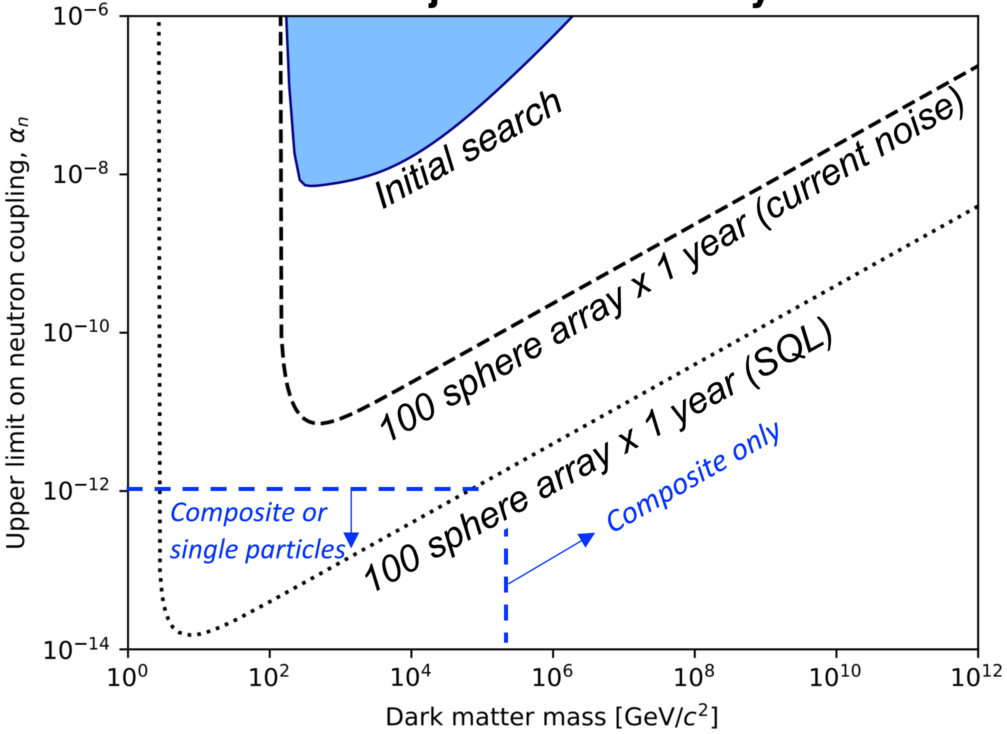
Molecules:



Anderegg et al., Science. 365, 1156 (2019)

Microspheres (vacuum), Yale:

Projected sensitivity:



DCM and A. Geraci, Quantum Sci. Tech. 6 014008 (2021), arXiv:2008.13197

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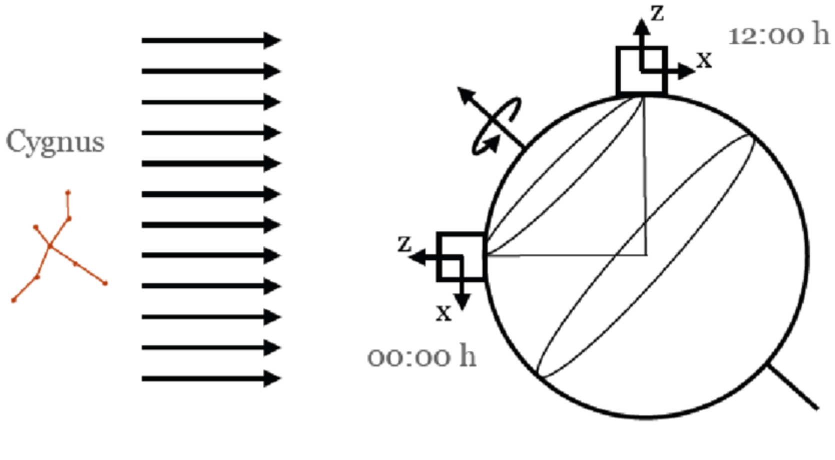
Natural directionality → any detection would be definitive!



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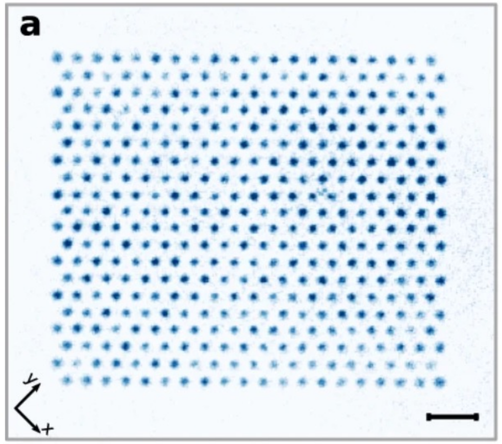

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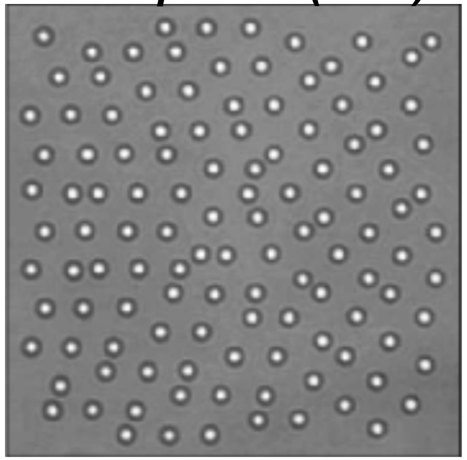

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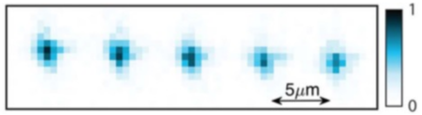

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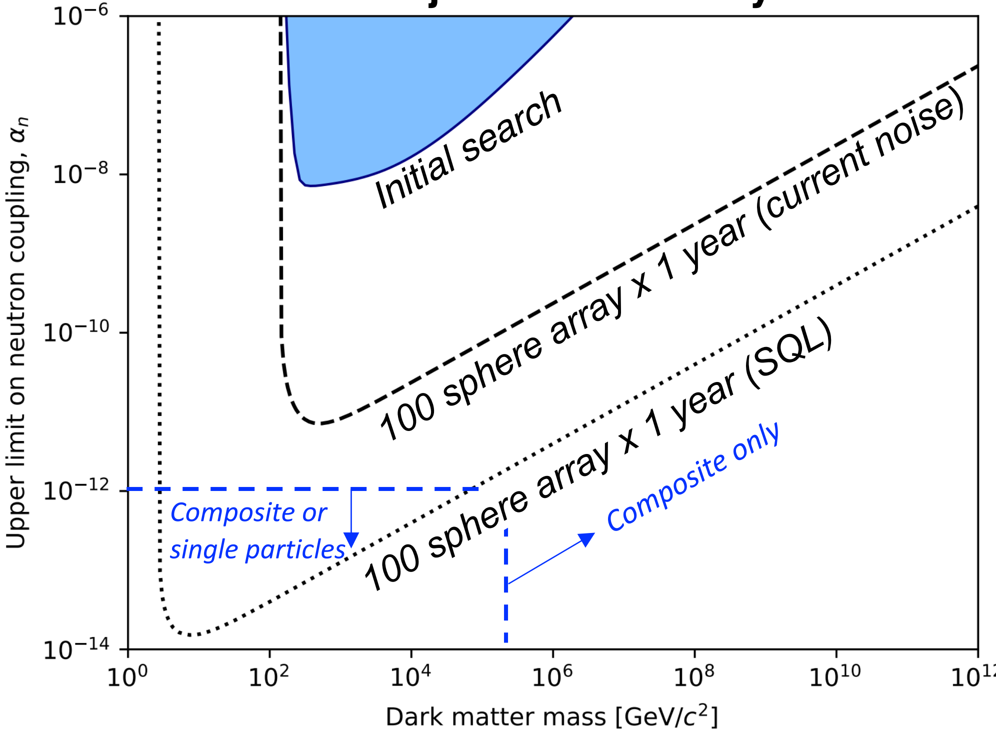

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Summary

- Optomechanical systems may provide completely new methods for searching for dark matter in terrestrial detectors
- We have recently performed searches for mechanical recoils from passing dark matter and relic millicharged particles bound in matter
- Other optomechanical systems may also open new possibilities for DM searches
- Ultimate goal of gravitational only detection is still far away, but might in principle be possible – lots of interesting searches on the way there!