# Mechanical quantum sensing in the search for dark matter

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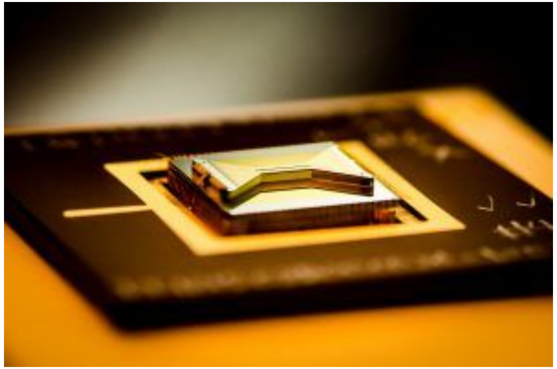
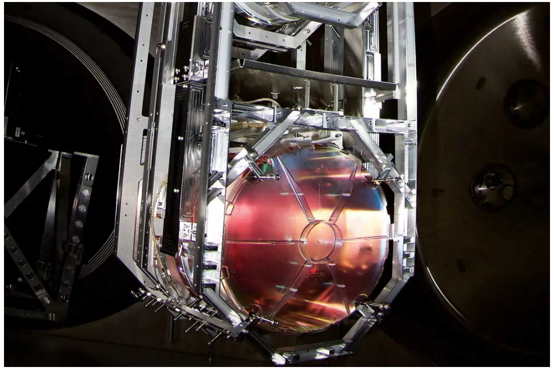
# Macroscopic quantum coherence





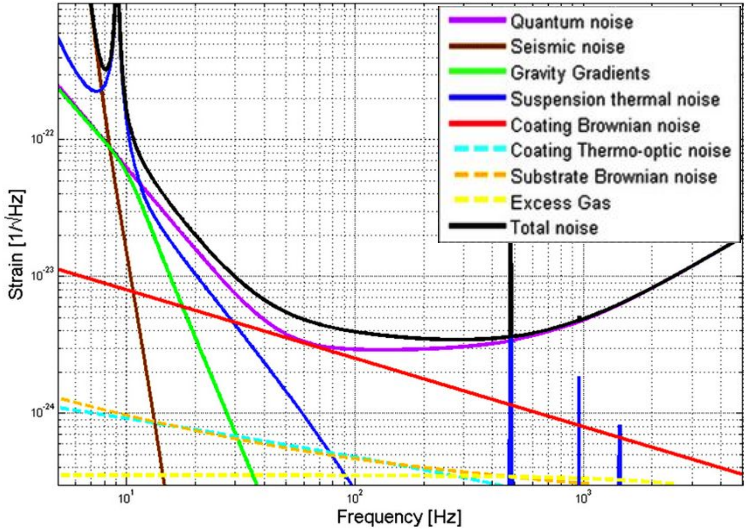
New, open frontier: quantum coherence, entanglement with many particles, large volumes, distances, …

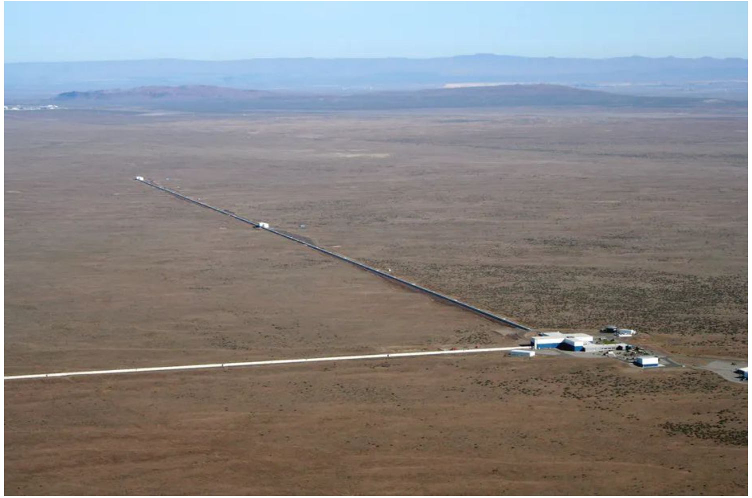
Sensing at the level of vacuum fluctuations of macroscopic objects becoming routine

True quantum control of larger systems possible

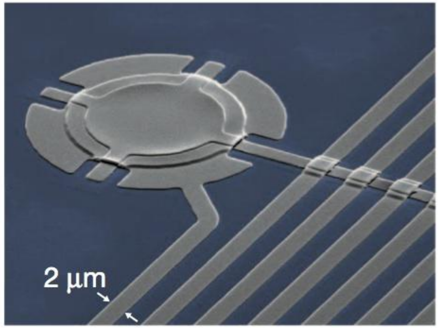
Technology ⟷ theory

# Quantum-limited detection

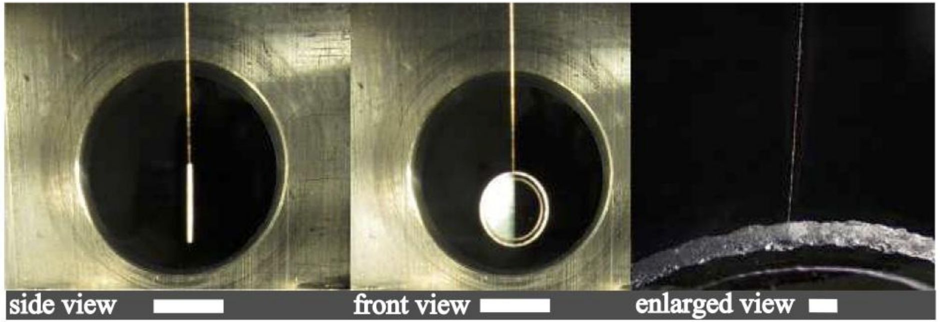


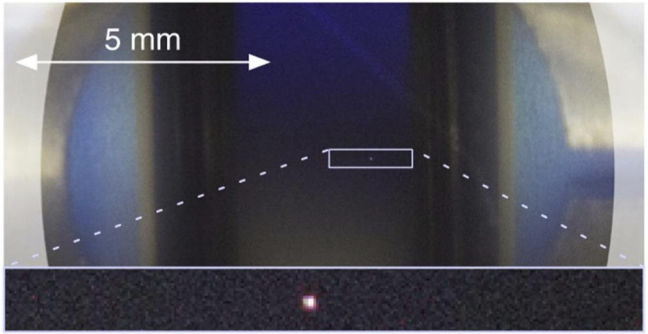
*The Sensitivity of the Advanced LIGO Detectors at the Beginning of Gravitational Wave Astronomy*
**LIGO Collaboration** 1604.00439



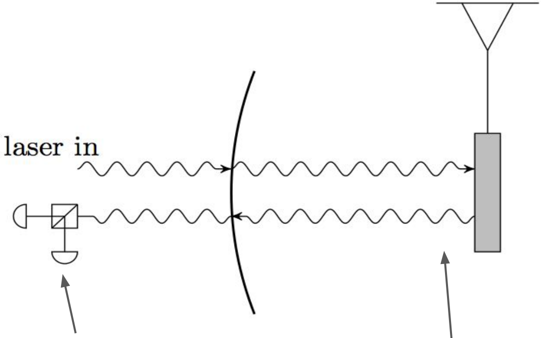

Teufel et al, Nature 2011




Matsumoto et al, PRA 2015




Aspelmeyer ICTP slides 2013




Quantum-limited: sensitivity set by vacuum fluctuations (of light + mechanics)

light phase shift ~ x(t)

PHYSICAL REVIEW LETTERS



Featured in Physics

# Demonstration of Displacement Sensing of a mg-Scale Pendulum for mm- and mg-Scale Gravity Measurements

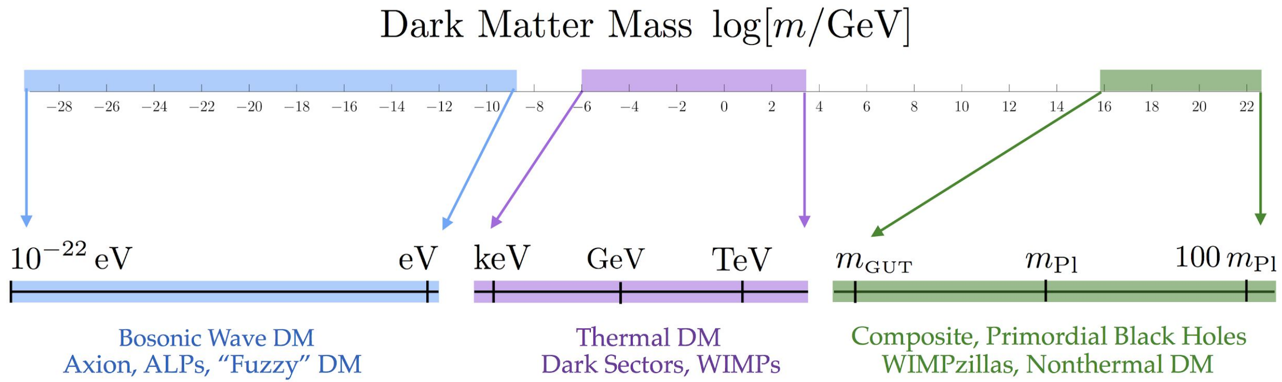
Nobuyuki Matsumoto, Seth B. Cataño-Lopez, Masakazu Sugawara, Seiya Suzuki, Naofumi Abe, Kentaro Komori, Yuta Michimura, Yoichi Aso, and Keiichi Edamatsu

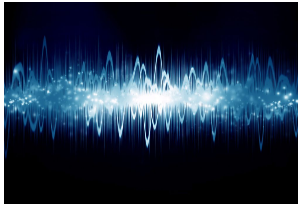
Phys. Rev. Lett. **122**, 071101 – Published 19 February 2019

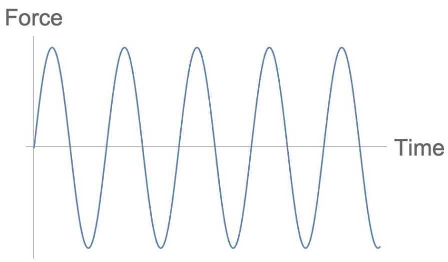
Physics See Synopsis: Gravity of the Ultralight

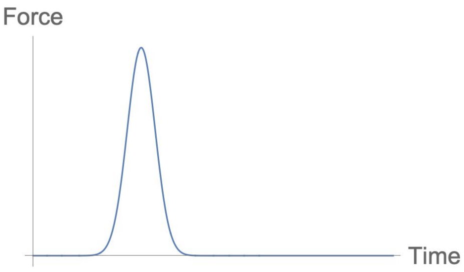
$F_{grav} = G_N\, m^2/d^2 \sim 10^{-17}$ N for two masses m = mg separated by d = mm

cf. $10^{-21}$ N/√Hz (and better) sensitivities achieved optomechanically






Part 1: ultralight DM detection

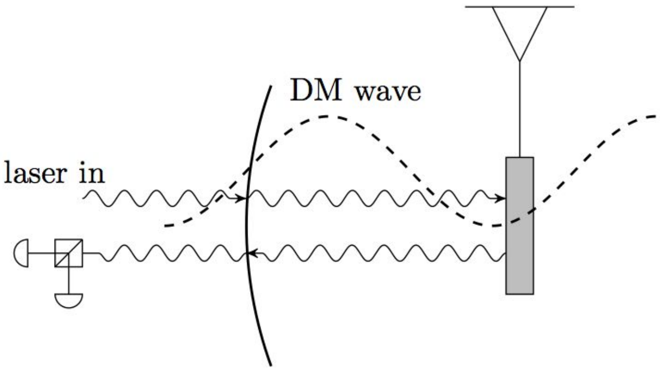
Part 2: "heavy" DM detection

# Ultralight DM detection

Ex: DM coupled to *neutrons* (B-L charge), m$\phi \lesssim$ 1 meV ($\lambda\!\!\!^{-} \gtrsim 10^{-3}$ m).

Coherent, persistent, oscillating force on mechanical sensor → acceleration signal

$$\mathcal{L}_{int} = g_{B-L} \not{A} \bar{n} n \longrightarrow F = g_{B-L} N_n F_0 \sin(\omega_s t)$$

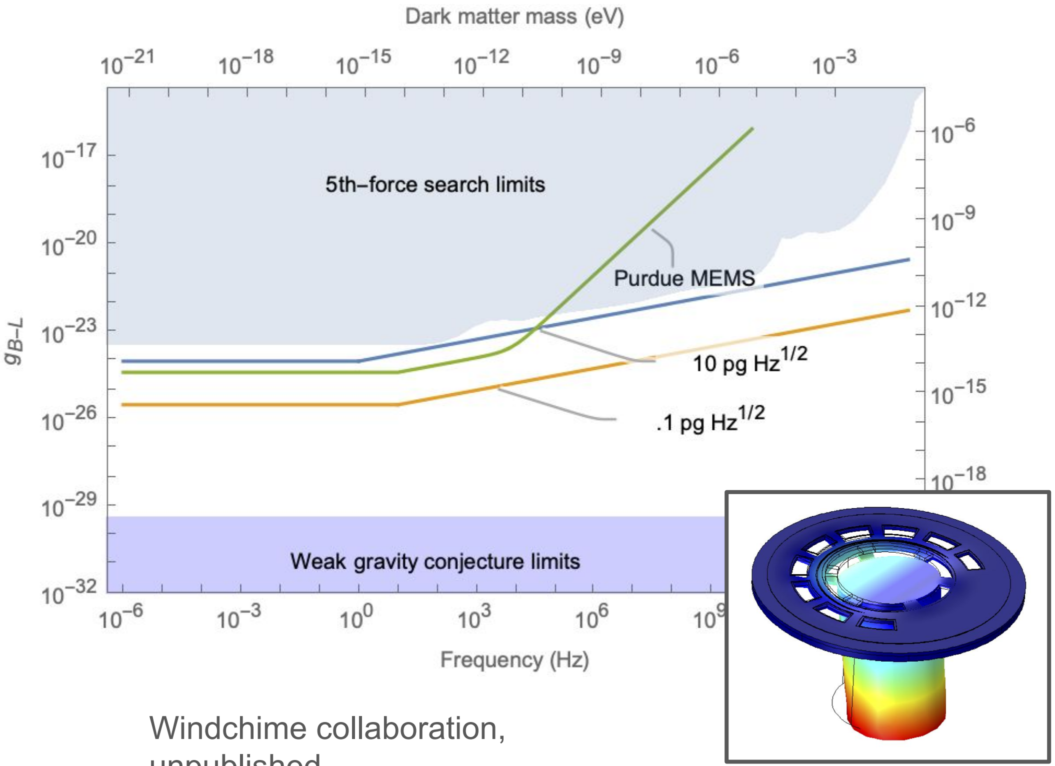



Different couplings to different neutron/proton ratios ("EP-violating")
→ use two sensors, material types to eliminates common mode backgrounds

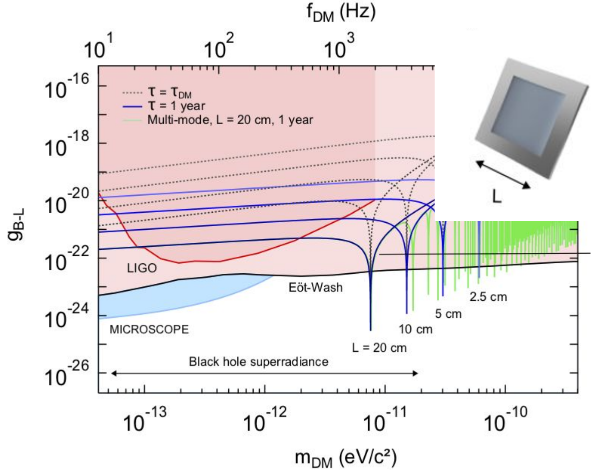
*Ultralight dark matter detection with mechanical quantum sensors*
**Carney**, Hook, Liu, Taylor, Zhao 1908.04797 (NJP)

*Dark matter direct detection with accelerometers*
Graham et al 1512.06165 (PRD)

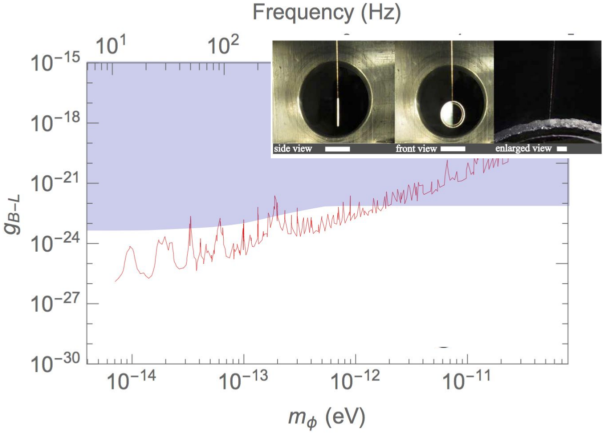
# Some upcoming experiments




Windchime collaboration, unpublished

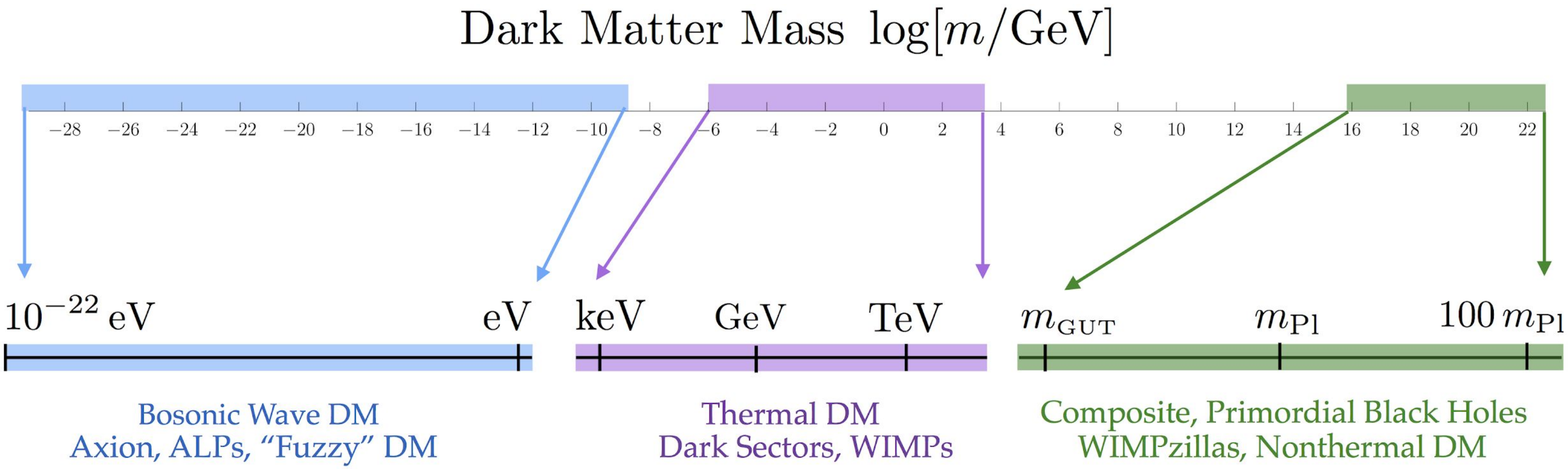



Manley, Chowdhury, Grin, Singh, Wilson 2007.04899




Matsumoto et al PRL 2019

# Particle DM detection




$$n_{DM} \approx \frac{0.3}{\mathrm{cm}^3}\left(\frac{1\ \mathrm{GeV}}{m_\chi}\right)$$

# Impulse detection


Sharp, rapid impulse signal (eg. particle colliding with a sensor)

Highly broadband in frequency domain--**what are the quantum limits?**

(NB on terminology: impulse = $\int F dt$ = momentum transfer)

# Quantum limits in impulse sensing

Standard quantum limit for momentum transfer:

$$\Delta p_{SQL} = \sqrt{\hbar m_s \omega}$$

→ 600 keV (m = 1 ng, $\omega$ = 1 kHz)

→ 5 μeV (m = 1 $m_e$, $\omega$ = 1 kHz)

Again this is just a benchmark. “Simple” and natural ways to go below this level:

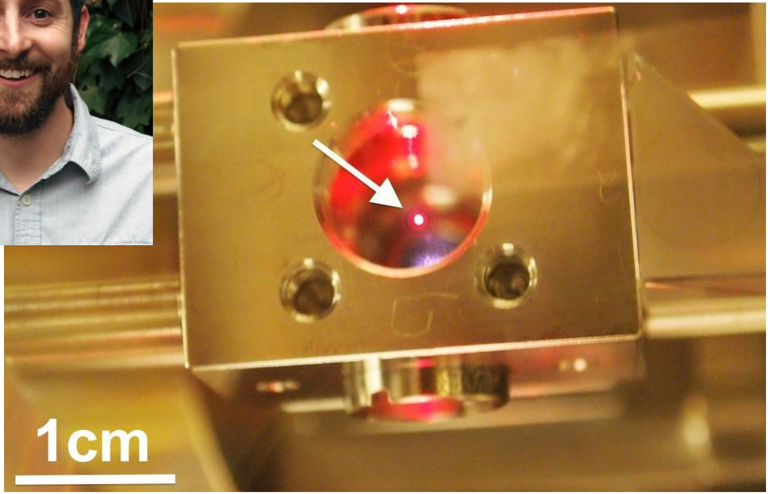
- Squeezing
- Non-demolition/backaction-evasion

*Back-action evading impulse measurements with mechanical quantum sensors*
Ghosh, **Carney**, Shawhan, Taylor 1910.11892 (PRA)

See Clerk PRB 2004 for review

# Yale experiment

Search for new Interactions in a Microsphere Precision Levitation Experiment (SIMPLE) @ D. Moore group

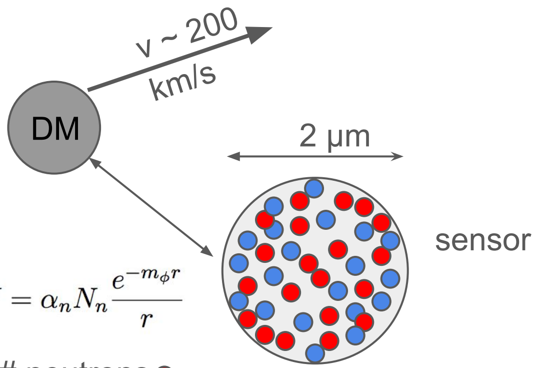



~ 1 ng dielectric spheres, optically levitated, stable for days

~ 75 MeV momentum transfer resolution (~ 100 x SQL), currently technical-noise limited

Continuous monitoring of two or three spatial axes → directional sensitivity

Search for composite DM (“dark nucleons”), coupled to SM via some long-range force (for example, B-L boson).

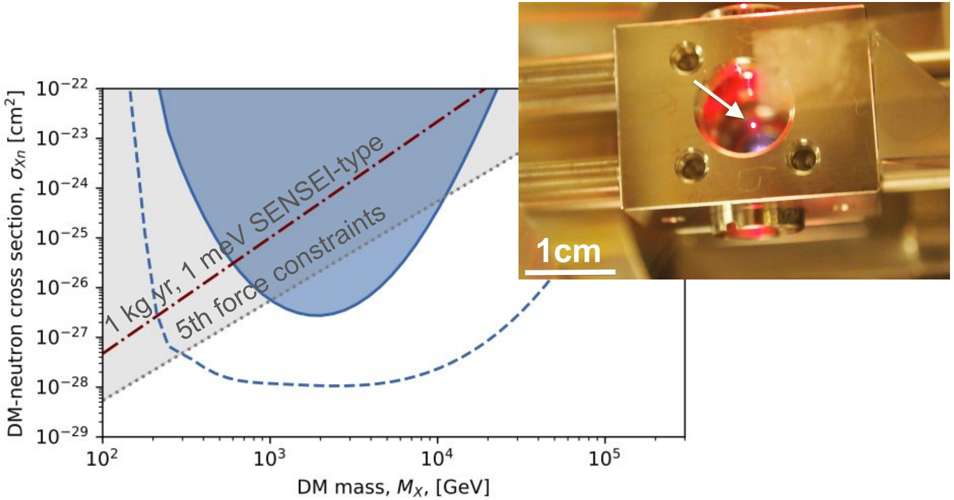



$$V = \alpha_n N_n \frac{e^{-m_\phi r}}{r}$$

$N_n$ = # neutrons

Some model realizations:
Lin, Yu, Zurek 1111.0293
Krnjaic, Sigurdson 1406.1171

Novel constraints with ~1 day of data, impulse bump search:

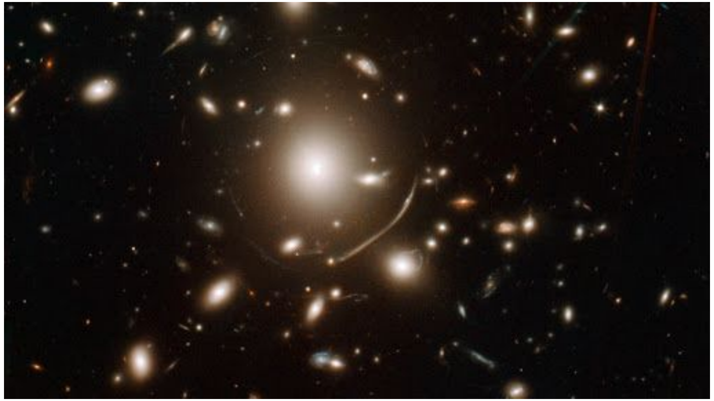



Monteiro, Afek, **Carney**, Krnjaic, Wang, Moore 2007.12067 (PRL)

# Gravitational direct detection of dark matter

The *only coupling dark matter is guaranteed to have* is through gravity.

Roughly one proton mass per cubic cm of dark matter--hopeless to try to detect it gravitationally in a local lab. Right?



Extremely hard, but maybe possible...

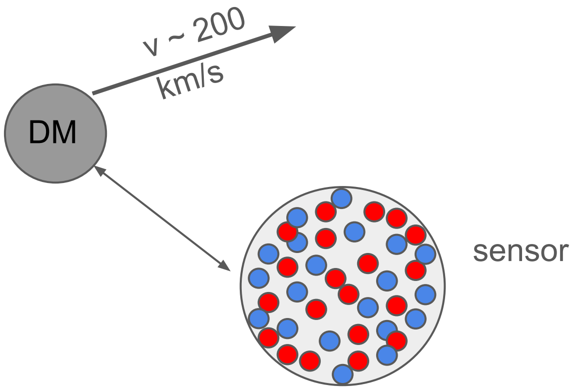
# The issues

$$F = \frac{G_N m_s m_\chi}{r^2}$$

Signal ~ $G_N m_s / b^2$
→ want heavy DM, heavy device, small impact parameter

$$n_{DM} \approx \frac{0.3}{\text{cm}^3} \left( \frac{1\ \text{GeV}}{m_\chi} \right)$$

Observable flux ~ $A/m_\chi$
→ want large area



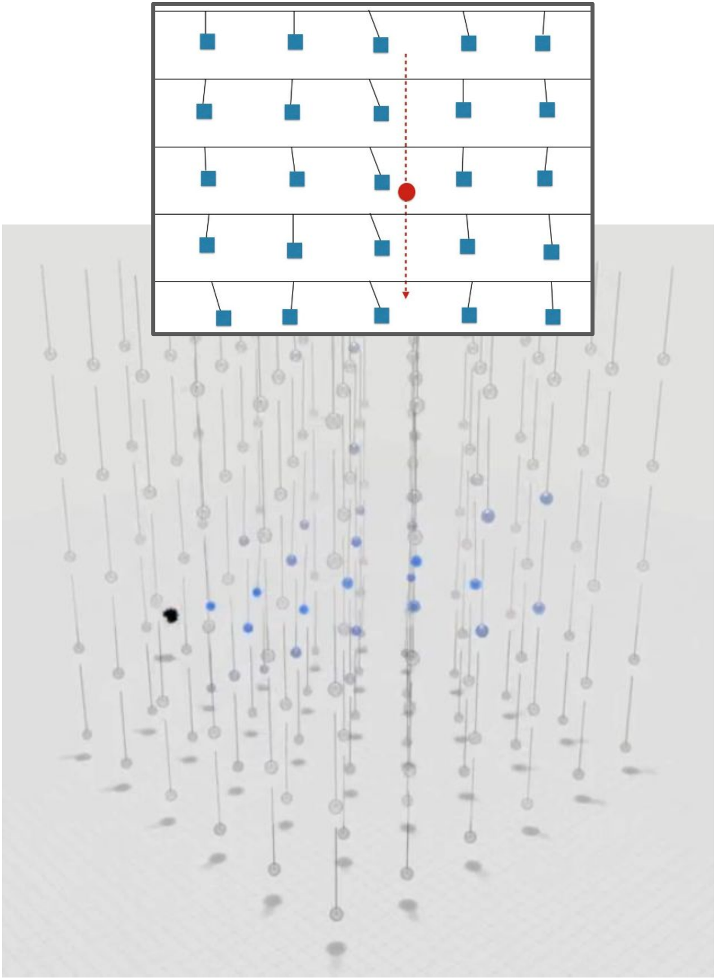
# The solution: array

Signal = correlated track of macroscopic motion

Complete directional info

Exquisite background rejection

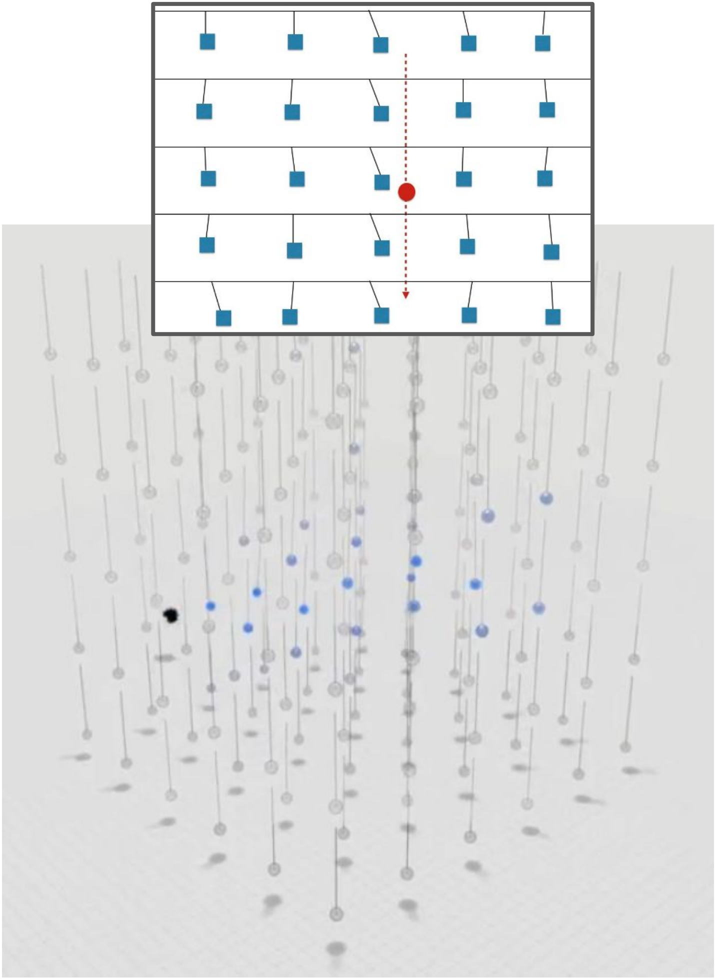
NB: here drawing pendulums w/o readout. In practice, probably don't want to use optics. Microwave circuit readout more likely, many other possibilities.



# The situation

~10 million sensors, mg-scale, mm-cm spacing
~thermally limited detection (substantially sub-SQL)

→ **DM of mass ~ $m_{Planck}$ detectable @ 1-10 events/yr**



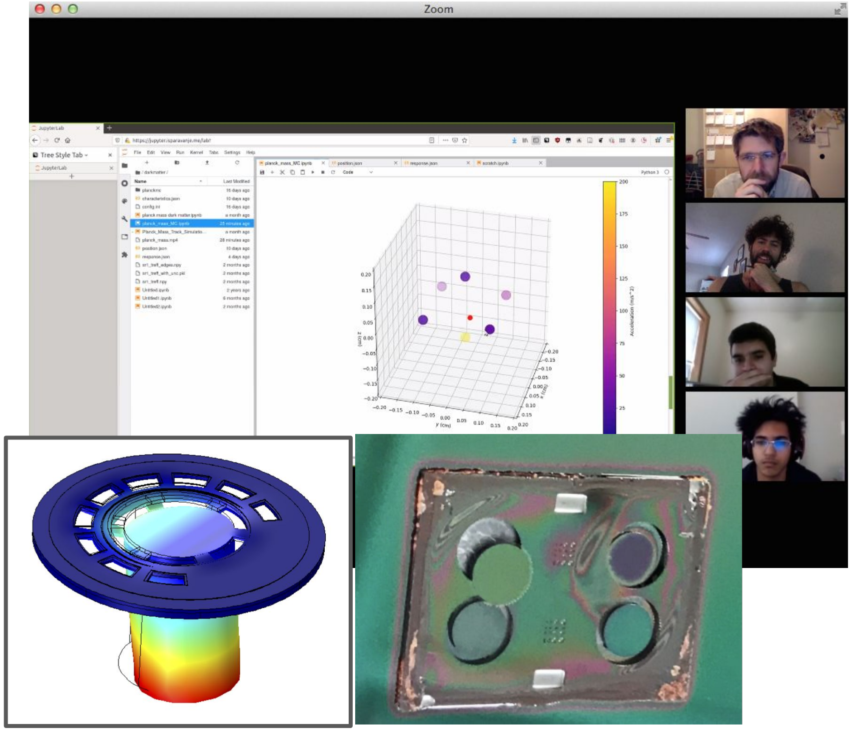
This is primarily a proof-of-principle that this could be possible with concrete setup

Just the beginning of the story--many improvements possible! Better optimized architecture, quantum track reconstruction, frequency multiplexing, …

*Gravitational Direct Detection of Dark Matter*
**Carney**, Ghosh, Krnjaic, Taylor 1903.00492 (PRD)

# Windchime collaboration

Rafael Lang




2020-21 goals:

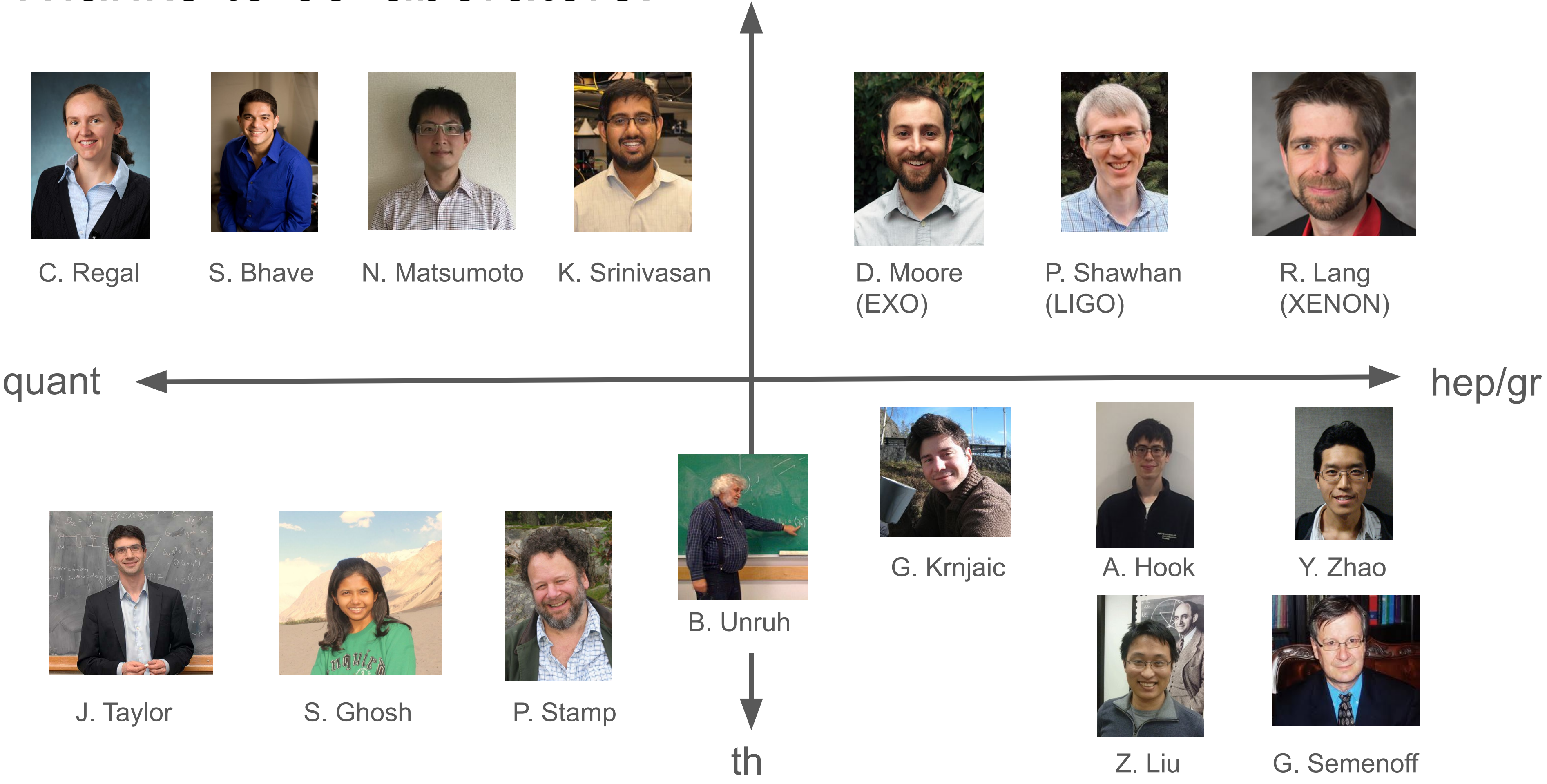
Build array of ~100 sensors

70 mg masses (two types: Si and Ge → EP violation sensitive), chip-etched, mass-producible by S. Bhave (Purdue mech eng), optical readout

Demonstrate track sensing and ultralight DM search capacity

Collaboration members: Purdue, Fermilab, Berkeley Lab, Oak Ridge Lab, Minnesota, Maryland
Funded by US National Quantum Initiative

# Thanks to collaborators!



# Conclusions & future

- Quantum mechanics of measurement imposes fundamental noise floor
- Meso-to-macroscopic mechanical devices offer range of exciting possibilities in DM detection
- Many experiments online now or planned. All first-gen pathfinders. Next step: scale up
- Improvements to sensitivity: squeezing/backaction evasion to get below SQL, QEC-assisted sensing, quantum coherent readout/track reconstruction, ...
- What other physics targets can we aim for??

Gravitational direct detection of dark matter: 1903.00492 **DC**, Ghosh, Krnjaic, Taylor

Ultralight dark matter detection with mechanical quantum sensors: 1908.04797 **DC**, Hook, Liu, Taylor, Zhao

First experimental result with optomechanical detection (not Windchime): 2007.12067 Monteiro, Afek, **DC**, Krnjaic, Wang, Moore

Review paper: 2008.06074 **DC,** Krnjaic, Regal, Moore + 35 others