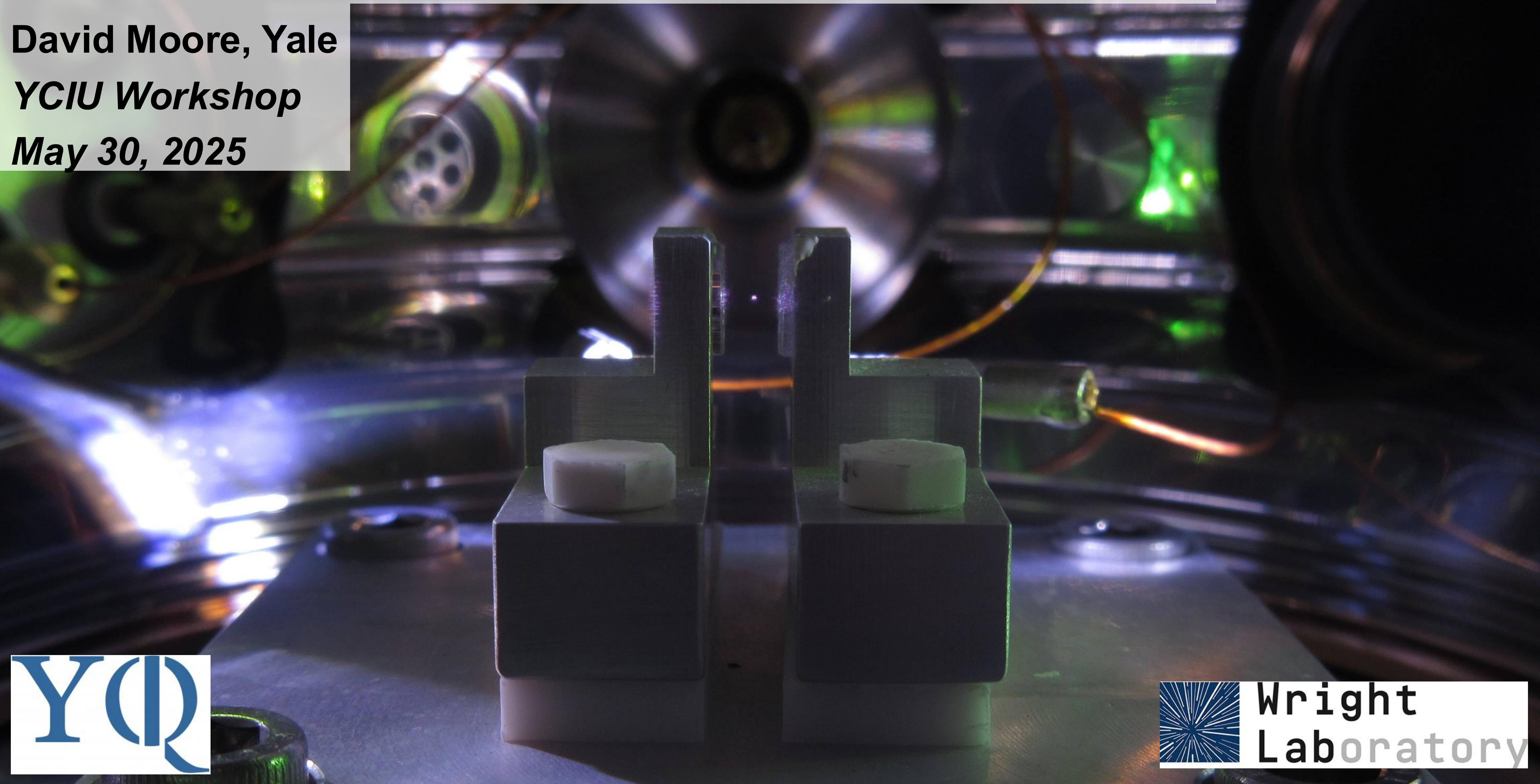
Mechanical sensors for dark matter

David Moore, Yale

YCIU Workshop

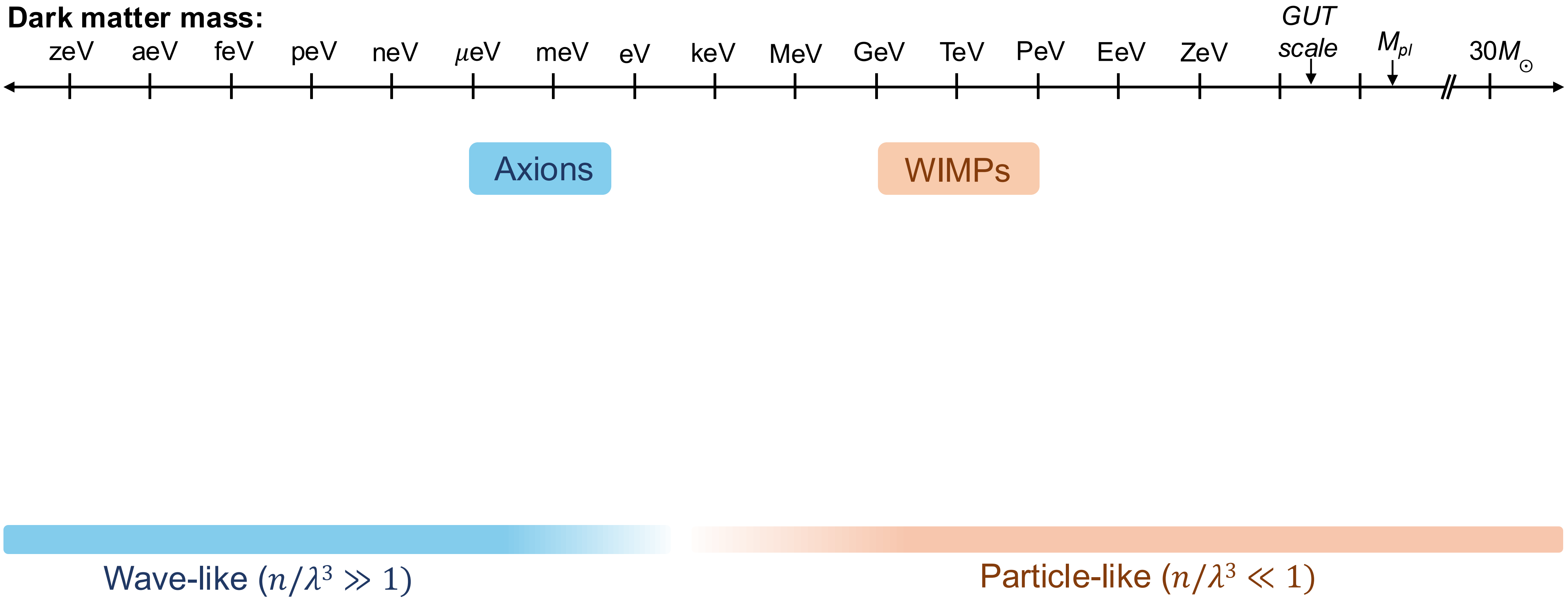
May 30, 2025



Wright Laboratory

Dark matter candidates

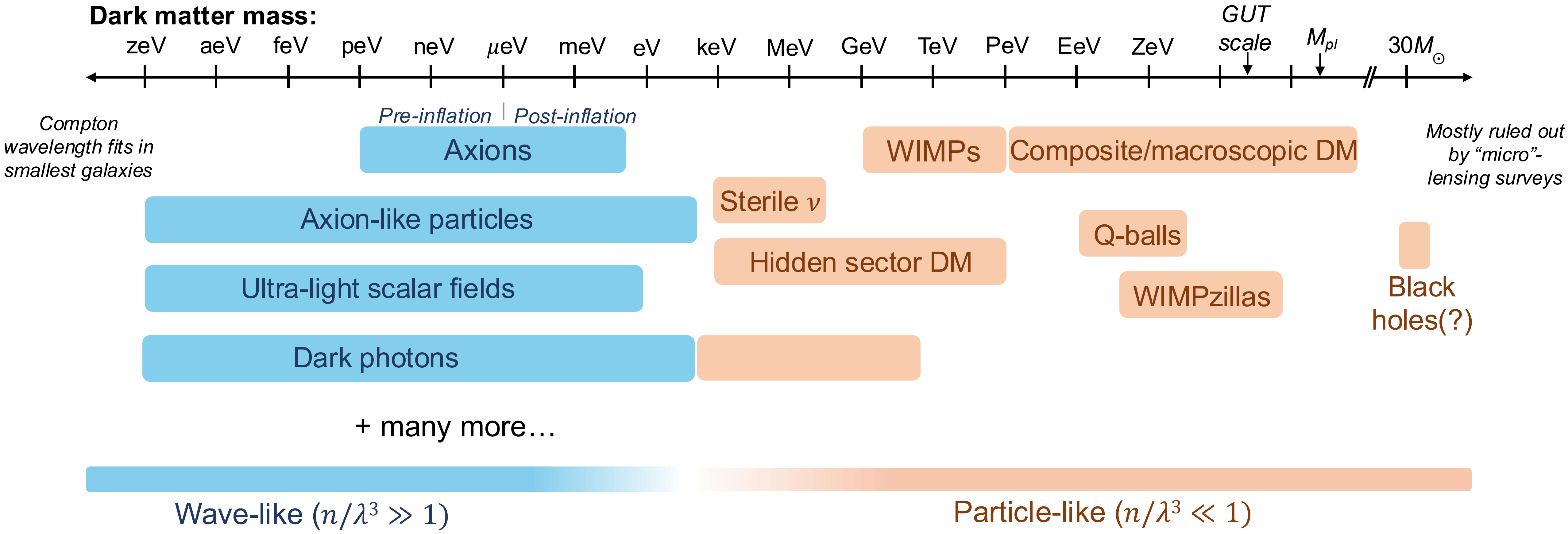
- There is astrophysical evidence for dark matter spanning from galactic to cosmological length scales
  - WIMPs and Axions are compelling candidates for this DM



Adapted from US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report, arXiv:1707.04591

Dark matter candidates

- There is astrophysical evidence for dark matter spanning from galactic to cosmological length scales
  - WIMPs and Axions are compelling candidates for this DM… but a much larger set of models is consistent with astrophysical observations

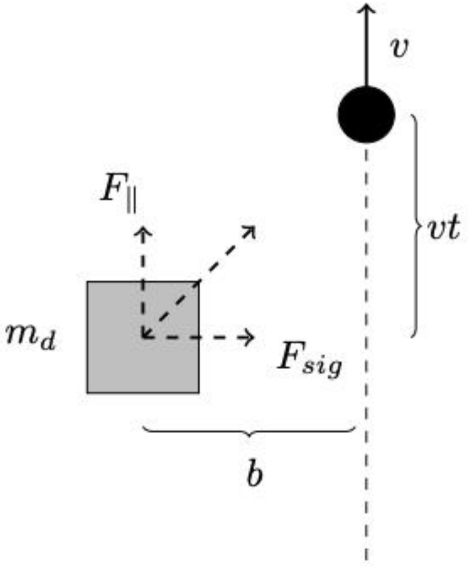


Adapted from US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report, arXiv:1707.04591

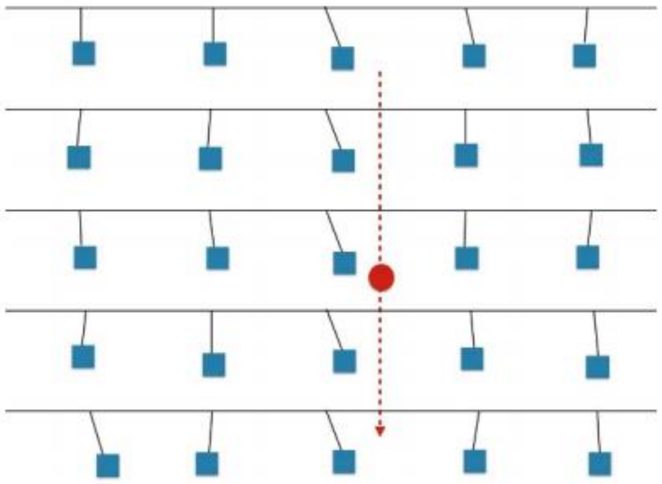
Model independent search

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

Gravitational impulse:



Array of sensors:



Thermal noise (levitated sensor @ 10^{-12} mbar):

Dark matter mass

Sensor mass

$$\mathrm{SNR}^2 \approx 10^4 \times \left(\frac{m_\chi}{1\ \mathrm{mg}}\right)^2 \left(\frac{m_s}{1\ \mathrm{mg}}\right)^2 \left(\frac{1\ \mathrm{mm}}{d}\right)^4$$

Dark Matter rate:

Planck mass $\sim 20\ \mu$g

$$R = \frac{\rho_\chi v A_d}{m_\chi} \sim \frac{1}{\mathrm{year}} \left(\frac{m_{\mathrm{Pl}}}{m_\chi}\right) \left(\frac{A_d}{1\ \mathrm{m}^2}\right)$$

Array of d = 1 mm
→ 10^9 sensors!

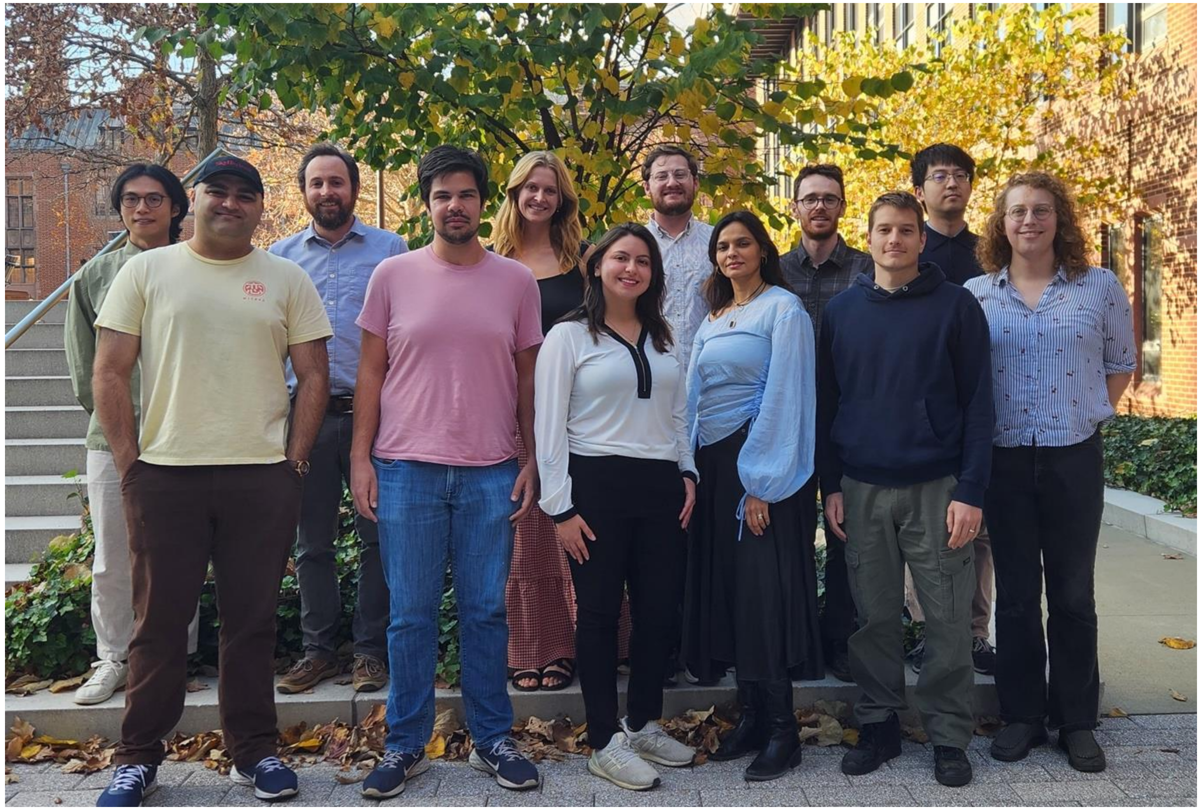
Carney et al., "Proposal for gravitational direct detection of dark matter," PRD 102, 072003 (2020), arXiv:1903.00492

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

The SIMPLE team at Yale:

(***S****earch for new* ***I****nteractions in a* ***M****icrosphere* ***P****recision* ***L****evitation* ***E****xperiment*)

Jackie Baeza-Rubio	David Moore
Lucas Darroch	Isabelle Ong
Cecily Lowe	Tom Penny
Vasilisa Malenkiy	Ben Siegel
Aaron Markowitz	Yu-Han Tseng
Siddhant Mehrotra	Jiaxiang Wang
	Molly Watts



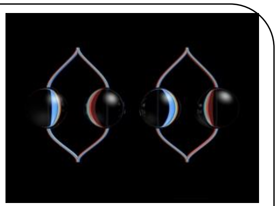
With collaborators:

QuIPs:

(***Qu****antum* ***I****nvisible* ***P****article* ***S****earch*)

MAST-QG:

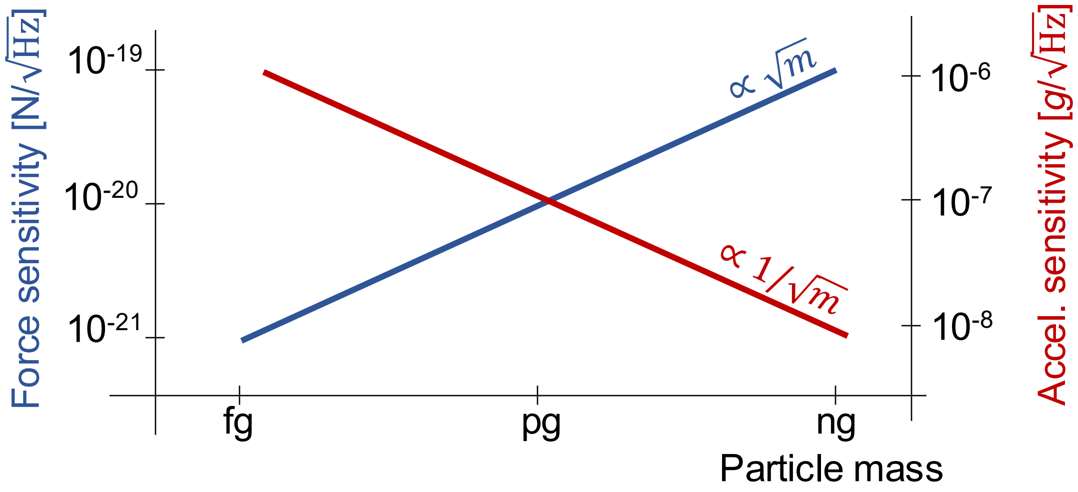
(***Ma****croscopic* ***S****uperpositions* ***T****owards Witnessing the* ***Q****uantum nature of* ***G****ravity*)



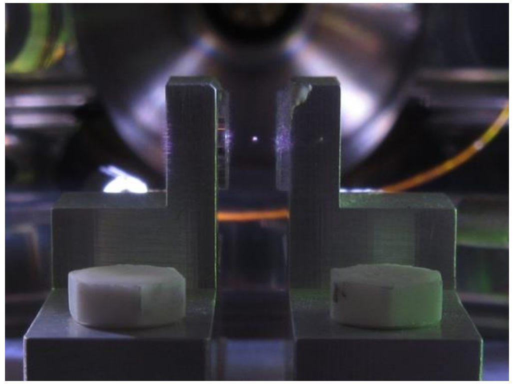
Levitated optomechanics

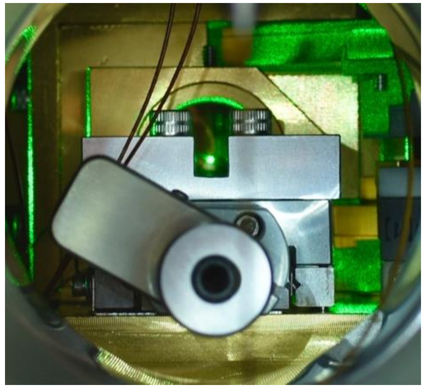
- Nano- to micro-sized dielectric masses can be optically trapped with ~100 mW of laser power
- Optical tweezers are a common tool in biophysics to measure ~pN forces
- Levitated masses are isolated both electrically and thermally
  → Force sensitivities at the zN level and acceleration sensitivities near a nano-g

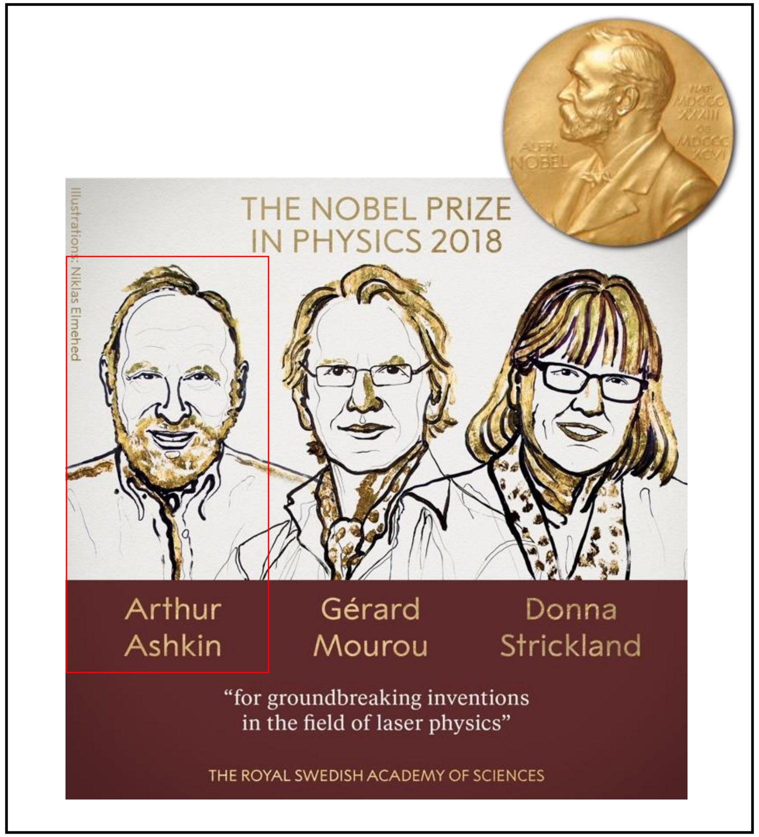
Force and acceleration sensitivity vs particle mass:



Photographs of trapped nano/micro particles at Yale:





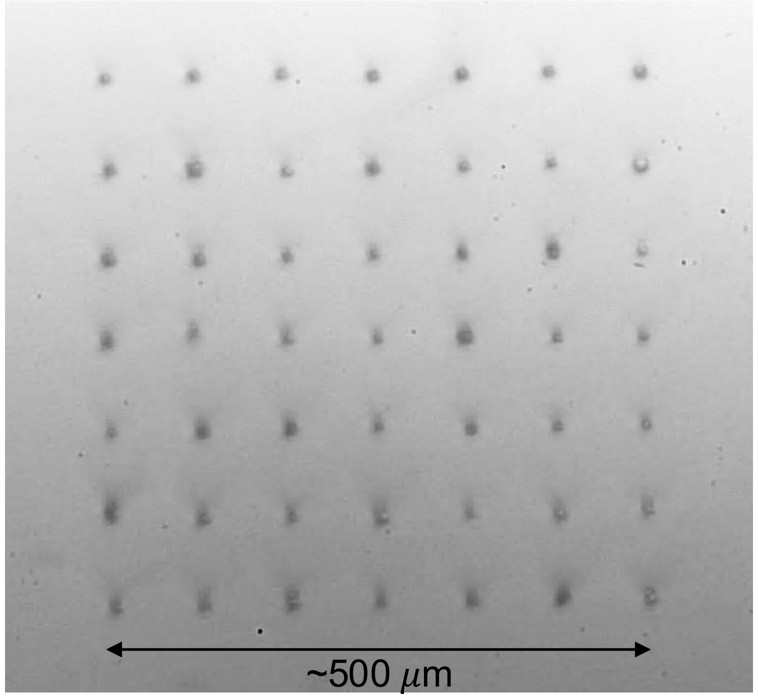


Levitation trap (~1 – 30 μm):
~1 pg – 30 ng

Microsphere arrays

- Microsphere trap has been upgraded w
  ~10 x 10 arrays
- Similar technology to tweezer arrays fo
  → Real time control over trap position

7x7 array of spheres (~1 mbar):



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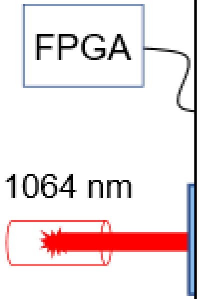
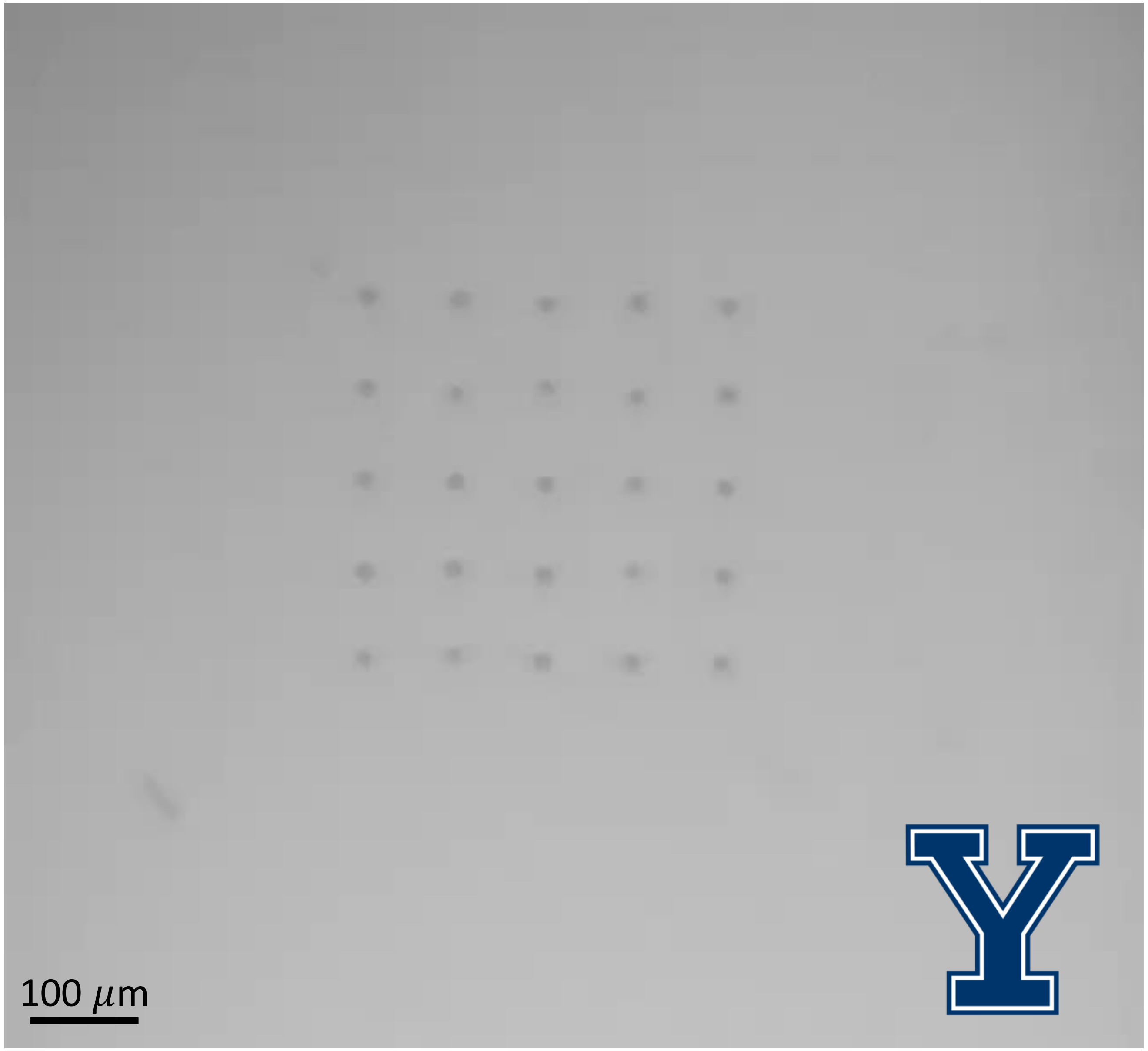


Rearrangement example (10 μm spheres @ ~1 mbar):

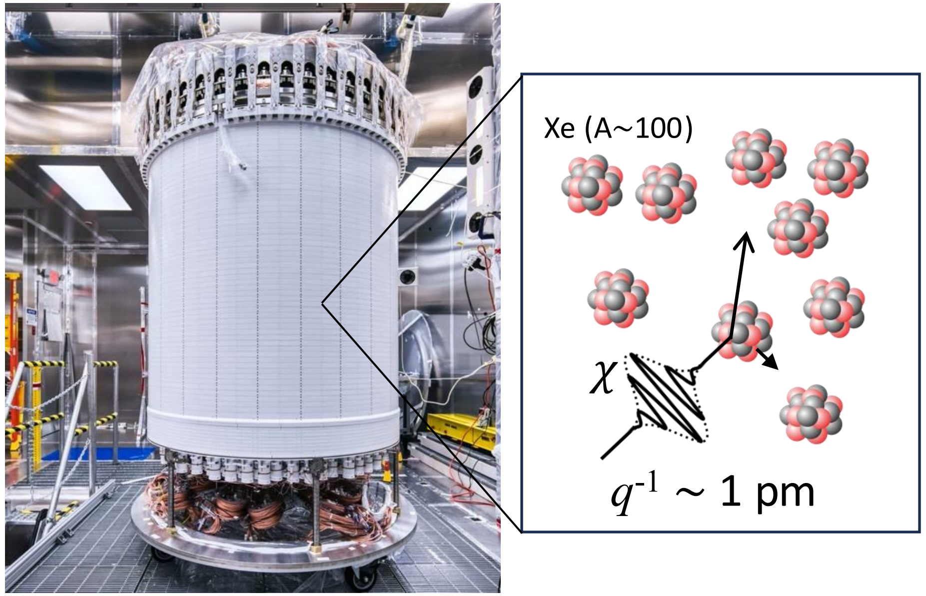


Played at 8x speed

Kinematic detection of (particle) dark matter

- While the momentum sensitivity is sufficient to detect dark matter scatters, the rate of scatters can be very small
- Most sensitive to dark matter models that primarily interact coherently with entire objects

Ton-scale WIMP detectors (e.g. LZ, DarkSide, …):

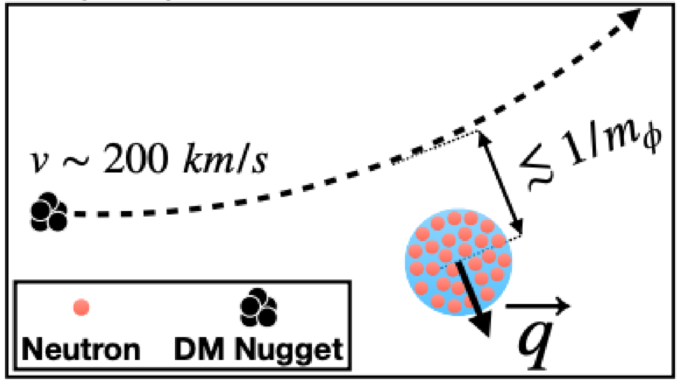


Coherence only over a single nucleus:

$$\text{Rate} \propto \underset{\gg 10^{23}}{N_T}\, \underset{\sim 10^{4}}{A^2}\, \sigma_n$$

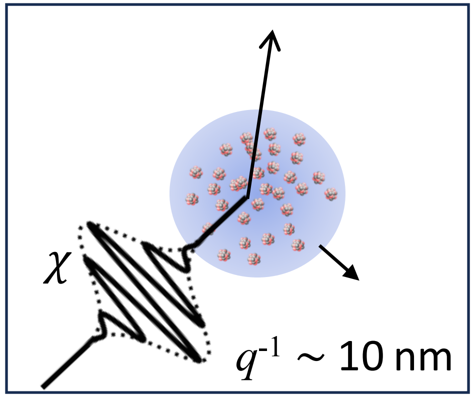
fg-ng scale trapped objects:

Long range force:



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

Low momentum transfer:



Afek et al., PRL 128, 101301 (2022), arXiv:2111.03597

Coherence over an entire nano- or micro-sized object:

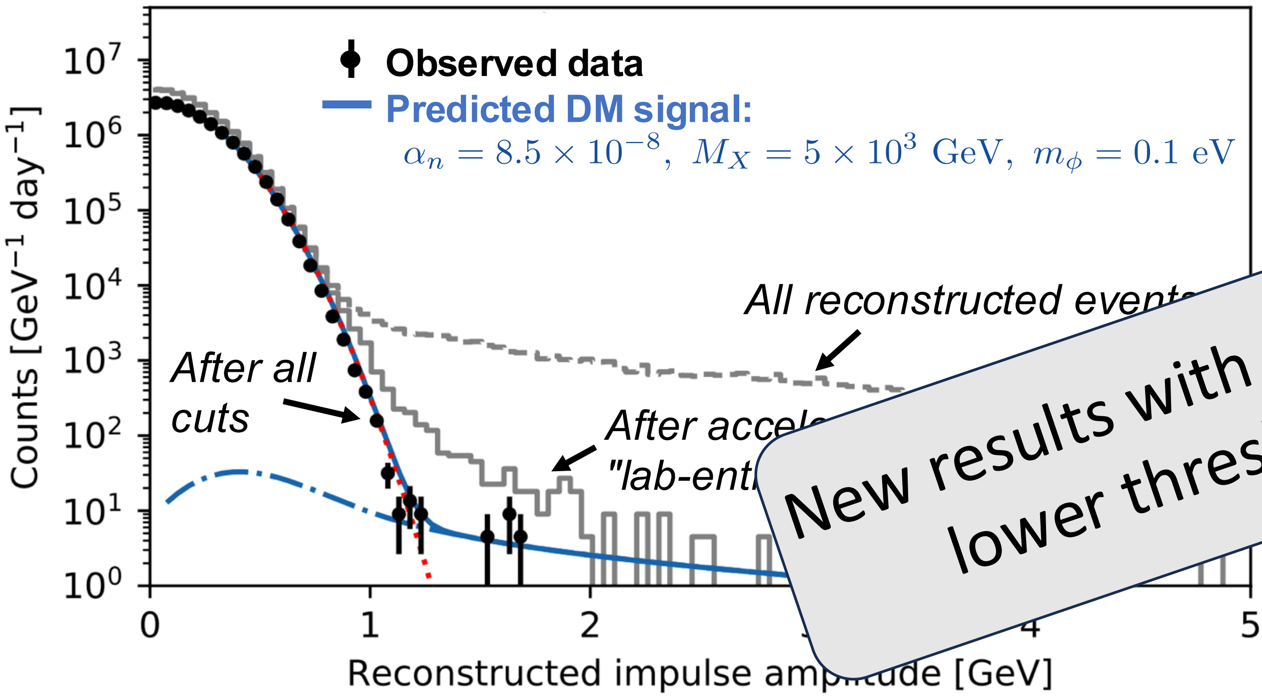
$$\text{Rate} \propto \underset{\sim (10^9)^2 \text{ to } (10^{14})^2}{(N_T)^2}\, \sigma_n$$

Can rival Avogadro's number!

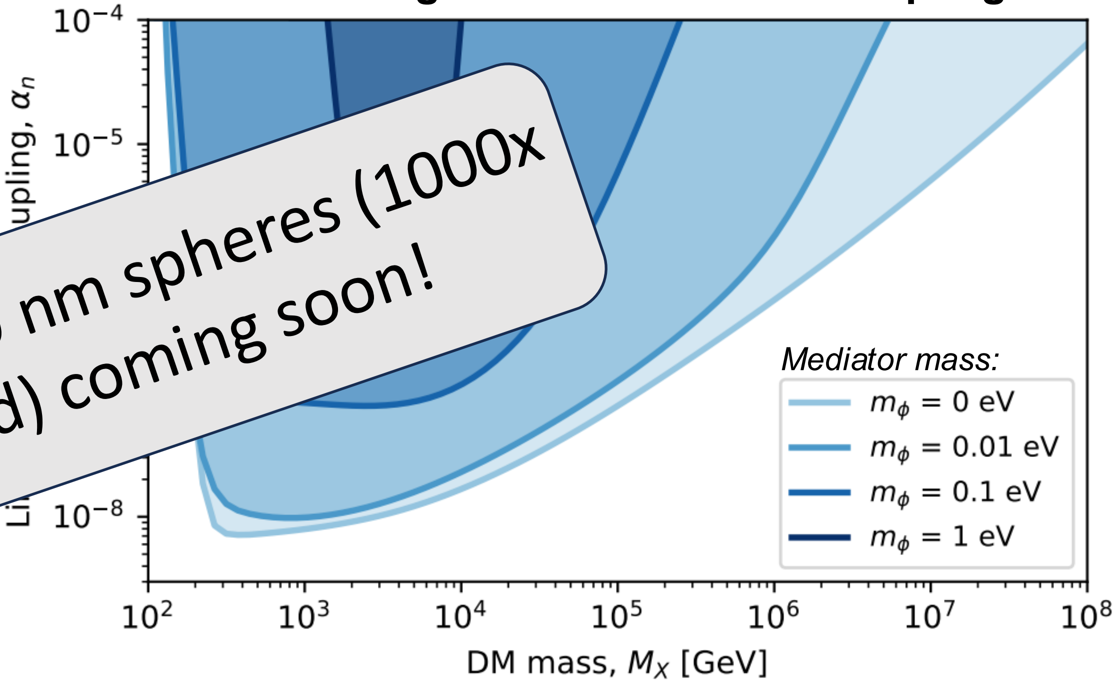
Dark matter search (long range force)

- Acquired 5 days of dark matter search data in June 2020, four candidate events remain in non-Gaussian tail of distribution after all cuts
- Conservatively set limits on neutron coupling assuming candidates could arise from DM

Measured spectrum of impulses:



Limits on generic DM-neutron coupling:



New results with 100 nm spheres (1000x lower threshold) coming soon!

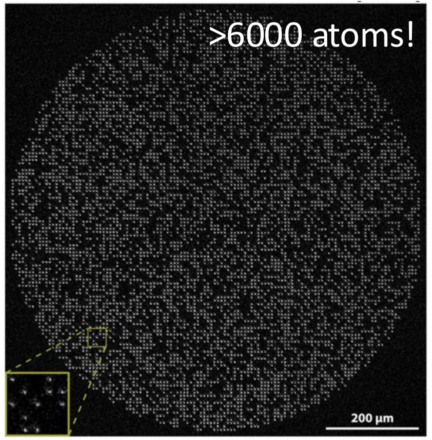
Monteiro et al., PRL 125, 181102 (2020), arXiv:2007.12067

Future sensitivity

- This first proof-of-principle search for DM with mechanical de beyond existing searches for certain classes of models
- Next steps:
  - Continue to push towards SQL (and beyond?)
  - Develop large arrays of sensors, and longer exposures

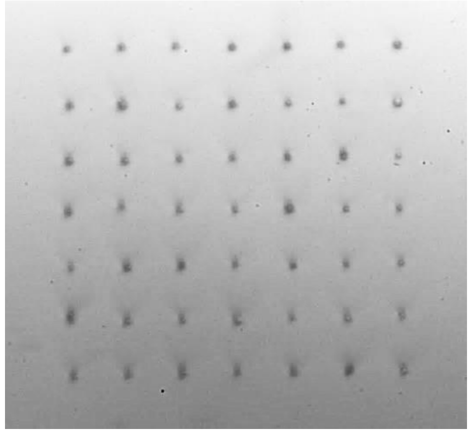
Tweezer arrays:

Atoms:



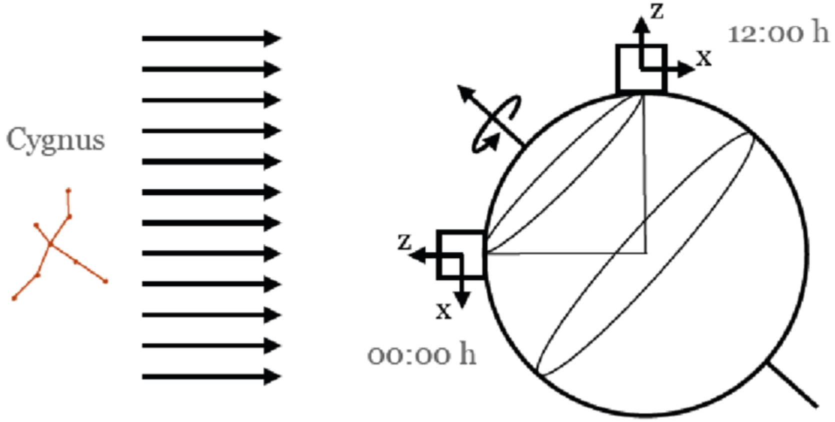
Manetsch et al., arXiv:2403.12021 (2024)

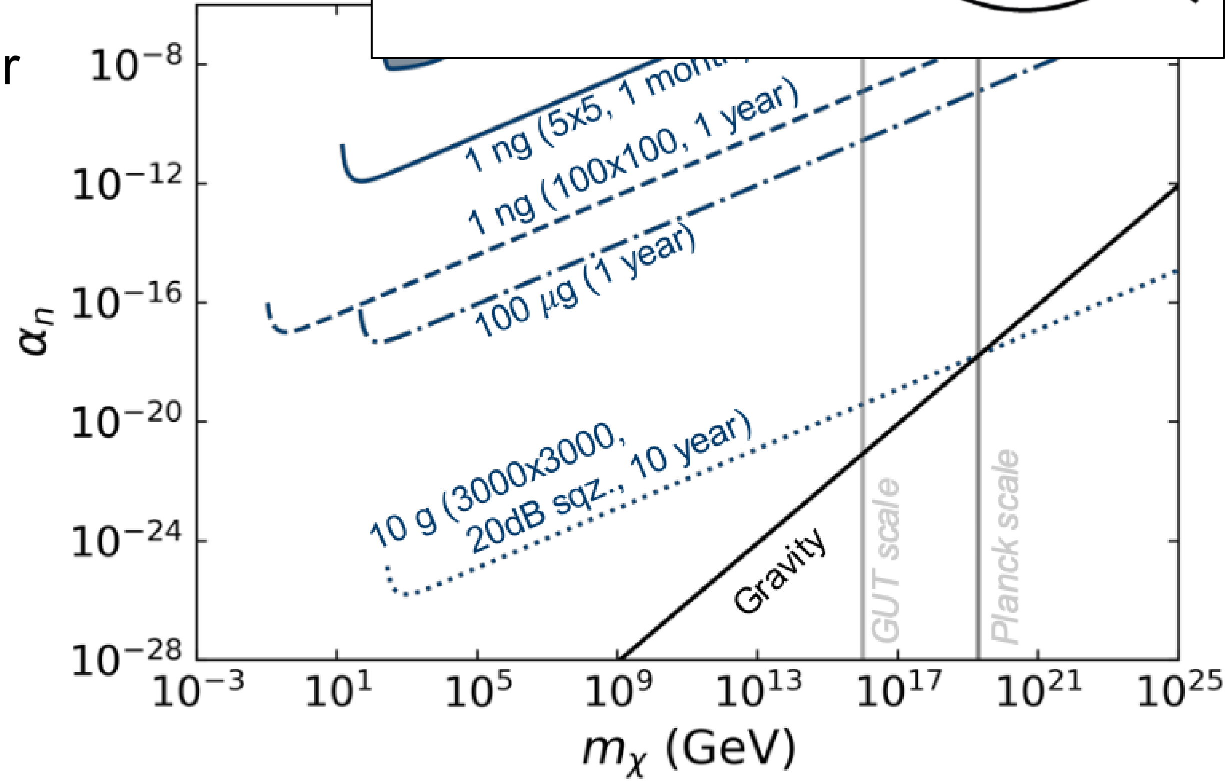
μspheres (vacuum):



B. Siegel (Yale)

Natural directionality → any detection would be definitive!





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

Summary

- Optomechanical systems may provide completely new methods for searching for dark matter or other new weakly coupled particles

- We have recently performed searches for mechanical recoils from passing dark matter, and similar sensors may have applications to neutrino physics

- Ambitious future extensions of these techniques are likely possible well beyond existing searches, providing new tools to probe the invisible universe!