



Searching for ultraheavy dark matter using mechanical sensors

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Based on: Juehang Qin, Dorian W. P. Amaral, Sunil A. Bhave,
Erqian Cai, Daniel Carney, Rafael F. Lang, Shengchao Li,
Claire Marvinney, Alberto M. Marino, Jared R. Newton, Jacob
M. Taylor, Christopher Tunnell, arXiv: 2503.11645



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Introduction

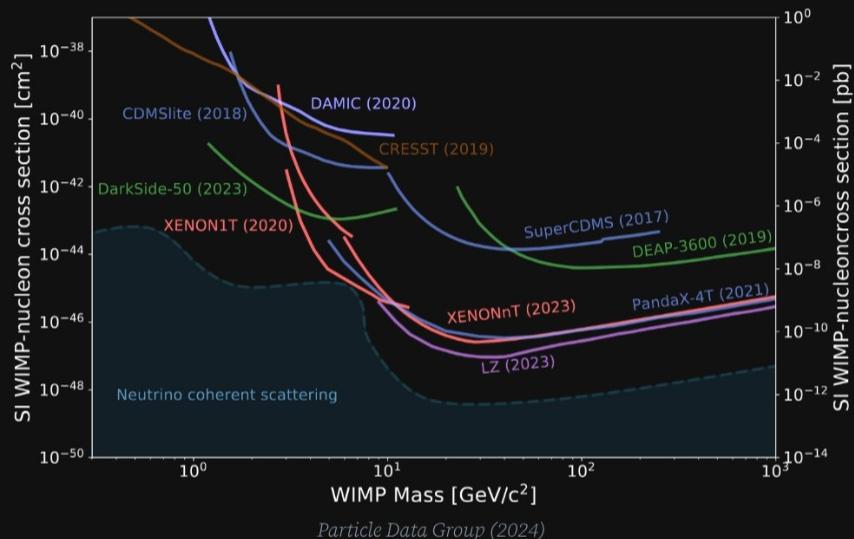
The culmination of a decades-long search

We know that dark matter exists, but where should we look? Weakly Interacting Massive Particles (WIMPs) have been a favoured candidate due to strong theoretical motivation.

And yet! We have not found WIMPs, and we are nearing the neutrino fog.

There will likely be one last generation of WIMP searches with PandaX-xT, XLZD, and ARGO over the coming decades.

(To be clear, I am not saying we should stop searching for WIMPs.)



The culmination of a decades-long search

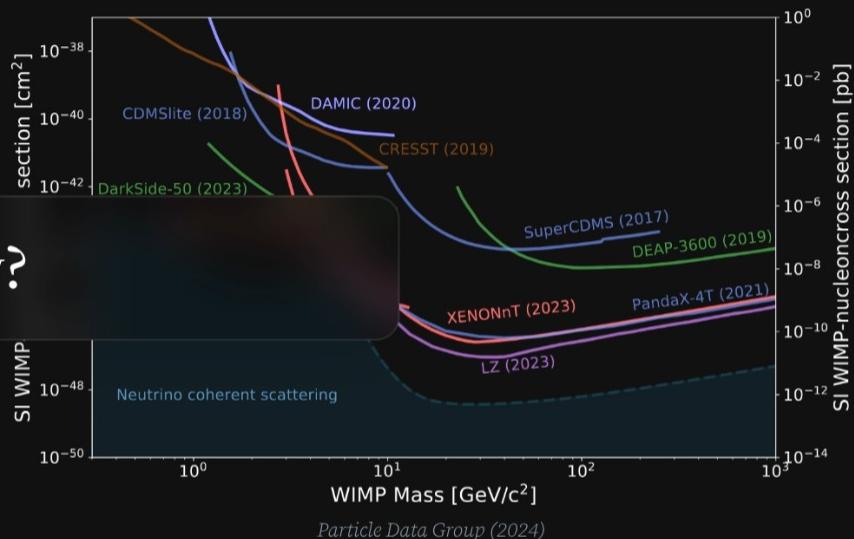
We know that dark matter exists, but where should we look? Weakly Interacting Massive Particles (WIMPs) have been a favoured candidate due to strong theoretical motivation.

And yet! We have not found WIMPs
the neutrino fog.

So...what now?

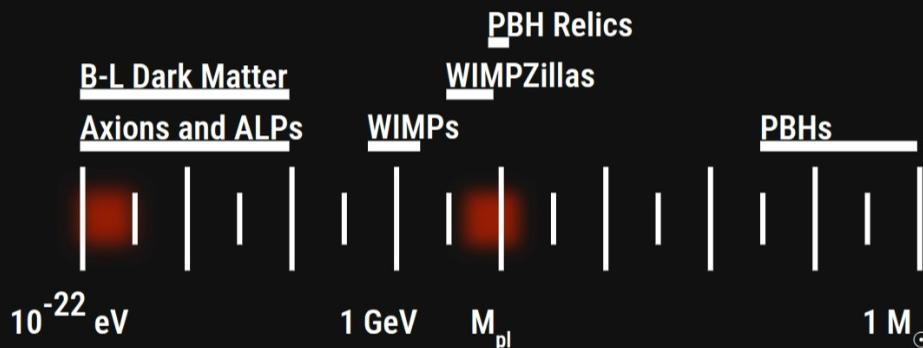
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What about other models?

- In part due to the lack of WIMP discovery, there has been a lot of interest in other dark matter candidates.
- For this talk, we will focus on **ultraheavy dark matter (UHDM)**: DM candidates with masses just below and around the Planck mass ($\sim 10^{19}$ GeV/c²).



It is worth noting that the experimental concept we will discuss today can also be used to search for ultralight dark matter. See [arXiv:2409.03814](https://arxiv.org/abs/2409.03814) for more details.

Why should we look for UHDM?

- The Planck mass is a natural place to look for BSM physics.
 - Many models in this space! Eg. Primordial black hole relics, WIMPzillas, composite models like Q-balls, etc.
 - Experimentally less explored space: if there is more experimental work, maybe this will be more theoretically interesting?
- The Planck mass provides an upper limit on the dark matter mass that is experimentally accessible:

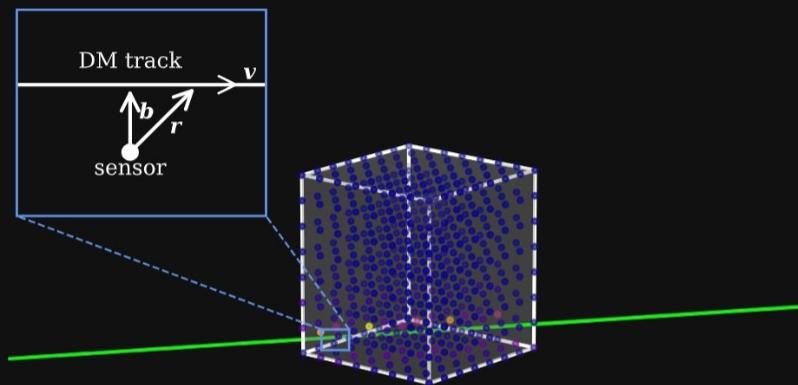
$$\Phi_\chi = \frac{\rho_\chi}{m_\chi} v_0 \simeq 0.2 / \text{yr} / \text{m}^2 \left(\frac{m_{\text{Pl}}}{m_\chi} \right)$$

- Detecting Planck-mass dark matter purely gravitationally has been proposed! (Dan Carney et al., arXiv: 1903.00492)
 - If possible, this would be the holy grail of direct detection. We know that dark matter interacts gravitationally!

Experimental approach

How can we detect ultraheavy dark matter with impulse sensors?

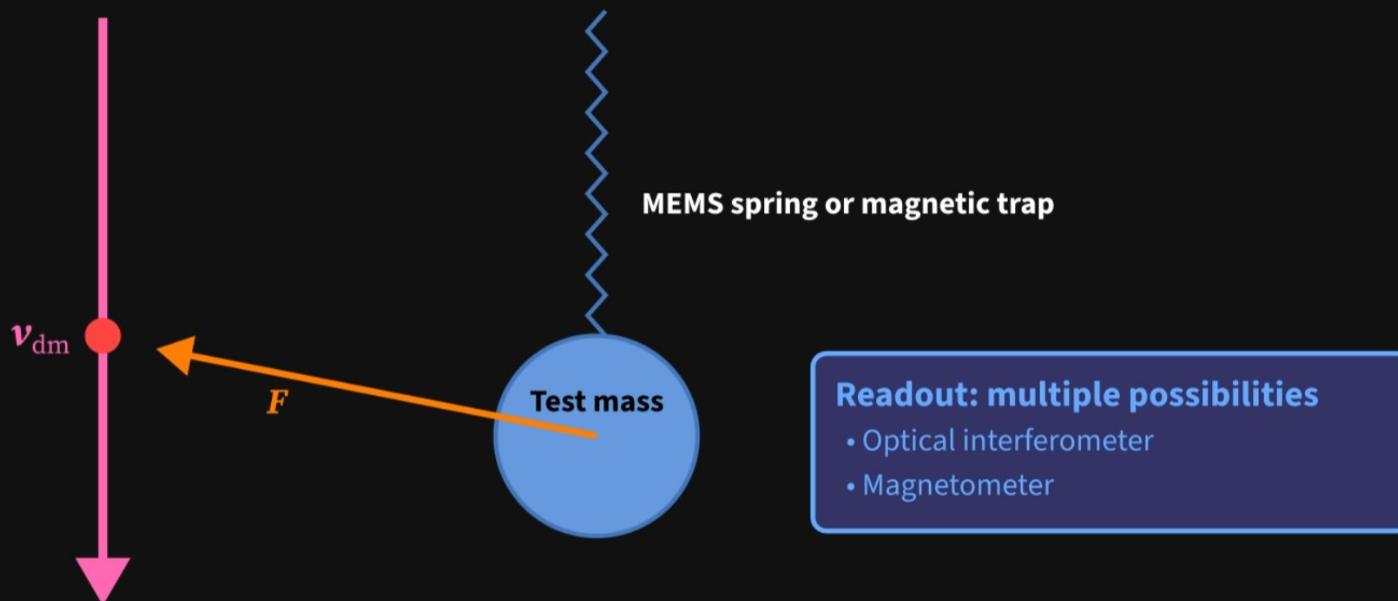
Detector concept



We can use a mechanical sensor array to detect long range forces from DM tracks. Track reconstruction gives background rejection, and the signal-to-noise ratio (SNR) increases as array size increases.

DM velocity is $\sim 10^{-3}c$, so individual sensors measure very fast impulses.

Sensing paradigm



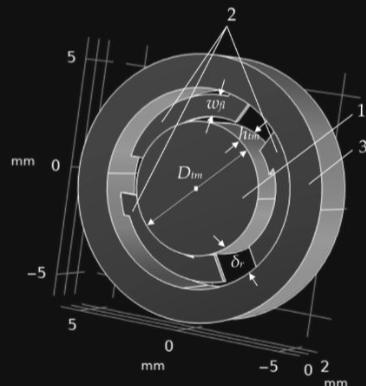
$$F = \frac{\alpha \hbar c N_{\text{nuclei}}}{r^2}$$

Key challenges

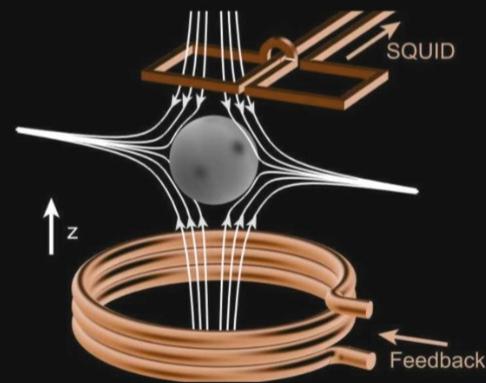
Just how difficult is it to construct and operate such a detector?

Making the sensors

- It is challenging to make sensors that can be maximally sensitive to impulses, but are also scalable to large arrays.
- We consider two technologies with different trade-offs:
 - MEMS:** Micro-electromechanical systems, which are small and can be made in large numbers, but have low sensitivity.
 - Magnetically levitated sensors:** These are larger and more expensive, but have much higher sensitivity.

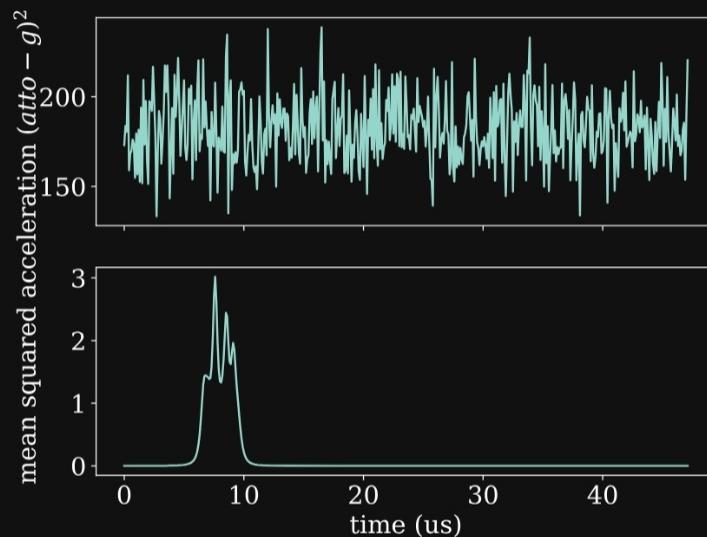


Marina Rezinkina and Claus Braxmaier (2024), <https://doi.org/10.3390/designs8040067>



Joachim Hofer et al. (2024), [arXiv:2211.06289](https://arxiv.org/abs/2211.06289)

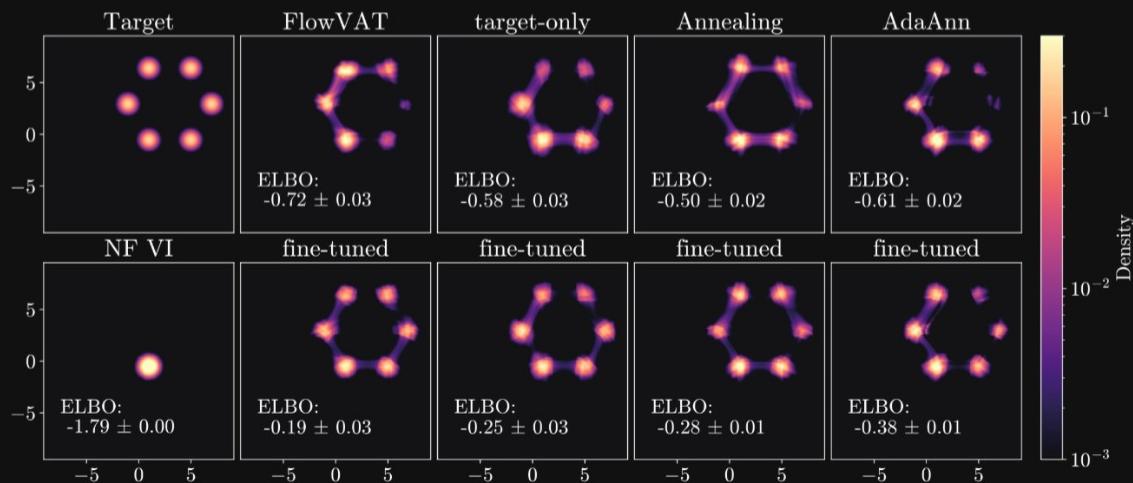
Data analysis



Main challenge: Even for tracks with high SNR, individual sensor signals will be below the noise floor. Track-finding has to be done statistically across all sensors!

Further work is needed here!

- We can do track finding with template matching or bayesian inference, but both are slow.
- Orders of magnitude speedup needed; not necessarily possible with pure computation improvements.
- How can we make a trigger where there isn't a triggerable signal on any individual sensor?
 - ML approaches may be useful here, eg. a 3D CNN might work as a trigger.
 - Probabilistic track finding might be replaceable with amortised variational inference. (See my paper [arXiv:2505.10466](https://arxiv.org/abs/2505.10466) for an example of an applicable approach!)



(This is not directly related to the topic of this talk, but I thought it would be interesting to share!)

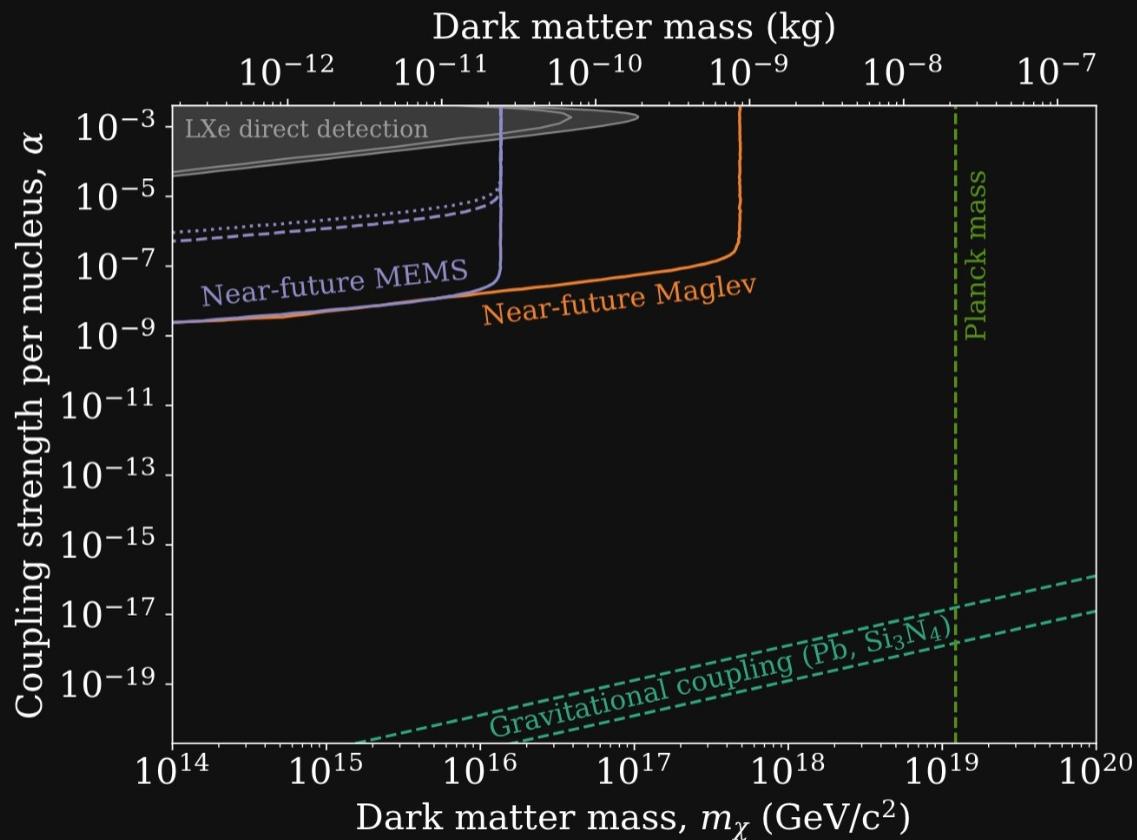
Sensitivity

What can we probe?

Sensitivity projection methodology

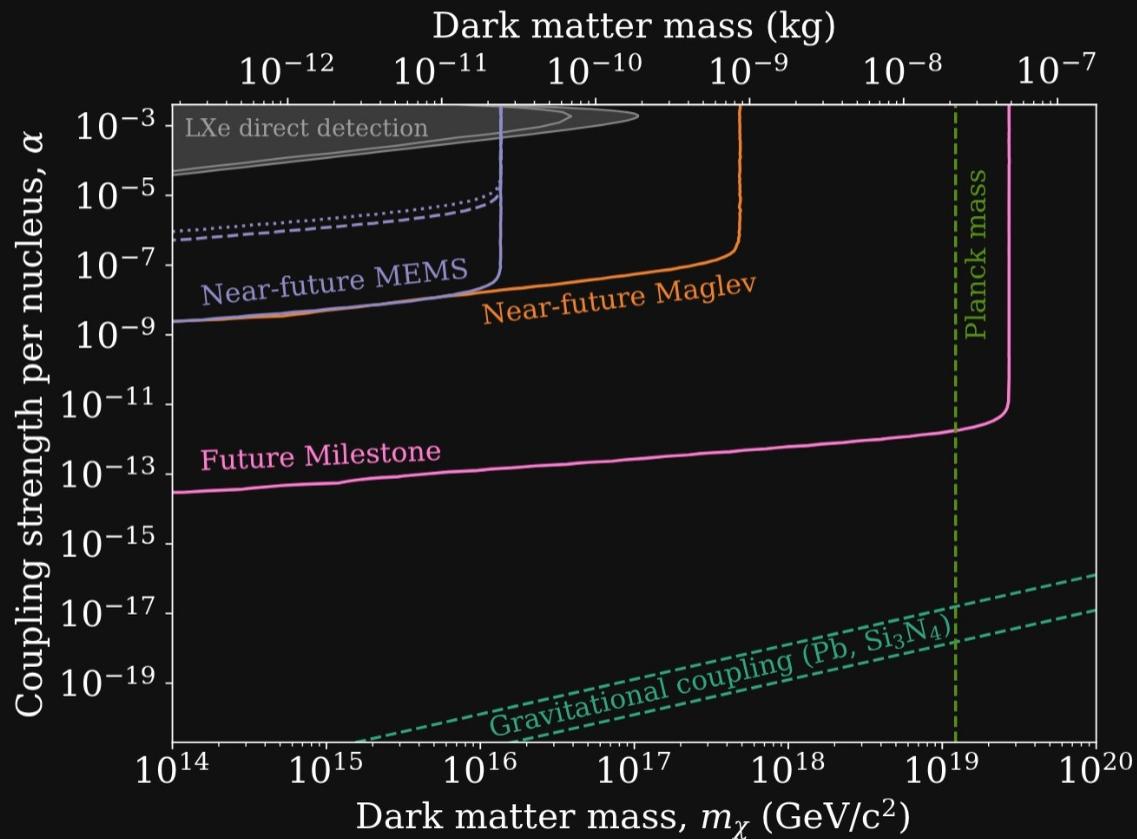
- We already discussed computational challenges in track finding.
 - This means that we cannot use a full Monte Carlo simulation!
- We use a *semi-analytical approach*:
 1. Sample a large number of tracks with random parameters incident on a sensor array.
 2. For each track, compute the expected SNR on each sensor *analytically*.
 3. Compute the probability of getting a track with SNR above the threshold ($\text{SNR} > 10$) for a given interaction strength.
 4. Determine the detection probability for a given exposure and particle flux using Poisson statistics.
 5. Repeat for different interaction strengths and masses to get the sensitivity curve.

Near-term sensitivity projections



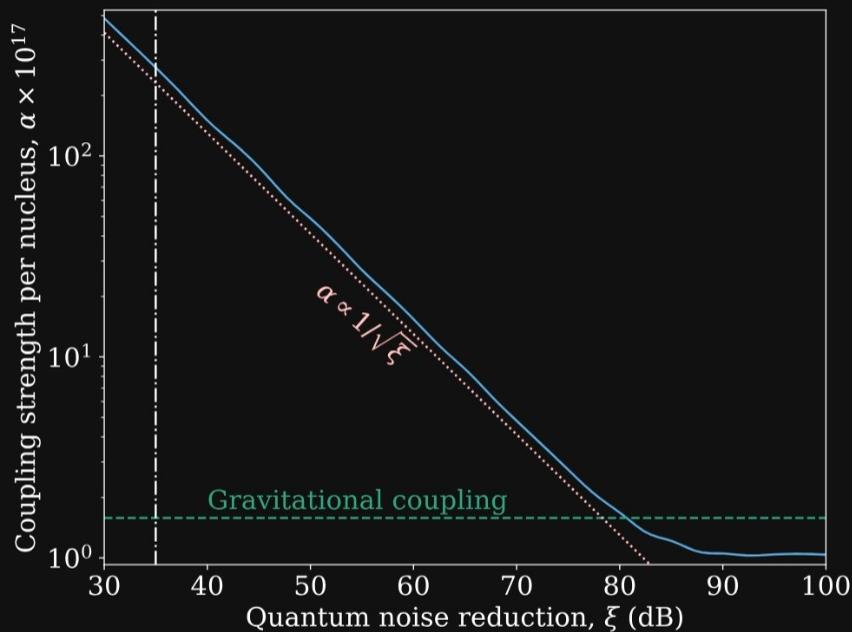
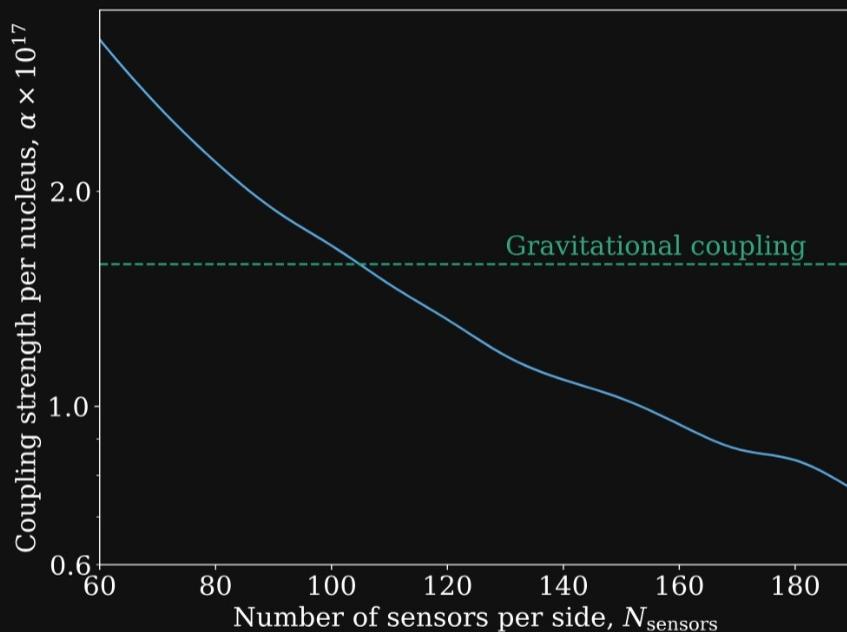
We can see that we can probe significant regions of new parameter space! But what about a more futuristic setup?

Future milestone sensitivity projections

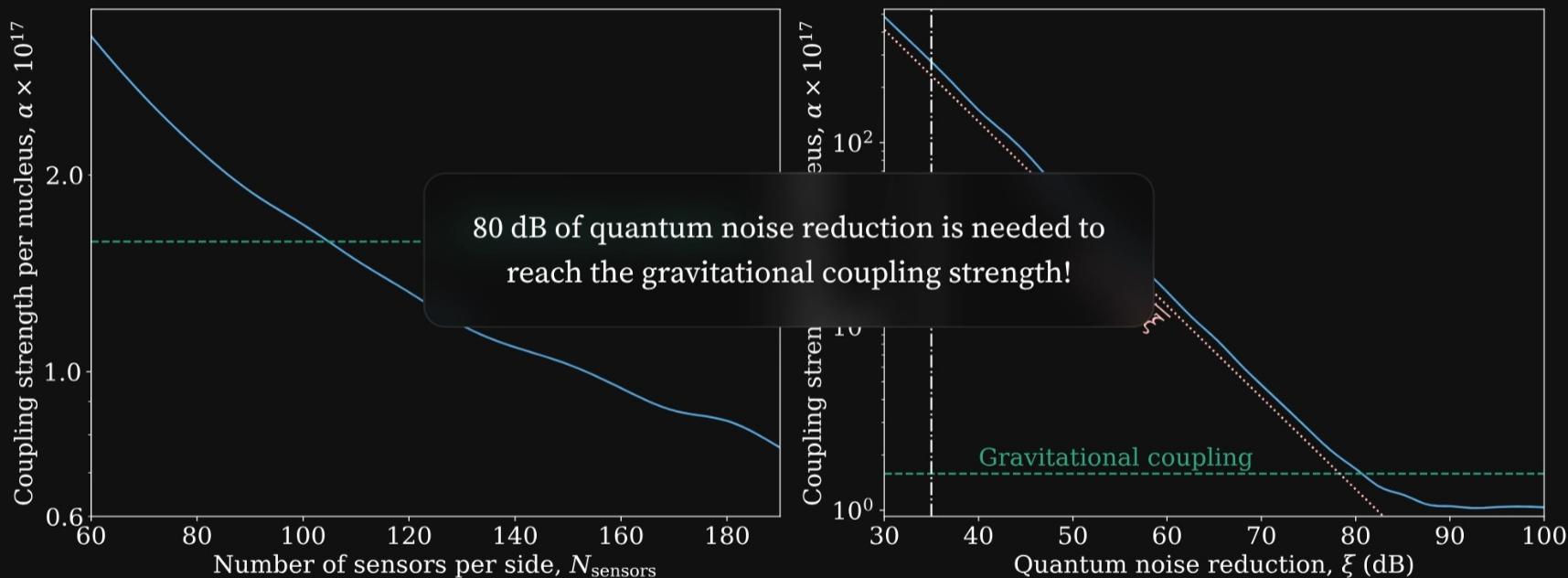


We can probe even more parameter space, and even reach the Planck mass! However, we still cannot reach the gravitational coupling strength.

What would it take to reach the gravitational coupling strength?



What would it take to reach the gravitational coupling strength?



What does this mean for gravitational detection?

Gravitational detection is not theoretically impossible, but there is no clear path to reach the gravitational coupling strength with current technology. Here is a non-exhaustive list of what has been achieved so far:

- Squeezing of 9 dB ([arXiv:1802.00410](https://arxiv.org/abs/1802.00410)), 15 dB ([arXiv:2411.07379](https://arxiv.org/abs/2411.07379)) in lab-scale experiments.
- 2.2 dB in LIGO ([arXiv:1310.0383](https://arxiv.org/abs/1310.0383)).

Also, some theoretical schemes that have not been demonstrated:

- Up to 30 dB improvement over SQL possible with backaction-evading optomechanical measurement scheme([arXiv:1910.11892](https://arxiv.org/abs/1910.11892)).
- Up to 39 dB improvement over SQL possible with backaction-evading magnetomechanical measurement scheme([arXiv:2311.09587](https://arxiv.org/abs/2311.09587)).

We do not come close to the 80 dB needed to reach the gravitational coupling strength, even considering theoretical schemes that have not been demonstrated.

Outlook

The Good:

- Mechanical sensors can do much better than scintillation experiments for UHDM with long-range couplings.
- Importantly, we can expect to do better essentially as soon as we build dedicated experiments!
- Relatively rich parameter space to explore!
- A lot of exciting work to be done, both in hardware and software!
- Experimental setup can also be used for ultralight dark matter! See: [2409.03814](#) for more details.

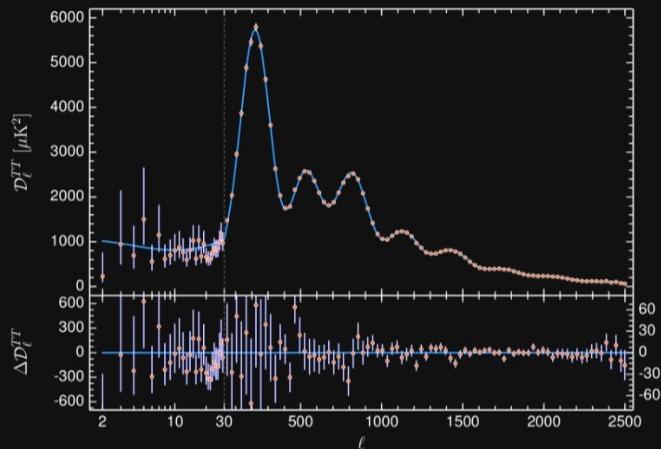
The Bad:

- We cannot reach the gravitational coupling strength with current technology.

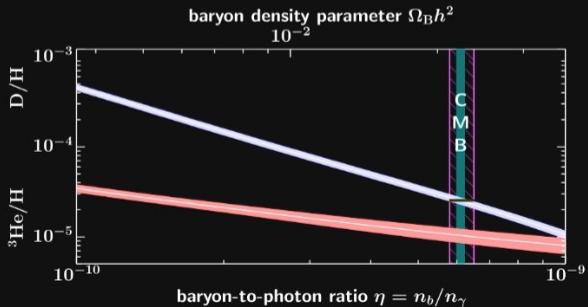
What's next?

- I hope to work with some quantum groups to actually set some real limits with existing data!

We are confident that dark matter exists!



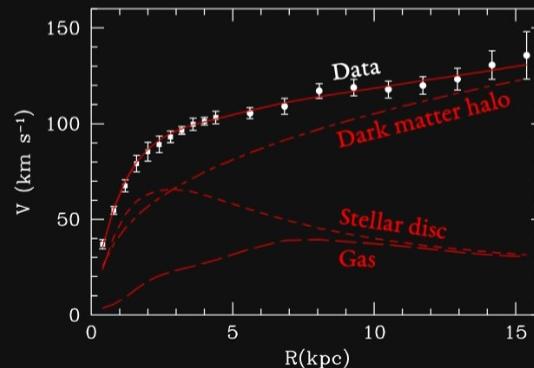
Planck (2018), arXiv:1807.06209



Particle Data Group (2022)

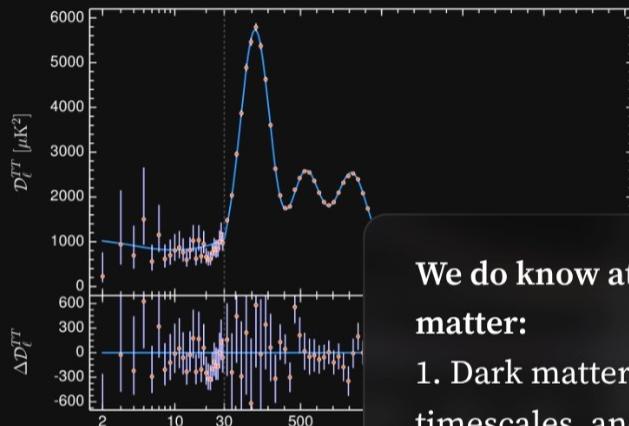


Detailed citation at <https://apod.nasa.gov/apod/ap170115.html>



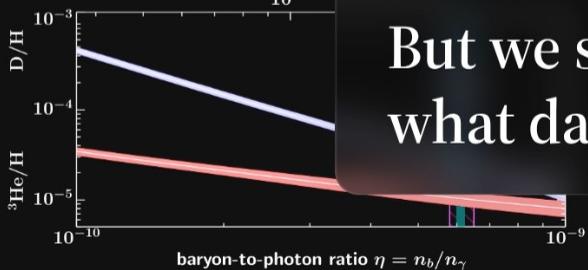
E. Corbelli, P. Salucci (2000), arXiv:astro-ph/9909252

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Planck (2018), arXiv

baryon density pa
 10^{-2}



Particle Data Group (2022)

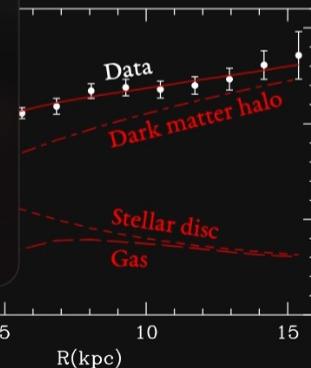


apod.nasa.gov/apod/ap170115.html

We do know at least two things about dark matter:

1. Dark matter is stable on cosmological timescales, and
2. The amount of dark matter in the universe is well constrained.

But we still don't know what dark matter is!



E. Corbelli, P. Salucci (2000), arXiv:astro-ph/9909252

Signal model

We parameterise the signal as a force that scales with the number of nuclei in the sensor to avoid model-dependence.

$$F = \frac{\alpha \hbar c N_{\text{nuclei}}}{r^2}$$

The impulse on a sensor is given by

$$\begin{aligned} \Delta p &= \int_{-b/v}^{b/v} \frac{\alpha \hbar c N_{\text{nuclei}}}{(b^2 + v^2 t^2)^{3/2}} b(\hat{\mathbf{b}} \cdot \hat{\mathbf{n}}) dt \\ &= \frac{\sqrt{2} \alpha \hbar c N_{\text{nuclei}}}{bv} (\hat{\mathbf{b}} \cdot \hat{\mathbf{n}}) \end{aligned}$$

α is a dimensionless interaction strength; we will use this parameter for sensitivity studies.

Noise model for SNR calculation

We take noise to be a combination of thermal noise and quantum noise, such that

$$\delta I^2 = \delta I_{\text{thermal}}^2 + \delta I_{\text{quantum}}^2$$

Thermal noise is given by

$$\delta I_{\text{thermal}}^2 = 4mk_bT\gamma\tau$$

Quantum noise is less trivial; we use the following which comes from computing impulse by subtracting successive position measurements and the Heisenberg uncertainty:

$$\delta I_{\text{quantum}}^2 = \frac{4m\hbar}{\tau\xi^2}$$

The extra ξ term is used to parameterise quantum noise reduction, eg. backaction evasion or squeezing.

Additional noise considerations

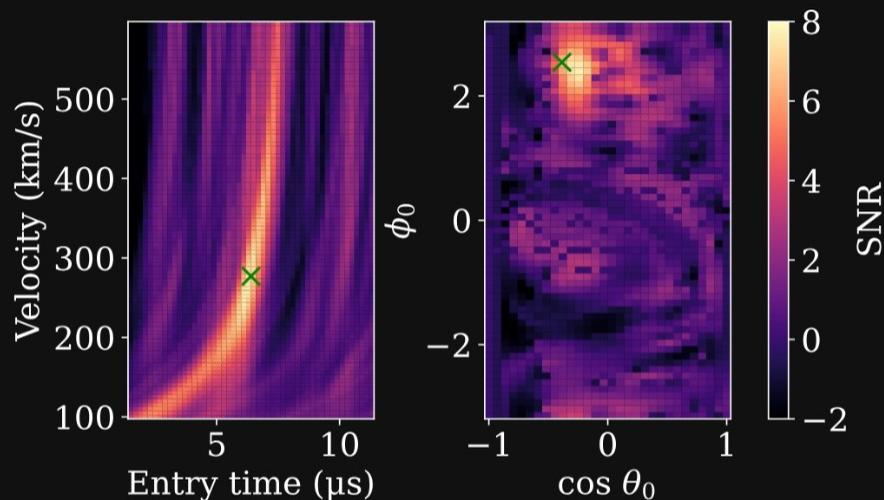
We can see that we can optimise τ , the measurement time, to minimise the noise. This is done in our sensitivity projections, but with two restrictions:

1. The measurement time must be longer than $2b/v$, where b is the impact parameter and v is the DM velocity.
2. The measurement time must not be so long that the noise level drops below the ground state fluctuations, given by $m\hbar\omega/\xi^2$.

We thus get a piecewise function for the noise level:

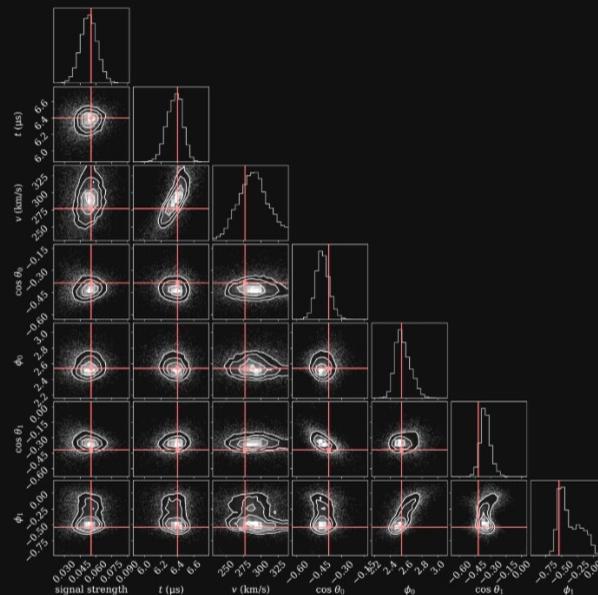
$$\delta I_{\text{noise}}^2 = \begin{cases} \frac{2mv\hbar}{b\xi^2} + \Gamma_{\text{thermal}} \frac{2b}{v} & \text{if } \frac{2b}{v} \geq \tau_{\text{opt}} \\ \frac{4}{\xi} \sqrt{\hbar m \Gamma_{\text{thermal}}} & \text{if } \frac{1}{\omega} > \tau_{\text{opt}} > \frac{2b}{v} \\ \frac{m\hbar\omega}{\xi^2} + \Gamma_{\text{thermal}} \frac{1}{\omega} & \text{if } \frac{1}{4\omega} \leq \tau_{\text{opt}} \end{cases}$$

Template matching



We can use a template across all sensors as a function of track parameters (ie. position, direction, speed, time) to find tracks.

Bayesian track finding



Alternatively, we can use the signal and noise models to compute the likelihood of a track given the sensor data, and then use a sampling method such as nested sampling to find the posterior distribution of the track parameters.

Experimental setups

Parameter	Near-term MEMS	Near-term maglev	Future milestone
Mechanical quality factor Q_m	10^7	10^7	10^{10}
Resonance frequency ω_m	20 kHz	1 Hz	20 mHz
Sensor mass m_s	20 mg	100 mg	100 g
Sensor density	$3.2 \times 10^3 \text{ kg/m}^3$	$1.13 \times 10^4 \text{ kg/m}^3$	$1.13 \times 10^4 \text{ kg/m}^3$
Temperature T	15 mK	15 mK	15 mK
Quantum noise reduction ξ	10 dB	0 dB	15 dB
Sensor count	$10 \times 10 \times 2$	$2 \times 2 \times 1$	$20 \times 20 \times 20$
Sensor array size	0.1 m	0.6 m	2 m
Exposure	1 year	1 year	5 years

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Resonance frequency ω_m	20 kHz	1 Hz	20 mHz
Sensor mass m_s	20 mg	100 mg	100 g
Sensor density	<p>The near-term setups are based on existing technologies, while the future milestone setup is a more futuristic setup that is challenging but not forbidden by current technology.</p>		$1.13 \times 10^4 \text{ kg/m}^3$
Temperature T			15 mK
Quantum noise reduction ξ			15 dB
Sensor count			$10 \times 10 \times 2$
Sensor array size	0.1 m	0.6 m	2 m
Exposure	1 year	1 year	5 years

Whither gravitational detection?

In [arXiv:1903.00492](https://arxiv.org/abs/1903.00492), Dan Carney et al. proposed a gravitational detection scheme for Planck-mass dark matter. Why can't we reach this even with the futuristic setup?

There is one key difference in the noise model. Carney et al. use:

$$\delta I_{\text{quantum}}^2 = \frac{m\hbar\omega}{\xi^2}$$

We use:

$$\delta I_{\text{quantum}}^2 = \frac{4m\hbar}{\tau\xi^2},$$

while $\tau \leq 4/\omega$. This is because when the measurement time is short, the quantum noise is dominated by the backaction of the measurement instead of the ground state fluctuations.

Importantly, this means that quantum noise is much larger when the measurement time is short.